CIPANP-2000 Quebec, Canada, May 22-28, 2000
Session 4: Lepton-Hadron and Hadron-Hadron Scattering

Diffractive Physics at HERA

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representing

Outline

- Introduction
  - – Why diffraction? Why at HERA?
  - – Experimental techniques
  - – Modelling diffraction in DIS
- Diffraction in Photoproduction
  - – Soft $I\!P$ in glory: $\sigma_{\rm tot}^{\gamma p}$
  - – Soft $I\!P$ in trouble: elastic J/ψ
- Diffraction in DIS
  - – Low x DIS and the Pomeron
  - – Exclusive diffraction: DVCS
  - – Inclusive diffraction: $F_2^{D(3)}$
  - – Jets
  - – D^*
- Isolating Hard Pomeron
  - - Rapidity Gap between jets
- Summary and Outlook

Introduction

Diffraction in HEP =
Colorless exchange carrying vacuum quantum numbers
$\Rightarrow$ Physics of the Pomeron

To understand Pomeron means
to understand Strong Interactions

There were two partly successful attempts undertaken:

1. Regge phenomenology (60's)
2. QCD (80's)

Goal: To finalize these attempts
(Ex: Effective field theory of reggeized gluons – L.Lipatov et al.)

RFT:	Universal ('soft') $I\!P$ (phenomenological D-L fit)	$\alpha(t) = 1.08 + 0.25t$
QCD:	? ... trying hard ...	$\alpha(t) \simeq 1.2\pm$?

★ **Due to its unique possibilities HERA is presently leading this field of research**

Regge theory – side remark

A common prejudice:

Regge approach represents an outdated, old-fashioned phenomenology, which now is fully substituted by QCD.

$\Rightarrow$ This is wrong !

In Gribov's formulation Regge theory is a very general relativistic field theory for any two body scattering at high energies, provided the processes involving large virtual masses are damped
(i.e. short range forces have non singular behavior)

$$(t/s << 1, \;\; s \to \infty \qquad \mathrm{DIS}: \;\; Q^2/sy << 1 \;\Rightarrow\; x \to 0)$$

Recent example:

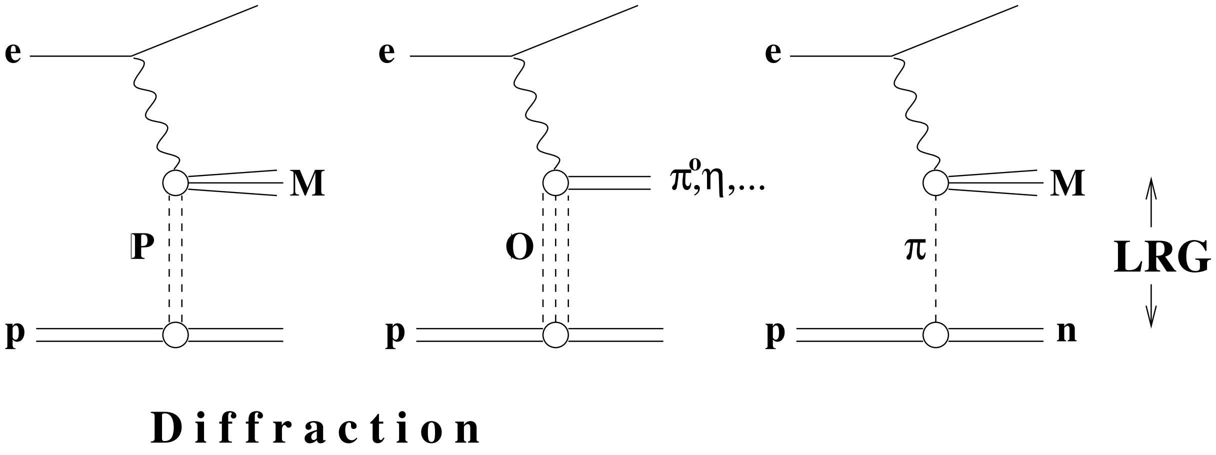
A Model for High Energy Scattering in Quantum Gravity
by T.Banks and W. Fischler, hep-th/9906038

- discussing two body scattering at $\sqrt{s}$ bigger than Plank scale
- formation, decaying (and perhaps scattering?) of black holes

Remember also:

A string theory was originally invented as a model to reproduce a Regge behavior for high energy scattering in hadron physics.

Diffraction at HERA



- $\gamma^*(Q^2)$ provides varying resolution power
  $(10^{-8} < Q^2 < 10^5$ GeV$^2)$

- $x/Q^2 \geq 10^{-5}$ GeV^{-2} $\rightarrow$ low x regime
  $\rightarrow$ high parton densities

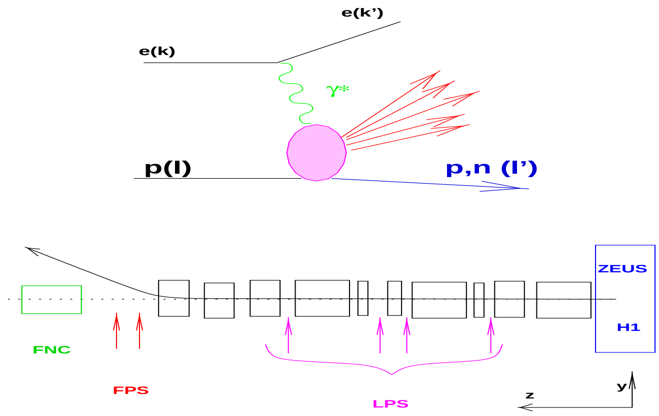
- asymmetric beam configuration (27.5 $\times$ 820(920) GeV) $\rightarrow$
  excellent acceptance for γ^* diffractive dissociation system

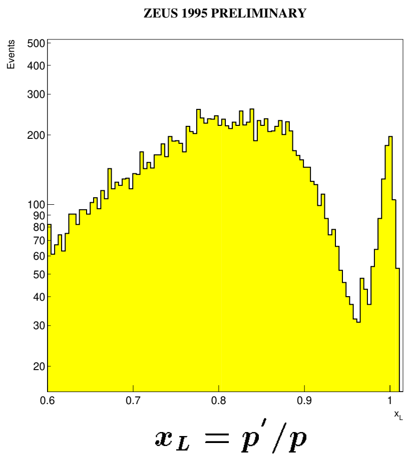
- clean channels for Odderon search $\rightarrow$
  no $I\!P$ "background" in the reactions $\gamma p \rightarrow (\pi^0, \eta, \eta', ...)p'$

$\Rightarrow$ **Unique facility to probe partonic content of diffractive exchange ($I\!P$) and to study the transition from soft to hard regime**

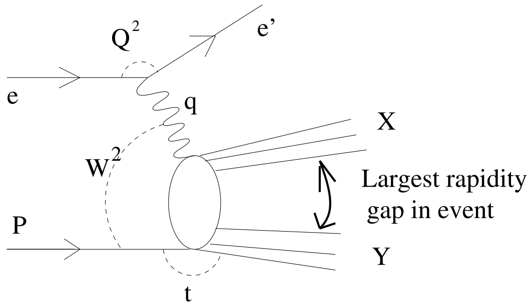
Selecting Diffractive Events

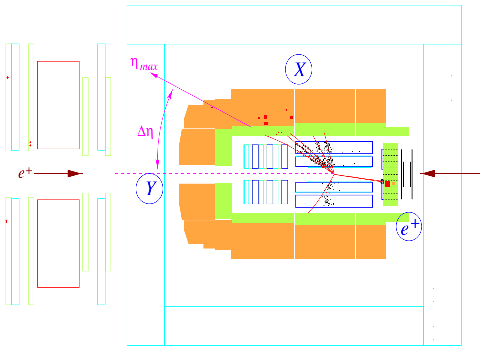
- **Tagging leading protons by Roman Pots (H1-FPS, ZEUS-LPS)**



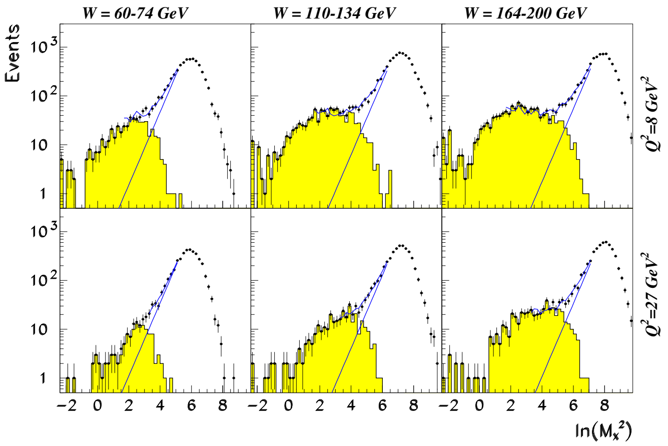


- **Selecting Large Rapidity Gap (LRG) events, $3.0 < \eta_{gap} < 7.5$**





- **Analysing mass distribution of the hadronic final state (ZEUS)**

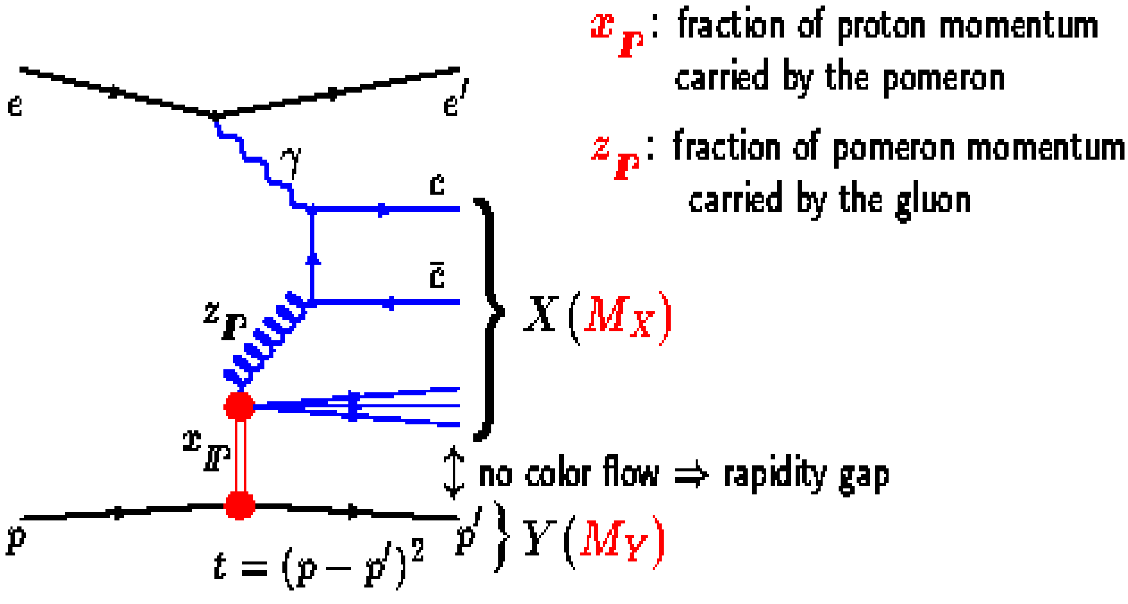


Models of diffractive DIS

Three approaches to describe diffractive processes in DIS:

- **Regge motivated models with factorizable Pomeron**
- **Perturbative QCD calculations (2-gluon exchange, BFKL ladder)**
- **Non-pomeron mechanisms, generating large rapidity gap events**

• Resolved Pomeron (e.g. Ingelmann, Schlein)



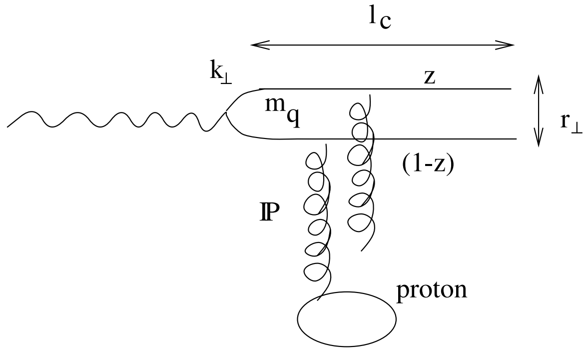
$$\frac{d^4\sigma}{d\beta dQ^2 dx_{I\!P} dt} = \frac{4\pi\alpha^4}{\beta Q^4}(1 - y + \frac{y^2}{2(1+R_D)})F_2^{D(4)}(Q^2, x_{I\!P}, \beta, t)$$

with (assuming factorization)

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

Models: 2g exchange, SCI

• pQCD exchange (BFKL, e.g. Ryskin et al, or 2-gluon model, e.g. Bartels, Jung, Wüsthoff)

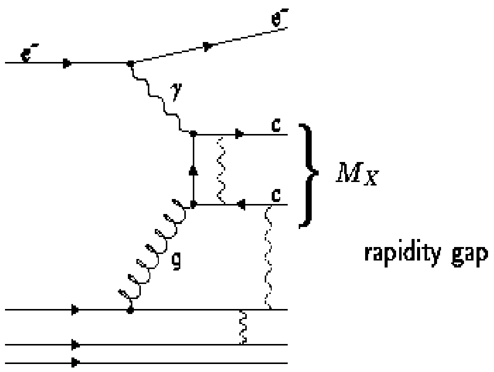


Those usually exploit Gribov's idea to describe the process in the *proton rest frame*, which is very convenient at low x.

$$\gamma \to q\bar{q},\ q\bar{q}g,\ \dots$$

$$\sigma \sim |x_{I\!P} G_p(x_{I\!P}, \mu^2)|^2 \quad \text{at scale} \quad \mu^2 = (k_\perp^2 + m_q^2)/(1-\beta)$$

• Soft Colour Interactions (e.g. Ingelmann, Rastman) – Mimic non-perturbative effects

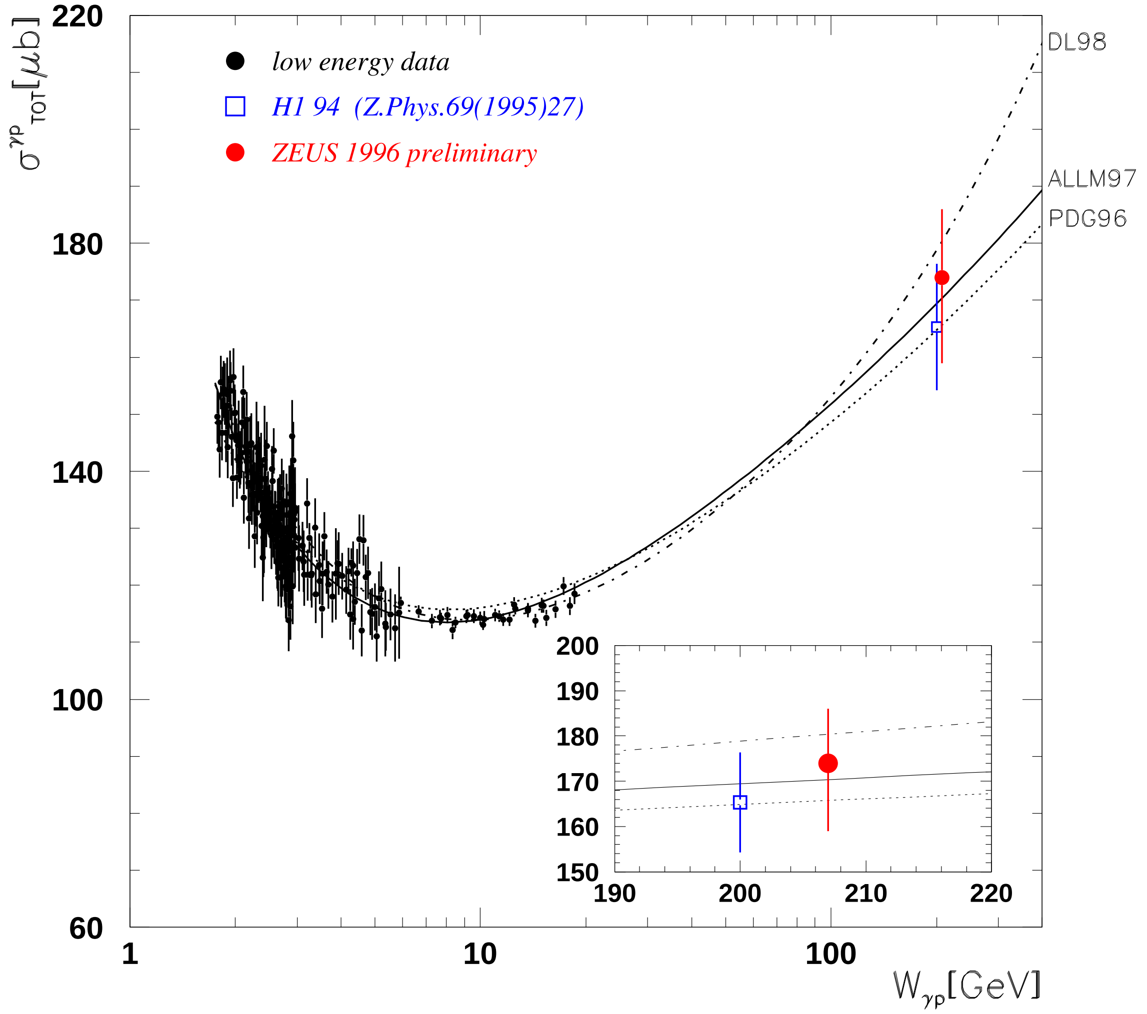


LRG are produced by the normal BGF with additional emittion of soft gluons, neutralizing the colour flow.

$\Rightarrow$ leading gluon behaviour

$\sigma_{\rm tot}^{\gamma p}$ at HERA

Using e tagger in the tunnel: $e^+p \to e^+X$ $(<Q^2>\approx 10^{-4}\ \mathrm{GeV}^2)$

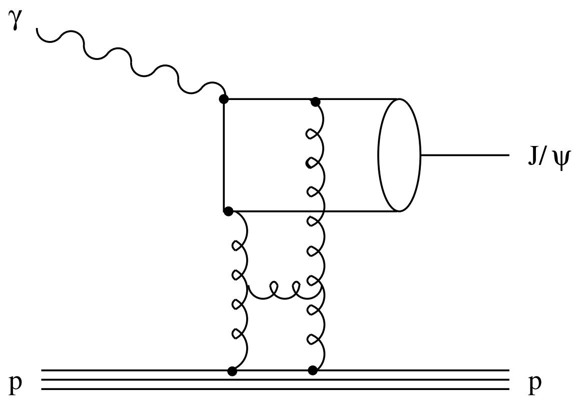


$$\mathbf{H1:}\quad \sigma_{\rm tot}^{\gamma p}(W_{\gamma p}=200\ \mathrm{GeV}) = 165 \pm 2 \pm 11\ \mu\mathrm{b}$$

$$\mathbf{ZEUS:}\quad \sigma_{\rm tot}^{\gamma p}(W_{\gamma p}=207\ \mathrm{GeV}) = 172 \pm 1^{+13}_{-15}\ \mu\mathrm{b}$$

★ $\gamma p \approx hh$. Universal soft $I\!\!P$ in full glory

Elastic J/ψ photoproduction



Expectations:

Soft $I\!P$: $\alpha_{I\!P}(t) = 1.08 + 0.25t$

BFKL $I\!P$: $\alpha_{I\!P}(t) = 1.17$

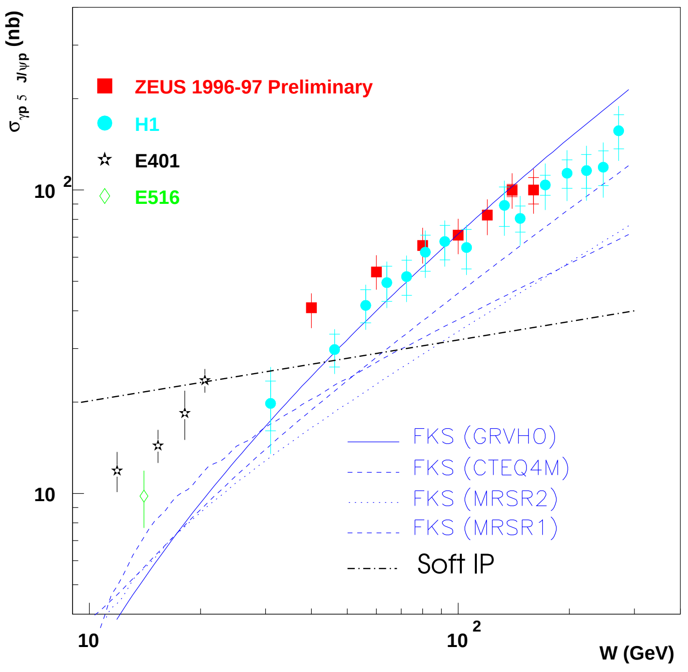
QCD: $\sigma(W) \propto [\alpha_s(q^2)\bar{x}g(\bar{x},q^2)]^2$

$(\bar{x} = (Q^2+M_V^2)/W^2)$

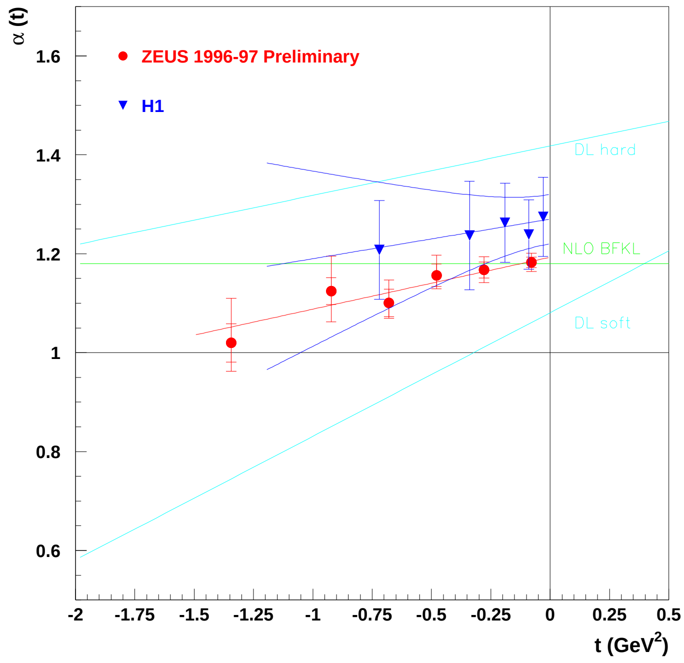
Measurement:

$$\frac{d\sigma}{dt} = f(t)W^{4(\alpha_{I\!P}-1)}$$

cross section vs energy



Regge tragectory



$$\mathrm{H1:}\quad \alpha_{I\!P}(t) = (1.27 \pm 0.05) + (0.08 \pm 0.17) \cdot t/\mathrm{GeV}^2$$

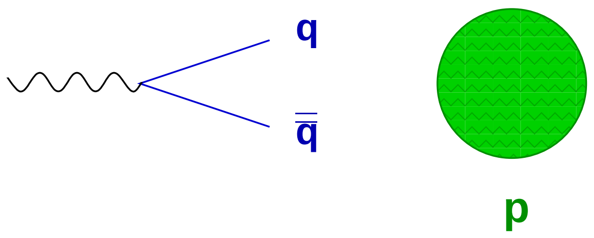
$$\mathrm{ZEUS:}\quad \alpha_{I\!P}(t) = (1.193 \pm 0.019) + (0.105 \pm 0.033) \cdot t/\mathrm{GeV}^2$$

★ **Soft Pomeron does not describe this process**

Colour dipole approach to DIS

Goal: Combine both soft and hard processes within a common framework

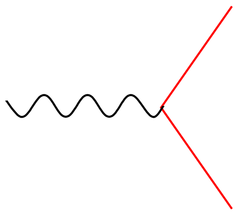
Basic idea: (B.L.Ioffe in 1969, S.Brodsky et al. in 1992, J.D.Bjorken in 1993, ...)
Consider DIS in a proton rest frame.
At low x $\tau \approx \frac{1}{xM_p} \Rightarrow \sim 1000$ fm at HERA



$\Rightarrow$ factorizes into $\Psi_{q\bar{q}} \times \sigma_{(q\bar{q})p}$

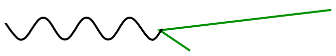
$$|\gamma> \; = \; q\bar{q} + q\bar{q}g + \ldots \quad \text{Fock states}$$

Hard interactions:



Large $k_\perp$ = small dipole size
$\rightarrow$ small cross section (σ_L)

Soft interactions:



Small $k_\perp$ = large dipole size
$\rightarrow$ large cross section (σ_T)

$$\sigma_{\rm DIS}(Q^2) = \Psi_{q\bar{q}}^{\rm hard}(Q^2) \cdot \sigma_L(Q^2) + \Psi_{q\bar{q}}^{\rm soft}(Q^2) \cdot \sigma_T(Q^2)$$

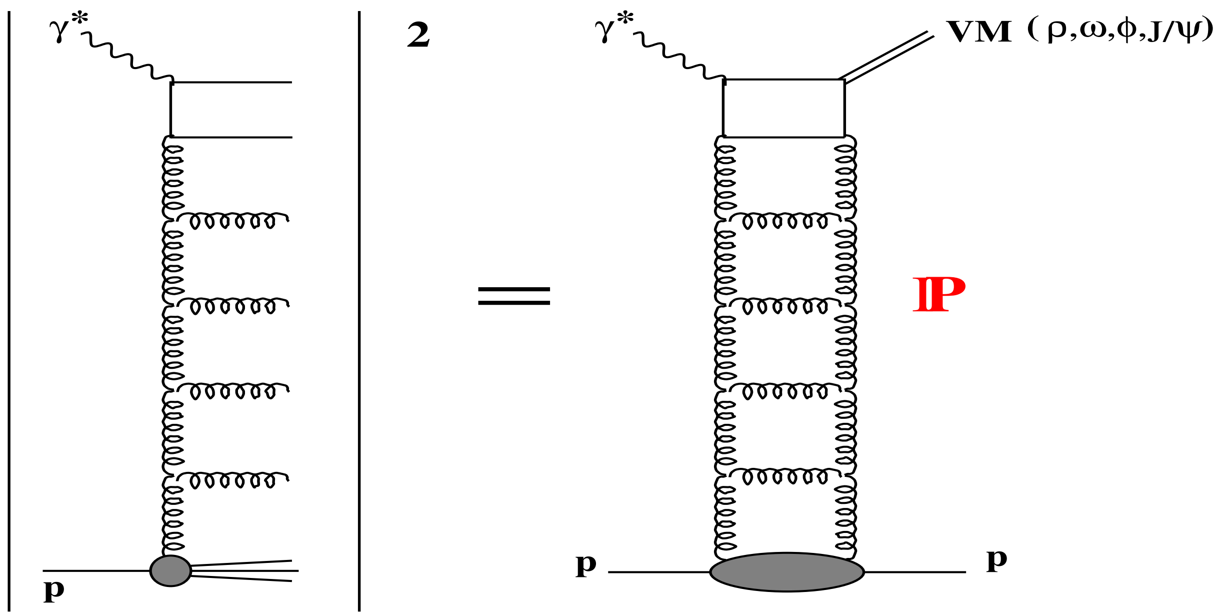
Diffraction in DIS: Strategy

- **Is diffractive DIS predominantly soft, or predominantly hard?**
  - ▷ Cross section depends on the size of $q\bar{q}$ pair:
    'soft' – 'large' configuration - large σ, but suppressed $\sim 1/Q^2$
    'hard' – 'small' configuration - small σ, but enhanced
    $\Rightarrow$ soft-hard interplay
  - ▷ Select 'small' configurations to allow for reliable pQCD calculation

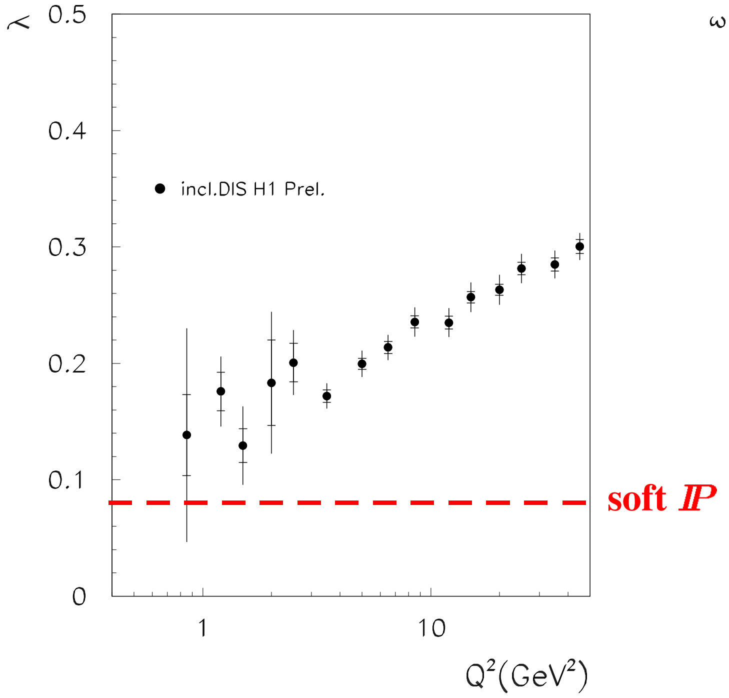
- **What is the partonic structure of diffractive exchange?**
  - ▷ Assume factorizable $I\!P$ with partonic structure
  - ▷ Measure F_2^D
  - ▷ Extract pdf's of the $I\!P$
  - ▷ Are they universal at HERA? $\rightarrow$ confront with final state properties
  - ▷ Are they generally universal? $\rightarrow$ HERA vs Tevatron

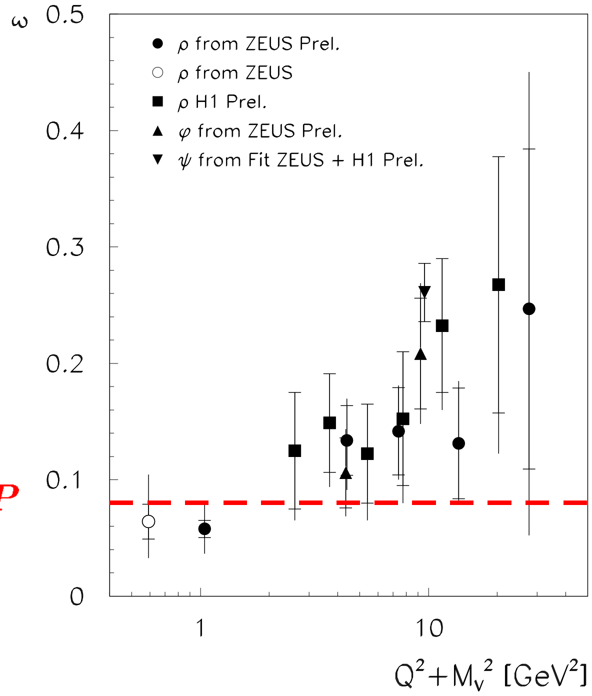
Low x physics and the Pomeron

Relating $F_2^p(s,Q^2) \sim \sigma_{tot}^{\gamma^* p}$ with elastic scattering via optical theorem:



$$\sigma_{tot}^{\gamma^* p} \sim s^{\epsilon} \qquad \sigma_{el}(\gamma^* p \to V p) \sim s^{2\epsilon}$$

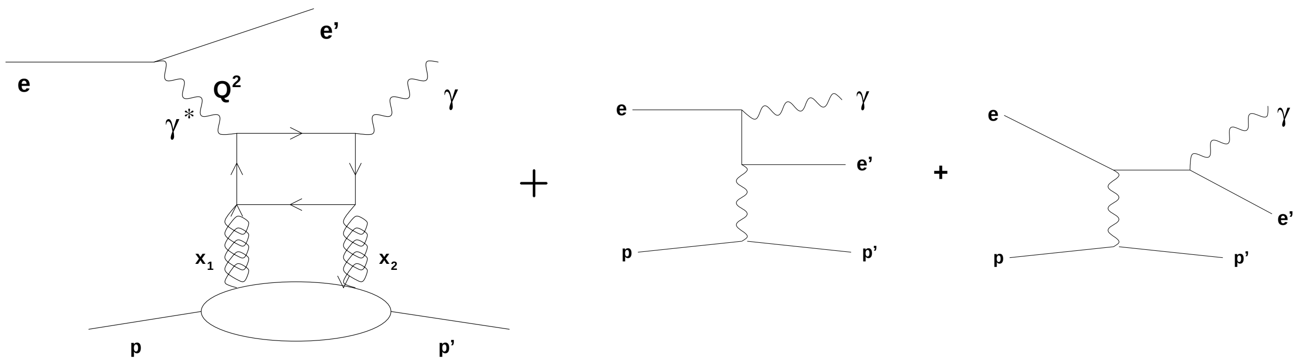




★ Striking similarity !

DVCS: $ep \to e\gamma\mathbf{p}$

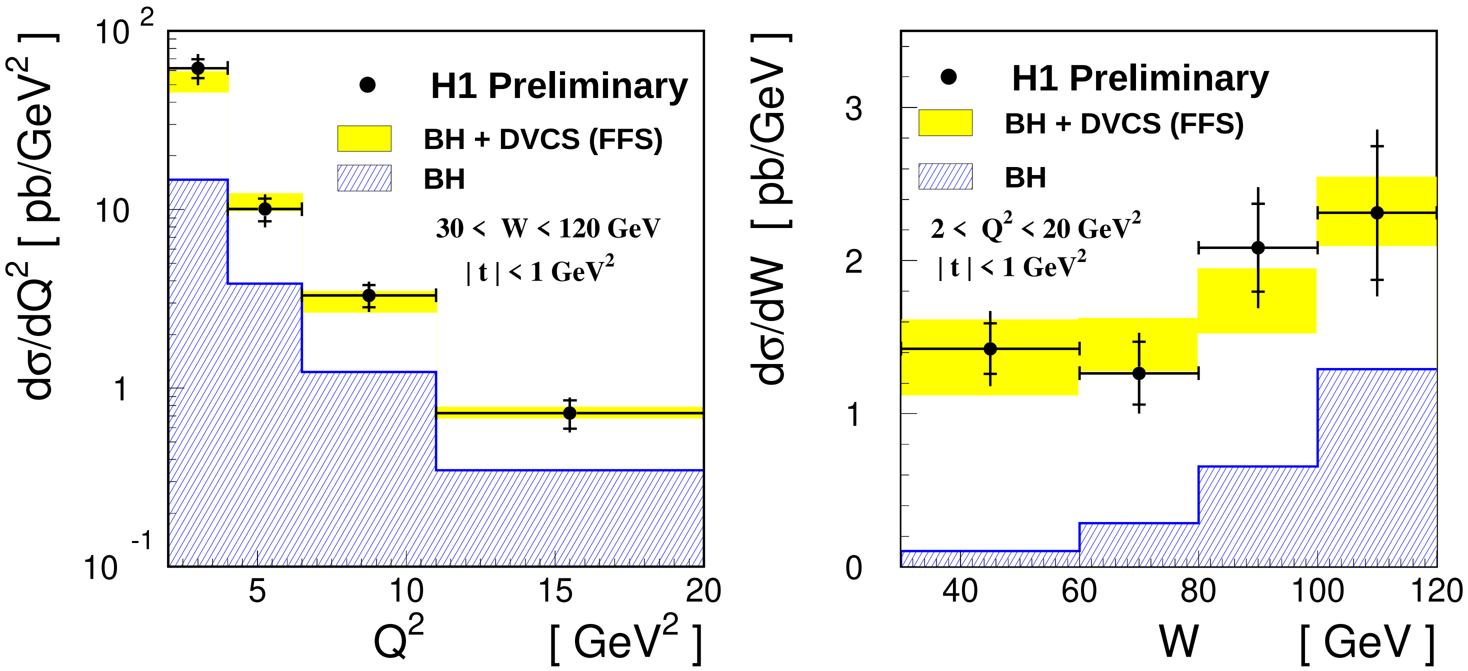
DVCS (QCD) **Bethe-Heitler (QED)**



- sensitive to $G(x_1, x_2, Q^2)$
- fully calculable in pQCD (no Ψ_{VM})

  a) L.Frankfurt, A.Freunf and M.Strikman **(FFS)**

  b) A.belitsky, D.Müller, L.Niedermeier and A.Schäfer



★ **DVCS process has been observed by both ZEUS and H1**

★ **Measurements are in excellent agreement with FFS predictions**

Inclusive diffraction: $\alpha_{I\!P}(0)$

ZEUS low Q^2 data

M_X method

$$\frac{d\sigma_{\gamma * p \to XY}}{dM_X} \sim W^{4(\alpha_{I\!P}-1)}$$

$0.22 < Q^2 < 0.7$ GeV^2

$90 < W < 220$ GeV

$3 < M_X < 12$ GeV

LPS method

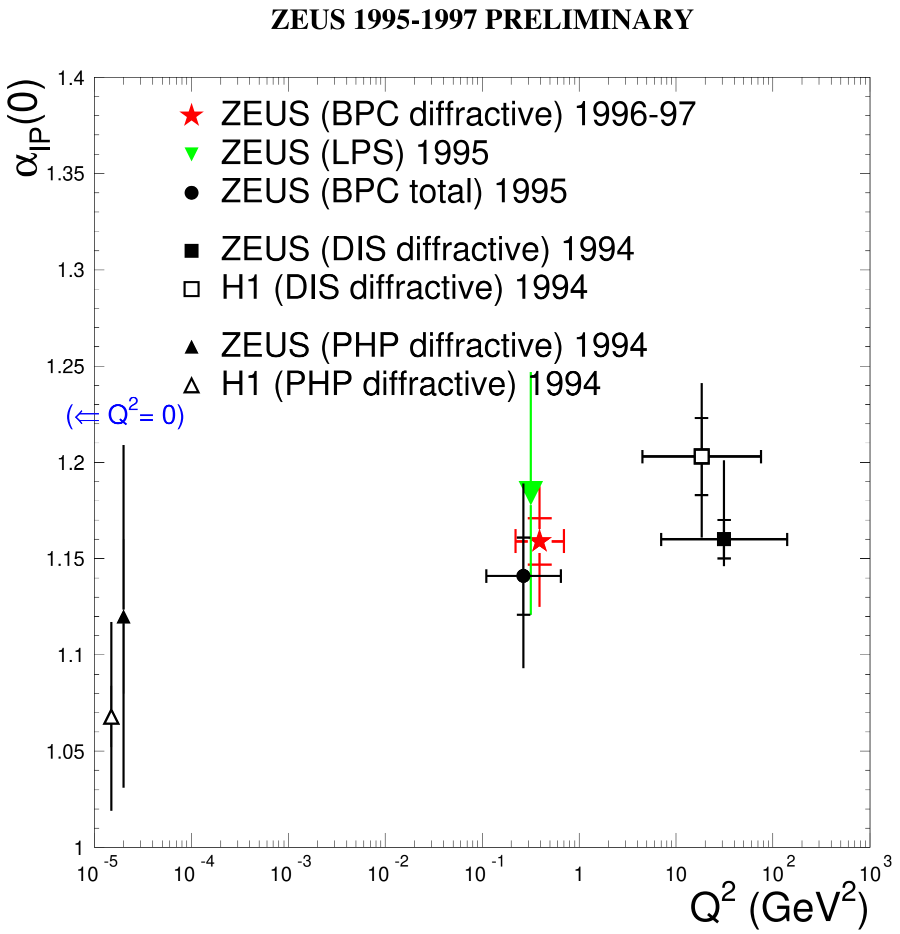
$$x_{I\!P} F_2^{D(4)} = \frac{1}{x_{I\!P}^{(2\alpha_{I\!P}-1)}} F_2^{D(3)}$$

$0.14 < Q^2 < 0.7$ GeV^2

$90 < W < 220$ GeV

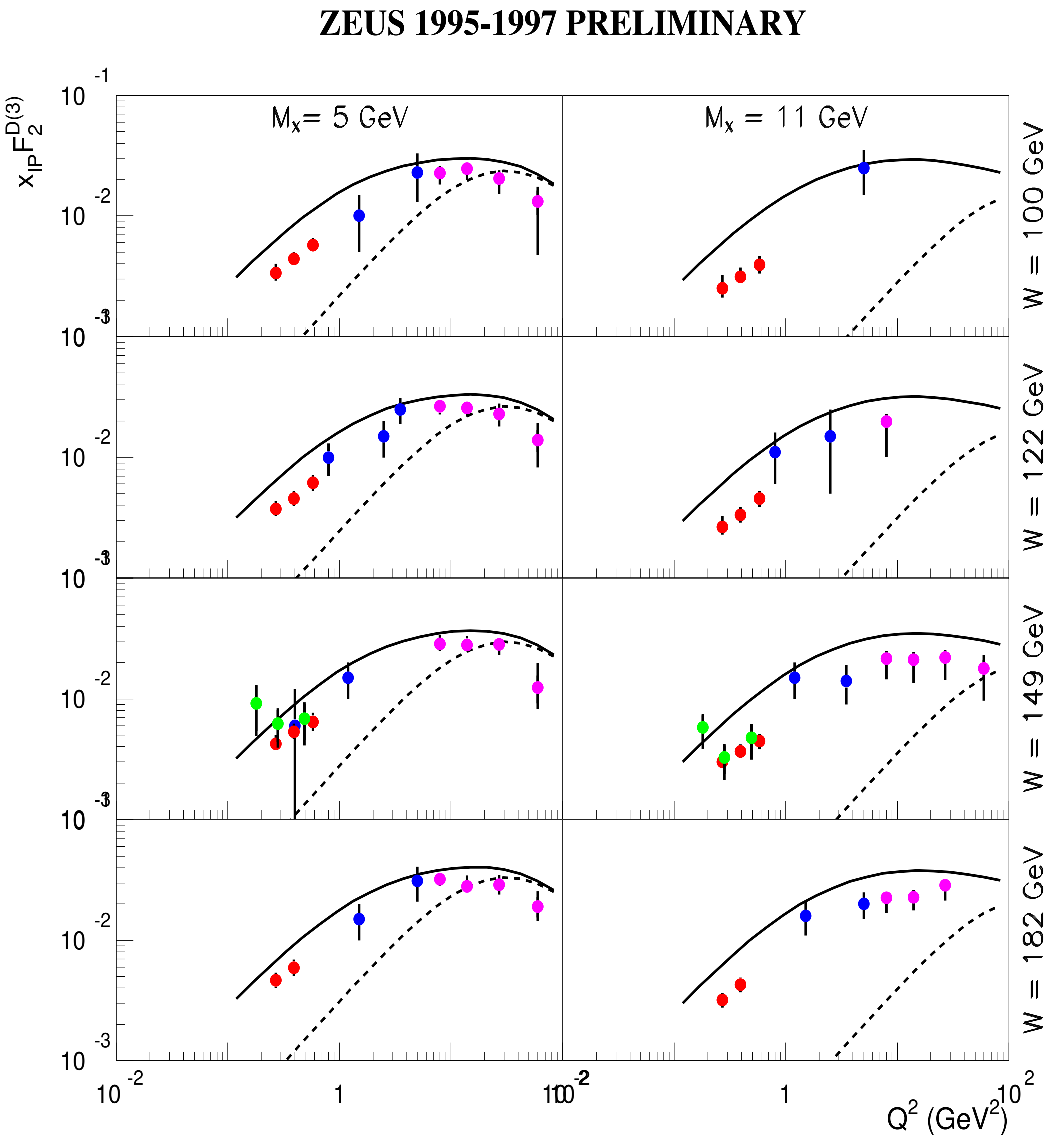
$3 < M_X < 32$ GeV

$0.073 < |t| < 0.4$ GeV^2



★ **Transition from soft to hard regime**

Inclusive diffraction: $F_2^{D(3)}$ at low Q^2



ZEUS BPC 96-97 PRELIMINARY (Method I)

ZEUS LPS 95 PRELIMINARY (Method II)

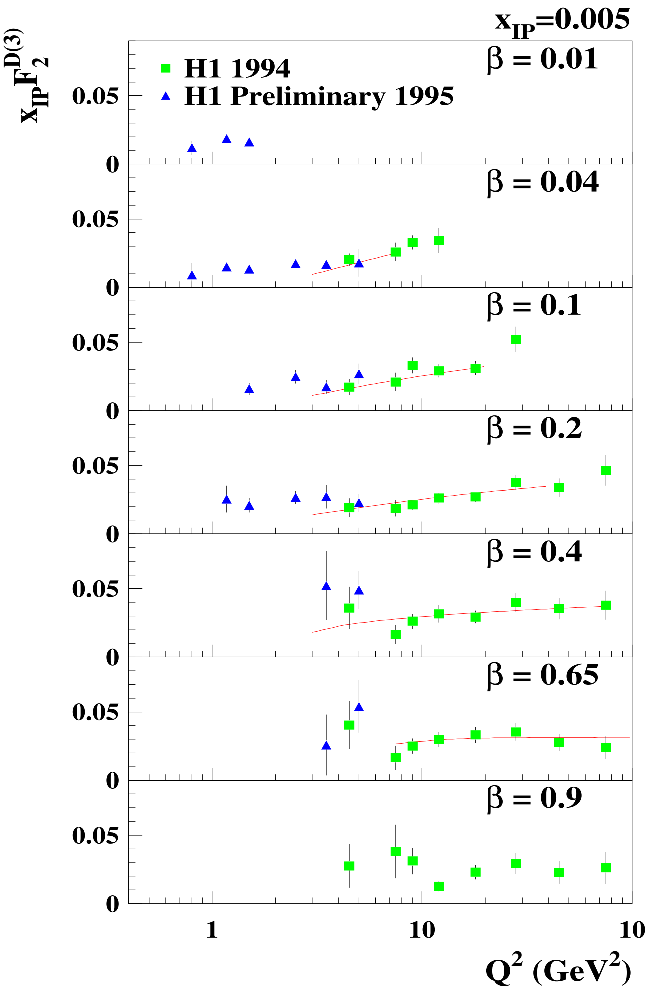
H1 shifted vertex 95 PRELIMINARY

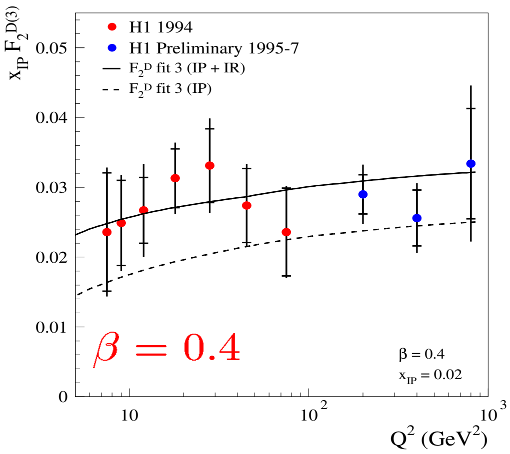
ZEUS DIS 94

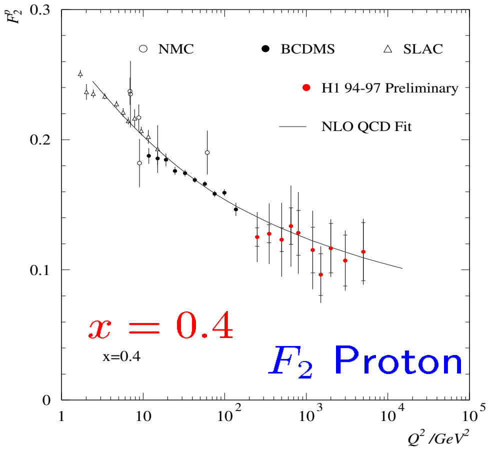
Curves by K. Golec-Biernat (private comunication)

Important contribution of $q\bar{q}g$ at low Q^2?

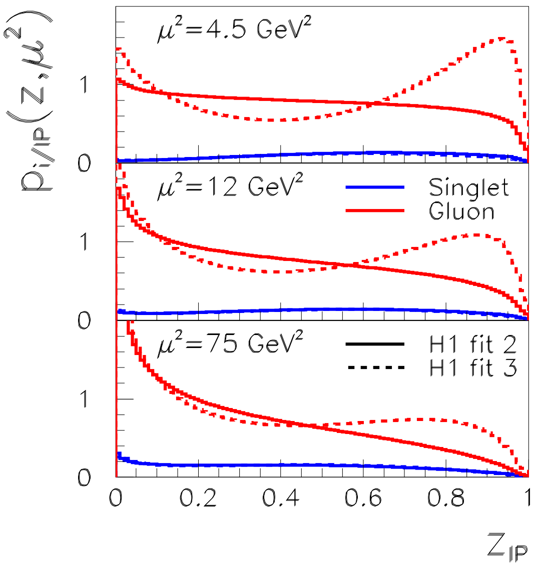
Scaling violation of F_2^D







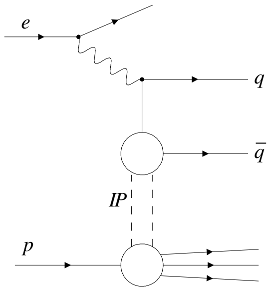
$\Rightarrow$ Gluon dominated mechanism

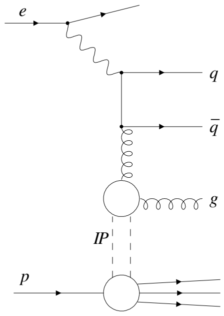


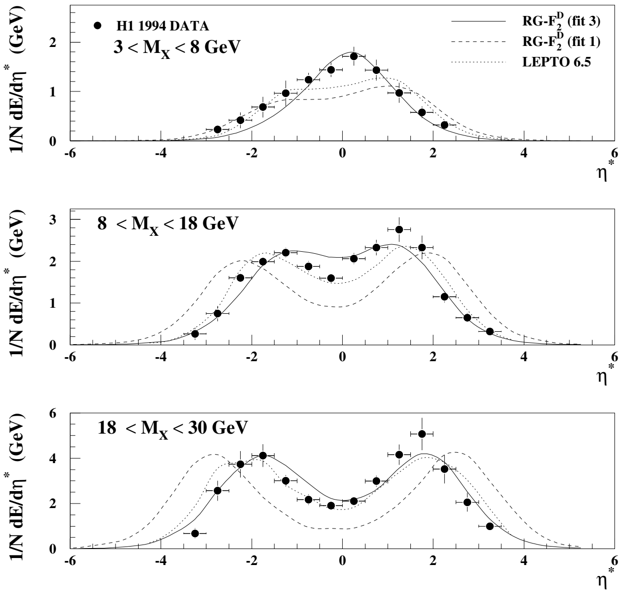
$\Leftarrow$ DGLAP QCD fit of $F_2^{D(3)}$

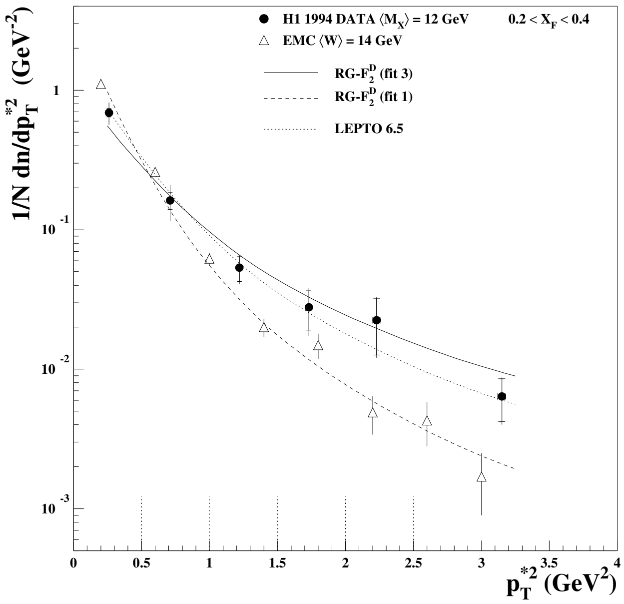
$\Rightarrow$ Implement into Monte Carlo and test final state properties – consistent?
(E-flow, jets, charm, ...)

Diffractive Final State Properties



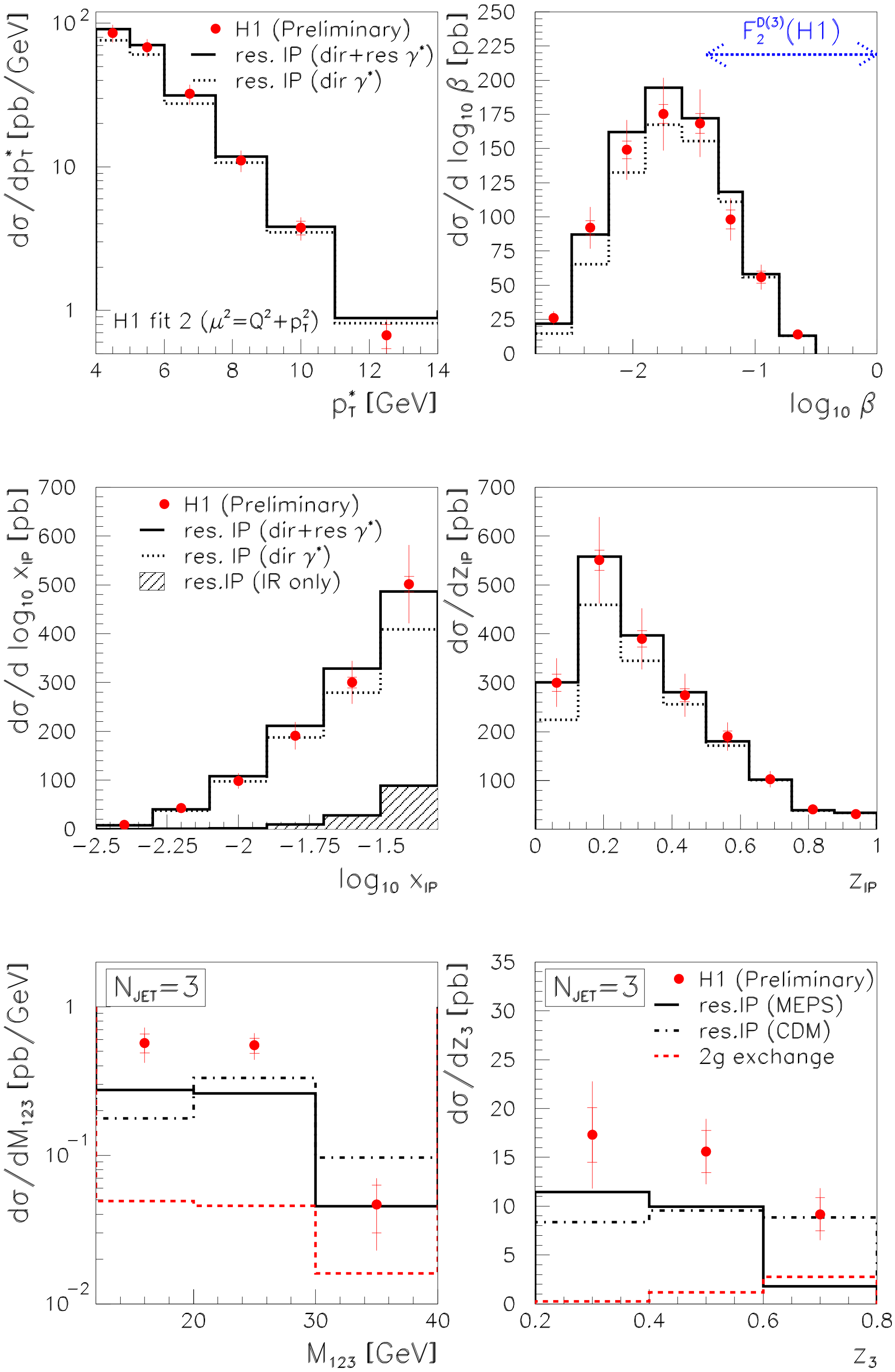






$\Rightarrow$ Consistent with gluon dominated $I\!P$

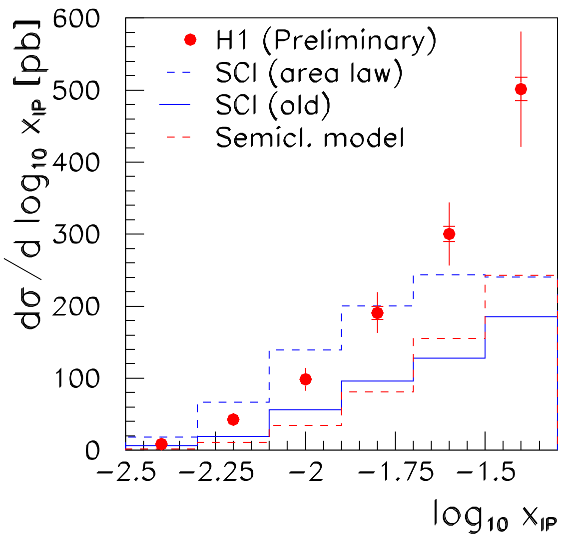
Diffractive 2- and 3-jet electroproduction

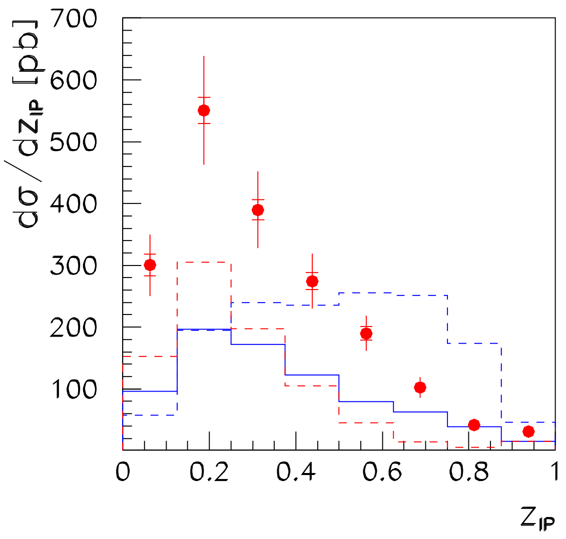


⇒ **Good description by "Resolved $I\!P$" model with pdf's from $F_2^{D(3)}$ fit**

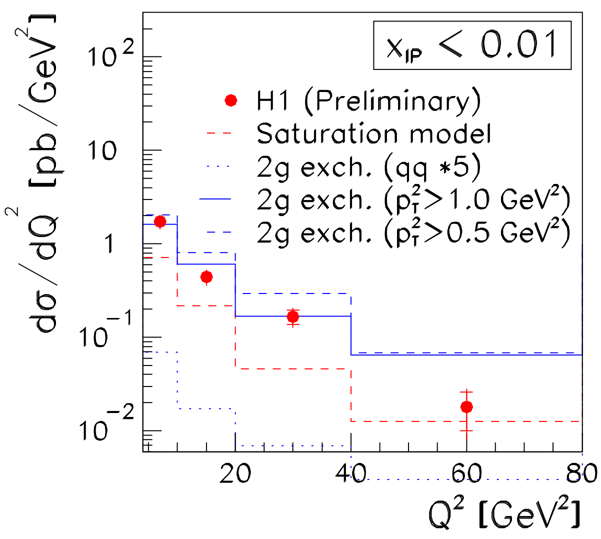
Note: resolved γ^* contribution improves the description

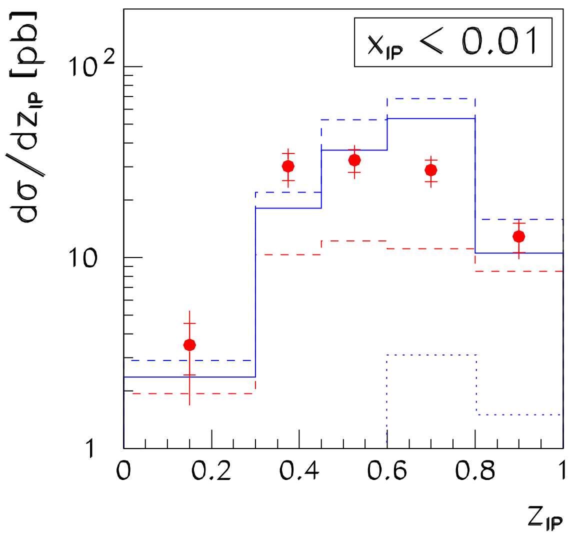
Jets vs SCI and 2g models





⇒ **SCI models fail both in shape and normalization**



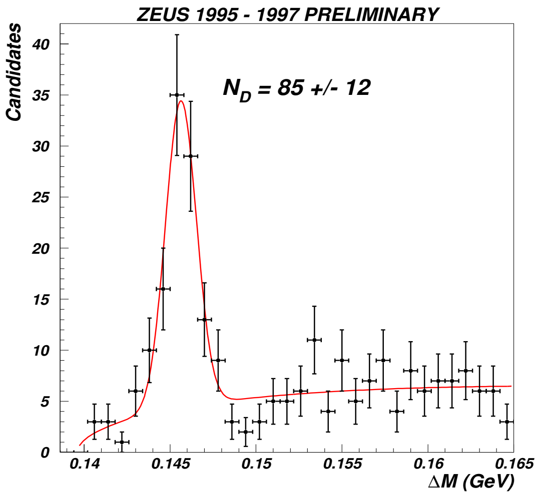


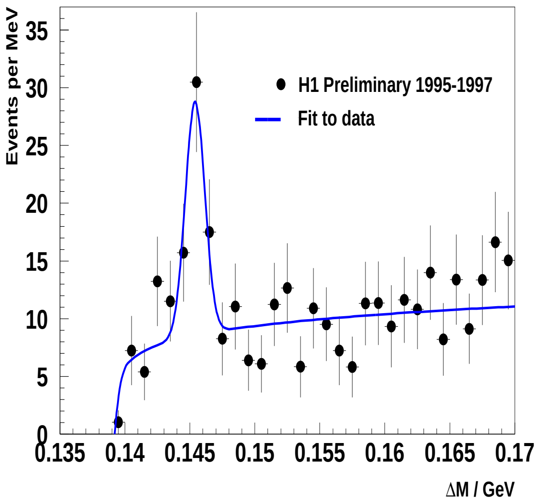
⇒ **Saturation model** (`Golec-Biernat, Wüsthoff`) **falls too low**

⇒ **$2g$ model of Bartels et al. gives fair description when using both $q\bar{q}$ and $q\bar{q}g$ contributions**

Diffractive D^* production in DIS

ZEUS **H1**





ZEUS:

$D^* \to K2\pi$ ($\mathcal{L} = 44$ pb^{-1})
$4 < Q^2 < 400$ GeV^2
$0.02 < y < 0.7$
$1.5 < p_T(D^{*\pm}) < 8$ GeV^2
$x_{I\!P} < 0.016$

H1:

$D^* \to K2\pi$ ($\mathcal{L} = 21$ pb^{-1})
$1 < Q^2 < 100$ GeV^2
$0.05 < y < 0.7$
$p_T(D^{*\pm}) > 2$ GeV^2
$x_{I\!P} < 0.04$

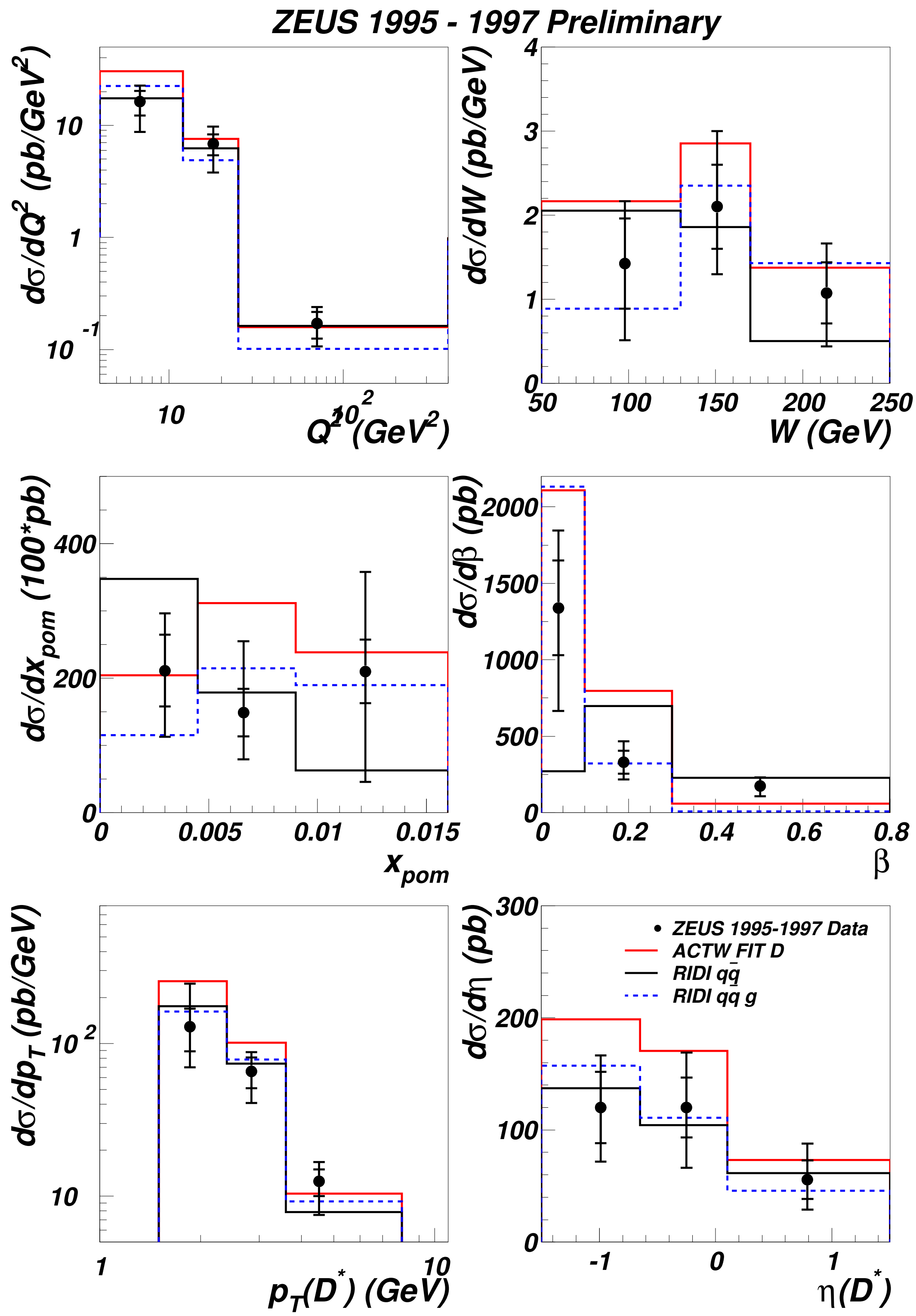
Indirect cross section comparison

- ZEUS: $281 \pm 41(stat)^{+79}_{-73}(syst)$ pb
  - RP model ($I\!P$ only): 309 ± 9 pb
  - RP model ($I\!P + I\!R$): 320 ± 12 pb

- H1: $154 \pm 40(stat) \pm 35(syst)$ pb
  - RP model ($I\!P$ only): 466 ± 12 pb
  - RP model ($I\!P + I\!R$): 504 ± 15 pb

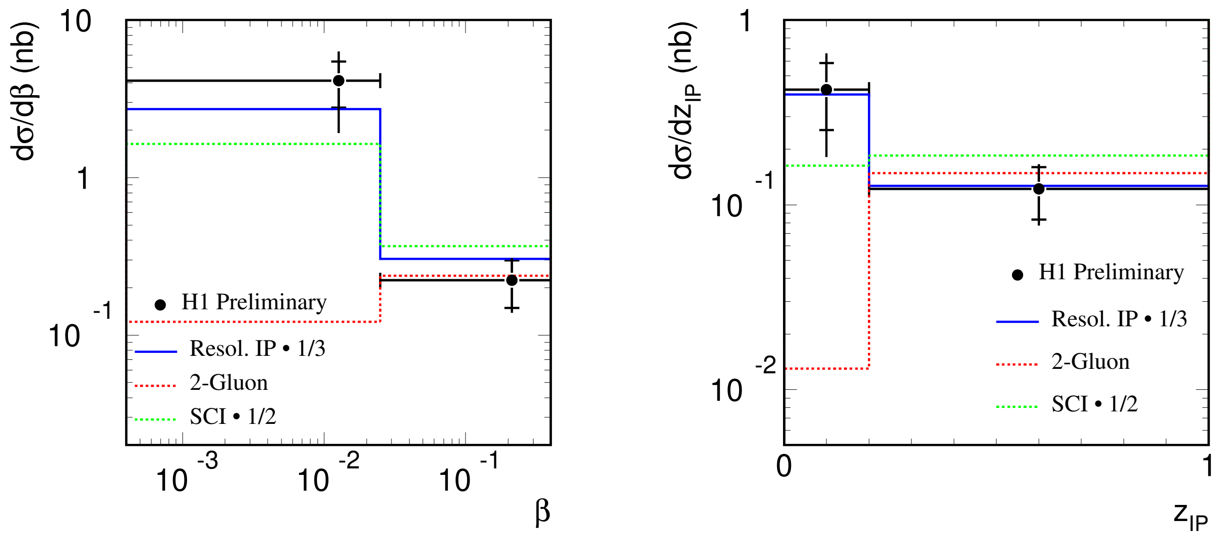
$\Rightarrow$ Discrepancy between the results (not understood)

D^* differential cross sections

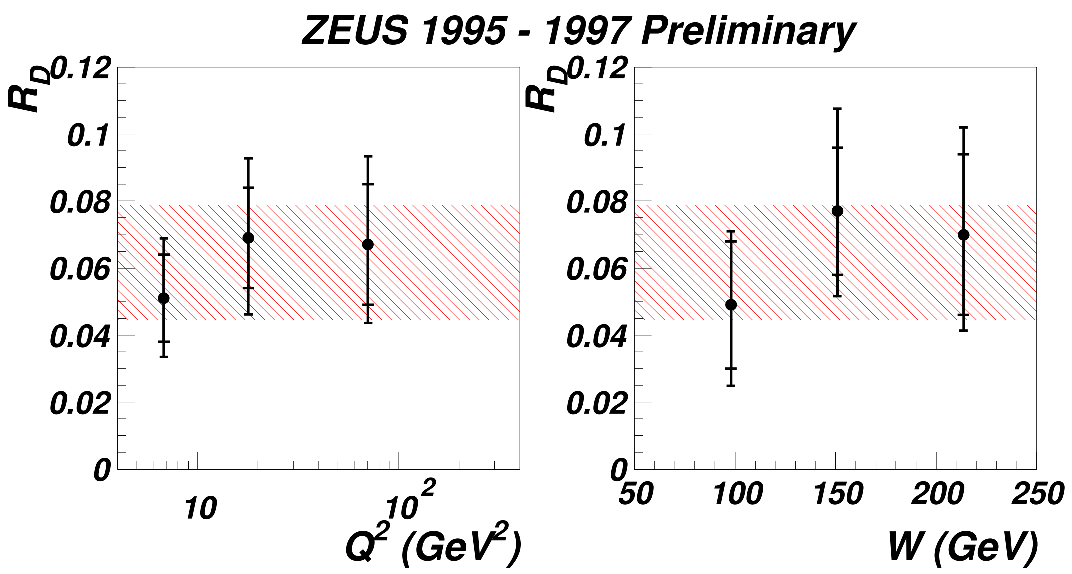


★ **Fair description except β distribution**

D^* differential cross sections

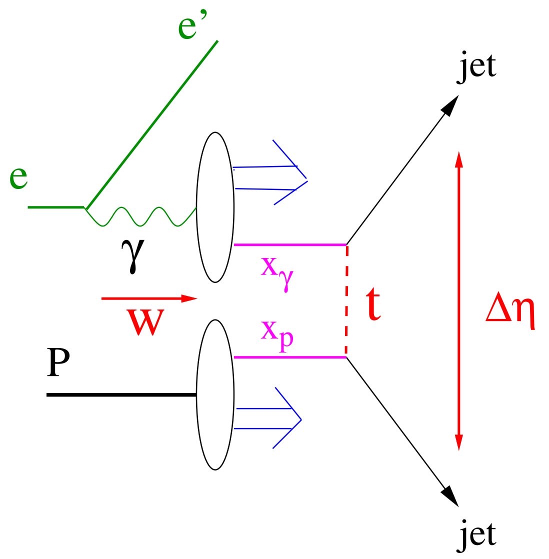


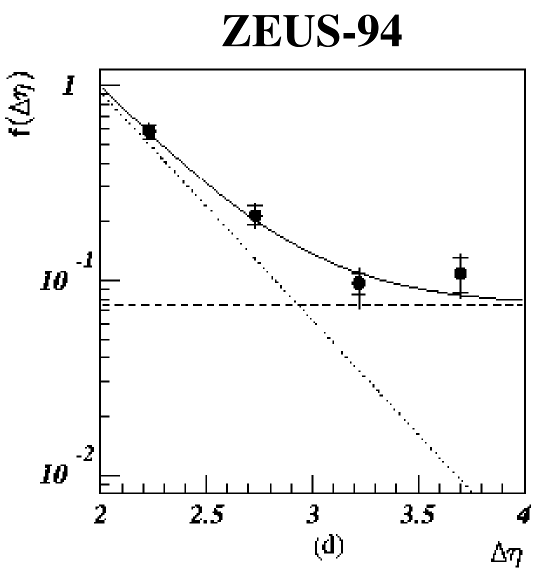
⇒ **H1: Resolved $I\!P$ model describes shapes, but not normalization**



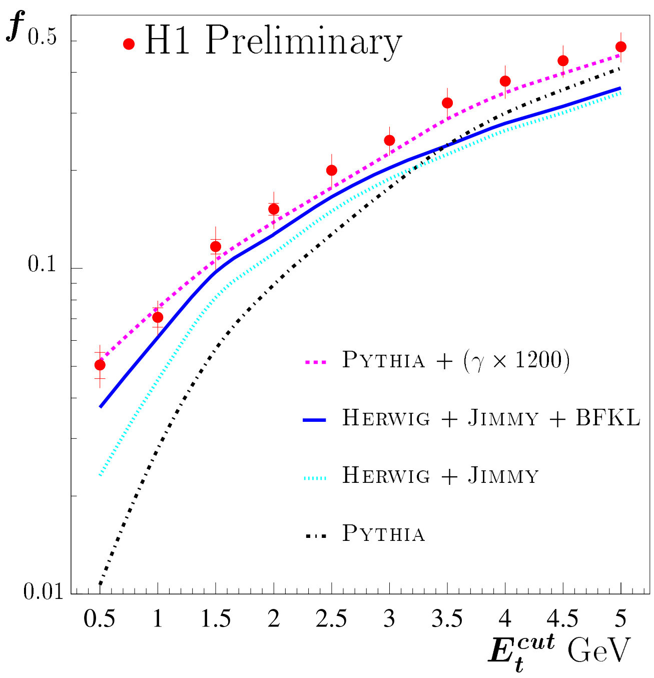
⇒ **Ratio $R_D = \frac{\sigma_{diff}(D^*)}{\sigma_{tot}(D^*)}$ is independent on Q^2 and W**

Isolating Hard Pomeron





$\gamma p \rightarrow$ Jet-gap-Jet



$\Rightarrow$ Jets found by inclusive k_t algorithm

$p_t^{j1} > 6$ GeV, $p_t^{j2} > 5$ GeV $\rightarrow$

$|t| > 30$ GeV^2

$(\Delta\eta > 2.5)$

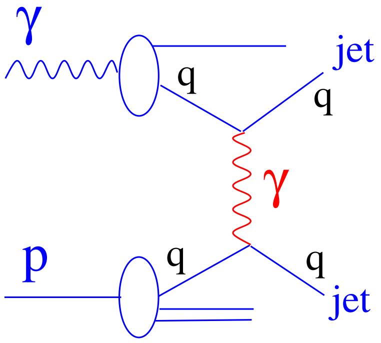
Gap fraction $f = \frac{N_{gap}}{N_{incl}}$

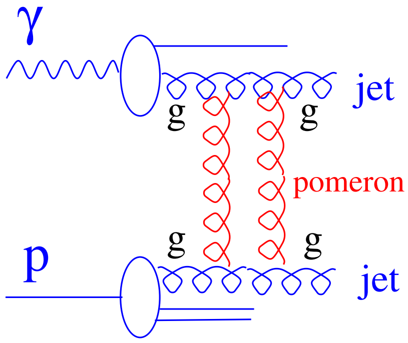
(N_{gap} = # events with $E_t^{gap} < E_t^{cut}$)

$\Rightarrow$ Large excess over standard γp Monte Carlo models

$\Rightarrow$ Color singlet object coupled to q or to g describe the trend

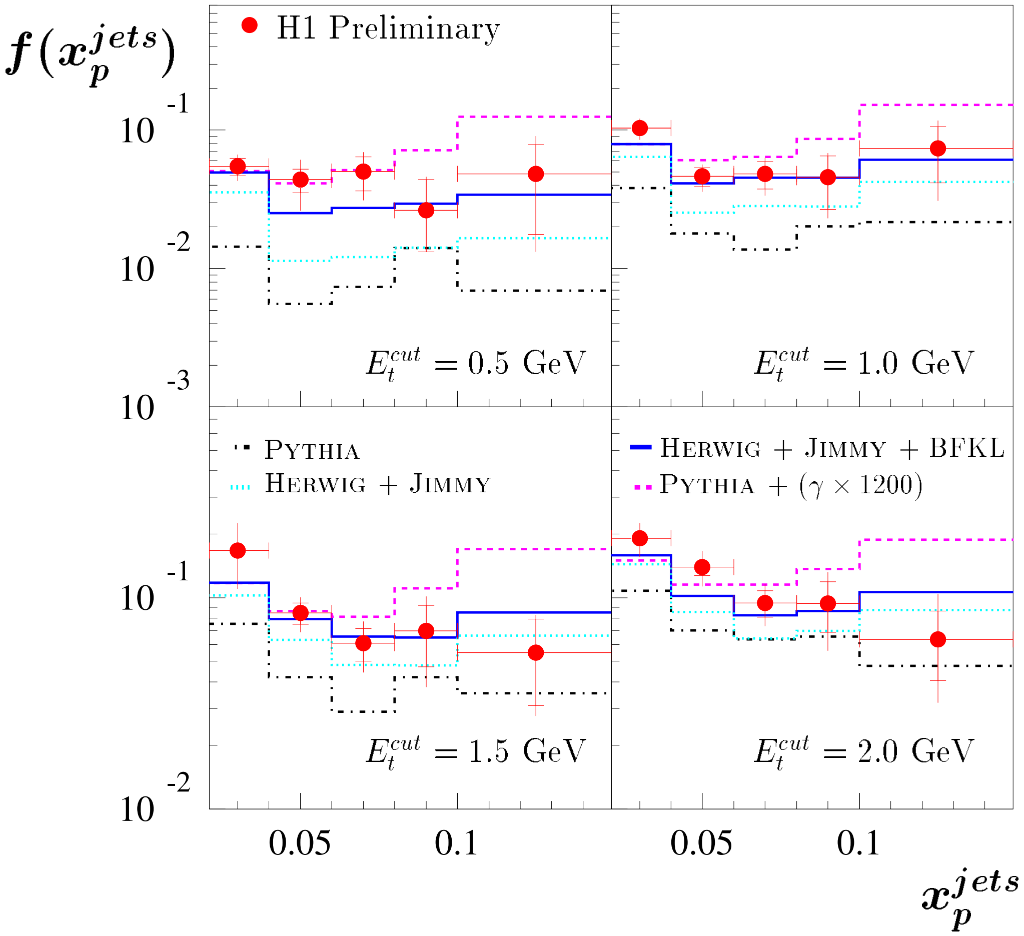
Gap fraction differential in x_p





PYTHIA 5.7 + high-t γ exchange ($\times 1200$)

HERWIG 5.9 + JIMMY(mia) + BFKL $I\!P$ ($\alpha_s = 0.17$)



$\Rightarrow$ Sensitive to underlying dynamics

Summary

- A relation between F_2^p at low x and Deeply Virtual Compton Scattering amplitude (or VM electroproduction) suggests the Pomeron is a gluonic ladder in DIS. For the first time HERA allows the partonic content of the Pomeron to be probed and thus to shed new light on the nature of diffractive phenomena

- Both inclusive measurements and the properties of the hadronic final states require a high gluonic content of the Pomeron, $\sim 70\% - 90\%$ (at scales $4 < Q^2 < 75$ GeV^2)

- An intercept of the Pomeron in a presence of hard scale, $\alpha_{I\!P}(0) \sim 1.2$, is found to be larger than that of the 'soft' $\alpha_{I\!P}(0) \sim 1.1$, known from hadron-hadron scattering. A slope of the Pomeron trajectory $\alpha'_{I\!P} \simeq 0.1$ in elastic J/ψ photoproduction found to be smaller than $\alpha'_{I\!P} \simeq 0.25$ as established in soft hadron collisions

- The observed scale dependence of the intercept value $\alpha_{I\!P}(0)$ implies, in Regge framework, either two Pomerons, or large unitarity corrections in soft processes already at present energies

- Within the present accuracy of diffractive measurements, Resolved Pomeron aproach provides most consistent description of HERA data

- In the proton rest frame picture (colour dipole models) $q\bar{q}g$ contribution from the $|\gamma>$ Fock states is significant at HERA

Outlook

- **Presently released results on diffraction at HERA correspond to $2 \div 35$ pb^{-1}. Until the shutdown, in total of about 100 pb^{-1} per experiment will be available**

- **Luminosity Upgrades at the Tevatron and HERA (by 2001) will bring yet a lot more data, allowing for precision measurements of hard diffraction**

- **Heavy nuclei option at HERA (for 2006) would allow to extend QCD studies in DIS in the environment of strong color field. To make this possible an active support from HEP community is necessary**

- **QCD at LHC ($\geq$ 2006) – New insights into the hadronic sector of the Standard Model**

An ultimate goal: To formulate an effective field theory for high energy particle scattering, bridging pQCD and RFT
