ISMD 2000 Tihany, Hungary, October 9-15, 2000
Session: Diffractive Production and Small-x

Pomeron under the HERA microscope

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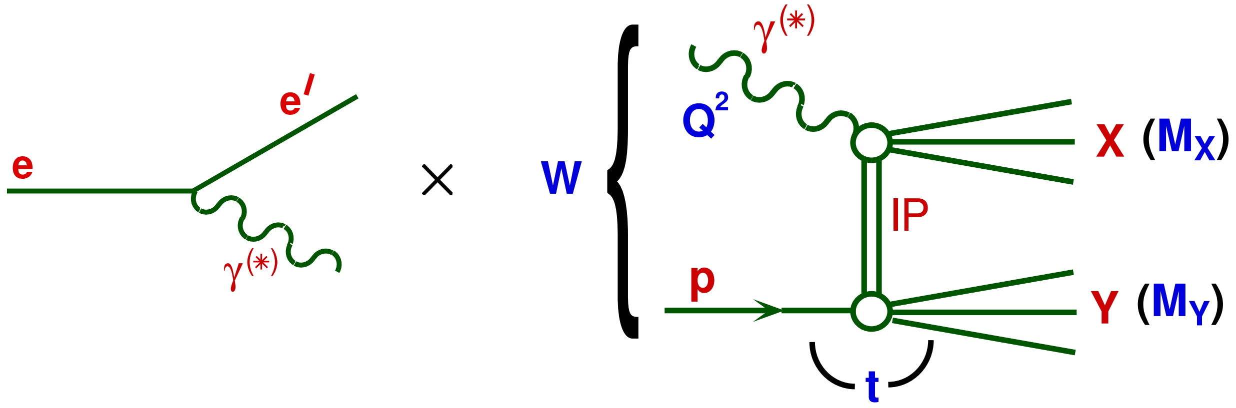
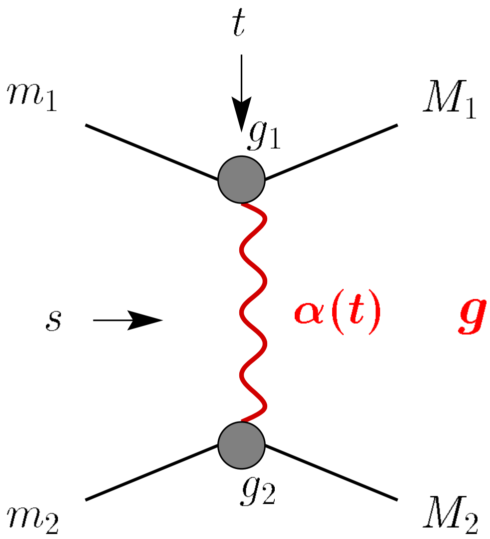
DESY, Hamburg and LPI, Moscow



- Diffraction at HERA
- Inclusive cross sections: $\sigma_{tot}^{\gamma p}$, F_2^D
- Final state properties: jets, E-flow
- Exclusive diffraction: VM, DVCS

Two approaches to Strong Interactions

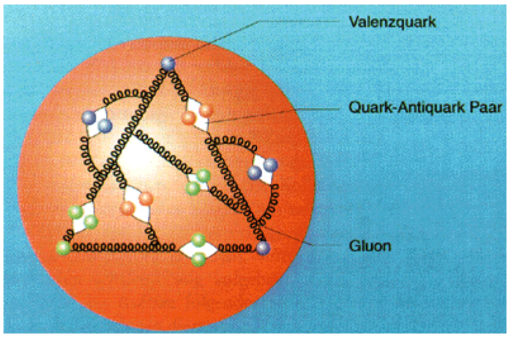
1. Regge Pole Model ⇒ RFT



$$A(s,t) = g_1(m_1, M_1, t)\, g_2(m_2, M_2, t) \frac{s^{\alpha(t)} \pm (-s)^{\alpha(t)}}{\sin(\pi\alpha(t))}$$

hadronic language

2. Quark-Parton Model ⇒ QCD



$$\sigma_{ab} = \int f_{i/a}(x_i, \mu^2) \cdot f_{j/b}(x_j, \mu^2) \cdot \hat{\sigma}_{ij}(x_i, x_j, \mu^2)$$

sub-hadronic language

RFT: soft hh scattering vs QCD: deep inelastic ep scattering

RFT: soft hh scattering

- Hadronic degrees of freedom
- Validity: large $s \gg t$
- $I\!P$ dominates: $\alpha_{I\!P}(0) > \alpha_{I\!R}(0)$
  $\rightarrow \sigma_{\rm tot} \; \propto \; s^{\alpha_{I\!P}(0)-1}$
- Unitarity corrections unavoidable
  $(\sigma_{\rm tot} \leq \ln^2(s/s_0)$ at $s \rightarrow \infty)$
- When? $s_{sat} = ?$
- First to be seen in diffraction:
  $\sigma_{diff} \; \propto \; s^{2(\alpha-1)}$

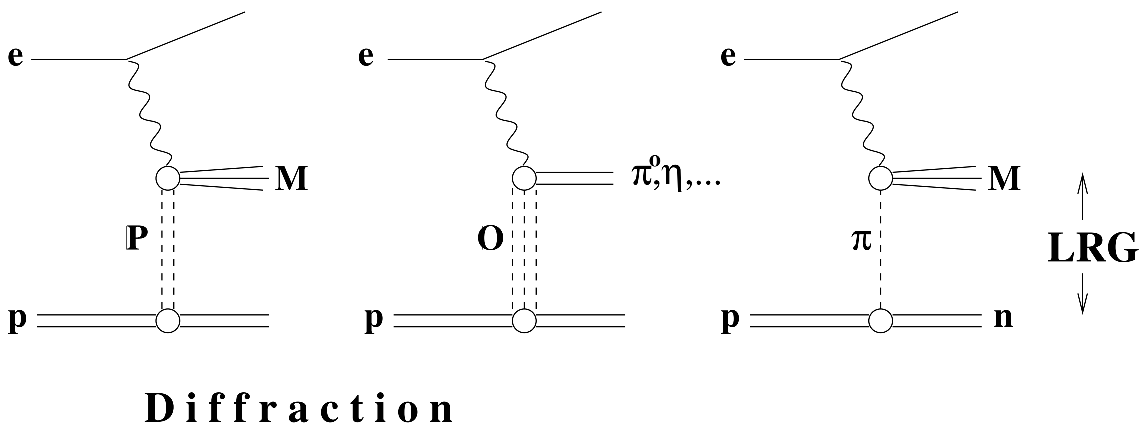
$\Rightarrow$ Diffraction $\equiv$ Physics of the $I\!P$
– the essence of strong inter.

QCD: deep inelastic ep scattering

- Partonic degrees of freedom
- Low x: $W^2 \gg Q^2, t \; (Q^2/W^2 \simeq x \ll 1)$
- gluons dominate: $xg(x) \gg xq_{val}(x)$
  $F_2(x,Q^2) \; \propto \; xg(x) \; \sim \; x^{-\lambda}$
- Saturation of the $xg(x)$
- $x_{sat} = ?$
- First to be seen in diffraction:
  $\sigma_{diff} \; \propto \; |xg(x)|^2$

$\Rightarrow$ Diffraction $\equiv$ Gluodynamics
– the essence of QCD

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

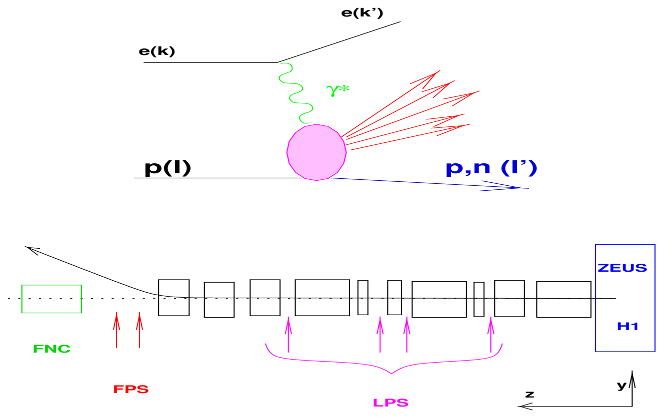
- asymmetric beam configuration (27.5 $\times$ 820(920) GeV)
  $\rightarrow$ excellent acceptance for γ^* diffractive dissociation system

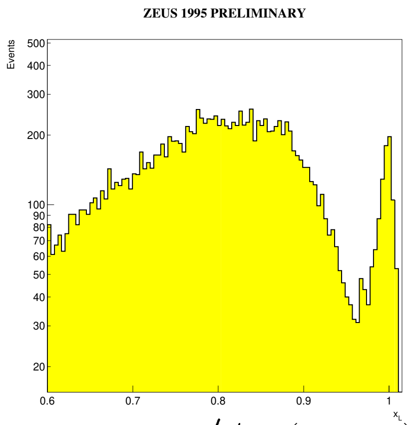
- clean channels for Odderon search $\rightarrow$
  no $I\!P$ “background” in the reactions $\gamma p \rightarrow (\pi^0, \eta, \eta', ...)p'$

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

Selecting Diffractive Events

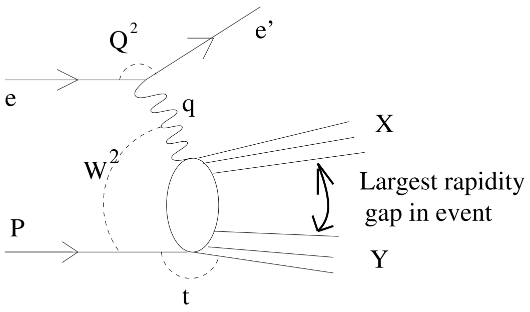
- Tagging leading protons by Roman Pots (H1-FPS, ZEUS-LPS)

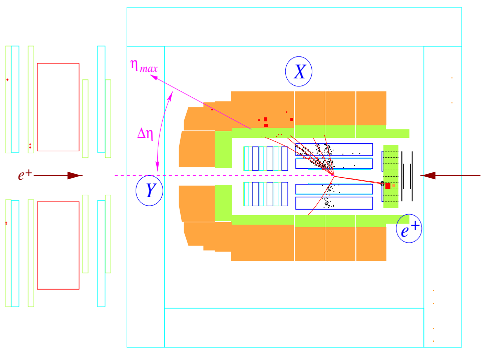




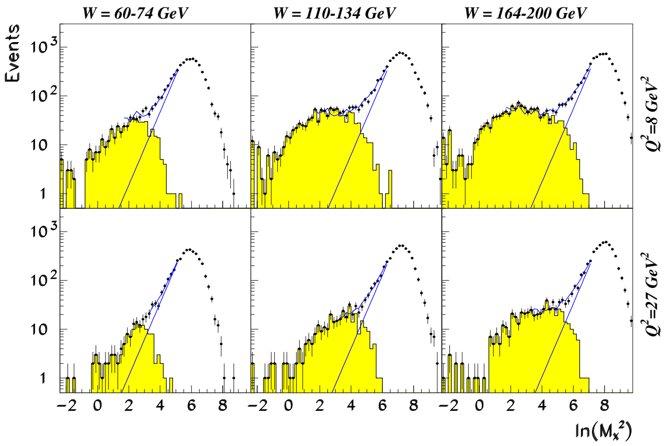
$x_L = p'/p \quad (> 0.97)$

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



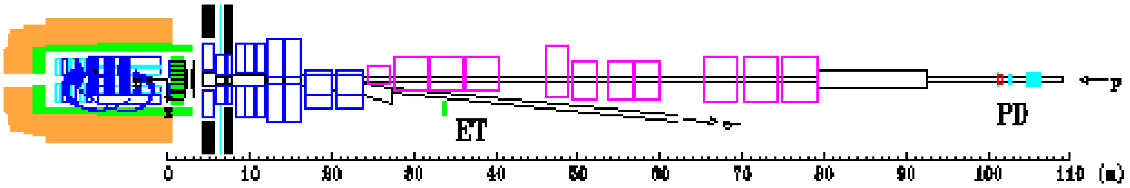


- Analysing mass distribution of the hadronic final state (ZEUS)



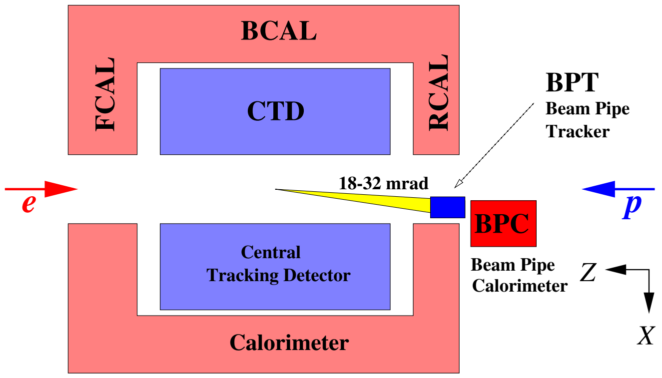
Data Samples 94-97 (ZEUS, H1)

- Photoproduction ($Q^2 < 0.02$ GeV^2): $\mathcal{L}$ =50 nb^{-1}



- Low Q^2:

$\mathcal{L}$ = 7.1 pb^{-1} 0.12 pb^{-1}
Q^2 = 0.2÷0.7 GeV^2 0.4 ÷ 5 GeV^2



Shifted vertex collisions

(Similar H1 VLQ detector was installed only during 1998-2000 data taking)

- Medium Q^2:

$\mathcal{L}$ = 2.6 pb^{-1} 2.0 pb^{-1}
Q^2 = 7÷ 140 GeV^2 4.5 ÷ 75 GeV^2

- High Q^2:

$\mathcal{L}$ = 31.7 pb^{-1}
Q^2 = 200 ÷ 800 GeV^2

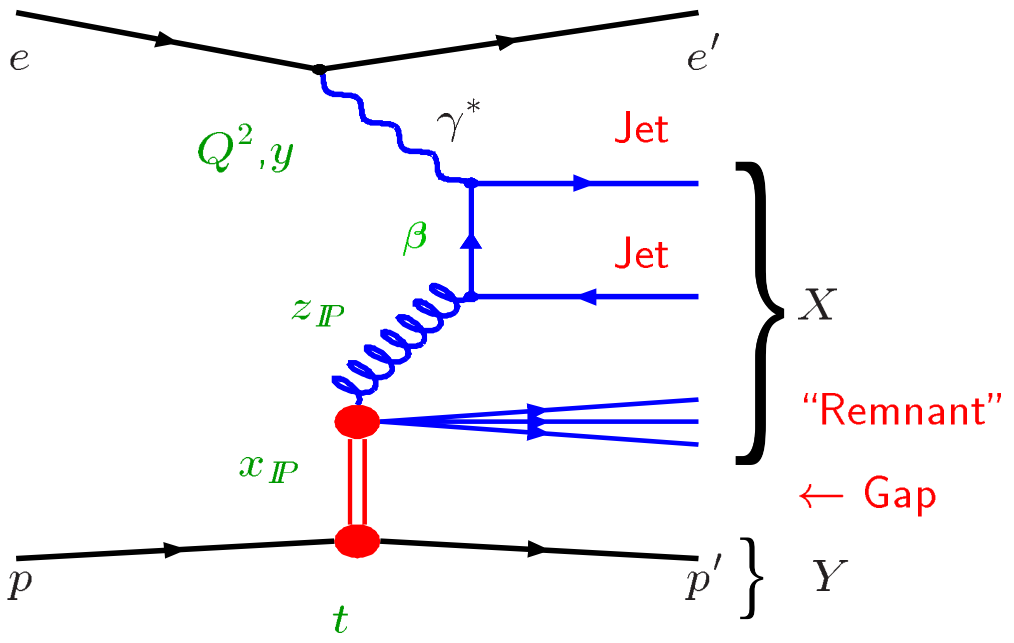
Typical precision (in the bulk region): $\boxed{10 \div 20\%}$

Models of diffractive DIS

Three approaches to describe diffractive processes in DIS:

- Regge motivated models with factorizable Pomeron
- Colour dipole and 2-gluon exchange models
- Non-pomeron mechanisms, generating large rapidity gap events

- **Resolved Pomeron** **(e.g. Ingelmann, Schlein)**



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

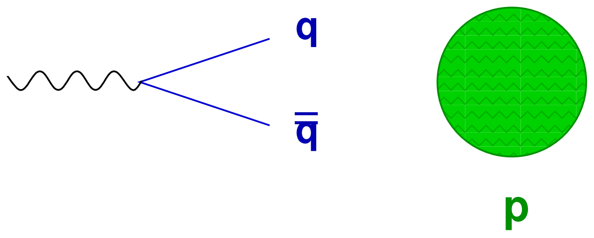
with (assuming factorization)

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

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

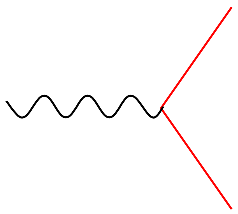


$\Rightarrow$ factorizes into $\Psi_{q\bar{q}} \times \sigma_{(q\bar{q})p}$

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

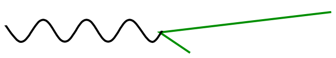
(diffraction is then modelled as colour singlet exchange between the dipole and p, e.g. $2g$)

Hard interactions:



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

Soft interactions:

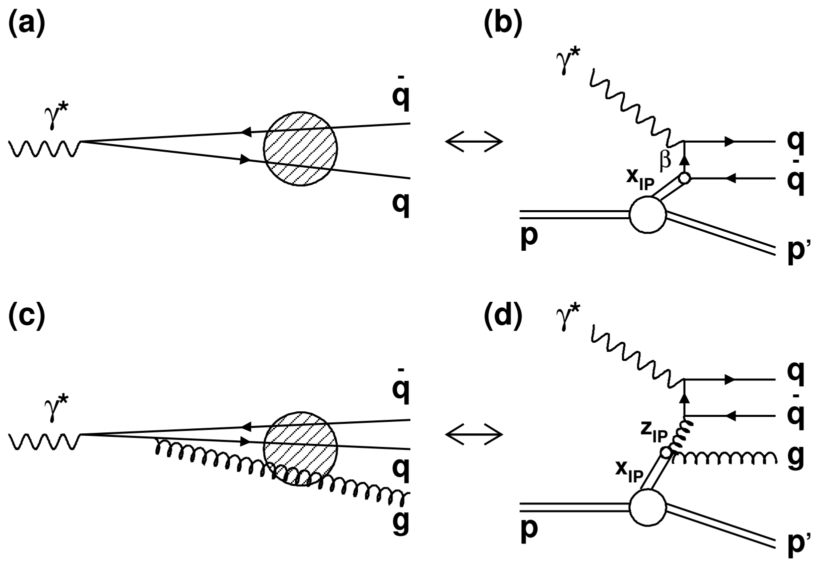


Small $k_\perp$ = large dipole size
$\rightarrow$ large cross section (σ_T)

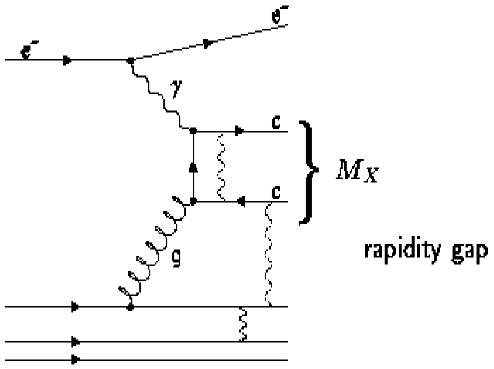
$$\sigma_{\mathrm{DIS}}(Q^2) = \Psi_{q\bar{q}}^{\mathrm{hard}}(Q^2) \cdot \sigma_L(Q^2) + \Psi_{q\bar{q}}^{\mathrm{soft}}(Q^2) \cdot \sigma_T(Q^2)$$

Models continued

Proton rest frame vs proton infinite momentum frame



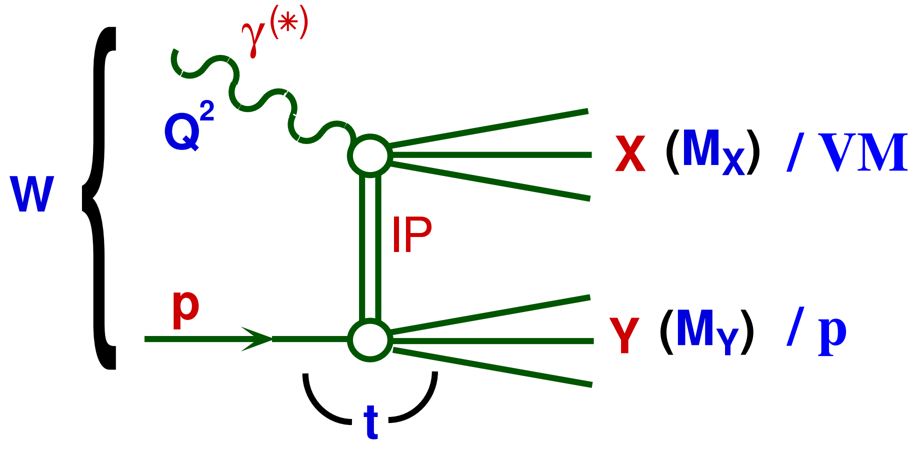
• **Soft Colour Interactions** (e.g. Ingelmann, Rastman) – Mimic non-perturbative effects



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

Knobs selecting different regimes

- Scales at photon and proton vertecies: $Q^2,\ M_V^2,\ t$

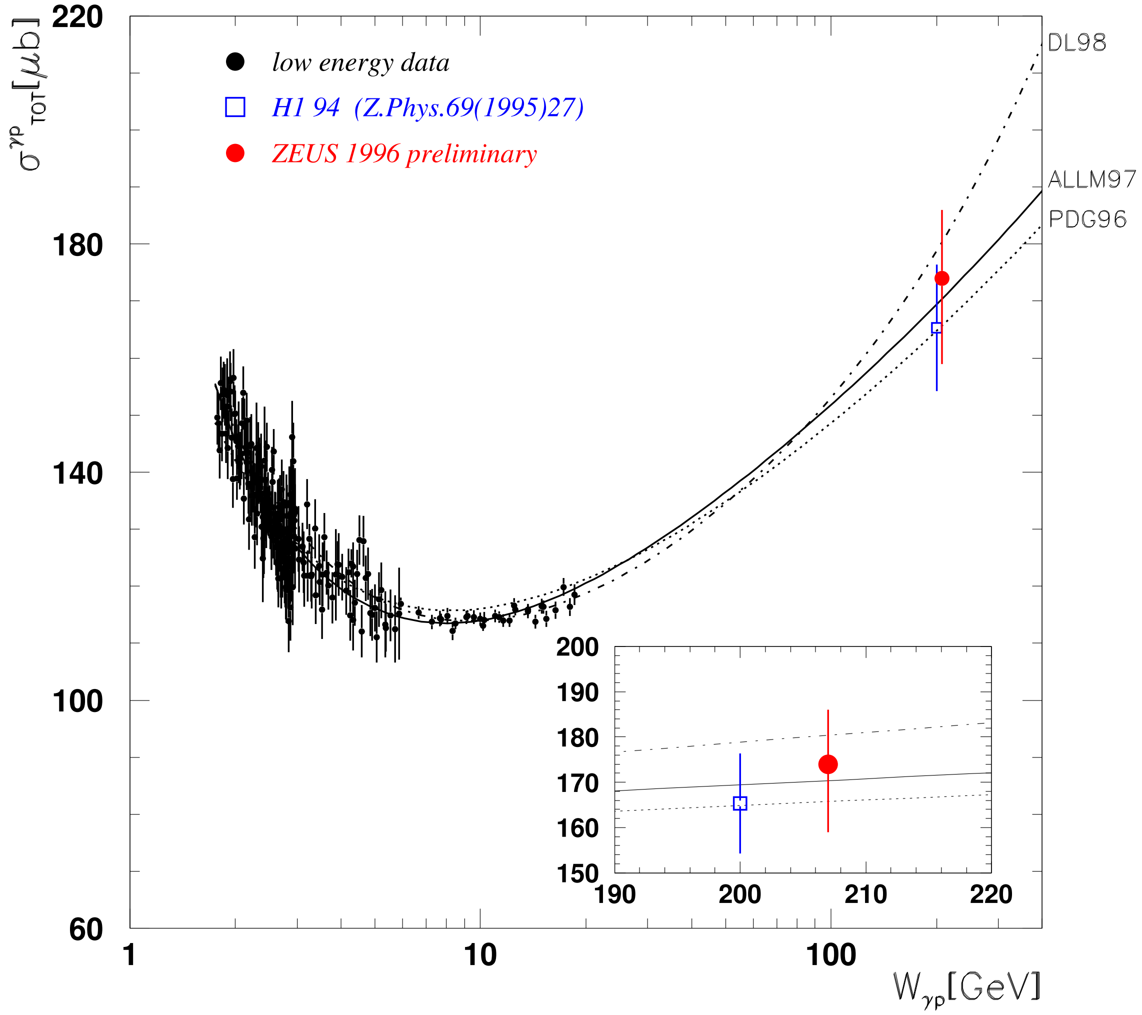


- Universal soft $I\!\!P$ and its limitations. Alternatives:
  - ▷ 2 Pomerons (DL-98)
  - ▷ Bare $I\!\!P$ + UC (CKMT)
  - ▷ ... ?

- Partonic content of the $I\!\!P$
  - ▷ Interprete F_2^D in terms of diffractive parton distributions (hard factorization: Collins, 1997 – for ep)
  - ▷ Extract pdf's of the $I\!\!P$ (Regge factorization)
  - ▷ Consistent picture? $\rightarrow$ confront with final state properties
  - ▷ Are they universal? $\rightarrow$ HERA vs Tevatron

$\sigma^{\gamma p}_{tot}$ at HERA

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

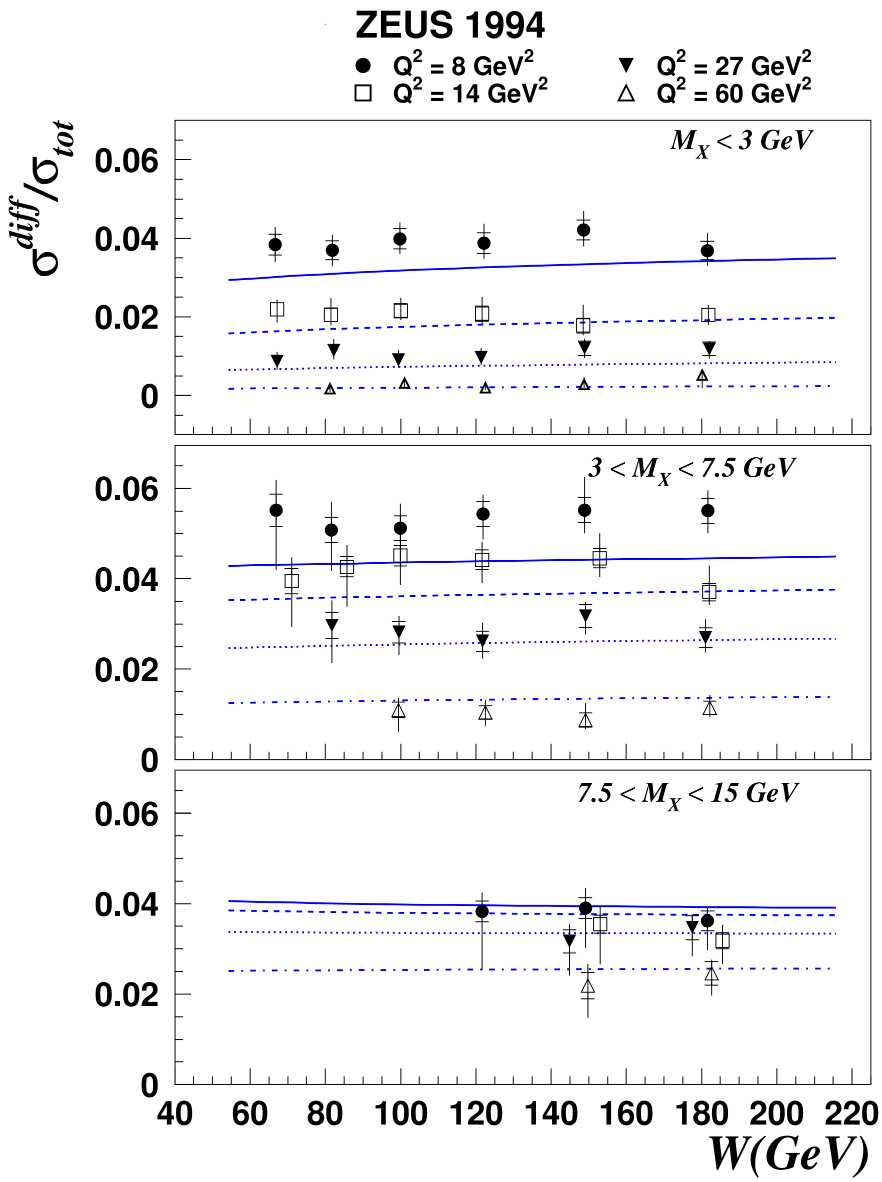


$$\mathbf{H1:} \quad \sigma^{\gamma p}_{tot}(W_{\gamma p} = 200 \text{ GeV}) = 165 \pm 2 \pm 11 \ \mu b$$

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

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

Inclusive Diffraction: Energy Dependence

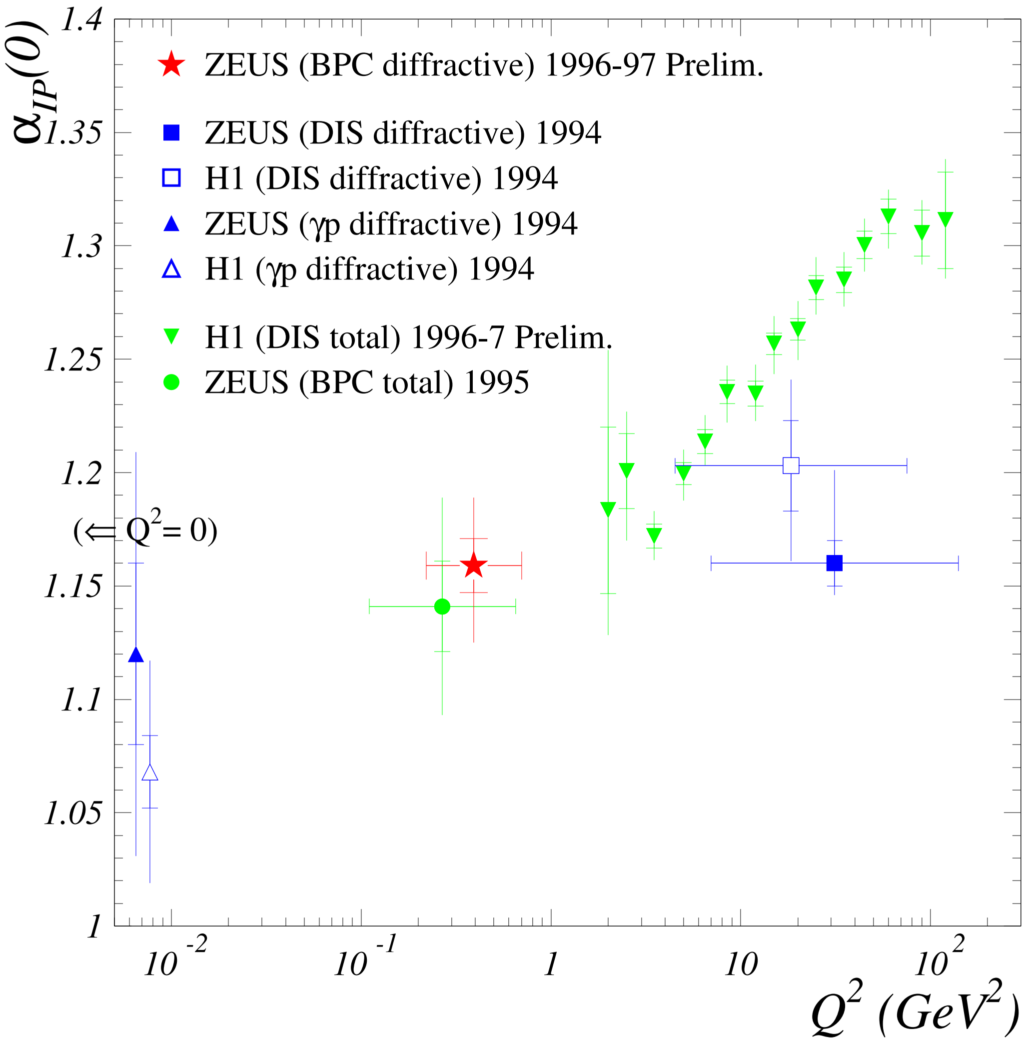


$$\frac{\sigma^{diff}}{\sigma^{tot}} \equiv \frac{\int_{M_a}^{M_b} dM_x \frac{d\sigma^{diff}}{dM_x}}{\sigma^{tot}_{\gamma^* p}}$$

- Diffraction has the same energy dependence as the total cross section
- Contradicts expectation ($xg(x)$ vs $|xg(x)|^2$)

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

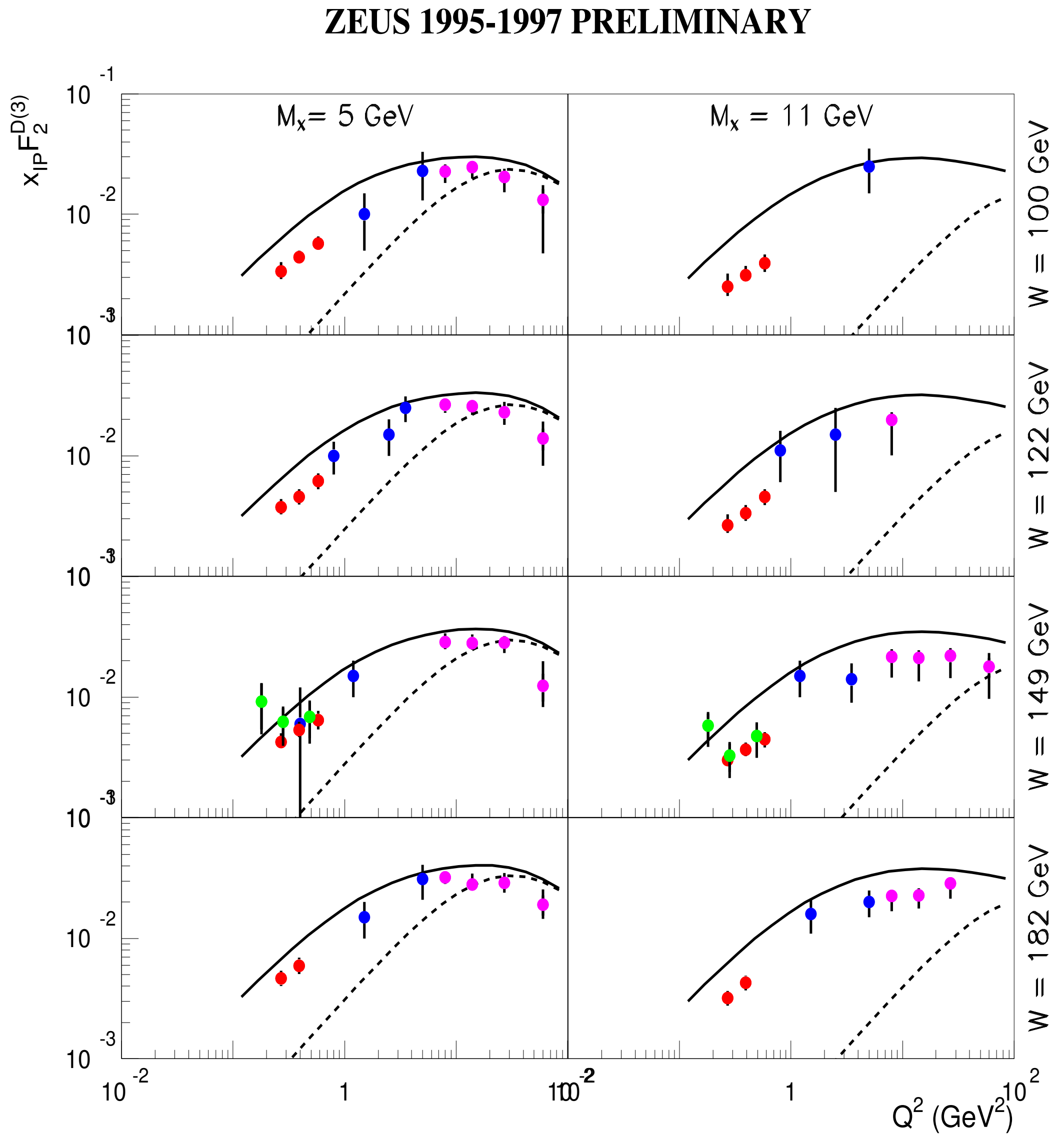
Effective Pomeron intercept $\alpha_{I\!P}(0)$, corrected for finite t:



★ Smooth transition from soft to hard regime

★ At low Q^2 diffractive and inclusive $\alpha_{I\!P}(0)$ compatible, but at higher Q^2 $\alpha_{I\!P}(0)$ becomes incompatible

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



ZEUS BPC 96-97 PRELIMINARY (Method I)

ZEUS LPS 95 PRELIMINARY (Method II)

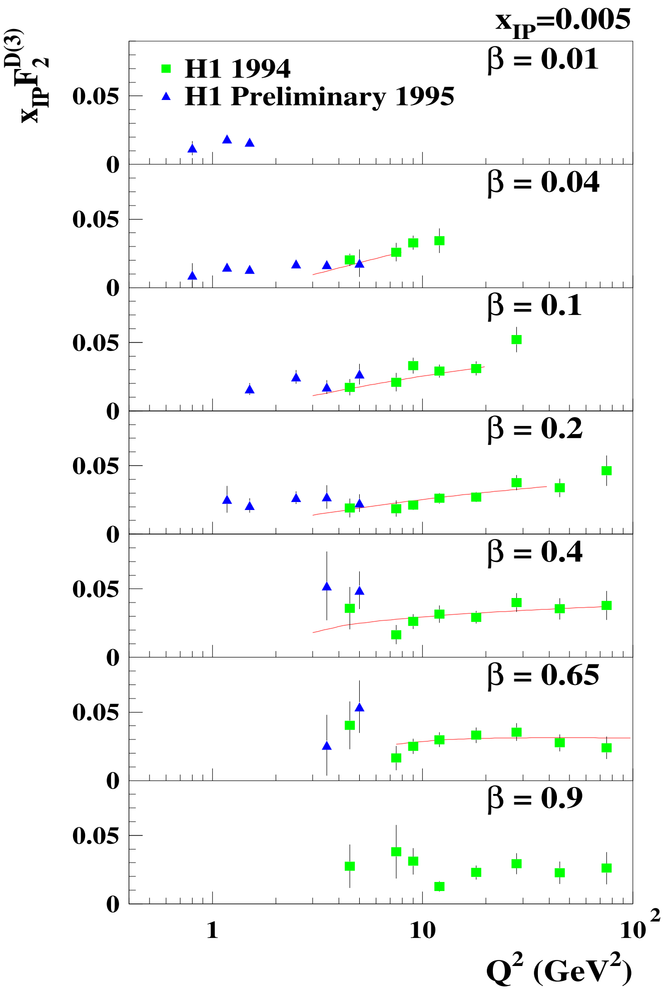
H1 shifted vertex 95 PRELIMINARY

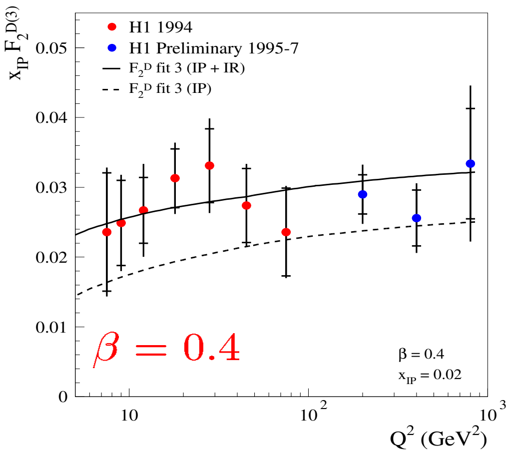
ZEUS DIS 94

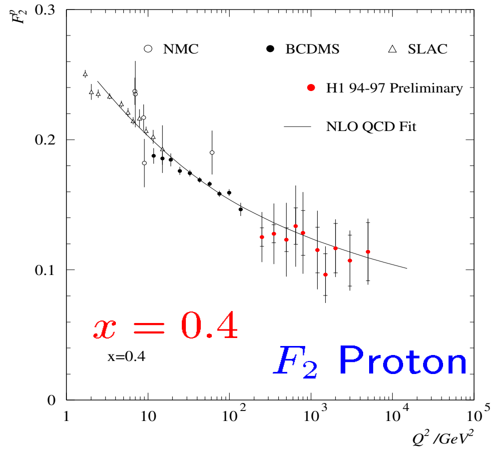
Curves by K. Golec-Biernat (private comunication)

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

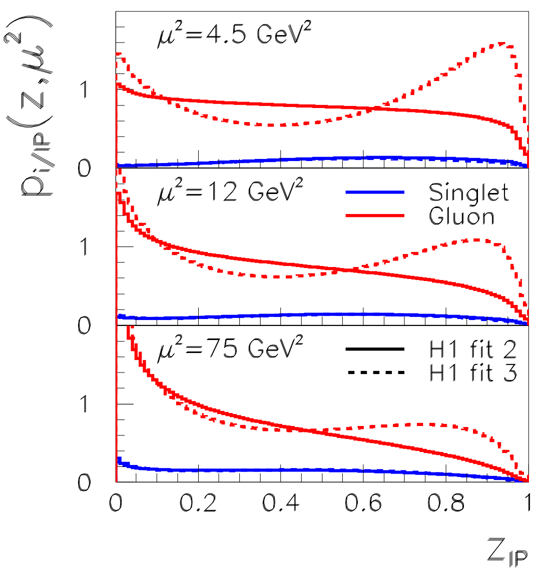
Scaling violation of F_2^D







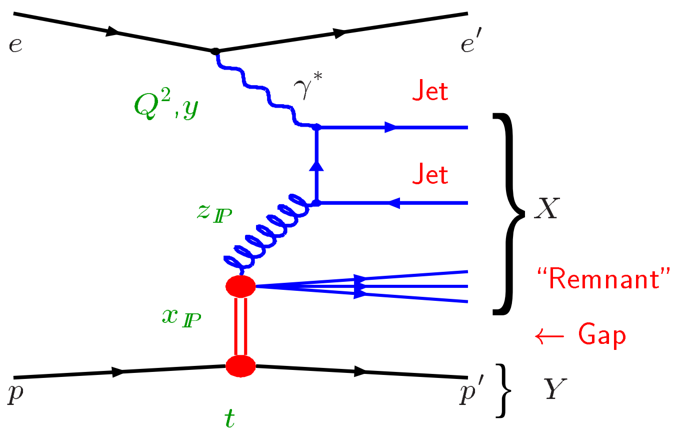
⇒ **Gluon dominated mechanism**



⇐ DGLAP QCD fit of $F_2^{D(3)}$

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

Diffractive 2- and 3-jet electroproduction



H1 96+97:

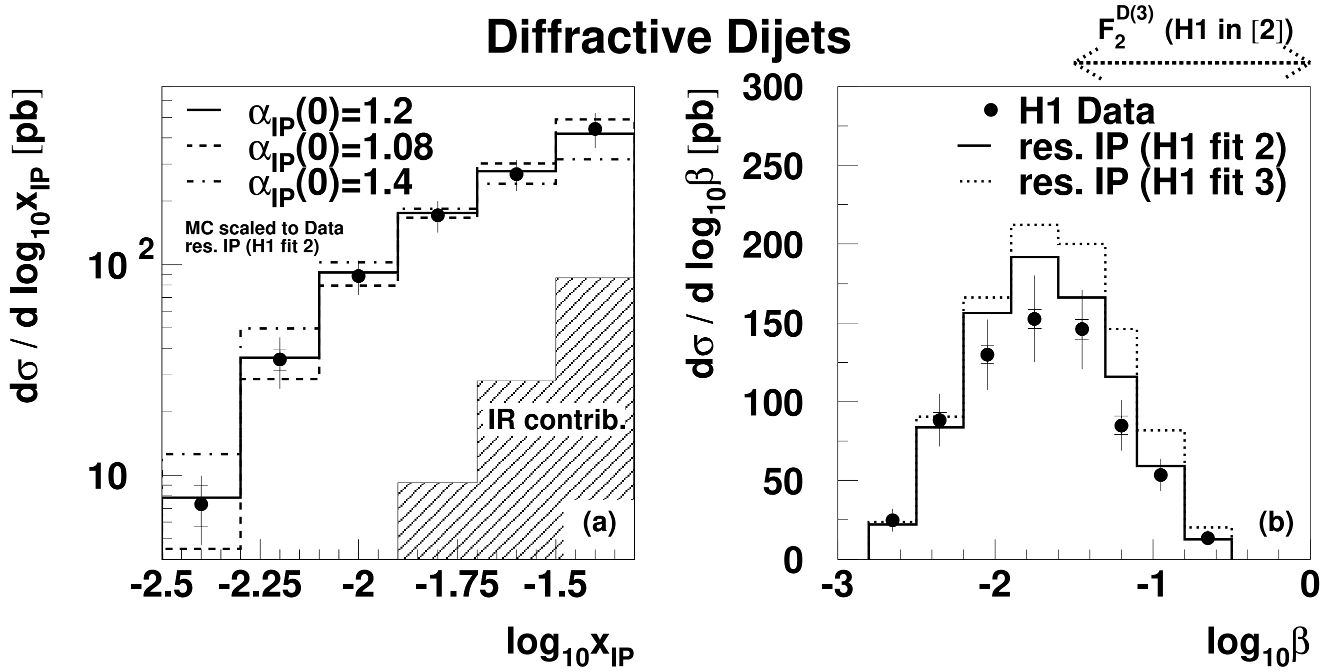
Cone jets ($R = 1$) in $\gamma^* p$ CMS

$p_t^* > 4$ GeV, $-3 < \eta_j^* < 0$

$x_{I\!P} < 0.05, \quad 4 < Q^2 < 80$ GeV^2

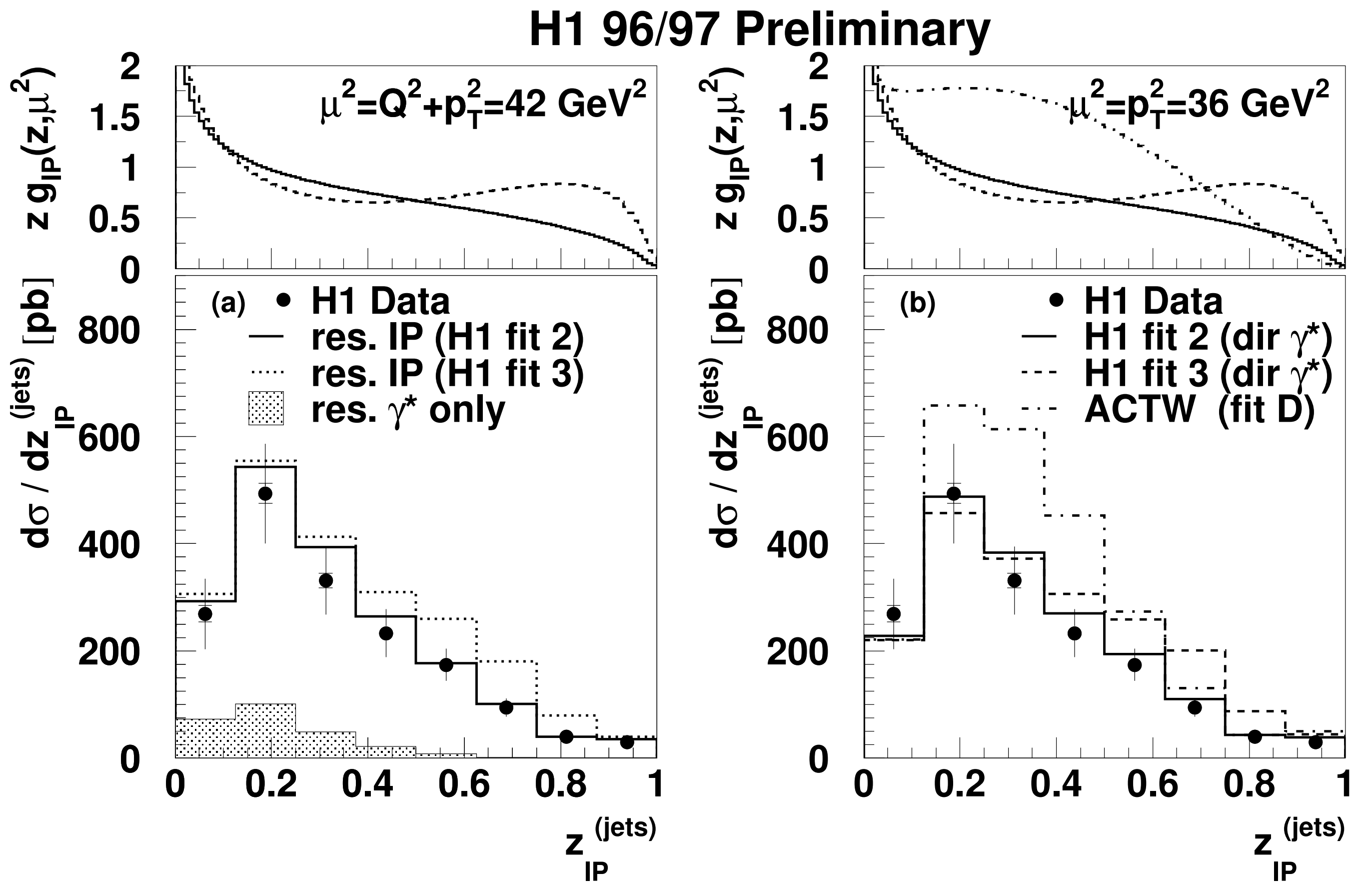
2500 2-jet and 130 3-jet events

$\Rightarrow$ direct sensitivity to the gluons in the $I\!P$



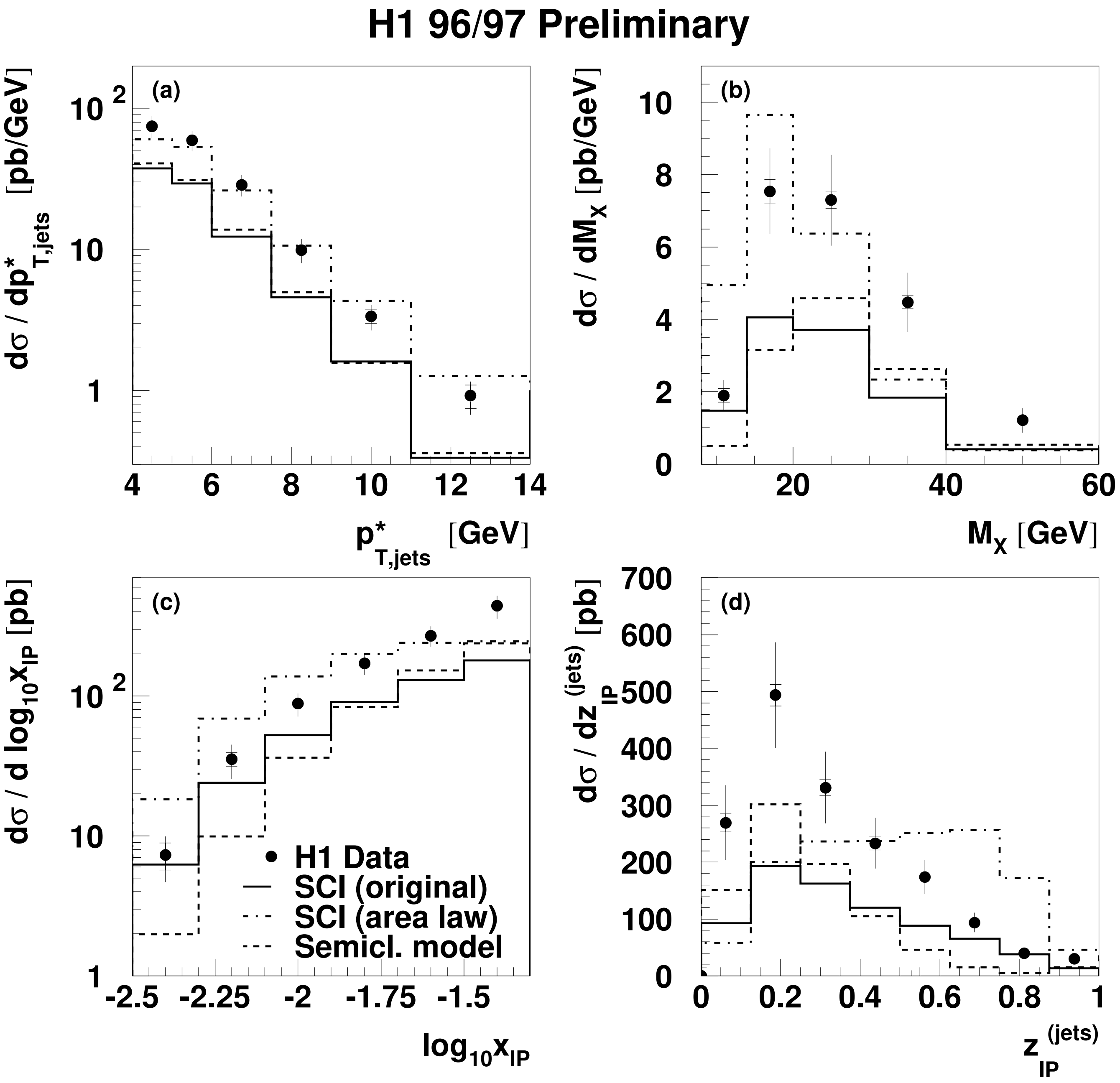
- Good description by RP model (non-trivial, different β)
- $\alpha_{I\!P}(0)$ consistent with the intercept from $F_2^{D(3)}$ analysis

Diffractive Dijets vs RP model



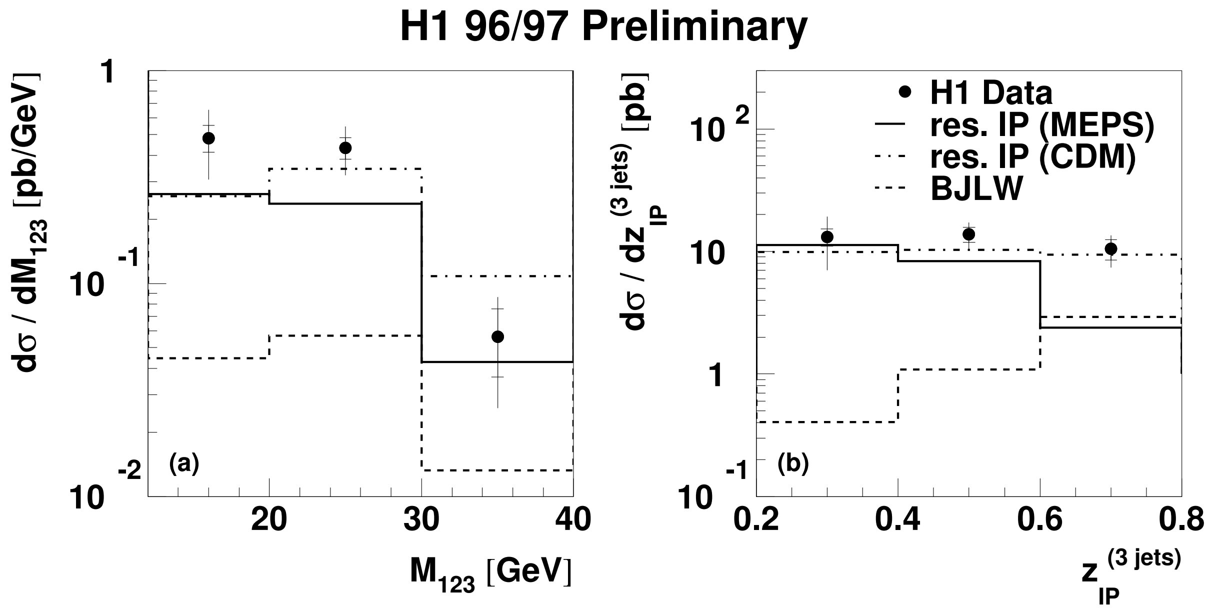
- RP model with gluon dominated Pomeron is successful
- Direct sensitivity to $g/I\!P$ – flat gluon is preferred

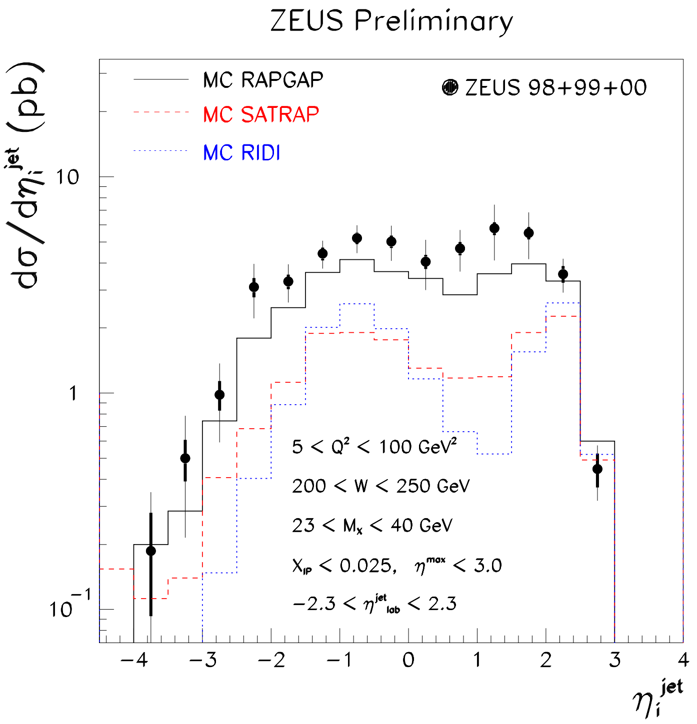
Diffractive Dijets vs SCI model



- SCI class of models fails in shape and/or normalization

Diffractive 3-jets

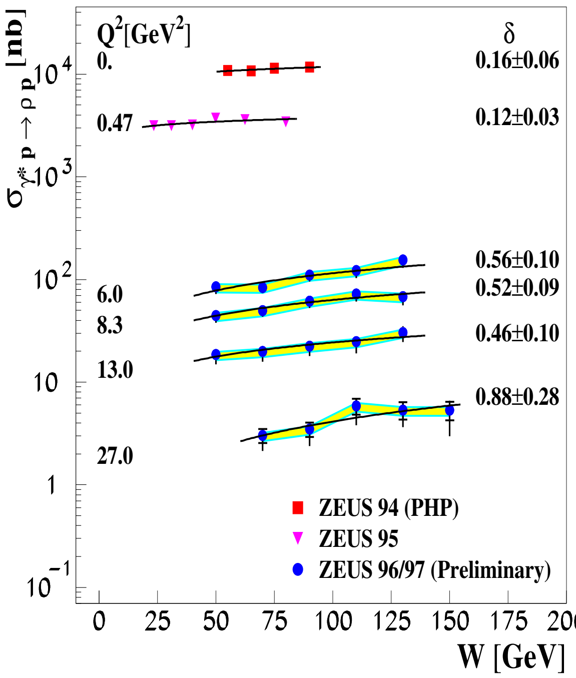




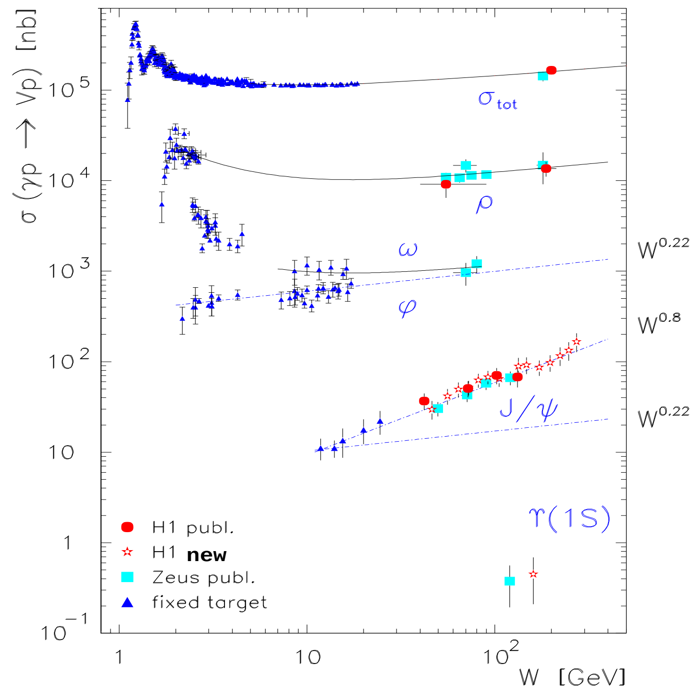
- RP model with gluon-dominated $I\!P$ gives fair description
- Saturation model and pQCD calculations fall too low

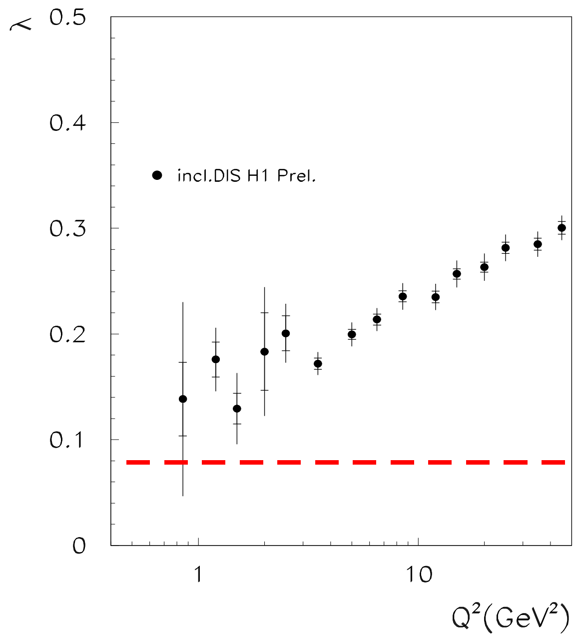
Exclusive VM: Energy Dependence

$$\sigma \propto W^{\delta(Q^2)}$$

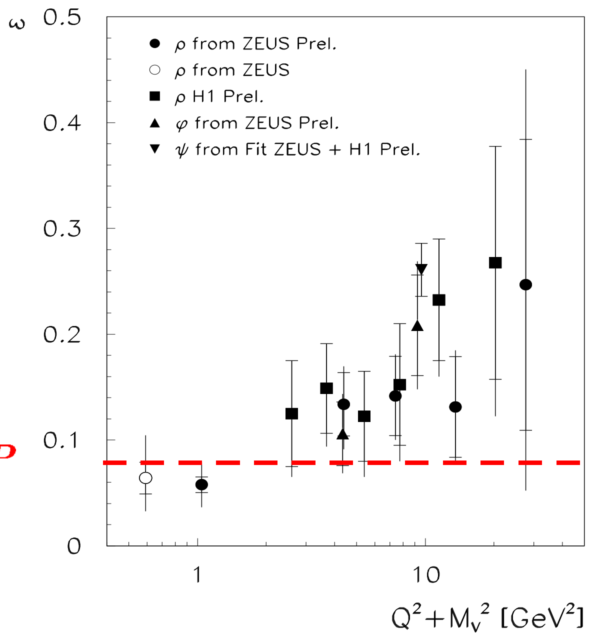


$$\sigma \propto W^{\delta(M_V^2)}$$





soft $I\!P$

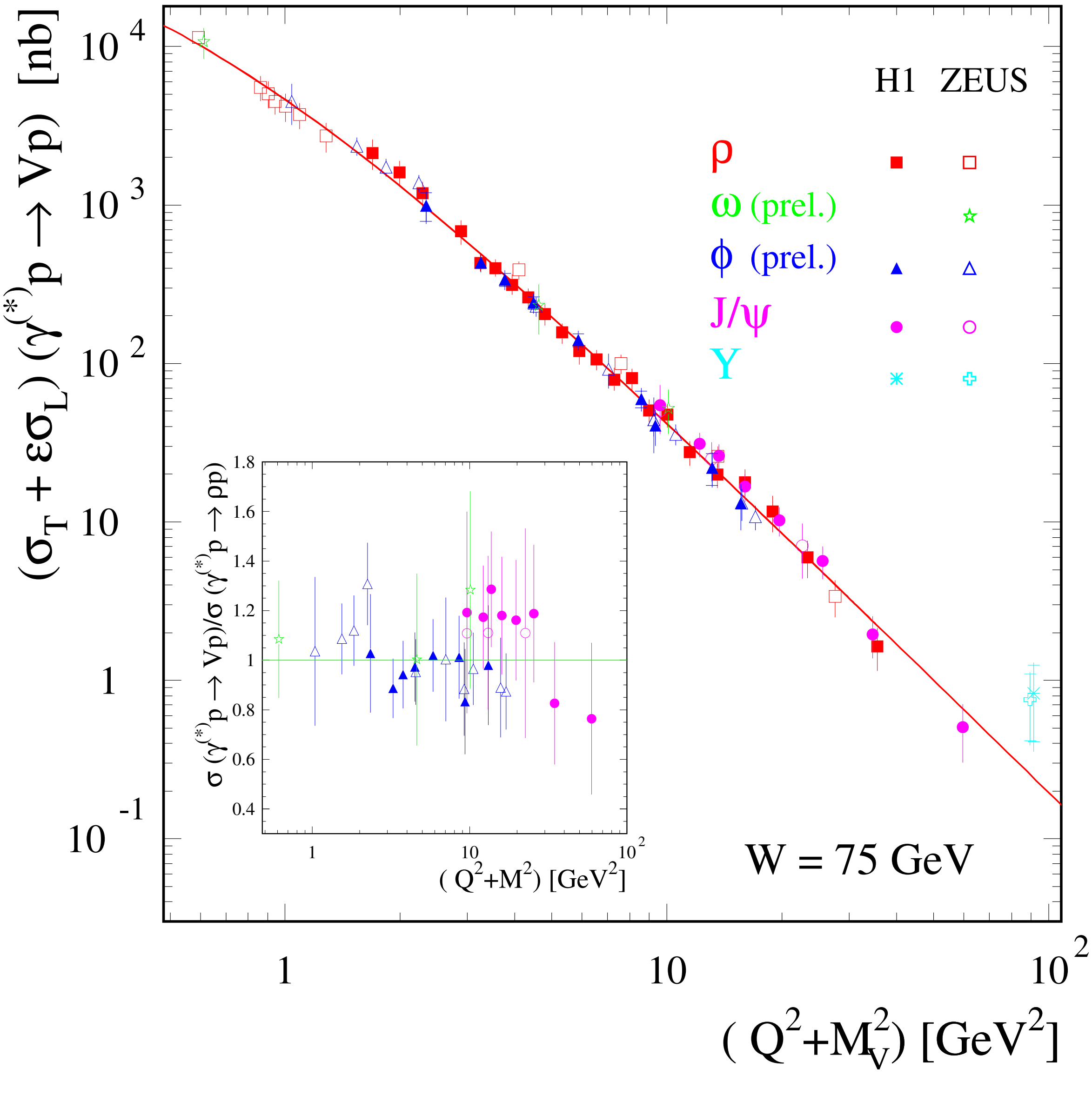


$$\sigma_{tot}^{\gamma^* p} \sim s^{\lambda} \qquad \Leftarrow \text{OT} \Rightarrow \qquad \sigma_{el}(\gamma^* p \to V p) \sim s^{2\lambda}$$

Exclusive VM: Flavour Independence

VM cross sections, scaled by SU(4) factors:

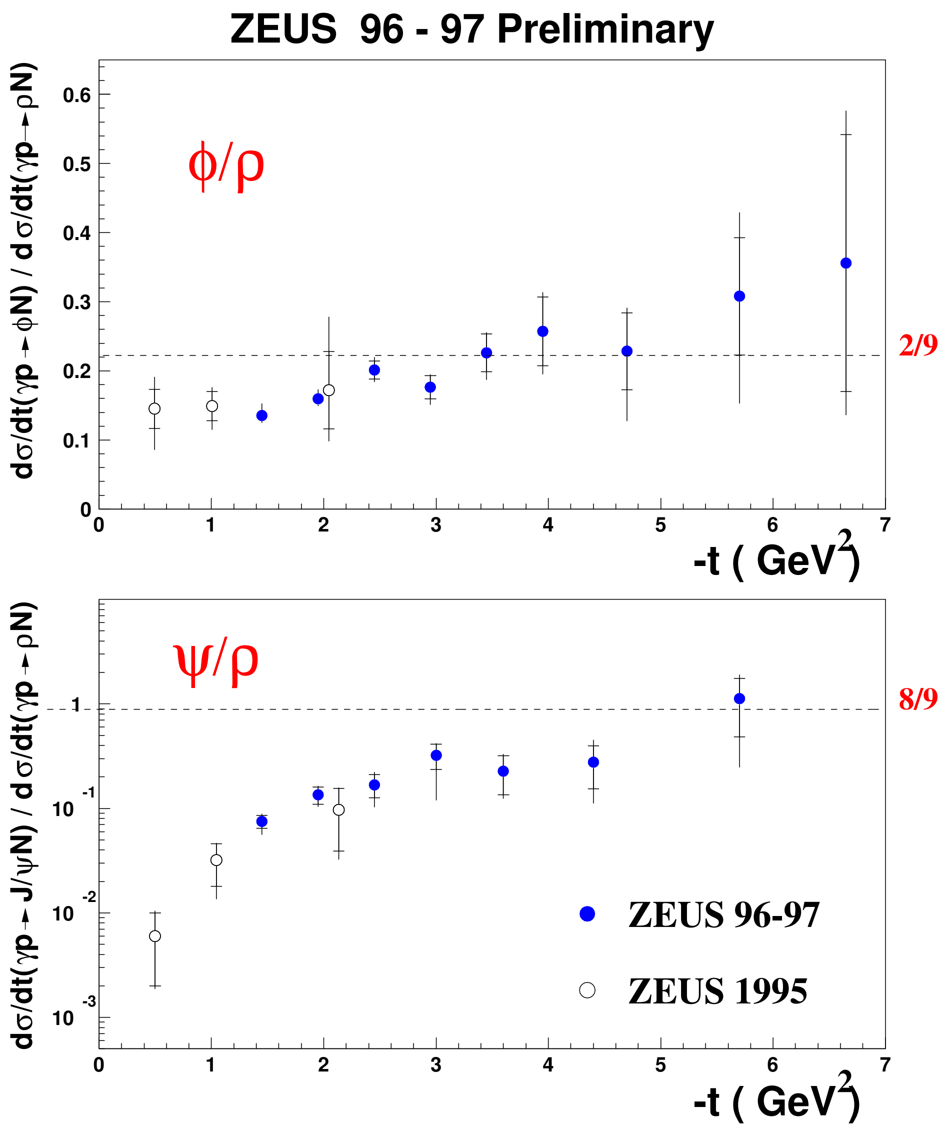
$\rho : \omega : \phi : J/\psi : \Upsilon = 9 : 1 : 2 : 8 : 2$



★ Universal behaviour as a function of $Q^2 + M_V^2$

VM: SU(4) restoration at large t

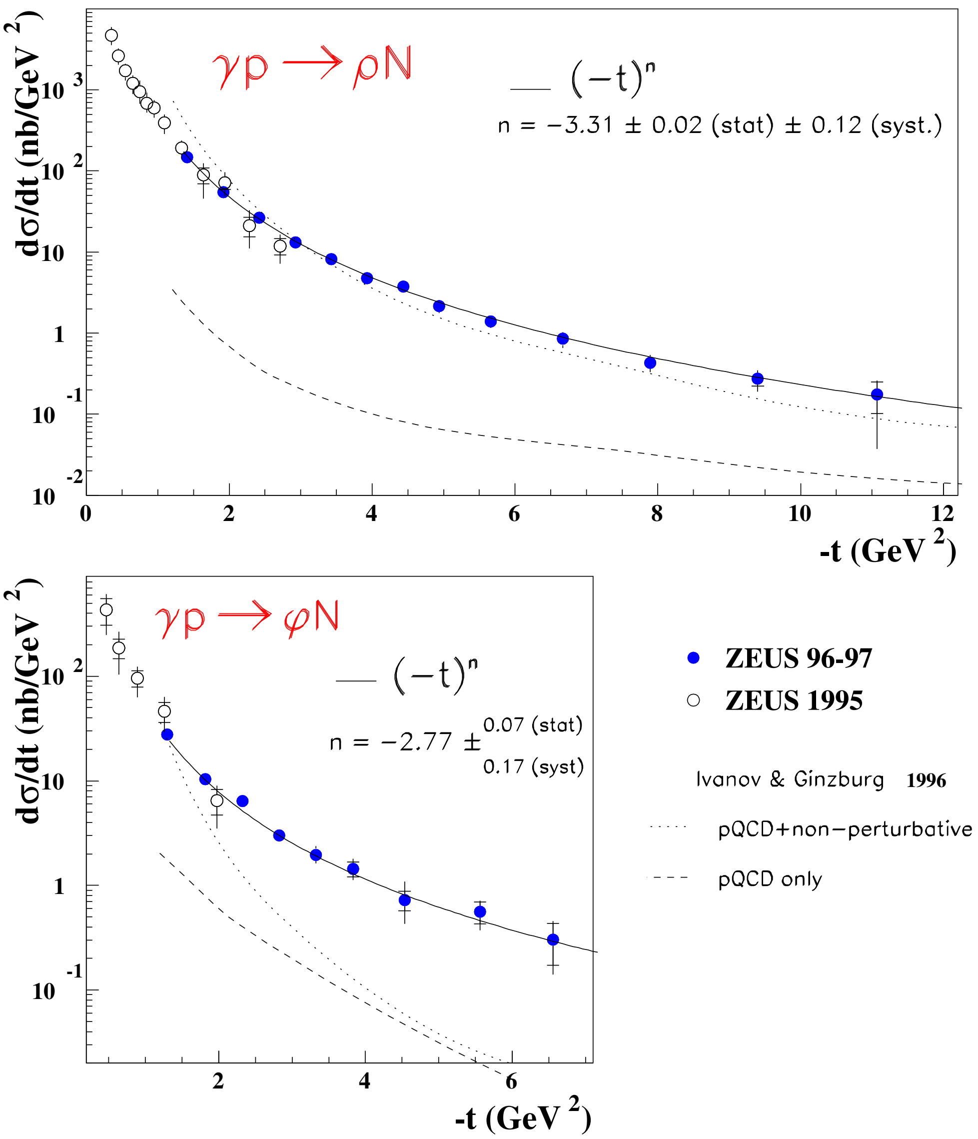
Consider hard scale at the proton vertex: t



- SU(4) symmetry gets restored at $|t| \simeq 3 \div 5$ GeV^2
  Is it sufficient for pQCD to be applicable?

Exclusive VM: $t-$dependence

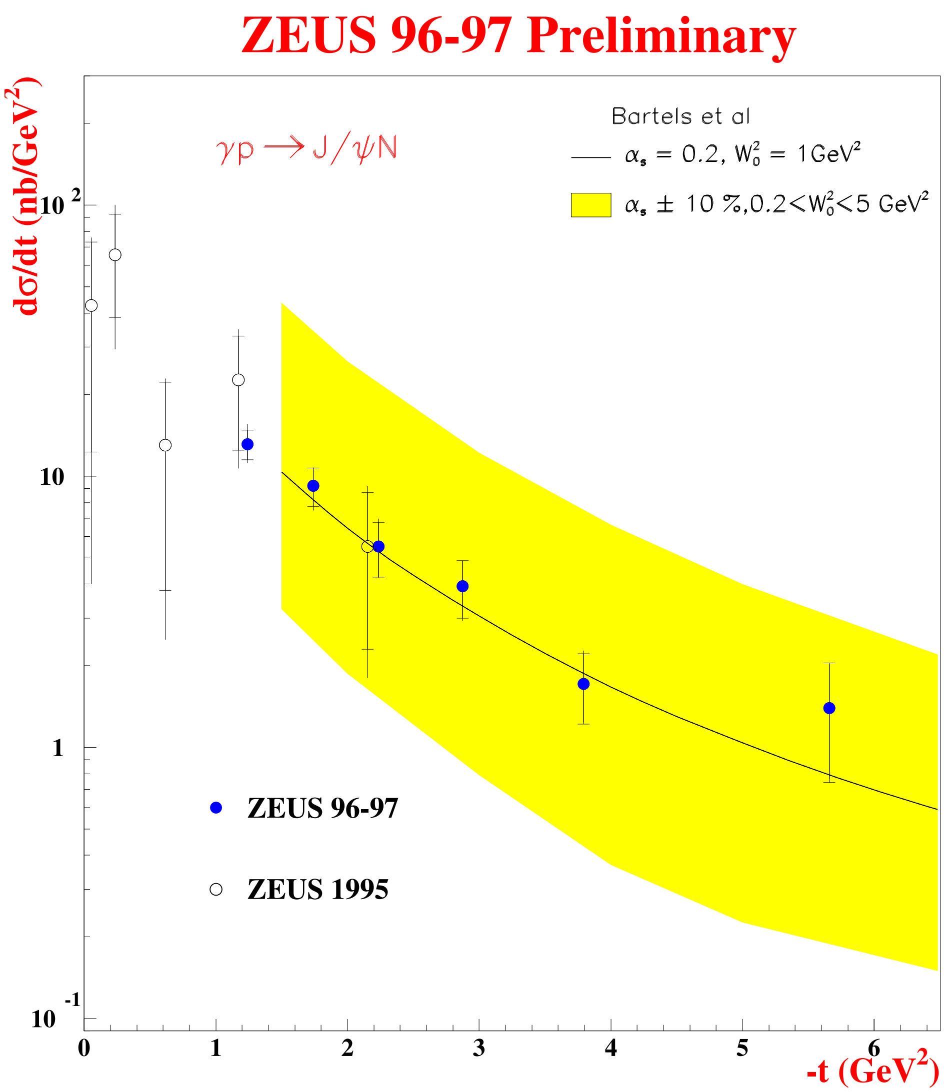
ZEUS 96 - 97 Preliminary



- Power like behavior, as expected in pQCD
- Non-perturbative contributions dominate. Quantitative description is poor

J/ψ photoproduction at high t

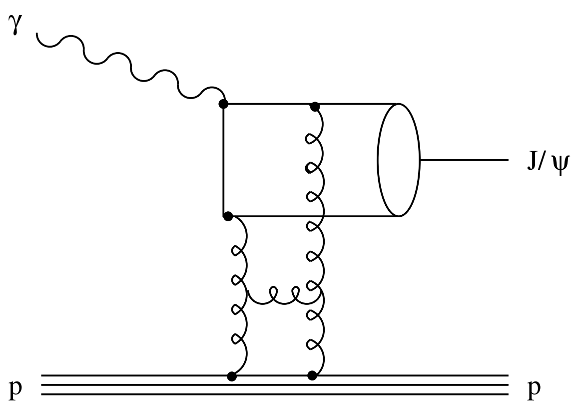
Hard scale at the both ends of the Pomeron:
M_V^2 at the photon vertex, t at the proton vertex



- Measured power $n = -1.7 \pm 0.2(\mathrm{stat}) \pm 0.2(\mathrm{syst})$

- BFKL calculation describes J/ψ cross section (yet with large uncertainty $\rightarrow$ NLO?)

Elastic J/ψ photoproduction



Expectations:

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

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

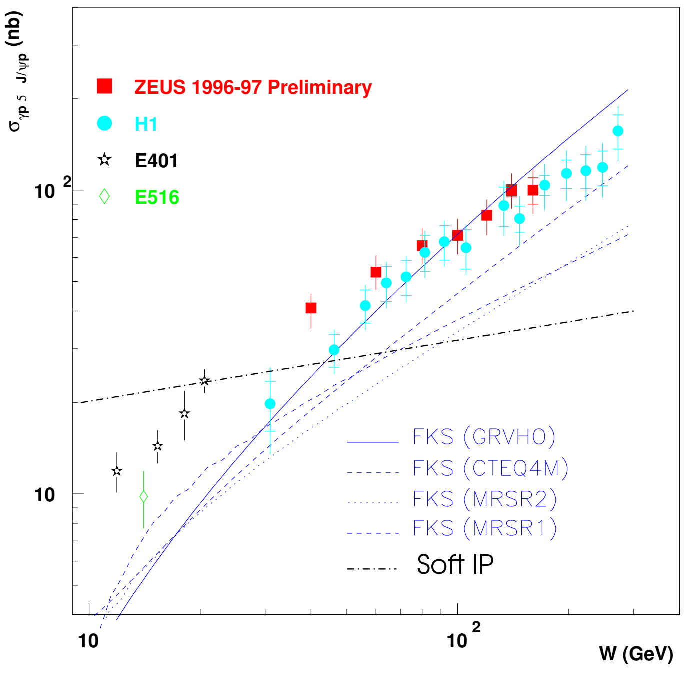
QCD: $\sigma(W) \propto [\alpha_s(q^2)\bar{x}g(\bar{x}, q^2)]^2$

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

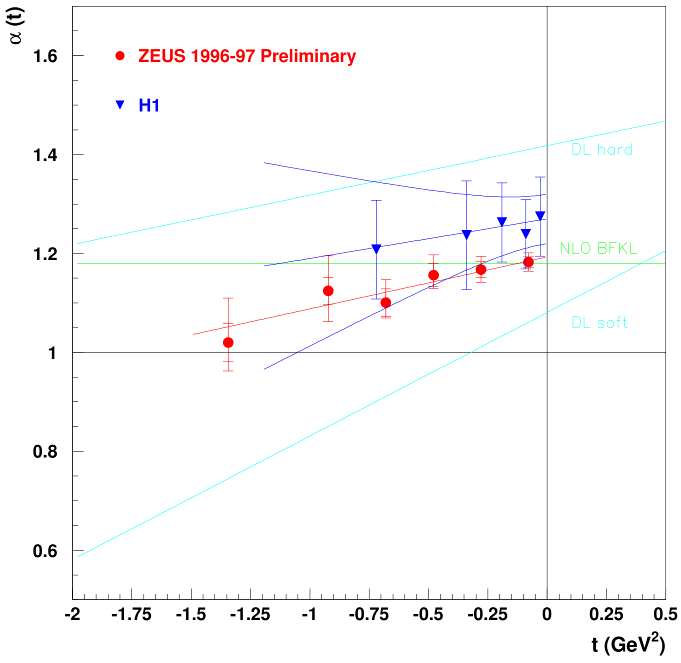
Measurement:

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

cross section vs energy



Regge tragectory



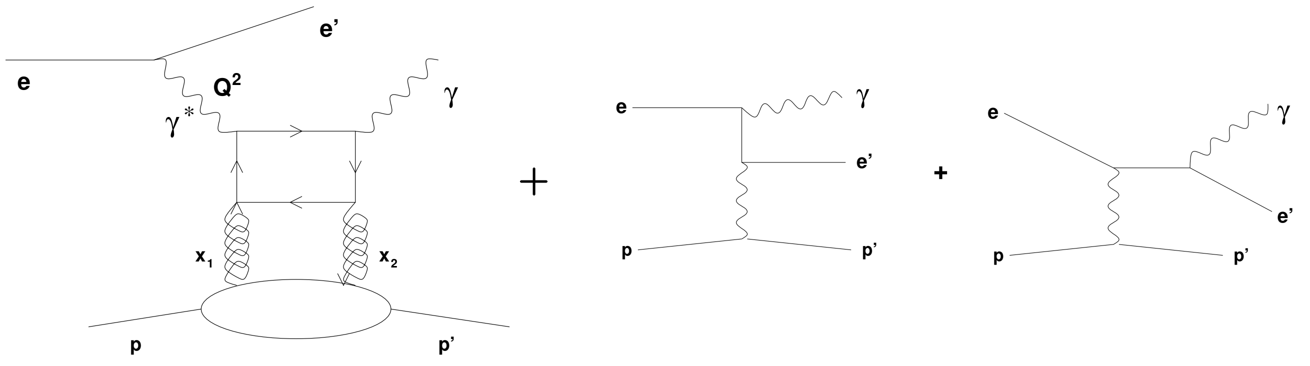
H1 : $\alpha_{I\!P}(t) = (1.27 \pm 0.05) + (0.08 \pm 0.17) \cdot t/\text{GeV}^2$

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

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

DVCS: $ep \rightarrow e\gamma p$

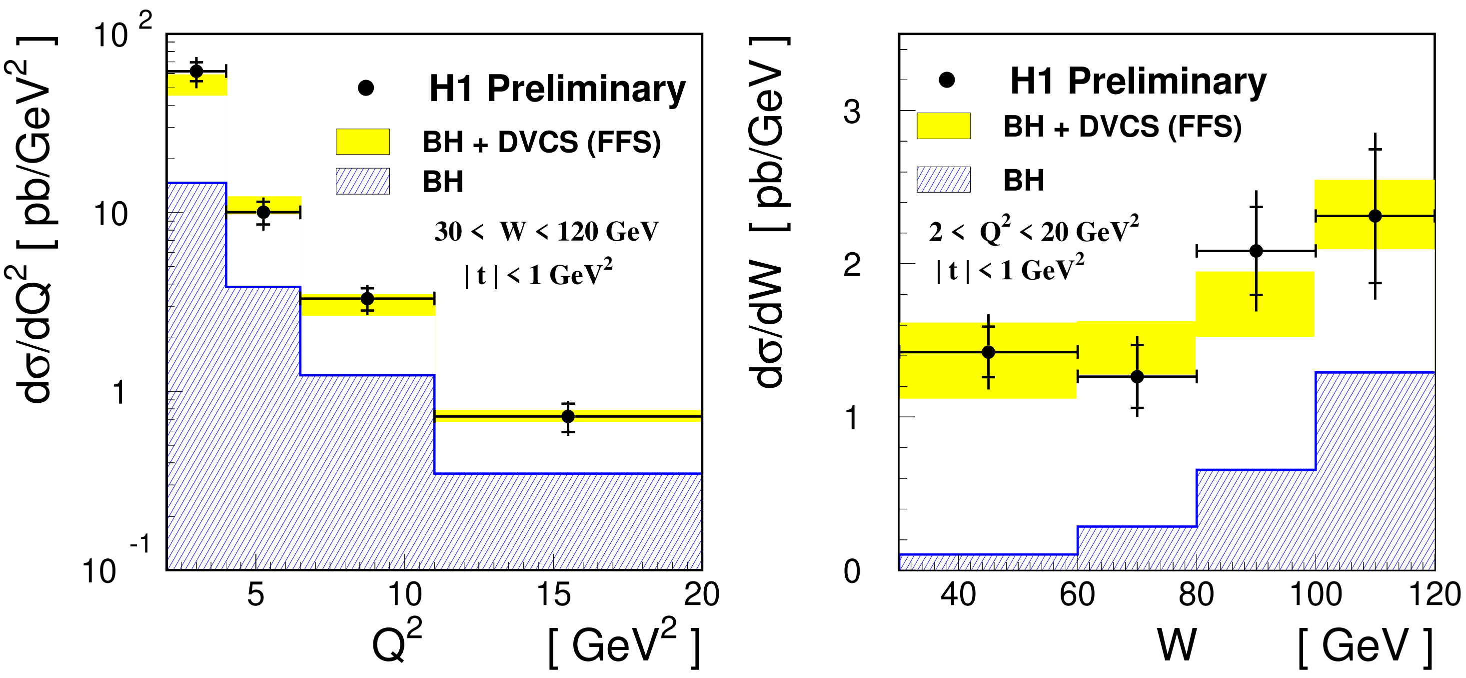
DVCS (QCD) **Bethe-Heitler (QED)**



- 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**

Summary

- 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 state 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 model 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. Colour dipole approach has good potential in describing the transition region from partonic to hadronic degrees of freedom in DIS

Outlook

- ~ 70 pb^{-1} of 1999-2000 data on tape per experiment $\Rightarrow$ Odderon (?), Improved $F_2^{D(3)}$, charm, ...

- HERA upgrade in 2001 $\Rightarrow$ 1 fb^{-1} physics

- Future options under discussion (needs strong support from the community) $\Rightarrow$ intense colour fields, saturation

  1. (Heavy) Nuclei at HERA
  2. THERA (TESLA-e $\times$ HERA-p)