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# Jet Production in Diffractive *ep* scattering

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**Abstract**

Jet production in deep inelastic scattering events with a large rapidity gap is a powerful way to test our understanding of the nature of diffraction. The ZEUS and H1 collaborations have measured cross sections for two and three jet production in diffractive deep inelastic scattering and compared them to predictions of various theoretical models. No model is able to describe all aspects of the data. The resolved Pomeron model still provides the best description of the experimental results, but two gluon exchange models start to become competitive.

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# Jet Production in Diffractive *ep* scattering

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## INTRODUCTION

The electron–proton collider HERA provides a unique opportunity to study deep inelastic *ep* collisions at center–of–mass energies up to $\sqrt{s} = 320\,\mathrm{GeV}$ and to observe the hadronic final states in these interactions. Diffractive deep–inelastic scattering (DIS) events were first observed in 1993 [1]. These events are distinguished from "ordinary" DIS events by the absence of hadronic activity around the direction of the outgoing proton remnant (called "forward direction" at HERA), so that a large interval in rapidity between the unobserved proton remnant and the current jet is void of hadrons. This interval is termed the "rapidity gap". Subsequent studies have shown that in these large rapidity gap events the proton remnant consists mostly of a single proton [2], or a low–mass excitation of the nucleon.

## MODELS AND MONTE CARLO GENERATORS

The closer investigation of this class of events started with the measurement of the semi–inclusive structure function ${F_2}^{\mathrm{D}(3)}$, which parametrizes the *ep*–cross section for events with a large rapidity gap [3,4]. Today a QCD factorization theorem exists [5] which proves that this is indeed a valid approach.

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**The Resolved Pomeron Model:** Rapidity gap events can be interpreted as the scattering of the electron off a colorless object that is emitted by the proton and behaves rather like a hadron. In the framework of Regge theory [6], this object is identified with the pomeron, as was predicted already in 1985 by Ingelman and Schlein [7]. Their so–called resolved Pomeron model, which describes diffractive events as the emission of a Pomeron[2], whose interaction with the electron in DIS events the $eI\!P$ cross section is parametrized by a structure function, is today still the model that best describes the properties of large rapidity gap events. It has been implemented in the Monte Carlo generator RAPGAP [8], which additionally incorporates also the models of Bartels et al., the saturation model, and the semiclassical model of Buchmüller et al. that are described below.

**Two–Gluon and Color–Dipole Models:** Attempts to describe diffraction in terms of QCD started with a proposal from Low and Nussinov [9] that Pomeron exchange may be modeled as the exchange of two gluons.

Different calculations exist for the process $ep \to e'p'X$, where $X$ is a hadronic system separated in rapidity from the final state proton $p'$, in the framework of two–gluon models. Bartels, Jung, Lotter, and Wüsthoff [10] calculate the cross section for processes where the photon splits into a $q\bar{q}$ pair or a $q\bar{q}g$ state before the interaction with the proton, using the unintegrated gluon distribution in the proton[3]. To avoid divergencies, a lower cutoff must be applied on the gluon $p_{\mathrm{t}}$ in $q\bar{q}g$ states, which has to be tuned to the data.

Ryskin [11] also considers contributions from $q\bar{q}$ and $q\bar{q}g$ states, but only in the leading log approximation, taking only $k_{\mathrm{t}}$ ordered contributions into account. This model is implemented in the Monte Carlo generator RIDI [12].

The saturation model from Golec–Biernat and Wüsthoff [13] models the gluon $k_{\mathrm{t}}$ distribution down to 0, and can therefore be applied to diffractive and non–diffractive DIS and photoproduction with few free parameters, which are all fixed by non–diffractive DIS.

**Semiclassical Model:** The semiclassical model of Buchmüller, Gehrmann, and Hebecker [14] treats the interaction of the $q\bar{q}(g)$ state with the proton as an interaction with a color field, similar to the saturation model. This leads to a prediction for the gluon distribution the proton and hence to a prediction of the rate of diffractive events.

**Soft Color Interactions:** Somewhat similar to the semiclassical model, the model of soft color interactions by Edin, Ingelman, and Rathsman [15] links diffractive and non–diffractive topologies in $ep$ scattering. It is assumed that $q\bar{q}$ states originating from photon–gluon fusion can be transformed from a color octett to a singlet state by the exchange of soft gluons between the $q\bar{q}$ system and the proton remnant. This model, which was recently further developed [16], is implemented in the Monte Carlo generator LEPTO [17].

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2) In certain kinematic regions additional Regge trajectories, especially four degenerate trajectories termed collectively "Reggeon," must also be included in this picture.

3) Compared to the "normal" gluon distribution, which depends on Bjorken $x$ and $Q^2$, the unintegrated gluon distribution additionally depends on the $k_{\mathrm{t}}$ of the gluon.

# H1 MEASUREMENTS OF DIFFRACTIVE DI– AND THREE-JET PRODUCTION

The H1 Collaboration has used data taken in 1996–97, when HERA collided 820 GeV protons with 27.5 GeV positrons, to measure cross sections for diffractive production of two or three jets [18], extending a previous measurement [19]. The data correspond to an integrated luminosity of 18 pb$^{-1}$. They use a cone algorithm in the $\gamma p$ center–of–mass system to identify jets with a transverse momentum $p_{\mathrm{T}}$ greater than 4 GeV. The kinematic range covered by the analysis is $4 < Q^2 < 80\,\mathrm{GeV}^2$ and $x_{\mathbb{P}} < 0.05$. Diffractive events are identified by requiring a rapidity gap visible in the detector and no activity in the forward direction. This restricts the mass of the proton remnant to values of $M_{\mathrm{Y}} < 1.6\,\mathrm{GeV}$.

## *Comparison to the Resolved Pomeron Model*

The left side of Fig. 1 shows a comparison of the measured spectrum of $z_{\mathbb{P}}$ with predictions from the resolved Pomeron model. The quantity $z_{\mathbb{P}}$ is defined as

$$z_{\mathbb{P}} = \frac{Q^2 + M_{12}^2}{Q^2 + M_{\mathrm{X}}^2},$$

where $M_{12}$ and $M_{\mathrm{X}}$ are the mass of the dijet system and the diffractive hadronic system (*i. e.* the $\gamma I\!P$ system), respectively. It can be interpreted as the fractional momentum

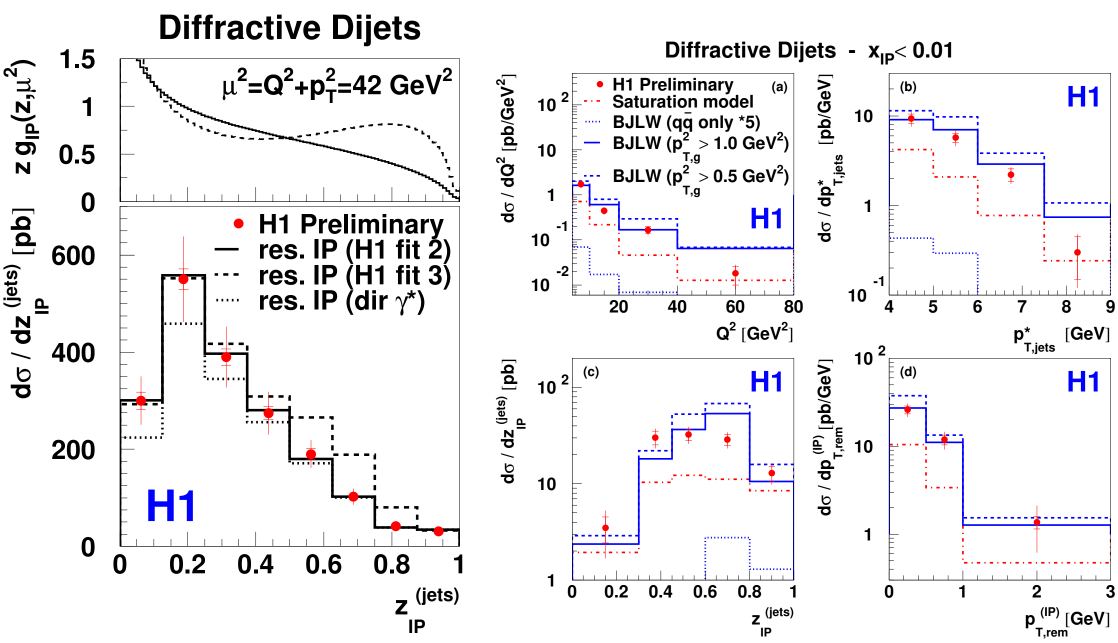


**FIGURE 1.** H1 dijets events. Left: Comparison of the $z_{\mathbb{P}}$ distribution to the resolved Pomeron model for various gluon densities in the Pomeron. Right: Comparison of the H1 dijet data to the two–gluon exchange model of Bartels et al. and the saturation model.

of the parton, particularly the gluon, in the Pomeron that enters the hard interaction with the photon. The measurement is compared to predictions for two gluon density parametrisations of the Pomeron, derived in Ref. [4]: "H1 fit 2" is a gluon density which is flat at the starting scale $Q_0^2$, whereas "H1 fit 3" is strongly peaked at $z_{\mathbb{P}} = 1$ for $Q_0^2$ (at $Q_0^2$, the H1 fit 3 gluon looks like a single gluon, which is accompanied or "dressed" by a very soft gluon). Both these gluon distributions fit the inclusive diffractive data from H1 equally well, whereas the dijet data are directly sensitive to the gluon distribution and prefer the "fit 2" gluon density, as seen in Fig. 1.

## *Comparison to Two–Gluon Models*

In order to make a comparison of the H1 dijet data with the two–gluon model of Bartels et al. (BJLW) and the saturation model, an additional cut of $x_{\mathbb{P}} < 0.01$ was applied to the data, to restrict the comparison to a kinematic range which is expected to be dominated by gluon–exchange. The right side of Fig. 1 shows a comparison of the data to these two models. For the BJLW model, curves are shown for two different values ($0.5\,\mathrm{GeV}^2$ and $1.0\,\mathrm{GeV}^2$ of the cutoff for the gluon $p_{\mathrm{T}}^2$, plus a curve where only $q\bar{q}$ states are taken into account in the calculation. Shown are the distributions of $Q^2$, the transverse momentum $p^*_{\mathrm{T,jets}}$ of the jets, of $z_{\mathbb{P}}$ , and the quantity $p^{(\mathbb{P})}_{\mathrm{T,rem}}$, which is the total transverse momentum of all particles in the Pomeron hemisphere that do not belong to one of the jets.

As can be seen, the BJLW model describes the data reasonably well in shape and normalization for a cutoff value of the gluon $p_{\mathrm{t}}^2 > 1.0\,\mathrm{GeV}^2$, although the $z_{\mathbb{P}}^{(\mathrm{jets})}$ distribution shows some deviations from the data. Clearly the consideration of $q\bar{q}$ states alone leads to jet rates more than an order of magnitude too low. The saturation model describes the shapes of the distributions comparably well; however, with the present set of parameters the normalization is low by a factor of about 2.

The ability of these two models to describe the shape and partially also the normalization of the data can be regarded as a major success of these calculations.

## *Comparison to the Soft Color Interaction and Semiclassical Models*

Fig. 2 shows a comparison of the Soft Color Interaction (SCI) model (in its original form and with the generalized area law) and the Semiclassical model to the data. Plotted are the distributions of $p_{\mathrm{T,jets}}{}^*$, $M_{\mathrm{X}}$, $\log_{10} x_{\mathbb{P}}$, and $z_{\mathrm{pom}}$. The Semiclassical and the original SCI model give very similar predictions, which are both too low by about a factor of 2 in normalization; the generalized area law version of the SCI model predicts approximately the correct rate of two–jet events, but fails to correctly describe any of the kinematic distributions.

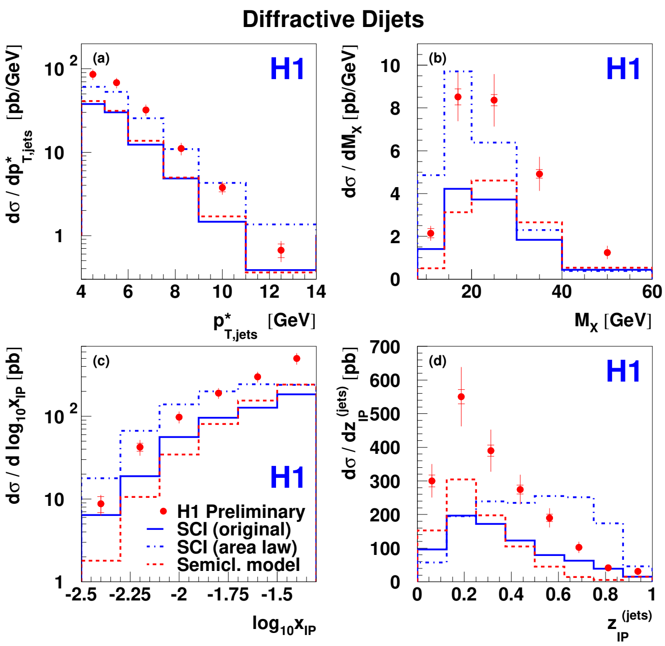


**FIGURE 2.** H1 dijet data compared to the soft color interaction and the semiclassical Model.

## *Three–Jet Events*

Apart from about 2500 dijet events, also 130 three–jet events were found in the H1 data sample. The invariant mass $M_{123}$ of the three jets and $z_{\mathbb{P}}$ distributions for these events are shown in Fig. 3, in comparison with the resolved Pomeron and the BJLW models. The resolved Pomeron model predicts about a factor of 2 too few events, regardless of whether parton showers (MEPS) or color dipole radiation (CDM) are used to approximate higher order contributions to jet production. The BJLW model is about a factor of 10 too low.

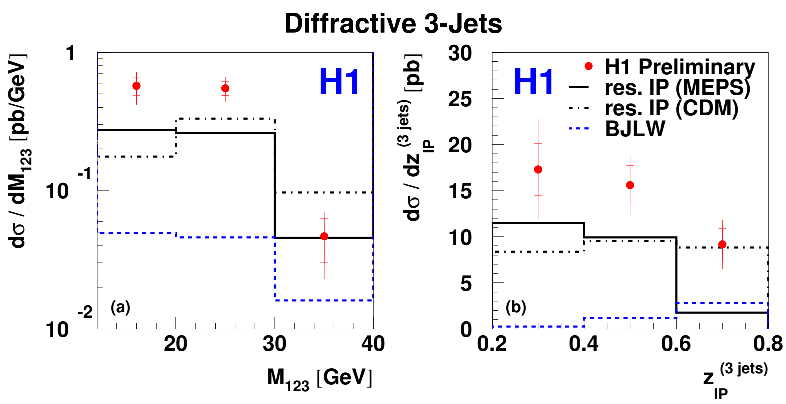


**FIGURE 3.** H1 three–jet event data, compared to the predictions from the resolved Pomeron model and the two–gluon model by Bartels et al.

# ZEUS MEASUREMENT OF DIFFRACTIVE THREE–JET PRODUCTION

The ZEUS Collaboration has analysed [20] data taken in 1998–2000, when HERA collided 920 GeV protons with 27.5 GeV electrons or positrons, extending an earlier measurement [21]. The data correspond to an integrated luminosity of about 39 $\mathrm{pb}^{-1}$. Diffractive events were identified by requiring a rapidity gap in the calorimeter and no activity in the forward direction, especially the newly installed forward plug calorimeter [22]. The kinematic range covered is given by $5 < Q^2 < 100\,\mathrm{GeV}$, $200 < W < 250\,\mathrm{GeV}$ ($W$ is the $\gamma p$ invariant mass), $23 < M_{\mathrm{X}} < 40\,\mathrm{GeV}$, and $x_{\mathbb{P}} < 0.025$. Jets are identified in the center–of–mass system of the observed hadronic final state using the Durham ($k_{\mathrm{t}}$) algorithm [23]. Studying the rates of two versus three jet events gives an insight into the relative importance of $q\bar{q}$ and $q\bar{q}g$ parton configurations; additionally, the jet topologies are sensitve to the $p_{\mathrm{t}}$ of the partons in the pomeron and therefore allow to test various models in a new domain.

Fig. 4 shows the dependency of the reconstructed number of jets on the jet resolution parameter $y_{\mathrm{cut}}$, for data and three Monte Carlo models: the resolved Pomeron model (RAPGAP), the saturation model (SATRAP), and the two–gluon model by Ryskin (RIDI). A resolution parameter of 0.05 gives a good jet–parton correlation, with about 20 % three–jet events, and was therefore chosen for the analysis. A total number of 678 three-jet events were such found.

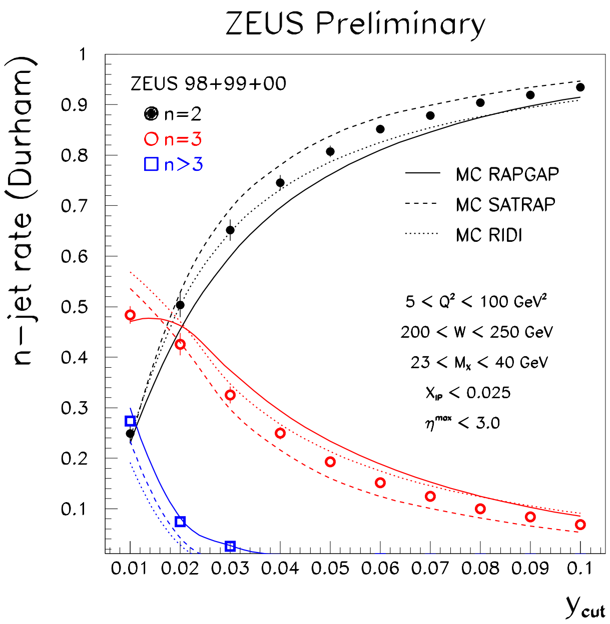


**FIGURE 4.** ZEUS measurement of jet rates as function of the jet resolution parameter $y_{\mathrm{cut}}$, compared to the predictions from the resolved Pomeron model (RAPGAP), the saturation model (SATRAP), and the two–gluon model by Ryskin (RIDI).

## *Three–Jet Final–State Topology*

The topology of a three–jet configuration can be described by introducing the variables $x_{\rm i} = 2\,E_{\rm i}/M_{\rm X}$, where $E_{\rm i}$ $(i = 1, 2, 3)$ are the jet energies, ordered such that $E_1 > E_2 > E_3$. Two of these three variables are sufficient to describe the jet topology. Following studies of three–jet production in $e^+e^-$ collisions at PETRA [24], the quantities $x_1$ versus $(x_2 - x_3)/x_1$ were plotted in Fig. 5. As can be seen, all possible three-jet topologies are present in the data. The right side of Fig. 5 shows the energy flow in the three–jet plane in two regions of the $(x_1, (x_2 - x_3)/x_1)$ plane, namely $(x_2 - x_3)/x_1 > 0.4$ (upper right) and $x_1 < 0.8, (x_2 - x_3)/x_1 < 0.4$ (lower right). The resolved Pomeron model (RAPGAP) and the saturation model (SATRAP) give a good description of the observed energy flow, while the RIDI model, although somewhat too peaked, is still reasonable.

## *Jet Rapidity Distribution*

The ZEUS Collaboration has also measured the differential jet cross section $d\sigma/d\eta^{\rm jet}$ as function of the pseudorapidity $\eta^{\rm jet}$ of the jets in the hadronic center–of–mass system (the direction of $\eta^{\rm jet}$ is defined such that $\eta^{\rm jet} < 0$ corresponds to the direction of the virtual photon). The result is shown in Fig. 6. Only the resolved Pomeron model (RAPGAP) is

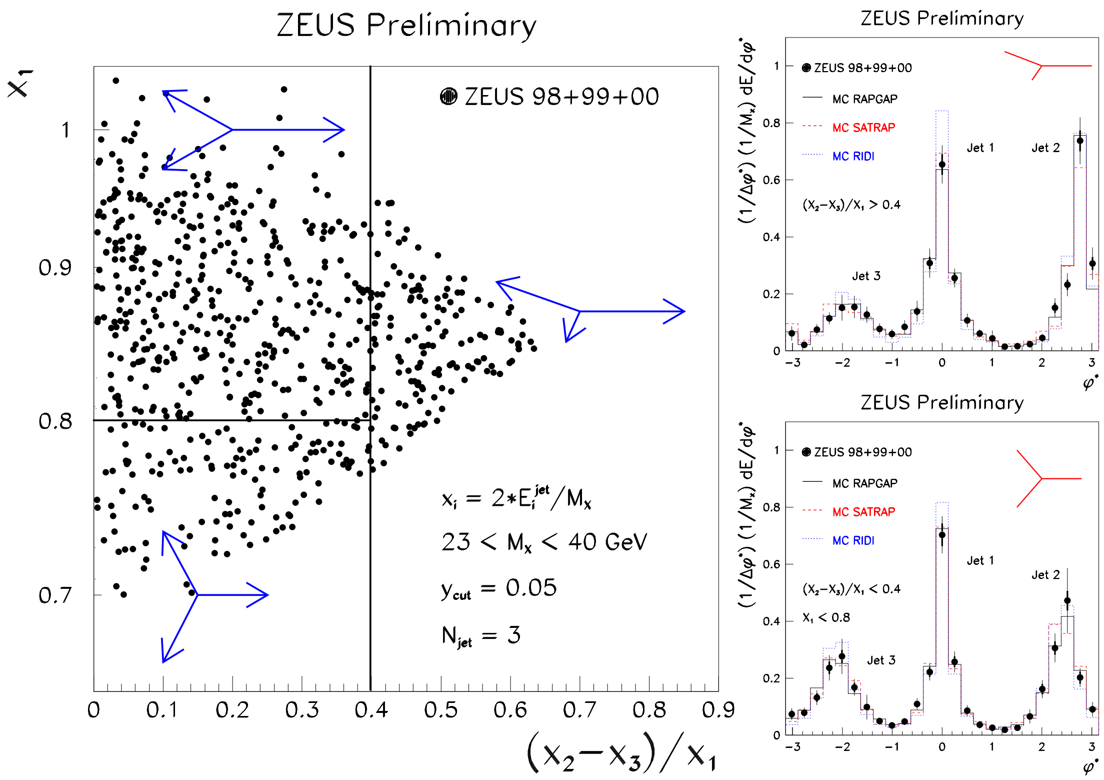


**FIGURE 5.** Three jet topologies as observed by the ZEUS collaboration and energy flow in the three–jet plane for two different in the $(x_1, (x_2 - x_3)/x_1)$ plane.

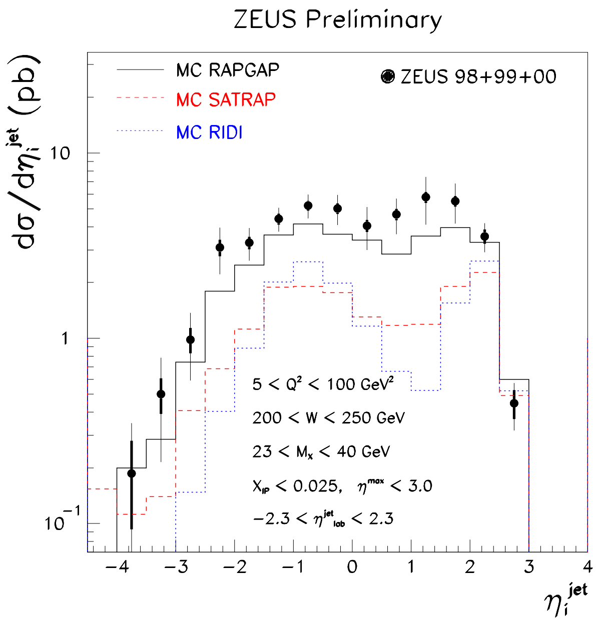


**FIGURE 6.** The differential jet cross section $\mathrm{d}\sigma/\mathrm{d}\eta^{\mathrm{jet}}$ as a function of the pseudorapidity $\eta^{\mathrm{jet}}$ of the jets in the hadronic center–of–mass system, measured by ZEUS, in comparison to the Monte Carlo models.

able to describe the observed data in shape and normalization; it is still low by a factor of about 1.5, which may be attributable to the remaining proton dissociation events in the data, which are not modeled in the Monte Carlo sample.

By comparison, both the saturation model (SATRAP) and the Ryskin model (RIDI) lie about a factor of 3 below the data. Moreover, the RIDI model shows a marked dip around $\eta^{\mathrm{jet}} = 1$. It seems that in the RIDI model the Pomeron remnant is too much aligned with the Pomeron direction, which may be an indication that the gluons that enter the hard interaction carry too little $p_{\mathrm{t}}$ in this model.

## SUMMARY AND CONCLUSIONS

Both the H1 and ZEUS Collaborations have measured jet production cross sections in diffractive deep inelastic scattering. The data demonstrate clearly that the Pomeron is a gluon–dominated object, and are sensitive to the gluon distribution in the Pomeron. No single model is able to perfectly describe all aspects of the data. The resolved Pomeron model is still “the model to beat,” as it provides overall the most satisfactory description of the data. However, models based on perturbative QCD that rest on firmer ground than the resolved pomeron model are becoming more successful. This may open the door to a solid theoretical understanding of diffraction in terms of QCD.

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