Diffractive Phenomena at HERA

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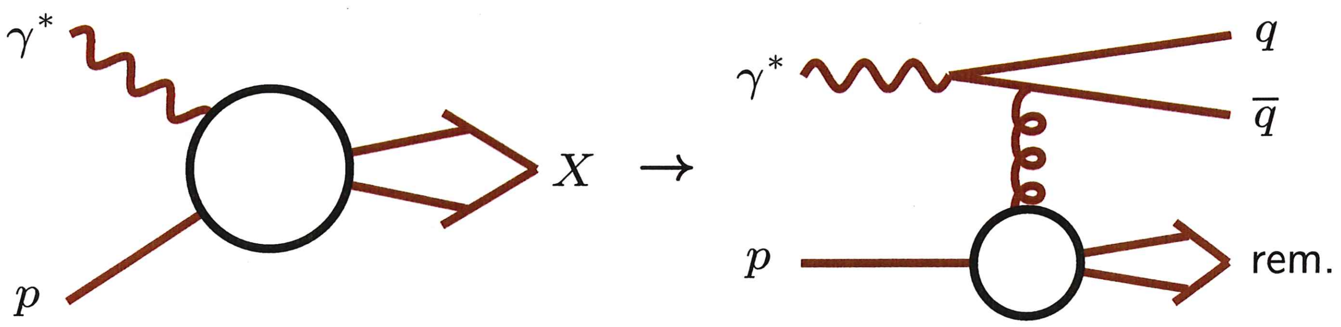
Outline of this talk

- Why diffraction?
- Diffractive DIS at low Q^2
- Jets in diffraction

Why study diffractive deep inelastic scattering ?

Deep inelastic scattering (DIS):

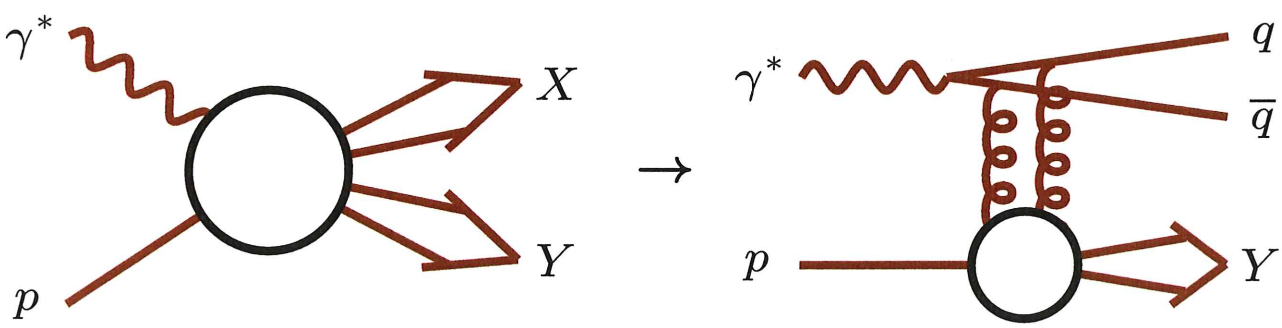


Leading twist DIS = sum of scatterings on free quarks in the proton:

$$F_2 = x \sum_q e_q^2 f_q(x) + \text{QCD evolution}$$

Diffractive deep inelastic scattering (DDIS):

10% of DIS events exhibit a large rapidity gap in the final state.

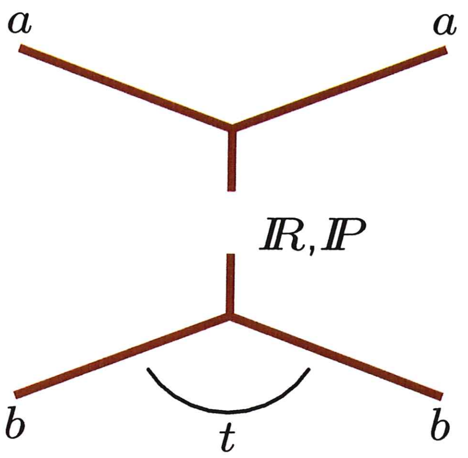


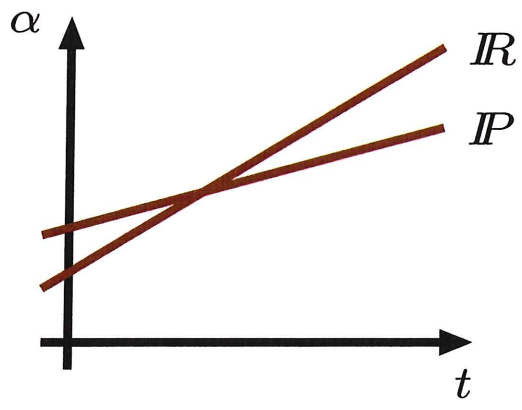
New coherent phenomena? Higher twist? Multiple exchanges? Confinement? Scattering on an extended object?

→ DDIS gives us an opportunity to expand our understanding of QCD.

Diffractive phenomena and the pomeron

Soft hadron scattering is described by Regge phenomenology:





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

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

- 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, 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?

Classification of diffractive processes

At HERA:

$$\gamma^* + p \to \quad VM + p \quad \text{(elastic)} \tag{1}$$

$$\gamma^* + p \to \quad VM + Y \quad \text{(proton dissociation)} \tag{2}$$

$$\gamma^* + p \to \quad X + p \quad \text{(single dissociation)} \tag{3}$$

$$\gamma^* + p \to \quad X + Y \quad \text{(double dissociation)} \tag{4}$$

- this talk: mostly about (3)

At Tevatron:

$$\overline{p} + p \to \quad \overline{p} + p \quad \text{(elastic)} \tag{5}$$

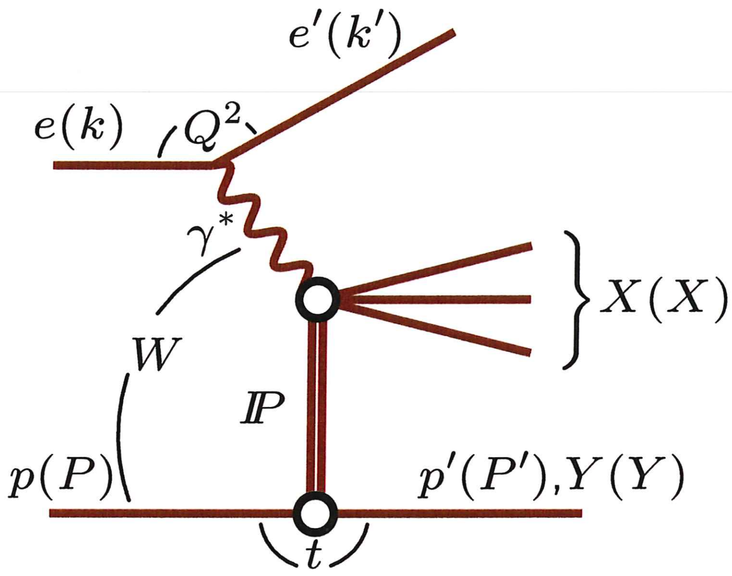
$$\overline{p} + p \to \quad X + p \quad \text{(single dissociation)} \tag{6}$$

$$\overline{p} + p \to \quad \overline{p} + Y \quad \text{(single dissociation)} \tag{7}$$

$$\overline{p} + p \to \quad X + Y \quad \text{(double dissociation)} \tag{8}$$

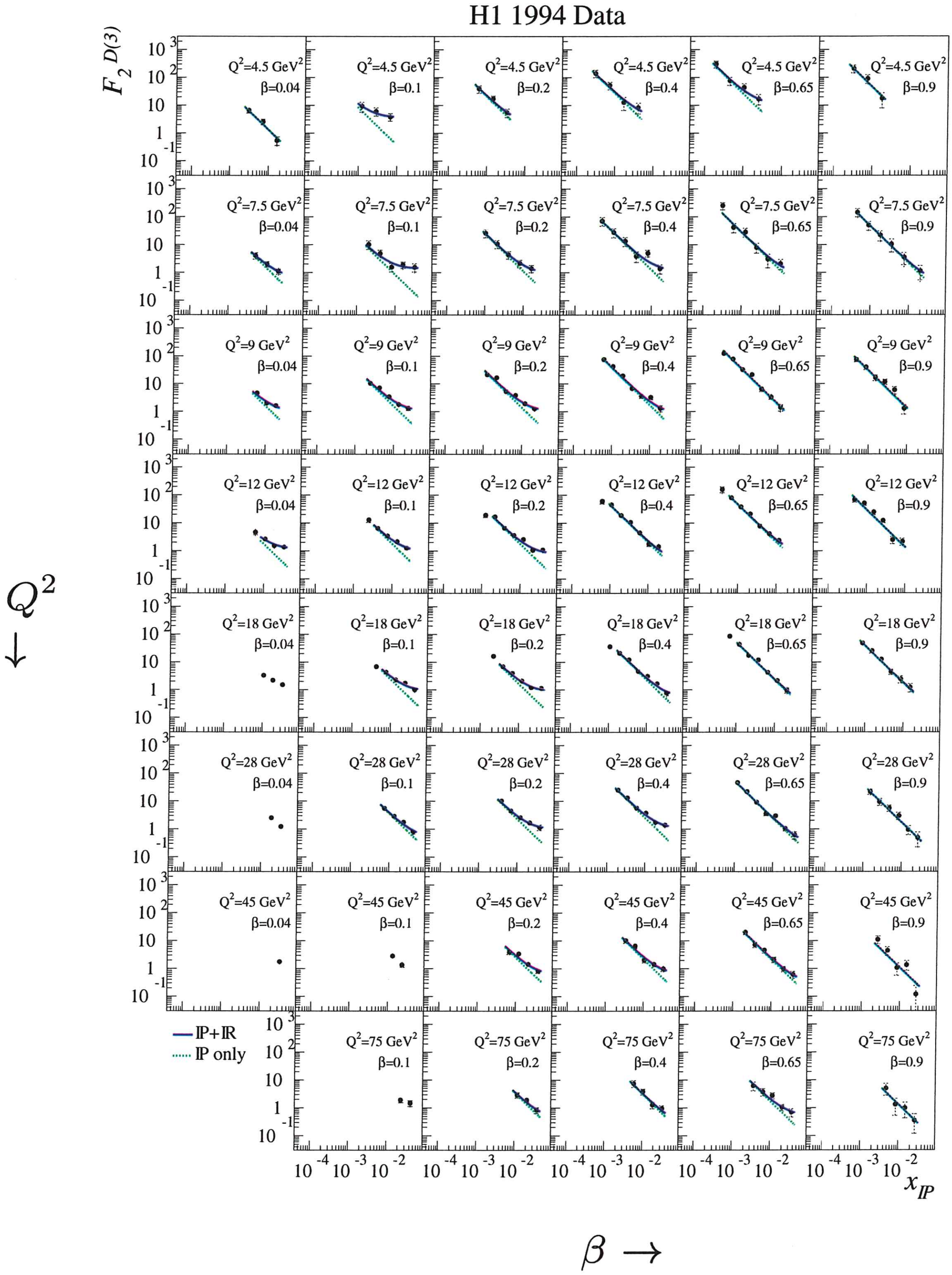
- this talk: mostly about (7)

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
$t = (P-P')^2$	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

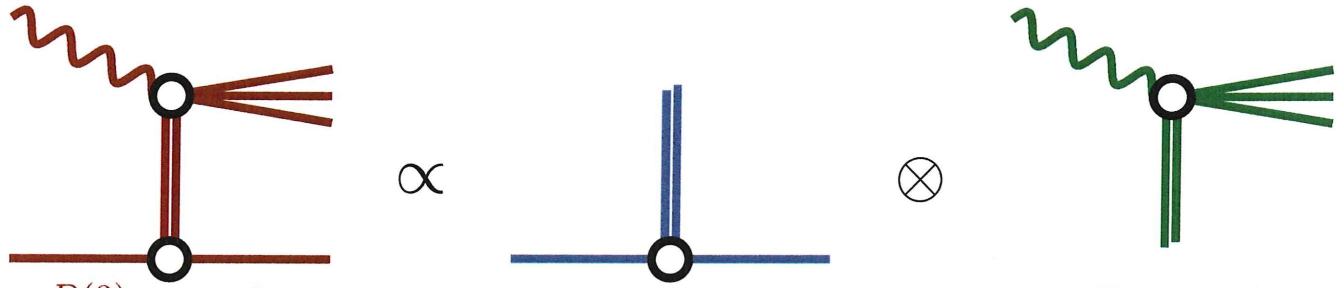


$$\frac{d\sigma^{ep\to eXY}}{d\beta dQ^2 dx_{I\!P}} = \frac{4\pi\alpha^2}{\beta Q^4}\left(1 - y + \frac{y^2}{2}\right) F_2^{D(3)}(\beta, Q^2, x_{I\!P})$$

→ QCD factorization allows interpretation in terms of pdf's.

Regge-like parametrisation of the cross section

Regge factorisation:



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

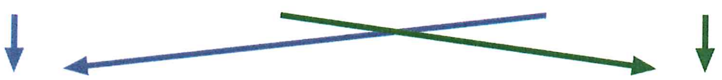
$\rightarrow$ $x_{I\!P}$ dependence is universal at all β and Q^2 ($\sim \frac{1}{x_{I\!P}}$)

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:

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

(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.

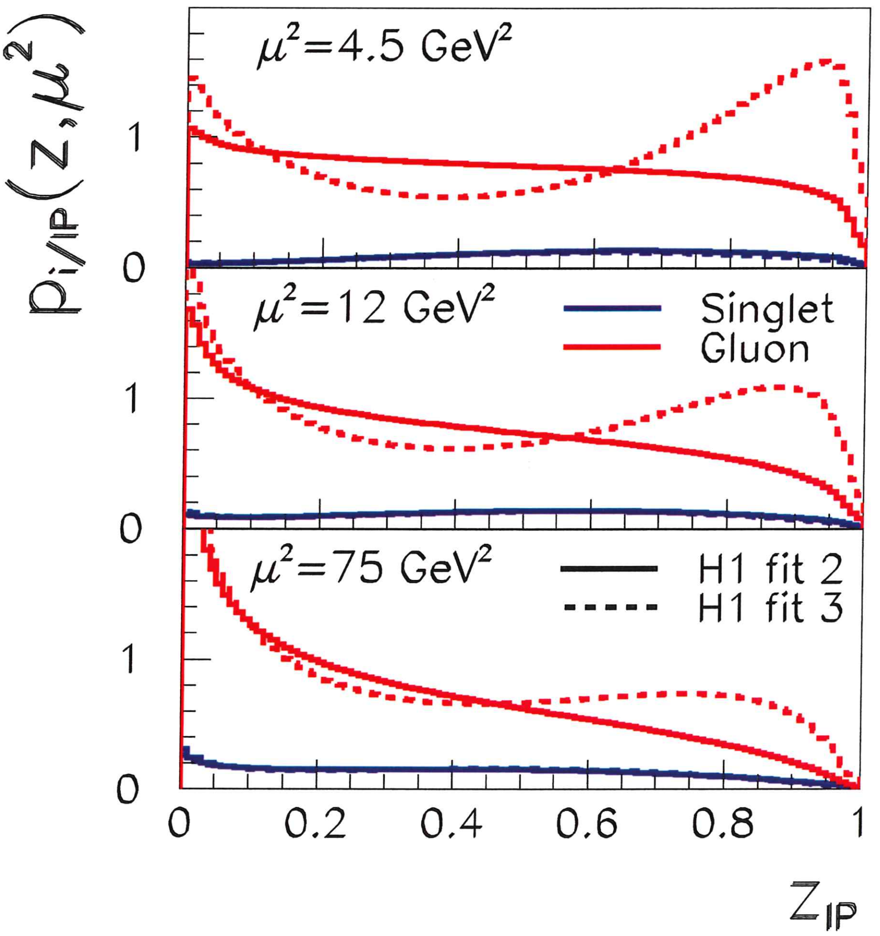
The partonic pomeron

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.

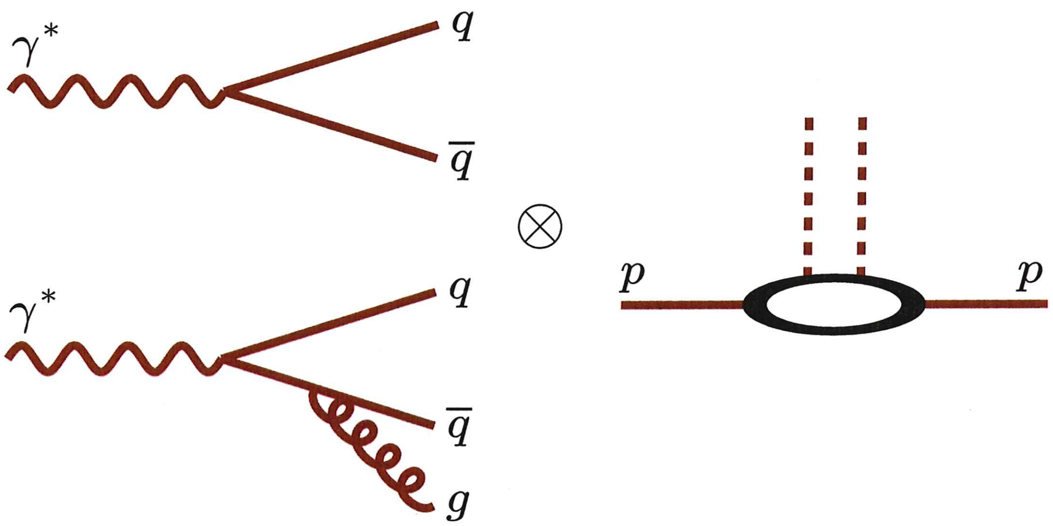
- assume a π structure function for $I\!R$
- take Q^2 evolution from NLO DGLAP equations
- extract parton density functions $p_{q/I\!P}(z, \mu^2)$ (directly) and $p_{g/I\!P}(z, \mu^2)$ (through scaling violations)



→ $I\!P$ dominated by "hard" gluons

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.



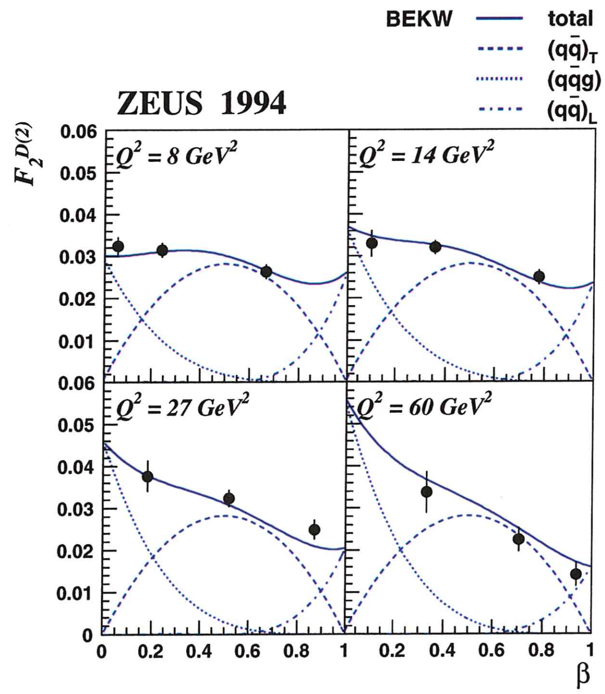
Decomposition into leading / higher twist contributions, longitudinal / transverse photon interactions and $q\overline{q}$ / $q\overline{q}g$ states

β dependence fixed by dipole wave function from perturbation theory:

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

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

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



→ clear prediction for the partonic composition of the final state X

Photon fluctuation models (2)

Photon fluctuation models differ in the way they treat the dipole cross section:

- **Saturation model** (Golec-Biernat, Wüsthoff) :
  Attempt to desribe saturation of the inclusive cross section at low Q^2, low x leads to an alternative model for the dipole cross section:

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

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

- **Semiclassical model** (Buchmüller, McDermott, Gehrmann, Hebecker) :
  $q\overline{q}/q\overline{q}g$ scatters off a superposition of target colour fields, averaged using an approximation for very large hadrons.

- **2-gluon exchange model** (Bartels, Jung, Wüsthoff) :
  Elastic scattering of $q\overline{q}/q\overline{q}g$ off the proton through the exchange of two gluons in a net colour-singlet configuration.
  Full pQCD calculation that requires high transverse momentum for all outgoing partons and $x_{I\!P} < 0.01$ to avoid valence quark region

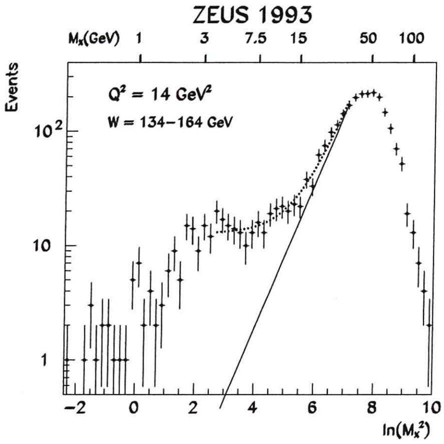
Experimental techniques

Selection of diffraction events by H1 and ZEUS:

- M_X subtraction method (ZEUS):

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

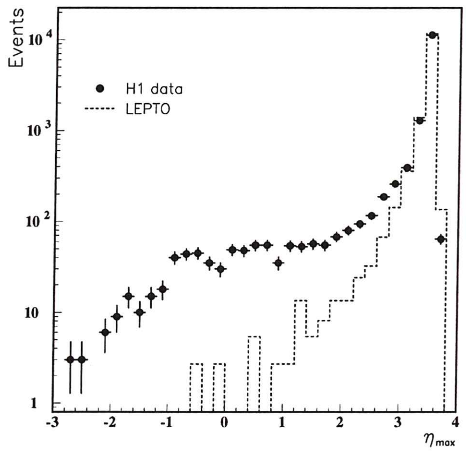
$\rightarrow$ DD background $\lesssim 30\%$



- large rapidity gap selection (H1 & ZEUS):

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

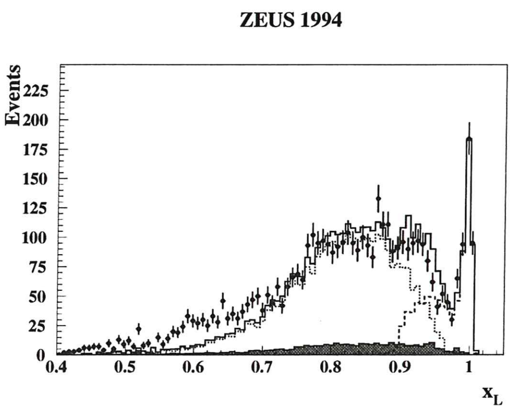
$\rightarrow$ DD background $\lesssim 10\%$



- leading proton spectrometer (H1 & ZEUS):

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

$\rightarrow$ DD background $\lesssim 3\%$



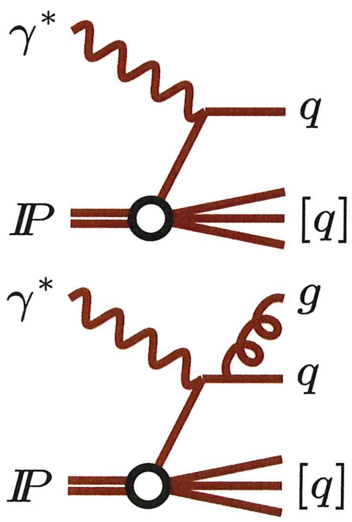
Study of the hadronic final state

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

- event shapes
- energy flow and particle spectra
- charged particle multiplicities and correlations

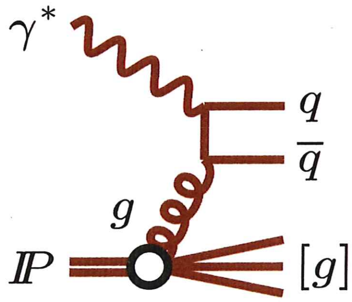
These observables are expected to be sensitive to the partonic structure of the final state:

- in terms of the partonic pomeron we can distinguish between quark or gluon initiated processes
- in terms of photon fluctuation 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 $3_c\overline{3}_c$

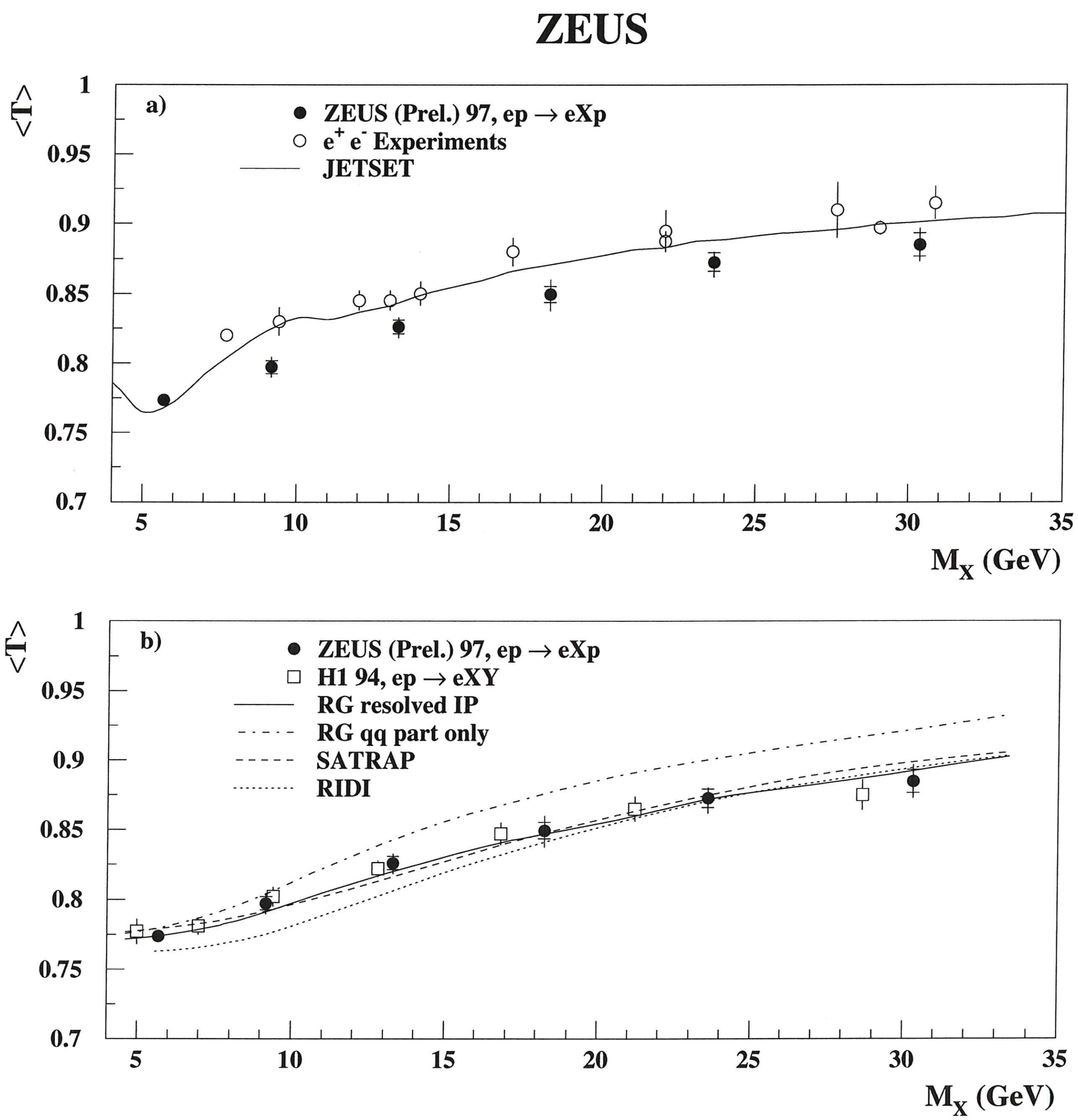


gluonic $I\!P$

- dominantly $q\overline{q}g$
- boson-gluon fusion
- high p_T, non-aligned
- many jets
- fragmentation of 8_c8_c

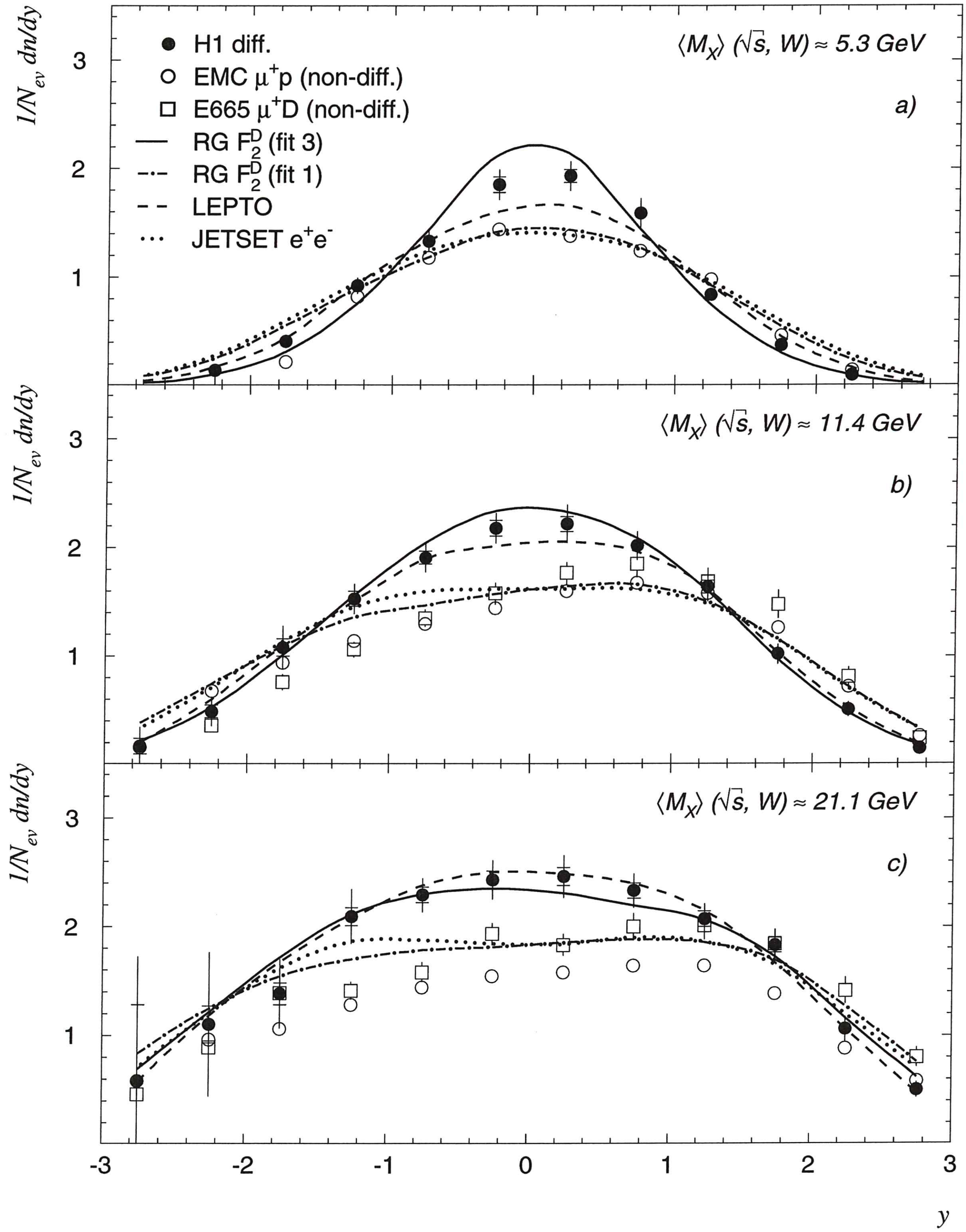
Event shapes

$$\text{thrust} : T = \max_{\vec{n}} \frac{\sum_i \vec{n} \cdot \vec{p_i}}{\sum_i |\vec{p_i}|}$$



- $\langle T \rangle$ becomes larger as M_X increases
- $\langle T \rangle$ is smaller and (not shown) thrust-P_T is larger in diffractive DIS than in e^+e^- at $\sqrt{s} = M_X$

Charged particle rapidity spectra



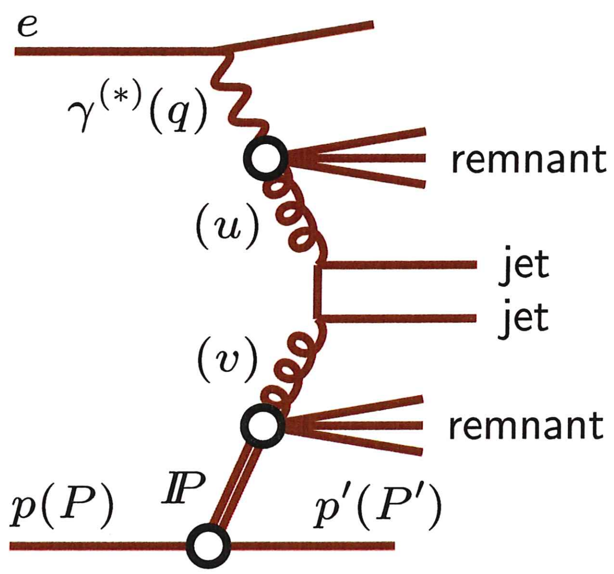
- diffractive data exhibit higher density in central rapidity plateau

→ Final state provides qualitative support for gluon dominated $I\!P$

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



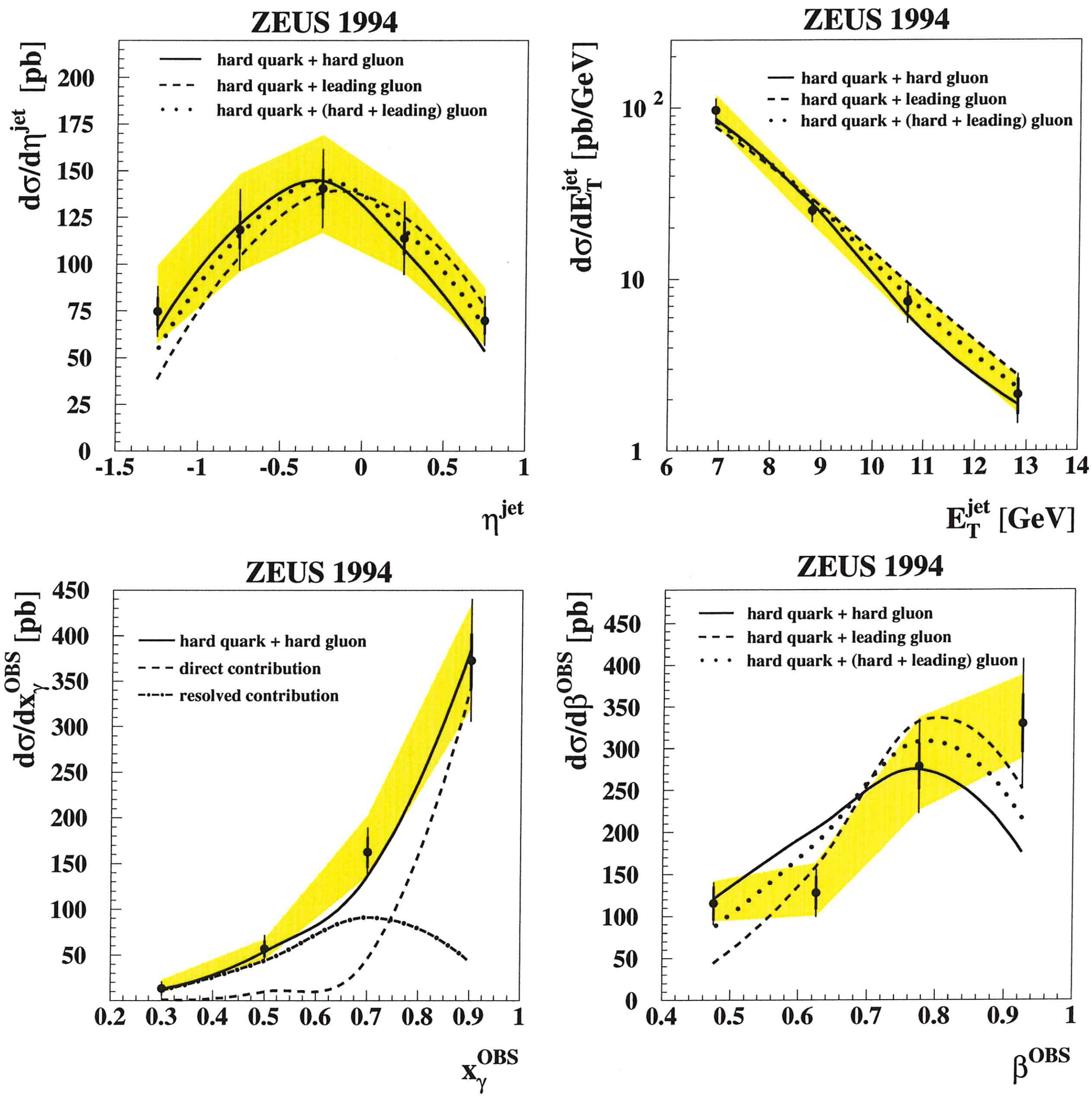
Experimental measurement:

- 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 photoproduction



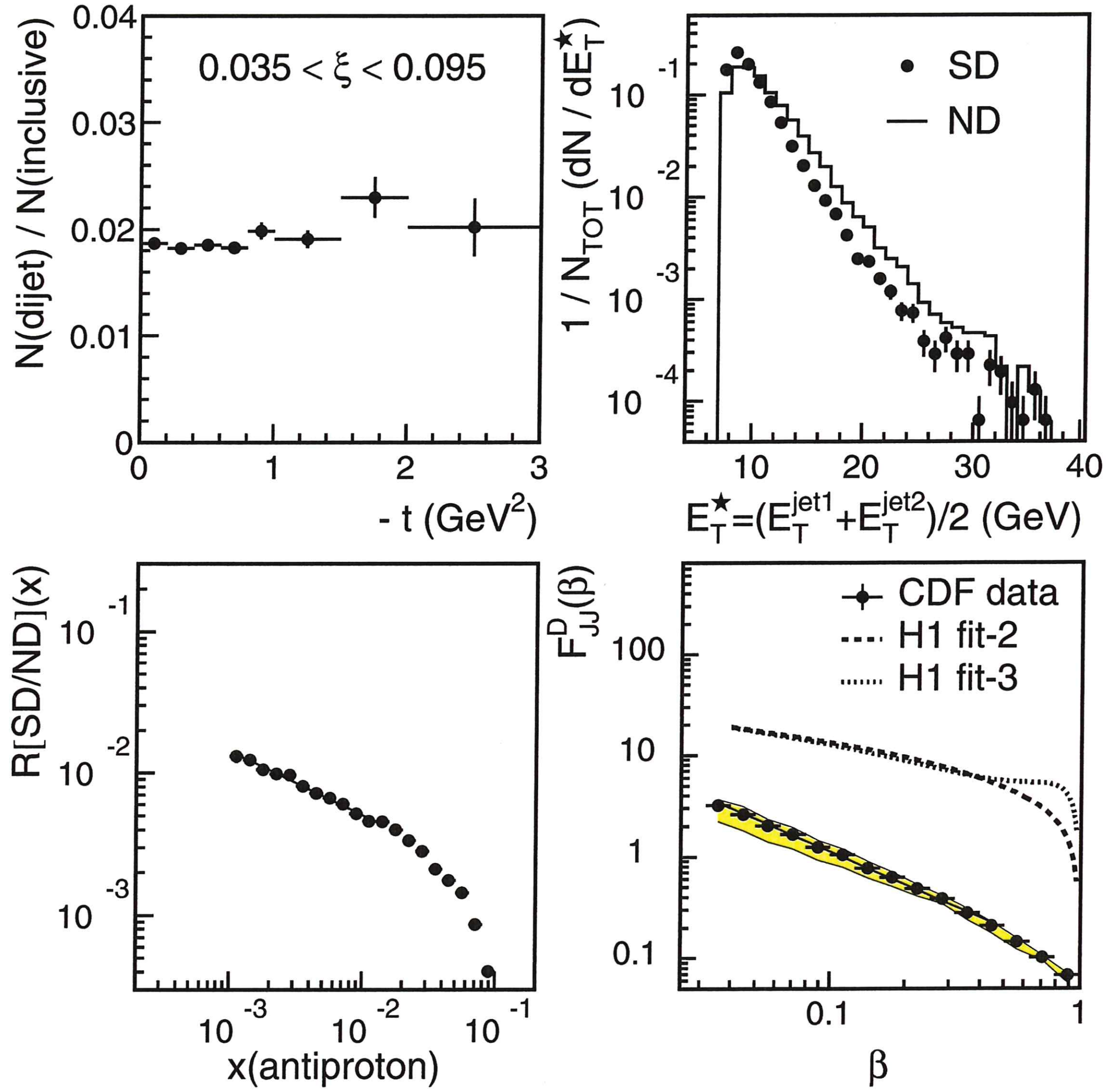
- experimental definition of x_γ and $z_{I\!P}$:

$$x_\gamma^{OBS} = \frac{\sum_{jets}(E - p_z)}{\sum_X (E - p_z)} \qquad \beta^{OBS} = \frac{\sum_{jets}(E + p_z)}{\sum_X (E + p_z)}$$

- both direct ($x_\gamma = 1$) and resolved ($x_\gamma < 1$) contributions are observed ($\rightarrow$ rapidity gap survival probability!)

- a combined DGLAP fit to F_2^D and photoproduction dijets requires the pomeron to be dominated by "hard" gluons ($70\% - 90\%$ of the pomeron momentum is carried by gluons)

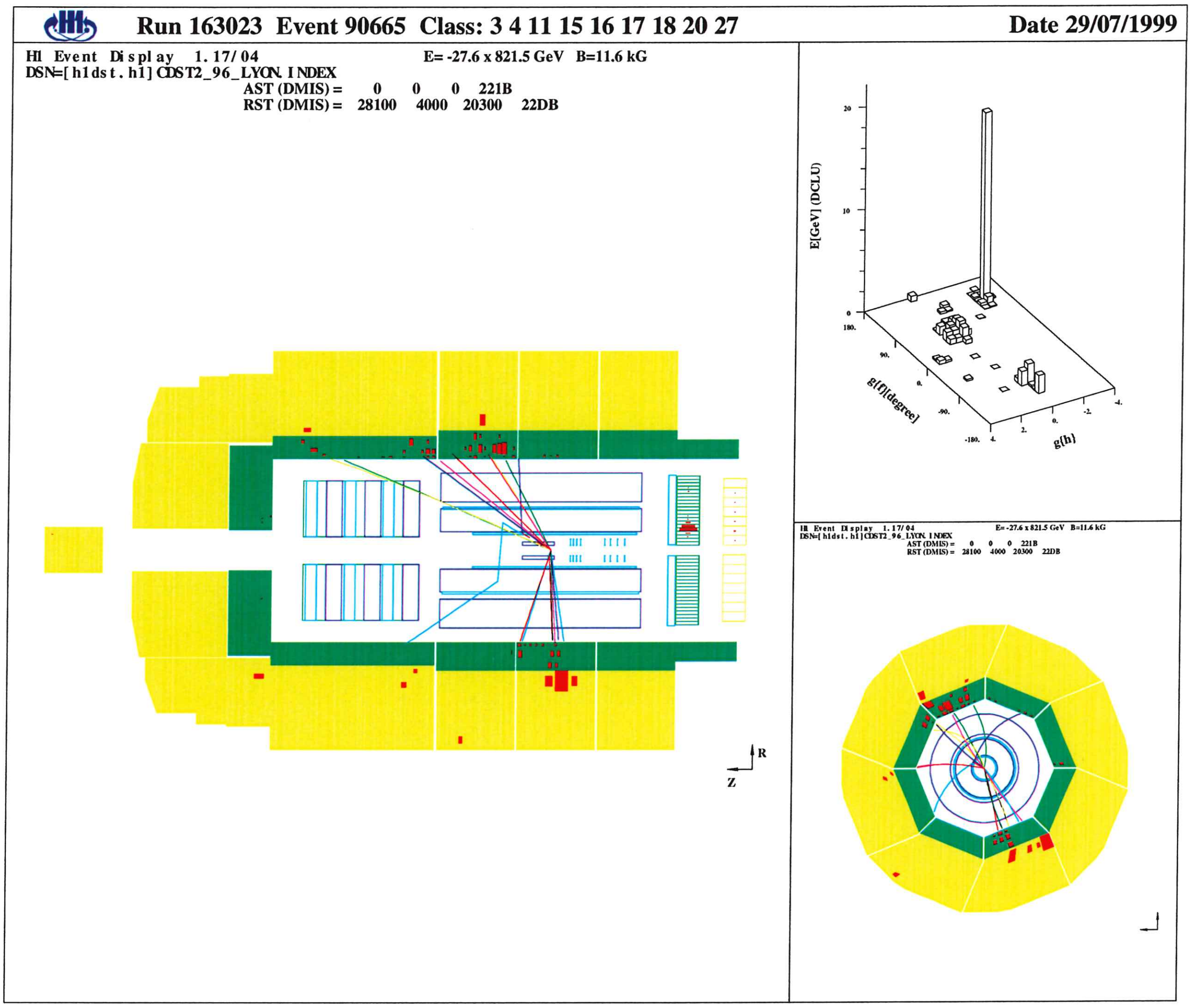
Dijet events in diffraction at the Tevatron



- leading antiproton tagged with Roman pot spectrometer
- ratio of dijet to inclusive SD event rates is independent of t
- E_T^{jet} distribution is slightly steeper for SD than for ND events
- ratio of SD to ND rates increases with decreasing x_{Bj}
- the CDF F_{JJ}^D is steeper than and severely suppressed relative to the predictions based on extrapolations of H1 fits

$\rightarrow$ breakdown of QCD factorization!

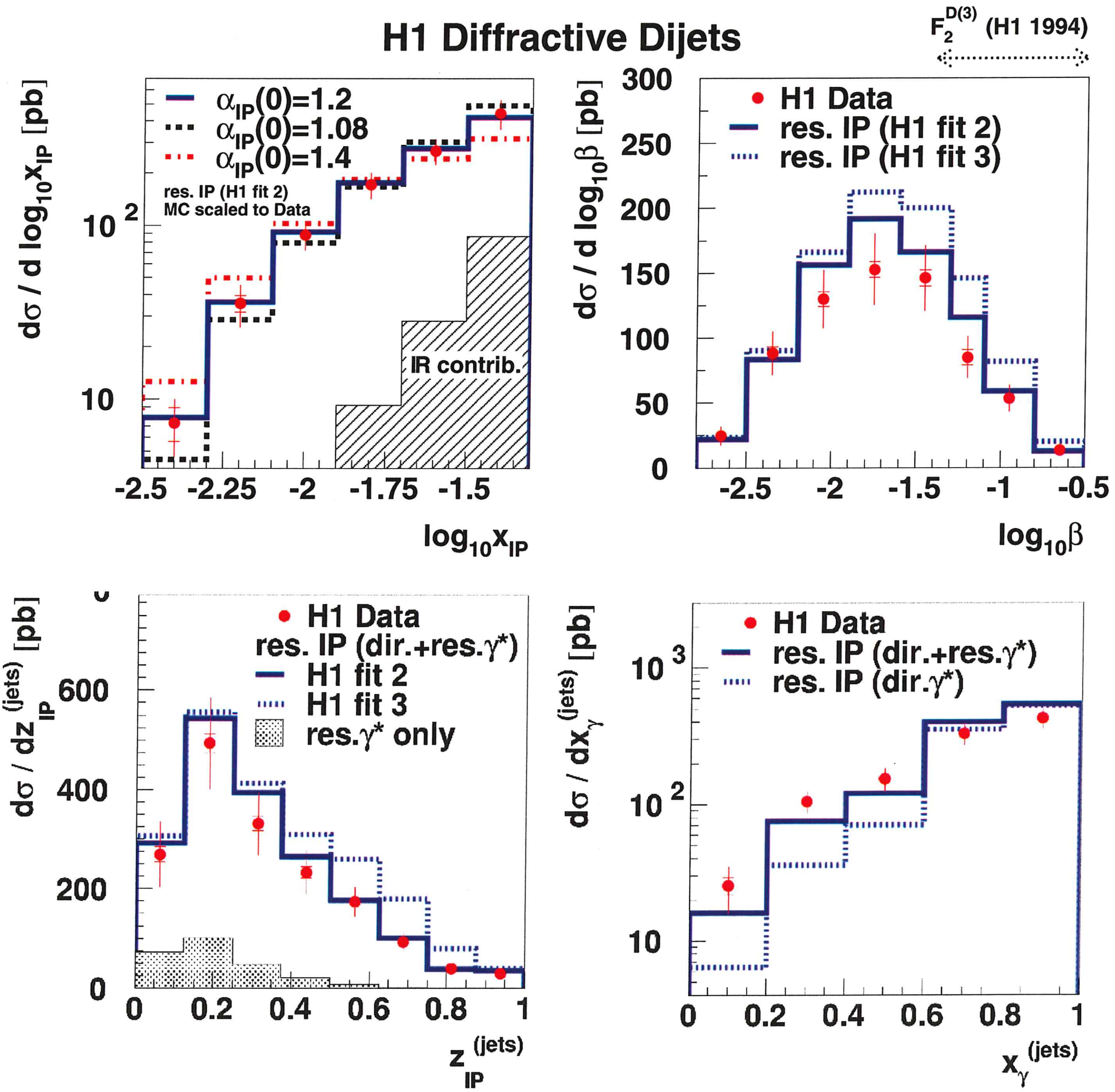
High-E_T jets in diffractive DIS



H1 measurement:

- based on $L_{int} = 18$ 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 $z_{I\!P}$: $z_{I\!P} = \dfrac{Q^2 + M_{jj}^2}{Q^2 + M_X^2}$

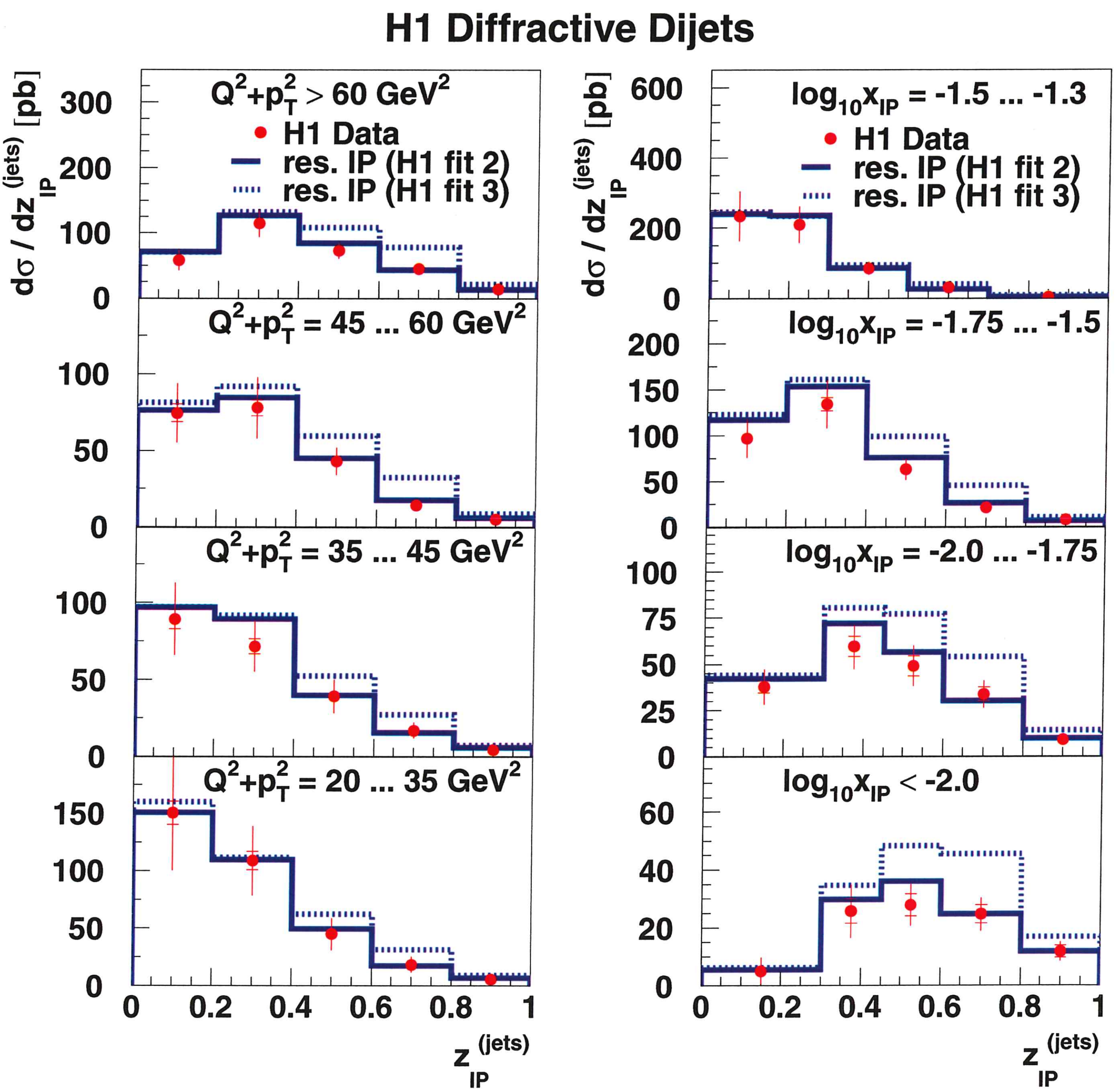
Comparison to partonic pomeron model



- 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

$z_{I\!P}$ in bins of $x_{I\!P}$ $\qquad$ $z_{I\!P}$ in bins of $\mu^2 = Q^2 + p_T^2$

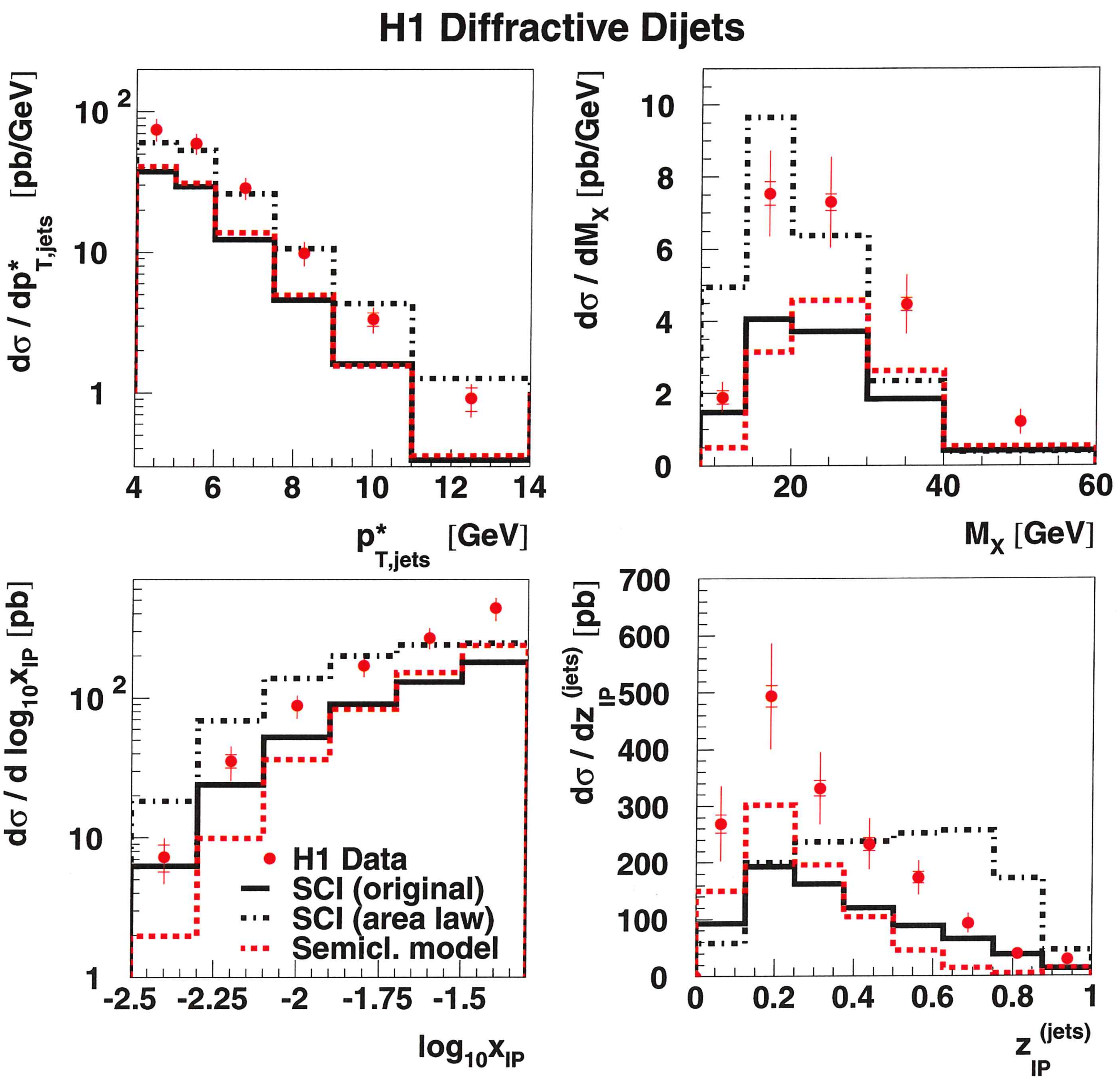


- data are compatible with Regge factorisation:

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

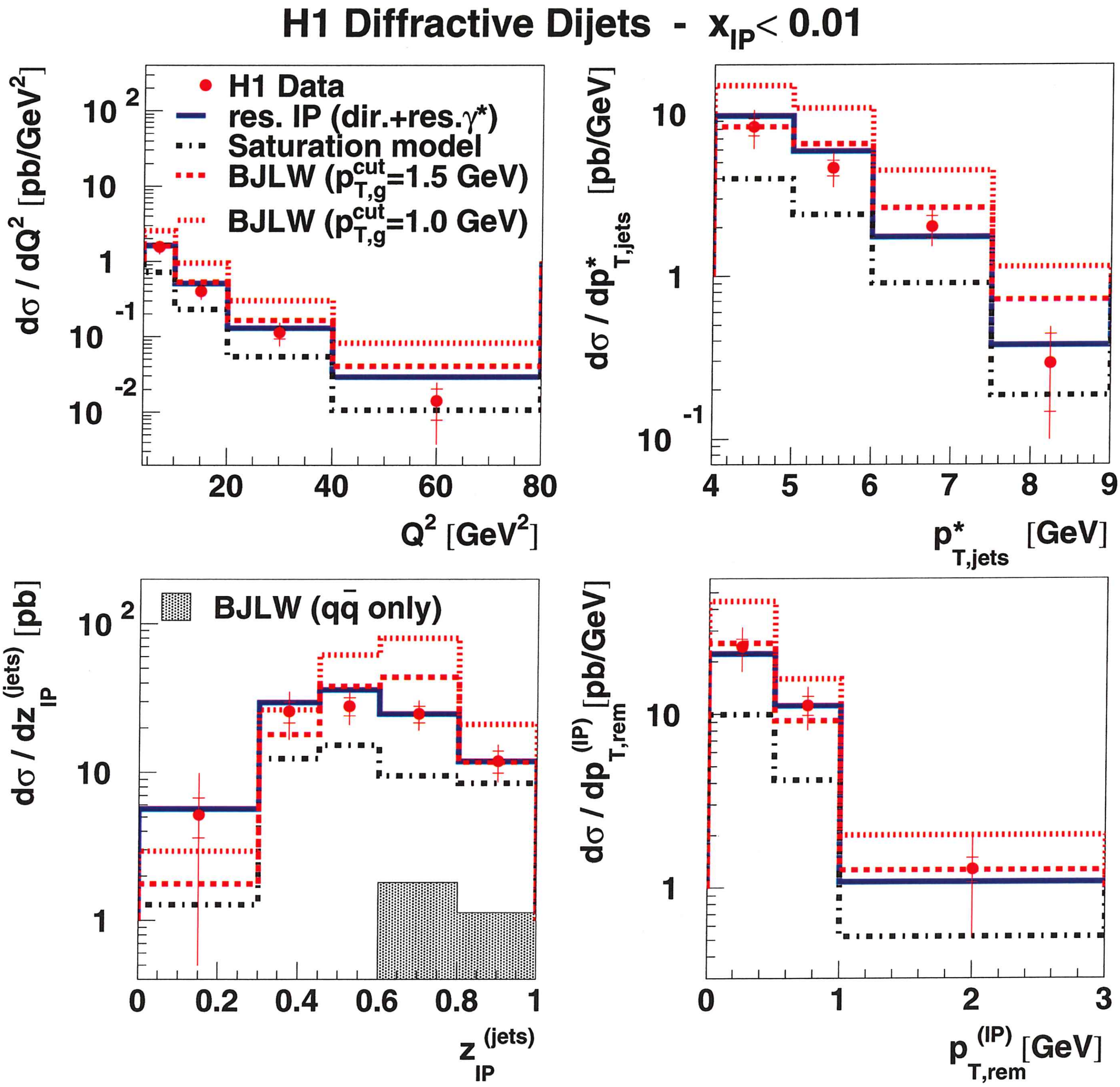
- "fit 2" (flat gluon) agrees well with data
  "fit 3" (peaked gluon) is too high at high $z_{I\!P}$

Comparison to soft colour neutralisation models



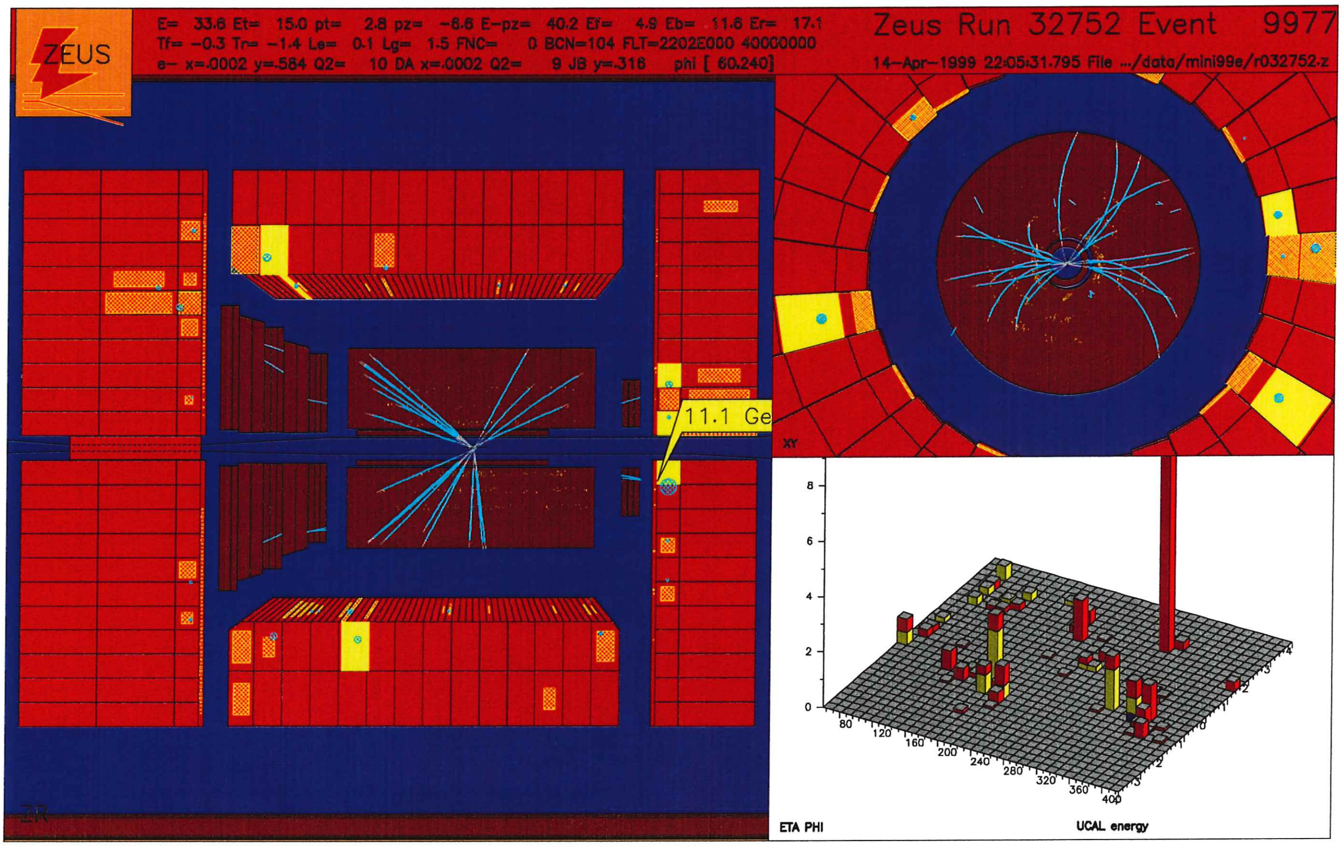
- old SCI and semiclassical model roughly agree, but are too low by factor two when compared to the data
- new SCI (generalised area law) has good normalisation, but the shape does not agree with data

Comparison to 2-gluon exchange 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 $L_{int} = 8$ pb^{-1} (680 3-jet events)
- "rapidity gap" selection ($\eta_{max} = 2.8$ GeV)
- uncorrected distribution are presented for:
  - $Q^2 > 5$ GeV^2, $200 < W < 250$ GeV
  - $M_X > 23$ GeV, $x_{I\!P} < 0.025$
  - jets are found with a k_T clustering algorithm ($y_{cut} = 0.05$)

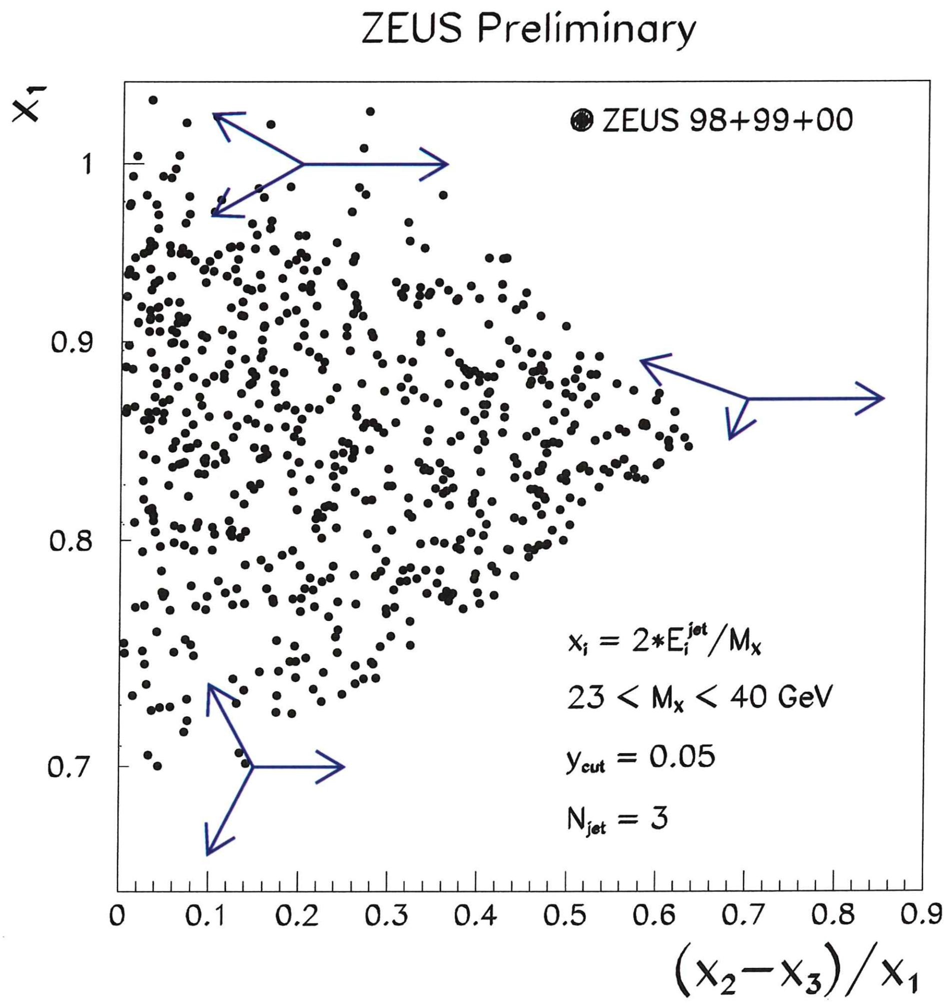
3-jet event observed topologies (1)

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:

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

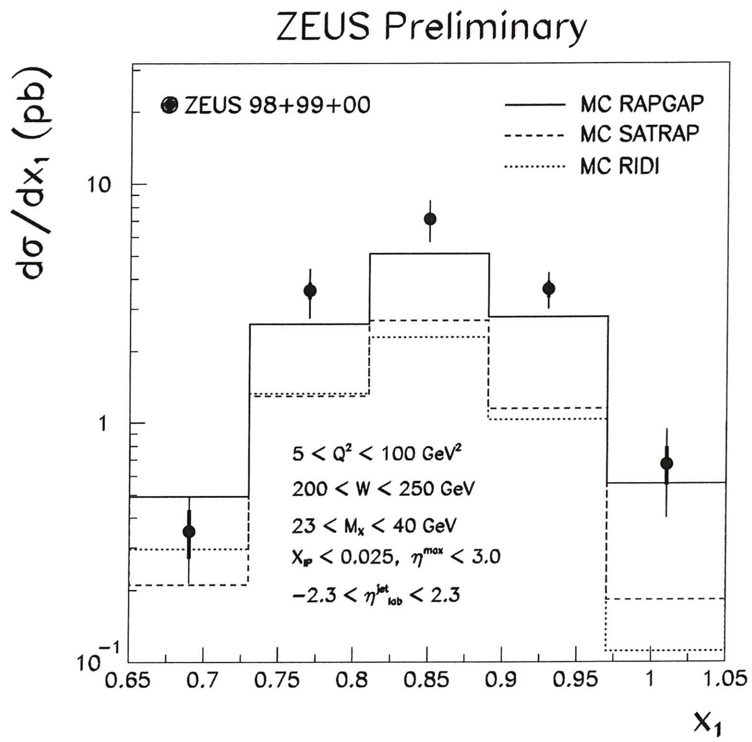
$$X_1 > X_2 > X_3, \qquad X_1 + X_2 + X_3 = 2$$

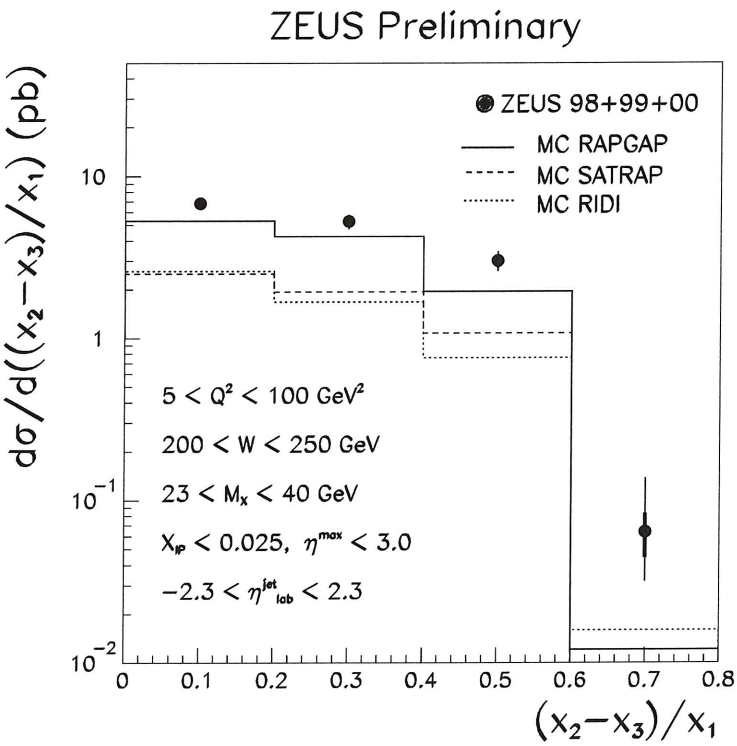
Different regions in this plane define different topologies in the 3-jet final state.



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

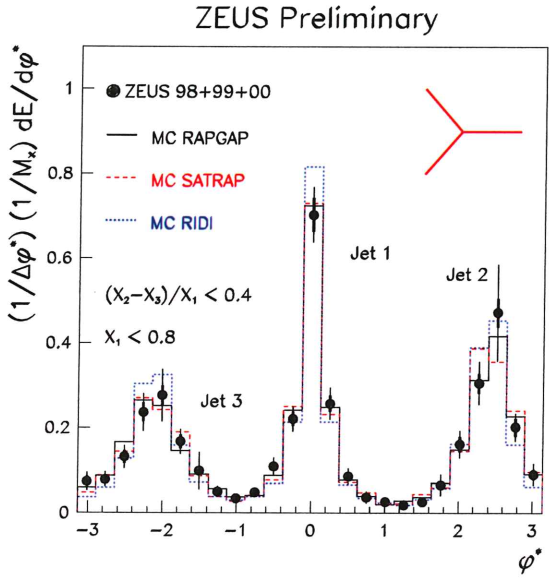
3-jet event observed topologies (2)

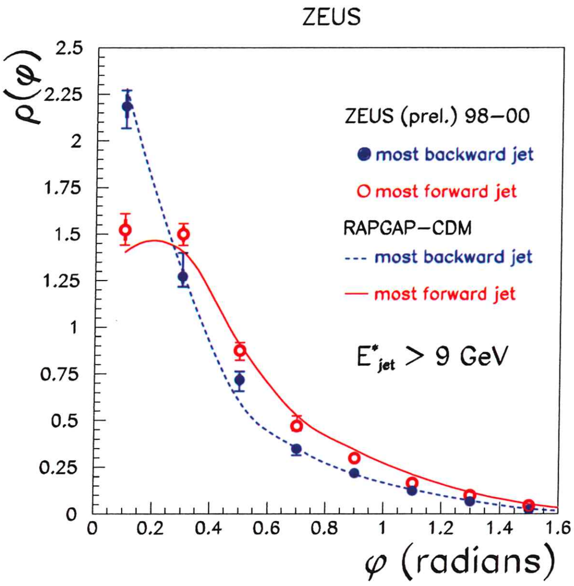




- the 2-gluon exchange model (with $q\bar{q}g$) provides a good description of how the plane is populated

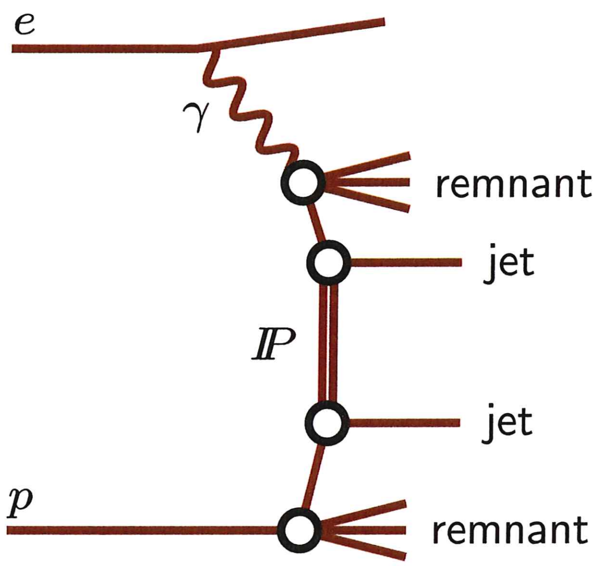
3-jet production in diffractive DIS





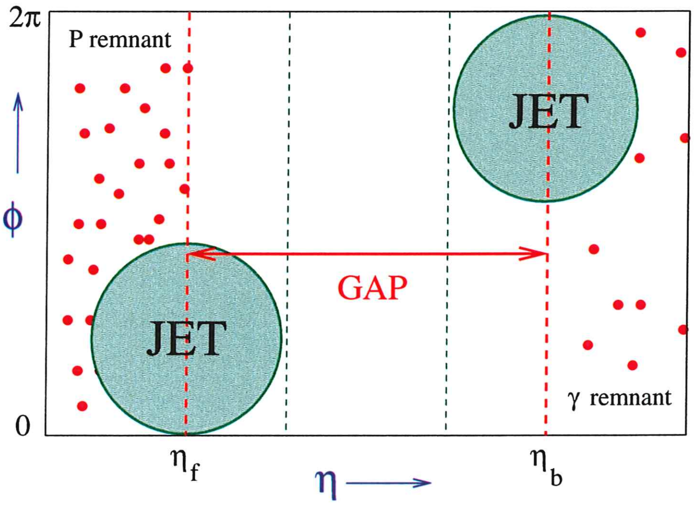
- diffractive events are selected by requiring a large rapidity gap, $M_X > 23$ GeV and jets are reconstructed with exclusive k_T algorithm
- energy flow is measured vs. ϕ, the azimuthal angle in the plane defined by the two most energetic jets
- differential jet shape $\rho(\phi)$ is calculated from the energy deposition in an annulus between $\phi - \delta\phi/2$ and $\phi + \delta\phi/2$
- jet in pomeron (forward) hemisphere is "fatter" $\longrightarrow$ support for $q\bar{q}g$ states where the gluon is aligned with the "pomeron remnant"

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 $\longrightarrow$ 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 !):

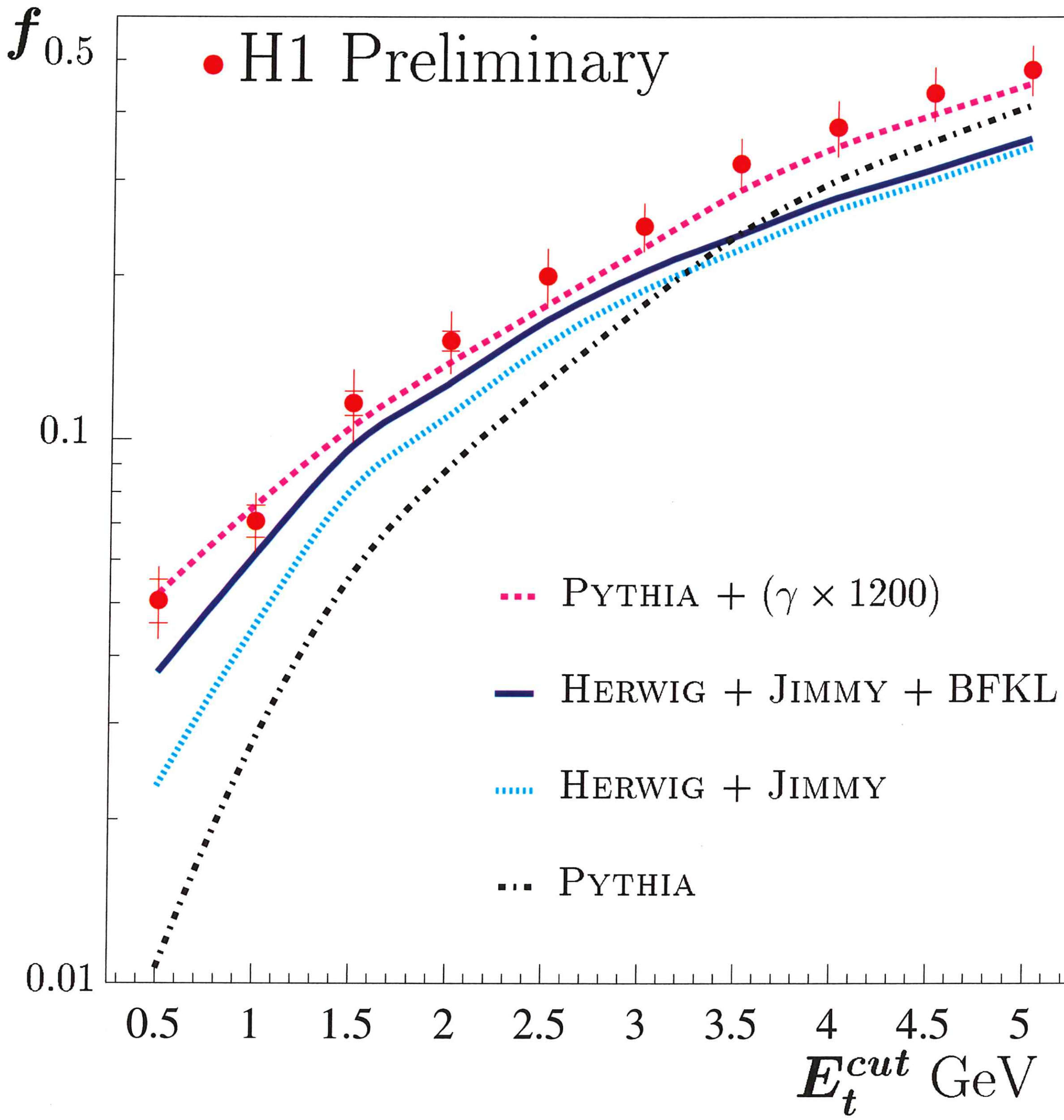
$$\frac{d\sigma(qq \to qq)}{dt} \approx (C_F \alpha_S)^4 \frac{2\pi^3}{t^2} \frac{\exp(2\omega_0 y)}{(7\alpha_S C_A \zeta(3) y)^3}$$

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

But:

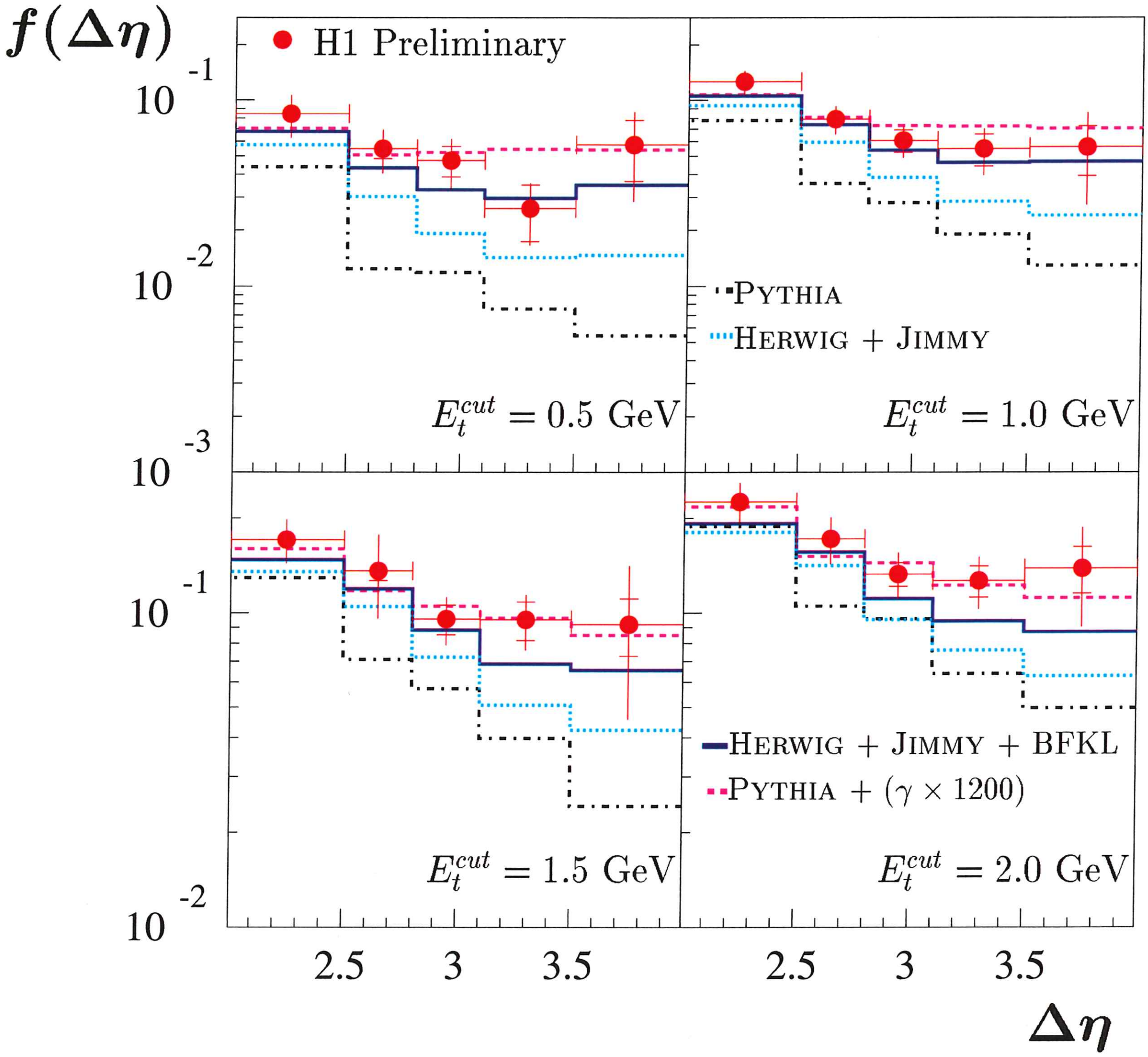
- complications due to rapidity gap survival probability and/or underlying events
- unique place to study interplay between long and short distance physics

Inclusive gap fractions



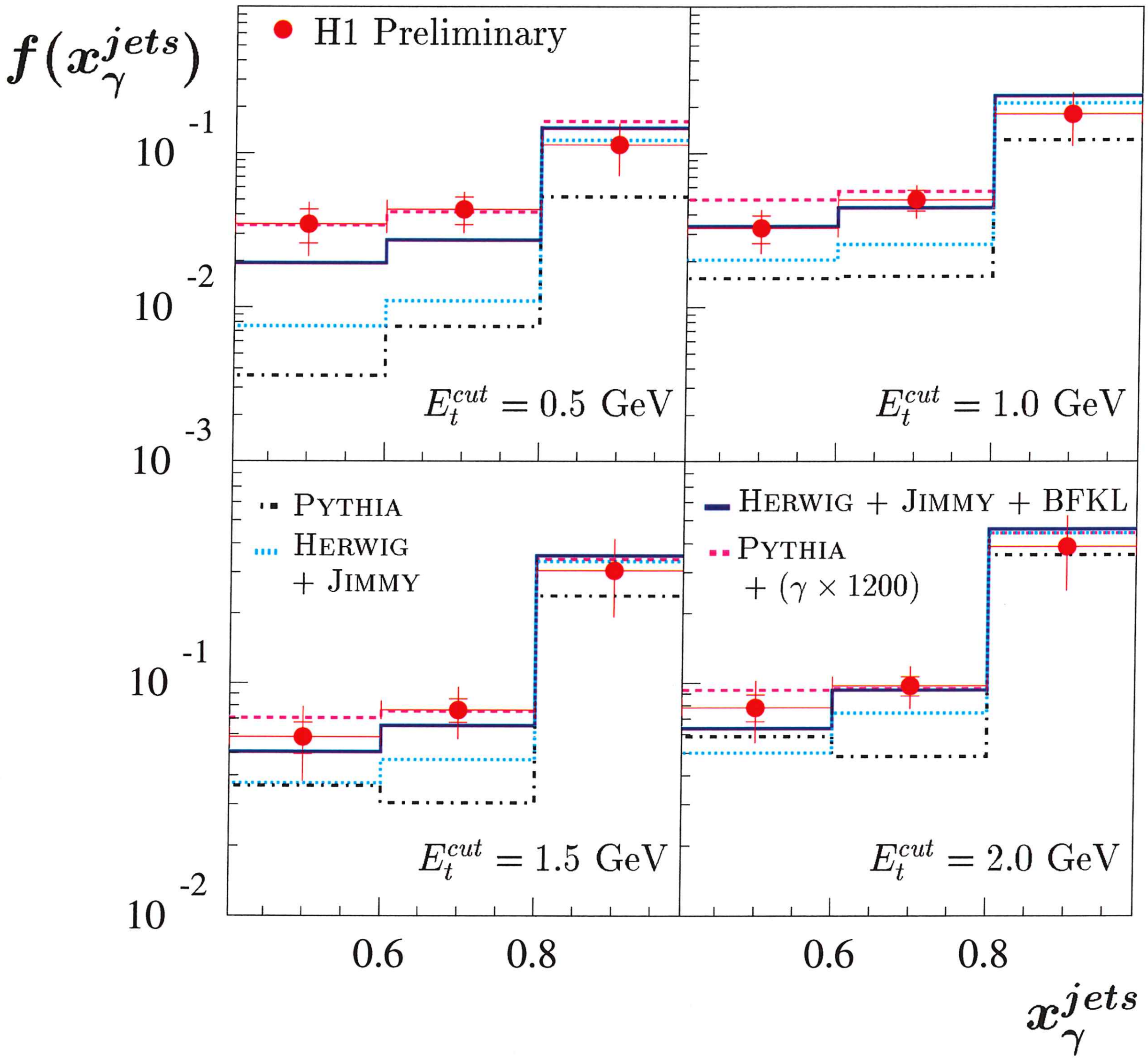
- the data show a large excess over the non colour-singlet exchange models PYTHIA and HERWIG
- predictions are very sensitive to the treatment of underlying events
- predictions are not not very sensitive to differences in the colour singlet models

Gap fraction differential in $\Delta\eta$



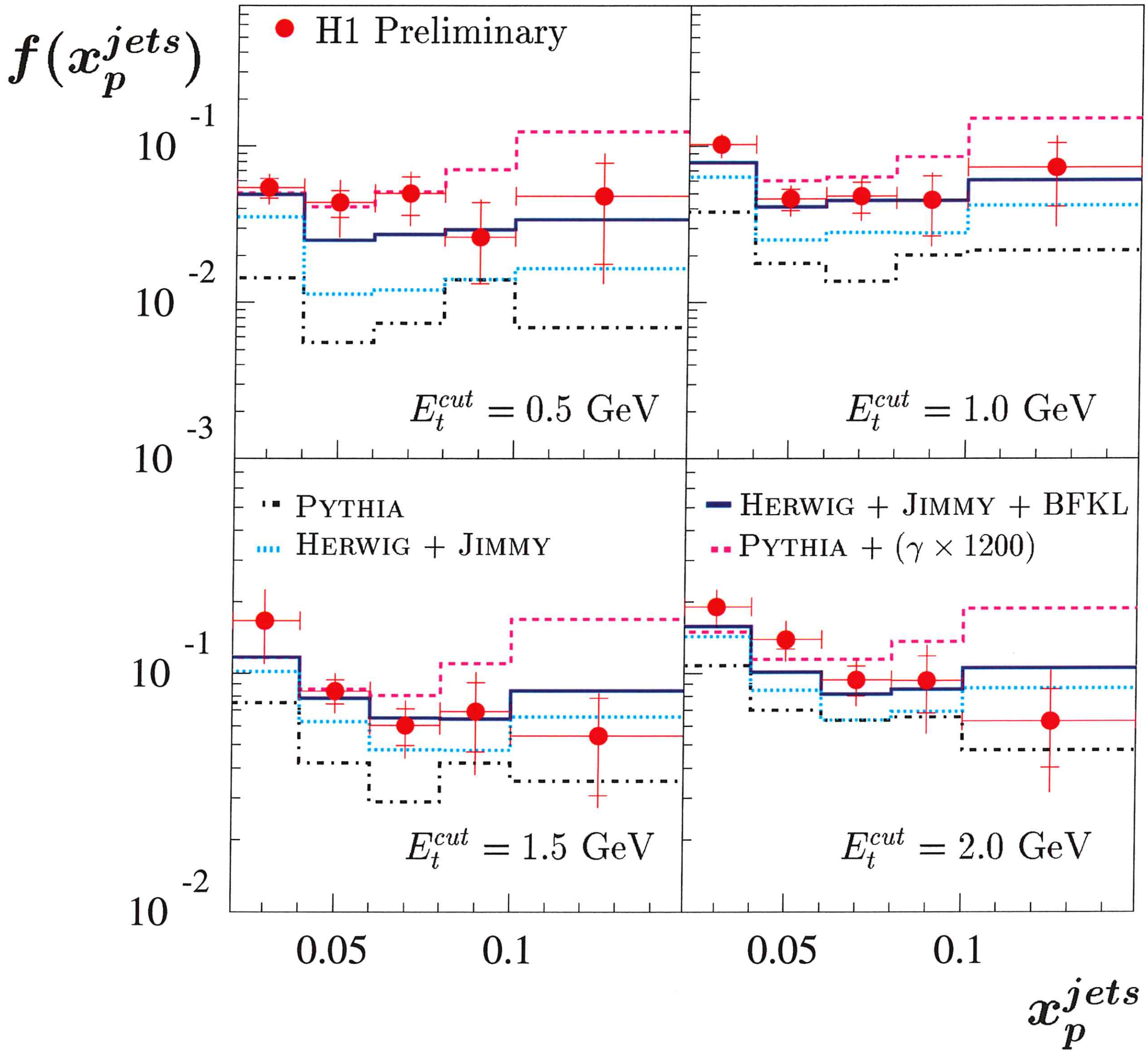
- no sensitivity to the underlying dynamics of the colour singlet exchange
- LO BFKL + HERWIG + JIMMY (for m.i.) describes the data in normalisation and in shape

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

Diffraction is a very active and rich field of study:

- Theoretical models are rapidly evolving. Both perturbative QCD calculations and semiclassical models are attempting to provide a deeper understanding of the phenomenological QCD-Regge parametrisations.

- A first generation of analyses of the hadronic final state in diffraction resulted in the qualitative indication that the dynamics of colour singlet exchange is dominated by gluons.

- New analyses are focussing on specific processes (high-E_T jets, open charm, etc.) and attempt to test theoretical models in a quantitative way. This results in a rich interplay between theory and experiment.

- (not mentioned here) Studies of exclusive vector meson production attack the pomeron from a different angle. Transition from "soft" to "hard" diffraction, . . .)

- Some measurements are still limited by large statistic and/or systematic uncertainties. The upcoming HERA luminosity upgrade and VFPS project promise an interesting and bright future for diffraction at HERA!