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Evidence For A Super-Hard Pomeron Structure

(UA8 Collaboration)

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Abstract

Results are presented from a study of jet production in $p\bar{p}$ interactions with $\sqrt{s} = 630$ GeV at the CERN S$p\bar{p}$S-Collider, which are tagged by a proton or antiproton which possesses more than 90% of the incident beam momentum. The hard scattering which occurs between a parton in a beam particle and another in the soft residual component (Pomeron-dominated) of the tagged proton allows the Pomeron's partonic structure to be investigated. The observed jet distributions are in good agreement with expectations for hard parton-parton scattering in QCD. The Pomeron exhibits a hard structure like (1-x). However, there is an additional significant (30%) δ-function-like component, in which the entire momentum of the Pomeron seems to participate in the hard scattering.

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Ingelman and Schlein[1] pointed out that the partonic structure of the Pomeron could be established and studied in jet-producing $p\bar{p}$ interactions, which are tagged with leading protons or antiprotons with Feynman-$x_p > 0.90$. The relevant reaction is:

$$p_i + \bar{p} \rightarrow p_f + (jets + X) \quad + \quad c.c., \tag{1}$$

where c.c. refers to the complex-conjugate reaction. The incident $\bar{p}$ of Reaction 1 interacts with a soft (1-x_p) Pomeron-dominated component of p_i and yields the bracketed system with energy-squared, s'. This is kinematically related to the total initial state energy-squared, s, by the relation: $s' = s(1 - x_p)$. The hard-scattering takes place between a parton in the $\bar{p}$ and a parton in the Pomeron. At the S$p\bar{p}$S-Collider ($\sqrt{s} = 630$ GeV), x_p values of 0.9 and 0.95 correspond, respectively, to $\sqrt{s'}$ of 200 and 140 GeV. Except for the fact that we are considering only the hard scattering component, this process is a conventional diffractive process[2, 3], which is dominated by the exchange of a Pomeron Regge trajectory.

Data from a short test run of Experiment UA8 in 1985 were observed[4] to contain jets which possessed typical QCD properties, thus establishing that the Pomeron exhibits partonic structure in hard interactions. Ref. [4] also demonstrated that the observed cross section for React. 1 lies within the expected range[1].

Since the appearance of Ref. [1], there have been several theoretical developments in this field, which has been termed[5] "Diffractive Hard Scattering". Ingelman[6] estimated that there is negligible QCD background to the Ingelman-Schlein process due to proton formation in conventional inclusive 2-jet events. Donnachie and Landshoff[7] argued that quark structure should dominate the Pomeron and calculated its form to be approximately $xq(x) = 0.2x(1-x)$, where x is the fraction of the Pomeron's momentum carried by the parton and the coefficient represents a violation of the momentum sum rule assumed in Ref. [1]. Berger et al.[5] pointed out that there existed no derivation of the sum rule for the Pomeron and that an important goal of further research on this subject should be to examine its validity.

Frankfurt and Strikman[8] derived formulae for the triple Reggeon limit in perturbative QCD and found that the Pomeron structure function contains a δ-function-like component, implying that the entire momentum of the Pomeron would enter into the hard scattering. Although at the time they estimated that the range of validity for perturbative QCD was for momentum transfer (between p$_i$ and p$_f$ in Reaction 1) larger than about 4 GeV^2, more recent work[9] indicates that conditions for the validity of perturbative QCD may already exist for $|t|$ in the range 1-2 GeV^2. Abramovsky and Betman[10] have presented other arguments, based on an eikonal approach, for a δ-function in the Pomeron structure function.

In the present Letter, we present final results on Reaction 1 from the 1988-1989 S$p\bar{p}$S-Collider runs of Experiment UA8. The p_f proton remnant of p_i with momentum fraction x_p is observed in one of four small angle spectrometers[11] and the final state jets in the s' state in React. 1 are observed in the upgraded UA2 calorimeter system[12, 13]. For the data reported here, t is in the range $\simeq 1 - 2$ GeV^2. The data acquisition trigger logic required a proton or antiproton signal in one of the spectrometers, with an acceptable online momentum calculation[11, 14], and a total transverse energy, $\Sigma\, E_t > 18$ GeV in the UA2 calorimeter system (this cut was increased to 22 GeV in the offline analysis).

In Ref. [4], the short running time and the pseudorapidity coverage of the UA2 calorimeter before its upgrade, $|\eta| < 1$, limited the data sample to 114 (7) events with one (two) detected jets. The 1988-1989 runs, utilizing the upgraded UA2 detector[13] with coverage extended to

$|\eta| < 3$, provided a significant sample of 2-jet events, as discussed below. The data were recorded with the completed UA8 trigger and Roman pot spectrometer system[11], and a more thorough study of pileup (multiple interactions in a bunch crossing), background and calibration questions could be performed[15]. The redundancies in the complete spectrometer system allowed more careful analysis of many potential problems.

The calorimeter cell energies are used to search for jet structure using a conventional cone algorithm. All calorimeter cells with transverse energy larger than 1.5 GeV are used as "initiator" cells. If the sum of transverse energies of all cells within a cone of unit radius in the $\eta - \phi$ (azimuthal angle) plane around the direction of an initiator cell is larger than 8 GeV, a candidate jet is accepted. The process is iterated two more times with the cone taken with respect to the cluster axis (E_t-weighted sum of the cluster's cells). A fiducial cut, $|\eta_{jet}| < 2$, requires jets to be fully contained in the calorimeter. Cells used in a jet are eliminated from the cell list and the jet search continues until all initiators in the event are tested.

Fig. 1(a) is a θ vs. ϕ projection in the UA2 calorimeter system of a typical event with two found jets, each with $E_t > 8$ GeV. A recoil proton with $x_p \simeq 0.94$ has carried away much of the initial state energy, leaving an effective interaction energy $\sqrt{s'} \simeq 150$ GeV. The jets are clearly defined, with little underlying event background. Moreover, they are separated by about 180° in azimuthal angle, as expected for the hard scattering of two partons (more detail on these events are given below). Such events are evidence for a partonic structure of the Pomeron.

Fig. 1(b), on the other hand, shows an event with the same 2-jet requirement, but ***without*** a large x_p proton and therefore with the full $\sqrt{s} = 630$ GeV available in the interaction. The "noise" from the many low energy cells in the underlying event is so pervasive that jets with $E_t > 8$ GeV can not be distinguished visually from the background.

Table 1 lists our complete jet event sample with jet $E_t > 8$ GeV, and with recoil p or $\bar{p}$ momentum in the indicated ranges of x_p. A total of 1559 events are found which have at least one such jet. 300 of these events have two jets which, in 249 events, are coplanar with azimuthal angle difference of more than 135^o.

As in Refs. [1, 4], in order to compare the calorimeter data with theoretical models, a modified version of the PYTHIA 4.8 event generator[16] is used, in which the Pomeron is defined as a beam particle and a proton is the target particle. Hard Pomeron-proton interactions at any $\sqrt{s'}$ can then be calculated for an assumed effective Pomeron structure function. The jet production is calculated from standard QCD hard parton-parton $2 \rightarrow 2$ scattering matrix elements with initial and final state radiation and JETSET 6.3[17] is used for the hadronization according to the Lund string model[18]. The generated Monte Carlo events were boosted from the Pomeron-proton system to the laboratory frame and passed through a UA2 detector simulation program[19] (based on parameterizations of test beam data) and data analysis software in order to subject the Monte Carlo events to the same experimental effects as the real data. As in Refs. [1, 4], two plausible but extreme Pomeron structure functions are considered, $(1-x)^5$ and $x(1-x)$. In this Letter we refer to these as "soft" and "hard", respectively.

The PYTHIA event generator, whose parameters have been tuned[20] to $p\bar{p}$ interactions with $\sqrt{s} = 630$ GeV, is found to somewhat underestimate the activity of the underlying event in Reaction 1, when run for energy $\sqrt{s'}$. However, we find that tuning the event generator to improve its agreement with the observed properties of the underlying events has no effect on any of the conclusions in this Letter. Further details on the underlying events will be published elsewhere[15].

The 2-jet events in Table 1 allow us to verify that the data have the features which are characteristic of QCD hard parton-parton $2 \to 2$ scattering, as was done earlier by the UA2 collaboration for inclusive 2-jet production[21, 22, 19]. Figs. 2(a-d) compare the observed distributions of several variables with their corresponding Monte Carlo predictions. Since these variables are found to vary slowly with x_p, the data in the three bins of x_p in Table 1 are combined in the figure. The variables shown are also observed to be rather insensitive to the hardness of the Pomeron structure and to whether quarks or gluons are involved; thus the predictions are only shown for the hard $x(1-x)$ gluonic structure case.

All the distributions in Figs. 2 are seen to be well described by the Monte Carlo predictions. Fig. 2(a) shows the difference in azimuthal angle ($\Delta\phi$) between the two jets in the plane perpendicular to the beam axis and displays the pronounced enhancement at 180°, which is characteristic of parton-parton scattering. Fig. 2(b) shows the azimuthal dependence of the transverse energy flow with respect to one of the jet axes. Fig. 2(c) shows the 2-jet invariant mass distribution, calculated assuming that the calorimeter cell energies arise from massless particles. The slow increase of average invariant mass with jet E_t (not shown here) is also found to be well-described by the Monte Carlo.

Fig. 2(d) shows the scattering angle distribution in the 2-jet rest frame, using the notation of Collins and Soper[23]. θ^* is the angle between the di-jet axis and the bisector of the beam directions in the center of mass frame of the 2-jet system. A requirement $M_{JJ} > 30$ GeV, used only in (d), selects events with good acceptance for larger $|\cos\theta^*|$ values and allows the rising behavior due to QCD vector exchange to be visible.

Having demonstrated that the data display the expected QCD characteristics, we now turn to an examination of those variables which are sensitive to the Pomeron structure. As explained in Refs. [1, 4], the primary variable used, x(1-jet), is the momentum component of a jet in the s' center-of-mass along the incident Pomeron-proton axis, normalized to its maximum possible value of $\sqrt{s'}/2$. Note that the boost of a jet 4-vector to the s' frame is uniquely defined for each event by its recoil proton momentum. Because of the motion of the s' system in the lab, there is essentially full acceptance in the Pomeron hemisphere, where x(1-jet) > 0, but somewhat smaller acceptance in the proton hemisphere. A hard structure in the Pomeron of the type $x(1-x)$ or $(1-x)$ leads to a forward-backward asymmetry in the x(1-jet) variable and hence to a more extended tail[1] in the Pomeron hemisphere.

The x(1-jet) distributions are shown in Figs. 3(a,b,c) for the three bins of x_p, together with the Monte Carlo predictions for the hard and soft effective Pomeron structure functions. Again, since there are essentially no differences between predictions for gluon and quark structure of the Pomeron, only the gluonic predictions are shown. The hard structure function is in rather good agreement with the data for all x_p ranges, while the soft structure function is clearly disfavored. For example, the curves agree with the data in Fig. 3(b) with χ^2 per degree of freedom of 4.4 and 23.3 for the hard and soft functions, respectively[2]. Note that we do not expect ideal χ^2/DF

[1] Clearly, a distortion of this distribution occurs if the correct boost of each jet to its s' frame is not made. An incorrect boost can occur if the detected proton is itself part of an excited system (i.e. the event is an example of double diffractive excitation) and, for example, a slow pion is lost. Then the x_p used to define the boost is underestimated and, correspondingly, s' is overestimated. However, we believe this effect is negligible in our experiment. In any case, this type of background would lead to a ***decrease*** in the asymmetry of the x(1-jet) distribution and could not be responsible for the effects reported in this Letter.

[2] This situation may be compared with that in Ref. [4] where, with its much smaller sample (114 1-jet events), corresponding χ^2/DF values of 3.4 and 1.1 were found for hard and soft structure functions, respectively. In view of our present results with a much larger and better data sample (and with an improved low-energy calibration of the UA2 calorimeter[19]), the weak preference for the soft structure in Ref. [4] was not statistically significant.

values, because we are not "measuring" the structure function, but simply testing the relative compatibility of two extreme hypotheses with the data.

A variable related to x(1-jet), the pseudo-rapidity η(1-jet) of a jet axis in the laboratory, is shown in Figs. 3(d,e,f). The hard Monte Carlo is again preferred over the soft one with χ^2 per degree of freedom (χ^2/DF) of 6.5 and 25.0, respectively, in Fig. 3(e).

At large values of η(1-jet) in Figs. 3(d,e,f), there appears to be an excess of events over the hard structure function predictions, visible in all bins of x_p. This same effect is also present, although less obviously, in Figs. 3(a,b,c). We come back to this matter below in a discussion of the events with two jets.

We have investigated possible sensitivities of the conclusions from Figs. 3 on many possible systematic uncertainties in the Monte Carlo generation and in the data[15]. For example, we have carried out the analysis independently for the 1-jet and 2-jet samples in Table 1 and find no significant differences. Similarly, the analysis has been repeated for: (a) jet E_t thresholds of 6 and 10 GeV; (b) with and without ΣE_t being used in the online trigger; (c) with and without tuning the Monte Carlo generation to agree with the underlying event; (d) using, in turn, the EHLQ and Duke-Owens parameterizations of the proton structure; (e) with various settings of the minimum transverse momentum, QTMIN, for the parton-parton hard scattering in the PYTHIA event generation; (f) with and without resolution smearing within an x_p bin; (g) with and without various fiducial cuts made on the calorimeter data. No sensitivity of the conclusions on any of these procedures can be found. We thus believe that the preference for the harder structure function is sound although, as in Ref. [4], it should be noted that we have no discriminating power on whether or not the factor x exists in $x(1-x)$.

The longitudinal momentum of the complete 2-jet system along the Pomeron-proton axis in the s' system more directly reflects the differences between the parton distributions in the Pomeron and in the proton. Thus, we define the variable x(2-jet), which is this longitudinal momentum normalized to $\sqrt{s'}/2$. In the absence of gluon radiation, jet-finding and detector effects, x(2-jet) in a given event is related to the parton momenta in Pomeron and proton, respectively, by:

$$x(\text{2-jet}) = x(Pomeron) - x(proton) \tag{2}$$

The observed x(2-jet) distribution is shown in Fig. 4(a) and compared with expectations for the same hard and soft structure functions used in Figs. 3. We see a remarkable effect, in that the data have a component at large x(2-jet), which is harder than predicted by the hard $x(1-x)$ function. This effect is similar to, but more visible than, the one seen above in Figs. 3, because x(2-jet) is more sensitive to this enhanced tail. ***These results show that an unexpectedly large fraction of the Pomeron's momentum participates in the hard scattering a significant fraction of the time.***

If all the momentum of the Pomeron enters into the hard scattering process, as predicted for a perturbative Pomeron by Frankfurt and Strikman[8], where the Pomeron structure function has a δ-function like component, Eq. 2 reduces to:

$$x(\text{2-jet}) = 1 - x(proton) \tag{3}$$

This parton level distribution is shown as the solid curve in Fig. 4(b) for $x_p = 0.93$ and has a shape which mirrors the proton structure function, $x(proton)$.

Predictions for this "Super-Hard" process have been estimated with the use of our Monte Carlo chain, with the approximation in PYTHIA that the Pomeron is a 2-gluon system, with one gluon constrained to carry 99% of the Pomeron momentum. The other (soft) gluon acts as a spectator and insures that color is conserved. The dashed curve in Fig. 4(b) is a first estimate of the x(2-jet) distribution, after final state radiation, hadronization and jet finding in an idealized calorimeter, but before the full UA2 calorimeter simulation. The peak is broader and shifted to lower x(2-jet) values. Finally, the dotted curve shows the expected x(2-jet) distribution after the UA2 calorimeter simulation.

It is evident from the dotted curve in Fig. 4, that a component of this type added to the hard structure function we have been discussing could adequately account for the observed distribution in x(2-jet) . We have fit the data to a sum of these two components and find that the data require about a 30% contribution from the Super-Hard mechanism. This magnitude is found to be essentially independent of whether or not we also allow an admixture of the soft $(1-x)^5$ distribution, but an acceptable fit can not be obtained with only soft and Super-Hard contributions. When all three possibilities are used in the fit, we find 30% Super-Hard, 57% hard and 13% soft (χ^2/DF = 0.6). When soft is not included, the fit yields 29% Super-Hard and 71% hard (χ^2/DF = 0.9).

To check the internal consistency of our data, we have also independently performed fits of this model to the x(1-jet) distributions from the 2-jet and total event samples in Table 1. Approximately the same amount of Super-Hard component is consistently found (29% for the 2-jet events and 26% for all events). The amounts of hard and soft components are close to the above values.

There are 25 events in Fig. 4 which have x(2-jet) > 0.7, where no events are expected from a soft or hard Pomeron structure. In order to demonstrate that the observed events in this "pure" Super-Hard region display QCD properties, Figs. 5 compare various distributions with their QCD predictions, using the hard gluon model described above. The $\Delta\phi$ and M_{jj} distributions are in good agreement, as shown above in Figs. 2 for the entire 2-jet sample. Fig. 5(b) shows the difference in the two jet transverse energies. This distribution, whose shape is dominated by initial state gluon radiation, as discussed in Ref. [21], and also by experimental resolution and other effects, is seen to agree rather well with predictions. The pseudo-rapidity of the total 2-jet vector in the laboratory, shown in (d), is greatly influenced by the transverse energy difference of the 2-jets, but is also in reasonable agreement with expectations. Thus, the events at the extreme values of x(2-jet) are well behaved and our conclusion that the entire momentum of the Pomeron participates in the hard scattering should be reliable.

We note that none of the results reported here exhibit any dependence on the momentum transfer, t, in Reaction 1 over the range covered. For example, the fraction of events (triggers) which are found to have jets is (0.384 ± 0.010) for the t-range 0.9-1.4 GeV^2 and (0.376 ± 0.010) for the range 1.7-2.3 GeV^2. Moreover, neither the x(1-jet) nor x(2-jet) distributions in Figs. 3 and 4, respectively, exhibit any dependence on t (not shown here) over the range covered by our data[15].

Finally, we note that the absolute cross section for React. 1 depends on knowledge of the t-dependence of p_f over its entire range and also on detailed corrections for the imperfect detector acceptance of the jets. The uncertainties inherent in evaluating these corrections limit our sensitivity to a violation of the momentum sum rule for the Pomeron. However, we are carrying out this analysis and the results will soon be available.

In conclusion, we have found an extreme Super-Hard component in the Pomeron structure. This may be the perturbative Pomeron effect of Frankfurt and Strikman[8], although other predictions of the perturbative Pomeron remain to be tested. Another possibility, suggested by

x_p	$\sqrt{s'}$	≥1-jet	2-jets	$\Delta\phi > 135°$
0.90-0.92	189	606	97	77
0.92-0.94	167	527	103	86
0.94-0.96	141	426	100	86
TOTAL		1559	300	249

Table 1: Numbers of events with jet $E_t > 8$ GeV.

Donnachie and Landshoff[24, 25] to explain our results, is that the events with large x(2-jet) could be due to a diagram in which both the quark and antiquark in their model of the Pomeron[7] give rise to jets.

New experiments with higher energy $p\bar{p}$ interactions will allow the study of the effects reported in this Letter over a larger range of t and Q^2 (jet E_t). Although the Pomeron structure function is operationally well defined in Ref. [1], possible dependence on these variables could be studied and the factorization hypothesis could also be tested. Does the Pomeron have an effective structure function in the proton, as conjectured in Ref. [1], or does it depend on energy or reaction type?

Measurements of the analogue of Reaction 1 in e^-p experiments will provide additional information[1, 26, 25] on the validity of factorization in hard diffractive scattering and should shed light on the relative contributions of quarks and gluons in the Pomeron to hard scattering. Most recently, Collins et al.[27] predict a breakdown of factorization in perturbative QCD between Reaction 1 and its e^-p analogue.

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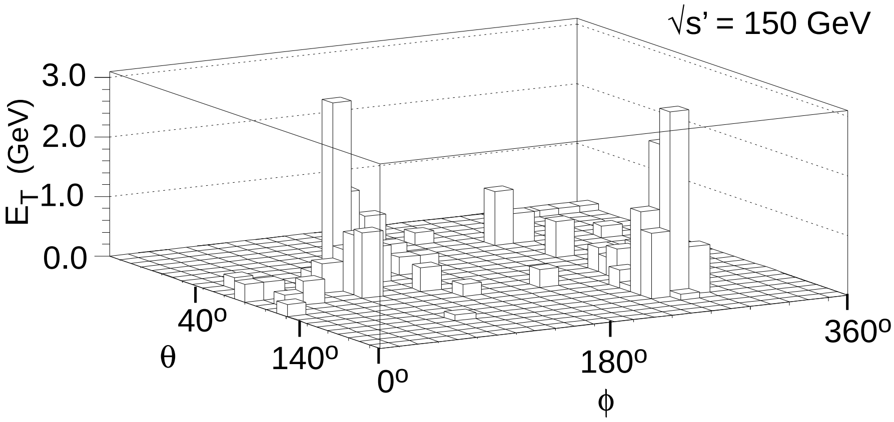

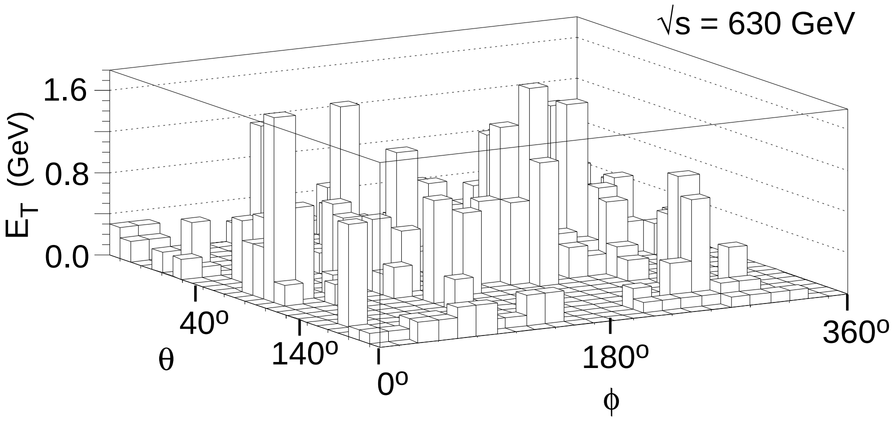

Figure 1: Calorimeter event displays in the $\theta - \phi$ plane for events with two found jets, each with $\Sigma\, E_t > 8$ GeV. (a) UA8 event with $\sqrt{s'} = 150$ GeV; (b) Event with no detected proton ($\sqrt{s} = 630$ GeV). The ordinate for each $\Delta\theta$-$\Delta\phi$ cell displays the transverse energy in the cell. The full θ scale shown contains 26 cells covering $|\eta| < 3.0$. 22 of them cover the range $|\eta| < 2.2$, while the last 2 on either side have $\Delta\eta = 0.3$ and 0.5, respectively.

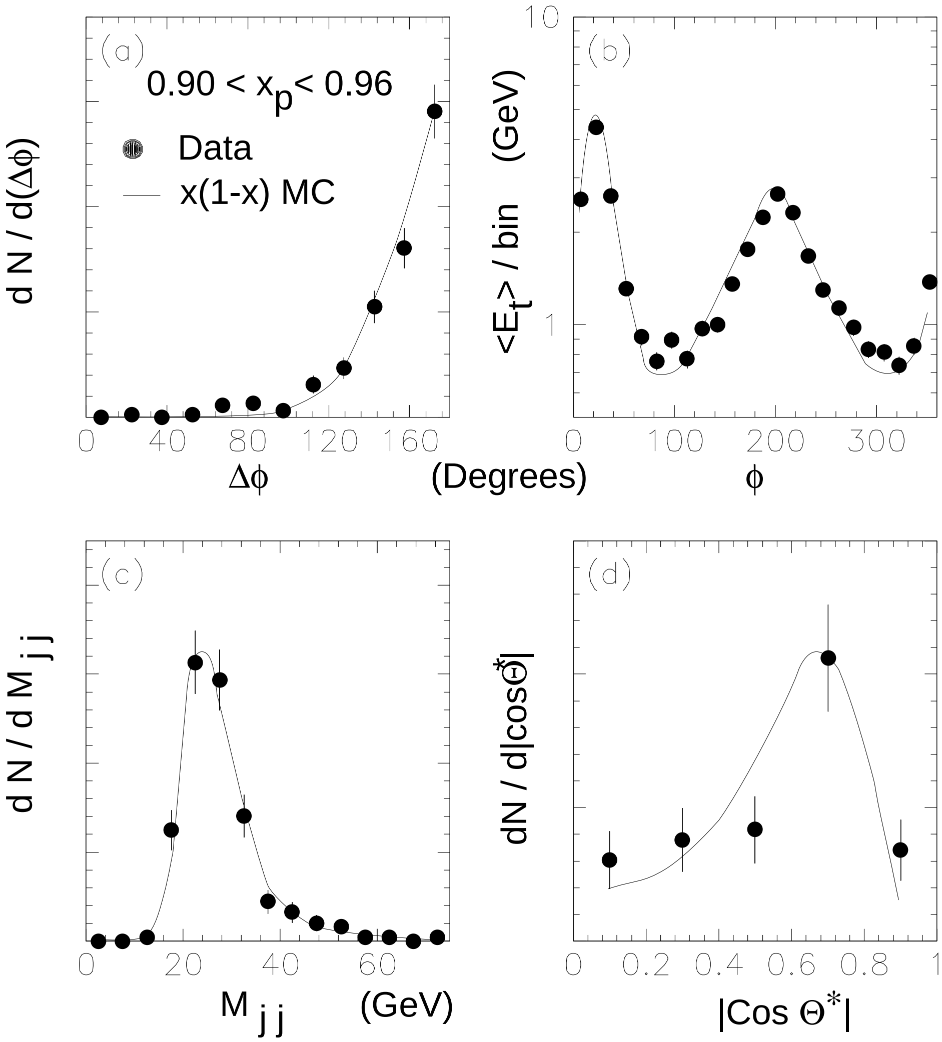

Figure 2: Comparisons of hard (gluon) structure function Monte Carlo predictions with 300 events which contain two found jets, each with $\Sigma E_t > 8$ GeV. Soft or quark structure function predictions are indistinguishable from those shown here, as discussed in the text; (a) Difference of jet azimuthal angles; (b) Average E_t per $\Delta\phi = 15°$ cell, with one jet centered in second bin; (c) Jet-jet invariant mass when $\Delta\phi > 135°$; (d) Scattering angle in 2-jet center of mass when $M_{jj} > 30$ GeV and $\Delta\phi > 135°$, as described in text. The drop-off for $\cos(\theta^*) > 0.8$ is an acceptance loss. Distributions in (a, c, d) are normalized to unit area.

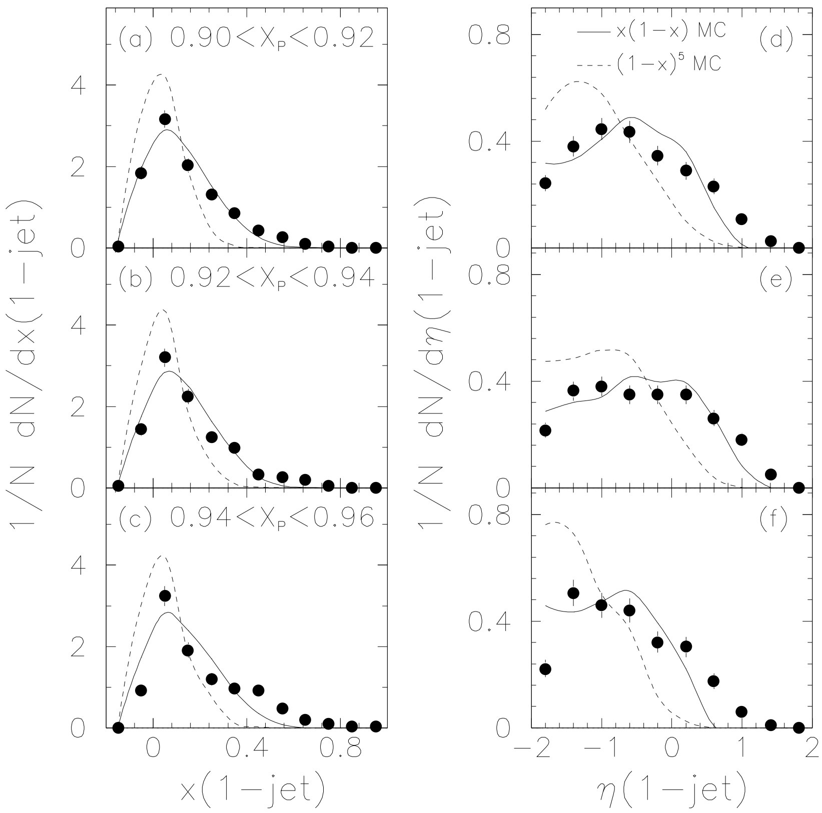

Figure 3: Discrimination between hard and soft Pomeron structure functions, as described in the text. (a-c) x(1-jet) for the three bins of x_p shown in Table 1. All jets in the total event sample are used. See text for definition of x(1-jet). Some of the fall-off below x(1-jet) about 0.1 is due to acceptance loss, as discussed in the text. (d-f) Pseudorapidity in the laboratory of individual jets for same events used in (a-c). Solid curves are predictions for $x(1-x)$ structure function; dashed curves are for $(1-x)^5$. All distributions are normalized to unit area.

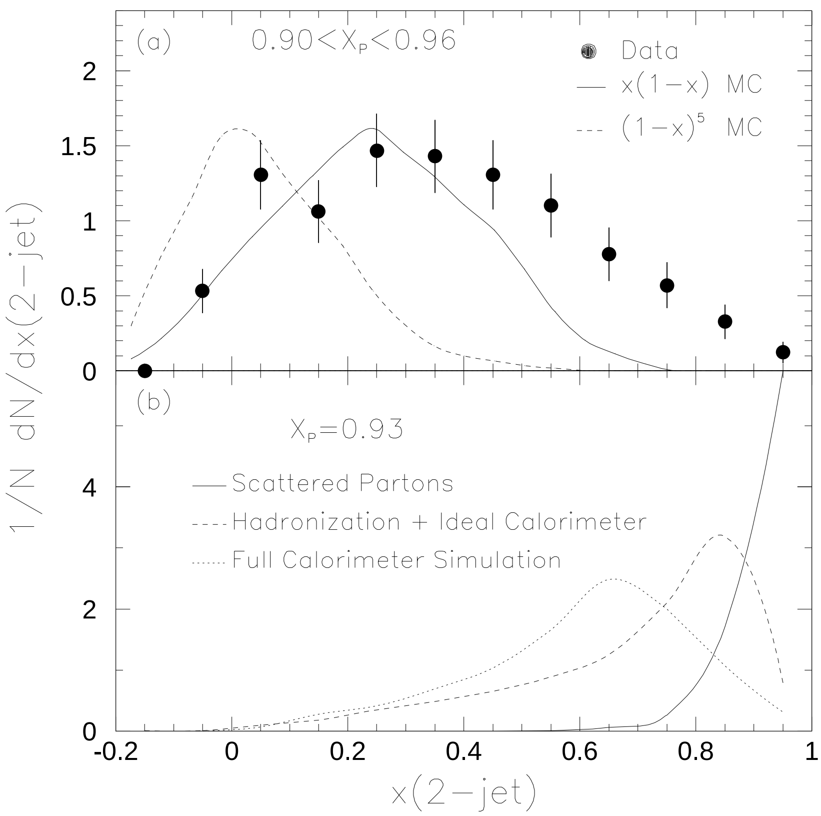

Figure 4: (a) Observed x(2-jet) distribution for 249 events in Table 1 with $0.90 < x_p < 0.96$. The two curves show the expected distributions for the hard and soft structure functions with arbitrary normalizations. (b) Results of x(2-jet) calculation in PYTHIA for x_p =0.93, assuming the entire momentum of the Pomeron participates in the hard scattering, as explained in the text. The solid line is the scattered parton distribution before hadronization. The dashed curve is after hadronization and assuming an idealized calorimeter with cell structure the same as the UA2 calorimeter. The dotted curve shows the result of a full UA2 detector simulation.

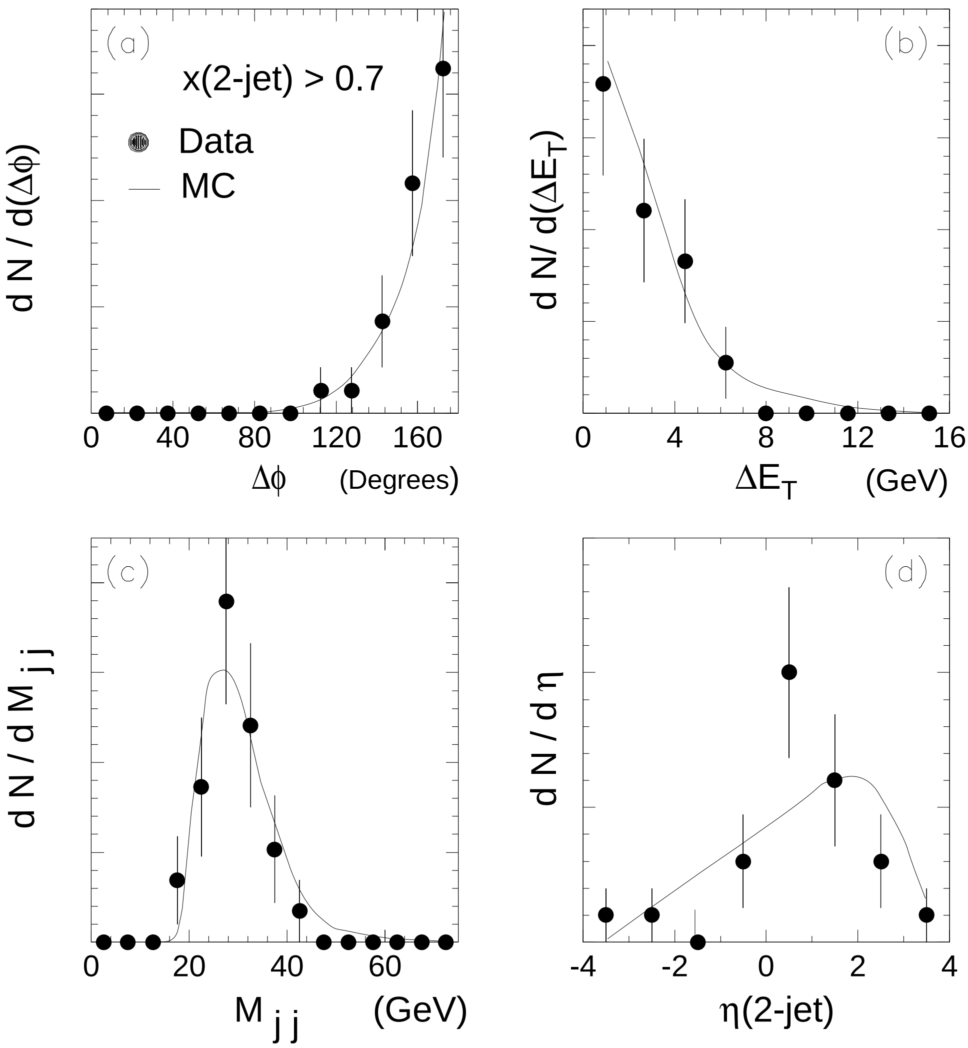

Figure 5: Comparisons of Super-Hard (gluon) structure function predictions as described in the text with those 2-jet events which have x(2-jet) > 0.7. (a) Difference of jet azimuthal angles; (b) Difference between jet transverse energies for the two jets; (c) Jet-jet invariant mass; (d) Pseudo-rapidity of the 2-jet axis in the laboratory. All distributions are normalized to unit area.