# Diffraction:experimental challenges and physics outlook

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- The HERA program completed data taking last year with the H1 and ZEUS detectors.
- Many results on diffraction are yet to be published.
- What lessons have we learned both in physics and in experimental technique?
- Implications for future e-p,A colliders

# Outline

- Hera detectors and auxiliary equipment
- Techniques for measuring diffractive cross sections
- Kinematics and factorisations.Regge factorisation holds approximately.Hard scattering factorisation OK
- Vector meson production (and DVCS) : soft and hard diffraction.
- The hard pomeron in QCD
- Inclusive cross sections.The problem of proton breakup.
- Compare to F2 inclusive.The importance of having two detectors.
- Diffraction dominated by gluons.
- Massive breakdown of universality c.f. Tevatron
- Resolved and direct photoproduction:the mystery deepens
- Absorbtive corrections essential in predicting diffractive Higgs production at LHC
- Validate with leading neutron data. Compare to leading protons:Regge model
- BEKW dipole ansatz
- Open questions.Direct pomeron coupling? Where is the odderon?

# Some History

- 1960's Extensive studies of two-body hadronic reactions.Rapidly falling cross sections except for elastic scattering and

a few other examples

e.g.pip→3pip

0-     1+

L=1

Became known as "Diffractive Dissociation"

Good and Walker optical analogy

1970's ISR and Fermilab observed high mass diffraction because of much higher CM energy.

Regge Pole industry: Diffraction ascribed to exchange of Pomeron
other reactions from Reggion exchange pi rho etc

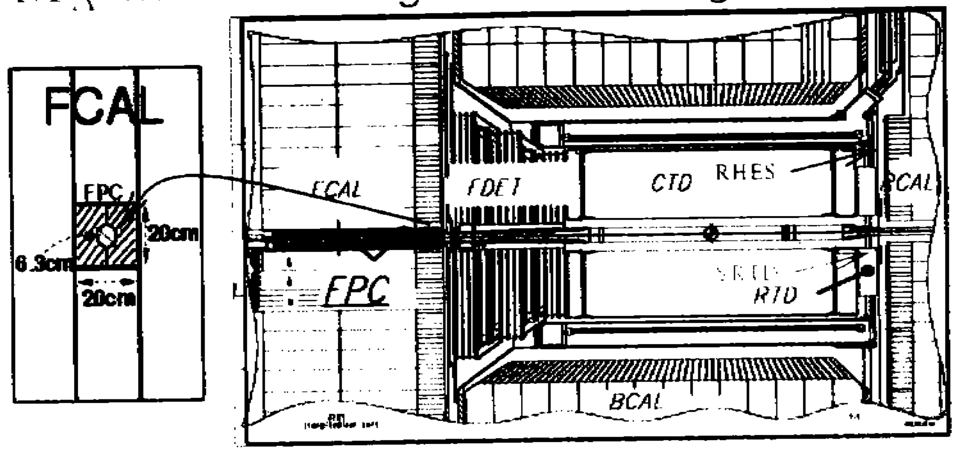
Fits to pp total cross section data by Donnichie and Landshoff gave Pomeron trajectory

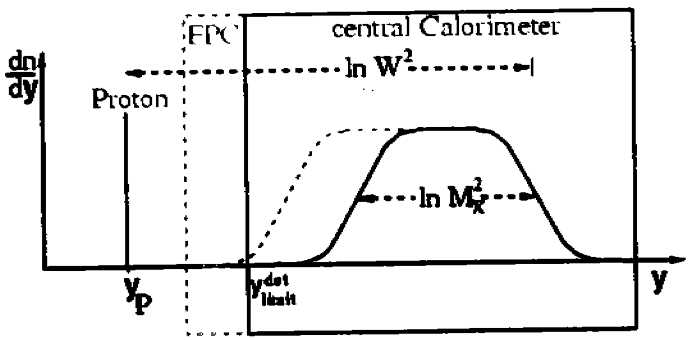
Predictions by D&L , Streng and others that diffractive reactions would occer at the several percent level at HERA and wold give insight into the structure of the Pomeron.Not taken too seriously by experimenters so discovery of such processes in 1993 was a surprise.HERA detectors were not optimised for this physics.

ZEUS Leading Particle Spectrometer was built to study leading particle effects in general.

# Details of ZEUS for FPC data

$M_X$ method using Forward Plug Calorimeter




rapidity : $\mathcal{Y} = \frac{1}{2} \ln \frac{E + p_Z}{E - p_Z}$

pseudo-rapidity : $\eta = -\ln \tan(\frac{\theta}{2})$

with small mass ($E \simeq |p|$)

- **Forward Plug Calorimter (FPC) : Shashlik type**
  - **→ Lead(1.5 cm)-Scintillator(0.26 cm)**
  - **→ $N_{tot}$ of readout channel=60(EMC)+16(HAC)**
- **Extend calorimeter acceptance by 1 unit in pseudorapidity from $\eta$ =4 to $\eta$ =5.**
  - **→ Increase the accessible $M_X$ range by a factor of 1.7**
- **For 1998-1999,**
  - ∘ FPC → **higher $M_X$ and lower $W$**
  - ∘ Smaller RCAL beamhole → **lower $Q^2$ and higher $W$**

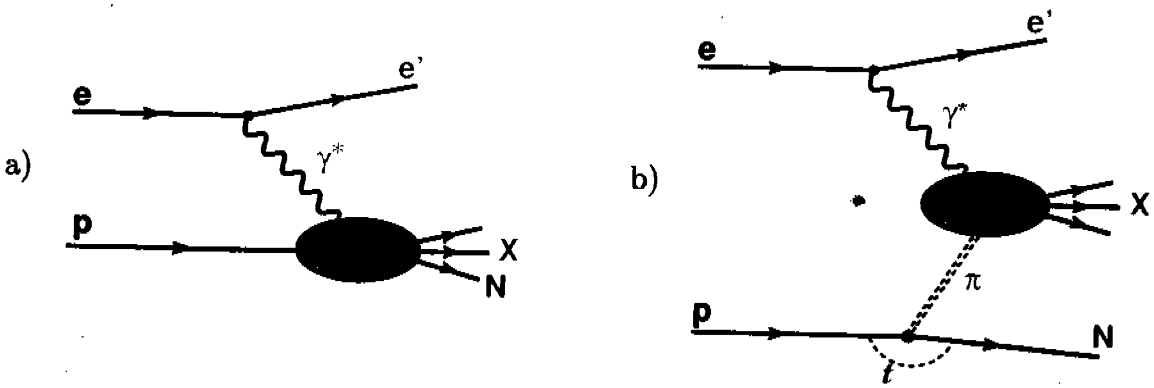



**Figure 1:** *a) HERA ep scattering event with the final-state baryon in the proton-fragmentation system, X. b) Leading baryon production via an exchange process.*

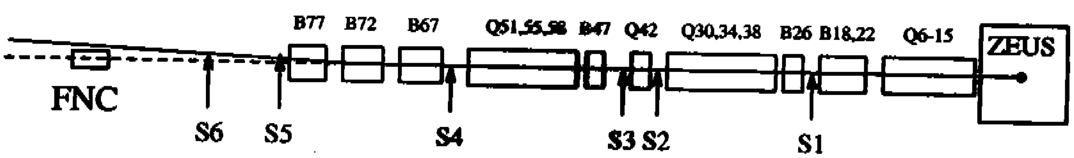
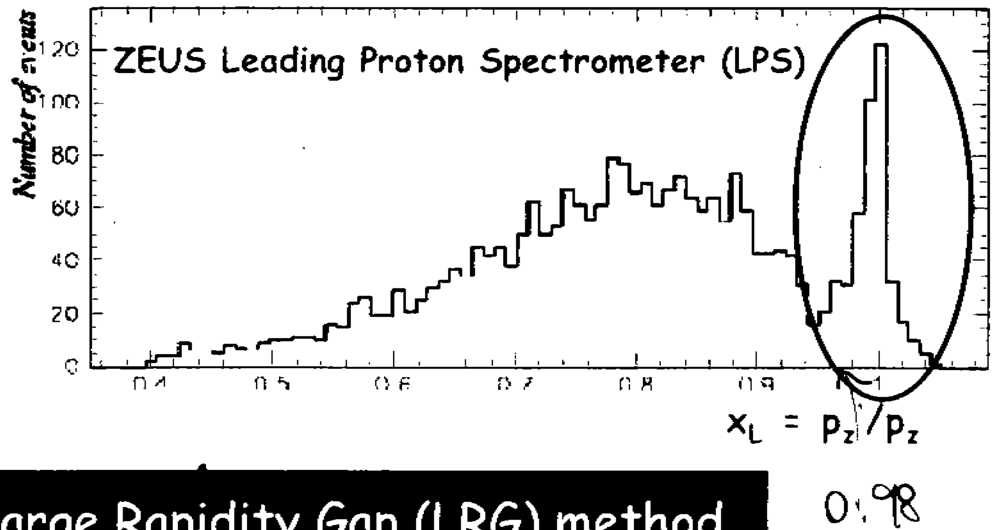



**Figure 2:** *Side view of the proton beamline downstream from the ZEUS interaction region. The protons are moving from right to left. The labels for the HERA components, e.g. B47, indicate the horizontal distance in meters from the interaction point. The horizontal and vertical axes are not to scale. The proton beam is bent upward by approximately 6 mrad by the dipole magnets B67–B77 near Z=+70 m. The FNC is located on the zero-degree line at Z=+105.5 m. S1–S6 indicate the locations of the ZEUS leading-proton spectrometer stations [26].*

DIS08 London, M. Ruspa 07/04/08

# Diffractive event selection

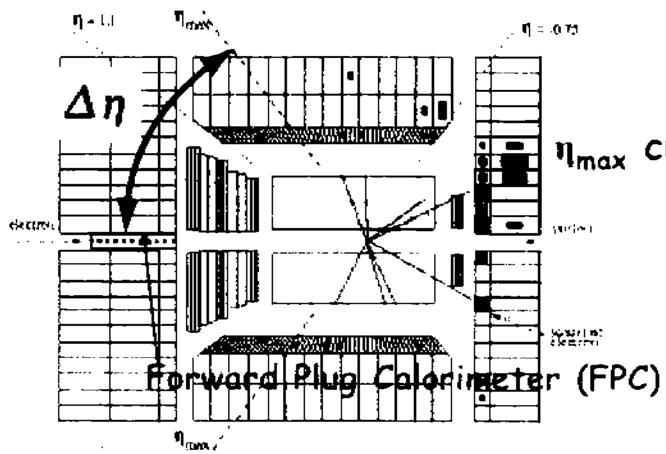



## LPS method

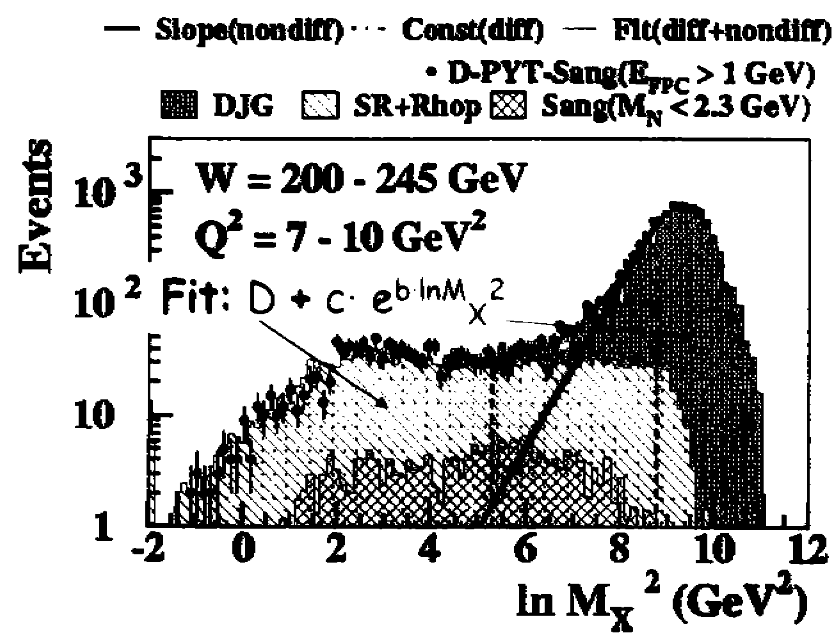
PROS: no p-diss. background
direct measurement of t, $x_{IP}$
high $x_{IP}$ accessible

CONS: low statistics

## Large Rapidity Gap (LRG) method




## $M_x$ method

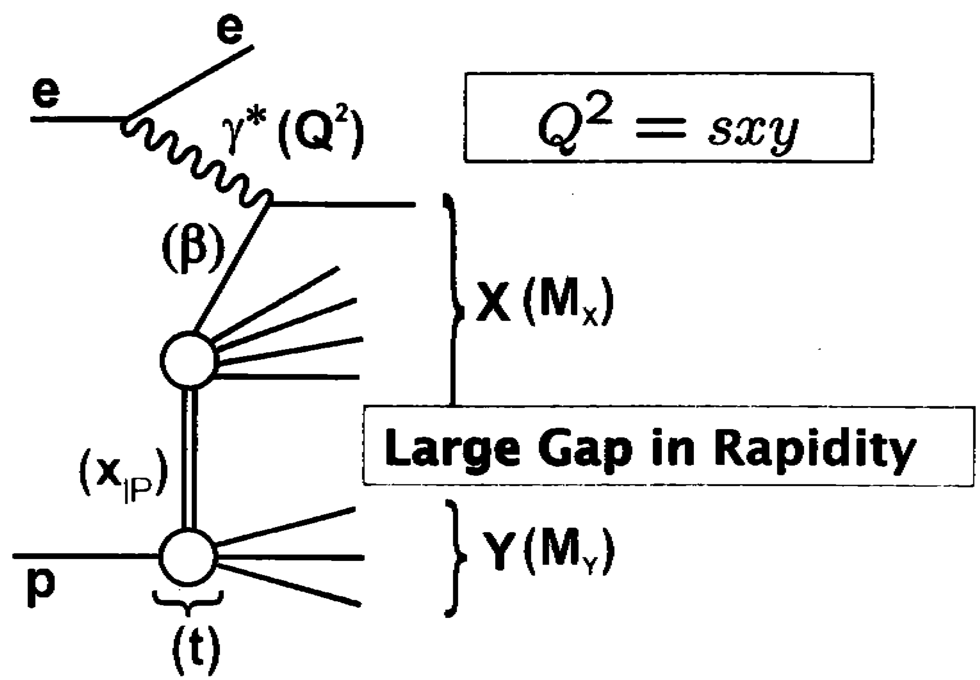


# Diffractive DIS Kinematics and Observables

$$x = x_{\mathbb{P}}\beta$$

$$\beta = \frac{Q^2}{Q^2+M_X^2}$$

$$x_{\mathbb{P}} = \frac{Q^2+M_X^2}{Q^2+W^2}$$




$$Q^2 = sxy$$

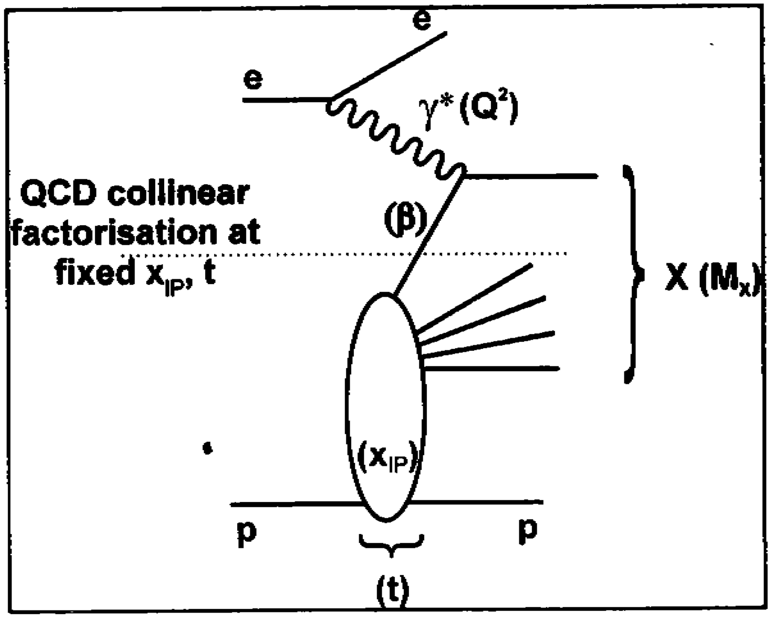
$$Y_+ = 1 + (1-y)^2$$

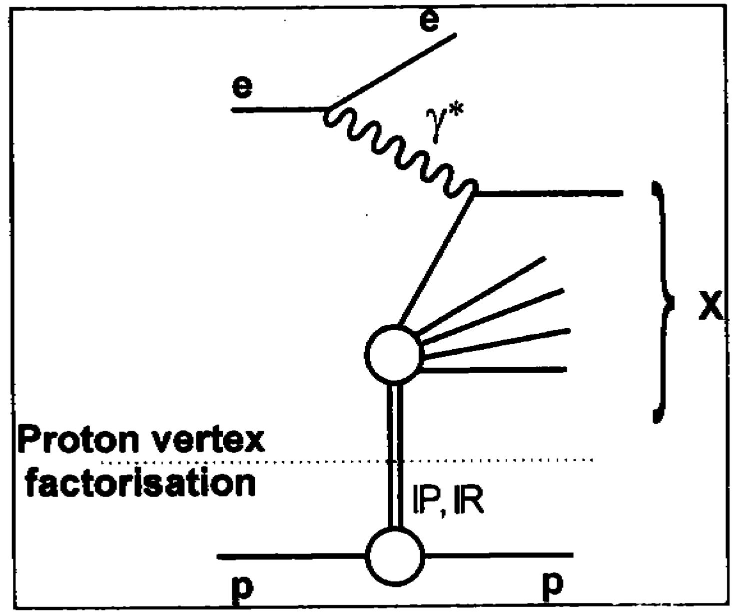
Cross section: $$\frac{d^4\sigma^{ep\to eXp}}{dx\,dQ^2\,dx_{\mathbb{P}}\,dt} = \frac{4\pi\alpha^2}{xQ^4}\,Y_+\,\sigma_r^{D(4)}(x, Q^2, x_{\mathbb{P}}, t)$$

$$\sigma_r^{D(4)} = F_2^{D(4)} - \frac{y^2}{Y_+}F_L^{D(4)}$$

$$\sigma_r^{D(3)} = \int_{-1}^{t_{min}} \sigma_r^{D(4)}\,dt$$

# Two Levels of Factorisation




QCD hard scattering collinear factorisation (Collins) at fixed $x_{IP}$ and $t$

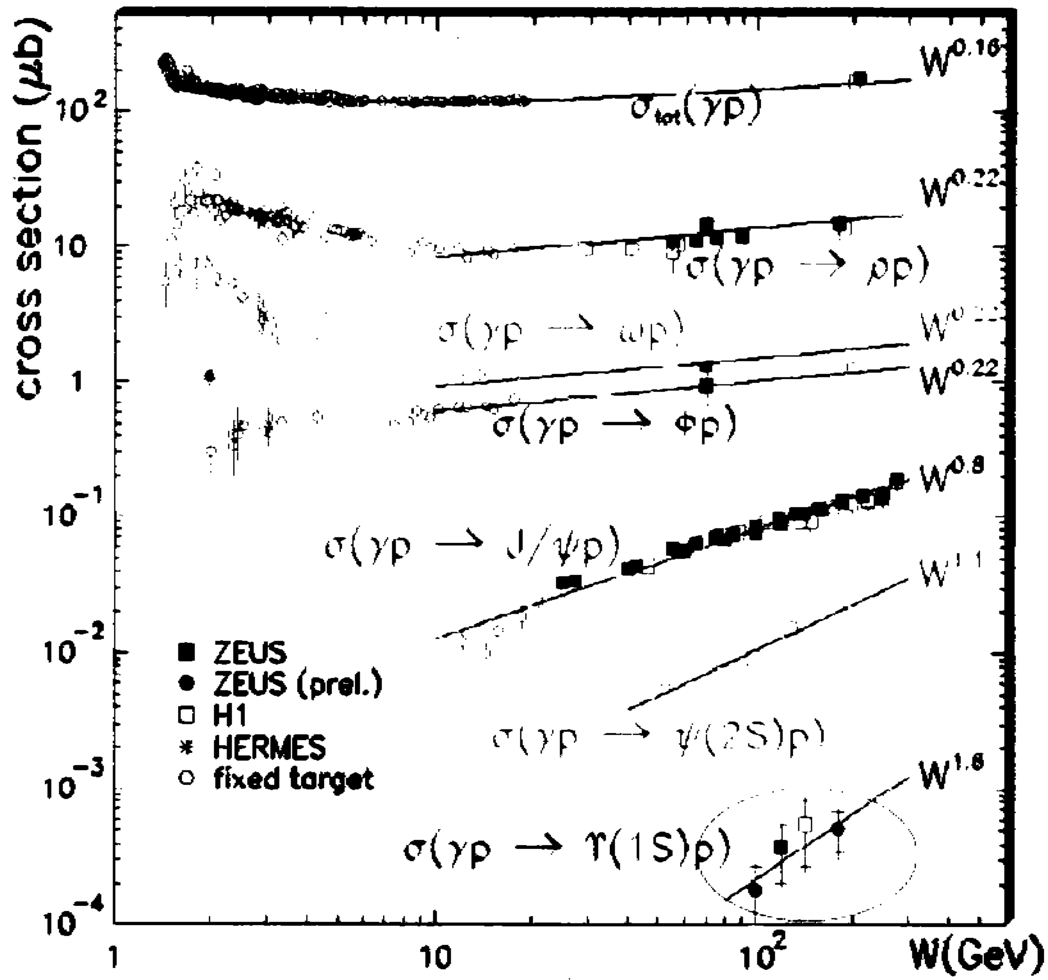
$$d\sigma_{partoni}(ep \rightarrow eXY) = f_i^D(x, Q^2, x_{I\!P}, t)) \otimes d\sigma^{ei}(x, Q^2)$$

Applied after integration over measured $M_Y$ and $t$ ranges

'Proton vertex' factorisation of $\beta$ and $Q^2$ from $x_{IP}$, $t$, and $M_Y$ dependences

$$f_i^D(x, Q^2, x_{I\!P}, t) = f_{I\!P/p}(x_{I\!P}, t) \cdot f_i^{I\!P}(\beta = \frac{x}{x_{I\!P}}, Q^2)$$

# Compilation γp cross sections



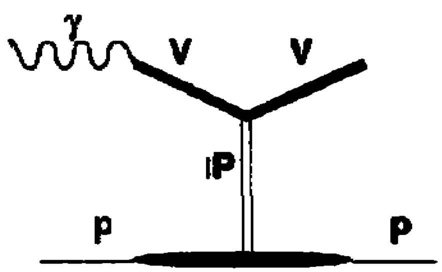

$\sigma \propto W^{\delta} \quad \delta = f(M_V)$

***Process becomes hard as scale (mass) becomes larger.***

***$\delta$= 1.6 ± 0.8 comes from the fit to 4 (ZEUS +H1) points.***

# *Soft production mechanism*

***Non- perturbative description based on Regge theory and Vector Dominance Model***




- *Photon fluctuates into a Vector Meson*
- *Vector Meson interacts with the proton by soft Pomeron exchange.*

***Slow increase of $\gamma p$ cross section with energy:***

$$\frac{d\sigma(\gamma p \to Vp)}{dt} \propto e^{-b_0|t|}\left(W^2/{W_0}^2\right)^{2(\alpha(t)-1)}$$

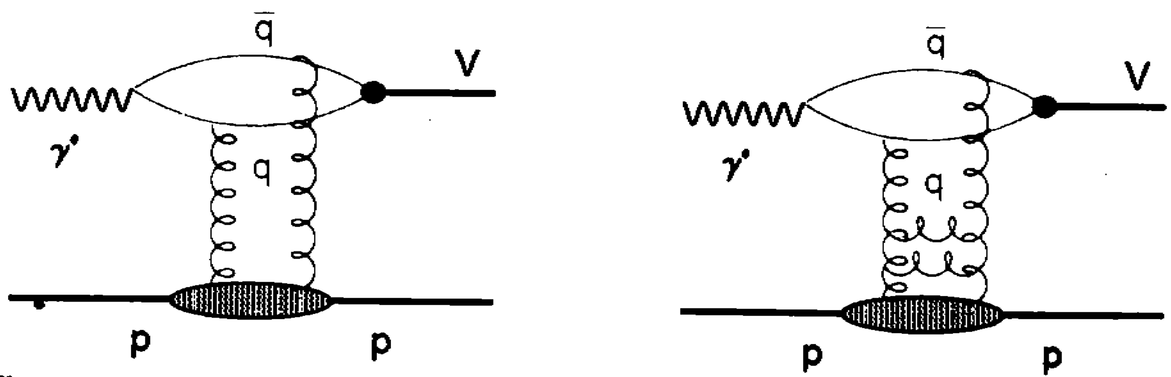
***Experimental determination:***

$$\alpha(t) = \alpha(0) + \alpha' t = 1.08 + 0.25t$$

$$b(W) \propto b_0 + 2\alpha' ln\left(W^2/{W_0}^2\right) \qquad b_0 \sim 10GeV^{-2}$$

# hard production mechanism

***Perturbative QCD applicable.***



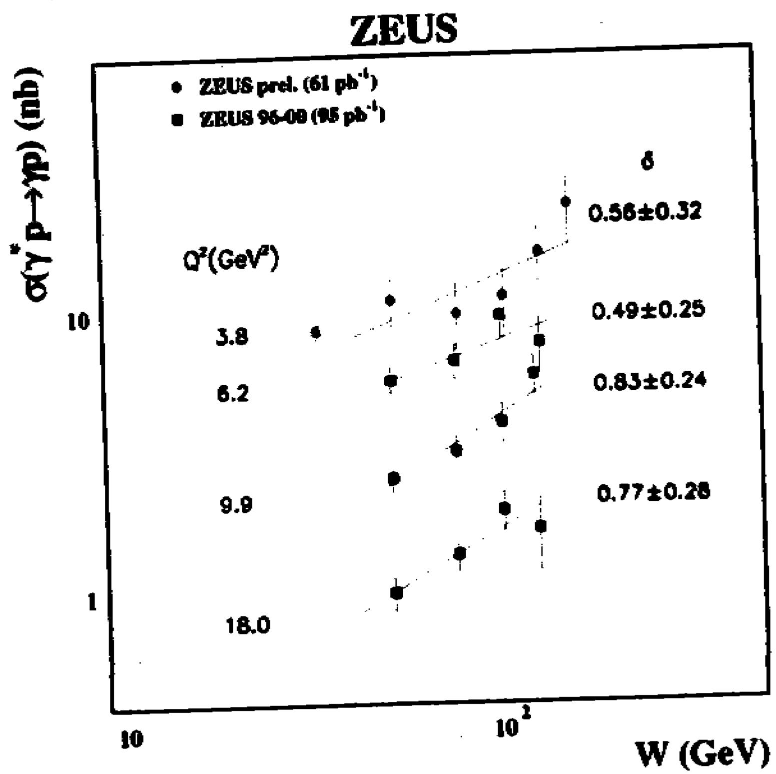

- *Photon fluctuates into a $q\bar{q}$ pair*
- *$q\bar{q}$ pair interacts with the proton by at least two gluon exchange (color singlet –QCD pomeron)*
- *$q\bar{q}$ pair forms a vector meson*

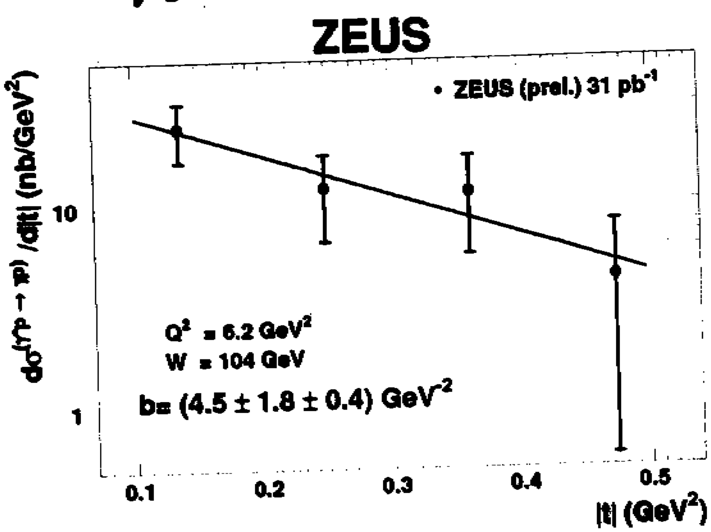
***Fast increase of the cross-section with $W\gamma p$ - related to gluon density in the proton:***

$$\sigma(W) \propto [\alpha_s(\mu^2)\bar{x}g(\bar{x},\mu^2)]^2$$ *$\mu$ - hard scale*

$$\bar{x} \propto \frac{Q^2 + M_V^2}{W_{\gamma p}}$$

# Cross section $\gamma^* p \rightarrow \gamma p$




*First direct measurement of differential cross section as a function of t using LPS*

*Steep rise for large $Q^2$ observed in ZEUS*

- *Similar behaviour to heavy Vector Mesons*
- *DVCS shows hard behaviour even at low $Q^2$*
- *May suggest that the most sensitive part to soft scale is the wave function.*

# LRG: correction to $M_N = m_p$

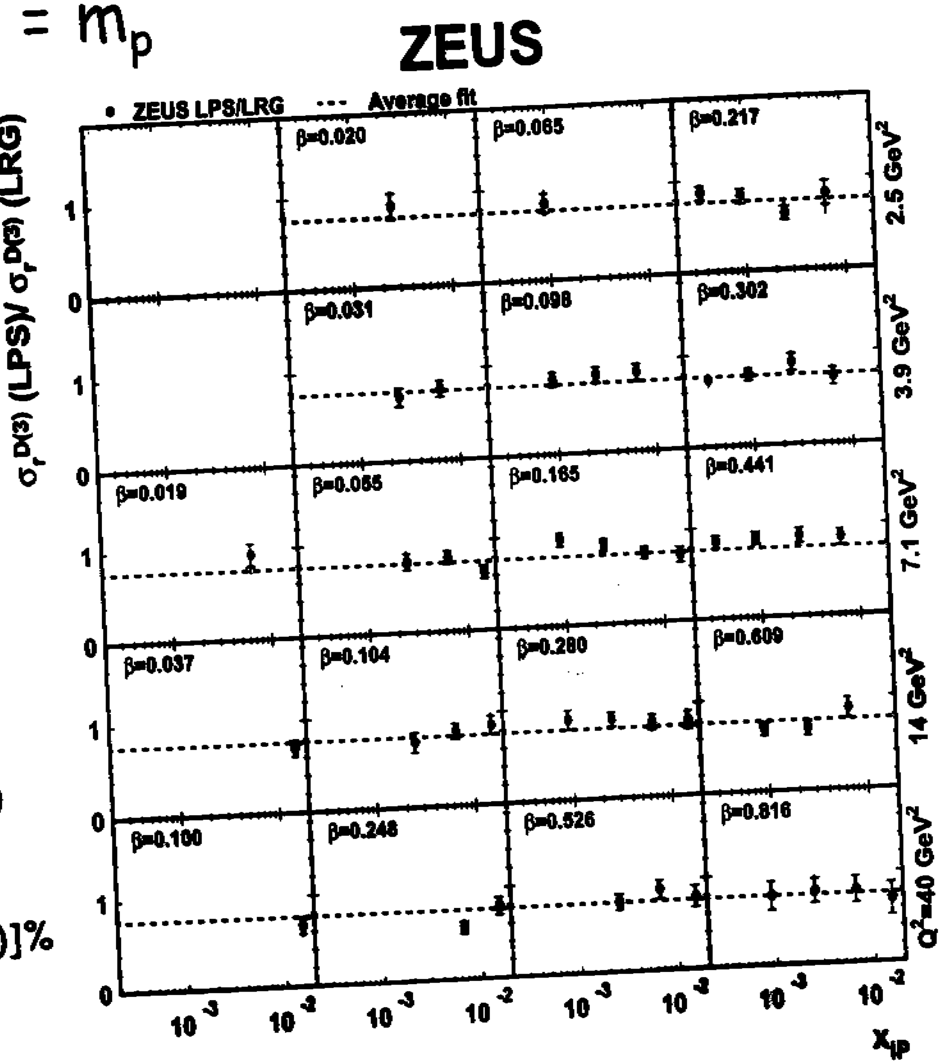
i) ratio LPS/LRG

→ **LPS/LRG independent of $Q^2$, $x_{IP}$, β**

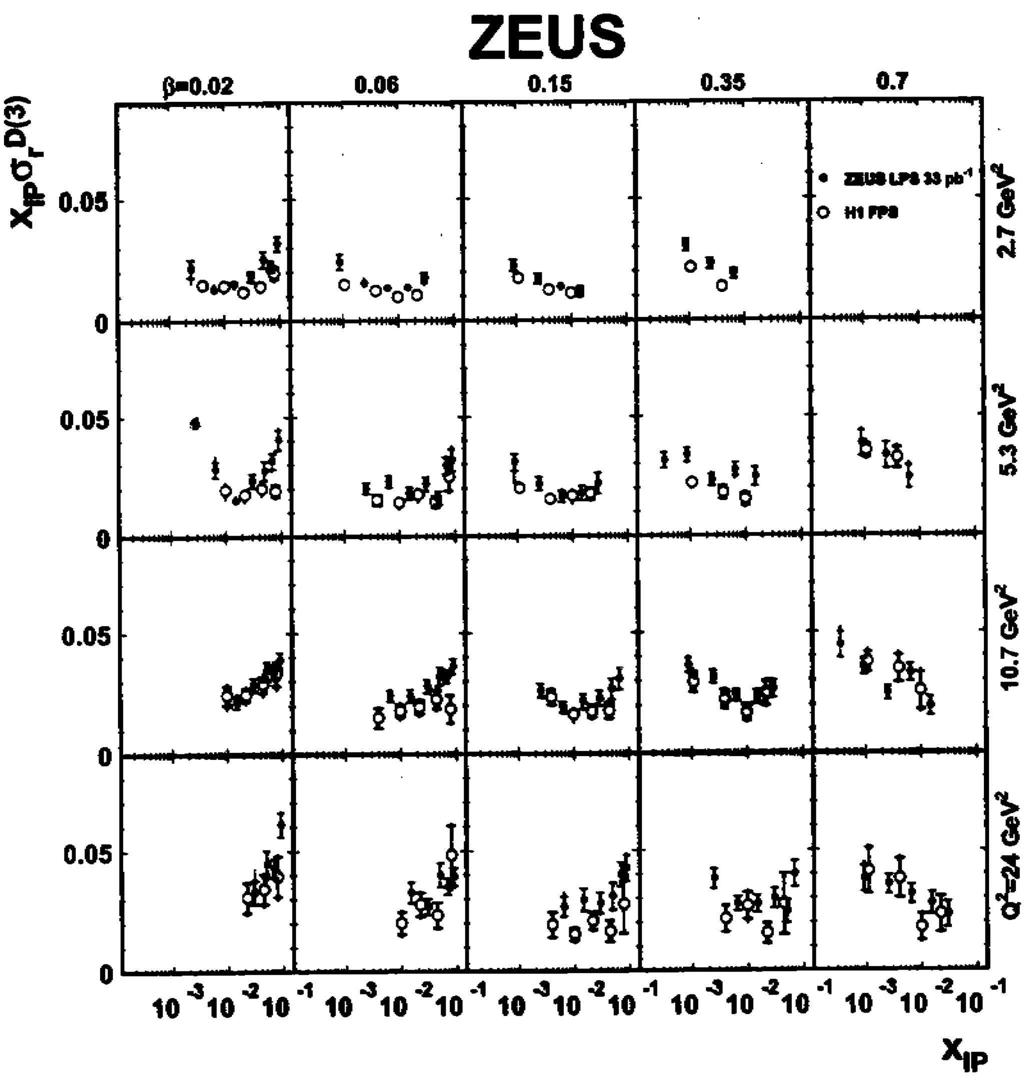
LPS/LRG = 0.76 +-0.01(stat) +0.03-0.02(sys) +0.08-0.05 (norm)

→ p-diss. background in LRG data:

[24 +-1(stat) +2-3(sys) +5-8(norm)]%



# $\sigma_r^{D(3)}$ LPS vs H1 FPS

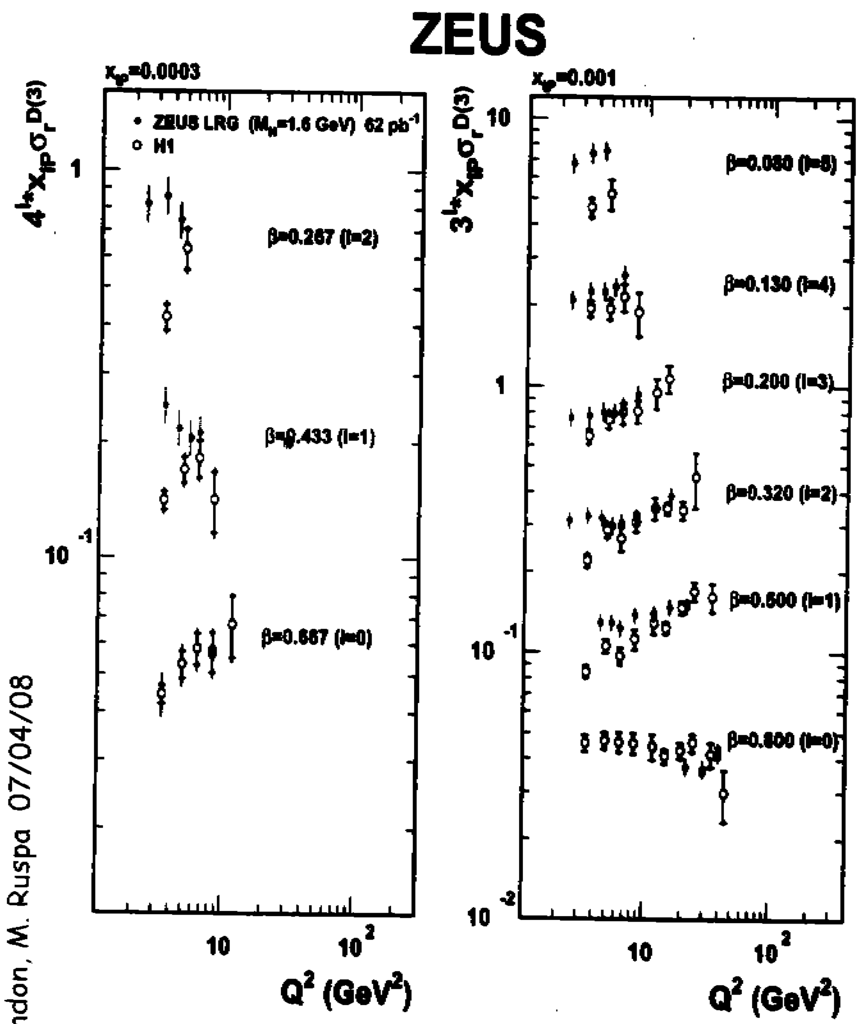


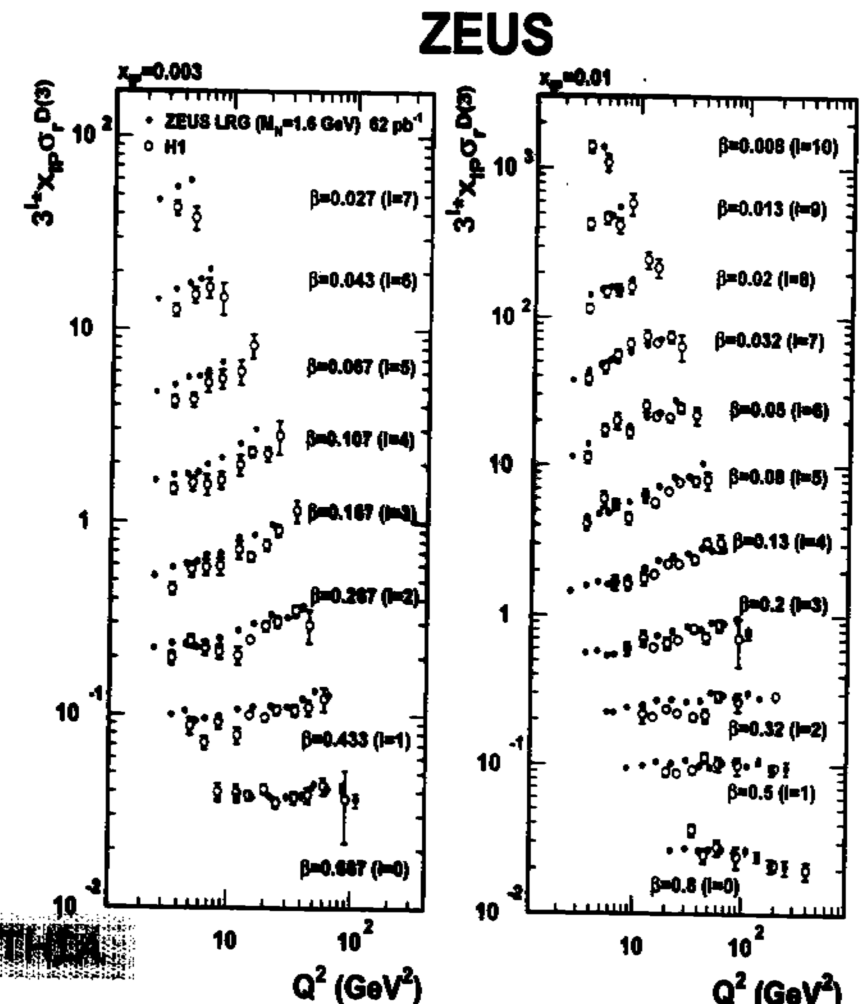

**The cleanest possible comparison in principle...**

**...but large normalisation uncertainties (LPS:+11-7%, FPS: +-10%)**

→ ZEUS and H1 proton-tagged data agree within normalisation uncertainties

# $\sigma_r^{D(3)}$ LRG ZEUS vs H1



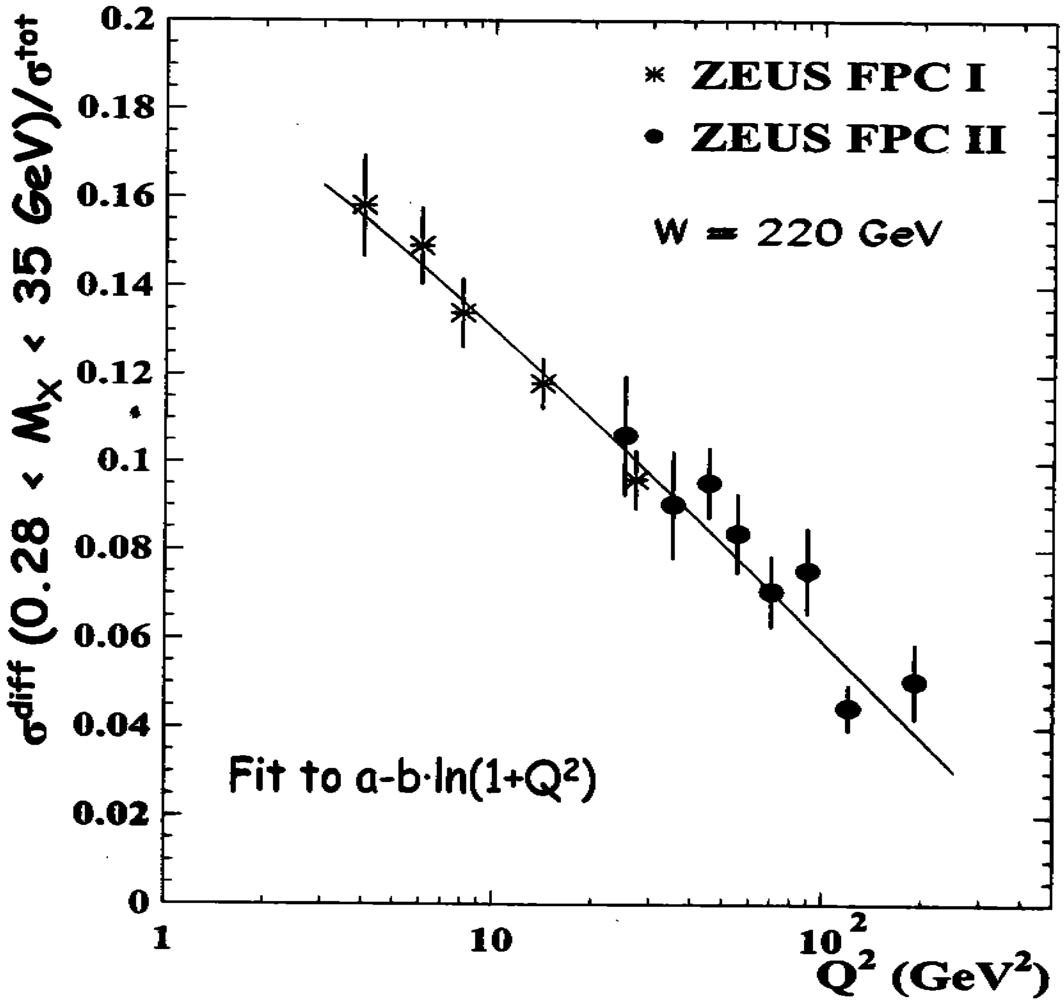

ZEUS corrected to $M_N$ < 1.6 GeV with PYTHIA

→ Remaining normalisation difference of 13% (global fit) covered by uncertainty on p-diss. correction (8%) and relative normalisation uncertainty (7%)

→ Shape agreement ok except low $Q^2$

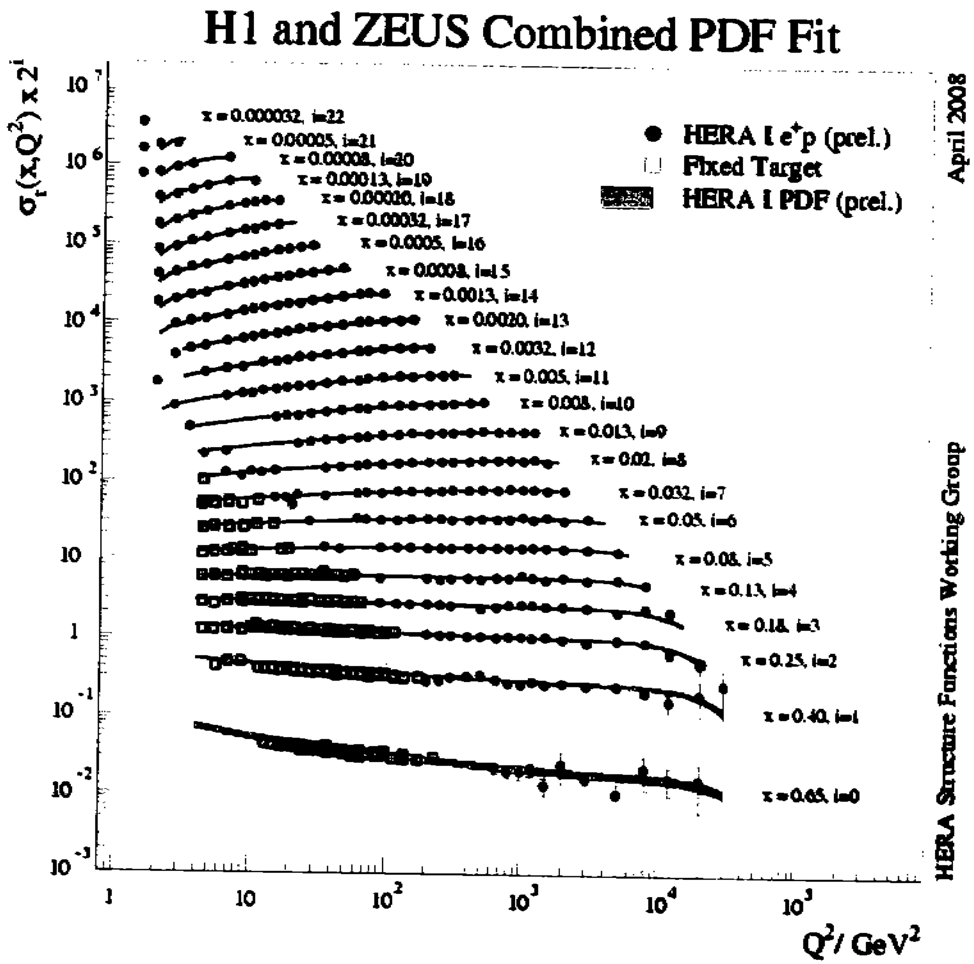
# Diffractive contribution to the total cross section

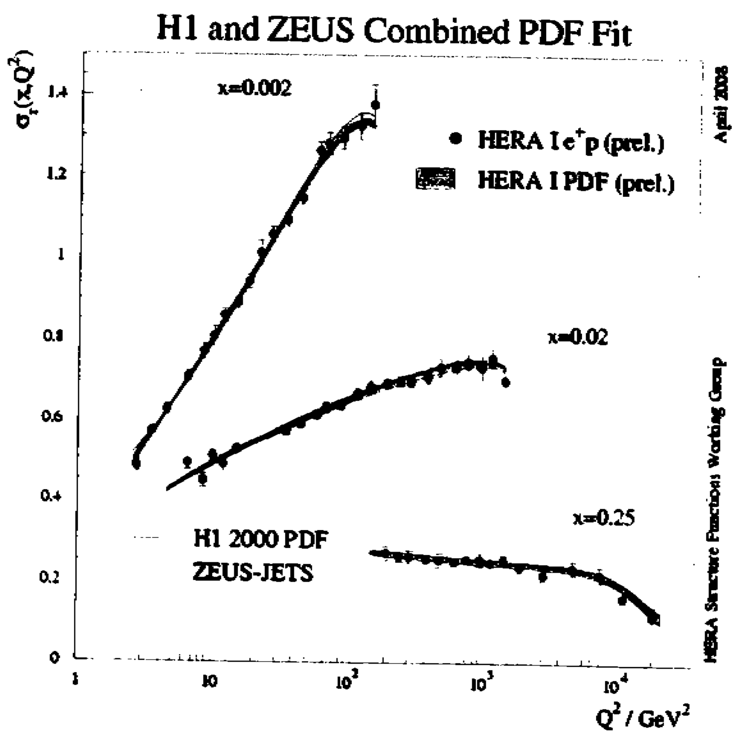
$M_X$ data




→ $\sigma^{diff}/\sigma^{tot}$ decreases logarithmically with $Q^2$

# HERA I data !



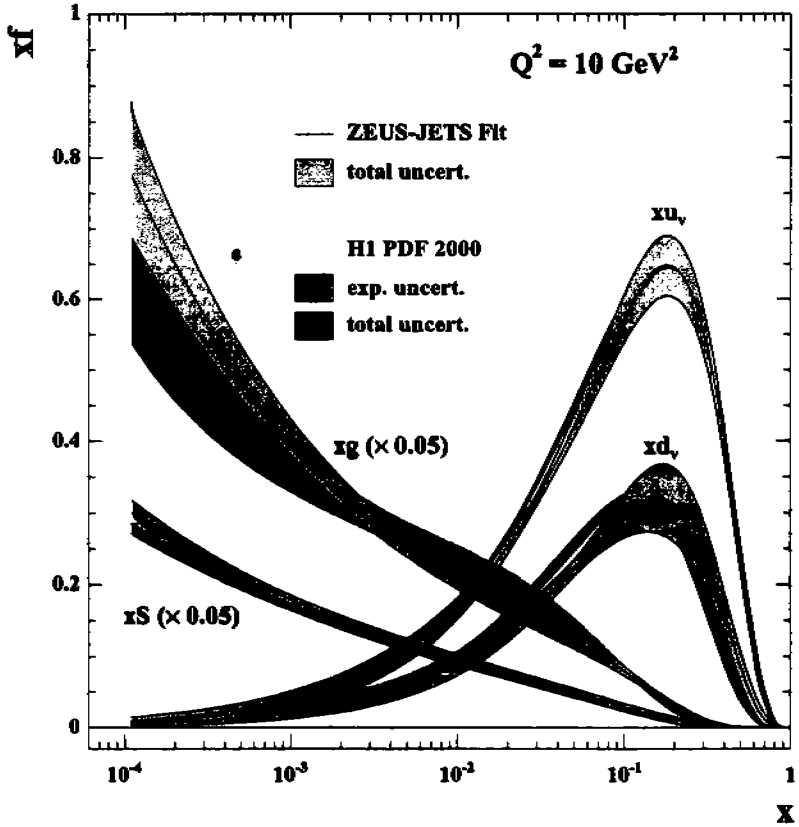



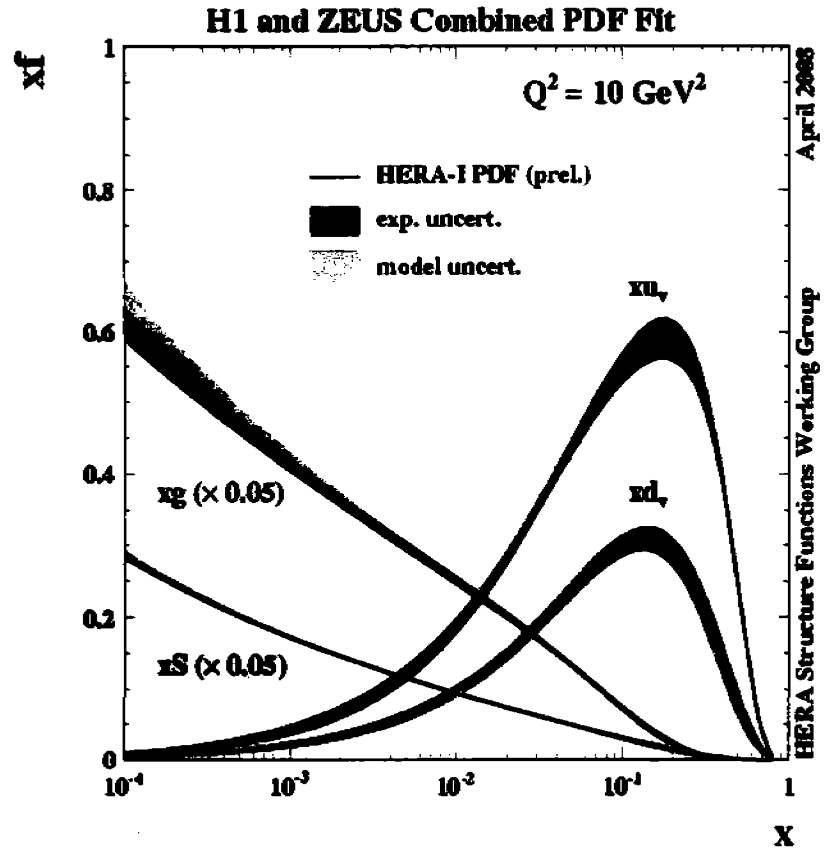

New HERA-I PDF fit predictions vs. H1/ZEUS combined data for NC $e^+p$.
on the PDF fit predictions are included but can barely be resolved.

Blow up just three x values to see older ZEUS-JETS PDF and H12000 PDF plus new

# Compare to published ZEUS/H1 results which also used only HERA data

Note in published PDFs H1 has alphas variation included in model error, ZEUS does not.




Resolution of previous discrepancies, improvement in level of uncertainty

# Combined fit DPDFs from H1

— H1 2007 Jets DPDF
■ exp. uncertainty
■ exp. + theo. uncertainty
········ H1 2006 DPDF fit A
------ H1 2006 DPDF fit B

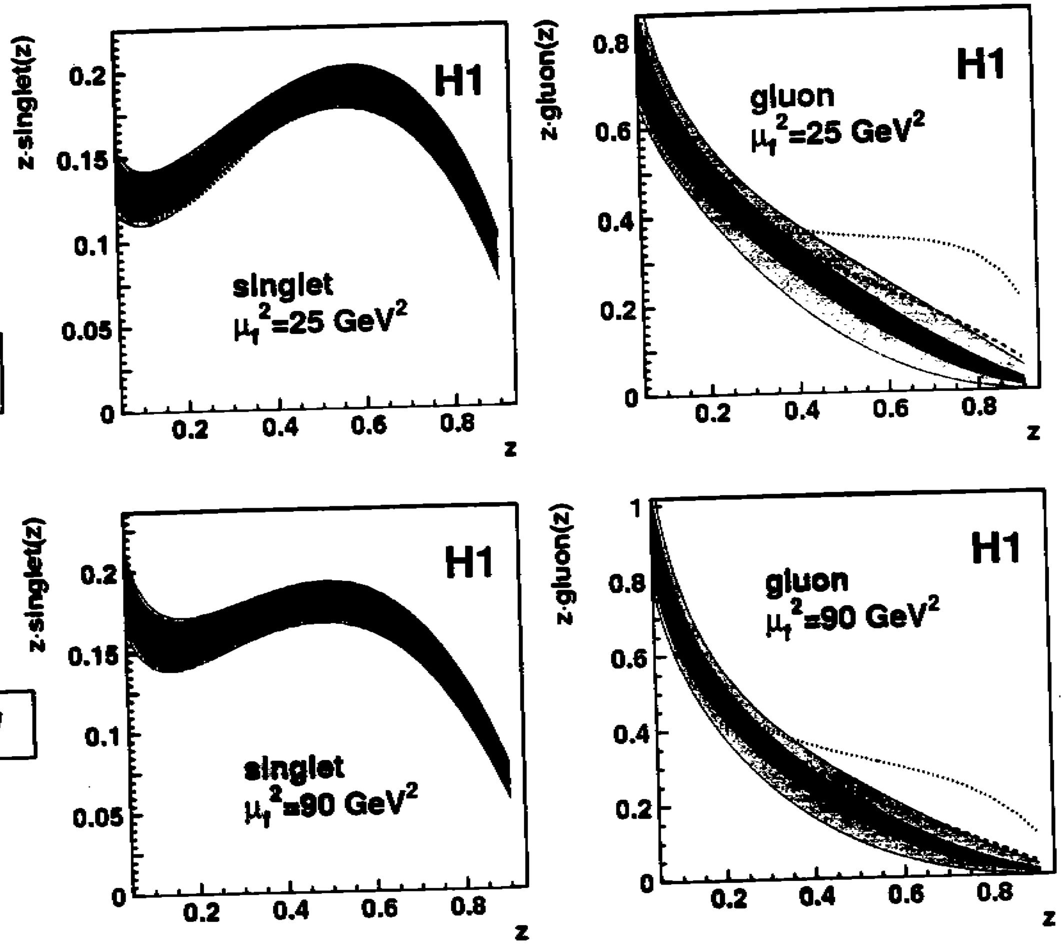
Singlet: $z\Sigma(z,Q_0^2) = A_q z^{B_q}(1-z)^{C_q}$

Gluon Fit A: $z_g(z,Q_0^2) = A_g(1-z)^{C_g}$

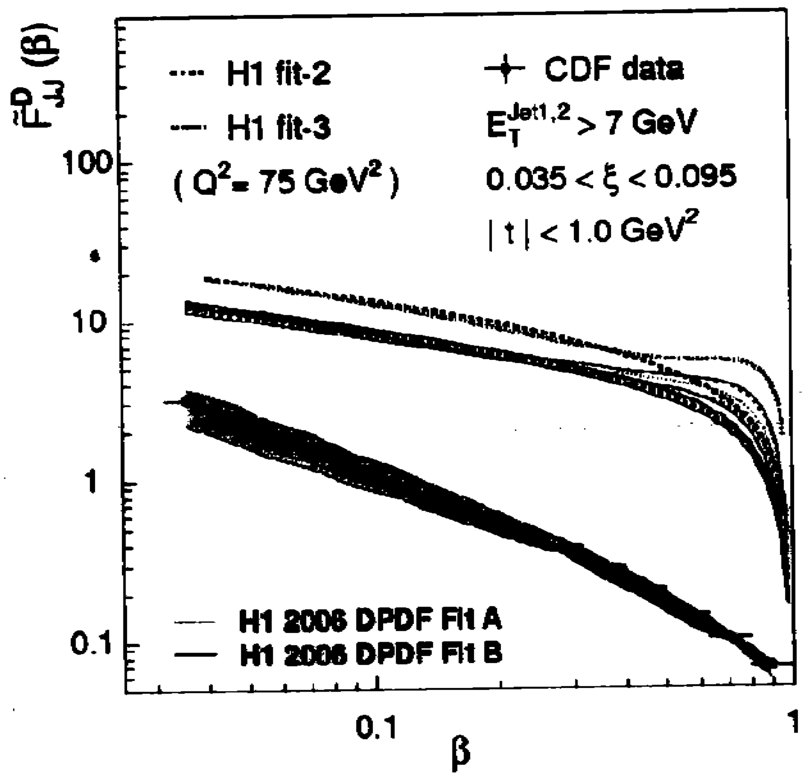
Fit B: $z_g(z,Q_0^2) = A_g$

Jets: $z_g(z,Q_0^2) = A_g z^{B_g}(1-z)^{C_g}$

The singlet and gluon are constrained with similar precision across the whole kinematic range



# Example Comparison with Tevatron: CDF Jets




- Fit A and fit B predictions in good agreement at low $\beta$.
- ~30% lower than earlier predictions, because gluon smaller and meson smaller.
- Basic conclusion of large factorisation breaking holds
- **Reassess gap survival factors?**
- High $\beta$ still problematic

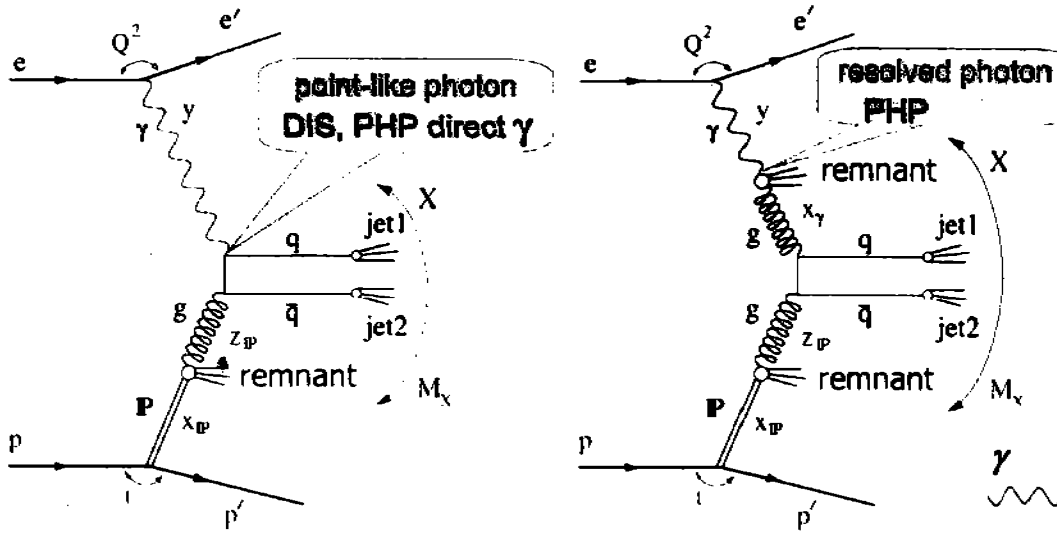


slide: Paul Newman, HERALHC worshop, March 07

# Dijets in Diffractive DIS and PhP

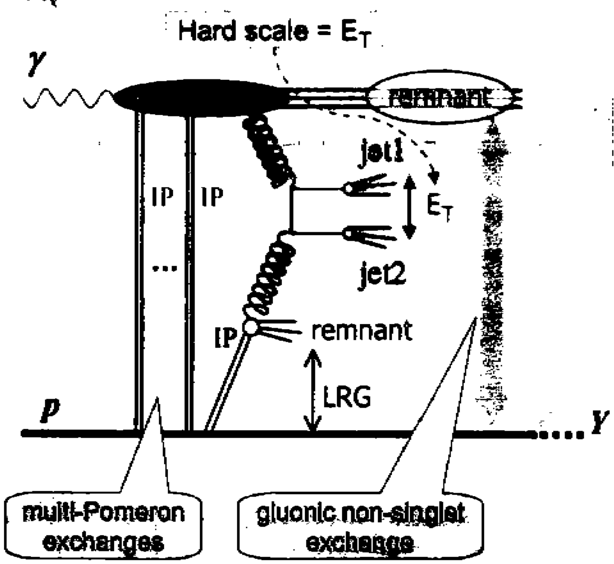
**W.Slominski**

**LO intuitive view**




## Rescattering leads to:

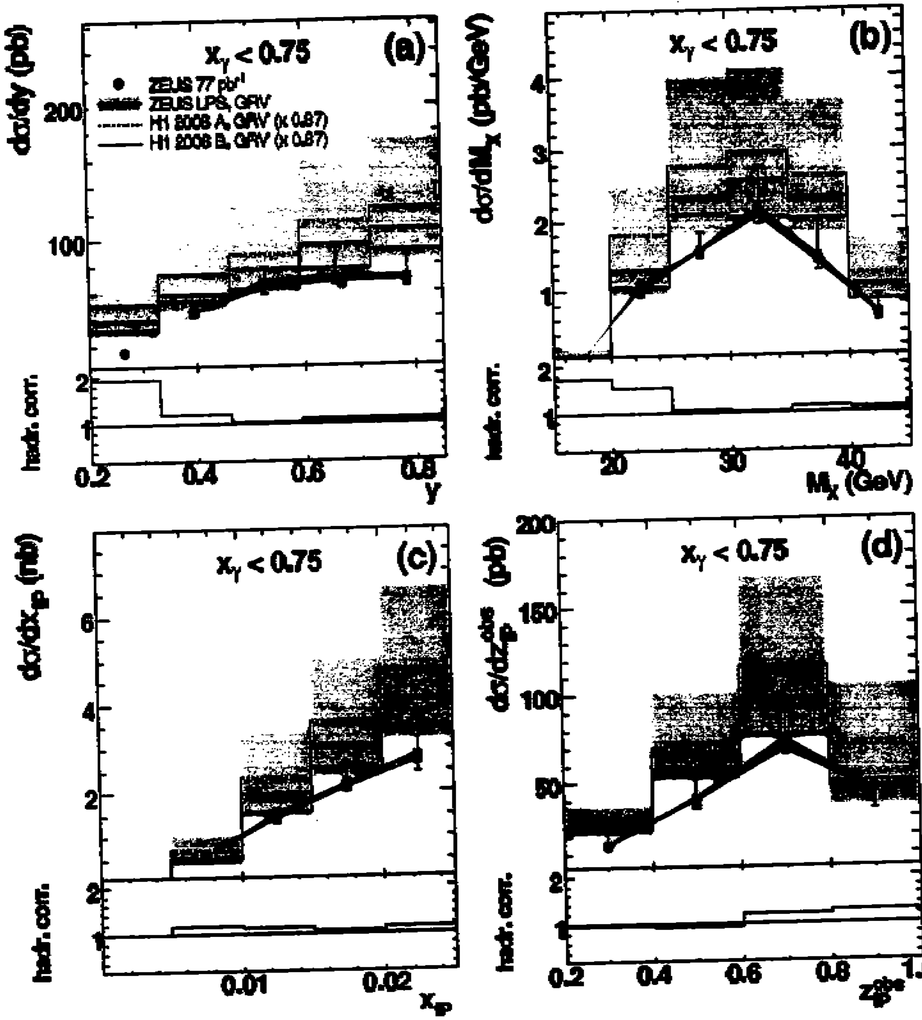
- ➢Factorisation breaking
- ➢Screening
- ➢Rapidity gap fill-up



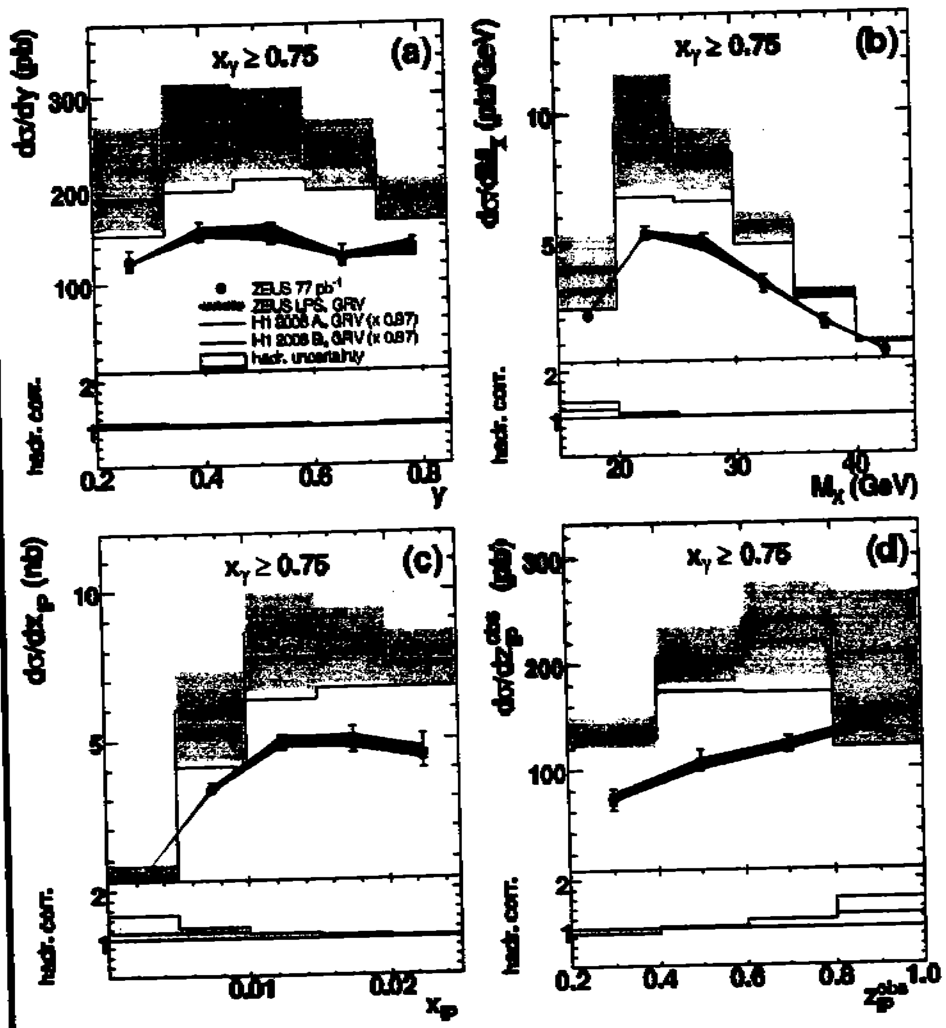

- Does factorisation hold for the diffractive dijet photoproduction where ...?
  - known to be strongly broken in *pp* diffraction
  - Factorisation should hold for <u>direct</u> photon – $x_\gamma$=1
  - Suppression – if any – expected for <u>resolved</u> photon – $x_\gamma$<1

# Resolved- vs. Direct-enriched PHP

$x_\gamma^{obs} < 0.75$




$x_\gamma^{obs} \geq 0.75$



FORWARD NEUTRON PRODUCTION
IN PHP

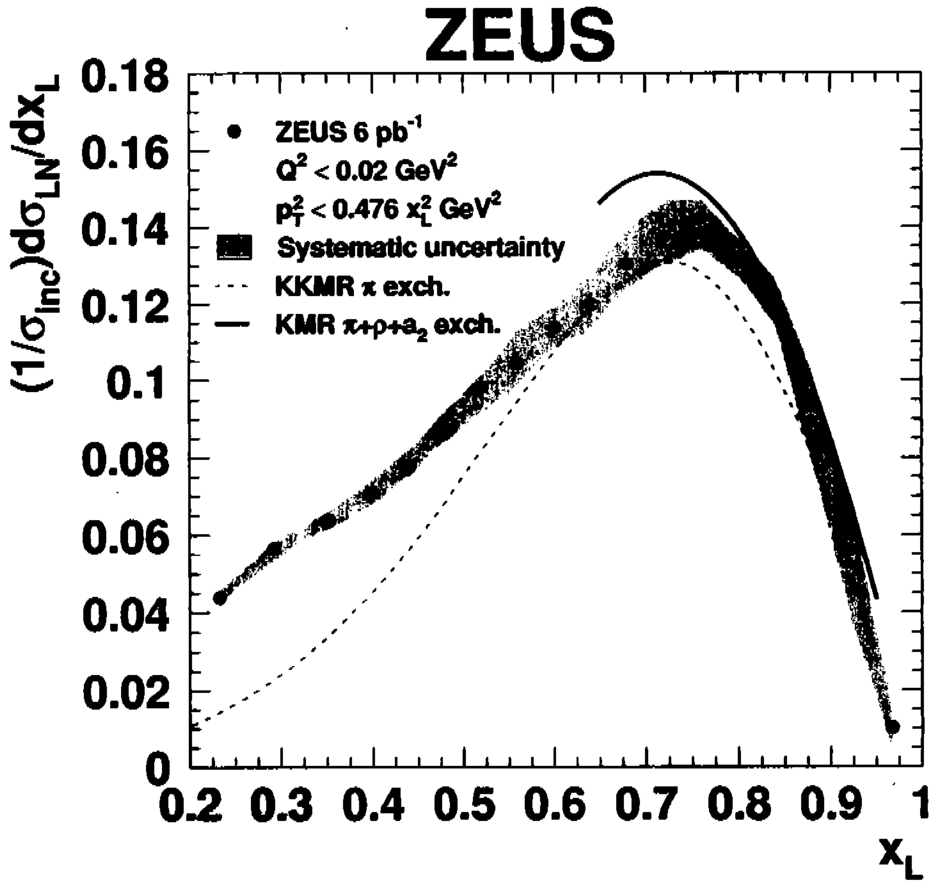



**Figure 22:** *$x_L$ distribution for photoproduction. The error bars show the statistical uncertainties; the shaded band shows the systematic uncertainties. The band does not include the overall normalization uncertainty of 5.5%. The dashed curve shows the prediction of a model with enhanced neutron absorption and migration for pion exchange only [15]. The solid curve shows the same model including also $\rho$ and $a_2$ exchanges [16].*

FORWARD PROTON PRODUCTION IN DIS

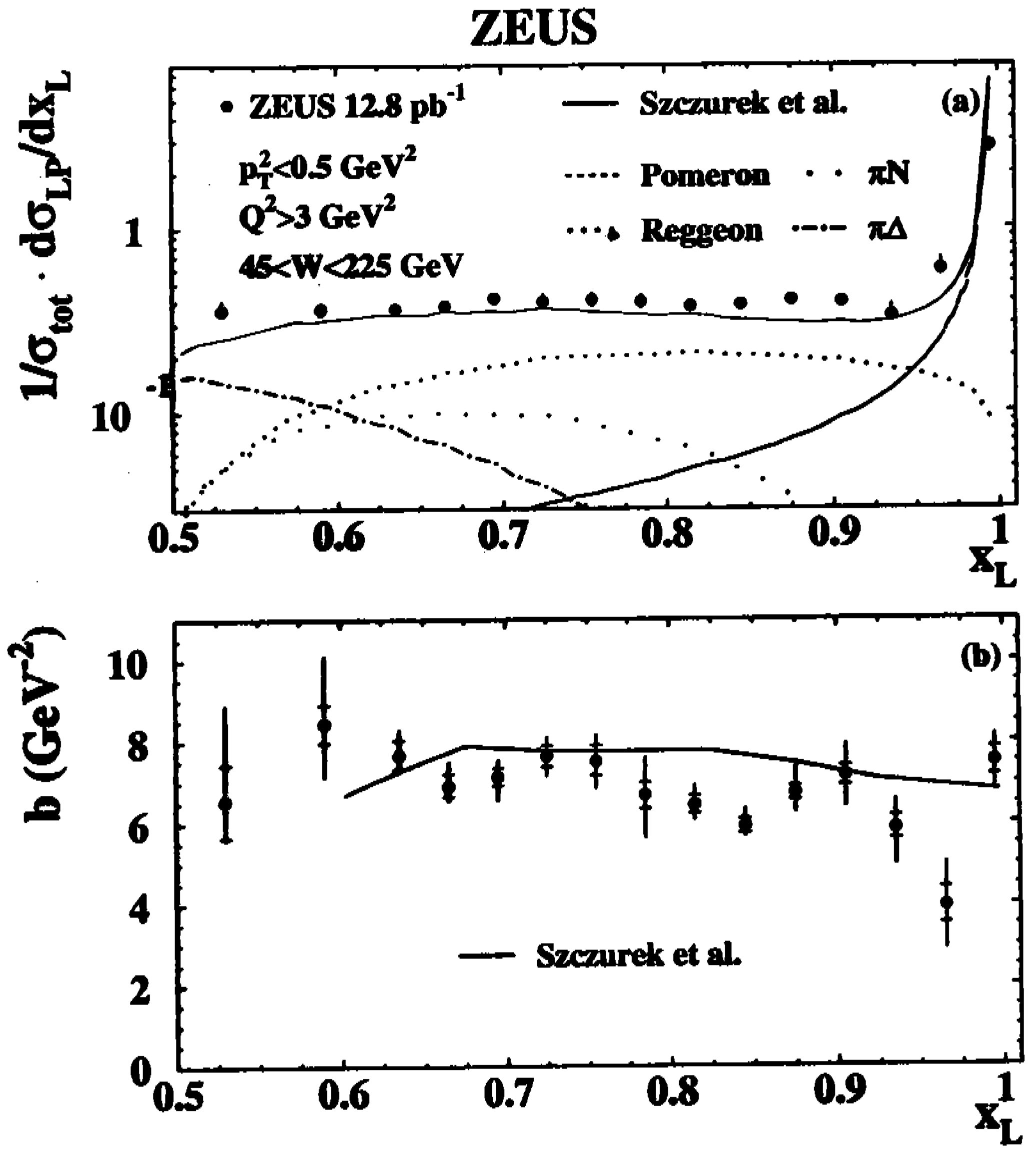
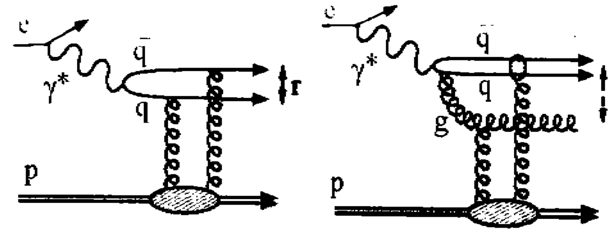



**Figure 18:** *The single differential cross section* $1/\sigma_{tot} \cdot d\sigma_{LP}/dx_L$ *(a) and the slopes of the* $p_T^2$ *distributions (b) compared to a model based on Reggeon-exchange [11] .*

# ZEUS modified BEKW Fit

Fit with BEKW model

**(Bartels, Ellis, Kowalski and Wüsthoff, 1998)**




- $$x_{I\!P} F_2^{D(3)} = c_T \cdot F^T_{q\bar{q}} + c_L \cdot F^L_{q\bar{q}} + c_g \cdot F^T_{q\bar{q}g}$$

$$F^T_{q\bar{q}} = \left(\frac{x_0}{x_{I\!P}}\right)^{n_T(Q^2)} \cdot \beta(1-\beta)\,,$$

$$F^L_{q\bar{q}} = \left(\frac{x_0}{x_{I\!P}}\right)^{n_L(Q^2)} \cdot \frac{Q_0^2}{Q^2+Q_0^2} \cdot \left[\ln\left(\frac{7}{4} + \frac{Q^2}{4\beta Q_0^2}\right)\right]^2 \cdot \beta^3(1-2\beta)^2\,,$$

$$F^T_{q\bar{q}g} = \left(\frac{x_0}{x_{I\!P}}\right)^{n_g(Q^2)} \cdot \ln\left(1 + \frac{Q^2}{Q_0^2}\right) \cdot (1-\beta)^{\gamma}$$

assume $n_T(Q^2) = c_4 + c_7 \ln\left(1 + \frac{Q^2}{Q_0^2}\right)$, $n_L(Q^2) = c_5 + c_8 \ln\left(1 + \frac{Q^2}{Q_0^2}\right)$,

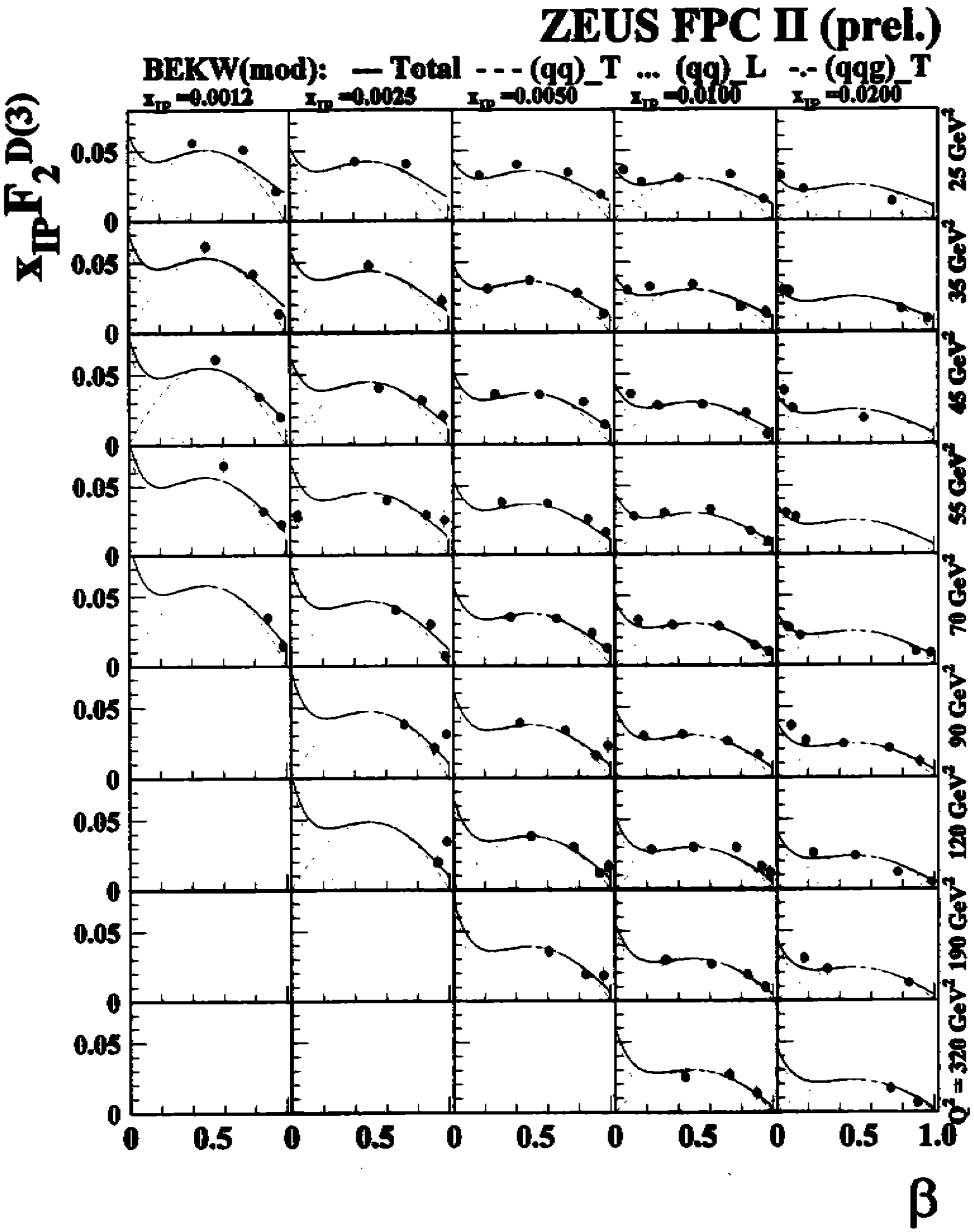
$$n_g(Q^2) = c_6 + c_9 \ln\left(1 + \frac{Q^2}{Q_0^2}\right)$$

The ZEUS data support taking $n_T(Q^2) = n_g(Q^2) = n_1 \cdot ln(1+Q^2/Q^2_0)$ and $n_L = 0$

Taking $x_0 = 0.01$ and $Q^2_0 = 0.4\ GeV^2$ results in the modified BEKW model (BEKW(mod)) with the 5 free papameters :

$c_T$ , $c_L$ , $c_g$ , $n_1^{T,g}$ , $\gamma$

## $x_{IP}F_2D(3)$ Results from the FPC I +II $M_X$-Analyses with BEKW(mod) Fit ( III)

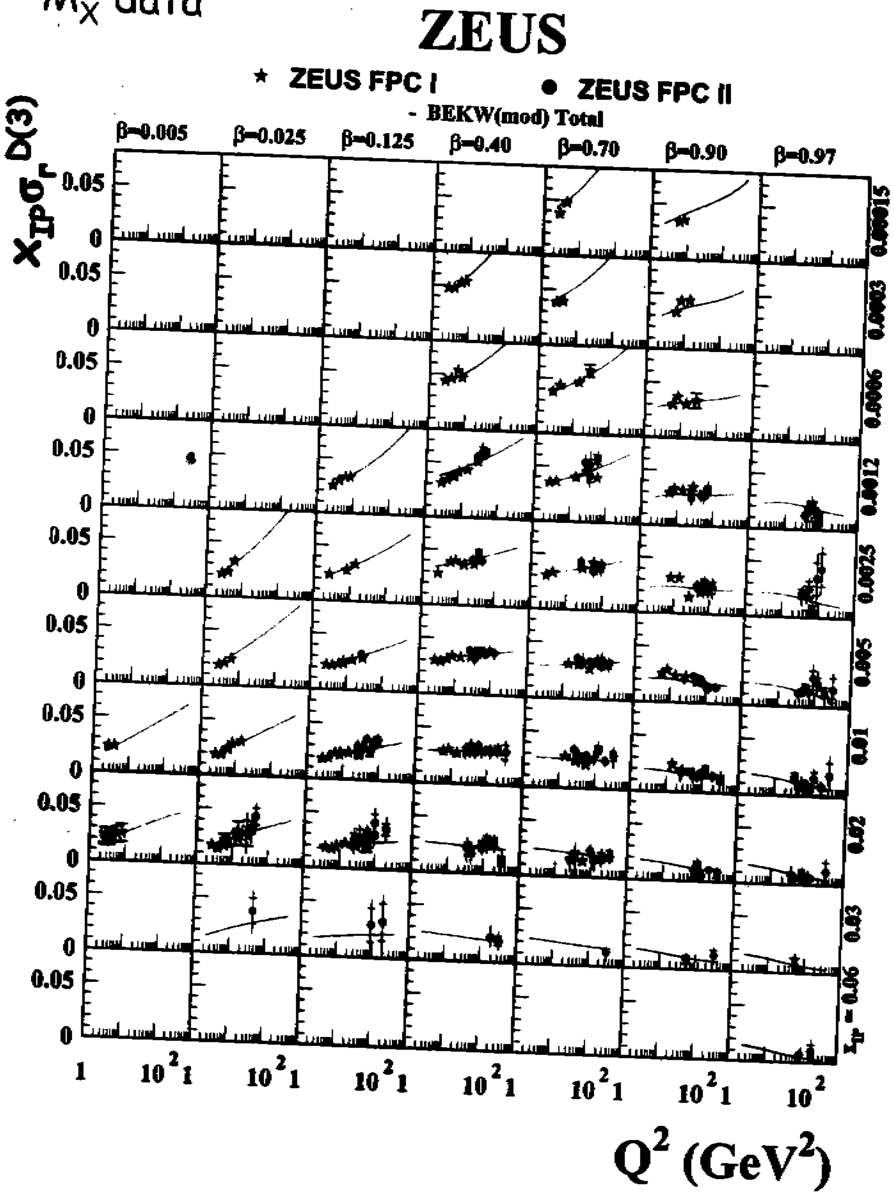



$x_{IP}F_2D(3)$ exhibits :

- a broad maximum around β=0.5 which is due to the transverse $q\bar{q}$-contribution,
- a steep rise towards small β which is generated by the $q\bar{q}g$-contribution,
- a longitudinal $q\bar{q}g$-contribution which is sizeable only at very high β and causes the structure function not to vanish at β = 1.

# $Q^2$ dependence of $\sigma_r^{D(3)}$

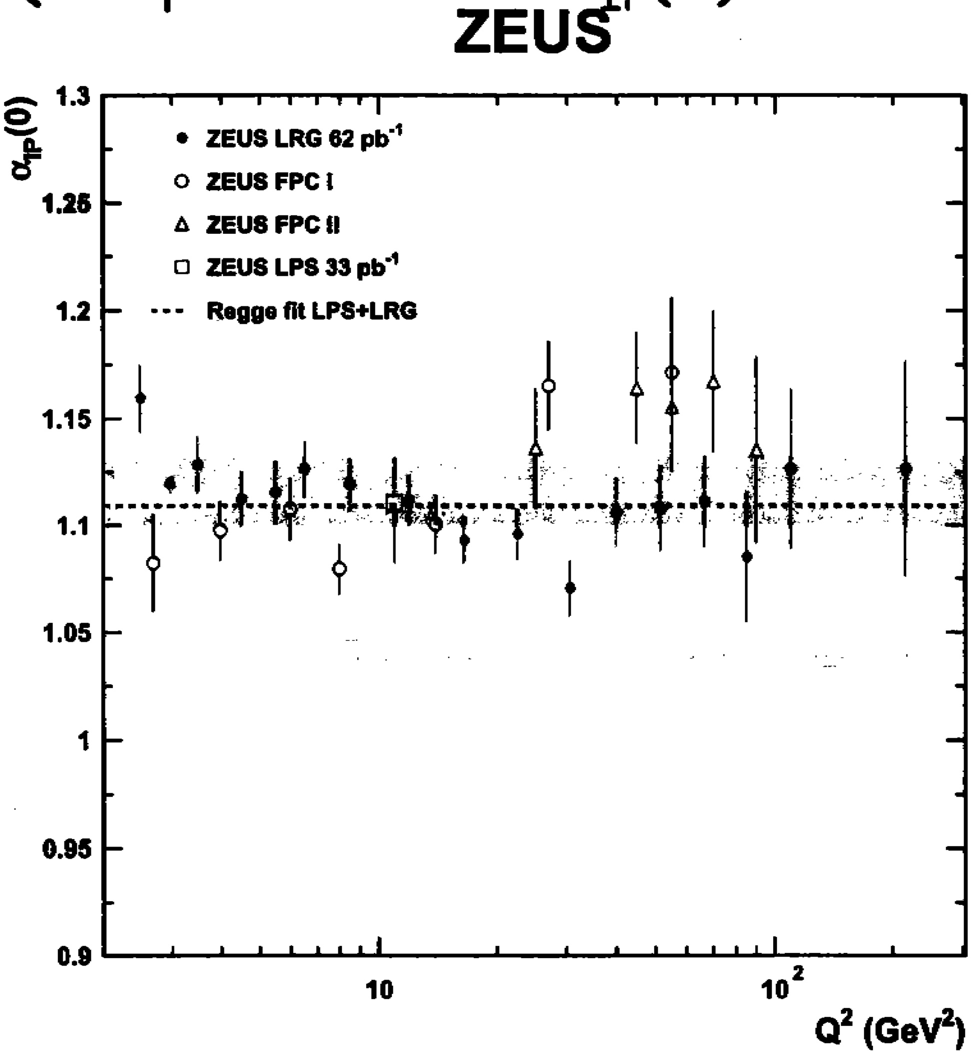
$M_X$ data




→ **Positive scaling violations up to high-β values:** diffractive exchange is gluon-dominated

fit fixed β shape depends on $x_{IP}$ violates Regge factorisation

# $Q^2$ dependance of $\alpha_{IP}(0)$




→ $\alpha_{IP}(0)$ does not exhibit a significant dependance on $Q^2$

# Puzzle of Odderon

High energy scattering in QCD $\longrightarrow$ 2 color neutral reggeons with intercepts around 1:
Pomeron ($C = +1$) and Odderon ($C = -1$)

Pomeron: Total cross sections and diffraction
Odderon: Difference between cross sections for $AB$ and $A\bar{B}$ and exclusive processes

Searches for Odderon at HERA: $\gamma p \to p\pi^0$, $\gamma p \to \eta_c$, $\gamma p \to \eta_c X$,
asymmetries in diffractive charm and pion pair production $\longrightarrow$ no signal found

Some weak evidence for Odderon in elastic $pp$ and $p\bar{p}$ scattering at CERN-ISR at $\sqrt{s} = 53$ GeV in the dip region $|t| \sim 1.5$ GeV$^2$

Odderon is important element of the theory
The first reggeon beyond Pomeron that fulfills BKP equation; [J. Bartels, J. Kwieciński, M. Praszalowicz];
relevant for considerations of integrability in QCD [L. Lipatov]

# Diffractive physics program for new e-p facility

- Extend HERA measurements to new kinematic region with much improved precision % level rather than 10-20%
- Measure the diffractive longitudinal SF FlD
- Clarify proton breakup fraction
- Does Regge factorisation hold?
- Why is hadron-hadron diffraction so different from e-p?
- Does direct pomeron coupling exist?
- Where is the odderon?
- Quantify gap-filling probability.May be solved in context of LHC diffractive Higgs
- Clarify soft to hard transition using extensive DVCS measurements.Avoids VM wave function uncertainties.
- Build two detectors with complementary properties.Dipole and solenoid?