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PRODUCTION OF HIGH-p_t JETS IN HADRON-NUCLEUS COLLISIONS

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ABSTRACT

We present results on the production of jets and "jet-like" clusters in 800 GeV/c proton-nucleus (pA) collisions. Events with high values of transverse energy in the central kinematic region were selected for nuclear targets of H, Be, C, Cu and Pb. A jet-finding algorithm was used in analyzing the data. The A-dependence of the jet and di-jet cross sections was parameterized as A^{α}. The values of α for events with "jet-like" cluster pairs found by the algorithm without any additional kinematic cuts reach a plateau of approximately 1.5 at di-jet transverse energies >11 GeV. The collimation of observed "jet-like" clusters decreases with A, and the fragmentation is softer for heavier target nuclei. However, nuclear effects become less pronounced with the increasing cluster or cluster-pair transverse energy. We argue that the observed nuclear enhancement for the production of "jet-like" clusters is due to soft-scattering contributions to the heavy nuclei data. We show that the nuclear enhancement becomes consistent with a value of α within 0.10 from unity once kinematic cuts enhancing contributions from hard scattering are applied to the data.

1. Introduction

High-p_t jets dominate the event structure in hadronic collisions at high center of mass (c.m.) energies, $\sqrt{s}$, when sufficiently large transverse energy, E_t , is required. This was demonstrated by experiments at $\sqrt{s}$ =63 GeV[1] , at $\sqrt{s}$ =540 GeV[2] and at $\sqrt{s}$ =1800 GeV.[3] At lower $\sqrt{s}$, because of contributions from mechanisms such as initial- and final-state gluon bremsstrahlung and multiple scattering of quarks and gluons, the event structure rarely exhibits di-jet topology and the jet signal is rather difficult to extract experimentally.[4,5] Nevertheless, several attempts to extract the jet signal produced results consistent with QCD predictions and with extrapolations of jet cross sections from higher c.m. energies.[6,7]

Measurements of jets at fixed-target energies of $\sqrt{s} \simeq 40$ GeV are important for several reasons. They widen the energy range of jet studies and, in addition, enable extension of these studies into a new realm of colliding particles: meson-nucleon and hadron-nucleus interactions. The methods employed to extract jets at moderate c.m. energies depend heavily on Monte Carlo models. Therefore, the absolute cross sections for jet production determined at these energies are subject to large systematic errors. However, the relative dependence of jet production and properties from different nuclear targets should be less sensitive to the assumed jet size and background. In our analysis we have concentrated on such studies in an attempt to establish, in a model-independent way, the nuclear dependence for jet production in proton-nucleus (pA) collisions.

Experiments analyzing production of jets from nuclear targets provide information on the propagation of colored objects through nuclear matter. The generally accepted picture of the hard-scatter reactions initiated by energetic hadrons assumes that: (a) the beam hadrons break up at the nuclear surface, but their valence partons propagate through the nucleus with little change in their momenta, and (b) final- state hadrons are formed outside the nucleus. Therefore, the main questions of interest are how partons propagate through nuclear matter to and from a hard interaction, and whether there is evidence for their energy attenuation and/or multiple scattering. We analyze the experimental data from this qualitative point of view. A more quantitative comparison with QCD model predictions is premature at this stage of data accuracy and sensitivity of model predictions.

The A-dependence for jet production is a subject of several recent review articles.[8–10] It was found for the first time in the hadronic production of high-p_t single hadrons from nuclei that the observed cross section increases with the atomic number, A, faster than A^1 : the measured values of α in the parametrization $d\sigma/dp_t \propto A^\alpha$ were found to be close to 1.2 at $p_t = 4$ GeV/c .[11] This enhancement seems to diminish with increasing c.m. energy. New data from Fermilab experiment E605[12] on pA interactions at 800 GeV/c ($\sqrt{s}$= 38.8 GeV) extended the range of p_t studied to 10 GeV/c and yielded values of α less than 1.1 . Similarily, new results on di-hadron production from E605[12] and E711,[13] also obtained at 800 GeV/c incoming proton momentum, showed values of α close to 1.0, regardless of the di-hadron pair mass or charge combination.

Several models were proposed to account for the observed effects. In addition to Fermi motion effects and scattering of the incoming hadron prior to point-like interactions, the calculations included rescattering of high-p_t partons from nucleons and multiple jet production.[14–16] The quantitative interpretation of the data was, however, obscured by the fact that rather than observing a parton itself, only one of the fragments of a parton hadronization into jets is observed.

A previous experiment (Fermilab E260) looking for jet production from nuclei[17] was performed at $\sqrt{s}$ =20 GeV, and nuclear effects were studied by comparing results from hydrogen and aluminium targets only. The experiment reported a strong enhancement of jet rates and a relative broadening of jets produced from aluminium. The conclusions from E260 were obscured by the subsequent observation of an even stronger nuclear enhancement for isotropic-type events[18,19] that was consistent with the behaviour of the multiplicity tails in the KNO distributions for hadron-nucleus interactions, and could be accounted for by soft scatterings of incoming hadronic matter within the nucleus. Therefore, two competing mechanisms are believed to be responsible for pA collisions that produce large transverse-energy relative to the incident beam direction. They are:

— (*i*) multiple soft scattering involving many nucleons within the nucleus, and

— (*ii*) hard scattering of constituents that can produce high-p_t jets which then propagate through the nucleus.

In this paper, resulting from Fermilab experiment E557, we analyze events produced with high values of transverse energy in 800 GeV/c proton-nucleus collisions. In a previous publication[20] we reported a strong A-dependence in the cross section for producing events with a given E_t . The A-dependence at a given E_t was parametrized as A^α. The values of α were found to be close to 1.7 for high-E_t GLOBAL events (see Section 2), and somewhat less (about 1.5) for small-aperture triggers. Moreover, we note that "jet-like" events, selected by requiring a large value of the planarity variable,[4] exhibited an A-dependence consistent with $\alpha \simeq 1.1$, while α was much larger for more isotropic events. These observations were fully confirmed by Fermilab E609 performed at $\sqrt{s}$ =27.4 GeV.[21]

The planarity variable[4] was commonly used by previous experiments to extract the jet signal,[16] therefore, values of α at high planarity could reflect the A-dependence for the jet production rates. However, we noticed that values of α determined by such analysis are sensitive to both the A-dependence for the jet production rates and possible changes in the jet fragmentation with A. In this paper we attempt to investigate these two effects.

The paper is organized as follows: Sections 2 describes the apparatus, the data base, the calorimeter track algorithm, data reduction, and the cuts used in the analysis. The jet-finding algorithm is described in Section 3. In Section 4, we discuss event structure in the transverse plane for di-jet events. Cross sections for single jets and di-jets and their A-dependence are presented in Section 5. The A-dependence for di-jet production for various polar angle configurations of the two jets is summarized in Section 6. The nuclear dependence of jet fragmentation is discussed in Section 7. The correlations between high-pt jets and a beam-spectator jet are discussed in Section 8. Finally, our conclusions are listed in Section 9. Preliminary results of this analysis were included in Refs. 10 and 22.

2. Apparatus and Data Analysis

The experimental procedure as well as details of the apparatus have already been described in our previous publications.[20] We describe here the main features of the apparatus relevant to the present analysis.

The layout of the experiment is shown in Fig. 1. The magnetic spectrometer is followed by series of highly segmented calorimeters denoted by the names "wide angle" (WAN), "insert" (INS), "forward" (FWD), and "beam" (BEAM). Each of these calorimeters consisted of an electromagnetic section followed immediately downstream by a fully absorptive hadronic section. The geometry and the granularity of the WAN,INS and FWD calorimeters are shown in Fig. 2. For pp data, the 800 GeV/c beam was incident on a 45-cm liquid hydrogen target; for pA data, nuclear targets of Be, C, Cu and Pb replaced the hydrogen target. The nuclear targets were constructed of three successive foils, sufficiently thin (less than 6% interaction length, total) to avoid significant rescattering.

The apparatus was triggered on events in which a large amount of transverse energy, E_t, was deposited within an aperture of the calorimeter located at 90° in the c.m.s. Two classes of triggers are discussed here (see Fig. 3):

(a) the GLOBAL trigger, with 2π azimuthal and 45° - 135° c.m. polar angle coverage;

(b) the BB trigger, a sum of signals from two apertures back-to-back in azimuth, with $\pi/2$ azimuthal and 45° - 135° c.m. polar angle coverage for each component.

At $\sqrt{s} \simeq 40$ GeV, GLOBAL triggers predominantly select non-jet events,[4,5] whereas BB trigger data sample should contain a larger fraction of hard scatters.[1] GLOBAL trigger data are used to check against possible trigger biases inherent in reduced aperture triggers like BB. On the other hand the BB trigger, requiring two approximately opposite jets (di-jet), is unbiased with respect to intrinsic parton transverse momentum or gluon bremsstrahlung effects, which are known to bias single-jet triggers at low $\sqrt{s}$. It is also expected to be more efficient than a single-jet trigger in selecting hard scatters from the soft-scatters background.

The E557 apparatus had an almost 4π coverage and was able to observe, on the average, 93% of the incident 800 GeV energy. The total energy distribution (not shown) had an average value of 740 GeV with a FWHM of 150 GeV.[20]

In the off-line analysis, events were processed through a cluster-finding procedure for the calorimeters to form "calorimeter tracks".[23] The cluster was designated to be electromagnetic or hadronic, depending on its energy deposition pattern in the electromagnetic and hadronic calorimeter sections. All hadronic "tracks" were assumed to be due to pions, and all electromagnetic "tracks" to be due to photons. Our Monte Carlo studies indicate that the calorimeter tracks reproduce the actual track multiplicity at the interaction vertex to within 15%. We have checked that the "track" distributions are symmetric around $\theta^* = 90^\circ$ for the pp data, and that the average amount of forward c.m. energy ($\theta^* < 90^\circ$) is equal to 18 GeV, approximatelly equal to $\sqrt{s}/2$, independent of the trigger type and E_t.[23]

The inherent calorimeter energy resolution, calibration uncertainty, energy leakage from modules, and the p_t kick of the spectrometer magnet all contribute to the experimental p_t resolution function for jets. These effects were simulated using ISAJET Monte Carlo model and a calorimeter shower parametrization in order to determine the p_t resolution.[20] The net effect on the exponentially falling jet p_t distributions presented in Section 5 was a decrease of 7% in the p_t scale. After including this p_t shift, we estimated the total uncertainty in the p_t scale to be 7% .

We have also benchmarked the transverse momentum distributions of hadronic tracks against inclusive p_t cross sections measured in other experiments.[23] The hadronic "track" data agree to within 15% with published cross sections[11] over the wide range 1.0 GeV/c$<p_t<$8.0 GeV/c. This agreement[23] gives us confidence in the performance of our cluster-finding algorithm and in the calibrated E_t scale of the experiment.

3. Jet-finding Algorithm

The events selected with various triggers were processed through a jet-finding algorithm which worked as follows:

(i) The track with the highest p_t (at least 1.5 GeV/c) was selected.

(ii) The vector sum of the momenta of all tracks in a cone with radius R (see below) in the ϕ-η space centered around the track with maximum p_t was calculated. The resulting vector defined a new jet axis.

(iii) Step (ii) was iterated three times using the jet axis found in the previous iteration.

(iv) If the p_t of the resulting cluster was greater than a minimum value $p_{t,min}$ (jet) = 5 GeV/c, the cluster was accepted as a jet and all tracks used to form it were removed from the track list.

(v) The procedure was repeated for the next available track with largest p_t.

We refer to the "jet-like" clusters of energy found by this algorithm as jets. The analysis was performed for values of R equal to 0.85 and 1.0. The lower value corresponds approximately to a cone whose half opening angle is 46° (44° and 49° in polar and azimuthal angles, respectively) and will be used except as noted otherwise. The above values of R are consistent with jet sizes predicted for *pp* interactions in our energy range by ISAJET,[24] and are comparable to values used by other experiments.[1,6,25] The granularity of our calorimetry in the ϕ-η plane, with the two assumed jet sizes superimposed, is shown in Fig. 4a. The search for jets covered the c.m. rapidity range $-1.0 < \eta^* < 1.5$. We have checked the sensitivity of our results to the p_t cutoff for the initializing track, the number of iterations, and the value of $p_{t,min}$(jet). Our results for high-p_t jets are not sensitive to reasonable variations of these variables.[22]

The precise determination of the jet size is obscured by the non-jet background. The background can be due either to the presence of soft scatters in our sample or to contributions from spectator-jet fragmentation. Separation of the pure jet signal is impossible without Monte Carlo calculations, which are not very reliable, particularly when applied to hadron-nucleus interactions. Our analysis is intended to avoid strong dependence on model assumptions. Thus, we study production of "jet-like" clusters from nuclei as a function of the cluster p_t and cone size R. Previous experiments implied that the fraction of hard scatters increases with increasing p_t of the cluster. Observing the trends in the data analyzed under variety of conditions should provide a better understanding of nuclear effects than an analysis based on model-dependent attempts to rigorously identify jets.

4. Event Structure for Di-jet E_t Triggers

A clear di-jet event structure is observed in our data for events obtained with the BB trigger. For a trigger threshold of E_t =13 GeV, two or more jets with $p_t > 5$ GeV/c and within R = 0.85 were found for 65% and 55% of *pp* and *pPb* events, respectively. An example of such an event is shown in Fig. 4b, where the p_t of tracks are plotted in bins of its azimuthal angle ϕ and pseudorapidity η. The number of observed two-jet events increases to approximately 80% for R=1.0, independent of the target used.

We concentrate on discussing events selected with the BB trigger for which two jets were found (in the pseudorapidity range $-0.4 < \eta^* < 0.4$), and for which the scalar sum of the transverse momenta, E_t^{jj}, exceeds 13 GeV/c. This sample of the data consists of 175, 550 and 1900 *H*, *C* and *Pb* events, respectively.

The transverse-momentum flows as functions of the azimuthal angle difference are shown in Fig. 5a. The azimuthal angle difference is calculated with respect to the jet axis approximated by calculating the vector sum of the particle momenta within a cone of a radius R = 0.85 in the ϕ-η space around the jet axis. The transverse momentum in Fig. 5 is normalized by the p_t of the more energetic jet. The data for hydrogen exhibit clear maxima attributed to the "trigger" (higher p_t) jets and "away" jets. The observed transverse-momentum flow for *pp* data is in good agreement with published results from the AFS experiment at the ISR.[26] The width of the distribution implies the size of the jet is such as to be contained within an R of 0.9 ± 0.1. The carbon and lead data indicate significant smearing of the di-jet structure for heavier nuclei. This is partially due to widening of jets with A, and mainly to smearing in the position in azimuth of the "away" jet around 180° for heavier nuclei (see Fig. 6a). The two jet momenta are less balanced for the *Pb* data than for the *H* data (see Fig. 6b). Figure 5a also shows that the level of an underlying event is 50% higher for the *Pb* data relative to *H*. The effects of increased underlying event and widening of jets with A are also observed in the pseudorapidity variable (not shown).

The differences between nuclear targets are much less pronounced when events with large planarity, P > 0.85, are selected, as shown in Fig. 5b. This planarity cut selects 40%, 12% and 4.5% of the *H*, *C* and *Pb* two-jet ($E_t^{jj}>$

13 GeV) data, respectively. For this sample of events, the nuclear enhancement parameter α is 1.06$\pm$ 0.03, compared with α = 1.48$\pm$ 0.02 for the uncut sample (errors are statistical only).

5. Jet Production Cross Sections in pA Interactions.

GLOBAL and BB trigger data were used to calculate cross sections for jets and di-jets. The acceptance-corrected cross sections, $d^2\sigma/dp_t d\eta^*$, for single jets obtained with R=0.85 are shown in Fig. 7a. Only jets in the range $-0.4 < \eta^* < 0.4$ were included in the cross section calculations. We have checked that the measured rates do not depend on the azimuthal position of the jets, and are symmetric around $\eta^* = 0$ for the *pp* data. We have also verified consistency of jet cross sections obtained with different types of triggers. However, we have noticed a significant dependence of cross section on the assumed jet size, R. The measured *pp* rates change by a factor of approximately two when R is increased from 0.85 to 1.0.

The c.m. energy-dependent parametrization of jet cross sections for the *pp* interactions,[6] based on results of other experiments, is also shown in Fig.7a. There is very good agreement between our *pp* results and a world data parametrization. Therefore, we conclude that the "jet-like" clusters observed in this experiment with the hydrogen target are produced with rates expected for jets.

The rates for the central "jet-like" cluster production from various nuclei are also shown in Fig. 7a. We have checked that the standard A^α parametrization for the A-dependence is consistent with the data, including the pp results. Fitted values of α are plotted vs p_t in Fig. 7b. The parameter α is found to increase with p_t to a plateau of approximately 1.5 for $p_t > 7$ GeV/c. There is also an indication for α decreasing with p_t for $p_t > 10$ GeV/c. The parameter α exhibits a small variation (less than 0.1) if R is increased from 0.85 to 1.0. Therefore, we observe a strong nuclear enhancement for all reasonable dimensions of "jet-like" clusters.

The di-jet cross sections, $d^3\sigma/dE_t^{jj} d\eta^*{}_1 d\eta^*{}_2$, are shown as functions of E_t^{jj} in Fig. 8a. Figure 8b shows the variation of α with E_t^{jj}. Again, both jets were required to be within the range $-0.4 < \eta^* < 0.4$. Although the values of α are about 1.5 at E_t^{jj}= 13 GeV, they decrease at larger values of E_t^{jj}. As shown in Fig. 8b, there is very good agreement between values of α obtained with the GLOBAL and BB triggers, implying that the BB trigger event sample is adequately unbiased for studying nuclear effects.

The interpretation of the observed enhancement requires some caution. First, the values of α have not been corrected for two compensating effects. A correction for the possible widening of jets (by increasing R) with A should lead to an even stronger measured nuclear enhancement, while corrections for leakage of the underlying event into the jet cone would tend to reduce the enhancement. Using the distributions presented in Fig. 5a, we have estimated that the latter effect should reduce α by less than 0.1. Secondly, as we have mentioned in the introduction, the two competing mechanisms are believed to be responsible for the nuclear enhancement in the production of high-E_t events: multiple soft scattering and high-p_t jet rescattering. Therefore, before we accept a hard scattering interpretation of the phenomena, we should consider effects of a possible soft scattering contamination in the event sample. It is possible that at the value of $\sqrt{s}$ and the jet p_t range available in this experiment the hard-scattering mechanism already dominates the *pp* data, whereas soft scattering may still be dominant for the heavy nuclei data.

6. Di-jet Polar Angle Configuration Dependence

The soft-scattering interpretation of nuclear enhancement, discussed in the previous section, is reinforced by analysis of di-jet events in regions of phase space corresponding to the emission of both jets backward in the nucleon-nucleon c.m., or both jets forward. As seen from Fig. 9a the proton-proton data exhibit a good backward-forward symmetry, whereas the pPb cross sections for the two cases differ by more than an order of magnitude. The pPb jets in the backward hemisphere are expected to be contaminated by the target fragmentation. The values of α for the configuration with both jets forward (see Fig.9b) are consistent with $\alpha = 1.0$ for E_t^{jj} greater than 15 GeV, whereas they are equal to 1.6 for the backward configuration. It is difficult to conceive a parton rescaterring model, which could reproduce such a strong change in α over this limited rapidity range.

7. Properties of "Jet-like" Clusters

Properties of "jet-like" clusters are discussed for clusters belonging to di-jet events with $E_t^{jj} > 13$ GeV. We compare results for all events, and for events selected with a planarity cut $P > 0.85$. We employ several variables based on calorimeter tracks.

(a) Cluster collimation

The jet collimation is defined as the ratio of the jet transverse momentum contained within a cone of radius R/2 to that in a cone of radius R around the jet axis (determined using R). The collimation distributions for R = 0.85 are shown in Fig. 10. The distributions for nuclear targets are significantly shifted towards smaller values, reflecting a broadening of "jet-like" clusters with A.

(b) Cluster hadronic multiplicity

The absolute values of hadronic multiplicities constituting a jet are known in this experiment to a limited accuracy of about 15%. On the average a 7 GeV/c "jet-like" cluster for the *pp* data contains 3.2 hadronic calorimeter tracks for R = 0.85. The corresponding number for *pPb* data is 3.9. The planarity cut reduces multiplicities to 2.9 and 3.2 for *H* and *Pb* targets, respectively. The average hadronic multiplicities increase by approximately 1.0 when R=1.0 is used in the jet algorithm.

(c) Cluster fragmentation

The longitudinal structure within a jet can be described by the variable $z = p_l / p_t(\text{jet})$, where p_l is the projection of the track momentum onto the jet direction and $p_t(\text{jet})$ is the total transverse momentum of the jet. The z distributions for hadronic tracks are shown in Fig. 11. The jets produced from nuclear targets are softer than those observed for *pp* data. A disappearance of the most energetic particles is observed for heavy nuclei.

Experiments triggering on single high-p_t hadrons select jet fragments from the large-z fragmentation tail. The effects of nuclear enhancement in production rates for "jet-like" clusters (discussed in Section 5) and nuclear suppression of large-z hadrons (seen in Fig. 11a) compete, resulting in an approximately $d\sigma/dp_t \propto A^1$ nuclear dependence for single hadrons. Our results are fully compatible with those from single high-p_t particle experiments.

The nuclear effect in the z-distributions disapears when high planarity events (P>0.85) are examined, as shown in Fig. 11b.

(d) Dependence of cluster properties on E_t^{jj}.

The nuclear effect in the z-distributions is also reduced when events with higher di-jet transverse energy ($E_t^{jj} > 16$ GeV) are examined, as shown in Fig. 12a. for the *pPb* data. The z-distributions for the *pp* data do not change significantly over the discussed E_t^{jj} range. There is little variation in the collimation of *pPb* events with E_t^{jj} as shown in Fig. 12b.

8. Beam-Jet Fragmentation

Fermilab experiment E609 reported[21] a significant drop in forward ($\theta^* < 40°$) energy flow with atomic number, A, for both low- and high-planarity events. This could indicate an attenuation of the beam spectator jet inside the nucleus. We have repeated this analysis for our data.

Our results are shown in Fig. 13, where we plot average laboratory frame energies in two forward regions coresponding to (i) $\theta^* < 25°$ (Fig. 13a) and (ii) $25° < \theta^* < 45°$ (Fig. 13b) as functions of A for low-planarity (P<0.6) and high-planarity (P>0.85) events. The amount of beam energy in the very forward cone is seen to be 40% lower for the *Pb* target as compared to the *H* target for both planarity ranges. There is little nuclear or planarity dependence of energy flow in the intermediate region. Therefore, the beam jet collimation, defined as a ratio of energies in the two regions, increases strongly with planarity, an observation reported by us previously.[27] The collimation decreases with the A value of the target for both low- and high-planarity events, indicating that the beam spectator jet is attenuated inside the nucleus, regardless of whether the event is due to hard or soft scattering.

9. Conclusions

We have demonstrated that production of "jet-like" clusters and cluster pairs is strongly enhanced for nuclear targets, with values of the parameter α in the form $d\sigma/dp_t \propto A^\alpha$ being close to 1.5. The clusters observed in pA collisions are broader than jets found in pp interactions. Similar nuclear dependence of production rates and properties of "jet-like" clusters were obtained independently by Fermilab E609 at 400 GeV/c incident momentum.[25,10]

There are two possible interpretations for the observed enhancement and the broadening of the "jet-like" clusters. One interpretation explains the enhancement as a result of jet rescattering within the nucleus. Such rescattering could also be responsible for changes in the properties of jets as observed for the heavy-target data for which the fragmentation is softer. The values of α close to 1 for high-planarity events would then reflect cases where there was no jet rescattering. However, it is likely that at values of $\sqrt{s}$ and jet p_t available in this experiment the hard scattering mechanism already dominates the pp data, whereas the soft scattering is still a dominant mechanism for the heavy nuclei data. This interpretation is supported by the decrease of the nuclear effects with increasing jet

p_t, and by the behaviour observed when additional cuts are applied to enhance hard- scattering contributions. We have discussed two examples of such cuts (a high-planarity requirement, and a forward di-jet configuration), which led to a nuclear dependence consistent with an A^1 parametrization of the jet production rates at a given E_t^{jj}.

Therefore, we conclude that all available data on the hadroproduction of jets, independent of the technique used to detect high-pt jets (whether single energetic hadrons, hadron pairs, high-E_t planar events, or even "jet-like" clusters when additional kinematic cuts are imposed), are consistent with a rather modest nuclear enhancement (the parameter α not exceeding 1.10), diminishing with the p_t of the studied object.

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FIGURE CAPTIONS

1) E557 experimental layout.

2) Calorimeter segmentation. (a) WAN-INS;(b) FWD.

3) Trigger apertures.(a) GLOBAL; (b) Back to back (BB).

4) (a) Segmentation of the calorimeters in the ϕ-η space. The circles represent the two values of jet cone size, R, used in the analysis (R=0.85, 1.0) ; (b) Event display of track p_t in ϕ-η space ("lego" plot).

5) Transverse momentum flow vs the azimuthal angle relative to the "trigger" jet axis, ϕ, normalized to the p_t of the "trigger" jet. BB trigger data with $E_t^{jj} > 13$ GeV are shown. (a) no planarity cut; (b) P >0.85 .

6) (a) Distribution of the difference in azimuth between the two jet momentum vectors; (b) Distribution of the asymmetry of the momentum imbalance between the two jets. BB trigger data with $E_t^{jj} > 13$ GeV are shown

7) (a) Dependence of $d^2\sigma/dp_t d\eta^*$ on jet p_t for pA interactions at 800 GeV/c. The dashed line represents the c.m. energy-dependent parametrization of jet cross sections for the pp interactions.[6] (b) α vs p_t.

8) (a) Dependence of $d^3\sigma/dE_t^{jj}d\eta^*{}_1 d\eta^*{}_2$ on di-jet E_t^{jj} for pA interactions at 800 GeV/c, where E_t^{jj} is the scalar sum of transverse energy of the two jets. (b) α vs E_t^{jj}.

9) Polar angle dependence of $d^3\sigma/dE_t^{jj}d\eta^*{}_1 d\eta^*{}_2$. Cross sections are shown for: both jets emitted forward ($0 < \eta^* < 0.4$) and backward ($-0.4 < \eta^* < 0$) in the nucleon-nucleon c.m. (a) pp and pPb data (b) α vs E_t^{jj}.

10) Distribution of jet collimation for pp, pC and pPb data. The BB trigger data with $E_t^{jj} > 13$ GeV are shown.(a) no planarity cut; (b) P>0.85.

11) The jet fragmentation function for hadronic tracks. The BB trigger data with $E_t^{jj} > 13$ GeV are shown. (a) no planarity cut; (b) P>0.85.

12) Jet fragmentation properties shown for two ranges of E_t^{jj} for pPb data. (a) Fragmentation function (b) Jet collimation.

13) Average laboratory energies in two polar regions coresponding to: (a) $\theta^* < 25°$, and (b) $25° < \theta^* < 45°$ as a function of A, for planar and non-planar events.The BB trigger data with $E_t^{jj} > 13$ GeV are shown.

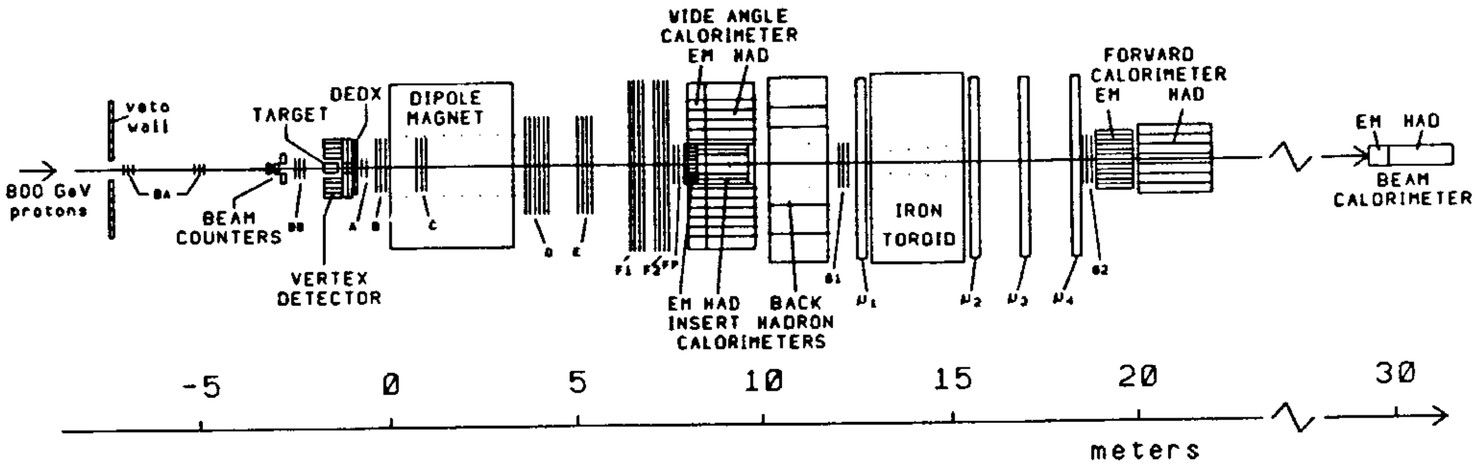


Figure 1

C. Stewart et al.

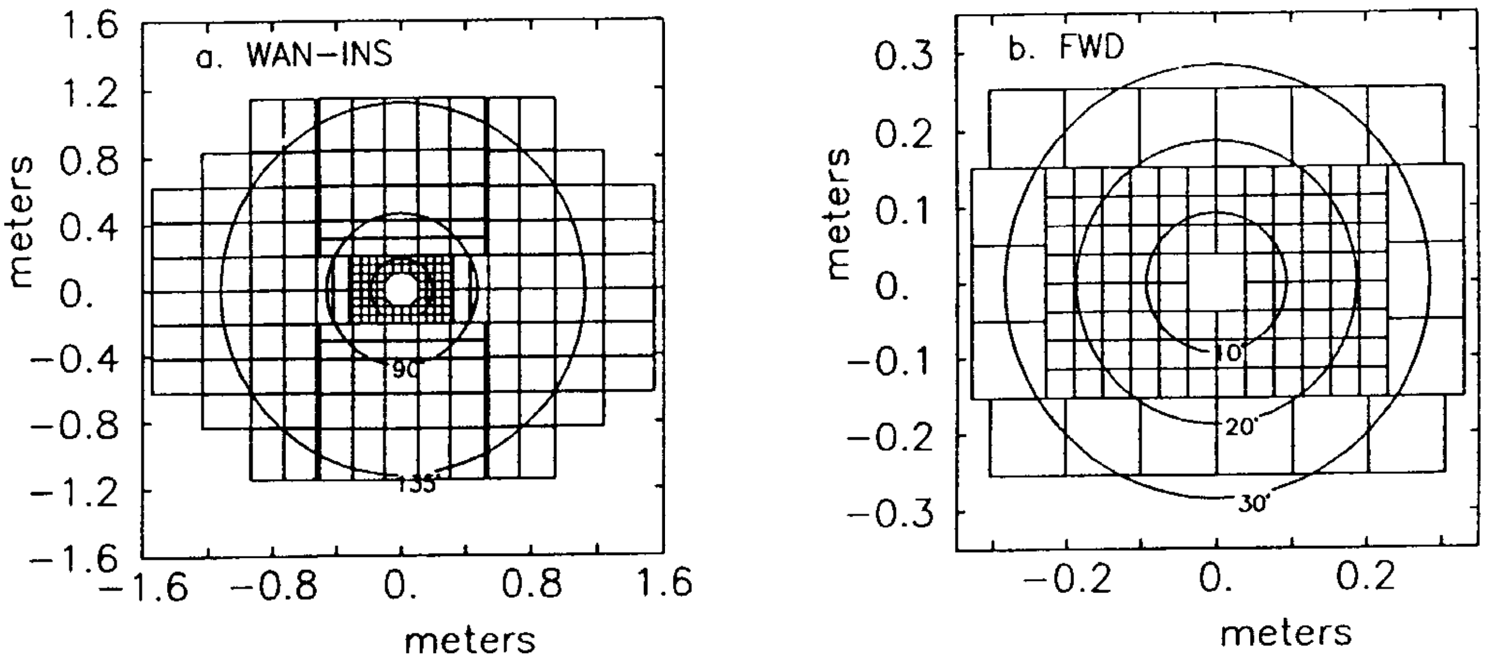


Figure 2

C. Stewart et al.

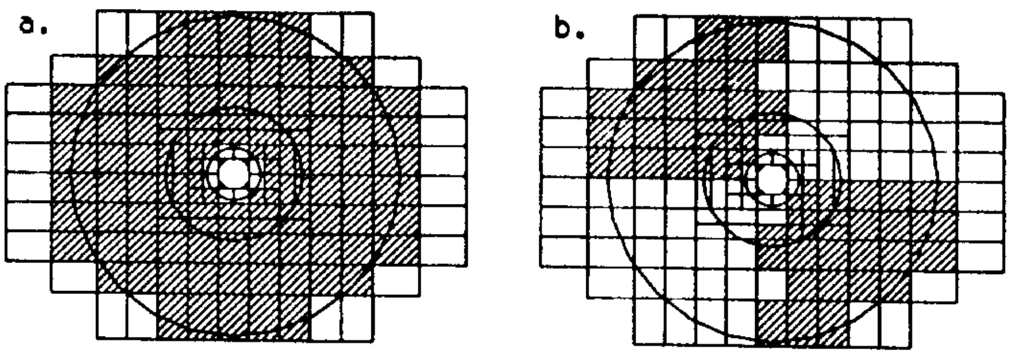


Figure 3

C. Stewart et al.

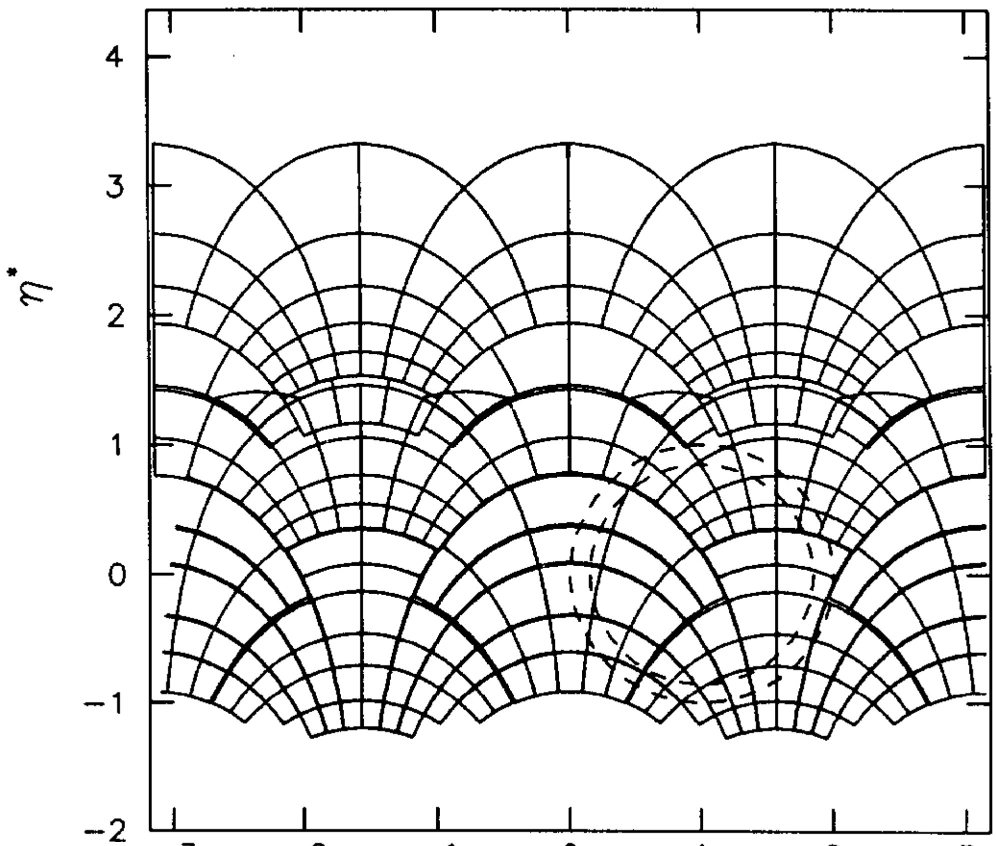


Figure 4a

C. Stewart et al

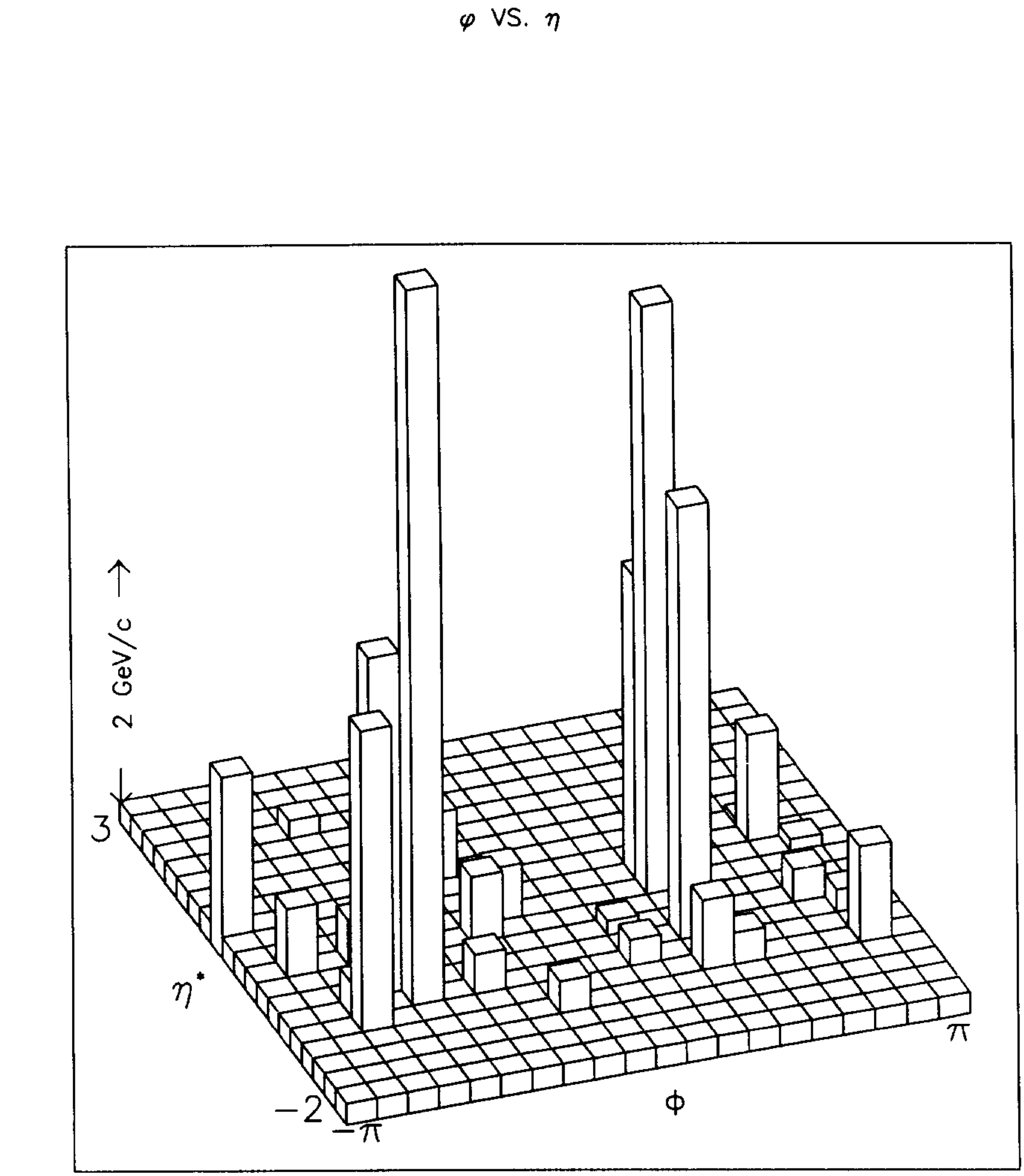
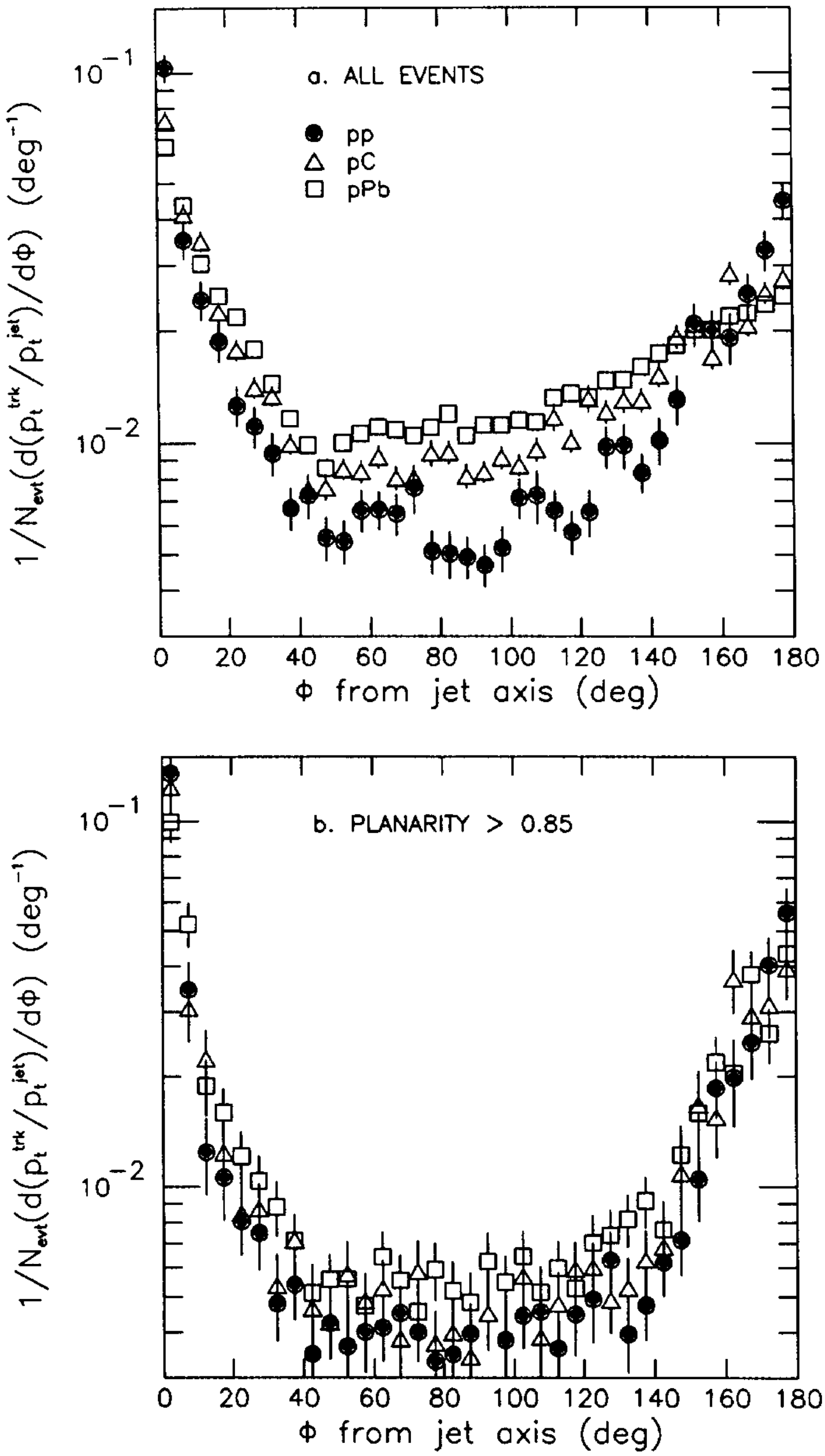


Figure 4b

C. Stewart et al.


a. ALL EVENTS
pp
pC
pPb
b. PLANARITY > 0.85
10^{-1}
10^{-2}
$1/N_{evt}(d(p_t^{trk}/p_t^{jet})/d\Phi)$ (deg^{-1})
0 20 40 60 80 100 120 140 160 180
Φ from jet axis (deg)

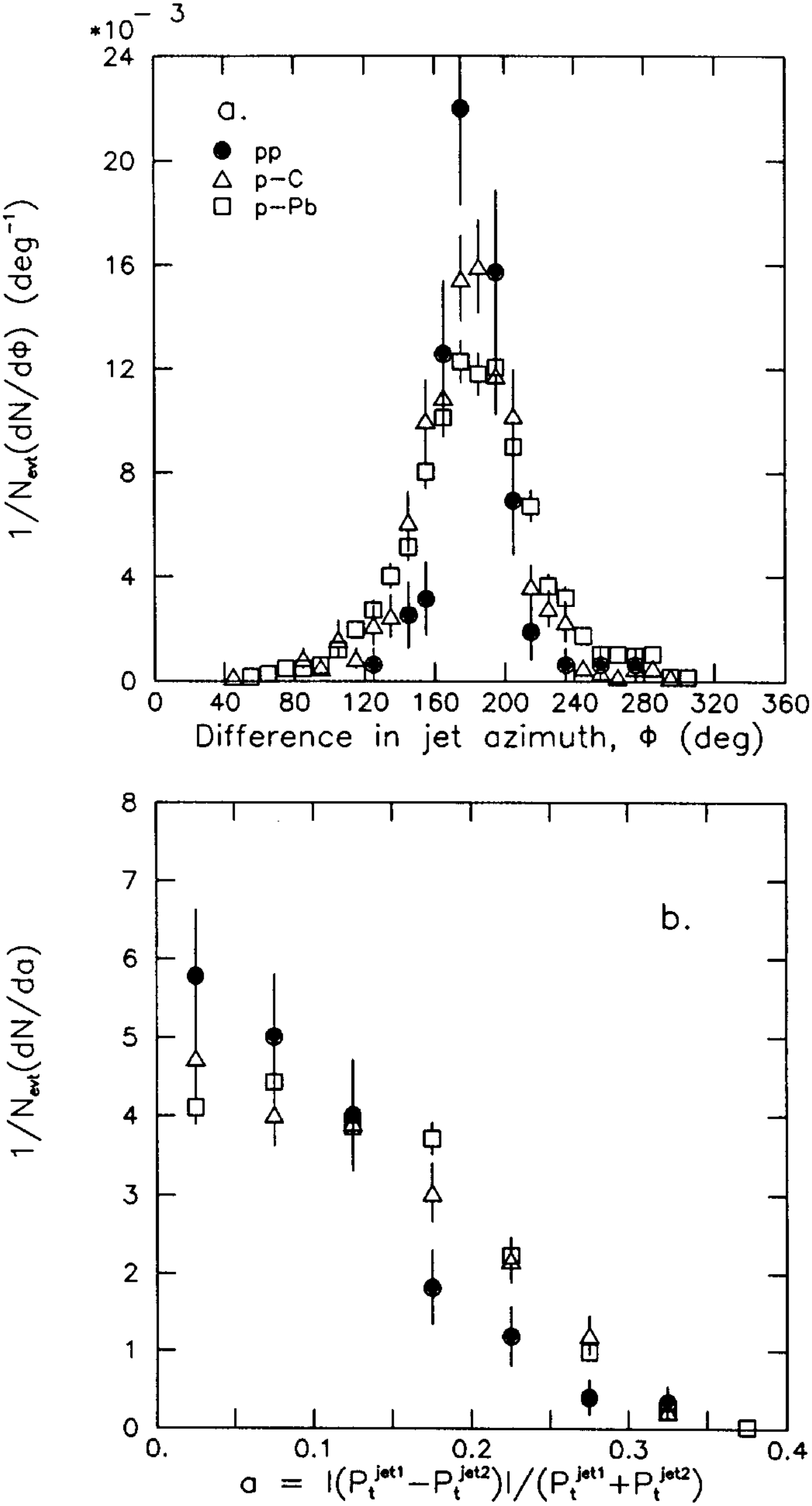
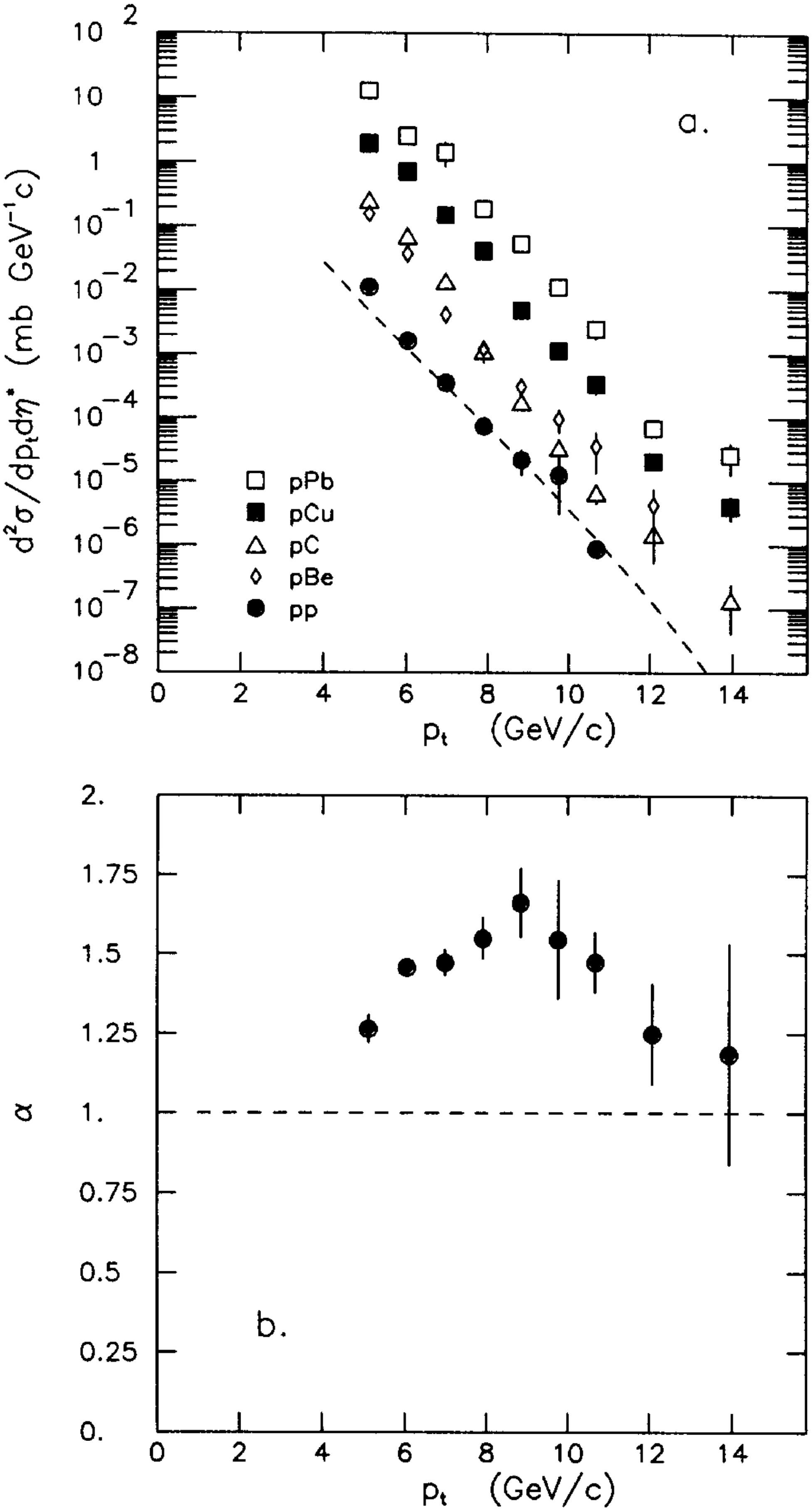

*10^-3
a.
pp
p-C
p-Pb
1/N_evt(dN/dΦ) (deg^-1)
Difference in jet azimuth, Φ (deg)
b.
1/N_evt(dN/da)
a = |(P_t^jet1 - P_t^jet2)|/(P_t^jet1 + P_t^jet2)

Figure 7



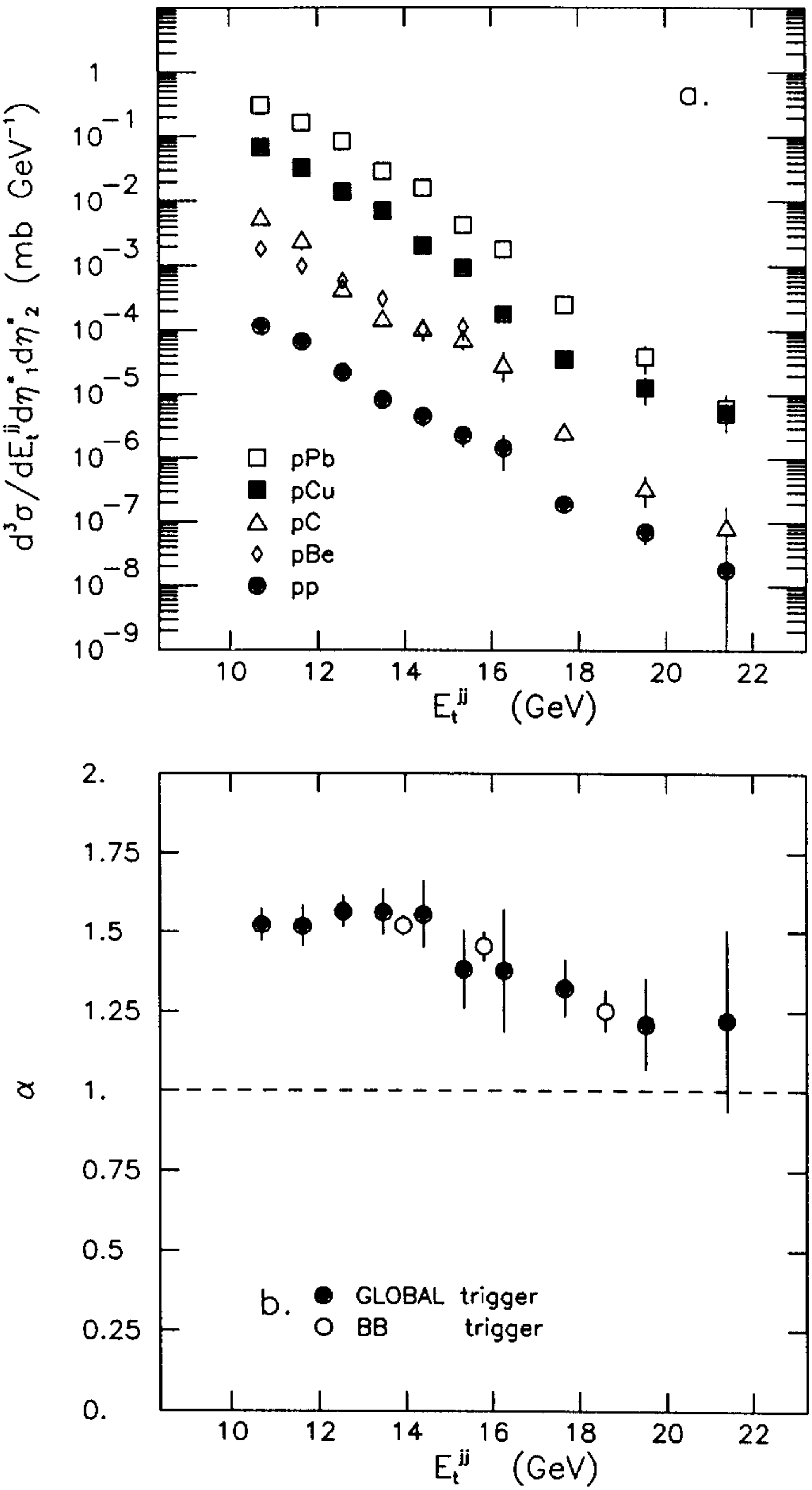
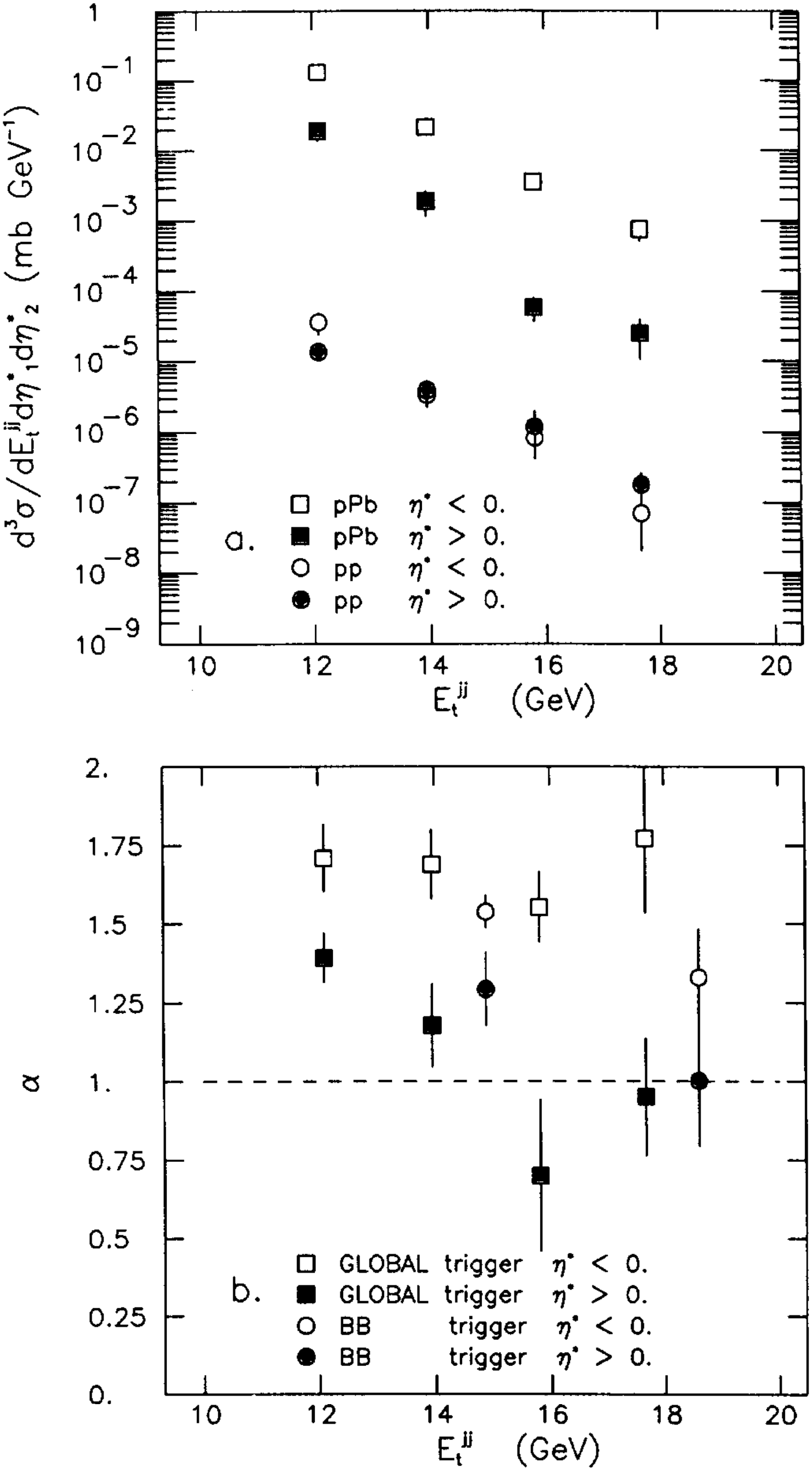

1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
$d^3\sigma/dE_t^{jj}d\eta^*_1 d\eta^*_2$ (mb GeV^{-1})
a.
pPb
pCu
pC
pBe
pp
10
12
14
16
18
20
22
E_t^{jj} (GeV)
2.
1.75
1.5
1.25
1.
0.75
0.5
0.25
0.
α
b.
GLOBAL trigger
BB trigger
10
12
14
16
18
20
22
E_t^{jj} (GeV)

Figure 9



a.
pPb η* < 0.
pPb η* > 0.
pp η* < 0.
pp η* > 0.
d³σ/dE_t^jj dη*_1 dη*_2 (mb GeV⁻¹)
E_t^jj (GeV)
b.
GLOBAL trigger η* < 0.
GLOBAL trigger η* > 0.
BB trigger η* < 0.
BB trigger η* > 0.
α
E_t^jj (GeV)

 Figure 10

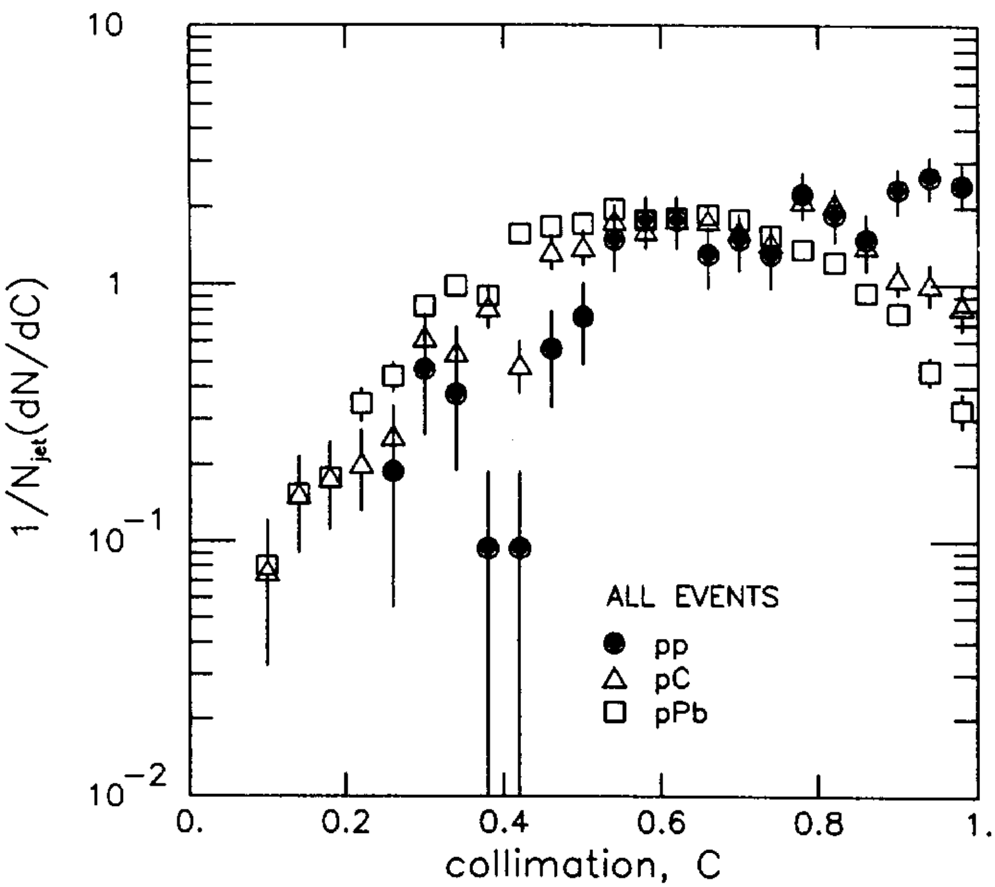
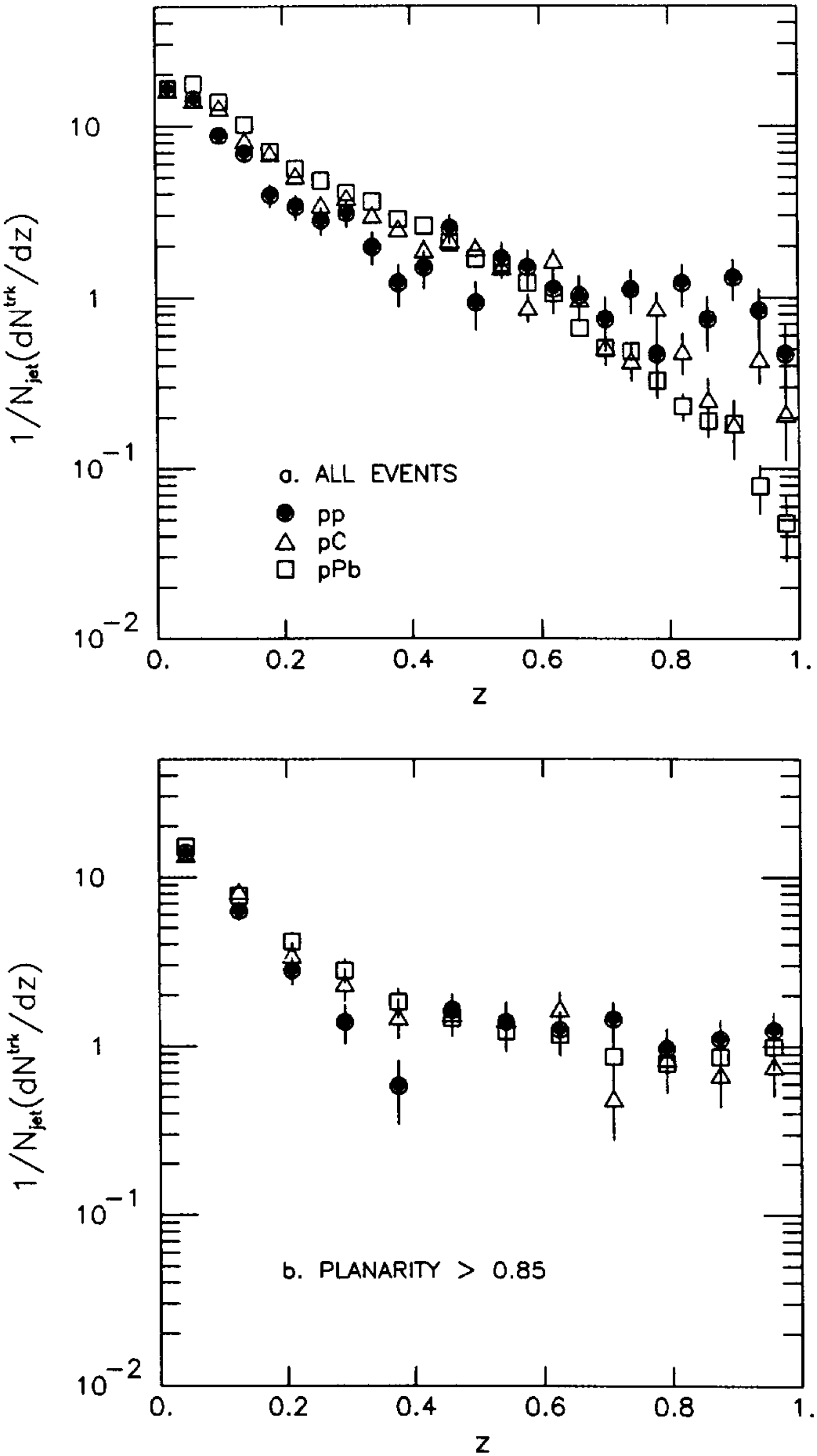
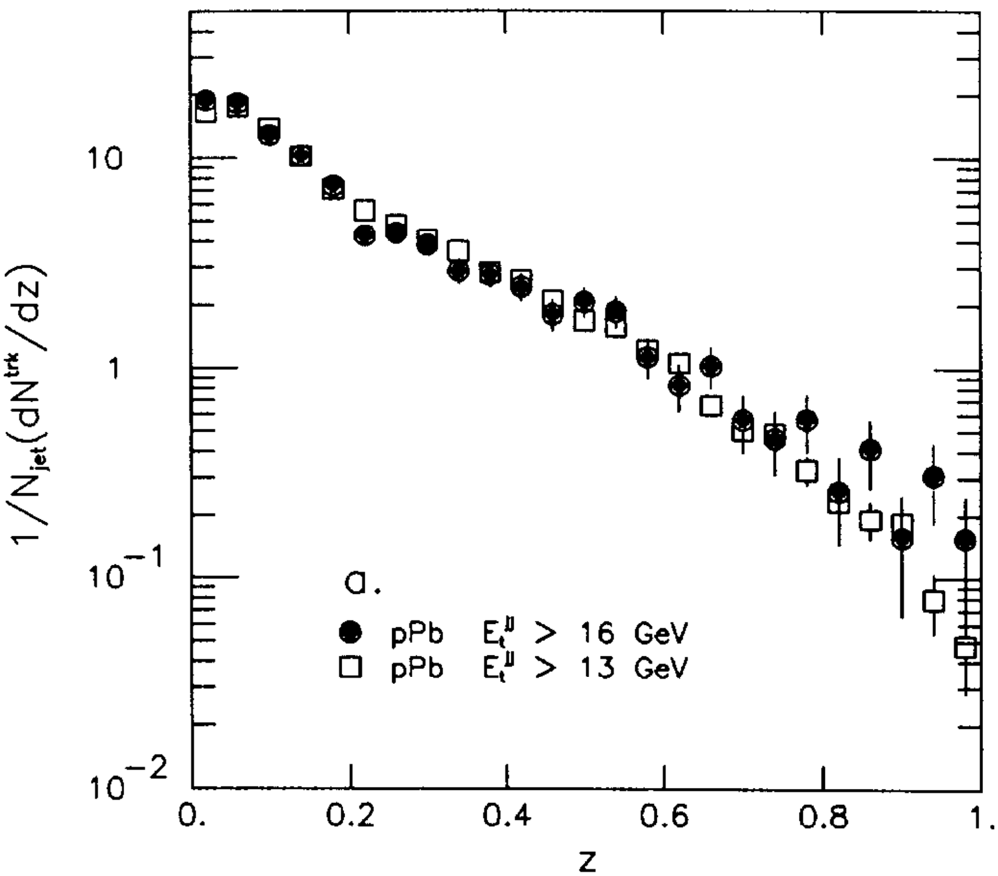
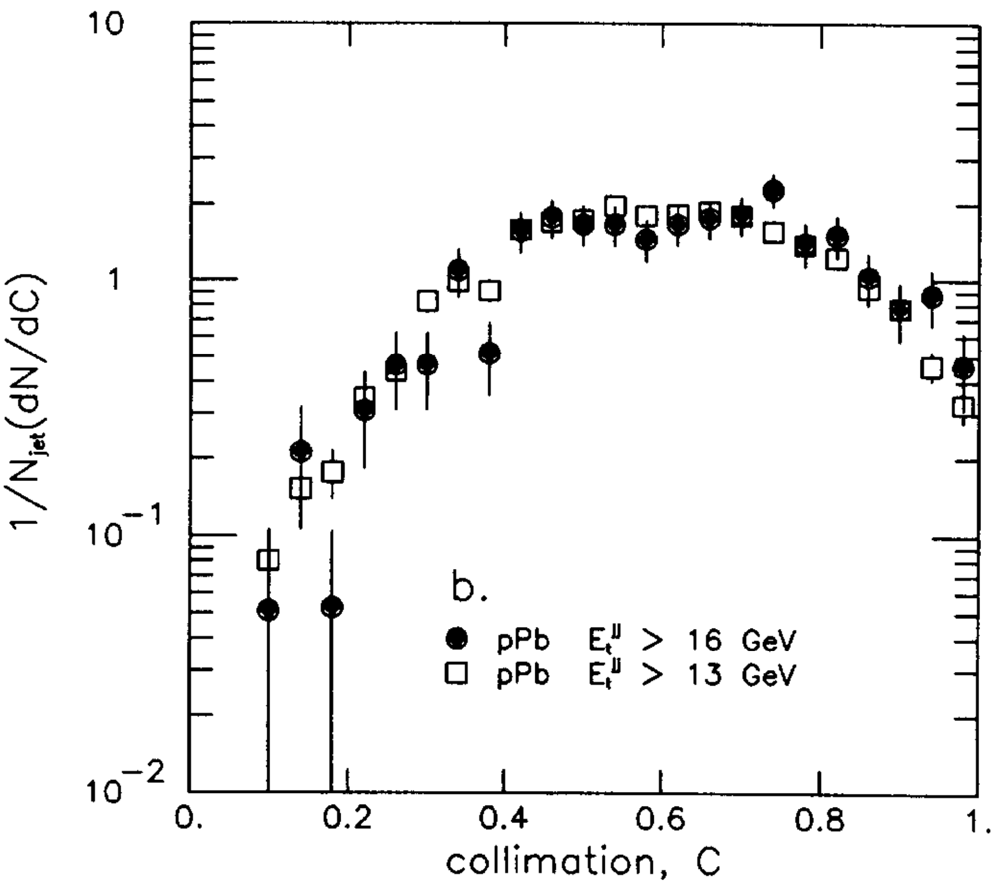

10
1
10^{-1}
10^{-2}
0.
0.2
0.4
0.6
0.8
1.
collimation, C
$1/N_{jet}(dN/dC)$
ALL EVENTS
pp
pC
pPb

 Figure 11



10
1
10^{-1}
10^{-2}
$1/N_{jet}(dN^{trk}/dz)$
0.
0.2
0.4
0.6
0.8
1.
z
a. ALL EVENTS
pp
pC
pPb
b. PLANARITY > 0.85


a.
pPb E_t^{jj} > 16 GeV
pPb E_t^{jj} > 13 GeV
$1/N_{jet}(dN^{trk}/dz)$
z
10
1
10^{-1}
10^{-2}
0.
0.2
0.4
0.6
0.8
1.


b.
pPb E_t^{jj} > 16 GeV
pPb E_t^{jj} > 13 GeV
$1/N_{jet}(dN/dC)$
collimation, C
10
1
10^{-1}
10^{-2}
0.
0.2
0.4
0.6
0.8
1.

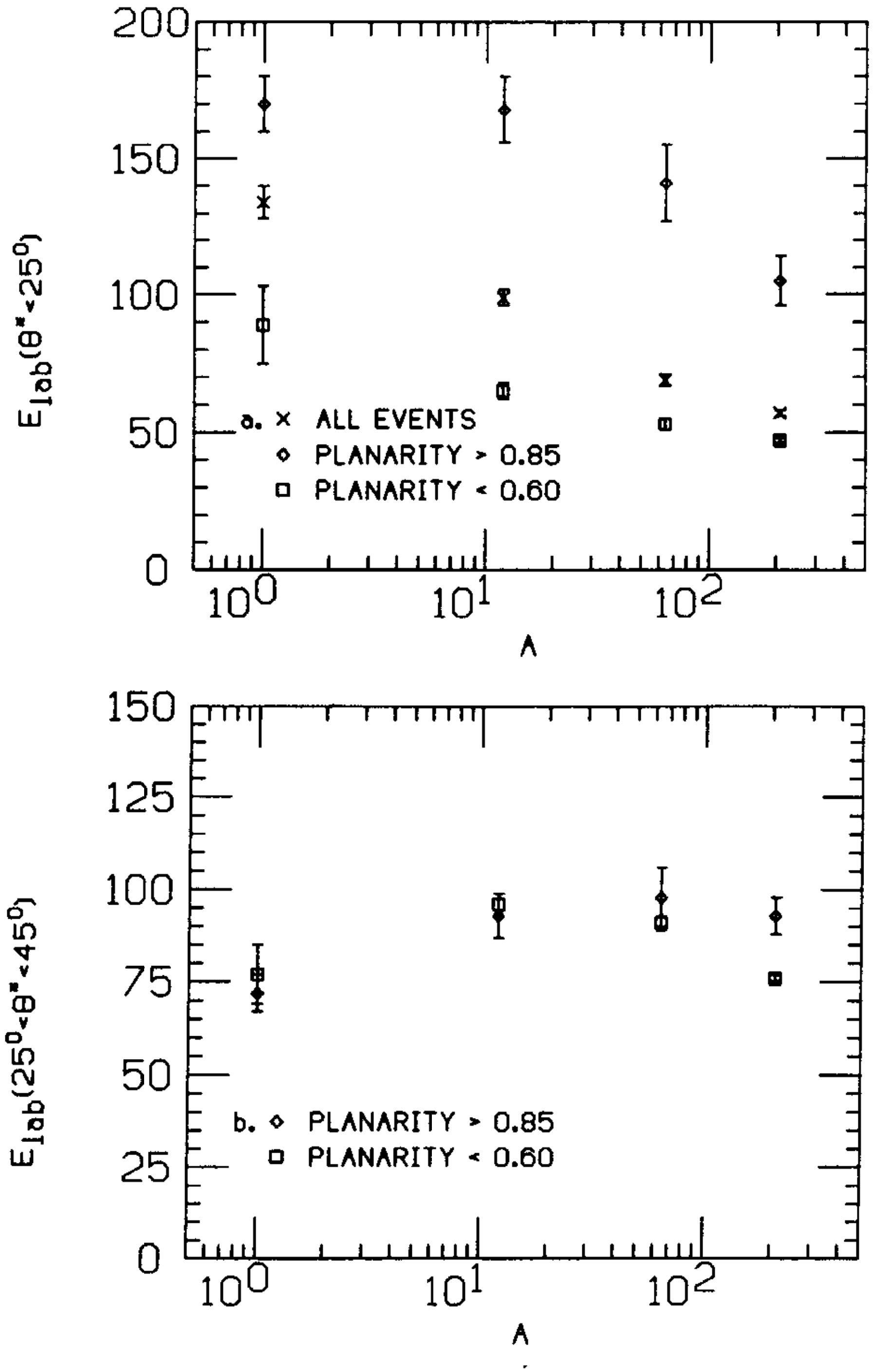

200
150
100
50
0
$E_{lab}(\theta^* < 25^0)$
a. × ALL EVENTS
◇ PLANARITY > 0.85
□ PLANARITY < 0.60
10^0
10^1
10^2
A
150
125
100
75
50
25
0
$E_{lab}(25^0 < \theta^* < 45^0)$
b. ◇ PLANARITY > 0.85
□ PLANARITY < 0.60
10^0
10^1
10^2
A

Figure 13