

UC Irvine

UC Irvine Previously Published Works

Title

Search for leptonic charge asymmetry in $t\bar{t}W$ production in final states with three leptons at $s = 13$ TeV

Permalink

<https://escholarship.org/uc/item/1g15t0d6>

Journal

Journal of High Energy Physics, 2023(7)

ISSN

1126-6708

Authors

Aad, G

Abbott, B

Abbott, DC

et al.

Publication Date

2023

DOI

10.1007/jhep07(2023)033

Copyright Information

This work is made available under the terms of a Creative Commons Attribution License, available at <https://creativecommons.org/licenses/by/4.0/>

Peer reviewed

Search for leptonic charge asymmetry in $t\bar{t}W$ production in final states with three leptons at $\sqrt{s} = 13$ TeV



The ATLAS collaboration

E-mail: atlas.publications@cern.ch

ABSTRACT: A search for the leptonic charge asymmetry (A_c^ℓ) of top-quark-antiquark pair production in association with a W boson ($t\bar{t}W$) is presented. The search is performed using final states with exactly three charged light leptons (electrons or muons) and is based on $\sqrt{s} = 13$ TeV proton-proton collision data collected with the ATLAS detector at the Large Hadron Collider at CERN during the years 2015–2018, corresponding to an integrated luminosity of 139 fb^{-1} . A profile-likelihood fit to the event yields in multiple regions corresponding to positive and negative differences between the pseudorapidities of the charged leptons from top-quark and top-antiquark decays is used to extract the charge asymmetry. At reconstruction level, the asymmetry is found to be -0.12 ± 0.14 (stat.) ± 0.05 (syst.). An unfolding procedure is applied to convert the result at reconstruction level into a charge-asymmetry value in a fiducial volume at particle level with the result of -0.11 ± 0.17 (stat.) ± 0.05 (syst.). The Standard Model expectations for these two observables are calculated using Monte Carlo simulations with next-to-leading-order plus parton shower precision in quantum chromodynamics and including next-to-leading-order electroweak corrections. They are $-0.084_{-0.003}^{+0.005}$ (scale) ± 0.006 (MC stat.) and $-0.063_{-0.004}^{+0.007}$ (scale) ± 0.004 (MC stat.) respectively, and in agreement with the measurements.

KEYWORDS: Hadron-Hadron Scattering , Top Physics

ARXIV EPRINT: [2301.04245](https://arxiv.org/abs/2301.04245)

Contents

1	Introduction	1
2	The ATLAS detector	4
3	Data and simulated event samples	5
4	Event reconstruction	8
5	Event selection and definitions of control and signal regions	10
6	Lepton–top-quark matching	11
7	Systematic uncertainties in background and signal estimation	12
7.1	Detector-related uncertainties	12
7.2	Signal and background modelling uncertainties	13
8	Extraction of the charge asymmetry at reconstruction level	14
9	Unfolding and extraction of the charge asymmetry at particle level	22
9.1	Particle-level objects	22
9.2	Particle-level fiducial volume	23
9.3	Unfolding procedure and charge-asymmetry extraction	23
10	Conclusions	26
	The ATLAS collaboration	35

1 Introduction

The production of a top-quark–antiquark ($t\bar{t}$) pair in association with a W boson, commonly referred to as $t\bar{t}W$, is a rare process in the Standard Model (SM) that can be produced at the Large Hadron Collider (LHC). State-of-the-art cross-section calculations for the $t\bar{t}W$ process are especially complex, as large corrections arise from higher powers of both the strong and weak couplings [1]. Thus, measurements of the $t\bar{t}W$ process represent a sensitive test of the predictions of quantum chromodynamics (QCD) and the electroweak (EW) sector of the SM, as well as their interplay. Both the inclusive and differential cross-section measurements are very relevant, as they can provide indirect hints of new physics beyond the SM (BSM) in scenarios where at least one of the SM couplings is modified [2]. Furthermore, the $t\bar{t}W$ process can be one of the main backgrounds in searches for BSM phenomena, such as supersymmetric squark or gluino production or vector-like quarks [3, 4]. It also represents

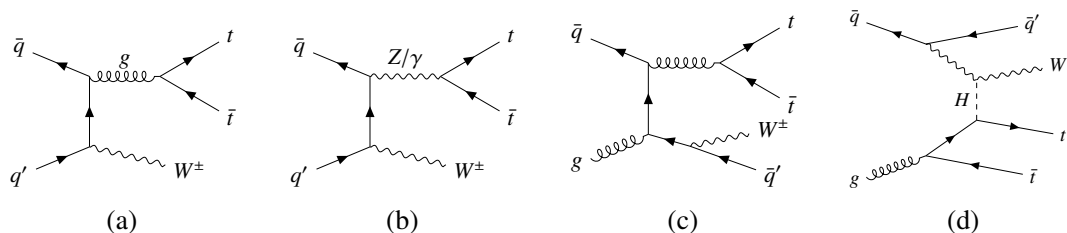


Figure 1. Examples of Feynman diagrams of $t\bar{t}W$ production at (a,b) LO and (c,d) NLO with one extra parton. The diagrams show (a,c) QCD and (b,d) EW $t\bar{t}W$ production.

an irreducible background in many measurements of SM processes such as $t\bar{t}$ production in association with a Higgs boson ($t\bar{t}H$) or the production of four top quarks ($t\bar{t}t\bar{t}$) [5, 6]. The inclusive cross-section of $t\bar{t}W$ production has been measured by both the ATLAS and CMS collaborations at $\sqrt{s} = 13$ TeV using partial and full LHC Run 2 datasets [7, 8], respectively.

Illustrative Feynman diagrams contributing to $t\bar{t}W$ production at leading order (LO) and next-to-leading order (NLO) for both QCD and EW production are shown in figure 1 where q' indicates a quark of different flavour from that of the other initial-state quark. At LO, only the $q\bar{q}'$ initial state is present (figure 1 a,b). At NLO, the quark-gluon (qg) channels open up (figure 1 c,d), whereas gluon-gluon (gg) fusion production does not contribute until next-to-next-to-leading-order (NNLO) corrections are included.

In $t\bar{t}$ production, the top quark (top antiquark) is preferentially produced in the direction of the incoming quark (antiquark). This is due to the interference effects between amplitudes in the $q\bar{q}$ initial state and results in a difference in the rapidity distribution between top quarks and top antiquarks.¹ In proton-proton (pp) collisions at the LHC, this production asymmetry results in a central-forward rapidity charge asymmetry as top quarks (antiquarks) are produced with more forward (central) rapidities. Given that $t\bar{t}$ production at the LHC is dominated by the charge-symmetric gg initial state, such asymmetry is a subtle (order of 1%) effect. This is different from the situation at the Tevatron collider ($p\bar{p}$ collisions), where a forward-backward asymmetry can be defined with respect to the proton beam, and $q\bar{q}$ collisions dominate over gg , yielding a more sizable signal (10%) [9].

The top-quark-based rapidity charge asymmetry ($A_{c,y}^t$) is defined by

$$A_{c,y}^t = \frac{N(\Delta y^t > 0) - N(\Delta y^t < 0)}{N(\Delta y^t > 0) + N(\Delta y^t < 0)}, \quad (1.1)$$

where $\Delta y^t = |y_t| - |y_{\bar{t}}|$ is the difference between the absolute rapidities of the top quark ($|y_t|$) and top antiquark ($|y_{\bar{t}}|$), respectively.

In $t\bar{t}W$ production, the relative dominance of the $q\bar{q}'$ initial state leads to a larger rapidity charge asymmetry than in $t\bar{t}$ production [10, 11]. Furthermore, the W boson present

¹ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point in the centre of the detector and the z -axis along the beam pipe. The x -axis points from the interaction point to the centre of the LHC ring, and the y -axis points upwards. Cylindrical coordinates (r, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the z -axis. The rapidity (y) of a particle is given by $y = 1/2 \ln(E + p_z)/(E - p_z)$. The pseudorapidity (η) is defined in terms of the polar angle θ as $\eta = -\ln \tan(\theta/2)$. The angular distance is measured in units of $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$.

in $t\bar{t}W$ production is typically radiated from the initial $q\bar{q}'$ state and, therefore, serves as a polarity filter of the initial $q\bar{q}'$ state and in turn the final $t\bar{t}$ state. This polarisation further enhances the asymmetry between the decay products of the top quarks and top antiquarks. The prospects for experimental observation of these asymmetries are greatest in the case of the charged leptons originating from the top-quark (antiquark) decays. This is due to the precision with which the lepton kinematics can be reconstructed and the power with which reducible background processes can be suppressed. The leptonic charge asymmetry (A_c^ℓ), in the following just referred to as “charge asymmetry”, is defined analogously to eq. (1.1), but based on the pseudorapidities of the leptons from the top-quark and top-antiquark decays:

$$A_c^\ell = \frac{N(\Delta\eta^\ell > 0) - N(\Delta\eta^\ell < 0)}{N(\Delta\eta^\ell > 0) + N(\Delta\eta^\ell < 0)}, \tag{1.2}$$

where $\Delta\eta^\ell = |\eta_\ell| - |\eta_{\bar{\ell}}|$ is the difference between the absolute pseudorapidities of the leptons that originate from the top quark ($|\eta_\ell|$) and top antiquark ($|\eta_{\bar{\ell}}|$), respectively.

Reference [10] gives a comparison of NLO QCD matrix elements (MEs) matched to parton shower (PS) calculations of the top-quark-based and leptonic charge asymmetries of $t\bar{t}$ and $t\bar{t}W$ production in the full phase space at $\sqrt{s} = 13$ TeV. The charge asymmetry for $t\bar{t}W$ is larger than for $t\bar{t}$ production at the expense of a smaller cross-section for the process. In addition to being sensitive to BSM physics, such as axigluons and Standard Model Effective Field Theory (SMEFT) scenarios corresponding to four-fermion operators (examples given in refs. [10] and [12]), charge asymmetry measurements have the potential to discriminate between new physics signals with different chiral structures that would be indistinguishable using only cross-section observables.

At the Tevatron, forward-backward asymmetries in $t\bar{t}$ production have been measured, with results found to be in agreement with SM calculations that include higher-order corrections [9, 13]. The ATLAS and CMS collaborations performed measurements of the top-quark-based charge asymmetry for $t\bar{t}$ production. A combination of these ATLAS and CMS results at $\sqrt{s} = 7$ TeV and 8 TeV for the top-quark-based charge asymmetry is reported in ref. [14] and updated measurements have been published by ATLAS and CMS using $\sqrt{s} = 13$ TeV data [15, 16]. The measurements reported by CMS in ref. [17] include an extraction of the leptonic charge asymmetry for $t\bar{t}$ production in a particle-level fiducial volume. A measurement of the top-quark-based charge asymmetry for $t\bar{t}$ production in association with a photon has been reported by ATLAS in ref. [18]. None of these measurements show significant deviations from the SM expectations. In ref. [11], NLO QCD calculations of A_c^ℓ have been performed including top-quark off-shell effects, which also include the impact of different renormalisation and factorisation scale choices on A_c^ℓ in the multi-lepton channel at the LHC at $\sqrt{s} = 13$ TeV.²

This paper presents a search for the leptonic charge asymmetry in $t\bar{t}W$ production using pp collision data at $\sqrt{s} = 13$ TeV in the trilepton (3ℓ) channel with the full Run 2 data sample, corresponding to an integrated luminosity of 139 fb^{-1} . The paper is organised as follows. Section 2 provides a brief description of the ATLAS detector. In section 3, the

²These results are given in terms of the rapidities of the leptons ($A_{c,y}^\ell$) and not the pseudorapidities.

data sample as well as the simulated signal and background processes are discussed. The reconstructed particle candidates are defined in section 4. Section 5 gives an overview of the event selection and of the definitions of the control and signal regions. The algorithm used to identify reconstructed leptons originating from top quarks (antiquarks) is explained in section 6. In section 7, the sources of systematic uncertainties that affect the search are discussed. The result for the charge asymmetry measurement at reconstruction level is presented in section 8. The unfolding procedure and the extraction of the charge asymmetry at particle level are presented in section 9. In section 10, the conclusions are drawn.

2 The ATLAS detector

The ATLAS detector [19] at the LHC covers nearly the entire solid angle around the collision point. It consists of an inner tracking detector surrounded by a thin superconducting solenoid, electromagnetic and hadronic calorimeters, and a muon spectrometer incorporating three sets of large superconducting toroidal magnets, each consisting of eight separate coils. The inner-detector system is immersed in a 2 T axial magnetic field and provides charged-particle tracking in the range $|\eta| < 2.5$.

The high-granularity silicon pixel detector covers the vertex region and typically provides four measurements per track, with the first hit typically being detected in the insertable B-layer installed before Run 2 [20, 21]. It is followed by the silicon microstrip tracker, which usually provides eight measurements per track. These silicon detectors are complemented by the transition radiation tracker (TRT), which enables radially extended track reconstruction up to $|\eta| = 2.5$. The TRT also provides electron identification information based on the fraction of hits above a higher energy-deposit threshold corresponding to transition radiation. Typically, around 30 TRT hits are measured in total per track.

The calorimeter system covers the pseudorapidity range $|\eta| < 4.9$. In the region $|\eta| < 3.2$, electromagnetic calorimetry is provided by barrel and endcap high-granularity lead/liquid-argon (LAr) calorimeters, with an additional thin LAr presampler covering $|\eta| < 1.8$ to correct for energy loss in material upstream of the calorimeters. Hadronic calorimetry is provided by the steel/scintillator-tile calorimeter, segmented into three barrel structures with $|\eta| < 1.7$, and two copper/LAr hadronic endcap calorimeters. The solid angle coverage is extended with forward copper/LAr and tungsten/LAr calorimeter modules optimised for electromagnetic and hadronic measurements respectively.

The muon spectrometer comprises separate trigger and high-precision tracking chambers measuring the deflection of muons in a magnetic field generated by the superconducting air-core toroids. The field integral of the toroids ranges between 2.0 and 6.0 Tm across most of the detector. A set of precision chambers covers the region $|\eta| < 2.7$ with three layers of monitored drift tubes, complemented by cathode-strip chambers in the forward region, where the background rates are highest. The muon trigger system covers the range $|\eta| < 2.4$ with resistive-plate chambers in the barrel, and thin-gap chambers in the endcap regions.

Relevant events are selected to be recorded by the first-level trigger system implemented in custom hardware, followed by selections made by algorithms implemented in software in the high-level trigger [22]. The first-level trigger accepts events from the 40 MHz bunch

crossings at a rate below 100 kHz, which the high-level trigger reduces to record events to disk at about 1 kHz.

An extensive software suite [23] is used in data simulation, in the reconstruction and analysis of real and simulated data, in detector operations, and in the trigger and data acquisition systems of the experiment.

3 Data and simulated event samples

The analysis is performed on data from pp collisions at $\sqrt{s} = 13$ TeV delivered by the LHC and recorded by the ATLAS detector in the years 2015–2018. The bunch spacing for this data-taking period was 25 ns with a typical number of pp interactions per bunch crossing (“pile-up”) that varies by year and LHC beam conditions and was in the range from 10 to 70 for almost all events. After requirements on the stability of the beams, the operational status of all ATLAS detector components, and the quality of the recorded data, the total integrated luminosity of the data sample corresponds to 139 fb^{-1} with an uncertainty of 1.7%. This value is derived from the calibration of the luminosity scale using x - y beam-separation scans, following a methodology similar to that detailed in ref. [24], and using the LUCID-2 detector [25] for the baseline luminosity measurements.

Simulated Monte Carlo (MC) samples are used to model the contributions from the various SM processes. The MC generators used for the hard-scattering, as well as the PS, underlying event and hadronisation, are explained in the following. For some processes, in addition to the nominal simulation, alternative MC samples are available that are used to evaluate the effects of different MC modelling uncertainties (see section 7.2). All MC samples were generated using a 25 ns bunch-spacing configuration.

The effect of pile-up was modelled by overlaying the hard-scattering event with simulated minimum-bias events generated with PYTHIA 8.186 [26] using the NNPDF2.3LO [27] set of parton distribution functions (PDFs) and the A3 set of tuned MC parameters [28]. Separate MC production campaigns were used to model the different pile-up distributions observed in data for the years 2015/16, 2017 and 2018. The simulated samples were reweighted to reproduce the observed distribution of the average number of collisions per bunch crossing. The simulation of detector effects was performed with either a full ATLAS detector simulation based on the GEANT4 [29] framework or a fast simulation (ATLFAST-II) using a parameterisation of the performance of the electromagnetic and hadronic calorimeters and GEANT4 for the other detector components [30].

The signal process ($t\bar{t}W$) was simulated at NLO precision in QCD with SHERPA 2.2.10 [31] and the NNPDF3.0NNLO PDF set [32]. In this set-up, multiple MEs were matched and merged with the SHERPA PS model based on the Catani-Seymour dipole factorisation scheme [33, 34]. The virtual QCD corrections for MEs at NLO accuracy were provided by the OPENLOOPS library [35, 36]. Up to one additional parton was included in the NLO ME, and two, three or four additional partons were included at LO in QCD. The merging scale parameter, which sets a threshold to determine what part of the phase-space is filled by the PS or the ME generator, was set to an energy of 30 GeV. Additional partons beyond ME-level accuracy and below the merging scale threshold were therefore described

by the PS. The choice of renormalisation and factorisation scales was $\mu_R = \mu_F = H_T/2$, where H_T is defined as the scalar sum of the transverse masses $\sqrt{p_T^2 + m^2}$ of all final state particles. The masses of the top quark and the W boson were set to 172.5 GeV and 80.4 GeV, respectively [37]. In addition to the nominal prediction at NLO in QCD (order of α_s^3),³ higher-order corrections related to EW $t\bar{t}W$ contributions were also added as part of the signal definition. The α^3 and $\alpha^2\alpha_s^2$ corrections were added through MC event weights derived using the virtual additive corrections in the formalism described in ref. [38].

An alternative $t\bar{t}W$ sample uses MADGRAPH5_AMC@NLO 2.9.3 [39, 40] (in the following denoted by MG5_AMC@NLO) for the ME and was interfaced to PYTHIA 8.245 [41] for the PS, underlying event and hadronisation modelling. This sample was generated with the FxFx algorithm [42] with up to one additional parton at NLO accuracy and up to two additional partons at LO accuracy in QCD. The expected accuracy of this sample is similar to that of the nominal SHERPA 2.2.10 sample. This multi-leg configuration makes use of complex functional forms for the renormalisation and factorisation scales that are chosen dynamically and depend on the kinematics of the event after the merging of the core process with the additional partons following the FxFx merging prescription [42–44]. They depend on the phase-space configuration and are related to the clustering scales of the additional partons and on the core process. The merging scale parameter was set to 30 GeV. The sample was simulated using the NNPDF3.0NLO PDF set and the A14 set of tuned MC parameters [45], henceforth referred to as the “A14 MC tune”. Top-quark decays were simulated at LO using the MADSPIN program [46, 47]. Further alternative $t\bar{t}W$ samples were simulated with the POWHEG [48] generator providing ME calculations at NLO in α_s with the NNPDF3.0NLO PDF set and the A14 MC tune. These POWHEG $t\bar{t}W$ samples were interfaced either with PYTHIA 8.245 or with HERWIG 7.2.1 [49–51] for the simulation of the PS, underlying event and hadronisation. All the alternative $t\bar{t}W$ samples were normalised to the same cross-section as the nominal SHERPA 2.2.10 sample in order not to be sensitive to overall normalisation differences when comparing the two simulations.

The $t\bar{t}W$ EW corrections at the order of $\alpha^3\alpha_s$ were simulated by an independent SHERPA 2.2.10 sample, produced at LO in QCD with the same configuration as the nominal signal sample. Since the charge asymmetry from these processes is negligible compared to the nominal signal contribution, this MC sample is treated as a background in the analysis.

The production of a $t\bar{t}$ pair in association with a Z boson ($t\bar{t}Z$) was simulated at NLO precision with the MG5_AMC@NLO 2.8.1 generator for the ME and PYTHIA 8.244 for the PS, underlying event and hadronisation, together with the NNPDF3.0NLO PDF set and the A14 MC tune. The mass of the Z boson was set to 91.2 GeV [37]. The $t\bar{t}\gamma^*$ contribution and Z/γ^* interference effects were taken into account, with the samples including events with dilepton invariant masses ($m_{\ell\ell}$) down to 1 GeV, where ℓ is an electron or muon. Additional $t\bar{t}Z$ samples using MG5_AMC@NLO 2.8.1 for the ME, but HERWIG 7.2.1 for the PS along with the HERWIG standard set of tuned parameters and the NNPDF3.0NLO PDF set were used for the evaluation of systematic uncertainties associated with the PS and hadronisation. Further alternative $t\bar{t}Z$ samples with the same settings as the nominal samples, but using

³ α and α_s denote the EW and strong coupling constants, respectively.

the A14 eigentune variation Var3c [45], are used to evaluate the uncertainty associated with the initial-state radiation (ISR). Similarly to $t\bar{t}W$, the alternative $t\bar{t}Z$ samples were normalised to the same cross-section as the nominal sample.

The production of $t\bar{t}$, $t\bar{t}H$ and tW events was simulated at NLO with the POWHEG generator for the ME, together with the NNPDF3.0NLO PDF set and the A14 MC tune. The h_{damp} parameter, which controls the matching in POWHEG and regulates the high- p_T radiation against which the $t\bar{t}$ system recoils, was set to 1.5 times the nominal top-quark mass [52]. The events were interfaced to PYTHIA 8.230 for the PS, underlying event and hadronisation. The $t\bar{t}$ cross-section was normalised to next-to-next-to-leading-logarithmic order (NNLL) in QCD, including the resummation of NNLL soft-gluon terms (NNLO + NNLL) [53, 54]. The $t\bar{t}H$ samples were normalised to NLO (QCD and EW) using the calculations documented in ref. [55]. The tW sample was normalised to NLO in QCD including NNLL soft-gluon corrections [56]. An alternative $t\bar{t}$ simulation was used with the same set-up for the ME, but the events were interfaced to HERWIG 7.1.3 [57] for the PS, underlying event and hadronisation modelling. The HERWIG standard set of tuned parameters and the NNPDF3.0NLO PDF set were used. Alternative $t\bar{t}H$ samples were used, where either the ME generator (MG5_AMC@NLO 2.6.0) or the PS algorithm (HERWIG 7.2.1) was changed with respect to the nominal $t\bar{t}H$ simulation.

A MC sample featuring the production of $t\bar{t}$ events in association with photons ($t\bar{t}\gamma$) was simulated at LO in QCD with MG5_AMC@NLO 2.3.3 and interfaced to PYTHIA 8.212, together with the NNPDF3.0NLO PDF set and the A14 MC tune. This sample is, however, only used to assign an extra uncertainty to additional photon radiation in the nominal $t\bar{t}$ prediction. Details of this procedure can be found in section 7.2.

The production of a single top quark (or antiquark) in association with a Z boson and one extra parton (tZq) was simulated using the MG5_AMC@NLO 2.3.3 generator at NLO with the NNPDF3.0NNLO PDF set. The events were interfaced to PYTHIA 8.245 using the A14 MC tune. The tZq simulation also includes off-shell Z boson decays into dilepton pairs with invariant masses in the range $m_{\ell\ell} > 5$ GeV. Single top quark (antiquark) production in association with both a W and a Z boson (tWZ) was simulated at NLO with MG5_AMC@NLO 2.2.2 and the NNPDF3.0NNLO PDF set, using PYTHIA 8.235 for the PS simulation. The interference between $t\bar{t}Z$ and tWZ was removed following a diagram-removal (DR) approach referred to as the “DR1 scheme” [58].

The MC samples featuring Z + jets production were simulated at NLO with the POWHEG generator for the ME and interfaced to PYTHIA 8.186 for the PS. The AZNLO [59] set of tuned parameters and the NNPDF3.0NNLO PDF set were used. An alternative Z + jets simulation was done with the SHERPA 2.2.11 generator where the default SHERPA PS set-up was used along with the NNPDF3.0NNLO PDF set. The Z + jets samples feature events with $m_{\ell\ell}$ down to 10 GeV. The sample cross-sections were normalised to NNLO predictions [60]. The POWHEG + PYTHIA 8 sample used PHOTOS [61] for final-state radiation (FSR).

For the simulation of Z boson production in association with a photon ($Z\gamma$), SHERPA 2.2.11 was used with the NNPDF3.0NNLO PDF set. The events were simulated at NLO precision.

Diboson processes featuring the production of three charged leptons and one neutrino or four charged leptons (denoted by $WZ + \text{jets}$ or $ZZ + \text{jets}$, respectively) were simulated using the SHERPA 2.2.2 generator, with a similar set-up to that described for $Z + \text{jets}$. Events with up to one extra parton were simulated at NLO, and with two or three partons at LO precision. MC samples featuring Higgs boson production in association with a W or Z boson ($H + W/Z$) were generated at NLO using POWHEG interfaced to PYTHIA 8.230/8.235 for the PS, together with the NNPDF3.0NLO PDF set and the AZNLO MC tune.

The production of four top quarks ($t\bar{t}t\bar{t}$) was modelled at NLO with SHERPA 2.2.11 together with the NNPDF3.0NNLO PDF set. The production of three top quarks ($t\bar{t}\bar{t}$) and the production of a $t\bar{t}$ pair with two W bosons ($t\bar{t}WW$) were simulated at LO using MG5_AMC@NLO 2.2.2 interfaced to PYTHIA 8.186 with the A14 MC tune and the NNPDF2.3LO PDF set. Fully leptonically decaying triboson processes (WWW , WWZ , WZZ and ZZZ) with up to six leptons in the final states were simulated with SHERPA 2.2.2 and the NNPDF3.0NLO PDF set. Final states with no additional partons were calculated at NLO, whereas final states with one, two or three additional partons were calculated at LO.

For all MC samples except the SHERPA ones, the decays of b - and c -hadrons were simulated using the EVTGEN 1.2.0 program [62].

4 Event reconstruction

Electron candidates are reconstructed from clusters of energy deposits in the electromagnetic calorimeter that are matched to tracks in the inner detector. They are required to satisfy $p_T > 10$ GeV, $|\eta| < 2.47$ and need to pass a “Tight” working point (WP), defined by a likelihood-based electron identification (ID) requirement [63]. To reject non-prompt electrons, the reconstructed track associated with the electron must satisfy the requirements $|z_0 \sin(\theta)| < 0.5$ mm and $|d_0|/\sigma(d_0) < 5$, where z_0 describes the longitudinal impact parameter relative to the reconstructed primary vertex,⁴ d_0 is the transverse impact parameter relative to the beam axis, and $\sigma(d_0)$ is the uncertainty in d_0 . Electron candidates are excluded if their calorimeter energy clusters lie within $1.37 < |\eta| < 1.52$, the transition region between the barrel and the endcap of the electromagnetic calorimeter.

Additional requirements are applied to the electron candidates to suppress the contribution of electrons originating from converted photons (γ -conversions). Electrons can be identified as internal- or material-conversion candidates by checking for additional tracks close to the calorimeter energy clusters associated with the electrons and the existence of conversion vertices. Electrons that are identified as either internal- or material-conversion candidates are rejected. These requirements are referred to in the following as “ e/γ ambiguity requirements”.

Furthermore, the electrons selected for the signal regions (SRs) of the analysis have to satisfy an isolation requirement. An isolation WP is defined using a multivariate likelihood

⁴The primary vertex is defined as the vertex (at least two associated tracks with $p_T > 500$ MeV) with the highest scalar sum of the squared transverse momenta of the associated tracks.

discriminant that combines electromagnetic shower shapes and track information from the inner detector to distinguish prompt electrons from non-prompt/fake electrons originating from hadronic jets, γ -conversions and heavy-flavour hadron decays. The electrons satisfying the isolation requirements are henceforth referred to as *tight* electrons, whereas *loose* electrons are defined by the conditions listed in the previous paragraph and do not need to satisfy the isolation requirement.

Muon candidates have to satisfy $p_T > 10$ GeV, $|\eta| < 2.5$ and an ID selection, corresponding to a “Medium” WP. This sets requirements on the number of hits in the different inner detector and muon spectrometer subsystems, and on the muon p_T and charge-to-momentum ratio variables [64, 65]. If a muon has insufficient momentum resolution, the entire event is removed. Requirements on the impact parameters of the reconstructed track associated with the muon candidate are applied to reject non-prompt muons. The track is required to have $|z_0 \sin(\theta)| < 0.5$ mm and $|d_0|/\sigma(d_0) < 3$.

As with electrons, an isolation requirement is applied to the muons used in the SRs, using the same approach based on a multivariate likelihood discriminant to distinguish prompt muons from non-prompt/fake muons. Muons are referred to as *tight* or *loose*, depending on whether or not they satisfy this isolation requirement in addition to the criteria listed above.

Jets are reconstructed using the anti- k_t jet algorithm [66] on particle-flow objects [67] with the radius parameter set to $R = 0.4$, as implemented in the FASTJET package [68]. The anti- k_t algorithm is used to reconstruct jets with a four-momentum recombination scheme, using the particle-flow objects as inputs. The jet calibration is performed using a standard procedure that corrects the jet energy to match, on average, the particle-level jet energy in simulation and applies an in situ correction for data [69]. To suppress jets from additional pp interactions within the same bunch crossing, a “jet vertex tagger” (JVT) [70, 71] is applied to select jets. The jets are only kept if they have $p_T > 20$ GeV and are in a pseudorapidity range of $|\eta| < 2.5$. In addition, $JVT > 0.2$ is required for jets with $p_T < 60$ GeV and $|\eta| < 2.4$, corresponding to a “Medium” JVT WP.

The selection of jets containing b -hadrons (“ b -tagging”) is performed with a multivariate deep-learning algorithm [72, 73]. A selection that provides a 77% efficiency for identifying jets containing b -hadrons (“ b -jets”) in simulated $t\bar{t}$ events, with a rejection factor of 130 against light-flavour jets and of five against jets containing c -hadrons, is used.

Associated scale factors are applied as multiplicative factors to the MC event weights, to correct for the mis-modelling of efficiencies associated with the reconstruction, identification, isolation and trigger selection of electrons and muons, as well as the JVT and b -tagging selection for jets.

The missing transverse momentum is defined as the negative vector sum of the transverse momenta of all selected and calibrated particle candidates (electrons, muons and jets). Low-momentum tracks from the primary vertex that are not associated with any of the reconstructed particle candidates described previously are also included as a “soft term” in the calculation [74]. The magnitude of the missing transverse momentum vector is denoted by E_T^{miss} .

Objects can satisfy both the jet and lepton selection criteria, and therefore a procedure called “overlap removal” is applied to avoid double counting the same energy clusters

or tracks as different object types and to ensure that objects are matched to a unique hypothesis. If any electron candidate shares a track with a muon, the electron is removed. Similarly, if any jet is close to an electron (within $\Delta R < 0.2$), the closest jet is removed. After that, electrons close to jets (within $\Delta R < 0.4$) are removed to reduce the impact of non-prompt leptons. If the ΔR between any remaining jet and a muon candidate is less than 0.4, the muon candidate is removed if the jet has more than two associated tracks, otherwise, the jet is discarded. This sequential procedure is applied before the scale factors are determined for all objects, so any mis-modelling of the overlap removal is factored into the scale factors and their associated uncertainties.

5 Event selection and definitions of control and signal regions

Events were selected with either single-lepton or dilepton (dielectron, dimuon and electron-muon) triggers with their minimum p_T thresholds varying from 12 to 26 GeV, depending on the lepton flavour, the trigger type and the data-taking period [75, 76]. A logical “OR” between the triggers was applied. Only events with exactly three charged light leptons (electrons or muons), as defined in section 4, are selected. If additional *tight* electrons or muons are found in the event, the event is rejected. The transverse momenta of the three charged leptons have to be larger than 30, 20 and 15 GeV for the leading, sub-leading and third lepton, respectively. A geometrical matching between these selected leptons and the ones reconstructed by the trigger algorithms is required. Furthermore, the p_T of the lepton that fires a trigger needs to be above the p_T threshold of the respective trigger to ensure that the trigger is maximally efficient.

The selected events are classified into four SRs, depending on their jet and b -jet multiplicities, as well as their E_T^{miss} . In addition, four control regions (CRs) are defined to constrain the dominant backgrounds ($t\bar{t}Z$ and $t\bar{t}$, tW , or Z + jets events containing non prompt leptons from heavy flavour decays or γ -conversions). In $t\bar{t}W$ production with three charged leptons in the final state, two jets originating from b -quarks are expected from the hard process. Additional jet activity due to gluon radiation and showering effects can occur. However, background $t\bar{t}Z$ events containing three leptons will typically contain extra jets from a hadronically-decaying top quark. Thus, the introduction of separate SRs with low and high jet multiplicities results in regions with improved signal over background ratios.

The definitions of the SRs and CRs are summarised in table 1. The sum of the three lepton charges must be ± 1 . A requirement that the invariant mass of the opposite-sign-same-flavour lepton pair ($m_{\ell\ell}^{\text{OSSF}}$) be at least 30 GeV is applied to remove the contributions from low-mass lepton resonances (e.g. $J/\psi \rightarrow \ell^+\ell^-$). The number of Z boson candidates ($N_{Z\text{-cand.}}$) is defined by the number of OSSF lepton pairs found in the event that have an invariant mass in the range $[m_Z - 10 \text{ GeV}, m_Z + 10 \text{ GeV}]$. Exactly one Z boson candidate is required for the CR for the $t\bar{t}Z$ background, but zero for all the other regions. The CRs targeting non-prompt electron/muons arising from heavy-flavour (HF) hadron decays (CR-HF $_e$ and CR-HF $_\mu$) are separated by the flavour of the third lepton. The third lepton must fail the isolation requirements in order to enrich these regions with HF leptons. The CR for γ -conversions (CR- γ -conv) requires at least one of the leptons to be an electron candidate that

		Preselection			
$N_\ell (\ell = e/\mu)$		= 3			
p_T^ℓ (1 st /2 nd /3 rd)		≥ 30 GeV, ≥ 20 GeV, ≥ 15 GeV			
Sum of lepton charges		± 1			
$m_{\ell\ell}^{\text{OSPF}}$		≥ 30 GeV			
		Region-specific requirements			
		SR-1b-low N_{jets}	SR-1b-high N_{jets}	SR-2b-low N_{jets}	SR-2b-high N_{jets}
N_{jets}		[2, 3]	≥ 4	[2, 3]	≥ 4
$N_{b\text{-jets}}$		= 1	= 1	≥ 2	≥ 2
E_T^{miss}		≥ 50 GeV	≥ 50 GeV	—	—
$N_{Z\text{-cand.}}$		= 0			
Lepton criteria		TTT			
e/γ ambiguity-cuts		satisfy all			
		CR- $t\bar{t}Z$	CR-HF $_e$	CR-HF $_\mu$	CR- γ -conv
$\ell^{\text{1st/2nd/3rd}}$		lll	lle	$ll\mu$	lle, lel, ell
N_{jets}		≥ 4	≥ 2	≥ 2	≥ 2
$N_{b\text{-jets}}$		≥ 2	= 1	= 1	≥ 1
E_T^{miss}		—	< 50 GeV	< 50 GeV	< 50 GeV
$N_{Z\text{-cand.}}$		= 1	= 0	= 0	= 0
Lepton criteria		TTT	TT \bar{T}	TT \bar{T}	TTT
e/γ ambiguity-cuts		satisfy all	satisfy all	satisfy all	≥ 1 fail

Table 1. Summary of the requirements applied to define the signal and control regions of the analysis. N_{jets} includes b -tagged and non- b -tagged jets. The labels “T” and “ \bar{T} ” refer to *tight* leptons that satisfy all selection requirements described in section 4 (T) and *loose* leptons that fail to satisfy the isolation requirements (\bar{T}).

fails the e/γ ambiguity requirements defined in section 4. The contribution from electrons with misidentified electric charge has been studied in MC and found to be negligible in the SRs.

Although the SR with two b -jets and low jet multiplicity (SR-2b-low N_{jets}) is the most sensitive to $t\bar{t}W$ production, the best result can be obtained from a statistical combination of all SRs and CRs (see section 8).

6 Lepton–top–quark matching

In the $t\bar{t}W$ process, the leptonic charge asymmetry is calculated only from the charged leptons that originate from the top quark and top antiquark. Since this search targets events with three charged leptons, a problem arises when selecting the two leptons used to calculate the difference between their absolute pseudorapidities ($\Delta\eta^\ell$) and ultimately the A_c^ℓ value (as defined in eq. (1.2)). The leptons that originate from a $t\bar{t}$ pair always have opposite-sign charges. In a $t\bar{t}W$ event with three charged leptons, the two leptons with the

same charge cannot both come from the $t\bar{t}$ pair and will always contain one lepton from a top-quark or top-antiquark decay and one lepton from the decay of the W boson produced in association with the $t\bar{t}$ pair. This same-sign pair of leptons is henceforth referred to as the “even” leptons. The remaining lepton with opposite charge, referred to as the “odd” lepton, will always originate from a top quark or top antiquark. The problem of selecting the two leptons from top quark or top-antiquark decays is hence reduced to selecting one of the even leptons to calculate $\Delta\eta^\ell$.

This problem is addressed using a boosted decision tree (BDT) classifier algorithm that computes a discriminator value for each even lepton in each event. Large discriminator values correspond to large probabilities that a given lepton originated from a top-quark decay. The lepton with the highest BDT discriminator score is selected to calculate $\Delta\eta^\ell$. The $\Delta\eta^\ell$ values calculated with the selected lepton and the odd lepton are denoted by $\Delta\eta_{\text{BDT}}^\ell$. Five input variables that each discriminate between leptons from top-quark or top-antiquark decays and leptons from associated W boson decays are defined. They are the masses of the two systems formed from the lepton and the closest and second closest b -jets, as well as the angular distances between the lepton and these b -jets: $m_{\ell b_0}$, $m_{\ell b_1}$, $\Delta R_{\ell b_0}$, $\Delta R_{\ell b_1}$. The last variable is the lepton p_T . For events with only one b -tagged jet, if any of the remaining jets pass a looser b -tagging discriminant WP with respect to the default selection described in section 4, the jet with the highest discriminant score is selected. If none of the other jets pass any b -tagging WP, the variables are constructed with the closest untagged jet.

The training of the classifier is performed using the nominal $t\bar{t}W$ SHERPA MC sample. The BDT classifier is implemented using the SCIKIT-learn [77] package. A k -fold cross validation with five folds is used for the training and testing samples. The fraction of events in the $t\bar{t}W$ sample in which the even lepton with the highest BDT discriminator value originates from a top-quark or top-antiquark decay is estimated to be about 71%, using the information from the MC event record.

7 Systematic uncertainties in background and signal estimation

The predictions of the $t\bar{t}W$ signal and the SM backgrounds are, in addition to the statistical uncertainties of their corresponding MC samples, affected by several sources of experimental and theoretical systematic uncertainty. These uncertainties are classified into the different categories that are described in the following.

7.1 Detector-related uncertainties

Detector-related uncertainties include the simulation of pile-up events, the integrated luminosity, and effects related to the reconstruction and ID of the particle candidates used in the analysis.

The uncertainty in the combined 2015–2018 integrated luminosity is 1.7% [24], obtained using the LUCID-2 detector [25] for the primary luminosity measurements. This systematic uncertainty affects all processes modelled using MC simulations apart from the processes

where the associated normalisation factors are obtained from data in the simultaneous fit (see section 8).

Uncertainties in the lepton reconstruction, ID, isolation and trigger efficiencies [63, 64, 78], electron energy and muon momentum scale and resolution [63, 64] are considered. Uncertainties associated with jets arise from the jet energy scale (JES), the jet energy resolution (JER) and the JVT jet selection requirement [69]. In addition, uncertainties associated with the pile-up rejection [70], the scale and resolution of the E_T^{miss} [74], and the b -tagging efficiencies [72, 79, 80] are considered.

7.2 Signal and background modelling uncertainties

Different sources of systematic uncertainty in the theoretical predictions of the $t\bar{t}W$ signal are considered. To evaluate the effect of μ_r and μ_f uncertainties, the scale factors used in the ME of the SHERPA $t\bar{t}W$ sample are varied simultaneously, as well as individually, by factors of 2.0 and 0.5 relative to their nominal values (but not including combinations where the variations differ by a factor of four). Uncertainties associated with the PDF sets are evaluated according to the PDF4LHC prescription [81]. They include internal variations of the nominal PDF sets that are added in quadrature, uncertainties due to the choice of PDF set, as well as variations of the α_s parameter. The systematic uncertainties due to the modelling of the ME are evaluated by comparing the prediction of the nominal MC sample with that of an alternative $t\bar{t}W$ sample simulated with MG5_AMC@NLO + PYTHIA and the FxFx algorithm. Furthermore, to evaluate the systematic uncertainties due to the PS, the hadronisation and the underlying event, the $t\bar{t}W$ POWHEG + PYTHIA samples are compared with the POWHEG + HERWIG samples and their relative differences are applied as uncertainties in the nominal SHERPA prediction. As explained in section 3, the alternative samples employed for the evaluation of modelling uncertainties are normalised to the same cross-sections as the respective nominal samples, so that the systematic uncertainties cover only differences between the shapes of kinematic variable distributions, but not the overall normalisations of the processes.

For the theoretical systematic uncertainties in the $t\bar{t}Z$ background, the same prescriptions as for the $t\bar{t}W$ process are used to evaluate the effects of the μ_r and μ_f uncertainties. For the systematic uncertainties due to the PS, the hadronisation and the underlying event, the nominal $t\bar{t}Z$ prediction is compared with that of an alternative $t\bar{t}Z$ sample simulated with the same ME generator (MG5_AMC@NLO), but interfaced to HERWIG instead of PYTHIA. Further alternative $t\bar{t}Z$ samples using a set of variations of the A14 tune's parameters are used to evaluate the uncertainty associated with the ISR, as mentioned in section 3.

For the $t\bar{t}H$, tZq and $WZ/ZZ + \text{jets}$ backgrounds, μ_r and μ_f uncertainties are considered. To evaluate the uncertainty in the ME, the PS, the hadronisation and the underlying event of $t\bar{t}H$, the nominal prediction is compared with those from the alternative $t\bar{t}H$ MC samples that use either a different ME generator (MG5_AMC@NLO) or PS algorithm (HERWIG). Furthermore, a normalisation uncertainty of +5.8% and -9.2% is applied for $t\bar{t}H$, following the NLO (QCD + EW) calculations from ref. [55]. For the tZq process, a normalisation uncertainty of 14% is applied, based on the dedicated ATLAS tZq measurement described

in ref. [82]. For the $WZ/ZZ + \text{jets}$ backgrounds, a conservative normalisation uncertainty of 20% is used to account for differences in the quality of $WZ/ZZ + \text{jets}$ modelling for different b -jet multiplicities. This uncertainty is derived from the level of agreement between data and MC simulation in several validation regions enriched in $WZ/ZZ + \text{jets}$ and reflects the level of agreement between data and MC simulations in [83].

For the $t\bar{t}$ and $Z + \text{jets}$ backgrounds, which can only contribute to 3ℓ final states via the presence of an additional fake or non-prompt lepton, μ_r and μ_f uncertainties are also considered. For the $t\bar{t}$ process, the PS, the hadronisation and the underlying event uncertainties are evaluated by comparing the nominal MC sample (POWHEG + PYTHIA) with an equivalent $t\bar{t}$ sample with the same ME generator, but interfaced to HERWIG. An extra uncertainty associated with the photon radiation in $t\bar{t}$ events is applied by comparing the predictions from $t\bar{t}$ and $t\bar{t} + t\bar{t}\gamma$. The overlap between the photons radiated within the PS in the $t\bar{t}$ ($Z + \text{jets}$) simulation and the photons coming from $t\bar{t}\gamma$ ($Z\gamma$) is removed from $t\bar{t}$ ($Z + \text{jets}$) for this comparison. This is done at particle level, where final-state photons that do not originate from prompt particle decays are removed if they are inside the kinematic phase-space covered by the $t\bar{t}\gamma$ ($Z\gamma$) simulation. For $Z + \text{jets}$, the uncertainties in the ME, the PS, the hadronisation and the underlying event are evaluated from a comparison between the nominal MC samples (POWHEG + PYTHIA) and alternative $Z + \text{jets}$ ($Z\gamma$) samples, which are simulated with SHERPA. The same approach as for $t\bar{t}$ is followed to account for the uncertainty associated with the photon radiation in $Z + \text{jets}$ events.

For the other (minor) background processes (tWZ , $t\bar{t}WW$, $H + W/Z$, VVV ($V = W/Z$), $t\bar{t}\bar{t}$ and $t\bar{t}t\bar{t}$), which typically contribute less than 2% to the total event yields in the SRs, a normalisation uncertainty of 30% is applied. This is a conservative approach, based on the precision of the latest cross section measurement of $t\bar{t}\bar{t}$ [84], which should cover the known theoretical uncertainties of these backgrounds. The same also applies to the MC sample generated with $t\bar{t}W$ EW corrections at the order $\alpha^3\alpha_s$, as this is treated as a background (see section 3).

8 Extraction of the charge asymmetry at reconstruction level

To extract the leptonic charge asymmetry from the reconstructed leptons (detector level), a simultaneous fit to the numbers of observed events in the SRs and CRs, as defined in section 5, is performed. The fit is based on the profile-likelihood technique, with a binned likelihood function defined as a product of Poisson probabilities of the observed event yields in all the regions. Systematic uncertainties (see section 7) are taken into account in the likelihood function, each as a nuisance parameter constrained by a Gaussian probability density function [85].

The normalisation factors for the most relevant background processes in the SRs, namely $t\bar{t}Z$, non-prompt electrons/muons from HF decays and electrons from γ -conversions, are allowed to float freely in the fit. Events containing non-prompt leptons from HF decays and electrons from γ -conversions are selected from processes that cannot contribute directly to the 3ℓ final state: $t\bar{t}$, tW and $Z + \text{jets}$. These events are identified by requiring at least one lepton to originate from either a b/c -hadron ($\text{HF}_{e/\mu}$) or a converted photon (γ -conversion)

according to the MC event records of the selected leptons. The variables used as input to the binned likelihood fit are the p_T of the third (softest) lepton in CR-HF $_e$ and CR-HF $_\mu$, as well as the scalar sum of the p_T of the selected jets in the event (H_T) in CR- $t\bar{t}Z$, since their distributions show a sizeable shape difference between the targeted processes and the other SM backgrounds. In the SRs and CR- γ -conv, the total numbers of events are used.

Each of the four SRs is separated into $\Delta\eta_{\text{BDT}}^\ell \leq 0$ ($\Delta\eta^-$) and $\Delta\eta_{\text{BDT}}^\ell > 0$ ($\Delta\eta^+$) regions. For the $\Delta\eta^-$ ($\Delta\eta^+$) set of regions, a single factor $\mathcal{N}_{\Delta\eta^-}$ ($\mathcal{N}_{\Delta\eta^+}$) models the normalisations of the signal yields (relatively to the SM cross-section) across the four SRs. Accordingly, the A_c^ℓ value is extracted as a function of these normalisation factors. Similarly, separate normalisation factors in the $\Delta\eta^-$ and $\Delta\eta^+$ sets of regions for the major background processes are allowed to float freely in the fit to avoid a bias from an assumption of SM asymmetries for these processes in data.⁵ An “injection test” is performed to verify that the fit result matches an injected non-SM A_c^ℓ value and the fit can deal correctly with the fact that the different SRs have different charge asymmetries.

The predicted and observed numbers of events in the SRs and CRs before performing the simultaneous fit (“pre-fit”) are shown in table 2. The indicated uncertainties consider statistical as well as all experimental and theoretical systematic uncertainties described in section 7. The numbers of events in the SRs and CRs after the fit to data (“post-fit”) are given in table 3. Comparisons between data and the post-fit predictions for $\Delta\eta^-$ and $\Delta\eta^+$ in the four SRs are shown in figure 2. Data and the post-fit SM predictions for the variables that are used for the binned likelihood fit are depicted in figure 3 for CR-HF $_e$ and CR-HF $_\mu$, and in figure 4 for CR- $t\bar{t}Z$ and CR- γ -conv.

The normalisation factors for the major background processes, $\mathcal{N}_{t\bar{t}Z}$, $\mathcal{N}_{\gamma\text{-conv}}^e$, $\mathcal{N}_{\text{HF}}^e$ and $\mathcal{N}_{\text{HF}}^\mu$ (all obtained separately for $\Delta\eta^-$ and $\Delta\eta^+$), together with $\mathcal{N}_{\Delta\eta^-}$ and the A_c^ℓ value for the $t\bar{t}W$ signal, are given in figure 5. The normalisation factor for the $t\bar{t}W$ process was checked and found to be (within its uncertainty) compatible with the latest ATLAS and CMS $t\bar{t}W$ cross-section measurements [7, 8]. Tests using MC simulation were also performed to validate that the extracted A_c^ℓ value is not biased by the absolute normalisation of the $t\bar{t}W$ process.

The normalisation factors for some of the background processes (in particular $\mathcal{N}_{t\bar{t}Z}$ and $\mathcal{N}_{\gamma\text{-conv}}^e$) show small differences between $\Delta\eta^-$ and $\Delta\eta^+$. As these processes are not expected to have significant charge asymmetries in the SM at this level of precision, there is an uncertainty on how best to model this data. In the nominal fit, due to the independent normalisation factors for $\Delta\eta^-$ and $\Delta\eta^+$ in the CRs, the observed background asymmetries are precisely modelled. To account for the possibility that the observed asymmetry is due to a statistical fluctuation, an alternative fit is performed where only one normalisation factor is assigned to each of these processes (thus fixing their asymmetries to the SM expectation). The difference between the results of these two fit set-ups is assigned as an extra systematic uncertainty in the extracted A_c^ℓ value. This uncertainty (denoted as $\Delta\eta^\pm$ CR-dependency) is found to be 0.05 and is one of the leading systematic uncertainties.

⁵The inclusive charge asymmetries at parton level for the simulated $t\bar{t}Z$ and $t\bar{t}$ samples are $A_c^\ell = -0.015$ and 0.004, respectively.

Process	CR- $t\bar{t}Z$		CR-HF $_e$		CR-HF $_\mu$		CR- γ -conv	
	$\Delta\eta^-$	$\Delta\eta^+$	$\Delta\eta^-$	$\Delta\eta^+$	$\Delta\eta^-$	$\Delta\eta^+$	$\Delta\eta^-$	$\Delta\eta^+$
$t\bar{t}W$ (QCD)	1.8 ± 0.4	1.49 ± 0.19	1.18 ± 0.19	1.13 ± 0.18	1.72 ± 0.20	1.37 ± 0.28	4.1 ± 0.7	2.92 ± 0.18
$t\bar{t}W$ (EW)	0.18 ± 0.07	0.16 ± 0.06	0.10 ± 0.04	0.09 ± 0.04	0.09 ± 0.04	0.14 ± 0.05	0.23 ± 0.08	0.36 ± 0.12
$t\bar{t}Z$	107 ± 6	107 ± 6	1.42 ± 0.23	1.5 ± 0.4	2.20 ± 0.23	2.00 ± 0.14	4.04 ± 0.19	3.65 ± 0.32
HF $_e$	—	—	350 ± 40	362 ± 27	0.18 ± 0.11	0.20 ± 0.09	1.0 ± 0.6	0.67 ± 0.35
HF $_\mu$	0.14 ± 0.08	0.19 ± 0.09	0.20 ± 0.09	0.28 ± 0.10	520 ± 40	530 ± 50	0.9 ± 0.5	1.1 ± 0.9
γ -conv.	0.55 ± 0.14	0.41 ± 0.13	3.8 ± 2.5	4.7 ± 2.9	2.6 ± 2.4	3.3 ± 2.5	18.8 ± 1.4	17.5 ± 1.3
$t\bar{t}H$	3.3 ± 0.4	3.20 ± 0.32	0.87 ± 0.13	0.89 ± 0.11	1.18 ± 0.11	1.22 ± 0.22	1.48 ± 0.20	1.5 ± 0.4
tZq	12.6 ± 2.2	11.0 ± 1.9	0.48 ± 0.11	0.43 ± 0.09	0.95 ± 0.18	0.81 ± 0.15	0.68 ± 0.12	0.70 ± 0.13
WZ/ZZ + jets	12 ± 4	12 ± 4	3.0 ± 0.9	3.3 ± 1.0	7.2 ± 2.4	7.9 ± 2.5	3.1 ± 0.9	2.9 ± 0.8
Other	10.7 ± 3.3	10.2 ± 3.3	14 ± 4	13 ± 5	17 ± 7	17 ± 6	1.6 ± 0.8	1.5 ± 0.6
SM total	148 ± 10	146 ± 10	380 ± 40	387 ± 28	550 ± 40	560 ± 50	35.9 ± 2.4	32.9 ± 2.3
Data	156	176	315	373	551	592	34	40

Process	SR-1b-low N_{jets}		SR-1b-high N_{jets}		SR-2b-low N_{jets}		SR-2b-high N_{jets}	
	$\Delta\eta^-$	$\Delta\eta^+$	$\Delta\eta^-$	$\Delta\eta^+$	$\Delta\eta^-$	$\Delta\eta^+$	$\Delta\eta^-$	$\Delta\eta^+$
$t\bar{t}W$ (QCD)	19.0 ± 2.8	17 ± 4	9.2 ± 1.1	8.2 ± 1.1	25 ± 7	21 ± 6	14.7 ± 3.4	12.2 ± 1.9
$t\bar{t}W$ (EW)	1.06 ± 0.34	1.3 ± 0.4	1.05 ± 0.34	1.07 ± 0.34	1.2 ± 0.4	1.3 ± 0.4	1.8 ± 0.6	1.6 ± 0.5
$t\bar{t}Z$	12.0 ± 1.0	12.1 ± 1.1	15.5 ± 1.4	15.5 ± 1.1	11.4 ± 1.4	10.8 ± 1.4	26.2 ± 1.8	25.8 ± 1.7
HF $_e$	7.2 ± 1.2	7.5 ± 1.5	1.7 ± 0.7	1.6 ± 0.6	0.7 ± 0.5	0.6 ± 0.5	0.69 ± 0.35	0.37 ± 0.19
HF $_\mu$	12.5 ± 2.0	13 ± 4	3.2 ± 0.8	3.5 ± 1.3	1.35 ± 0.34	1.11 ± 0.33	1.0 ± 0.4	0.9 ± 0.5
γ -conv.	6.7 ± 0.9	6.1 ± 1.0	3.1 ± 0.5	3.4 ± 0.8	6.1 ± 0.8	6.9 ± 0.8	4.4 ± 0.7	4.6 ± 0.6
$t\bar{t}H$	5.5 ± 0.8	5.6 ± 0.8	8.6 ± 0.8	8.7 ± 0.9	5.5 ± 1.1	5.5 ± 1.0	14.1 ± 1.8	14.2 ± 1.7
tZq	5.1 ± 0.9	4.2 ± 0.7	1.40 ± 0.31	1.15 ± 0.27	2.8 ± 0.5	2.3 ± 0.4	1.92 ± 0.34	1.64 ± 0.30
WZ/ZZ + jets	15 ± 4	14 ± 4	8.0 ± 2.8	7.6 ± 2.5	2.9 ± 0.9	2.2 ± 0.7	2.2 ± 0.7	2.2 ± 0.7
Other	5.6 ± 2.0	5.1 ± 1.6	4.5 ± 2.4	4.7 ± 1.5	2.6 ± 1.1	2.9 ± 1.3	10 ± 6	9 ± 5
SM total	89 ± 6	85 ± 7	56 ± 6	56 ± 6	59 ± 9	55 ± 7	77 ± 8	73 ± 7
Data	94	89	50	69	84	81	89	81

Table 2. The predicted and observed numbers of events in the control and signal regions. The predictions are shown before the fit to data. The indicated uncertainties consider statistical as well as all experimental and theoretical systematic uncertainties, with the exception of the $\Delta\eta^\pm$ CR-dependency uncertainty. Background categories with event yields shown as “—” do contribute less than 0.01 to a region.

The leptonic charge asymmetry in $t\bar{t}W$ is found to be

$$A_c^\ell(t\bar{t}W) = -0.12 \pm 0.14 \text{ (stat.)} \pm 0.05 \text{ (syst.)}.$$

This is consistent with the SM expectation of

$$A_c^\ell(t\bar{t}W)_{\text{SM}} = -0.084^{+0.005}_{-0.003} \text{ (scale)} \pm 0.006 \text{ (MC stat.)},$$

calculated using the nominal $t\bar{t}W$ SHERPA simulation. The contributions from the most relevant uncertainties are summarised in table 4. The uncertainties are symmetrised and grouped into several type-related categories and are shown together with the total systematic and statistical uncertainties. The dominant systematic uncertainties are the $\Delta\eta^\pm$ CR-dependency, the JER, as well as the modelling uncertainties of the $t\bar{t}W$ and $t\bar{t}Z$ MC processes detailed in section 7. Overall, the result is limited by the statistical uncertainty of the data.

Process	CR- $t\bar{t}Z$		CR-HF $_e$		CR-HF $_\mu$		CR- γ -conv	
	$\Delta\eta^-$	$\Delta\eta^+$	$\Delta\eta^-$	$\Delta\eta^+$	$\Delta\eta^-$	$\Delta\eta^+$	$\Delta\eta^-$	$\Delta\eta^+$
$t\bar{t}W$ (QCD)	3.2 ± 0.7	2.2 ± 0.7	1.8 ± 0.5	1.7 ± 0.5	2.6 ± 0.8	1.8 ± 0.8	7.0 ± 1.3	4.4 ± 1.3
$t\bar{t}W$ (EW)	0.18 ± 0.06	0.16 ± 0.05	0.10 ± 0.03	0.09 ± 0.03	0.09 ± 0.03	0.14 ± 0.04	0.23 ± 0.07	0.36 ± 0.11
$t\bar{t}Z$	114 ± 13	138 ± 14	1.45 ± 0.27	1.7 ± 0.4	2.3 ± 0.4	2.55 ± 0.35	4.3 ± 0.6	4.6 ± 0.6
HF $_e$	—	—	290 ± 18	346 ± 20	0.15 ± 0.02	0.19 ± 0.02	0.59 ± 0.27	0.52 ± 0.17
HF $_\mu$	0.133 ± 0.012	0.201 ± 0.020	0.195 ± 0.018	0.277 ± 0.029	516 ± 25	556 ± 25	0.8 ± 0.4	1.3 ± 0.8
γ -conv.	0.40 ± 0.18	0.52 ± 0.16	2.8 ± 2.2	6 ± 4	1.9 ± 2.0	4.2 ± 3.4	14 ± 6	22 ± 7
$t\bar{t}H$	3.3 ± 0.4	3.23 ± 0.31	0.86 ± 0.13	0.87 ± 0.10	1.16 ± 0.11	1.19 ± 0.22	1.49 ± 0.20	1.6 ± 0.4
tZq	12.6 ± 2.2	11.0 ± 1.9	0.47 ± 0.10	0.42 ± 0.08	0.95 ± 0.17	0.79 ± 0.14	0.68 ± 0.11	0.70 ± 0.12
WZ/ZZ + jets	10.2 ± 2.9	10.6 ± 3.1	2.6 ± 0.7	2.8 ± 0.7	6.3 ± 1.7	6.7 ± 1.8	2.6 ± 0.7	2.5 ± 0.6
Other	10.8 ± 3.2	10.0 ± 2.9	14 ± 4	13 ± 5	18 ± 7	18 ± 6	1.7 ± 0.8	1.7 ± 0.6
SM total	155 ± 12	175 ± 13	315 ± 18	373 ± 19	550 ± 23	591 ± 24	33 ± 6	40 ± 6
Data	156	176	315	373	551	592	34	40

Process	SR-1b-low N_{jets}		SR-1b-high N_{jets}		SR-2b-low N_{jets}		SR-2b-high N_{jets}	
	$\Delta\eta^-$	$\Delta\eta^+$	$\Delta\eta^-$	$\Delta\eta^+$	$\Delta\eta^-$	$\Delta\eta^+$	$\Delta\eta^-$	$\Delta\eta^+$
$t\bar{t}W$ (QCD)	32 ± 6	27 ± 6	14 ± 4	12.1 ± 3.4	46 ± 9	36 ± 8	26 ± 6	19 ± 5
$t\bar{t}W$ (EW)	1.04 ± 0.32	1.3 ± 0.4	1.04 ± 0.32	1.05 ± 0.32	1.2 ± 0.4	1.3 ± 0.4	1.8 ± 0.5	1.6 ± 0.5
$t\bar{t}Z$	12.4 ± 2.0	15.0 ± 2.2	16.0 ± 2.2	19.6 ± 2.3	12.3 ± 2.3	14.3 ± 2.6	27.6 ± 3.3	33.2 ± 3.5
HF $_e$	6.4 ± 1.0	6.8 ± 0.8	1.5 ± 0.5	1.7 ± 0.4	0.40 ± 0.20	0.79 ± 0.35	0.45 ± 0.14	0.39 ± 0.14
HF $_\mu$	12.5 ± 1.5	13.6 ± 2.5	3.1 ± 0.6	3.6 ± 0.9	1.30 ± 0.23	1.19 ± 0.19	1.04 ± 0.29	0.9 ± 0.5
γ -conv.	4.9 ± 2.3	7.7 ± 2.6	2.3 ± 1.1	4.3 ± 1.6	4.6 ± 2.1	8.8 ± 2.9	3.3 ± 1.5	5.9 ± 1.9
$t\bar{t}H$	5.4 ± 0.8	5.5 ± 0.8	8.4 ± 0.8	8.6 ± 0.8	5.5 ± 1.1	5.6 ± 1.0	14.3 ± 1.7	14.4 ± 1.7
tZq	5.0 ± 0.9	4.1 ± 0.7	1.38 ± 0.27	1.16 ± 0.24	2.8 ± 0.5	2.3 ± 0.4	1.93 ± 0.33	1.65 ± 0.29
WZ/ZZ + jets	12.6 ± 3.0	12.3 ± 3.0	6.7 ± 2.0	6.5 ± 1.8	2.5 ± 0.7	1.9 ± 0.5	1.9 ± 0.6	1.9 ± 0.5
Other	6.0 ± 2.1	5.2 ± 1.6	3.6 ± 1.8	4.6 ± 1.4	2.9 ± 1.2	3.3 ± 1.3	8 ± 4	8 ± 4
SM total	99 ± 6	98 ± 6	58 ± 4	63 ± 4	80 ± 8	75 ± 7	85 ± 6	86 ± 5
Data	94	89	50	69	84	81	89	81

Table 3. The predicted and observed numbers of events in the control and signal regions. The predictions are shown after the fit to data. The indicated uncertainties consider statistical as well as all experimental and theoretical systematic uncertainties, with the exception of the $\Delta\eta^\pm$ CR-dependency uncertainty. Background categories with event yields shown as “—” do contribute less than 0.01 to a region.

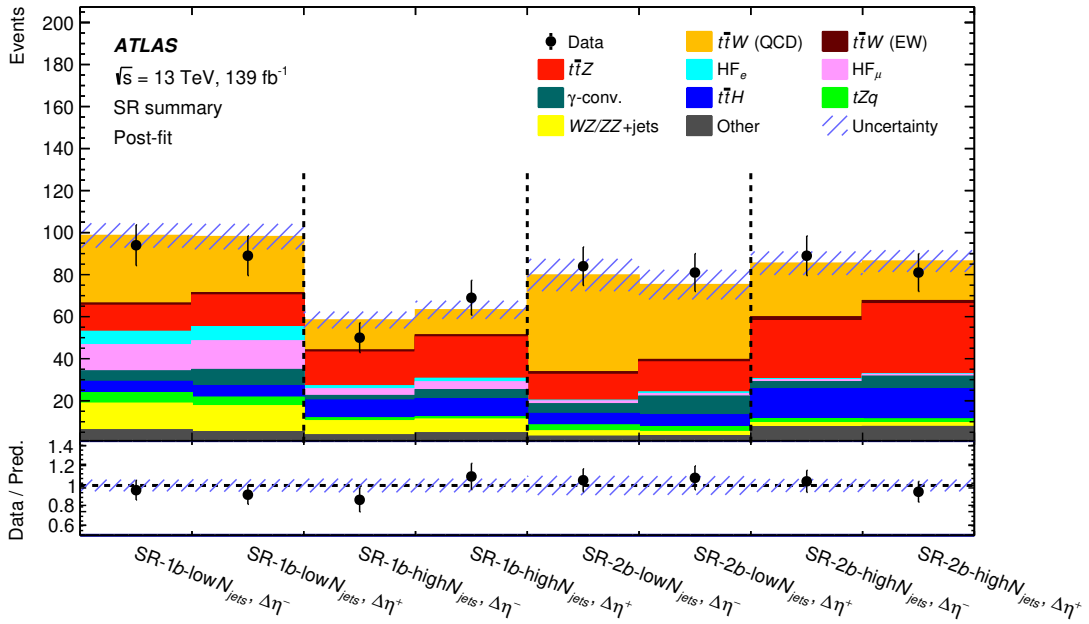


Figure 2. Comparison between data and the post-fit predictions for $\Delta\eta_{\text{BDT}}^\ell \leq 0$ ($\Delta\eta^-$) and $\Delta\eta_{\text{BDT}}^\ell > 0$ ($\Delta\eta^+$) in the four SRs. The error band includes the total uncertainties of the post-fit predictions, with the exception of the $\Delta\eta^\pm$ CR-dependency uncertainty. The ratio of the data to the total post-fit predictions is shown in the lower panel.

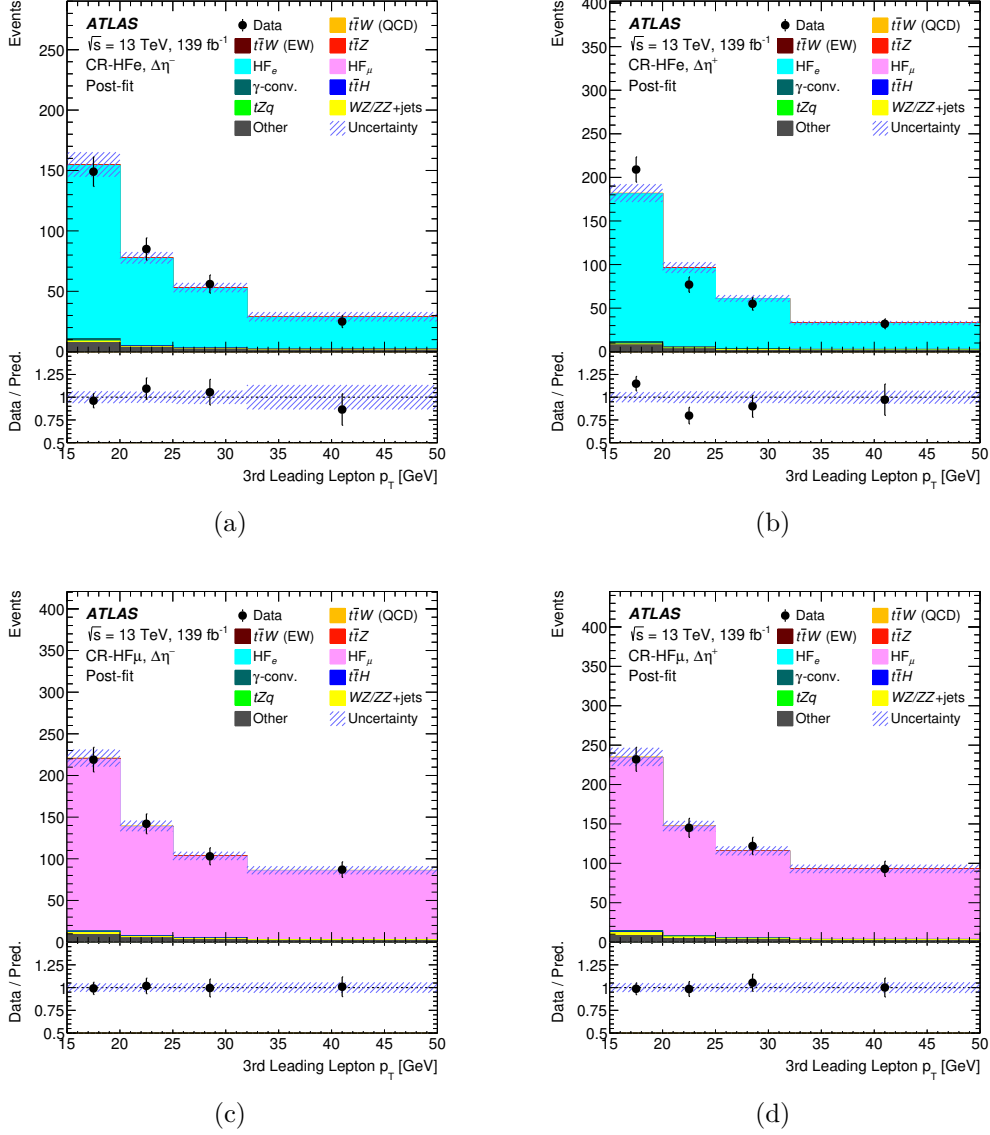


Figure 3. Comparison between data and the post-fit predictions in (a,b) CR-HF_e and (c,d) CR-HF_μ. The distributions show the p_T of the third lepton (electron or muon), which is the variable that is used for the binned likelihood fit. The regions are separated between $\Delta\eta_{\text{BDT}}^\ell \leq 0$ ($\Delta\eta^-$) and $\Delta\eta_{\text{BDT}}^\ell > 0$ ($\Delta\eta^+$). The error bands include the total uncertainties in the post-fit predictions, with the exception of the $\Delta\eta^\pm$ CR-dependency uncertainty. The ratios of the data to the total post-fit predictions are shown in the lower panels. Events with the p_T of the third lepton above 50 GeV are included in the rightmost bins.

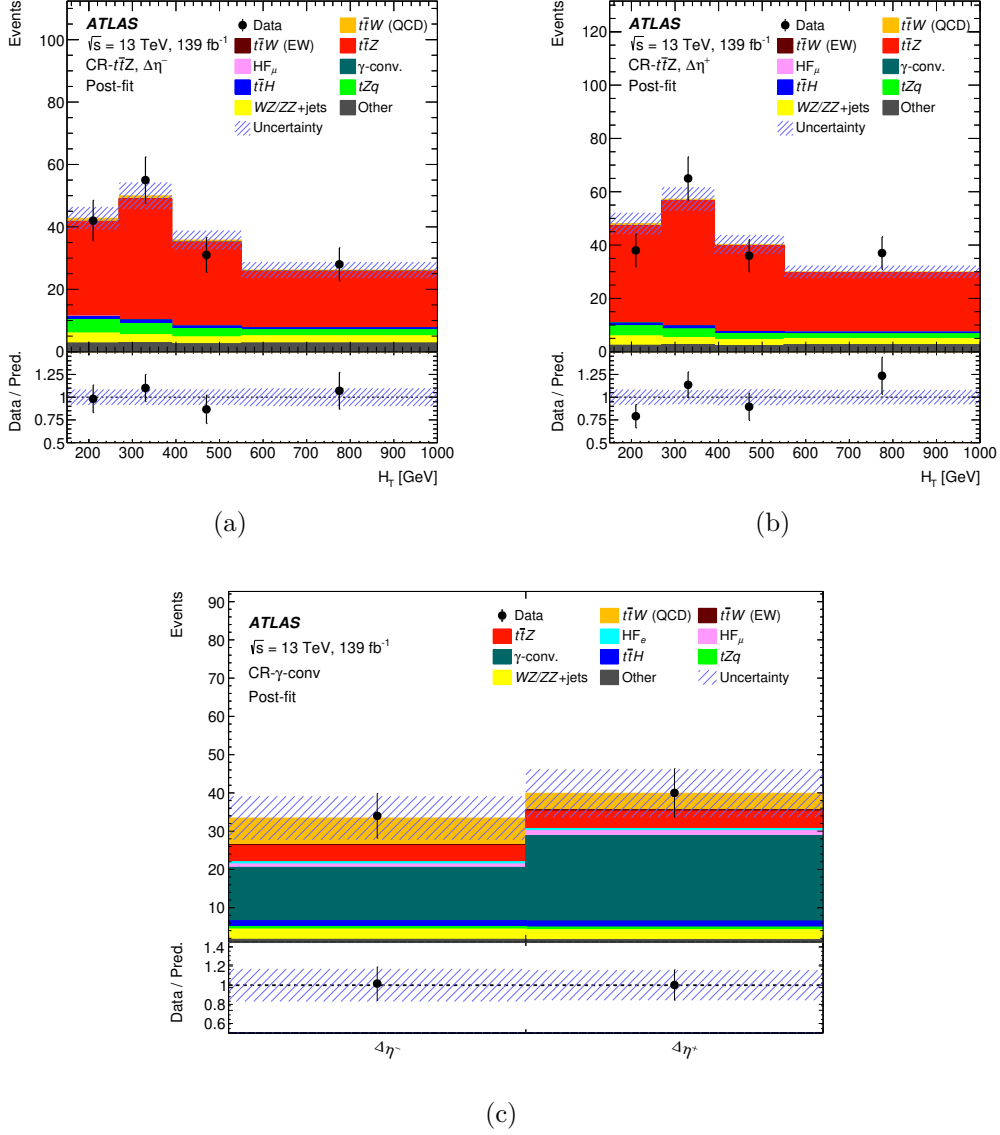


Figure 4. Comparison between data and the post-fit predictions in (a,b) CR- $t\bar{t}Z$ and (c) CR- γ -conv. The distributions are shown for the variables that are used for the binned likelihood fit: H_T for CR- $t\bar{t}Z$ and the total event yields for CR- γ -conv. The regions are separated between $\Delta\eta_{\text{BDT}}^\ell \leq 0$ ($\Delta\eta^-$) and $\Delta\eta_{\text{BDT}}^\ell > 0$ ($\Delta\eta^+$). The error bands include the total uncertainties in the post-fit predictions, with the exception of the $\Delta\eta^\pm$ CR-dependency uncertainty. The ratios of the data to the total post-fit predictions are shown in the lower panels. Events with an H_T above 1 TeV are included in the rightmost bins of (a) and (b).

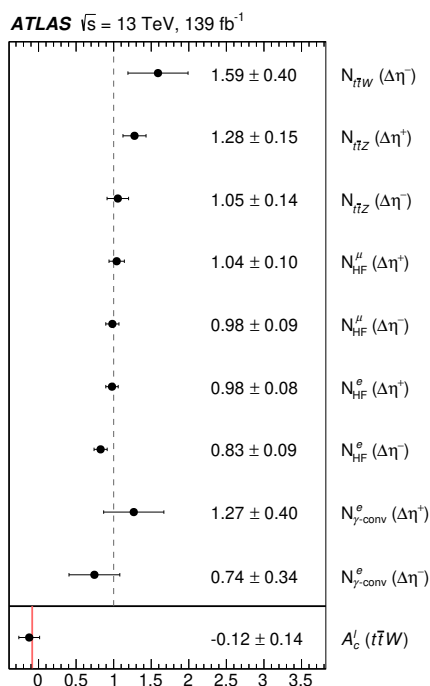


Figure 5. Normalisation factors for the major background processes, together with $\mathcal{N}_{\Delta\eta^-}$ for $t\bar{t}W$ and the A_c^ℓ value extracted from the fit to data in the CRs and SRs at detector level. The normalisation factors, $\mathcal{N}_{t\bar{t}Z}$, $\mathcal{N}_{\gamma\text{-conv}}^e$, $\mathcal{N}_{\text{HF}}^e$ and $\mathcal{N}_{\text{HF}}^\mu$, are obtained separately for $\Delta\eta_{\text{BDT}}^\ell \leq 0$ ($\Delta\eta^-$) and $\Delta\eta_{\text{BDT}}^\ell > 0$ ($\Delta\eta^+$). The indicated uncertainties consider statistical as well as systematic uncertainties, with the exception of the $\Delta\eta^\pm$ CR-dependency uncertainty. The solid vertical line in the last entry shows the A_c^ℓ SM expectation, calculated using the $t\bar{t}W$ SHERPA simulation.

9 Unfolding and extraction of the charge asymmetry at particle level

To obtain the charge asymmetry at particle level in a specific fiducial volume, an unfolding procedure is performed to correct for detector effects, as well as for signal efficiency and acceptance effects. The procedure and the relevant definitions are explained in the following.

9.1 Particle-level objects

Particle-level objects in simulated events are defined using quasi-stable particles (with a mean lifetime greater than 30 ps) originating from pp collisions. They are selected after hadronisation but before the interaction with the various detector components or consideration of pile-up effects.

Particle-level electrons or muons are required to not originate from a hadron in the MC generator event record, whether directly or through a τ -lepton decay. This ensures that they originate from a Z or W boson (where the W boson can come either from prompt W production or a top-quark decay), without requiring a direct match with the parent particle. The four-momenta of the bare leptons are modified (“dressed”) by adding the four-momenta of all radiated photons within a cone of size $\Delta R = 0.1$, excluding photons from hadron decays, to take into account FSR photons.

	$\Delta A_c^\ell(t\bar{t}W)$
Experimental uncertainties	
Jet energy resolution	0.013
Pile-up	0.007
b -tagging	0.005
Leptons	0.004
E_T^{miss}	0.004
Jet energy scale	0.0032
Luminosity	0.0006
MC modelling uncertainties	
$t\bar{t}W$ modelling	0.013
$t\bar{t}Z$ modelling	0.010
HF $_{e/\mu}$ modelling	0.006
$t\bar{t}H$ modelling	0.005
Other uncertainties	
$\Delta\eta^\pm$ CR-dependency	0.05
MC statistical uncertainty	
	0.019
Data statistical uncertainty	
	0.14
Total uncertainty	
	0.15

Table 4. List of the most relevant systematic and statistical uncertainties in the extracted leptonic charge asymmetry $A_c^\ell(t\bar{t}W)$ from the simultaneous fit. For this table, the uncertainties are symmetrised and grouped into categories. The sum in quadrature of the individual uncertainties is not necessarily equal to the total uncertainty due to correlations introduced by the fit.

Particle-level jets are reconstructed with the anti- k_t algorithm with a radius parameter of $R = 0.4$ applied to all stable particles, but excluding the neutrinos originating from W or Z bosons and the selected electrons, muons and photons used in the definition of the charged leptons. If b -hadrons with $p_T > 5$ GeV are found in the MC event record, they are clustered into stable-particle jets with their energies set to negligible positive values (referred to as “ghost-matching”) [86]. Particle-level jets containing at least one of these b -hadrons are considered as b -jets. The particle-level missing transverse momentum is defined as the vectorial sum of the transverse momenta of all neutrinos found in the MC simulation history of the event, excluding those originating from hadron decays.

9.2 Particle-level fiducial volume

The particle-level fiducial volume is defined by the following requirements on the particle-level objects, as defined in section 9.1:

- Three electrons or muons with $p_T > 15$ GeV and $|\eta| < 2.5$.
- The invariant mass of all OSSF lepton pairs has to be larger than 25 GeV.
- No Z -candidate (as defined in section 5) among the leptons.
- At least two jets with $p_T > 20$ GeV, $|\eta| < 2.5$ and least one of them identified as a b -jet.

9.3 Unfolding procedure and charge-asymmetry extraction

The unfolding procedure is applied to the observed number of data events in the SRs. Analogously to the method used at detector level, described in section 6, a method of matching leptons to top quarks (antiquarks) is required to obtain the response matrix, essential to the unfolding procedure. To reproduce the particle-level fiducial volume, a simpler scheme is adopted that is independent of the generator-specific MC event record and any multivariate algorithm. Each lepton is combined with the closest b -jet in the ΔR space. The ℓ - b system that yields a mass closest to the most probable mass for a ℓ - b system originating from a top-quark decay (according to the nominal $t\bar{t}W$ simulation) is used to select the even and odd leptons. This procedure has an efficiency of approximately 65% to identify the correct leptons.

The following formula is used for the unfolding:

$$N_i^{\text{folded}} = \frac{1}{\alpha_i} \underbrace{\sum_j \varepsilon_j M_{ij}}_{R_{ij}} N_j^{\text{fid}} \quad \text{with} \quad M_{ij} = \frac{N_{ij}^{(\text{reco} \cap \text{fid})}}{N_j^{(\text{reco} \cap \text{fid})}}, \quad \alpha_i = \frac{N_i^{(\text{reco} \cap \text{fid})}}{N_i^{\text{reco}}}, \quad \varepsilon_j = \frac{N_j^{(\text{reco} \cap \text{fid})}}{N_j^{\text{fid}}}, \quad (9.1)$$

with the number N_j^{fid} representing the content of bin j in the fiducial volume, N_i^{reco} being the events in bin i that satisfy the detector level selection and the symbol \cap represents the logical intersection of the two regions. The N_i^{folded} represents the bin content (i) after the folding of the particle level bins (j) has been performed through the response matrix (R_{ij}).

This matrix is constructed from the migration matrix (M_{ij}) and the acceptance and efficiency correction terms (α_i and ε_j) for each bin. The entries in the migration matrix represent the fractions of events at particle level in a y -axis bin that are reconstructed at detector level in an x -axis bin. They are normalised such that the sum of entries in each row is equal to one. The acceptance corrections α_i account for events that are generated outside the fiducial volume but satisfy the selection at detector level, as described in section 5. The efficiency corrections ε_j account for events that are in the fiducial volume but fail to satisfy the detector-level selection.

The migration matrices, as well as the acceptance and efficiency correction terms, are built separately for each of the SRs defined in table 1. As an example, figure 6 shows (a) the migration matrix, as well as (b) the efficiency and (c) the acceptance correction factors that are used for SR-2b-low N_{jets} , which is the region with the highest $t\bar{t}W$ purity. The fraction of events in the diagonal elements of the migration matrix shows the quality of the resolution for $\Delta\eta^\ell$, which is around 90%. The efficiency corrections are at a level of 11%–12% and the acceptance corrections are around 95%. None show any notable dependence on $\Delta\eta^\ell$.

The unfolding procedure is the same as in ref. [18] and based on a profile-likelihood approach (“profile-likelihood unfolding”). With this approach, the unfolding problem is transformed into a standard problem of fitting normalisations of distributions. Each bin in the particle-level distribution is “folded” through the response matrix via eq. (9.1), resulting in the same numbers of bins at detector level. The particle-level bins are treated as separate subsamples that are multiplied by their respective entries in the response matrix and freely floating parameters are assigned to each of these subsamples at detector level. Analogously to the fit described in section 8, the freely floating parameters are assigned to the major backgrounds in the SRs: $\mathcal{N}_{t\bar{t}Z}$, $\mathcal{N}_{\gamma\text{-conv}}^e$, $\mathcal{N}_{\text{HF}}^e$ and $\mathcal{N}_{\text{HF}}^\mu$. These normalisations and the analysis regions are split into $\Delta\eta^+$ and $\Delta\eta^-$, in the same way as the detector-level results. Thus, the detector-level distributions are scaled by some factors, determined by fitting the data, and these factors are then used to scale the corresponding particle-level bins, which gives the desired unfolded result. The charge asymmetry is defined as the parameter of interest and is related to the normalisation factors in the unfolded bins. For the CRs, no response matrices are built. However, as the signal contamination in these regions is very small compared with the total event yields, an approximation is made whereby the signal is treated as an additional background. An exception is CR- γ -conv where, due to the high signal contamination, response matrices are also built. No regularisation is applied in the unfolding.

The systematic uncertainties in the signal and background processes considered for the unfolded results are the same as for the results at detector level (described in section 7). Systematic uncertainties in the background processes are propagated to the unfolded distributions by varying the detector-level distributions within their uncertainties and repeating the unfolding procedure. The modelling uncertainties of the $t\bar{t}W$ signal are propagated through the unfolding procedure, using variations of the response matrices.

An injection test is performed to verify that non-SM A_c^ℓ values can be recovered in the unfolding procedure. This is done by injecting the non-SM A_c^ℓ values into the particle-level predictions, which are propagated to detector level and treated as pseudo-data in the fit.

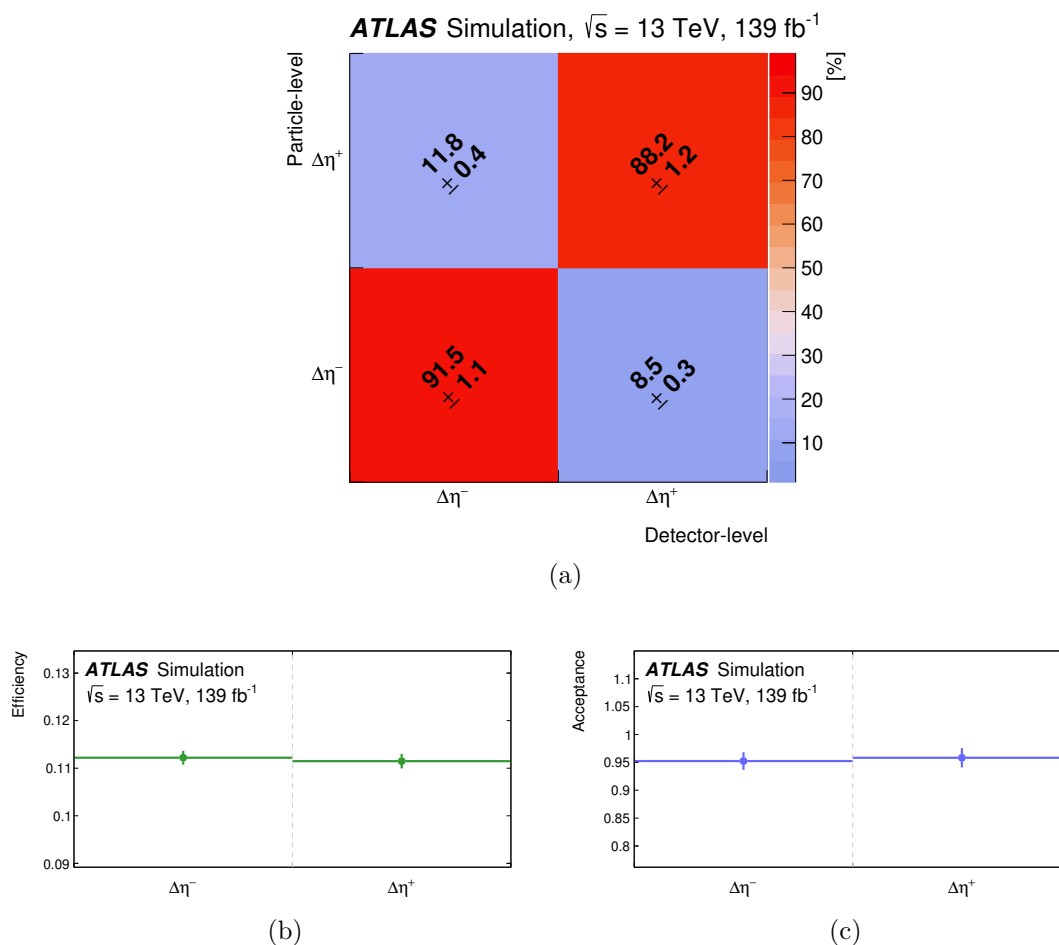


Figure 6. (a) The migration matrix and (b,c) the efficiency/acceptance corrections that are used as input for the unfolding of $SR\text{-}2b\text{-low}N_{\text{jets}}$. The matrices are normalised such that the sum of any given row is 100%, although small differences may be present due to rounding. The error bars of the efficiency/acceptance correction terms represent the MC statistical uncertainties per bin based on the nominal $t\bar{t}W$ SHERPA sample.

The unfolding procedure is then performed on this pseudo-data for several positive and negative deviations from the SM A_c^ℓ to compute the relation between the injected and extracted A_c^ℓ values and to estimate the bias that the fit procedure introduces. After the fit to real data, the observed A_c^ℓ is substituted into the relation to extract the bias. The bias estimated from this procedure is found to be 0.004. Although this value is well covered by the systematic uncertainties, it is added as an extra uncertainty in the unfolded A_c^ℓ value to account for this effect.

The charge asymmetry value, unfolded to particle level (PL) in the fiducial volume defined in section 9.2, is found to be

$$A_c^\ell(t\bar{t}W)^{\text{PL}} = -0.11 \pm 0.17 \text{ (stat.)} \pm 0.05 \text{ (syst.)},$$

with a SM expectation calculated using the nominal $t\bar{t}W$ SHERPA simulation of

$$A_c^\ell(t\bar{t}W)_{\text{SM}}^{\text{PL}} = -0.063^{+0.007}_{-0.004} (\text{scale}) \pm 0.004 (\text{MC stat.}).$$

The nominal values for the background normalisations are the same as reported in section 8. The contributions from the most relevant uncertainties in the charge asymmetry at particle level are given in table 5. The sources of uncertainty are similar to the ones reported in table 4, with the $\Delta\eta^\pm$ CR-dependency, the modelling of the $t\bar{t}W$ and $t\bar{t}Z$ MC processes and the statistical uncertainty being the dominant ones. The statistical uncertainty is slightly increased relative to the detector-level result due to the unfolding procedure.

In principle, the $t\bar{t}W$ A_c^ℓ has sensitivity to certain linear combinations of SMEFT coefficients that parameterise the effect of operators involving four quarks. However, the constraints on the coefficients obtainable with this result are not competitive with those from $t\bar{t}$ production cross-sections in the boosted regime and asymmetries [15, 87–89]. Moreover, they are not expected to be competitive even with the large datasets of the High-Luminosity LHC.

10 Conclusions

This paper presents a search for the leptonic charge asymmetry in $t\bar{t}W$ production using pp collision data at $\sqrt{s} = 13$ TeV with the full Run 2 data sample collected with the ATLAS detector at the LHC, corresponding to an integrated luminosity of 139 fb^{-1} . The leptonic charge asymmetry is defined as the pseudorapidity difference between the two reconstructed charged leptons associated with top quarks (or top antiquarks). The search is performed in 3ℓ final states using reconstructed light leptons (electrons or muons), together with jets and b -jets. To correctly match the leptons to either top quarks or top antiquarks, a technique based on a BDT is used.

The charge asymmetry at reconstruction level is obtained by performing a simultaneous profile-likelihood fit to data in different signal and control regions optimised for either the $t\bar{t}W$ process or the major SM background processes ($t\bar{t}Z$, non-prompt leptons from HF decays or electrons from γ -conversions). The charge asymmetry is extracted together with the normalisations for these background processes and is found to be

$$A_c^\ell(t\bar{t}W) = -0.12 \pm 0.14 (\text{stat.}) \pm 0.05 (\text{syst.}).$$

This is consistent with the SM expectation of

$$A_c^\ell(t\bar{t}W)_{\text{SM}} = -0.084^{+0.005}_{-0.003} (\text{scale}) \pm 0.006 (\text{MC stat.}),$$

calculated using the nominal $t\bar{t}W$ SHERPA simulation. An unfolding procedure is used to obtain the charge asymmetry at particle level in a specific fiducial volume in the 3ℓ channel. The unfolding is based on a profile-likelihood approach, where the unfolding is performed together with fitting normalisations of the major background processes, using the same procedure used to derive the charge asymmetry at reconstruction level. The charge asymmetry at particle level yields

$$A_c^\ell(t\bar{t}W)^{\text{PL}} = -0.11 \pm 0.17 (\text{stat.}) \pm 0.05 (\text{syst.}),$$

	$\Delta A_c^\ell(t\bar{t}W)^{\text{PL}}$
Experimental uncertainties	
Leptons	0.014
Jet energy resolution	0.011
Pile-up	0.008
Jet energy scale	0.004
E_T^{miss}	0.0015
Luminosity	0.0011
Jet vertex tagger	0.00027
MC modelling uncertainties	
$t\bar{t}W$ modelling	0.022
$t\bar{t}Z$ modelling	0.017
$\text{HF}_{e/\mu}$ modelling	0.015
Others modelling	0.015
WZ/ZZ + jets modelling	0.014
$t\bar{t}H$ modelling	0.006
Other uncertainties	
Unfolding bias	0.004
$\Delta\eta^\pm$ CR-dependency	0.04
MC statistical uncertainty	0.027
Response matrix	0.009
Data statistical uncertainty	0.17
Total uncertainty	0.18

Table 5. List of the most relevant systematic and statistical uncertainties in the leptonic charge asymmetry at particle level $A_c^\ell(t\bar{t}W)^{\text{PL}}$. For this table, the uncertainties are symmetrised and grouped into categories. The sum in quadrature of the individual uncertainties is not necessarily equal to the total uncertainty due to correlations introduced by the fit.

with a SM expectation calculated using the nominal $t\bar{t}W$ SHERPA simulation of

$$A_c^\ell(t\bar{t}W)_{\text{SM}}^{\text{PL}} = -0.063_{-0.004}^{+0.007} (\text{scale}) \pm 0.004 (\text{MC stat.}).$$

The most relevant systematic uncertainties affecting this search are the $\Delta\eta^\pm$ CR-dependency of the fit, as well as the modelling uncertainties of the $t\bar{t}W$ and $t\bar{t}Z$ MC processes in the 3ℓ channel. However, both the reconstruction- and particle-level results are severely limited by the statistical uncertainties of the data.

Acknowledgments

We thank CERN for the very successful operation of the LHC, as well as the support staff from our institutions without whom ATLAS could not be operated efficiently.

We acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWFW and FWF, Austria; ANAS, Azerbaijan; SSTC, Belarus; CNPq and FAPESP, Brazil; NSERC, NRC and CFI, Canada; CERN; ANID, Chile; CAS, MOST and NSFC, China; Minciencias, Colombia; MEYS CR, Czech Republic; DNRF and DNSRC, Denmark; IN2P3-CNRS and CEA-DRF/IRFU, France; SRNSFG, Georgia; BMBF, HGF and MPG, Germany; GSRI, Greece; RGC and Hong Kong SAR, China; ISF and Benozio Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; NWO, Netherlands; RCN, Norway; MEiN, Poland; FCT, Portugal; MNE/IFA, Romania; JINR; MES of Russia and NRC KI, Russian Federation; MESTD, Serbia; MSSR, Slovakia; ARRS and MIZŠ, Slovenia; DSI/NRF, South Africa; MICINN, Spain; SRC and Wallenberg Foundation, Sweden; SERI, SNSF and Cantons of Bern and Geneva, Switzerland; MOST, Taiwan; TENMAK, Türkiye; STFC, United Kingdom; DOE and NSF, United States of America. In addition, individual groups and members have received support from BCKDF, CANARIE, Compute Canada and CRC, Canada; COST, ERC, ERDF, Horizon 2020 and Marie Skłodowska-Curie Actions, European Union; Investissements d’Avenir Labex, Investissements d’Avenir Idex and ANR, France; DFG and AvH Foundation, Germany; Herakleitos, Thales and Aristeia programmes co-financed by EU-ESF and the Greek NSRF, Greece; BSF-NSF and GIF, Israel; Norwegian Financial Mechanism 2014–2021, Norway; NCN and NAWA, Poland; La Caixa Banking Foundation, CERCA Programme Generalitat de Catalunya and PROMETEO and GenT Programmes Generalitat Valenciana, Spain; Göran Gustafssons Stiftelse, Sweden; The Royal Society and Leverhulme Trust, United Kingdom.

The crucial computing support from all WLCG partners is acknowledged gratefully, in particular from CERN, the ATLAS Tier-1 facilities at TRIUMF (Canada), NDGF (Denmark, Norway, Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), ASGC (Taiwan), RAL (U.K.) and BNL (U.S.A.), the Tier-2 facilities worldwide and large non-WLCG resource providers. Major contributors of computing resources are listed in ref. [90].

Open Access. This article is distributed under the terms of the Creative Commons Attribution License ([CC-BY 4.0](https://creativecommons.org/licenses/by/4.0/)), which permits any use, distribution and reproduction in any medium, provided the original author(s) and source are credited. SCOAP³ supports the goals of the International Year of Basic Sciences for Sustainable Development.

References

- [1] A. Broggio et al., *Top-quark pair hadroproduction in association with a heavy boson at NLO+NNLL including EW corrections*, *JHEP* **08** (2019) 039 [[arXiv:1907.04343](https://arxiv.org/abs/1907.04343)] [[INSPIRE](#)].
- [2] B. Grzadkowski, M. Iskrzynski, M. Misiak and J. Rosiek, *Dimension-six terms in the Standard Model Lagrangian*, *JHEP* **10** (2010) 085 [[arXiv:1008.4884](https://arxiv.org/abs/1008.4884)] [[INSPIRE](#)].
- [3] ATLAS collaboration, *Search for squarks and gluinos in final states with same-sign leptons and jets using 139 fb^{-1} of data collected with the ATLAS detector*, *JHEP* **06** (2020) 046 [[arXiv:1909.08457](https://arxiv.org/abs/1909.08457)] [[INSPIRE](#)].
- [4] ATLAS collaboration, *Search for new phenomena in events with same-charge leptons and b-jets in pp collisions at $\sqrt{s} = 13\text{ TeV}$ with the ATLAS detector*, *JHEP* **12** (2018) 039 [[arXiv:1807.11883](https://arxiv.org/abs/1807.11883)] [[INSPIRE](#)].
- [5] ATLAS collaboration, *Evidence for the associated production of the Higgs boson and a top quark pair with the ATLAS detector*, *Phys. Rev. D* **97** (2018) 072003 [[arXiv:1712.08891](https://arxiv.org/abs/1712.08891)] [[INSPIRE](#)].
- [6] ATLAS collaboration, *Measurement of the $t\bar{t}\bar{t}$ production cross section in pp collisions at $\sqrt{s} = 13\text{ TeV}$ with the ATLAS detector*, *JHEP* **11** (2021) 118 [[arXiv:2106.11683](https://arxiv.org/abs/2106.11683)] [[INSPIRE](#)].
- [7] ATLAS collaboration, *Measurement of the $t\bar{t}Z$ and $t\bar{t}W$ cross sections in proton-proton collisions at $\sqrt{s} = 13\text{ TeV}$ with the ATLAS detector*, *Phys. Rev. D* **99** (2019) 072009 [[arXiv:1901.03584](https://arxiv.org/abs/1901.03584)] [[INSPIRE](#)].
- [8] CMS collaboration, *Measurement of the cross section of top quark-antiquark pair production in association with a W boson in proton-proton collisions at $\sqrt{s} = 13\text{ TeV}$* , [arXiv:2208.06485](https://arxiv.org/abs/2208.06485) [[INSPIRE](#)].
- [9] CDF and D0 collaborations, *Combined forward-backward asymmetry measurements in top-antitop quark production at the Tevatron*, *Phys. Rev. Lett.* **120** (2018) 042001 [[arXiv:1709.04894](https://arxiv.org/abs/1709.04894)] [[INSPIRE](#)].
- [10] F. Maltoni, M.L. Mangano, I. Tsinikos and M. Zaro, *Top-quark charge asymmetry and polarization in $t\bar{t}W^\pm$ production at the LHC*, *Phys. Lett. B* **736** (2014) 252 [[arXiv:1406.3262](https://arxiv.org/abs/1406.3262)] [[INSPIRE](#)].
- [11] G. Bevilacqua et al., *NLO QCD corrections to off-shell $t\bar{t}W^\pm$ production at the LHC: correlations and asymmetries*, *Eur. Phys. J. C* **81** (2021) 675 [[arXiv:2012.01363](https://arxiv.org/abs/2012.01363)] [[INSPIRE](#)].
- [12] I. Brivio and M. Trott, *The Standard Model as an Effective Field Theory*, *Phys. Rept.* **793** (2019) 1 [[arXiv:1706.08945](https://arxiv.org/abs/1706.08945)] [[INSPIRE](#)].
- [13] CDF collaboration, *Evidence for a mass dependent forward-backward asymmetry in top quark pair production*, *Phys. Rev. D* **83** (2011) 112003 [[arXiv:1101.0034](https://arxiv.org/abs/1101.0034)] [[INSPIRE](#)].
- [14] ATLAS and CMS collaborations, *Combination of inclusive and differential $t\bar{t}$ charge asymmetry measurements using ATLAS and CMS data at $\sqrt{s} = 7$ and 8 TeV* , *JHEP* **04** (2018) 033 [[arXiv:1709.05327](https://arxiv.org/abs/1709.05327)] [[INSPIRE](#)].

- [15] ATLAS collaboration, *Evidence for the charge asymmetry in $pp \rightarrow t\bar{t}$ production at $\sqrt{s} = 13$ TeV with the ATLAS detector*, [arXiv:2208.12095](#) [INSPIRE].
- [16] CMS collaboration, *Measurement of the $t\bar{t}$ charge asymmetry in events with highly Lorentz-boosted top quarks in pp collisions at $\sqrt{s} = 13$ TeV*, [arXiv:2208.02751](#) [INSPIRE].
- [17] CMS collaboration, *Measurements of $t\bar{t}$ differential cross sections in proton-proton collisions at $\sqrt{s} = 13$ TeV using events containing two leptons*, *JHEP* **02** (2019) 149 [[arXiv:1811.06625](#)] [INSPIRE].
- [18] ATLAS collaboration, *Measurement of the charge asymmetry in top-quark pair production in association with a photon with the ATLAS experiment*, [arXiv:2212.10552](#) [INSPIRE].
- [19] ATLAS collaboration, *The ATLAS Experiment at the CERN Large Hadron Collider*, 2008 *JINST* **3** S08003 [INSPIRE].
- [20] ATLAS collaboration, *ATLAS Insertable B-Layer Technical Design Report*, [ATLAS-TDR-2010-19](#) (2010).
- [21] ATLAS IBL collaboration, *Production and integration of the ATLAS Insertable B-Layer*, 2018 *JINST* **13** T05008 [[arXiv:1803.00844](#)] [INSPIRE].
- [22] ATLAS collaboration, *Performance of the ATLAS trigger system in 2015*, *Eur. Phys. J. C* **77** (2017) 317 [[arXiv:1611.09661](#)] [INSPIRE].
- [23] ATLAS collaboration, *The ATLAS Collaboration Software and Firmware*, [ATL-SOFT-PUB-2021-001](#), CERN, Geneva (2021).
- [24] ATLAS collaboration, *Luminosity determination in pp collisions at $\sqrt{s} = 13$ TeV using the ATLAS detector at the LHC*, [ATLAS-CONF-2019-021](#), CERN, Geneva (2019).
- [25] G. Avoni et al., *The new LUCID-2 detector for luminosity measurement and monitoring in ATLAS*, 2018 *JINST* **13** P07017 [INSPIRE].
- [26] T. Sjöstrand, S. Mrenna and P.Z. Skands, *A brief introduction to PYTHIA 8.1*, *Comput. Phys. Commun.* **178** (2008) 852 [[arXiv:0710.3820](#)] [INSPIRE].
- [27] R.D. Ball et al., *Parton distributions with LHC data*, *Nucl. Phys. B* **867** (2013) 244 [[arXiv:1207.1303](#)] [INSPIRE].
- [28] ATLAS collaboration, *The Pythia 8 A3 tune description of ATLAS minimum bias and inelastic measurements incorporating the Donnachie-Landshoff diffractive model*, [ATL-PHYS-PUB-2016-017](#), CERN, Geneva (2016).
- [29] GEANT4 collaboration, *GEANT4 — a simulation toolkit*, *Nucl. Instrum. Meth. A* **506** (2003) 250 [INSPIRE].
- [30] ATLAS collaboration, *The ATLAS Simulation Infrastructure*, *Eur. Phys. J. C* **70** (2010) 823 [[arXiv:1005.4568](#)] [INSPIRE].
- [31] SHERPA collaboration, *Event generation with Sherpa 2.2*, *SciPost Phys.* **7** (2019) 034 [[arXiv:1905.09127](#)] [INSPIRE].
- [32] NNPDF collaboration, *Parton distributions for the LHC run II*, *JHEP* **04** (2015) 040 [[arXiv:1410.8849](#)] [INSPIRE].
- [33] T. Gleisberg and S. Hoeche, *Comix, a new matrix element generator*, *JHEP* **12** (2008) 039 [[arXiv:0808.3674](#)] [INSPIRE].
- [34] S. Schumann and F. Krauss, *A parton shower algorithm based on Catani-Seymour dipole factorisation*, *JHEP* **03** (2008) 038 [[arXiv:0709.1027](#)] [INSPIRE].

- [35] F. Cascioli, P. Maierhöfer and S. Pozzorini, *Scattering Amplitudes with Open Loops*, *Phys. Rev. Lett.* **108** (2012) 111601 [[arXiv:1111.5206](#)] [[INSPIRE](#)].
- [36] A. Denner, S. Dittmaier and L. Hofer, *COLLIER: A fortran-based complex one-loop library in extended regularizations*, *Comput. Phys. Commun.* **212** (2017) 220 [[arXiv:1604.06792](#)] [[INSPIRE](#)].
- [37] PARTICLE DATA GROUP collaboration, *Review of Particle Physics*, *PTEP* **2022** (2022) 083C01 [[INSPIRE](#)].
- [38] S. Kallweit et al., *NLO QCD+EW predictions for $V + jets$ including off-shell vector-boson decays and multijet merging*, *JHEP* **04** (2016) 021 [[arXiv:1511.08692](#)] [[INSPIRE](#)].
- [39] J. Alwall et al., *MadGraph 5: going beyond*, *JHEP* **06** (2011) 128 [[arXiv:1106.0522](#)] [[INSPIRE](#)].
- [40] J. Alwall et al., *The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations*, *JHEP* **07** (2014) 079 [[arXiv:1405.0301](#)] [[INSPIRE](#)].
- [41] T. Sjöstrand et al., *An introduction to PYTHIA 8.2*, *Comput. Phys. Commun.* **191** (2015) 159 [[arXiv:1410.3012](#)] [[INSPIRE](#)].
- [42] R. Frederix and S. Frixione, *Merging meets matching in MC@NLO*, *JHEP* **12** (2012) 061 [[arXiv:1209.6215](#)] [[INSPIRE](#)].
- [43] S. Catani, F. Krauss, R. Kuhn and B.R. Webber, *QCD Matrix Elements + Parton Showers*, *JHEP* **11** (2001) 063 [[hep-ph/0109231](#)] [[INSPIRE](#)].
- [44] K. Hamilton, P. Nason and G. Zanderighi, *MINLO: multi-scale improved NLO*, *JHEP* **10** (2012) 155 [[arXiv:1206.3572](#)] [[INSPIRE](#)].
- [45] ATLAS collaboration, *ATLAS Pythia 8 tunes to 7 TeV data*, [ATL-PHYS-PUB-2014-021](#), CERN, Geneva (2014).
- [46] S. Frixione, E. Laenen, P. Motylinski and B.R. Webber, *Angular correlations of lepton pairs from vector boson and top quark decays in Monte Carlo simulations*, *JHEP* **04** (2007) 081 [[hep-ph/0702198](#)] [[INSPIRE](#)].
- [47] P. Artoisenet, R. Frederix, O. Mattelaer and R. Rietkerk, *Automatic spin-entangled decays of heavy resonances in Monte Carlo simulations*, *JHEP* **03** (2013) 015 [[arXiv:1212.3460](#)] [[INSPIRE](#)].
- [48] S. Frixione, P. Nason and C. Oleari, *Matching NLO QCD computations with parton shower simulations: the POWHEG method*, *JHEP* **11** (2007) 070 [[arXiv:0709.2092](#)] [[INSPIRE](#)].
- [49] G. Corcella et al., *HERWIG 6: an event generator for hadron emission reactions with interfering gluons (including supersymmetric processes)*, *JHEP* **01** (2001) 010 [[hep-ph/0011363](#)] [[INSPIRE](#)].
- [50] M. Bähr et al., *Herwig++ physics and manual*, *Eur. Phys. J. C* **58** (2008) 639 [[arXiv:0803.0883](#)] [[INSPIRE](#)].
- [51] J. Bellm et al., *Herwig 7.2 release note*, *Eur. Phys. J. C* **80** (2020) 452 [[arXiv:1912.06509](#)] [[INSPIRE](#)].
- [52] ATLAS collaboration, *Studies on top-quark Monte Carlo modelling for Top2016*, [ATL-PHYS-PUB-2016-020](#), CERN, Geneva (2016).

- [53] K. Melnikov, M. Schulze and A. Scharf, *QCD corrections to top quark pair production in association with a photon at hadron colliders*, *Phys. Rev. D* **83** (2011) 074013 [[arXiv:1102.1967](#)] [[INSPIRE](#)].
- [54] M. Czakon and A. Mitov, *NNLO corrections to top pair production at hadron colliders: the quark-gluon reaction*, *JHEP* **01** (2013) 080 [[arXiv:1210.6832](#)] [[INSPIRE](#)].
- [55] LHC HIGGS CROSS SECTION WORKING GROUP collaboration, *Handbook of LHC Higgs Cross Sections: 4. Deciphering the Nature of the Higgs Sector*, [arXiv:1610.07922](#) [[DOI:10.23731/CYRM-2017-002](#)] [[INSPIRE](#)].
- [56] N. Kidonakis, *Two-loop soft anomalous dimensions for single top quark associated production with a W^- or H^-* , *Phys. Rev. D* **82** (2010) 054018 [[arXiv:1005.4451](#)] [[INSPIRE](#)].
- [57] J. Bellm et al., *Herwig 7.1 Release Note*, [arXiv:1705.06919](#) [[INSPIRE](#)].
- [58] F. Demartin et al., *tWH associated production at the LHC*, *Eur. Phys. J. C* **77** (2017) 34 [[arXiv:1607.05862](#)] [[INSPIRE](#)].
- [59] ATLAS collaboration, *Measurement of the Z/γ^* boson transverse momentum distribution in pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector*, *JHEP* **09** (2014) 145 [[arXiv:1406.3660](#)] [[INSPIRE](#)].
- [60] K. Melnikov and F. Petriello, *Electroweak gauge boson production at hadron colliders through $\mathcal{O}(\alpha_s^2)$* , *Phys. Rev. D* **74** (2006) 114017 [[hep-ph/0609070](#)] [[INSPIRE](#)].
- [61] P. Golonka and Z. Was, *PHOTOS Monte Carlo: a precision tool for QED corrections in Z and W decays*, *Eur. Phys. J. C* **45** (2006) 97 [[hep-ph/0506026](#)] [[INSPIRE](#)].
- [62] D.J. Lange, *The EvtGen particle decay simulation package*, *Nucl. Instrum. Meth. A* **462** (2001) 152 [[INSPIRE](#)].
- [63] ATLAS collaboration, *Electron and photon performance measurements with the ATLAS detector using the 2015–2017 LHC proton-proton collision data*, *2019 JINST* **14** P12006 [[arXiv:1908.00005](#)] [[INSPIRE](#)].
- [64] ATLAS collaboration, *Muon reconstruction performance of the ATLAS detector in proton-proton collision data at $\sqrt{s} = 13$ TeV*, *Eur. Phys. J. C* **76** (2016) 292 [[arXiv:1603.05598](#)] [[INSPIRE](#)].
- [65] ATLAS collaboration, *Muon reconstruction and identification efficiency in ATLAS using the full Run 2 pp collision data set at $\sqrt{s} = 13$ TeV*, *Eur. Phys. J. C* **81** (2021) 578 [[arXiv:2012.00578](#)] [[INSPIRE](#)].
- [66] M. Cacciari, G.P. Salam and G. Soyez, *The anti- k_t jet clustering algorithm*, *JHEP* **04** (2008) 063 [[arXiv:0802.1189](#)] [[INSPIRE](#)].
- [67] ATLAS collaboration, *Jet reconstruction and performance using particle flow with the ATLAS Detector*, *Eur. Phys. J. C* **77** (2017) 466 [[arXiv:1703.10485](#)] [[INSPIRE](#)].
- [68] M. Cacciari, G.P. Salam and G. Soyez, *FastJet user manual*, *Eur. Phys. J. C* **72** (2012) 1896 [[arXiv:1111.6097](#)] [[INSPIRE](#)].
- [69] ATLAS collaboration, *Jet energy scale and resolution measured in proton-proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector*, *Eur. Phys. J. C* **81** (2021) 689 [[arXiv:2007.02645](#)] [[INSPIRE](#)].
- [70] ATLAS collaboration, *Tagging and suppression of pileup jets with the ATLAS detector*, [ATLAS-CONF-2014-018](#), CERN, Geneva (2014).

- [71] ATLAS collaboration, *Performance of pile-up mitigation techniques for jets in pp collisions at $\sqrt{s} = 8$ TeV using the ATLAS detector*, *Eur. Phys. J. C* **76** (2016) 581 [[arXiv:1510.03823](#)] [[INSPIRE](#)].
- [72] ATLAS collaboration, *ATLAS b-jet identification performance and efficiency measurement with $t\bar{t}$ events in pp collisions at $\sqrt{s} = 13$ TeV*, *Eur. Phys. J. C* **79** (2019) 970 [[arXiv:1907.05120](#)] [[INSPIRE](#)].
- [73] ATLAS collaboration, *ATLAS flavour-tagging algorithms for the LHC Run 2 pp collision dataset*, [arXiv:2211.16345](#) [[INSPIRE](#)].
- [74] ATLAS collaboration, *Performance of missing transverse momentum reconstruction with the ATLAS detector using proton-proton collisions at $\sqrt{s} = 13$ TeV*, *Eur. Phys. J. C* **78** (2018) 903 [[arXiv:1802.08168](#)] [[INSPIRE](#)].
- [75] ATLAS collaboration, *Performance of the ATLAS muon triggers in Run 2, 2020* *JINST* **15** P09015 [[arXiv:2004.13447](#)] [[INSPIRE](#)].
- [76] ATLAS collaboration, *Performance of electron and photon triggers in ATLAS during LHC Run 2*, *Eur. Phys. J. C* **80** (2020) 47 [[arXiv:1909.00761](#)] [[INSPIRE](#)].
- [77] F. Pedregosa et al., *Scikit-learn: machine learning in python*, *J. Machine Learning Res.* **12** (2011) 2825 [[arXiv:1201.0490](#)] [[INSPIRE](#)].
- [78] ATLAS collaboration, *Electron reconstruction and identification in the ATLAS experiment using the 2015 and 2016 LHC proton-proton collision data at $\sqrt{s} = 13$ TeV*, *Eur. Phys. J. C* **79** (2019) 639 [[arXiv:1902.04655](#)] [[INSPIRE](#)].
- [79] ATLAS collaboration, *Optimisation and performance studies of the ATLAS b-tagging algorithms for the 2017-18 LHC run*, [ATL-PHYS-PUB-2017-013](#), CERN, Geneva (2017).
- [80] ATLAS collaboration, *Calibration of light-flavour b-jet mistagging rates using ATLAS proton-proton collision data at $\sqrt{s} = 13$ TeV*, [ATLAS-CONF-2018-006](#), CERN, Geneva (2018).
- [81] J. Butterworth et al., *PDF4LHC recommendations for LHC Run II*, *J. Phys. G* **43** (2016) 023001 [[arXiv:1510.03865](#)] [[INSPIRE](#)].
- [82] ATLAS collaboration, *Observation of the associated production of a top quark and a Z boson in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector*, *JHEP* **07** (2020) 124 [[arXiv:2002.07546](#)] [[INSPIRE](#)].
- [83] ATLAS collaboration, *Measurement of $W^{\pm}Z$ production cross sections and gauge boson polarisation in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector*, *Eur. Phys. J. C* **79** (2019) 535 [[arXiv:1902.05759](#)] [[INSPIRE](#)].
- [84] ATLAS collaboration, *Observation of four-top-quark production in the multilepton final state with the ATLAS detector*, *Eur. Phys. J. C* **83** (2023) 496 [[arXiv:2303.15061](#)] [[INSPIRE](#)].
- [85] W. Verkerke and D. Kirkby, *The RooFit toolkit for data modeling*, [physics/0306116](#).
- [86] M. Cacciari, G.P. Salam and G. Soyez, *The catchment area of jets*, *JHEP* **04** (2008) 005 [[arXiv:0802.1188](#)] [[INSPIRE](#)].
- [87] ATLAS collaboration, *Measurements of differential cross-sections in top-quark pair events with a high transverse momentum top quark and limits on beyond the Standard Model contributions to top-quark pair production with the ATLAS detector at $\sqrt{s} = 13$ TeV*, *JHEP* **06** (2022) 063 [[arXiv:2202.12134](#)] [[INSPIRE](#)].

- [88] ATLAS collaboration, *Differential $t\bar{t}$ cross-section measurements using boosted top quarks in the all-hadronic final state with 139 fb^{-1} of ATLAS data*, *JHEP* **04** (2023) 080 [[arXiv:2205.02817](#)] [[INSPIRE](#)].
- [89] ATLAS collaboration, *Measurement of the energy asymmetry in $t\bar{t}j$ production at 13 TeV with the ATLAS experiment and interpretation in the SMEFT framework*, *Eur. Phys. J. C* **82** (2022) 374 [[arXiv:2110.05453](#)] [[INSPIRE](#)].
- [90] ATLAS collaboration, *ATLAS Computing Acknowledgements*, [ATL-SOFT-PUB-2021-003](#), CERN, Geneva (2021).

The ATLAS collaboration

G. Aad [ID](#)¹⁰², B. Abbott [ID](#)¹²⁰, D.C. Abbott [ID](#)¹⁰³, K. Abeling [ID](#)⁵⁵, S.H. Abidi [ID](#)²⁹,
A. Abouhorma [ID](#)^{35e}, H. Abramowicz [ID](#)¹⁵¹, H. Abreu [ID](#)¹⁵⁰, Y. Abulaiti [ID](#)¹¹⁷,
A.C. Abusleme Hoffman [ID](#)^{137a}, B.S. Acharya [ID](#)^{69a,69b,p}, C. Adam Bourdarios [ID](#)⁴, L. Adamczyk [ID](#)^{85a},
L. Adamek [ID](#)¹⁵⁵, S.V. Addepalli [ID](#)²⁶, J. Adelman [ID](#)¹¹⁵, A. Adiguzel [ID](#)^{21c}, S. Adorni [ID](#)⁵⁶,
T. Adye [ID](#)¹³⁴, A.A. Affolder [ID](#)¹³⁶, Y. Afik [ID](#)³⁶, M.N. Agaras [ID](#)¹³, J. Agarwala [ID](#)^{73a,73b},
A. Aggarwal [ID](#)¹⁰⁰, C. Agheorghiesei [ID](#)^{27c}, J.A. Aguilar-Saavedra [ID](#)^{130f}, A. Ahmad [ID](#)³⁶,
F. Ahmadov [ID](#)^{38,z}, W.S. Ahmed [ID](#)¹⁰⁴, S. Ahuja [ID](#)⁹⁵, X. Ai [ID](#)⁴⁸, G. Aielli [ID](#)^{76a,76b},
M. Ait Tamlihat [ID](#)^{35e}, B. Aitbenchikh [ID](#)^{35a}, I. Aizenberg [ID](#)¹⁶⁹, M. Akbiyik [ID](#)¹⁰⁰,
T.P.A. Åkesson [ID](#)⁹⁸, A.V. Akimov [ID](#)³⁷, K. Al Khoury [ID](#)⁴¹, G.L. Alberghi [ID](#)^{23b}, J. Albert [ID](#)¹⁶⁵,
P. Albicocco [ID](#)⁵³, S. Alderweireldt [ID](#)⁵², M. Aleksa [ID](#)³⁶, I.N. Aleksandrov [ID](#)³⁸, C. Alexa [ID](#)^{27b},
T. Alexopoulos [ID](#)¹⁰, A. Alfonsi [ID](#)¹¹⁴, F. Alfonsi [ID](#)^{23b}, M. Alhroob [ID](#)¹²⁰, B. Ali [ID](#)¹³², S. Ali [ID](#)¹⁴⁸,
M. Aliev [ID](#)³⁷, G. Alimonti [ID](#)^{71a}, W. Alkahi [ID](#)⁵⁵, C. Allaire [ID](#)⁶⁶, B.M.M. Allbrooke [ID](#)¹⁴⁶,
C.A. Allendes Flores [ID](#)^{137f}, P.P. Allport [ID](#)²⁰, A. Aloisio [ID](#)^{72a,72b}, F. Alonso [ID](#)⁹⁰, C. Alpigiani [ID](#)¹³⁸,
M. Alvarez Estevez [ID](#)⁹⁹, A. Alvarez Fernandez [ID](#)¹⁰⁰, M.G. Alviggi [ID](#)^{72a,72b}, M. Aly [ID](#)¹⁰¹,
Y. Amaral Coutinho [ID](#)^{82b}, A. Ambler [ID](#)¹⁰⁴, C. Amelung [ID](#)³⁶, M. Amerl [ID](#)¹, C.G. Ames [ID](#)¹⁰⁹,
D. Amidei [ID](#)¹⁰⁶, S.P. Amor Dos Santos [ID](#)^{130a}, K.R. Amos [ID](#)¹⁶³, V. Ananiev [ID](#)¹²⁵,
C. Anastopoulos [ID](#)¹³⁹, T. Andeen [ID](#)¹¹, J.K. Anders [ID](#)³⁶, S.Y. Andrean [ID](#)^{47a,47b},
A. Andreatta [ID](#)^{71a,71b}, S. Angelidakis [ID](#)⁹, A. Angerami [ID](#)^{41,ab}, A.V. Anisenkov [ID](#)³⁷, A. Annovi [ID](#)^{74a},
C. Antel [ID](#)⁵⁶, M.T. Anthony [ID](#)¹³⁹, E. Antipov [ID](#)¹²¹, M. Antonelli [ID](#)⁵³, D.J.A. Antrim [ID](#)^{17a},
F. Anulli [ID](#)^{75a}, M. Aoki [ID](#)⁸³, T. Aoki [ID](#)¹⁵³, J.A. Aparisi Pozo [ID](#)¹⁶³, M.A. Aparo [ID](#)¹⁴⁶,
L. Aperio Bella [ID](#)⁴⁸, C. Appelt [ID](#)¹⁸, N. Aranzabal [ID](#)³⁶, V. Araujo Ferraz [ID](#)^{82a}, C. Arcangeletti [ID](#)⁵³,
A.T.H. Arce [ID](#)⁵¹, E. Arena [ID](#)⁹², J-F. Arguin [ID](#)¹⁰⁸, S. Argyropoulos [ID](#)⁵⁴, J.-H. Arling [ID](#)⁴⁸,
A.J. Armbruster [ID](#)³⁶, O. Arnaez [ID](#)¹⁵⁵, H. Arnold [ID](#)¹¹⁴, Z.P. Arrubarrena Tame [ID](#)¹⁰⁹,
G. Artoni [ID](#)^{75a,75b}, H. Asada [ID](#)¹¹¹, K. Asai [ID](#)¹¹⁸, S. Asai [ID](#)¹⁵³, N.A. Asbah [ID](#)⁶¹, J. Assahsah [ID](#)^{35d},
K. Assamagan [ID](#)²⁹, R. Astalos [ID](#)^{28a}, R.J. Atkin [ID](#)^{33a}, M. Atkinson [ID](#)¹⁶², N.B. Atlay [ID](#)¹⁸,
H. Atmani [ID](#)^{62b}, P.A. Atmasiddha [ID](#)¹⁰⁶, K. Augsten [ID](#)¹³², S. Auricchio [ID](#)^{72a,72b}, A.D. Auriol [ID](#)²⁰,
V.A. Austrup [ID](#)¹⁷¹, G. Avner [ID](#)¹⁵⁰, G. Avolio [ID](#)³⁶, K. Axiotis [ID](#)⁵⁶, G. Azuelos [ID](#)^{108,ad}, D. Babal [ID](#)^{28a},
H. Bachacou [ID](#)¹³⁵, K. Bachas [ID](#)^{152,r}, A. Bachiu [ID](#)³⁴, F. Backman [ID](#)^{47a,47b}, A. Badae [ID](#)⁶¹,
P. Bagnaia [ID](#)^{75a,75b}, M. Bahmani [ID](#)¹⁸, A.J. Bailey [ID](#)¹⁶³, V.R. Bailey [ID](#)¹⁶², J.T. Baines [ID](#)¹³⁴,
C. Bakalis [ID](#)¹⁰, O.K. Baker [ID](#)¹⁷², P.J. Bakker [ID](#)¹¹⁴, E. Bakos [ID](#)¹⁵, D. Bakshi Gupta [ID](#)⁸,
S. Balaji [ID](#)¹⁴⁷, R. Balasubramanian [ID](#)¹¹⁴, E.M. Baldin [ID](#)³⁷, P. Balek [ID](#)¹³³, E. Ballabene [ID](#)^{71a,71b},
F. Balli [ID](#)¹³⁵, L.M. Baltés [ID](#)^{63a}, W.K. Balunas [ID](#)³², J. Balz [ID](#)¹⁰⁰, E. Banas [ID](#)⁸⁶,
M. Bandieramonte [ID](#)¹²⁹, A. Bandyopadhyay [ID](#)²⁴, S. Bansal [ID](#)²⁴, L. Barak [ID](#)¹⁵¹, E.L. Barberio [ID](#)¹⁰⁵,
D. Barberis [ID](#)^{57b,57a}, M. Barbero [ID](#)¹⁰², G. Barbour [ID](#)⁹⁶, K.N. Barends [ID](#)^{33a}, T. Barillari [ID](#)¹¹⁰,
M-S. Barisits [ID](#)³⁶, T. Barklow [ID](#)¹⁴³, R.M. Barnett [ID](#)^{17a}, P. Baron [ID](#)¹²², D.A. Baron Moreno [ID](#)¹⁰¹,
A. Baroncelli [ID](#)^{62a}, G. Barone [ID](#)²⁹, A.J. Barr [ID](#)¹²⁶, L. Barranco Navarro [ID](#)^{47a,47b}, F. Barreiro [ID](#)⁹⁹,
J. Barreiro Guimarães da Costa [ID](#)^{14a}, U. Barron [ID](#)¹⁵¹, M.G. Barros Teixeira [ID](#)^{130a}, S. Barsov [ID](#)³⁷,
F. Bartels [ID](#)^{63a}, R. Bartoldus [ID](#)¹⁴³, A.E. Barton [ID](#)⁹¹, P. Bartos [ID](#)^{28a}, A. Basalaeu [ID](#)⁴⁸,
A. Basan [ID](#)¹⁰⁰, M. Baselga [ID](#)⁴⁹, I. Bashta [ID](#)^{77a,77b}, A. Bassalat [ID](#)^{66,b}, M.J. Basso [ID](#)¹⁵⁵,
C.R. Basson [ID](#)¹⁰¹, R.L. Bates [ID](#)⁵⁹, S. Batlamous [ID](#)^{35e}, J.R. Batley [ID](#)³², B. Batool [ID](#)¹⁴¹,
M. Battaglia [ID](#)¹³⁶, D. Battulga [ID](#)¹⁸, M. Bause [ID](#)^{75a,75b}, P. Bauer [ID](#)²⁴, J.B. Beacham [ID](#)⁵¹,

T. Beau [ID](#)¹²⁷, P.H. Beauchemin [ID](#)¹⁵⁸, F. Becherer [ID](#)⁵⁴, P. Bechtle [ID](#)²⁴, H.P. Beck [ID](#)^{19,q}, K. Becker [ID](#)¹⁶⁷, A.J. Beddall [ID](#)^{21d}, V.A. Bednyakov [ID](#)³⁸, C.P. Bee [ID](#)¹⁴⁵, L.J. Beemster¹⁵, T.A. Beermann [ID](#)³⁶, M. Begalli [ID](#)^{82d,82d}, M. Biegel [ID](#)²⁹, A. Behera [ID](#)¹⁴⁵, J.K. Behr [ID](#)⁴⁸, C. Beirao Da Cruz E Silva [ID](#)³⁶, J.F. Beirer [ID](#)^{55,36}, F. Beisiegel [ID](#)²⁴, M. Belfkir [ID](#)¹⁵⁹, G. Bella [ID](#)¹⁵¹, L. Bellagamba [ID](#)^{23b}, A. Bellerive [ID](#)³⁴, P. Bellos [ID](#)²⁰, K. Beloborodov [ID](#)³⁷, K. Belotskiy [ID](#)³⁷, N.L. Belyaev [ID](#)³⁷, D. Benчекroun [ID](#)^{35a}, F. Bendebba [ID](#)^{35a}, Y. Benhammou [ID](#)¹⁵¹, D.P. Benjamin [ID](#)²⁹, M. Benoit [ID](#)²⁹, J.R. Bensinger [ID](#)²⁶, S. Bentvelsen [ID](#)¹¹⁴, L. Beresford [ID](#)³⁶, M. Beretta [ID](#)⁵³, E. Bergeaas Kuutmann [ID](#)¹⁶¹, N. Berger [ID](#)⁴, B. Bergmann [ID](#)¹³², J. Beringer [ID](#)^{17a}, S. Berlendis [ID](#)⁷, G. Bernardi [ID](#)⁵, C. Bernius [ID](#)¹⁴³, F.U. Bernlochner [ID](#)²⁴, T. Berry [ID](#)⁹⁵, P. Berta [ID](#)¹³³, A. Berthold [ID](#)⁵⁰, I.A. Bertram [ID](#)⁹¹, S. Bethke [ID](#)¹¹⁰, A. Betti [ID](#)^{75a,75b}, A.J. Bevan [ID](#)⁹⁴, M. Bhamjee [ID](#)^{33c}, S. Bhatta [ID](#)¹⁴⁵, D.S. Bhattacharya [ID](#)¹⁶⁶, P. Bhattacharai [ID](#)²⁶, V.S. Bhopatkar [ID](#)¹²¹, R. Bi^{29,ag}, R.M. Bianchi [ID](#)¹²⁹, O. Biebel [ID](#)¹⁰⁹, R. Bielski [ID](#)¹²³, M. Biglietti [ID](#)^{77a}, T.R.V. Billoud [ID](#)¹³², M. Bindi [ID](#)⁵⁵, A. Bingul [ID](#)^{21b}, C. Bini [ID](#)^{75a,75b}, A. Biondini [ID](#)⁹², C.J. Birch-sykes [ID](#)¹⁰¹, G.A. Bird [ID](#)^{20,134}, M. Birman [ID](#)¹⁶⁹, M. Biros [ID](#)¹³³, T. Bisanz [ID](#)³⁶, E. Bisceglie [ID](#)^{43b,43a}, D. Biswas [ID](#)¹⁷⁰, A. Bitadze [ID](#)¹⁰¹, K. Bjørke [ID](#)¹²⁵, I. Bloch [ID](#)⁴⁸, C. Blocker [ID](#)²⁶, A. Blue [ID](#)⁵⁹, U. Blumenschein [ID](#)⁹⁴, J. Blumenthal [ID](#)¹⁰⁰, G.J. Bobbink [ID](#)¹¹⁴, V.S. Bobrovnikov [ID](#)³⁷, M. Boehler [ID](#)⁵⁴, D. Bogavac [ID](#)³⁶, A.G. Bogdanchikov [ID](#)³⁷, C. Bohm [ID](#)^{47a}, V. Boisvert [ID](#)⁹⁵, P. Bokan [ID](#)⁴⁸, T. Bold [ID](#)^{85a}, M. Bomben [ID](#)⁵, M. Bona [ID](#)⁹⁴, M. Boonekamp [ID](#)¹³⁵, C.D. Booth [ID](#)⁹⁵, A.G. Borbély [ID](#)⁵⁹, H.M. Borecka-Bielska [ID](#)¹⁰⁸, L.S. Borgna [ID](#)⁹⁶, G. Borissov [ID](#)⁹¹, D. Bortoletto [ID](#)¹²⁶, D. Boscherini [ID](#)^{23b}, M. Bosman [ID](#)¹³, J.D. Bossio Sola [ID](#)³⁶, K. Bouaouda [ID](#)^{35a}, N. Bouchhar [ID](#)¹⁶³, J. Boudreau [ID](#)¹²⁹, E.V. Bouhova-Thacker [ID](#)⁹¹, D. Boumediene [ID](#)⁴⁰, R. Bouquet [ID](#)⁵, A. Boveia [ID](#)¹¹⁹, J. Boyd [ID](#)³⁶, D. Boye [ID](#)²⁹, I.R. Boyko [ID](#)³⁸, J. Bracinik [ID](#)²⁰, N. Brahimy [ID](#)^{62d}, G. Brandt [ID](#)¹⁷¹, O. Brandt [ID](#)³², F. Braren [ID](#)⁴⁸, B. Brau [ID](#)¹⁰³, J.E. Brau [ID](#)¹²³, K. Brendlinger [ID](#)⁴⁸, R. Brenner [ID](#)¹⁶⁹, L. Brenner [ID](#)¹¹⁴, R. Brenner [ID](#)¹⁶¹, S. Bressler [ID](#)¹⁶⁹, D. Britton [ID](#)⁵⁹, D. Britzger [ID](#)¹¹⁰, I. Brock [ID](#)²⁴, G. Brooijmans [ID](#)⁴¹, W.K. Brooks [ID](#)^{137f}, E. Brost [ID](#)²⁹, L.M. Brown [ID](#)¹⁶⁵, T.L. Bruckler [ID](#)¹²⁶, P.A. Bruckman de Renstrom [ID](#)⁸⁶, B. Brüers [ID](#)⁴⁸, D. Bruncko [ID](#)^{28b,*}, A. Bruni [ID](#)^{23b}, G. Bruni [ID](#)^{23b}, M. Bruschi [ID](#)^{23b}, N. Bruscinò [ID](#)^{75a,75b}, T. Buanes [ID](#)¹⁶, Q. Buat [ID](#)¹³⁸, P. Buchholz [ID](#)¹⁴¹, A.G. Buckley [ID](#)⁵⁹, I.A. Budagov [ID](#)^{38,*}, M.K. Bugge [ID](#)¹²⁵, O. Bulekov [ID](#)³⁷, B.A. Bullard [ID](#)¹⁴³, S. Burdin [ID](#)⁹², C.D. Burgard [ID](#)⁴⁹, A.M. Burger [ID](#)⁴⁰, B. Burghgrave [ID](#)⁸, J.T.P. Burr [ID](#)³², C.D. Burton [ID](#)¹¹, J.C. Burzynski [ID](#)¹⁴², E.L. Busch [ID](#)⁴¹, V. Büscher [ID](#)¹⁰⁰, P.J. Bussey [ID](#)⁵⁹, J.M. Butler [ID](#)²⁵, C.M. Buttar [ID](#)⁵⁹, J.M. Butterworth [ID](#)⁹⁶, W. Buttinger [ID](#)¹³⁴, C.J. Buxo Vazquez¹⁰⁷, A.R. Buzykaev [ID](#)³⁷, G. Cabras [ID](#)^{23b}, S. Cabrera Urbán [ID](#)¹⁶³, D. Caforio [ID](#)⁵⁸, H. Cai [ID](#)¹²⁹, Y. Cai [ID](#)^{14a,14d}, V.M.M. Cairo [ID](#)³⁶, O. Cakir [ID](#)^{3a}, N. Calace [ID](#)³⁶, P. Calafiura [ID](#)^{17a}, G. Calderini [ID](#)¹²⁷, P. Calfayan [ID](#)⁶⁸, G. Callea [ID](#)⁵⁹, L.P. Caloba^{82b}, D. Calvet [ID](#)⁴⁰, S. Calvet [ID](#)⁴⁰, T.P. Calvet [ID](#)¹⁰², M. Calvetti [ID](#)^{74a,74b}, R. Camacho Toro [ID](#)¹²⁷, S. Camarda [ID](#)³⁶, D. Camarero Munoz [ID](#)²⁶, P. Camarri [ID](#)^{76a,76b}, M.T. Camerlingo [ID](#)^{72a,72b}, D. Cameron [ID](#)¹²⁵, C. Camincher [ID](#)¹⁶⁵, M. Campanelli [ID](#)⁹⁶, A. Camplani [ID](#)⁴², V. Canale [ID](#)^{72a,72b}, A. Canesse [ID](#)¹⁰⁴, M. Cano Bret [ID](#)⁸⁰, J. Cantero [ID](#)¹⁶³, Y. Cao [ID](#)¹⁶², F. Capocasa [ID](#)²⁶, M. Capua [ID](#)^{43b,43a}, A. Carbone [ID](#)^{71a,71b}, R. Cardarelli [ID](#)^{76a}, J.C.J. Cardenas [ID](#)⁸, F. Cardillo [ID](#)¹⁶³, T. Carli [ID](#)³⁶, G. Carlino [ID](#)^{72a}, J.I. Carlotto [ID](#)¹³, B.T. Carlson [ID](#)^{129,s}, E.M. Carlson [ID](#)^{165,156a}, L. Carminati [ID](#)^{71a,71b}, M. Carnesale [ID](#)^{75a,75b}, S. Caron [ID](#)¹¹³, E. Carquin [ID](#)^{137f}, S. Carrá [ID](#)^{71a,71b}, G. Carratta [ID](#)^{23b,23a}, F. Carrio Argos [ID](#)^{33g}, J.W.S. Carter [ID](#)¹⁵⁵, T.M. Carter [ID](#)⁵², M.P. Casado [ID](#)^{13,j}, A.F. Casha¹⁵⁵, E.G. Castiglia [ID](#)¹⁷², F.L. Castillo [ID](#)^{63a}, L. Castillo Garcia [ID](#)¹³,

V. Castillo Gimenez [ID](#)¹⁶³, N.F. Castro [ID](#)^{130a,130e}, A. Catinaccio [ID](#)³⁶, J.R. Catmore [ID](#)¹²⁵,
V. Cavaliere [ID](#)²⁹, N. Cavalli [ID](#)^{23b,23a}, V. Cavasinni [ID](#)^{74a,74b}, E. Celebi [ID](#)^{21a}, F. Celli [ID](#)¹²⁶,
M.S. Centonze [ID](#)^{70a,70b}, K. Cerny [ID](#)¹²², A.S. Cerqueira [ID](#)^{82a}, A. Cerri [ID](#)¹⁴⁶, L. Cerrito [ID](#)^{76a,76b},
F. Cerutti [ID](#)^{17a}, A. Cervelli [ID](#)^{23b}, S.A. Cetin [ID](#)^{21d}, Z. Chadi [ID](#)^{35a}, D. Chakraborty [ID](#)¹¹⁵,
M. Chala [ID](#)^{130f}, J. Chan [ID](#)¹⁷⁰, W.Y. Chan [ID](#)¹⁵³, J.D. Chapman [ID](#)³², B. Chargeishvili [ID](#)^{149b},
D.G. Charlton [ID](#)²⁰, T.P. Charman [ID](#)⁹⁴, M. Chatterjee [ID](#)¹⁹, S. Chekanov [ID](#)⁶, S.V. Chekulaev [ID](#)^{156a},
G.A. Chelkov [ID](#)^{38,a}, A. Chen [ID](#)¹⁰⁶, B. Chen [ID](#)¹⁵¹, B. Chen [ID](#)¹⁶⁵, H. Chen [ID](#)^{14c}, H. Chen [ID](#)²⁹,
J. Chen [ID](#)^{62c}, J. Chen [ID](#)¹⁴², S. Chen [ID](#)¹⁵³, S.J. Chen [ID](#)^{14c}, X. Chen [ID](#)^{62c}, X. Chen [ID](#)^{14b,ac},
Y. Chen [ID](#)^{62a}, C.L. Cheng [ID](#)¹⁷⁰, H.C. Cheng [ID](#)^{64a}, S. Cheong [ID](#)¹⁴³, A. Cheplakov [ID](#)³⁸,
E. Cheremushkina [ID](#)⁴⁸, E. Cherepanova [ID](#)¹¹⁴, R. Cherkaoui El Moursli [ID](#)^{35e}, E. Cheu [ID](#)⁷,
K. Cheung [ID](#)⁶⁵, L. Chevalier [ID](#)¹³⁵, V. Chiarella [ID](#)⁵³, G. Chiarelli [ID](#)^{74a}, N. Chiedde [ID](#)¹⁰²,
G. Chiodini [ID](#)^{70a}, A.S. Chisholm [ID](#)²⁰, A. Chitan [ID](#)^{27b}, M. Chitishvili [ID](#)¹⁶³, Y.H. Chiu [ID](#)¹⁶⁵,
M.V. Chizhov [ID](#)³⁸, K. Choi [ID](#)¹¹, A.R. Chomont [ID](#)^{75a,75b}, Y. Chou [ID](#)¹⁰³, E.Y.S. Chow [ID](#)¹¹⁴,
T. Chowdhury [ID](#)^{33g}, L.D. Christopher [ID](#)^{33g}, K.L. Chu [ID](#)^{64a}, M.C. Chu [ID](#)^{64a}, X. Chu [ID](#)^{14a,14d},
J. Chudoba [ID](#)¹³¹, J.J. Chwastowski [ID](#)⁸⁶, D. Cieri [ID](#)¹¹⁰, K.M. Ciesla [ID](#)^{85a}, V. Cindro [ID](#)⁹³,
A. Ciocio [ID](#)^{17a}, F. Ciotto [ID](#)^{72a,72b}, Z.H. Citron [ID](#)^{169,m}, M. Citterio [ID](#)^{71a}, D.A. Ciubotaru [ID](#)^{27b},
B.M. Ciungu [ID](#)¹⁵⁵, A. Clark [ID](#)⁵⁶, P.J. Clark [ID](#)⁵², J.M. Clavijo Columbie [ID](#)⁴⁸, S.E. Clawson [ID](#)¹⁰¹,
C. Clement [ID](#)^{47a,47b}, J. Clercx [ID](#)⁴⁸, L. Clissa [ID](#)^{23b,23a}, Y. Coadou [ID](#)¹⁰², M. Cokal [ID](#)^{69a,69c},
A. Coccaro [ID](#)^{57b}, R.F. Coelho Barrue [ID](#)^{130a}, R. Coelho Lopes De Sa [ID](#)¹⁰³, S. Coelli [ID](#)^{71a},
H. Cohen [ID](#)¹⁵¹, A.E.C. Coimbra [ID](#)^{71a,71b}, B. Cole [ID](#)⁴¹, J. Collot [ID](#)⁶⁰, P. Conde Muno [ID](#)^{130a,130g},
M.P. Connell [ID](#)^{33c}, S.H. Connell [ID](#)^{33c}, I.A. Connelly [ID](#)⁵⁹, E.I. Conroy [ID](#)¹²⁶, F. Conventi [ID](#)^{72a,ae},
H.G. Cooke [ID](#)²⁰, A.M. Cooper-Sarkar [ID](#)¹²⁶, F. Cormier [ID](#)¹⁶⁴, L.D. Corpe [ID](#)³⁶, M. Corradi [ID](#)^{75a,75b},
E.E. Corrigan [ID](#)⁹⁸, F. Corriveau [ID](#)^{104,x}, A. Cortes-Gonzalez [ID](#)¹⁸, M.J. Costa [ID](#)¹⁶³, F. Costanza [ID](#)⁴,
D. Costanzo [ID](#)¹³⁹, B.M. Cote [ID](#)¹¹⁹, G. Cowan [ID](#)⁹⁵, J.W. Cowley [ID](#)³², K. Cranmer [ID](#)¹¹⁷,
S. Crepe-Renaudin [ID](#)⁶⁰, F. Crescioli [ID](#)¹²⁷, M. Cristinziani [ID](#)¹⁴¹, M. Cristoforetti [ID](#)^{78a,78b,d},
V. Croft [ID](#)¹⁵⁸, G. Crosetti [ID](#)^{43b,43a}, A. Cueto [ID](#)³⁶, T. Cuhadar Donszelmann [ID](#)¹⁶⁰, H. Cui [ID](#)^{14a,14d},
Z. Cui [ID](#)⁷, W.R. Cunningham [ID](#)⁵⁹, F. Curcio [ID](#)^{43b,43a}, P. Czodrowski [ID](#)³⁶, M.M. Czurylo [ID](#)^{63b},
M.J. Da Cunha Sargedas De Sousa [ID](#)^{62a}, J.V. Da Fonseca Pinto [ID](#)^{82b}, C. Da Via [ID](#)¹⁰¹,
W. Dabrowski [ID](#)^{85a}, T. Dado [ID](#)⁴⁹, S. Dahbi [ID](#)^{33g}, T. Dai [ID](#)¹⁰⁶, C. Dallapiccola [ID](#)¹⁰³, M. Dam [ID](#)⁴²,
G. D'amen [ID](#)²⁹, V. D'Amico [ID](#)¹⁰⁹, J. Damp [ID](#)¹⁰⁰, J.R. Dandoy [ID](#)¹²⁸, M.F. Daneri [ID](#)³⁰,
M. Danninger [ID](#)¹⁴², V. Dao [ID](#)³⁶, G. Darbo [ID](#)^{57b}, S. Darmora [ID](#)⁶, S.J. Das [ID](#)²⁹, S. D'Auria [ID](#)^{71a,71b},
C. David [ID](#)^{156b}, T. Davidek [ID](#)¹³³, D.R. Davis [ID](#)⁵¹, B. Davis-Purcell [ID](#)³⁴, I. Dawson [ID](#)⁹⁴, K. De [ID](#)⁸,
R. De Asmundis [ID](#)^{72a}, M. De Beurs [ID](#)¹¹⁴, N. De Biase [ID](#)⁴⁸, S. De Castro [ID](#)^{23b,23a}, N. De Groot [ID](#)¹¹³,
P. de Jong [ID](#)¹¹⁴, H. De la Torre [ID](#)¹⁰⁷, A. De Maria [ID](#)^{14c}, A. De Salvo [ID](#)^{75a}, U. De Sanctis [ID](#)^{76a,76b},
A. De Santo [ID](#)¹⁴⁶, J.B. De Vivie De Regie [ID](#)⁶⁰, D.V. Dedovich [ID](#)³⁸, J. Degens [ID](#)¹¹⁴, A.M. Deiana [ID](#)⁴⁴,
F. Del Corso [ID](#)^{23b,23a}, J. Del Peso [ID](#)⁹⁹, F. Del Rio [ID](#)^{63a}, F. Deliot [ID](#)¹³⁵, C.M. Delitzsch [ID](#)⁴⁹,
M. Della Pietra [ID](#)^{72a,72b}, D. Della Volpe [ID](#)⁵⁶, A. Dell'Acqua [ID](#)³⁶, L. Dell'Asta [ID](#)^{71a,71b},
M. Delmastro [ID](#)⁴, P.A. Delsart [ID](#)⁶⁰, S. Demers [ID](#)¹⁷², M. Demichev [ID](#)³⁸, S.P. Denisov [ID](#)³⁷,
L. D'Eramo [ID](#)¹¹⁵, D. Derendarz [ID](#)⁸⁶, F. Derue [ID](#)¹²⁷, P. Dervan [ID](#)⁹², K. Desch [ID](#)²⁴, K. Dette [ID](#)¹⁵⁵,
C. Deutsch [ID](#)²⁴, F.A. Di Bello [ID](#)^{57b,57a}, A. Di Ciaccio [ID](#)^{76a,76b}, L. Di Ciaccio [ID](#)⁴,
A. Di Domenico [ID](#)^{75a,75b}, C. Di Donato [ID](#)^{72a,72b}, A. Di Girolamo [ID](#)³⁶, G. Di Gregorio [ID](#)⁵,
A. Di Luca [ID](#)^{78a,78b}, B. Di Micco [ID](#)^{77a,77b}, R. Di Nardo [ID](#)^{77a,77b}, C. Diaconu [ID](#)¹⁰², F.A. Dias [ID](#)¹¹⁴,
T. Dias Do Vale [ID](#)¹⁴², M.A. Diaz [ID](#)^{137a,137b}, F.G. Diaz Capriles [ID](#)²⁴, M. Didenko [ID](#)¹⁶³,

E.B. Diehl [106](#), L. Diehl [54](#), S. Díez Cornell [48](#), C. Diez Pardos [141](#), C. Dimitriadi [24,161](#),
 A. Dimitrievska [17a](#), J. Dingfelder [24](#), I-M. Dinu [27b](#), S.J. Dittmeier [63b](#), F. Dittus [36](#),
 F. Djama [102](#), T. Djobava [149b](#), J.I. Djuvsland [16](#), C. Doglioni [101,98](#), J. Dolejsi [133](#),
 Z. Dolezal [133](#), M. Donadelli [82c](#), B. Dong [107](#), J. Donini [40](#), A. D’Onofrio [77a,77b](#),
 M. D’Onofrio [92](#), J. Dopke [134](#), A. Doria [72a](#), M.T. Dova [90](#), A.T. Doyle [59](#),
 M.A. Draguet [126](#), E. Drechsler [142](#), E. Dreyer [169](#), I. Drivas-koulouris [10](#), A.S. Drobac [158](#),
 M. Drozdova [56](#), D. Du [62a](#), T.A. du Pree [114](#), F. Dubinin [37](#), M. Dubovsky [28a](#),
 E. Duchovni [169](#), G. Duckeck [109](#), O.A. Ducu [27b](#), D. Duda [110](#), A. Dudarev [36](#),
 E.R. Duden [26](#), M. D’uffizi [101](#), L. Dufflot [66](#), M. Dührssen [36](#), C. Dülsen [171](#),
 A.E. Dumitriu [27b](#), M. Dunford [63a](#), S. Dungs [49](#), K. Dunne [47a,47b](#), A. Duperrin [102](#),
 H. Duran Yildiz [3a](#), M. Düren [58](#), A. Durglishvili [149b](#), B.L. Dwyer [115](#), G.I. Dyckes [17a](#),
 M. Dyndal [85a](#), S. Dych [101](#), B.S. Dziedzic [86](#), Z.O. Earnshaw [146](#), B. Eckerova [28a](#),
 S. Eggebrecht [55](#), M.G. Eggleston [51](#), E. Egidio Purcino De Souza [127](#), L.F. Ehrke [56](#),
 G. Eigen [16](#), K. Einsweiler [17a](#), T. Ekelof [161](#), P.A. Ekman [98](#), Y. El Ghazali [35b](#),
 H. El Jarrari [35e,148](#), A. El Moussaouy [35a](#), V. Ellajosyula [161](#), M. Ellert [161](#),
 F. Ellinghaus [171](#), A.A. Elliot [94](#), N. Ellis [36](#), J. Elmsheuser [29](#), M. Elsing [36](#),
 D. Emeliyanov [134](#), A. Emerman [41](#), Y. Enari [153](#), I. Ene [17a](#), S. Epari [13](#), J. Erdmann [49](#),
 P.A. Erland [86](#), M. Errenst [171](#), M. Escalier [66](#), C. Escobar [163](#), E. Etzion [151](#),
 G. Evans [130a](#), H. Evans [68](#), M.O. Evans [146](#), A. Ezhilov [37](#), S. Ezzarqtouni [35a](#),
 F. Fabbri [59](#), L. Fabbri [23b,23a](#), G. Facini [96](#), V. Fadeyev [136](#), R.M. Fakhruddinov [37](#),
 S. Falciano [75a](#), L.F. Falda Ulhoa Coelho [36](#), P.J. Falke [24](#), S. Falke [36](#), J. Faltova [133](#),
 Y. Fan [14a](#), Y. Fang [14a,14d](#), G. Fanourakis [46](#), M. Fanti [71a,71b](#), M. Faraj [69a,69b](#),
 Z. Farazpay [97](#), A. Farbin [8](#), A. Farilla [77a](#), T. Farooque [107](#), S.M. Farrington [52](#), F. Fassi [35e](#),
 D. Fassouliotis [9](#), M. Fauci Giannelli [76a,76b](#), W.J. Fawcett [32](#), L. Fayard [66](#),
 P. Federicova [131](#), O.L. Fedin [37,a](#), G. Fedotov [37](#), M. Feickert [170](#), L. Feligioni [102](#),
 A. Fell [139](#), D.E. Fellers [123](#), C. Feng [62b](#), M. Feng [14b](#), Z. Feng [114](#), M.J. Fenton [160](#),
 A.B. Fenyuk [37](#), L. Ferencz [48](#), R.A.M. Ferguson [91](#), S.I. Fernandez Luengo [137f](#), J. Ferrando [48](#),
 A. Ferrari [161](#), P. Ferrari [114,113](#), R. Ferrari [73a](#), D. Ferrere [56](#), C. Ferretti [106](#), F. Fiedler [100](#),
 A. Filipčić [93](#), E.K. Filmer [1](#), F. Filthaut [113](#), M.C.N. Fiolhais [130a,130c,c](#), L. Fiorini [163](#),
 F. Fischer [141](#), W.C. Fisher [107](#), T. Fitschen [101](#), I. Fleck [141](#), P. Fleischmann [106](#),
 T. Flick [171](#), L. Flores [128](#), M. Flores [33d](#), L.R. Flores Castillo [64a](#), F.M. Follega [78a,78b](#),
 N. Fomin [16](#), J.H. Foo [155](#), B.C. Forland [68](#), A. Formica [135](#), A.C. Forti [101](#), E. Fortin [102](#),
 A.W. Fortman [61](#), M.G. Foti [17a](#), L. Fountas [9](#), D. Fournier [66](#), H. Fox [91](#),
 P. Francavilla [74a,74b](#), S. Francescato [61](#), S. Franchellucci [56](#), M. Franchini [23b,23a](#),
 S. Franchino [63a](#), D. Francis [36](#), L. Franco [113](#), L. Franconi [19](#), M. Franklin [61](#), G. Frattari [26](#),
 A.C. Freegard [94](#), P.M. Freeman [20](#), W.S. Freund [82b](#), N. Fritzsche [50](#), A. Froch [54](#),
 D. Froidevaux [36](#), J.A. Frost [126](#), Y. Fu [62a](#), M. Fujimoto [118](#), E. Fullana Torregrosa [163,*](#),
 J. Fuster [163](#), A. Gabrielli [23b,23a](#), A. Gabrielli [155](#), P. Gadow [48](#), G. Gagliardi [57b,57a](#),
 L.G. Gagnon [17a](#), G.E. Gallardo [126](#), E.J. Gallas [126](#), B.J. Gallop [134](#), R. Gamboa Goni [94](#),
 K.K. Gan [119](#), S. Ganguly [153](#), J. Gao [62a](#), Y. Gao [52](#), F.M. Garay Walls [137a,137b](#),
 B. Garcia [29,ag](#), C. García [163](#), J.E. García Navarro [163](#), M. Garcia-Sciveres [17a](#),
 R.W. Gardner [39](#), D. Garg [80](#), R.B. Garg [143](#), C.A. Garner [155](#), V. Garonne [29](#),
 C.M. Garvey [33a](#), S.J. Gasiorowski [138](#), P. Gaspar [82b](#), G. Gaudio [73a](#), V. Gautam [13](#),

P. Gauzzi [ID](#)^{75a,75b}, I.L. Gavrilenko [ID](#)³⁷, A. Gavrilyuk [ID](#)³⁷, C. Gay [ID](#)¹⁶⁴, G. Gaycken [ID](#)⁴⁸,
 E.N. Gazis [ID](#)¹⁰, A.A. Geanta [ID](#)^{27b,27e}, C.M. Gee [ID](#)¹³⁶, J. Geisen [ID](#)⁹⁸, C. Gemme [ID](#)^{57b},
 M.H. Genest [ID](#)⁶⁰, S. Gentile [ID](#)^{75a,75b}, S. George [ID](#)⁹⁵, W.F. George [ID](#)²⁰, T. Geralis [ID](#)⁴⁶,
 L.O. Gerlach [ID](#)⁵⁵, P. Gessinger-Befurt [ID](#)³⁶, M.E. Geyik [ID](#)¹⁷¹, M. Ghasemi Bostanabad [ID](#)¹⁶⁵,
 M. Ghneimat [ID](#)¹⁴¹, K. Ghorbanian [ID](#)⁹⁴, A. Ghosal [ID](#)¹⁴¹, A. Ghosh [ID](#)¹⁶⁰, A. Ghosh [ID](#)⁷,
 B. Giacobbe [ID](#)^{23b}, S. Giagu [ID](#)^{75a,75b}, P. Giannetti [ID](#)^{74a}, A. Giannini [ID](#)^{62a}, S.M. Gibson [ID](#)⁹⁵,
 M. Gignac [ID](#)¹³⁶, D.T. Gil [ID](#)^{85b}, A.K. Gilbert [ID](#)^{85a}, B.J. Gilbert [ID](#)⁴¹, D. Gillberg [ID](#)³⁴, G. Gilles [ID](#)¹¹⁴,
 N.E.K. Gillwald [ID](#)⁴⁸, L. Ginabat [ID](#)¹²⁷, D.M. Gingrich [ID](#)^{2,ad}, M.P. Giordani [ID](#)^{69a,69c},
 P.F. Giraud [ID](#)¹³⁵, G. Giugliarelli [ID](#)^{69a,69c}, D. Giugni [ID](#)^{71a}, F. Giuli [ID](#)³⁶, I. Gkialas [ID](#)^{9,k},
 L.K. Gladilin [ID](#)³⁷, C. Glasman [ID](#)⁹⁹, G.R. Gledhill [ID](#)¹²³, M. Glisic [ID](#)¹²³, I. Gnesi [ID](#)^{43b,g}, Y. Go [ID](#)^{29,ag},
 M. Goblirsch-Kolb [ID](#)²⁶, B. Gocke [ID](#)⁴⁹, D. Godin [ID](#)¹⁰⁸, B. Gokturk [ID](#)^{21a}, S. Goldfarb [ID](#)¹⁰⁵,
 T. Golling [ID](#)⁵⁶, M.G.D. Gololo [ID](#)^{33g}, D. Golubkov [ID](#)³⁷, J.P. Gombas [ID](#)¹⁰⁷, A. Gomes [ID](#)^{130a,130b},
 G. Gomes Da Silva [ID](#)¹⁴¹, A.J. Gomez Delegido [ID](#)¹⁶³, R. Goncalves Gama [ID](#)⁵⁵, R. Gonçalo [ID](#)^{130a,130c},
 G. Gonella [ID](#)¹²³, L. Gonella [ID](#)²⁰, A. Gongadze [ID](#)³⁸, F. Gonnella [ID](#)²⁰, J.L. Gonski [ID](#)⁴¹,
 R.Y. González Andana [ID](#)⁵², S. González de la Hoz [ID](#)¹⁶³, S. Gonzalez Fernandez [ID](#)¹³,
 R. Gonzalez Lopez [ID](#)⁹², C. Gonzalez Renteria [ID](#)^{17a}, R. Gonzalez Suarez [ID](#)¹⁶¹,
 S. Gonzalez-Sevilla [ID](#)⁵⁶, G.R. Gonzalvo Rodriguez [ID](#)¹⁶³, L. Goossens [ID](#)³⁶, N.A. Gorasia [ID](#)²⁰,
 P.A. Gorbounov [ID](#)³⁷, B. Gorini [ID](#)³⁶, E. Gorini [ID](#)^{70a,70b}, A. Gorišek [ID](#)⁹³, A.T. Goshaw [ID](#)⁵¹,
 M.I. Gostkin [ID](#)³⁸, S. Goswami [ID](#)¹²¹, C.A. Gottardo [ID](#)³⁶, M. Gouighri [ID](#)^{35b}, V. Goumarre [ID](#)⁴⁸,
 A.G. Goussiou [ID](#)¹³⁸, N. Govender [ID](#)^{33c}, C. Goy [ID](#)⁴, I. Grabowska-Bold [ID](#)^{85a}, K. Graham [ID](#)³⁴,
 E. Gramstad [ID](#)¹²⁵, S. Grancagnolo [ID](#)¹⁸, M. Grandi [ID](#)¹⁴⁶, V. Gratchev [ID](#)^{37,*}, P.M. Gravila [ID](#)^{27f},
 F.G. Gravili [ID](#)^{70a,70b}, H.M. Gray [ID](#)^{17a}, M. Greco [ID](#)^{70a,70b}, C. Grefe [ID](#)²⁴, I.M. Gregor [ID](#)⁴⁸,
 P. Grenier [ID](#)¹⁴³, C. Grieco [ID](#)¹³, A.A. Grillo [ID](#)¹³⁶, K. Grimm [ID](#)^{31,n}, S. Grinstein [ID](#)^{13,u},
 J.-F. Grivaz [ID](#)⁶⁶, E. Gross [ID](#)¹⁶⁹, J. Grosse-Knetter [ID](#)⁵⁵, C. Grud [ID](#)¹⁰⁶, J.C. Grundy [ID](#)¹²⁶,
 L. Guan [ID](#)¹⁰⁶, W. Guan [ID](#)¹⁷⁰, C. Gubbels [ID](#)¹⁶⁴, J.G.R. Guerrero Rojas [ID](#)¹⁶³, G. Guerrieri [ID](#)^{69a,69b},
 F. Guescini [ID](#)¹¹⁰, R. Gugel [ID](#)¹⁰⁰, J.A.M. Guhit [ID](#)¹⁰⁶, A. Guida [ID](#)⁴⁸, T. Guillemin [ID](#)⁴,
 E. Guillon [ID](#)^{167,134}, S. Guindon [ID](#)³⁶, F. Guo [ID](#)^{14a,14d}, J. Guo [ID](#)^{62c}, L. Guo [ID](#)⁶⁶, Y. Guo [ID](#)¹⁰⁶,
 R. Gupta [ID](#)⁴⁸, S. Gurbuz [ID](#)²⁴, S.S. Gurdasani [ID](#)⁵⁴, G. Gustavino [ID](#)³⁶, M. Guth [ID](#)⁵⁶,
 P. Gutierrez [ID](#)¹²⁰, L.F. Gutierrez Zagazeta [ID](#)¹²⁸, C. Gutsche [ID](#)⁹⁶, C. Guyot [ID](#)¹³⁵,
 C. Gwenlan [ID](#)¹²⁶, C.B. Gwilliam [ID](#)⁹², E.S. Haaland [ID](#)¹²⁵, A. Haas [ID](#)¹¹⁷, M. Habedank [ID](#)⁴⁸,
 C. Haber [ID](#)^{17a}, H.K. Hadavand [ID](#)⁸, A. Hadeef [ID](#)¹⁰⁰, S. Hadzic [ID](#)¹¹⁰, E.H. Haines [ID](#)⁹⁶,
 M. Haleem [ID](#)¹⁶⁶, J. Haley [ID](#)¹²¹, J.J. Hall [ID](#)¹³⁹, G.D. Hallewell [ID](#)¹⁰², L. Halser [ID](#)¹⁹, K. Hamano [ID](#)¹⁶⁵,
 H. Hamdaoui [ID](#)^{35e}, M. Hamer [ID](#)²⁴, G.N. Hamity [ID](#)⁵², J. Han [ID](#)^{62b}, K. Han [ID](#)^{62a}, L. Han [ID](#)^{14c},
 L. Han [ID](#)^{62a}, S. Han [ID](#)^{17a}, Y.F. Han [ID](#)¹⁵⁵, K. Hanagaki [ID](#)⁸³, M. Hance [ID](#)¹³⁶, D.A. Hangal [ID](#)^{41,ab},
 H. Hanif [ID](#)¹⁴², M.D. Hank [ID](#)³⁹, R. Hankache [ID](#)¹⁰¹, J.B. Hansen [ID](#)⁴², J.D. Hansen [ID](#)⁴²,
 P.H. Hansen [ID](#)⁴², K. Hara [ID](#)¹⁵⁷, D. Harada [ID](#)⁵⁶, T. Harenberg [ID](#)¹⁷¹, S. Harkusha [ID](#)³⁷,
 Y.T. Harris [ID](#)¹²⁶, N.M. Harrison [ID](#)¹¹⁹, P.F. Harrison [ID](#)¹⁶⁷, N.M. Hartman [ID](#)¹⁴³, N.M. Hartmann [ID](#)¹⁰⁹,
 Y. Hasegawa [ID](#)¹⁴⁰, A. Hasib [ID](#)⁵², S. Haug [ID](#)¹⁹, R. Hauser [ID](#)¹⁰⁷, M. Havranek [ID](#)¹³²,
 C.M. Hawkes [ID](#)²⁰, R.J. Hawkins [ID](#)³⁶, S. Hayashida [ID](#)¹¹¹, D. Hayden [ID](#)¹⁰⁷, C. Hayes [ID](#)¹⁰⁶,
 R.L. Hayes [ID](#)¹⁶⁴, C.P. Hays [ID](#)¹²⁶, J.M. Hays [ID](#)⁹⁴, H.S. Hayward [ID](#)⁹², F. He [ID](#)^{62a}, Y. He [ID](#)¹⁵⁴,
 Y. He [ID](#)¹²⁷, M.P. Heath [ID](#)⁵², N.B. Heatley [ID](#)⁹⁴, V. Hedberg [ID](#)⁹⁸, A.L. Heggelund [ID](#)¹²⁵,
 N.D. Hehir [ID](#)⁹⁴, C. Heidegger [ID](#)⁵⁴, K.K. Heidegger [ID](#)⁵⁴, W.D. Heidorn [ID](#)⁸¹, J. Heilman [ID](#)³⁴,
 S. Heim [ID](#)⁴⁸, T. Heim [ID](#)^{17a}, J.G. Heinlein [ID](#)¹²⁸, J.J. Heinrich [ID](#)¹²³, L. Heinrich [ID](#)¹¹⁰, J. Hejbal [ID](#)¹³¹,

L. Helary [ID](#)⁴⁸, A. Held [ID](#)¹⁷⁰, S. Hellesund [ID](#)¹²⁵, C.M. Helling [ID](#)¹⁶⁴, S. Hellman [ID](#)^{47a,47b},
C. Helsens [ID](#)³⁶, R.C.W. Henderson⁹¹, L. Henkelmann [ID](#)³², A.M. Henriques Correia³⁶, H. Herde [ID](#)⁹⁸,
Y. Hernández Jiménez [ID](#)¹⁴⁵, L.M. Herrmann [ID](#)²⁴, T. Herrmann [ID](#)⁵⁰, G. Herten [ID](#)⁵⁴,
R. Hertenberger [ID](#)¹⁰⁹, L. Hervas [ID](#)³⁶, N.P. Hessey [ID](#)^{156a}, H. Hibi [ID](#)⁸⁴, E. Higón-Rodríguez [ID](#)¹⁶³,
S.J. Hillier [ID](#)²⁰, I. Hinchliffe [ID](#)^{17a}, F. Hinterkeuser [ID](#)²⁴, M. Hirose [ID](#)¹²⁴, S. Hirose [ID](#)¹⁵⁷,
D. Hirschbuehl [ID](#)¹⁷¹, T.G. Hitchings [ID](#)¹⁰¹, B. Hiti [ID](#)⁹³, J. Hobbs [ID](#)¹⁴⁵, R. Hobincu [ID](#)^{27e},
N. Hod [ID](#)¹⁶⁹, M.C. Hodgkinson [ID](#)¹³⁹, B.H. Hodgkinson [ID](#)³², A. Hoecker [ID](#)³⁶, J. Hofer [ID](#)⁴⁸,
D. Hohn [ID](#)⁵⁴, T. Holm [ID](#)²⁴, M. Holzbock [ID](#)¹¹⁰, L.B.A.H. Hommels [ID](#)³², B.P. Honan [ID](#)¹⁰¹,
J. Hong [ID](#)^{62c}, T.M. Hong [ID](#)¹²⁹, J.C. Honig [ID](#)⁵⁴, B.H. Hooberman [ID](#)¹⁶², W.H. Hopkins [ID](#)⁶,
Y. Horii [ID](#)¹¹¹, S. Hou [ID](#)¹⁴⁸, A.S. Howard [ID](#)⁹³, J. Howarth [ID](#)⁵⁹, J. Hoya [ID](#)⁶, M. Hrabovsky [ID](#)¹²²,
A. Hrynevich [ID](#)⁴⁸, T. Hryn'ova [ID](#)⁴, P.J. Hsu [ID](#)⁶⁵, S.-C. Hsu [ID](#)¹³⁸, Q. Hu [ID](#)⁴¹, Y.F. Hu [ID](#)^{14a,14d,af},
D.P. Huang [ID](#)⁹⁶, S. Huang [ID](#)^{64b}, X. Huang [ID](#)^{14c}, Y. Huang [ID](#)^{62a}, Y. Huang [ID](#)^{14a}, Z. Huang [ID](#)¹⁰¹,
Z. Hubacek [ID](#)¹³², M. Huebner [ID](#)²⁴, F. Huegging [ID](#)²⁴, T.B. Huffman [ID](#)¹²⁶, M. Huhtinen [ID](#)³⁶,
S.K. Huiberts [ID](#)¹⁶, R. Hulsken [ID](#)¹⁰⁴, N. Huseynov [ID](#)^{12,a}, J. Huston [ID](#)¹⁰⁷, J. Huth [ID](#)⁶¹,
R. Hyneman [ID](#)¹⁴³, S. Hyrych [ID](#)^{28a}, G. Iacobucci [ID](#)⁵⁶, G. Iakovidis [ID](#)²⁹, I. Ibragimov [ID](#)¹⁴¹,
L. Iconomidou-Fayard [ID](#)⁶⁶, P. Iengo [ID](#)^{72a,72b}, R. Iguchi [ID](#)¹⁵³, T. Iizawa [ID](#)⁵⁶, Y. Ikegami [ID](#)⁸³,
A. Ilg [ID](#)¹⁹, N. Ilic [ID](#)¹⁵⁵, H. Imam [ID](#)^{35a}, T. Ingebretsen Carlson [ID](#)^{47a,47b}, G. Introzzi [ID](#)^{73a,73b},
M. Iodice [ID](#)^{77a}, V. Ippolito [ID](#)^{75a,75b}, M. Ishino [ID](#)¹⁵³, W. Islam [ID](#)¹⁷⁰, C. Issever [ID](#)^{18,48}, S. Istin [ID](#)^{21a},
H. Ito [ID](#)¹⁶⁸, J.M. Iturbe Ponce [ID](#)^{64a}, R. Iuppa [ID](#)^{78a,78b}, A. Ivina [ID](#)¹⁶⁹, J.M. Izen [ID](#)⁴⁵, V. Izzo [ID](#)^{72a},
P. Jacka [ID](#)^{131,132}, P. Jackson [ID](#)¹, R.M. Jacobs [ID](#)⁴⁸, B.P. Jaeger [ID](#)¹⁴², C.S. Jagfeld [ID](#)¹⁰⁹, P. Jain [ID](#)⁵⁴,
G. Jäkel [ID](#)¹⁷¹, K. Jakobs [ID](#)⁵⁴, T. Jakoubek [ID](#)¹⁶⁹, J. Jamieson [ID](#)⁵⁹, K.W. Janas [ID](#)^{85a},
G. Jarlskog [ID](#)⁹⁸, A.E. Jaspan [ID](#)⁹², M. Javurkova [ID](#)¹⁰³, F. Jeanneau [ID](#)¹³⁵, L. Jeanty [ID](#)¹²³,
J. Jejelava [ID](#)^{149a,aa}, P. Jenni [ID](#)^{54,h}, C.E. Jessiman [ID](#)³⁴, S. Jézéquel [ID](#)⁴, C. Jia [ID](#)^{62b}, J. Jia [ID](#)¹⁴⁵,
X. Jia [ID](#)⁶¹, X. Jia [ID](#)^{14a,14d}, Z. Jia [ID](#)^{14c}, Y. Jiang [ID](#)^{62a}, S. Jiggins [ID](#)⁵², J. Jimenez Pena [ID](#)¹¹⁰,
S. Jin [ID](#)^{14c}, A. Jinaru [ID](#)^{27b}, O. Jinnouchi [ID](#)¹⁵⁴, P. Johansson [ID](#)¹³⁹, K.A. Johns [ID](#)⁷,
J.W. Johnson [ID](#)¹³⁶, D.M. Jones [ID](#)³², E. Jones [ID](#)¹⁶⁷, P. Jones [ID](#)³², R.W.L. Jones [ID](#)⁹¹, T.J. Jones [ID](#)⁹²,
R. Joshi [ID](#)¹¹⁹, J. Jovicevic [ID](#)¹⁵, X. Ju [ID](#)^{17a}, J.J. Junggeburth [ID](#)³⁶, T. Junkermann [ID](#)^{63a},
A. Juste Rozas [ID](#)^{13,u}, S. Kabana [ID](#)^{137e}, A. Kaczmarska [ID](#)⁸⁶, M. Kado [ID](#)^{75a,75b}, H. Kagan [ID](#)¹¹⁹,
M. Kagan [ID](#)¹⁴³, A. Kahn⁴¹, A. Kahn [ID](#)¹²⁸, C. Kahra [ID](#)¹⁰⁰, T. Kaji [ID](#)¹⁶⁸, E. Kajomovitz [ID](#)¹⁵⁰,
N. Kakati [ID](#)¹⁶⁹, C.W. Kalderon [ID](#)²⁹, A. Kamenshchikov [ID](#)¹⁵⁵, S. Kanayama [ID](#)¹⁵⁴, N.J. Kang [ID](#)¹³⁶,
D. Kar [ID](#)^{33g}, K. Karava [ID](#)¹²⁶, M.J. Kareem [ID](#)^{156b}, E. Karentzos [ID](#)⁵⁴, I. Karkanias [ID](#)^{152,f},
S.N. Karpov [ID](#)³⁸, Z.M. Karpova [ID](#)³⁸, V. Kartvelishvili [ID](#)⁹¹, A.N. Karyukhin [ID](#)³⁷, E. Kasimi [ID](#)^{152,f},
C. Kato [ID](#)^{62d}, J. Katzy [ID](#)⁴⁸, S. Kaur [ID](#)³⁴, K. Kawade [ID](#)¹⁴⁰, K. Kawagoe [ID](#)⁸⁹, T. Kawamoto [ID](#)¹³⁵,
G. Kawamura⁵⁵, E.F. Kay [ID](#)¹⁶⁵, F.I. Kaya [ID](#)¹⁵⁸, S. Kazakos [ID](#)¹³, V.F. Kazanin [ID](#)³⁷, Y. Ke [ID](#)¹⁴⁵,
J.M. Keaveney [ID](#)^{33a}, R. Keeler [ID](#)¹⁶⁵, G.V. Kehris [ID](#)⁶¹, J.S. Keller [ID](#)³⁴, A.S. Kelly⁹⁶, D. Kelsey [ID](#)¹⁴⁶,
J.J. Kempster [ID](#)¹⁴⁶, K.E. Kennedy [ID](#)⁴¹, P.D. Kennedy [ID](#)¹⁰⁰, O. Kepka [ID](#)¹³¹, B.P. Kerridge [ID](#)¹⁶⁷,
S. Kersten [ID](#)¹⁷¹, B.P. Kerševan [ID](#)⁹³, S. Keshri [ID](#)⁶⁶, L. Keszeghova [ID](#)^{28a}, S. Ketabchi Haghghat [ID](#)¹⁵⁵,
M. Khandoga [ID](#)¹²⁷, A. Khanov [ID](#)¹²¹, A.G. Kharlamov [ID](#)³⁷, T. Kharlamova [ID](#)³⁷, E.E. Khoda [ID](#)¹³⁸,
T.J. Khoo [ID](#)¹⁸, G. Khoriauli [ID](#)¹⁶⁶, J. Khubua [ID](#)^{149b}, Y.A.R. Khwaira [ID](#)⁶⁶, M. Kiehn [ID](#)³⁶,
A. Kilgallon [ID](#)¹²³, D.W. Kim [ID](#)^{47a,47b}, E. Kim [ID](#)¹⁵⁴, Y.K. Kim [ID](#)³⁹, N. Kimura [ID](#)⁹⁶,
A. Kirchhoff [ID](#)⁵⁵, D. Kirchmeier [ID](#)⁵⁰, C. Kirfel [ID](#)²⁴, J. Kirk [ID](#)¹³⁴, A.E. Kiryunin [ID](#)¹¹⁰,
T. Kishimoto [ID](#)¹⁵³, D.P. Kisluk¹⁵⁵, C. Kitsaki [ID](#)¹⁰, O. Kivernyk [ID](#)²⁴, M. Klassen [ID](#)^{63a}, C. Klein [ID](#)³⁴,
L. Klein [ID](#)¹⁶⁶, M.H. Klein [ID](#)¹⁰⁶, M. Klein [ID](#)⁹², S.B. Klein [ID](#)⁵⁶, U. Klein [ID](#)⁹², P. Klimek [ID](#)³⁶,

A. Klimentov [ID](#)²⁹, F. Klimpel [ID](#)¹¹⁰, T. Klioutchnikova [ID](#)³⁶, P. Kluit [ID](#)¹¹⁴, S. Kluth [ID](#)¹¹⁰,
 E. Kneringer [ID](#)⁷⁹, T.M. Knight [ID](#)¹⁵⁵, A. Knue [ID](#)⁵⁴, D. Kobayashi⁸⁹, R. Kobayashi [ID](#)⁸⁷,
 M. Kocian [ID](#)¹⁴³, P. Kodyš [ID](#)¹³³, D.M. Koeck [ID](#)¹⁴⁶, P.T. Koenig [ID](#)²⁴, T. Koffas [ID](#)³⁴, M. Kolb [ID](#)¹³⁵,
 I. Koletsou [ID](#)⁴, T. Komarek [ID](#)¹²², K. Köneke [ID](#)⁵⁴, A.X.Y. Kong [ID](#)¹, T. Kono [ID](#)¹¹⁸,
 N. Konstantinidis [ID](#)⁹⁶, B. Konya [ID](#)⁹⁸, R. Kopeliansky [ID](#)⁶⁸, S. Koperny [ID](#)^{85a}, K. Korcyl [ID](#)⁸⁶,
 K. Kordas [ID](#)^{152.f}, G. Koren [ID](#)¹⁵¹, A. Korn [ID](#)⁹⁶, S. Korn [ID](#)⁵⁵, I. Korolkov [ID](#)¹³, N. Korotkova [ID](#)³⁷,
 B. Kortman [ID](#)¹¹⁴, O. Kortner [ID](#)¹¹⁰, S. Kortner [ID](#)¹¹⁰, W.H. KostECKa [ID](#)¹¹⁵, V.V. Kostyukhin [ID](#)¹⁴¹,
 A. Kotsokechagia [ID](#)¹³⁵, A. Kotwal [ID](#)⁵¹, A. Koulouris [ID](#)³⁶, A. Kourkumeli-Charalampidi [ID](#)^{73a,73b},
 C. Kourkumelis [ID](#)⁹, E. Kourlitis [ID](#)⁶, O. Kovanda [ID](#)¹⁴⁶, R. Kowalewski [ID](#)¹⁶⁵, W. Kozanecki [ID](#)¹³⁵,
 A.S. Kozhin [ID](#)³⁷, V.A. Kramarenko [ID](#)³⁷, G. Kramberger [ID](#)⁹³, P. Kramer [ID](#)¹⁰⁰, M.W. Krasny [ID](#)¹²⁷,
 A. Krasznahorkay [ID](#)³⁶, J.A. Kremer [ID](#)¹⁰⁰, T. Kresse [ID](#)⁵⁰, J. Kretzschmar [ID](#)⁹², K. Kreul [ID](#)¹⁸,
 P. Krieger [ID](#)¹⁵⁵, S. Krishnamurthy [ID](#)¹⁰³, M. Krivos [ID](#)¹³³, K. Krizka [ID](#)^{17a}, K. Kroeninger [ID](#)⁴⁹,
 H. Kroha [ID](#)¹¹⁰, J. Kroll [ID](#)¹³¹, J. Kroll [ID](#)¹²⁸, K.S. Krowpman [ID](#)¹⁰⁷, U. Kruchonak [ID](#)³⁸, H. Krüger [ID](#)²⁴,
 N. Krumnack⁸¹, M.C. Kruse [ID](#)⁵¹, J.A. Krzysiak [ID](#)⁸⁶, O. Kuchinskaia [ID](#)³⁷, S. Kuday [ID](#)^{3a},
 D. Kuechler [ID](#)⁴⁸, J.T. Kuechler [ID](#)⁴⁸, S. Kuehn [ID](#)³⁶, R. Kuesters [ID](#)⁵⁴, T. Kuhl [ID](#)⁴⁸, V. Kukhtin [ID](#)³⁸,
 Y. Kulchitsky [ID](#)^{37,a}, S. Kuleshov [ID](#)^{137d,137b}, M. Kumar [ID](#)^{33g}, N. Kumari [ID](#)¹⁰², A. Kupco [ID](#)¹³¹,
 T. Kupfer⁴⁹, A. Kupich [ID](#)³⁷, O. Kuprash [ID](#)⁵⁴, H. Kurashige [ID](#)⁸⁴, L.L. Kurchaninov [ID](#)^{156a},
 Y.A. Kurochkin [ID](#)³⁷, A. Kurova [ID](#)³⁷, M. Kuze [ID](#)¹⁵⁴, A.K. Kvam [ID](#)¹⁰³, J. Kvita [ID](#)¹²², T. Kwan [ID](#)¹⁰⁴,
 K.W. Kwok [ID](#)^{64a}, N.G. Kyriacou [ID](#)¹⁰⁶, L.A.O. Laatu [ID](#)¹⁰², C. Lacasta [ID](#)¹⁶³, F. Lacava [ID](#)^{75a,75b},
 H. Lacker [ID](#)¹⁸, D. Lacour [ID](#)¹²⁷, N.N. Lad [ID](#)⁹⁶, E. Ladygin [ID](#)³⁸, B. Laforge [ID](#)¹²⁷, T. Lagouri [ID](#)^{137e},
 S. Lai [ID](#)⁵⁵, I.K. Lakomic [ID](#)^{85a}, N. Lalloue [ID](#)⁶⁰, J.E. Lambert [ID](#)¹²⁰, S. Lammers [ID](#)⁶⁸, W. Lampl [ID](#)⁷,
 C. Lampoudis [ID](#)^{152.f}, A.N. Lancaster [ID](#)¹¹⁵, E. Lançon [ID](#)²⁹, U. Landgraf [ID](#)⁵⁴, M.P.J. Landon [ID](#)⁹⁴,
 V.S. Lang [ID](#)⁵⁴, R.J. Langenberg [ID](#)¹⁰³, A.J. Lankford [ID](#)¹⁶⁰, F. Lanni [ID](#)³⁶, K. Lantzsck [ID](#)²⁴,
 A. Lanza [ID](#)^{73a}, A. Lapertosa [ID](#)^{57b,57a}, J.F. Laporte [ID](#)¹³⁵, T. Lari [ID](#)^{71a}, F. Lasagni Manghi [ID](#)^{23b},
 M. Lassnig [ID](#)³⁶, V. Latonova [ID](#)¹³¹, A. Laudrain [ID](#)¹⁰⁰, A. Laurier [ID](#)¹⁵⁰, S.D. Lawlor [ID](#)⁹⁵,
 Z. Lawrence [ID](#)¹⁰¹, M. Lazzaroni [ID](#)^{71a,71b}, B. Le¹⁰¹, B. Leban [ID](#)⁹³, A. Lebedev [ID](#)⁸¹, M. LeBlanc [ID](#)³⁶,
 T. LeCompte [ID](#)⁶, F. Ledroit-Guillon [ID](#)⁶⁰, A.C.A. Lee⁹⁶, G.R. Lee [ID](#)¹⁶, S.C. Lee [ID](#)¹⁴⁸, S. Lee [ID](#)^{47a,47b},
 T.F. Lee [ID](#)⁹², L.L. Leeuw [ID](#)^{33c}, H.P. Lefebvre [ID](#)⁹⁵, M. Lefebvre [ID](#)¹⁶⁵, C. Leggett [ID](#)^{17a},
 K. Lehmann [ID](#)¹⁴², G. Lehmann Miotto [ID](#)³⁶, M. Leigh [ID](#)⁵⁶, W.A. Leight [ID](#)¹⁰³, A. Leisos [ID](#)^{152,t},
 M.A.L. Leite [ID](#)^{82c}, C.E. Leitgeb [ID](#)⁴⁸, R. Leitner [ID](#)¹³³, K.J.C. Leney [ID](#)⁴⁴, T. Lenz [ID](#)²⁴, S. Leone [ID](#)^{74a},
 C. Leonidopoulos [ID](#)⁵², A. Leopold [ID](#)¹⁴⁴, C. Leroy [ID](#)¹⁰⁸, R. Les [ID](#)¹⁰⁷, C.G. Lester [ID](#)³²,
 M. Levchenko [ID](#)³⁷, J. Levêque [ID](#)⁴, D. Levin [ID](#)¹⁰⁶, L.J. Levinson [ID](#)¹⁶⁹, M.P. Lewicki [ID](#)⁸⁶,
 D.J. Lewis [ID](#)⁴, A. Li [ID](#)⁵, B. Li [ID](#)^{62b}, C. Li [ID](#)^{62a}, C-Q. Li [ID](#)^{62c}, H. Li [ID](#)^{62a}, H. Li [ID](#)^{62b}, H. Li [ID](#)^{14c},
 H. Li [ID](#)^{62b}, J. Li [ID](#)^{62c}, K. Li [ID](#)¹³⁸, L. Li [ID](#)^{62c}, M. Li [ID](#)^{14a,14d}, Q.Y. Li [ID](#)^{62a}, S. Li [ID](#)^{14a,14d},
 S. Li [ID](#)^{62d,62c,e}, T. Li [ID](#)^{62b}, X. Li [ID](#)¹⁰⁴, Z. Li [ID](#)^{62b}, Z. Li [ID](#)¹²⁶, Z. Li [ID](#)¹⁰⁴, Z. Li [ID](#)⁹², Z. Li [ID](#)^{14a,14d},
 Z. Liang [ID](#)^{14a}, M. Liberatore [ID](#)⁴⁸, B. Liberti [ID](#)^{76a}, K. Lie [ID](#)^{64c}, J. Lieber Marin [ID](#)^{82b}, H. Lien [ID](#)⁶⁸,
 K. Lin [ID](#)¹⁰⁷, R.A. Linck [ID](#)⁶⁸, R.E. Lindley [ID](#)⁷, J.H. Lindon [ID](#)², A. Linss [ID](#)⁴⁸, E. Lipeles [ID](#)¹²⁸,
 A. Lipniacka [ID](#)¹⁶, A. Lister [ID](#)¹⁶⁴, J.D. Little [ID](#)⁴, B. Liu [ID](#)^{14a}, B.X. Liu [ID](#)¹⁴², D. Liu [ID](#)^{62d,62c},
 J.B. Liu [ID](#)^{62a}, J.K.K. Liu [ID](#)³², K. Liu [ID](#)^{62d,62c}, M. Liu [ID](#)^{62a}, M.Y. Liu [ID](#)^{62a}, P. Liu [ID](#)^{14a},
 Q. Liu [ID](#)^{62d,138,62c}, X. Liu [ID](#)^{62a}, Y. Liu [ID](#)^{14c,14d}, Y.L. Liu [ID](#)¹⁰⁶, Y.W. Liu [ID](#)^{62a}, M. Livan [ID](#)^{73a,73b},
 J. Llorente Merino [ID](#)¹⁴², S.L. Lloyd [ID](#)⁹⁴, E.M. Lobodzinska [ID](#)⁴⁸, P. Loch [ID](#)⁷, S. Loffredo [ID](#)^{76a,76b},
 T. Lohse [ID](#)¹⁸, K. Lohwasser [ID](#)¹³⁹, E. Loiacono [ID](#)⁴⁸, M. Lokajicek [ID](#)¹³¹, J.D. Long [ID](#)¹⁶²,
 I. Longarini [ID](#)¹⁶⁰, L. Longo [ID](#)^{70a,70b}, R. Longo [ID](#)¹⁶², I. Lopez Paz [ID](#)⁶⁷, A. Lopez Solis [ID](#)⁴⁸,

J. Lorenz [ID](#)¹⁰⁹, N. Lorenzo Martinez [ID](#)⁴, A.M. Lory [ID](#)¹⁰⁹, X. Lou [ID](#)^{47a,47b}, X. Lou [ID](#)^{14a,14d},
A. Lounis [ID](#)⁶⁶, J. Love [ID](#)⁶, P.A. Love [ID](#)⁹¹, J.J. Lozano Bahilo [ID](#)¹⁶³, G. Lu [ID](#)^{14a,14d}, M. Lu [ID](#)⁸⁰,
S. Lu [ID](#)¹²⁸, Y.J. Lu [ID](#)⁶⁵, H.J. Lubatti [ID](#)¹³⁸, C. Luci [ID](#)^{75a,75b}, F.L. Lucio Alves [ID](#)^{14c}, A. Lucotte [ID](#)⁶⁰,
F. Luehring [ID](#)⁶⁸, I. Luise [ID](#)¹⁴⁵, O. Lukianchuk [ID](#)⁶⁶, O. Lundberg [ID](#)¹⁴⁴, B. Lund-Jensen [ID](#)¹⁴⁴,
N.A. Luongo [ID](#)¹²³, M.S. Lutz [ID](#)¹⁵¹, D. Lynn [ID](#)²⁹, H. Lyons⁹², R. Lysak [ID](#)¹³¹, E. Lytken [ID](#)⁹⁸,
F. Lyu [ID](#)^{14a}, V. Lyubushkin [ID](#)³⁸, T. Lyubushkina [ID](#)³⁸, M.M. Lyukova [ID](#)¹⁴⁵, H. Ma [ID](#)²⁹,
L.L. Ma [ID](#)^{62b}, Y. Ma [ID](#)⁹⁶, D.M. Mac Donell [ID](#)¹⁶⁵, G. Maccarrone [ID](#)⁵³, J.C. MacDonald [ID](#)¹³⁹,
R. Madar [ID](#)⁴⁰, W.F. Mader [ID](#)⁵⁰, J. Maeda [ID](#)⁸⁴, T. Maeno [ID](#)²⁹, M. Maerker [ID](#)⁵⁰, H. Maguire [ID](#)¹³⁹,
D.J. Mahon [ID](#)⁴¹, A. Maio [ID](#)^{130a,130b,130d}, K. Maj [ID](#)^{85a}, O. Majersky [ID](#)⁴⁸, S. Majewski [ID](#)¹²³,
N. Makovec [ID](#)⁶⁶, V. Maksimovic [ID](#)¹⁵, B. Malaescu [ID](#)¹²⁷, Pa. Malecki [ID](#)⁸⁶, V.P. Maleev [ID](#)³⁷,
F. Malek [ID](#)⁶⁰, D. Malito [ID](#)^{43b,43a}, U. Mallik [ID](#)⁸⁰, C. Malone [ID](#)³², S. Maltezos¹⁰, S. Malyukov³⁸,
J. Mamuzic [ID](#)¹³, G. Mancini [ID](#)⁵³, G. Manco [ID](#)^{73a,73b}, J.P. Mandalia [ID](#)⁹⁴, I. Mandić [ID](#)⁹³,
L. Manhaes de Andrade Filho [ID](#)^{82a}, I.M. Maniatis [ID](#)¹⁶⁹, J. Manjarres Ramos [ID](#)⁵⁰,
D.C. Mankad [ID](#)¹⁶⁹, A. Mann [ID](#)¹⁰⁹, B. Mansoulie [ID](#)¹³⁵, S. Manzoni [ID](#)³⁶, A. Marantis [ID](#)¹⁵²,
G. Marchiori [ID](#)⁵, M. Marcisovsky [ID](#)¹³¹, C. Marcon [ID](#)^{71a,71b}, M. Marinescu [ID](#)²⁰, M. Marjanovic [ID](#)¹²⁰,
E.J. Marshall [ID](#)⁹¹, Z. Marshall [ID](#)^{17a}, S. Marti-Garcia [ID](#)¹⁶³, T.A. Martin [ID](#)¹⁶⁷, V.J. Martin [ID](#)⁵²,
B. Martin dit Latour [ID](#)¹⁶, L. Martinelli [ID](#)^{75a,75b}, M. Martinez [ID](#)^{13,u}, P. Martinez Agullo [ID](#)¹⁶³,
V.I. Martinez Outschoorn [ID](#)¹⁰³, P. Martinez Suarez [ID](#)¹³, S. Martin-Haugh [ID](#)¹³⁴, V.S. Martoiu [ID](#)^{27b},
A.C. Martyniuk [ID](#)⁹⁶, A. Marzin [ID](#)³⁶, S.R. Maschek [ID](#)¹¹⁰, D. Mascione [ID](#)^{78a,78b}, L. Masetti [ID](#)¹⁰⁰,
T. Mashimo [ID](#)¹⁵³, J. Masik [ID](#)¹⁰¹, A.L. Maslennikov [ID](#)³⁷, L. Massa [ID](#)^{23b}, P. Massarotti [ID](#)^{72a,72b},
P. Mastrandrea [ID](#)^{74a,74b}, A. Mastroberardino [ID](#)^{43b,43a}, T. Masubuchi [ID](#)¹⁵³, T. Mathisen [ID](#)¹⁶¹,
N. Matsuzawa¹⁵³, J. Maurer [ID](#)^{27b}, B. Maček [ID](#)⁹³, D.A. Maximov [ID](#)³⁷, R. Mazini [ID](#)¹⁴⁸,
I. Maznas [ID](#)^{152,f}, M. Mazza [ID](#)¹⁰⁷, S.M. Mazza [ID](#)¹³⁶, C. Mc Ginn [ID](#)²⁹, J.P. Mc Gowan [ID](#)¹⁰⁴,
S.P. Mc Kee [ID](#)¹⁰⁶, E.F. McDonald [ID](#)¹⁰⁵, A.E. McDougall [ID](#)¹¹⁴, J.A. Mcfayden [ID](#)¹⁴⁶,
G. Mchedlidge [ID](#)^{149b}, R.P. McKenzie [ID](#)^{33g}, T.C. Mclachlan [ID](#)⁴⁸, D.J. Mclaughlin [ID](#)⁹⁶,
K.D. McLean [ID](#)¹⁶⁵, S.J. McMahon [ID](#)¹³⁴, P.C. McNamara [ID](#)¹⁰⁵, C.M. Mcpartland [ID](#)⁹²,
R.A. McPherson [ID](#)^{165,x}, T. Megy [ID](#)⁴⁰, S. Mehlhase [ID](#)¹⁰⁹, A. Mehta [ID](#)⁹², B. Meirose [ID](#)⁴⁵,
D. Melini [ID](#)¹⁵⁰, B.R. Mellado Garcia [ID](#)^{33g}, A.H. Melo [ID](#)⁵⁵, F. Meloni [ID](#)⁴⁸,
E.D. Mendes Gouveia [ID](#)^{130a}, A.M. Mendes Jacques Da Costa [ID](#)²⁰, H.Y. Meng [ID](#)¹⁵⁵, L. Meng [ID](#)⁹¹,
S. Menke [ID](#)¹¹⁰, M. Mentink [ID](#)³⁶, E. Meoni [ID](#)^{43b,43a}, C. Merlassino [ID](#)¹²⁶, L. Merola [ID](#)^{72a,72b},
C. Meroni [ID](#)^{71a}, G. Merz¹⁰⁶, O. Meshkov [ID](#)³⁷, J. Metcalfe [ID](#)⁶, A.S. Mete [ID](#)⁶, C. Meyer [ID](#)⁶⁸,
J.-P. Meyer [ID](#)¹³⁵, M. Michetti [ID](#)¹⁸, R.P. Middleton [ID](#)¹³⁴, L. Mijović [ID](#)⁵², G. Mikenberg [ID](#)¹⁶⁹,
M. Mikestikova [ID](#)¹³¹, M. Mikuž [ID](#)⁹³, H. Mildner [ID](#)¹³⁹, A. Milic [ID](#)³⁶, C.D. Milke [ID](#)⁴⁴,
D.W. Miller [ID](#)³⁹, L.S. Miller [ID](#)³⁴, A. Milov [ID](#)¹⁶⁹, D.A. Milstead^{47a,47b}, T. Min^{14c},
A.A. Minaenko [ID](#)³⁷, I.A. Minashvili [ID](#)^{149b}, L. Mince [ID](#)⁵⁹, A.I. Mincer [ID](#)¹¹⁷, B. Mindur [ID](#)^{85a},
M. Mineev [ID](#)³⁸, Y. Mino [ID](#)⁸⁷, L.M. Mir [ID](#)¹³, M. Miralles Lopez [ID](#)¹⁶³, M. Mironova [ID](#)¹²⁶,
M.C. Missio [ID](#)¹¹³, T. Mitani [ID](#)¹⁶⁸, A. Mitra [ID](#)¹⁶⁷, V.A. Mitsou [ID](#)¹⁶³, O. Miu [ID](#)¹⁵⁵,
P.S. Miyagawa [ID](#)⁹⁴, Y. Miyazaki⁸⁹, A. Mizukami [ID](#)⁸³, J.U. Mjörnmark [ID](#)⁹⁸, T. Mkrtchyan [ID](#)^{63a},
M. Mlinarevic [ID](#)⁹⁶, T. Mlinarevic [ID](#)⁹⁶, M. Mlynarikova [ID](#)³⁶, T. Moa [ID](#)^{47a,47b}, S. Mobius [ID](#)⁵⁵,
K. Mochizuki [ID](#)¹⁰⁸, P. Moder [ID](#)⁴⁸, P. Mogg [ID](#)¹⁰⁹, A.F. Mohammed [ID](#)^{14a,14d}, S. Mohapatra [ID](#)⁴¹,
G. Mokgatitswane [ID](#)^{33g}, B. Mondal [ID](#)¹⁴¹, S. Mondal [ID](#)¹³², K. Mönig [ID](#)⁴⁸, E. Monnier [ID](#)¹⁰²,
L. Monsonis Romero¹⁶³, J. Montejo Berlingen [ID](#)⁸³, M. Montella [ID](#)¹¹⁹, F. Monticelli [ID](#)⁹⁰,
N. Morange [ID](#)⁶⁶, A.L. Moreira De Carvalho [ID](#)^{130a}, M. Moreno Llácer [ID](#)¹⁶³, C. Moreno Martinez [ID](#)⁵⁶,

P. Morettini [ID](#)^{57b}, S. Morgenstern [ID](#)¹⁶⁷, M. Morii [ID](#)⁶¹, M. Morinaga [ID](#)¹⁵³, A.K. Morley [ID](#)³⁶,
F. Morodei [ID](#)^{75a,75b}, L. Morvaj [ID](#)³⁶, P. Moschovakos [ID](#)³⁶, B. Moser [ID](#)³⁶, M. Mosidze [ID](#)^{149b},
T. Moskalets [ID](#)⁵⁴, P. Moskvitina [ID](#)¹¹³, J. Moss [ID](#)^{31,o}, E.J.W. Moyses [ID](#)¹⁰³, O. Mtintsilana [ID](#)^{33g},
S. Muanza [ID](#)¹⁰², J. Mueller [ID](#)¹²⁹, D. Muenstermann [ID](#)⁹¹, R. Müller [ID](#)¹⁹, G.A. Mullier [ID](#)¹⁶¹,
J.J. Mullin [ID](#)¹²⁸, D.P. Mungo [ID](#)¹⁵⁵, J.L. Munoz Martinez [ID](#)¹³, D. Munoz Perez [ID](#)¹⁶³,
F.J. Munoz Sanchez [ID](#)¹⁰¹, M. Murin [ID](#)¹⁰¹, W.J. Murray [ID](#)^{167,134}, A. Murrone [ID](#)^{71a,71b},
J.M. Muse [ID](#)¹²⁰, M. Muškinja [ID](#)^{17a}, C. Mwewa [ID](#)²⁹, A.G. Myagkov [ID](#)^{37,a}, A.J. Myers [ID](#)⁸,
A.A. Myers [ID](#)¹²⁹, G. Myers [ID](#)⁶⁸, M. Myska [ID](#)¹³², B.P. Nachman [ID](#)^{17a}, O. Nackenhorst [ID](#)⁴⁹,
A. Nag [ID](#)⁵⁰, K. Nagai [ID](#)¹²⁶, K. Nagano [ID](#)⁸³, J.L. Nagle [ID](#)^{29,ag}, E. Nagy [ID](#)¹⁰², A.M. Nairz [ID](#)³⁶,
Y. Nakahama [ID](#)⁸³, K. Nakamura [ID](#)⁸³, H. Nanjo [ID](#)¹²⁴, R. Narayan [ID](#)⁴⁴, E.A. Narayanan [ID](#)¹¹²,
I. Naryshkin [ID](#)³⁷, M. Naseri [ID](#)³⁴, C. Nass [ID](#)²⁴, G. Navarro [ID](#)^{22a}, J. Navarro-Gonzalez [ID](#)¹⁶³,
R. Nayak [ID](#)¹⁵¹, A. Nayaz [ID](#)¹⁸, P.Y. Nechaeva [ID](#)³⁷, F. Nechansky [ID](#)⁴⁸, L. Nedic [ID](#)¹²⁶, T.J. Neep [ID](#)²⁰,
A. Negri [ID](#)^{73a,73b}, M. Negrini [ID](#)^{23b}, C. Nellist [ID](#)¹¹³, C. Nelson [ID](#)¹⁰⁴, K. Nelson [ID](#)¹⁰⁶,
S. Nemecek [ID](#)¹³¹, M. Nessi [ID](#)^{36,i}, M.S. Neubauer [ID](#)¹⁶², F. Neuhaus [ID](#)¹⁰⁰, J. Neundorf [ID](#)⁴⁸,
R. Newhouse [ID](#)¹⁶⁴, P.R. Newman [ID](#)²⁰, C.W. Ng [ID](#)¹²⁹, Y.S. Ng [ID](#)¹⁸, Y.W.Y. Ng [ID](#)⁴⁸, B. Ngair [ID](#)^{35e},
H.D.N. Nguyen [ID](#)¹⁰⁸, R.B. Nickerson [ID](#)¹²⁶, R. Nicolaidou [ID](#)¹³⁵, J. Nielsen [ID](#)¹³⁶, M. Niemeyer [ID](#)⁵⁵,
N. Nikiforou [ID](#)³⁶, V. Nikolaenko [ID](#)^{37,a}, I. Nikolic-Audit [ID](#)¹²⁷, K. Nikolopoulos [ID](#)²⁰, P. Nilsson [ID](#)²⁹,
I. Ninca [ID](#)⁴⁸, H.R. Nindhito [ID](#)⁵⁶, G. Ninio [ID](#)¹⁵¹, A. Nisati [ID](#)^{75a}, N. Nishu [ID](#)², R. Nisius [ID](#)¹¹⁰,
J-E. Nitschke [ID](#)⁵⁰, E.K. Nkadimeng [ID](#)^{33g}, S.J. Noacco Rosende [ID](#)⁹⁰, T. Nobe [ID](#)¹⁵³, D.L. Noel [ID](#)³²,
Y. Noguchi [ID](#)⁸⁷, T. Nommensen [ID](#)¹⁴⁷, M.A. Nomura [ID](#)²⁹, M.B. Norfolk [ID](#)¹³⁹, R.R.B. Norisam [ID](#)⁹⁶,
B.J. Norman [ID](#)³⁴, J. Novak [ID](#)⁹³, T. Novak [ID](#)⁴⁸, O. Novgorodova [ID](#)⁵⁰, L. Novotny [ID](#)¹³²,
R. Novotny [ID](#)¹¹², L. Nozka [ID](#)¹²², K. Ntekas [ID](#)¹⁶⁰, N.M.J. Nunes De Moura Junior [ID](#)^{82b}, E. Nurse [ID](#)⁹⁶,
F.G. Oakham [ID](#)^{34,ad}, J. Ocariz [ID](#)¹²⁷, A. Ochi [ID](#)⁸⁴, I. Ochoa [ID](#)^{130a}, S. Oerdek [ID](#)¹⁶¹,
J.T. Offermann [ID](#)³⁹, A. Ogrodnik [ID](#)^{85a}, A. Oh [ID](#)¹⁰¹, C.C. Ohm [ID](#)¹⁴⁴, H. Oide [ID](#)⁸³, R. Oishi [ID](#)¹⁵³,
M.L. Ojeda [ID](#)⁴⁸, Y. Okazaki [ID](#)⁸⁷, M.W. O’Keefe [ID](#)⁹², Y. Okumura [ID](#)¹⁵³, A. Olariu [ID](#)^{27b},
L.F. Oleiro Seabra [ID](#)^{130a}, S.A. Olivares Pino [ID](#)^{137e}, D. Oliveira Damazio [ID](#)²⁹,
D. Oliveira Goncalves [ID](#)^{82a}, J.L. Oliver [ID](#)¹⁶⁰, M.J.R. Olsson [ID](#)¹⁶⁰, A. Olszewski [ID](#)⁸⁶,
J. Olszowska [ID](#)^{86,*}, Ö.O. Öncel [ID](#)⁵⁴, D.C. O’Neil [ID](#)¹⁴², A.P. O’Neill [ID](#)¹⁹, A. Onofre [ID](#)^{130a,130e},
P.U.E. Onyisi [ID](#)¹¹, M.J. Oreglia [ID](#)³⁹, G.E. Orellana [ID](#)⁹⁰, D. Orestano [ID](#)^{77a,77b}, N. Orlando [ID](#)¹³,
R.S. Orr [ID](#)¹⁵⁵, V. O’Shea [ID](#)⁵⁹, R. Ospanov [ID](#)^{62a}, G. Otero y Garzon [ID](#)³⁰, H. Otono [ID](#)⁸⁹,
P.S. Ott [ID](#)^{63a}, G.J. Ottino [ID](#)^{17a}, M. Ouchrif [ID](#)^{35d}, J. Ouellette [ID](#)^{29,ag}, F. Ould-Saada [ID](#)¹²⁵,
M. Owen [ID](#)⁵⁹, R.E. Owen [ID](#)¹³⁴, K.Y. Oyulmaz [ID](#)^{21a}, V.E. Ozcan [ID](#)^{21a}, N. Ozturk [ID](#)⁸,
S. Ozturk [ID](#)^{21d}, J. Pacalt [ID](#)¹²², H.A. Pacey [ID](#)³², K. Pachal [ID](#)⁵¹, A. Pacheco Pages [ID](#)¹³,
C. Padilla Aranda [ID](#)¹³, G. Padovano [ID](#)^{75a,75b}, S. Pagan Griso [ID](#)^{17a}, G. Palacino [ID](#)⁶⁸,
A. Palazzo [ID](#)^{70a,70b}, S. Palestini [ID](#)³⁶, J. Pan [ID](#)¹⁷², T. Pan [ID](#)^{64a}, D.K. Panchal [ID](#)¹¹,
C.E. Pandini [ID](#)¹¹⁴, J.G. Panduro Vazquez [ID](#)⁹⁵, H. Pang [ID](#)^{14b}, P. Pani [ID](#)⁴⁸, G. Panizzo [ID](#)^{69a,69c},
L. Paolozzi [ID](#)⁵⁶, C. Papadatos [ID](#)¹⁰⁸, S. Parajuli [ID](#)⁴⁴, A. Paramonov [ID](#)⁶, C. Paraskevopoulos [ID](#)¹⁰,
D. Paredes Hernandez [ID](#)^{64b}, T.H. Park [ID](#)¹⁵⁵, M.A. Parker [ID](#)³², F. Parodi [ID](#)^{57b,57a},
E.W. Parrish [ID](#)¹¹⁵, V.A. Parrish [ID](#)⁵², J.A. Parsons [ID](#)⁴¹, U. Parzefall [ID](#)⁵⁴, B. Pascual Dias [ID](#)¹⁰⁸,
L. Pascual Dominguez [ID](#)¹⁵¹, V.R. Pascuzzi [ID](#)^{17a}, F. Pasquali [ID](#)¹¹⁴, E. Pasqualucci [ID](#)^{75a},
S. Passaggio [ID](#)^{57b}, F. Pastore [ID](#)⁹⁵, P. Pasuwan [ID](#)^{47a,47b}, P. Patel [ID](#)⁸⁶, J.R. Pater [ID](#)¹⁰¹, T. Pauly [ID](#)³⁶,
J. Pearkes [ID](#)¹⁴³, M. Pedersen [ID](#)¹²⁵, R. Pedro [ID](#)^{130a}, S.V. Peleganchuk [ID](#)³⁷, O. Penc [ID](#)³⁶,
E.A. Pender [ID](#)⁵², C. Peng [ID](#)^{64b}, H. Peng [ID](#)^{62a}, K.E. Penski [ID](#)¹⁰⁹, M. Penzin [ID](#)³⁷, B.S. Peralva [ID](#)^{82d,82d},

A.P. Pereira Peixoto [ID](#)⁶⁰, L. Pereira Sanchez [ID](#)^{47a,47b}, D.V. Perepelitsa [ID](#)^{29,ag},
 E. Perez Codina [ID](#)^{156a}, M. Perganti [ID](#)¹⁰, L. Perini [ID](#)^{71a,71b,*}, H. Pernegger [ID](#)³⁶, S. Perrella [ID](#)³⁶,
 A. Perrevoort [ID](#)¹¹³, O. Perrin [ID](#)⁴⁰, K. Peters [ID](#)⁴⁸, R.F.Y. Peters [ID](#)¹⁰¹, B.A. Petersen [ID](#)³⁶,
 T.C. Petersen [ID](#)⁴², E. Petit [ID](#)¹⁰², V. Petousis [ID](#)¹³², C. Petridou [ID](#)^{152,f}, A. Petrukhin [ID](#)¹⁴¹,
 M. Pettee [ID](#)^{17a}, N.E. Pettersson [ID](#)³⁶, A. Petukhov [ID](#)³⁷, K. Petukhova [ID](#)¹³³, A. Peyaud [ID](#)¹³⁵,
 R. Pezoa [ID](#)^{137f}, L. Pezzotti [ID](#)³⁶, G. Pezzullo [ID](#)¹⁷², T.M. Pham [ID](#)¹⁷⁰, T. Pham [ID](#)¹⁰⁵,
 P.W. Phillips [ID](#)¹³⁴, M.W. Phipps [ID](#)¹⁶², G. Piacquadio [ID](#)¹⁴⁵, E. Pianori [ID](#)^{17a}, F. Piazza [ID](#)^{71a,71b},
 R. Piegaiia [ID](#)³⁰, D. Pietreanu [ID](#)^{27b}, A.D. Pilkington [ID](#)¹⁰¹, M. Pinamonti [ID](#)^{69a,69c}, J.L. Pinfold [ID](#)²,
 B.C. Pinheiro Pereira [ID](#)^{130a}, C. Pitman Donaldson [ID](#)⁹⁶, D.A. Pizzi [ID](#)³⁴, L. Pizzimento [ID](#)^{76a,76b},
 A. Pizzini [ID](#)¹¹⁴, M.-A. Pleier [ID](#)²⁹, V. Plesanovs [ID](#)⁵⁴, V. Pleskot [ID](#)¹³³, E. Plotnikova [ID](#)³⁸, G. Poddar [ID](#)⁴,
 R. Poettgen [ID](#)⁹⁸, L. Poggioli [ID](#)¹²⁷, I. Pogrebnyak [ID](#)¹⁰⁷, D. Pohl [ID](#)²⁴, I. Pokharel [ID](#)⁵⁵, S. Polacek [ID](#)¹³³,
 G. Polesello [ID](#)^{73a}, A. Poley [ID](#)^{142,156a}, R. Polifka [ID](#)¹³², A. Polini [ID](#)^{23b}, C.S. Pollard [ID](#)¹⁶⁷,
 Z.B. Pollock [ID](#)¹¹⁹, V. Polychronakos [ID](#)²⁹, E. Pompa Pacchi [ID](#)^{75a,75b}, D. Ponomarenko [ID](#)¹¹³,
 L. Pontecorvo [ID](#)³⁶, S. Popa [ID](#)^{27a}, G.A. Popeneciu [ID](#)^{27d}, D.M. Portillo Quintero [ID](#)^{156a},
 S. Pospisil [ID](#)¹³², P. Postolache [ID](#)^{27c}, K. Potamianos [ID](#)¹²⁶, P.P. Potepa [ID](#)^{85a}, I.N. Potrap [ID](#)³⁸,
 C.J. Potter [ID](#)³², H. Potti [ID](#)¹, T. Poulsen [ID](#)⁴⁸, J. Poveda [ID](#)¹⁶³, M.E. Pozo Astigarraga [ID](#)³⁶,
 A. Prades Ibanez [ID](#)¹⁶³, M.M. Prapa [ID](#)⁴⁶, J. Pretel [ID](#)⁵⁴, D. Price [ID](#)¹⁰¹, M. Primavera [ID](#)^{70a},
 M.A. Principe Martin [ID](#)⁹⁹, R. Privara [ID](#)¹²², M.L. Proffitt [ID](#)¹³⁸, N. Proklova [ID](#)¹²⁸, K. Prokofiev [ID](#)^{64c},
 G. Proto [ID](#)^{76a,76b}, S. Protopopescu [ID](#)²⁹, J. Proudfoot [ID](#)⁶, M. Przybycien [ID](#)^{85a}, J.E. Puddefoot [ID](#)¹³⁹,
 D. Pudzha [ID](#)³⁷, P. Puzo [ID](#)⁶⁶, D. Pyatiiybyantseva [ID](#)³⁷, J. Qian [ID](#)¹⁰⁶, D. Qichen [ID](#)¹⁰¹, Y. Qin [ID](#)¹⁰¹,
 T. Qiu [ID](#)⁹⁴, A. Quadt [ID](#)⁵⁵, M. Queitsch-Maitland [ID](#)¹⁰¹, G. Quetant [ID](#)⁵⁶, G. Rabanal Bolanos [ID](#)⁶¹,
 D. Rafanoharana [ID](#)⁵⁴, F. Ragusa [ID](#)^{71a,71b}, J.L. Rainbolt [ID](#)³⁹, J.A. Raine [ID](#)⁵⁶, S. Rajagopalan [ID](#)²⁹,
 E. Ramakoti [ID](#)³⁷, K. Ran [ID](#)^{48,14d}, N.P. Raphecha [ID](#)^{33g}, V. Raskina [ID](#)¹²⁷, D.F. Rassloff [ID](#)^{63a},
 S. Rave [ID](#)¹⁰⁰, B. Ravina [ID](#)⁵⁵, I. Ravinovich [ID](#)¹⁶⁹, M. Raymond [ID](#)³⁶, A.L. Read [ID](#)¹²⁵,
 N.P. Radioff [ID](#)¹³⁹, D.M. Rebutti [ID](#)^{73a,73b}, G. Redlinger [ID](#)²⁹, K. Reeves [ID](#)⁴⁵, J.A. Reidelsturz [ID](#)¹⁷¹,
 D. Reikher [ID](#)¹⁵¹, A. Rej [ID](#)¹⁴¹, C. Rembser [ID](#)³⁶, A. Renardi [ID](#)⁴⁸, M. Renda [ID](#)^{27b}, M.B. Rendel [ID](#)¹¹⁰,
 F. Renner [ID](#)⁴⁸, A.G. Rennie [ID](#)⁵⁹, S. Resconi [ID](#)^{71a}, M. Ressegotti [ID](#)^{57b,57a}, E.D. Resseguie [ID](#)^{17a},
 S. Rettie [ID](#)³⁶, J.G. Reyes Rivera [ID](#)¹⁰⁷, B. Reynolds [ID](#)¹¹⁹, E. Reynolds [ID](#)^{17a}, M. Rezaei Estabragh [ID](#)¹⁷¹,
 O.L. Rezanova [ID](#)³⁷, P. Reznicek [ID](#)¹³³, N. Ribaric [ID](#)⁹¹, E. Ricci [ID](#)^{78a,78b}, R. Richter [ID](#)¹¹⁰,
 S. Richter [ID](#)^{47a,47b}, E. Richter-Was [ID](#)^{85b}, M. Ridel [ID](#)¹²⁷, S. Ridouani [ID](#)^{35d}, P. Rieck [ID](#)¹¹⁷,
 P. Riedler [ID](#)³⁶, M. Rijssenbeek [ID](#)¹⁴⁵, A. Rimoldi [ID](#)^{73a,73b}, M. Rimoldi [ID](#)⁴⁸, L. Rinaldi [ID](#)^{23b,23a},
 T.T. Rinn [ID](#)²⁹, M.P. Rinnagel [ID](#)¹⁰⁹, G. Ripellino [ID](#)¹⁶¹, I. Riu [ID](#)¹³, P. Rivadeneira [ID](#)⁴⁸,
 J.C. Rivera Vergara [ID](#)¹⁶⁵, F. Rizatdinova [ID](#)¹²¹, E. Rizvi [ID](#)⁹⁴, C. Rizzi [ID](#)⁵⁶, B.A. Roberts [ID](#)¹⁶⁷,
 B.R. Roberts [ID](#)^{17a}, S.H. Robertson [ID](#)^{104,x}, M. Robin [ID](#)⁴⁸, D. Robinson [ID](#)³²,
 C.M. Robles Gajardo [ID](#)^{137f}, M. Robles Manzano [ID](#)¹⁰⁰, A. Robson [ID](#)⁵⁹, A. Rocchi [ID](#)^{76a,76b},
 C. Roda [ID](#)^{74a,74b}, S. Rodriguez Bosca [ID](#)^{63a}, Y. Rodriguez Garcia [ID](#)^{22a}, A. Rodriguez Rodriguez [ID](#)⁵⁴,
 A.M. Rodríguez Vera [ID](#)^{156b}, S. Roe [ID](#)³⁶, J.T. Roemer [ID](#)¹⁶⁰, A.R. Roepe-Gier [ID](#)¹³⁶, J. Roggel [ID](#)¹⁷¹,
 O. Røhne [ID](#)¹²⁵, R.A. Rojas [ID](#)¹⁰³, B. Roland [ID](#)⁵⁴, C.P.A. Roland [ID](#)⁶⁸, J. Roloff [ID](#)²⁹,
 A. Romaniouk [ID](#)³⁷, E. Romano [ID](#)^{73a,73b}, M. Romano [ID](#)^{23b}, A.C. Romero Hernandez [ID](#)¹⁶²,
 N. Rompotis [ID](#)⁹², L. Roos [ID](#)¹²⁷, S. Rosati [ID](#)^{75a}, B.J. Rosser [ID](#)³⁹, E. Rossi [ID](#)⁴, E. Rossi [ID](#)^{72a,72b},
 L.P. Rossi [ID](#)^{57b}, L. Rossini [ID](#)⁴⁸, R. Rosten [ID](#)¹¹⁹, M. Rotaru [ID](#)^{27b}, B. Rottler [ID](#)⁵⁴, C. Rougier [ID](#)¹⁰²,
 D. Rousseau [ID](#)⁶⁶, D. Rousso [ID](#)³², G. Rovelli [ID](#)^{73a,73b}, A. Roy [ID](#)¹⁶², S. Roy-Garand [ID](#)¹⁵⁵,
 A. Rozanov [ID](#)¹⁰², Y. Rozen [ID](#)¹⁵⁰, X. Ruan [ID](#)^{33g}, A. Rubio Jimenez [ID](#)¹⁶³, A.J. Ruby [ID](#)⁹²,

V.H. Ruelas Rivera [ID](#)¹⁸, T.A. Ruggeri [ID](#)¹, F. Rühr [ID](#)⁵⁴, A. Ruiz-Martinez [ID](#)¹⁶³, A. Rummeler [ID](#)³⁶, Z. Rurikova [ID](#)⁵⁴, N.A. Rusakovich [ID](#)³⁸, H.L. Russell [ID](#)¹⁶⁵, J.P. Rutherford [ID](#)⁷, K. Rybacki [ID](#)⁹¹, M. Rybar [ID](#)¹³³, E.B. Rye [ID](#)¹²⁵, A. Ryzhov [ID](#)³⁷, J.A. Sabater Iglesias [ID](#)⁵⁶, P. Sabatini [ID](#)¹⁶³, L. Sabetta [ID](#)^{75a,75b}, H.F.-W. Sadrozinski [ID](#)¹³⁶, F. Safai Tehrani [ID](#)^{75a}, B. Safarzadeh Samani [ID](#)¹⁴⁶, M. Safdari [ID](#)¹⁴³, S. Saha [ID](#)¹⁰⁴, M. Sahinsoy [ID](#)¹¹⁰, M. Saimpert [ID](#)¹³⁵, M. Saito [ID](#)¹⁵³, T. Saito [ID](#)¹⁵³, D. Salamani [ID](#)³⁶, G. Salamanna [ID](#)^{77a,77b}, A. Salnikov [ID](#)¹⁴³, J. Salt [ID](#)¹⁶³, A. Salvador Salas [ID](#)¹³, D. Salvatore [ID](#)^{43b,43a}, F. Salvatore [ID](#)¹⁴⁶, A. Salzburger [ID](#)³⁶, D. Sammel [ID](#)⁵⁴, D. Sampsonidis [ID](#)^{152,f}, D. Sampsonidou [ID](#)^{62d,62c}, J. Sánchez [ID](#)¹⁶³, A. Sanchez Pineda [ID](#)⁴, V. Sanchez Sebastian [ID](#)¹⁶³, H. Sandaker [ID](#)¹²⁵, C.O. Sander [ID](#)⁴⁸, J.A. Sandesara [ID](#)¹⁰³, M. Sandhoff [ID](#)¹⁷¹, C. Sandoval [ID](#)^{22b}, D.P.C. Sankey [ID](#)¹³⁴, T. Sano [ID](#)⁸⁷, A. Sansoni [ID](#)⁵³, L. Santi [ID](#)^{75a,75b}, C. Santoni [ID](#)⁴⁰, H. Santos [ID](#)^{130a,130b}, S.N. Santpur [ID](#)^{17a}, A. Santra [ID](#)¹⁶⁹, K.A. Saoucha [ID](#)¹³⁹, J.G. Saraiva [ID](#)^{130a,130d}, J. Sardain [ID](#)⁷, O. Sasaki [ID](#)⁸³, K. Sato [ID](#)¹⁵⁷, C. Sauer [ID](#)^{63b}, F. Sauerburger [ID](#)⁵⁴, E. Sauvan [ID](#)⁴, P. Savard [ID](#)^{155,ad}, R. Sawada [ID](#)¹⁵³, C. Sawyer [ID](#)¹³⁴, L. Sawyer [ID](#)⁹⁷, I. Sayago Galvan [ID](#)¹⁶³, C. Sbarra [ID](#)^{23b}, A. Sbrizzi [ID](#)^{23b,23a}, T. Scanlon [ID](#)⁹⁶, J. Schaarschmidt [ID](#)¹³⁸, P. Schacht [ID](#)¹¹⁰, D. Schaefer [ID](#)³⁹, U. Schäfer [ID](#)¹⁰⁰, A.C. Schaffer [ID](#)^{66,44}, D. Schaile [ID](#)¹⁰⁹, R.D. Schamberger [ID](#)¹⁴⁵, E. Schanet [ID](#)¹⁰⁹, C. Scharf [ID](#)¹⁸, M.M. Schefer [ID](#)¹⁹, V.A. Schegelsky [ID](#)³⁷, D. Scheirich [ID](#)¹³³, F. Schenck [ID](#)¹⁸, M. Schernau [ID](#)¹⁶⁰, C. Scheulen [ID](#)⁵⁵, C. Schiavi [ID](#)^{57b,57a}, Z.M. Schillaci [ID](#)²⁶, E.J. Schioppa [ID](#)^{70a,70b}, M. Schioppa [ID](#)^{43b,43a}, B. Schlag [ID](#)¹⁰⁰, K.E. Schleicher [ID](#)⁵⁴, S. Schlenker [ID](#)³⁶, J. Schmeing [ID](#)¹⁷¹, M.A. Schmidt [ID](#)¹⁷¹, K. Schmieden [ID](#)¹⁰⁰, C. Schmitt [ID](#)¹⁰⁰, S. Schmitt [ID](#)⁴⁸, L. Schoeffel [ID](#)¹³⁵, A. Schoening [ID](#)^{63b}, P.G. Scholer [ID](#)⁵⁴, E. Schopf [ID](#)¹²⁶, M. Schott [ID](#)¹⁰⁰, J. Schovancova [ID](#)³⁶, S. Schramm [ID](#)⁵⁶, F. Schroeder [ID](#)¹⁷¹, H.-C. Schultz-Coulon [ID](#)^{63a}, M. Schumacher [ID](#)⁵⁴, B.A. Schumm [ID](#)¹³⁶, Ph. Schune [ID](#)¹³⁵, H.R. Schwartz [ID](#)¹³⁶, A. Schwartzman [ID](#)¹⁴³, T.A. Schwarz [ID](#)¹⁰⁶, Ph. Schwemling [ID](#)¹³⁵, R. Schwienhorst [ID](#)¹⁰⁷, A. Sciandra [ID](#)¹³⁶, G. Sciolla [ID](#)²⁶, F. Scuri [ID](#)^{74a}, F. Scutti [ID](#)¹⁰⁵, C.D. Sebastiani [ID](#)⁹², K. Sedlaczek [ID](#)⁴⁹, P. Seema [ID](#)¹⁸, S.C. Seidel [ID](#)¹¹², A. Seiden [ID](#)¹³⁶, B.D. Seidlitz [ID](#)⁴¹, C. Seitz [ID](#)⁴⁸, J.M. Seixas [ID](#)^{82b}, G. Sekhniaidze [ID](#)^{72a}, S.J. Sekula [ID](#)⁴⁴, L. Selem [ID](#)⁴, N. Semprini-Cesari [ID](#)^{23b,23a}, S. Sen [ID](#)⁵¹, D. Sengupta [ID](#)⁵⁶, V. Senthilkumar [ID](#)¹⁶³, L. Serin [ID](#)⁶⁶, L. Serkin [ID](#)^{69a,69b}, M. Sessa [ID](#)^{77a,77b}, H. Severini [ID](#)¹²⁰, F. Sforza [ID](#)^{57b,57a}, A. Sfyrila [ID](#)⁵⁶, E. Shabalina [ID](#)⁵⁵, R. Shaheen [ID](#)¹⁴⁴, J.D. Shahinian [ID](#)¹²⁸, D. Shaked Renous [ID](#)¹⁶⁹, L.Y. Shan [ID](#)^{14a}, M. Shapiro [ID](#)^{17a}, A. Sharma [ID](#)³⁶, A.S. Sharma [ID](#)¹⁶⁴, P. Sharma [ID](#)⁸⁰, S. Sharma [ID](#)⁴⁸, P.B. Shatalov [ID](#)³⁷, K. Shaw [ID](#)¹⁴⁶, S.M. Shaw [ID](#)¹⁰¹, Q. Shen [ID](#)^{62c,5}, P. Sherwood [ID](#)⁹⁶, L. Shi [ID](#)⁹⁶, C.O. Shimmin [ID](#)¹⁷², Y. Shimogama [ID](#)¹⁶⁸, J.D. Shinner [ID](#)⁹⁵, I.P.J. Shipsey [ID](#)¹²⁶, S. Shirabe [ID](#)⁶⁰, M. Shiyakova [ID](#)³⁸, J. Shlomi [ID](#)¹⁶⁹, M.J. Shochet [ID](#)³⁹, J. Shojaii [ID](#)¹⁰⁵, D.R. Shope [ID](#)¹²⁵, S. Shrestha [ID](#)^{119,ah}, E.M. Shrif [ID](#)^{33g}, M.J. Shroff [ID](#)¹⁶⁵, P. Sicho [ID](#)¹³¹, A.M. Sickles [ID](#)¹⁶², E. Sideras Haddad [ID](#)^{33g}, A. Sidoti [ID](#)^{23b}, F. Siegert [ID](#)⁵⁰, Dj. Sijacki [ID](#)¹⁵, R. Sikora [ID](#)^{85a}, F. Sili [ID](#)⁹⁰, J.M. Silva [ID](#)²⁰, M.V. Silva Oliveira [ID](#)³⁶, S.B. Silverstein [ID](#)^{47a}, S. Simion [ID](#)⁶⁶, R. Simoniello [ID](#)³⁶, E.L. Simpson [ID](#)⁵⁹, H. Simpson [ID](#)¹⁴⁶, L.R. Simpson [ID](#)¹⁰⁶, N.D. Simpson [ID](#)⁹⁸, S. Simsek [ID](#)^{21d}, S. Sindhu [ID](#)⁵⁵, P. Sinervo [ID](#)¹⁵⁵, S. Singh [ID](#)¹⁴², S. Singh [ID](#)¹⁵⁵, S. Sinha [ID](#)⁴⁸, S. Sinha [ID](#)^{33g}, M. Sioli [ID](#)^{23b,23a}, I. Siral [ID](#)³⁶, S.Yu. Sivoklokov [ID](#)^{37,*}, J. Sjölin [ID](#)^{47a,47b}, A. Skaf [ID](#)⁵⁵, E. Skorda [ID](#)⁹⁸, P. Skubic [ID](#)¹²⁰, M. Slawinska [ID](#)⁸⁶, V. Smakhtin [ID](#)¹⁶⁹, B.H. Smart [ID](#)¹³⁴, J. Smiesko [ID](#)³⁶, S.Yu. Smirnov [ID](#)³⁷, Y. Smirnov [ID](#)³⁷, L.N. Smirnova [ID](#)^{37,a}, O. Smirnova [ID](#)⁹⁸, A.C. Smith [ID](#)⁴¹, E.A. Smith [ID](#)³⁹, H.A. Smith [ID](#)¹²⁶, J.L. Smith [ID](#)⁹², R. Smith [ID](#)¹⁴³, M. Smizanska [ID](#)⁹¹, K. Smolek [ID](#)¹³², A. Smykiewicz [ID](#)⁸⁶, A.A. Snesarev [ID](#)³⁷, H.L. Snoek [ID](#)¹¹⁴, S. Snyder [ID](#)²⁹, R. Sobie [ID](#)^{165,x},

A. Soffer [ID](#)¹⁵¹, C.A. Solans Sanchez [ID](#)³⁶, E.Yu. Soldatov [ID](#)³⁷, U. Soldevila [ID](#)¹⁶³, A.A. Solodkov [ID](#)³⁷, S. Solomon [ID](#)⁵⁴, A. Soloshenko [ID](#)³⁸, K. Solovieva [ID](#)⁵⁴, O.V. Solovyanov [ID](#)⁴⁰, V. Solovyev [ID](#)³⁷, P. Sommer [ID](#)³⁶, A. Sonay [ID](#)¹³, W.Y. Song [ID](#)^{156b}, J.M. Sonneveld [ID](#)¹¹⁴, A. Sopczak [ID](#)¹³², A.L. Sopio [ID](#)⁹⁶, F. Sopkova [ID](#)^{28b}, V. Sothilingam [ID](#)^{63a}, S. Sottocornola [ID](#)⁶⁸, R. Soualah [ID](#)^{116b}, Z. Soumami [ID](#)^{35e}, D. South [ID](#)⁴⁸, S. Spagnolo [ID](#)^{70a,70b}, M. Spalla [ID](#)¹¹⁰, F. Spanò [ID](#)⁹⁵, D. Sperlich [ID](#)⁵⁴, G. Spigo [ID](#)³⁶, M. Spina [ID](#)¹⁴⁶, S. Spinali [ID](#)⁹¹, D.P. Spiteri [ID](#)⁵⁹, M. Spousta [ID](#)¹³³, E.J. Staats [ID](#)³⁴, A. Stabile [ID](#)^{71a,71b}, R. Stamen [ID](#)^{63a}, M. Stamenkovic [ID](#)¹¹⁴, A. Stampekiš [ID](#)²⁰, M. Standke [ID](#)²⁴, E. Stanecka [ID](#)⁸⁶, M.V. Stange [ID](#)⁵⁰, B. Stanislaus [ID](#)^{17a}, M.M. Stanitzki [ID](#)⁴⁸, M. Stankaityte [ID](#)¹²⁶, B. Stapf [ID](#)⁴⁸, E.A. Starchenko [ID](#)³⁷, G.H. Stark [ID](#)¹³⁶, J. Stark [ID](#)¹⁰², D.M. Starko [ID](#)^{156b}, P. Staroba [ID](#)¹³¹, P. Starovoitov [ID](#)^{63a}, S. Stärz [ID](#)¹⁰⁴, R. Staszewski [ID](#)⁸⁶, G. Stavropoulos [ID](#)⁴⁶, J. Steentoft [ID](#)¹⁶¹, P. Steinberg [ID](#)²⁹, A.L. Steinhebel [ID](#)¹²³, B. Stelzer [ID](#)^{142,156a}, H.J. Stelzer [ID](#)¹²⁹, O. Stelzer-Chilton [ID](#)^{156a}, H. Stenzel [ID](#)⁵⁸, T.J. Stevenson [ID](#)¹⁴⁶, G.A. Stewart [ID](#)³⁶, M.C. Stockton [ID](#)³⁶, G. Stoica [ID](#)^{27b}, M. Stolarski [ID](#)^{130a}, S. Stonjek [ID](#)¹¹⁰, A. Straessner [ID](#)⁵⁰, J. Strandberg [ID](#)¹⁴⁴, S. Strandberg [ID](#)^{47a,47b}, M. Strauss [ID](#)¹²⁰, T. Strebler [ID](#)¹⁰², P. Strizenec [ID](#)^{28b}, R. Ströhmer [ID](#)¹⁶⁶, D.M. Strom [ID](#)¹²³, L.R. Strom [ID](#)⁴⁸, R. Stroynowski [ID](#)⁴⁴, A. Strubig [ID](#)^{47a,47b}, S.A. Stucci [ID](#)²⁹, B. Stugu [ID](#)¹⁶, J. Stupak [ID](#)¹²⁰, N.A. Styles [ID](#)⁴⁸, D. Su [ID](#)¹⁴³, S. Su [ID](#)^{62a}, W. Su [ID](#)^{62d,138,62c}, X. Su [ID](#)^{62a,66}, K. Sugizaki [ID](#)¹⁵³, V.V. Sulim [ID](#)³⁷, M.J. Sullivan [ID](#)⁹², D.M.S. Sultan [ID](#)^{78a,78b}, L. Sultanaliyeva [ID](#)³⁷, S. Sultansoy [ID](#)^{3b}, T. Sumida [ID](#)⁸⁷, S. Sun [ID](#)¹⁰⁶, S. Sun [ID](#)¹⁷⁰, O. Sunneborn Gudnadottir [ID](#)¹⁶¹, M.R. Sutton [ID](#)¹⁴⁶, M. Svatos [ID](#)¹³¹, M. Swiatkowski [ID](#)^{156a}, T. Swirski [ID](#)¹⁶⁶, I. Sykora [ID](#)^{28a}, M. Sykora [ID](#)¹³³, T. Sykora [ID](#)¹³³, D. Ta [ID](#)¹⁰⁰, K. Tackmann [ID](#)^{48,v}, A. Taffard [ID](#)¹⁶⁰, R. Tafirout [ID](#)^{156a}, J.S. Tafoya Vargas [ID](#)⁶⁶, R.H.M. Taibah [ID](#)¹²⁷, R. Takashima [ID](#)⁸⁸, K. Takeda [ID](#)⁸⁴, E.P. Takeva [ID](#)⁵², Y. Takubo [ID](#)⁸³, M. Talby [ID](#)¹⁰², A.A. Talyshev [ID](#)³⁷, K.C. Tam [ID](#)^{64b}, N.M. Tamir [ID](#)¹⁵¹, A. Tanaka [ID](#)¹⁵³, J. Tanaka [ID](#)¹⁵³, R. Tanaka [ID](#)⁶⁶, M. Tanasini [ID](#)^{57b,57a}, J. Tang [ID](#)^{62c}, Z. Tao [ID](#)¹⁶⁴, S. Tapia Araya [ID](#)^{137f}, S. Tapprogge [ID](#)¹⁰⁰, A. Tarek Abouelfadl Mohamed [ID](#)¹⁰⁷, S. Tarem [ID](#)¹⁵⁰, K. Tariq [ID](#)^{62b}, G. Tarna [ID](#)^{102,27b}, G.F. Tartarelli [ID](#)^{71a}, P. Tas [ID](#)¹³³, M. Tasevsky [ID](#)¹³¹, E. Tassi [ID](#)^{43b,43a}, A.C. Tate [ID](#)¹⁶², G. Tateno [ID](#)¹⁵³, Y. Tayalati [ID](#)^{35e,w}, G.N. Taylor [ID](#)¹⁰⁵, W. Taylor [ID](#)^{156b}, H. Teagle [ID](#)⁹², A.S. Tee [ID](#)¹⁷⁰, R. Teixeira De Lima [ID](#)¹⁴³, P. Teixeira-Dias [ID](#)⁹⁵, J.J. Teoh [ID](#)¹⁵⁵, K. Terashi [ID](#)¹⁵³, J. Terron [ID](#)⁹⁹, S. Terzo [ID](#)¹³, M. Testa [ID](#)⁵³, R.J. Teuscher [ID](#)^{155,x}, A. Thaler [ID](#)⁷⁹, O. Theiner [ID](#)⁵⁶, N. Themistokleous [ID](#)⁵², T. Theveneaux-Pelzer [ID](#)¹⁸, O. Thielmann [ID](#)¹⁷¹, D.W. Thomas [ID](#)⁹⁵, J.P. Thomas [ID](#)²⁰, E.A. Thompson [ID](#)^{17a}, P.D. Thompson [ID](#)²⁰, E. Thomson [ID](#)¹²⁸, E.J. Thorpe [ID](#)⁹⁴, Y. Tian [ID](#)⁵⁵, V. Tikhomirov [ID](#)^{37,a}, Yu.A. Tikhonov [ID](#)³⁷, S. Timoshenko [ID](#)³⁷, E.X.L. Ting [ID](#)¹, P. Tipton [ID](#)¹⁷², S. Tisserant [ID](#)¹⁰², S.H. Tlou [ID](#)^{33g}, A. Tmourji [ID](#)⁴⁰, K. Todome [ID](#)^{23b,23a}, S. Todorova-Nova [ID](#)¹³³, S. Todt [ID](#)⁵⁰, M. Togawa [ID](#)⁸³, J. Tojo [ID](#)⁸⁹, S. Tokár [ID](#)^{28a}, K. Tokushuku [ID](#)⁸³, O. Toldaiev [ID](#)⁶⁸, R. Tombs [ID](#)³², M. Tomoto [ID](#)^{83,111}, L. Tompkins [ID](#)¹⁴³, K.W. Topolnicki [ID](#)^{85b}, P. Tornambe [ID](#)¹⁰³, E. Torrence [ID](#)¹²³, H. Torres [ID](#)⁵⁰, E. Torró Pastor [ID](#)¹⁶³, M. Toscani [ID](#)³⁰, C. Tosciri [ID](#)³⁹, M. Tost [ID](#)¹¹, D.R. Tovey [ID](#)¹³⁹, A. Traeet [ID](#)¹⁶, I.S. Trandafir [ID](#)^{27b}, T. Trefzger [ID](#)¹⁶⁶, A. Tricoli [ID](#)²⁹, I.M. Trigger [ID](#)^{156a}, S. Trincaz-Duvoid [ID](#)¹²⁷, D.A. Trischuk [ID](#)²⁶, B. Trocmé [ID](#)⁶⁰, C. Troncon [ID](#)^{71a}, L. Truong [ID](#)^{33c}, M. Trzebinski [ID](#)⁸⁶, A. Trzupek [ID](#)⁸⁶, F. Tsai [ID](#)¹⁴⁵, M. Tsai [ID](#)¹⁰⁶, A. Tsiamis [ID](#)^{152,f}, P.V. Tsiarshka [ID](#)³⁷, S. Tsigaridas [ID](#)^{156a}, A. Tsirigotis [ID](#)^{152,t}, V. Tsiskaridze [ID](#)¹⁴⁵, E.G. Tskhadadze [ID](#)^{149a}, M. Tsopoulou [ID](#)^{152,f}, Y. Tsujikawa [ID](#)⁸⁷, I.I. Tsukerman [ID](#)³⁷, V. Tsulaia [ID](#)^{17a}, S. Tsuno [ID](#)⁸³, O. Tsur [ID](#)¹⁵⁰, D. Tsybychev [ID](#)¹⁴⁵, Y. Tu [ID](#)^{64b}, A. Tudorache [ID](#)^{27b}, V. Tudorache [ID](#)^{27b}, A.N. Tuna [ID](#)³⁶, S. Turchikhin [ID](#)³⁸, I. Turk Cakir [ID](#)^{3a}, R. Turra [ID](#)^{71a}, T. Turtuvshin [ID](#)^{38,y},

P.M. Tuts [ID](#)⁴¹, S. Tzamarias [ID](#)^{152,f}, P. Tzanis [ID](#)¹⁰, E. Tzovara [ID](#)¹⁰⁰, K. Uchida [ID](#)¹⁵³, F. Ukegawa [ID](#)¹⁵⁷, P.A. Ulloa Poblete [ID](#)^{137c}, E.N. Umaka [ID](#)²⁹, G. Unal [ID](#)³⁶, M. Unal [ID](#)¹¹, A. Undrus [ID](#)²⁹, G. Unel [ID](#)¹⁶⁰, J. Urban [ID](#)^{28b}, P. Urquijo [ID](#)¹⁰⁵, G. Usai [ID](#)⁸, R. Ushioda [ID](#)¹⁵⁴, M. Usman [ID](#)¹⁰⁸, Z. Uysal [ID](#)^{21b}, L. Vacavant [ID](#)¹⁰², V. Vacek [ID](#)¹³², B. Vachon [ID](#)¹⁰⁴, K.O.H. Vadla [ID](#)¹²⁵, T. Vafeiadis [ID](#)³⁶, A. Vaitkus [ID](#)⁹⁶, C. Valderanis [ID](#)¹⁰⁹, E. Valdes Santurio [ID](#)^{47a,47b}, M. Valente [ID](#)^{156a}, S. Valentinetti [ID](#)^{23b,23a}, A. Valero [ID](#)¹⁶³, A. Vallier [ID](#)¹⁰², J.A. Valls Ferrer [ID](#)¹⁶³, D.R. Van Arneman [ID](#)¹¹⁴, T.R. Van Daalen [ID](#)¹³⁸, P. Van Gemmeren [ID](#)⁶, M. Van Rijnbach [ID](#)^{125,36}, S. Van Stroud [ID](#)⁹⁶, I. Van Vulpen [ID](#)¹¹⁴, M. Vanadia [ID](#)^{76a,76b}, W. Vandelli [ID](#)³⁶, M. Vandenbroucke [ID](#)¹³⁵, E.R. Vandewall [ID](#)¹²¹, D. Vannicola [ID](#)¹⁵¹, L. Vannoli [ID](#)^{57b,57a}, R. Vari [ID](#)^{75a}, E.W. Varnes [ID](#)⁷, C. Varni [ID](#)^{17a}, T. Varol [ID](#)¹⁴⁸, D. Varouchas [ID](#)⁶⁶, L. Varriale [ID](#)¹⁶³, K.E. Varvell [ID](#)¹⁴⁷, M.E. Vasile [ID](#)^{27b}, L. Vaslin [ID](#)⁴⁰, G.A. Vasquez [ID](#)¹⁶⁵, F. Vazeille [ID](#)⁴⁰, T. Vazquez Schroeder [ID](#)³⁶, J. Veatch [ID](#)³¹, V. Vecchio [ID](#)¹⁰¹, M.J. Veen [ID](#)¹⁰³, I. Veliscek [ID](#)¹²⁶, L.M. Veloce [ID](#)¹⁵⁵, F. Veloso [ID](#)^{130a,130c}, S. Veneziano [ID](#)^{75a}, A. Ventura [ID](#)^{70a,70b}, A. Verbytskyi [ID](#)¹¹⁰, M. Verducci [ID](#)^{74a,74b}, C. Vergis [ID](#)²⁴, M. Verissimo De Araujo [ID](#)^{82b}, W. Verkerke [ID](#)¹¹⁴, J.C. Vermeulen [ID](#)¹¹⁴, C. Vernieri [ID](#)¹⁴³, P.J. Verschuuren [ID](#)⁹⁵, M. Vessella [ID](#)¹⁰³, M.C. Vetterli [ID](#)^{142,ad}, A. Vgenopoulos [ID](#)^{152,f}, N. Viaux Maira [ID](#)^{137f}, T. Vickey [ID](#)¹³⁹, O.E. Vickey Boeriu [ID](#)¹³⁹, G.H.A. Viehhauser [ID](#)¹²⁶, L. Vigani [ID](#)^{63b}, M. Villa [ID](#)^{23b,23a}, M. Villaplana Perez [ID](#)¹⁶³, E.M. Villhauer [ID](#)⁵², E. Vilucchi [ID](#)⁵³, M.G. Vincter [ID](#)³⁴, G.S. Virdee [ID](#)²⁰, A. Vishwakarma [ID](#)⁵², C. Vittori [ID](#)³⁶, I. Vivarelli [ID](#)¹⁴⁶, V. Vladimirov [ID](#)¹⁶⁷, E. Voevodina [ID](#)¹¹⁰, F. Vogel [ID](#)¹⁰⁹, P. Vokac [ID](#)¹³², J. Von Ahnen [ID](#)⁴⁸, E. Von Toerne [ID](#)²⁴, B. Vormwald [ID](#)³⁶, V. Vorobel [ID](#)¹³³, K. Vorobev [ID](#)³⁷, M. Vos [ID](#)¹⁶³, K. Voss [ID](#)¹⁴¹, J.H. Vossebeld [ID](#)⁹², M. Vozak [ID](#)¹¹⁴, L. Vozdecky [ID](#)⁹⁴, N. Vranjes [ID](#)¹⁵, M. Vranjes Milosavljevic [ID](#)¹⁵, M. Vreeswijk [ID](#)¹¹⁴, R. Vuillermet [ID](#)³⁶, O. Vujanovic [ID](#)¹⁰⁰, I. Vukotic [ID](#)³⁹, S. Wada [ID](#)¹⁵⁷, C. Wagner [ID](#)¹⁰³, W. Wagner [ID](#)¹⁷¹, S. Wahdan [ID](#)¹⁷¹, H. Wahlberg [ID](#)⁹⁰, R. Wakasa [ID](#)¹⁵⁷, M. Wakida [ID](#)¹¹¹, V.M. Walbrecht [ID](#)¹¹⁰, J. Walder [ID](#)¹³⁴, R. Walker [ID](#)¹⁰⁹, W. Walkowiak [ID](#)¹⁴¹, A.M. Wang [ID](#)⁶¹, A.Z. Wang [ID](#)¹⁷⁰, C. Wang [ID](#)¹⁰⁰, C. Wang [ID](#)^{62c}, H. Wang [ID](#)^{17a}, J. Wang [ID](#)^{64a}, R.-J. Wang [ID](#)¹⁰⁰, R. Wang [ID](#)⁶¹, R. Wang [ID](#)⁶, S.M. Wang [ID](#)¹⁴⁸, S. Wang [ID](#)^{62b}, T. Wang [ID](#)^{62a}, W.T. Wang [ID](#)⁸⁰, X. Wang [ID](#)^{14c}, X. Wang [ID](#)¹⁶², X. Wang [ID](#)^{62c}, Y. Wang [ID](#)^{62d}, Y. Wang [ID](#)^{14c}, Z. Wang [ID](#)¹⁰⁶, Z. Wang [ID](#)^{62d,51,62c}, Z. Wang [ID](#)¹⁰⁶, A. Warburton [ID](#)¹⁰⁴, R.J. Ward [ID](#)²⁰, N. Warrack [ID](#)⁵⁹, A.T. Watson [ID](#)²⁰, H. Watson [ID](#)⁵⁹, M.F. Watson [ID](#)²⁰, G. Watts [ID](#)¹³⁸, B.M. Waugh [ID](#)⁹⁶, A.F. Webb [ID](#)¹¹, C. Weber [ID](#)²⁹, H.A. Weber [ID](#)¹⁸, M.S. Weber [ID](#)¹⁹, S.M. Weber [ID](#)^{63a}, C. Wei [ID](#)^{62a}, Y. Wei [ID](#)¹²⁶, A.R. Weidberg [ID](#)¹²⁶, E.J. Weik [ID](#)¹¹⁷, J. Weingarten [ID](#)⁴⁹, M. Weirich [ID](#)¹⁰⁰, C. Weiser [ID](#)⁵⁴, C.J. Wells [ID](#)⁴⁸, T. Wenaus [ID](#)²⁹, B. Wendland [ID](#)⁴⁹, T. Wengler [ID](#)³⁶, N.S. Wenke [ID](#)¹¹⁰, N. Vermes [ID](#)²⁴, M. Wessels [ID](#)^{63a}, K. Whalen [ID](#)¹²³, A.M. Wharton [ID](#)⁹¹, A.S. White [ID](#)⁶¹, A. White [ID](#)⁸, M.J. White [ID](#)¹, D. Whiteson [ID](#)¹⁶⁰, L. Wickremasinghe [ID](#)¹²⁴, W. Wiedenmann [ID](#)¹⁷⁰, C. Wiel [ID](#)⁵⁰, M. Wielers [ID](#)¹³⁴, C. Wigglesworth [ID](#)⁴², L.A.M. Wiik-Fuchs [ID](#)⁵⁴, D.J. Wilbern [ID](#)¹²⁰, H.G. Wilkens [ID](#)³⁶, D.M. Williams [ID](#)⁴¹, H.H. Williams [ID](#)¹²⁸, S. Williams [ID](#)³², S. Willocq [ID](#)¹⁰³, P.J. Windischhofer [ID](#)¹²⁶, F. Winklmeier [ID](#)¹²³, B.T. Winter [ID](#)⁵⁴, J.K. Winter [ID](#)¹⁰¹, M. Wittgen [ID](#)¹⁴³, M. Wobisch [ID](#)⁹⁷, R. Wölker [ID](#)¹²⁶, J. Wollrath [ID](#)¹⁶⁰, M.W. Wolter [ID](#)⁸⁶, H. Wolters [ID](#)^{130a,130c}, V.W.S. Wong [ID](#)¹⁶⁴, A.F. Wongel [ID](#)⁴⁸, S.D. Worm [ID](#)⁴⁸, B.K. Wosiek [ID](#)⁸⁶, K.W. Woźniak [ID](#)⁸⁶, K. Wraight [ID](#)⁵⁹, J. Wu [ID](#)^{14a,14d}, M. Wu [ID](#)^{64a}, M. Wu [ID](#)¹¹³, S.L. Wu [ID](#)¹⁷⁰, X. Wu [ID](#)⁵⁶, Y. Wu [ID](#)^{62a}, Z. Wu [ID](#)^{135,62a}, J. Wuerzinger [ID](#)¹²⁶, T.R. Wyatt [ID](#)¹⁰¹, B.M. Wynne [ID](#)⁵², S. Xella [ID](#)⁴², L. Xia [ID](#)^{14c}, M. Xia [ID](#)^{14b}, J. Xiang [ID](#)^{64c}, X. Xiao [ID](#)¹⁰⁶, M. Xie [ID](#)^{62a}, X. Xie [ID](#)^{62a}, S. Xin [ID](#)^{14a,14d}, J. Xiong [ID](#)^{17a}, I. Xioutidis [ID](#)¹⁴⁶,

D. Xu [ID](#)^{14a}, H. Xu^{62a}, H. Xu [ID](#)^{62a}, L. Xu [ID](#)^{62a}, R. Xu [ID](#)¹²⁸, T. Xu [ID](#)¹⁰⁶, W. Xu [ID](#)¹⁰⁶, Y. Xu [ID](#)^{14b}, Z. Xu [ID](#)^{62b}, Z. Xu [ID](#)^{14a}, B. Yabsley [ID](#)¹⁴⁷, S. Yacoob [ID](#)^{33a}, N. Yamaguchi [ID](#)⁸⁹, Y. Yamaguchi [ID](#)¹⁵⁴, H. Yamauchi [ID](#)¹⁵⁷, T. Yamazaki [ID](#)^{17a}, Y. Yamazaki [ID](#)⁸⁴, J. Yan^{62c}, S. Yan [ID](#)¹²⁶, Z. Yan [ID](#)²⁵, H.J. Yang [ID](#)^{62c,62d}, H.T. Yang [ID](#)^{62a}, S. Yang [ID](#)^{62a}, T. Yang [ID](#)^{64c}, X. Yang [ID](#)^{62a}, X. Yang [ID](#)^{14a}, Y. Yang [ID](#)⁴⁴, Y. Yang^{62a}, Z. Yang [ID](#)^{62a,106}, W-M. Yao [ID](#)^{17a}, Y.C. Yap [ID](#)⁴⁸, H. Ye [ID](#)^{14c}, H. Ye [ID](#)⁵⁵, J. Ye [ID](#)⁴⁴, S. Ye [ID](#)²⁹, X. Ye [ID](#)^{62a}, Y. Yeh [ID](#)⁹⁶, I. Yeletsikh [ID](#)³⁸, B.K. Yeo [ID](#)^{17a}, M.R. Yexley [ID](#)⁹¹, P. Yin [ID](#)⁴¹, K. Yorita [ID](#)¹⁶⁸, S. Younas [ID](#)^{27b}, C.J.S. Young [ID](#)⁵⁴, C. Young [ID](#)¹⁴³, Y. Yu [ID](#)^{62a}, M. Yuan [ID](#)¹⁰⁶, R. Yuan [ID](#)^{62b,l}, L. Yue [ID](#)⁹⁶, X. Yue [ID](#)^{63a}, M. Zaazoua [ID](#)^{35e}, B. Zabinski [ID](#)⁸⁶, E. Zaid⁵², T. Zakareishvili [ID](#)^{149b}, N. Zakharchuk [ID](#)³⁴, S. Zambito [ID](#)⁵⁶, J.A. Zamora Saa [ID](#)^{137d,137b}, J. Zang [ID](#)¹⁵³, D. Zanzi [ID](#)⁵⁴, O. Zaplatilek [ID](#)¹³², S.V. Zeißner [ID](#)⁴⁹, C. Zeitnitz [ID](#)¹⁷¹, J.C. Zeng [ID](#)¹⁶², D.T. Zenger Jr [ID](#)²⁶, O. Zenin [ID](#)³⁷, T. Ženiš [ID](#)^{28a}, S. Zenz [ID](#)⁹⁴, S. Zerradi [ID](#)^{35a}, D. Zerwas [ID](#)⁶⁶, M. Zhai [ID](#)^{14a,14d}, B. Zhang [ID](#)^{14c}, D.F. Zhang [ID](#)¹³⁹, J. Zhang [ID](#)^{62b}, J. Zhang [ID](#)⁶, K. Zhang [ID](#)^{14a,14d}, L. Zhang [ID](#)^{14c}, P. Zhang^{14a,14d}, R. Zhang [ID](#)¹⁷⁰, S. Zhang [ID](#)¹⁰⁶, T. Zhang [ID](#)¹⁵³, X. Zhang [ID](#)^{62c}, X. Zhang [ID](#)^{62b}, Y. Zhang [ID](#)^{62c,5}, Z. Zhang [ID](#)^{17a}, Z. Zhang [ID](#)⁶⁶, H. Zhao [ID](#)¹³⁸, P. Zhao [ID](#)⁵¹, T. Zhao [ID](#)^{62b}, Y. Zhao [ID](#)¹³⁶, Z. Zhao [ID](#)^{62a}, A. Zhemchugov [ID](#)³⁸, X. Zheng [ID](#)^{62a}, Z. Zheng [ID](#)¹⁴³, D. Zhong [ID](#)¹⁶², B. Zhou¹⁰⁶, C. Zhou [ID](#)¹⁷⁰, H. Zhou [ID](#)⁷, N. Zhou [ID](#)^{62c}, Y. Zhou⁷, C.G. Zhu [ID](#)^{62b}, C. Zhu [ID](#)^{14a,14d}, H.L. Zhu [ID](#)^{62a}, J. Zhu [ID](#)¹⁰⁶, Y. Zhu [ID](#)^{62c}, Y. Zhu [ID](#)^{62a}, X. Zhuang [ID](#)^{14a}, K. Zhukov [ID](#)³⁷, V. Zhulanov [ID](#)³⁷, N.I. Zimine [ID](#)³⁸, J. Zinsser [ID](#)^{63b}, M. Ziolkowski [ID](#)¹⁴¹, L. Živković [ID](#)¹⁵, A. Zoccoli [ID](#)^{23b,23a}, K. Zoch [ID](#)⁵⁶, T.G. Zorbas [ID](#)¹³⁹, O. Zormpa [ID](#)⁴⁶, W. Zou [ID](#)⁴¹, L. Zwalinski [ID](#)³⁶

¹ Department of Physics, University of Adelaide, Adelaide; Australia

² Department of Physics, University of Alberta, Edmonton AB; Canada

³ ^(a) Department of Physics, Ankara University, Ankara; ^(b) Division of Physics, TOBB University of Economics and Technology, Ankara; Türkiye

⁴ LAPP, Univ. Savoie Mont Blanc, CNRS/IN2P3, Annecy; France

⁵ APC, Université Paris Cité, CNRS/IN2P3, Paris; France

⁶ High Energy Physics Division, Argonne National Laboratory, Argonne IL; United States of America

⁷ Department of Physics, University of Arizona, Tucson AZ; United States of America

⁸ Department of Physics, University of Texas at Arlington, Arlington TX; United States of America

⁹ Physics Department, National and Kapodistrian University of Athens, Athens; Greece

¹⁰ Physics Department, National Technical University of Athens, Zografou; Greece

¹¹ Department of Physics, University of Texas at Austin, Austin TX; United States of America

¹² Institute of Physics, Azerbaijan Academy of Sciences, Baku; Azerbaijan

¹³ Institut de Física d'Altes Energies (IFAE), Barcelona Institute of Science and Technology, Barcelona; Spain

¹⁴ ^(a) Institute of High Energy Physics, Chinese Academy of Sciences, Beijing; ^(b) Physics Department, Tsinghua University, Beijing; ^(c) Department of Physics, Nanjing University, Nanjing; ^(d) University of Chinese Academy of Science (UCAS), Beijing; China

¹⁵ Institute of Physics, University of Belgrade, Belgrade; Serbia

¹⁶ Department for Physics and Technology, University of Bergen, Bergen; Norway

¹⁷ ^(a) Physics Division, Lawrence Berkeley National Laboratory, Berkeley CA; ^(b) University of California, Berkeley CA; United States of America

¹⁸ Institut für Physik, Humboldt Universität zu Berlin, Berlin; Germany

¹⁹ Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern; Switzerland

²⁰ School of Physics and Astronomy, University of Birmingham, Birmingham; United Kingdom

- ²¹ ^(a) Department of Physics, Bogazici University, Istanbul; ^(b) Department of Physics Engineering, Gaziantep University, Gaziantep; ^(c) Department of Physics, Istanbul University, Istanbul; ^(d) Istinye University, Sariyer, Istanbul; Türkiye
- ²² ^(a) Facultad de Ciencias y Centro de Investigaciones, Universidad Antonio Nariño, Bogotá; ^(b) Departamento de Física, Universidad Nacional de Colombia, Bogotá; Colombia
- ²³ ^(a) Dipartimento di Fisica e Astronomia A. Righi, Università di Bologna, Bologna; ^(b) INFN Sezione di Bologna; Italy
- ²⁴ Physikalisches Institut, Universität Bonn, Bonn; Germany
- ²⁵ Department of Physics, Boston University, Boston MA; United States of America
- ²⁶ Department of Physics, Brandeis University, Waltham MA; United States of America
- ²⁷ ^(a) Transilvania University of Brasov, Brasov; ^(b) Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest; ^(c) Department of Physics, Alexandru Ioan Cuza University of Iasi, Iasi; ^(d) National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj-Napoca; ^(e) University Politehnica Bucharest, Bucharest; ^(f) West University in Timisoara, Timisoara; ^(g) Faculty of Physics, University of Bucharest, Bucharest; Romania
- ²⁸ ^(a) Faculty of Mathematics, Physics and Informatics, Comenius University, Bratislava; ^(b) Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice; Slovak Republic
- ²⁹ Physics Department, Brookhaven National Laboratory, Upton NY; United States of America
- ³⁰ Universidad de Buenos Aires, Facultad de Ciencias Exactas y Naturales, Departamento de Física, y CONICET, Instituto de Física de Buenos Aires (IFIBA), Buenos Aires; Argentina
- ³¹ California State University, CA; United States of America
- ³² Cavendish Laboratory, University of Cambridge, Cambridge; United Kingdom
- ³³ ^(a) Department of Physics, University of Cape Town, Cape Town; ^(b) iThemba Labs, Western Cape; ^(c) Department of Mechanical Engineering Science, University of Johannesburg, Johannesburg; ^(d) National Institute of Physics, University of the Philippines Diliman (Philippines); ^(e) University of South Africa, Department of Physics, Pretoria; ^(f) University of Zululand, KwaDlangezwa; ^(g) School of Physics, University of the Witwatersrand, Johannesburg; South Africa
- ³⁴ Department of Physics, Carleton University, Ottawa ON; Canada
- ³⁵ ^(a) Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies — Université Hassan II, Casablanca; ^(b) Faculté des Sciences, Université Ibn-Tofail, Kénitra; ^(c) Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech; ^(d) LPMR, Faculté des Sciences, Université Mohamed Premier, Oujda; ^(e) Faculté des sciences, Université Mohammed V, Rabat; ^(f) Institute of Applied Physics, Mohammed VI Polytechnic University, Ben Guerir; Morocco
- ³⁶ CERN, Geneva; Switzerland
- ³⁷ Affiliated with an institute covered by a cooperation agreement with CERN
- ³⁸ Affiliated with an international laboratory covered by a cooperation agreement with CERN
- ³⁹ Enrico Fermi Institute, University of Chicago, Chicago IL; United States of America
- ⁴⁰ LPC, Université Clermont Auvergne, CNRS/IN2P3, Clermont-Ferrand; France
- ⁴¹ Nevis Laboratory, Columbia University, Irvington NY; United States of America
- ⁴² Niels Bohr Institute, University of Copenhagen, Copenhagen; Denmark
- ⁴³ ^(a) Dipartimento di Fisica, Università della Calabria, Rende; ^(b) INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati; Italy
- ⁴⁴ Physics Department, Southern Methodist University, Dallas TX; United States of America
- ⁴⁵ Physics Department, University of Texas at Dallas, Richardson TX; United States of America
- ⁴⁶ National Centre for Scientific Research “Demokritos”, Agia Paraskevi; Greece
- ⁴⁷ ^(a) Department of Physics, Stockholm University; ^(b) Oskar Klein Centre, Stockholm; Sweden
- ⁴⁸ Deutsches Elektronen-Synchrotron DESY, Hamburg and Zeuthen; Germany
- ⁴⁹ Fakultät Physik, Technische Universität Dortmund, Dortmund; Germany
- ⁵⁰ Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden; Germany
- ⁵¹ Department of Physics, Duke University, Durham NC; United States of America
- ⁵² SUPA — School of Physics and Astronomy, University of Edinburgh, Edinburgh; United Kingdom

- ⁵³ INFN e Laboratori Nazionali di Frascati, Frascati; Italy
- ⁵⁴ Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg; Germany
- ⁵⁵ II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen; Germany
- ⁵⁶ Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève; Switzerland
- ⁵⁷ ^(a) Dipartimento di Fisica, Università di Genova, Genova; ^(b) INFN Sezione di Genova; Italy
- ⁵⁸ II. Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen; Germany
- ⁵⁹ SUPA — School of Physics and Astronomy, University of Glasgow, Glasgow; United Kingdom
- ⁶⁰ LPSC, Université Grenoble Alpes, CNRS/IN2P3, Grenoble INP, Grenoble; France
- ⁶¹ Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge MA; United States of America
- ⁶² ^(a) Department of Modern Physics and State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Hefei; ^(b) Institute of Frontier and Interdisciplinary Science and Key Laboratory of Particle Physics and Particle Irradiation (MOE), Shandong University, Qingdao; ^(c) School of Physics and Astronomy, Shanghai Jiao Tong University, Key Laboratory for Particle Astrophysics and Cosmology (MOE), SKLPPC, Shanghai; ^(d) Tsung-Dao Lee Institute, Shanghai; China
- ⁶³ ^(a) Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg; ^(b) Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg; Germany
- ⁶⁴ ^(a) Department of Physics, Chinese University of Hong Kong, Shatin, N.T., Hong Kong; ^(b) Department of Physics, University of Hong Kong, Hong Kong; ^(c) Department of Physics and Institute for Advanced Study, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong; China
- ⁶⁵ Department of Physics, National Tsing Hua University, Hsinchu; Taiwan
- ⁶⁶ IJCLab, Université Paris-Saclay, CNRS/IN2P3, 91405, Orsay; France
- ⁶⁷ Centro Nacional de Microelectrónica (IMB-CNM-CSIC), Barcelona; Spain
- ⁶⁸ Department of Physics, Indiana University, Bloomington IN; United States of America
- ⁶⁹ ^(a) INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine; ^(b) ICTP, Trieste; ^(c) Dipartimento Politecnico di Ingegneria e Architettura, Università di Udine, Udine; Italy
- ⁷⁰ ^(a) INFN Sezione di Lecce; ^(b) Dipartimento di Matematica e Fisica, Università del Salento, Lecce; Italy
- ⁷¹ ^(a) INFN Sezione di Milano; ^(b) Dipartimento di Fisica, Università di Milano, Milano; Italy
- ⁷² ^(a) INFN Sezione di Napoli; ^(b) Dipartimento di Fisica, Università di Napoli, Napoli; Italy
- ⁷³ ^(a) INFN Sezione di Pavia; ^(b) Dipartimento di Fisica, Università di Pavia, Pavia; Italy
- ⁷⁴ ^(a) INFN Sezione di Pisa; ^(b) Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa; Italy
- ⁷⁵ ^(a) INFN Sezione di Roma; ^(b) Dipartimento di Fisica, Sapienza Università di Roma, Roma; Italy
- ⁷⁶ ^(a) INFN Sezione di Roma Tor Vergata; ^(b) Dipartimento di Fisica, Università di Roma Tor Vergata, Roma; Italy
- ⁷⁷ ^(a) INFN Sezione di Roma Tre; ^(b) Dipartimento di Matematica e Fisica, Università Roma Tre, Roma; Italy
- ⁷⁸ ^(a) INFN-TIFPA; ^(b) Università degli Studi di Trento, Trento; Italy
- ⁷⁹ Universität Innsbruck, Department of Astro and Particle Physics, Innsbruck; Austria
- ⁸⁰ University of Iowa, Iowa City IA; United States of America
- ⁸¹ Department of Physics and Astronomy, Iowa State University, Ames IA; United States of America
- ⁸² ^(a) Departamento de Engenharia Elétrica, Universidade Federal de Juiz de Fora (UFJF), Juiz de Fora; ^(b) Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro; ^(c) Instituto de Física, Universidade de São Paulo, São Paulo; ^(d) Rio de Janeiro State University, Rio de Janeiro; Brazil
- ⁸³ KEK, High Energy Accelerator Research Organization, Tsukuba; Japan
- ⁸⁴ Graduate School of Science, Kobe University, Kobe; Japan
- ⁸⁵ ^(a) AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow; ^(b) Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow; Poland
- ⁸⁶ Institute of Nuclear Physics Polish Academy of Sciences, Krakow; Poland
- ⁸⁷ Faculty of Science, Kyoto University, Kyoto; Japan
- ⁸⁸ Kyoto University of Education, Kyoto; Japan

- ⁸⁹ *Research Center for Advanced Particle Physics and Department of Physics, Kyushu University, Fukuoka; Japan*
- ⁹⁰ *Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata; Argentina*
- ⁹¹ *Physics Department, Lancaster University, Lancaster; United Kingdom*
- ⁹² *Oliver Lodge Laboratory, University of Liverpool, Liverpool; United Kingdom*
- ⁹³ *Department of Experimental Particle Physics, Jožef Stefan Institute and Department of Physics, University of Ljubljana, Ljubljana; Slovenia*
- ⁹⁴ *School of Physics and Astronomy, Queen Mary University of London, London; United Kingdom*
- ⁹⁵ *Department of Physics, Royal Holloway University of London, Egham; United Kingdom*
- ⁹⁶ *Department of Physics and Astronomy, University College London, London; United Kingdom*
- ⁹⁷ *Louisiana Tech University, Ruston LA; United States of America*
- ⁹⁸ *Fysiska institutionen, Lunds universitet, Lund; Sweden*
- ⁹⁹ *Departamento de Física Teórica C-15 and CIAFF, Universidad Autónoma de Madrid, Madrid; Spain*
- ¹⁰⁰ *Institut für Physik, Universität Mainz, Mainz; Germany*
- ¹⁰¹ *School of Physics and Astronomy, University of Manchester, Manchester; United Kingdom*
- ¹⁰² *CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille; France*
- ¹⁰³ *Department of Physics, University of Massachusetts, Amherst MA; United States of America*
- ¹⁰⁴ *Department of Physics, McGill University, Montreal QC; Canada*
- ¹⁰⁵ *School of Physics, University of Melbourne, Victoria; Australia*
- ¹⁰⁶ *Department of Physics, University of Michigan, Ann Arbor MI; United States of America*
- ¹⁰⁷ *Department of Physics and Astronomy, Michigan State University, East Lansing MI; United States of America*
- ¹⁰⁸ *Group of Particle Physics, University of Montreal, Montreal QC; Canada*
- ¹⁰⁹ *Fakultät für Physik, Ludwig-Maximilians-Universität München, München; Germany*
- ¹¹⁰ *Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München; Germany*
- ¹¹¹ *Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya; Japan*
- ¹¹² *Department of Physics and Astronomy, University of New Mexico, Albuquerque NM; United States of America*
- ¹¹³ *Institute for Mathematics, Astrophysics and Particle Physics, Radboud University/Nikhef, Nijmegen; Netherlands*
- ¹¹⁴ *Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam; Netherlands*
- ¹¹⁵ *Department of Physics, Northern Illinois University, DeKalb IL; United States of America*
- ¹¹⁶ ^(a) *New York University Abu Dhabi, Abu Dhabi;* ^(b) *University of Sharjah, Sharjah; United Arab Emirates*
- ¹¹⁷ *Department of Physics, New York University, New York NY; United States of America*
- ¹¹⁸ *Ochanomizu University, Otsuka, Bunkyo-ku, Tokyo; Japan*
- ¹¹⁹ *Ohio State University, Columbus OH; United States of America*
- ¹²⁰ *Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK; United States of America*
- ¹²¹ *Department of Physics, Oklahoma State University, Stillwater OK; United States of America*
- ¹²² *Palacký University, Joint Laboratory of Optics, Olomouc; Czech Republic*
- ¹²³ *Institute for Fundamental Science, University of Oregon, Eugene, OR; United States of America*
- ¹²⁴ *Graduate School of Science, Osaka University, Osaka; Japan*
- ¹²⁵ *Department of Physics, University of Oslo, Oslo; Norway*
- ¹²⁶ *Department of Physics, Oxford University, Oxford; United Kingdom*
- ¹²⁷ *LPNHE, Sorbonne Université, Université Paris Cité, CNRS/IN2P3, Paris; France*
- ¹²⁸ *Department of Physics, University of Pennsylvania, Philadelphia PA; United States of America*
- ¹²⁹ *Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA; United States of America*
- ¹³⁰ ^(a) *Laboratório de Instrumentação e Física Experimental de Partículas — LIP, Lisboa;* ^(b) *Departamento de Física, Faculdade de Ciências, Universidade de Lisboa, Lisboa;* ^(c) *Departamento de Física, Universidade de Coimbra, Coimbra;* ^(d) *Centro de Física Nuclear da Universidade de Lisboa, Lisboa;* ^(e) *Departamento de Física, Universidade do Minho, Braga;* ^(f) *Departamento de Física Teórica y*

- del Cosmos, Universidad de Granada, Granada (Spain);^(g) Departamento de Física, Instituto Superior Técnico, Universidade de Lisboa, Lisboa; Portugal
- ¹³¹ Institute of Physics of the Czech Academy of Sciences, Prague; Czech Republic
- ¹³² Czech Technical University in Prague, Prague; Czech Republic
- ¹³³ Charles University, Faculty of Mathematics and Physics, Prague; Czech Republic
- ¹³⁴ Particle Physics Department, Rutherford Appleton Laboratory, Didcot; United Kingdom
- ¹³⁵ IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette; France
- ¹³⁶ Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz CA; United States of America
- ¹³⁷ ^(a) Departamento de Física, Pontificia Universidad Católica de Chile, Santiago;^(b) Millennium Institute for Subatomic physics at high energy frontier (SAPHIR), Santiago;^(c) Instituto de Investigación Multidisciplinario en Ciencia y Tecnología, y Departamento de Física, Universidad de La Serena;^(d) Universidad Andres Bello, Department of Physics, Santiago;^(e) Instituto de Alta Investigación, Universidad de Tarapacá, Arica;^(f) Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso; Chile
- ¹³⁸ Department of Physics, University of Washington, Seattle WA; United States of America
- ¹³⁹ Department of Physics and Astronomy, University of Sheffield, Sheffield; United Kingdom
- ¹⁴⁰ Department of Physics, Shinshu University, Nagano; Japan
- ¹⁴¹ Department Physik, Universität Siegen, Siegen; Germany
- ¹⁴² Department of Physics, Simon Fraser University, Burnaby BC; Canada
- ¹⁴³ SLAC National Accelerator Laboratory, Stanford CA; United States of America
- ¹⁴⁴ Department of Physics, Royal Institute of Technology, Stockholm; Sweden
- ¹⁴⁵ Departments of Physics and Astronomy, Stony Brook University, Stony Brook NY; United States of America
- ¹⁴⁶ Department of Physics and Astronomy, University of Sussex, Brighton; United Kingdom
- ¹⁴⁷ School of Physics, University of Sydney, Sydney; Australia
- ¹⁴⁸ Institute of Physics, Academia Sinica, Taipei; Taiwan
- ¹⁴⁹ ^(a) E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi;^(b) High Energy Physics Institute, Tbilisi State University, Tbilisi;^(c) University of Georgia, Tbilisi; Georgia
- ¹⁵⁰ Department of Physics, Technion, Israel Institute of Technology, Haifa; Israel
- ¹⁵¹ Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv; Israel
- ¹⁵² Department of Physics, Aristotle University of Thessaloniki, Thessaloniki; Greece
- ¹⁵³ International Center for Elementary Particle Physics and Department of Physics, University of Tokyo, Tokyo; Japan
- ¹⁵⁴ Department of Physics, Tokyo Institute of Technology, Tokyo; Japan
- ¹⁵⁵ Department of Physics, University of Toronto, Toronto ON; Canada
- ¹⁵⁶ ^(a) TRIUMF, Vancouver BC;^(b) Department of Physics and Astronomy, York University, Toronto ON; Canada
- ¹⁵⁷ Division of Physics and Tomonaga Center for the History of the Universe, Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba; Japan
- ¹⁵⁸ Department of Physics and Astronomy, Tufts University, Medford MA; United States of America
- ¹⁵⁹ United Arab Emirates University, Al Ain; United Arab Emirates
- ¹⁶⁰ Department of Physics and Astronomy, University of California Irvine, Irvine CA; United States of America
- ¹⁶¹ Department of Physics and Astronomy, University of Uppsala, Uppsala; Sweden
- ¹⁶² Department of Physics, University of Illinois, Urbana IL; United States of America
- ¹⁶³ Instituto de Física Corpuscular (IFIC), Centro Mixto Universidad de Valencia — CSIC, Valencia; Spain
- ¹⁶⁴ Department of Physics, University of British Columbia, Vancouver BC; Canada
- ¹⁶⁵ Department of Physics and Astronomy, University of Victoria, Victoria BC; Canada
- ¹⁶⁶ Fakultät für Physik und Astronomie, Julius-Maximilians-Universität Würzburg, Würzburg; Germany
- ¹⁶⁷ Department of Physics, University of Warwick, Coventry; United Kingdom
- ¹⁶⁸ Waseda University, Tokyo; Japan

- ¹⁶⁹ *Department of Particle Physics and Astrophysics, Weizmann Institute of Science, Rehovot; Israel*
- ¹⁷⁰ *Department of Physics, University of Wisconsin, Madison WI; United States of America*
- ¹⁷¹ *Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal; Germany*
- ¹⁷² *Department of Physics, Yale University, New Haven CT; United States of America*
- ^a *Also Affiliated with an institute covered by a cooperation agreement with CERN*
- ^b *Also at An-Najah National University, Nablus; Palestine*
- ^c *Also at Borough of Manhattan Community College, City University of New York, New York NY; United States of America*
- ^d *Also at Bruno Kessler Foundation, Trento; Italy*
- ^e *Also at Center for High Energy Physics, Peking University; China*
- ^f *Also at Center for Interdisciplinary Research and Innovation (CIRI-AUTH), Thessaloniki; Greece*
- ^g *Also at Centro Studi e Ricerche Enrico Fermi; Italy*
- ^h *Also at CERN, Geneva; Switzerland*
- ⁱ *Also at Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève; Switzerland*
- ^j *Also at Departament de Física de la Universitat Autònoma de Barcelona, Barcelona; Spain*
- ^k *Also at Department of Financial and Management Engineering, University of the Aegean, Chios; Greece*
- ^l *Also at Department of Physics and Astronomy, Michigan State University, East Lansing MI; United States of America*
- ^m *Also at Department of Physics, Ben Gurion University of the Negev, Beer Sheva; Israel*
- ⁿ *Also at Department of Physics, California State University, East Bay; United States of America*
- ^o *Also at Department of Physics, California State University, Sacramento; United States of America*
- ^p *Also at Department of Physics, King's College London, London; United Kingdom*
- ^q *Also at Department of Physics, University of Fribourg, Fribourg; Switzerland*
- ^r *Also at Department of Physics, University of Thessaly; Greece*
- ^s *Also at Department of Physics, Westmont College, Santa Barbara; United States of America*
- ^t *Also at Hellenic Open University, Patras; Greece*
- ^u *Also at Institutio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona; Spain*
- ^v *Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg; Germany*
- ^w *Also at Institute of Applied Physics, Mohammed VI Polytechnic University, Ben Guerir; Morocco*
- ^x *Also at Institute of Particle Physics (IPP); Canada*
- ^y *Also at Institute of Physics and Technology, Ulaanbaatar; Mongolia*
- ^z *Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku; Azerbaijan*
- ^{aa} *Also at Institute of Theoretical Physics, Ilija State University, Tbilisi; Georgia*
- ^{ab} *Also at Lawrence Livermore National Laboratory, Livermore; United States of America*
- ^{ac} *Also at The Collaborative Innovation Center of Quantum Matter (CICQM), Beijing; China*
- ^{ad} *Also at TRIUMF, Vancouver BC; Canada*
- ^{ae} *Also at Università di Napoli Parthenope, Napoli; Italy*
- ^{af} *Also at University of Chinese Academy of Sciences (UCAS), Beijing; China*
- ^{ag} *Also at University of Colorado Boulder, Department of Physics, Colorado; United States of America*
- ^{ah} *Also at Washington College, Maryland; United States of America*
- ^{*} *Deceased*