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Inclusive and Elastic Diffraction at HERA

New Trends in High-Energy Physics
Yalta, Crimea, Ukraine

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On behalf of ZEUS and H1

Overview

- Introduction to Diffraction
- Diffraction in Hadronic Collisions
- Inclusive Diffraction in Deep Inelastic Scattering (DIS)
- Jets in Diffractive final states in DIS
- Exclusive Diffraction (VM and DVCS production)
- Summary

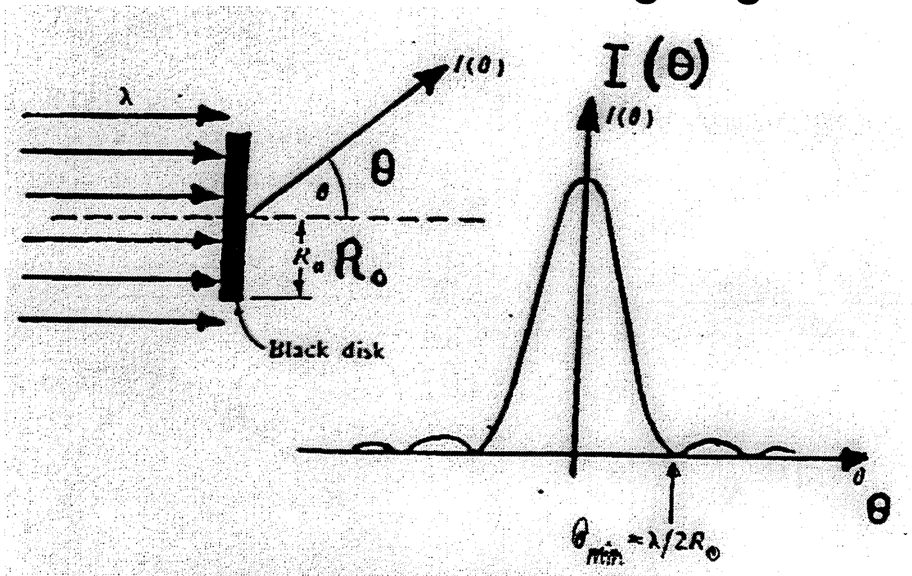
Introduction to diffraction

Optical diffraction:

Consider light striking an opaque object:

γ **+ target** $\longrightarrow$ γ **+ target**

Wave fronts on an absorbing target:



Optical diffraction pattern produced by a black disk.

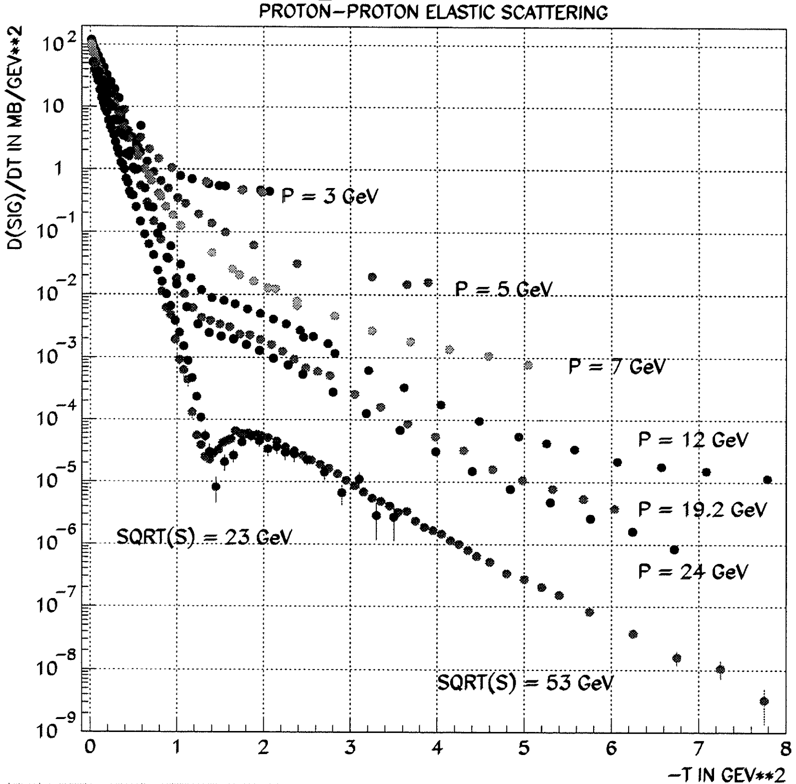
$$\frac{I}{I_0} = \frac{[2J_1(x)]^2}{x^2} \approx 1 - \frac{R_0^2}{4}(k\theta)^2$$

where k **is the wave number**

and $x = R_0 k sin\theta \approx R_0 k\theta$

Hadronic diffraction:

p **+ target** $\longrightarrow$ p **+ target (elastic diffraction)**

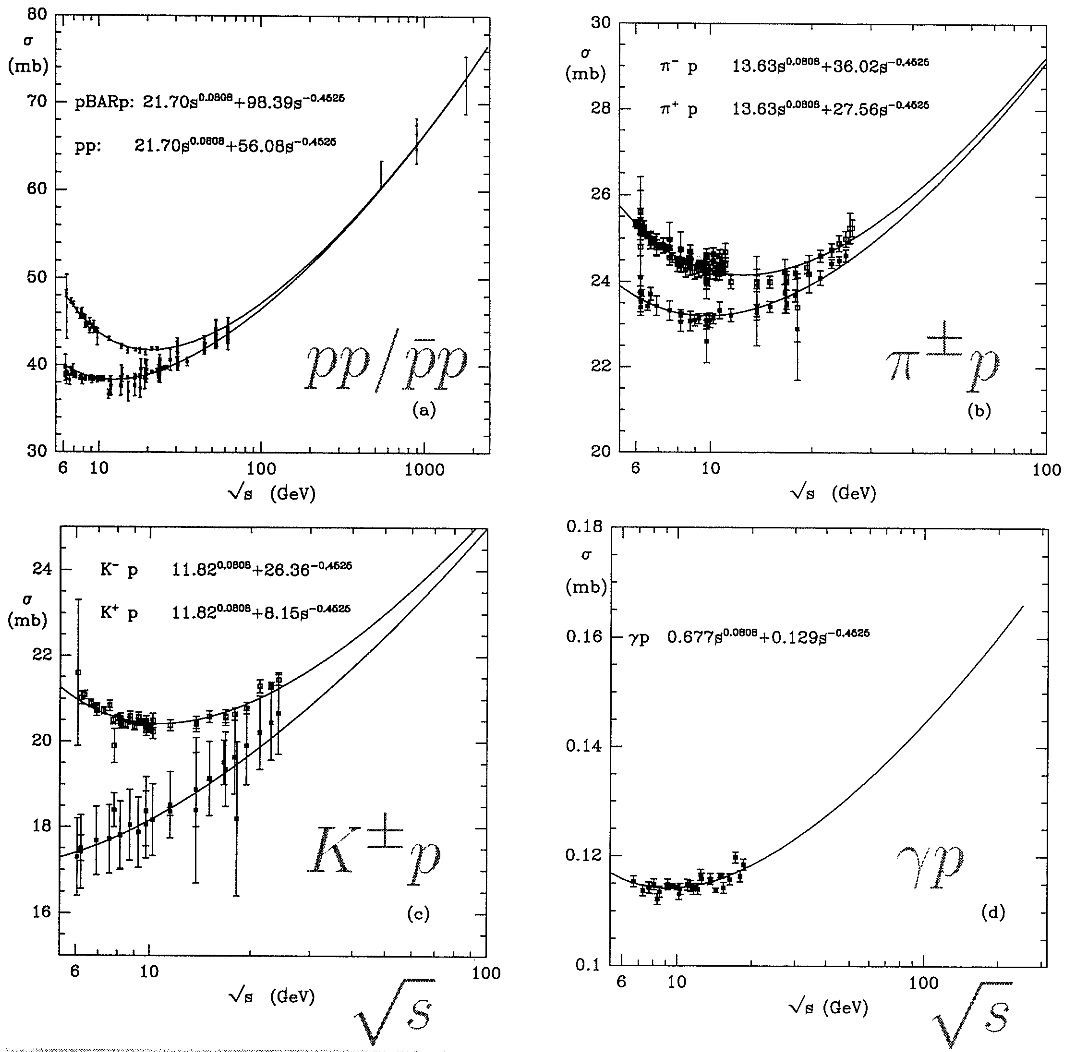


$$\frac{d\sigma/dt}{(d\sigma/dt)_{t=0}} = e^{bt} \approx 1 - b(p\theta)^2$$

where p **is the incident proton momentum**

and $b = R_0^2/4$

Hadronic Total cross sections



$$\sigma_{tot} = As^{0.0808} + Bs^{-0.4525} \rightarrow \textbf{D-L}$$

▷ **Regge Theory:**

$$\frac{d\sigma}{dt} = \frac{|A(s,t)|^2}{16\pi s^2} \sim s^{2\alpha(0)-2} e^{bt}$$

▷ **Optical Theorem:**

$$\sigma_{tot} = \frac{1}{s} Im A(s, t=0) \sim s^{\alpha(0)-1}$$

where:

$$\alpha_{I\!P}(t) = 1 + 0.0808 + 0.25t$$
$$\alpha_R(t) = 1 - 0.4525 + t$$
$$b = b_0 + 2\alpha' ln(s/s_0)$$

$\rightarrow$ **Shrinkage of elastic peak**

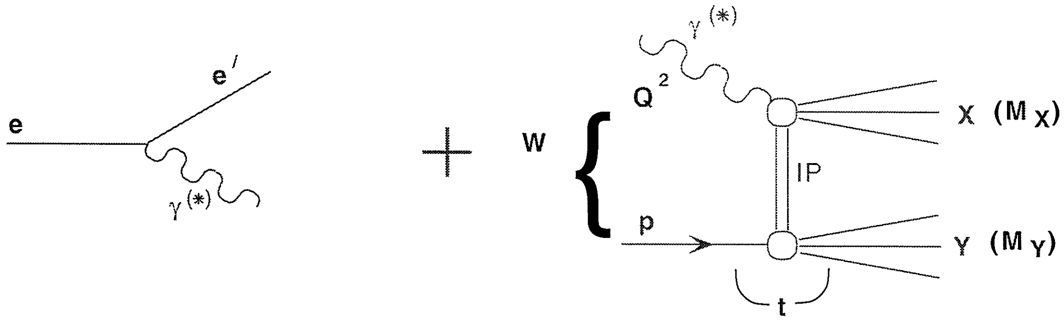
Optical analogy:

increase $s \rightarrow$ **smaller** λ

diffraction peak steepens, b **larger**

Introduction to DIS Diffraction

Inclusive diffraction vs. elastic diffraction:



▷ **Double dissociation:**

$\gamma^* \to X$ **(with mass** M_X**)**

$p \to Y$ **(prot dissoc., mass** M_Y**)**

▷ **Single dissociation:**

$\gamma^* \to X$

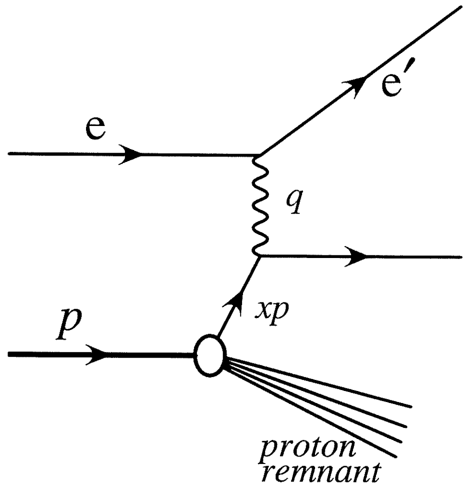
$p \to Y = p$

▷ **Elastic scattering:**

$\gamma^* \to X = VM, \gamma$

$p \to Y = p$

Standard DIS



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

the photon virtuality

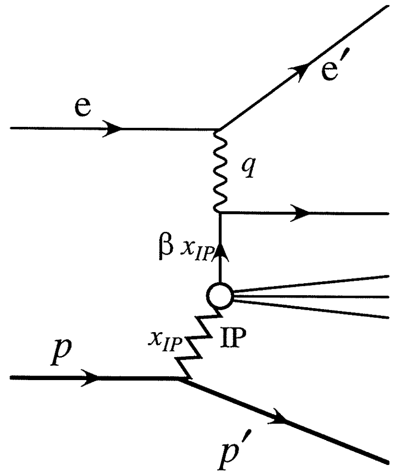
$$x \equiv \frac{Q^2}{2p \cdot q}$$

the fraction of proton's momentum carried by the struck parton

$$W^2 = (p + q)^2$$

$\gamma^* p$ **cm energy squared**

Diffractive DIS



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

4-momentum transfer squared

$$x_{I\!P} \equiv \frac{q \cdot (p - p')}{q \cdot p} \approx \frac{Q^2 + M_X^2}{Q^2 + W^2}$$

fraction of the p momentum in $I\!P$

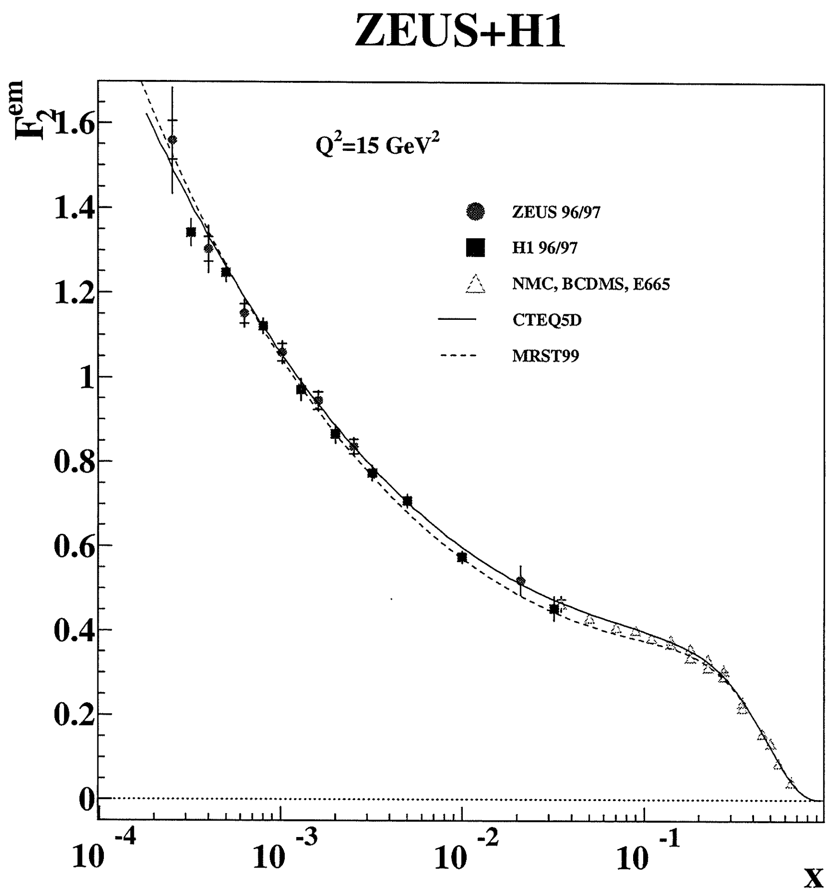
$$\beta \equiv \frac{Q^2}{2q \cdot (p - p')} \approx \frac{Q^2}{Q^2 + M_X^2} = \frac{x}{x_{I\!P}}$$

fraction of the $I\!P$ momentum in the quark coupling to γ^*

Introduction to DIS

Standard Deep Inelastic Scattering, DIS:

$$\frac{d^2\sigma}{dxdQ^2} = \frac{4\pi\alpha^2}{xQ^4}[(1-y+\frac{y^2}{2})F_2 - \frac{y^2}{2}F_L]$$



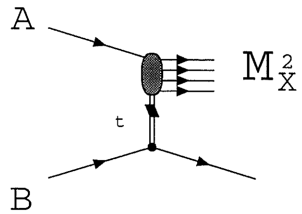
▷ **At low** x: $F_2 \sim x^{-\lambda}$ **and** $W^2 \approx \frac{Q^2}{x}$

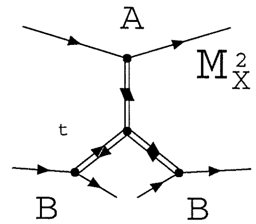
$$\frac{d^4\sigma^{diff}}{d\beta dQ^2 dx_{I\!P} dt} = \frac{4\pi\alpha^2}{\beta Q^4}[(1-y+\frac{y^2}{2})F_2^{D(4)} - \frac{y^2}{2}F_L^{D(4)}]$$

DIS Diffraction

▷ **Bj: A process is Diffractive if, and only if, there is a large rapidity gap in the produced-particle phase space which is not exponentially suppressed.**

For the triple Pomeron description:





$$\frac{d^2\sigma}{dtdM_X^2} = \frac{1}{16\pi}\beta^2_{B I\!P}(t)G_{3I\!P}(t)\beta_{AI\!P}(0)(\frac{s}{M_X^2})^{2\alpha_{I\!P}(t)-2}(M_X^2)^{\alpha_{I\!P}(0)-2}$$
$$+\frac{1}{16\pi}\Sigma\,\beta^2_{BR}(t)G_{RRI\!P}(t)\beta_{AI\!P}(0)(\frac{s}{M_X^2})^{2\alpha_R(t)-2}(M_X^2)^{\alpha_{I\!P}(0)-2}$$

For $I\!P$: $\alpha_{I\!P}(t) \sim 1 + \alpha'_{I\!P}t$ **For R:** $\alpha_R(t) \sim \frac{1}{2} + \alpha'_R t$

Hence for $I\!P$: $\frac{d^2\sigma}{dtdM_X^2} \sim (\frac{s}{M_X^2})^0\frac{1}{M_X^2} \sim (e^y)^0\frac{1}{M_X^2}$

So for $I\!P$: rapidity: No dependence, flat M_X^2: $\frac{1}{M_X^2}$ dependence

And for R: $\frac{d^2\sigma}{dtdM_X^2} \sim (\frac{s}{M_X^2})^{-1}\frac{1}{M_X^2} \sim (e^{-y})\frac{1}{M_X^2}$

So for R: rapidity: exponentially falling

DIS Diffraction

▷ Bj: Hard Diffraction is the set of strong interaction processes which contain jets in the final state phase space.

▷ This can be modified: Hard Diffraction at HERA is the set of processes which has some large scale.

→ The interest in studying diffraction at HERA is that if there is a large scale then QCD should be applicable (in contrast to the situation for "soft", long distance, diffraction which cannot be calculated in pQCD).

→ At HERA, both long and short distance interactions can be studied in electroproduction by varying the size (resolving power) of the probe (Q^2):

- $Q^2 = 0$, photoproduction $\sim$ hadronic regime
- $Q^2 < 1$ GeV^2, transition region
- $Q^2 > 1$ GeV^2, deep inelastic scattering regime

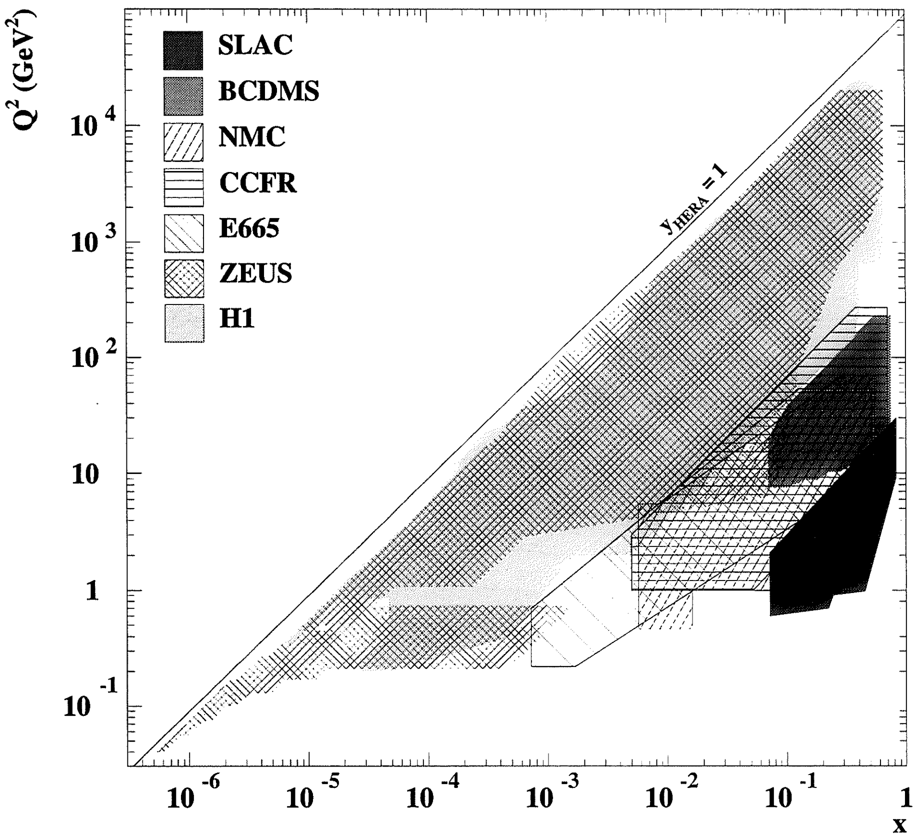
DIS Diffraction

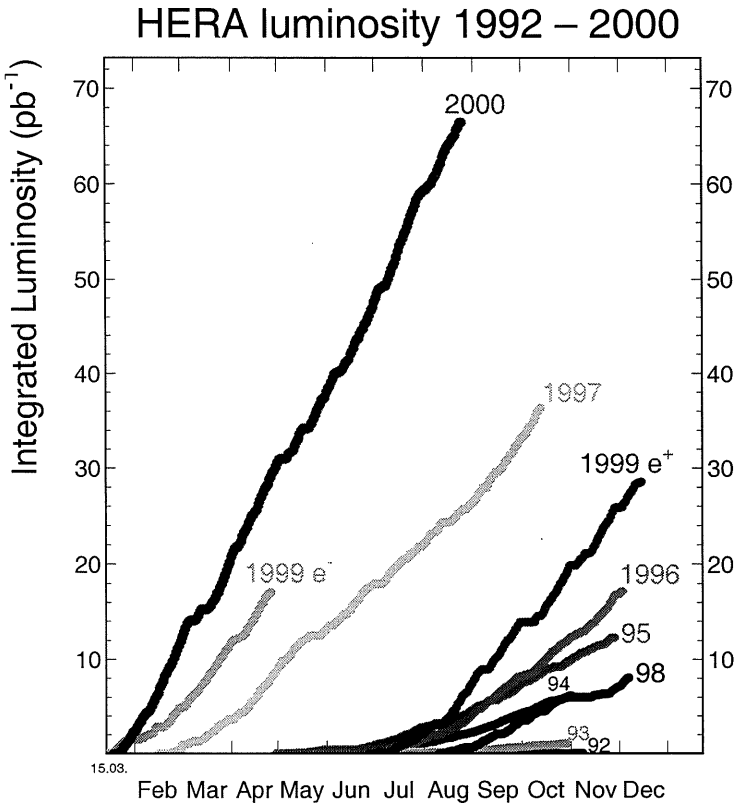
▷ **What are the possible hard scales in the process?**

1. **High Q^2 total cross section $\sim F_2$**
   - $\sigma_{tot}^{\gamma^* p} \approx \frac{4\pi^2\alpha}{Q^2} F_2 \approx \frac{4\pi^2\alpha}{Q^2} x^{-\lambda} \sim (W^2)^{\lambda_{eff}}$
   - **Remember:** $\sigma_{tot} \sim s^{\alpha_{I\!P}(0)-1} = (W^2)^{\alpha_{I\!P}(0)-1}$ **at Q^2= 0**
2. **High Q^2 inclusive diffraction $\sim F_2^{D(4)}$**
3. **High P_T^2 jets or heavy quarks produced in diffractive events**
4. **Exclusive production of Vector Mesons and DVCS:**
   - **at high Q^2**
   - **for large mass M_V^2**
   - **at high t**

Introduction to HERA

▷ **HERA: 27.5 GeV e$^{\pm}$ on 920 (820) GeV protons** $\rightarrow$ $\sqrt{s} = 318\ (300)\ \mathrm{GeV}$

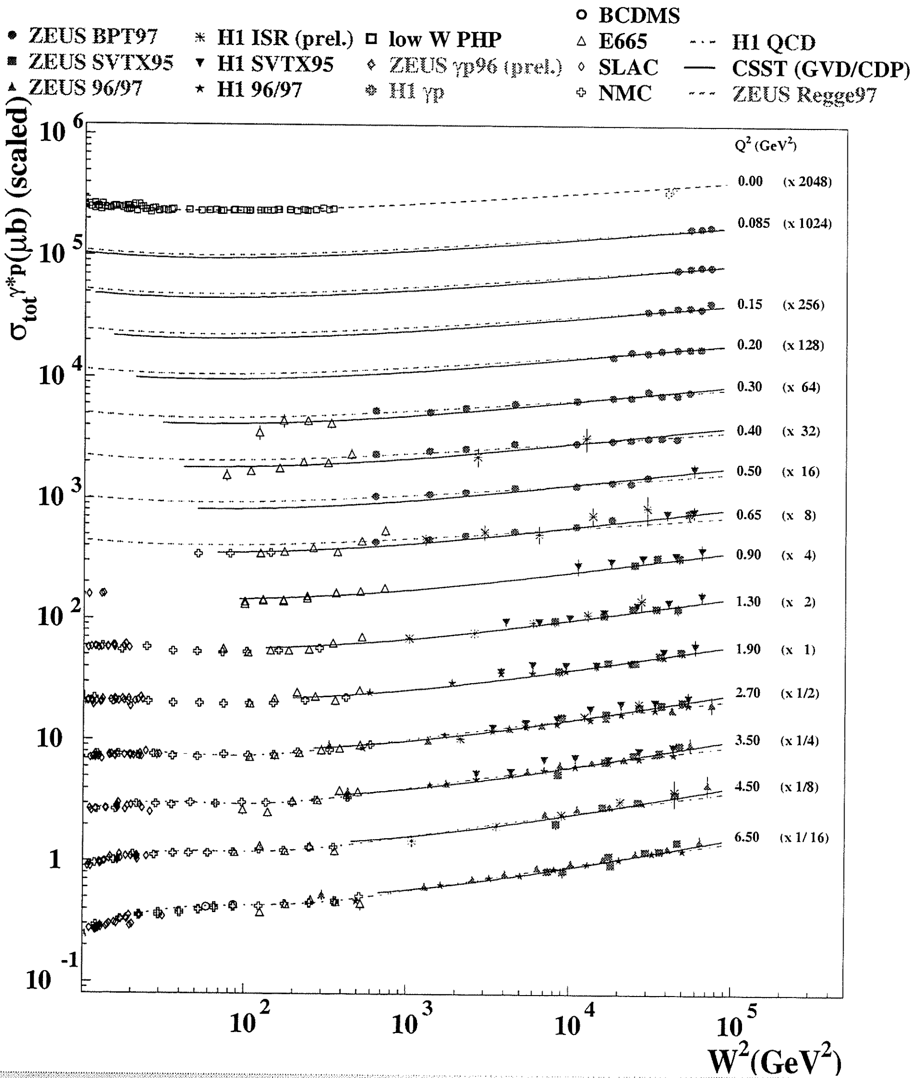


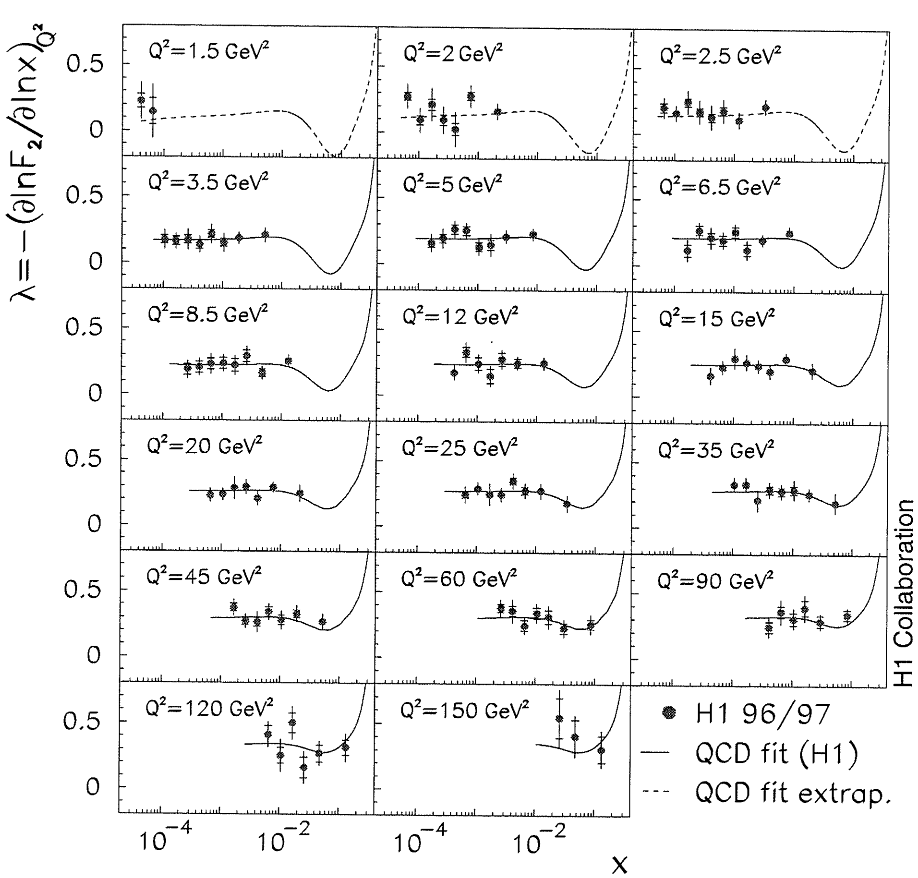


Spans 6 orders in x and Q^2

Data: ~114 (16) pb^{-1} for e^+p (e^-p)

W^2 dependence of $\sigma_{tot}^{\gamma^*}$

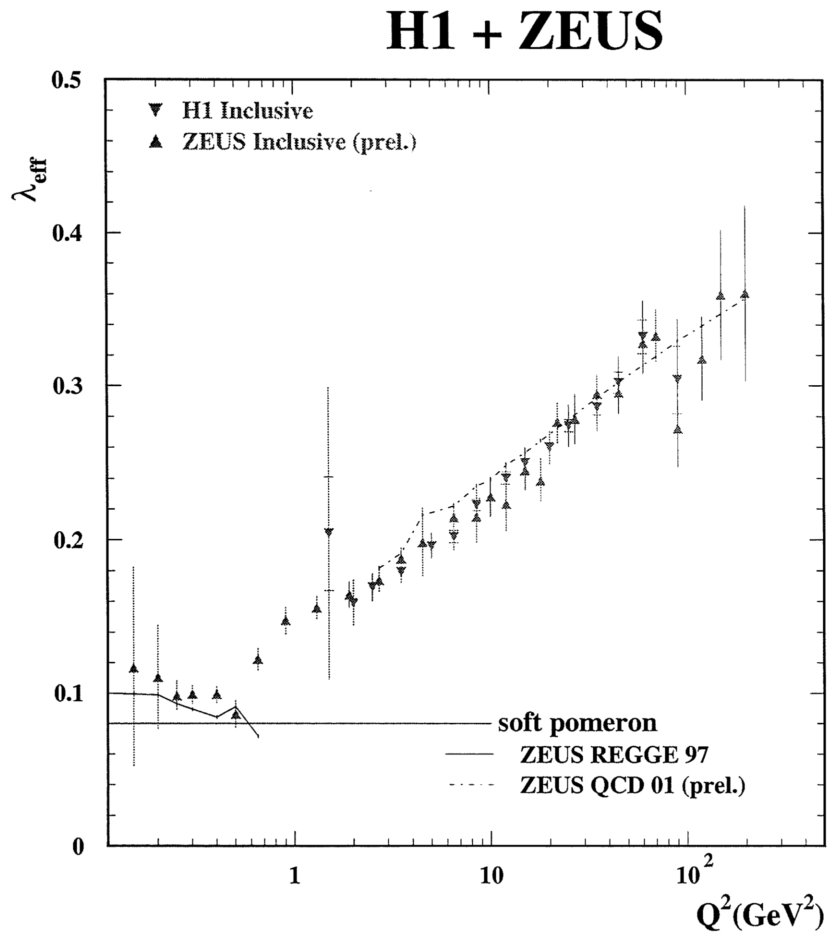




Slope steepens as Q^2 increases

- **λ independent of x at small x**
- $F_2(x, Q^2) = C(Q^2)x^{-\lambda(Q^2)}$

W^2 dependence of $\sigma_{tot}^{\gamma^*}$



Look at slope as a function of Q^2

$$\sigma_{tot} \sim (W^2)^{\lambda_{eff}} \sim (W^2)^{\alpha_{I\!P}(0)-1}$$

For low Q^2: Regge Theory expects

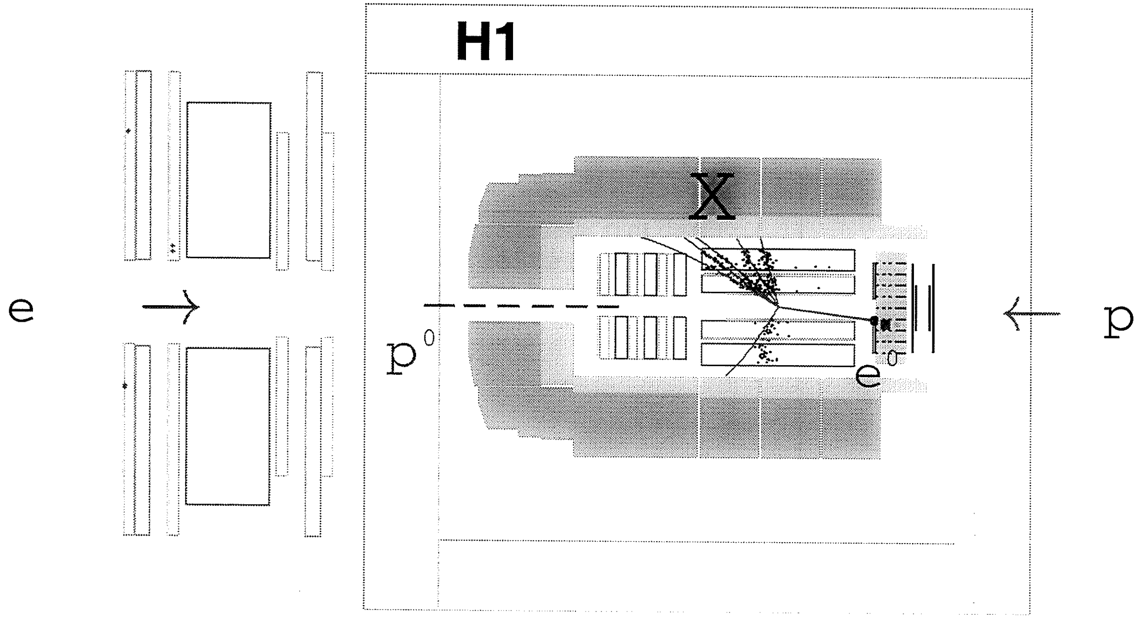
$\lambda \rightarrow$ constant $\sim$ 0.1

For high Q^2: NLO QCD agrees

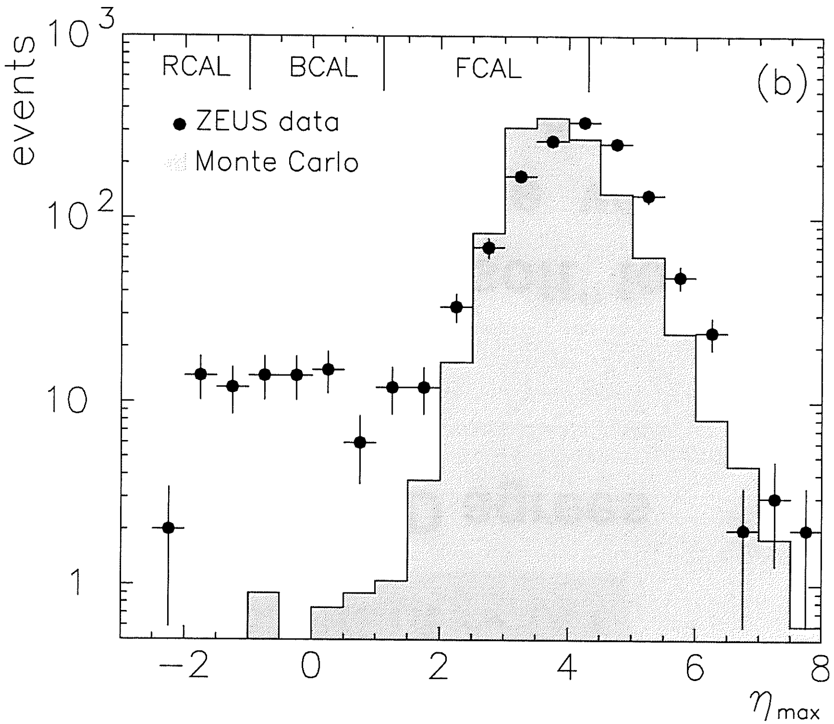
See the transition from "soft" to "hard" at $Q^2 \approx$ 1 GeV^2, above which the pomeron intercept increases with Q^2

Selection of Diffractive Events (1)

▷ **Require a large rapidity gap between p' and X**



Observed first in 1993:



$\sim$10% of all DIS events have little or no activity in the forward (proton) direction

No activity $\rightarrow$ no radiation $\rightarrow$ color singlet exchange

Determine kinematics from M_X

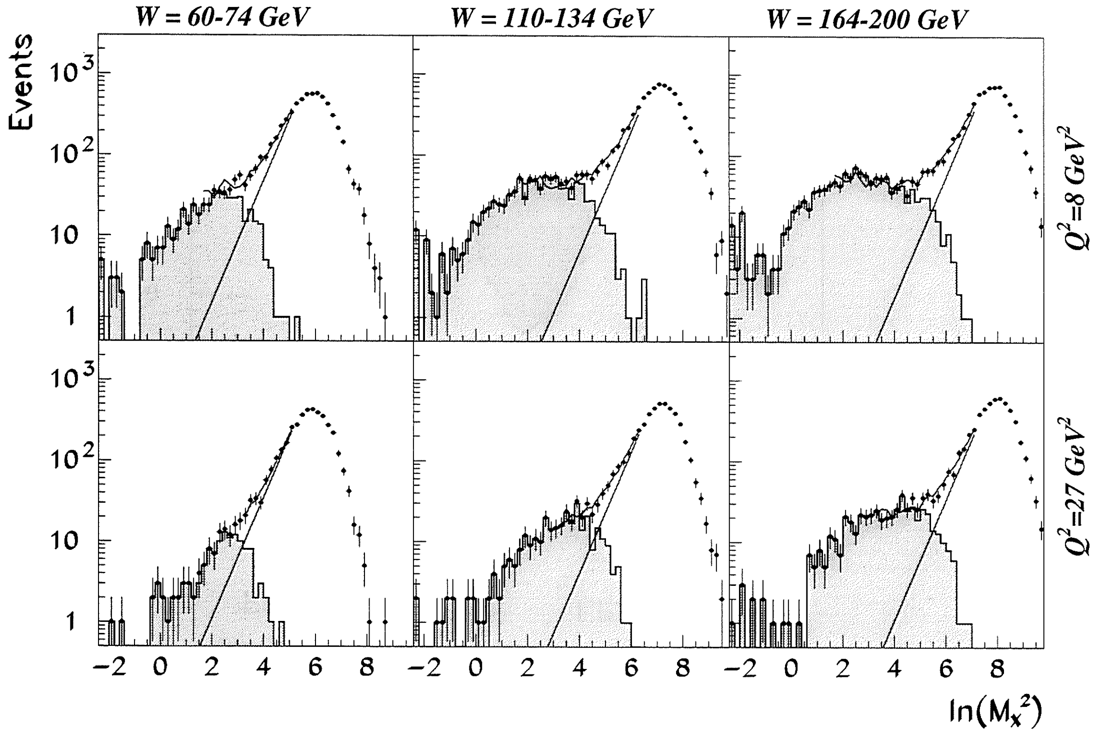
Integrate over t and M_Y ($<$ few GeV)

Advantage: large statistics

Disadvantage: proton diss. and non-diffractive included

Selection of Diffractive Events (2)

Analysis of the mass in the detector:



For $I\!\!P$:

$$\frac{d\sigma}{dM_X^2} \sim \frac{1}{M_X^2};$$

$$\frac{d\sigma}{dln(M_X^2)} \sim const.$$

For non-diffractive:

$$\frac{d\sigma}{dln(M_X^2)} \sim e^{-lnM_X^2}$$

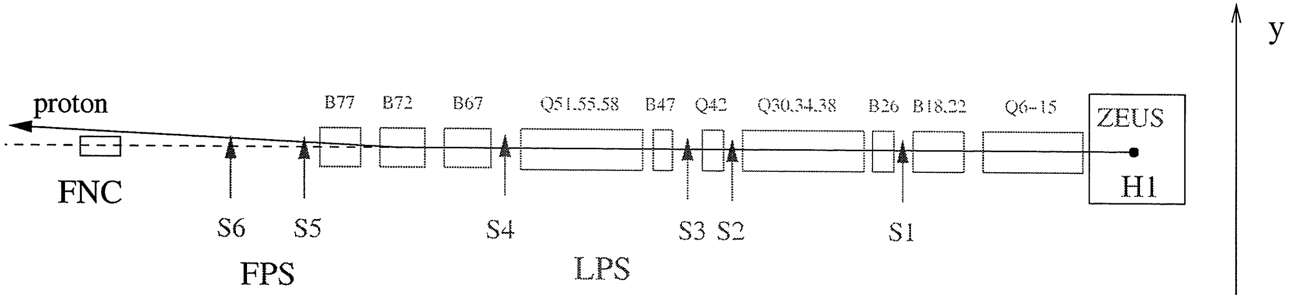
Diffractive events correspond to the excess of events above the exponential

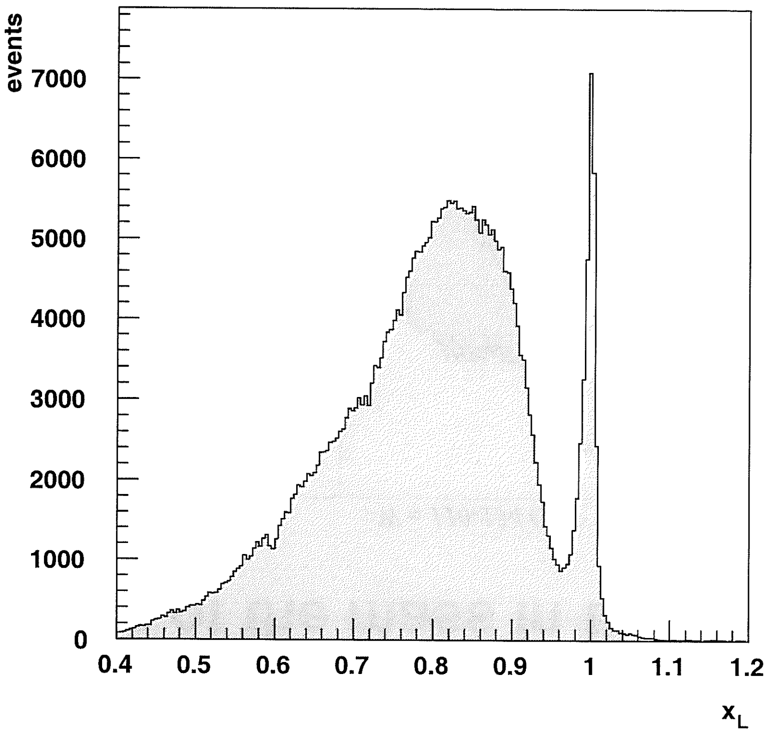
Advantage: large statistics and removes some non-diffractive (R)

Disadvantage: proton dissociation included

Selection of Diffractive Events (3)

▷ **Measure the scattered proton in Roman Pots**





$$x_L = \frac{E_p'}{E_p}$$

fractional energy

$$x_{I\!P} = 1 - x_L$$

fractional energy

$$t = (p-p')^2 \approx -\frac{(p_T')^2}{x_L}$$

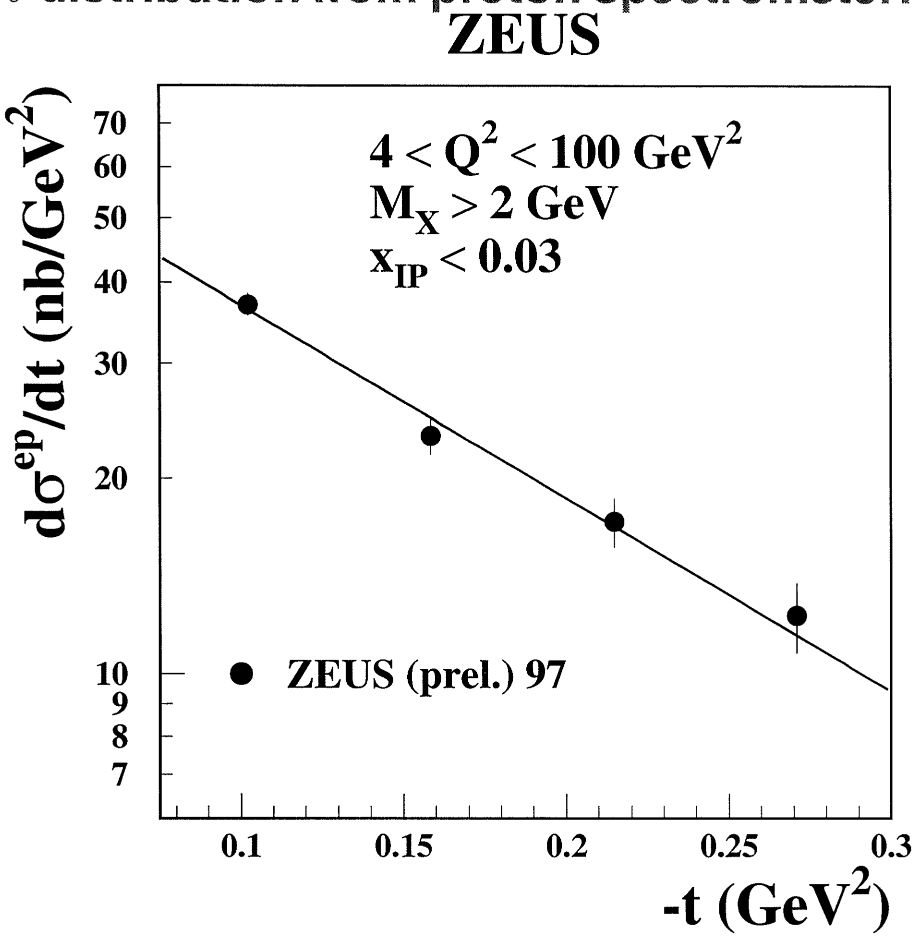
4-momentum transfer squared

Advantage: no proton dissoc., measure t

Disadvantage: low acceptance

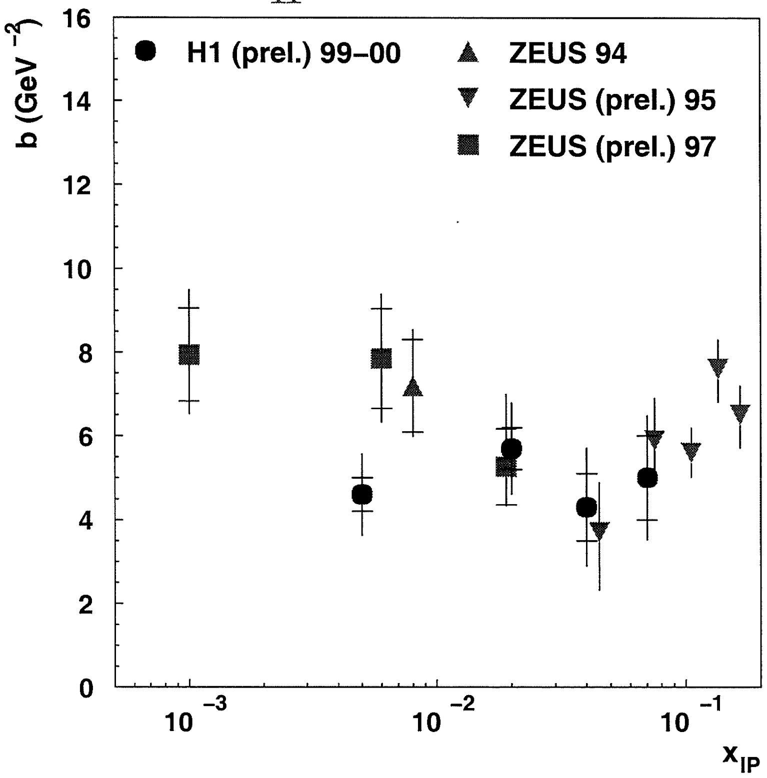
Diffractive Structure Functions (1)

t distribution from proton spectrometer:



$$b = 6.8 \pm 0.6(stat.)^{+1.2}_{-0.7}(syst.)$$

Slope vs. x_{IP}:

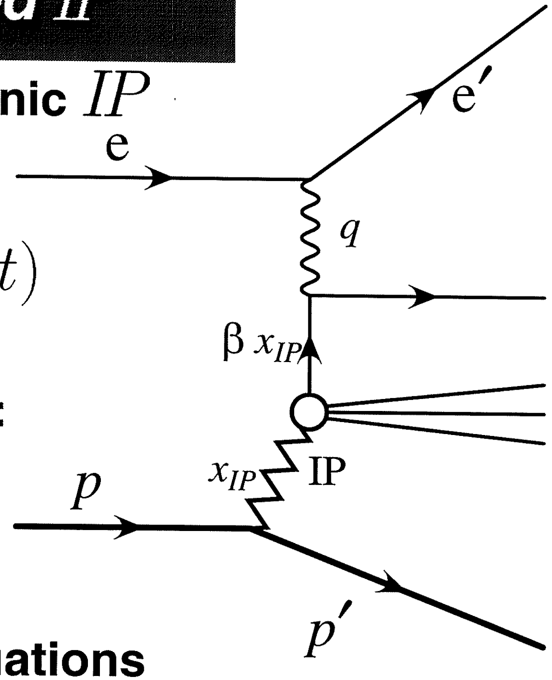


Regge expects shrinkage:

$$b = b_0 + 2\alpha' ln(s/s_0)$$
$$= b_0 + 2\alpha' ln(1/x_{IP})$$

Results: Data are inconclusive

Models of Diffraction - Resolved $I\!P$



Resolved $I\!P$ approach (Ingelman + Schlein, 1985) $\rightarrow$ partonic $I\!P$

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

Hard scattering factorization for diffraction (J. Collins, 1997):

$$F_2^D \sim f^D \otimes \hat{\sigma}$$

when one of the initial particles is a lepton

f^D are the diffractive PDFs and obey the usual DGLAP equations

Assuming Regge factorization:

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

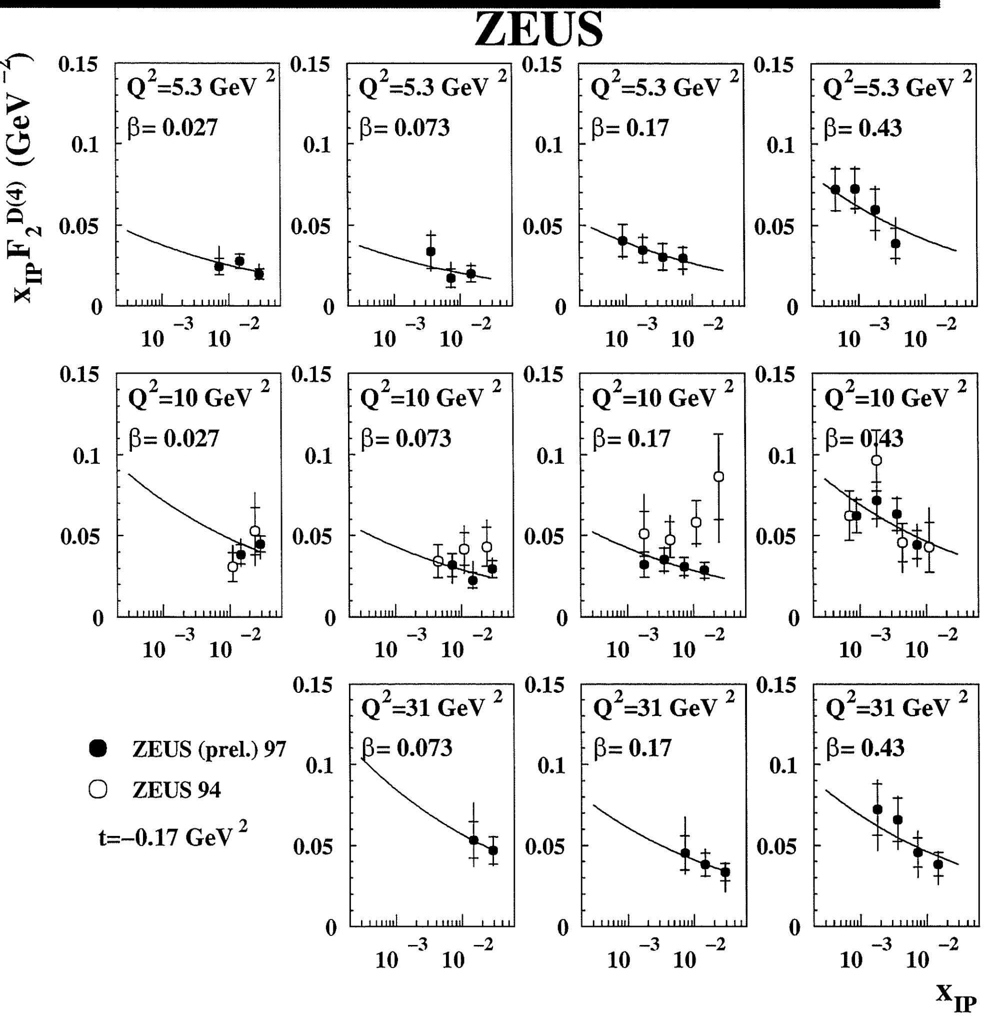
The pomeron flux factor, $\Phi(x_{I\!P}, t) \sim (\frac{1}{x_{I\!P}})^{2\alpha_{I\!P}(t)-1} \sim \frac{1}{x_{I\!P}}$

▷ **Do NLO DGLAP analysis of $F_2^{I\!P}$ in an analogous way to F_2 to determine PDFs**

1. **What is $\alpha_{I\!P}$?**
2. **What is the diffractive partonic content of the proton ($I\!P$)?**

Diffractive Structure Functions (2)

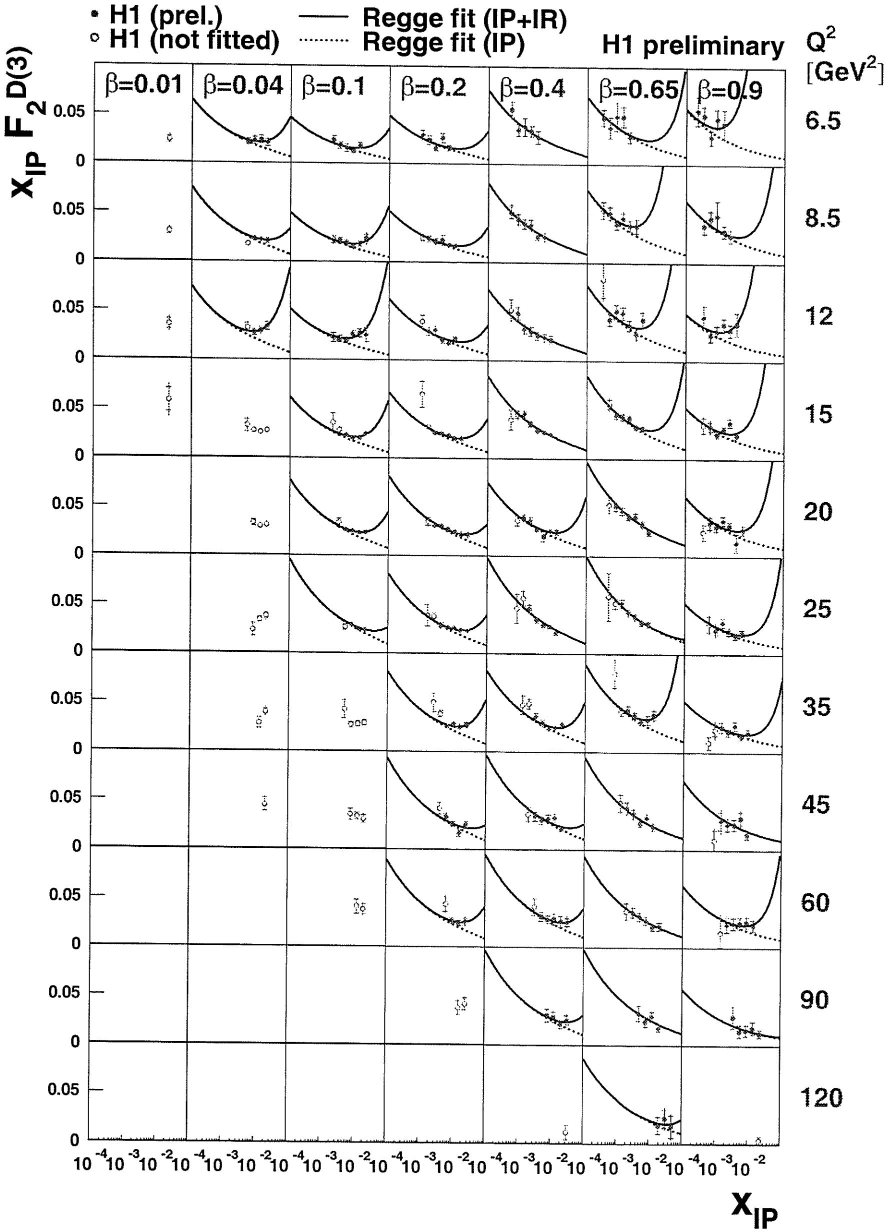
Measure $F_2^{D(4)}$:



Fit the x_{IP} dependence assuming a factorizable IP flux $\sim (\frac{1}{x_{IP}})^{2\alpha_{IP}(t)-1}$**:**

Result: $\alpha_{IP}(0) = 1.13 \pm 0.03(stat.)^{+0.03}_{-0.01}(syst.)$

Diffractive Structure Functions (3)



New measurements from H1:

$6.5 < Q^2 < 120$ **GeV**^{2}

$|t| < 1$ **GeV**^{2}

$0.0001 < x_{IP} < 0.05$

$0.01 < \beta < 0.9$

$$F_2^{D(3)} = \int F_2^{D(4)} dt$$

Results:

▷ **Data are well described by** IP **and** R **exchanges:**

▷ **Good description of the** x_{IP} **dependence (**χ^2**/ndf = 0.95) with**

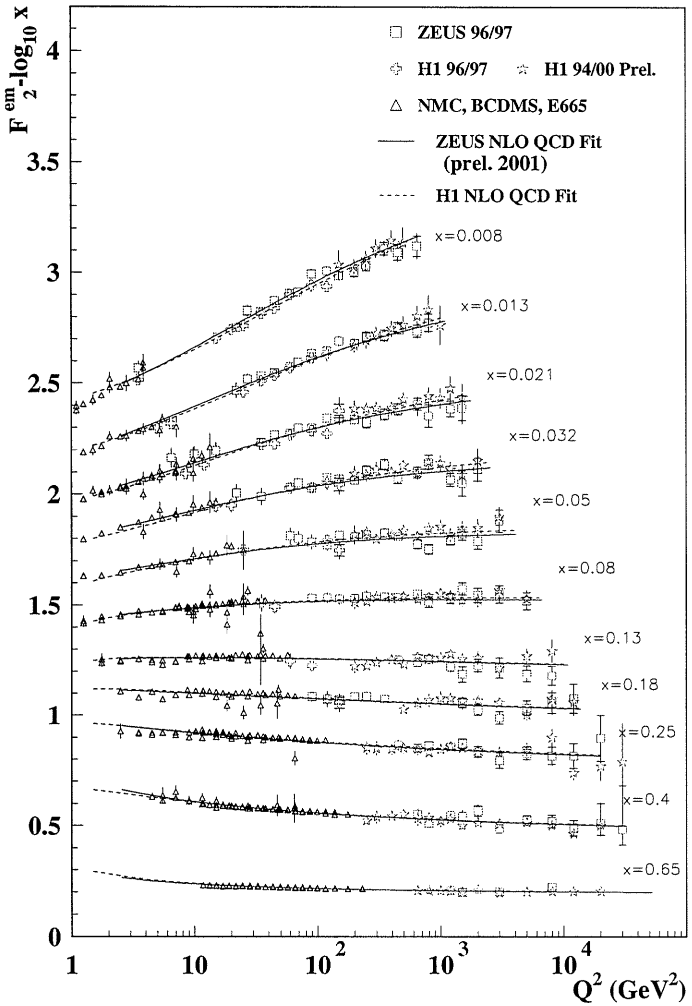
$\alpha_{IP}(0) = 1.173 \pm 0.018(stat.) \pm 0.017(syst.)^{+0.063}_{-0.035}(model)$

Fixed: $\alpha_R(0) = 0.50 \pm 0.16$

and $F_L^D = 0$

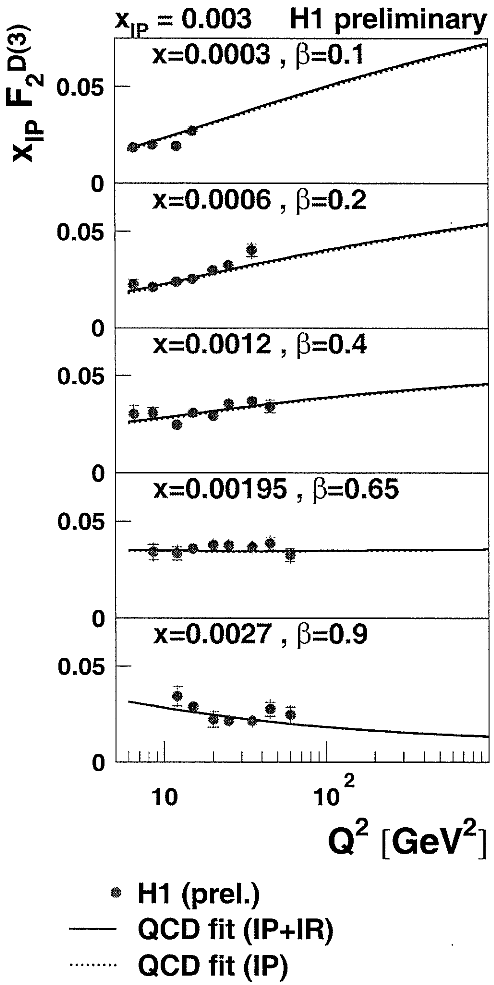
Diffractive Structure Functions - Scaling Violations

Normal DIS:



Scaling observed at $x \sim 0.2$

Diffractive DIS:

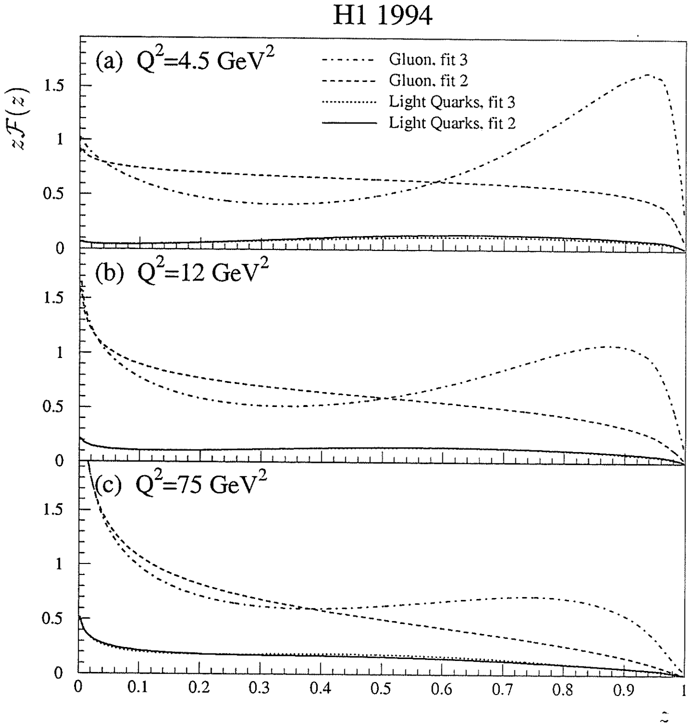


Scaling observed at $\beta \sim 0.65$

$\rightarrow$ gluons at large β in diffraction

Diffractive Parton Distributions

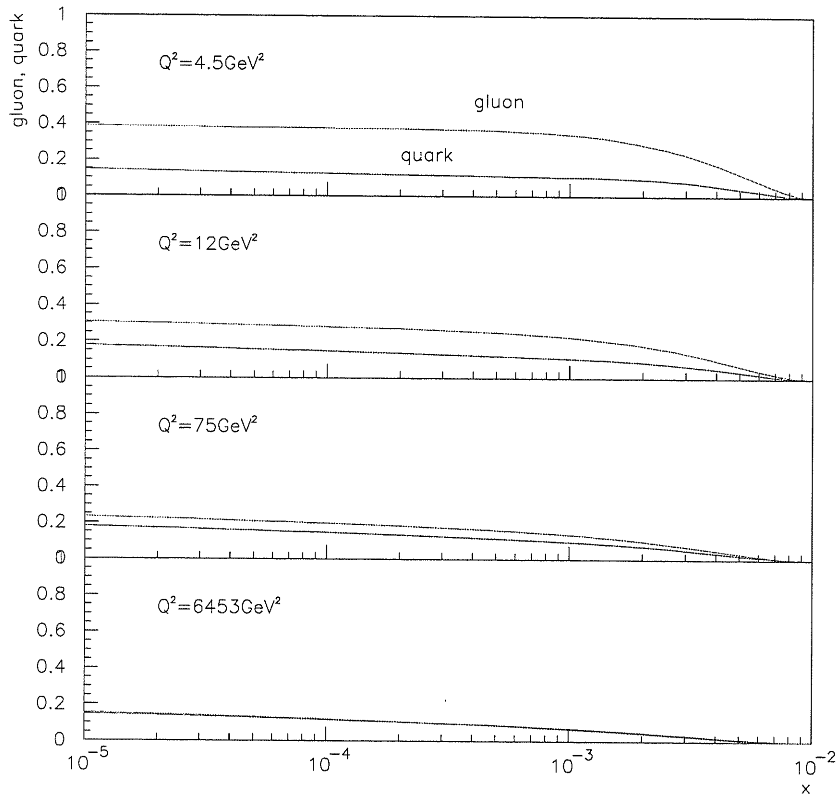
$I\!P$ PDFs from H1:



z = **fractional momentum of the $I\!P$ carried by the struck parton**

$\longrightarrow$ **Gluon dominated $I\!P$ (carries 90% at Q^2 = 4.5 GeV^2 and 80% at Q^2 = 75 GeV^2)**

Proton diffractive PDFs from ACTW:

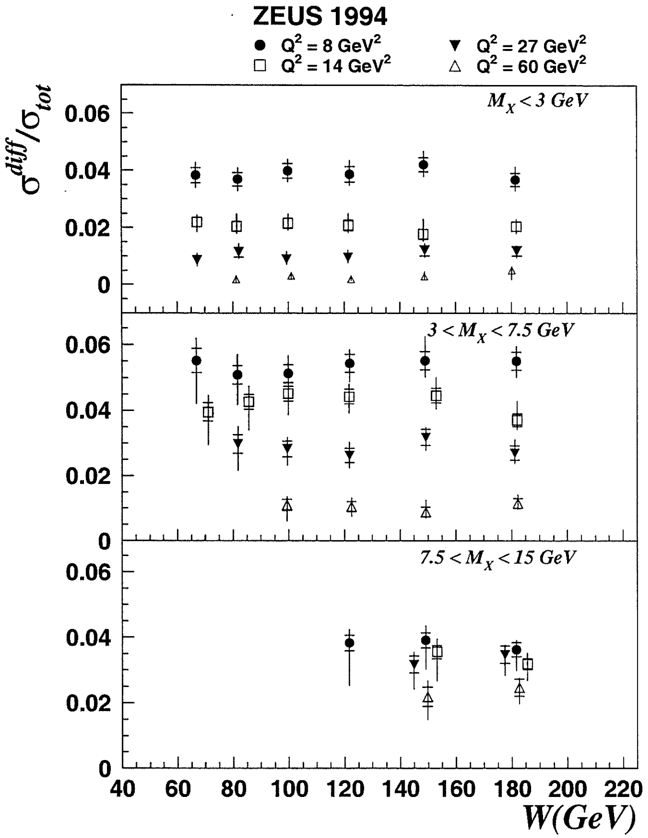


$\longrightarrow$ **gluons at large β in diffraction**

$\longrightarrow$ **Proton PDFs have same x dependence as 'normal' PDFs at small x**

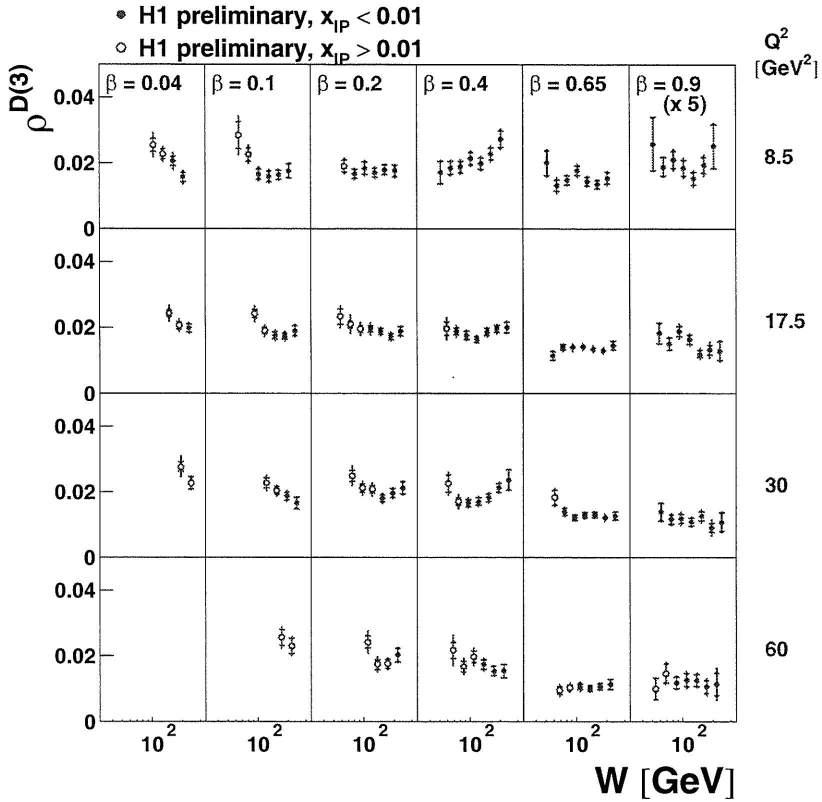
Energy dependence of inclusive diffraction

ZEUS results:



Ratio of diffractive to total is independent of W

H1 results:

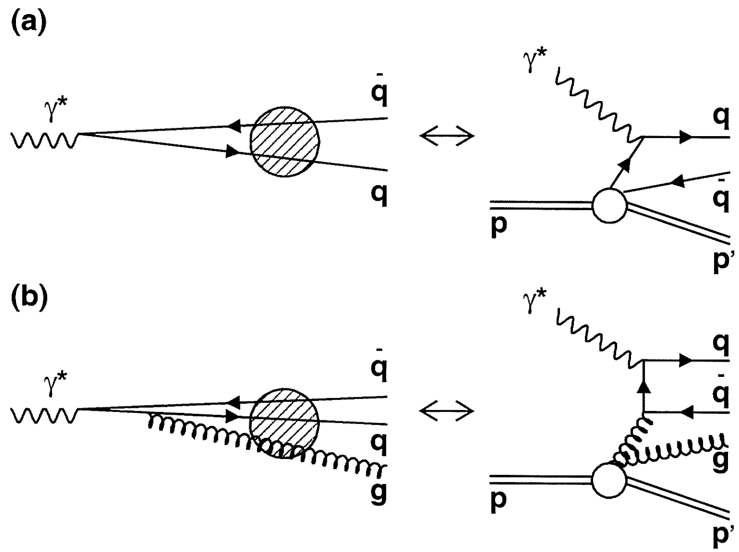


At low W and small β (large M_X), diffractive cross section falls faster with W than the total.

Dipole model

▷ The γ^* dissociates into a dipole ($q\bar{q}$ or $q\bar{q}g$) well before the collision with the proton

proton rest frame proton infinite mom frame



▷ When boosted to the proton infinite momentum frame $\rightarrow$ resolved $I\!P$ picture

▷ The interaction between the dipole and the proton is expressed in terms of the dipole (process independent) cross section $\hat{\sigma}_{dipole}(x,r)$ where

r is the transverse separation of the $q\bar{q}$, and x represents the PDF in the proton

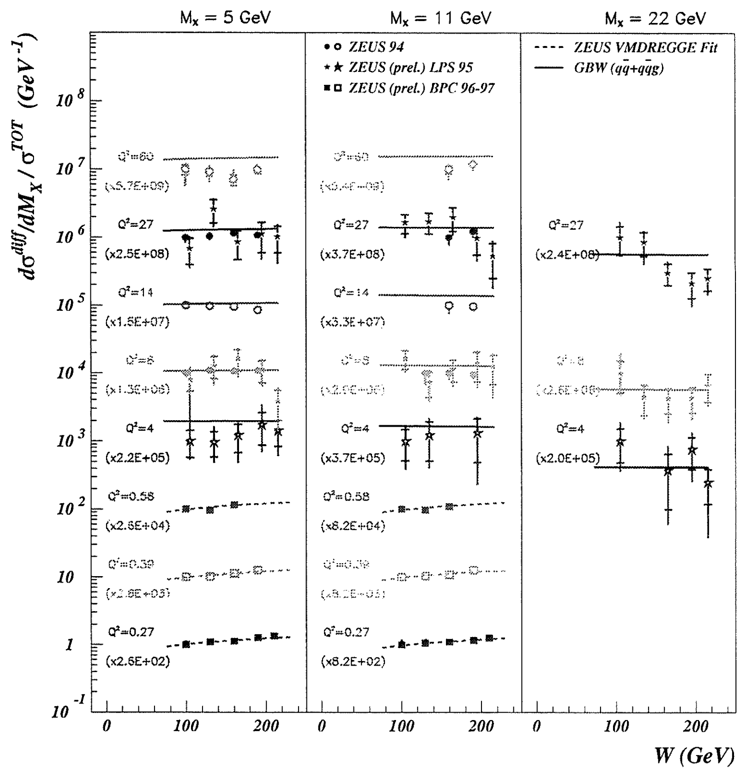
▷ $\hat{\sigma}_{dipole}(x,r) \sim r^2$ for small r (color transparency); saturates at large r

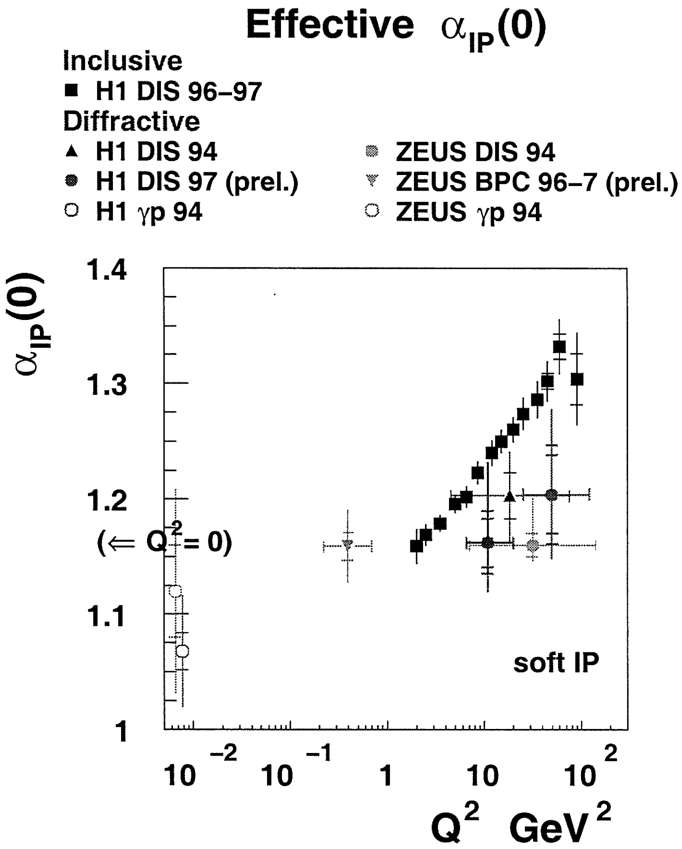
▷ This model (G-BW) is applied to F_2 from which the parameters are fixed

$\sigma^{diff} \sim \int d^2r \int dz |\Psi(z,r)|^2 \hat{\sigma}^2_{dipole}(x,r)$ ▷ Remember to look at 2 and 3 jet events!

Energy dependence of diffractive SF

▷ **Compare** $\alpha_{I\!P}(0)$ **from** $F_2 \sim (\frac{1}{x})^{\alpha_{I\!P}(0)-1}$ **and** $x_{I\!P} F_2^{D(3)} \sim (\frac{1}{x})^{2<\alpha_{I\!P}(t)>-2}$





▷ **Ratio of diff/incl rises with** W **at small** Q^2

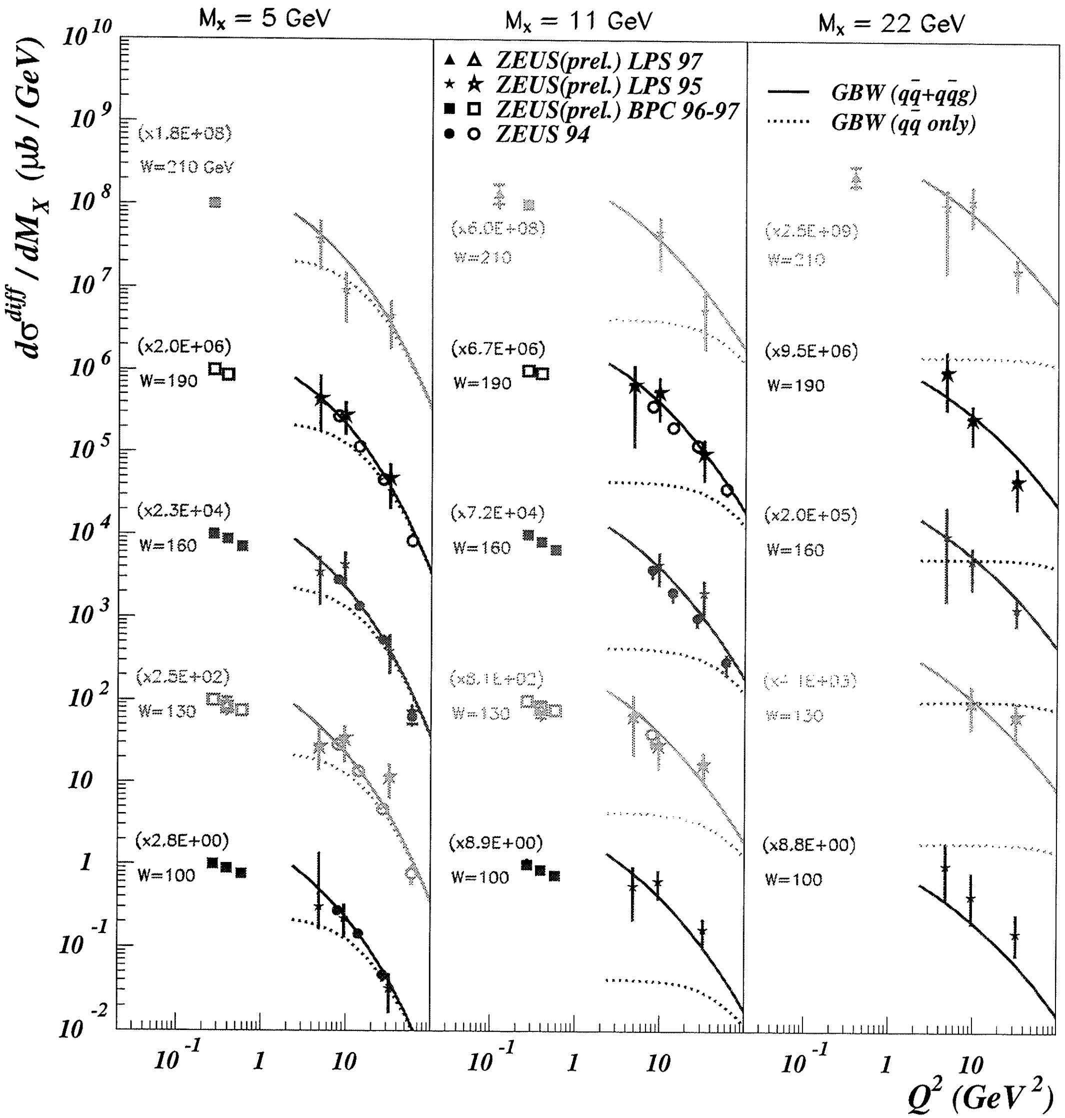
▷ **Independent at high** Q^2

▷ **dipole model OK for** $Q^2 > 4$ **GeV**^{2}

▷ **growth of effective** $\alpha_{I\!P}(0)$ **is slower for diffractive than for the inclusive cross section**

Q^2 dependence of diffraction

Q^2 dependence of the diffractive cross section:



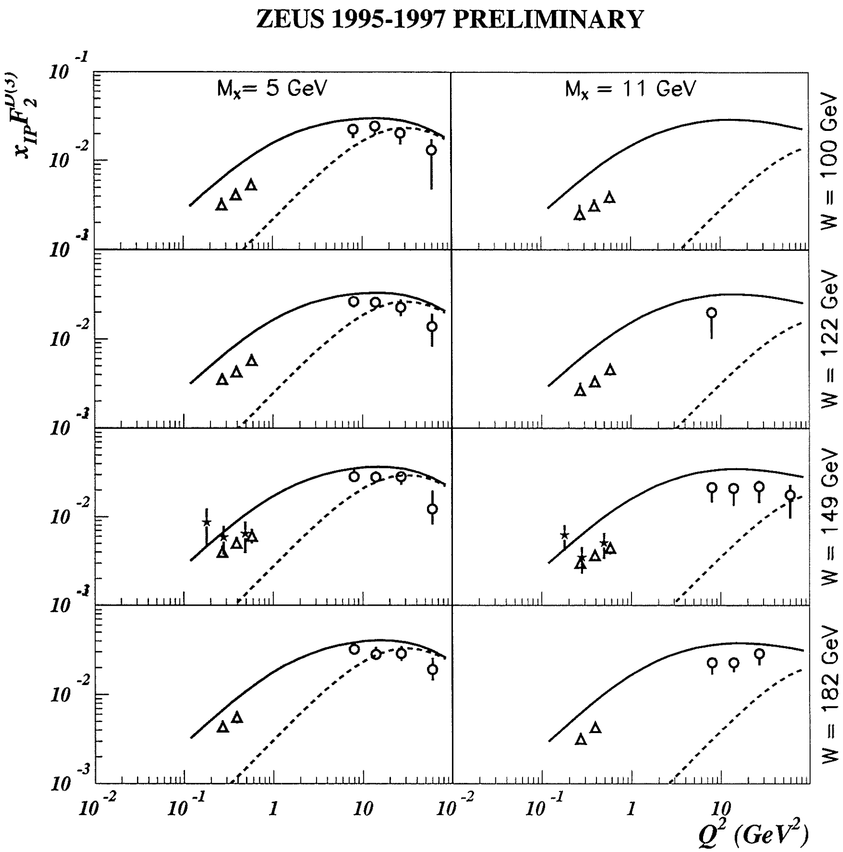
▷ Change in the Q^2 dependence from low Q^2 to DIS

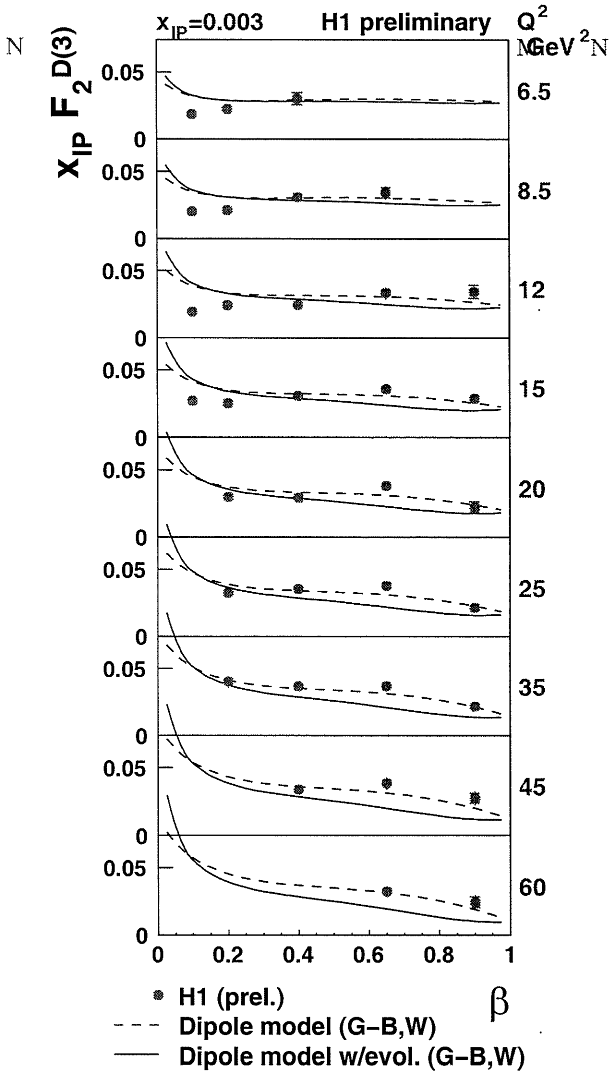
▷ Dipole model gives a reasonable description for $Q^2 > 2$ GeV^2

▷ Dominant $q\bar{q}g$ component at large M_X (or small β)

Q^2 and β dependence of F_2^D

▷ **Measure $x_{I\!P} F_2^{D(3)}$ vs, Q^2 and β:**





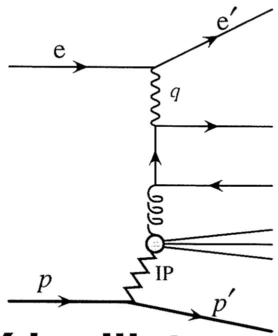
Dipole model (fitted to inclusive F_2 data) describes the main features of diffractive data which also show the need for the $q\bar{q}g$ component at low Q^2 and large M_X

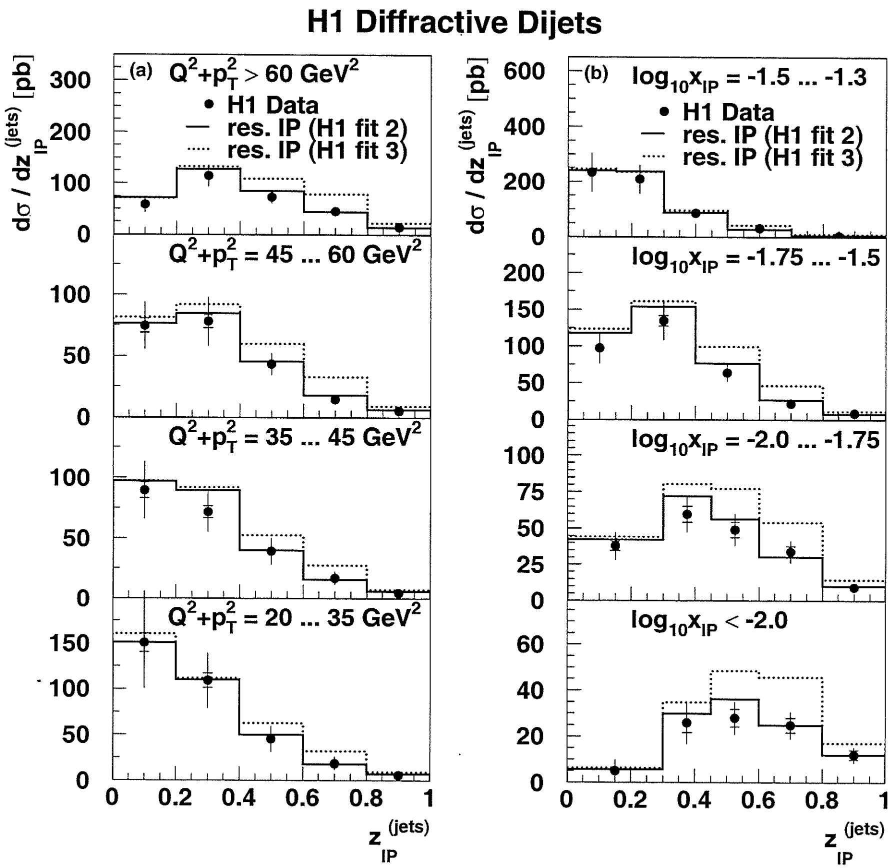
Dijet production in Diffractive events

▷ **Use diffractive PDFs to predict diffractive final states**

Diffractive dijet production:

$$ep \to e' jjXY$$





▷ $z_{I\!P}$ ~ **fraction of energy of X in dijets**

▷ **Sensitive to shape of gluon distribution**

▷ **Good description by the resolved** $I\!P$

▷ **Large and flatter gluon component preferred**

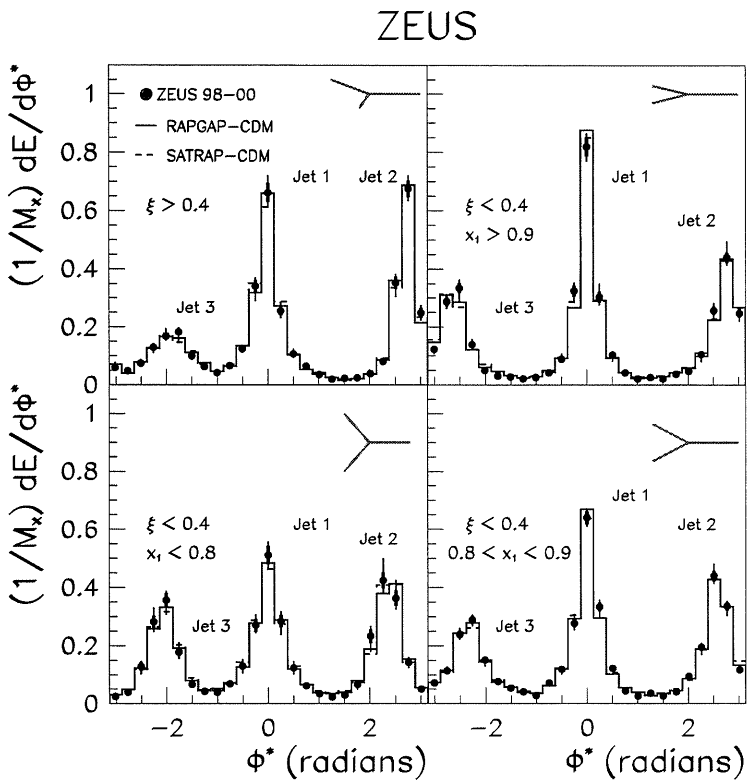
▷ $\alpha_{I\!P}(0)$ **consistent with values from** $F_2^{D(3)}$ **analysis (as a function of** $x_{I\!P}$**)**

▷ **DGLAP evolution holds (as a function of** Q^2**)**

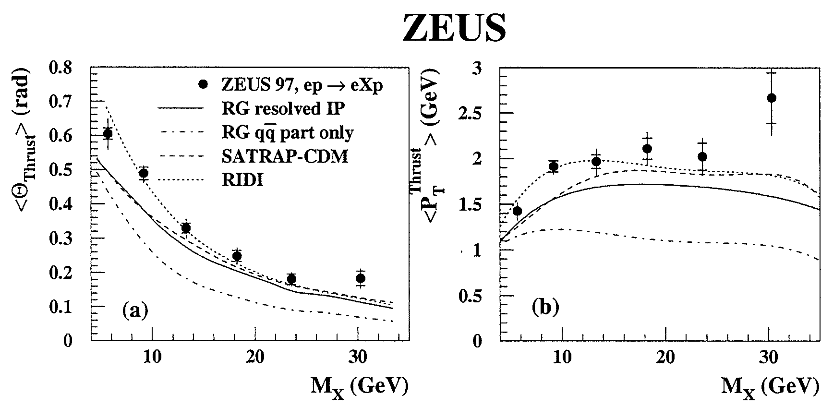
▷ **Results from diffractive charm production - similar conclusions**

Three Jet production in Diffraction

▷ **Clear structure in the energy flow for 3-jet events**



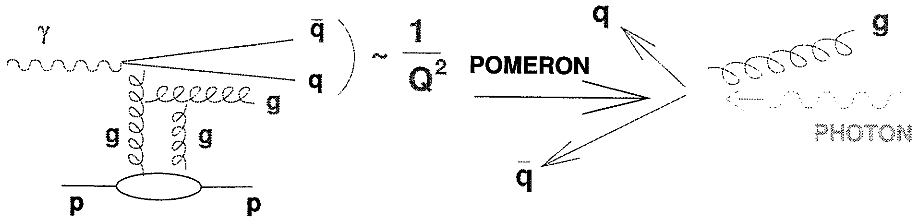
▷ **Study of the mean thrust angle and mean p_T:**



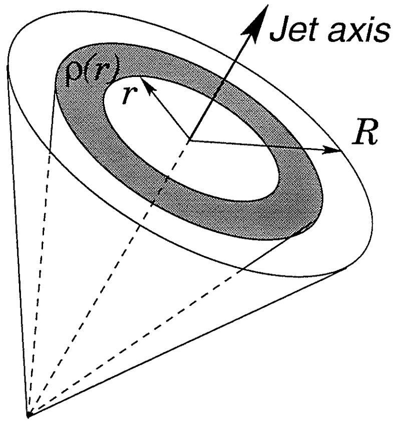
▷ **Clear need for the $q\bar{q}g$ component**

Three Jet production in Diffraction

In pQCD picture:

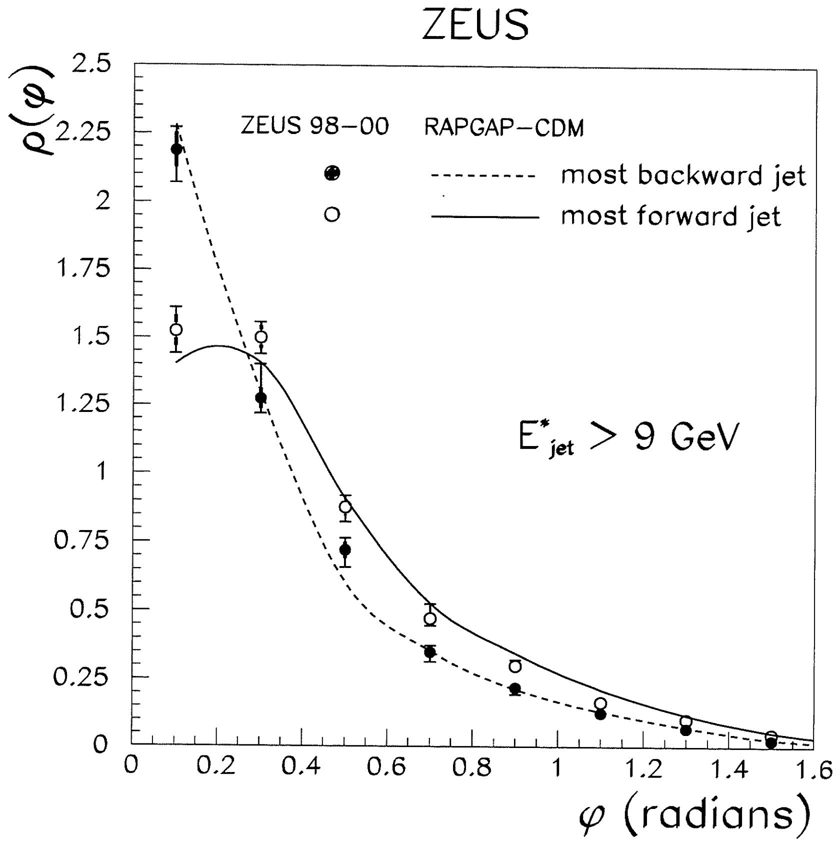


At same jet energy, gluon jets are broader



Plot jet profiles:

$$\rho(r) = \frac{1}{\delta r} \cdot \frac{E_{jet}(r \pm \delta r/2)}{E_{jet}}$$



▷ **Most forward jet broader (g in the $I\!P$ direction)**

▷ **Most backward jet narrower (q in the γ^* direction)**

Agrees with pQCD picture both for resolved $I\!P$ model and for dipole picure

Summary of inclusive hard diffraction

Many new results in diffraction at HERA

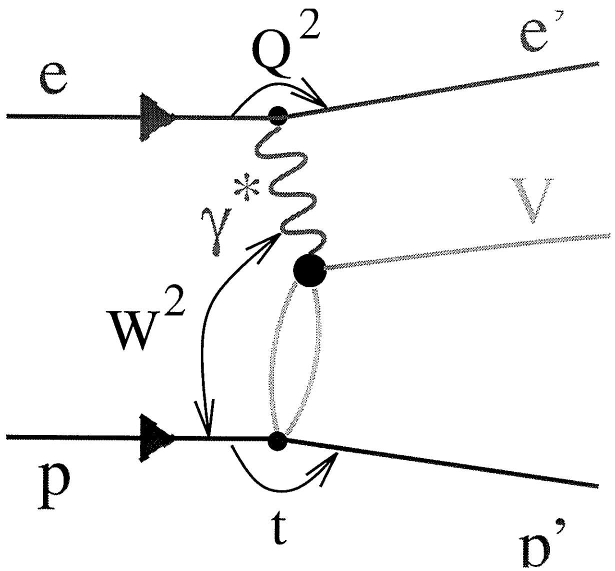
Diffraction:

- ▷ **Hard diffraction is very well established in many processes at HERA**
- ▷ **Can fit data to give diffractive parton densities**
- ▷ **Transition to low Q^2 regime similar to non-diffractive data**
- ▷ **Diffractive jet data consistent with resolved $I\!P$ model $\rightarrow$ gluon dominated $I\!P$**
- ▷ **Diffractive 3-jet data suggest a gluon-remnant from the $I\!P$**
- ▷ **Diffractive PDFs are dominated by the gluon**
- ▷ **What does the $I\!P$ trajectory mean?**

▷ **HERA - ideal place to study evolution schemes and the transition between *"soft"* and *"hard"* physics**

Elastic Vector Meson Production

▷ "Elastic" ⟶ Exclusive vector meson production



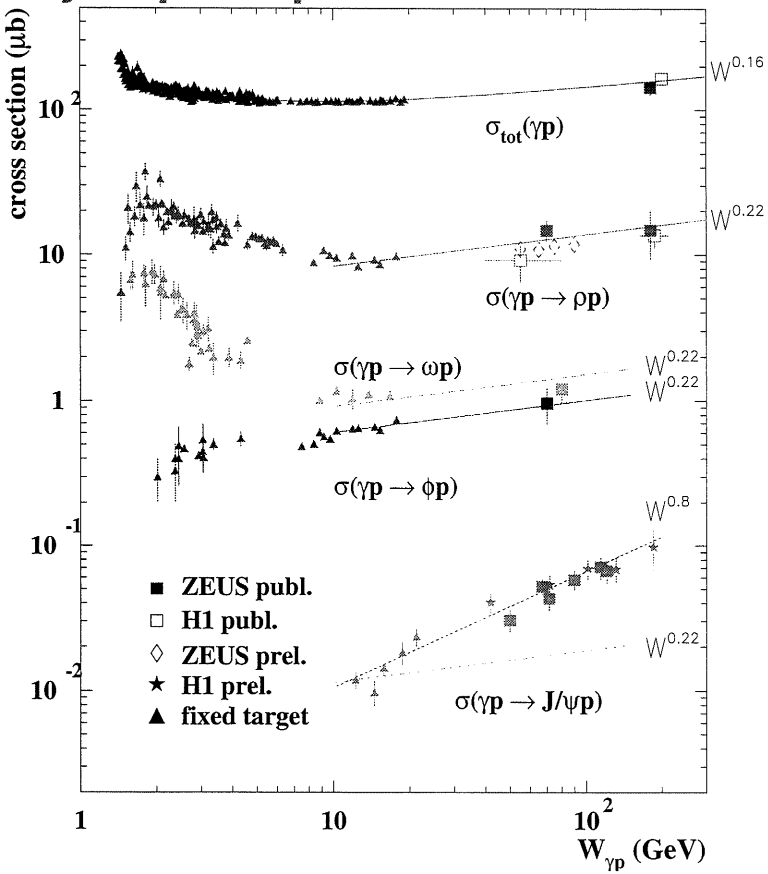
Vector meson production has proven to be an interesting testing ground for comparisons between data and pQCD models and studies of the transition from soft (non-perturbative) to hard scattering.

The different variables provide scales which can be either soft or hard:

Q^2	γ^* virtuality	$0 < Q^2 < 100$ GeV^2
W	$\gamma^* p$ cm energy	$20 < W < 290$ GeV
t	4-mom. transfer squared	$0 < \lvert t \rvert < 20$ GeV^2
VM	Vector meson mass	$\gamma, \rho^0, \omega, \phi, J/\psi, \psi', \upsilon$

Photoproduction of Vector mesons

Summary of photoproduction cross sections:



Fits are to W^{δ}:

Regge expectations:

$$\delta \sim 4(\alpha_{IP}(0) - \alpha'_{IP}/b - 1)$$
$$\sim 4(1.08 - 0.25/6 - 1) \sim 0.2$$

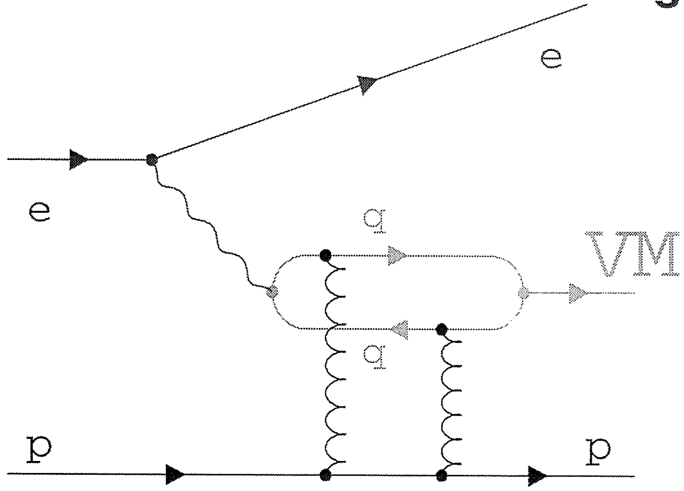
Note: J/ψ **is very different**

Regge model OK for $Q^2 = 0$ and light VM where there is no large scale present

Regge model fails for $Q^2 = 0$ and heavy VM where the mass of the J/ψ provides the large scale

PQCD expectations

Calculations are based on the diagram:



pQCD in lowest order (for color singlet exchange) is 2-gluon exchange

$$\sigma \sim [xg(x,Q^2)]^2 \sim [x^{-0.2}]^2,$$

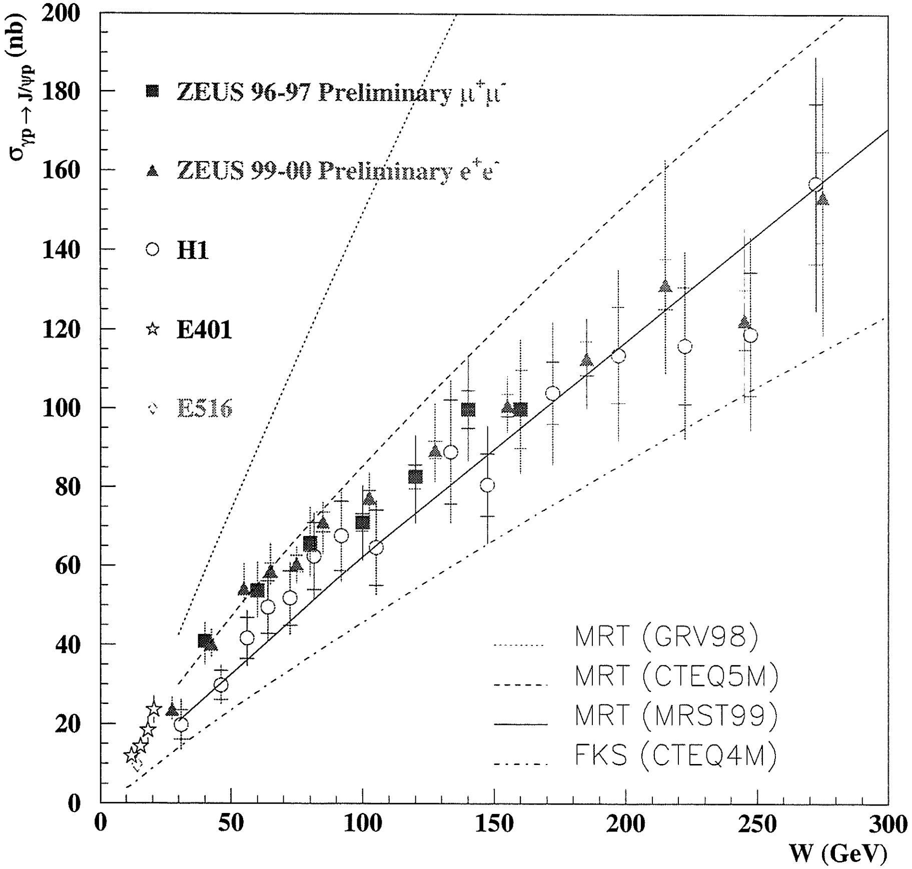
$$x = \frac{Q^2 + M_V^2}{W^2}$$

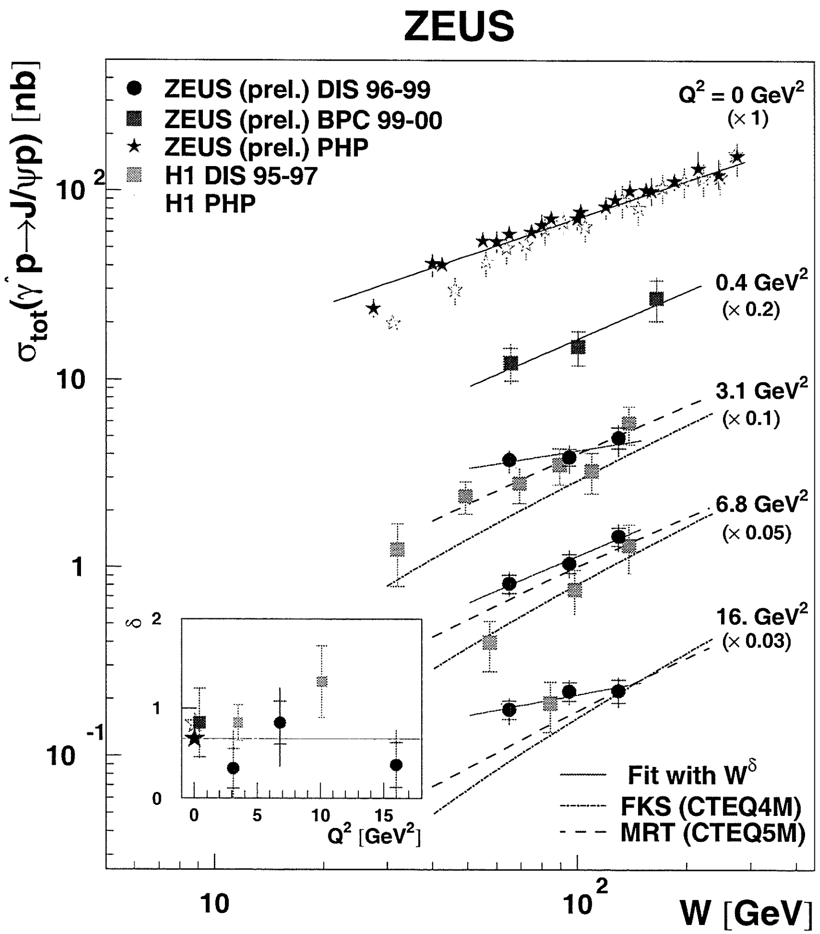
Expect:

- steep rise with W: $\sigma \sim W^{\delta}, \delta \sim 0.8$
- at large $|t|$: $d\sigma/dt \propto (-t)^n \rightarrow$ weaker dependence than at low $|t|$
- LO BFKL cross section calculations at large $|t| >$ few GeV^2
- universal b slope for t dependence: $e^{-b_{2g}|t|}$,
  with b_{2g} ~4-5 GeV^{-2}, independent of W, α' = 0; no shrinkage
- approximate restoration of flavor-independence:
  γ^* couples to quarks: $\rho : \omega : \phi : J/\psi$ as 9: 1(0.8): 2(1.2): 8(3.5)

J/ψ production at $Q^2 = 0$

▷ Measure the W dependence of the J/ψ cross section at different values of Q^2:



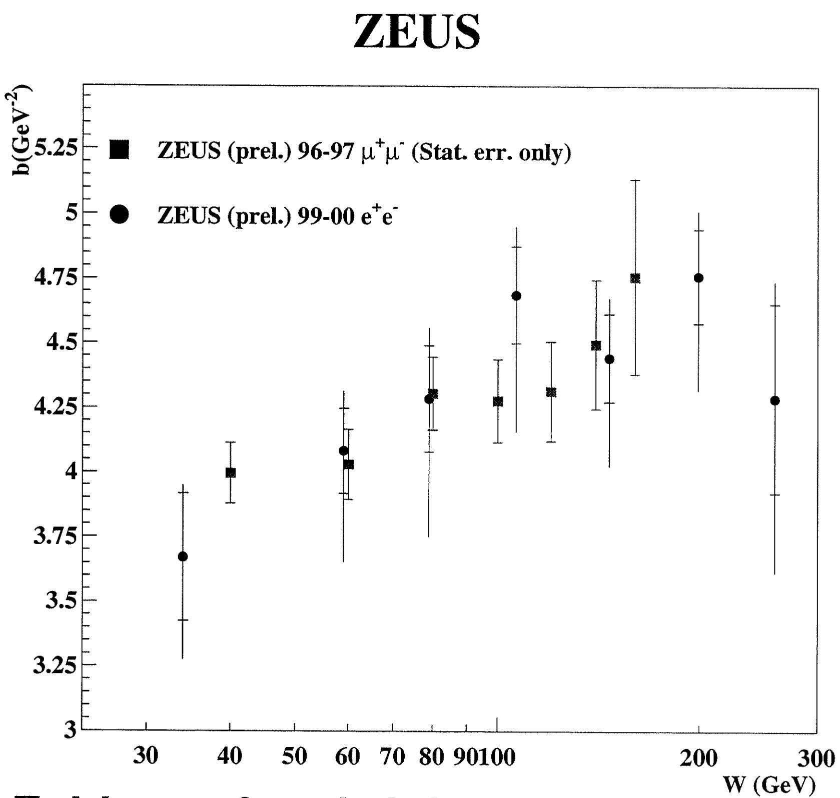


The gluon density $xg(x, Q^2)$ is the cause of both inclusive F_2 and the J/ψ elastic cross section rise with energy

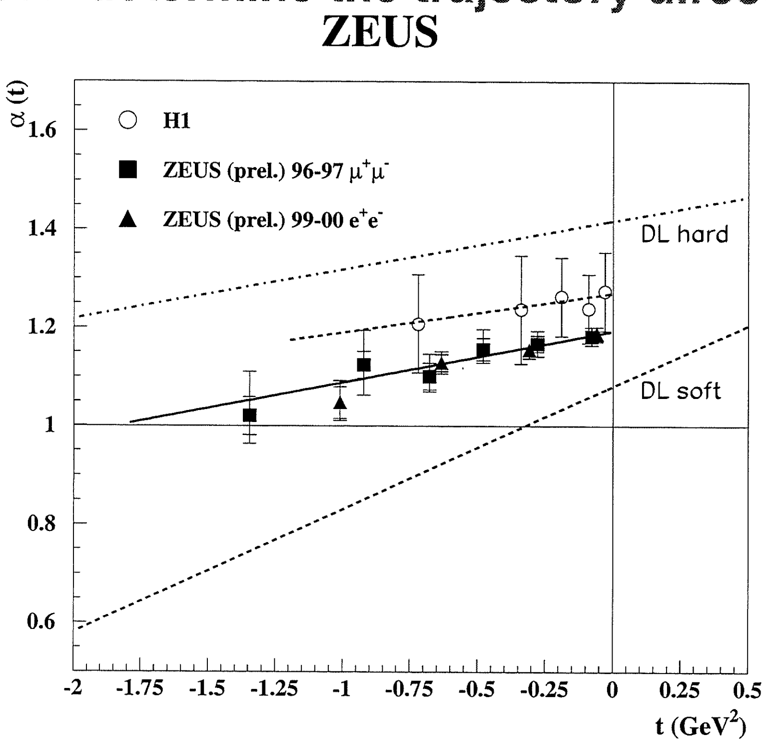
Little variation in δ with Q^2 for J/ψ production – $M^2_{J/\psi}$ is a hard scale

J/ψ production at $Q^2 = 0$

▷ **Slope b of the t distribution ($d\sigma/dt \sim e^{bt}$):**



▷ **Can determine the trajectory directly:**



▷ **Evidence for shrinkage**

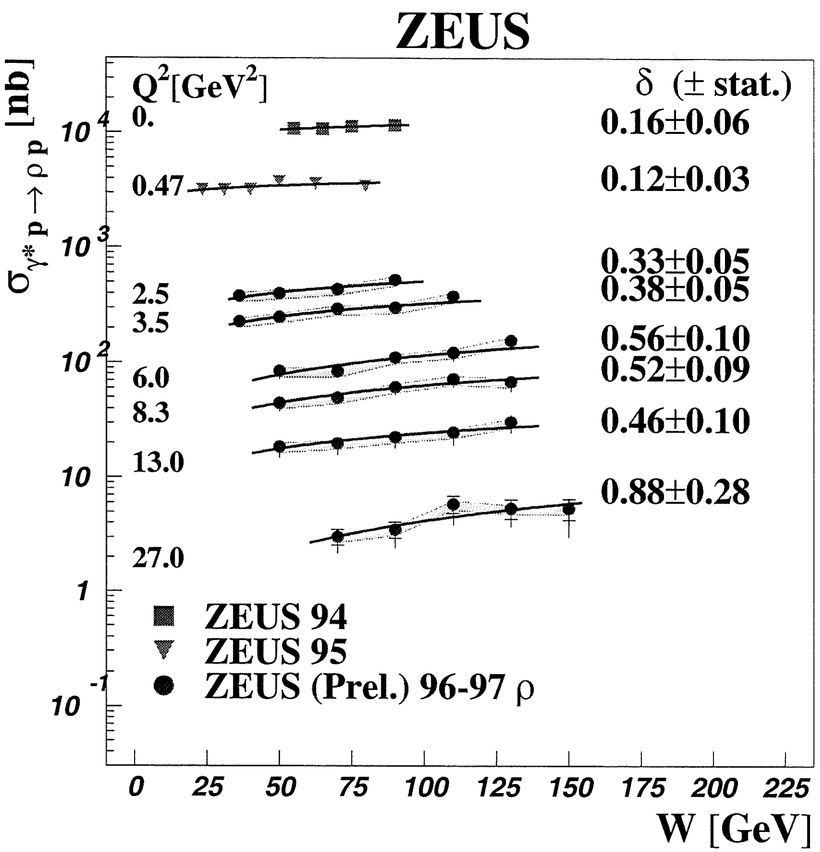
(1) $\alpha'_{IP} = 0.116 \pm 0.024(stat.)^{+0.012}_{-0.022}(syst.)$ **GeV**$^{-2}$

(2) $\alpha_{IP}(0) = 1.2 \pm 0.008(stat.)^{+0.003}_{-0.008}(syst.)$

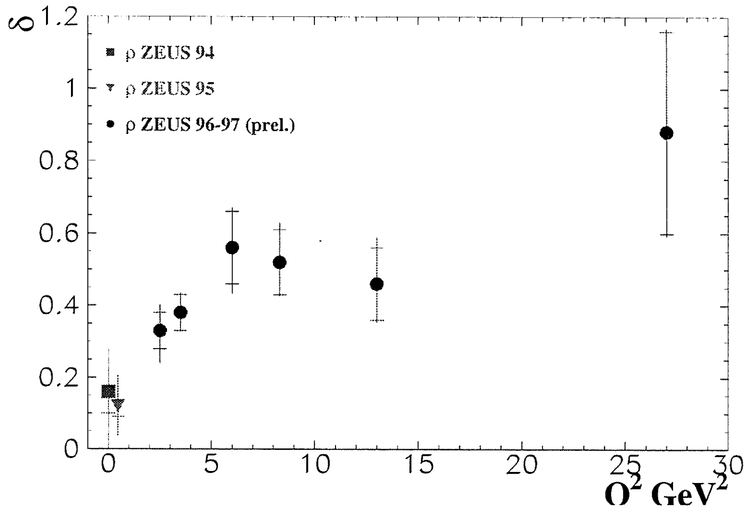
(3) $\alpha'_{IP} = 0.113 \pm 0.018(stat.)^{+0.009}_{-0.014}(syst.)$ **GeV**$^{-2}$

Rho meson in DIS (1)

▷ **Measure the ρ cross section vs W for different Q^2:**



Fits of $\sigma \sim W^\delta$ yield:

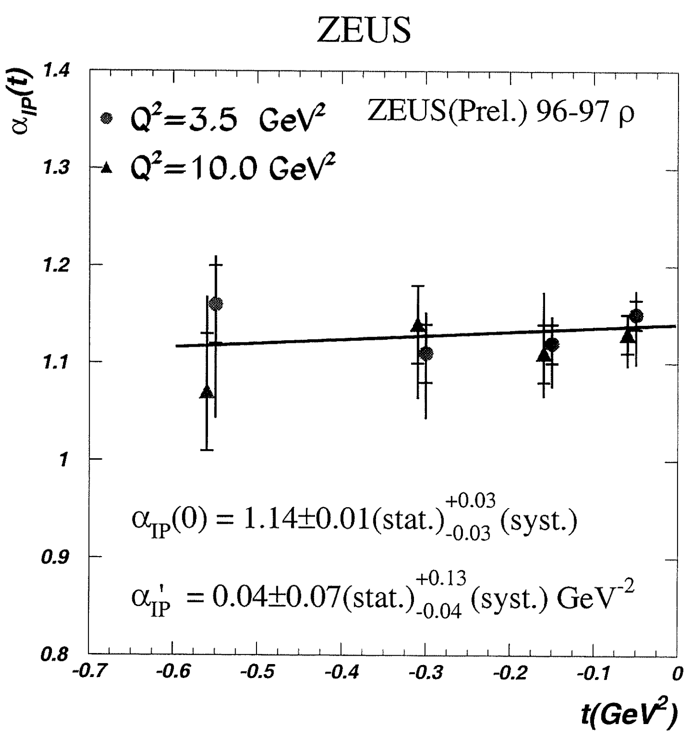


▷ **Transition from soft $\to$ hard regime**

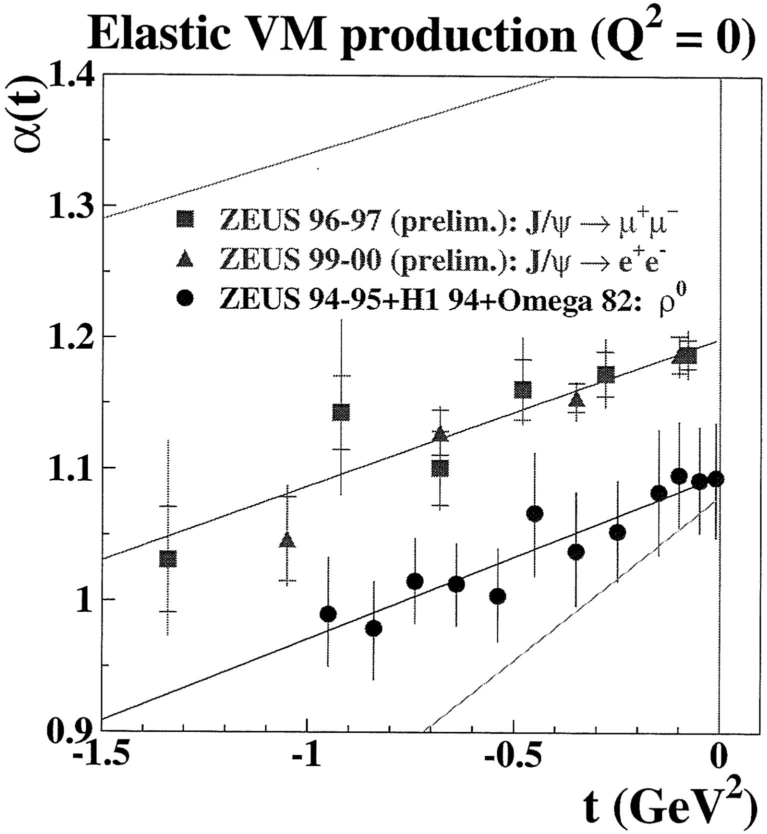
▷ **Energy dependence steepens with Q^2, reaching a hard-scale regime, $\delta \sim 0.7$, as for J/ψ**

Rho meson in DIS (2)

▷ **Determine the $I\!P$ trajectory**



Compare with other VM $I\!P$ determinations:

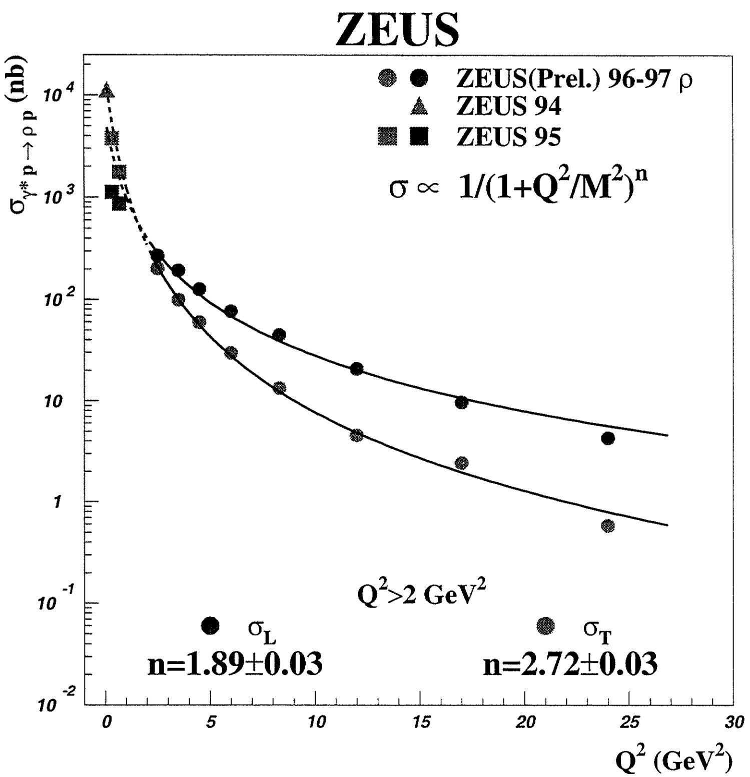


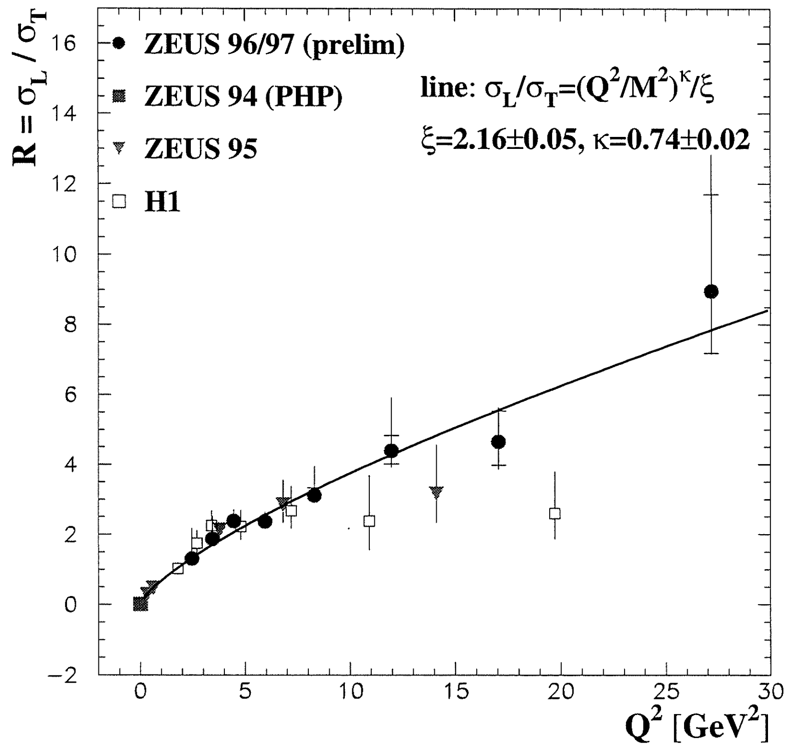
Green lines are the hard and soft $I\!P$

Conclusion: Intercept larger and slope smaller than for the soft $I\!P$

$Q2$ dependence of R

▷ Study the Q^2 dependence of $R = \frac{\sigma_L}{\sigma_T}$ (obtained from the decay angular distributions):



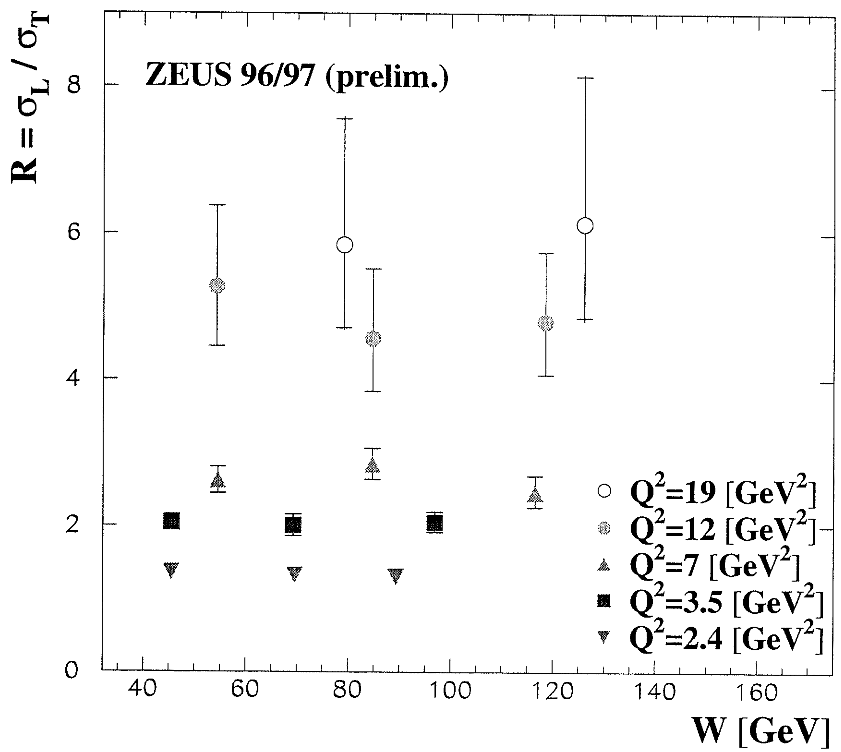


Early pQCD prediction for different Q^2 dependence for σ_L and $\sigma_T \to R$ should increase with Q^2

In agreement with the data

W dependence of R

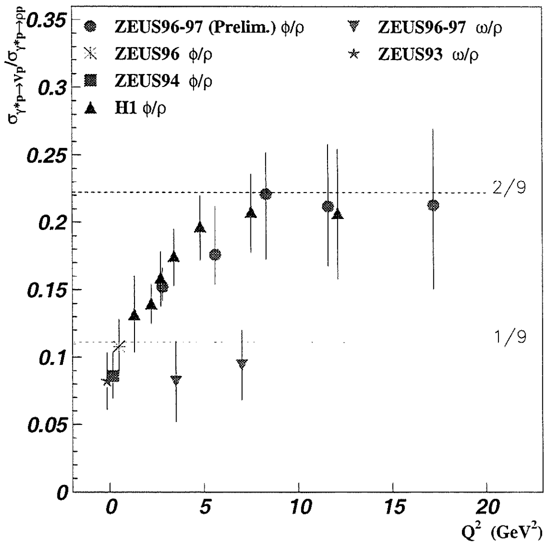
▷ **Study the W dependence of R:**

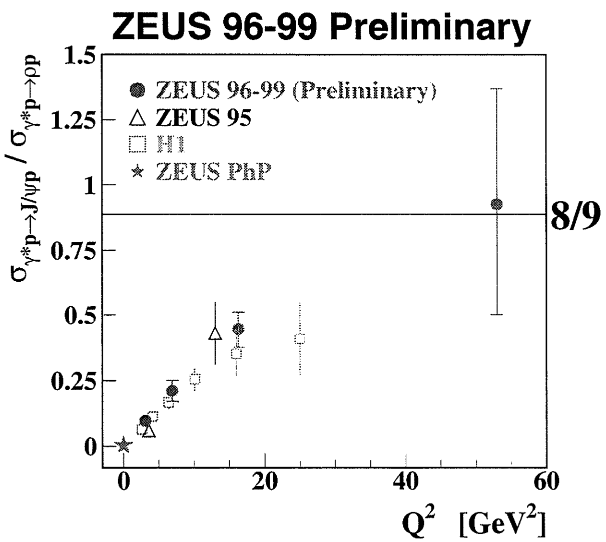


There is little W dependence for all Q^2 values
Is the dipole size independent of the γ^* polarization?

Scaling of Vector meson cross sections (1)

▷ **Compare with the naive SU(4) factors:**





Look as a function of $(Q^2 + M_V^2)$:

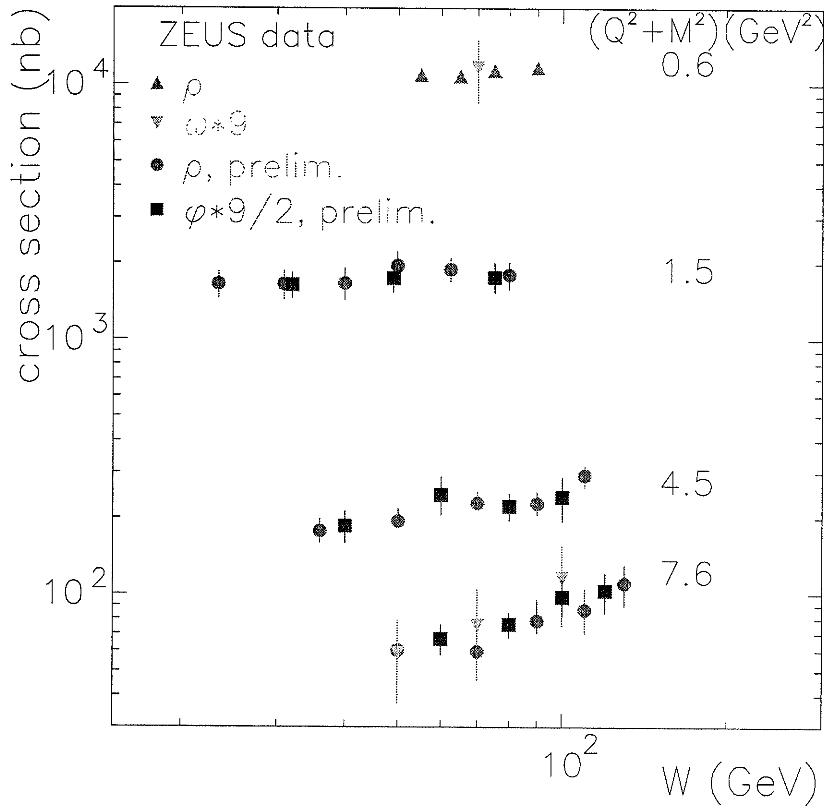
The plot is not here yet

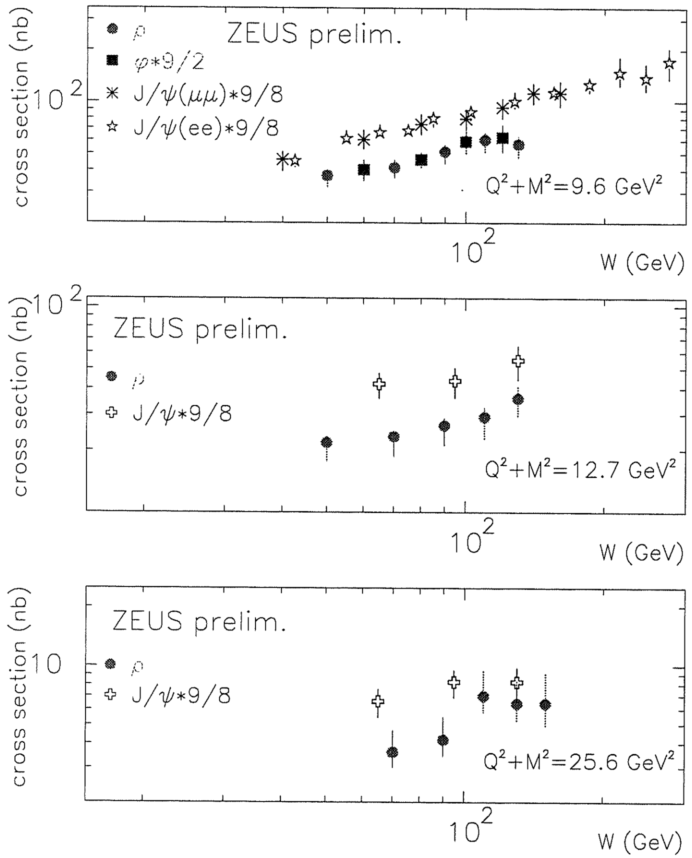
The J/ψ data do not seem to fit in this pattern?

▷ **Approach to SU(4) varies with mass of VM**

Scaling of Vector meson cross sections (2)

▷ **Look in more detail – at fixed values of $(Q^2 + M_V^2)$ as a function of W:**





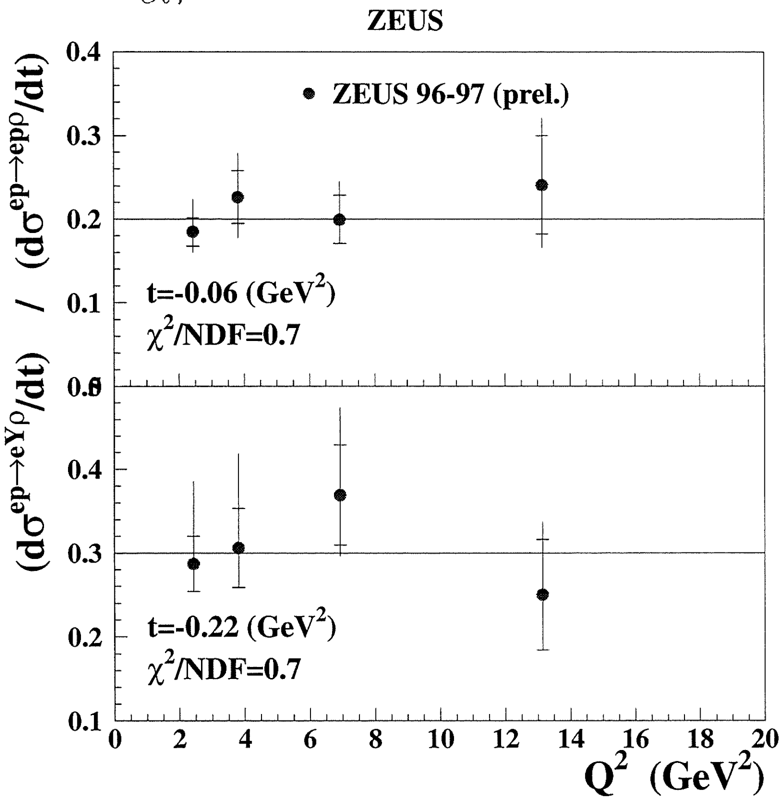
Light vector mesons track as a function of $(Q^2 + M_V^2)$

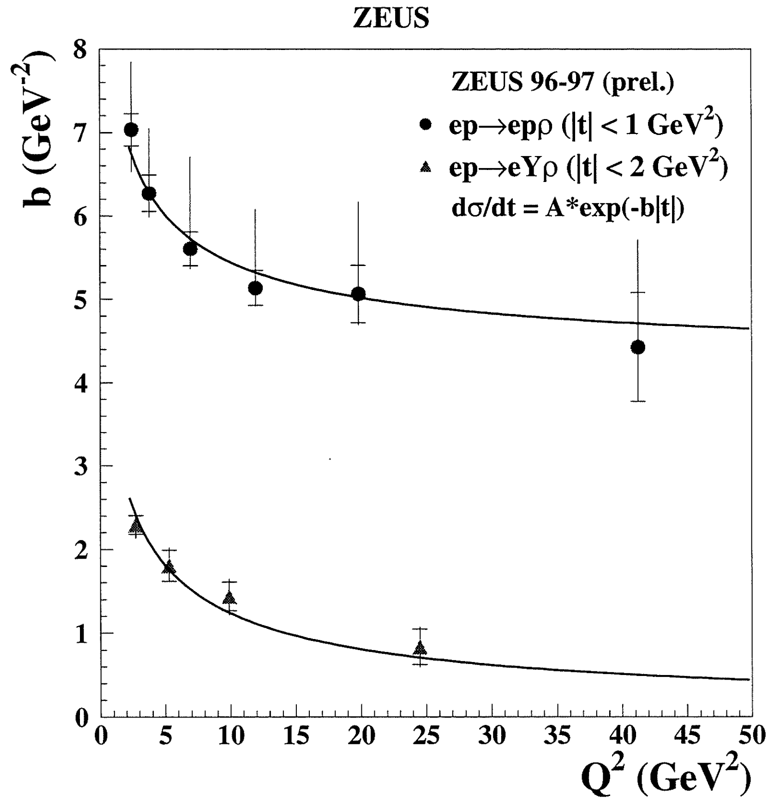
But the J/ψ do not

Tests of limiting fragmentation

▷ **Expect** $\frac{d^2\sigma_{pdis}/dtdM_X^2}{d\sigma_{el}/dt} \propto (\frac{g_{\gamma^*\rho}\cdot G_{pX}}{g_{\gamma^*\rho}\cdot g_{pp}})^2 = f(t, M_X)$ **where the** g, G**s are vertex functions. After integrating over** t**, assuming an exponential** t **dependence:**

▷ **Expect** $\frac{d\sigma_{pdis}/dt}{d\sigma_{el}/dt} = f_1(t)$ **and** $b_{el} - b_{pdis} = f_2$ **independent of** Q^2

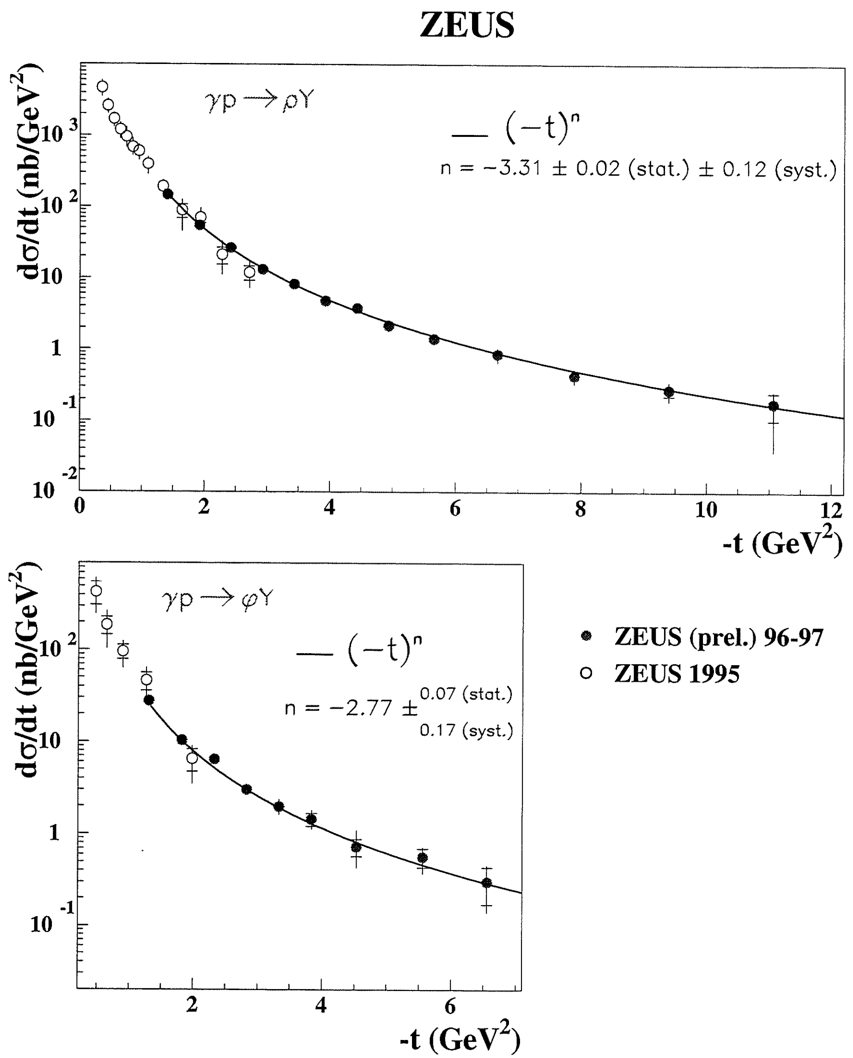




Data are in excellent agreement with the hypothesis

Vector mesons at high $|t|$

▷ **At high $|t|$, the proton breaks up – proton dissociation:**



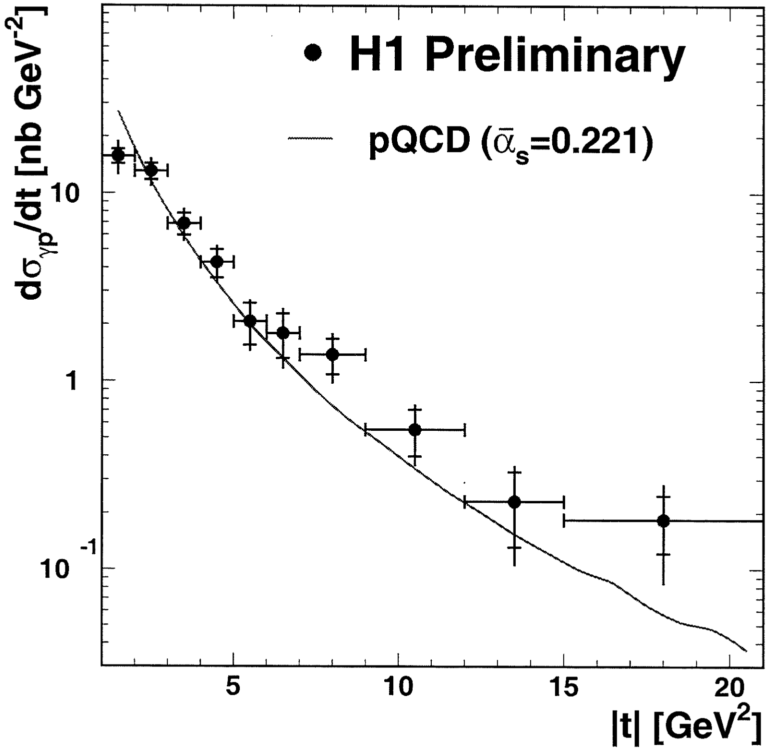
$$\sigma \sim (-t)^n$$

$n \sim 3$ **for both** ρ **and** ϕ

A power law, rather than the exponential observed at low $|t|$

VM cross sections at high $|t|$

▷ Several pQCD calculations for J/ψ cross section:
plot to come



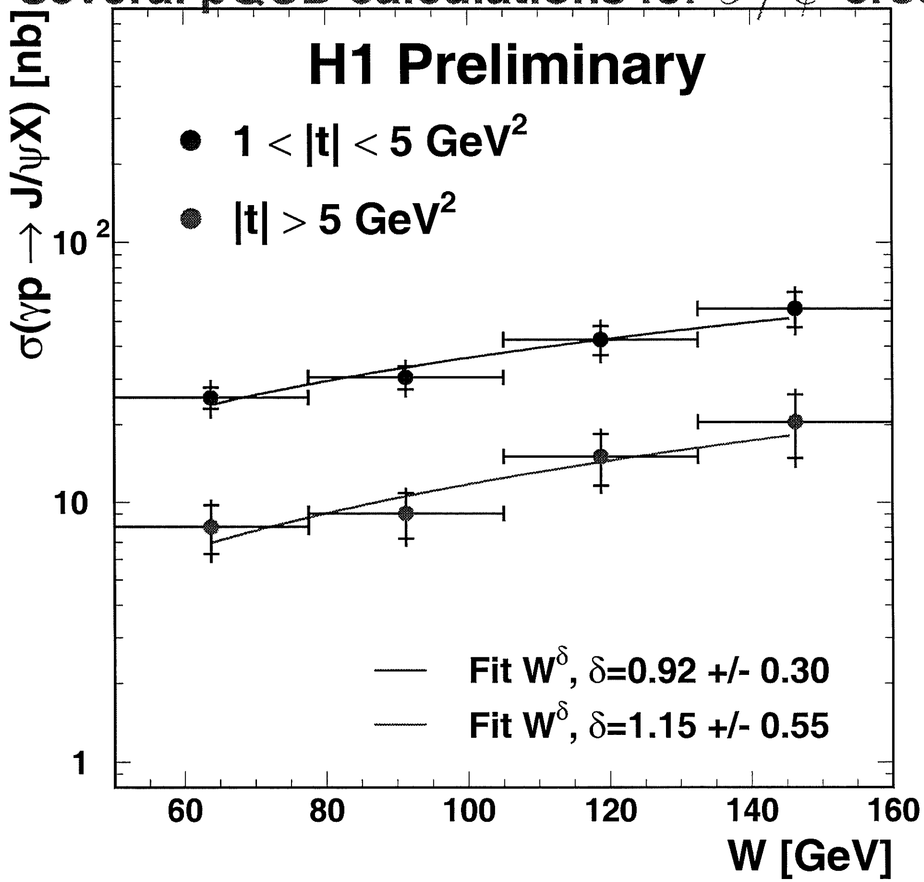
Large theoretical normalization uncertainty

$\sigma \sim (-t)^n$ with $n \sim 1.7$ for J/ψ

Shape of data well described by BFKL but large theory normalization uncertainty

VM cross sections at high $|t|$

▷ Several pQCD calculations for J/ψ cross section:



W **dependence at high $|t|$ is similar to that at low $|t|$**

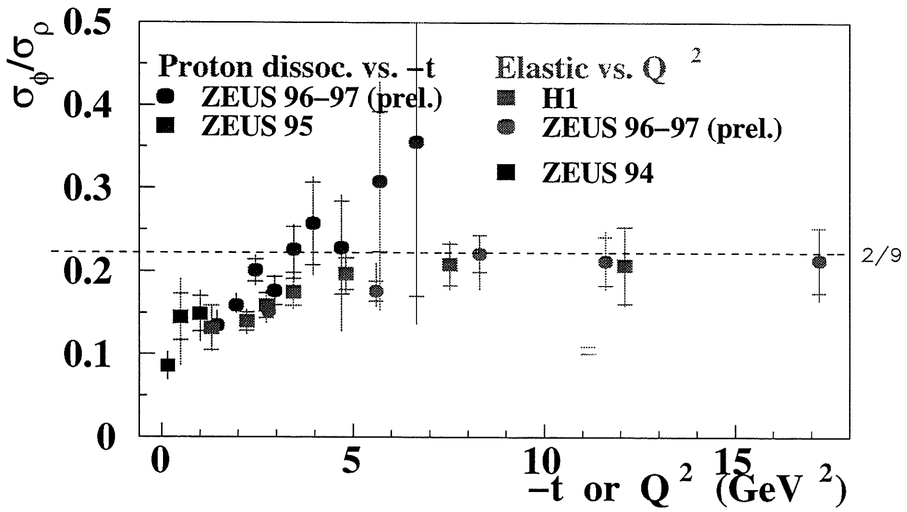
LO BFKL: $\sigma \propto W^{4(a_P(0)-1)}$

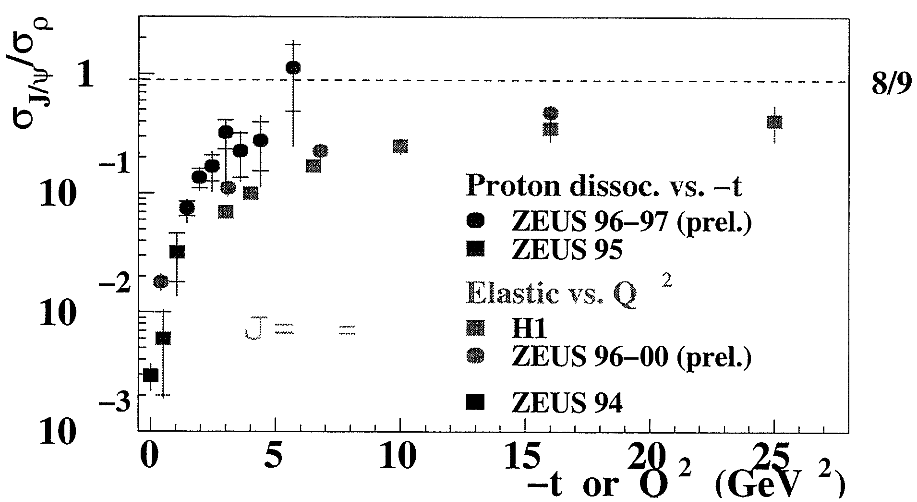
with $a_P(t) = 1 + 4\bar{\alpha_s} ln2$

$\bar{\alpha_s} \sim$ **0.2 gives fair agreement in $|t|$ and** W

t dependence of vector mesons

▷ Can $|t|$ also serve as a large scale?





Conclusion:

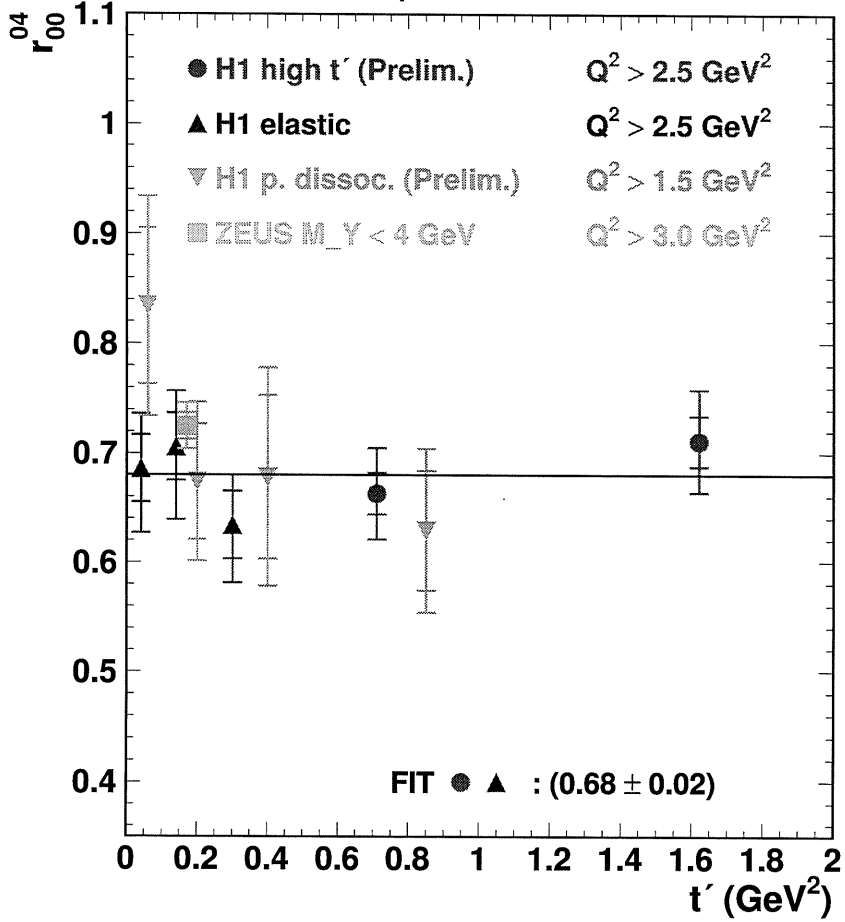
At small $|t|$ and Q^2: the rise in $|t|$ is steeper than for Q^2

At large $|t|$, it does appear to approach the SU(4) expectation

Helicity analysis at high $|t|$

▷ **Study the transitions between γ and VM helicity states**

H1 ρ Production



Look at helicity amplitudes: $T_{\lambda_{VM}} T_{\lambda_\gamma}$

SCHC: expect only $\gamma_T \rightarrow \rho_T$, $\gamma_L \rightarrow \rho_L$ **transitions**

$W(cos\theta) \propto 1 - r_{00}^{04} + (3r_{00}^{04} - 1)cos^2\theta$

$r_{00}^{04} \propto |T_{01}|^2 + |T_{00}|^2$

$R = \frac{1}{\epsilon}\frac{r_{00}^{04}}{1-r_{00}^{04}}$

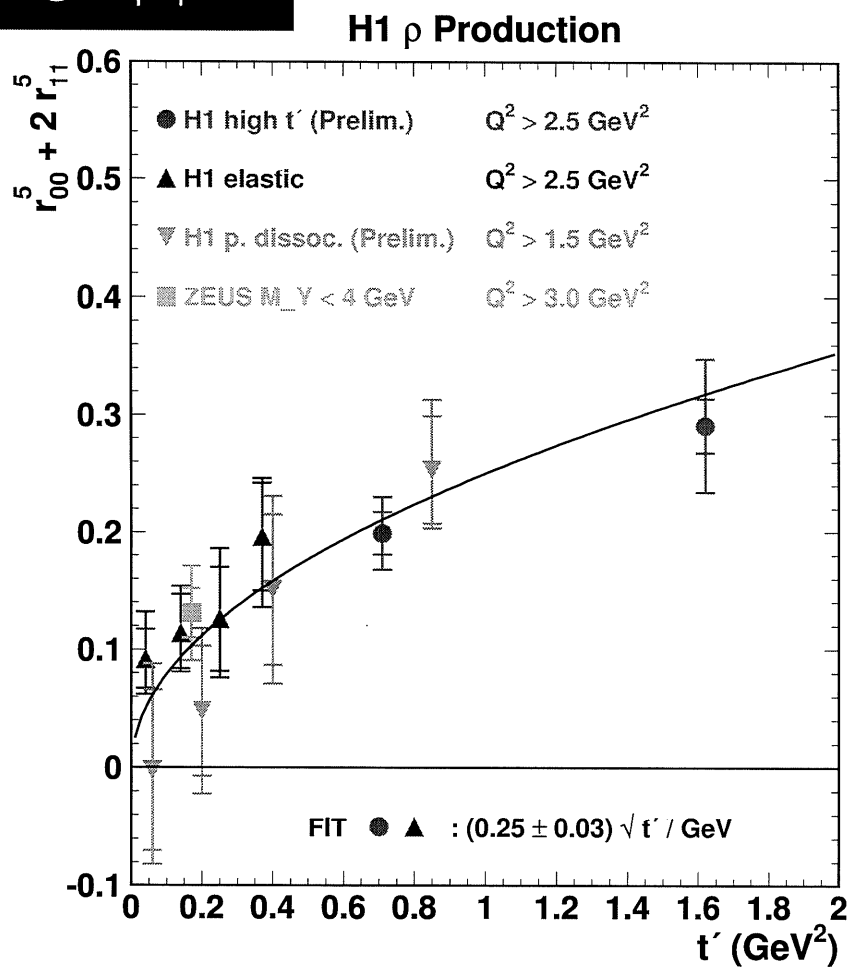
▷ **little $|t|$ dependence**

▷ **proton dissociation similar to elastic**

$\rightarrow$ **vertex factorization**

Helicity analysis at high $|t|$

$$W(cos\phi) \to r^5_{00} + 2r^5_{11}$$
$$r^5_{00} \propto T_{00}T^*_{01}$$
$$r^5_{11} \propto T_{10}T^*_{11} + T_{10}T^*_{1-1}$$

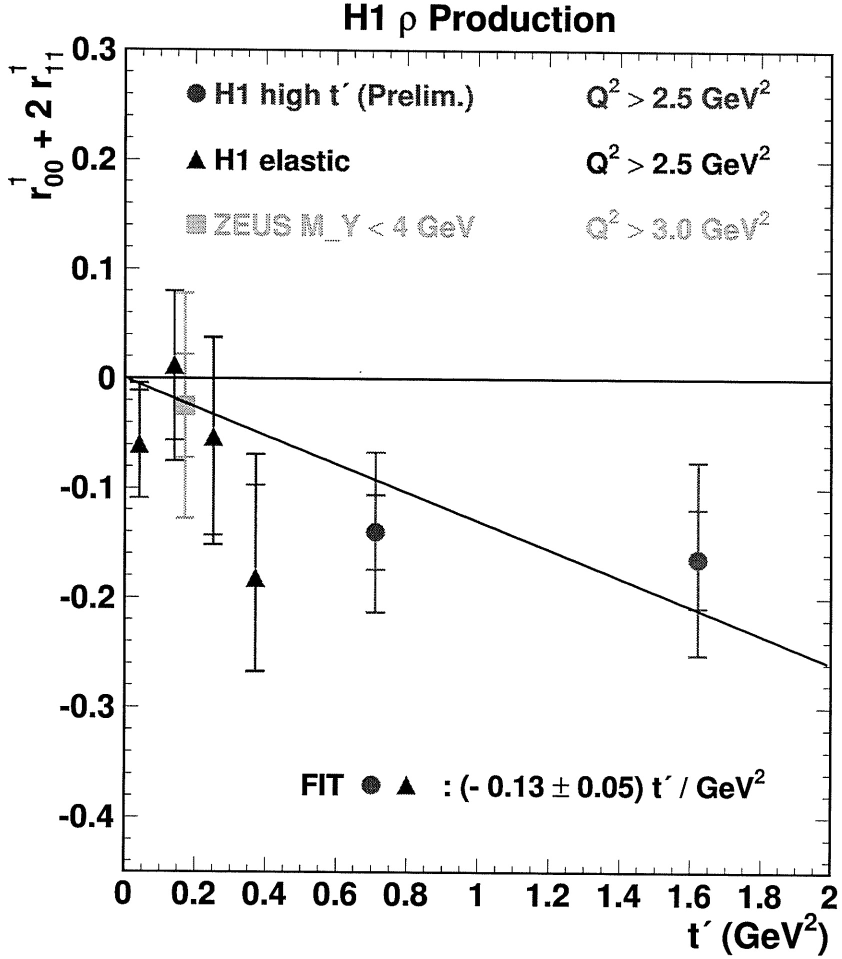


SCHC violation observed

The curve is pQCD motivated $\sqrt{-t}$ fit

Helicity analysis at high $|t|$

$$W(cos2\phi) \rightarrow r^1_{00} + 2r^1_{11}$$
$$r^1_{00} \propto -|T_{01}|^2$$
$$r^1_{11} \propto T_{1-1}T^*_{11} + T_{11}T^*_{1-1} \rightarrow$$ **double flip transition**

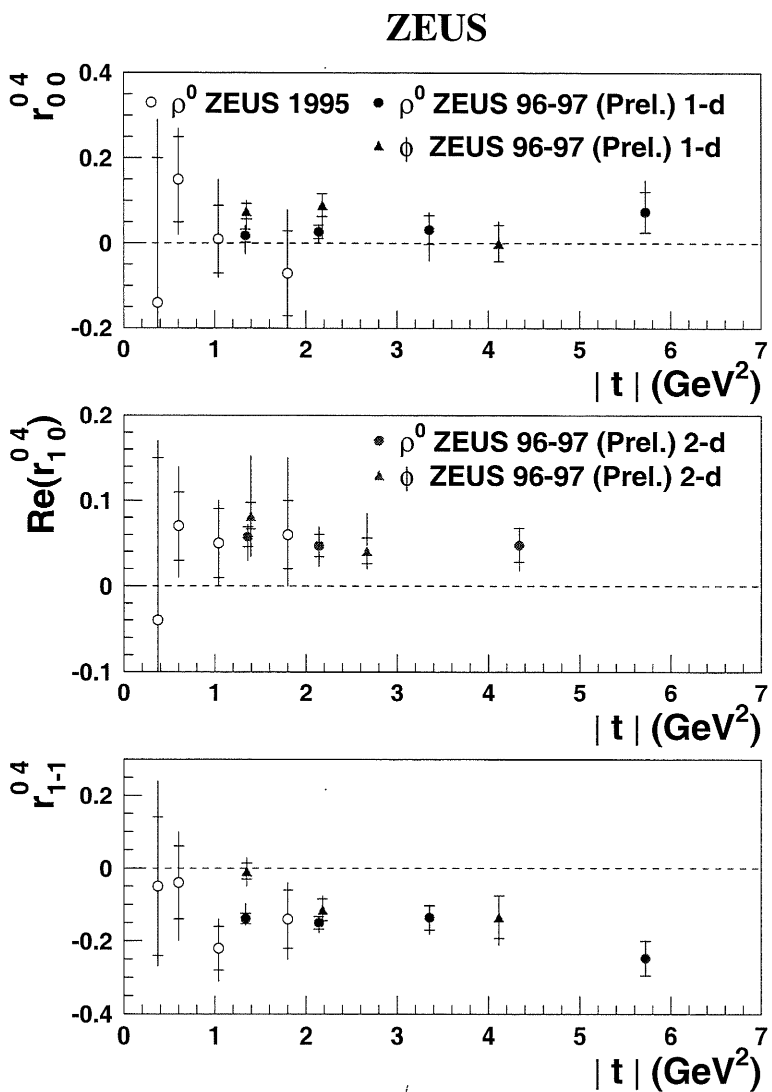


Data are described by pQCD-inspired fits

Helicity analysis at high $|t|$

$$W(cos^2\theta)$$
$$r^{04}_{00} \propto -|T_{01}|^2$$
$$W(sin2\theta cos\phi)$$
$$Re(r^{04}_{10}) \propto Re(T_{11}T^*_{01})$$
$\sigma T \rightarrow \rho_L$ **at a few %**
$$W(sin^2\theta cos2\phi)$$
$$r^{04}_{1-1} \propto Re(T_{11}T^*_{1-1})$$

Double flip tranmsition is non-zero



Results for ρ and ϕ are similar

Summary of vector meson production

▷ Exclusive VM production at HERA is an abundant source of pQCD tests of the soft/hard transition

▷ Signs of reaching the perturbative regime:

- SU(4) expectations approached?
- Strong W dependence for the cross section?
- Little shrinkage of the diffractive peak?
- Power law $(-t)^n$ dependence?

▷ These seem to be attained when:

- High Q^2?
- High M^2_{VM} i.e. $M^2_{J/\psi}$)?
- High t?

▷ SCHC violated at large $|t|$

▷ LO BFKL calculations describe the shape but with a large normalization uncertainty