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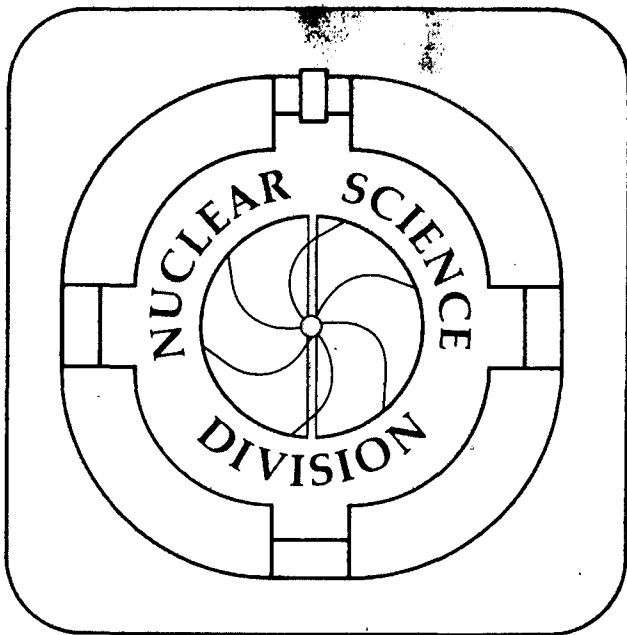
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$\alpha$ - $\alpha$  COLLISIONS AT THE CERN ISR

T.J.M. Symons

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$\alpha$ - $\alpha$  COLLISIONS AT THE CERN ISR

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## ABSTRACT

$\alpha$ - $\alpha$  and  $\alpha$ -p collisions have been studied at  $\sqrt{s} = 126$  GeV/c and  $\sqrt{s} = 88$  GeV, respectively, using colliding  $\alpha$ -particle and proton beams at the CERN intersecting storage rings. A brief review of the experimental results is given together with a discussion of future prospects in this field.

## INTRODUCTION

The CERN intersecting storage ring accelerator (ISR) is a unique facility in experimental high energy physics.<sup>1)</sup> From its first operation in 1971 until very recently, this machine has provided the highest centre of mass energies available anywhere in the world for the study of proton-proton collisions. Only in the past few months with the operation of the SPS as a  $p\bar{p}$  collider have higher energies become available. Although the ISR was designed to store proton beams, there is no intrinsic technical reason why heavier beams should not be stored provided that they can be accelerated in the CERN proton synchrotron for injection into the ISR. This was demonstrated in 1976 when deuteron beams were accelerated to study p-d and d-d collisions. In this experiment particular attention was paid to elastic scattering.<sup>2)</sup> No further runs with nuclear beams took place for several years until a letter of intent was submitted by the CERN-Heidelberg-Lund collaboration<sup>3)</sup> to accelerate and store  $\alpha$  particles in the ISR. This was subsequently expanded to a proposal that was approved, and the first experiments using  $\alpha$ -particle beams took place in the summer of 1980.

The scientific justification of these experiments is very broad. On the one hand, extensions of existing measurements to a new energy domain can be made, as, for example, in elastic scattering. On the other, the possibility exists that radically new phenomena may be observed that require the large energy densities over an extended spatial volume that a nucleus-nucleus collision can produce.

In this paper we will first describe the experimental facilities available and then give some examples of results that have been obtained from the 1980 runs. Finally, we give a brief discussion of future prospects for these experiments.

## EXPERIMENTAL PARAMETERS

The layout of the ISR in relation to other major accelerators at CERN is shown in fig. 1. Beams are first accelerated in the proton synchrotron (PS)

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and then transferred to the ISR. Several hundred individual beam pulses can be stacked in each ISR ring allowing surprisingly high interaction rates. Luminosities as high as  $10^{32} \text{ cm}^{-2} \text{ s}^{-1}$  have been achieved for p-p collisions. When this is combined with the inelastic p-p cross section of approximately 40 mb, it is seen that the interaction rate is ~4 MHz. The maximum momentum of the PS is 26 GeV/c but further acceleration of the stored beams is possible in the ISR up to a peak value of 31.4 GeV/c.

During the  $\alpha$ -particle run, the intensities available from the PS were substantially lower; nevertheless, two good runs were achieved during a one-week period. The luminosities obtained are summarized in table I. It should be noted that the  $\alpha$ -p luminosity is substantially higher than that for  $\alpha\alpha$ . This is due to the very much more intense proton beam.

TABLE I

Beams	$\sqrt{s}$ GeV	Luminosity $\text{cm}^{-2} \text{ s}^{-1}$	Time Hours
$\alpha$ - $\alpha$	52,63	$3 \times 10^{28}$	60
$\alpha$ -p	88	$8 \times 10^{29}$	60

The two stored beams intersect at eight places around the ring, six of which are available for experimental apparatus. During the 1980 run, five detectors were operational at four intersections, all of which took data. The five collaborations involved were as follows:

- i) Experiment R110 measured production of  $\pi^0$  with large transverse momenta (large  $p_T$ ) using an apparatus that consists of a superconducting solenoid magnet, cylindrical drift chambers, and lead-glass and lead/scintillator sandwich shower counters covering the central region.
- ii) Experiment R210/211, while setting up for a measurement of small-angle elastic  $\bar{p}p$  scattering, measured elastic scattering with a nonmagnetic detection system consisting of plastic-scintillator and drift-tube hodoscopes.
- iii) Experiment R418 measured elastic and inelastic interactions and production of charged particles with large  $p_T$  using the Split-Field Magnet (SFM) detector, a magnet equipped with multiwire proportional chambers (MWPCs) covering a solid angle close to  $4\pi$ .
- iv) Experiment R806 measured production of  $\pi^0$  with large  $p_T$  using liquid-argon/lead-plate calorimeters.
- v) Experiment R807 measured the production of charged hadrons with large  $p_T$  and normal inelastic interactions, using the Axial-Field-Magnet (AFM), a conventional C-type magnet with cylindrical drift chambers covering the central region, Cerenkov counters, and two forward calorimeters.

It is obvious that the  $\alpha\alpha$  experiment benefited very much from the prior existence of well-developed detector systems and from the wealth of experience obtained during p-p running. Although the running time was short, these factors allowed a remarkable variety of measurements to be made.

## EXPERIMENTAL RESULTS

The results of the  $\alpha\alpha$  and  $\alpha$ -p running periods have been comprehensively reviewed by several authors.<sup>4)</sup> In this paper, we shall mention only two aspects of the data, elastic scattering and production of particles with large transverse momentum.

### (i) ELASTIC SCATTERING

The success of the Glauber model in describing hadron-nucleus and nucleus-nucleus elastic scattering at high energy has demonstrated that the main features of the differential cross sections can be explained by the interference between single and multiple scattering terms<sup>5)</sup>. However, it has been speculated that at very high energies it is necessary to modify the Glauber formalism by the inclusion of terms arising from the coherent excitation of intermediate inelastic states (IIS). This is illustrated graphically in fig. 2, where we show diagrams for p- $\alpha$  scattering with single scattering, multiple scattering, and multiple scattering including IIS. In the last case, the nucleon is excited to a state of mass M and then decays at the second vertex. The intermediate excitation has to fulfill the coherence condition

$$q = (M^2 - m^2) / p_{inc} < \hbar / D$$

i.e., the momentum transfer, q, has to be smaller than the inverse distance, D, between the two scatterings so as not to destroy the nucleus or the coherence of the outgoing waves. This condition implies that with increasing momentum  $p_{inc}$ , higher masses M can be reached, introducing an energy dependence in the elastic scattering amplitude over and above that due to the elementary nucleon-nucleon amplitude.

The elastic scattering differential cross section was measured as a function of four-momentum transfer, t, by two groups. Measurements in the range  $0.2 < t < 0.8$  (GeV/c)<sup>2</sup> were made using the split field magnet,<sup>6)</sup> while measurements at smaller momentum transfers,  $0.05 < t < 0.3$  (GeV/c)<sup>2</sup>, were made by the CERN-MIT-Naples-Pisa-Stony Brook collaboration at intersection 2<sup>7)</sup>.

The experimental arrangement used at the split field magnet is shown in fig. 3. The trigger for an elastic event required a coincidence between the large scintillator arrays T1 and T2 and also the presence of two tracks passing through the multiwire proportional chambers (MWPCs) surrounding the beam pipe in the SFM compensator magnets. The measured distributions by the two collaborations are shown in fig. 4, for  $\alpha\alpha$  and  $\alpha$ p. Also shown are calculations made by Alberi et al.<sup>8)</sup> illustrating the effect of adding intermediate inelastic states to the Glauber calculation. From the results of experiment R418 at the Split Field Magnet, it appears that the agreement

between theory and the absolute magnitude of the cross section is very much better when IIS states are included. However, it is also apparent that there is considerable discrepancy between the two experiments at large momentum transfer. Further measurements will almost certainly be needed for a final resolution of this problem.

### (ii) LARGE $p_T$ PARTICLE PRODUCTION

The production of hadrons with large transverse momentum is a process with a small cross section that arises from the rare hard scattering of hadronic constituents. Naively, one might suppose that shadowing effects would be small and that the target mass dependence would be linear. However, measurements at FNAL by the Chicago-Princeton group<sup>10)</sup> showed that when the

invariant cross section,  $E \frac{d^3\sigma}{dp^3}$ , for proton-nucleus collisions at 200 GeV was

parameterized as  $A \alpha(p_T)$ , the power  $\alpha(p_T)$  grows to values larger than 1.0 for  $p_T$  greater than 2 GeV/c. This 'anomalous nuclear enhancement' has since been confirmed by other experiments and has been the subject of considerable theoretical speculation. The most straightforward ideas proposed to explain this effect have been Fermi motion, a 'trivial' nuclear effect, and multiple scattering, potentially a very interesting process if taking place at the constituent level.

Since three detectors at the ISR have operational large  $p_T$  trigger systems, this is an obvious topic for study in the  $\alpha\alpha$  and  $\alpha p$  systems. In the event, the results obtained have shown strong evidence for the existence of this effect in the  $\alpha\alpha$  system. This is illustrated in fig. 5, which shows the ratio of the invariant cross section for  $\pi^0$  production in  $\alpha\alpha$  and  $pp$  collisions at the same  $\sqrt{s_{NN}}$ .<sup>11)</sup> The enhancement above the  $pp$  cross section is spectacular, rising to a value of 40 at  $p_T \sim 6$  GeV/c. For charged mesons measured by the CERN-Heidelberg-Lund collaboration, the situation is less clear. Figure 6 shows the invariant cross sections measured by this collaboration for  $\alpha\alpha$  and  $\alpha p$  collisions<sup>12)</sup>. Also shown are cross sections for  $pp$  scattering at  $\sqrt{s_{NN}} = 31$  GeV measured by the British Scandinavian collaboration.<sup>13)</sup> Figure 7 shows the ratio of these cross sections as a function of transverse momentum. Also drawn on this figure are lines corresponding to  $\alpha = 1.0$  and to the results of Cronin et al. Unfortunately, there is evidence that some of the  $pp$  data may be internally inconsistent, and, since the cross sections are clearly rapidity dependent, it would be highly desirable to remeasure the  $pp$  cross sections with the identical detector configuration used for the  $\alpha\alpha$  and  $\alpha p$  experiments.

If the effect is present, as it certainly appears to be for the  $\pi^0$  measurements, what can be done to understand its origin? If the answer is accessible to experiment, it must lie in the structure of the whole event, not just in the inclusive cross section. This is illustrated in fig. 8. Figure 8(a) shows the jet structure that would be expected for single hard constituent scattering as in, for example, a  $pp$  collision. The two scattered partons fragment, producing jets of particles, one of which provides the large  $p_T$  trigger. The remnants of the two beam particles also fragment, producing back-to-back jets along the beam axis. This behaviour is indeed observed in

pp collisions, although there are considerable trigger bias effects that complicate the analysis. It turns out that triggering on a single large  $p_T$  particle is not an especially effective means of selecting large  $p_T$  jets, since it is more probable to pick out a relatively 'soft' jet with one particle of unusually large  $p_T$ . Figures 8(b) and 8(c) indicate the behaviour that might be expected if (b) Fermi momentum or (c) multiple hard scattering accounts for the nuclear enhancement. In the first case, (b), the outer momentum of the trigger jet will be taken up by the beam jets; in the second, (c), the away side jet will have lower average transverse momentum. First attempts to understand the behaviour of the associated particles in  $\alpha\alpha$  and  $\alpha p$  collisions are now being made. One example is the  $x_e$  distribution of these particles, where  $x_e$  is a scaling variable defined as

$$x_e = \frac{-\vec{p}_T \vec{p}_T(t_{rig})}{p_T(t_{rig})^2}$$

If multiple scattering plays a dominant role, the  $x_e$  distributions would presumably be steeper for  $\alpha\alpha$  than pp. The results of such a comparison are shown in fig. 9 where the  $x_e$  distributions are shown together with the ratios of  $\alpha\alpha$  and  $\alpha p$  to pp. There is evidence that the ratio is steepening below unity at large  $x_e$ , particularly in the  $\alpha p$  case. However, it should be realized that  $\sqrt{s_{nn}}$  is different for the  $\alpha\alpha$  ( $\sqrt{s_{nn}} = 31.4$ ) and pp ( $\sqrt{s_{nn}} = 53.8$ ) cases and that the trigger bias effects described above may be different in the two cases. Nevertheless, studies of this kind are expected to be very fruitful in pinning down the nature of the reaction mechanism.

#### SUMMARY

We have described two specific experimental results from the  $\alpha\alpha$  runs in some detail. However, it is important to emphasize that the selection that we have made is an arbitrary one and that many active areas of investigation (e.g., multiplicity distributions, strangeness composition, rapidity distributions and correlations, etc.) have been neglected. Indeed, in the final analysis, it may be that these other topics may provide the most interesting insights into nucleus-nucleus collisions. The reasons for this belief is the theoretical interest that is developing concerning the possibility of formation of a quark gluon plasma in very high energy nuclear collisions. The experimental signature for such a transition is still unclear but the strangeness composition of the final state and also the use of a weakly interacting probe such as dilepton pairs have both been suggested. Many authors are engaged in making the best possible estimates for the energy density that can be achieved in these high energy nuclear collisions, the conclusion of which may be that the  $\alpha$ - $\alpha$  system is too small for this transition to occur. Nevertheless, there seems little doubt that the present studies of  $\alpha\alpha$  collisions at the ISR are an important first stage in this field.

## ACKNOWLEDGEMENTS

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## FIGURE CAPTIONS

- 1) The CERN particle accelerator network with the proton synchrotron (PS), the intersecting storage rings (ISR), and a section of the Super-Proton Synchrotron (SPS).
- 2) Proton- $\alpha$  elastic scattering terms: (a) single scattering, (b) double scattering, (c) double scattering with IIS.
- 3) The experimental setup at the Split-Field Magnet. a) Horizontal view, showing main magnet (SFM) and the two compensator magnets (C1,C2), multiwire proportional chambers labeled 313, ..., 417, and the scintillator hodoscopes T1 and T2. b) Vertical view of the chambers, hodoscopes, and the vacuum tube. The 32-wire groups are indicated.



- 4) Differential  $\alpha p$  (a) and  $\alpha\alpha$  (b) elastic cross section,. The data are compared with Glauber model calculations by Proriot et al.<sup>9)</sup> and Alberi et al.<sup>8)</sup> with and without intermediate inelastic state (IIS) corrections.
- 5) Ratio of cross sections for  $\pi^0$  production in  $pp$  and  $\alpha\alpha$  collisions.
- 6) Inclusive cross sections  $d\sigma/\pi dy dp_T^2$  for negative tracks ( $h^-$ ) ( $R418$ )<sup>12)</sup> and  $\pi^0$  ( $R806$ )<sup>10)</sup> for a)  $\alpha p$  and b)  $\alpha\alpha$  interactions compared with  $pp$  data at the same  $\sqrt{s_{NN}}$ . The curves are exponential fits to the data.
- 7) Ratios of cross sections as a function of  $p_T$ : a)  $R_{p_T}(\alpha p/pp)$ ; the curve corresponds to the function  $4^\alpha(p_T)$  with  $\alpha(p_T)$  from ref. 10. b)  $R_{p_T}(\alpha\alpha/pp)$ ; the curve is a prediction (ref. 14).
- 8) Expected event structure for (a) single hard scattering, (b) single hard scattering with Fermi motion effects, and (c) multiple hard scattering.
- 9) Distribution in  $x_e$  of charged tracks in the central region for a)  $\alpha p$  and b)  $\alpha\alpha$  large- $p_T$  interactions compared with the  $x_e$  distribution for  $pp$  interactions ( $\sqrt{s_{pp}} = 63$  GeV,  $p_T > 3$  GeV/c) and for  $\alpha p$  and  $\alpha\alpha$  minimum bias interactions. c) Ratio  $R_{x_e}(\alpha p/pp)$  and d)  $R_{x_e}(\alpha\alpha/pp)$  of the  $x_e$  distributions. (Trigger track is not contained in the plots.)

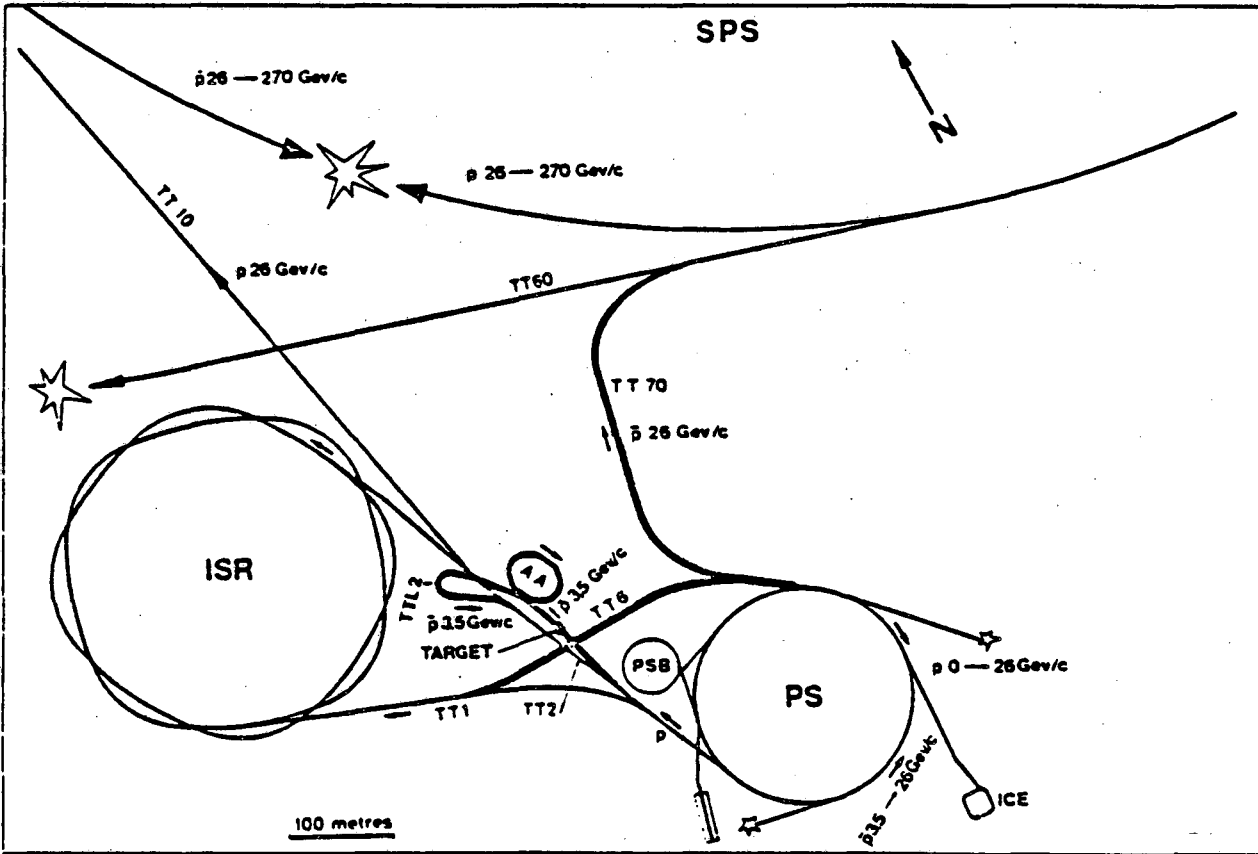
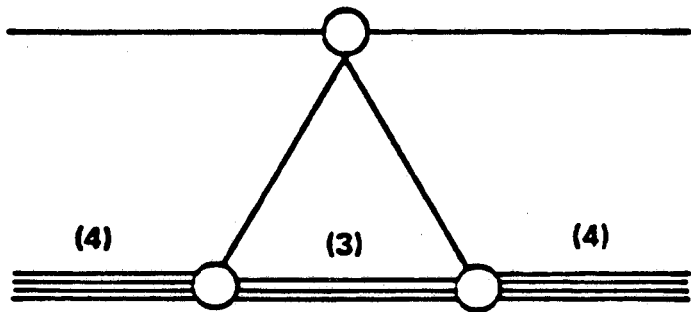
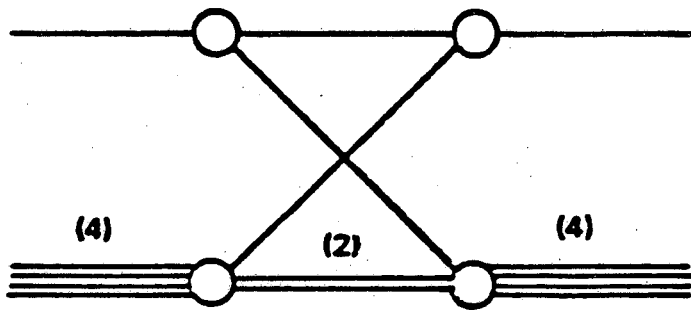


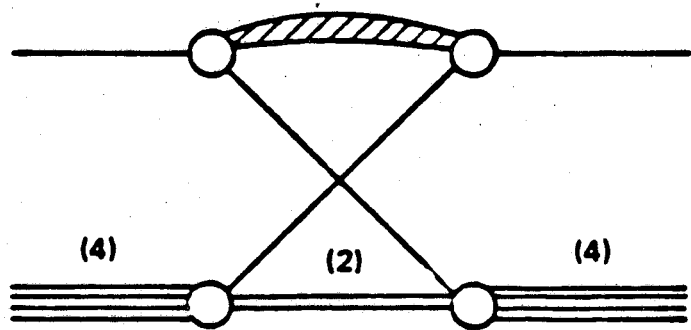
FIG. 1



Single scattering



Double scattering



Double scattering with intermediate excitation

FIG. 2

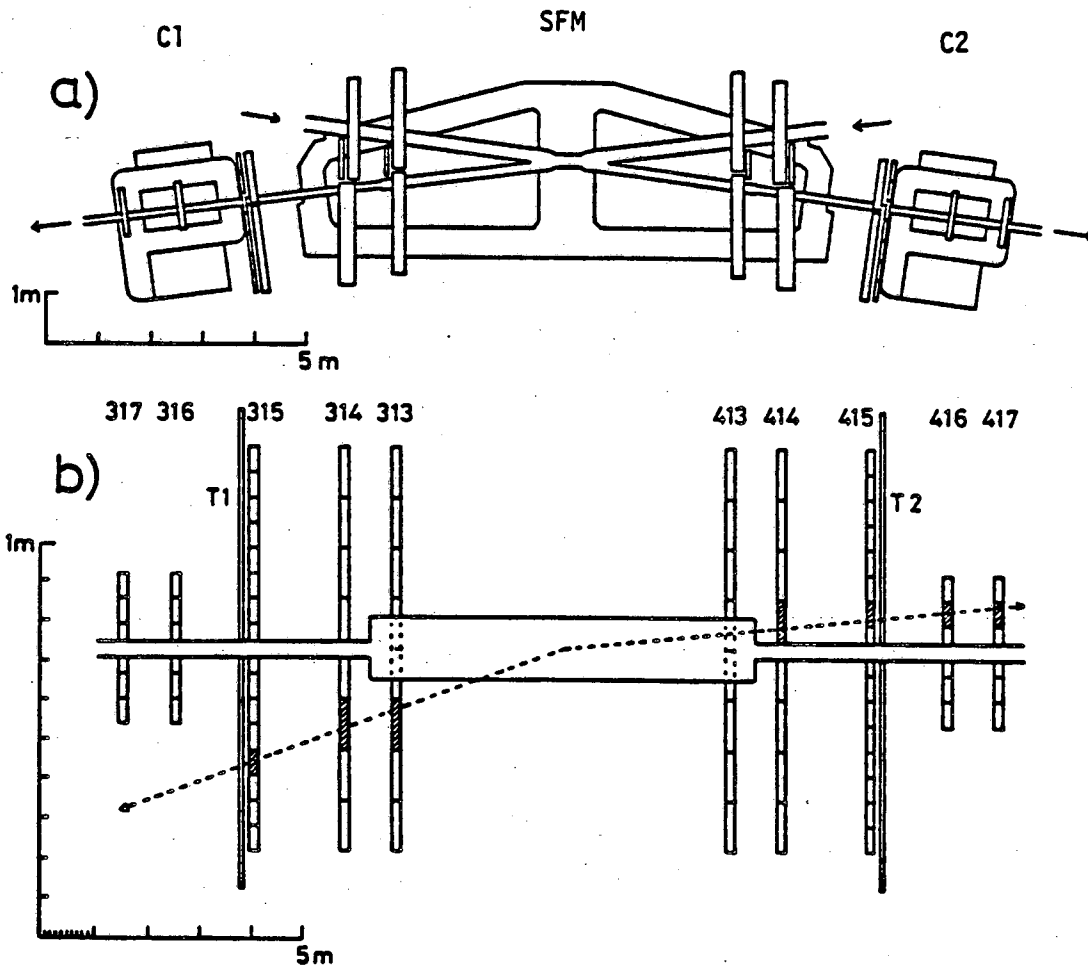


FIG. 3

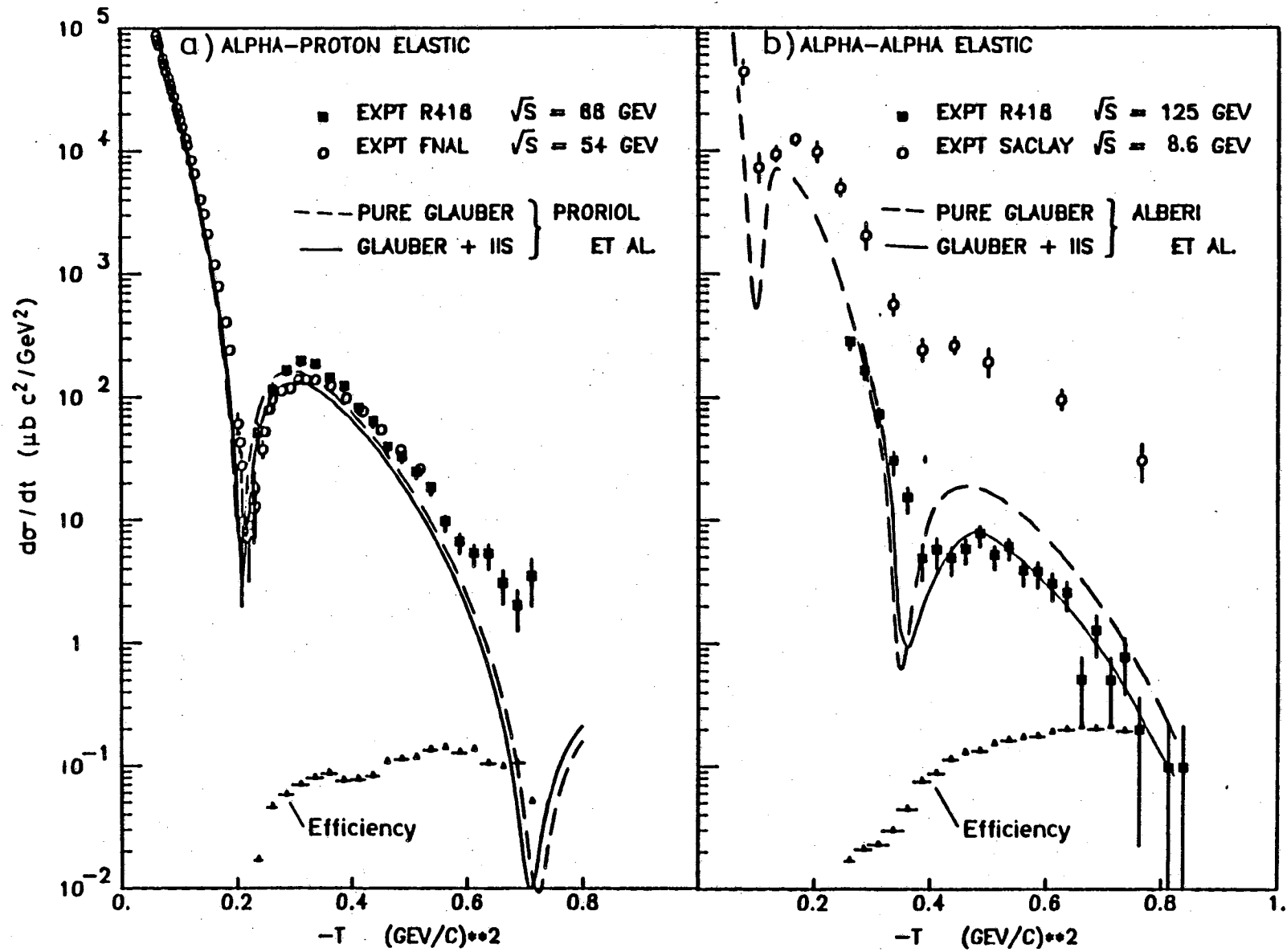


FIG. 4

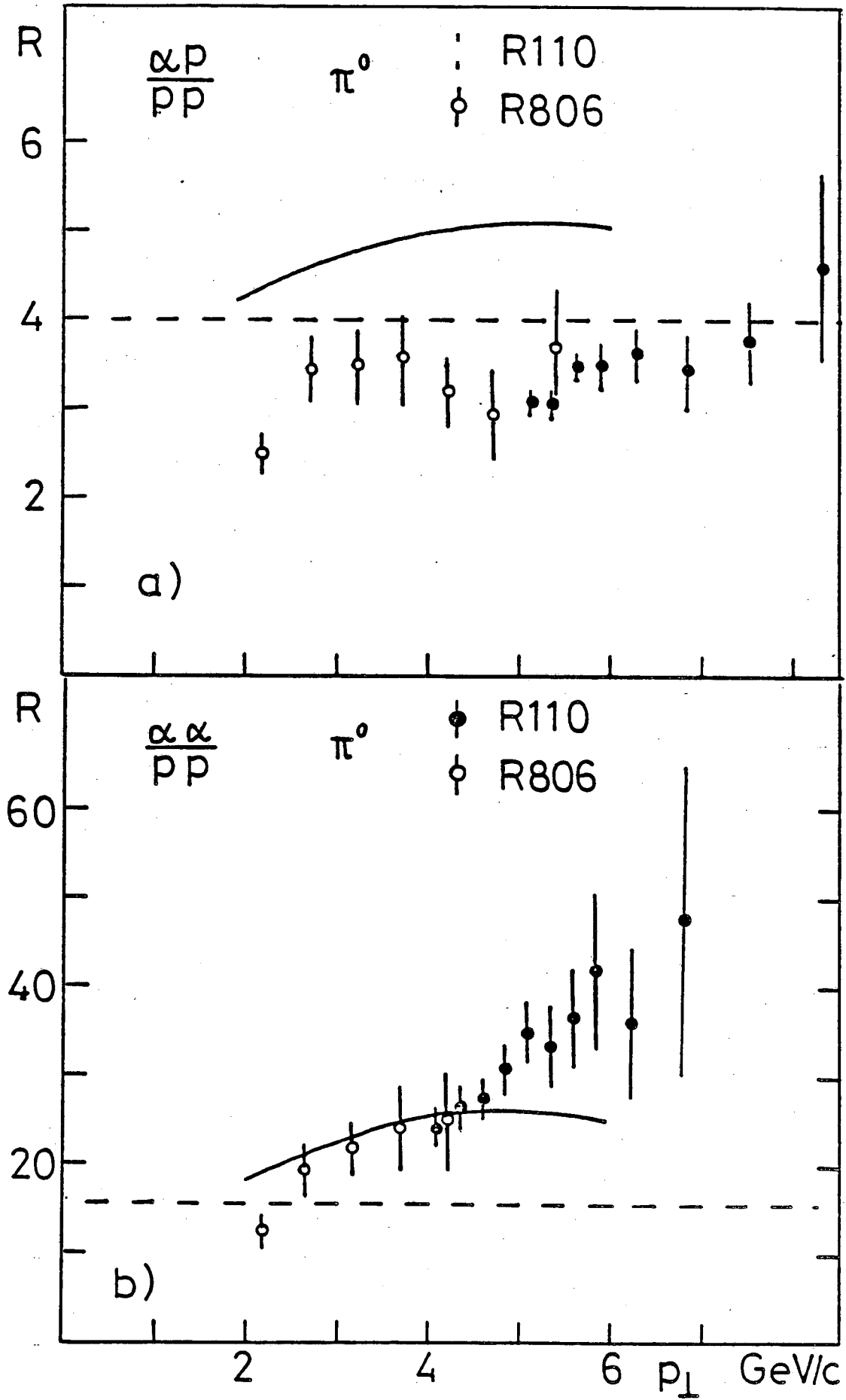


FIG. 5

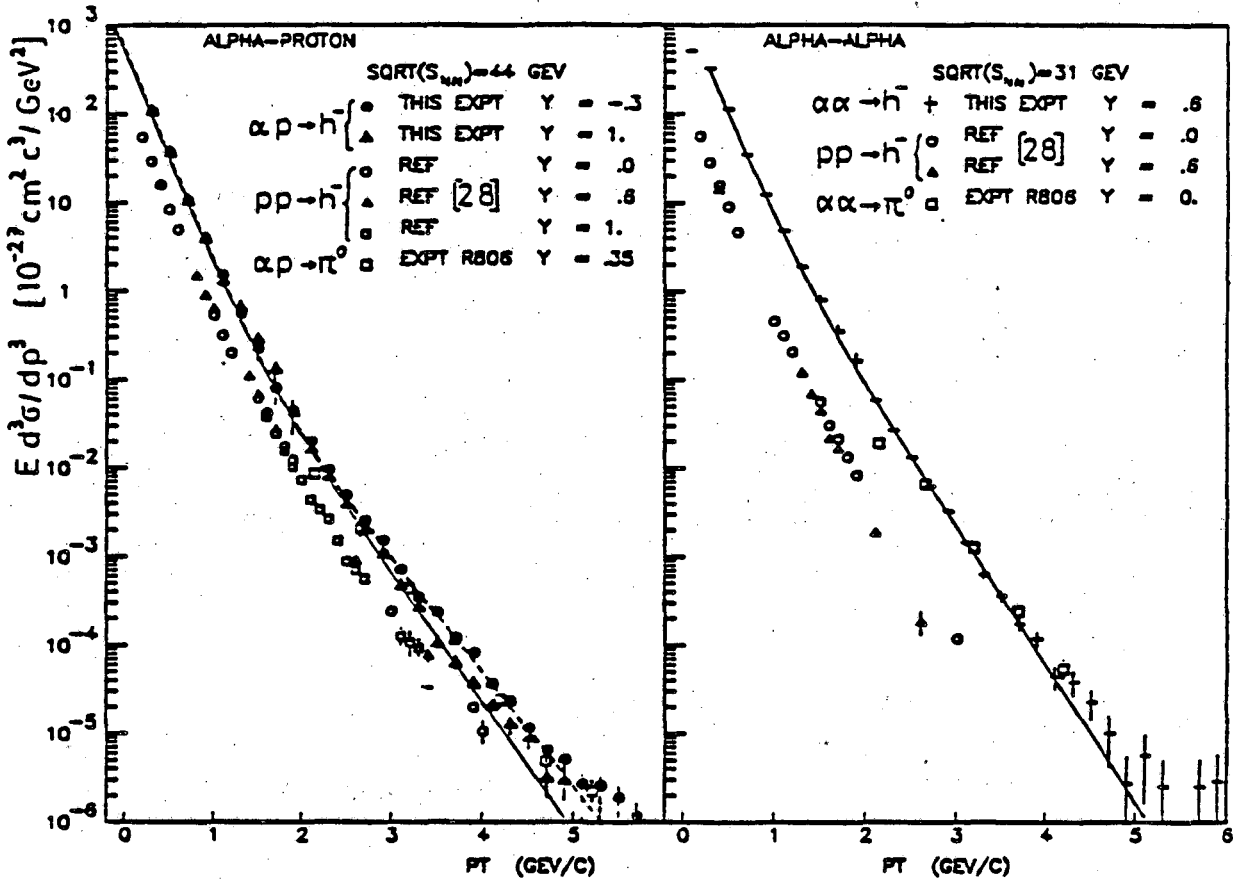


FIG. 6

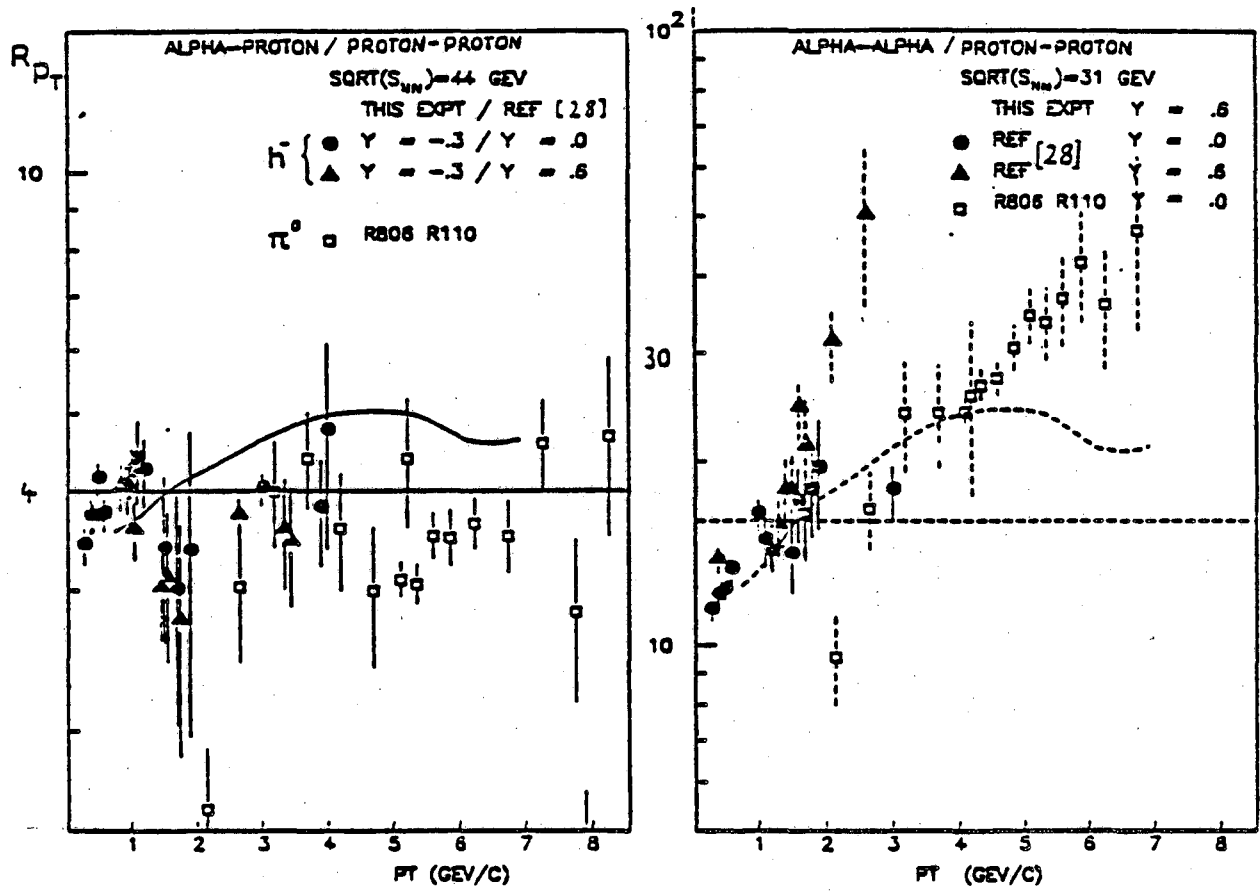


FIG. 7



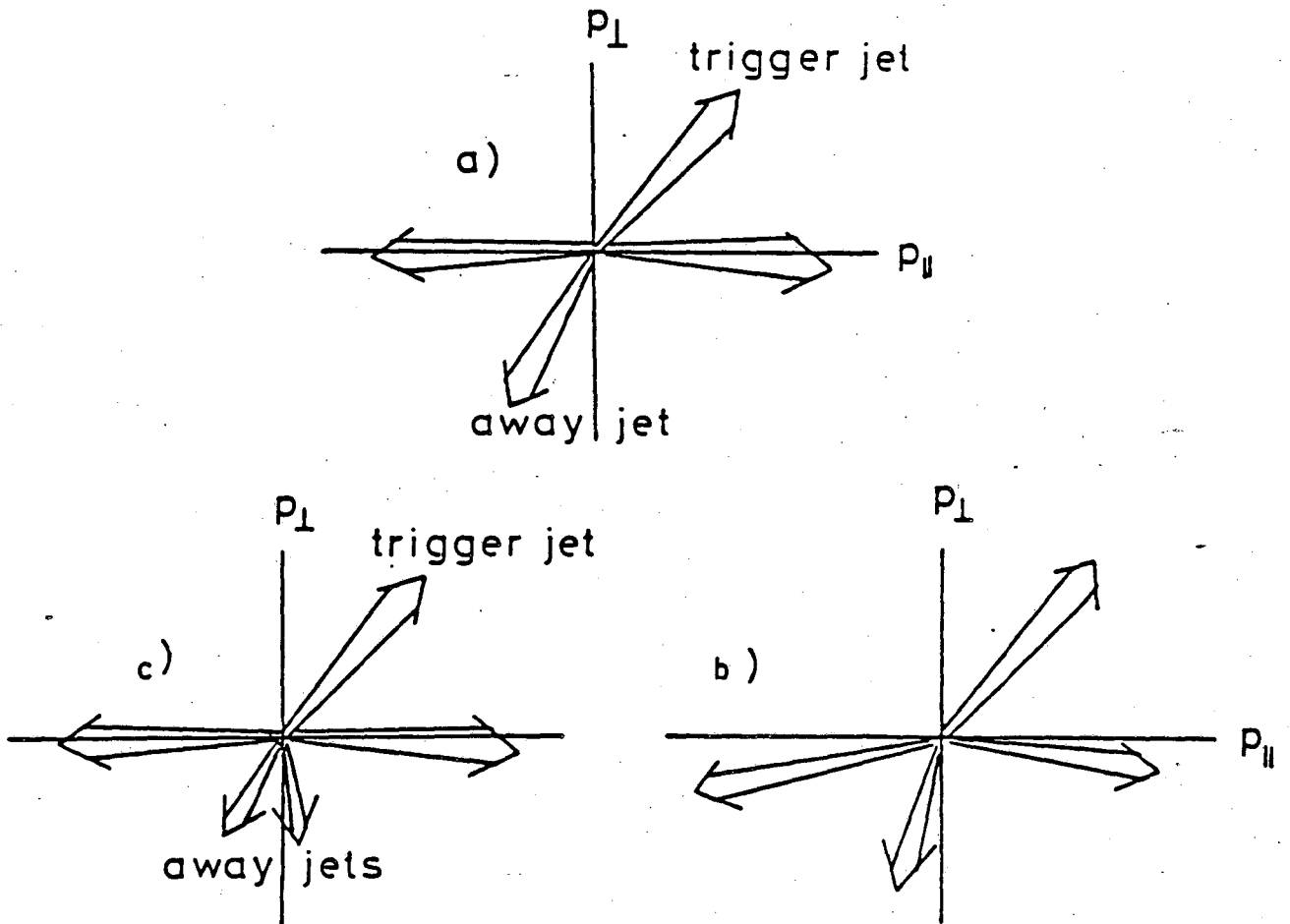


FIG. 8

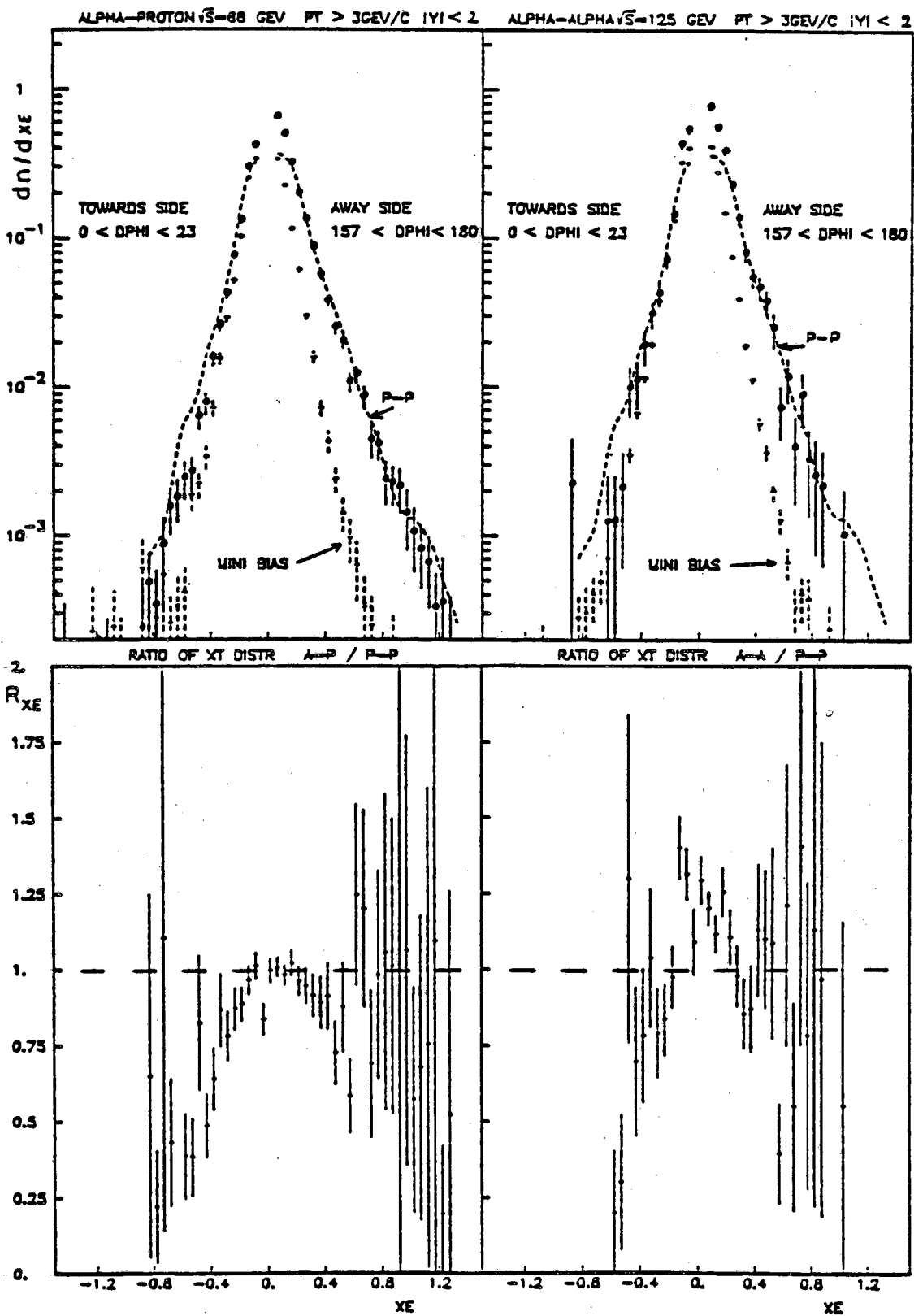


FIG. 9

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