Fermi National Accelerator Laboratory

FERMILAB-Pub-94/028-E

E683

A-Dependence of Photoproduced Dijets

D. Naples et al
The E683 Collaboration

Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

January 1994

Submitted to *Physical Review Letters*

Operated by Universities Research Association Inc. under Contract No. DE-AC02-76CHO3000 with the United States Department of Energy

A-Dependence of Photoproduced Dijets

E683 COLLABORATION

D. Naples[4,a], N. Akchurin[3], P. Birmingham[7], H. Breuer[4], C. C. Chang[4], S. Cihangir[2], M. D. Corcoran[6], W. L. Davis[1], H. R. Gustafson[5], H. Holmgren[4], P. Kasper[2], D. Lincoln [6], M. J. Longo[5], J. Marraffino[2], J. McPherson[3], H. E. Miettinen[6], G. Morrow[6], G. S. Mutchler[6], Y. Onel[3], G. P. Thomas[1], M. M. Traynor[6], J. W. Waters[7], M. S. Webster[7], J. P. Xu[6], Q. Zhu[6,b]

[1] *Ball State University, Muncie, IN 47306*

[2] *Fermilab, Batavia, IL 60510*

[3] *University of Iowa, Iowa City, IA 52242*

[4] *University of Maryland, College Park, MD 20742*

[5] *University of Michigan, Ann Arbor, MI 48109*

[6] *Rice University, Houston, TX 77251*

[7] *Vanderbilt University, Nashville, TN 37235*

[a] *Present address, Fermilab, Batavia, IL 60510*

[b] *Present address, University of California, Riverside, CA 92521*

We present a measurement of the A-dependence of $k_{T\phi}$, the out-of-plane component of the dijet transverse momentum, in dijet events produced with a real photon beam. We also present the same measurement for dijets produced from pion-nucleus collisions in our detector. Both data sets are taken at a mean $\sqrt{s}$ of 21 GeV in the p_T range 3-7 GeV/c. A clear A-dependence of comparable magnitude is seen in both processes. The energy dependence of the nuclear behavior is also extracted.

It has been twenty years since the first observation of the "anomalous nuclear enhancment" effect in proton-nucleus collisions [1]. In these pioneering experiments, it was observed that, for collisions producing particles at large momentum transverse to the beam direction (high p_T), the cross section could be paramaterized as $\sigma(pA) = A^{\alpha}\sigma(pp)$, with α greater than one for p_T's above about 2 GeV/c. In this expression A is the atomic weight of the target nucleus. This behavior is in contrast to the situation for low p_T interactions, where α is generally 2/3.

The nuclear dependence for low p_T scattering is understood to be due to the interaction of the incident hadron at the nuclear surface, so that the cross section scales as the surface area of the nucleus. A high-p_T particle, on the other hand, arises from a "hard scattering", that is, a scattering at the parton level, followed by the fragmentation of the parton into a jet of high p_T hadrons. Since such processes are rare, it was expected that the cross section should scale as the nuclear volume, or linearly with A. A value of α greater than one is generally understood as due to soft multiple scattering of the hard-scattered partons as they exit the nucleus [2].

There has been a sustained interest in hard scattering that takes place in nuclear media [3]. Such studies can provide information about interactions and the behavior of quarks and gluons at very short times after the hard interaction (before hadronization) as well as about hadronization times themselves. Anomalous nuclear enhancement has been observed in the hadroproduction of single high p_T hadrons, high p_T dihadrons, and high p_T jet pairs (dijets) [4]. This letter reports the first observation of the atomic weight dependence of hard scattering in real photon-nucleus collisions. M. Luo, J. Qui, and G. Sterman [5] have shown that this measurement can be related to the color Lorentz force experienced by partons undergoing multiple scattering in nuclear matter. This relation is extracted from non-leading power perturbative QCD.

We present results from the first study of the nuclear dependence for hard scattering in photon-nucleus interactions. Final states from hard scattering are dominated by dijet pairs at high p_T [6]. We select dijet events and study the nuclear dependence of the variable $k_{T\phi}$ which is related to a single component of the vector p_T imbalance of the dijet system. We define $k_{T\phi}$ as

$$k_{T\phi} = P_T \sin(\Delta\phi)$$

where P_T is the average jet transverse momentum of the event and $\Delta\phi$ is the azimuthal opening angle between the two jets. All plots show the mean value of the $k_{T\phi}^2$ distribution which is denoted $\langle k_{T\phi}^2 \rangle$. Most previous observations of nuclear dependence report the behavior of the cross section at fixed high p_T which is parameterized as A^{α} [4]. The kinematic variable $k_{T\phi}$ is more directly sensitive to the effects of multiple scattering. The relation between $k_{T\phi}$ and α has been discussed in reference [7].

The experiment was performed in the Wide Band beamline at Fermilab during the 1991 fixed target run. A more complete description of the experiment and the first results are presented in reference [8]. The data presented here are from an analysis of the entire data sample which consists of roughly $3.6\text{x}10^6$ triggered events on hydrogen, $3\text{x}10^6$ on deuterium, and a total of $3.5\text{x}10^6$ events on the six nuclear targets.

The Wide Band tagged photon beam energies ranged from 50 to 400 GeV. About 10% of the data were taken with a broad band tagged pion beam which ranged in energy from 160 to 380 GeV. The pion-nucleus data will also be presented for comparison. The triggered mean energy for both beam types was about 260 GeV. The targets studied include hydrogen, deuterium, Be, C, Al, Cu, Sn, and Pb. The thickness of each target was about 0.06 nuclear interaction lengths except for deuterium which was about 0.15 nuclear interaction lengths.

The main component of the E683 detector used in this analysis was the highly segmented, wide angle calorimeter (MCAL). The MCAL has full azimuthal acceptance and a polar angle acceptance in the γp center of mass of $25^\circ < \theta^* < 100^\circ$ at $\sqrt{s} = 21$ GeV. The MCAL face is segmented into 132 towers each subtending $\Delta\eta \simeq 0.3$ and $\Delta\phi \simeq 0.25$ rads, where η is the pseudorapidity and ϕ is the azimuthal angle. The MCAL resolution is estimated to be on the order of $\frac{35\%}{\sqrt{E}}$ for electromagnetic energy and $\frac{85\%}{\sqrt{E}}$ for hadronic energy. The absolute energy scale of the MCAL is uncertain to about 7%.

The MCAL was the basis for the high transverse energy (E_T) discrimination trigger. We used two high E_T triggers concurrently. The "two-high" trigger required at least two MCAL towers to have E_T greater than 0.5 GeV each. The "global" trigger required a minimum total E_T in the MCAL of 5 GeV. In the analysis either a global trigger threshold $E_T > 8$ GeV or a two-high threshold $E_T > 0.75$ GeV for each of the two hottest towers was required to remove hardware inefficiencies near the thresholds for each trigger. Additional "fake" high E_T triggers in the detector came from δ-ray production or bremsstrahlung by beam halo muons at wide angles or phototube breakdown in the MCAL itself. These events had low total energy and multiplicity and could easily be cut out of the data sample. Events which have passed these criteria will be refered to as the high E_T data sample.

Jets in the p_T range 3 to 7 GeV/c were reconstructed by applying a standard (η, ϕ) cone jetfinding algorithm to the data sample. A cone size of radius $R = 1.0$ was used, where $R^2 = \Delta\eta^2 + \Delta\phi^2$. Dijet events were required to have a jet $p_T \geq 3$ GeV/c for each jet. Events with three high p_T jets are not included in this analysis (they accounted for less than 2% of the high E_T data sample). Dijets make up 43% of the high E_T data sample. Also, the polar angle of the jet axis in the lab frame was restricted between $2^\circ < \theta_{\mathrm{LAB}} < 6^\circ$ to ensure jet containment in the calorimeter. A target dependent correction of between 10% and 20% was applied to the $k_{T\phi}$ distribution to correct for non-target related events.

The dependence of $\langle k_{T\phi}^2 \rangle$ on atomic weight for photon-nucleus (γA) and pion-nucleus (πA) collisions is shown in Figure 1 and Table I. Errors shown are statistical only. Systematic errors are discussed below. There is a clear A-dependence in both γA and πA data, as well as a significant offset between the two data sets which persists throughout the p_T range of the dijet sample. We will assume three contributions to $k_{T\phi}$ in this analysis. Contributions are expected from: (*i*) gluon radiation and intrinsic parton Fermi motion within the nucleon, (*ii*) resolution effects in jetfinding and calorimetry, (*iii*) nuclear effects (for A>1).

We first discuss the contribution to $\langle k_{T\phi}^2 \rangle$ that is due to the jetfinding and calorimetry. We determine the size of this contribution from a Monte Carlo study. The effects of energy resolution, spatial shower spreading, and position measurement granularity smear the found $k_{T\phi}$ distribution. These effects were taken into account in the simulation of the MCAL detector. Particle inclusion errors in jetfinding will also smear the $k_{T\phi}$ distribution by smearing the found jet p_T's and angles. To model the photon-proton data we used a mixture [1] of the LUND Monte Carlo event generators, LUCIFER and TWISTER[9] (with JETSET 6.3) with the Field-Feynman independent fragmentation option. This has been shown to be a good representation of the γp data [8]. The size of the jetfinding and calorimetry contribution to the measurement were determined as follows. The jetfinding algorithm was applied to the simulated calorimeter towers to reconstruct jets. The vector sum of the momenta of the particles originating from each hard-scattered parton defines the "true" jet. The difference between the $\langle k_{T\phi}^2\rangle$ of the found jets and that of the "true" jet is due to the calorimetry and jetfinding. In the γp case this contribution to $\langle k_{T\phi}^2\rangle$ is determined to be 0.6 ± 0.2 GeV^2/c^2. In the pion-proton case these contributions were found to be considerably larger, 2.6 ± 1.0 GeV^2/c^2. The jetfinding contribution and the difference in its value for γp and πp data are discussed further below. The error quoted on the value of the jetfinding contribution is an estimate of the systematic uncertainty in the measurement of $\langle k_{T\phi}^2\rangle$. Jetfinding introduces the dominant systematic error in $\langle k_{T\phi}^2\rangle$. However, we emphasize that this systematic uncertainty is not A-dependent (as will be shown below) and does not affect the A-dependence measurement. The remaining $\langle k_{T\phi}^2\rangle$ of 1.3 ± 0.2 GeV^2/c^2 in the γp case and 0.9 ± 0.5 GeV^2/c^2 in the πp case is interpreted as being due to the gluon radiation and intrinsic Fermi motion contributions.

Jetfinding is sensitive to the non-jet E_T from the underlying event, particularly at these low jet p_T's. The "underlying event" results from the interaction and fragmentation of the beam and target remnants which typically produce a spray of low E_T particles in the forward (beam jet) and backward (target jet) directions in the center of mass frame. In the pion-nucleus case there are more spectator quarks and gluons, so one would expect more underlying event, and the data are consistent with that expectation.

The additional E_T from the underlying event influences the jet reconstruction and the size of the jetfinding correction. If we use the same jetfinding parameters (in particular the cone size) for πp as for γp, we find the large jetfinding correction mentioned above. If instead we adjust the parameters of the jetfinder to compensate for the increased underlying event by reducing the cone size, both the raw $\langle k_{T\phi}^2\rangle$ and the jetfinding correction for πp are reduced. The corrected value of $\langle k_{T\phi}^2\rangle$ is unchanged. For example, for a jet cone of 0.7 rather than 1.0, we find for πp a jetfinding correction for p_T of 1.5 GeV^2/c^2 which give a value for the remaining contribution to $\langle k_{T\phi}^2\rangle$ which is the same as for the larger jet cone.

Evidence for a larger contribution from the underlying event in pion-nucleus collisions can be clearly seen in the data. Shown in Figure 2a is the average non-jet E_T fraction, which is the total E_T outside of the jet cone divided by the total E_T measured in the MCAL, for each target. The fraction of E_T outside of the jet cone is

---

[1] LUCIFER generates only direct coupling processes, and we expect to have contributions from the hadronic structure of the photon which TWISTER models.

about 20% higher in the pion-produced events than for photoproduced events. Note that the non-jet E_T fraction for both γA and πA interactions does not vary with A. Both the mean total E_T in the MCAL and the mean non-jet E_T are independent of A. This is justification that the jetfinding contributions to $\langle k_{T\phi}^2 \rangle$ are not A-dependent and thus that the dominant systematic uncertainty is independent of A. It also implies that the A-dependent $\langle k_{T\phi}^2 \rangle$ we see is coming from the hard scattering system itself and is not an artifact of the spectator system. The relative level of the hard scatter to the underlying event can be seen from the E_T flow plot for both data samples in Figure 2b. The E_T per 6° bin in azimuthal angle from the higher p_T jet's axis per event is plotted. These plots show that the underlying event in πp contains a somewhat larger fraction of the total event E_T.

To accurately determine the size of the jetfinding contribution in the pion-proton case it is crucial to have an adequate model of the underlying event. We found the Monte Carlo event generator HERWIG [10] to be a better model of the event structure in the πp data than TWISTER due to the inclusion of an enhanced underlying event [11]. HERWIG parameterizes this contribution using minimum bias data [12] and scales the underlying event to the appropriate energy. In the πp case the enhanced underlying event was modeled (using the HERWIG parameterization) and included in the Monte Carlo by hand in order to determine the jetfinding contribution. The modeling of the πp event E_T flow is shown in Figure 2b (dotted curve). The non-jet E_T and total E_T distributions are also well reproduced by the Monte Carlo for both γp and πp interactions.

We now discuss the nuclear contributions to $\langle k_{T\phi}^2 \rangle$. To obtain the A-dependence in $\langle k_{T\phi}^2 \rangle$ we fit the data in Figure 1 with the power law of the form $\langle k_{T\phi}^2 \rangle = C_\circ + C_1(A-1)^\alpha$. The three parameters, $C_\circ$, C_1, and α are determined from the minimum χ^2 fit to the data points. The resulting best fit curves are shown in figure 1. The value of α was found to be 0.32±0.08 for γA data and 0.39±0.15 for πA data. The values of the χ^2 per degree of freedom for the fits are 0.7 and 0.9 respectively. If the A=2 point is left out of the fit [2] the values of α found are not affected within the errors of the determination. (the values of α excluding the A=2 data points are .26±.09 and .34±.17 for γA and πA data respectively). The fits to both data sets indicate rough agreement with an $A^{\frac{1}{3}}$ behavior. Such a dependence would be expected for a phenomenon that depends on the length of nuclear matter traversed; such as independent multiple rescattering of the partons as they pass through the nucleus.

Because we had a broad band beam we were able to extract the behavior of the A-dependence with photon beam energy. This is shown in Figure 3 where the mean value of $k_{T\phi}^2$ for each target is plotted as a function of mean center of mass energy, $\sqrt{s}$. The data were grouped into three energy bins for this study and the mean $\sqrt{s}$ for each is shown in the plot. Some of the targets with similar atomic weights were grouped together to improve statistics (Be+C, Al+Cu, and Sn+Pb). The value of

---

[2] We do not expect the very low A nuclei to have a behavior related to that of many nucleon systems.

$\langle k_{T\phi}^2 \rangle$ for each target increases with center of mass energy. This is, at least in part, a consequence of the increase in underlying event with $\sqrt{s}$. The increase may also be due to an increase in gluon radiation contributions with energy. The mean value of $k_{T\phi}^2$ for the lead target is increasing faster with energy than that for hydrogen. Thus the nuclear contribution of $k_{T\phi}$ appears to increase with center of mass energy.

In conclusion, we have measured for the first time the A-dependence of $k_{T\phi}$ from photoproduced jets. We also observed that the A-dependent contribution appears to increase with center of mass energy. We compared our A-dependence measurements from photoproduction with our pion-nucleus data taken with the same detector and at the same mean $\sqrt{s}$ and found a comparable A-dependence in the two cases. For both data sets the A-dependence of $\langle k_{T\phi}^2 \rangle$ is found to be consistent with an $A^{\frac{1}{3}}$ power law behavior. The comparison of A-dependence in photoproduction with that seen in pA is more difficult since relevant pA measurements [13] were taken at higher center of mass energy and with different data cuts. Comparison of the A-dependence of $k_{T\phi}$ in pA with our results has been made in [11] where it is found that γA shows a somewhat weaker A-dependence than pA. It is particularly interesting to note that the nuclear dependence in γA is considerably stronger than that observed in Drell-Yan hadroproduction [14].

We wish to thank all those personnel, both at Fermilab and at the participating institutions, who have contributed to this experiment. The authors would like to thank Tom Fields, George Sterman, and John Ralston for useful discussions. This work was supported in part by the Particle Physics and Nuclear Physics divisions of the National Science Foundation, and the Nuclear Physics and High Energy Physics Divisions of the U. S. Department of Energy.

REFERENCES

[1] J. Cronin et al., Phys. Rev. Lett. **31** 1426 (1973).

[2] M. Lev and B. Petersson, Z. Phys **C21** 155 (1983); P. Chiappetta and H. Pirner, Nucl. Phys. **B291** 765 (1987); K. Kastella et al., Phys. Rev. **D39** 2586 (1989).

[3] S. Fredriksson, G. Eilam, G. Berlad, and L. Bergstrom, Physics Reports **144** 187 (1987); L. Frankfurt and M. Strikman, Physics Reports **160** 235 (1988).

[4] C. Bromberg et al., Phys. Rev. Lett. **42** 1202 (1979); Brown et al., Phys. Rev. Lett. **50** 11 (1983); M. Corcoran et al., Phys. Lett. **B259** 209 (1991).

[5] M. Luo, J. Qui, and G. Sterman, submitted to Phys. Rev. D; M. Luo, J. Qui, and G. Sterman, Phys. Lett. **B279** 377 (1992).

[6] J. F. Owens, Phys. Rev. **D21** 54 (1980).

[7] T. Fields, Nucl. Phys **A544** 565 (1992); T. Fields and M. Corcoran, Phys. Rev. Lett. **70** 143 (1993).

[8] D. Adams et al., Fermilab PUB-94/025-E, submitted to PRL.

[9] G. Ingelman and A. Weigand, Comp. Phys. Comm. **46** 241 (1987); G. Ingelman and A. Weigand, Comp. Phys. Comm. **46** 217 (1987); T. Sjostrand, Comp. Phys. Comm. **43** 367 (1987).

[10] G. Marchesini and B. Webber, Phys. Rev. **D38** 3419 (1988); G. Marchesini and B. Webber, Comp. Phys. Comm. **67** 465 (1992).

[11] D. Naples et al., *Proceedings of the 1992 Meeting of the Division of Particles and Fields of the American Physical Society*, Fermilab, November 1992, p 948.

[12] G. Alner et al., Nucl. Phys. **B291** 45 (1987).

[13] M. Corcoran et al., Phys. Lett. **B259** 209 (1991).

[14] D. Kaplan et al., Phys. Rev. Lett. **40** 435 (1978); P. Boraldo et al., Phys. Lett. **B193** 373 (1987); D. Alde et al., Phys. Rev. Lett. **64** 2479 (1990).

FIGURES

FIG. 1. $\langle k_{T\phi}^2 \rangle$ as a function of atomic weight for photon-nucleus (γA) and pion-nucleus (πA) data. The curves shown are the best power law fits to the form $\langle k_{T\phi}^2 \rangle = C_o + C_1(A-1)^{\alpha}$. For the photon data (lower curve) the minimum χ^2 fit yields $C_o = 1.85 \pm 0.10$, $C_1 = 0.24 \pm 0.10$, $\alpha = 0.32 \pm 0.08$ and for pion data (upper curve) the fit yields $C_o = 3.54 \pm 0.22$, $C_1 = 0.27 \pm 0.21$, $\alpha = 0.39 \pm 0.15$. The offset of the two data sets is explained in the text.

FIG. 2. (a.) Non-jet E_T fraction (ratio of E_T outside of the jet cone to total E_T in the MCAL) for each target. (b.) E_T flow per event.

FIG. 3. Dependence of $\langle k_{T\phi}^2 \rangle$ on the γ-proton center of mass energy for each target.

TABLES

TABLE I. Shown are the values of $\langle k_{T\phi}^2 \rangle$ for each target for photon-nucleus (γA) and pion-nucleus (πA) data (statistical errors shown in parentheses). The values are not corrected for jetfinding uncertainties.

Target	$\langle k_{T\phi}^2 \rangle$(Gev/c)^2	
A	γA	πA
1.0	1.90 (0.11)	3.57 (0.23)
2.0	1.99 (0.11)	3.46 (0.38)
9.0	2.25 (0.18)	4.37 (0.40)
12.0	2.50 (0.19)	4.41 (0.40)
27.0	2.72 (0.20)	4.88 (0.44)
63.6	2.76 (0.20)	4.45 (0.40)
118.7	3.03 (0.21)	5.20 (0.45)
207.2	2.99 (0.21)	5.95 (0.49)

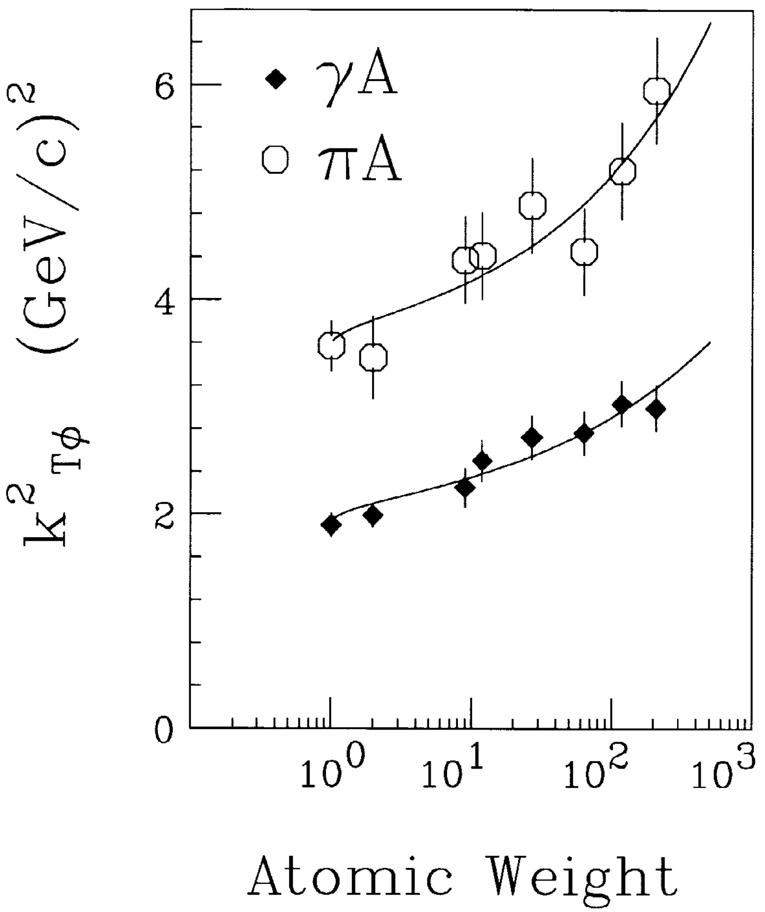
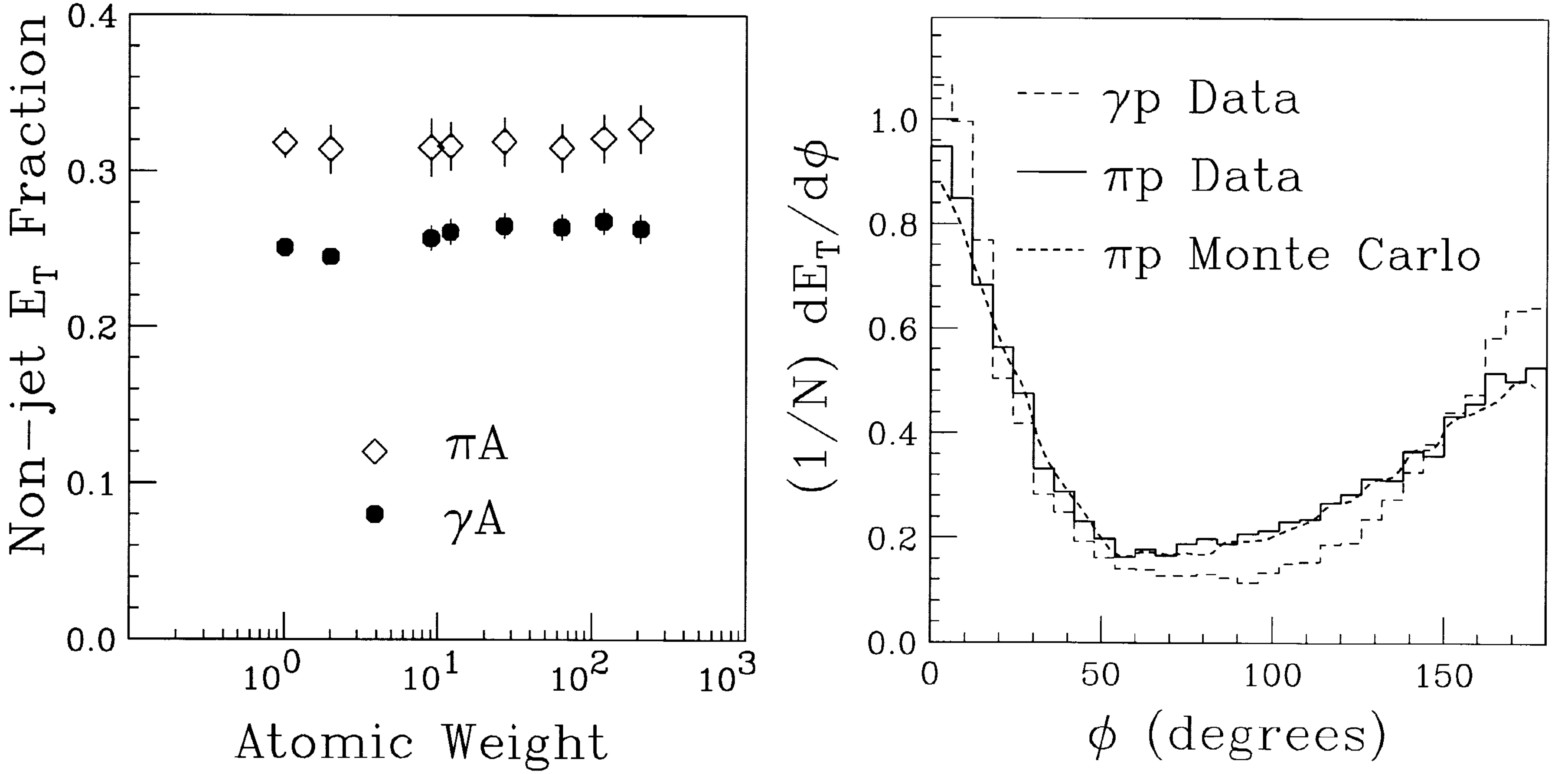

$k^2_{T\phi}$ $(\mathrm{GeV}/c)^2$
0
2
4
6
10^0
10^1
10^2
10^3
Atomic Weight
γA
πA

Figure 1

figure 2


Non-jet E_T Fraction
0.0
0.1
0.2
0.3
0.4
10^0
10^1
10^2
10^3
Atomic Weight
πA
γA
$(1/N)\ dE_T/d\phi$
0.0
0.2
0.4
0.6
0.8
1.0
0
50
100
150
ϕ (degrees)
γp Data
πp Data
πp Monte Carlo

(a) (b)

figure 3