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RESULTS FROM A HADRON JET EXPERIMENT AT $\sqrt{s}$ = 19.4 and 27.4 GeV

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In Fermilab experiment E609 we have studied the production of high p_t hadron jets by beams of protons at 200 and 400 GeV/c and pions at ± 200 GeV/c. Results for the single-jet and di-jet cross sections are given and are compared to QCD predictions. Leading-particle charge ratios from di-jet events are given and compared to QCD-motivated predictions. Evidence is presented concerning a higher twist effect in πp interactions as predicted by Berger and Brodsky. Preliminary results on high transverse energy events from nuclear targets are given. Finally, we present comparisons of our pp high E_t data with predictions from two Monte Carlo models.

I. INTRODUCTION

The existence of high p_t jets was predicted some years ago by Bjorken and others.[1] It was foreseen that these jets would give new insights into the fundamental constituent interactions and into the structure of hadrons. Early experiments at Fermilab and to the CERN SPS gave some interesting first indications of jet production.[2-4] Spectacular evidence of jet production became available when clear dijet events were observed at the SPS collider.[5-6] In order to test the QCD predictions for jet production, it is important to make measurements over a wide range of p_t and center-of-mass energy.

Our experiment was performed in the M6 beamline at Fermilab. The apparatus consisted of a large segmented calorimeter array and a magnetic spectrometer, as shown in Fig. 1 (a) (details of the apparatus have been described previously[7,8]). The calorimeter consisted of 528 modules segmented four times in depth and arranged in 132 towers as shown in Fig. 1(b). Its energy scale is uncertain to about 5-7%. The magnet was operated at low current providing a "p_t-kick" of about 100 MeV/c. Three crossed proportional wire chamber planes and 10 drift chambers were used to track the charged particles. In some phases of the experiment, a beam calorimeter placed downstream of the main calorimeter was used to measure beam jet energy.

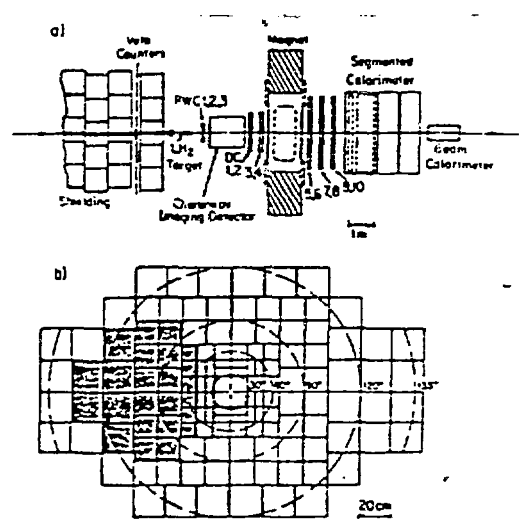

Fig. 1 (a) Plan view of the E609 apparatus, (b) Front face of the calorimeter array showing the cm angular coverage at $\sqrt{s}$ = 27.4 GeV.

II. MEASUREMENT OF THE SINGLE-JET INVARIANT CROSS SECTION AT FERMILAB

L.R. Cormell, University of Arizona

In this section we present results for the single-jet cross section from 400 GeV/c pp interactions. We compare this result to QCD-motivated predictions and to results obtained from the ISR and the SPS Collider. A trigger occurred when ΣE_t in the trigger towers (shaded region of Fig. 1b)

Several methods, involving the data itself and Monte Carlo models, were used to estimate background to the jet signal. All methods agree that there is little background above jet-p_t's of about 6 GeV/c, with background rising at lower p_t's to about 50% at 3 to 4 GeV/c. The trigger efficiency was calculated from Monte Carlo simulations and monotonically increases from 10% to 90% as jet-p_t goes from 3 to 9 GeV/c.

The results for the invariant cross section at 80 degrees c.m. are shown in Fig. 5. The data points have roughly an exponential p_t dependence, with slope parameter 1.75 +- 0.06. In a new run we obtained about 10 times greater integrated luminosity than shown here. Preliminary analysis of the new data shows reasonable agreement with these results, with the new data allowing measurement of the cross section out to 10 GeV/c.

The lines shown in Fig. 5 are the results of simple first-order QCD calculations, the various lines corresponding to different choices of the proton structure functions. Agreement is quite good, especially in the slope.

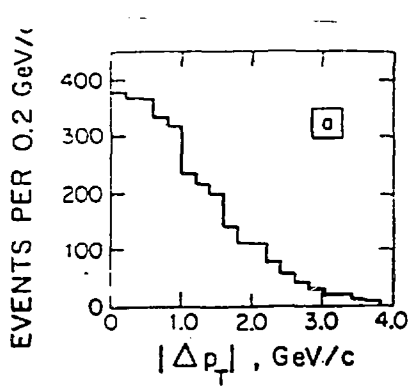

Fig. 4a. Distribution of dijet events in Δp_t.

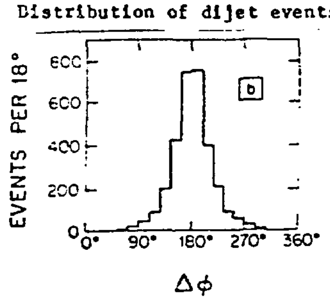

Fig. 4b. Distribution of dijet events in relative azimuth.

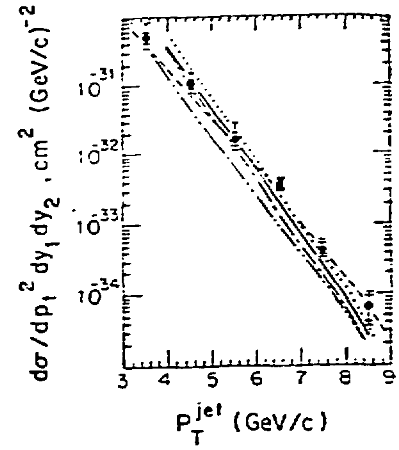

Fig. 5. Invariant cross section for dijet events at 80° cm.

IV. LEADING CHARGED PARTICLE CHARGE RATIOS
C. E. Kuehn, University of Wisconsin

The triggers used here are symmetric double-arm coplanar travsverse energy triggers centered on a c.m. angle of 60±5° (200 GeV/c π^- beam) or 80±3° (400 GeV/c p beam). Each arm of the trigger subtended 1.5 sr (π-p) or 2.5 sr (p-p).

All events in the two data samples (5319 πp, 5476 pp) were treated as dijet events. The transverse momentum of each jet, p_T^{jet}, was defined as the average p_T in the two trigger arms. The "leading charged particle (LCP) in a jet was defined as the charged particle track (pointing at a trigger arm) which had the largest p_T. The fragmentation parameter, z, for the LCP was defined:

$$z = \frac{p_T^{LCP}}{p_T^{jet}} \tag{1}$$

A cut eliminated LCP's with momentum below 10 GeV/c. Another cut eliminated LCP's with momentum above 40 GeV/c (π-p) and 35 GeV (p-p).

A plot of the LCP z distribution for pp data in two p_T^{jet} ranges is shown in Fig. 6. The histograms are Monte Carlo calculations assuming the FF model of parton fragmentation. Tracking errors and momentum cuts applied to the data are included in the calculation. The z distribution of LCP's in the data agrees with the Monte Carlo calculation in the high p_T^{jet} range. The same high p_T^{jet} agreement between data and Monte Carlo is observed for π^-p.

The average charge ratio, R_{avg}, is defined as the ratio of the number of + to - LCPs with $0.1 < z < z_{max}$ (z_{max} is at the endpoint of the z distribution for the data). R_{avg} is plotted for the p-p and π-p data sample in Figs. 7 and 8.

The three curves in Figs. 7 and 8 are predictions for R_{avg} using

$$R_{avg} = F_u R^d_{avg} + F_d R^d_{avg} + F_g R^g_{avg} + \ldots, \qquad (2)$$

where F_i is the fraction of flavor i partons in the jet sample, and R^i_{avg} is the average LCP charge ratio for jets from partons of flavor i. R^i_{avg} is calculated with the FF model of fragmentation for parton i. The calculation of parton fractions, F_i, assumes lowest order parton-parton QCD interactions. For example, for the p-p case

$$F_u = \frac{2\sigma_{uu} + \sigma_{ug} + \sigma_{ud}}{2\ (\sigma_{uu} + \sigma_{dd}\ \sigma_{gg} + \sigma_{gu} + \sigma_{dg}\ \sigma_{ud})}\ , \qquad (3)$$

$$\text{where}\quad \sigma_{ij} \sim (f^p_i(x_1) f^p_j(x_2) + f^p_j(x_1) f^p_i(x_2)) \frac{d\sigma}{dt}(q_i q_j + q_i q_j)\ . \qquad (4)$$

The π and p structure functions, f^p_i and f^π_i, used in the three calculations of R_{avg}, are identified in the figure captions. We conclude that the ratio (+/-) of the leading charged particles is consistent with soft gluon structure functions for both the proton and the pion.

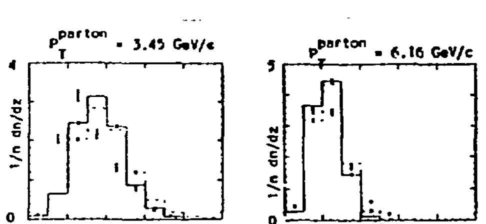

Fig. 6 Z distribution for LCP in p-p data for p_T^{jet} ~ 3.5,6 GeV/c. Dash histogram is Monte Carlo calculation for gluon jets; solid, for u quark jets.

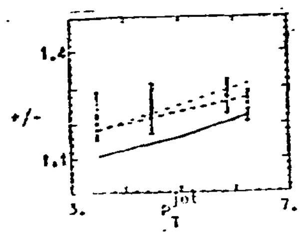

Fig. 7. Average LCP charge ratio vs. p_T^{jet} for p-p data (points). Curves are calculations for different 0 structure functions. Solid: Duke & Owens. Dash: quark, Feynman & Field; gluon, Cutler & Sivers (bag). Dotdash: q, Buras & Goemers; g, Owens & Reya (BG/OR).

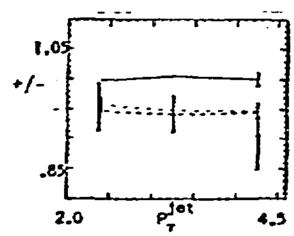

Fig. 8 Average LCP charge ratio vs. p_T^{jet} for π-p data (points). Curves are calculations for different π structure functions, p structure functions are BG/OR. Solid: q, Badier; g, McEwen. Dotdash: Owens & Reya. Dash: q, Badier; g, Owens & Reya.

V. πp → DIJETS AT 200 GeV

C. Naudet, Rice University

Using the 2-hi triggered events produced in pion-proton and proton-proton interactions at 200 GeV, we have made a detailed search for the higher-twist process proposed by Berger and Brodsky.[10] In this process, both pion quarks would participate in the hard scattering, resulting in two high-p_T jets plus a target jet but no beam jet. Hence, these dijet events would be characterized by little or no energy along the beam axis.

Two dijet requirements were initially imposed: that the center-of-mass polar angle of both jets be greater than 40 degrees and that the average jet p_T be greater than 3 GeV/c. Higher-twist dijet events candidates should have little or no forward energy and should be seen in only the pion induced events, allowing the proton induced events to be used as a control. A variable X_b was defined as the ratio of the forward energy flow (the beam calorimeter energy, corresponding to energy <25 degrees) to the total energy. The distribution of this variable was studied as a function of the planarity. For events with planarity less than .5 there was no observable difference between the pion-proton and the proton-proton X_b distributions.

For larger planarity, the X_b distributions were found to differ. Considering all events with planarity >.85 (Fig.9) the pion-proton energy distribution is found to be more forward; presumably this is due to the difference in the structure functions. Finally, when selecting extremely high planarities (Pl > .95) one finds a possible bump or knee in the pion-proton X_b distribution (Fig. 10). This corresponds to 75 πp events and only 3 pp events in that region. When these 75 events at X_b < .1 are examined, it is found that they are very well balanced in p_T (σ < .7 GeV) and typically have nearly all the beam energy in the dijets, as would be expected of higher-twist events.

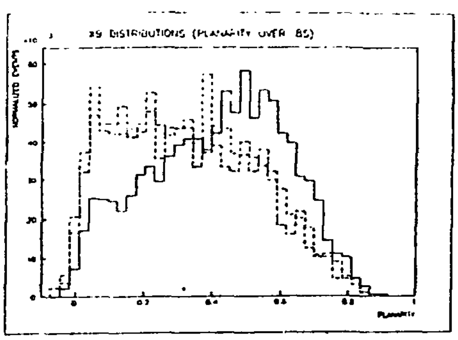

Fig. 9. X_b distribution of $\pi^{\pm}p$ events (dash = π^- and dot-dash = π^+) and pp events (solid), for planarity > 0.85

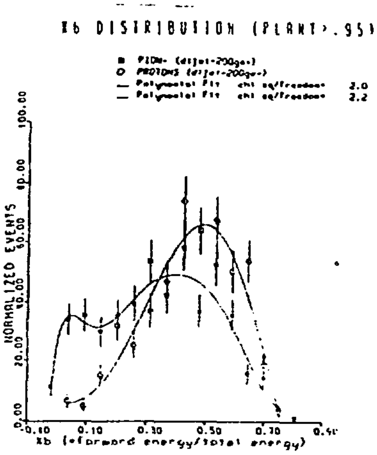

Fig. 10. X_b distribution of πp and pp high planarity events.

VI. LARGE E_T PROTON-NUCLEUS INTERACTIONS
H. Miettinen, Rice University

One of the goals of E-609 is to study the atomic number dependence of large E_T pA collisions at 400 GeV. This study may yield information about the space-time development of hadronization and the interactions of quasi-free partons in nuclear matter.

We used the global and the two-high triggers with seven nuclear targets (He, Be, C, Al, Cu, Sn, Pb). The solid targets were mounted on a target wheel which was rotated after each accelerator pulse, thus minimizing systematic errors. Results presented here are preliminary, based on ~20% of the available data, and include no tracking information.

Figure 11 shows the A dependence of large E_T cross sections for the global and the two-high triggers. We have plotted the ratio $\sigma_{pA}/A\ \sigma_{pp}$ versus A, where σ_{pA} is the cross section $d\sigma/dE_T$ integrated over the E_T range shown. The power law parameterization $\sigma_{pA}=\sigma_{pp}\ A^{\alpha}$ does not seem to be valid, at least for the global triggers (a power law would yield straight lines, with slopes equal to α-1). For high planarity (P>0.8) events, σ_{pA} increases only slightly faster than A. This may indicate that jet-like events originate from a single hard scattering inside the nucleus.

We have observed apparent dijet events from all nuclei with the two-high trigger. An example of such an event from Pb is shown in Fig. 12. The rate of such events (planarity P>0.8, p_T>3 GeV for both jets) is ~3-8% of all two-high triggers. We are presently studying background from non-jet events. Detailed studies of the production and fragmentation of jets from nuclei may be possible.

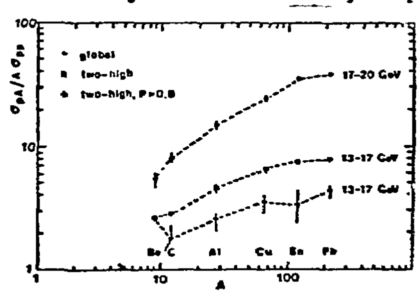

Fig. 11. Ratio $\sigma_{pA}/A\ \sigma pp$ for the global and two-high triggers

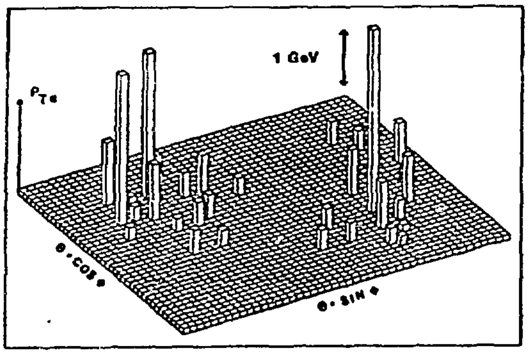

Fig. 12. Apparent dijet event from Pb target. The towers represent individual clusters ("particles").

VII. FOUR-JET MONTE CARLO STUDIES

M. Corcoran, Rice University

We have made Monte Carlo studies, using a four-jet model with Feynman-Field fragmentation, which indicate that the planarity distribution for global E_T triggered events is very sensitive to certain aspects of the calculation. Particularly critical are the methods used to ensure overall energy conservation and the choice of the cut-off in t, the momentum transfer in the parton-parton frame.

Details of the Monte Carlo program are given elsewhere.[11] The calculation uses QCD 2→2 subprocess cross sections with a cut-off in $|t|$ of 1.0 $(GeV/c)^2$. The spectator partons form beam and target jets along the beam axis. Care has been taken that the final jet structure agrees well with e^+e^- data. In Monte Carlos of this type, a problem with energy conservation arises because it is not possible to conserve both energy and momentum in the fragmentation of a massless parton. The compromise suggested by Feynman and Field is to require $\Sigma\,(E + p_z) = 2p_{parton}$, where the sum is over all particles in a jet, and E and p_z are a particle's energy and momentum in the parton direction. Using this procedure, the energy of the final jet is ~ 12% larger than the energy of the parton, and p_z is ~ 12% smaller. When the four jets are combined, the momentum components tend to average to zero in the overall CM. But the energies add, leaving the final event with a total energy (E_{tot}) greater than the correct CM energy. If an E_T trigger is now imposed, one finds that, as E_T increases, the total generated event energy also increases. This effect is due mostly to increased multiplicity; that is, events with higher total energy and E_T correspond to events with higher multiplicity.

The question of how to impose energy conservation is difficult since the correlation is large (~ 15-20%) and E_T dependent. Two possible methods for conserving energy in the overall CM, were studied:

1. All momentum components of all particles are scaled by a factor, determined iteratively, such that the total energy is within some tolerance of the correct value. This procedure decreases the observed E_T but does not change event shape.
2. Only momentum components parallel to the beam are scaled down. This procedure does not change either E_T or Pl (since Pl depends only on the transverse momentum components).

We found that the event structure and $\frac{d\sigma}{dE_T}$ are vastly different for the two methods of energy conservation. Figure 13 compares planarity distributions for final E_T > 11 GeV at $\sqrt{s}$ = 27.4 GeV. It should be emphasized that the only difference between the distributions shown in Fig. 13 is the method used to ensure overall energy conservation after the fragmentation is complete. The cross sections for the two methods also differ by about an order of magnitude.

The Monte Carlo results were also found to be sensitive to the cut-off in $|t|$ in the QCD subprocess. For example, raising the cut-off in t from 1 to 2 $(GeV/c)^2$ lowers the global cross section $d\sigma/dE_T$ nearly a factor of three and also shifts the planarity distributions to higher values. Figure 14 compares the planarity distribution for E609 data and Monte Carlo for observed E_T > 11 GeV, using method 2 and $|t|$ > 1.0 $(GeV/c)^2$. The agreement is good; agreement with $d\sigma/dE_T$ is also good.

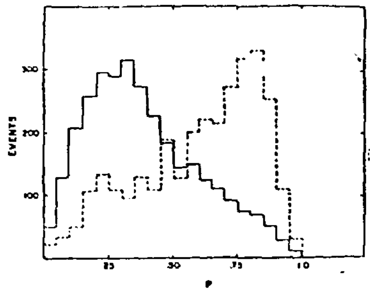

Fig. 13. Monte Carlo planarity distribution using method 1 (dashed) and method 2 (solid).

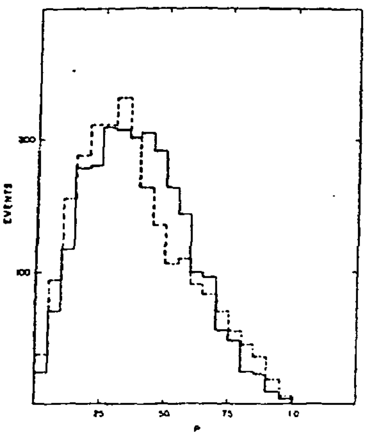

Fig. 14. Planarity distribution for data (solid) and Monte Carlo (dashed).

VIII. QCD MONTE CARLO STUDIES
K. Johns - Rice University

To study the possibility that high E_T events at 400 GeV may be better understood with the addition of gluon bremsstrahlung to the 2→2 hard scattering picture, we have used the Monte-Carlo program of Field-Fox-Wolfram[12] (FFW) which includes both initial and final state gluon radiation.

The E-609 data were analyzed by (1) applying a clustering algorithm to energy deposits in the main calorimeter to reconstruct the momenta of particles striking the calorimeter, and (2) applying a jet finding algorithm to these clusters (particles) to (arbitrarily) define jets. Each jet's P_T was required to be greater than 2.25 GeV/c.

For FFW Monte Carlo events, we simulated their particle showers in the calorimeter before applying the same event selection and analysis procedures. The preliminary results presented here focus on the 2-high trigger.

The average cluster (particle) multiplicity is shown in Table 1 for all 2-high triggers and that fraction (roughly 40%) of 2-high events found to contain 2 jets or 3 jets for both the E609 data and FFW. Good agreement between FFW and data is noted for the 2-high events, but FFW underestimates the multiplicity of the 2- and 3-jet E609 events. For the FFW 2- and 3-jet fraction a higher planarity and smaller (larger) energy flow into the main (beam) calorimeter than observed in the data thus follows.

The ratio of 3:2 jet events found in the E609 2-high data by our jet finder is roughly 8%. Of course, the origin of the third jet need not be a hard radiated gluon, since fluctuations in high multiplicity events or in fragmentation of the beam parton or scattered partons can satisfy the jet finder's definition for 3 jets. A fraction of the E-609 2-high events, however, look as in Figure 15. Here the energy flow into the beam calorimeter is 190 GeV which seems to preclude the third jet from being the beam jet.

In summary, good agreement is found between E609 data and FFW for the 2-high trigger events. Differences in multiplicity and angular distributions are seen when examining that fraction of 2-high events containing 2 or 3 jets. Such differences might indicate problems with the fragmentation of the strings containing the beam and target partons which typically make use of the Feynman-Field parameterization. Candidates for 3-jet events are observed in the 2-high triggers and preliminary analysis suggests that some are due to hard radiated gluons.

Table 1
Mean Cluster (particle) Multiplicity

Event Type	E609	FFW Monte Carlo
2 high	14 ± 1	13 ± 1
2 jet	17 ± 1	14 ± 1
3 jet	23 ± 1	18 ± 1

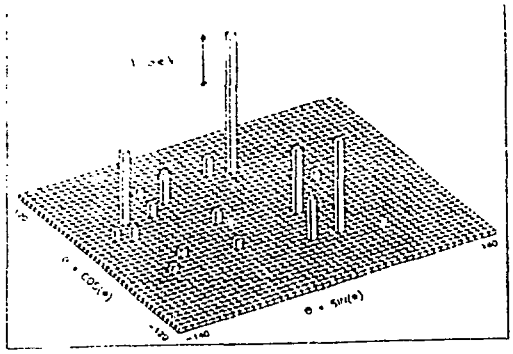

Fig. 15. A 3-jet candidate event.

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