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Study of interjet energy flow at HERA

ZEUS Collaboration

Abstract

Cross sections for the photoproduction of dijet events, where the two jets with the highest transverse energy are separated by a large gap in pseudorapidity, have been studied with the ZEUS detector using an integrated luminosity of 38.6 pb^{-1}. Rapidity-gap events are defined in terms of the energy flow between the jets, such that the total summed transverse energy in this region is less than some value $E_{\mathrm{T}}^{\mathrm{CUT}}$. The data show a clear excess above the predictions of standard photoproduction models. Models which include color-singlet exchange are able to describe the data.

1 Introduction

Events produced in hadronic collisions with two jets of high transverse energy separated by a large rapidity gap containing little or no energy provide an ideal environment to study the mechanism of color-singlet exchange in a regime where perturbative QCD should be applicable. The production mechanism for multiple jets is a hard interaction between partons from the incoming hadrons interacting via a quark or gluon propagator. This exchange of color quantum numbers gives final state jets that are color connected both to each other and to the hadronic remnants. This leads to energy flow that populates the pseudorapidity region both between the hadronic remnants and between the jets themselves. Events with a large rapidity gap between the jets would then be a signature for the exchange of a color-singlet object. This exchanged object could be either an electroweak boson or some strongly-interacting Pomeron-like object. The high transverse energy provides a perturbative hard scale at each end of the color-singlet exchange, so that the cross section should be fully calculable in perturbative QCD [1].

Previous studies have been made using $p\bar{p}$ collisions at the Tevatron [2,3]. At HERA, such events were first observed by ZEUS [4] and have been studied by H1 [5]. Photoproduction interactions were used where, at leading order, the photon can interact either directly in the hard sub-process, or by fluctuating into a hadronic state and interacting via a partonic constituent carrying some fraction, x_γ, of the photon momentum. At leading order, therefore, color-singlet exchange may take place only in resolved photoproduction.

Calculations [6] using the leading-logarithmic approximation (LLA) of BFKL [7], predict an excess of dijet events with a large rapidity gap over the expectation from standard QCD processes [8]. However, the possibility of secondary multiple hard-scatters, or multiparton interactions (MPI) between spectator partons in the hadronic remnants, could lead to additional energy flow between the two jets, thus destroying the gap and making absolute predictions difficult.

Problems relating to the infra-red safety of a gap definition based on multiplicity can be avoided by defining the gap in terms of transverse-energy flow, $E_T^{\rm GAP}$, within the gap [9]. This is the technique used in the present study. The differential cross section of all events with a certain pseudorapidity separation, the differential cross section of events with the pseudorapidity separation and $E_T^{\rm GAP} < E_T^{\rm CUT}$, and the ratio of these differential cross sections, called the gap fraction, are measured. The results are compared to available models.

2 Data selection

The results presented in this paper correspond to 38.6 ± 0.6 pb^{-1} of data taken with the ZEUS detector [10] during the 1996-1997 HERA running period. Positrons of 27.5 GeV collided with protons of 820 GeV, giving a center of mass energy of $\sqrt{s} = 300\,\text{GeV}$.

Photoproduction events were selected using similar criteria to those reported in a recent publication [11]. The contributions from beam-gas interactions, cosmic-ray showers and beam-halo muons were reduced using the requirement of a well reconstructed vertex consistent with the nominal interaction region. Neutral current deep inelastic scattering events with a well reconstructed positron candidate [12] in the uranium-scintillator calorimeter [13] were rejected.

The remaining sample consisted of events with small photon virtuality, $Q^2 < 1\,\text{GeV}^2$, with a median of $Q^2 \sim 10^{-3}\,\text{GeV}^2$. To ensure that the events were well reconstructed, the inelasticity variable, y, was restricted to the range $0.2 < y < 0.85$. For this selection, y was reconstructed with the Jacquet-Blondel method [14] using energy flow objects (EFOs), a combination of energy clusters reconstructed in the calorimeter and charged tracks reconstructed in the central tracking detector [15].

Jets were reconstructed from the EFOs using the k_T algorithm [16] in the longitudinally invariant inclusive mode [17]. In this mode, the algorithm merges all final-state objects uniquely into a list of massless jets ordered in transverse energy, E_T . Events in which the two highest-E_T jets satisfied the following criteria were then selected:

$$
\begin{aligned}
E_T^{jet1} \geq 6\,\text{GeV}; \qquad & E_T^{jet2} \geq 5\,\text{GeV}; \\
|\eta^{jet1,2}| \quad & < \quad 2.4; \\
|\frac{1}{2}\left(\eta^{jet1} + \eta^{jet2}\right)| \quad & < \quad 0.75.
\end{aligned}
$$

To ensure that the jets were well separated in pseudorapidity, an additional requirement on the absolute difference in pseudorapidity, $\Delta\eta \equiv |\eta^{jet1} - \eta^{jet2}|$,

$$2.5 < \Delta\eta < 4,$$

was made. The asymmetric cut on jet E_T reduces the contribution from regions where next-to-leading-order (NLO) QCD calculations may suffer from incomplete cancellation of real and virtual contributions.

The total energy flow between the two highest-E_T jets, E_T^{GAP}, was calculated in an infrared-safe way, as the sum of the transverse energy of all remaining jets lying in the pseudorapidity region between the two highest-E_T jets:

$$E_\mathrm{T}^{\mathrm{GAP}} = \sum_{i>2} E_\mathrm{T}^{jeti} \quad \eta^{jeti} \in \left(\eta^{jet}_{forward}, \eta^{jet}_{backward}\right). \tag{1}$$

Events were designated as gap events if this total transverse energy is less than some value $E_T^{\rm CUT}$. The gap fraction, f , was defined as the ratio of the cross section for events with a large separation in pseudorapidity between the highest-$E_{\rm T}$ jets and $E_T^{\rm GAP} < E_T^{\rm CUT}$ to that for all events with a large separation in pseudorapdidity between the highest-$E_{\rm T}$ jets.

3 Monte Carlo Simulations

The PYTHIA 6.1 [18] and HERWIG 6.1 [19] Monte Carlo (MC) generators were used to correct the data to the hadron level and for model comparisons. Models of multi-parton interactions were included in PYTHIA using the simplest MPI option available[1] and in HERWIG by interfacing to the JIMMY library [20]. Both MC programs were tuned to the ZEUS data sample used in this analysis after the application of kinematic cuts. The starting point for the tuning were the parameters determined by JETWEB [20], and then the minimum p_T of the interactions was varied to obtain the best fit to the data. The values of minimum p_T giving the best fit have been found to be $p_T^{Min1} = 1.9$ and $p_T^{Min2} = 1.7$ for PYTHIA and $p_T^{Min1} = 2.7$ for HERWIG.

Direct and resolved MC samples were generated separately and combined to give the best fit to the x_γ^{OBS} distribution of the ZEUS data. For PYTHIA the amounts were 30% direct and 70% resolved, and for HERWIG, 44% direct and 56% resolved.

The HERWIG generator was also used to simulate the color-singlet exchange. The simulation included an implementation of LLA BFKL color-singlet exchange using the model of Mueller and Tang [6]. In this model, the hard-Pomeron intercept, $1 + \omega_o$, is related to the strong coupling along the gluon ladder, α_s, by $\omega_o = \alpha_s C_A\,(4 \ln 2/\pi)$. For the present measurement, the value $\omega_o = 0.45$ ($\alpha_s = 0.17$) was chosen. The LLA BFKL HERWIG contribution was added to the sum of the direct and resolved samples in the ratios of the predicted cross sections.

Since PYTHIA does not contain the Pomeron-exchange option, high-t photon exchange was used instead to simulate the color-singlet contribution. Although high-t photon exchange is not the mechanism which creates the rapidity gaps, it allows one to test the sensitivity to the dynamics of color-singlet exchange.

[1] Multiparton interactions in PYTHIA were selected by setting MSTP(82)=1

4 Results

Figure 1 shows the inclusive dijet gap cross section as a function of $E_{\mathrm{T}}^{\mathrm{GAP}}$. Also shown are comparisons with two sets of simulations: HERWIG and PYTHIA with and without colour-singlet exchange. The PYTHIA cross section was scaled by 3.3 and the HERWIG cross section was scaled by 1.8 to give the best agreement with the data. The MCs without a color-singlet contribution do not describe the data in the two lowest $E_{\mathrm{T}}^{\mathrm{GAP}}$ bins. The amount of the color-singlet needed to give the best fit to the data is about 3-4% of the total inclusive dijet gap cross section integrated in the range between 0 and 12 GeV in $E_{\mathrm{T}}^{\mathrm{GAP}}$.

Using the scaling parameters described above, the inclusive dijet gap cross section, the cross section for events with energy in the rapidity gap less than $E_{\mathrm{T}}^{\mathrm{CUT}}$, and the gap fraction, as a function of the separation, $\Delta\eta$, of the two leading jets, can be compared to the MC predictions. Figure 2 presents results of such a comparison for $E_{\mathrm{T}}^{\mathrm{CUT}} = 1\,\mathrm{GeV}$. Both MC models with color-singlet exchange describe the data well. According to the MC models, the contribution of color-singlet exchange to the gap fraction increases from about 20% to about 50% as the dijet separation increases from 2.5 to 4 units in pseudorapidity.

Figure 3 shows the gap fraction as a function of the separation, $\Delta\eta$, for four values of $E_T^{\mathrm{CUT}} = 0.5, 1.0, 1.5$ and $2\,\mathrm{GeV}$. The data fall for increasing $\Delta\eta$ for all values of E_T^{CUT}, but level out as the size of the gap increases. This behavior is most pronounced for the lowest E_T^{CUT} value and is well reproduced by the MC models with color-singlet exchange added. The predictions of PYTHIA and HERWIG without colour-singlet exchange show an approximately exponential dependence on $\Delta\eta$, consistent with the purely statistical behaviour seen in studies of rapidity gaps in e^+e^- annihilation [21]. The predictions lie, in this case, much below the data for larger $\Delta\eta$ values. Each Monte Carlo was normalized separately to the data. The HERWIG MC was multiplied by 1.02 and the PYTHIA was multiplied by 0.98. The HERWIG BFKL MC was multiplied by 1.45 and the PYTHIA high-t photon MC was multiplied by 426.42.

5 Conclusions

Analysis of cross sections of dijet PHP events, where the two jets with the highest transverse energy are separated by a large gap in pseudorapidity show a clear excess above the predictions of standard PHP MC models. The same models, when 3-4% color-singlet exchange is included, are able to describe the data.

References

[1] J.R. Forshaw and P.J. Sutton, Eur. Phys. J. **C 1**, 285 (1998).

[2] DØ Coll. B. Abachi et al., Phys. Rev. Lett. **72**, 2332 (1994);
DØ Coll. B. Abachi et al., Phys. Rev. Lett. **76**, 734 (1996);
DØ Coll. B. Abbott et al., Phys. Lett. **440**, 189 (1998).

[3] CDF Coll., F. Abe et al., Phys. Rev. Lett. **74**, 855 (1995);
CDF Coll., F. Abe et al., Phys. Rev. Lett. **80**, 1156 (1998);
CDF Coll., F. Abe et al., Phys. Rev. Lett. **81**, 5278 (1998).

[4] ZEUS Coll., M. Derrick et al., Phys. Lett. **B 369**, 55 (1996).

[5] H1 Coll., C. Adloff et al., Eur. Phys. J. **C 24**, 517 (2002).

[6] A.H. Mueller and W.K. Tang, Phys. Lett. **B 284**, 123 (1992).

[7] L.N. Lipatov, Sov. J. Nucl. Phys. **23(3)**, 338 (1976);
Ya.Ya. Balitskii and L.N. Lipatov, Sov. J. Nucl. Phys. **28(6)**, 882 (1978);
E.A. Kuraev, L.N. Lipatov, and V.S. Fadin, Sov. Phys. JETP **45(2)**, 199 (1977).

[8] B.E. Cox, J.R. Forshaw, and L. Lonnblad, JHEP **10**, 023 (1999).

[9] G. Oderda and G. Sterman, Phys. Rev. Lett. **81**, 3591 (1998).

[10] ZEUS Coll., U. Holm (ed.), *The ZEUS Detector*. Status Report (unpublished), DESY (1993), available on `http://www-zeus.desy.de/bluebook/bluebook.html`.

[11] ZEUS Coll., S. Chekanov, et al., Eur. Phys. J. **C 23**, 615 (2002).

[12] H. Abramowicz, A. Caldwell and R. Sinkus, Nucl. Inst. Meth. **A 365**, 508 (1995).

[13] M. Derrick et al., Nucl. Inst. Meth. **A 309**, 77 (1991);
A. Andresen et al., Nucl. Inst. Meth. **A 309**, 101 (1991);
A. Bernstein et al., Nucl. Inst. Meth. **A 336**, 23 (1993);
A. Caldwell et al., Nucl. Inst. Meth. **A 321**, 356 (1992).

[14] F. Jacquet and A. Blondel, *Proceedings of the Study for an ep Facility for Europe*, U. Amaldi (ed.), p. 391. Hamburg, Germany (1979). Also in preprint DESY 79/48.

[15] N. Harnew et al., Nucl. Inst. Meth. **A 279**, 290 (1989);
B. Foster et al., Nucl. Phys. Proc. Suppl. **B 32**, 181 (1993);
B. Foster et al., Nucl. Inst. Meth. **A 338**, 254 (1994).

[16] S.Catani et al., Nucl. Phys. **B406**, 187 (1993).

[17] S.D. Ellis and D.E. Soper, Phys. Rev. **D 48**, 3160 (1993).

[18] T. Sjöstrand, Comp. Phys. Comm. **82**, 74 (1994).

[19] G. Marchesini et al., Comp. Phys. Comm. **67**, 465 (1992).

[20] J.M. Butterworth and J.R. Forshaw, J. R., J. Phys. **G 19**, 1657 (1993).

[21] M. Derrick, et al., Z. Phys. **C 35**, 323 (1987).

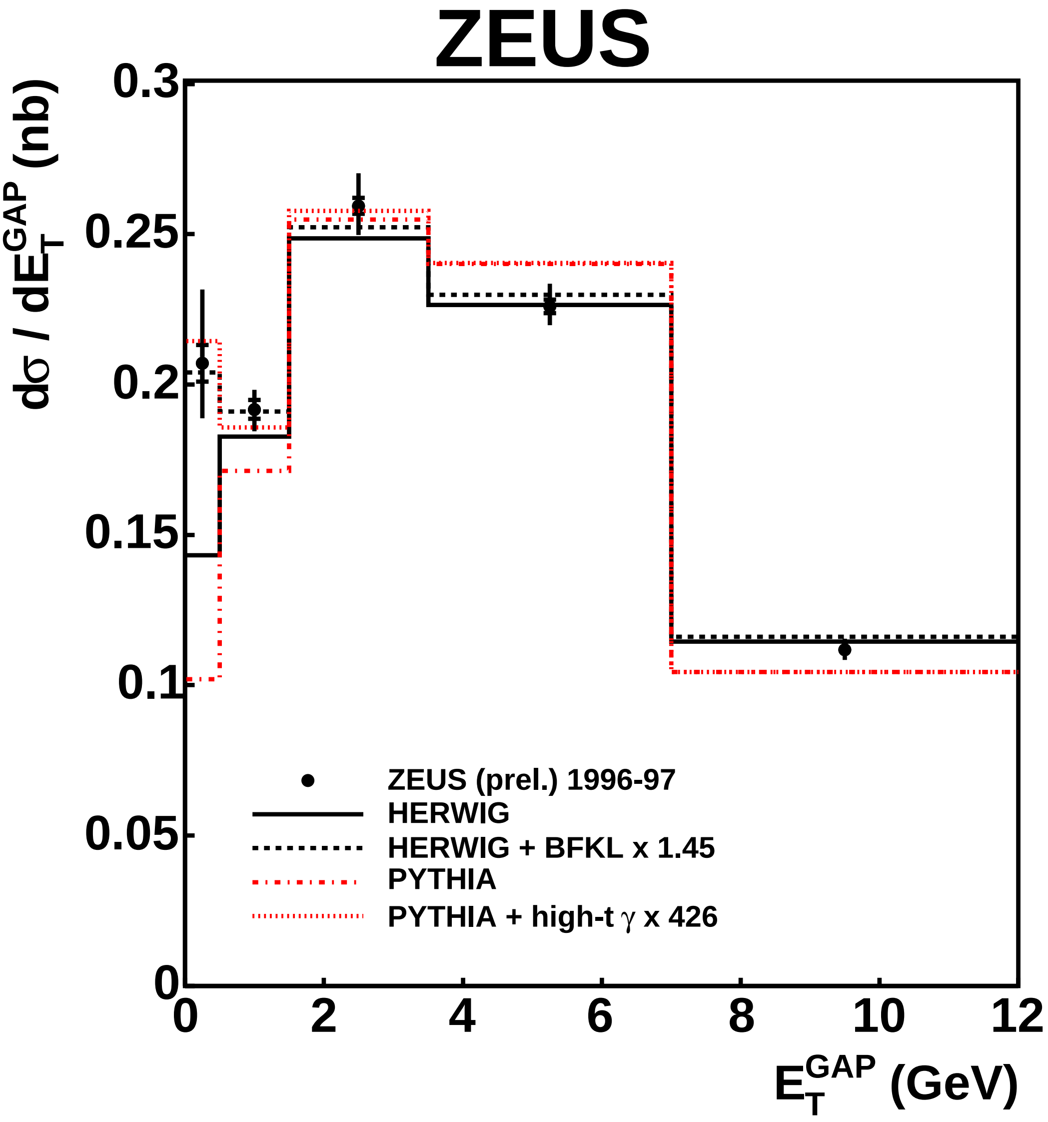

Figure 1: *The inclusive dijet gap cross section differential in $E_{\mathrm{T}}^{\mathrm{GAP}}$. The black circles represent the ZEUS data, with the inner error bars representing the statistical errors and the outer error bars representing the statistical and systematic uncertainties added in quadrature. The solid black line shows the prediction of* HERWIG *and the black dashed line shows the prediction of* HERWIG *plus* BFKL *Pomeron exchange. The dot-dashed line shows the prediction of* PYTHIA *and the dotted line shows the prediction of* PYTHIA *plus high-t photon exchange.*

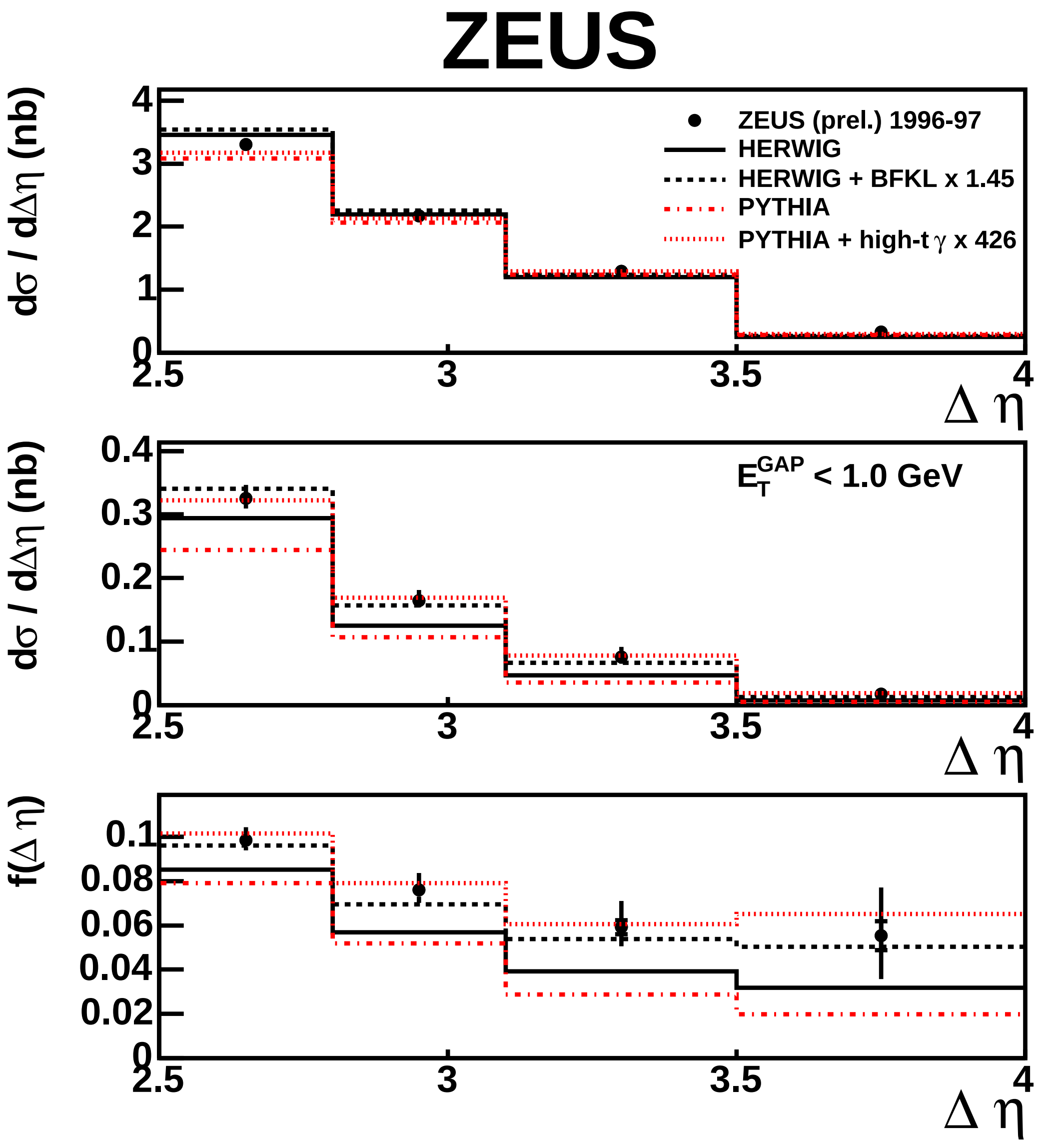

Figure 2: *The top plot is the inclusive dijet gap cross section differential in* $\Delta\eta$*, The middle plot is the cross section differential in* $\Delta\eta$ *requiring that* $E_{\mathrm{T}}^{\mathrm{GAP}} < 1$ *GeV, and the bottom plot is the gap fraction,* f*, in* $\Delta\eta$*. The black circles represent the ZEUS data, with the inner error bars representing the statistical errors and the outer error bars representing the statistical and systematics uncertainties added in quadrature. The solid black line shows the prediction of* HERWIG *and the black dashed line shows the prediction of* HERWIG *plus* BFKL *Pomeron exchange. The dot-dashed line shows the prediction of* PYTHIA *and the dotted line shows the prediction of* PYTHIA *plus high-t photon exchange.*

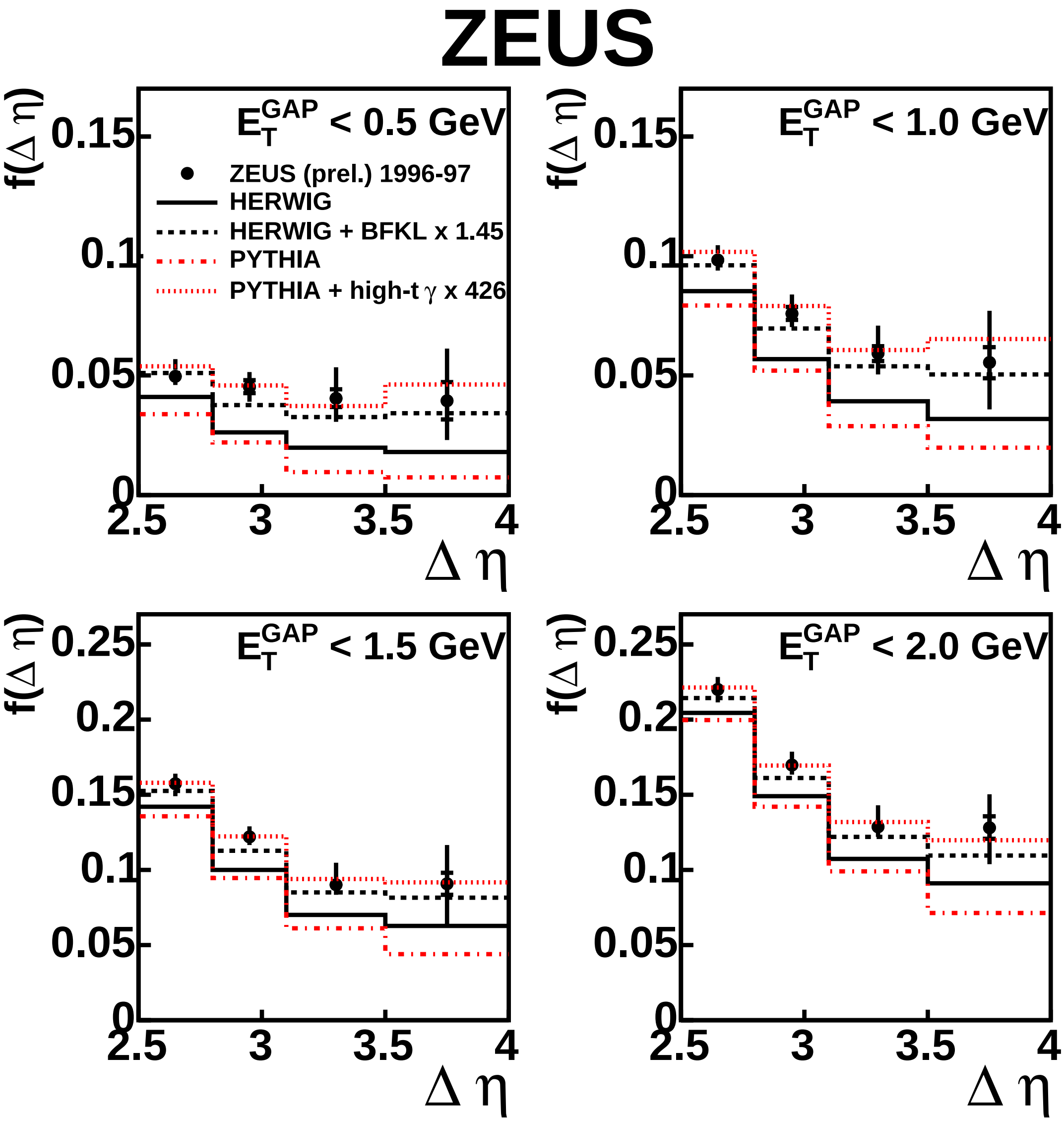

Figure 3: *The gap fraction, f, in $\Delta\eta$. The black circles represent the ZEUS data, with the inner error bars representing the statistical errors and the outer error bars representing the statistical and systematics uncertainties added in quadrature. The solid black line shows the prediction of* HERWIG *and the black dashed line shows the prediction of* HERWIG *plus* BFKL *Pomeron exchange. The dot-dashed line shows the prediction of* PYTHIA *and the dotted line shows the prediction of* PYTHIA *plus high-t photon exchange.*