Diffraction in ep Collisions at HERA

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

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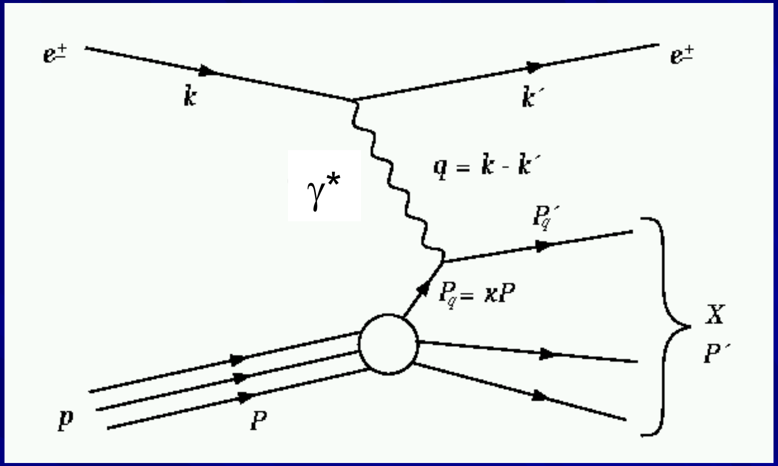
on behalf of the

H1 & ZEUS
Collaborations

Kinematics of Diffraction

Standard DIS variables:

x - fractional parton/proton momentum
Q^2 - neg. virtual photon momentum^2
y - fractional electron energy loss
W - γ-p center-of-mass energy
s - e-p center-of-mass energy

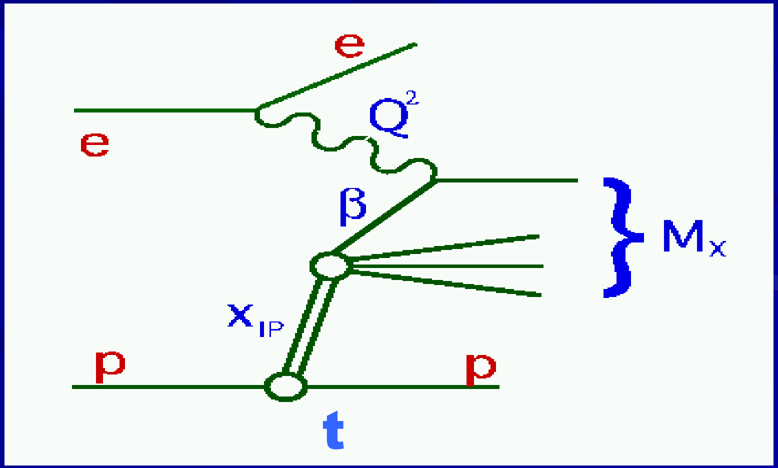


Additional for diffraction:

$x_P = Q^2 + M_X^2 / (Q^2 + W^2)$
fractional Pomeron momentum

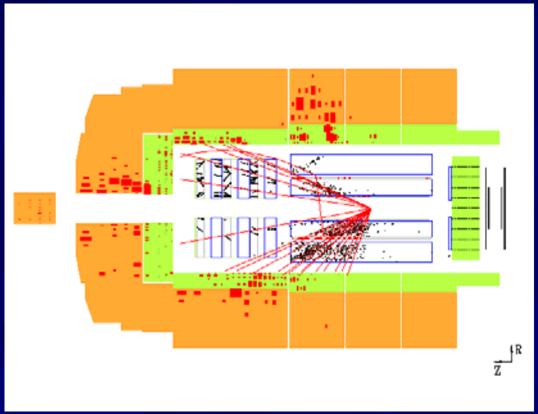
$\beta = Q^2 / (Q^2 + M_X^2)$
fractional parton/Pomeron momentum

$t = (p - p')^2$, proton momentum transfer^2

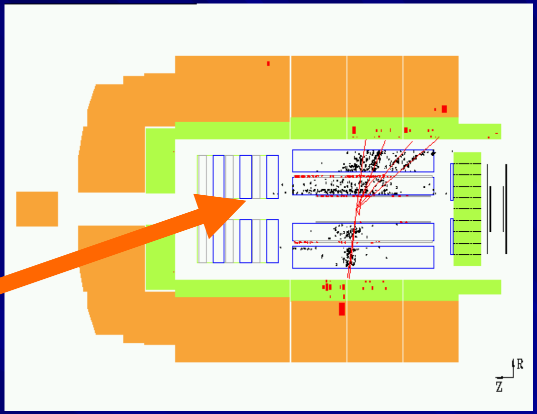


Signatures of Diffraction

non-diffractive event



diffractive event

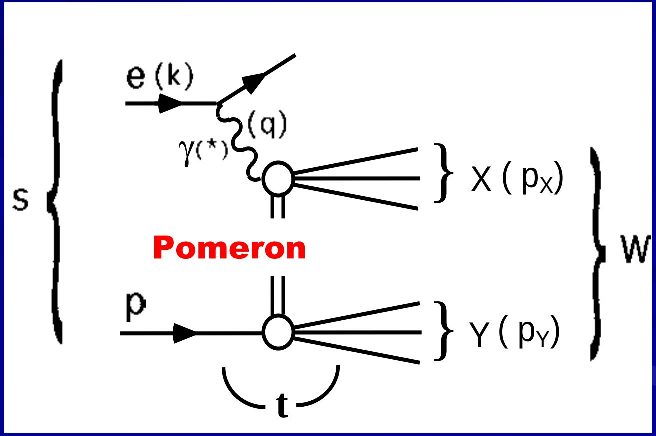


no visible forward activity

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

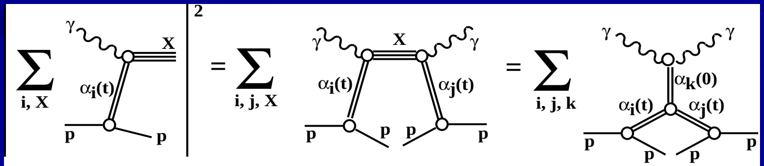
Notation: soft = non-perturbative process, hadron level

Regge model : diffraction described by exchange of Pomeron trajectory

$$\alpha_P(t) = \alpha_P(0) + \alpha_P' \cdot t, \alpha_P(0) = 1 + \varepsilon$$
$$\text{with} \quad \varepsilon = 0.08, \alpha_P' = 0.25\ GeV^{-2}$$

ε and α' result from fit of energy dependence of hadronic cross sections

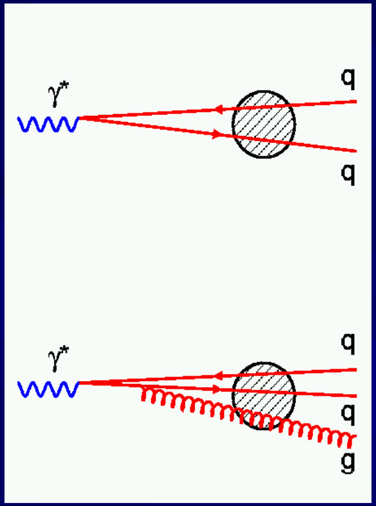
- slow increasing total cross section — $\sigma(W) = W^{\delta}$ with $\delta = 4(\varepsilon - \alpha'/B)$
- steep t-dependence with shrinkage — $\sigma(t) = exp(-Bt)$ with $B = B_0 + 2\alpha' \ln(W^2/W_0^2)$
- low M_X - pure Pomeron exchange — $\sigma(M_X) = M_X^{-2(1+2\varepsilon)}$
- large M_X - Reggeon & Pion exchange — Reggeon $\alpha_R(t) = 0.55 + 0.86\ GeV^{-2}\ t$; Pion $\alpha_\pi(t) = 0 + 1\ GeV^{-2}\ t$
- photon dissociation: triple Regge



Hard Diffraction Models

Notation: hard = perturbative process, parton level

Starting from alternative frames → two classes of models :

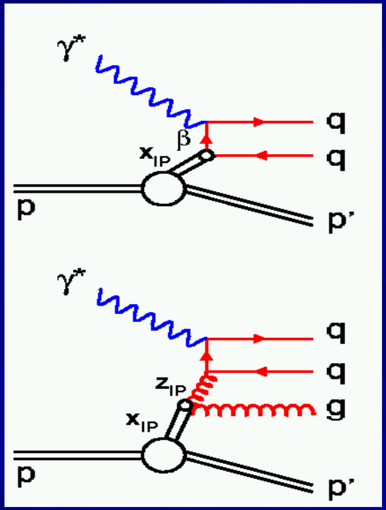


Proton rest frame

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

Breit frame

Standard DIS
scheme



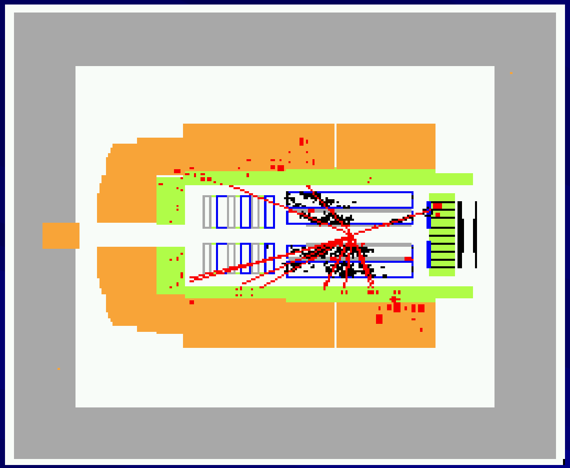
LO: 2 gluons , … gluon ladders	←	Exchange	→	object with partonic structure
fluctuates in colour dipoles $q\bar{q}$, $q\bar{q}$+g, …	←	Virtual photon	→	point-like couplings to partons, standard partonic cross sections
combine soft & hard processes by different parton transverse momentum	←	Dynamics	→	evolve diffractive PDFs in x / Q^2 by DGLAP / BFKL schemes

Colour Dipole Models

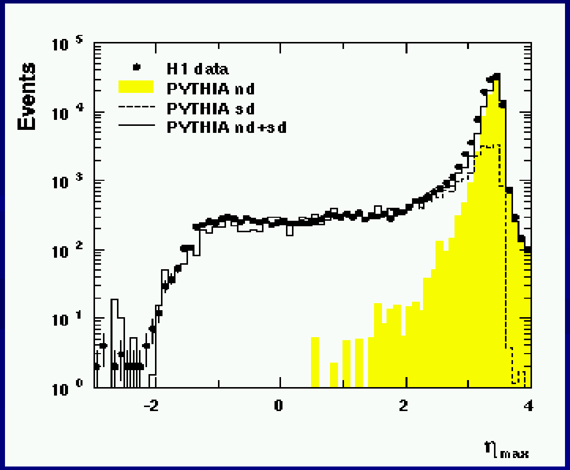
Resolved Pomeron Models

Selection Methods

1) Large Rapidity Gap / H1

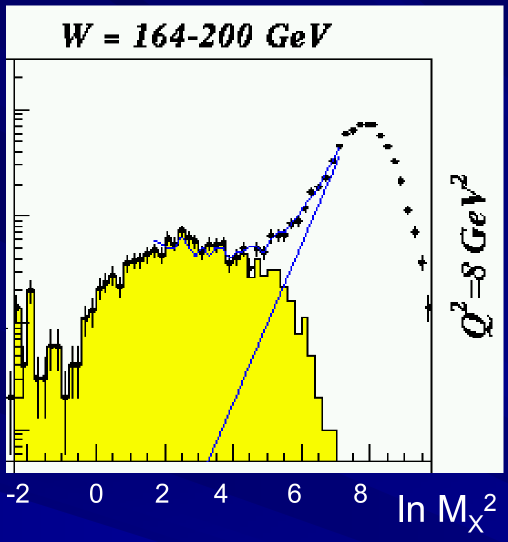


Typical cut: η_{max} < ~ 1.5 *)



*) η = -ln tan (Θ / 2)

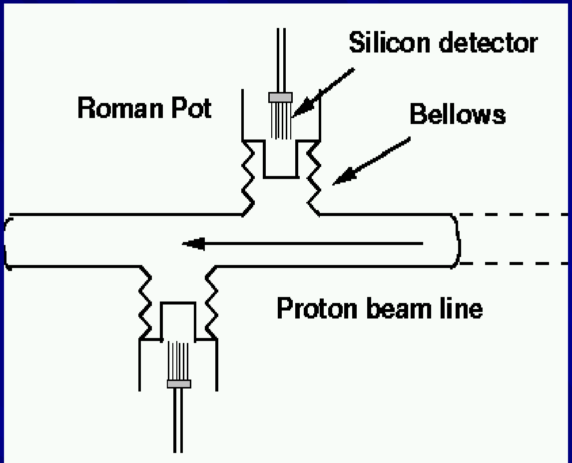
2) M_X– Method / ZEUS



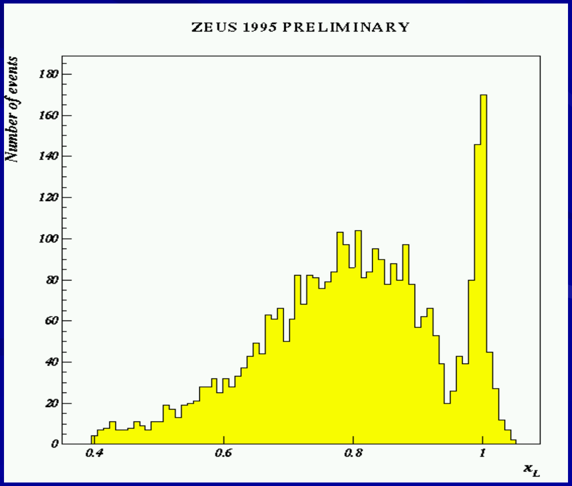
Fit excess above exponential fall-off

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

3) Proton Tagging / H1, ZEUS



FPS / LPS & beam line optics



HERA Domain

….or why diffraction at HERA ?

TOP 1 - Large kinematic range

920 GeV proton ↔ 27.5 GeV electron, $W \rightarrow 300$ GeV
$Q^2 \rightarrow 10^5$ GeV^2 photo- & electroproduction
$x = Q^2 / y\, s \rightarrow 10^{-5}$

TOP 2 - Large acceptance

H1/ZEUS ~ 4π to measure final state particles, important for γ^* dissociative system

TOP 3 - Large cross sections

~ 40 % of σ^{tot} , ~10 % of DIS is diffractive

TOP 4 - Point-like couplings

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

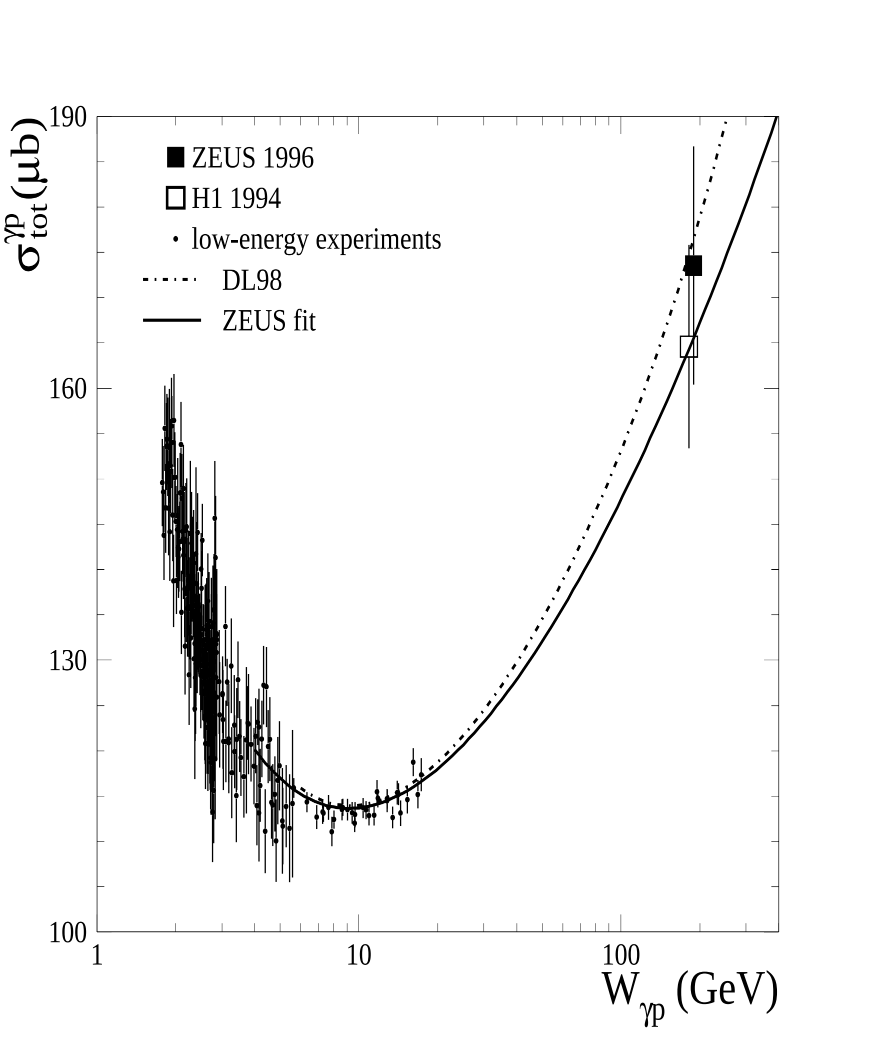
TOP 5 – Different varying scales

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

HERA opened a new window for diffraction

Total γp Cross Section

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



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

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

Fit: Pomeron + Reggeon contributions

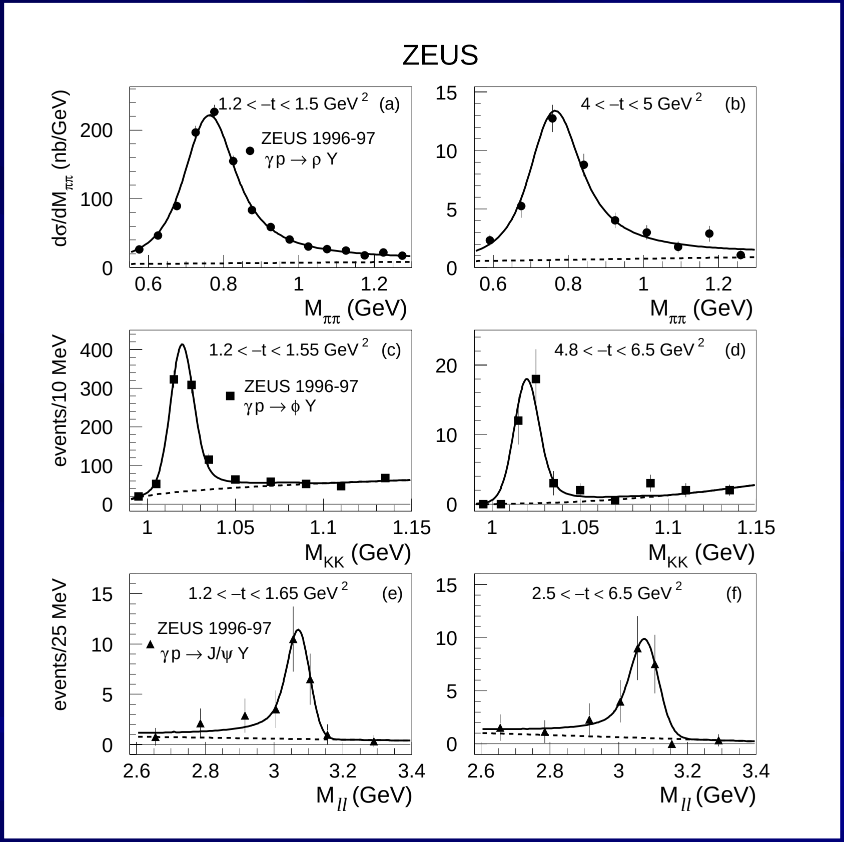
$$\sigma_{tot} = A \cdot W^{2\varepsilon} + B \cdot W^{-2\eta}$$
$$\varepsilon = 0.093 \pm 0.002$$

Energy dependence of γp resembles hadronic processes

Vector Mesons : Overview

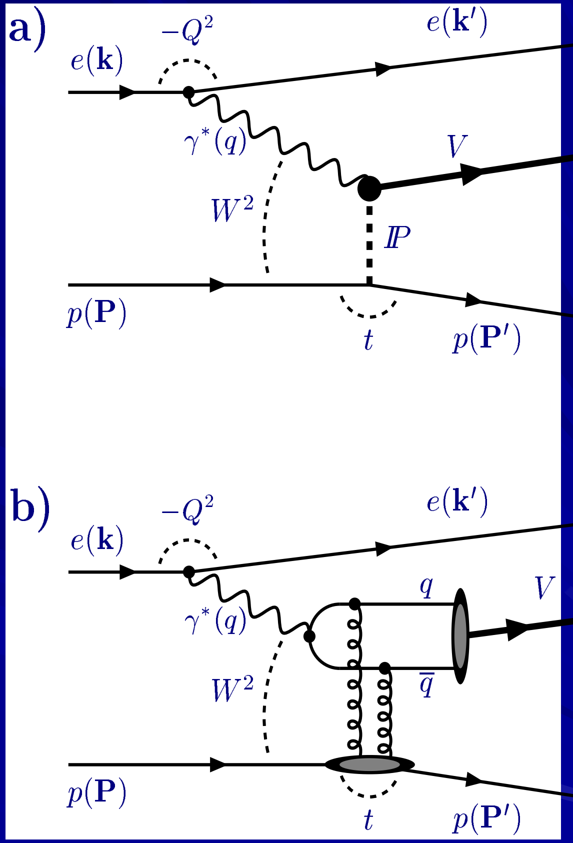
Exclusive processes in photo- and electroproduction : ρ, ω, φ, J/Ψ, Ψ(2S), Υ

Photoproduction ρ, φ, J/Ψ high t



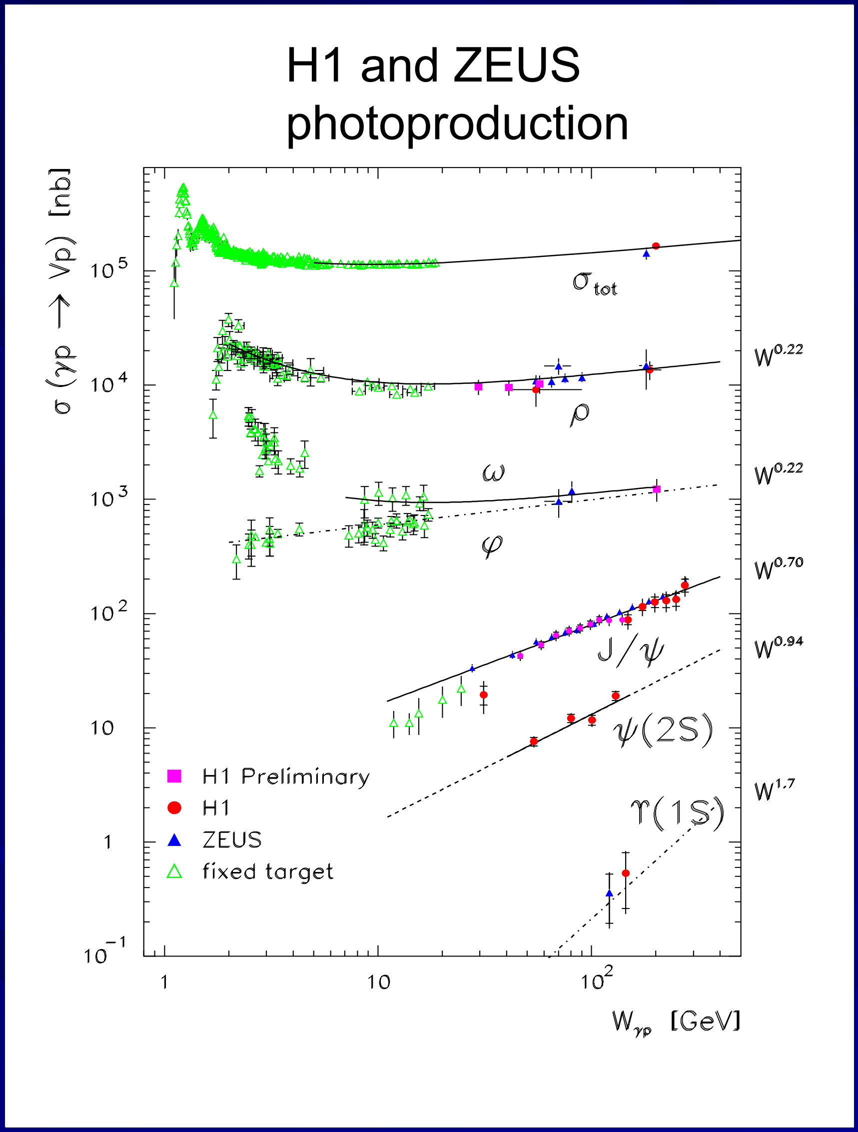
Hadron level:
Vector Meson
Dominance
& Regge model

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

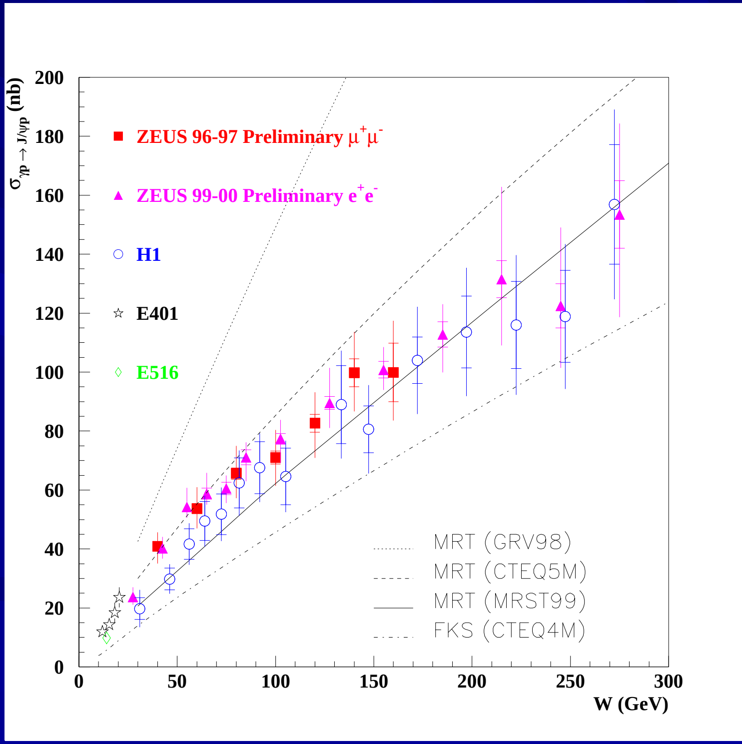


Fit: $\sigma \sim W^{\delta}$ with $\delta = 4(\alpha_P(0)\ \text{-}1)$

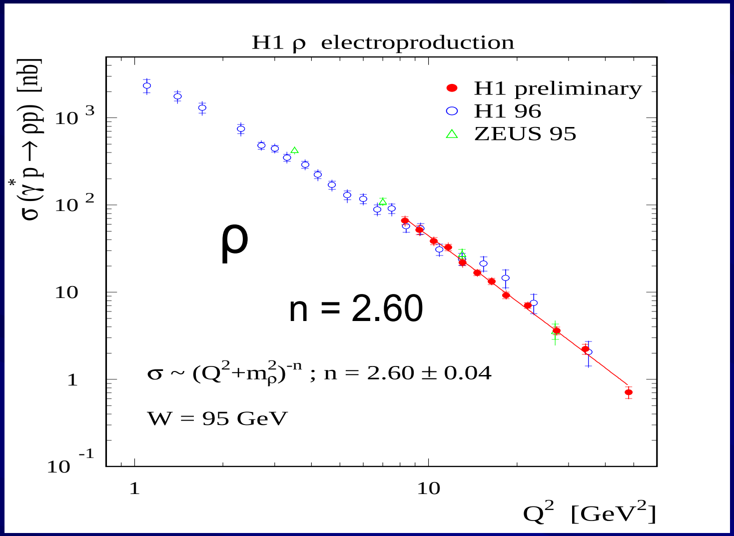
W-dependence steeper with M_V^2:

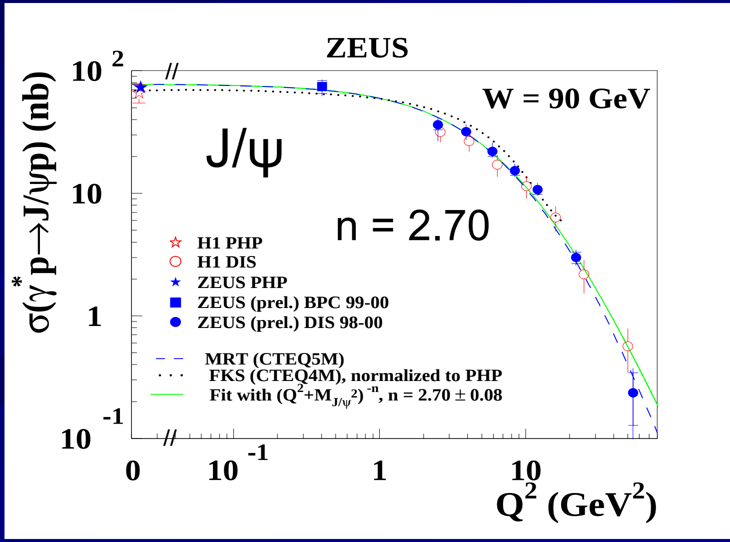
$\delta_\rho \sim 0.2$ --> $\delta_{\Psi(2S)} \sim 1.0$

Large M_V supplies a scale for hard processes → apply pQCD models



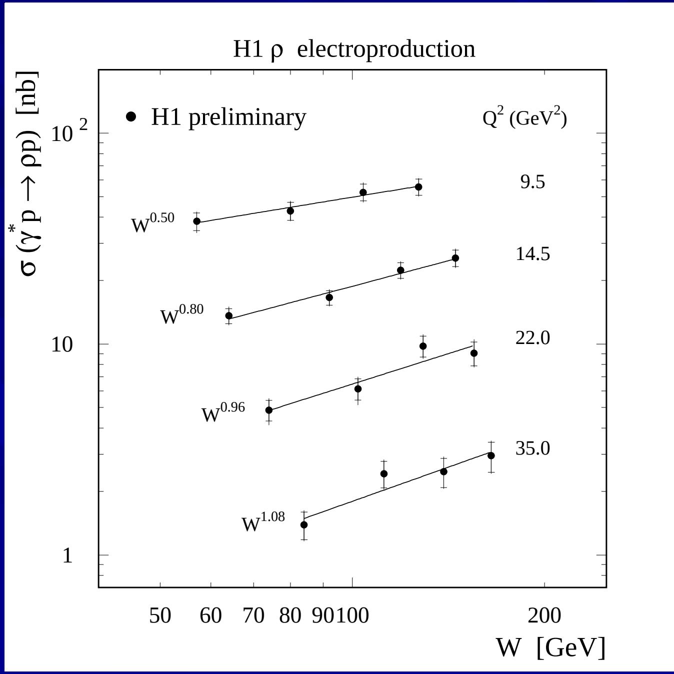
Vector Mesons: Q^2- Dependence





- 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

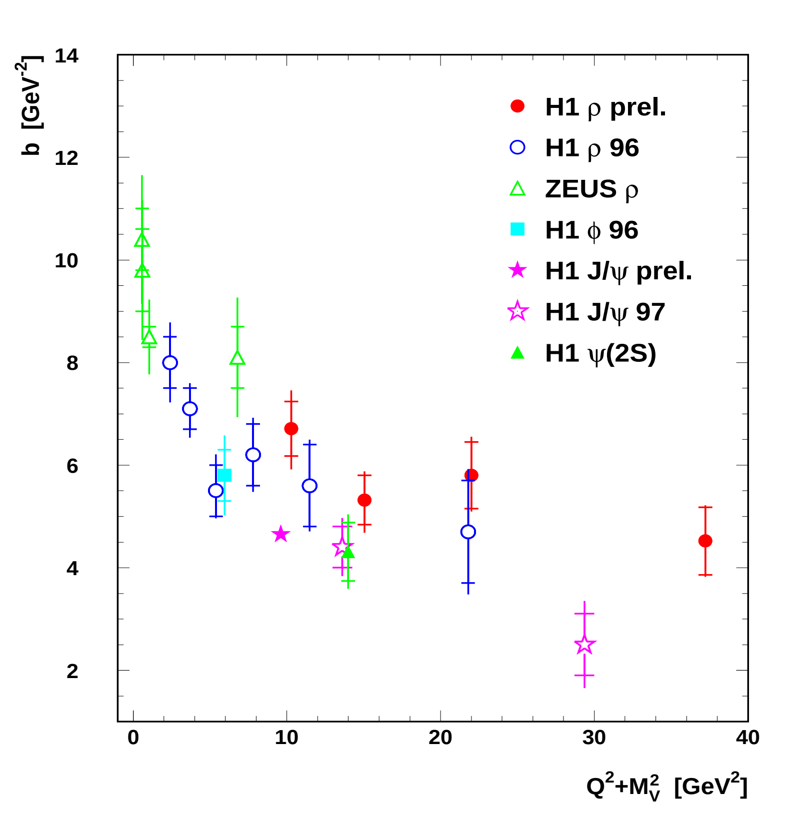


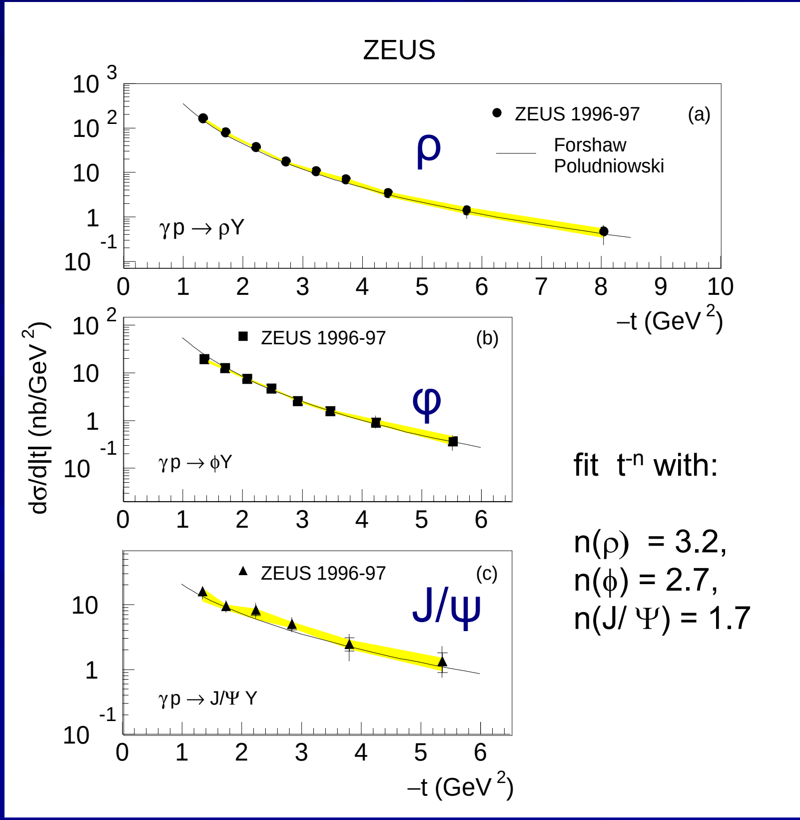
Increasing Q^2 → hard processes dominate, pQCD models in good agreement with data

Vector Mesons : *t* - Dependence

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

High *t* – region:
pQCD predicts non-exponential dependenc





fit t^{-n} with:

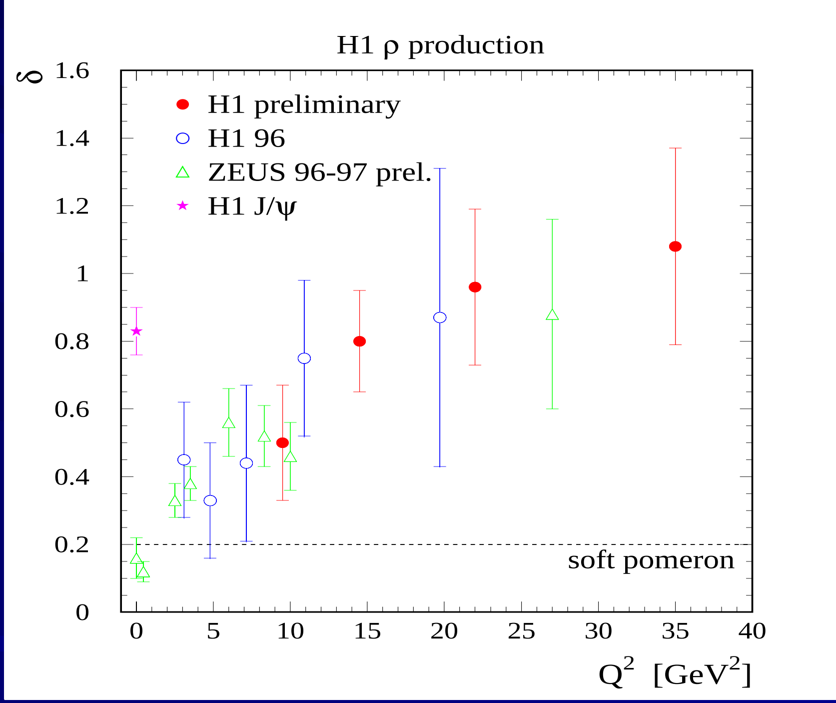
$n(\rho) = 3.2$,
$n(\phi) = 2.7$,
$n(J/\Psi) = 1.7$

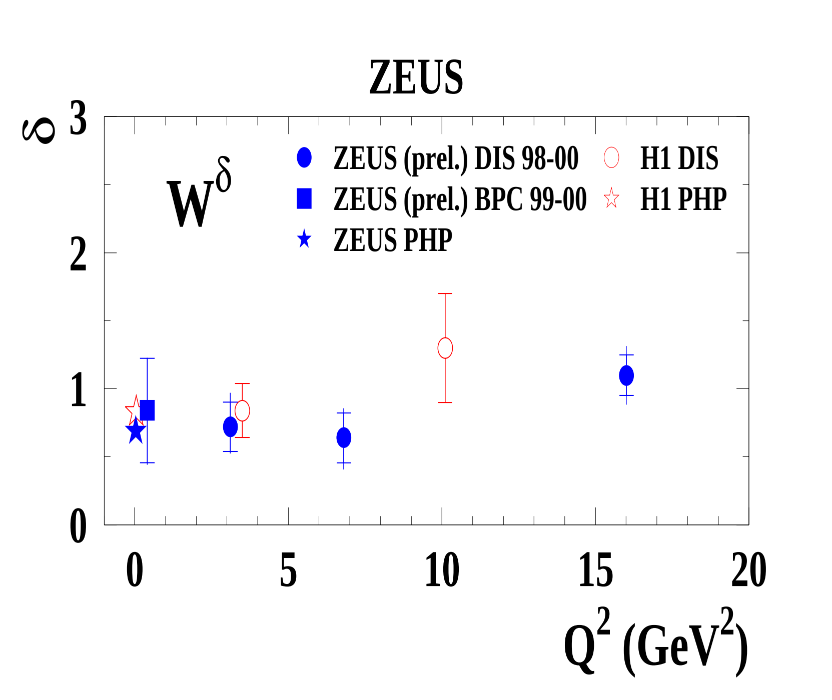
Universal *t*-dependence in scale Q^2 or M^2

pQCD model works fine at $t > 1$ GeV²

Vector Mesons: Soft & Hard Processes

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



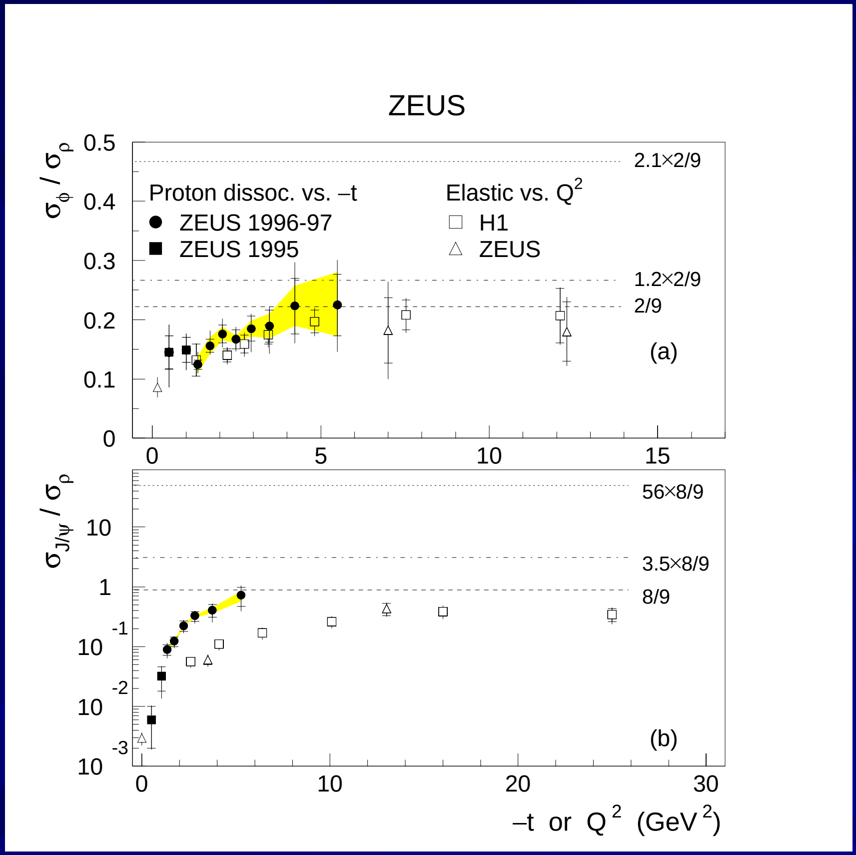


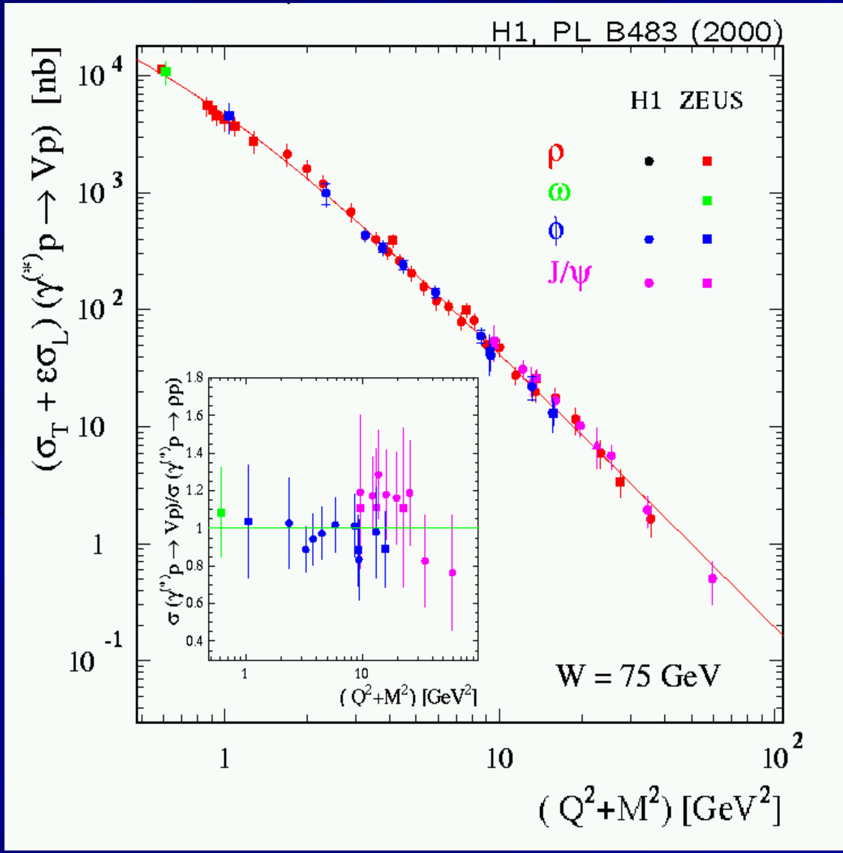
Light VM: smooth transition from soft to hard regime
Heavy VM: flat W-dependence, hard regime already at low Q^2

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:



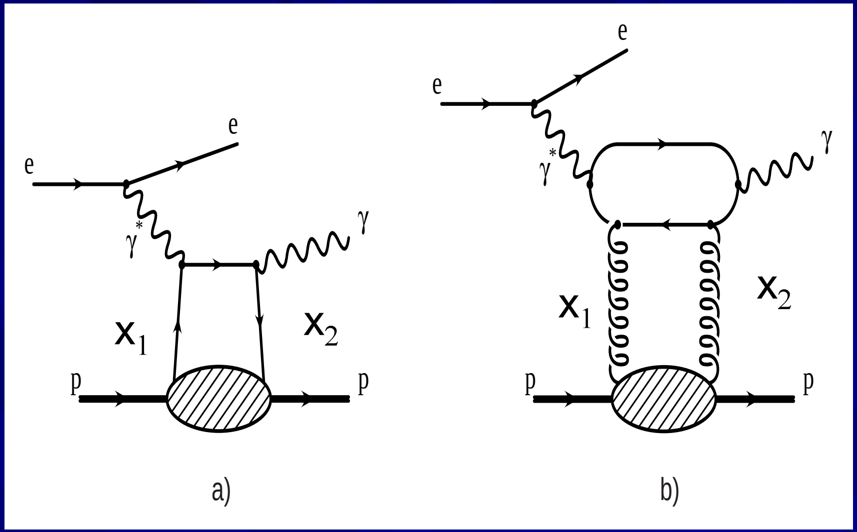


SU(4) restoration at $t \sim 5$ GeV^2, $Q^2 \sim 10$ GeV^2

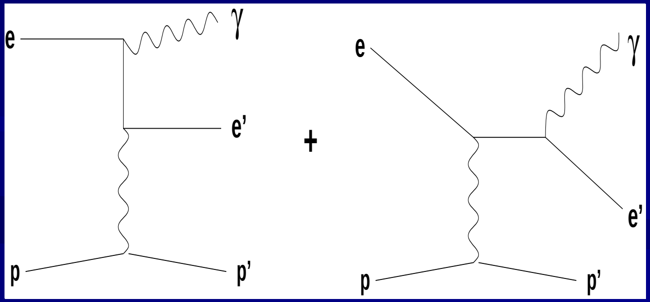
Universal $Q^2 + M^2$ dependence for all VM reflects common underlying dynamics

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 $G(x_1,x_2,Q^2)$



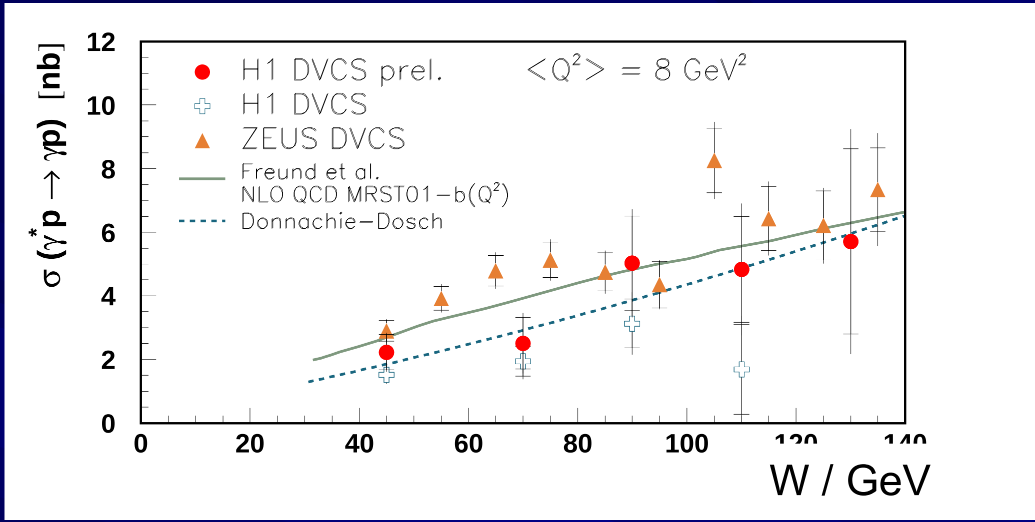
Measurement problem:



Bethe-Heitler QED process

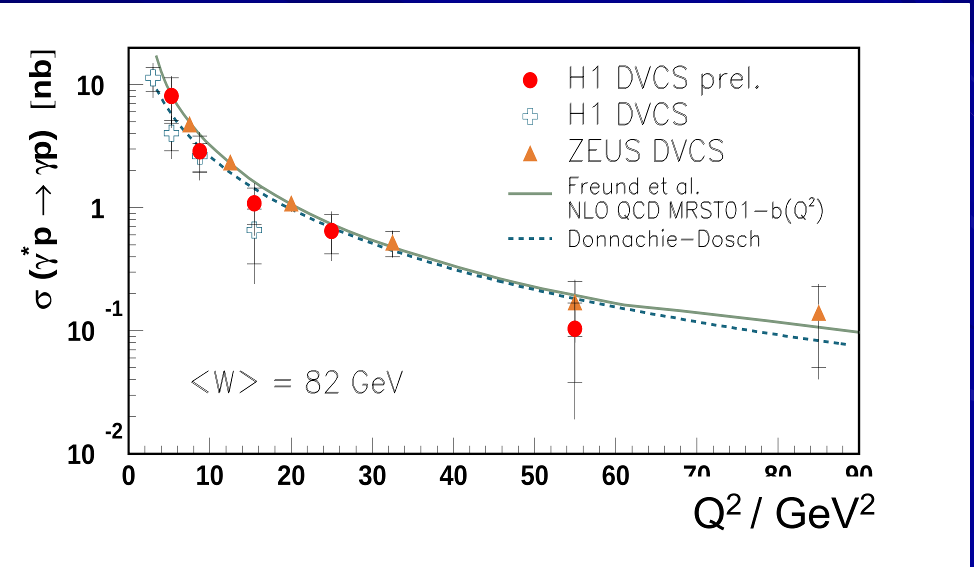
- elastic BH process has same signature, but much larger cross section, $\alpha_{em} \leftrightarrow \alpha_{em}{}^2$

DVCS: W and Q^2-Dependences



Fit W^{δ} with
δ ~ 1 indicates hard process

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

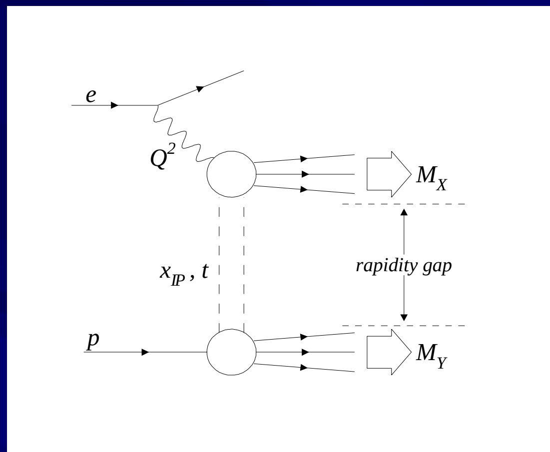


- NLO QCD Freund & with 2 sets of GPDFs
- Colour dipole models Donnachie &, Favart &

Both theoretical approaches consistent with measurements

Diffractive Deep Inelastic Scattering : σ_r^D

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

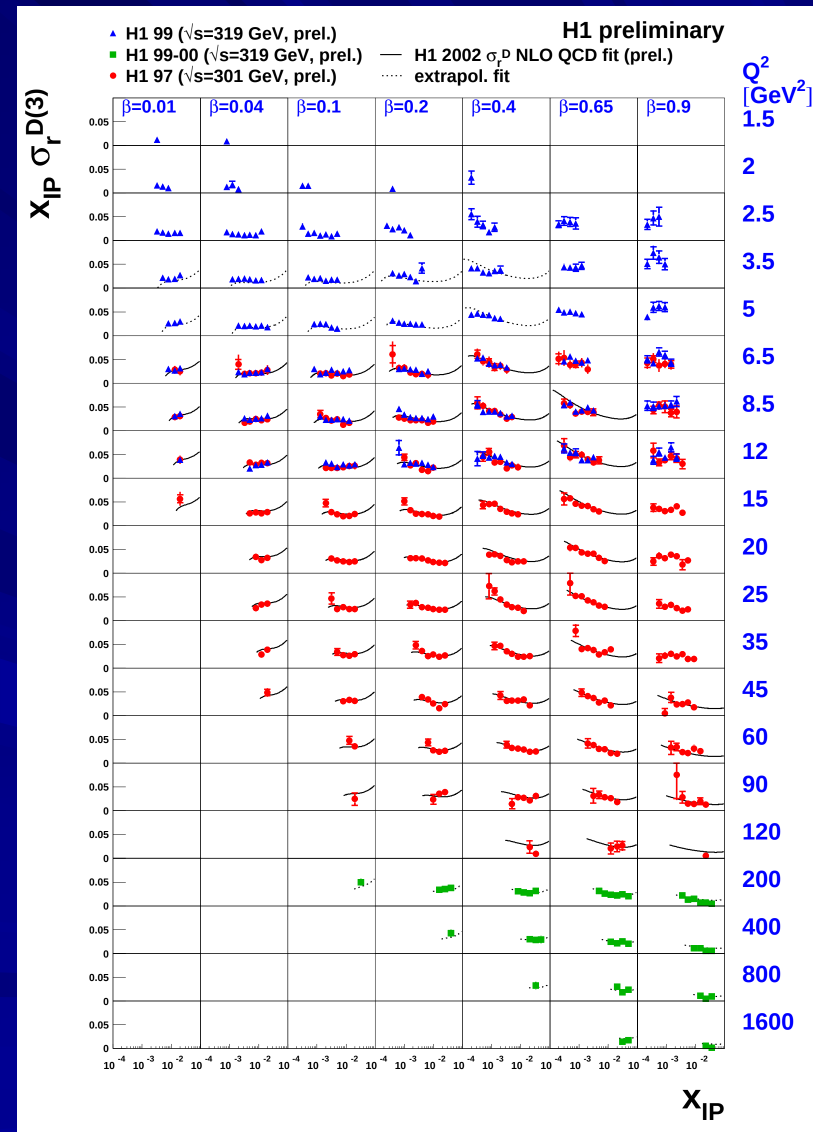


System *Y* not measured
→ integrate over M_Y < 1.6 / 2.3 GeV, t < 1GeV^2
and measure reduced cross section σ_r :

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

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

F_L unknown, $F_L = 0$ or $F_L = F_2$ → few % error



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

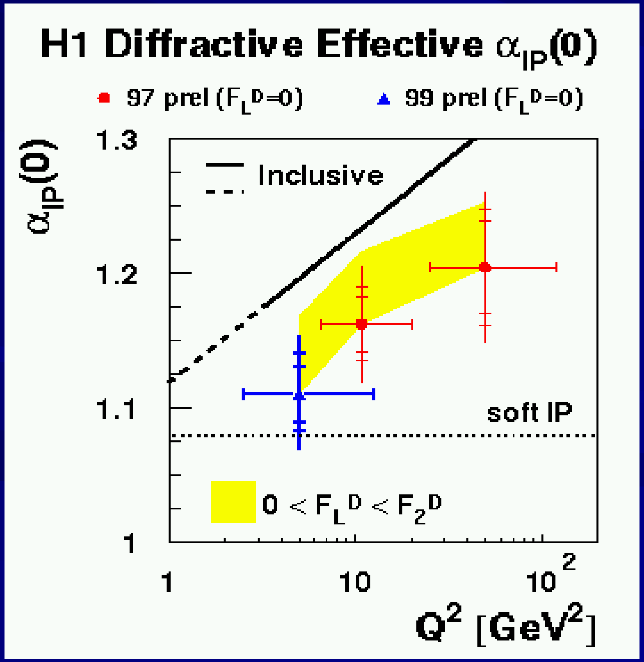
Use Ingelman&Schlein resolved Pomeron ansatz:

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

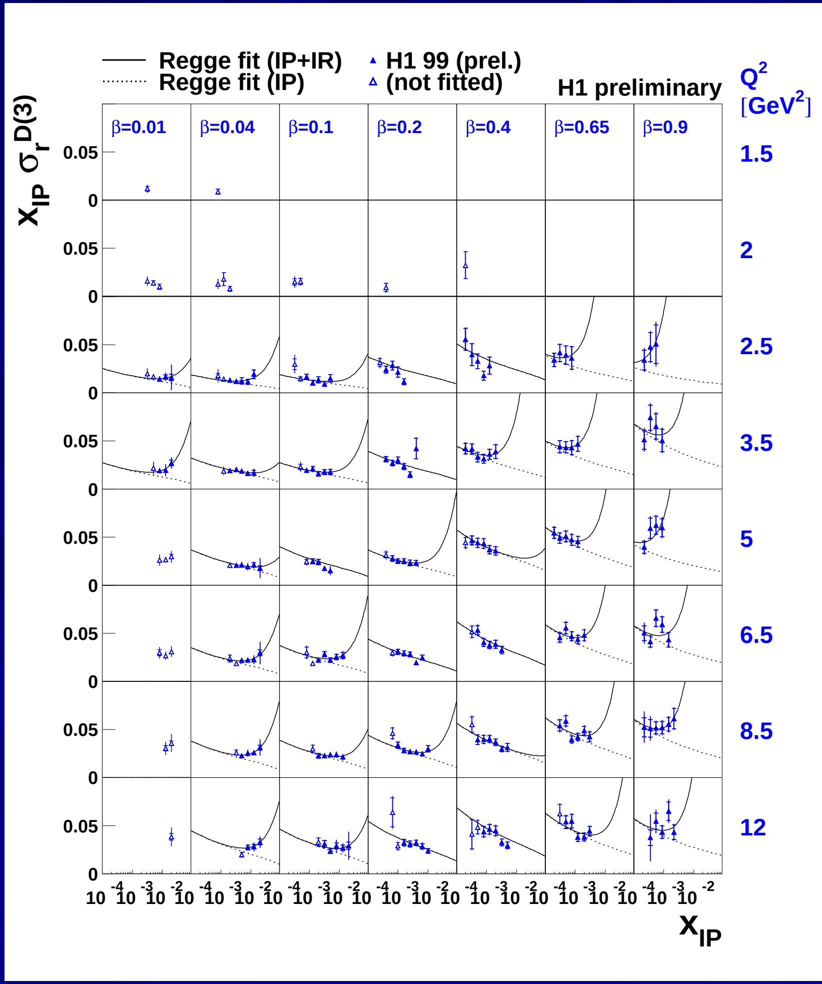
For large x_P **> 0.01** add Reggeon exchange :

$$\sigma_r^{D(3)}(x_{I\!P},\beta,Q^2) = f_{I\!P}(x_{I\!P})A_{I\!P}(\beta,Q^2) + f_{I\!R}(x_{I\!P})A_{I\!R}(\beta,Q^2)$$

with flux in Regge limit: $$f_{I\!P}(x_{I\!P}) = \int \frac{e^{b_{I\!P}t}}{x_{I\!P}^{2\alpha_{I\!P}(t)-1}}dt.$$



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



Reggeon essential at large x_P > ~ 0.01

Resoved Pomeron ansatz works for x_P-dependence fine

DDIS: QCD Analysis

QCD Fit Model:

1) Use QCD hard scattering factorization:

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

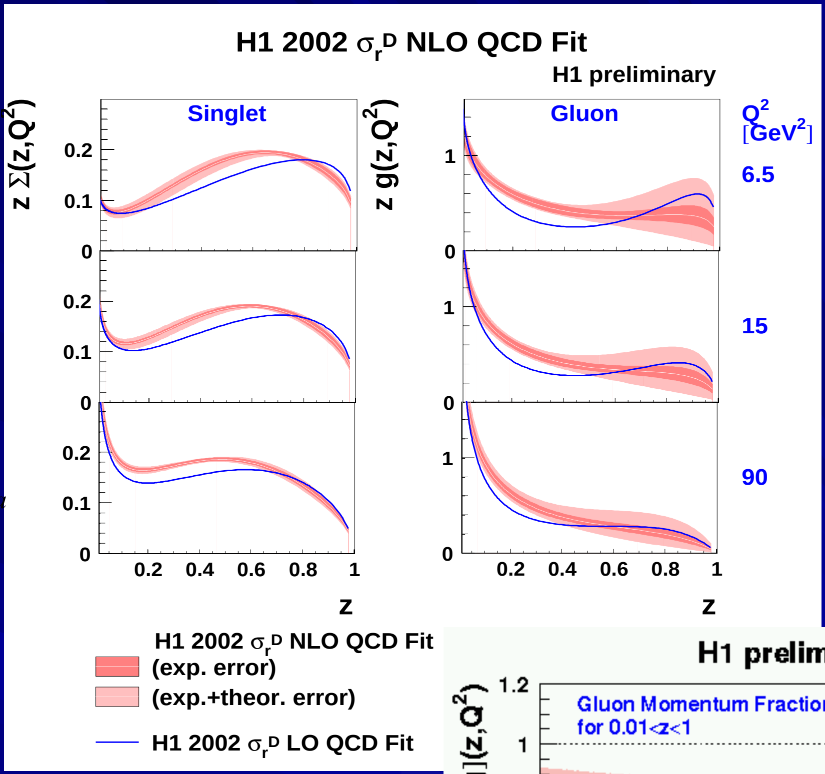
$\sigma^{\gamma^* i}$ = universal partonic cross section same as in inclusive DIS

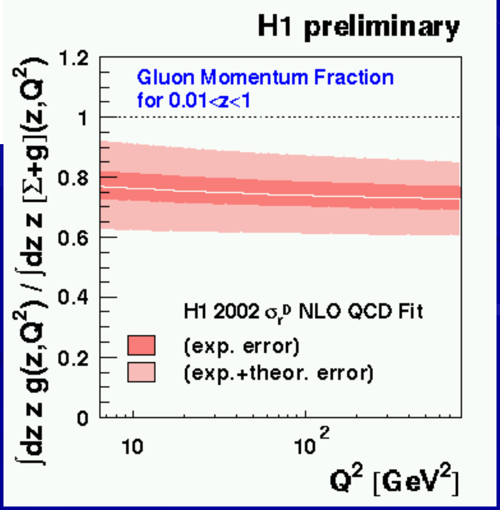
f_i^D = diffractive PDFs, x_P & t = const.

2) Parton ansatz for exchange:

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

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

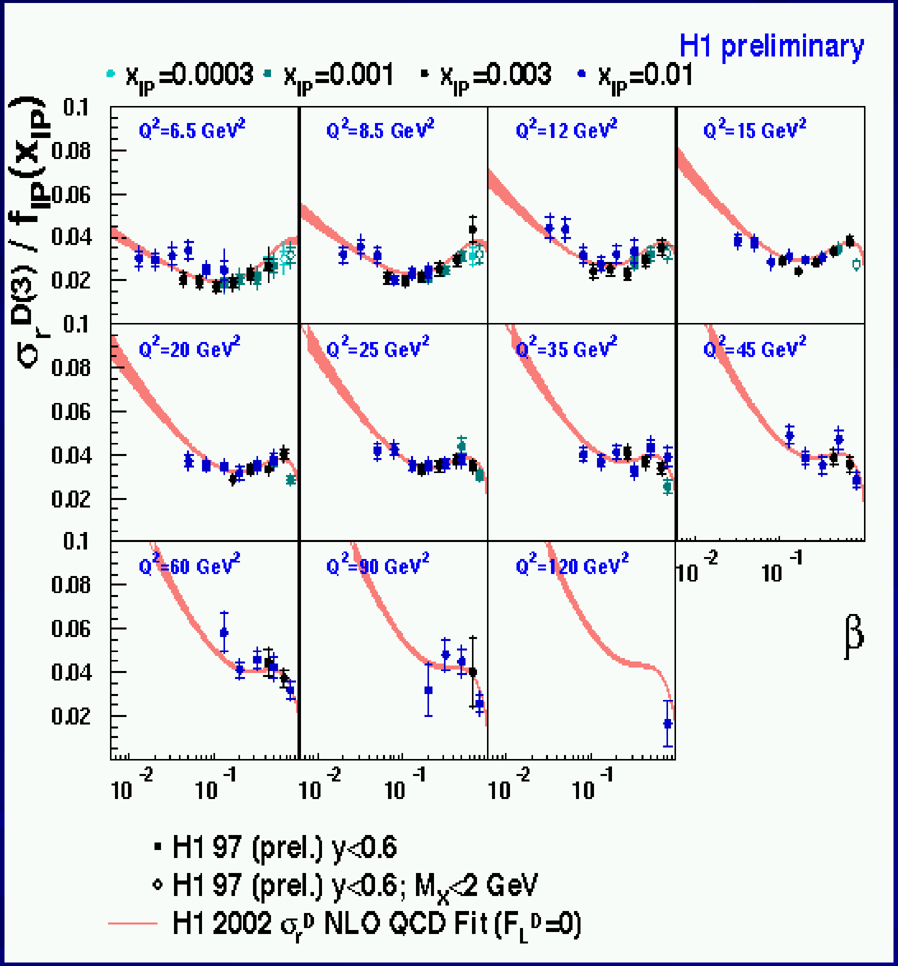


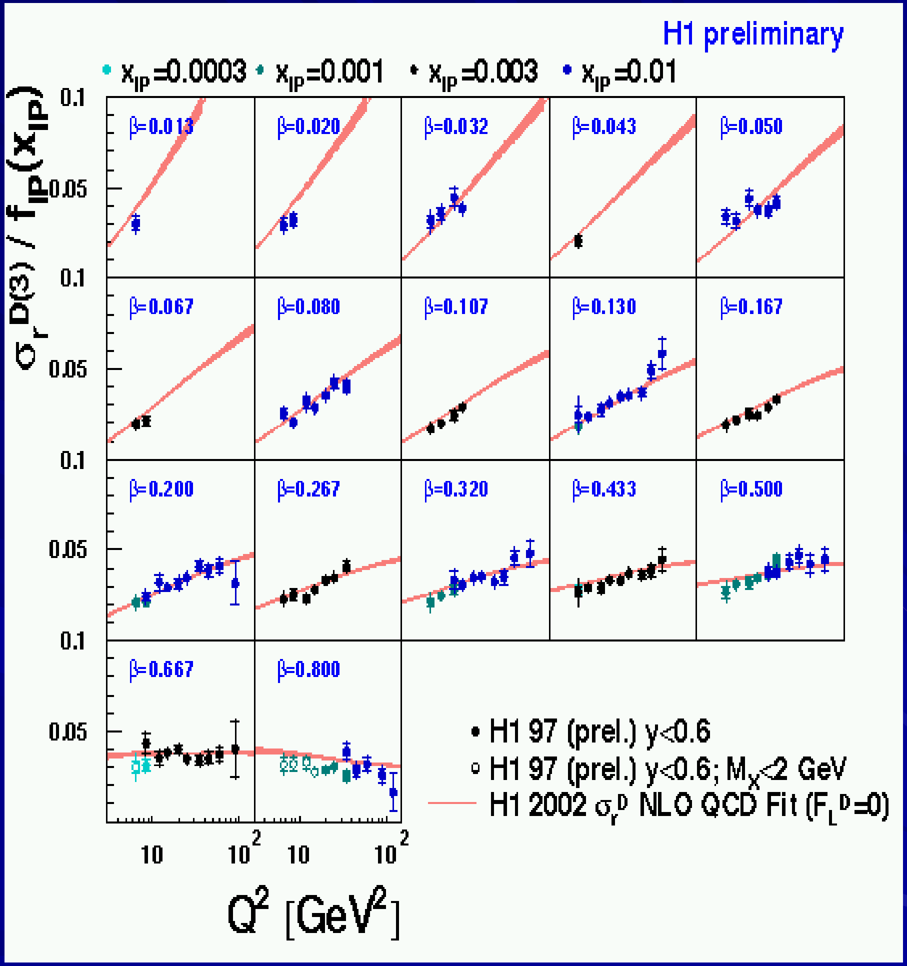


Gluon momentum fraction 75 ±15 % at $Q^2 = 10\ \mathrm{GeV}^2$ and remains large up to high Q^2

DDIS: β and Q^2-Dependences (1)

Fit region: $6 < Q^2 < 120$ GeV^2



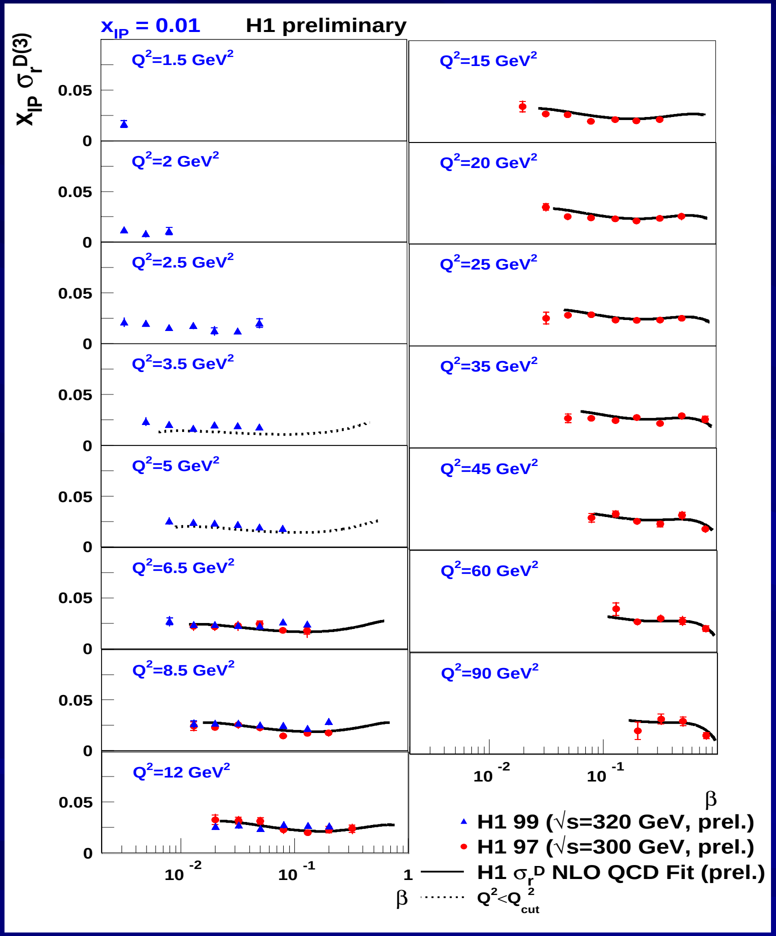


Flat up to high β, no x_P dependence
→ Regge factorization works

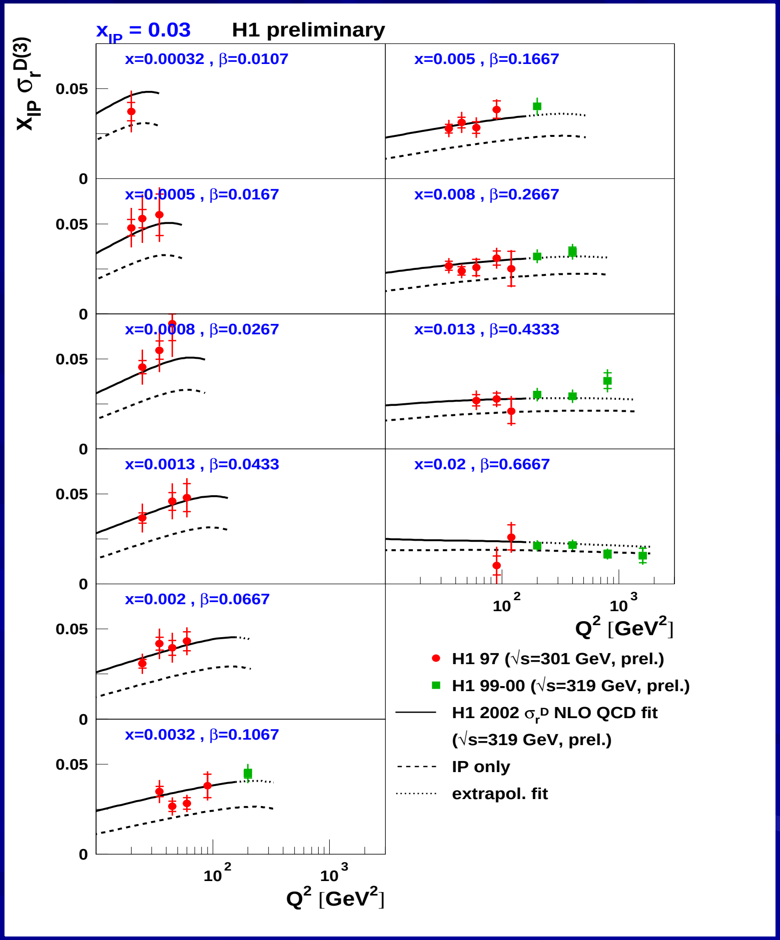
strong positive scaling violations up to high β → large gluon component

DDIS: Extrapolation of NLO QCD fit

$1.5 < Q^2 < 12$ GeV^2, $x_P < 0.01$



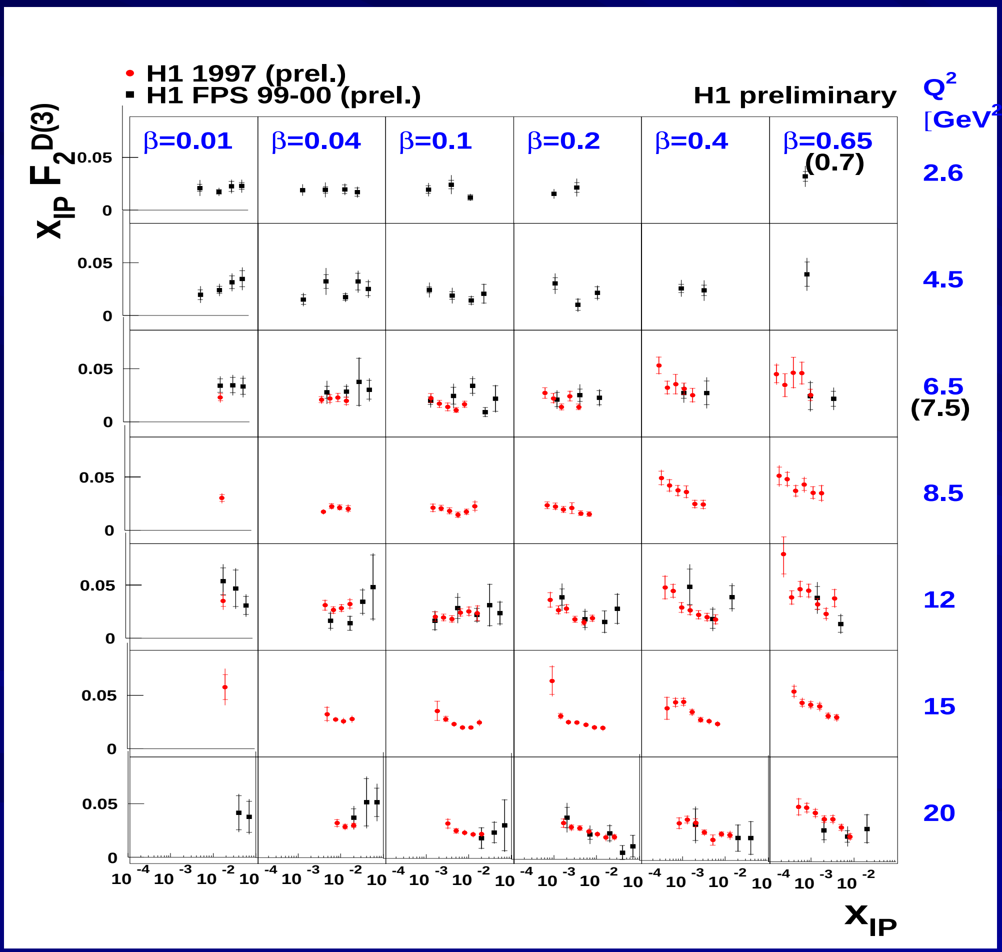
$200 < Q^2 < 1600$ GeV^2, $x_P < 0.03$

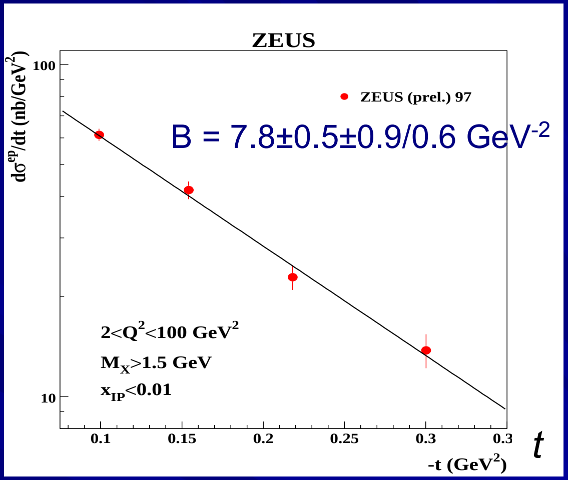


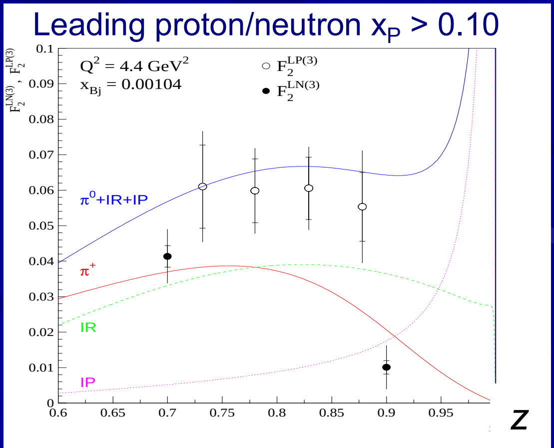
General in good agreement, confirm diffractive PDFs with gluon dominance

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 → F_2^{D4}, at least t – slope
3) Cross over to non-diffractive region at $x_P >$ 0.05, Reggeon & Pion exchange

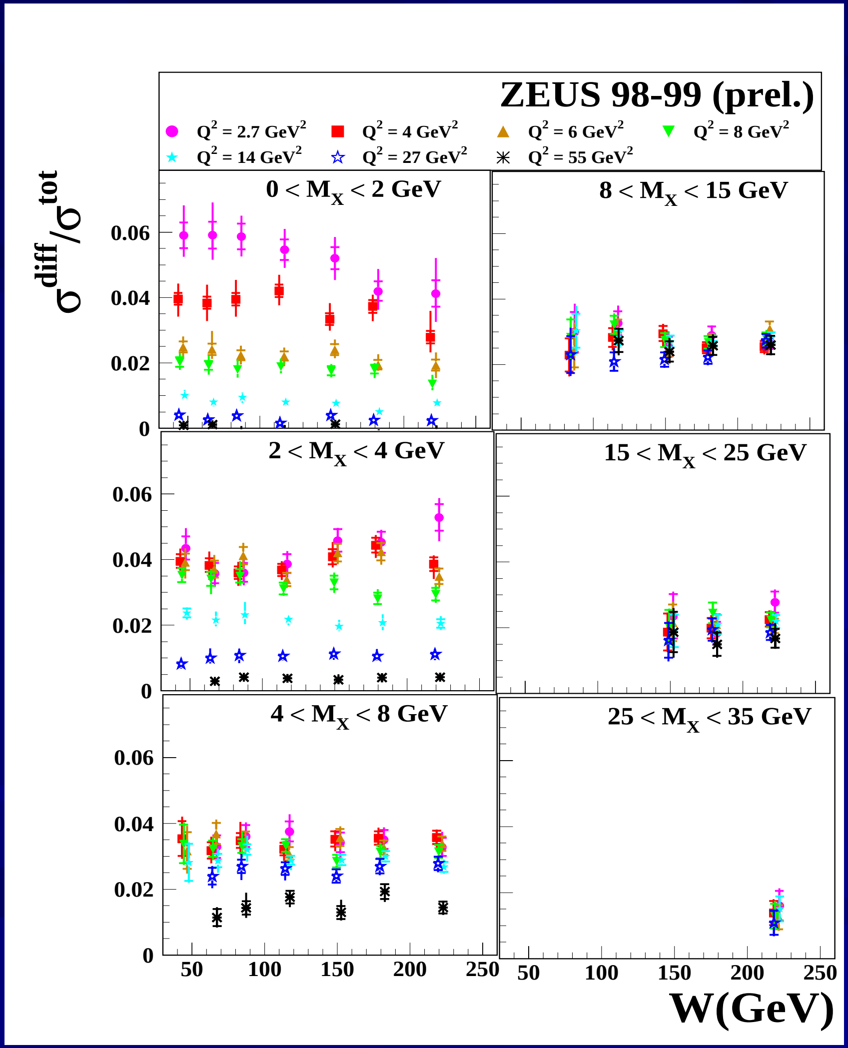






DDIS: Ratio $\sigma^{diff} / \sigma^{tot}$

ZEUS forward plug: $2 < Q^2 < 80$ GeV^2



Q^2-dependence: $M_X < 35$ GeV

decreases with Q^2

from ~ 20% at Q^2 = 2.7 GeV^2

to ~ 10% at Q^2 = 27 GeV^2

no Q^2-dependence for $M_X > 8$ GeV

W-dependence:

$M_X < 2$ GeV ratio falling

$M_X > 2$ GeV ratio constant

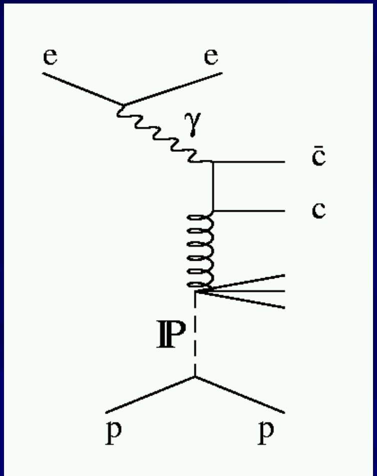
W-dependence of ratio surprising, since Regge model predicts :

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

and QCD 2-gluon models:

$x\,g(x)^2 \;/\; x\,g(x)$

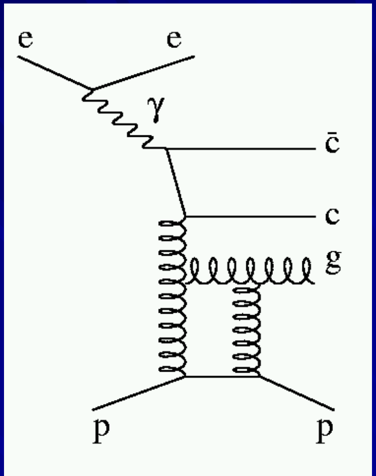
Final States : Open Charm in DDIS



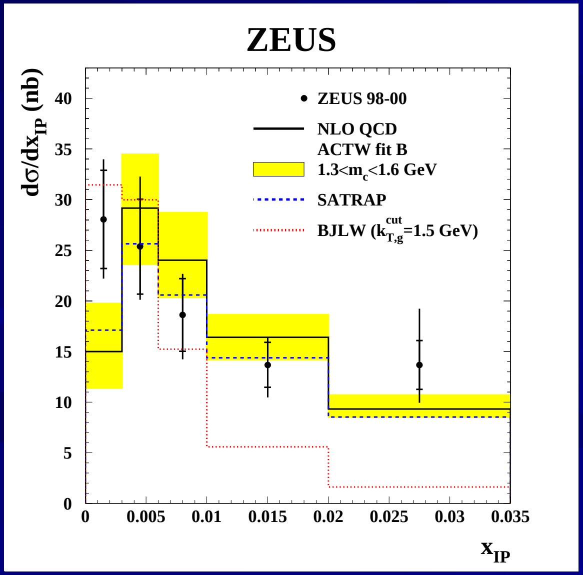
Open charm production very sensitive to the gluon/Pomeron component: $\gamma^* \rightarrow c\,\bar{c}$

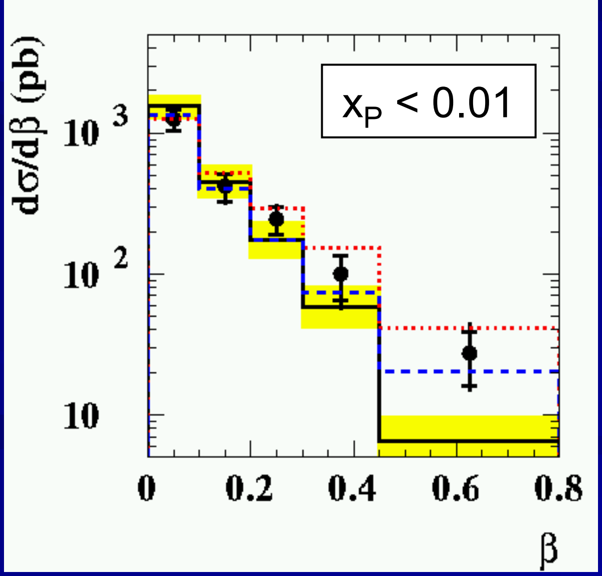
1) Resolved Pomeron - Boson-gluon fusion

2) Colour dipole 2 gluon exchange



~ 260 D* , 1.5 < Q^2 < 200 GeV^2



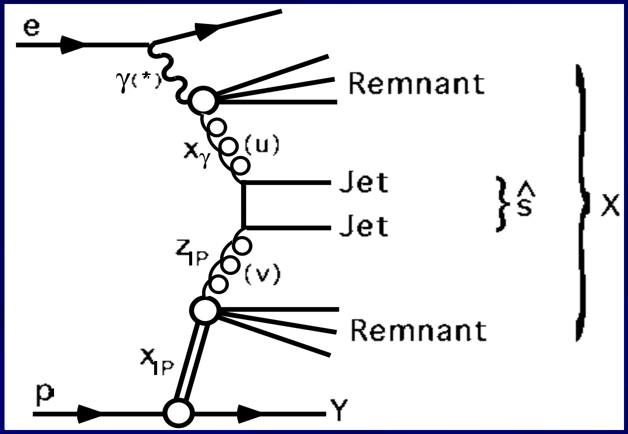


Resolved Pomeron :
- NLO fit Alvero &

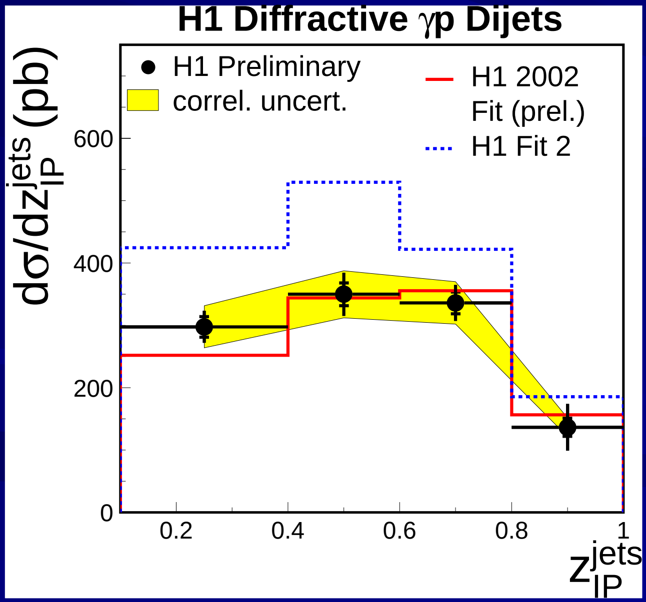
2-guon exchange $q\bar{q}$+g:
- Golec-Biernat &
- Bartels &

All models agree with data for x_P < 0.01

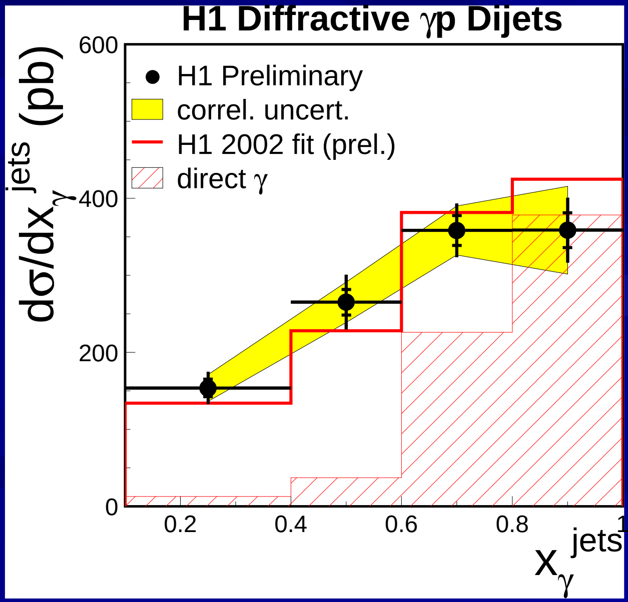
Final states: Jets in Photoproduction



- 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_γ : partonic momentum for dijet production

Resolved Pomeron in fine agreement with data – impoved 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 → 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 $\beta \sim 0.5$ → gluons dominate 75 ±15 % diffraction
  - ratio to inclusive DIS remarkable flat over W

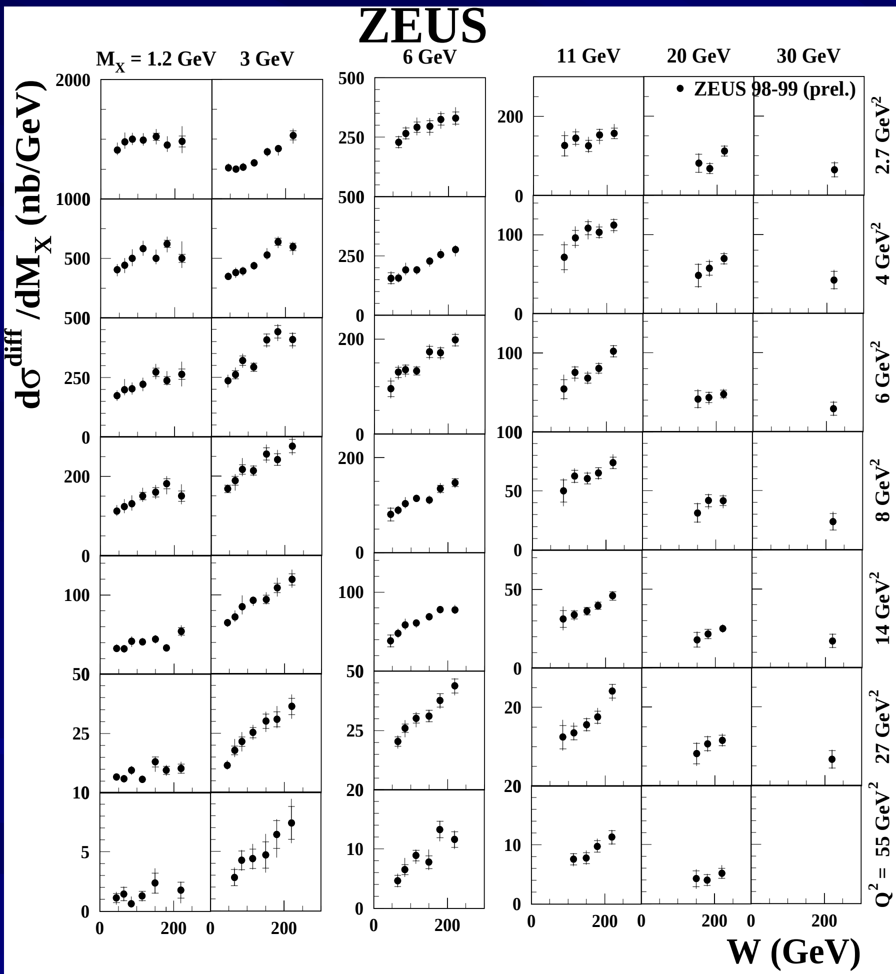
- Charm & Jets
  - Models with diffractive PDFs describe different processes well → confirm gluon dominance

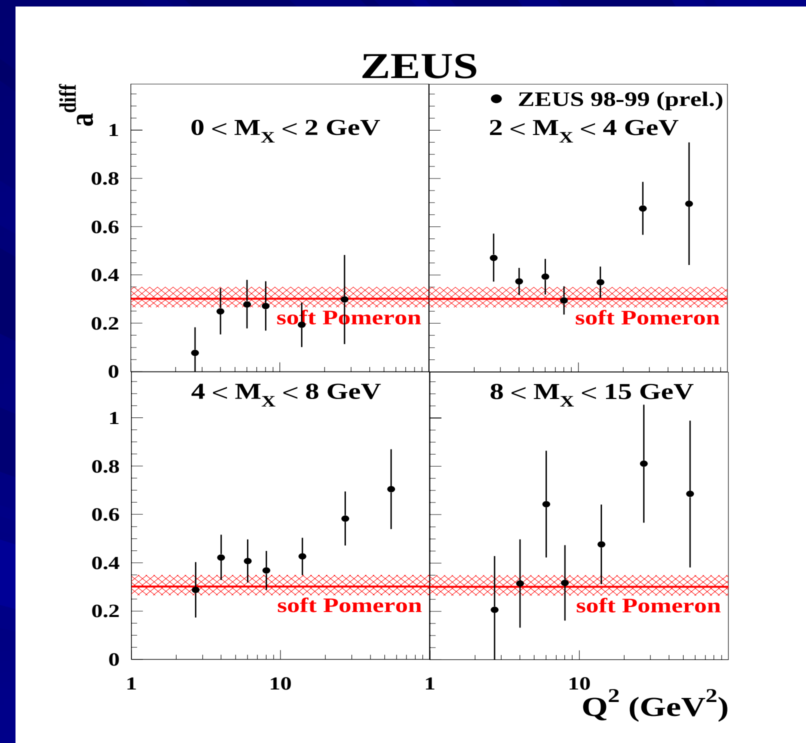
- pQCD Models
  - Resolved Pomeron model & Regge / QCD factorization very promising
  - Colour dipole models: $q\bar{q}$+g dominates at high Q^2

DDIS : M_X- Dependence

ZEUS forward plug : M_X < 35 GeV

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

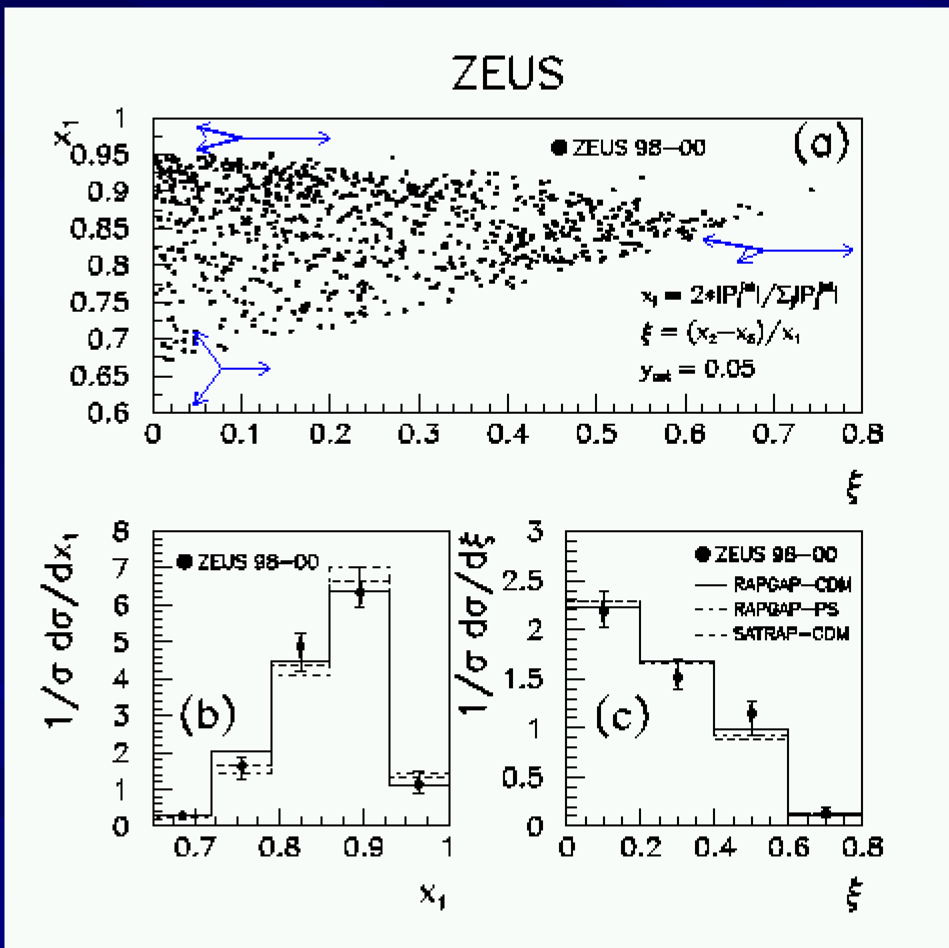




M_X < 2 GeV: vector mesons range
little W-dependence → soft
M_X > 2 GeV: steeper W-dependece with Q^2,
compatible with x_P-spectra

Application: Diffractive Jet Production (2)

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



- 3-Jet fraction ~ 30 %
- at high M_X dominant process photon → qq + g
- gluon jet in Pomeron direction and broader
- RAPGAP (resoved Pomeron) SATRAP (colour dipole) generators within 20 % range