Diffraction at HERA

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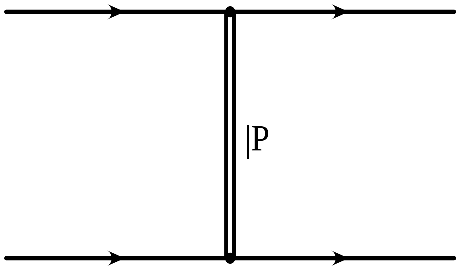
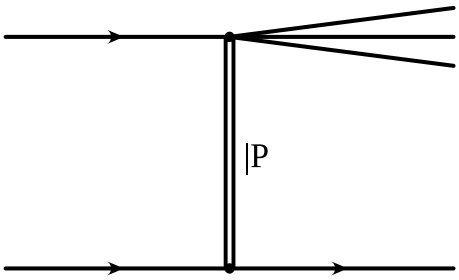
Presented for the H1 and ZEUS callaborations

- Exclusive diffractive processes
  - Vector meson production
  - DVCS
- Inclusive diffraction
  - Main characteristics
  - Diffractive structure functions
  - Hadronic final state
- Conclusions

Diffraction in soft interactions

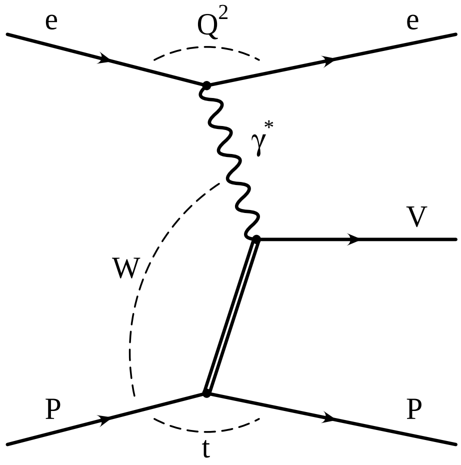




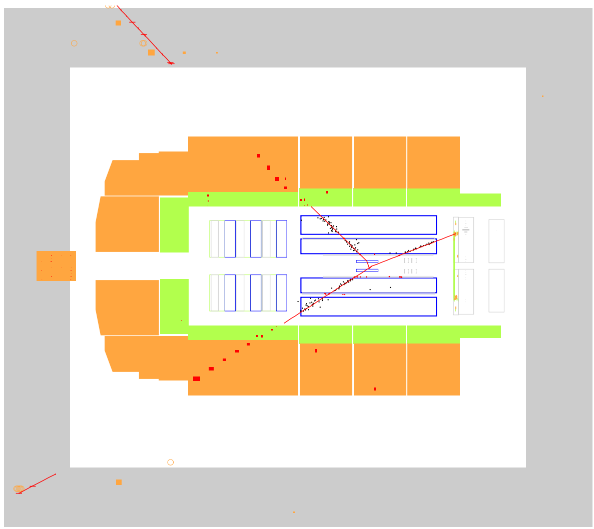
- **Pomeron trajectory** $\alpha_{I\!P}(t) = 1.08 + 0.25t$
- **Total cross section**
  - $\sigma_{TOT} \sim s^{\alpha_{I\!P}(0)-1} \sim s^{0.08}$
- **Elastic cross section**
  - $\frac{d\sigma^{el}}{dt} \sim s^{2(\alpha_{I\!P}(0)-1)} e^{2(b_0+\alpha'_{I\!P} lns)t}$
  - $\frac{d\sigma^{el}}{dt} \sim e^{bt} \qquad b \sim 10 \text{ GeV}^{-2}$
- **Diffractive cross section**
  - $\frac{d\sigma^{D}}{dt dM_x^2} \sim \frac{1}{M_X^2} \left(\frac{s}{M_X^2}\right)^{2(\alpha_{I\!P}(0)-1)} e^{2(b_0+\alpha'_{I\!P} ln\frac{s}{M_x^2})t}$
  - $\frac{d\sigma^{D}}{dt} \sim e^{bt} \qquad b \sim 7 \text{ GeV}^{-2}$
  - $\frac{d\sigma^{D}}{dM_X^2} \sim \frac{1}{M_X^2}$

Kinematics

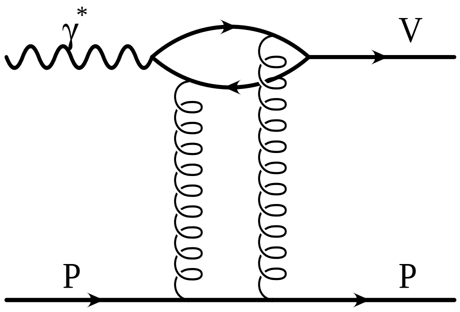
- $-Q^2 = (p_e - p_{e'})^2$
- $t = (p_p - p_{p'})^2$
- $W^2 = (p_\gamma + p_p)^2$



Event selection



QCD models

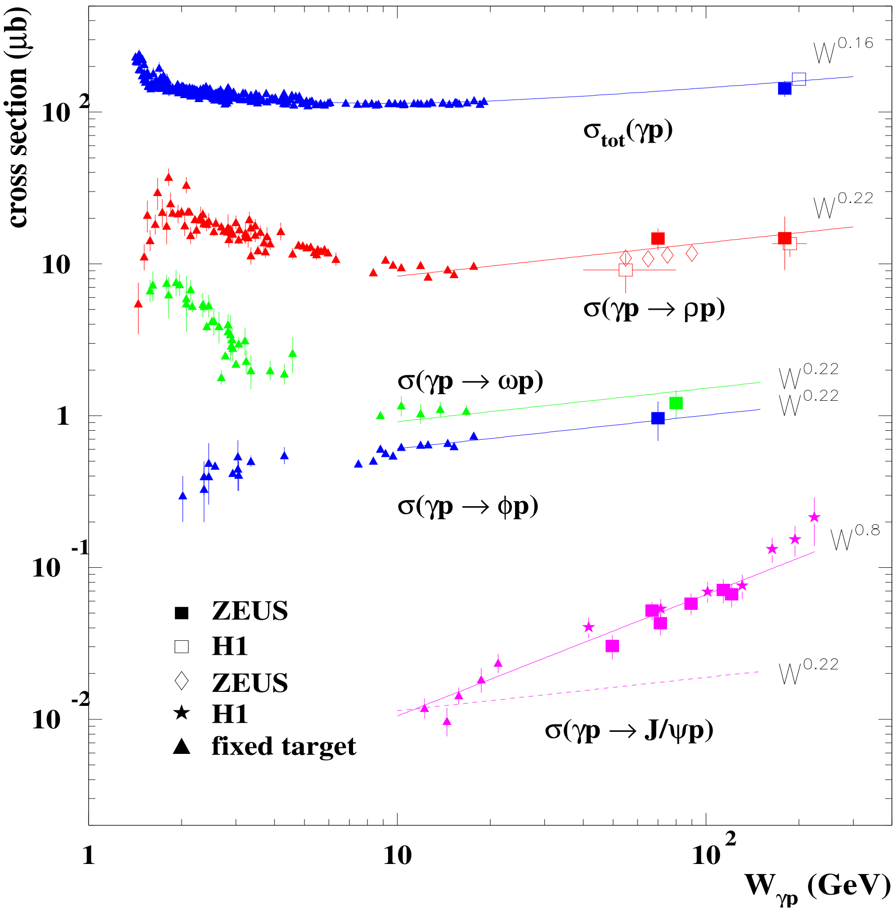


$$A = \Psi_{\gamma^\star \to q\bar{q}} \otimes M_{q\bar{q}+p\to q\bar{q}+p} \otimes A_{q\bar{q}\to V}$$

- **Hard scale:** Q^2, M_V^2, t
- $\sigma_L^{\gamma p} \propto \frac{\alpha_s^2(Q^2)}{Q^6} \left|xg(x,Q^2)\right|^2$ — **steeper W dependence**
- **universal t dependence** — $b \sim 4-5$ **GeV**$^{-2}$
- **flavour independence** — $\rho : \omega : \phi : J/\psi = 9:1:2:8$

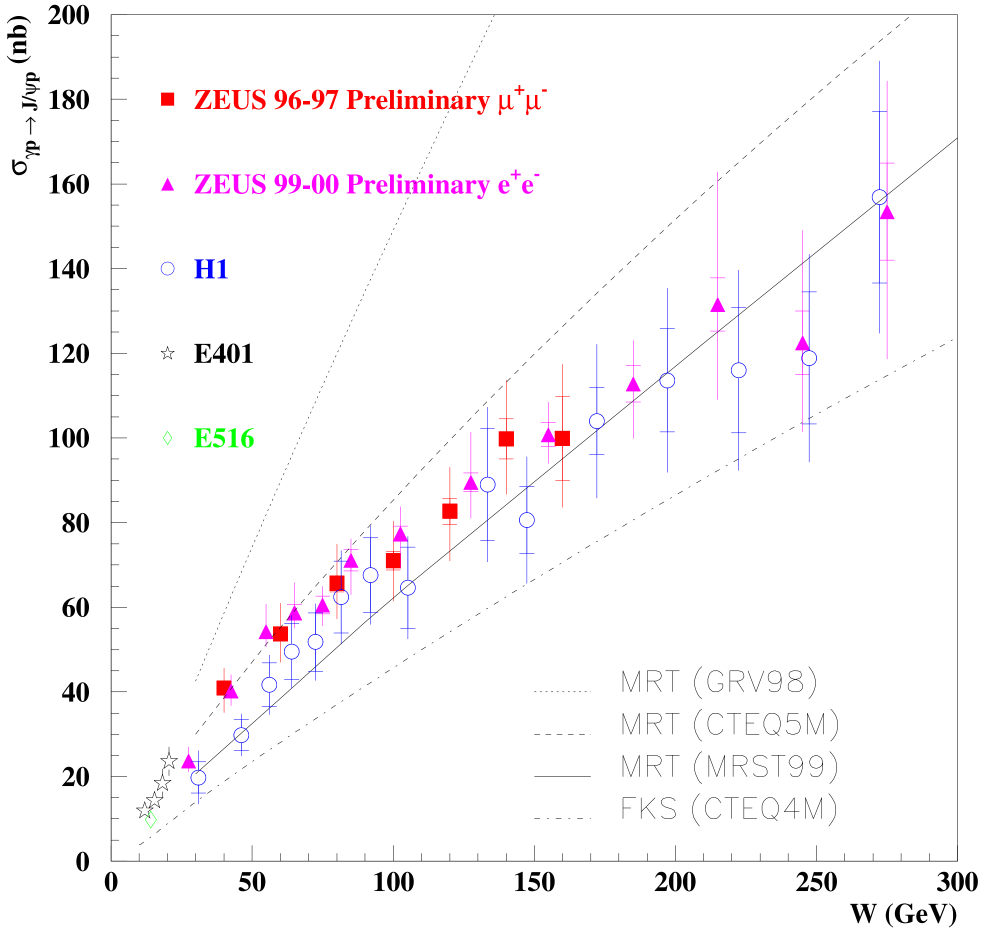
Brodsky et al.
Ryskin
Frankfurt et al.
Martin et al.
Nikolaev et al.

Cross section W dependence (photoproduction)



- Regge theory
  - $\frac{d\sigma^{\gamma p}}{dt} \propto e^{-b_0 t} \left(\frac{W^2}{W_0^2}\right)^{2(\alpha_P(t)-1)}$
  - "soft" (Donachie@Landshoff) Pomeron $\alpha_P(t) = 1.08 + 0.25t$
  - $\sigma(W) \sim W^{0.2}$
- Good description for light vector mesons

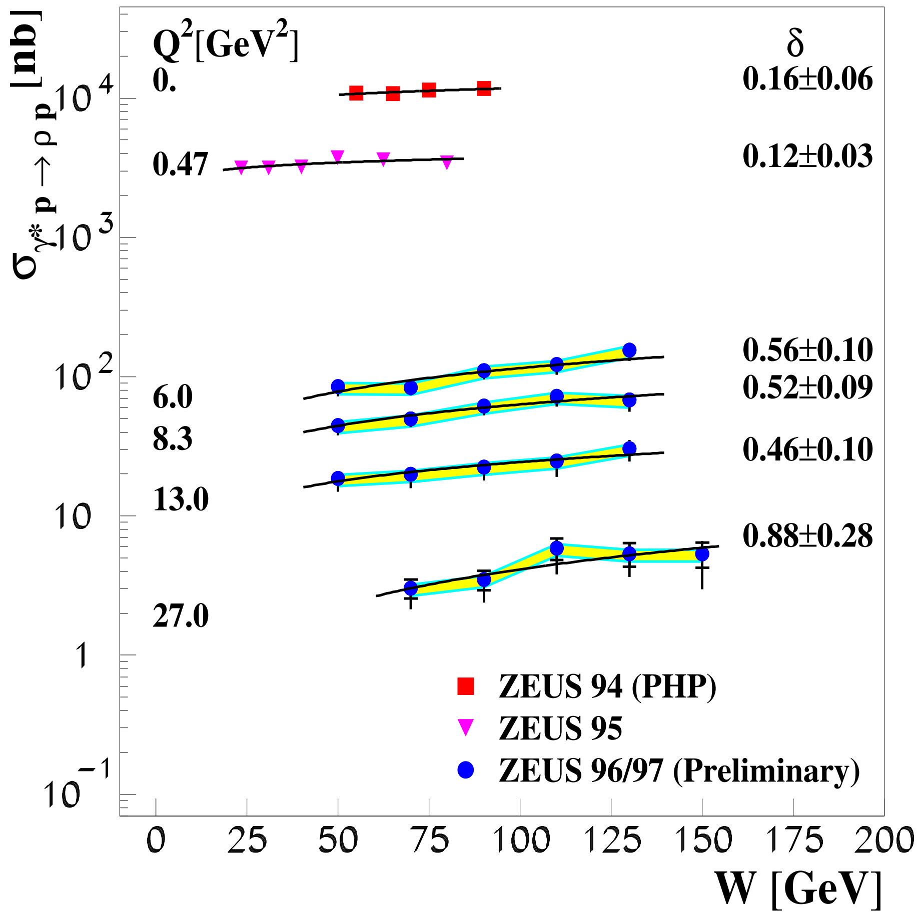
Cross section W dependence (J/ψ photoproduction)



- $\sigma(W) \sim W^{0.8}$
- $\alpha_{I\!P}(t) = (1.193 \pm 0.011^{+0.015}_{-0.010}) + (0.105 \pm 0.024^{+0.022}_{-0.020})t$ **(ZEUS)**

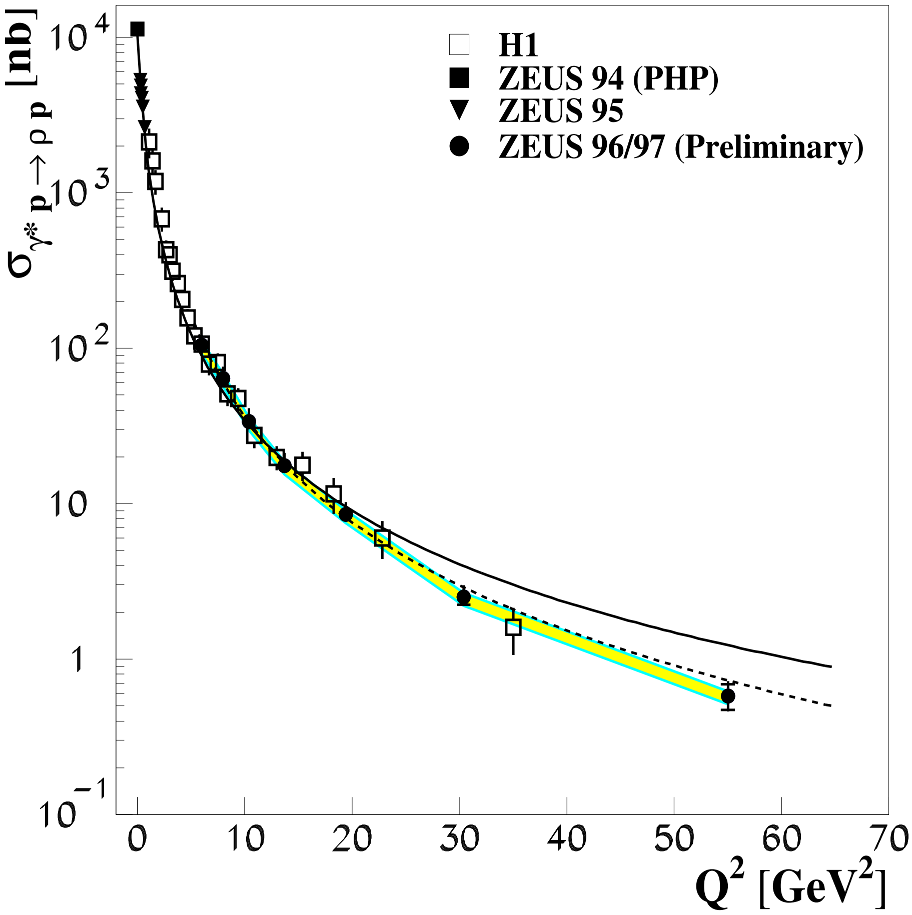
  $\alpha_{I\!P}(t) = (1.27 \pm 0.05) + (0.08 \pm 0.17)t$ **(H1)**
- **QCD models reproduce the steep rise of the cross section**

Cross section W dependence (ρ electroproduction)



- Cross section W dependence becomes steeper at high Q^2
- Q^2 provides a hard scale
- QCD: $\sigma_L \propto \left|xg(x,Q^2)\right|^2$

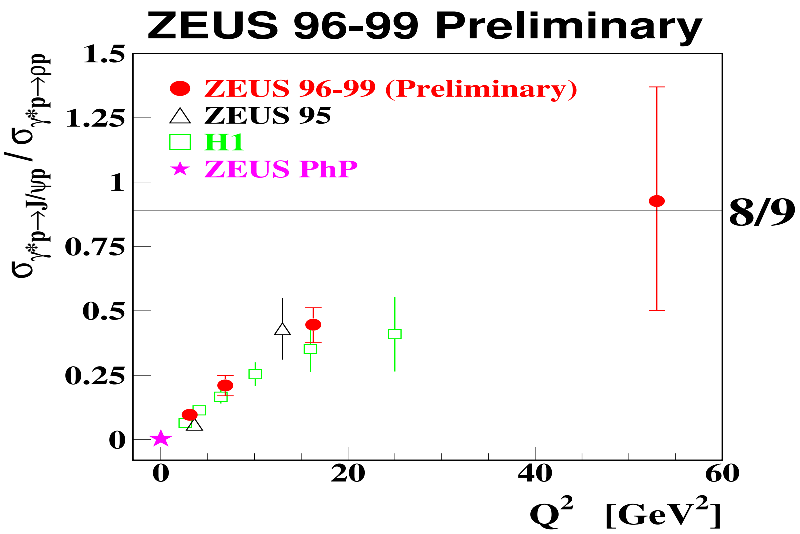
Cross section Q^2dependence (ρ electroproduction)



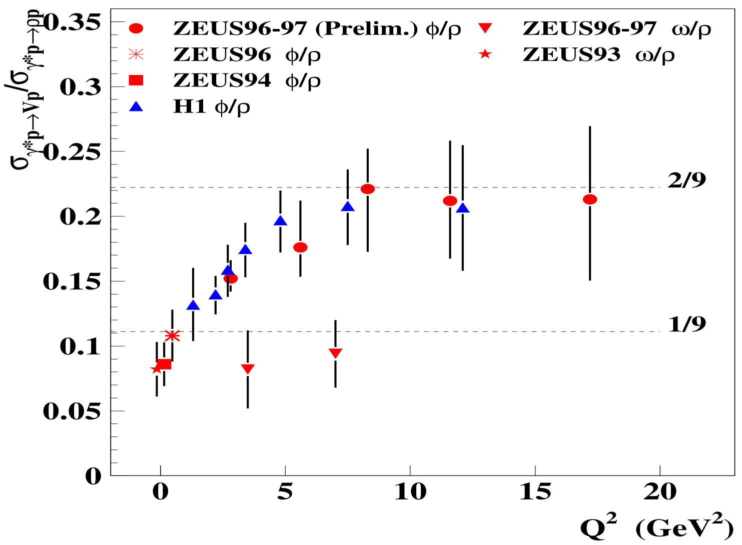
- **QCD:** $\sigma_L^{\gamma p} \propto \frac{\alpha_s(Q^2)}{Q^6} \left| xg(x, Q^2) \right|^2 \propto \frac{1}{Q^5}$

Cross section ratios

$\frac{J/\psi}{\rho}$

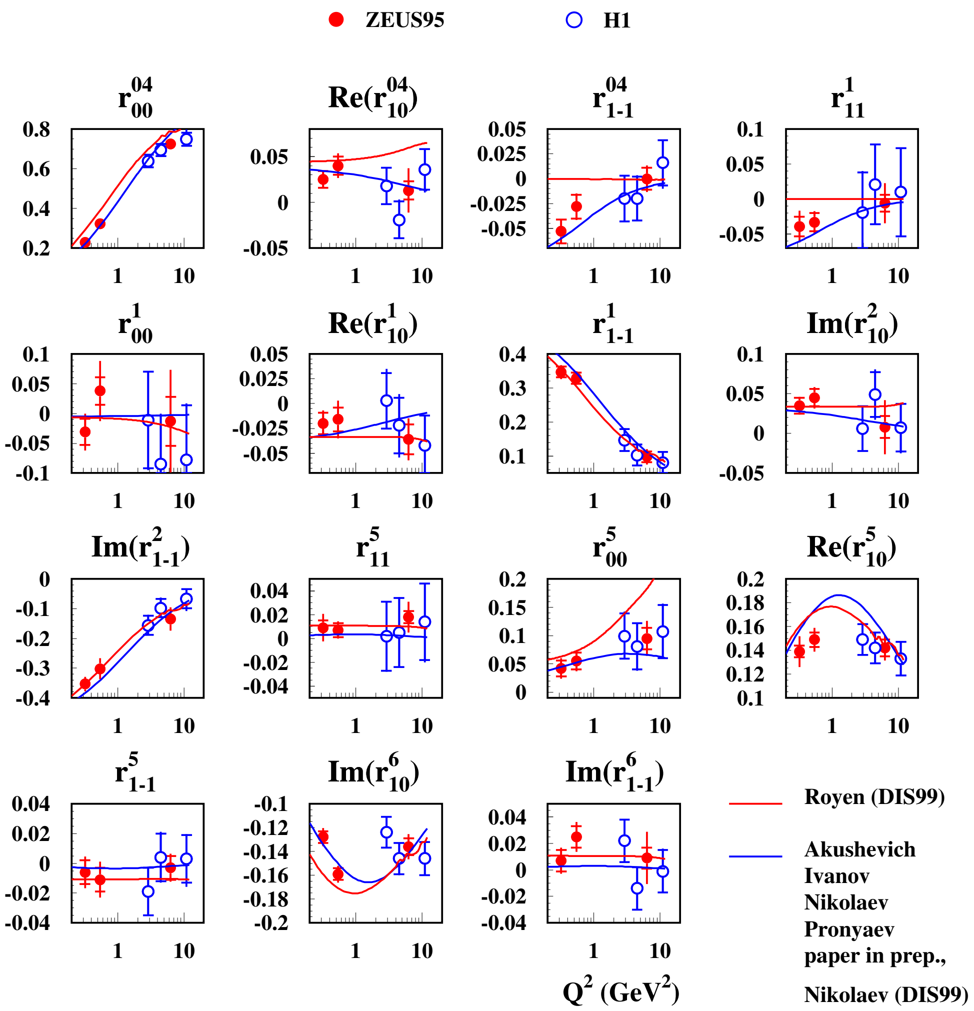


$\frac{\phi}{\rho}$



- **SU(4) restoration** $\quad \rho : \omega : \phi : J/\psi = 9 : 1 : 2 : 8$

Spin density matrix elements

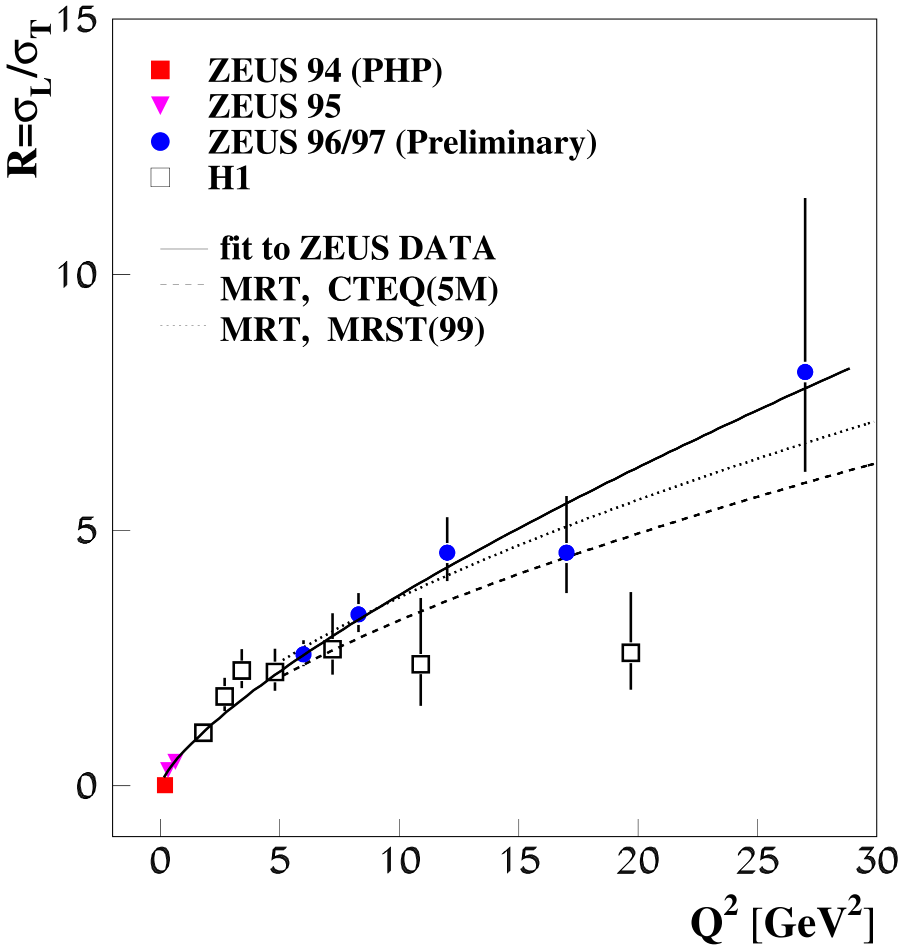


- r^{04}_{kl}, r^{α}_{kl} - combinations of helicity amplitudes $T_{\lambda_\rho \lambda_\gamma}$ $(\gamma^* p \Rightarrow \rho p)$ extracted from the angular distributions of the decay products $(\rho \Rightarrow \pi\pi)$
- QCD calculations are in agreement with data

Ivanov, Kirschner
Nikolaev et al
Royen, Cudell

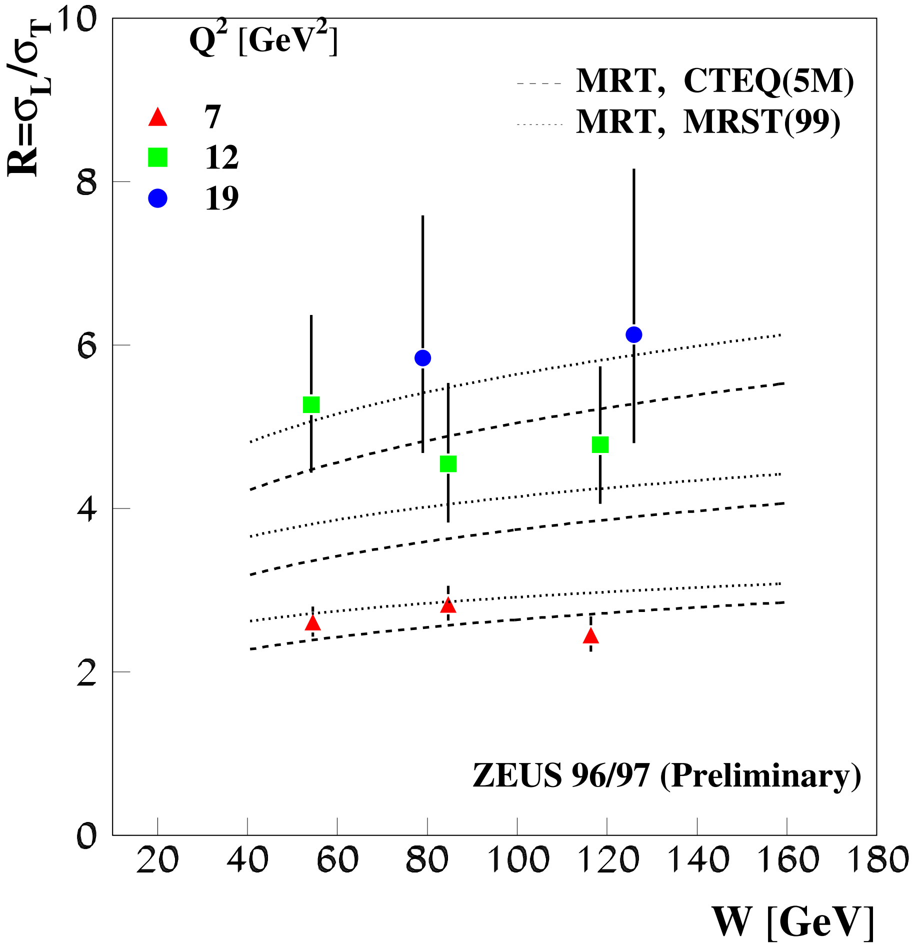
σ_L/σ_T vs Q^2

- $R = \frac{\sigma_L}{\sigma_T} = \frac{1}{\varepsilon}\frac{r^{04}_{00}}{1-r^{04}_{00}}$ (assuming SCHC)



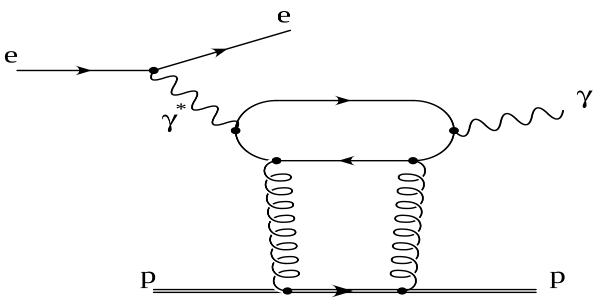
- non-linear rise of R with Q^2
- curves are from Martin, Ryskin and Teubner

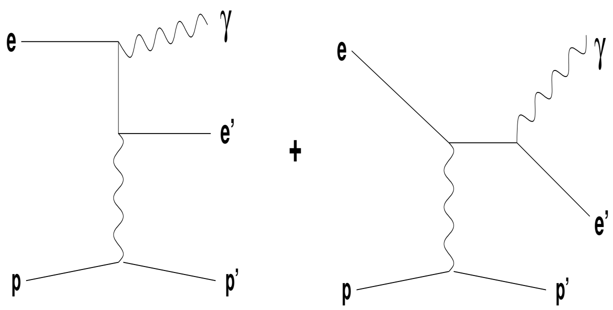
σ_L/σ_T *vs* W



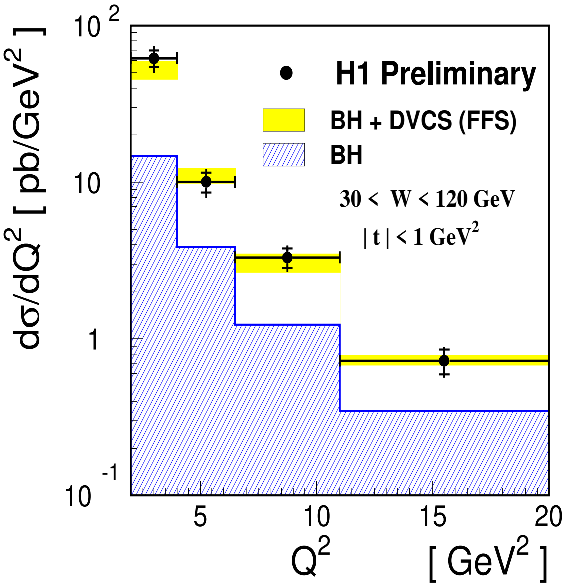
- curves are from Martin, Ryskin and Teubner

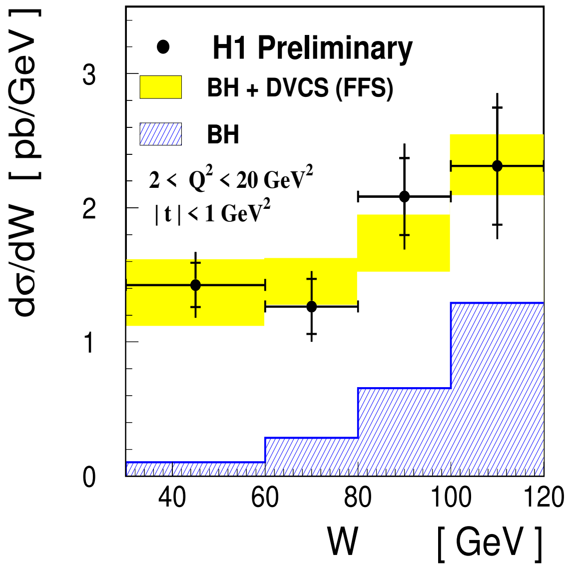
DVCS + Bethe-Heitler process





- New way to study diffration
- Calculable in pQCD (Frankfurt, Freund and Strikman)





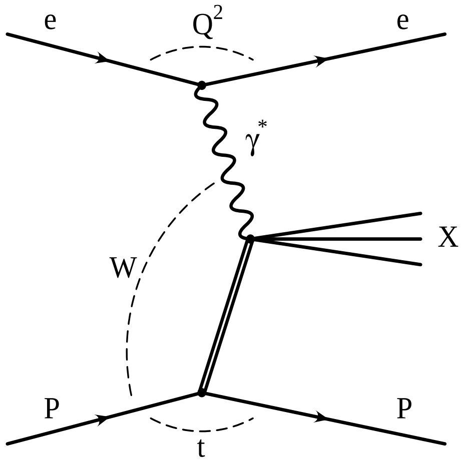
- Good agreement with QCD prediction

Summary on exclusive diffraction

- Light vector meson production at low Q^2 shows typical "soft" behavior
- Vector meson production in the presence of hard scale is described by QCD motivated models
  - Cross section W dependence
  - SU(4) restoration
  - Polarization properties of vector meson production
- First measurement of the DVCS process

Kinematics

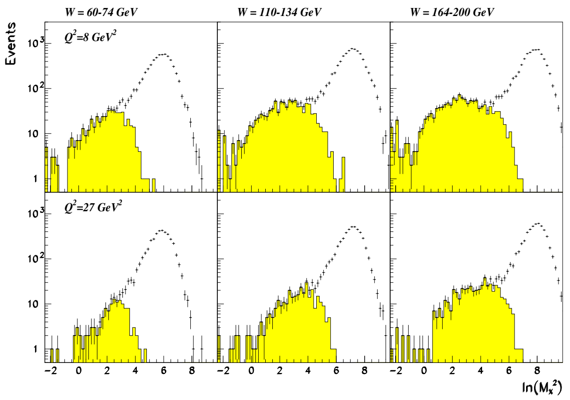
- $-Q^2 = (p_e - p_{e'})^2$
- $y = \frac{P \cdot q}{P \cdot k}$
- $t = (P - P')^2$
- $x_{I\!P} = \frac{q \cdot (P - P')}{q \cdot P} = \frac{Q^2 + M_X^2 - t}{Q^2 + W^2 - M_P^2}$
- $\beta = \frac{Q^2}{2q \cdot (P - P')} = \frac{Q^2}{Q^2 + M_X^2 - t}$



Event selections

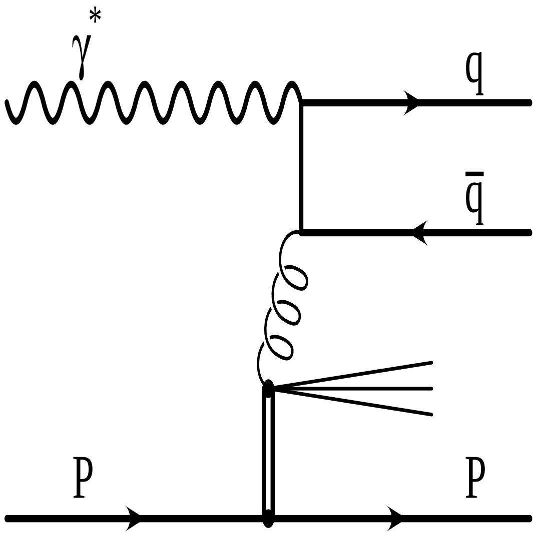
- **Tagging of leading proton**
- **Rapidity gap**
- **Decomposition of reconstructed mass distribution**

$$\frac{dN}{dlnM_x^2} = D + C\, exp(b\, lnM_x^2)$$



Diffractive DIS models

- **Resolved Pomeron** (Ingelman and Schlein)



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

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

Regge factorization

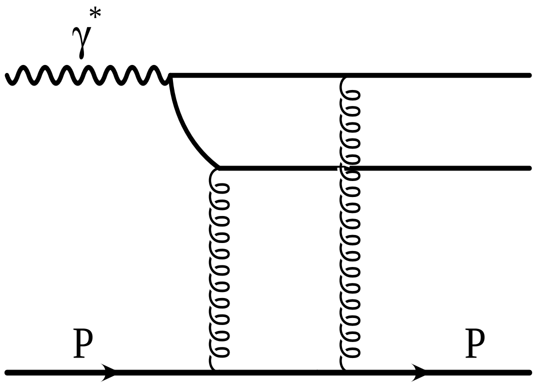
$$F_2^{D(4)} = \Phi(x_{I\!P}, t) F_2^D(\beta, Q^2)$$

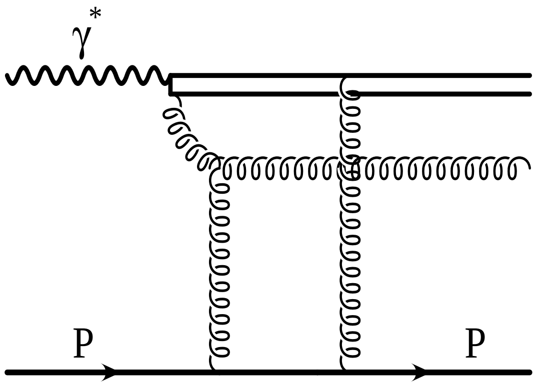
$$\Phi(x_{I\!P}, t) \sim e^{bt}\left(\frac{1}{x_{I\!P}}\right)^{2\alpha_{I\!P}(t)-1}$$

Diffractive DIS models

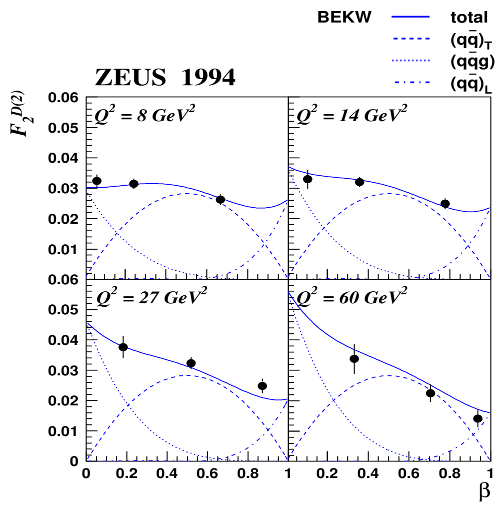
- **QCD based models**
  - **Color dipole interactions** (Nikolaev and Zakharov, Bialas and Peschanski...)
  - **pQCD approach** (Ryskin, Bartels, Ellis, Kowalski, Wusthoff..)

$$|\gamma>\Rightarrow q\bar{q}\ , q\bar{q}g$$

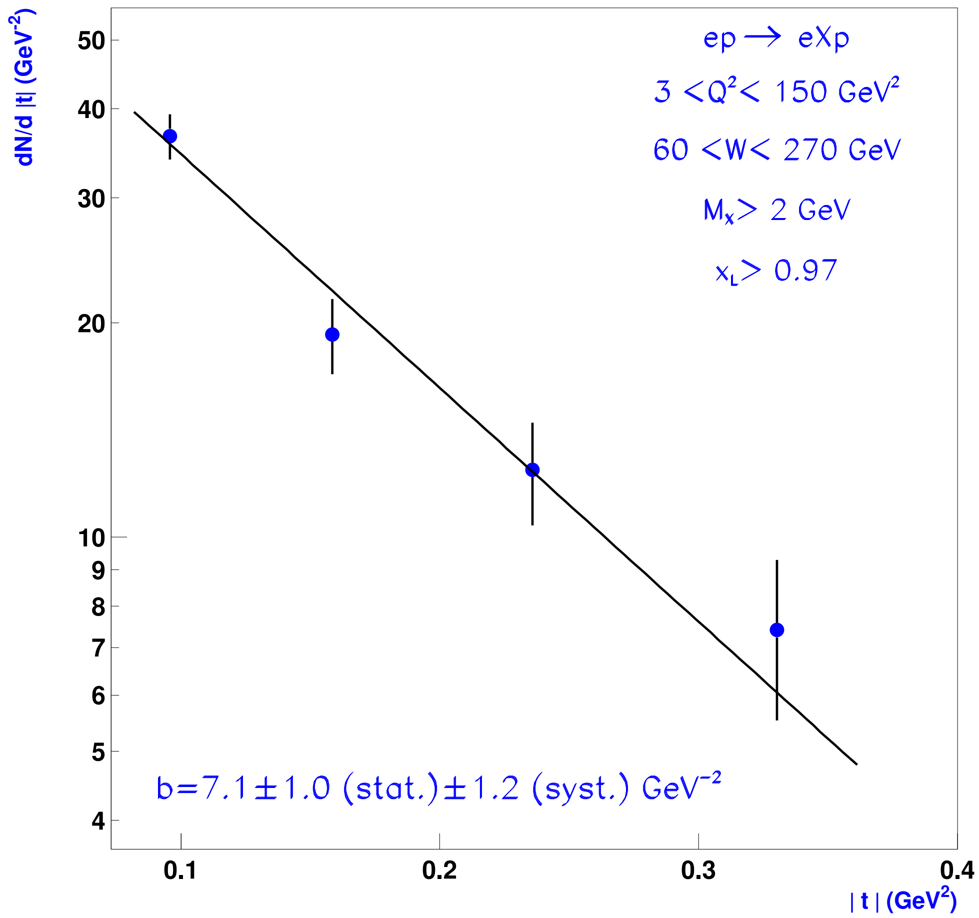




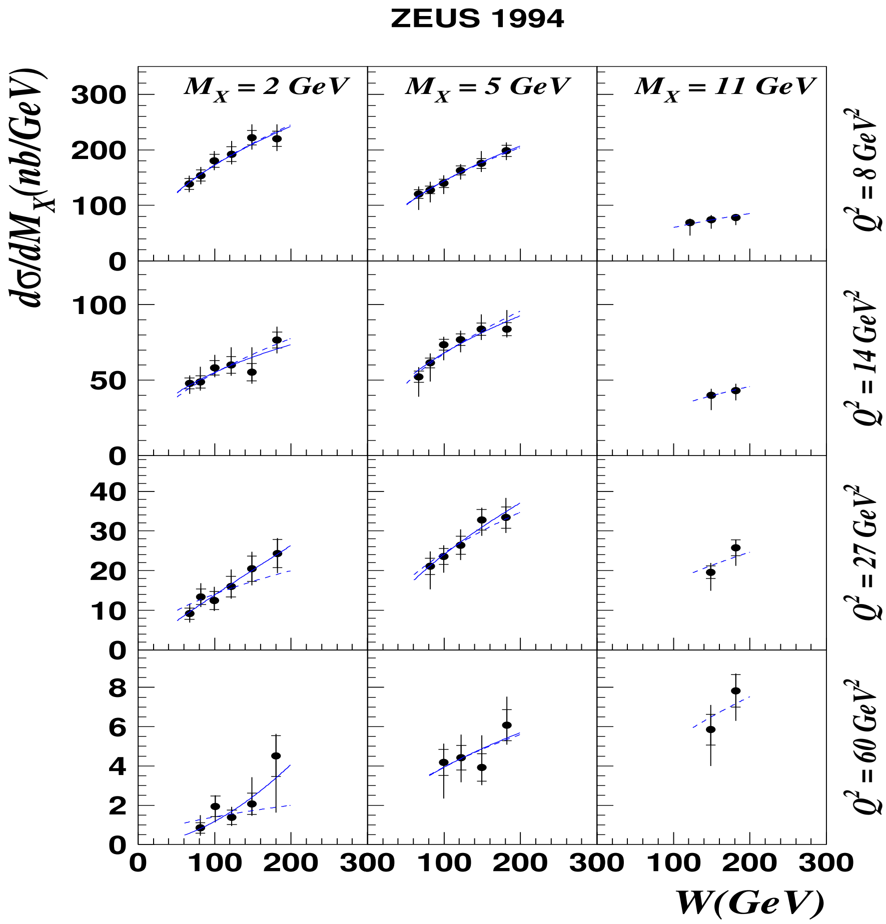
$$F_2^{D(3)} = c_T F_{q\bar{q}}^T + c_L F_{q\bar{q}}^L + c_g F_{q\bar{q}g}^T$$



t distribution



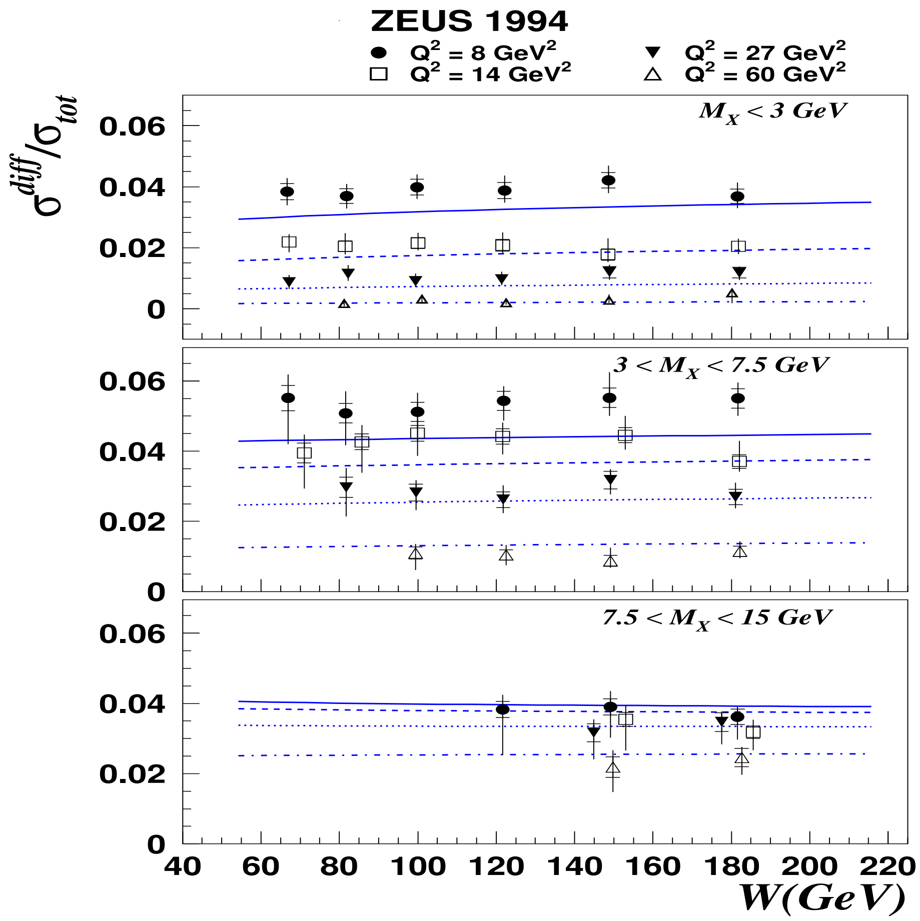
Cross section W dependence



- **Regge fit:** $\frac{d\sigma^D}{dM_X} \sim W^{4(\alpha_{I\!P}(t)-1)}$

$$\alpha_{I\!P}(0) = 1.16 \pm 0.01^{+0.04}_{-0.01}$$

σ_D/σ_{TOT} ratio

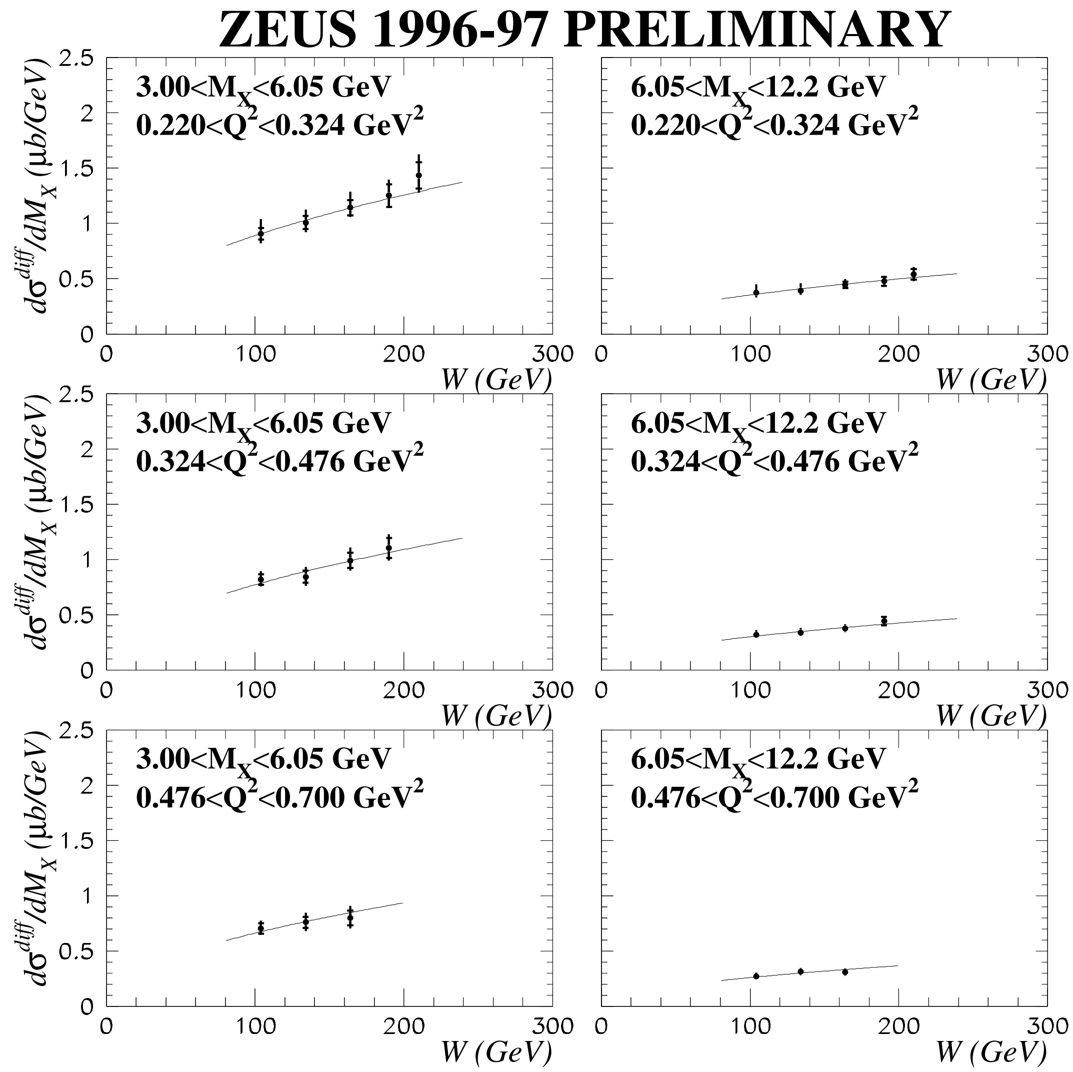


- Regge theory fails to describe the ratio
- Saturation model (Golec-Biernat,Wusthoff)

  Effective dipole cross section is parameterised

$$\sigma(x, r^2) = \sigma_0 \left\{ 1 - exp(-\frac{r^2}{4R_0^2(x)}) \right\}$$

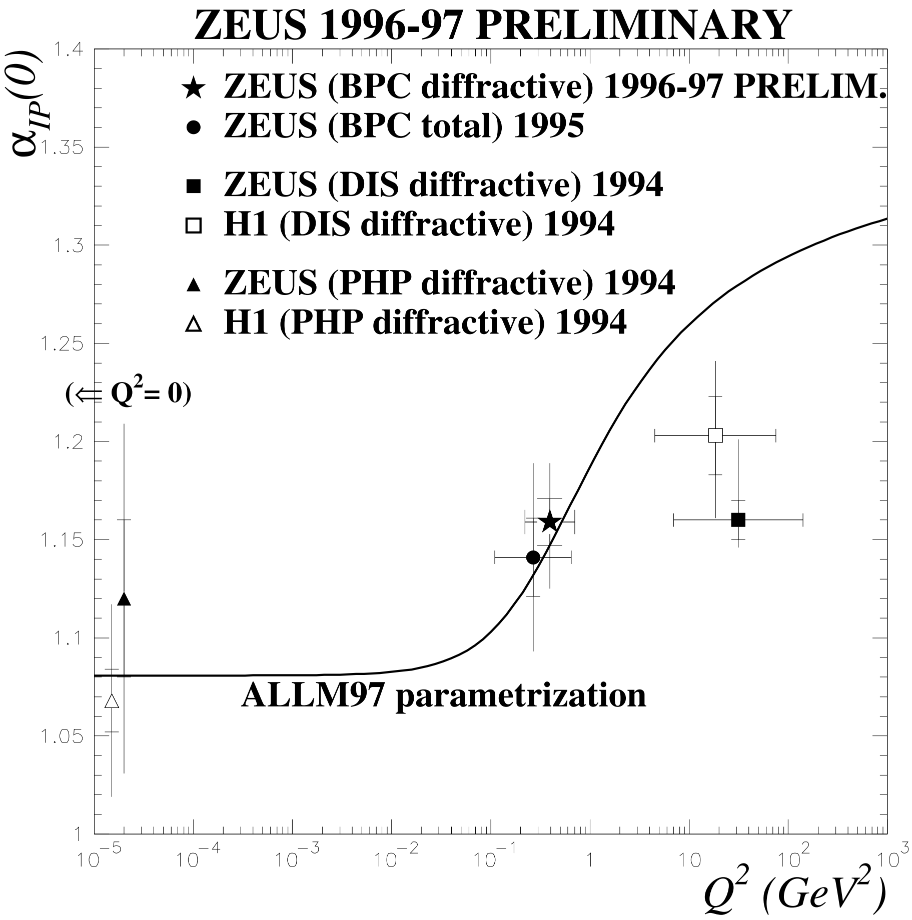
Cross section W dependence (low Q^2)



- **Regge fit:** $\frac{d\sigma^D}{dM_X} \sim W^{4(\alpha_{I\!P}(t)-1)}$

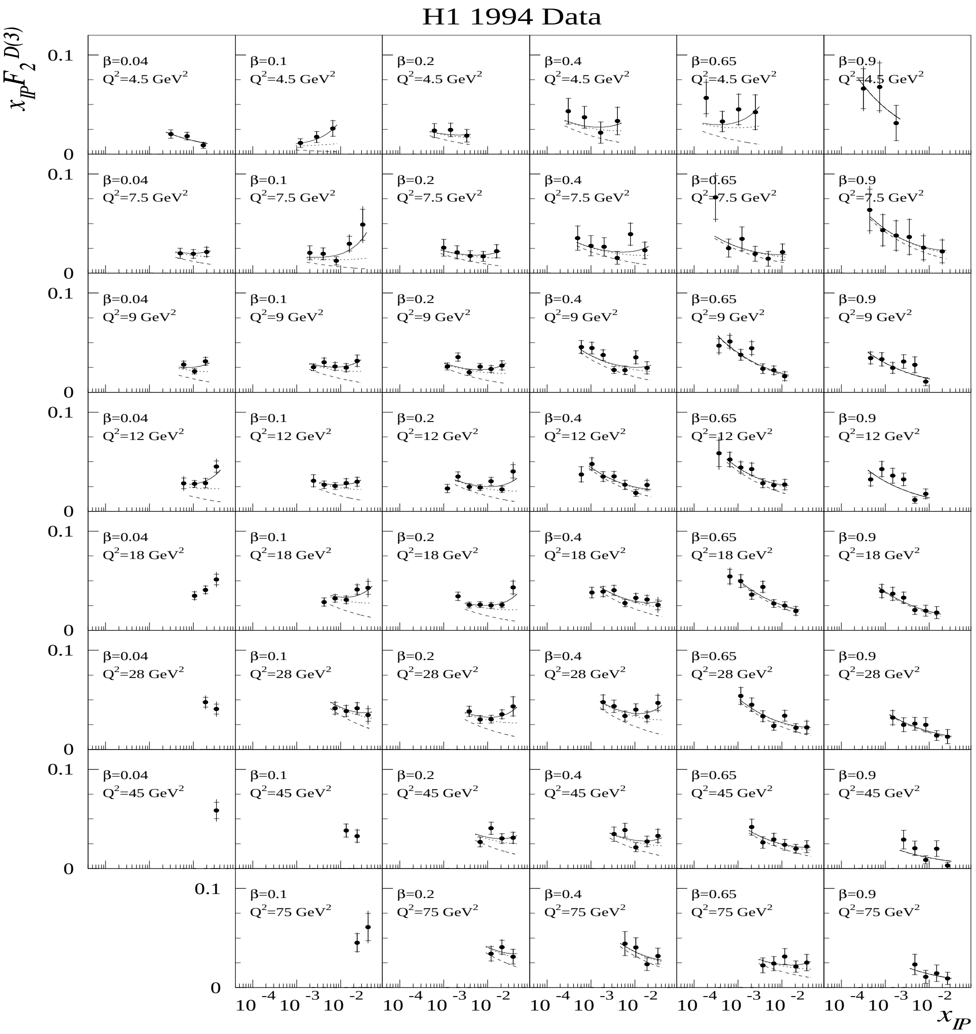
$$< \alpha_{I\!P} >= 1.126 \pm 0.012^{+0.027}_{-0.022}$$

$\alpha_{I\!P}(0)$ vs Q^2



- Transition from soft to hard regime

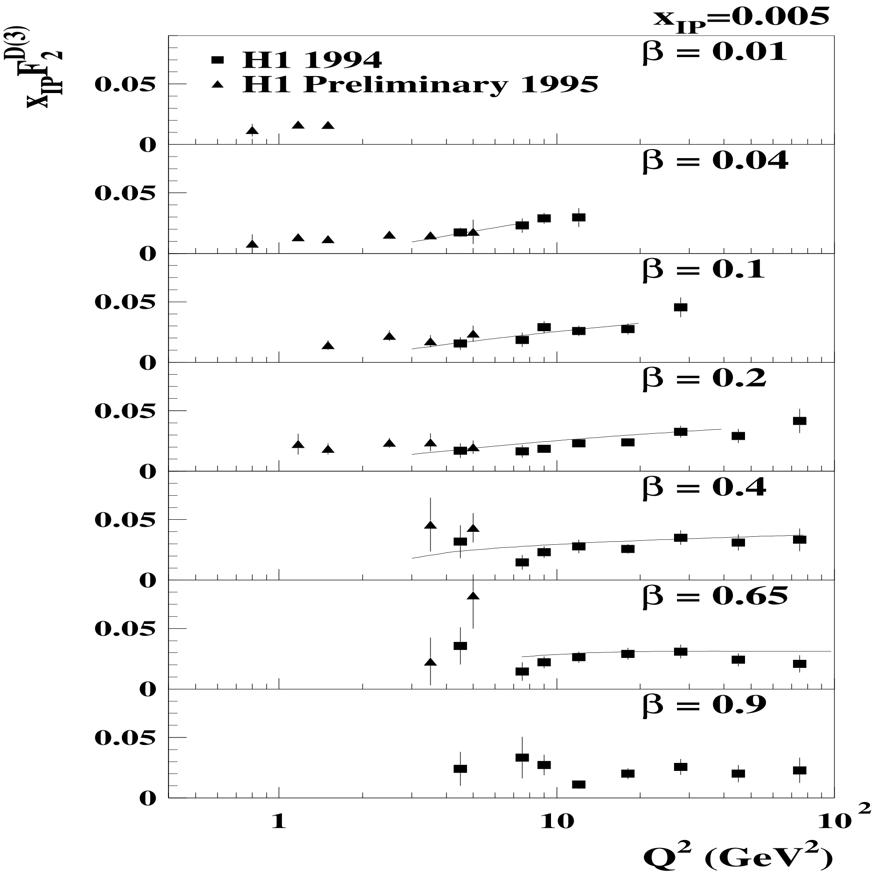
$F_2^{D(3)}$



- **Regge parameterisation**

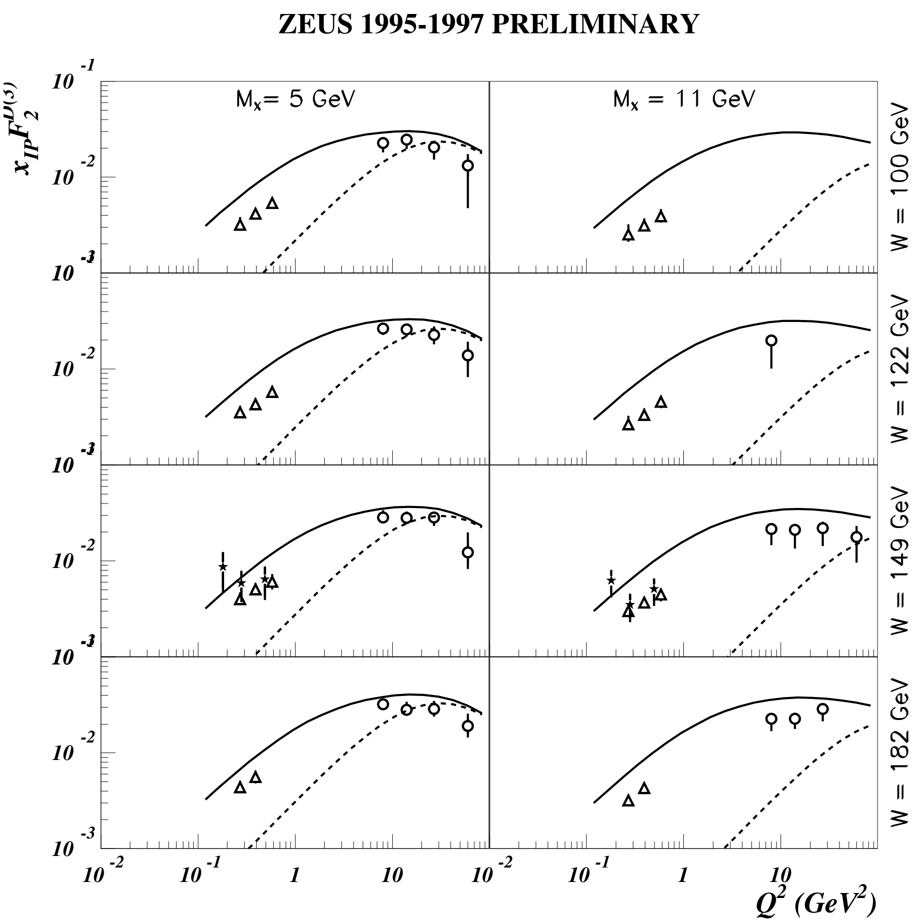
$$F_2^{D(3)}(\beta, Q^2, \alpha_{IP}) = \Phi^P(\alpha_{IP}) F_2^P(\beta, Q^2) + \Phi^R(\alpha_{IP}) F_2^R(\beta, Q^2)$$

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



- Scaling violation indicates a large contribution from gluons

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

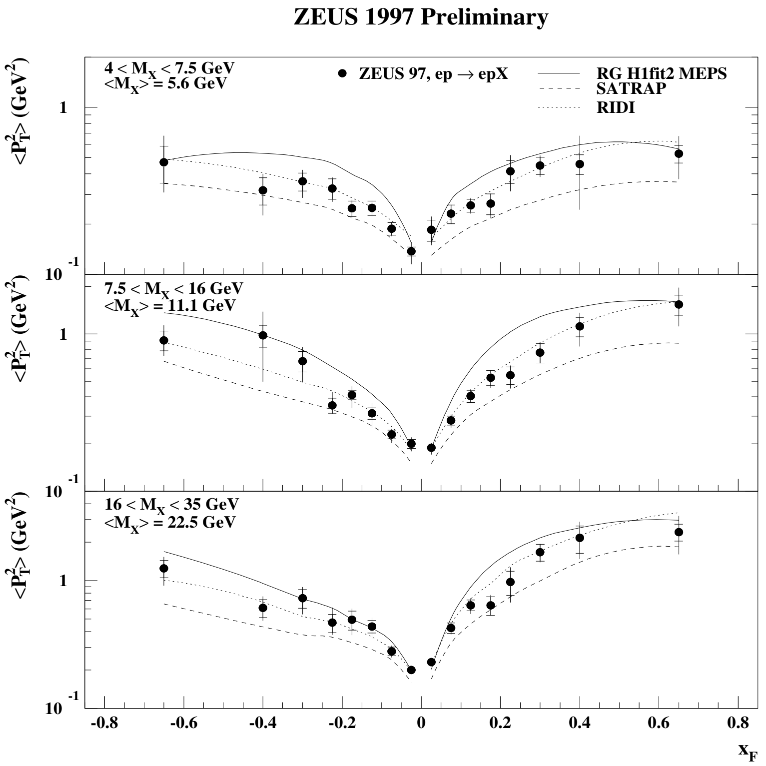


- Saturation model describes qualitatively the Q^2 behaviour

Event shapes

$4 < Q^2 < 100$ **GeV**^{2}
$70 < W < 250$ **GeV**
$x_{I\!P} < 0.03$
$4 < M_X < 35$ **GeV**

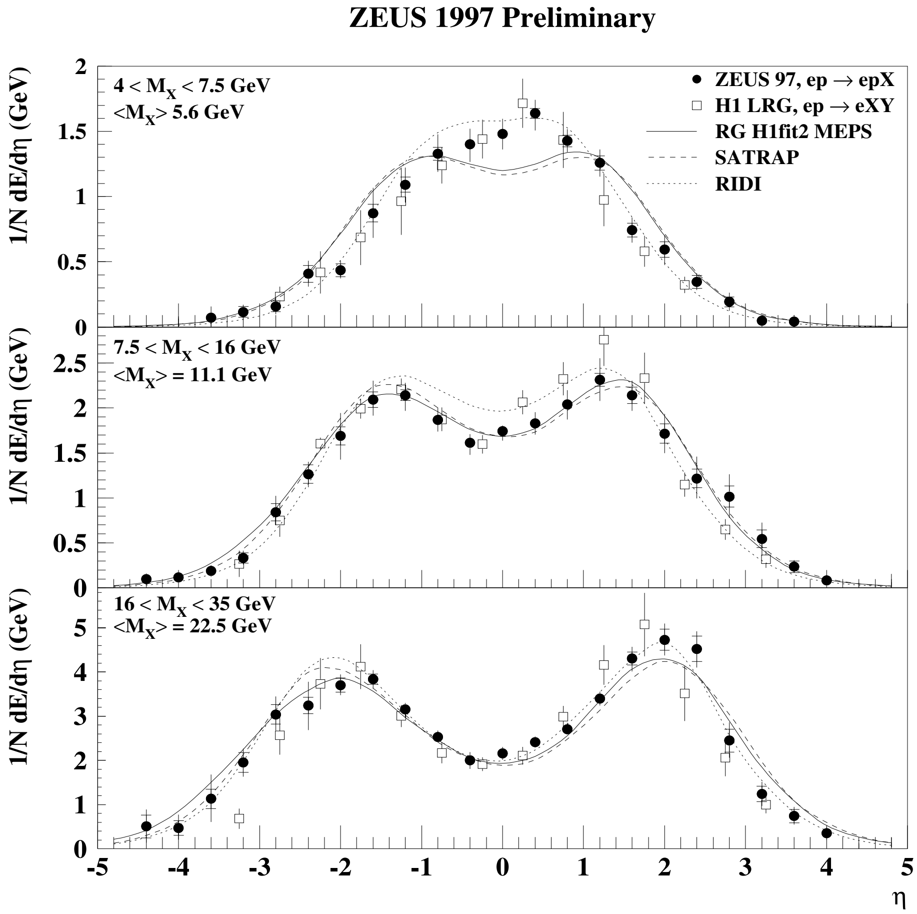
$<P_T^2>$ **VS** X_F



- MC models
  - RAPGAP (resolved Pomeron)
  - SATRAP (Saturation model)
  - RIDI (pQCD approach)

Event shapes

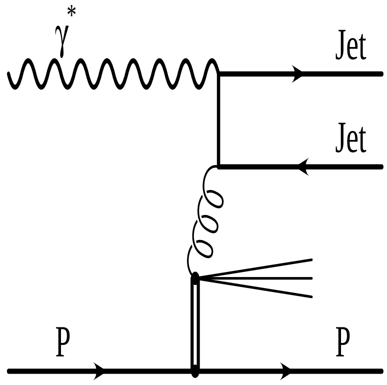
Energy flow as a function of pseudorapidity ($\gamma^* I\!P$ - CMS)



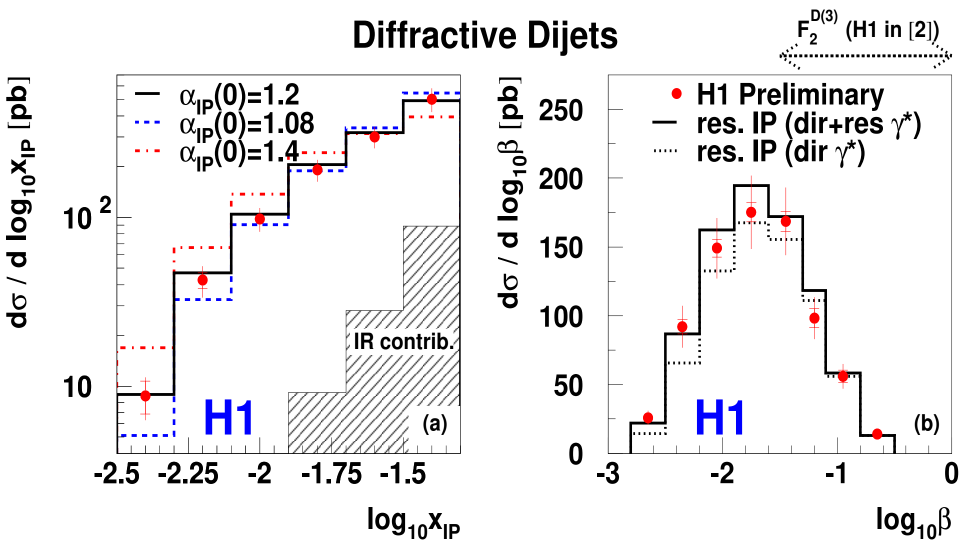
- MC models
  - RAPGAP (resolved Pomeron)
  - SATRAP (Saturation model)
  - RIDI (pQCD approach)

Dijet production

$4 < Q^2 < 80$ GeV^2
$0.1 < y < 0.7$
$x_{I\!P} < 0.05$
$p_{T,Jet} > 4$ GeV



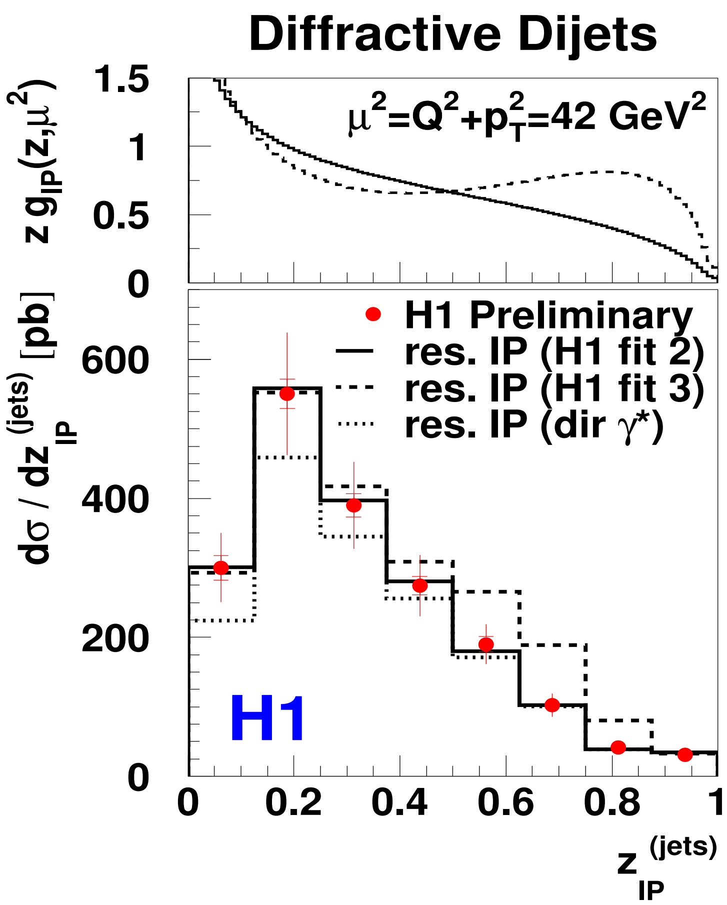
- Cone algorithm (R=1) in $\gamma^* p$ -CMS
- Resolved Pomeron model (parton distributions from $F_2^{D(3)}$ analysis)



- Dijet production is sensitive to Pomeron trajectory

- $\alpha_{I\!P}(0) \sim 1.2$

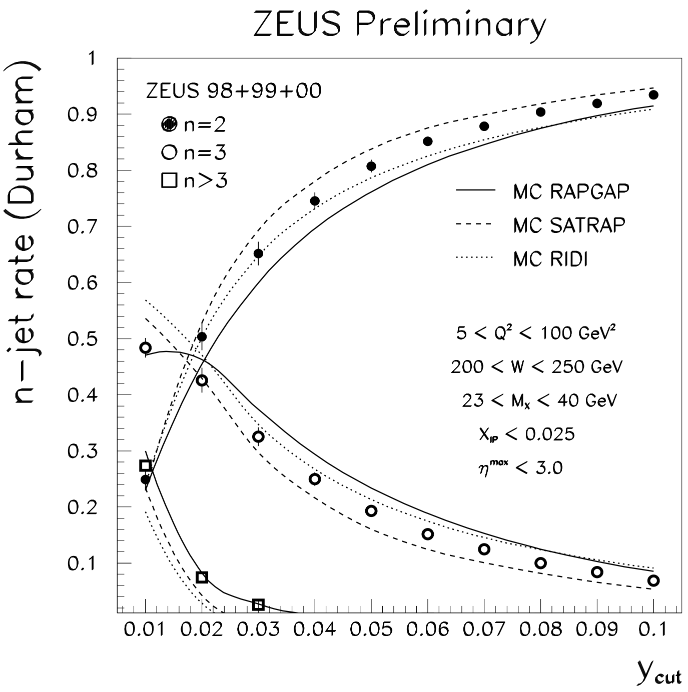
Dijet production



- $z_{I\!P}^{jets} = \frac{Q^2+M_{12}^2}{Q^2+M_X^2}$ (momentum fraction of exchange coupling to γ^*)
- Dijet production is sensitive to the Pomeron gluon distribution

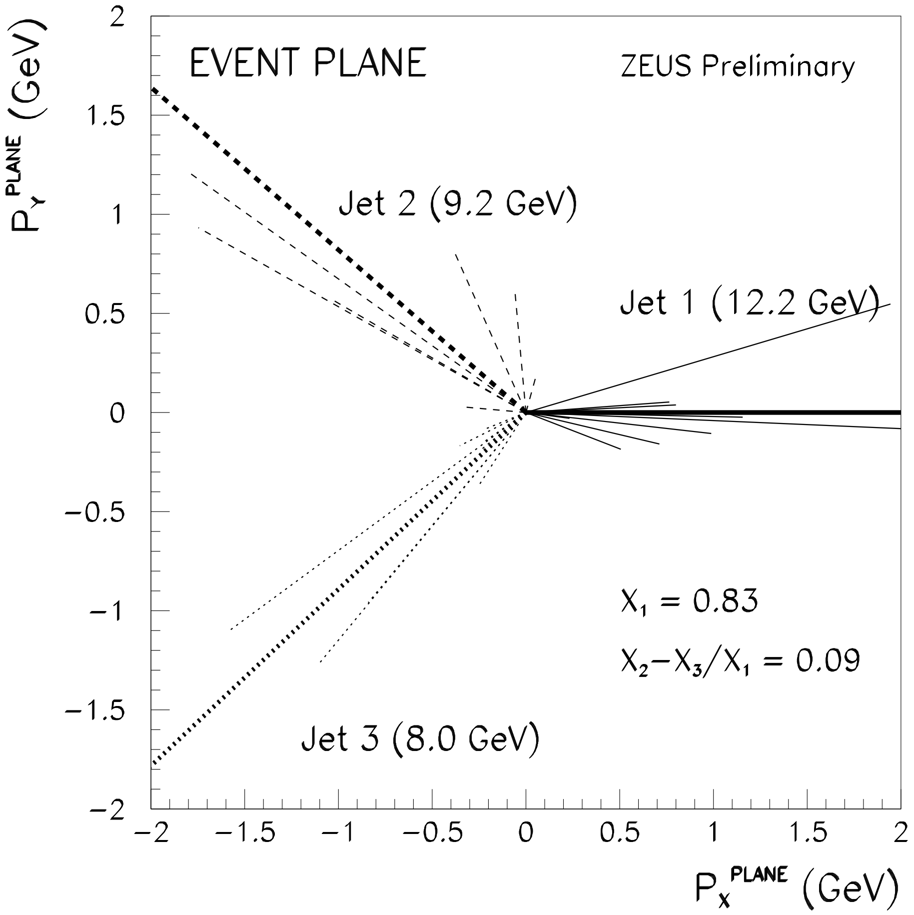
3-Jet production

$5 < Q^2 < 100$ $\mathbf{GeV}^2$
$200 < W < 250$ **GeV**
$x_{I\!P} < 0.025$
$23 < M_X < 40$ **GeV**



- **Exclusive k$_T$ algorithm in the** $\gamma^* I\!P - CMS$
- **Jet resolution parameter** $y_{cut} = 0.05$
- **MC models**
  - RAPGAP (resolved Pomeron)
  - SATRAP (Saturation model)
  - RIDI (pQCD approach)

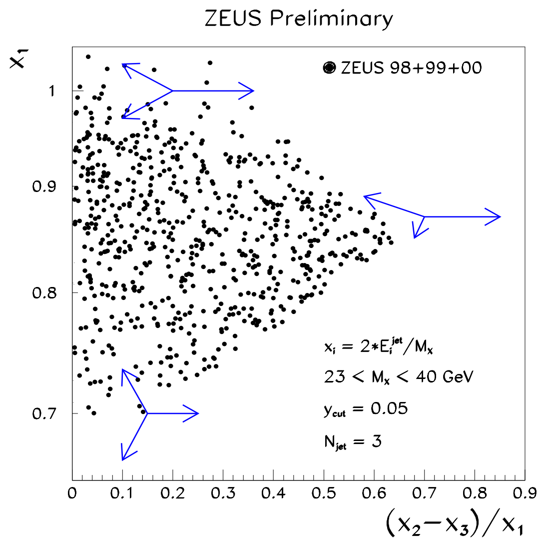
3-Jet production



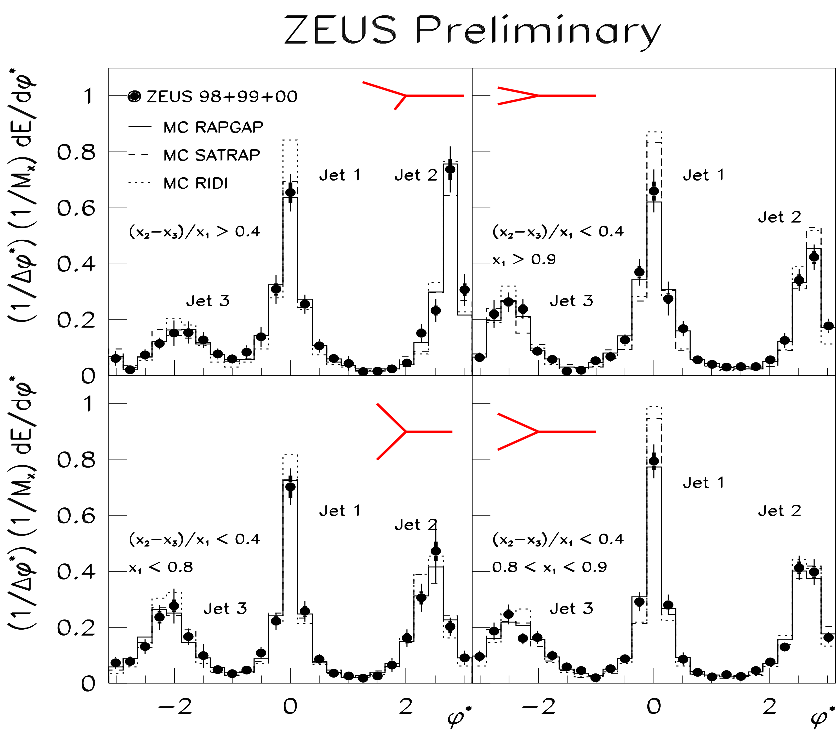
3-Jet production

x_1 , $(x_2 - x_3)/x_1$ plane

$$x_i = \frac{2E_i^{jet}}{M_X}$$
$$x_1 + x_2 + x_3 = 2$$
$$x_1 \geq x_2 \geq x_3$$

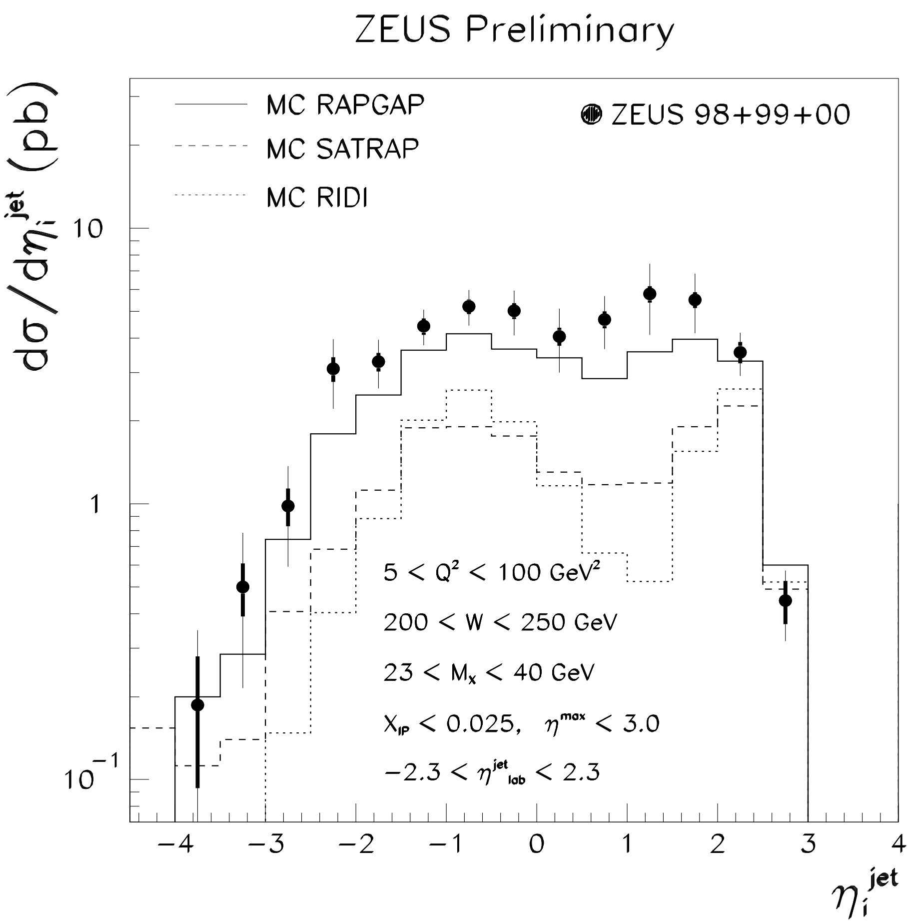


Energy flow in the event plane



3-Jet production

Cross section as a function of the jet pseudorapidity



Summary on inclusive diffraction

- **Many results in a wide range of Q^2**
  - **Diffractive structure function**
  - **Hadronic final states**
  - **Jet production**
- **Comparison with MC models suggests that a large gluon contribution is necessary**
- **First results from the transition region between "soft" and "hard" diffraction**