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Abstract

The intensity interferometry method has been used to measure pion source parameters in the reaction 1.70 A GeV ^{56}Fe + Fe $\rightarrow 2\pi^- + X$. The parameters show an oblate source for a narrow acceptance spectrometer near either 0° or 90° with respect to the beam axis in the center–of–mass frame. Intranuclear cascade model predictions show similar behavior and are compared to the experimental results.

In principle, pion interferometry is a direct probe of the space–time geometry of the interaction region in relativistic heavy–ion collisions. This is because pions are not present in the initial system but are created in the interaction region of the collision. The pion emission from the interaction region is modified somewhat by scattering and absorption in cold spectator matter. A measurement of the pion source parameters tests the collision geometry of models containing pion production and absorption, such as intranuclear cascade models,[1] which give quantities (e.g., baryon density) necessary to study the equation of state of nuclear matter.[2] In this Letter we present our measurements of pion source parameters, extracted through pion intensity interferometry, for the reaction 1.70 A GeV ^{56}Fe + Fe $\rightarrow 2\pi^- + X$, and make comparisons with intranuclear cascade model predictions.[3]

The pion interferometry method is based on the symmetry of the outgoing pionic wavefunction. This results in an intensity interference effect (the Hanbury-Brown–Twiss effect),[4,5] in which the probability of detecting a pair of pions with similar momenta is enhanced to an extent determined by the source geometry. We assume the pion source can be described by a Gaussian space–time distribution, symmetric about the beam axis. The correlation function, $C_2(q_\perp, q_\parallel, q_0)$, is then[6]

$$C_2(q_\perp, q_\parallel, q_0) = 1 + \lambda \exp\left[-\left(q_\perp^2 R_\perp^2 + q_\parallel^2 R_\parallel^2 + q_0^2 \tau^2\right)/2\right] , \quad (1)$$

where $q_\perp = |(\vec{p}_1 - \vec{p}_2)_\perp|$, $q_\parallel = |(\vec{p}_1 - \vec{p}_2)_\parallel|$, and $q_0 = |E_1 - E_2|$; $(\vec{p}_1, E_1)$ and $(\vec{p}_2, E_2)$ are the center–of–mass four–momenta of the two pions. $R_\perp$ and $R_\parallel$ are the transverse and longitudinal (with respect to the beam direction) radius parameters, and τ is the lifetime parameter. The λ parameter allows for correlations from effects other than Bose statistics,[7,8] and would be unity in their absence.

The correlation function is found through the definition

$$C_2(p_1, p_2) = A \, \frac{\dfrac{d^6\sigma}{dp_1^3\, dp_2^3}}{\dfrac{d^3\sigma}{dp_1^3}\,\dfrac{d^3\sigma}{dp_2^3}} , \quad (2)$$

where A is a normalization constant. In principle, one measures $d^6\sigma/dp_1^3\, dp_2^3$, the two–pion inclusive cross section, and $d^3\sigma/dp^3$, the single–pion inclusive cross section, to form $C_2(p_1, p_2)$, and then extracts $R_\perp$, $R_\parallel$, τ, and λ by fitting Eq. 1 to this function. In practice, only the two–pion inclusive cross section is measured and the Eq. 2 denominator is found from the two–pion data by "event mixing", pairing pions from distinct events. Residual correlations remain in the mixed events, and are removed by an iterative procedure.[9]

The Janus spectrometer is as shown in Fig. 1, and consists of two dipole magnets, four multiwire proportional counters (MWPC) for particle tracking, and a plastic scintillator counter array for triggering, time–of–flight (TOF) and pulse height (ADC) measurements. A complete description of the spectrometer, data acquisition system, and analysis are given elsewhere;[9] the experimental procedures will be described here briefly. Pairs of negative pions were detected in the Janus spectrometer, with data taken near two angles with respect to the beam: $\theta_{lab} \approx 0^\circ$ and 45°. The spectrometer properties at these angles are given in Table 1. Because the angular acceptance of the spectrometer is momentum dependent, the solid angle quoted in Table 1 is a weighted average based on extrapolations of the data in Ref. [10]. In Fig. 2 the weighted single–pion Monte Carlo tracks are shown on a rapidity vs. $p_\perp$ plot, for both configurations. The beam consisted of 1.70 A GeV ^{56}Fe ions from the LBL Bevalac and was directed onto a ~1 g/cm^2 target of natural Fe (45°) or stainless steel (0°).[11]

θ_{lab}	θ_{cm}	$\lvert\vec{p}_{cm}\rvert$, accepted	Solid Angle
$\sim 0^\circ$	$(0^\circ, 32^\circ)$	(100,400) MeV/c	12 msr
$\sim 45^\circ$	$(91^\circ, 106^\circ)$	(100,600) MeV/c	29 msr

Table 1: Spectrometer characteristics.

Particle trajectories were identified by effective edge track reconstruction, and requiring candidates to pass cuts on the TOF's and the ADC's. The final momenta were determined through a Chebyshev polynomial series expansion in terms of MWPC wire numbers, the coefficients being derived from a fit to simulated pion trajectories. The resolution for simulated tracks with multiple scattering and energy loss is 3.5 MeV/c (RMS) for any component of the laboratory momentum perpendicular to the beam, and 3 MeV/c (RMS) for the component parallel to the beam. This gives a resolution of 3 MeV (RMS) for q_0, 7 MeV/c (RMS) for $q_\perp$, and 3 MeV/c (RMS) for $q_\parallel$. With a bin width of 10 MeV/c in any component of q (or q_0/c), and the total variation in q of 250 MeV/c, $R_\perp$, $R_\parallel$, and $c\tau$ are resolvable in the range of ~ 1 to ~ 20 fm.

The data were corrected for the Coulomb interaction between pions and nuclear fragments with a momentum correction formula[12] (see also Ref.[9]), using an average collision impact parameter. A Gamow correction was applied to compensate for the final–state Coulomb interaction between the two pions, as in Ref.[9]. The effects of these corrections are illustrated in Table 2, where the parameters are shown as a function of the corrections, for 1/3 of the $\lvert\vec{p}_{proj}\rvert > 50$ MeV/c data (the data samples are defined below). The Coulomb correction gives changes of up to 3 standard deviations (σ). The Gamow correction gives changes of 1 to 2 σ for this data set.

Momentum cuts were applied to the data, as shown in Table 3 and Fig. 2. The cut on the momentum in the projectile frame for the 0° data, $\lvert\vec{p}_{proj}\rvert > 50$ MeV/c, was made to remove pions with velocities near that of projectile fragments; the large Coulomb attraction of the nuclear fragments would invalidate a separate pion–pion Coulomb correction, as used. The cut on the momentum in the center–of–mass frame for the 45° data, $\lvert\vec{p}_{cm}\rvert > 100$ MeV/c, is imposed by the spectrometer's acceptance. The additional, more

	0° $\|\vec{p}_{proj}\| > 50$ MeV/c ($\sim 10,000$ events)			
Coulomb correction	In	In	Out	Out
Gamow correction	In	Out	In	Out
$R_\perp$(fm)	4.6 ± 0.2	4.3 ± 0.3	5.9 ± 0.5	5.6 ± 0.6
$R_\parallel$(fm)	$1.5^{+0.7}_{-1.5}$	$0.4^{+1.2}_{-0.4}$	$2.9^{+0.5}_{-1.1}$	$2.2^{+0.8}_{-1.6}$
τ(fm/c)	3.8 ± 0.7	4.2 ± 0.4	3.7 ± 1.0	4.2 ± 1.1
λ	0.78 ± 0.04	0.65 ± 0.06	0.92 ± 0.08	0.77 ± 0.07
χ^2/ NDF	451/421	451/421	314/286	314/285

Table 2: Parameters as a function of the corrections applied, for a subset of the 0° data. Note that the $|\vec{p}_{proj}| > 50$ MeV/c cut is made after the corrections so that the number of events, hence the NDF, depends somewhat on the corrections applied.

stringent, cuts were made to study the dependence of the source parameters on pion momentum. The Gamow– and Coulomb–corrected correlation function was then fit to Eq. 1, giving $R_\perp$, $R_\parallel$, τ, λ, and a normalization constant for each data set. In Fig. 3 the correlation function for the 45° data with the $|\vec{p}_{cm}| > 100$ MeV/c cut is projected onto the $q_\perp$ axis to show the quality of its Gaussian fit. The χ^2 per degree of freedom for this fit is 362/345, showing that the Gaussian space–time distribution assumed in Eq. 1 is reasonable. Note the expected enhancement of $\langle C(q_\perp)\rangle$ at small $q_\perp$.

θ_{lab}	Momentum Cut	Events
$\sim 0^\circ$	$\|\vec{p}_{proj}\| > 50$ MeV/c	33,000
	$\|\vec{p}_{proj}\| > 100$ MeV/c	10,000
$\sim 45^\circ$	$\|\vec{p}_{cm}\| > 100$ MeV/c	8300
	$\|\vec{p}_{cm}\| > 150$ MeV/c	6900

Table 3: Momentum cuts applied.

Our measured source parameters are shown in Table 4, with 1 standard deviation (1σ) statistical uncertainties and, where calculated, systematic uncertainties. The systematic errors were examined by generating artificial data correlated according to Eq. 1, with known $R_\perp$, $R_\parallel$, τ, and λ, and analyzing this Monte Carlo data with the same programs used to analyze the experimental data. This data sample of 12,000 events was produced in the 0°, $|\vec{p}_{proj}| > 50$ MeV/c geometry, where the potential track–finding biases are the greatest. The track–finding biases were corrected until they were dominated by the statistical uncertainties for this data sample. The experimental data were tested for unremoved track–finding biases by re-fitting the data with the requirement that $q_\perp > 10$ MeV/c and $q_\parallel > 10$ MeV/c, which removes about 10% of the data. This cut removes data where the tracks have small spatial separations and are, therefore, harder to resolve. The shift in the parameters from this cut is considered to be due to track–finding biases, and part of the systematic uncertainty. There is good agreement between the Monte Carlo and experimental estimates of the track–finding bias uncertainties. The effect of the spectrometer's resolution on the value of the correlation function is less than 1% (FWHM). The systematic uncertainties for the 45° data, except for λ, are dominated by the statistical uncertainties and are not shown. Also shown in Table 4 are values from intranuclear cascade calculations, as given by Ref.[8], which is based on Cugnon's CASCADE code.[1] The experimental spectrometer acceptance and momentum cuts were imposed upon the CASCADE–generated pions, which were then symmetrized, and the source parameters were extracted in the same way as from the experimental data. The uncertainties shown for the CASCADE results are 1σ statistical uncertainties.

Perhaps the most striking feature of the measured source parameters is that, for both 0° and 45° acceptance angles and for all momentum cuts, $R_\perp/R_\parallel$ is significantly greater than 1, varying between 1.8 and 2.9. A spherical source shape was measured by Beavis *et al.*[13] ($R_\perp = 5.0 \pm 0.5$ fm $\approx R_\parallel = 5.0 \pm 1.5$ fm) for 1.5 A GeV ^{40}Ar + KCl with a 4π spectrometer acceptance, while Åkesson *et al.*[14] have measured (using a different analysis technique) prolate source shapes at the CERN ISR for pp and $p\bar{p}$ collisions. De Marzo *et al.*[15] have observed (using different techniques) oblate shapes where the ratio of the radii is 1.1 to 1.9, for p + Xe and $\bar{p}$ + Xe at the CERN SPS. Our observed oblateness cannot be explained as the simple Lorentz contraction of a spherical source, since $\gamma = 1.38$ in the nucleus–nucleus center–of–mass frame for our system. Although CASCADE predicts an oblate source for each acceptance in Table 4, there is an underprediction in the 45° acceptance cases due to an overprediction of $R_\parallel$. In the 0°, $|\vec{p}_{proj}| > 50$ MeV/c data CASCADE underpredicts the oblateness due to an underprediction of $R_\perp$, as well as the overprediction of $R_\parallel$. In the remaining case, the size of the source is well predicted. The experimental τ values are reasonably well predicted by CASCADE for the 45° acceptance, although the uncertainties in τ are large because of the small sample size. The experimental λ parameters are all significantly less than unity, as has been previously seen[9] (but not understood) in pion interferometry experiments. We do not observe any significant dependence of the source size on the pion momentum for either of the two acceptances.

In summary, we have observed an oblate pion source for the system 1.70 A GeV^{56}Fe + Fe using pion interferometry with a narrow acceptance spectrometer. The CASCADE model predicts the results fairly well, but overpredicts the $R_\parallel$ parameter for our 45° data and does not predict the small λ parameters in any of the studied cases.

	45° $|\vec{p}_{cm}| > 100$ MeV/c		45° $|\vec{p}_{cm}| > 150$ MeV/c	
	Experiment	CASCADE	Experiment	CASCADE
$R_\perp$(fm)	4.0 ± 0.5	4.2 ± 0.3	4.3 ± 0.6	4.2 ± 0.2
$R_\parallel$(fm)	$1.5^{+0.5}_{-0.9}$	3.0 ± 0.2	$1.5^{+0.5}_{-1.0}$	2.9 ± 0.2
τ(fm/c)	$1.7^{+1.5}_{-1.7}$	3.3 ± 0.6	$0.1^{+2.6}_{-0.1}$	3.2 ± 0.6
λ	$0.66 \pm 0.05 \pm 0.1$	1.00 ± 0.02	$0.58 \pm 0.06 \pm 0.1$	0.98 ± 0.02
χ^2/ NDF	381/403	1099/1082	362/345	1112/1039

	0° $|\vec{p}_{proj}| > 50$ MeV/c		0° $|\vec{p}_{proj}| > 100$ MeV/c	
	Experiment	CASCADE	Experiment	CASCADE
$R_\perp$(fm)	$4.8 \pm 0.2 \pm 0.1$	4.0 ± 0.1	$4.7 \pm 0.3 \pm 0.2$	4.4 ± 0.1
$R_\parallel$(fm)	$2.7 \pm 0.3 \pm 0.3$	3.3 ± 0.1	$2.1 \pm 0.5 \pm 0.8$	2.3 ± 0.1
τ(fm/c)	$2.7 \pm 0.6 \pm 0.4$	4.3 ± 0.2	$3.5 \pm 0.6 \pm 0.3$	4.4 ± 0.2
λ	$0.88 \pm 0.03 \pm 0.1$	1.00 ± 0.02	$0.75 \pm 0.05 \pm 0.1$	0.98 ± 0.02
χ^2/ NDF	939/729	1031/1061	470/395	374/376

Table 4: Comparison between experimental and CASCADE (Ref.[3]) pion source parameters for the reaction 1.70 A GeV ^{56}Fe + Fe $\rightarrow 2\pi^- + X$. Uncertainties shown are statistical followed by, where calculated, systematic.

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Figure Captions

FIG. 1 Plan view of the Janus spectrometer.

FIG. 2 Rapidity vs $p_\perp$ ($p_\perp$ in units of the pion mass) contour plots for single pion Monte Carlo tracks, with the spectrometer in the 45° and the 0° configuration. The pions were weighted by an exponential distribution in the pion energy in the center of mass. The locations of the momentum cuts for the two data sets are marked (A denotes the lower momentum cut, B the higher momentum cut, for each of data set, as in Table 3). The arrow points to the beam rapidity.

FIG. 3 Projection of the experimental correlation function and its Gaussian fit onto the $q_\perp$ axis for the 45° data with $|\vec{p}_{cm}| > 100$ MeV/c for the reaction 1.70 A GeV ^{56}Fe + Fe $\rightarrow 2\pi^- + X$. Only statistical errors are shown.

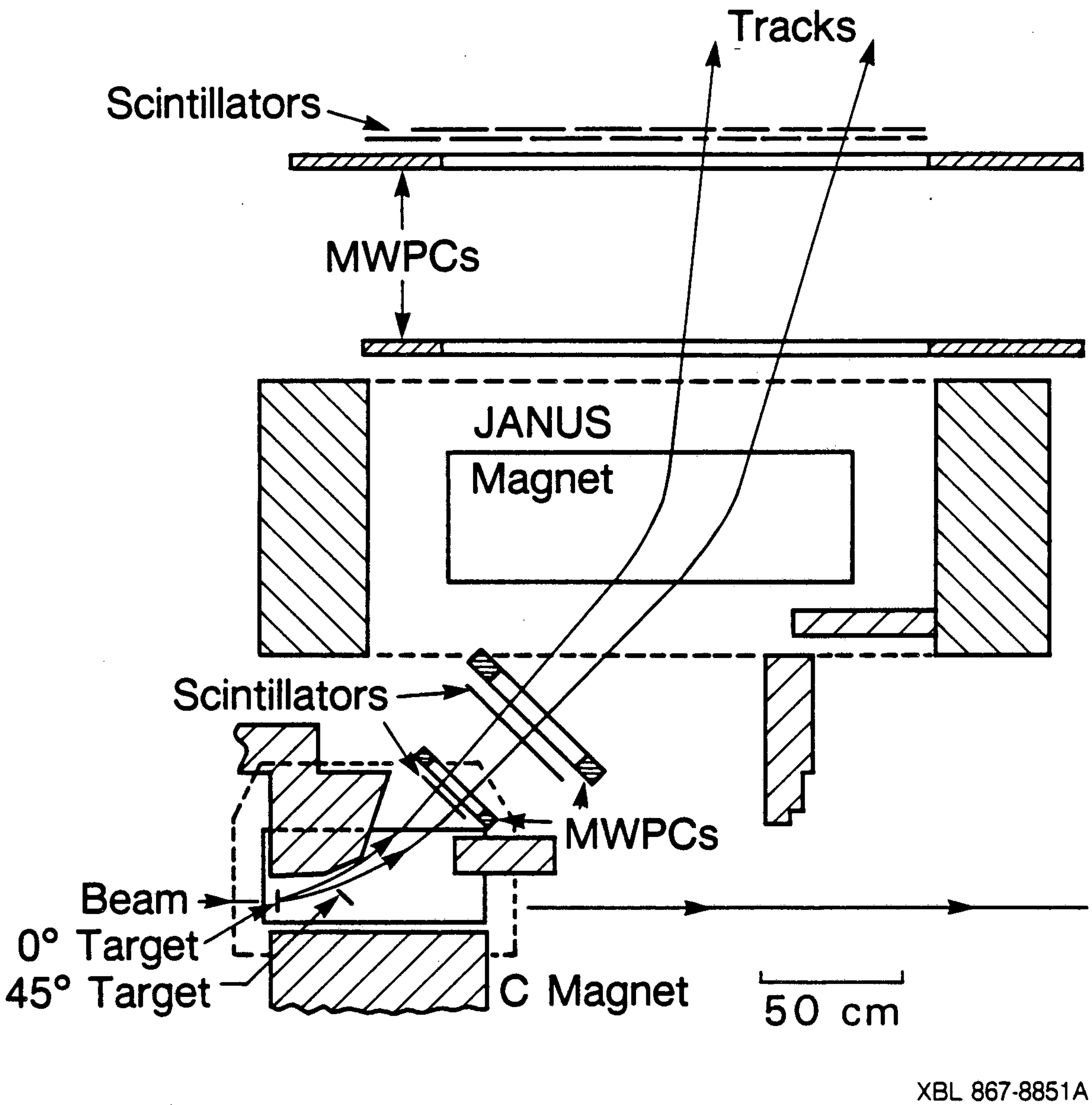
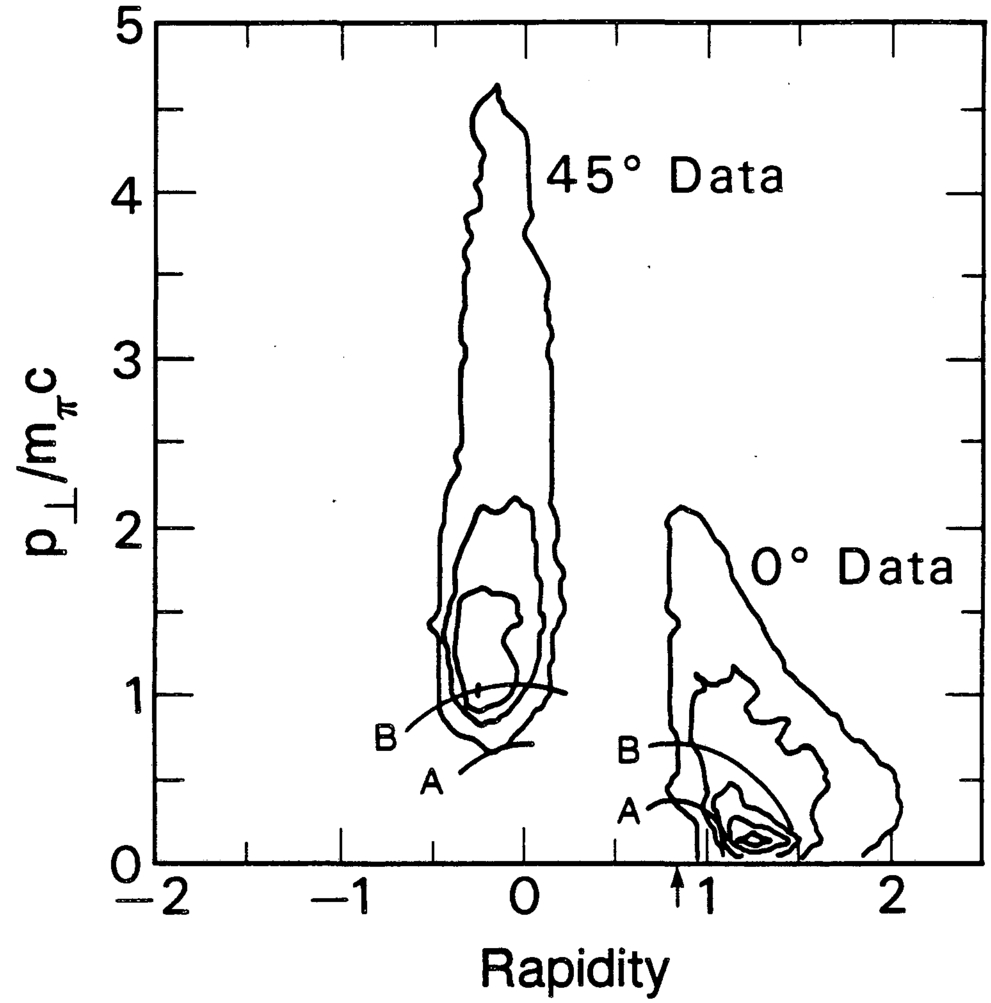

Tracks
Scintillators
MWPCs
JANUS
Magnet
Scintillators
MWPCs
Beam
0° Target
45° Target
C Magnet
50 cm
XBL 867-8851A

Fig. 1



XBL 867-8852 A

Fig. 2

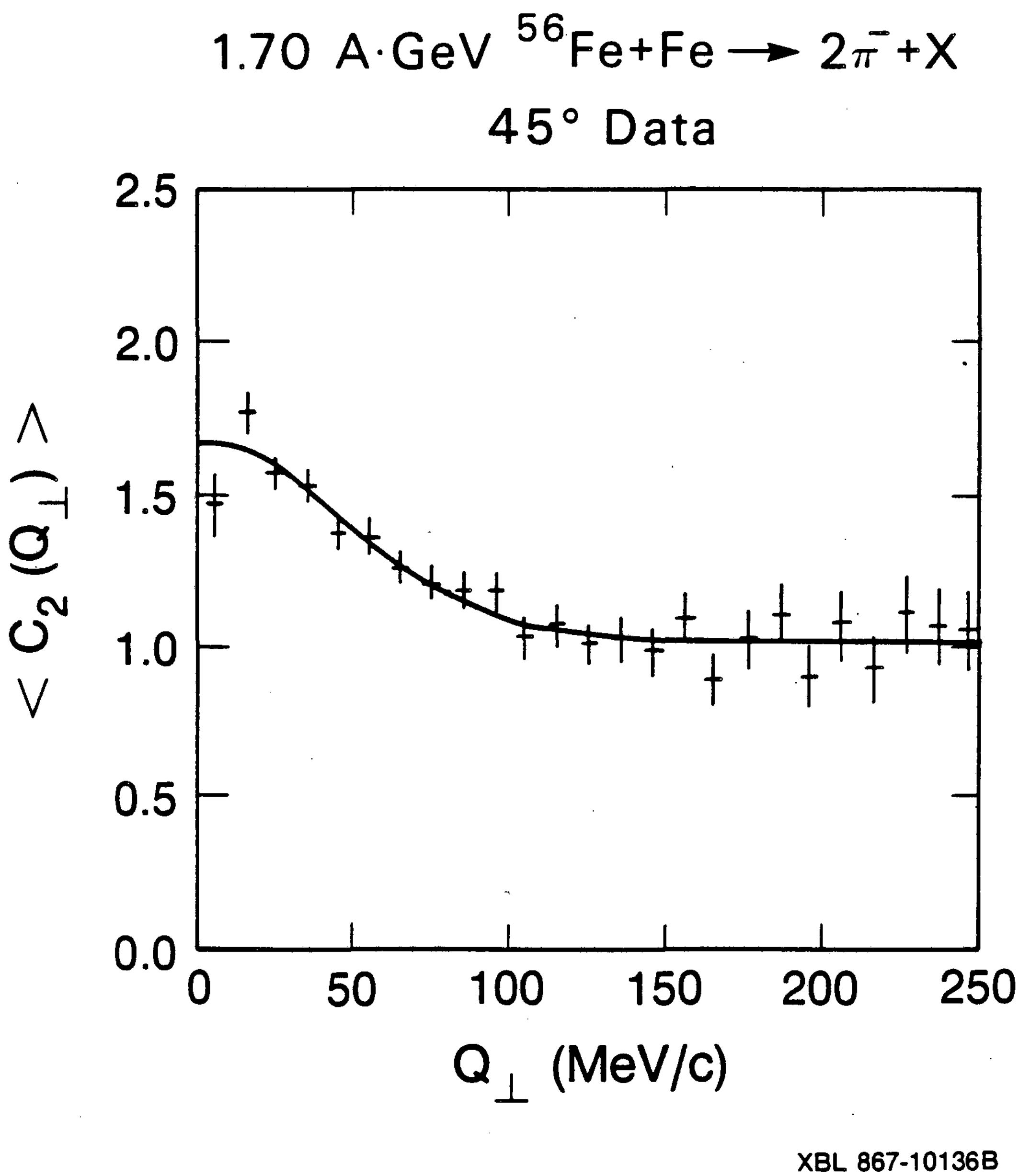

1.70 A·GeV 56Fe+Fe → 2π⁻+X
45° Data
2.5
2.0
1.5
1.0
0.5
0.0
< C2 (Q⊥) >
0
50
100
150
200
250
Q⊥ (MeV/c)
XBL 867-10136B

Fig. 3

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