Symposium on Future Prospects in High Energy Physics

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Diffraction at HERA

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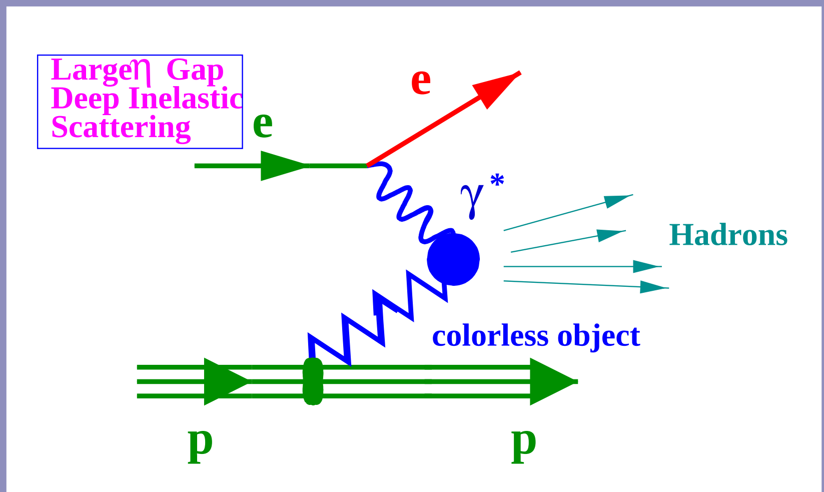
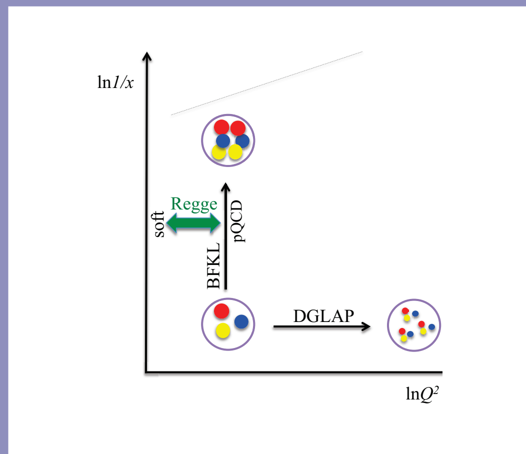
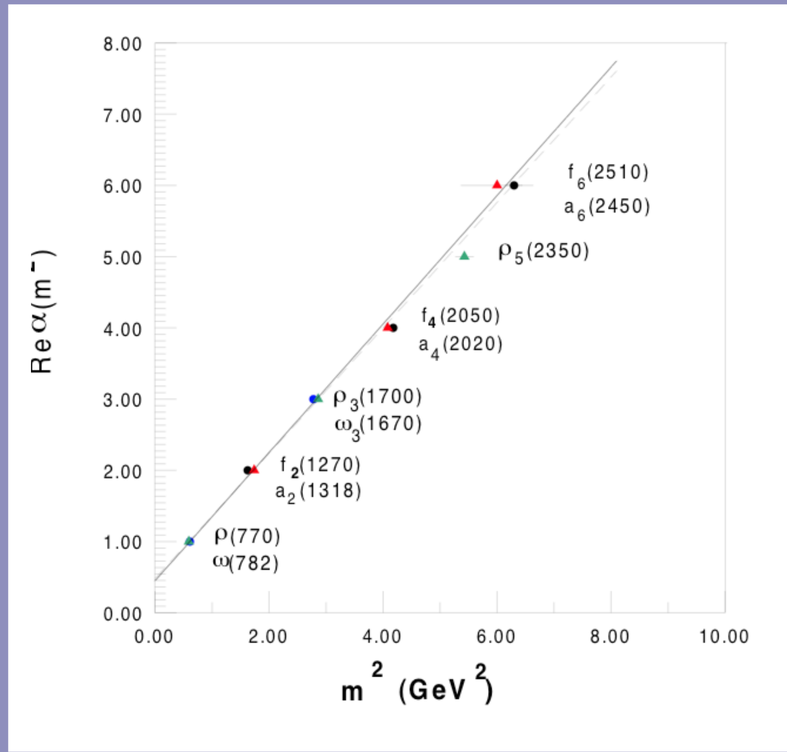




Introduction

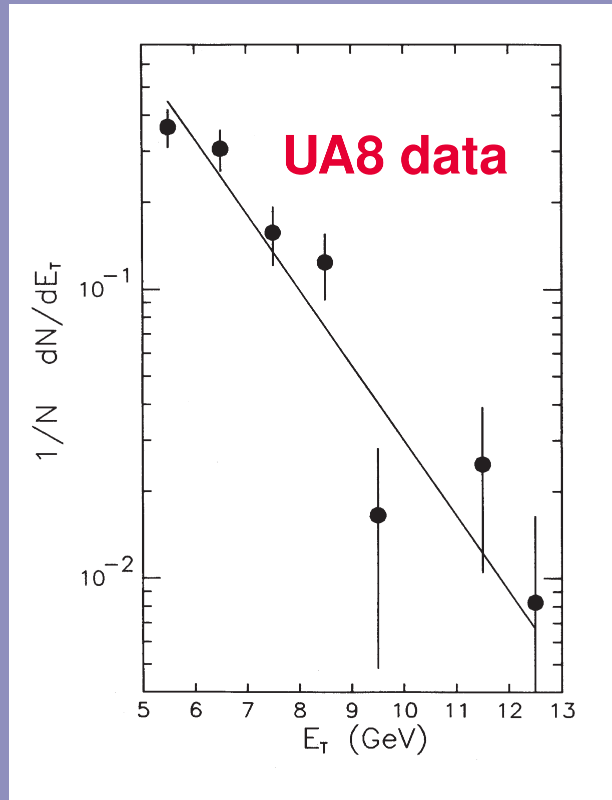
- According to Regge theory, the high-energy behaviour of an elastic hadron-scattering amplitude is controlled by a sequence of Regge trajectories corresponding to the exchange of families of particles with different spin



- Regge phenomenology successfully describes the energy dependence of the total cross sections and the properties of elastic and diffractive production in hadron-hadron interactions via the exchange of the pomeron
- Before the observations reported at HERA, Regge theory and pQCD have been subjects without much overlap, except for predictions regarding the $x \to 0$ behaviour of structure functions
- Ingelman and Schlein suggested in 1985 that the pomeron may have a partonic structure which could be probed in hard diffractive dissociation

Introduction

- UA8 reported in 1985 the measurement of high E_T jets in diffractively produced high-mass systems
  $\rightarrow$ strong evidence for the hard scattering originating from partons within the pomeron

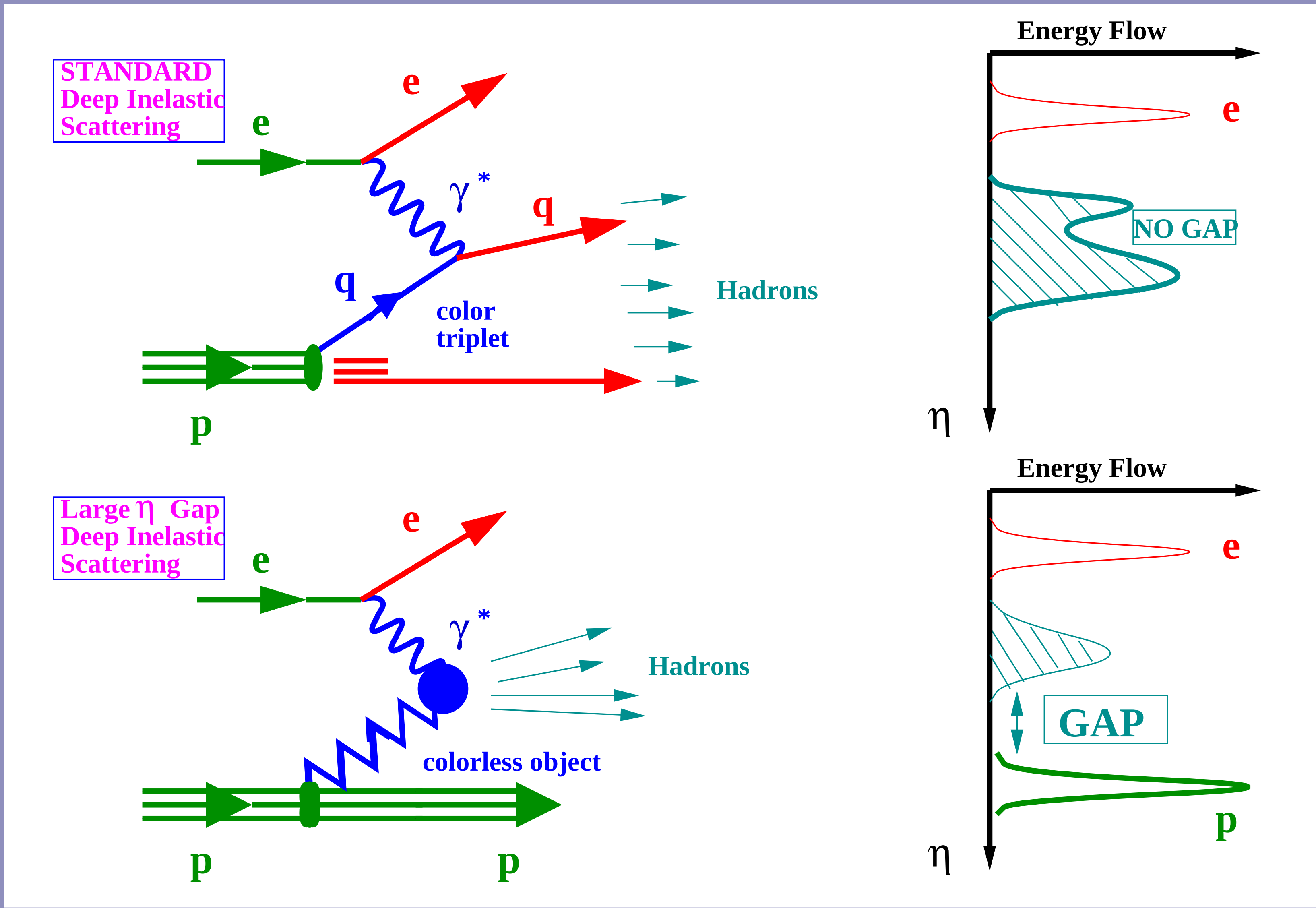


- The concept of pomeron structure functions has been studied in terms of pQCD since 1983

- The pomeron structure can be probed unambiguously in virtual-photon exchange at HERA

- The experimental signature of a pomeron exchange would consist of a quasi-elastically scattered proton, well separated in rapidity ("rapidity gap") from the remaining hadronic system

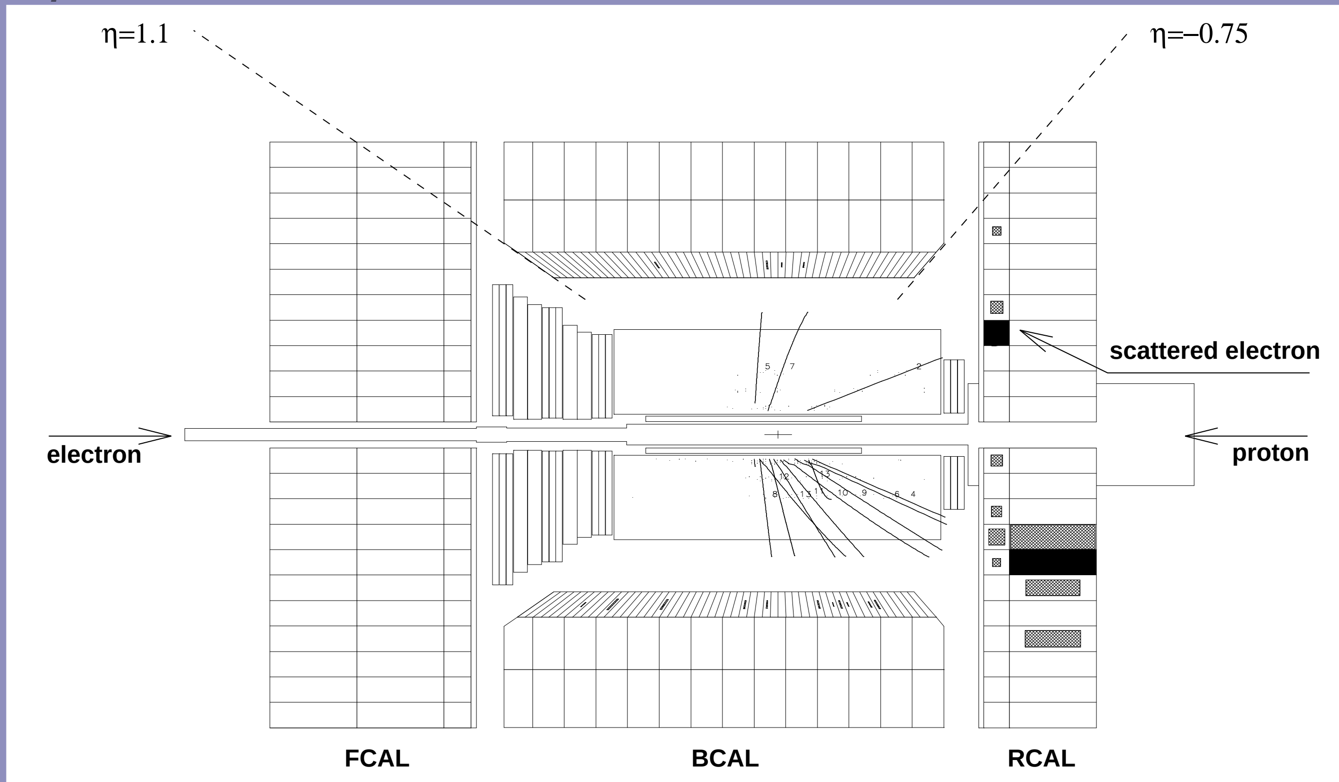
Experimental signature for diffraction at HERA



A **large rapidity gap** or a **fast-forward proton** in diffractive events at **HERA**

First observation of hard diffractive events at HERA

- In 1993, a class of DIS events was observed in which the hadronic energy deposit closest to the proton beam direction was at a large angle



- The events exhibited a sizeable difference between the pseudorapidity of the smallest detector angle ($\eta = 4.3$) and the pseudorapidity of the hadrons observed closest to the proton direction

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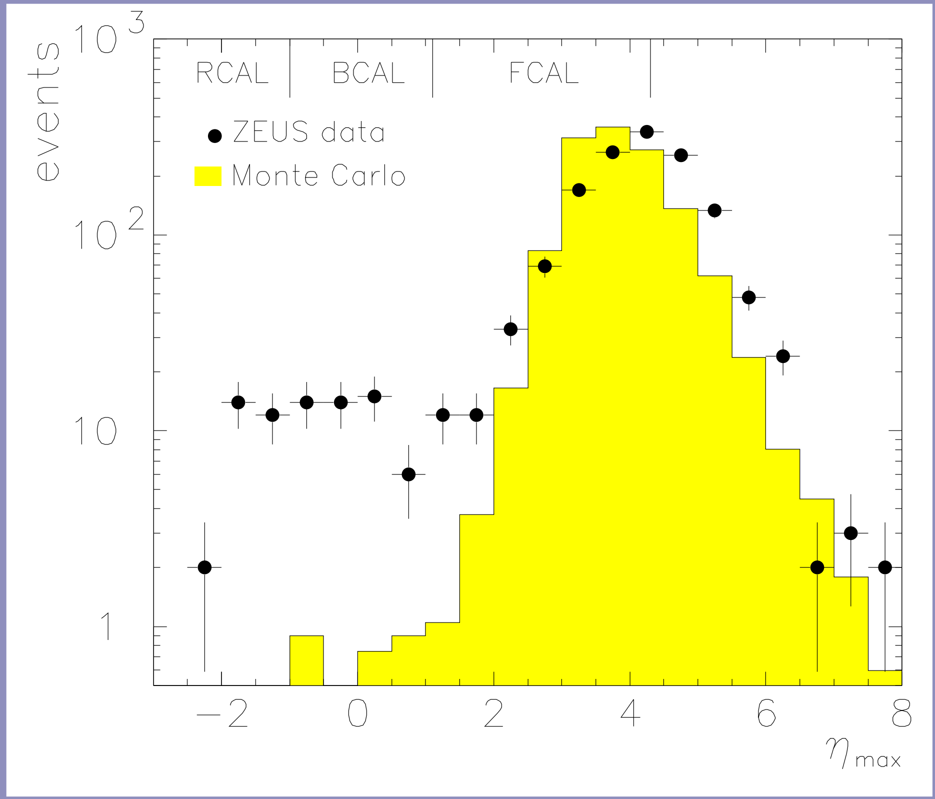
First observation of hard diffractive events at HERA

- $\eta_{\rm max}$: maximum pseudorapidity of all calorimeter clusters in an event



- A clear excess of events is observed for $\eta_{\rm max} < 1.5$ $\rightarrow$ "large rapidity gap" events
- Rapidity distribution of diffractive recoiling state expected to be constant
- These "large rapidity gap" events are not accounted for by standard QCD-inspired fragmentation models and their characteristics are compatible with those expected from diffractive dissociation involving pomeron exchange

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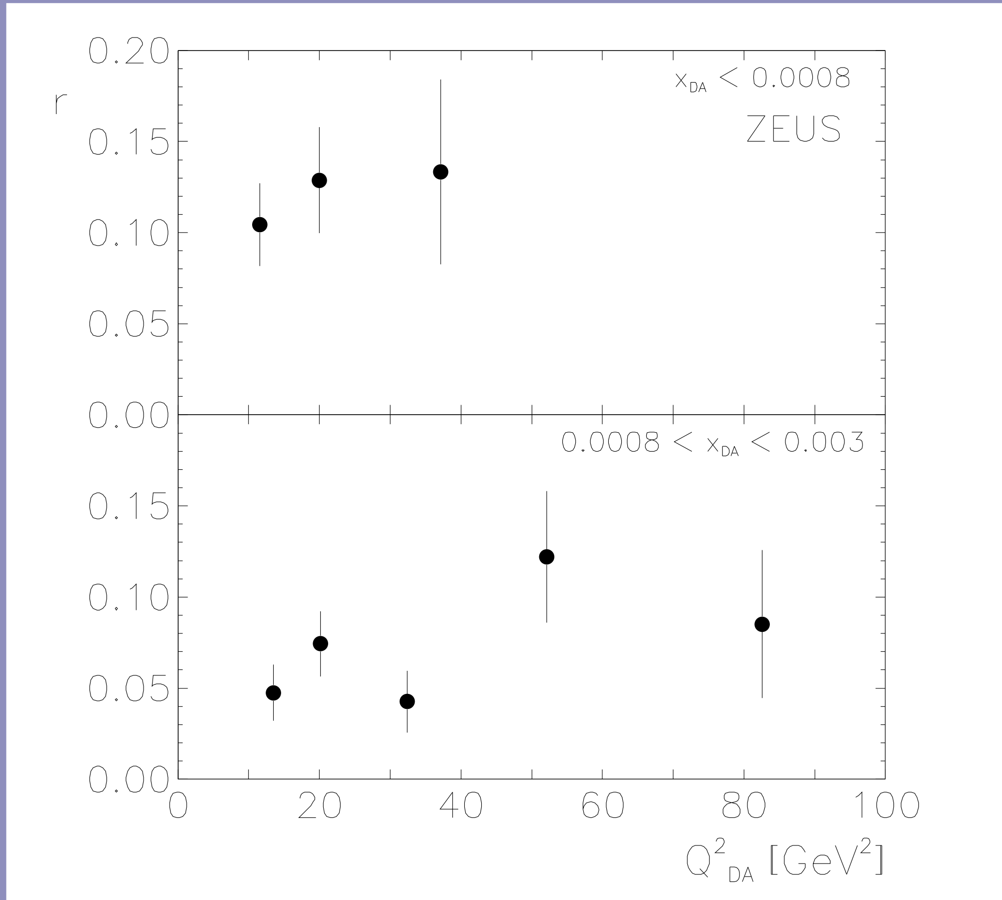
First observation of hard diffractive events at HERA

- Q^2 distribution for events with $\eta_{\max} < 1.5$ in two regions of x:



- The fraction of events with a large rapidity gap shows a weak dependence with Q^2
  $\rightarrow$ indication of a leading-twist contribution to the proton structure function

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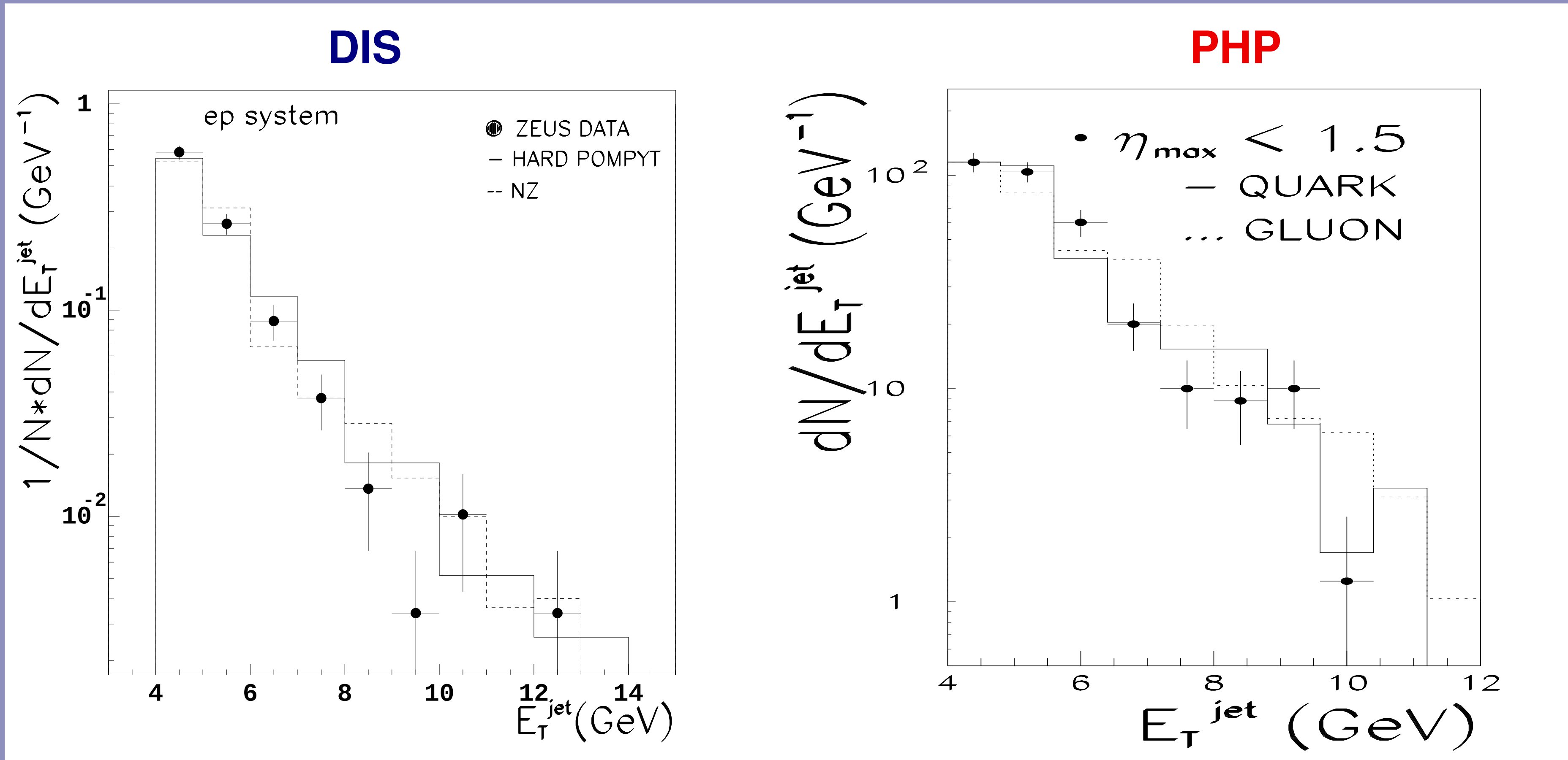
First observation of hard diffractive events at HERA

- Jet production in DIS and PHP for events with $\eta_{\max} < 1.5$:



- The natural interpretation of the observation of these events is the hard interaction of the virtual and real photon with a colourless object with partonic structure inside the proton: the pomeron

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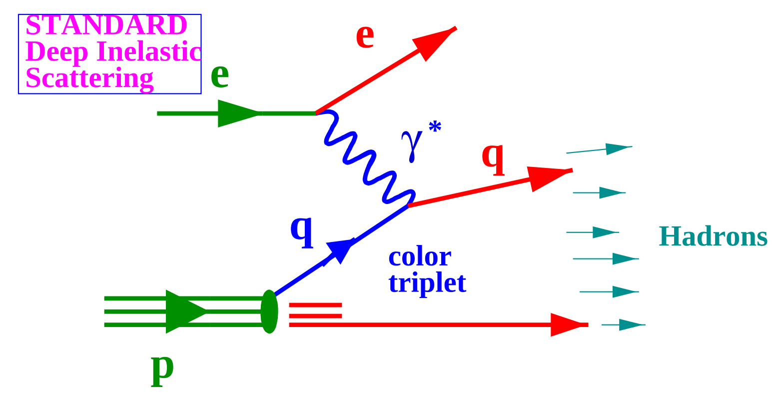
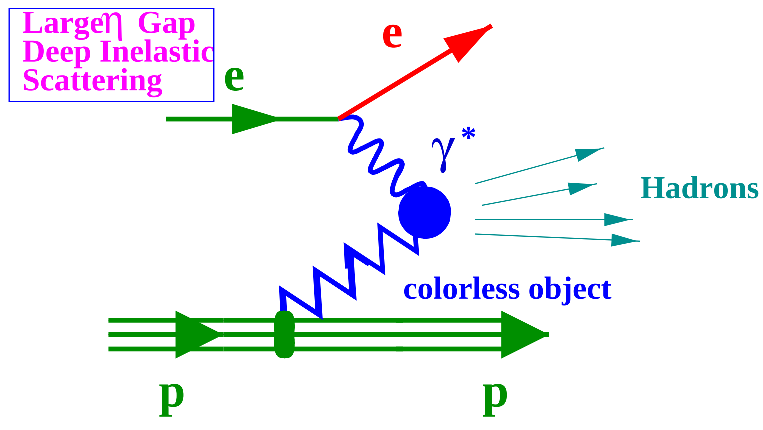
Kinematics of (diffractive) events in DIS





$$e(k) + p(P) \rightarrow e'(k') + X \qquad e(k) + p(P) \rightarrow e'(k') + p'(P') + X$$

$$Q^2 = -q^2 = -(k - k')^2$$

$$x = \frac{Q^2}{2P\cdot q} \qquad x_{I\!P} = \frac{(P-P').q}{P.q}$$

$$y = \frac{P\cdot q}{P\cdot k} \qquad \beta = \frac{Q^2}{2(P-P')\cdot q} = \frac{x}{x_{I\!P}}$$

$$W^2 = (q + P)^2 = \frac{Q^2(1-x)}{x} + M_p^2 \qquad t = (P - P')^2$$

Diffractive structure function

- Soft hadron-hadron data via pomeron exchange can be described by a pomeron-hadron coupling and a pomeron propagator
  $\Rightarrow$ in this picture, the pomeron can be treated as a quasi-real particle emitted by the hadron and described in terms of a parton density characterised by a structure function, $F_2^{I\!P}(\beta, Q^2)$

- For unpolarised beams, the differential cross section for single diffractive dissociation is given by:

$$\frac{d^4\sigma_{\rm diff}}{d\beta dQ^2 dx_{I\!P} dt} = \frac{2\pi\alpha^2}{\beta Q^4}[(1+(1-y)^2)F_2^{D(4)} - y^2 F_L^{D(4)}]$$

  where, assuming factorisation,

$$F_2^{D(4)}(\beta, Q^2, x_{I\!P}, t) = f_{I\!P}(x_{I\!P}, t) \cdot F_2^{I\!P}(\beta, Q^2)$$

  and $f_{I\!P}$ is the pomeron flux factor

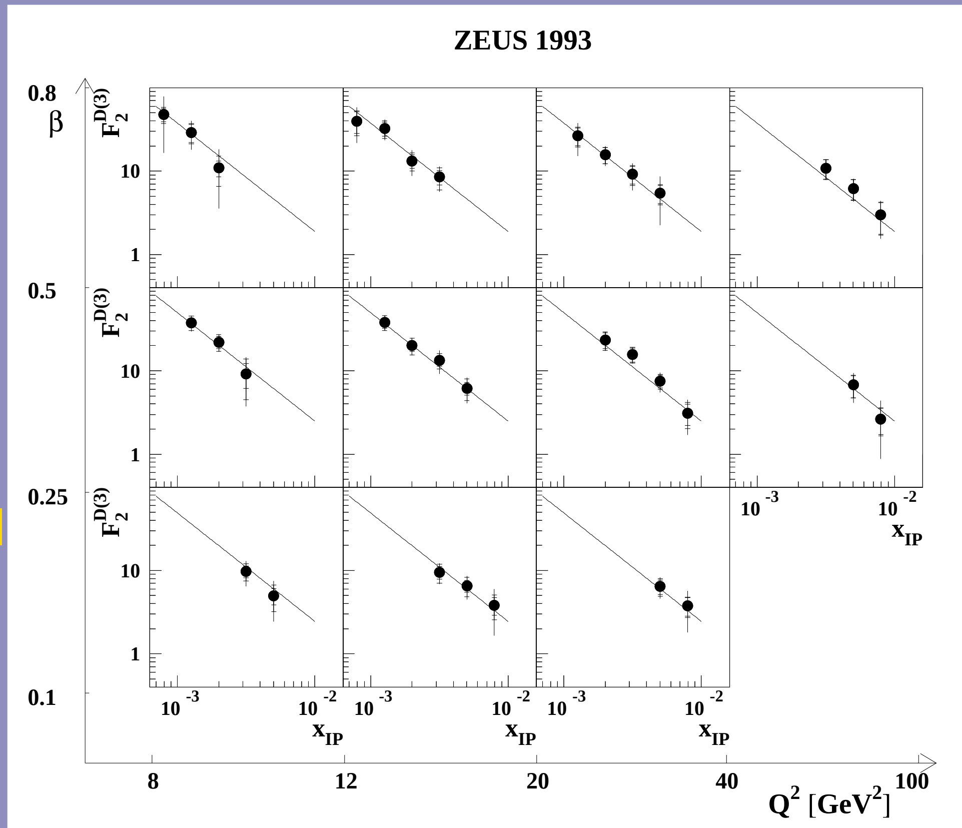
- Integrating over t,

$$\frac{d^3\sigma_{\rm diff}}{d\beta dQ^2 dx_{I\!P}} = \frac{2\pi\alpha^2}{\beta Q^4}[1+(1-y)^2]F_2^{D(3)}(\beta, Q^2, x_{I\!P})$$

First measurement of the diffractive structure function at HERA

- $F_2^{D(3)}(\beta, Q^2, x_{I\!P})$ measured in the kinematic range:

$0.08 < y < 0.5$
$8 < Q^2 < 100$ GeV^2
$6.3 \cdot 10^{-4} < x_{I\!P} < 10^{-2}$
$0.1 < \beta < 0.8$



- Data fall rapidly with increasing $x_{I\!P}$
- Dependence of $F_2^{D(3)}$ on Q^2 at fixed β is weak $\rightarrow$ consistent with hard interaction between the virtual photon and point-like constituents within the pomeron
- The data are consistent with the assumption of factorisation into a pomeron flux factor and a pomeron structure function
  $\rightarrow$ the $x_{I\!P}$ dependence is consistent with the form $(1/x_{I\!P})^a$ with
  $a = 1.30^{+0.11}_{-0.16}$ for all β and Q^2 regions

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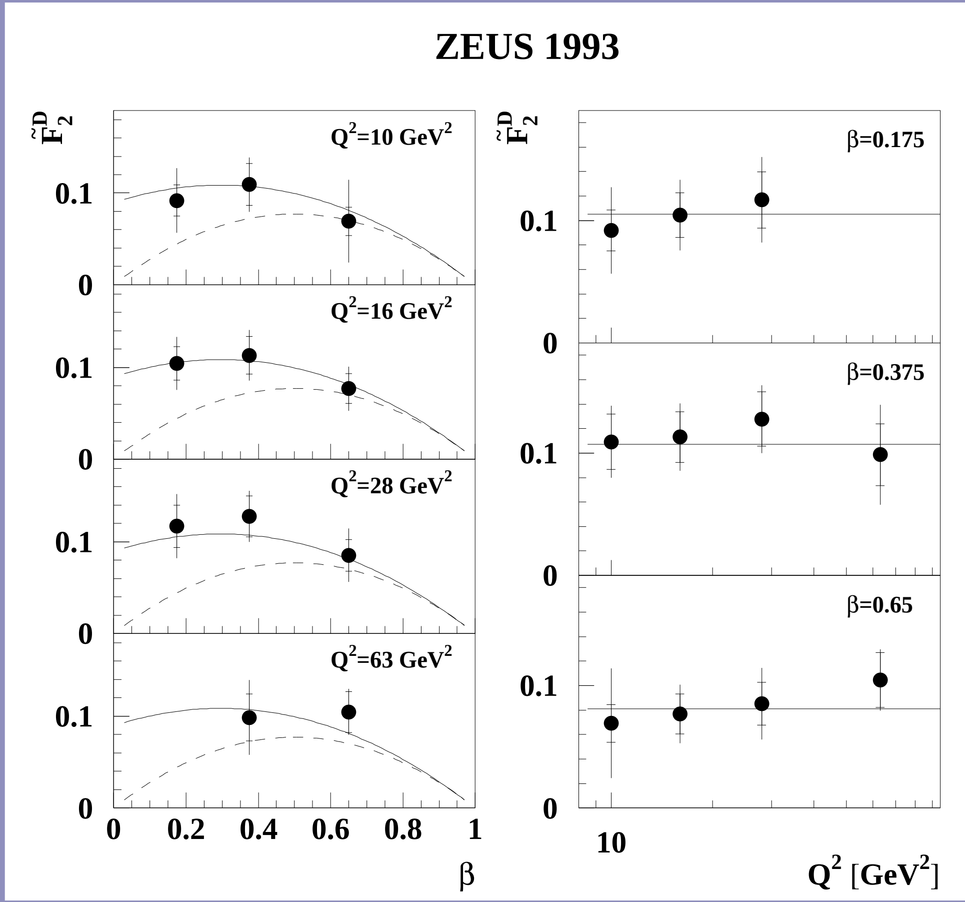
First measurement of the diffractive structure function at HERA

- Integrating $F_2^{D(3)}$ over $x_{I\!P}$ (universal $x_{I\!P}$ dependence assumed, taken from fit) in all β and Q^2 regions:



- Events characterised by the diffractive dissociation of virtual photons, $\gamma^* p \to X p$, constitute $\approx 10\%$ of the visible DIS cross section

- The extracted $\tilde{F}_2^D(\beta, Q^2)$ values are consistent with a flat β dependence for fixed Q^2 and are approximately independent of Q^2 for all β values

$\Rightarrow$ Picture consistent with the scattering of a virtual photon off point-like quarks within the pomeron

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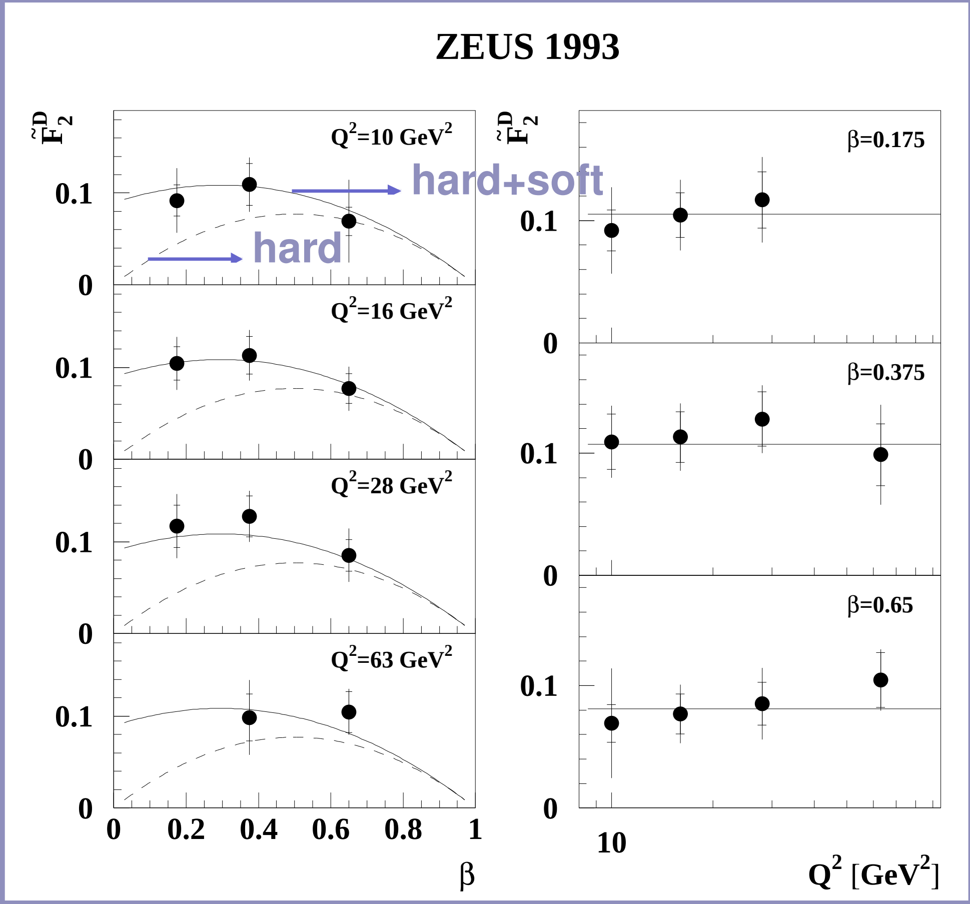
First determination of pomeron PDFs at HERA

- Fits to $F_2^{D(3)}$: $F_2^{D(3)} = (1/x_{I\!P})^a \cdot b \cdot [\beta(1-\beta) + \frac{c}{2} \cdot (1-\beta)^2]$
  with $a = 1.30$, assuming factorisation and no Q^2 dependence,
  $(1-\beta)^2$: soft contribution



- Results:
  $b = 0.018 \pm 0.001$(stat)± 0.005(syst)
  $c = 0.57 \pm 0.12$(stat)± 0.22(syst)

- The β-dependence of the pomeron structure function requires both a hard and a soft component

- It was also determined that the quarks within the pomeron do not saturate the momentum sum rule: gluon component needed!

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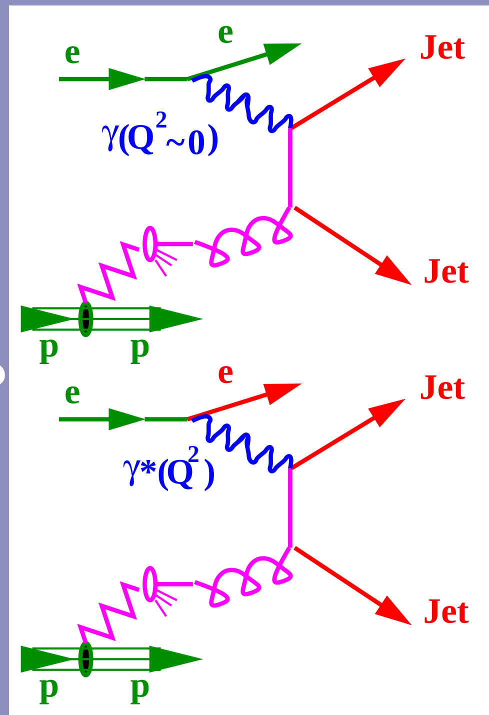
Diffractive picture starting to emerge...

- Observed Q^2 dependence indicative of a point-like nature of the interaction and a leading-twist mechanism
- Measurements consistent with a diffractive structure function which factorises into a pomeron flux factor ($x_{I\!P}$) and a pomeron structure function (Q^2 and β)
- The pomeron structure function scales with Q^2 and β
- Quarks within the pomeron do not saturate the momentum sum rule and indications of scaling violations point to a sizeable gluon component
- At LO QCD, diffractive DIS probes only the quark content of the pomeron:
  - $\rightarrow$ are the parton densities universal?
  - $\rightarrow$ what fraction of the pomeron momentum is carried by quarks and gluons?
  - $\rightarrow$ does a momentum sum rule apply to the pomeron?
- Study reactions sensitive to the quark and gluon content of the pomeron:
  - $\rightarrow$ jet production in DIS and photoproduction



Jet production in diffractive events

- In factorisable models of jet production, the pomeron is assumed to be a source of partons which interact with the (partons within) the photon,

$$\sigma = \int dy f_{\gamma/e}(y) \int\int dx_{I\!P} dt f_{I\!P/p}(x_{I\!P}, t)$$
$$\sum_i \int d\beta \sum_{j,k} \int d\hat{p}_T^2 \frac{d\hat{\sigma}_{i+\gamma\to j+k}}{d\hat{p}_T^2}(\hat{s}, \hat{p}_T^2, \mu^2) \;\; f_{i/I\!P}(\beta, \mu^2)$$

- Some possible parameterisations:

  $\rightarrow$ hard gluon density: $\beta f_{g/I\!P}(\beta, \mu^2) = 6\beta(1-\beta)$
  $\rightarrow$ soft gluon density: $\beta f_{g/I\!P}(\beta, \mu^2) = 6(1-\beta)^5$
  $\rightarrow$ hard quark density: $\beta f_{q/I\!P}(\beta, \mu^2) = \frac{6}{4}\beta(1-\beta)$

  normalised such that all of the pomeron momentum is carried by those partons: $\Sigma_{I\!P}(\mu^2) \equiv \int_0^1 d\beta \sum_i \beta f_{i/I\!P}(\beta, \mu^2) = 1$, and assuming momentum sum rule

- The Donnachie-Landshoff pomeron flux factor was assumed:

$$f_{I\!P/p}(x_{I\!P}, t) = \frac{9b_0^2}{4\pi^2} F_1(t)^2 x_{I\!P}^{1-2\alpha(t)}$$

  with $b_0 \simeq 1.8$ GeV^{-1} and $\alpha(t) = 1.085 + 0.25t$

Jet cross sections in diffractive events at HERA

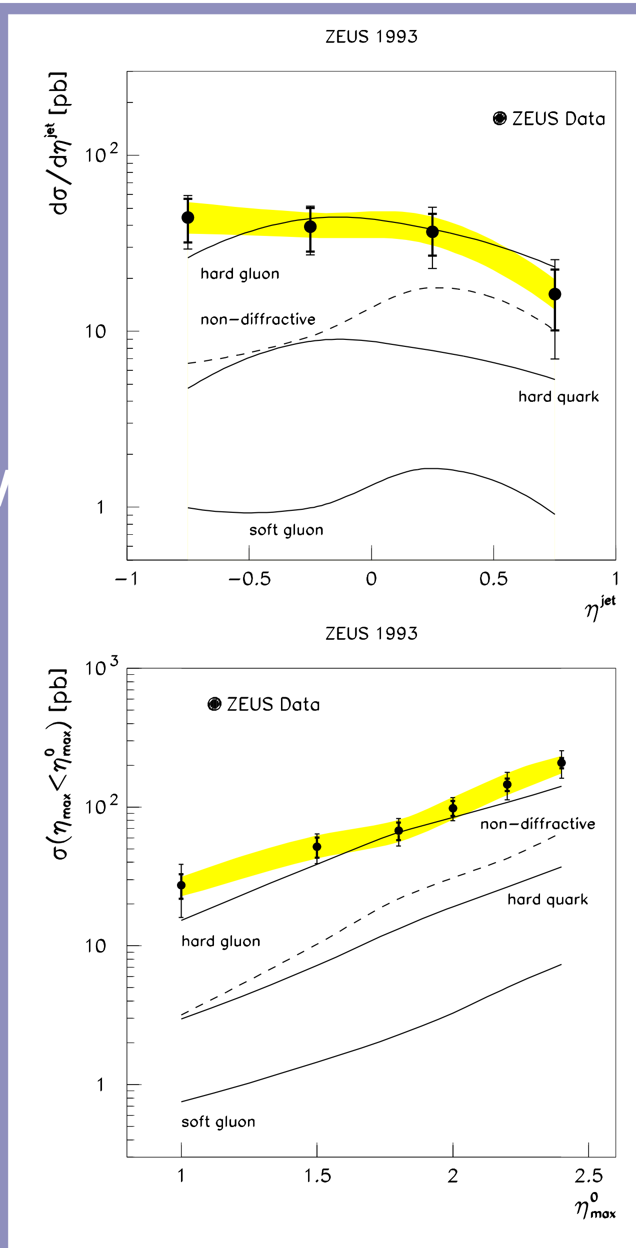
- First measurement of the cross sections for
  $$e + p \to (\text{jet} + X_r) + Y$$
  in the kinematic range:

  $Q^2 \approx 10^{-3}$ GeV^2, $130 < W < 270$ GeV,
  $\eta_{\max} < 1.8$ (GAP) and $M_Y < 4$ GeV

- At least one jet (cone algorithm) with $E_T^{\text{jet}} > 8$ GeV and $-1 < \eta^{\text{jet}} < 1$

- Comparison to predictions (assuming $\Sigma_{I\!P} = 1$):
  - $\to$ The non-diffractive contribution does not reproduce the measurements
  - $\to$ The shape of the data is well (not) reproduced by a hard (soft) parton density
  - $\to$ The calculations based on a hard quark (soft gluon) density are smaller than the data by factors 3-10 (20-50)
  - $\to$ The calculations based on a hard gluon density describe the data well

    $\Rightarrow$ Dominance of hard gluon component



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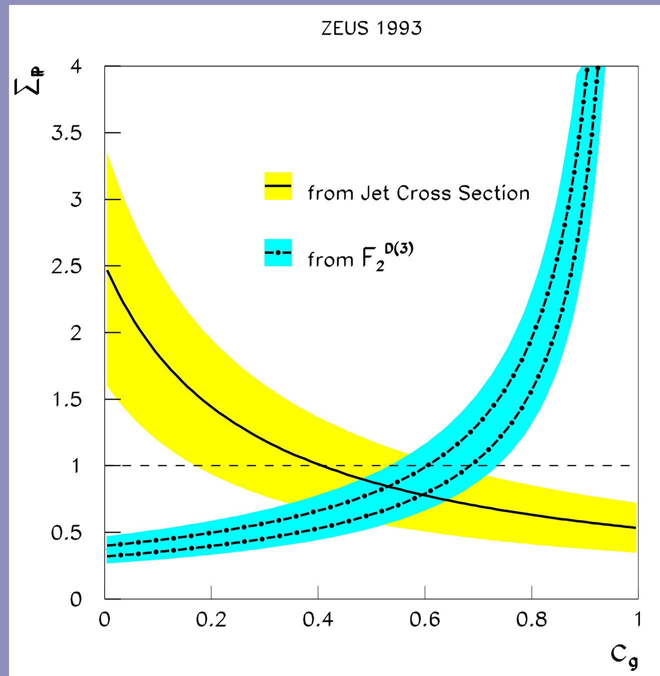
First direct evidence of the gluon content of the pomeron

- The quark and gluon contributions to the pomeron PDFs were extracted from the data (jet cross section in PHP + $F_2^{D(3)}$ in DIS):
  - → after subtracting double-dissociation and non-diffractive contributions
  - → the DL flux factor was assumed
  - → hard gluon ($6\beta(1-\beta)$) and hard quark ($\frac{6}{4}\beta(1-\beta)$) densities were considered, with fractions c_g for gluons and $c_q = 1 - c_g$ for quarks
  - → the overall normalisation $\Sigma_{I\!P}$ was left as a free parameter
- Results:
  - → from jet data alone: $1.4 < \Sigma_{I\!P} < 3.8$ for $c_g = 0$ and $0.3 < \Sigma_{I\!P} < 0.9$ for $c_g = 1$
  - → from DIS data alone: $\Sigma_{I\!P} \cdot (1 - c_g) = 0.32$ (0.40) for two (three) flavours

    ⇒ From the combined constraints: $0.4 < \Sigma_{I\!P} < 1.6$ and $0.3 < c_g < 0.8$

⇒ Between 30-80% of the momentum of the pomeron carried by partons is due to hard gluons, independently of the normalisation of the pomeron flux and assumptions on the momentum sum rule



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A QCD analysis of ZEUS diffractive data

- The diffractive reduced cross section:

$$\frac{d^3\sigma_{\rm diff}}{d\beta dQ^2 dx_{I\!P}} = \frac{2\pi\alpha^2}{\beta Q^4}[1+(1-y)^2]\sigma_r^{D(3)}(\beta, Q^2, x_{I\!P})$$

and diffractive DIS dijet data were used to constrain the quark and gluon parton densities and to extract the DPDFs

- The QCD factorisation theorem was assumed for the diffractive structure functions and the DGLAP evolution equations were used to obtain the scale dependence of the DPDFs

- The DPDFs were modelled at the starting scale $Q_0^2 = 1.8$ GeV^2 in terms of quark singlet, $f_+ = \sum_q (f_q + f_{\bar{q}})$, and gluon, f_g

$$z f_{d,u,s}(z, Q_0^2) = A_q z^{B_q}(1-z)^{C_q} \cdot D$$
$$z f_g(z, Q_0^2) = A_g z^{B_g}(1-z)^{C_g} \cdot D$$

with $D = e^{-0.001/(1-z)}$, $f_{\bar{q}} = f_q$, $f_u = f_d = f_s$, heavy quarks generated dynamically; z: longitudinal momentum fraction of the parton entering the hard subprocess relative to the diffractive exchange

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A QCD analysis of ZEUS diffractive data

- The $x_{I\!P}$ dependence was parameterised using pomeron and reggeon fluxes:

$$f_{I\!P,I\!R}(x_{I\!P},t) = \frac{A_{I\!P,I\!R}e^{B_{I\!P,I\!R}t}}{x_{I\!P}^{2\alpha_{I\!P,I\!R}(t)-1}}$$

with linear trajectories $\alpha_{I\!P,I\!R}(t)=\alpha_{I\!P,I\!R}(0)+\alpha'_{I\!P,I\!R}t$; the normalisation $A_{I\!P}$ was absorbed in $A_{q,g}$; the reggeon parton densities were taken from fits to pion data

- In total, 9 parameters were left free in the fits: $A_{q,g}$, $B_{q,g}$, $C_{q,g}$, the pomeron and reggeon intercepts $\alpha_{I\!P}(0)$ and $\alpha_{I\!R}(0)$, and the normalisation of the reggeon term, $A_{I\!R}$

- Data:

LRG data:
- $40 < W < 240$ GeV
- $2(5) < Q^2 < 305$ GeV^2
- $2 < M_X < 25$ GeV
- $0.0002 < x_{I\!P} < 0.02$

LPS data:
- $40 < W < 240$ GeV
- $2(5) < Q^2 < 120$ GeV^2
- $2 < M_X < 40$ GeV
- $0.002(0.02) < x_{I\!P} < 0.1$

Jet data:
- $E_T^{\rm jet} > 4$ GeV
- $x_{I\!P} < 0.03$

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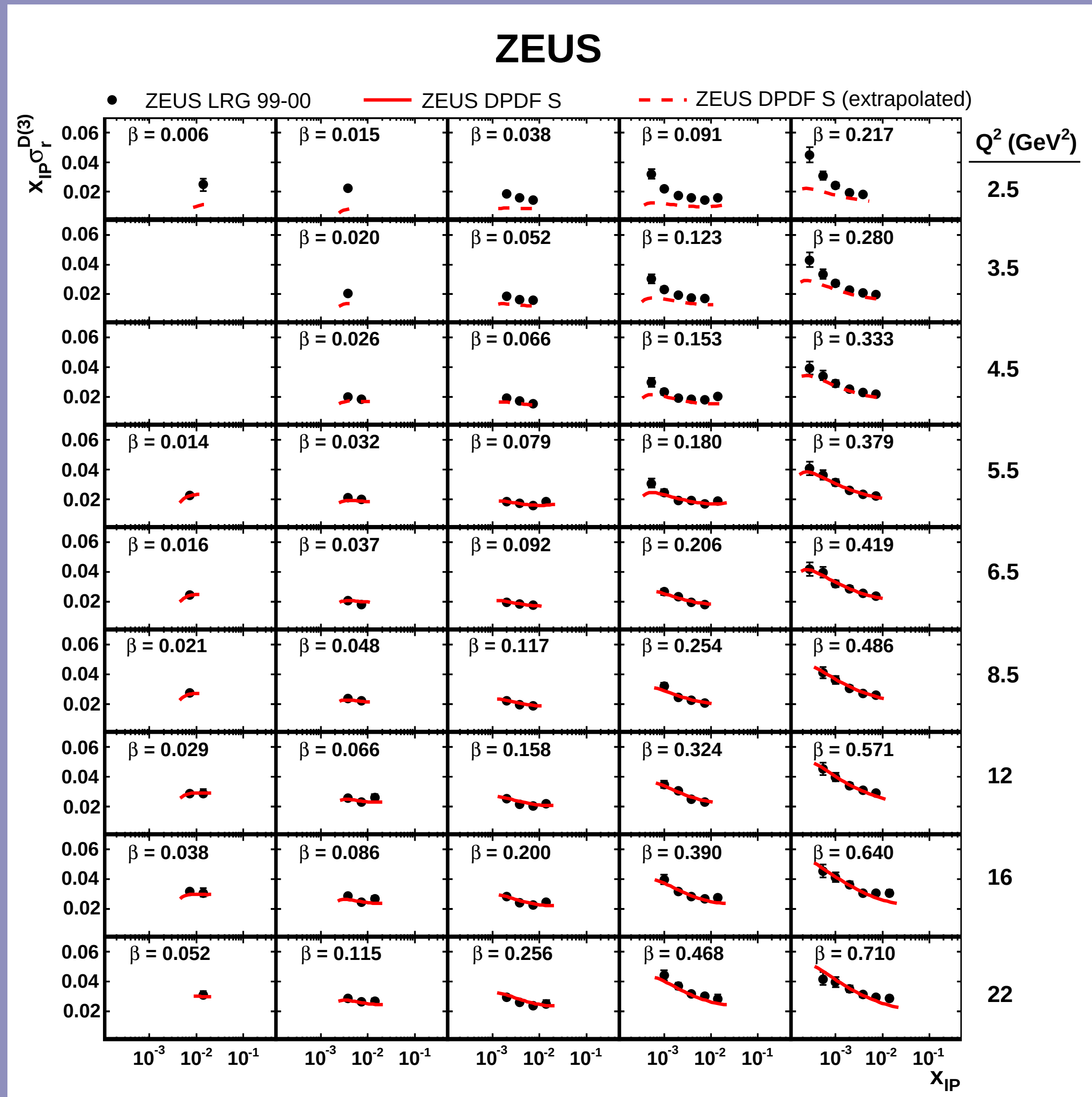
A QCD analysis of ZEUS diffractive data

- Fits to LRG+LPS data:
  - "Standard" with A_g, B_g and C_g as free parameters
  - "Constant" with $B_g = C_g = 0$



- Inclusive data sensitive to quark parameters (A_q, B_q and C_q), but show little sensitivity to gluon shape (B_g and C_g) since $F_2^{D(3)}$ is directly sensitive only to quarks

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A QCD analysis of ZEUS diffractive data

- Fits to LRG+LPS data:
  - "Standard" with A_g, B_g and C_g as free parameters
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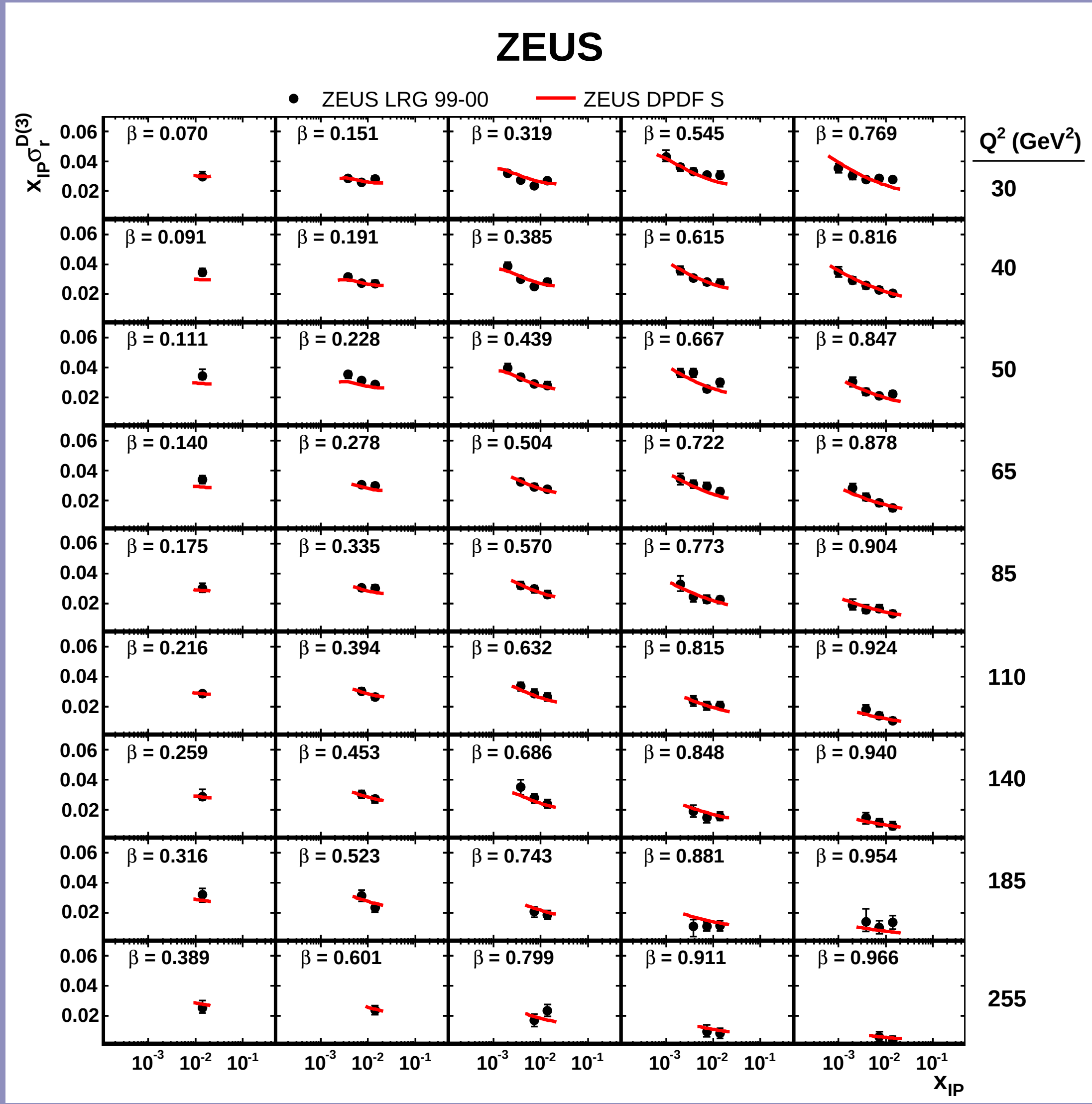

- Fits S and C are of equally good quality and the predicted reduced cross sections are indistinguishable

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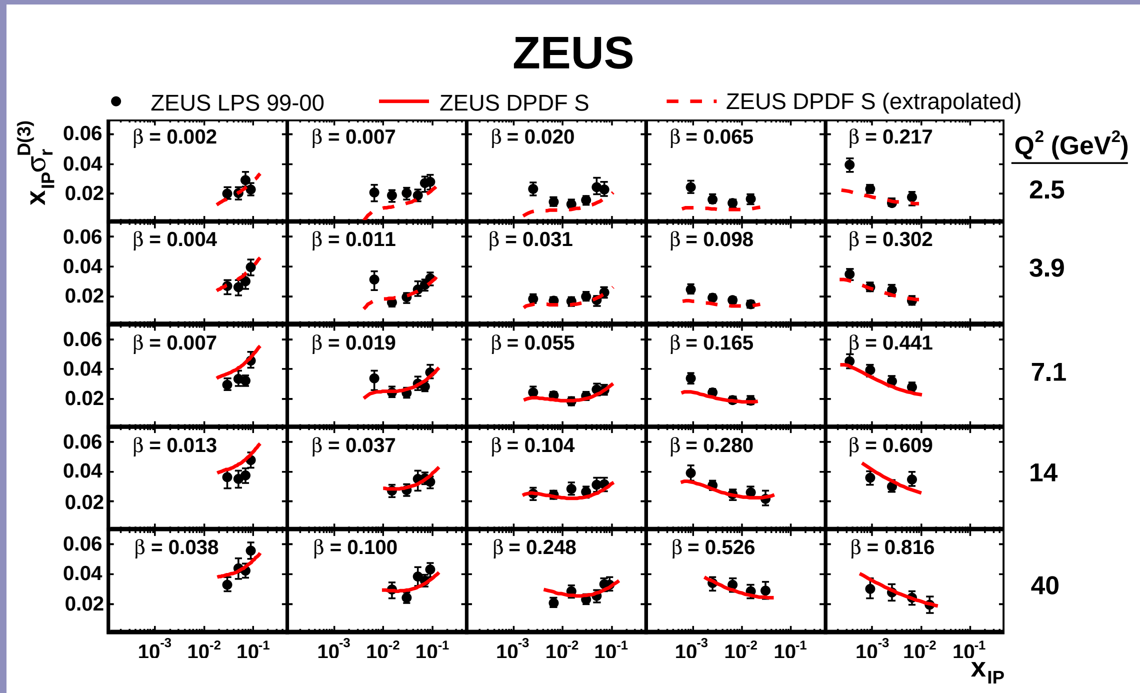
A QCD analysis of ZEUS diffractive data

- Fits to LRG+LPS data:
  - "Standard" with A_g, B_g and C_g as free parameters
  - "Constant" with $B_g = C_g = 0$
- Both data samples are well described by the fits
- For $Q^2 < 5$ GeV^2, the predictions are extrapolated and underestimate the LRG and LPS data for $x_{I\!P} < 0.005$
- The fit is above the LPS data in the low-β region, where there are no LRG data



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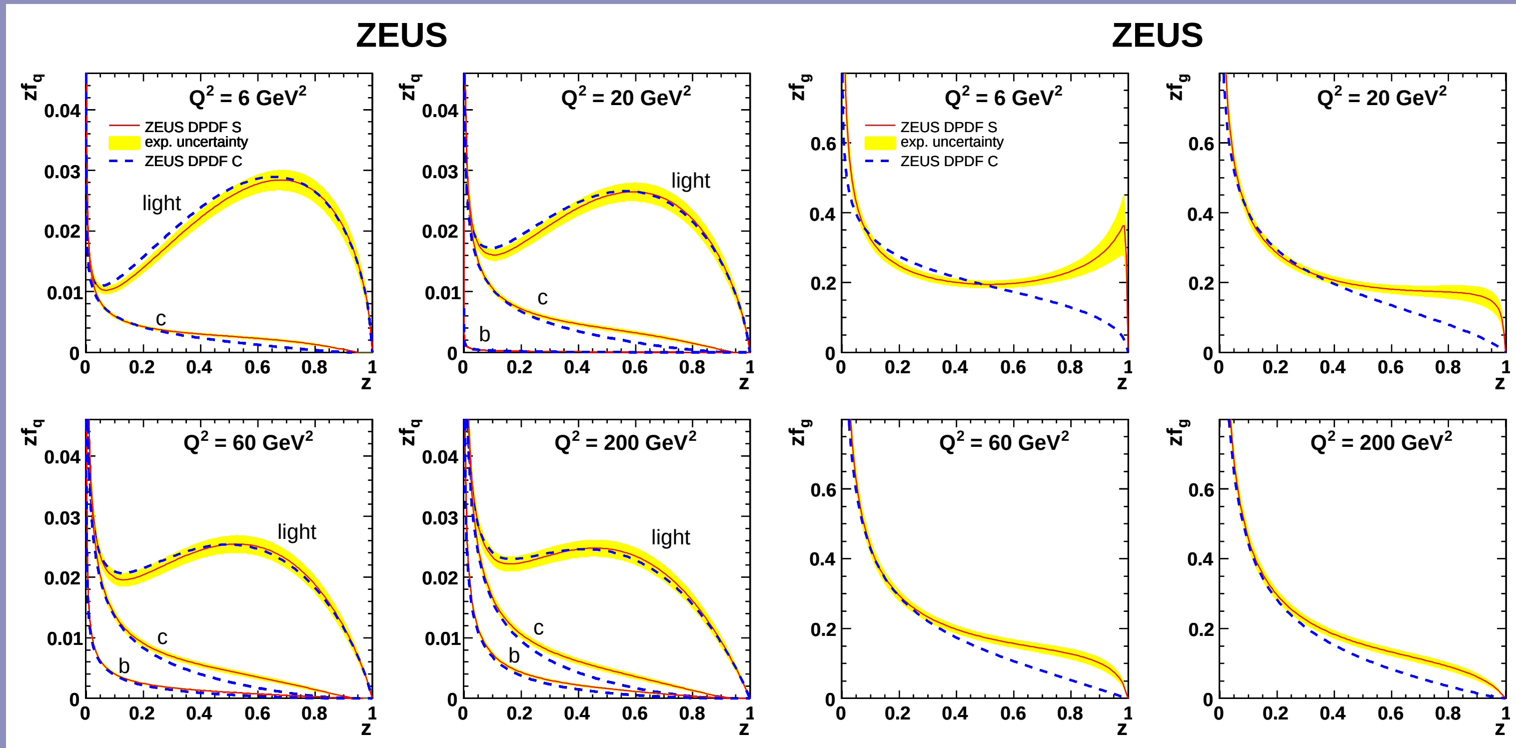
A QCD analysis of ZEUS diffractive data

- Quark and gluon densities from fits S and C:



- The quark distributions are very similar for the two fits while the gluon densities are significantly different

  → gluons from fit S grow rapidly at high z, while those from fit C vanish as $z \to 1$ in a smoother way: poor sensitivity of inclusive data to gluons

⇒ To constrain the gluons, a more exclusive process is needed where γg fusion contributes at leading order

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A QCD analysis of ZEUS diffractive data

- Comparison of fits S and C to diffractive dijet DIS data:
  - → at high $z_{I\!P}^{\rm obs}$, the predictions based on fit C (S) (fails to) describe the data
  - → diffractive dijet DIS data are sensitive to the glon density

- Fit SJ, including LRG+LPS+dijet data:
  - → predictions based on fit SJ cannot be distinguished from fits S and C when compared to inclusive data
  - → predictions based on fit SJ give a very good description of dijet data

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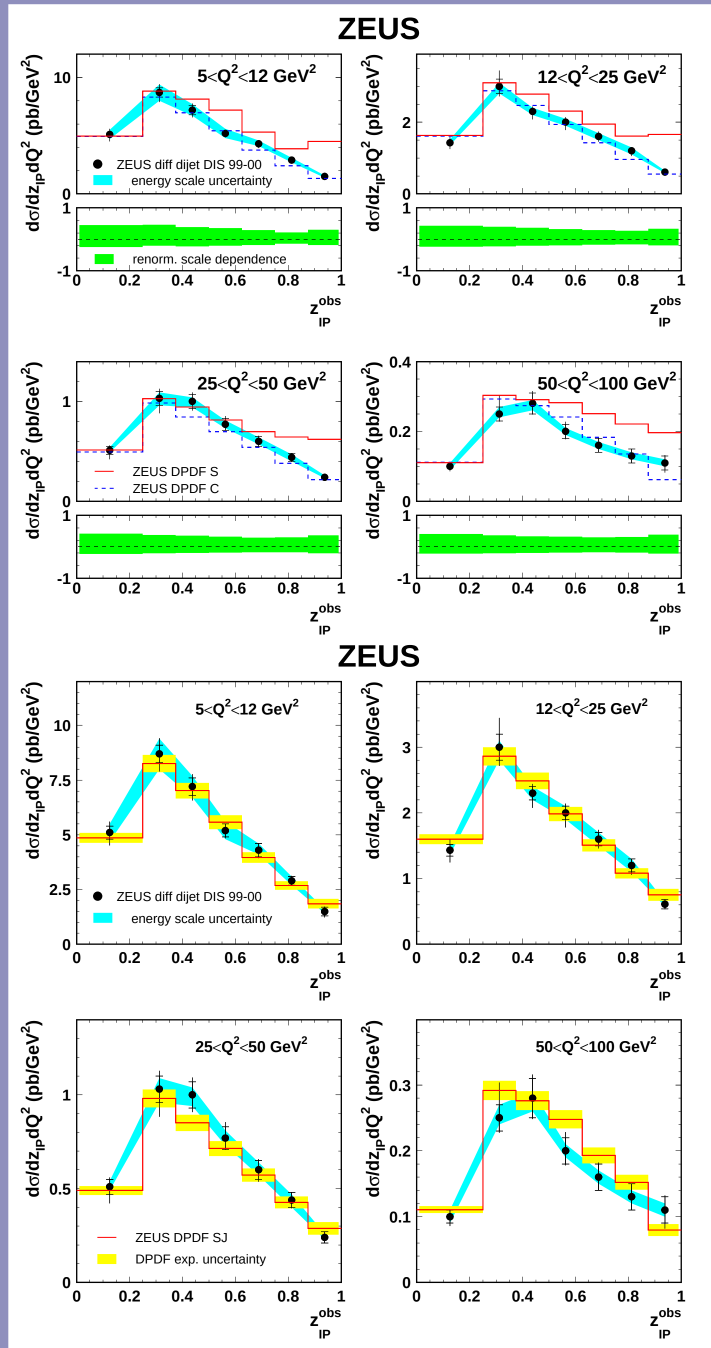
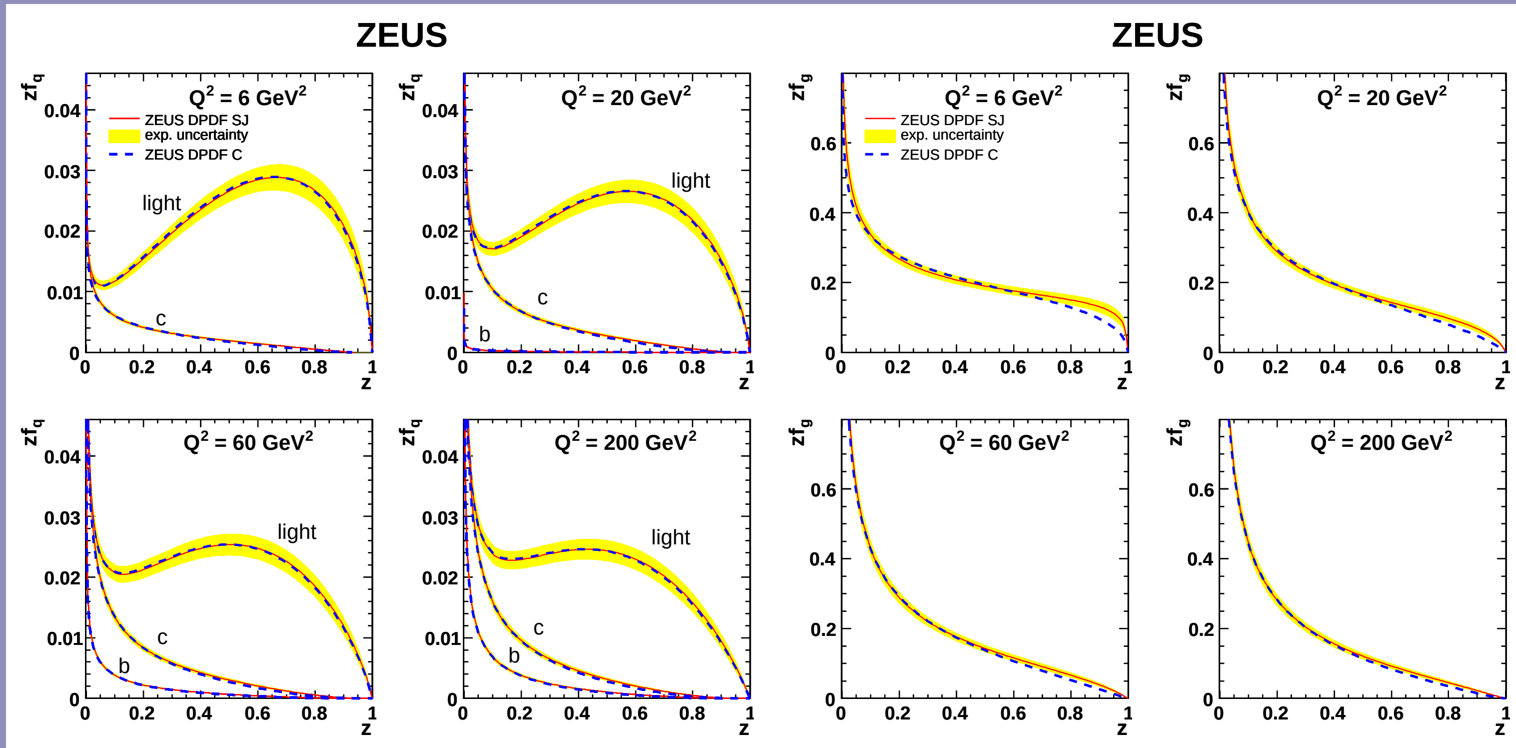


A QCD analysis of ZEUS diffractive data

- Quark and gluon densities from fit SJ, compared to fit C:



- Sizeable decrease in the uncertainty on the gluon distribution wrt the fits without jet data
- Combining inclusive and dijet data constrains the gluon and quark densities with compararable precision across the whole z range

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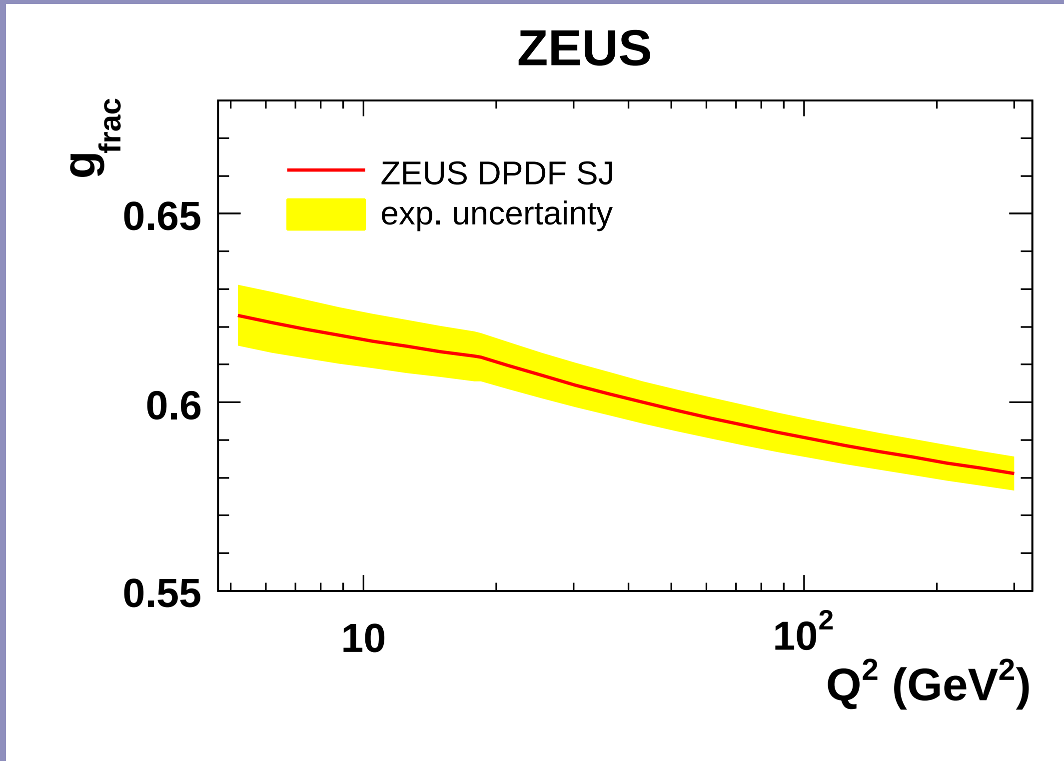
A QCD analysis of ZEUS diffractive data

- Q^2 dependence of the fraction of the longitudinal momentum of the diffractive exchange carried by gluons from fit SJ (integrated over $10^{-5} < z < 1$):

- The fraction amounts to $\approx 60\%$ for $5 < Q^2 < 300$ GeV^2
- The fall with Q^2 is a direct consequence of the DGLAP evolution, which forces $g_{\rm frac}$ to approach ≈ 0.5 at high Q^2
- The slope change at $Q = m_b$ reflects the change in the number of active flavours $(4 \to 5)$



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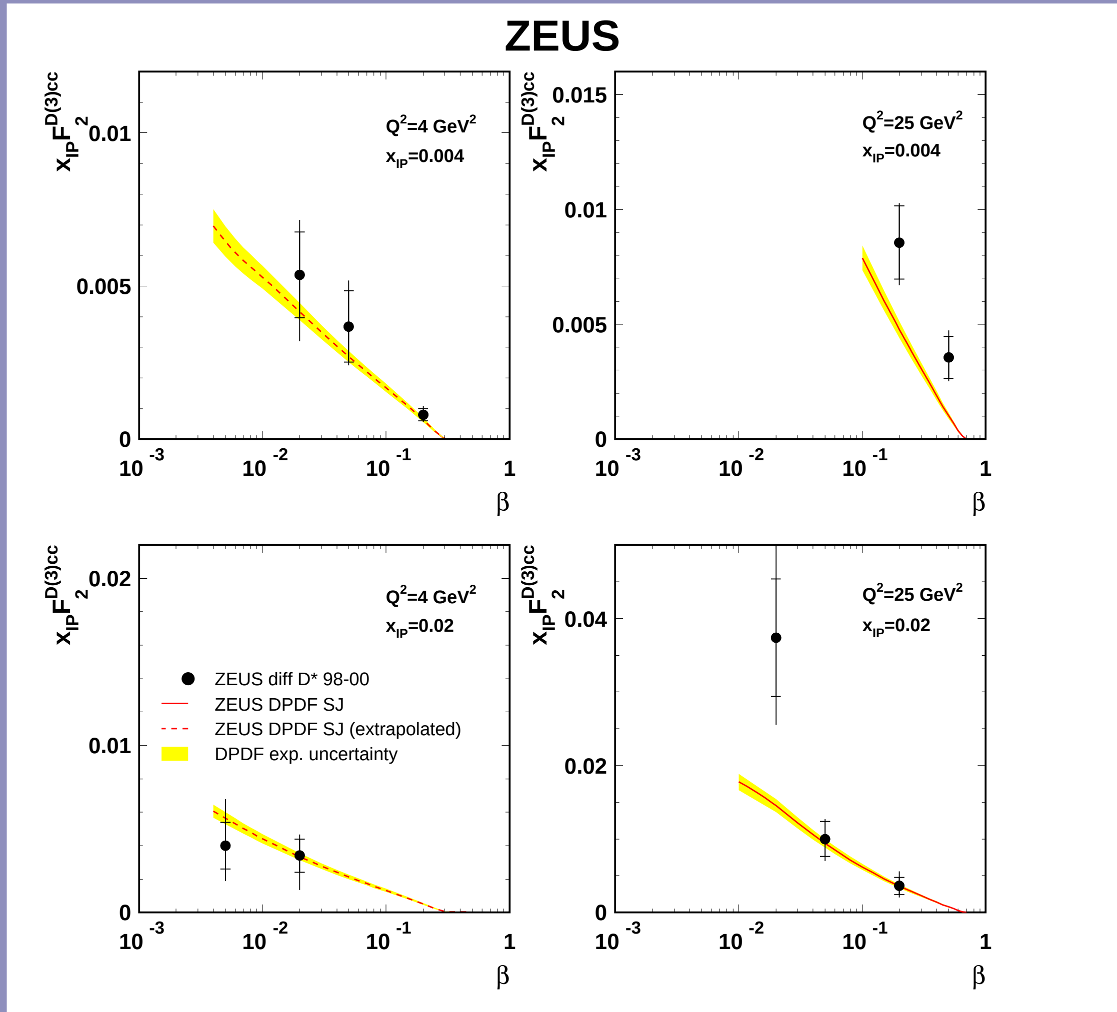
A QCD analysis of ZEUS diffractive data

- Comparison of predictions based on fit SJ to charm contribution to $F_2^{D(3)}$:



⇒ Reasonable description of data

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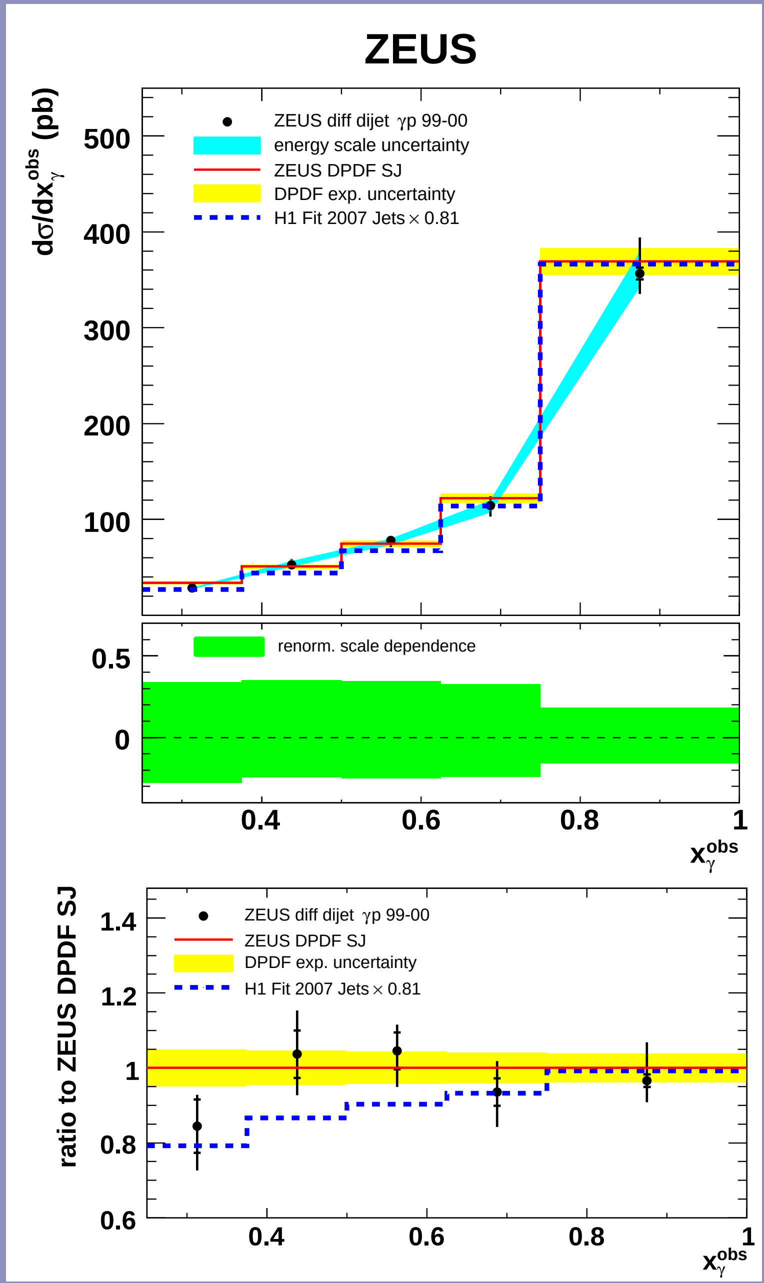
A QCD analysis of ZEUS diffractive data

- Comparison of predictions based on fit SJ to diffractive dijet photoproduction data provides a test of QCD factorisation:

- For resolved processes ($x_\gamma^{\rm obs} < 1$), as in hadron-hadron interactions, QCD factorisation is not expected to hold

- Adequate description of data
  $\Rightarrow$ results compatible with no suppression either of the resolved component or of both components globally



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Conclusions

- **Post-HERA picture of diffraction in QCD:**
  - → **Observation of events with a large rapidity gap**
    - ∗ $\approx 10\%$ of DIS events are diffractive
    - ∗ leading-twist contribution to the proton structure function
  - → **Observation of jet production in events with a large rapidity gap**
    - ∗ hard interaction between photons and point-like constituents within the pomeron
  - → **Measurement of pomeron structure function**
    - ∗ assumption of factorisation into a pomeron flux factor and a pomeron structure function holds
    - ∗ hard and soft quark and gluon contributions needed
  - → **Measurement of jet cross sections**
    - ∗ first direct evidence of gluon component: hard gluons carry $30-80\%$ of pomeron momentum carried by partons
  - → **Extraction of pomeron parton densities**
    - ∗ fits to LRG+LPS+dijet DIS data provide quark and gluon densities for the pomeron with comparable precision across the whole z range
    - ∗ predictions describe other data and provide test of QCD factorisation