

# Diffraction in ep Collisions at HERA

- Introduction
- Vector Mesons
- DVCS
- Diffractive DIS
- Final States:
  - Charm & Jets
- Summary

K.Hiller  
DESY Zeuthen

on behalf of the  
**H1 & ZEUS**  
Collaborations

# Kinematics of Diffraction

Standard DIS variables:

- $x$  - fractional parton/proton momentum
- $Q^2$  - neg. virtual photon momentum<sup>2</sup>
- $y$  - fractional electron energy loss
- $W$  -  $\gamma$ -p center-of-mass energy
- $s$  - e-p center-of-mass energy

Additional for diffraction:

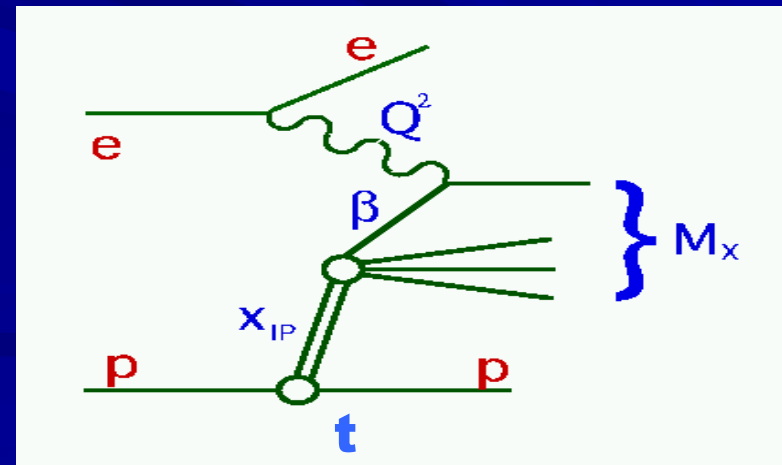
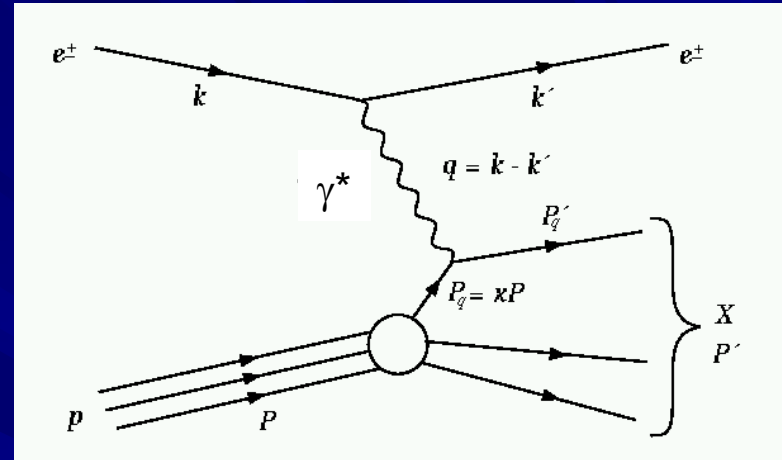
$$x_P = \frac{Q^2 + M_X^2}{Q^2 + W^2}$$

fractional Pomeron momentum

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

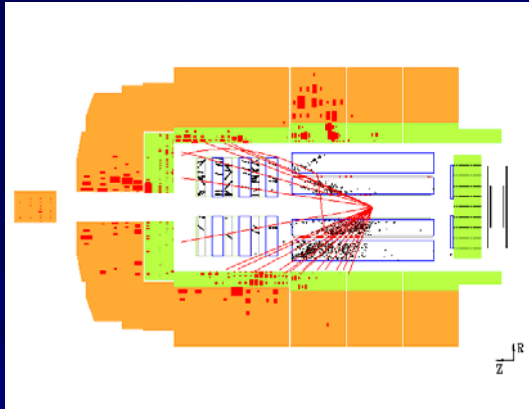
fractional parton/Pomeron momentum

$$t = (p - p')^2, \text{ proton momentum transfer}^2$$



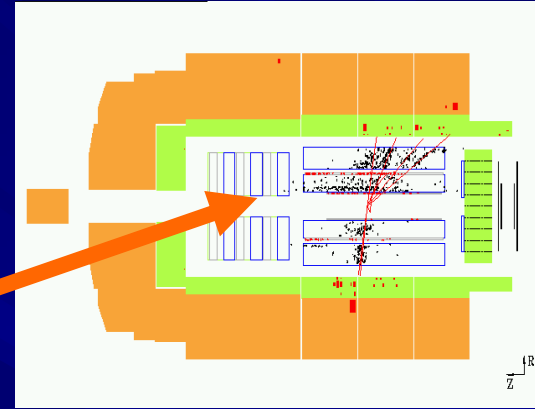
# Signatures of Diffraction

non-diffractive event



no visible  
forward  
activity

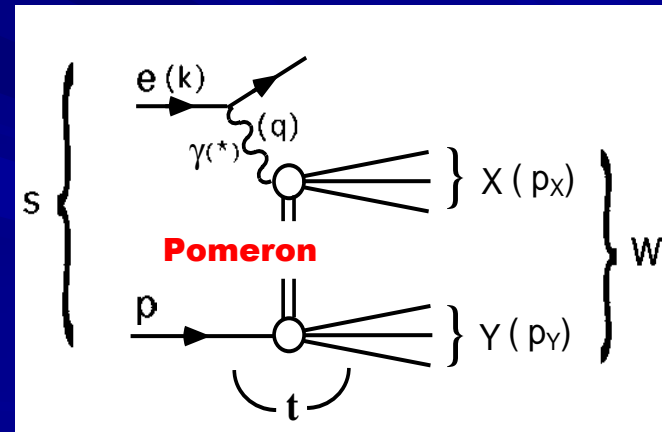
diffractive event



Two systems X and Y well separated in phase space with low masses  $M_X, M_Y \ll W$

System Y : proton or p-dissociation carries most of the hadronic energy

System X : vector meson, photon or photon-dissociation



Exchange of colourless object, Pomeron, with low momentum fraction  $x_P$

# Soft Diffraction Models

Notation: soft = non-perturbative process, hadron level

Regge model : diffraction described by exchange of Pomeron trajectory

$$\alpha_p(t) = \alpha_p(0) + \alpha'_p \cdot t, \alpha_p(0) = 1 + \varepsilon$$

with  $\varepsilon = 0.08, \alpha'_p = 0.25 \text{ GeV}^{-2}$

$\varepsilon$  and  $\alpha'$  result from fit of energy dependence of hadronic cross sections

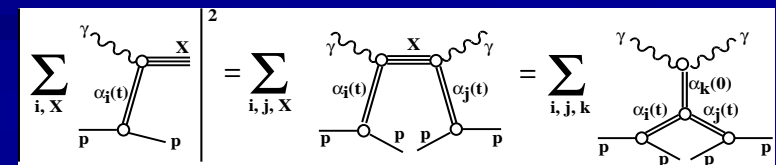
- slow increasing total cross section
- steep  $t$ -dependence with shrinkage
- low  $M_X$  - pure Pomeron exchange
- large  $M_X$  - Reggeon & Pion exchange
- photon dissociation: triple Regge

$$\sigma(W) = W^\delta \text{ with } \delta = 4(\varepsilon - \alpha'/B)$$

$$\sigma(t) = \exp(-Bt) \text{ with } B = B_0 + 2\alpha' \ln(W^2/W_0^2)$$

$$\sigma(M_X) = M_X^{-2(1+2\varepsilon)}$$

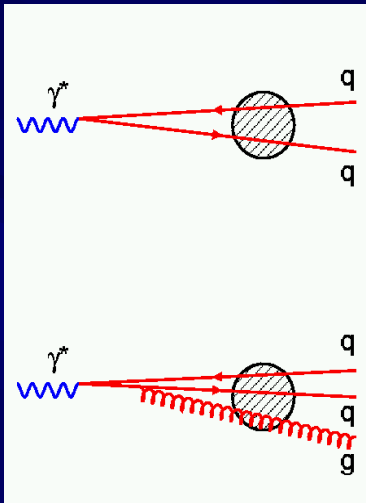
Reggeon  $\alpha_R(t) = 0.55 + 0.86 \text{ GeV}^{-2} t$   
 Pion  $\alpha_\pi(t) = 0 + 1 \text{ GeV}^{-2} t$



# Hard Diffraction Models

Notation: hard = perturbative process, parton level

Starting from alternative frames  $\rightarrow$  two classes of models :

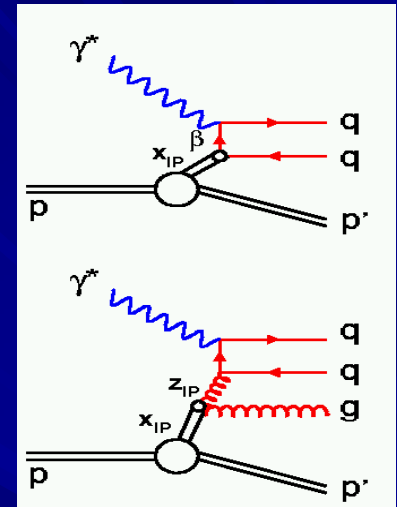


Proton rest frame

formation time  
 $\tau \sim 1 / M_p x$   
 long at small  $x$

Breit frame

Standard DIS  
 scheme



LO: 2 gluons , ... gluon ladders

$\leftarrow$  **Exchange**  $\rightarrow$

object with partonic structure

fluctuates in colour dipoles  
 $q\bar{q}$ ,  $q\bar{q}+g$ , ...

$\leftarrow$  **Virtual photon**  $\rightarrow$

point-like couplings to partons,  
 standard partonic cross sections

combine soft & hard processes by  
 different parton transverse momentum

$\leftarrow$  **Dynamics**  $\rightarrow$

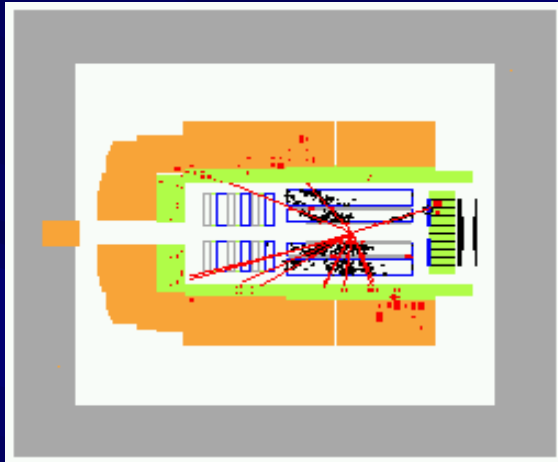
evolve diffractive PDFs in  $x / Q^2$   
 by DGLAP / BFKL schemes

Colour Dipole Models

Resolved Pomeron Models

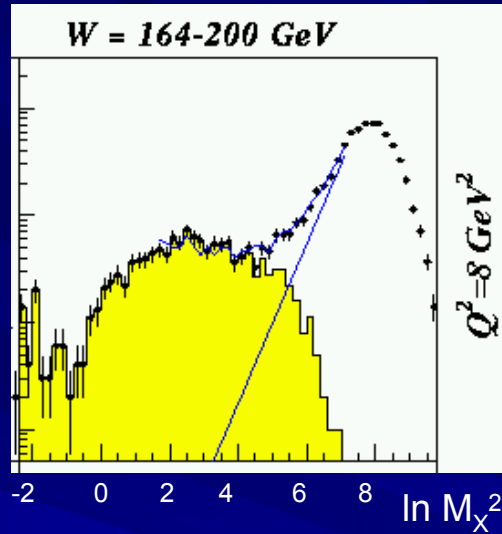
# Selection Methods

## 1) Large Rapidity Gap / H1



Typical cut:  $\eta_{\max} < \sim 1.5$  \*)

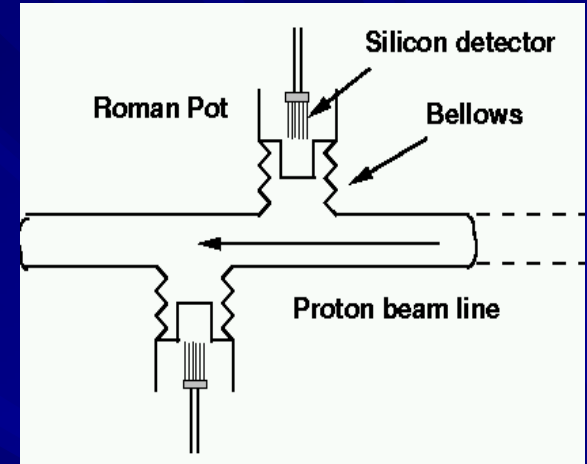
## 2) $M_X$ - Method / ZEUS



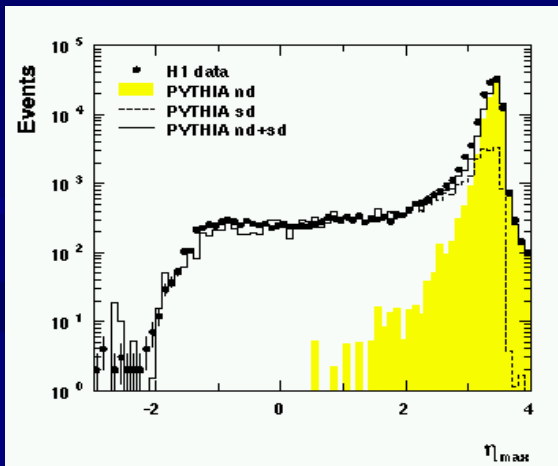
Fit excess above exponential fall-off

$$\frac{dN}{d \ln M_X^2} = D + c \exp(b \ln M_X^2),$$

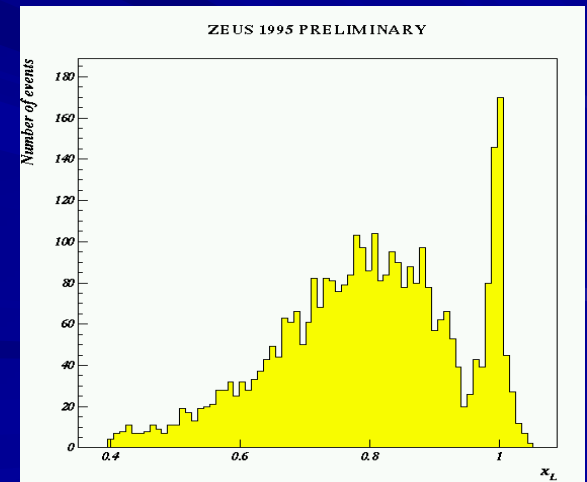
## 3) Proton Tagging / H1, ZEUS



FPS / LPS & beam line optics



\*)  $\eta = -\ln \tan(\Theta / 2)$



# HERA Domain

....or why diffraction at HERA ?

## TOP 1 - Large kinematic range

920 GeV proton  $\leftrightarrow$  27.5 GeV electron,  $W \rightarrow 300$  GeV

$Q^2 \rightarrow 10^5$  GeV<sup>2</sup> photo- & electroproduction

$x = Q^2 / y s \rightarrow 10^{-5}$

## TOP 2 - Large acceptance

H1/ZEUS  $\sim 4\pi$  to measure final state particles, important for  $\gamma^*$  dissociative system

## TOP 3 - Large cross sections

$\sim 40$  % of  $\sigma^{tot}$ ,  $\sim 10$  % of DIS is diffractive

## TOP 4 - Point-like couplings

to probe the Pomeron structure, not possible in hadron-hadron processes

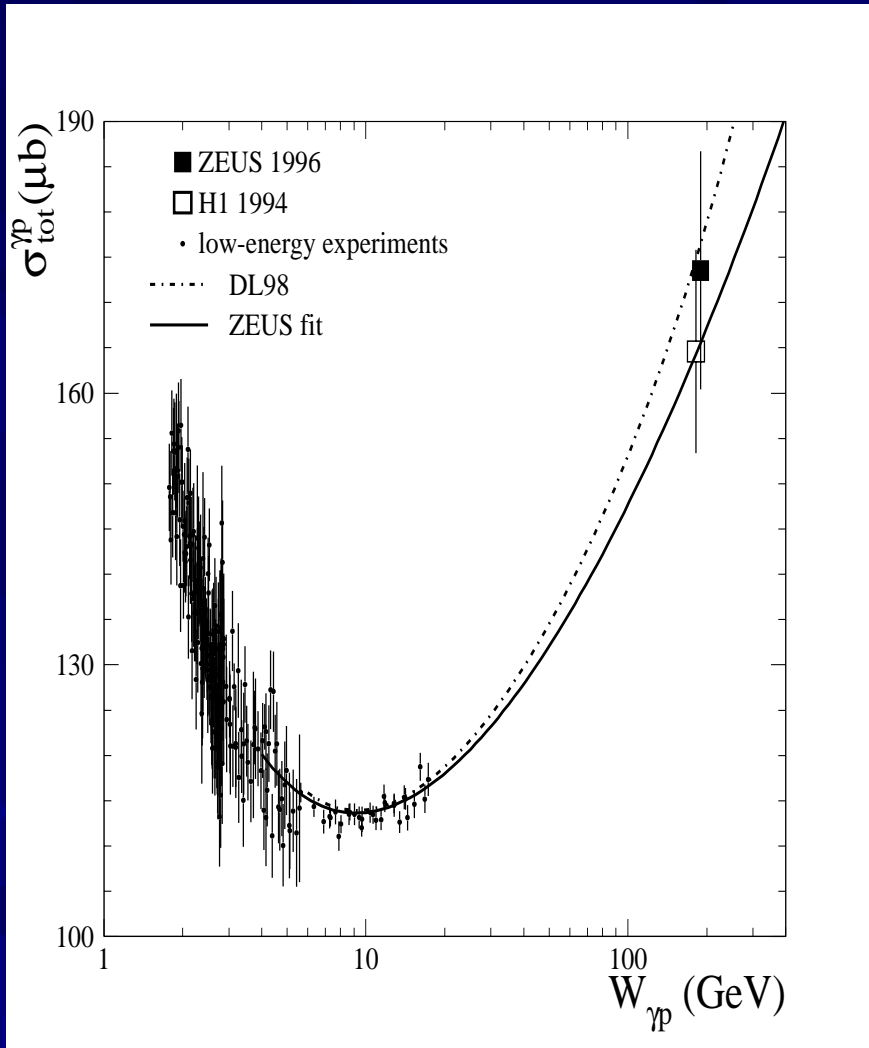
## TOP 5 – Different varying scales

$M_V^2$ ,  $Q^2$ ,  $t$  to access the transition region from soft to hard processes

HERA opened a new window for diffraction

# Total $\gamma p$ Cross Section

Typical soft process: quasi-real photon  $Q^2 \rightarrow 0$ , tag  $e^+$  at low angles



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

$$\text{ZEUS: } \sigma^{\text{tot}}(\gamma p) = 174 \pm 1 \pm 13 \mu\text{b} \\ W = 209 \text{ GeV}$$

Fit: Pomeron + Reggeon contributions

$$\sigma_{\text{tot}} = A \cdot W^{2\varepsilon} + B \cdot W^{-2\eta} \\ \varepsilon = 0.093 \pm 0.002$$

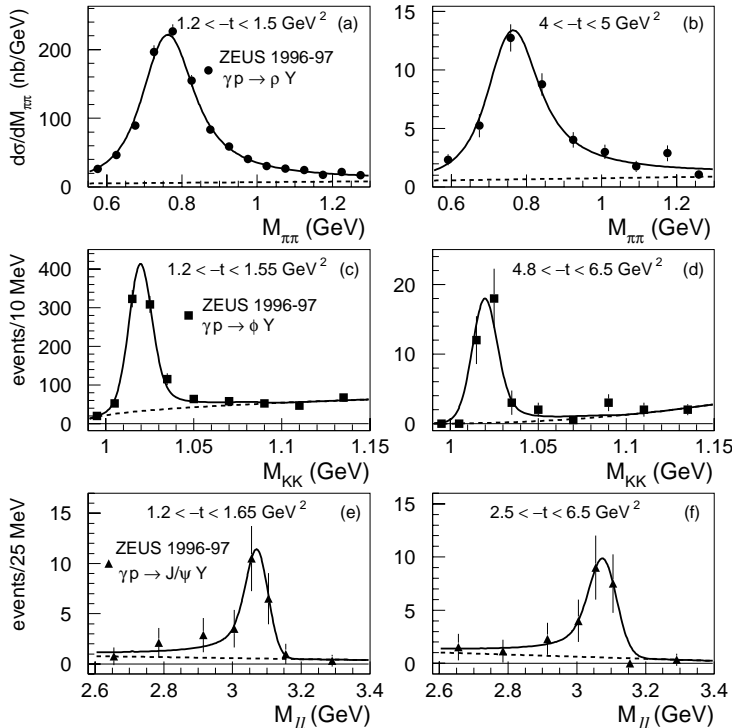
Energy dependence of  $\gamma p$   
resembles hadronic processes

# Vector Mesons : Overview

Exclusive processes in photo- and electroproduction :  $\rho$ ,  $\omega$ ,  $\phi$ ,  $J/\psi$ ,  $\Psi(2S)$ ,  $\Upsilon$

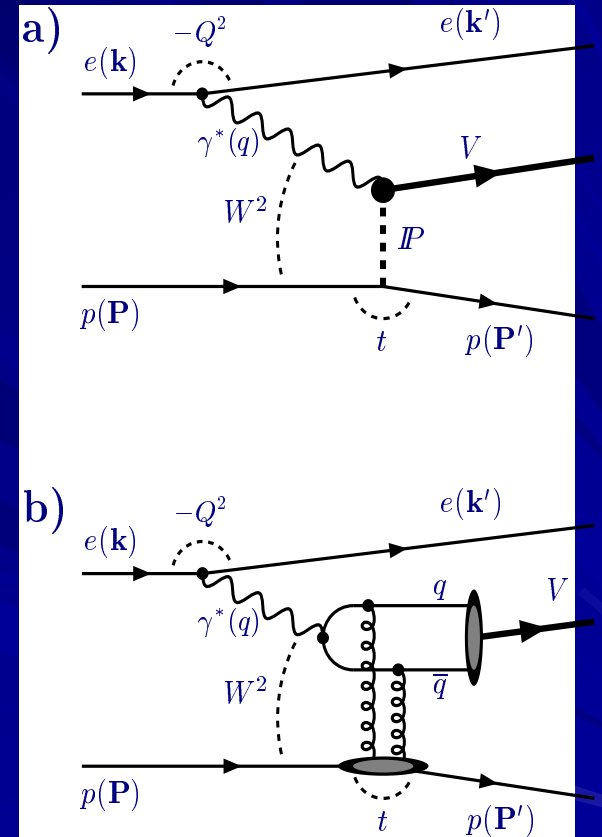
Photoproduction  $\rho$ ,  $\phi$ ,  $J/\psi$  high  $t$

ZEUS



Hadron level:  
Vector Meson  
Dominance  
& Regge model

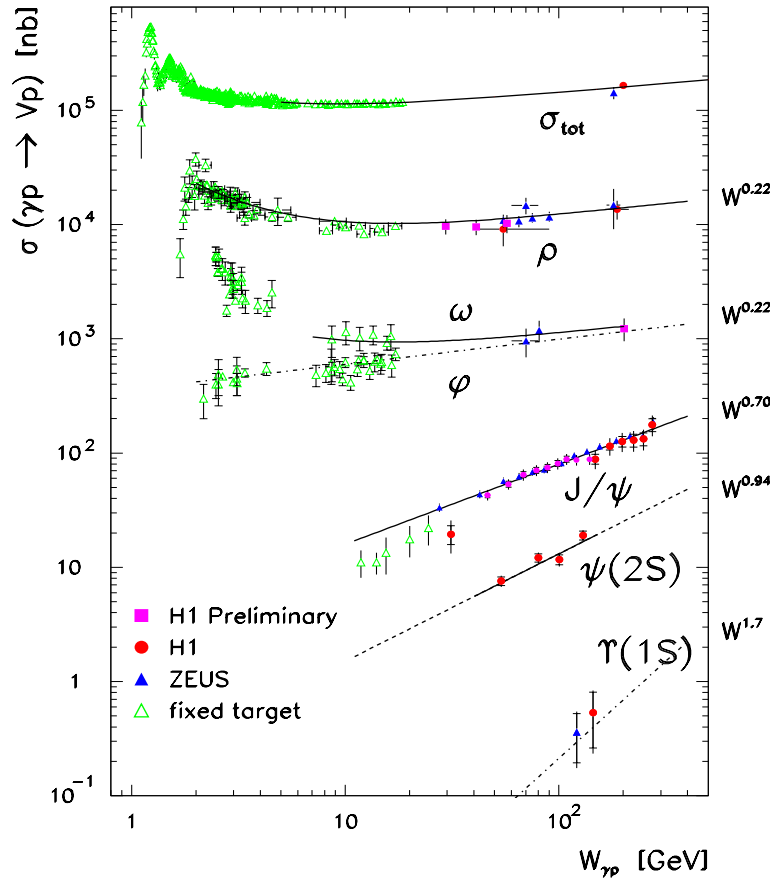
QCD level:  
with 2 gluon  
exchange



Large variety of processes to study dynamics versus scales:  $M_V^2$ ,  $Q^2$ ,  $t$

# Vector Mesons: $M_V^2$ - Dependence

H1 and ZEUS photoproduction

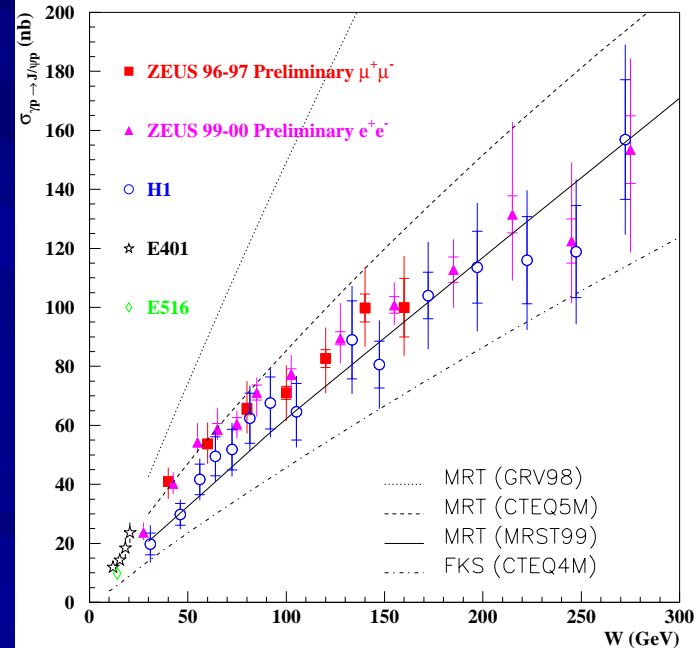


Fit:  $\sigma \sim W^\delta$  with  $\delta = 4(\alpha_P(0) - 1)$

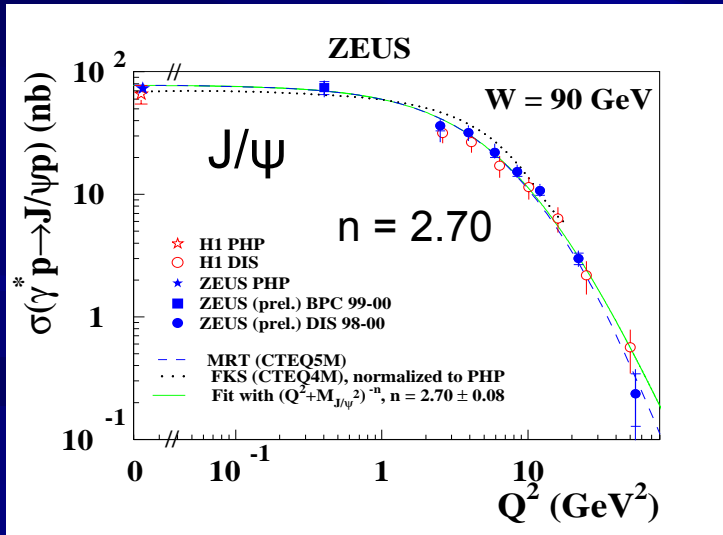
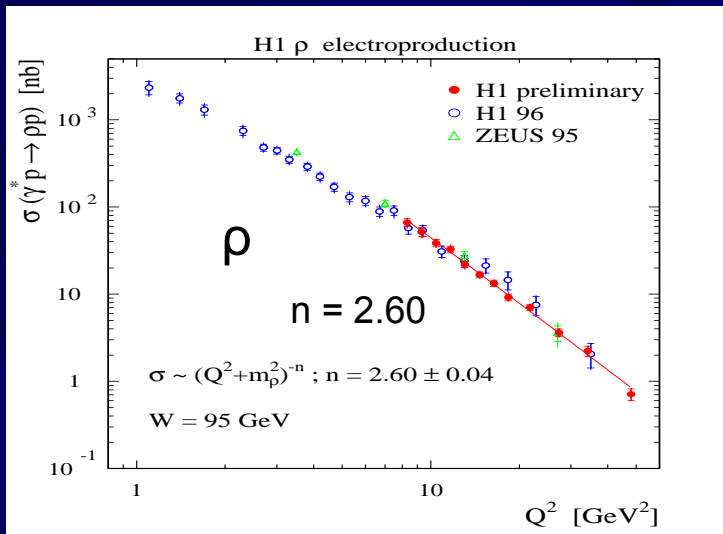
$W$ -dependence steeper with  $M_V^2$ :

$$\delta_\rho \sim 0.2 \longrightarrow \delta_{\psi(2S)} \sim 1.0$$

Large  $M_V$  supplies a scale for hard processes  $\rightarrow$  apply pQCD models

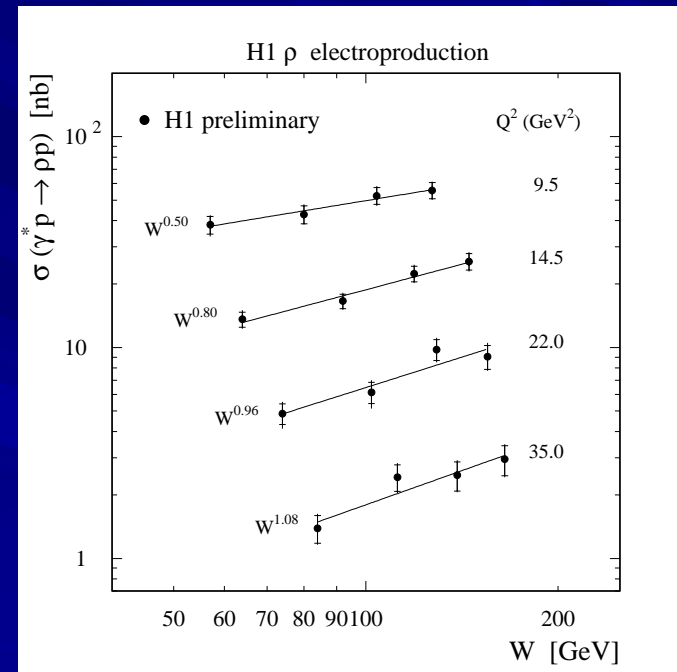


# Vector Mesons: $Q^2$ - Dependence



- Photoproduction of light VM well described by Regge Model
- pQCD predicts  $(Q^2 + M^2)^{-n}$  dependence for hard processes

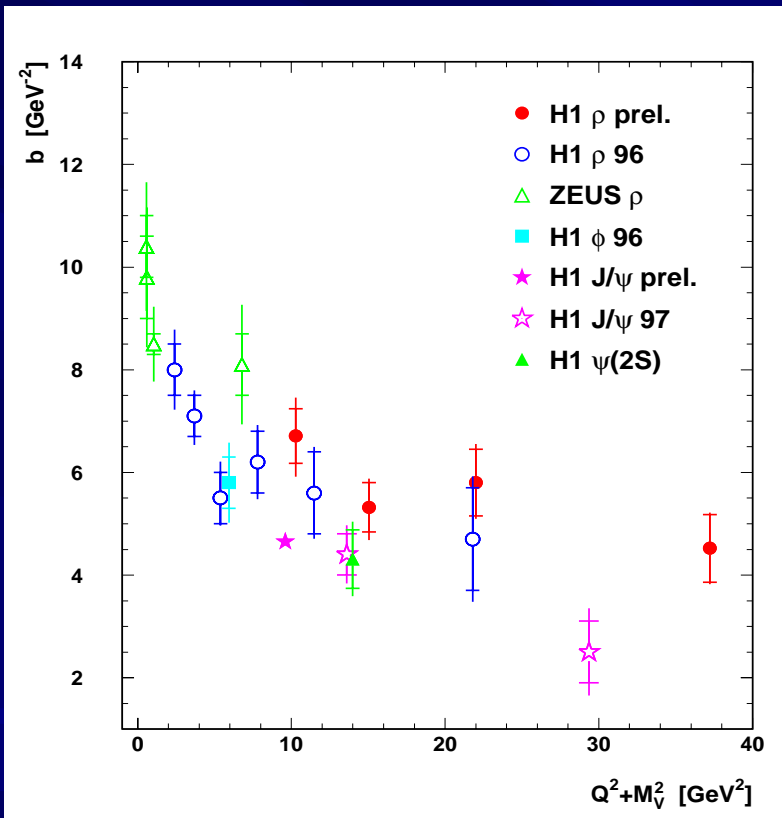
$W$ -dependence steeper with increasing  $Q^2$



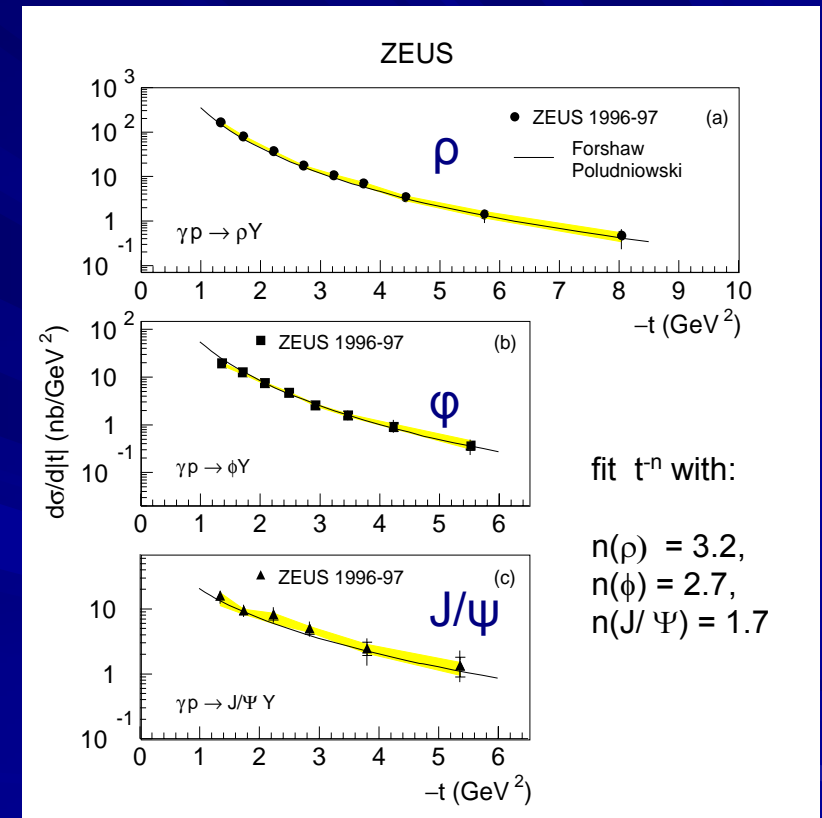
Increasing  $Q^2 \rightarrow$  hard processes dominate, pQCD models in good agreement with data

# Vector Mesons : $t$ - Dependence

Low  $t$  – region:  
well-described by  $\exp(-bt)$ , with  $b(W)$



High  $t$  – region:  
pQCD predicts non-exponential dependence

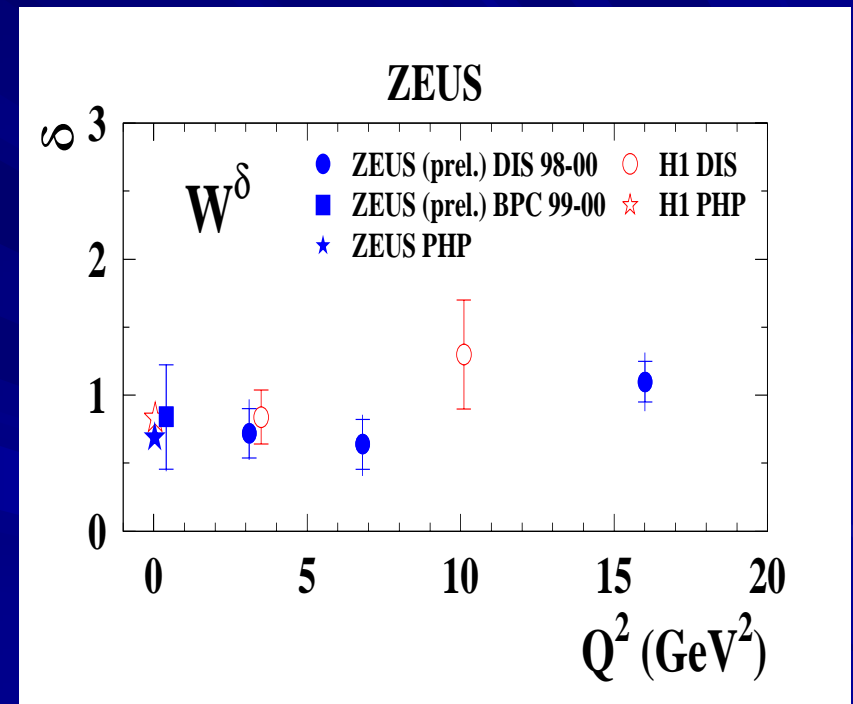
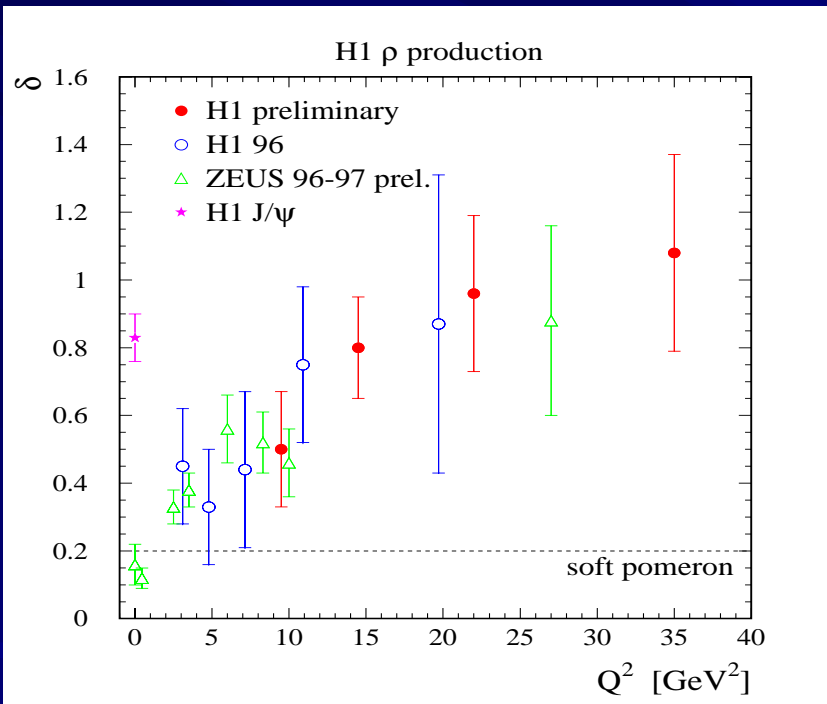


Universal  $t$ -dependence in scale  $Q^2$  or  $M^2$

pQCD model works fine at  $t > 1$  GeV<sup>2</sup>

# Vector Mesons: Soft & Hard Processes

Indicator:  $\sigma \sim W^\delta$  with  $\delta = 4(\bar{\alpha}_\rho(0) - 1)$  related to the exchanged object

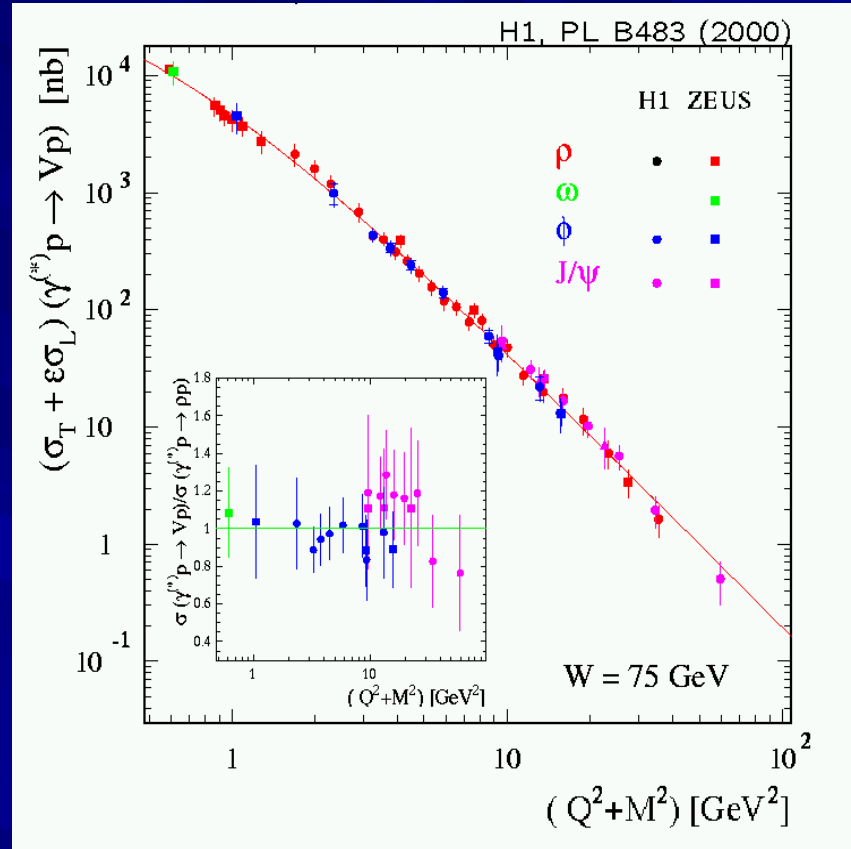
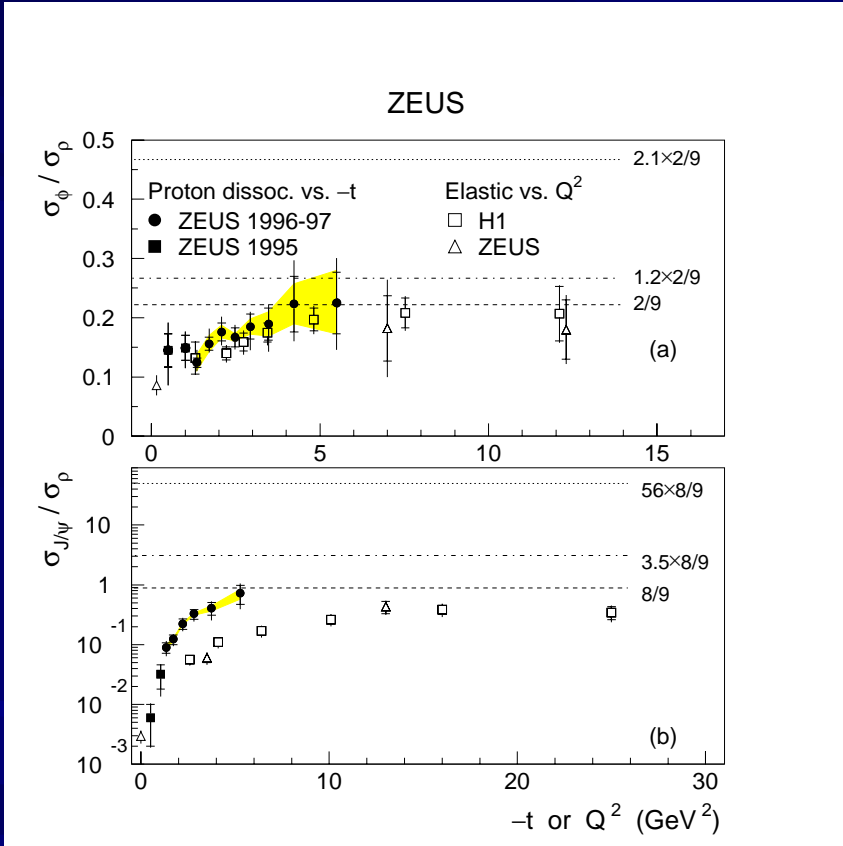


Light VM: smooth transition from soft to hard regime  
 Heavy VM: flat  $W$ -dependence, hard regime already at low  $Q^2$

# Vector Mesons : SU(4), Universality

SU(4) prediction :  $\rho : \omega : \phi : J/\psi = 1 : 1/9 : 2/9 : 8/9$   
 assume SCHC, neglecting masses, meson-WF

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

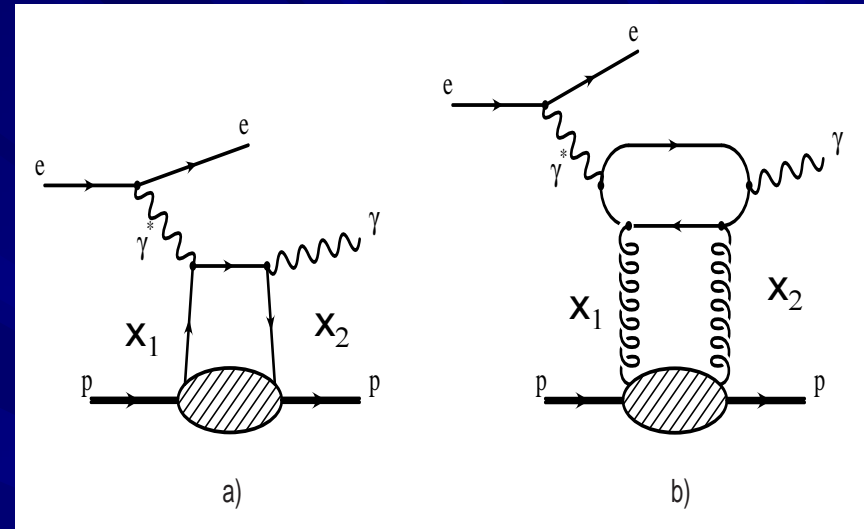


SU(4) restoration at  $t \sim 5$  GeV<sup>2</sup>,  $Q^2 \sim 10$  GeV<sup>2</sup>

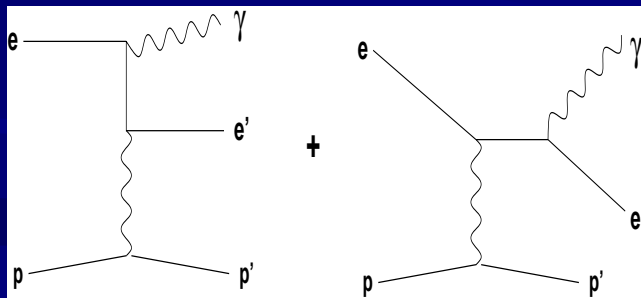
Universal  $Q^2 + M^2$  dependence for all VM reflects common underlying dynamics

# Deeply Virtual Compton Scattering

- measure electron and photon
- topology similar to VM production: replace the VM by a photon
- clean QCD process with point-like couplings, no wave function
- skewed / generalized PDFs  $G(x_1, x_2, Q^2)$



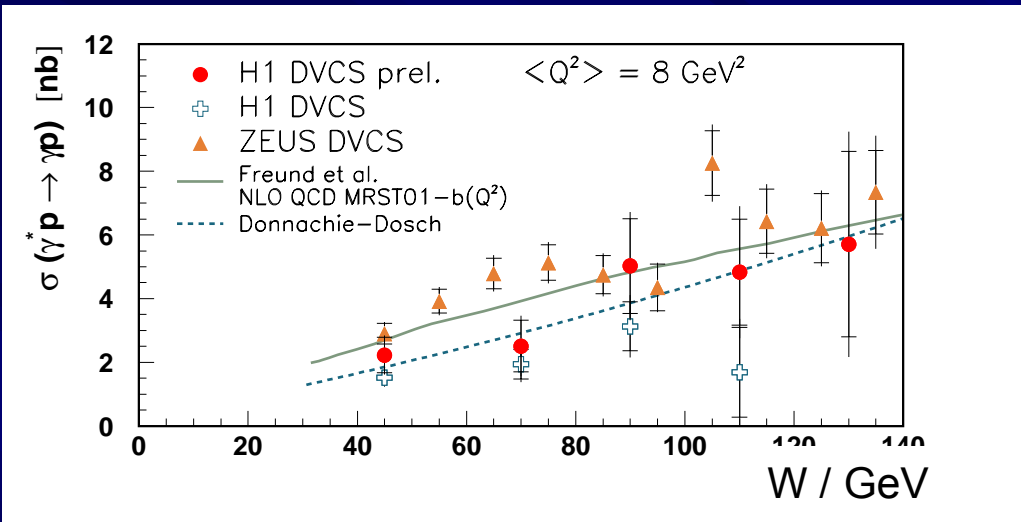
Measurement problem:



Bethe-Heitler QED process

- elastic BH process has same signature, but much larger cross section,  $\alpha_{em} \leftrightarrow \alpha_{em}^2$

# DVCS: $W$ and $Q^2$ -Dependences

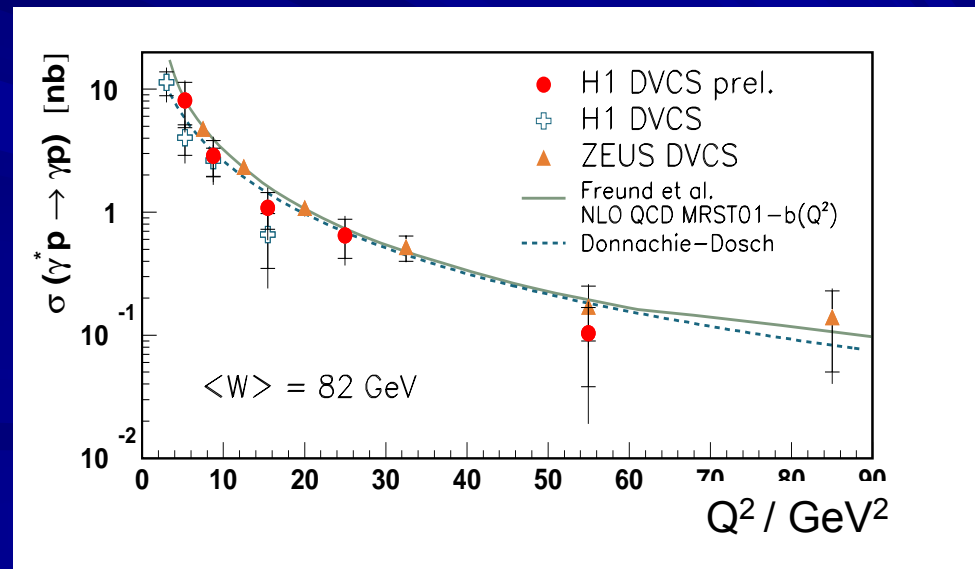


Fit  $W^\delta$  with  $\delta \sim 1$  indicates hard process

Fit  $\sigma \sim Q^{-3} \leftrightarrow \text{pQCD} \sim Q^{-4}$   
 $\rightarrow$  soft processes essential

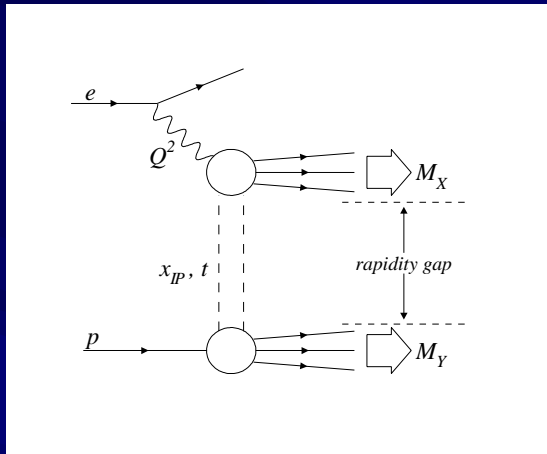
- NLO QCD Freund & with 2 sets of GPDFs
- Colour dipole models Donnachie &, Favart &

Both theoretical approaches consistent with measurements



# Diffractive Deep Inelastic Scattering : $\sigma_r^D$

Complete set of variables:  $Q^2, x_P, t, M_X, M_Y$



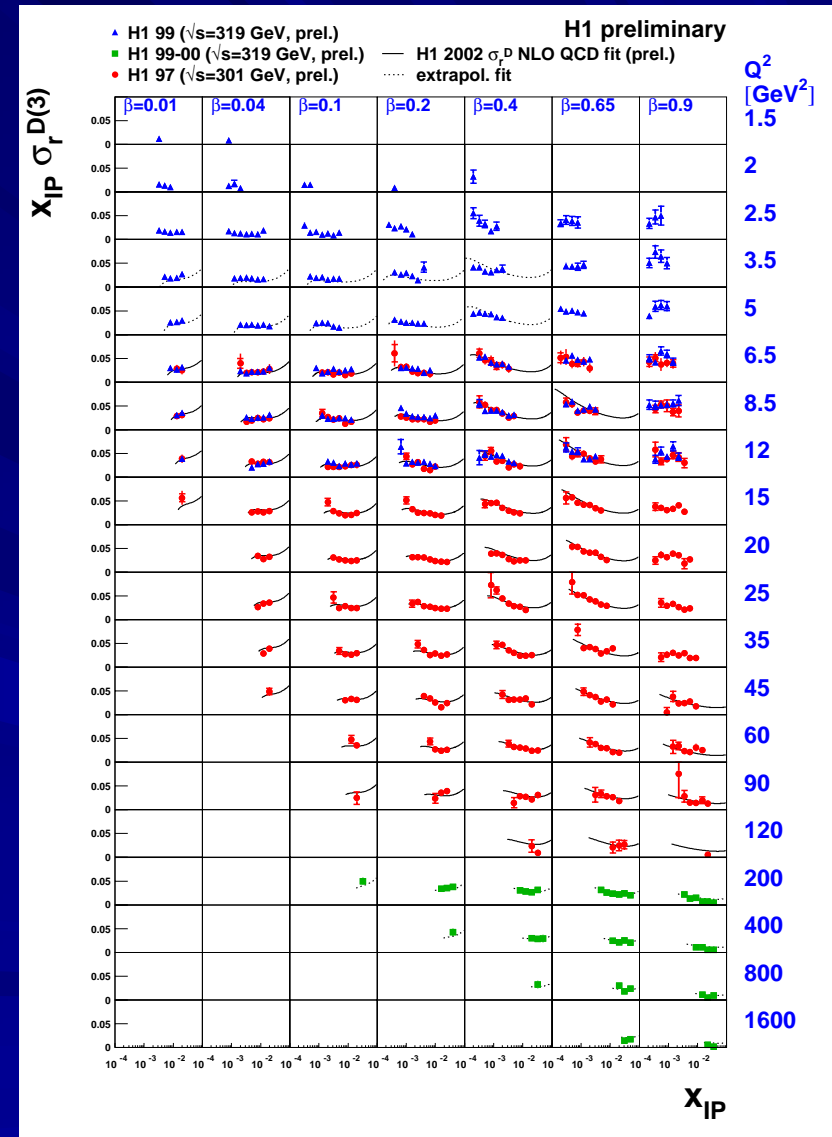
System Y not measured

→ integrate over  $M_Y < 1.6 / 2.3 \text{ GeV}, t < 1 \text{ GeV}^2$   
and measure reduced cross section  $\sigma_r$ :

$$\frac{d^3\sigma^D}{dx_P dx dQ^2} = \frac{4\pi\alpha^2}{xQ^4} \left(1 - y + \frac{y^2}{2}\right) \sigma_r^{D(3)}(x_P, x, Q^2)$$

$$\sigma_r^{D(3)} = F_2^{D(3)} - \frac{y^2}{1 + (1 - y)^2} F_L^{D(3)}$$

$F_L$  unknown,  $F_L = 0$  or  $F_L = F_2 \rightarrow$  few % error



# DDIS: $x_P$ -Dependence & $\alpha_P(0)$

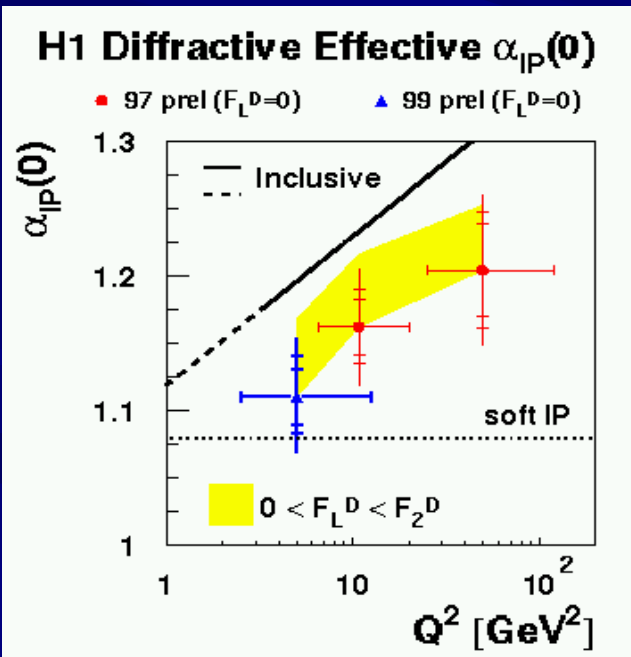
Use Ingelman&Schlein resolved Pomeron ansatz:

$$\sigma_r^{diff} = flux(x_P) \cdot object(\beta, Q^2)$$

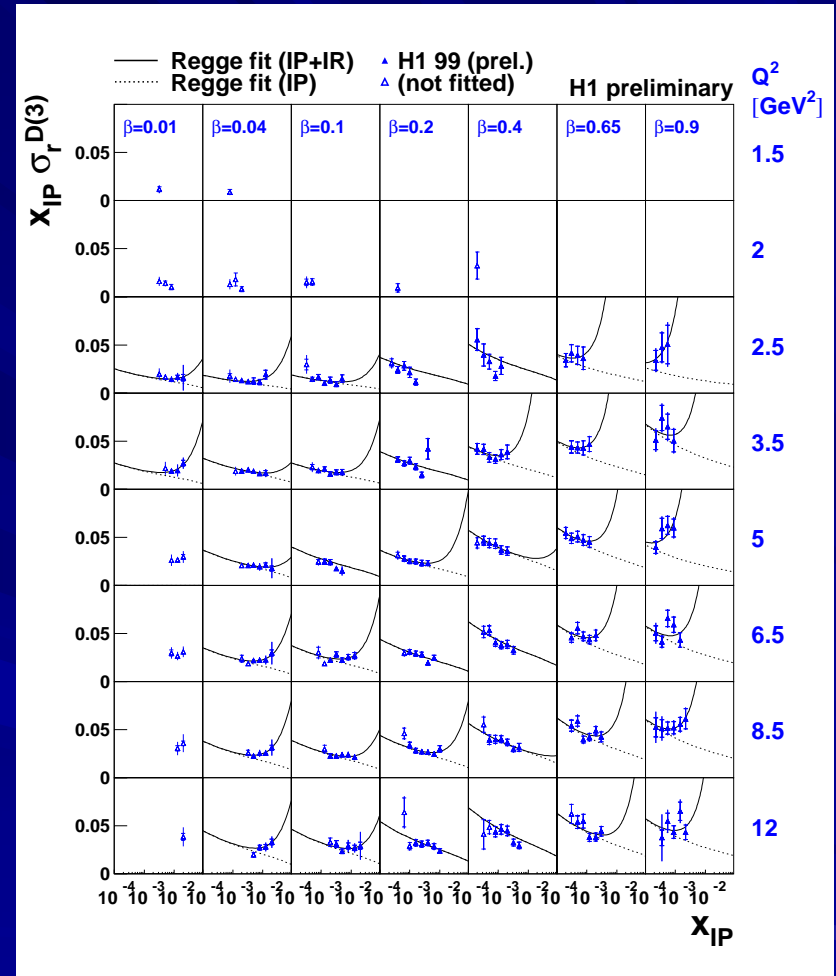
For large  $x_P > 0.01$  add Reggeon exchange :

$$\sigma_r^{D(3)}(x_P, \beta, Q^2) = f_P(x_P) A_P(\beta, Q^2) + f_R(x_P) A_R(\beta, Q^2)$$

with flux in Regge limit: 
$$f_P(x_P) = \int \frac{e^{b_{IP}t}}{x_{IP}^{2\alpha_{IP}(t)-1}} dt.$$



$\alpha_P(0)$  indicates hard Pomeron at high  $Q^2$



Reggeon essential at large  $x_P > \sim 0.01$

Resolved Pomeron ansatz works for  $x_P$ -dependence fine

# DDIS: QCD Analysis

## QCD Fit Model:

- 1) Use QCD hard scattering factorization:

$$\sigma^{\gamma^*p \rightarrow p'X} = \sigma^{\gamma^*i} \otimes f_i^D$$

$\sigma^{\gamma^*i}$  = universal partonic cross section  
same as in inclusive DIS

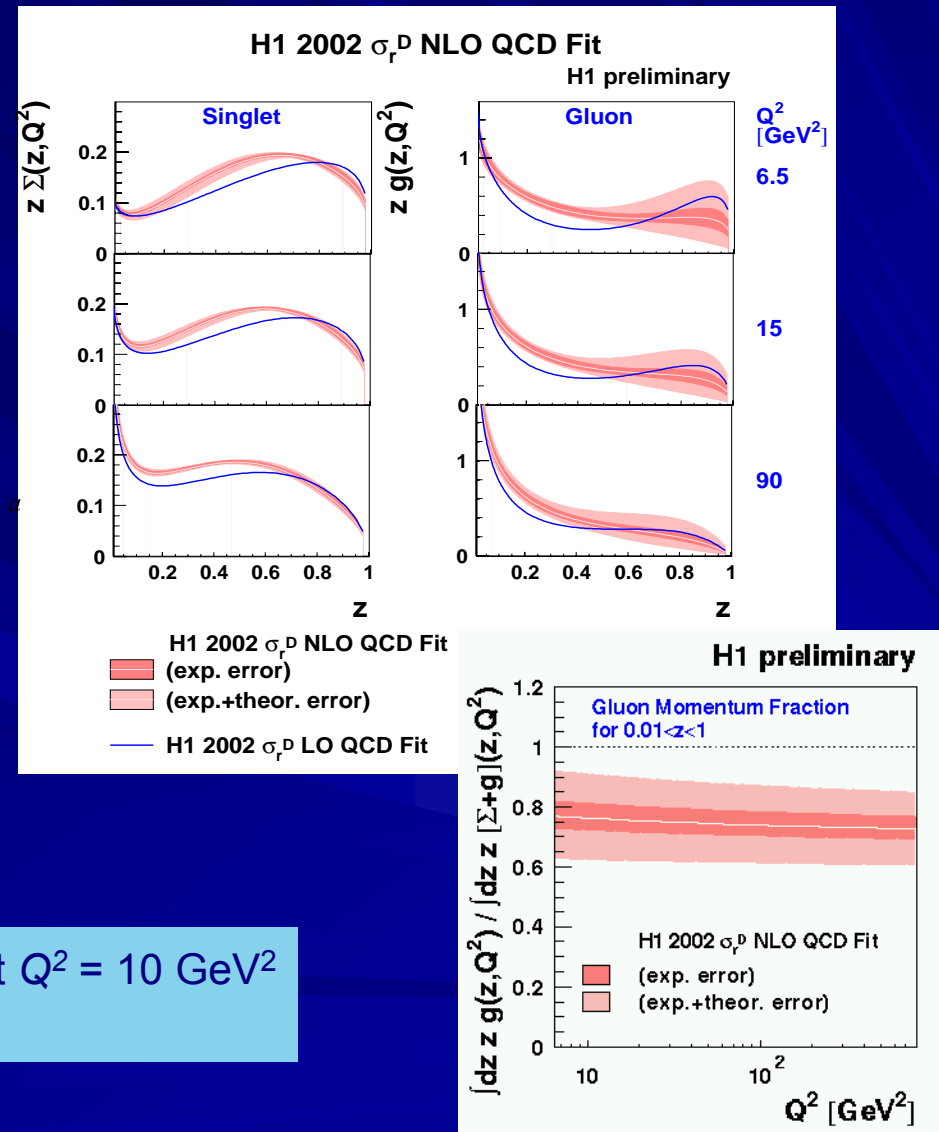
$f_i^D$  = diffractive PDFs,  $x_p$  &  $t = \text{const.}$

- 2) Parton ansatz for exchange:

$$\text{Pomeron} = \sum q(z) + \bar{q}(z) + g(z)$$

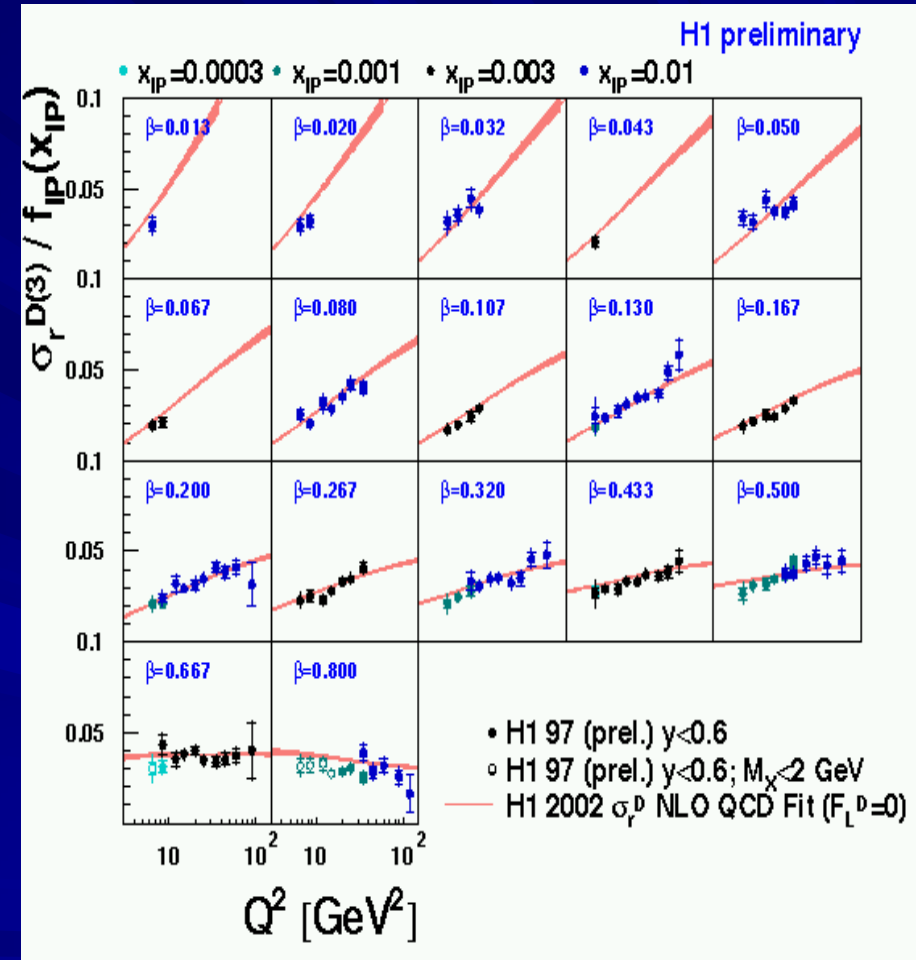
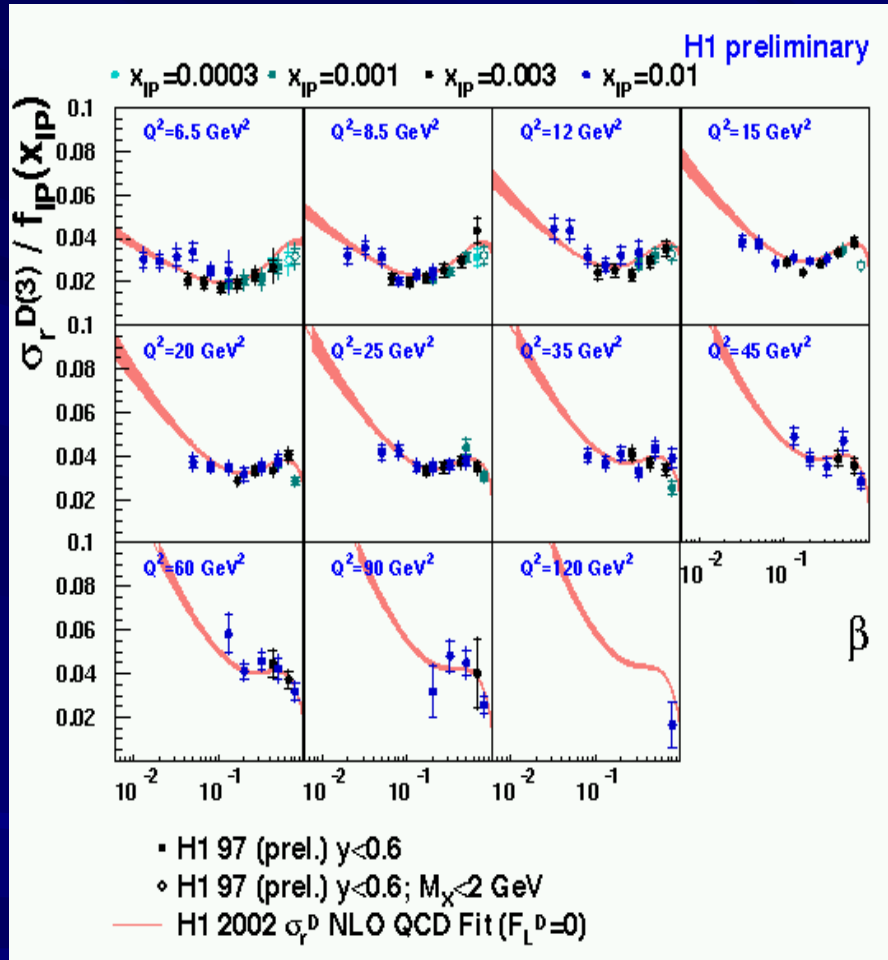
- 3) Use NLO DGLAP to evolve diffractive PDFs to  $Q^2 > Q_0^2 = 3 \text{ GeV}^2$

Gluon momentum fraction  $75 \pm 15 \%$  at  $Q^2 = 10 \text{ GeV}^2$   
and remains large up to high  $Q^2$



# DDIS: $\beta$ and $Q^2$ -Dependences (1)

Fit region:  $6 < Q^2 < 120 \text{ GeV}^2$

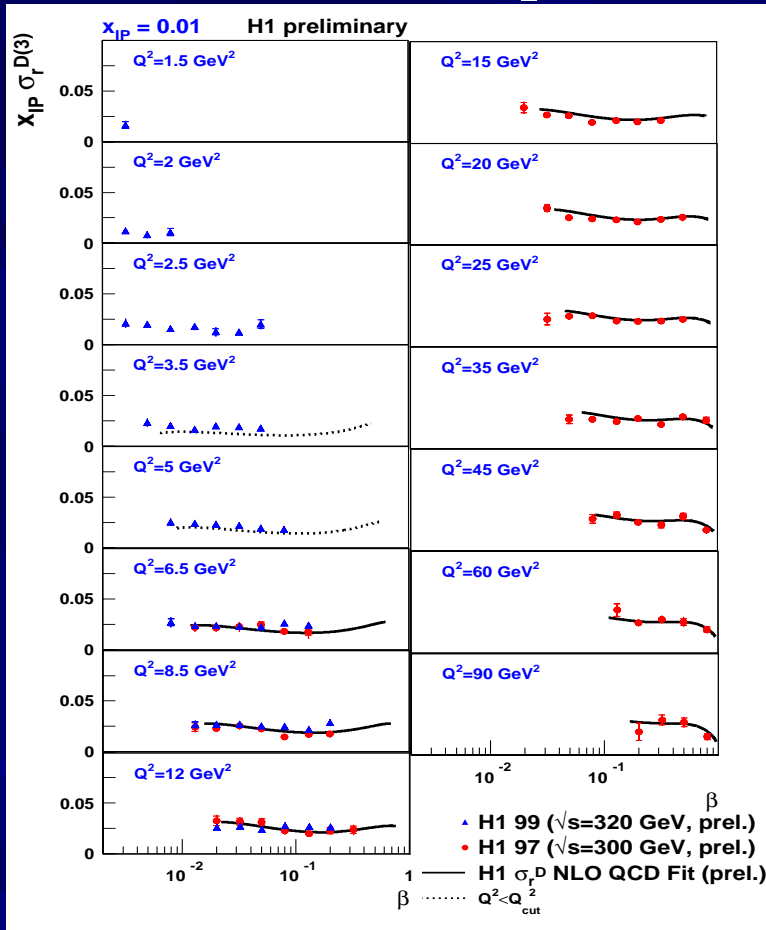


Flat up to high  $\beta$ , no  $x_P$  dependence  
 $\rightarrow$  Regge factorization works

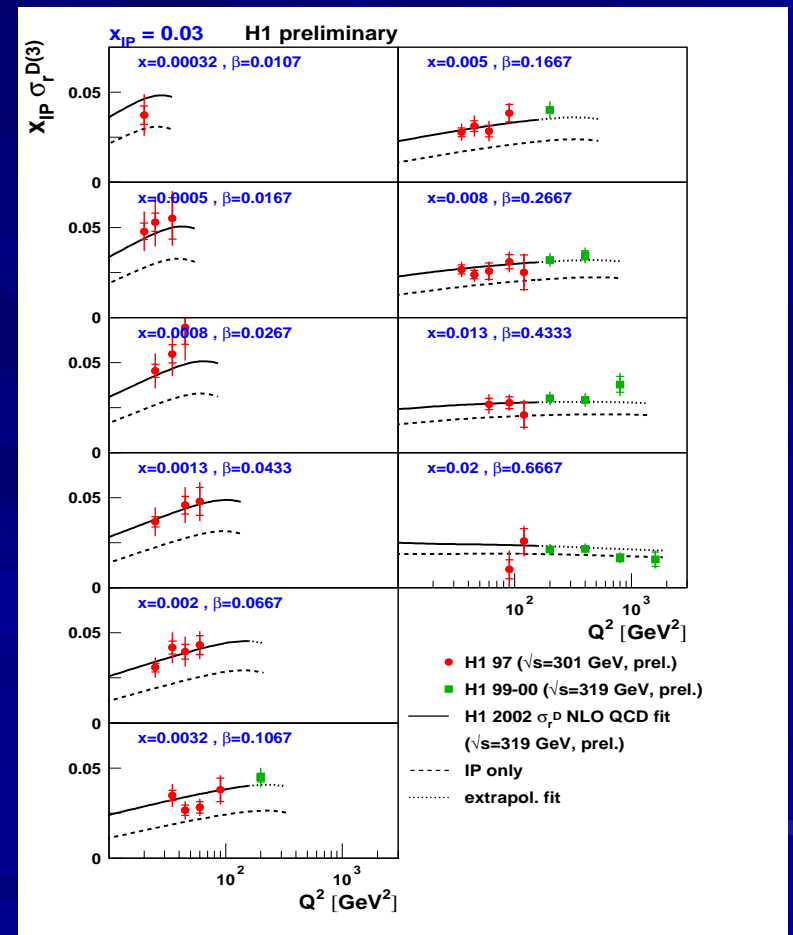
strong positive scaling violations up to  
 high  $\beta \rightarrow$  large gluon component

# DDIS: Extrapolation of NLO QCD fit

$1.5 < Q^2 < 12 \text{ GeV}^2$ ,  $x_p < 0.01$



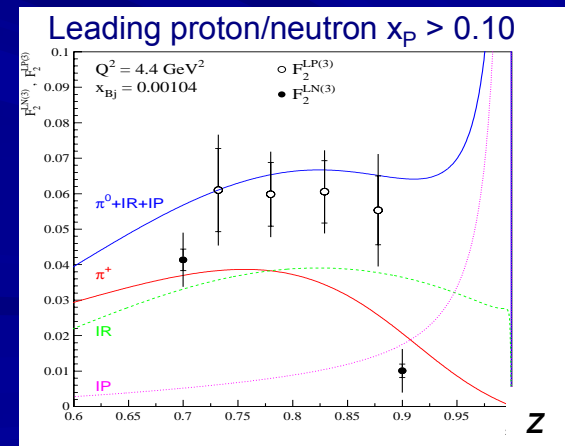
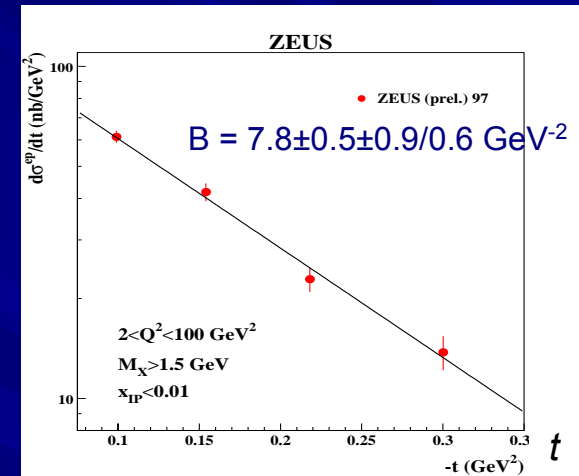
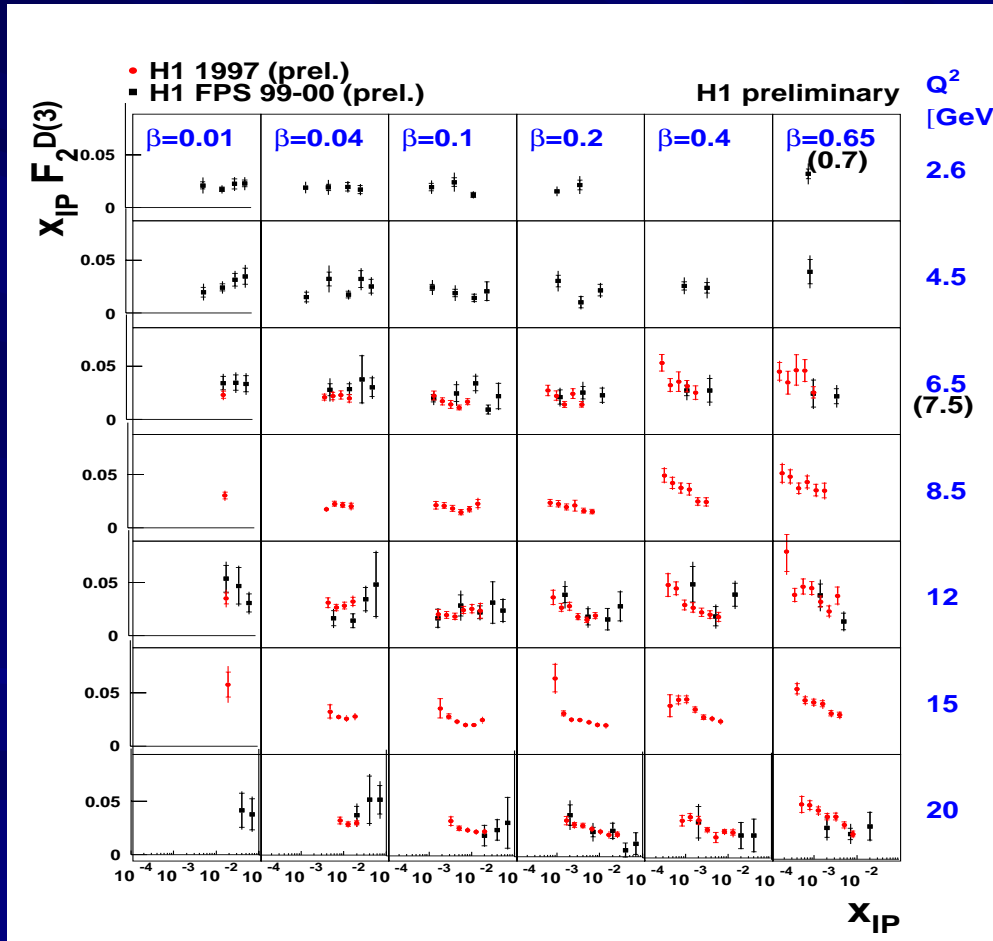
$200 < Q^2 < 1600 \text{ GeV}^2$ ,  $x_p < 0.03$



General in good agreement, confirm diffractive PDFs with gluon dominance

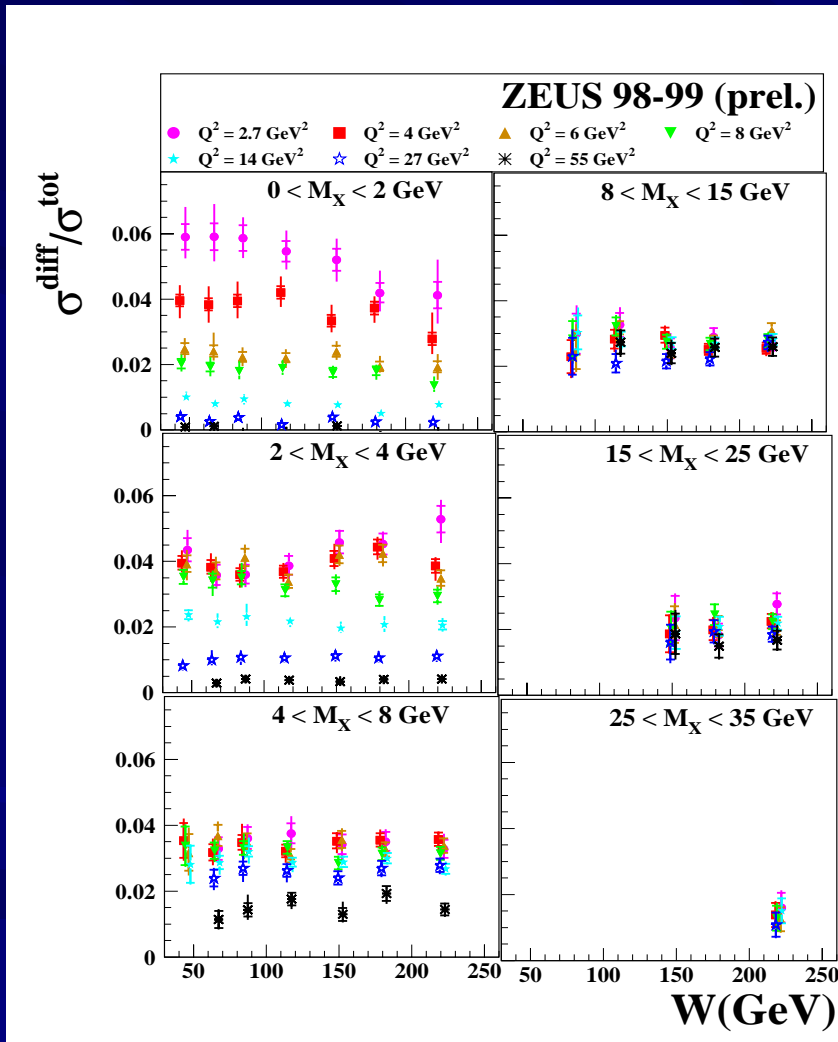
# DDIS : Forward Proton Tagging

- 1) free of unknown p-dissociation corrections, H1/ZEUS  $M_Y < 1.6 / 2.3$  GeV
- 2) measure momentum transfer  $t \rightarrow F_2^{D4}$ , at least  $t$ -slope
- 3) Cross over to non-diffractive region at  $x_p > 0.05$ , Reggeon & Pion exchange



# DDIS: Ratio $\sigma^{diff} / \sigma^{tot}$

ZEUS forward plug:  $2 < Q^2 < 80 \text{ GeV}^2$



**$Q^2$ -dependence:**  $M_X < 35 \text{ GeV}$

decreases with  $Q^2$

from  $\sim 20\%$  at  $Q^2 = 2.7 \text{ GeV}^2$

to  $\sim 10\%$  at  $Q^2 = 27 \text{ GeV}^2$

no  $Q^2$ -dependence for  $M_X > 8 \text{ GeV}$

**$W$ -dependence:**

$M_X < 2 \text{ GeV}$  ratio falling

$M_X > 2 \text{ GeV}$  ratio constant

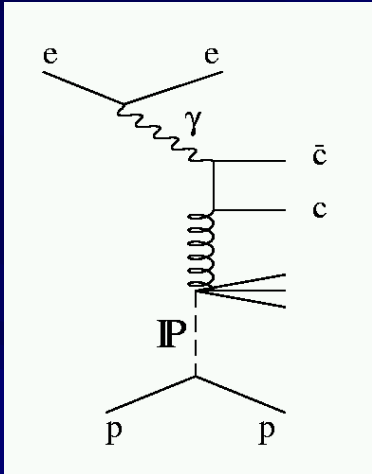
$W$ -dependence of ratio surprising,  
since Regge model predicts :

$$W^{4(\alpha(t) - 1)} / W^{2(\alpha(t) - 1)}$$

and QCD 2-gluon models:

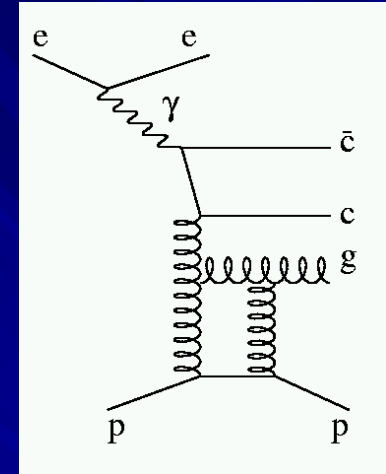
$$x g(x)^2 / x g(x)$$

# Final States : Open Charm in DDIS

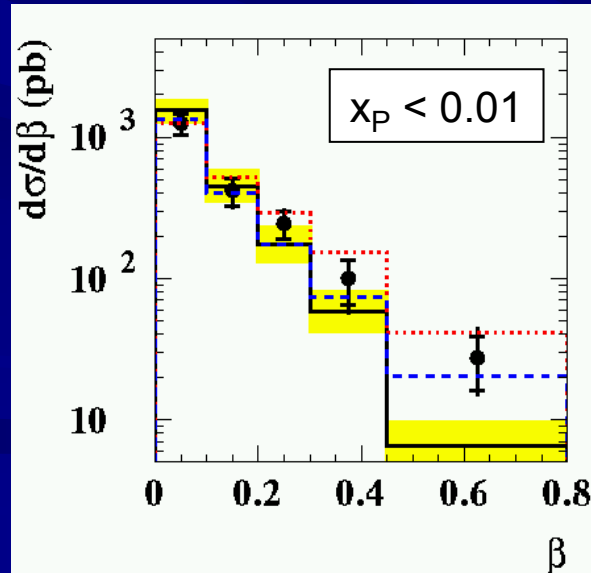
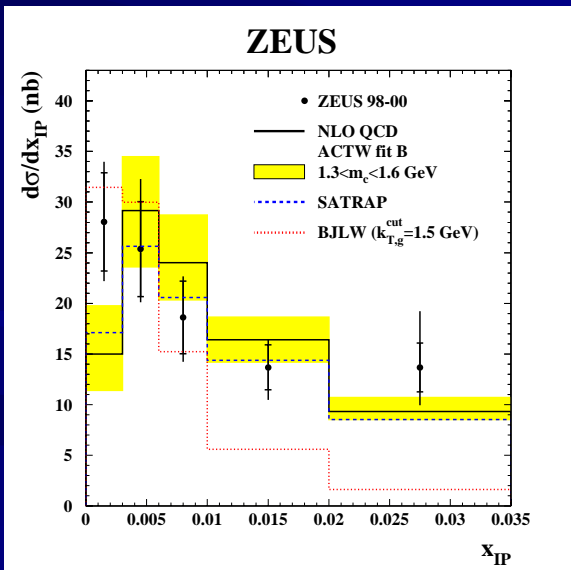


Open charm production very sensitive to the gluon/Pomeron component:  $\gamma^* \rightarrow c \bar{c}$

- 1) Resolved Pomeron - **Boson-gluon fusion**
- 2) Colour dipole **2 gluon exchange**



$\sim 260 D^*$ ,  $1.5 < Q^2 < 200 \text{ GeV}^2$



Resolved Pomeron :

- NLO fit Alvero &

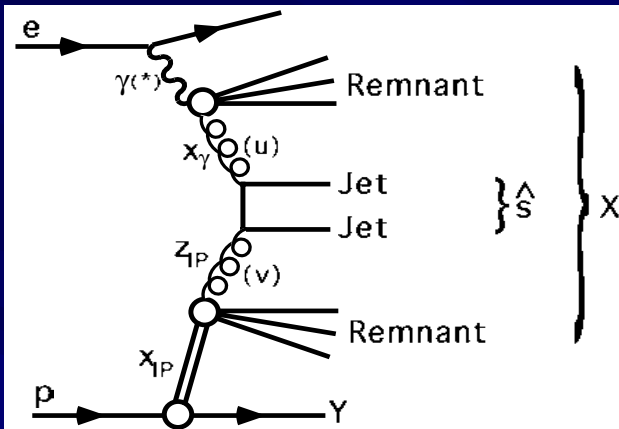
2-gluon exchange  $q\bar{q}+g$ :

- Golec-Biernat &

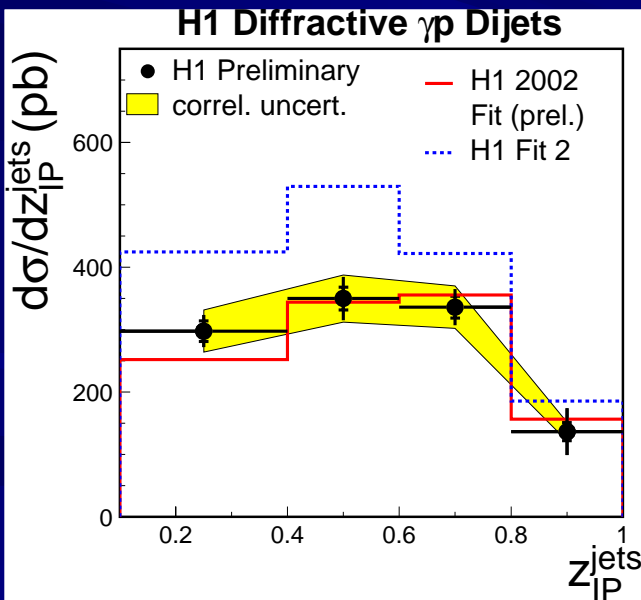
- Bartels &

All models agree with data for  $x_P < 0.01$

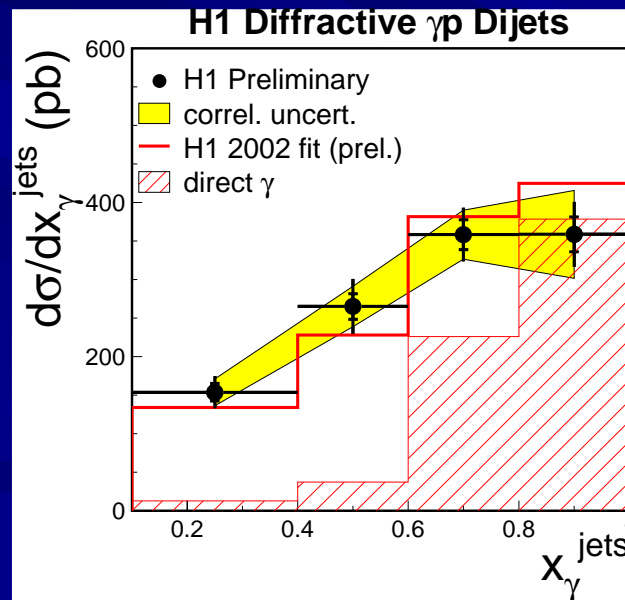
# Final states: Jets in Photoproduction



- Jet production sensitive to gluon component due to boson-gluon fusion
- Implement diffractive PDFs into Monte Carlo RAPGAP and compare with data
- Photon: direct and resolved processes with LO GRV PDFs



→ improved to LO fit



$z_P, x_\gamma$ :  
partonic momentum  
for dijet production

Resolved Pomeron  
in fine agreement  
with data – improved  
to LO PDFs

# Summary

## □ Vector Meson

- large  $M_V$  or  $Q^2$  or  $t$  provide a hard scale for application of pQCD models
- in the soft  $\rightarrow$  hard transition region the energy dependence becomes steeper

## □ DVCS

- tiny cross section measured, but needs more/HERA-2 data
- clean process to measure parton correlation by generalized PDFs  $G(x_1, x_2, Q_2)$

## □ Diffractive DIS

- positive scaling violations up to  $\beta \sim 0.5 \rightarrow$  gluons dominate  $75 \pm 15$  % diffraction
- ratio to inclusive DIS remarkable flat over  $W$

## □ Charm & Jets

- Models with diffractive PDFs describe different processes well  $\rightarrow$  confirm gluon dominance

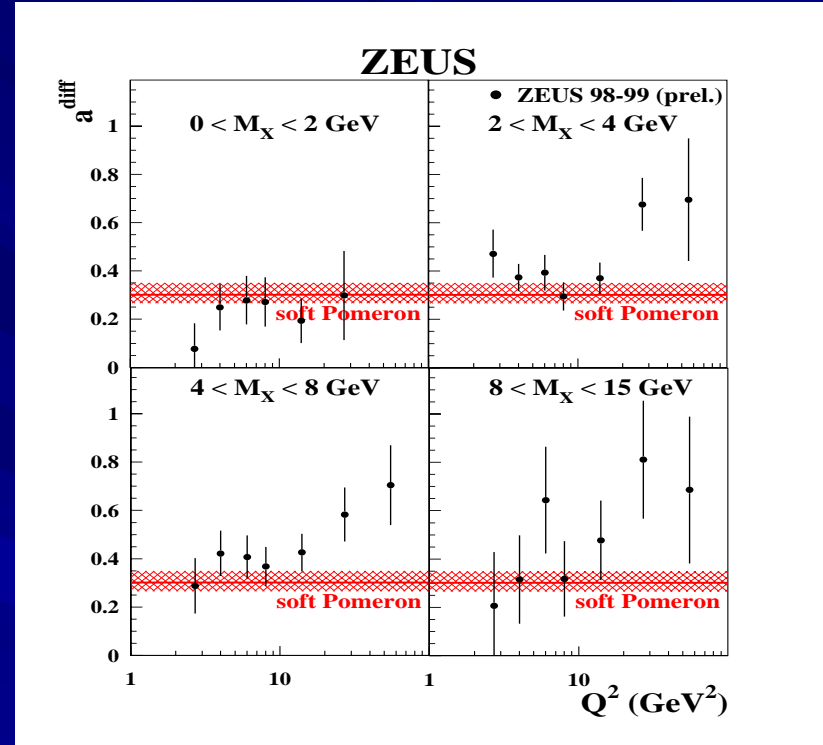
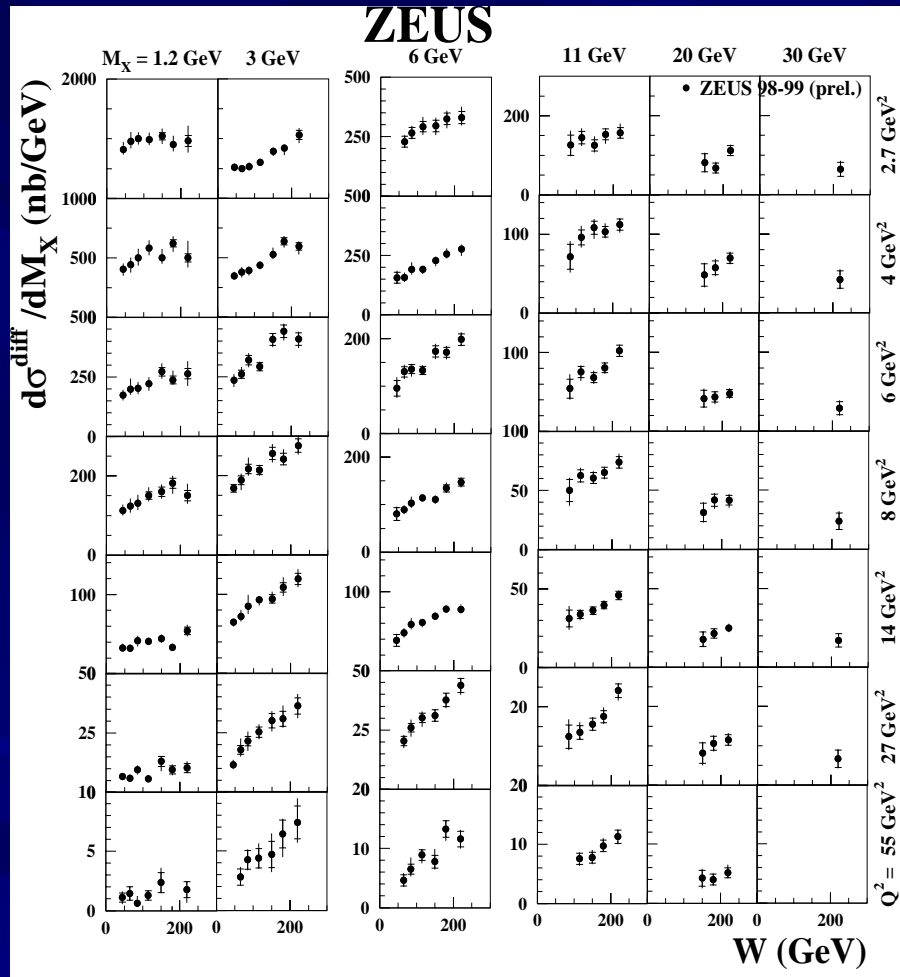
## □ pQCD Models

- Resolved Pomeron model & Regge / QCD factorization very promising
- Colour dipole models:  $q\bar{q}+g$  dominates at high  $Q^2$

# DDIS : $M_X$ - Dependence

ZEUS forward plug :  $M_X < 35$  GeV

$$\sigma^{\text{diff}} \sim W^{a_{\text{diff}}}, \quad a_{\text{diff}} = 4(\bar{\alpha}_P - 1)$$



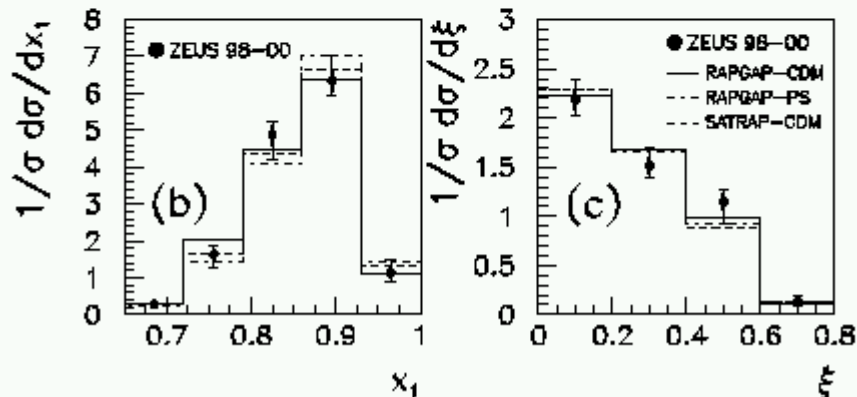
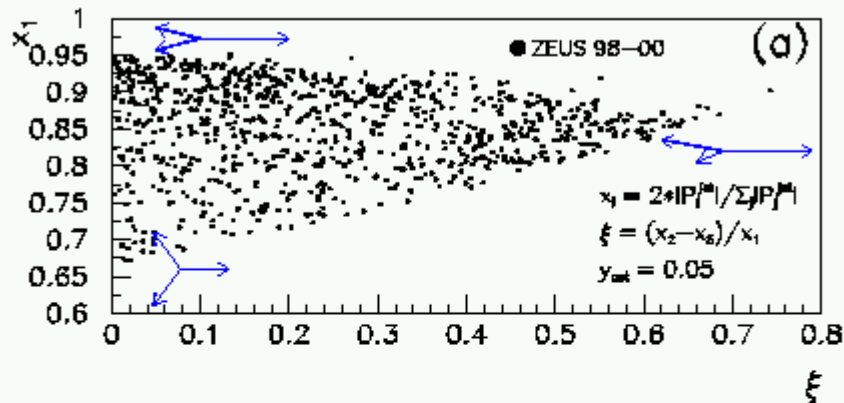
$M_X < 2$  GeV: vector mesons range  
little  $W$ -dependence  $\rightarrow$  soft

$M_X > 2$  GeV: steeper  $W$ -dependence with  $Q^2$ ,  
compatible with  $x_p$ -spectra

# Application: Diffractive Jet Production (2)

ZEUS: 3-jets in electroproduction  
 $5 < Q^2 < 100 \text{ GeV}^2$  ,  $M_X > 23 \text{ GeV}$

ZEUS



- 3-Jet fraction  $\sim 30 \%$
- at high  $M_X$  dominant process  
 $\text{photon} \rightarrow qq + g$
- gluon jet in Pomeron direction  
 and broader
- RAPGAP (resolved Pomeron)  
 SATRAP (colour dipole)  
 generators within 20 % range