Inclusive Diffraction at HERA

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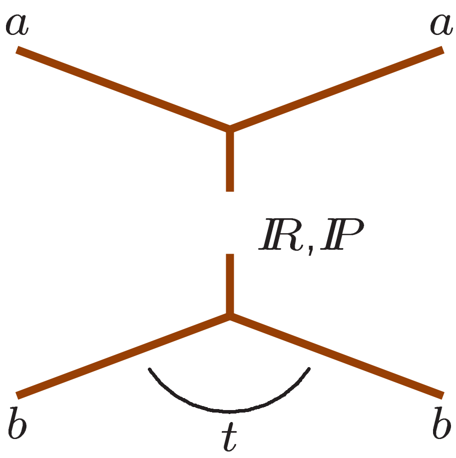
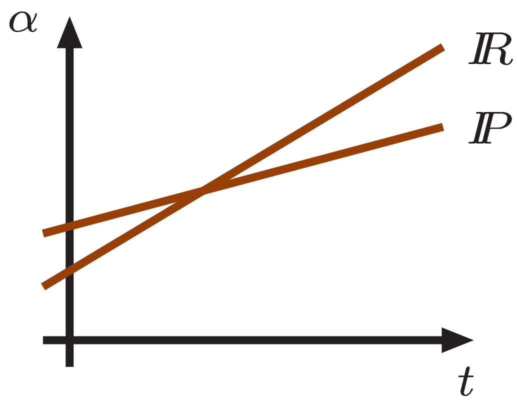
Outline of this talk

- Introduction
- Short update on current theory
- Inclusive cross section at low Q^2
- High-E_T jet production
- Energy flow between jets
- Conclusion

Diffractive phenomena and the pomeron

Soft hadron scattering is described by Regge phenomenology:





$$\frac{d\sigma_{el}^{ab}}{dt} = \sum_{k=I\!R, I\!P} [\beta] s^{2(\alpha_k(t)-1)}$$

$$\alpha_{I\!R}(t) = 0.5 + t$$
$$\alpha_{I\!P}(t) = 1.08 + 0.25 \cdot t$$

- elastic and total cross sections are related by the optical theorem
- also single and double dissociation can be described in terms of reggeon and pomeron exchange

At high energies, the pomeron dominates the cross section. However, until recently, no fundamental understanding of the pomeron exists in terms of QCD!

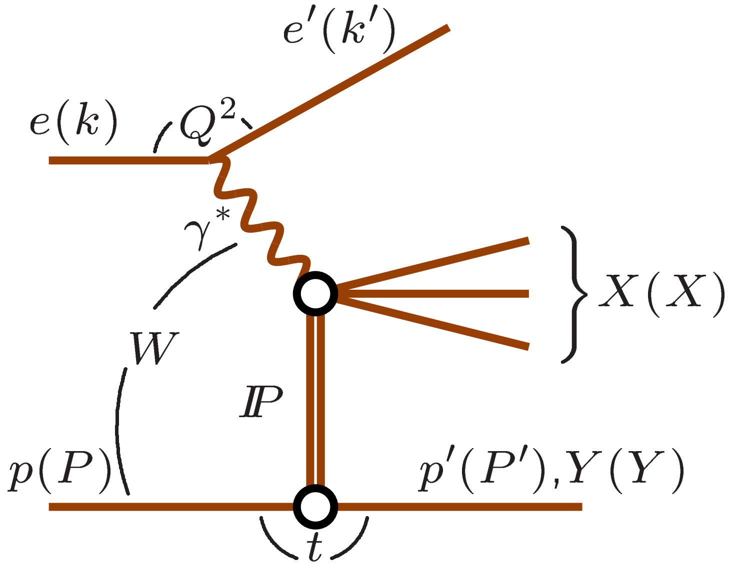
Why study diffraction at the HERA ep collider?

- small Bjorken-x $\rightarrow$ long hadronic lifetime of the photon
- "transverse size" of the photon varies with Q^2
- possibility to attack the pomeron with a hard scale

Questions:

- How can we understand the pomeron in terms of QCD?
- Does the pomeron have a partonic structure?
- Is it universal or is there a transition from the soft to hard regime?
- Do we need the pomeron at all?

Kinematics of diffractive ep scattering



$Q^2 = -q^2 = -(k - k')^2$ — photon virtuality

$x = \dfrac{Q^2}{2P \cdot q}$ — Bjorken scaling variable

$y = \dfrac{P \cdot q}{P \cdot k}$ — inelasticity

$W^2 = (P + q)^2$ — $\gamma^* p$ centre-of-mass energy

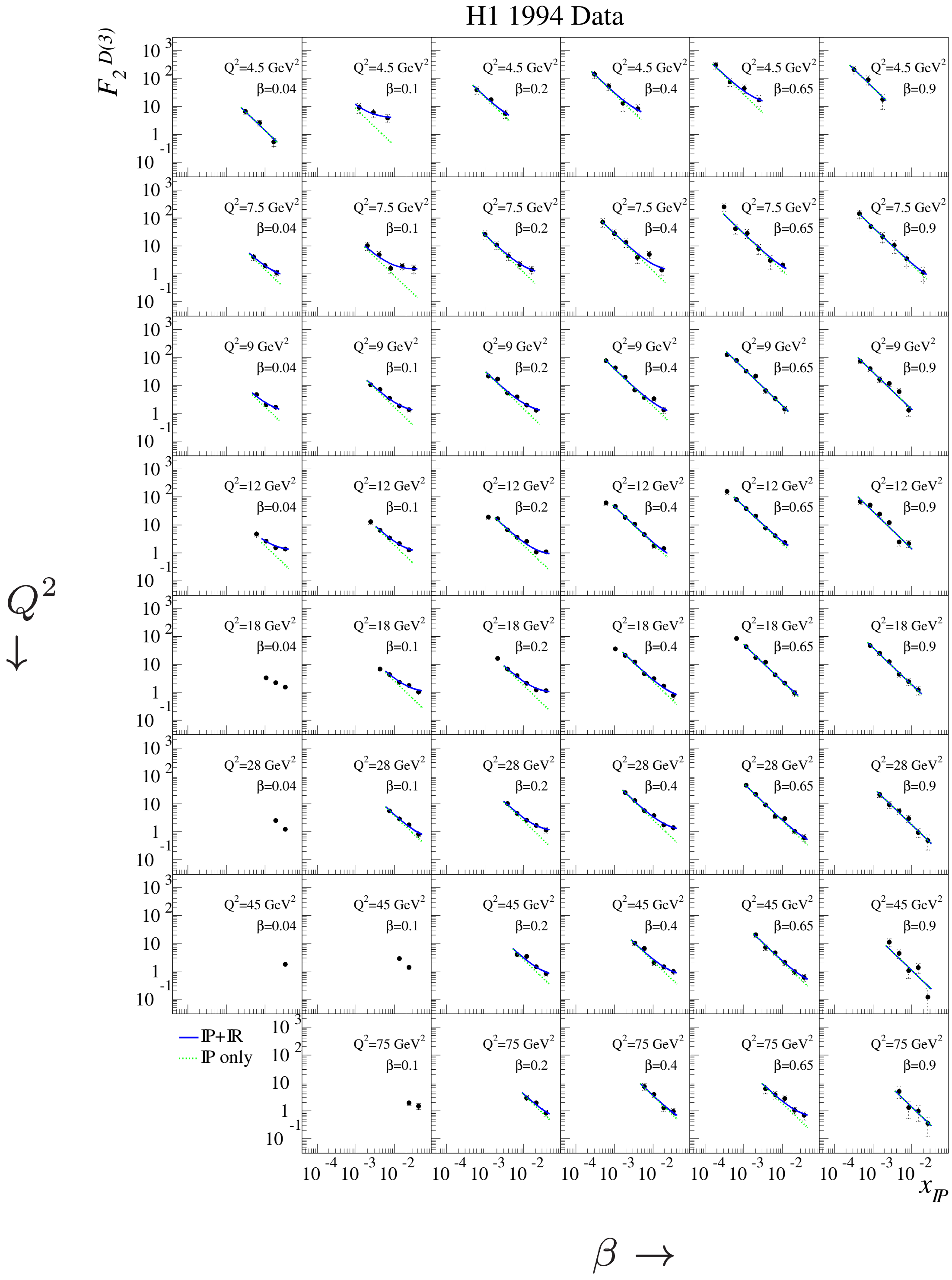
$t = \left(P - P'\right)^2$ — 4-momentum transfer squared

$M_X^2 = X^2$, $M_Y^2 = Y^2$ — invariant masses of X and Y

$x_{I\!P} = \dfrac{q \cdot (P - P')}{q \cdot P}$ — fraction of p momentum transferred to $I\!P$

$\beta = \dfrac{Q^2}{2q \cdot (P - P')}$ — fraction of the $I\!P$ momentum transferred to quark coupling to γ^*

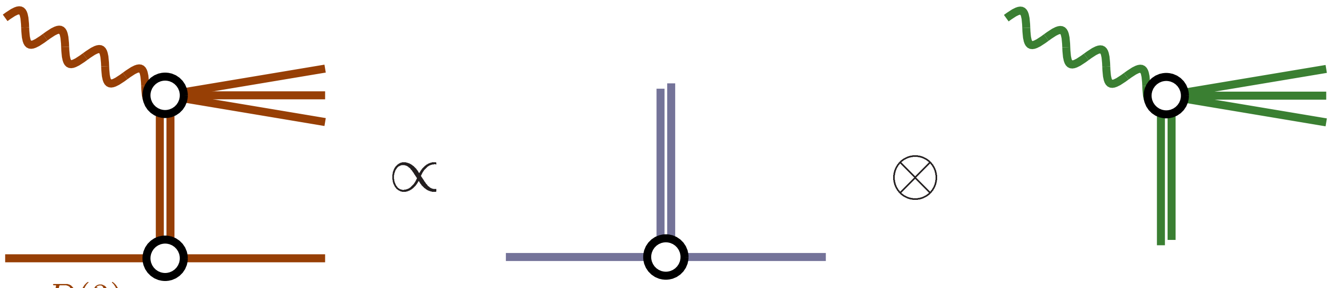
Measurement of the inclusive cross section



$$\frac{\mathrm{d}\sigma^{ep\to eXY}}{\mathrm{d}\beta \mathrm{d}Q^2 \mathrm{d}x_{I\!P}} = \frac{4\pi\alpha^2}{\beta Q^4}\left(1 - y + \frac{y^2}{2}\right) F_2^{D(3)}(\beta, Q^2, x_{I\!P})$$

Regge-like parametrisation of the cross section

Regge factorisation:



$$F_2^{D(3)}(\beta, Q^2, x_{I\!P}) \propto f_{I\!P/p}(x_{I\!P}) \otimes F_2^{I\!P}(\beta, Q^2)$$

$\rightarrow x_{I\!P}$ dependence is universal at all β and Q^2 ($\sim \frac{1}{x_{I\!P}}$)

This works, but data show deviations from this simple Regge model at large $x_{I\!P}$ and small β.

Regge-fits to $F_2^{D(3)}$:

With the addition of a subleading exchange, good fits to $F_2^{D(3)}$ are obtained througout the kinematic range.

$$F_2^{D(3)} = f_{I\!P/p}(x_{I\!P})\, F_2^{I\!P}\left(\beta, Q^2\right) + f_{I\!R/p}(x_{I\!P})\, F_2^{I\!R}\left(\beta, Q^2\right)$$

Regge theory allows to parametrise the long distance physics at the proton vertex:

$$f_{I\!P/p} = \int \left(\frac{1}{x_{I\!P}}\right)^{2\alpha_{I\!P}(t)-1} \mathrm{e}^{B_{I\!P}t}\mathrm{d}t$$

(and similar for $f_{I\!R/p}$)
$\alpha_{I\!P}(0)$ and $\alpha_{I\!R}(0)$ are obtained from a fit.

The short distance physics at the virtual photon vertex is contained in pomeron and reggeon "structure functions".

$F_2^{I\!P}$ and $F_2^{I\!R}$ are free fit parameters in this model.

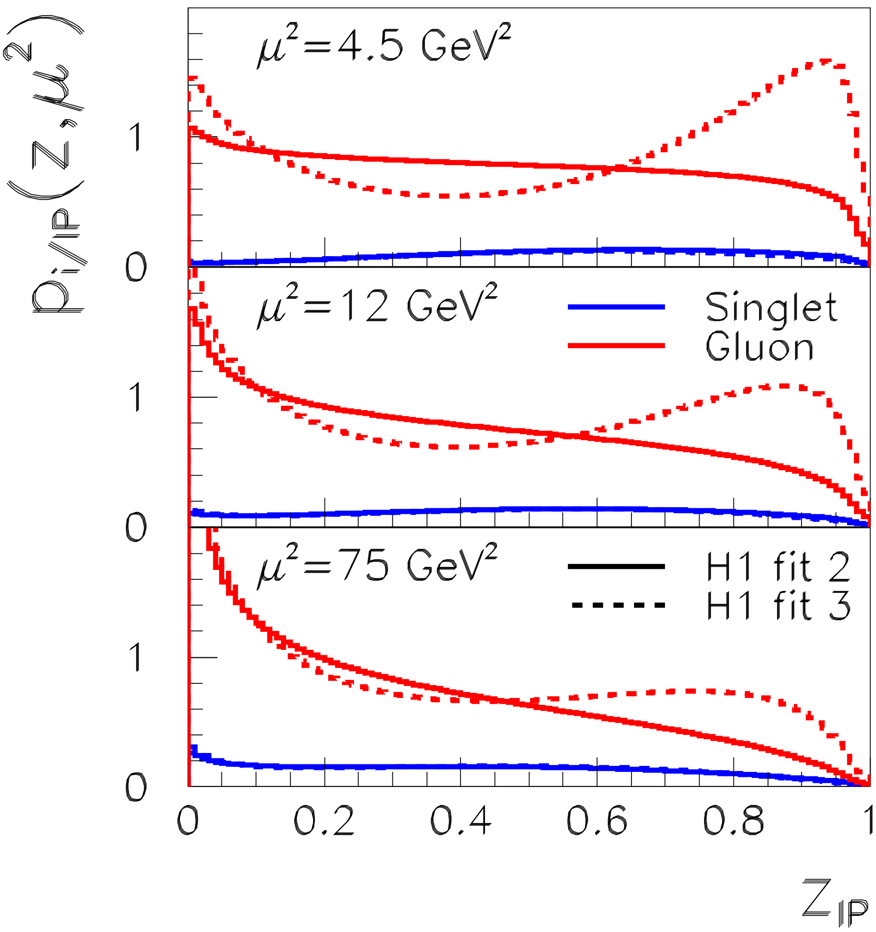
The partonic pomeron

Can we think of the pomeron as a partonic object with single partons entering the hard interaction?

Investigation of the deep-inelastic structure of the pomeron:

The Regge fits to the $x_{I\!P}$ dependence can be extended with a QCD motivated model for the (β, Q^2) dependence.

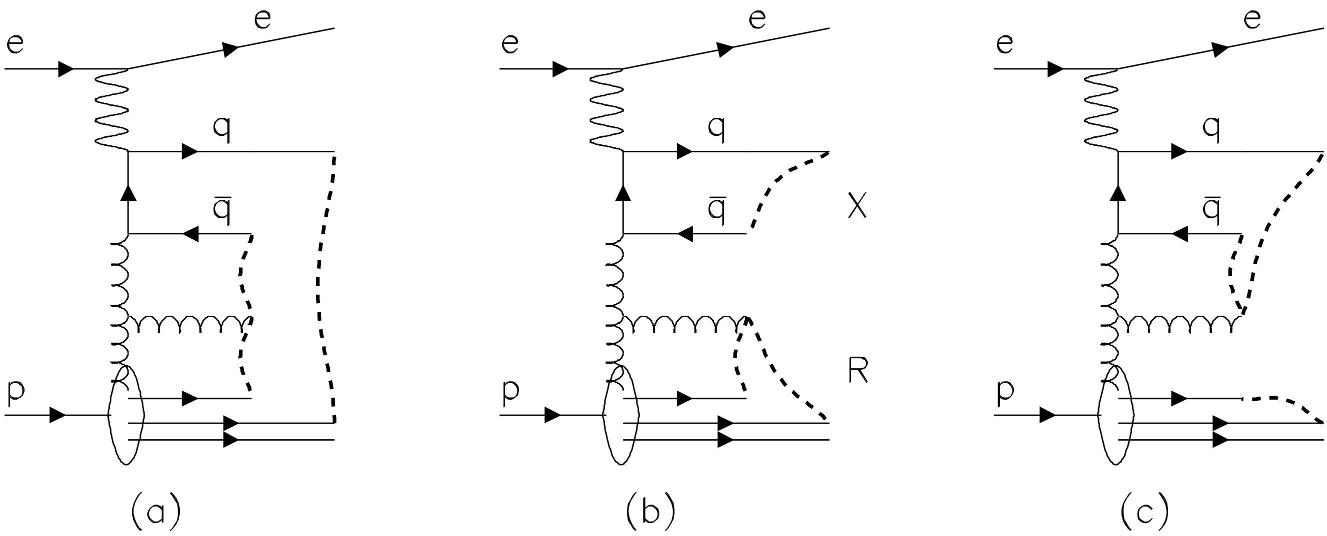
- assume a π structure function for $I\!R$
- take Q^2 evolution from NLO DGLAP equations
- extract parton density functions $p_{q/I\!P}(z,\mu^2)$ (directly) and $p_{g/I\!P}(z,\mu^2)$ (through scaling violations)



$\rightarrow$ $I\!P$ dominated by "hard" gluons

Soft colour interaction model

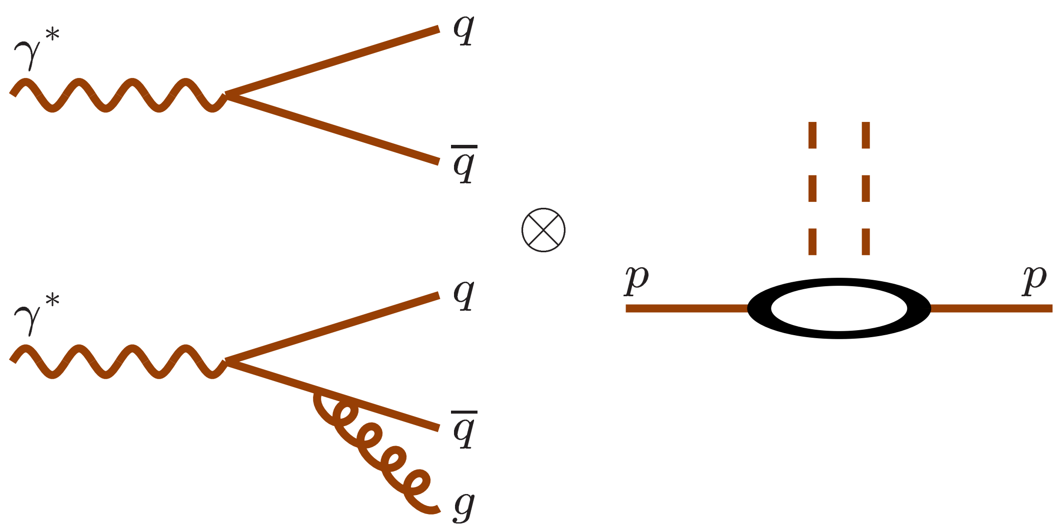
Model of Edin, Ingelman, Rathsmann



- the standard matrix element and parton shower description of $F_2(x, Q^2)$, dominated by boson-gluon fusion at low x, is used
- additional non-perturbative interactions affect the final state colour connections, but not the parton momenta
- an improved version based on the "generalised area law" favours soft colour interactions which make the strings shorter
- only one free parameter (probability for a soft colour interaction) has to be fixed by data!

Photon fluctuation models (1)

At low x, the photon can fluctuate in $q\overline{q}$ / $q\overline{q}g$ partonic configurations long before the actual interaction with the proton.



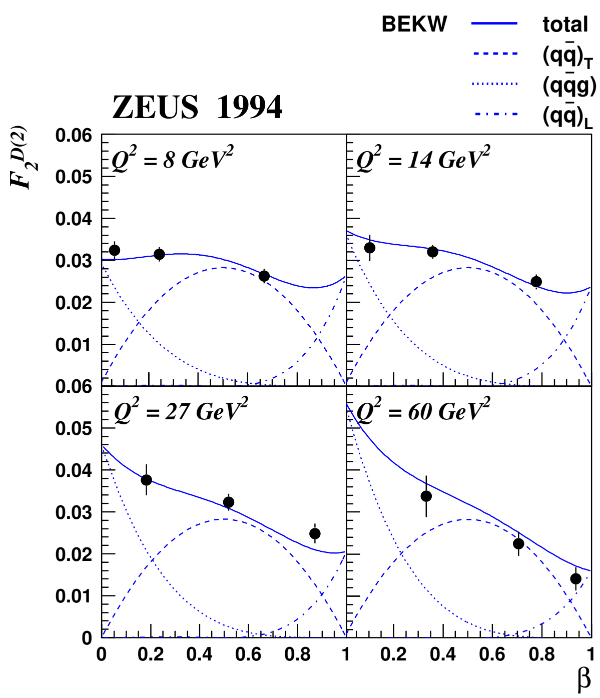
Decomposition into leading / higher twist contributions, longitudinal / transverse photon interactions and $q\overline{q}$ / $q\overline{q}g$ states

β dependence fixed by dipole wave function from perturbation theory:

$$F^L_{q\overline{q}} \propto \frac{Q_0^2}{Q^2} \ln\left(\frac{Q^2}{4Q_0^2\beta}\right) \beta^3 (1-2\beta)^2$$

$$F^T_{q\overline{q}} \propto \beta(1-\beta)$$

$$F^T_{q\overline{q}g} \propto \alpha_S \ln\left(\frac{Q^2}{Q_0^2}\right)(1-\beta)^3$$



$\rightarrow$ clear prediction for the partonic composition of the final state X

Photon fluctuation models (2)

Saturation model (Golec-Biernat, Wüsthoff)

Attempt to desribe saturation of the inclusive cross section at low Q^2, low x leads to a model for the dipole cross section:

$$\hat{\sigma}(x, r^2) = \sigma_0 \left[1 - \exp\left(-\frac{r^2}{4R_0^2(x)} \right) \right]$$

$$R_0(x) = \frac{1}{\mathrm{GeV}} \left(\frac{x}{x_0} \right)^{\lambda/2}$$

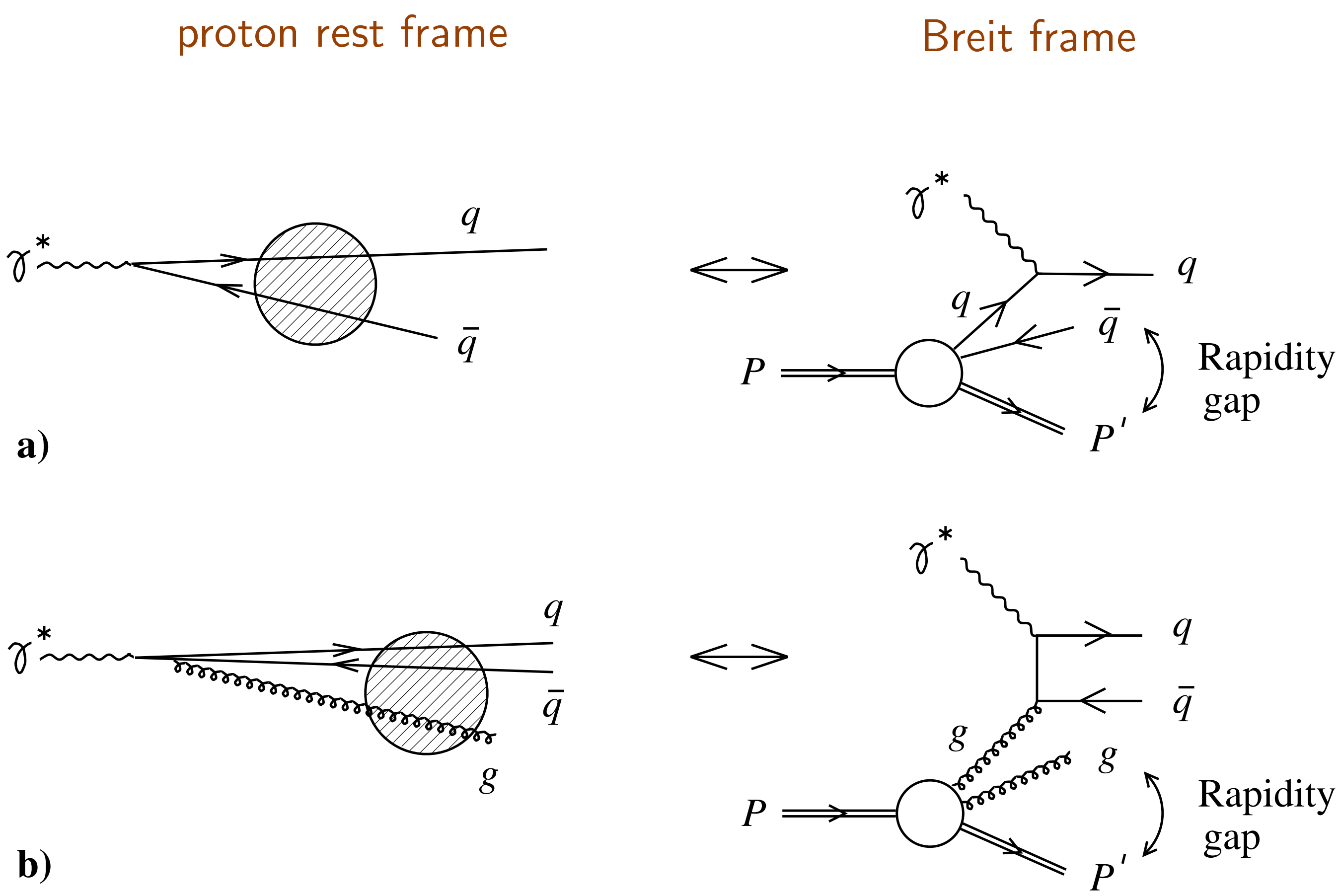
- colour transparency for small r
- saturation at large r
- low-x saturation built in by x-dependent radius R_0

$\rightarrow$ after a fit to inclusive F_2, the diffractive F_2^D follows as a prediction

$\rightarrow$ ratio of diffractive to inclusive cross sections is roughly constant

Photon fluctuation models (3)

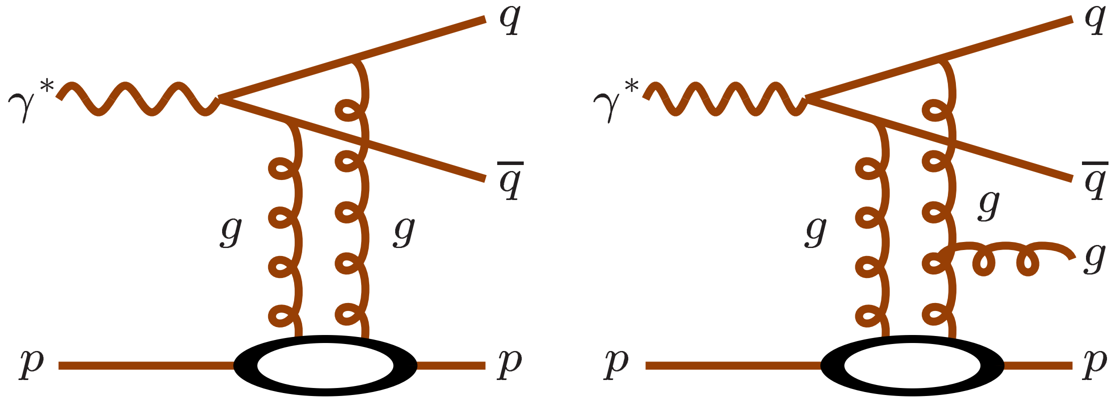
Semiclassical model
(Buchmüller, McDermott, Gehrmann, Hebecker)



- small-x DIS is described as the scattering of a partonic fluctuation of the photon off a superposition of target colour fields.
- the proton colour fields are averaged using an approximation for very large hadrons
- diffraction occurs if the partonic state is a colour singlet
- parton distributions are obtained from a DGLAP analysis of the diffractive and inclusive structure functions

Photon fluctuation models (4)

Two-gluon exchange model (Bartels, Jung, Wüsthoff)



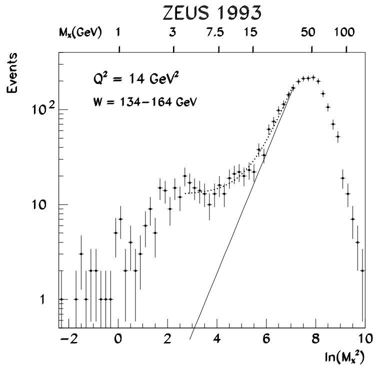
- partonic fluctuations of the photon ($q\overline{q}$, $q\overline{q}g$) scatter elastically off the proton through the exchange of two gluons in a net colour-singlet configuration
- cross section is proportional to the square of the gluon density inside the proton
- calculations require high transverse momentum for all outgoing partons $\rightarrow$ particularly suited for diffractive jet production
- avoid valence quark region and exclude secondary reggeon exchanges $\rightarrow$ model is restricted to $x_{I\!P} < 0.01$

Experimental techniques

Selection of diffraction events by H1 and ZEUS

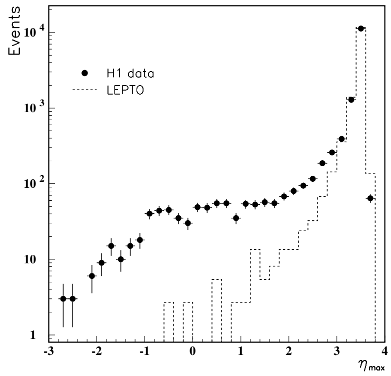
- M_X subtraction method:

$$\frac{\mathrm{d}N}{\mathrm{d}\ln M_X^2} = D + c \cdot \exp(b \ln M_X^2)$$



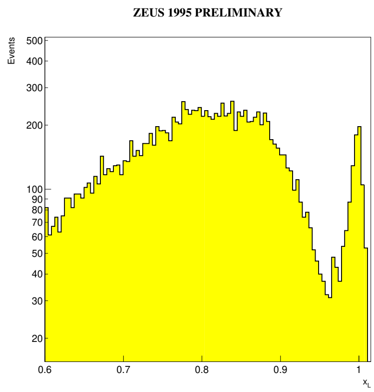
- large rapidity gap selection:

$$\eta_{\max} \quad = \quad \text{pseudorapidity of most forward energy deposit}$$



- leading proton spectrometer:

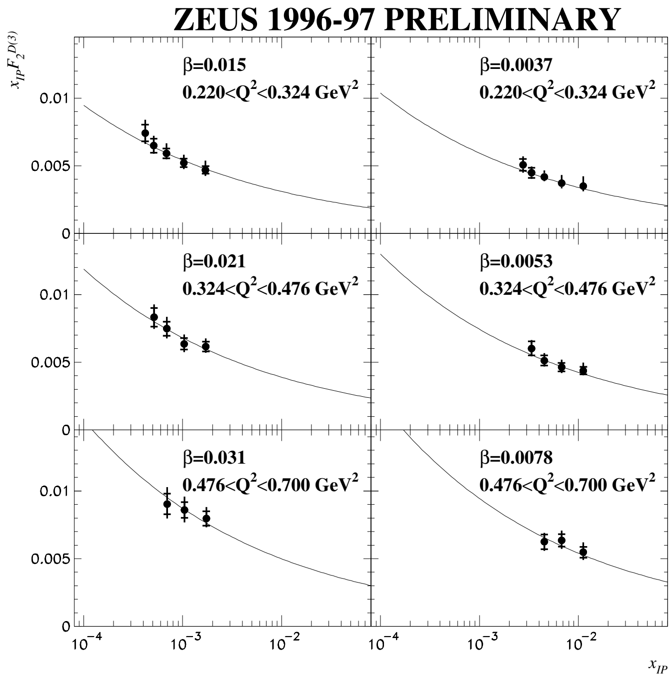
$$x_L = \frac{|p_f|}{|p_i|}$$



Double dissociation background

- problematic in M_X subtraction and large rapidity gap methods (ranging from 10% to 30%)
- differences in DD background for H1 and ZEUS tend to decrease with the use of new low-angle detectors.

Energy behaviour of the diffractive cross section



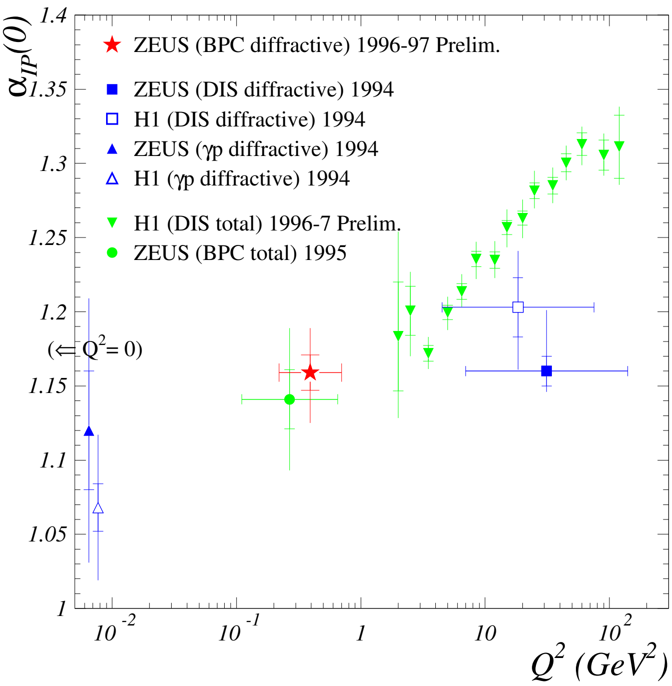
Using M_X subtraction method and BPC for measuring low Q^2:

$$0.22 < Q^2 < 0.70 \text{ GeV}^2$$

$$90 < W < 220 \text{ GeV}$$

$$3 < M_X < 12 \text{ GeV}$$

$$M_Y < 6 \text{ GeV}$$



Result of simple Regge fit:

$$x_{I\!P} F_2^{D(3)} \propto 1/x_{I\!P}^{2\overline{\alpha}_{I\!P}-2}$$

$$\overline{\alpha}_{I\!P} = \alpha_{I\!P}(0) + \alpha'_{I\!P}\overline{t}$$

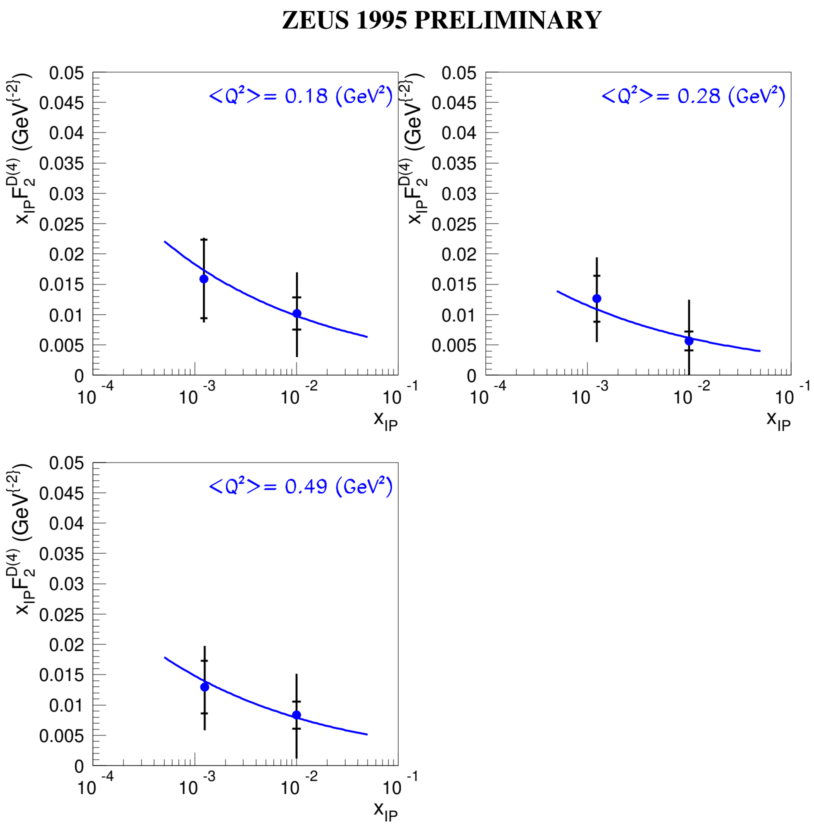
$$\alpha_{I\!P}(0) = 1.159 \pm 0.012^{+0.027}_{-0.032}$$

(assuming $\alpha'_{I\!P} = 0.25$ GeV^{-2} and $|\overline{t}| = 1/7.5$ GeV^2)

$\rightarrow$ data tend to show a rise of diffractive $\alpha_{I\!P}(0)$ with Q^2

Inclusive cross section at low Q^2 (2)

Measurement of $F_2^{D(4)}$ using LPS and BPC



$$x_L > 0.97$$

$$0.14 < Q^2 < 0.70 \text{ GeV}^2$$

$$0.073 < |t| < 0.4 \text{ GeV}^2$$

$$3 < M_X < 32 \text{ GeV}$$

$$90 < W < 220 \text{ GeV}$$

- Result from Regge fit:

$$x_{I\!P} F_2^{D(4)} \propto 1/x_{I\!P}^{2\alpha_{I\!P}-1}$$

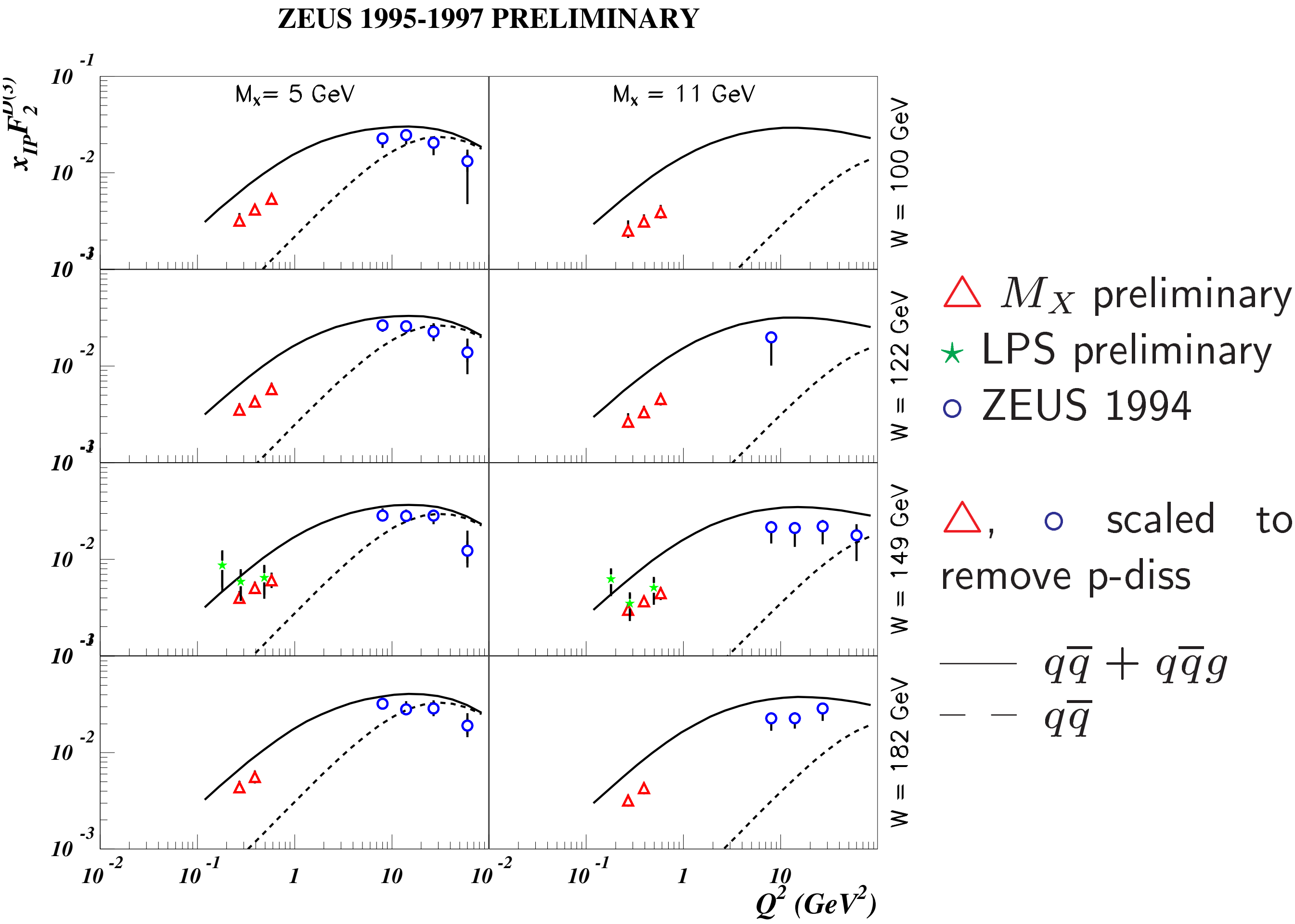
$$\alpha_{I\!P}(0) = 1.184 \pm 0.063^{+0.06}_{-0.09}$$

- Comparison of M_X subtraction and LPS methods yields estimate of proton dissociation background in M_X method:

$$\frac{\sigma^{Diff-M_X}}{\sigma^{Diff-LPS}} = 1.4 \pm 0.3$$

Inclusive cross section at low Q^2 (3)

Comparison with Saturation Model



- Clear transition at low Q^2, as for F_2 ($\propto Q^2$)
- $q\bar{q}g$ dominant at high M_X, low Q^2 (i.e. low β)
- qualitative features of low Q^2 transition are described

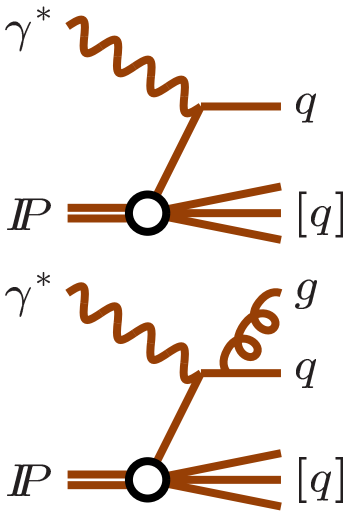
Study of the hadronic final state

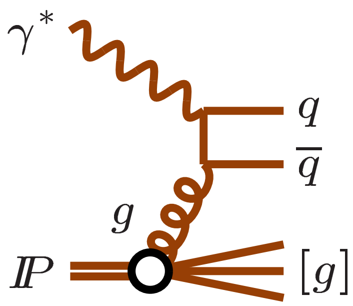
Many final state observables have been measured by H1 and ZEUS:

- thrust, sphericity
- energy flow and particle spectra
- charged particle multiplicities and correlations

These observables are expected to be sensitive to the partonic structure of the final state:

- in terms of the partonic pomeron we can distinguish between quark or gluon initiated processes
- in terms of 2-gluon exchange models, we can investigate the decomposition into $q\overline{q}$ and $q\overline{q}g$ final states.





quarkonic $I\!P$

- dominantly $q\overline{q}$
- QPM and QCD-Compton
- low p_T, aligned to $\gamma^* p$ axis
- few jets
- fragmentation of $3_c\overline{3}_c$

gluonic $I\!P$

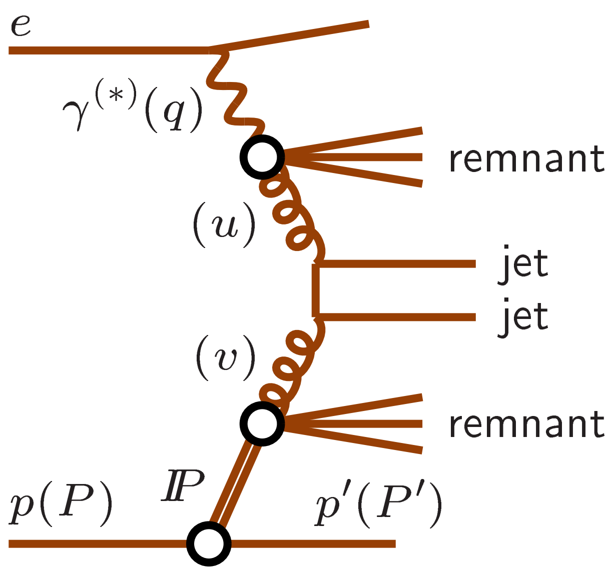
- dominantly $q\overline{q}g$
- boson-gluon fusion
- high p_T, non-aligned
- many jets
- fragmentation of $8_c 8_c$

$\rightarrow$ Final state analyses provide qualitative support for the gluon dominated pomeron

Diffractive high-E_T jet production

Hard jets are an ideal test of the dynamics of diffraction:

- the large E_T provides a hard scale for perturbative calculations
- the production mechanism is sensitive to the gluon content



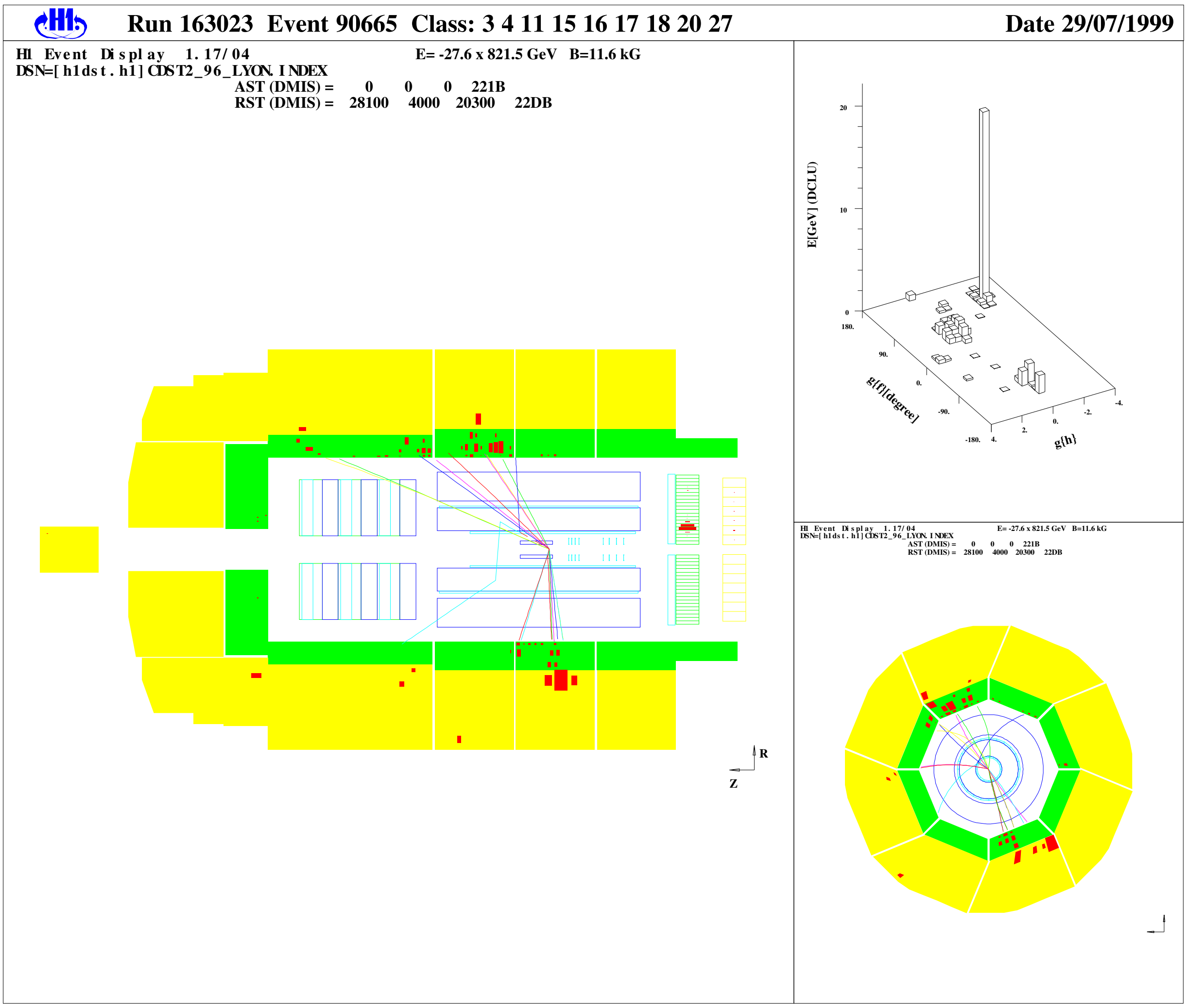
Experimental measurement:

- jets are identified as collimated energy depositions in η-ϕ space within a cone of radius $R = \sqrt{\Delta\eta^2 + \Delta\phi^2} = 1$
- η^{jet} and p_T^{jet} are defined relative to the $\gamma^{(*)}$ in the rest frame of X
- the fractions of the $\gamma^{(*)}$ and $I\!P$ momentum transferred to the system X (i.e. entering the hard scattering) are defined as:

$$x_\gamma = \frac{P \cdot u}{P \cdot q}$$

$$z_{I\!P} = \frac{q \cdot v}{q \cdot (P - P')}$$

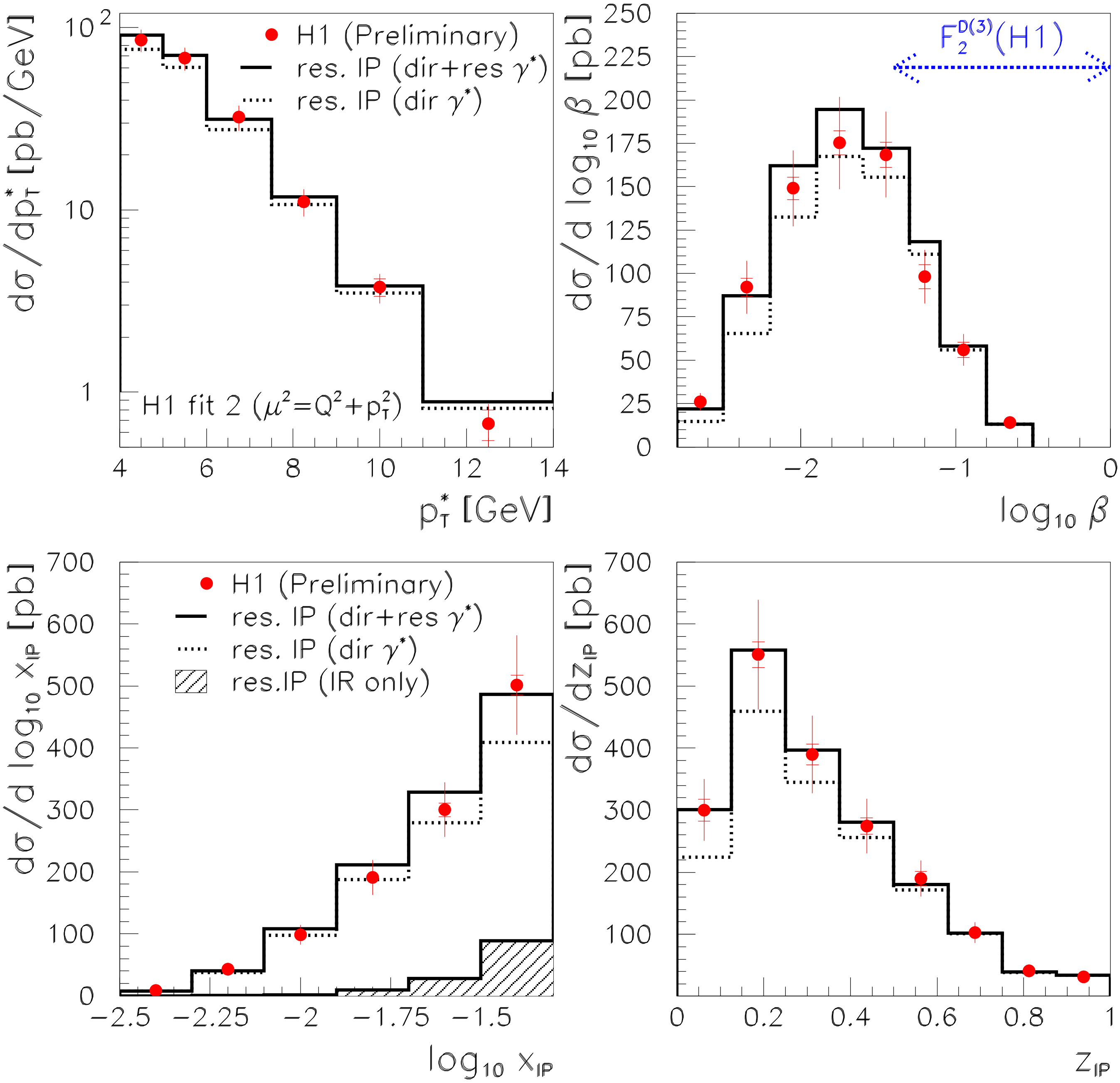
High-E_T jets in diffractive DIS



Preliminary H1 measurement:

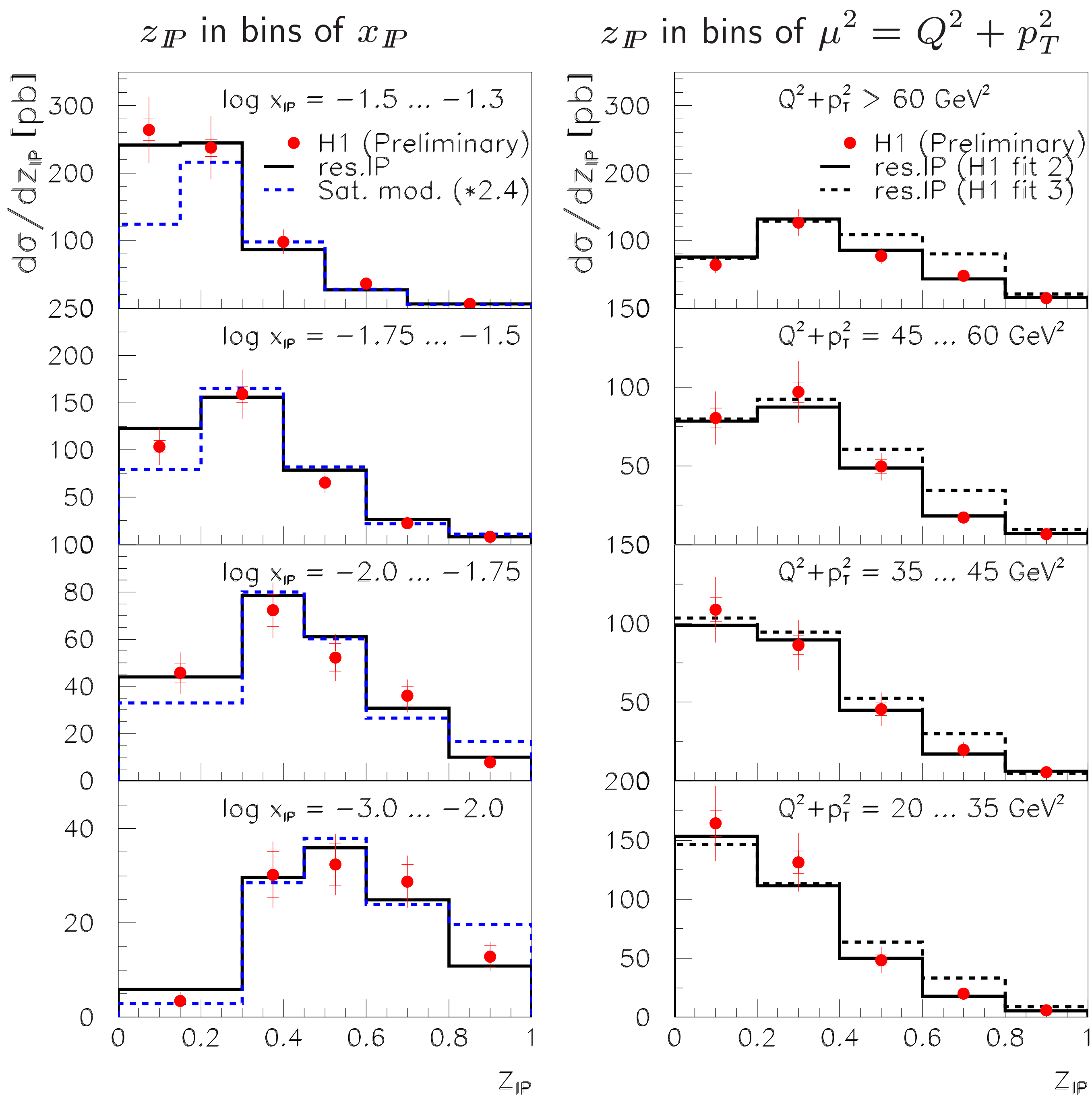
- based on $L_{int} = 17.9$ pb^{-1} (2500 dijet events)
- "rapidity gap selection" (excluding activity in $3.2 < \eta^{lab} < 7.5$)
- cross sections are measured in the kinematic region defined by:
  - $4 < Q^2 < 80$ GeV^2, $0.1 < y < 0.7$
  - $x_{I\!P} < 0.05$, $M_Y < 1.6$ GeV, $|t| < 1$ GeV^2
  - $p_T^{jet} > 4$ GeV , $-3 < \eta^{jet} < 0$
  - experimental definition of $z_{I\!P}$: $z_{I\!P} = \dfrac{Q^2 + M_{jj}^2}{Q^2 + M_X^2}$

Comparison to partonic pomeron model



- applying results of $F_2^{D(3)}$ QCD fits to jets works very well (although dijet events cover a very different range in β)
- the contribution from resolved photons improves the agreement with data
- the contribution from a subleading exchange is small

Regge factorisation and scale dependence

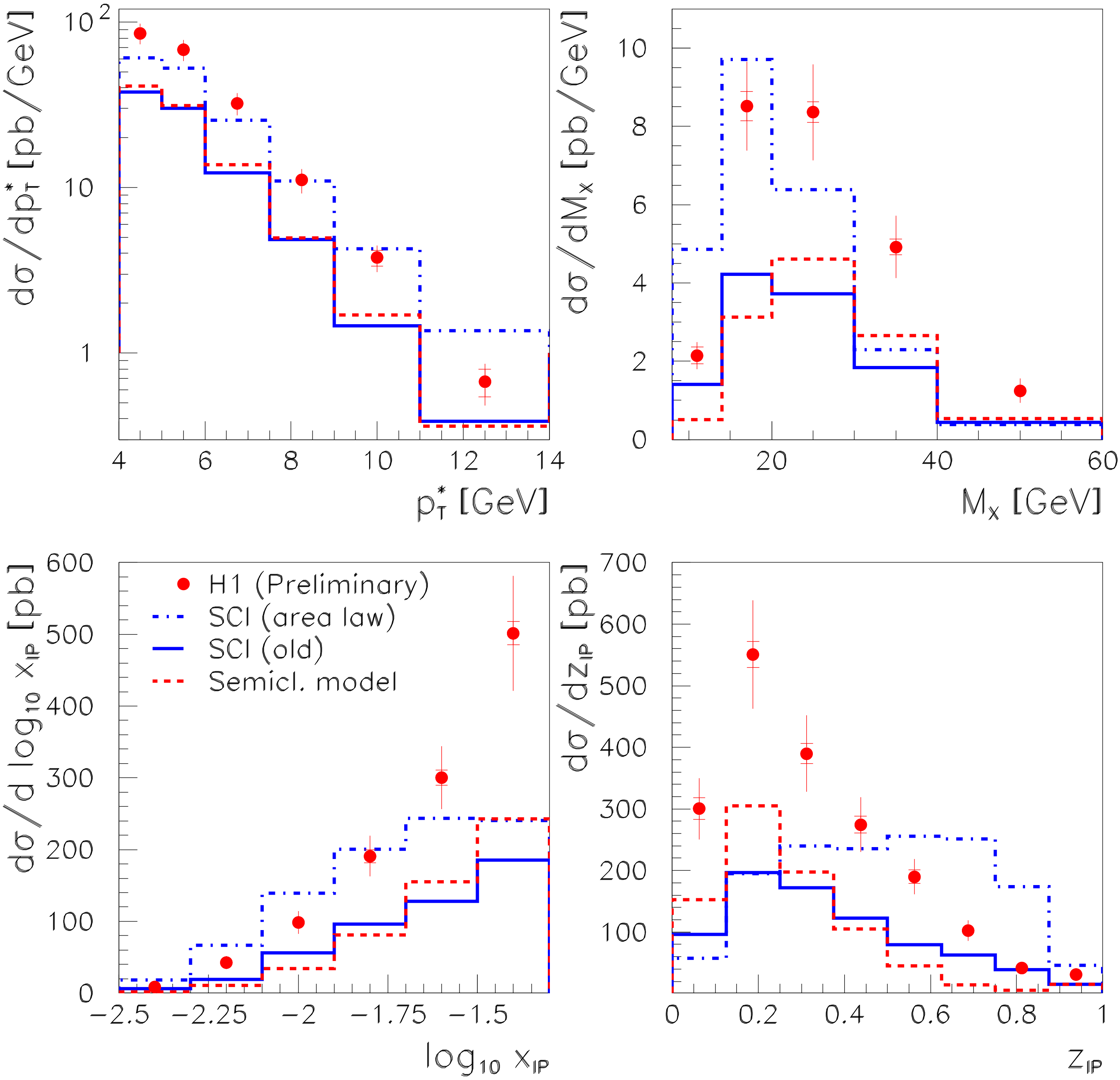


- data are compatible with Regge factorisation:

$$\sigma\left(x_{I\!P}, z_{I\!P}\right) = f_{I\!P}\left(x_{I\!P}\right) \cdot p_{i/I\!P}\left(z_{I\!P}\right)$$

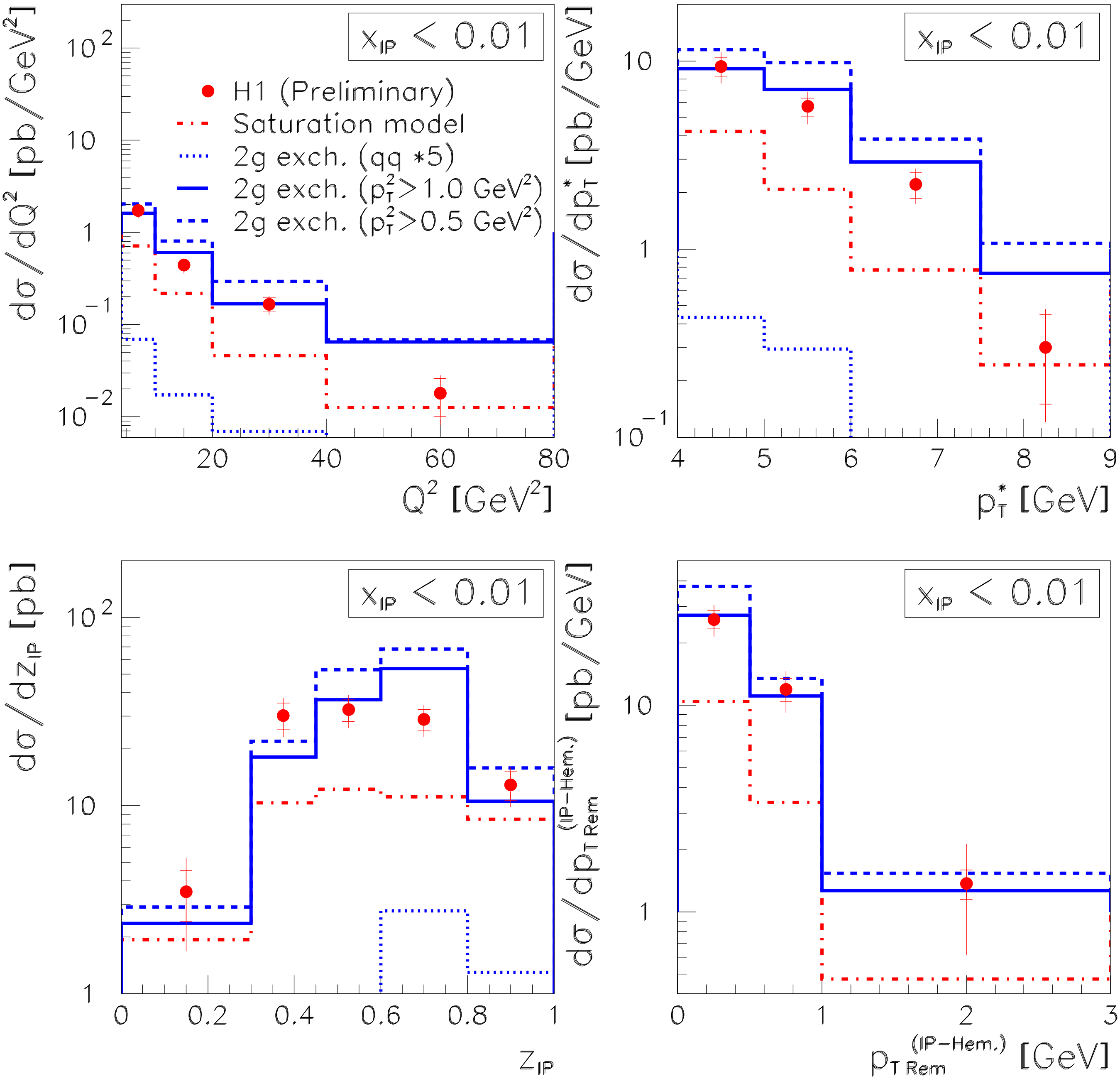
- "fit 2" (flat gluon) agrees well with data
  "fit 3" (peaked gluon) is too high at high $z_{I\!P}$

Comparison to soft colour neutralisation models



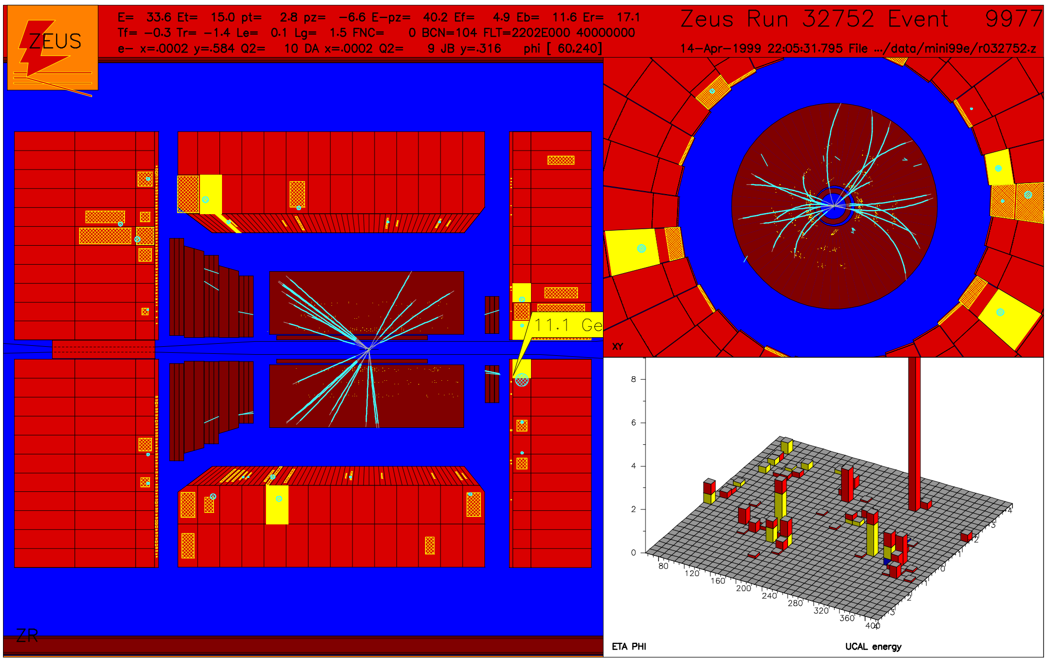
- old SCI and semiclassical model roughly agree, but are too low by factor two when compared to the data
- new SCI (generalised area law) has good normalisation, but the shape does not agree with data

Comparison to photon fluctuation models



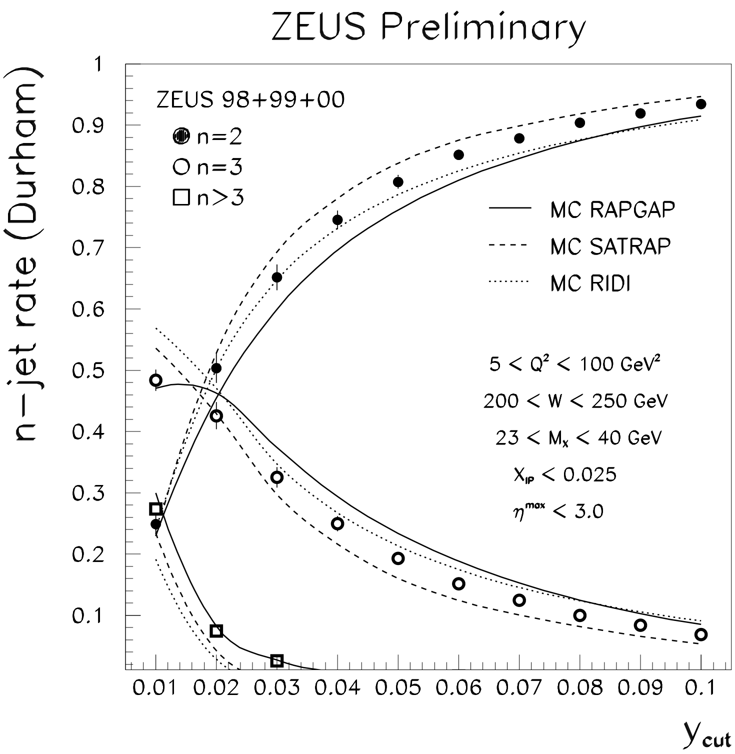
- cut on $x_{I\!P}$ to avoid valence region and subleading exchanges
- saturation model is too low
- Bartels et al. model:
  - the $q\overline{q}$ contribution is very small
  - the model roughly describes the data

3-jet production in diffractive DIS

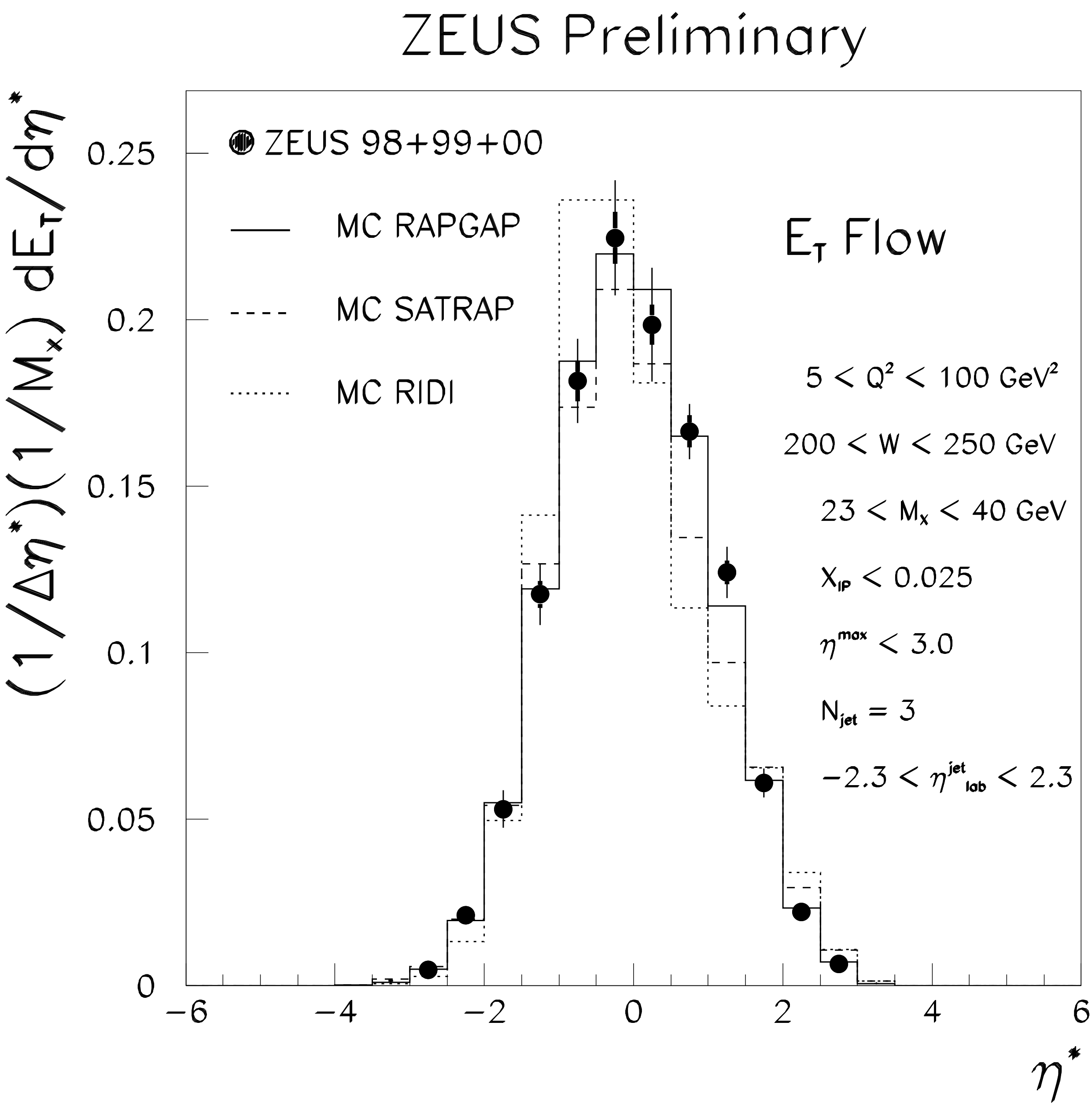


Preliminary ZEUS measurement:

- based on $L_{int} = 39$ pb^{-1} (5800 3-jet events)
- "rapidity gap" selection ($\eta_{max} = 3.0$)
- corrected distributions are presented for:
  - $5 < Q^2 < 100$ GeV^2, $200 < W < 250$ GeV
  - $23 < M_X > 40$ GeV, $x_{I\!P} < 0.025$
- jets are found with a k_T clustering algorithm: $y_{cut} = 0.05$ gives smallest hadronisation corrections



E_T-flow for 3-jet events



- Partonic pomeron model (RAPGAP) gives a very good description
- Saturation Model (SATRAP) and 2-gluon exchange models (RIDI) show a lack of large angle radiation in the pomeron hemisphere
- 2-gluon exchange model (RIDI) predicts a large asymmetry towards the photon hemisphere not observed in data

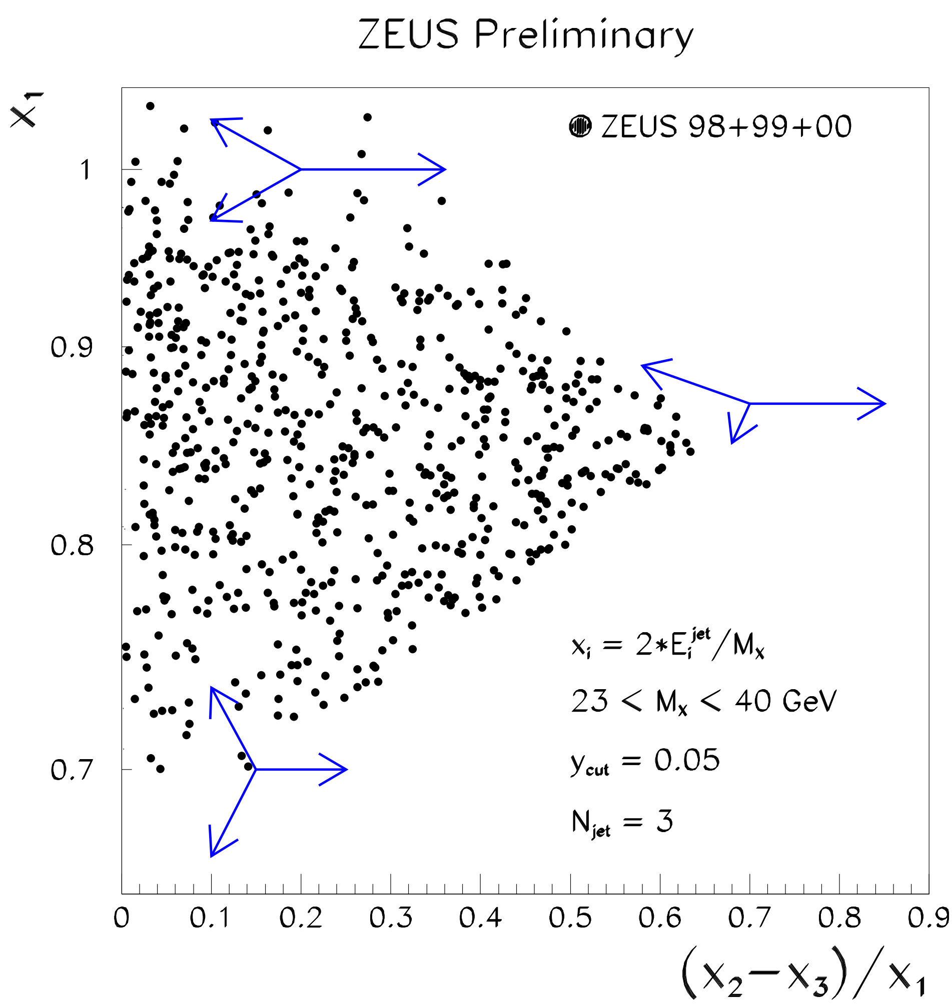
3-jet event observed topologies (1)

The observed 3-jet events are represented in the plane of X_1 versus $(X_2 - X_3)/X_1$ with jets sorted in energy and X_i defined as:

$$X_i = \frac{2 \cdot E_i^{jet}}{M_X}, \qquad \frac{2}{3} < X_i < 1$$

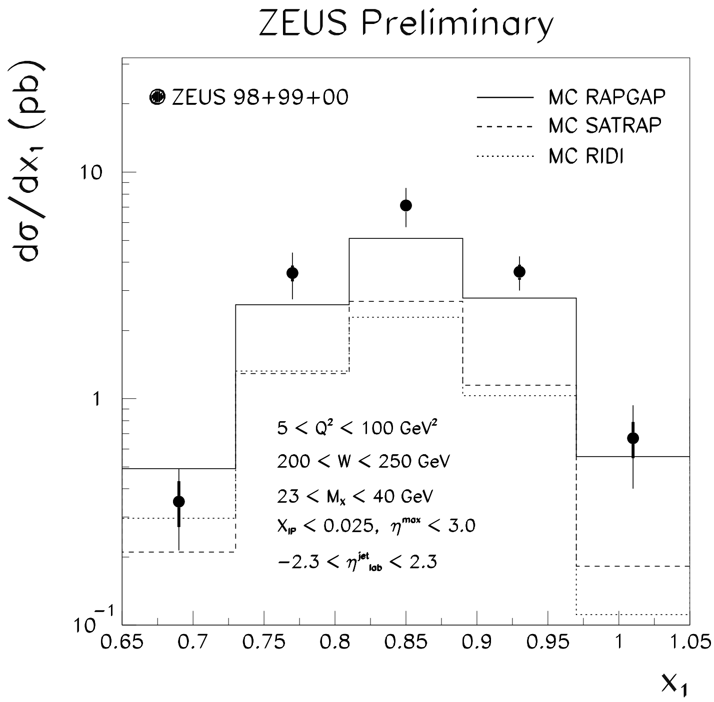
$$X_1 > X_2 > X_3, \qquad X_1 + X_2 + X_3 = 2$$

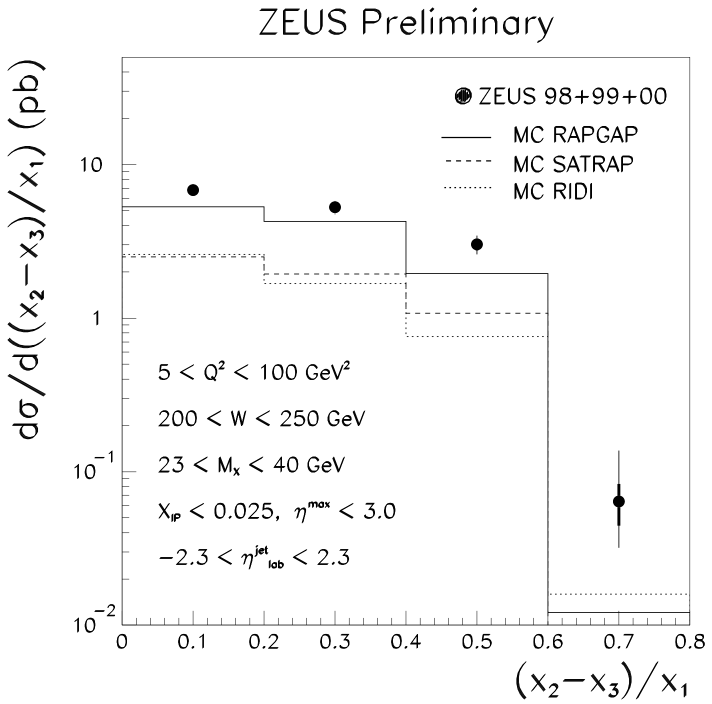
Different regions in this plane define different topologies in the 3-jet final state.



- all the possible configurations for a three-body final state are present

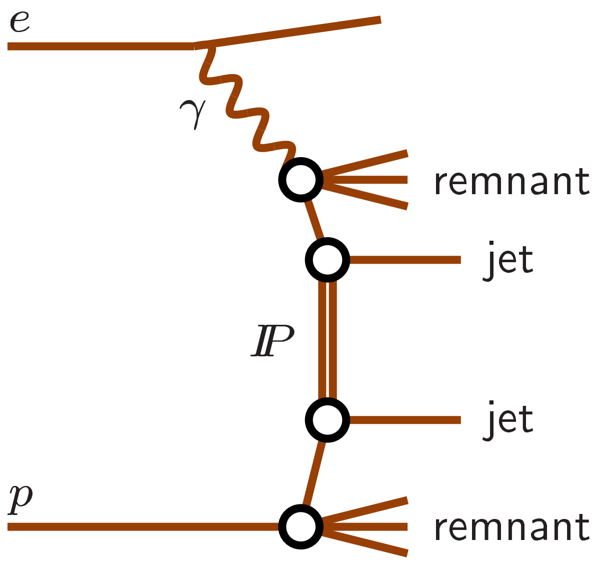
3-jet event observed topologies (2)





- shape well reproduced by all models
- Saturation model (SATRAP) and 2-gluon exchange model (RIDI) are too low by a factor of two
- Partonic pomeron model (RAPGAP) OK (given systematic errors and uncertain contribution from proton dissociation processes)

Energy flow between jets (1)



Experimental measurement:

- tagged photoproduction:

$$Q^2 < 0.01 \text{ GeV}^2, \qquad 165 < W < 233 \text{ GeV}$$

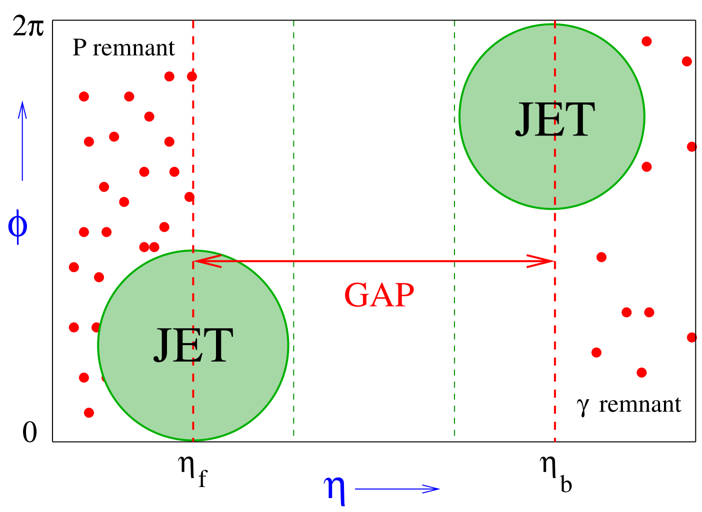
- jet finding with k_T algorithm $\rightarrow$ every object part of a (mini)jet:

$$p_T^{jet1} > 6 \text{ GeV}, \quad p_T^{jet2} > 5 \text{ GeV}, \quad \eta^{jet1,2} < 2.8 \quad \Delta\eta > 2.5$$

- other variables:

$$x_p^{jets} = \frac{\sum_{jets}(E + p_z)}{2E_p} \qquad x_\gamma^{jets} = \frac{\sum_{jets}(E - p_z)}{\sum_{all}(E - p_z)}$$

- a "gap event" is an event with transverse energy flow between the two hardest jets less than E_t^{cut}



Energy flow between jets (2)

Towards an completely perturbative colour singlet exchange?

- hard scale at both ends of the exchange
- LLA BFKL (high momentum exchange t !):

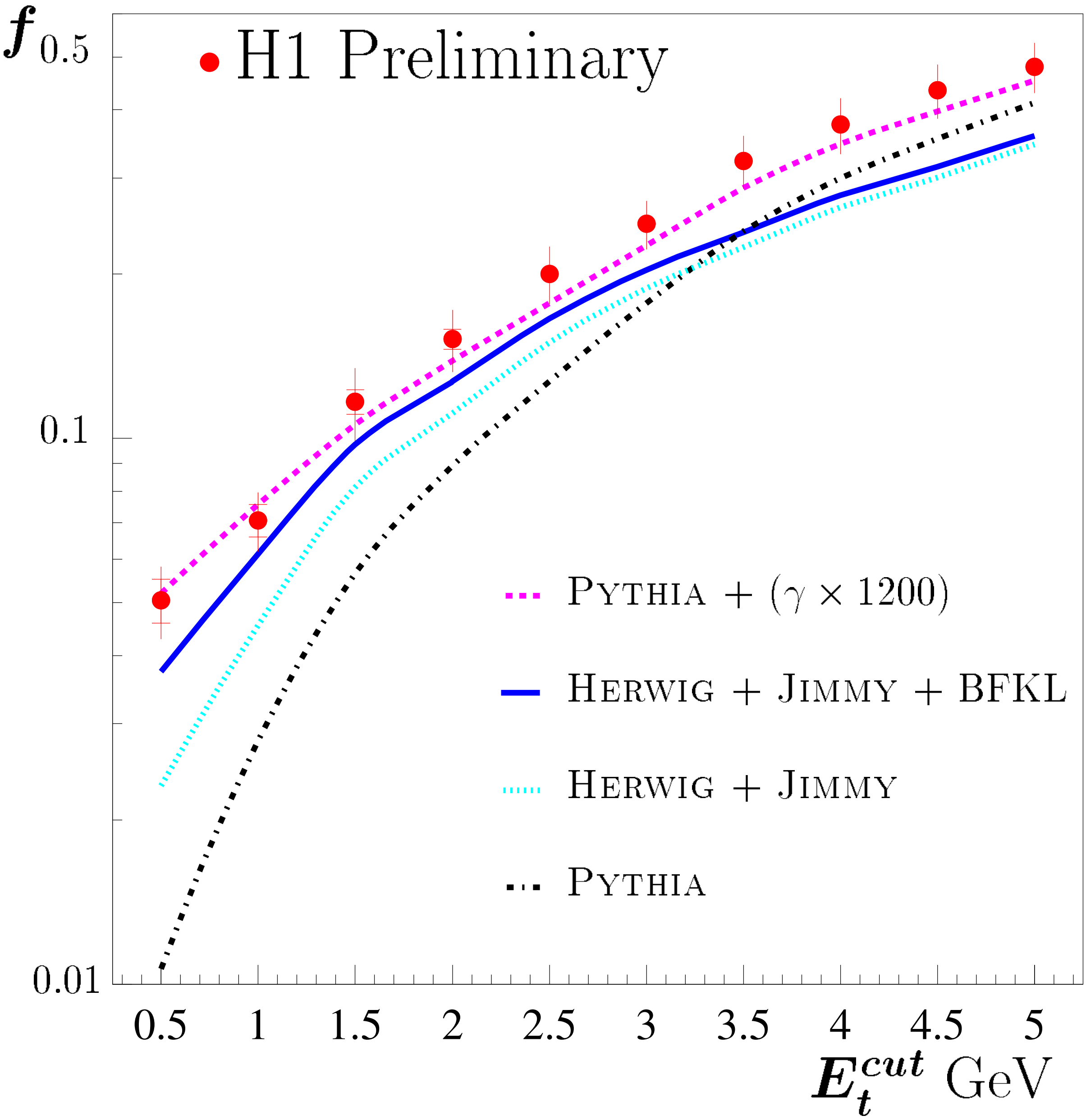
$$\frac{\mathrm{d}\sigma(qq \to qq)}{\mathrm{d}t} \approx (C_F \alpha_S)^4 \frac{2\pi^3}{t^2} \frac{\exp(2\omega_0 y)}{(7\alpha_S C_A \zeta(3) y)^3}$$

- purely perturbative (up to parton densities) calculation is possible if $E_t^{cut} \gg \Lambda_{QCD}$ (Oderda, Sterman)

But:

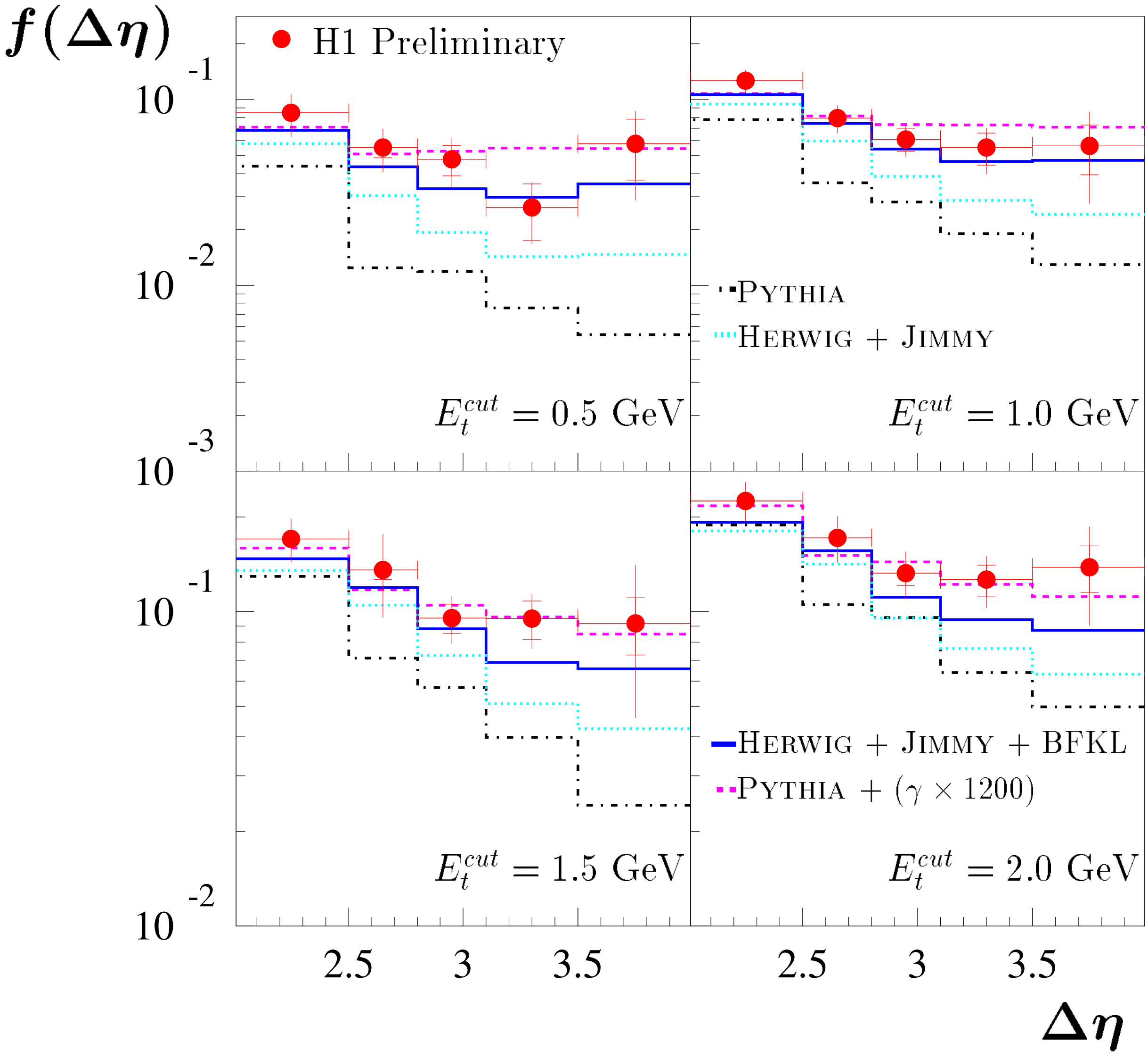
- complications due to rapidity gap survival probability and/or underlying events
- unique place to study interplay between long and short distance physics

Inclusive gap fractions



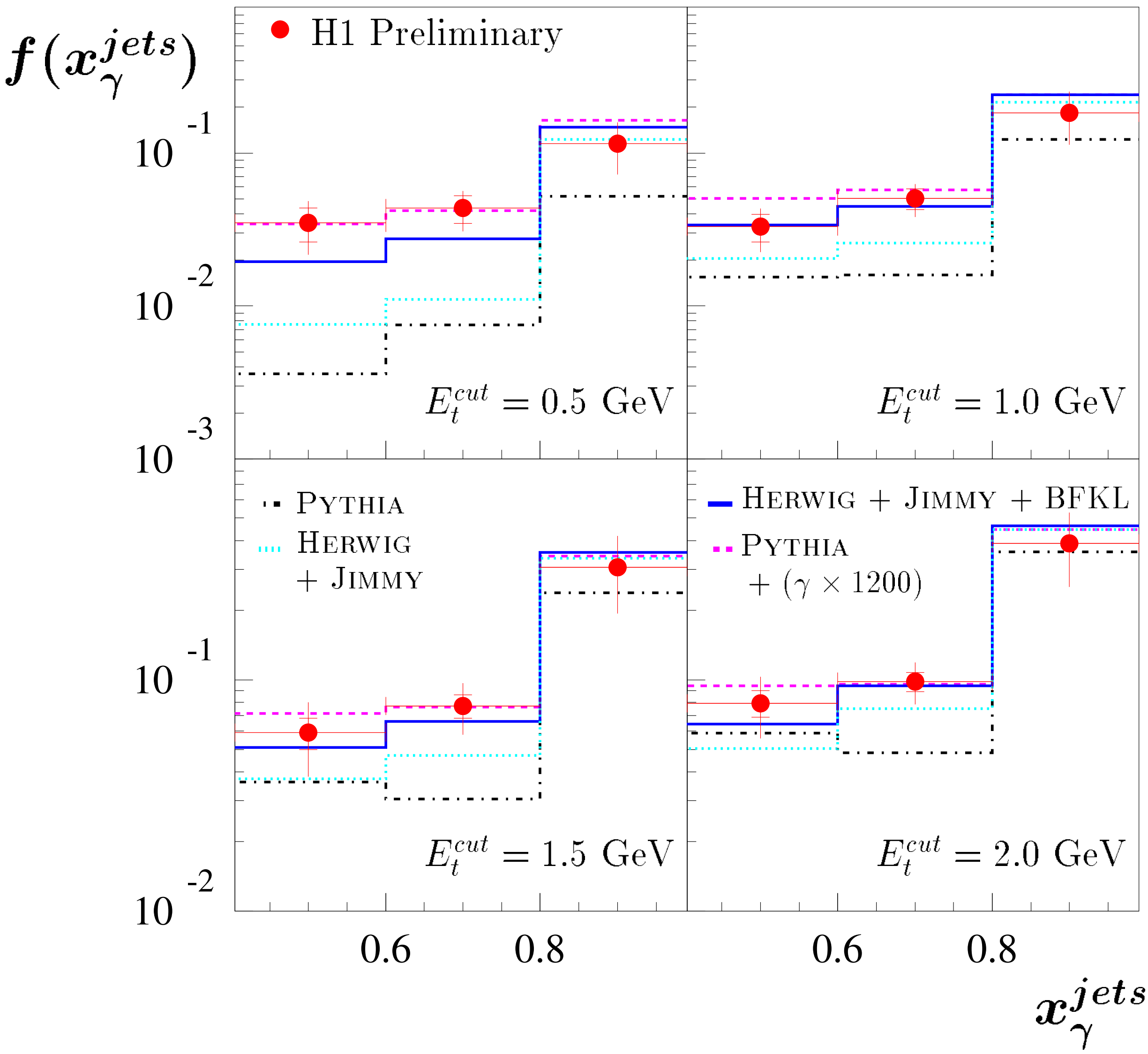
- the data show a large excess over the non colour-singlet exchange models PYTHIA and HERWIG
- predictions are very sensitive to the treatment of underlying events
- predictions are not very sensitive to differences in the colour singlet models

Gap fraction differential in $\Delta\eta$



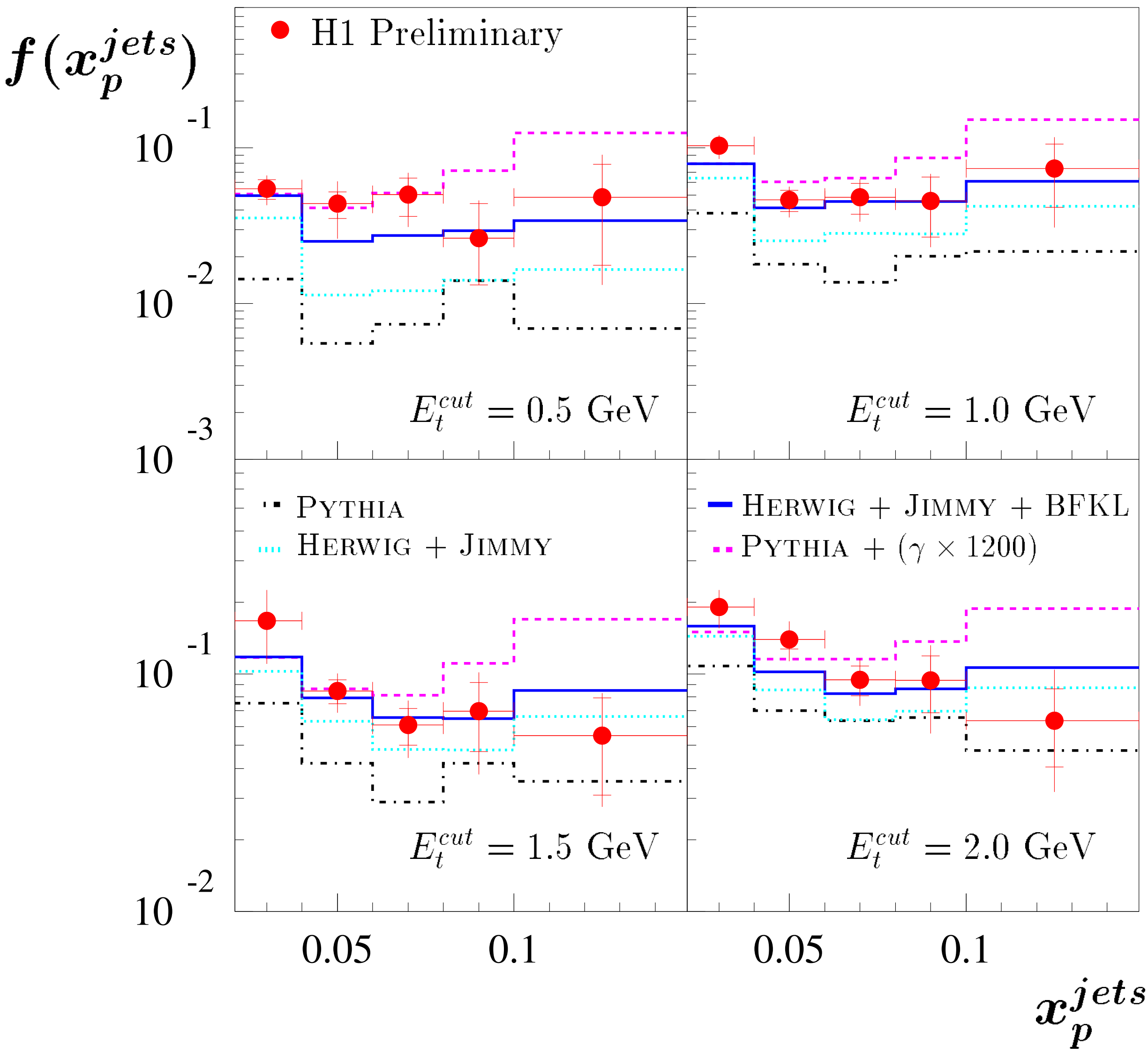
- no sensitivity to the underlying dynamics of the colour singlet exchange
- LO BFKL + HERWIG + JIMMY (for m.i.) describes the data in normalisation and in shape

Gap fraction differential in x_γ



- non colour-singlet "background" is largely at high x_γ
- direct events are more likely to produce gaps

Gap fraction differential in x_p



- the x_p^{jets} distribution is sensitive to the underlying dynamics of the colour singlet exchange!
- difference beteen PYTHIA high-t γ exchange and BFKL is visible!

Summary

Measurement of the inclusive cross section

- F_2^D has been measured over a very large range in Q^2
- Factorisable partonic pomeron model describes the data well, with an intercept that is larger than for the soft pomeron and with a possible indication for a dependence of $\alpha_{I\!P}(0)$ on Q^2
- Behaviour of F_2^D as $Q^2 \to 0$ is similar as in inclusive DIS
- Saturation Model is successful at reproducing the general features of the data

Study of the hadronic final state

- Factorisable partonic pomeron model derived from inclusive measurements describes the final state remarkably well
- Two-gluon exchange model describes data in a limited range of $x_{I\!P}$
- Saturation Model, Soft Color Interaction and semiclassical model are less successful and would need further tuning to describe the data
- Studying the energy flow between jets at large rapidity separations might give an opportunity to observe the BFKL-pomeron