DIFFRACTION AT HERA ON THE QUARK AND GLUON SCALE

The HERA Collider and the Experiments

Kinematics of Deep Inelastic (DIS) and Diffractive Reactions

Regge Phenomenology versus pQCD

Exclusive Vector Meson Production and

Inclusive Diffraction and Diffractive Structure Functions

Exclusive Diffractive Reactions: Jets and Heavy Quarks

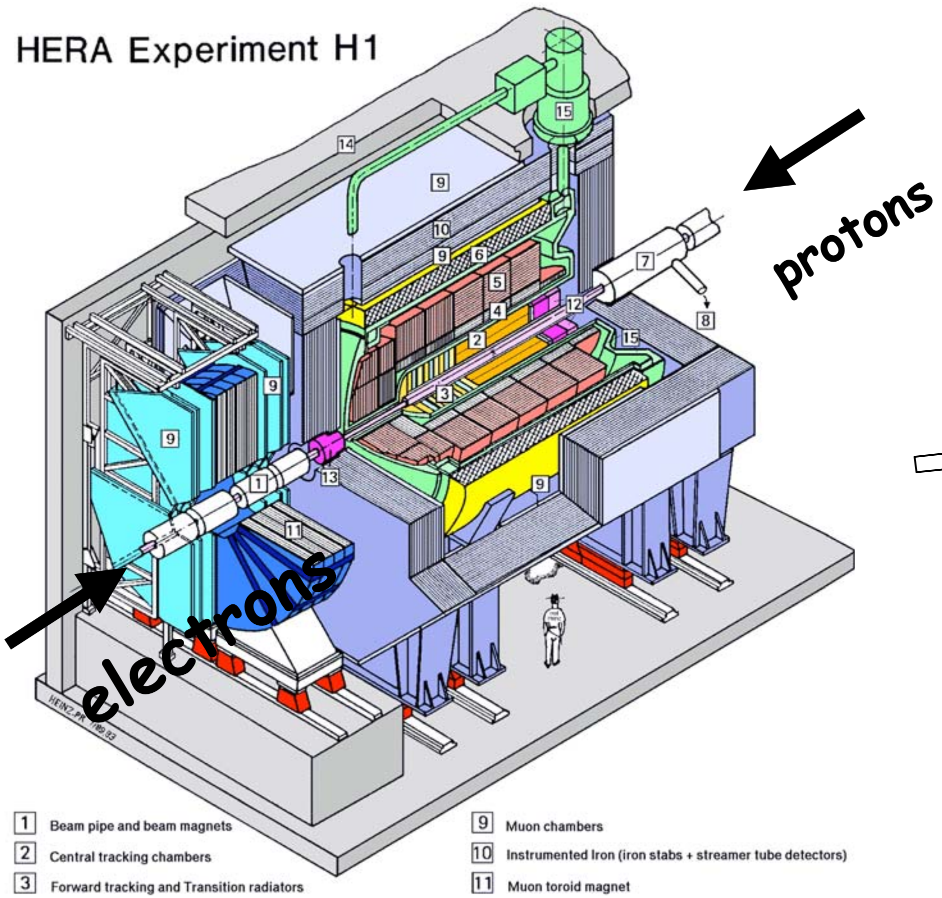
The HERA Collider

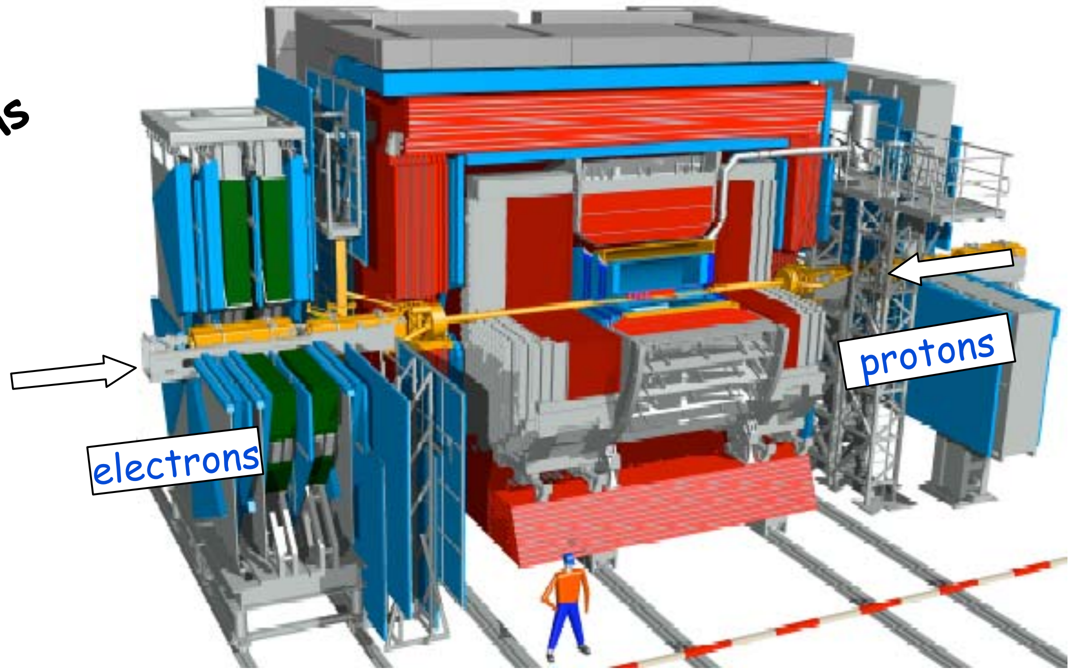
Electron - proton collisions

$e^{\pm}$ 27.5 GeV → ← 920 GeV p

The H1 Experiment

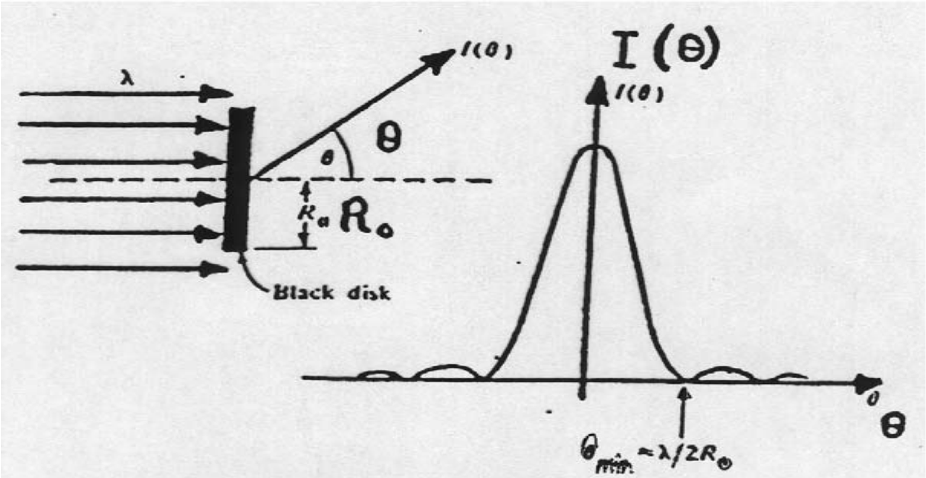
The ZEUS Experiment





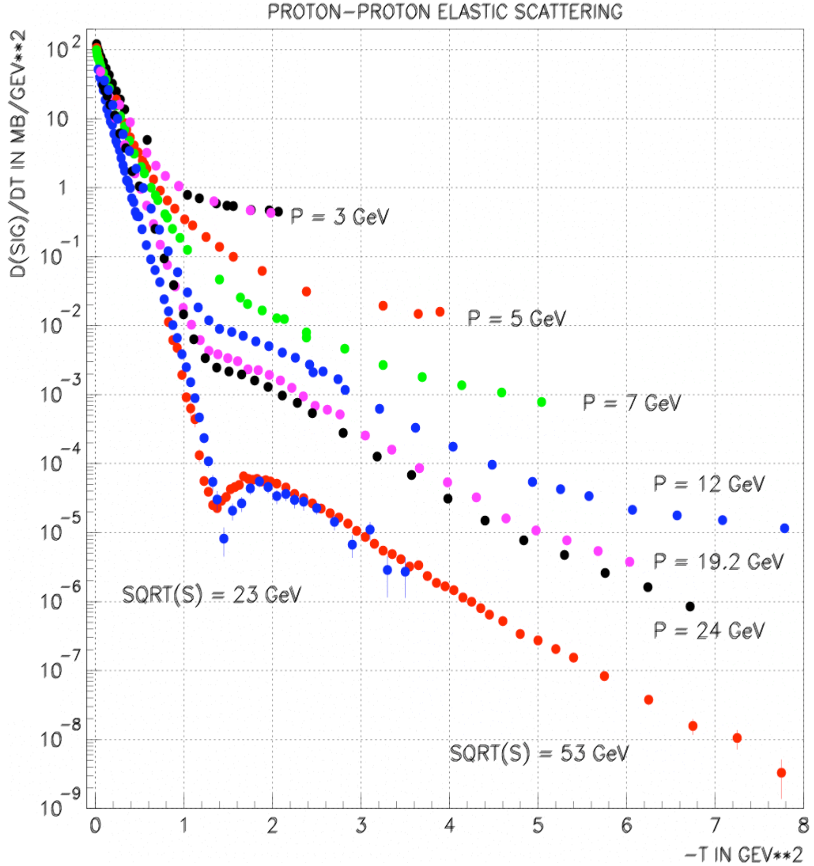
From Optical Diffraction to High Energy Particle Scattering

Optical diffraction



Optical diffraction pattern produced by a black disk.

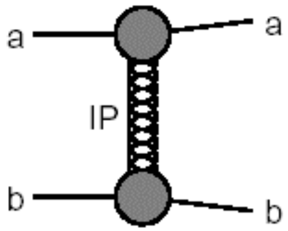
High energetic elastic scattering



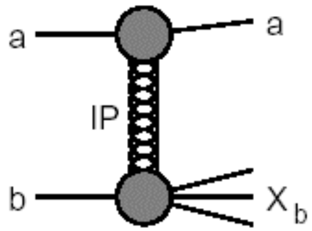
Generalization in high energy particle interactions :

Diffraction is the exchange of an object
with vacuum quantum numbers.

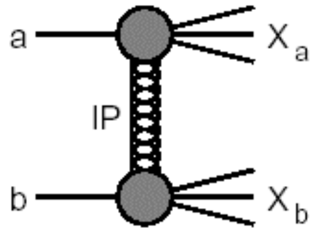
Hypothetical object : Pomeron IP



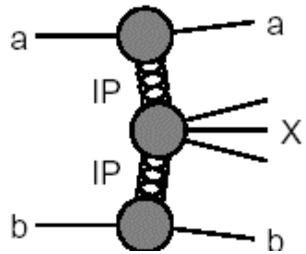
elastic



single dissociation



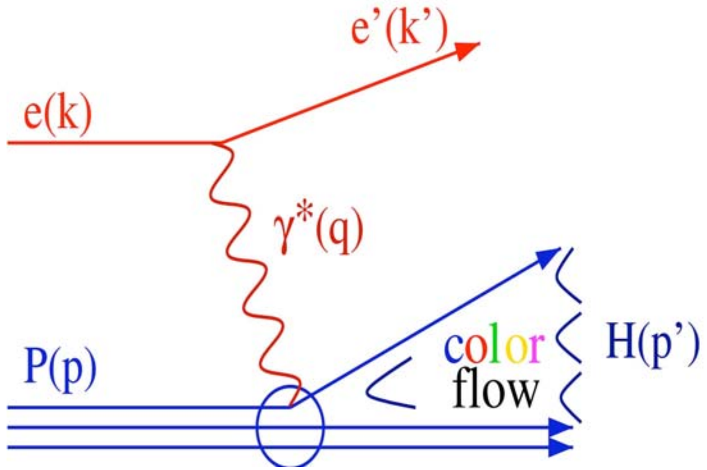
double dissociation



double Pomeron exchange

Kinematics of DIS and Diffraction

Inclusive DIS events :



$$\boxed{s = (k+p)^2}$$ center of mass energy squared

$$\boxed{Q^2 = -q^2 = -(k-k')^2}$$ virtuality, size of the probe

$$\boxed{W^2 = M_H^2 = (p+q)^2}$$ ã* - proton cms energy squared

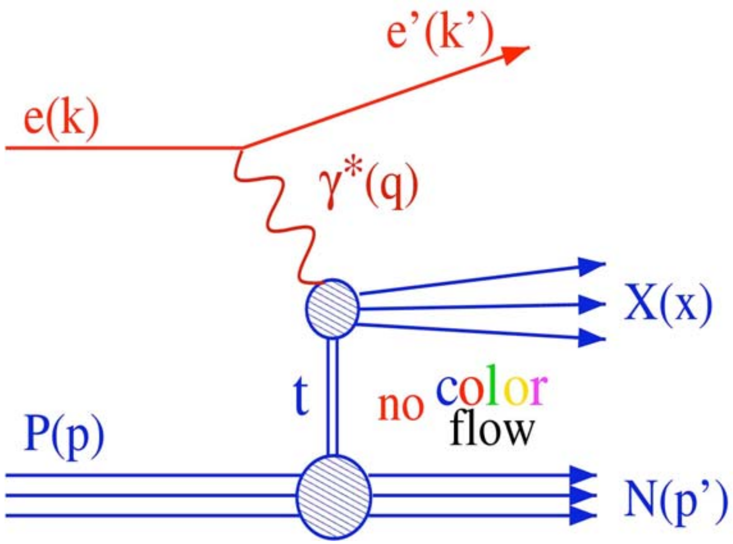
$$\boxed{x = \frac{Q^2}{2p \cdot q}} \quad \boxed{y = \frac{p \cdot q}{p \cdot k}}$$

x: fraction of the proton carried by the struck parton

y: inelasticity, fraction of the electron momentum carried by the virtual photon

$$\boxed{Q^2 = x \cdot y \cdot s}$$

Diffractive DIS events :



For diffractive events in addition 2 variables

$$\boxed{M_x}$$ mass of the diffractive system x

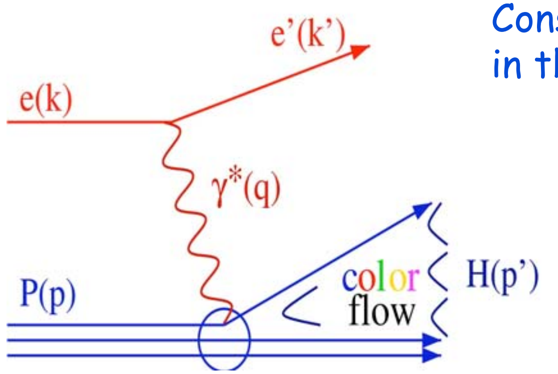
$$\boxed{t = (p-p')^2}$$ four-momentum transfer squared at the proton vertex

$$\boxed{x_{IP} = \frac{(p-p') \cdot q}{p \cdot q} = \frac{M_X^2 + Q^2}{W^2 + Q^2}}$$ momentum fraction of the proton carried by the Pomeron

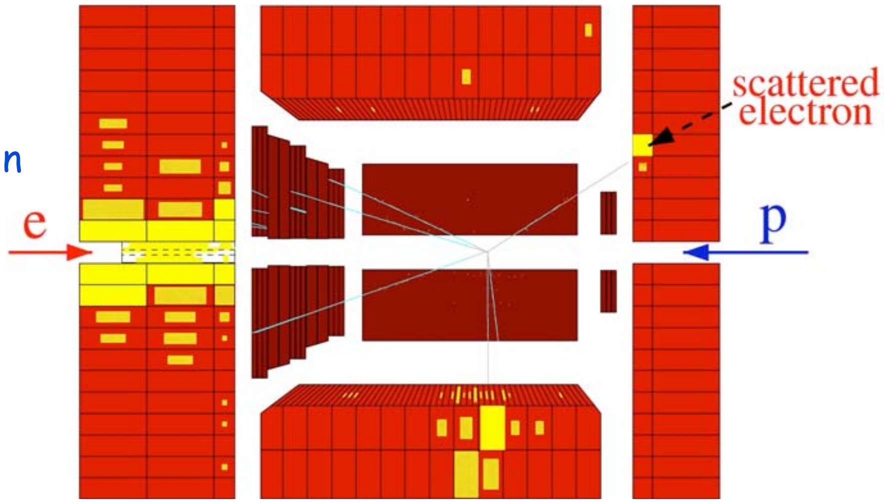
$$\boxed{\hat{a} = \frac{Q^2}{2(p-p') \cdot q} = \frac{x}{x_{IP}} = \frac{Q^2}{M_X^2 + Q^2}}$$ fraction of the Pomeron momentum which enters the hard scattering

DIS- and Diffractive Events

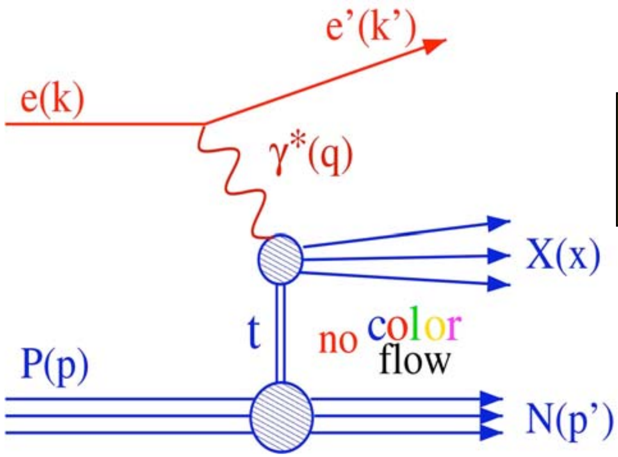
Inclusive DIS events :



Considerable energy flow
in the very forward direction



Diffractive DIS events

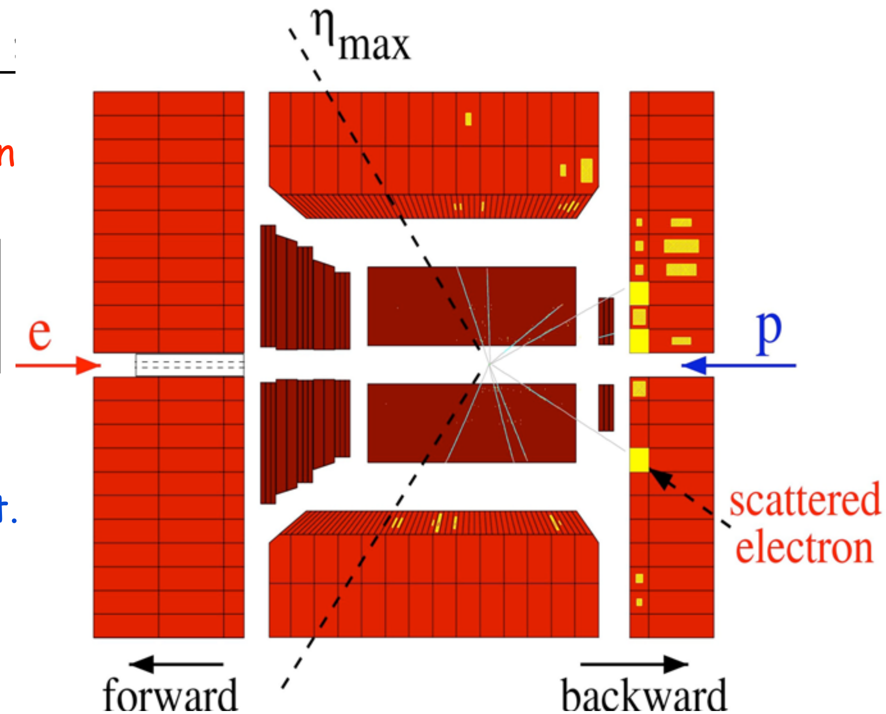


Large rapidity gap in
forward direction

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

Pseudo-Rapidity

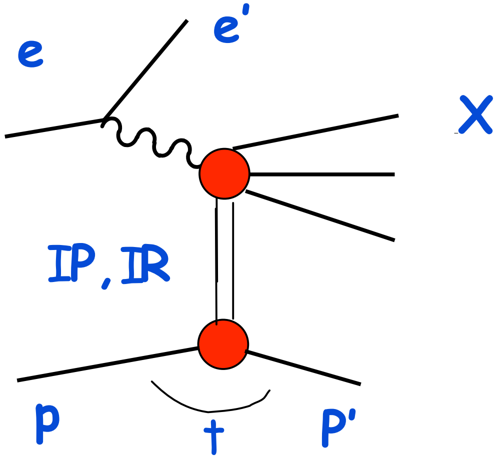
Θ is the angle w.r.t.
proton direction.

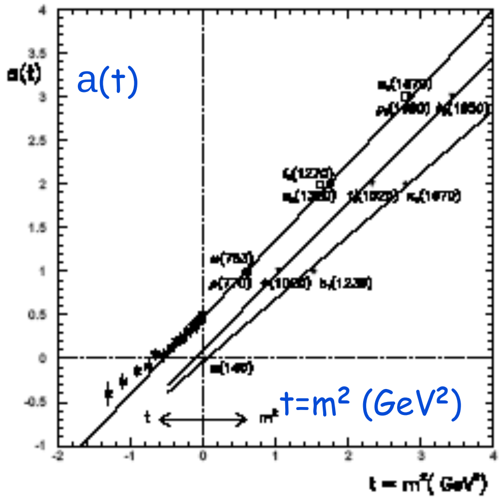


Regge Phenomenology vs. pQCD

Regge Phenomenology

Peripheral (soft)
processes





IR=Reggeon trajectory

$$\alpha_{IR}(t) = \alpha_{IR}(0) + \alpha' \cdot t$$

Diffraction

IP =Pomeron trajectory

$$\alpha_{IP}(t) = \alpha_{IP}(0) + \alpha' \cdot t$$

$$\frac{d\sigma}{dt} \propto e^{b(W)\cdot t}\left(\frac{W}{W_0}\right)^{4(\alpha_{IP}(t)-1)}$$

$$b(W) = b_0 + 4\alpha' \cdot \ln\left(\frac{W}{W_0}\right)$$

$$\sigma_{tot} \propto \left(\frac{W}{W_0}\right)^{2(\alpha_{IP}(0)-1)}$$

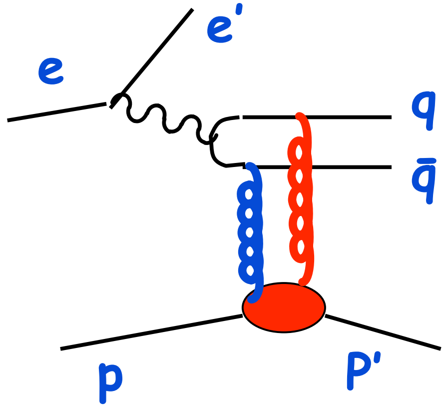
From fit to hadronic data : → shrinkage

$$\alpha_{IP}(t) = 1.08 + 0.25 \cdot t$$

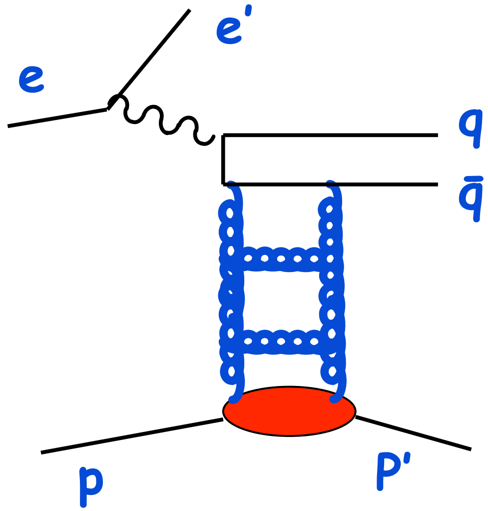
(Donnachie, Landshoff)

Perturbative QCD

Hard diffraction



simplest approach:
colorless
2 gluon exchange



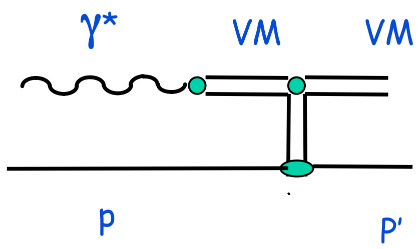
BFKL-type
gluon ladder
exchange

Various pQCD inspired models exist

→ little or no shrinkage

Exclusive Vectormeson Production

VMD+Regge



$$\frac{\text{dó}}{dt} = e^{b\cdot t}\left(\frac{W}{W_0}\right)^{4(\text{á}_{IP}(t)-1)} \longrightarrow \boxed{\text{ó}(W) \propto W^{\text{ä}} \;;\; \text{ä} \approx 0.22}$$

$$b(W) = b_0 + 4\text{á}'\cdot\ln\frac{W}{W_0} \longrightarrow \boxed{\text{Shrinkage} \;;\; b \propto r^2}$$

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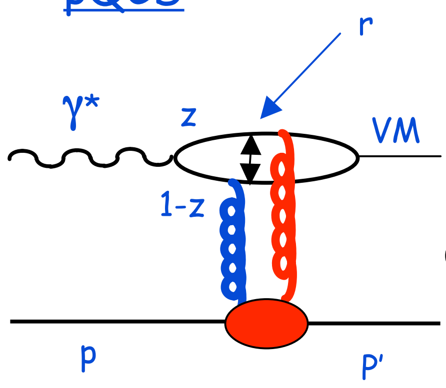
pQCD



$$r^2 = \left[z(1-z)Q^2 + m_q^2\right]^{-1} \longrightarrow \boxed{\text{r}^2 \text{ small if } Q^2 \text{ large or } M_V \text{ large}}$$

$$\text{ó}_L \propto \text{á}_s^2(Q_{eff}^2)\cdot|x\cdot g(x,Q_{eff}^2)|^2$$ Ryskin : $$Q_{eff}^2 = \frac{1}{4}\left(Q^2 + M_V^2 + |t|\right)$$

$$\longrightarrow \boxed{\text{ó}(w) \propto W^{\text{ä}} \;;\; \text{ä} \approx 0.8 \text{ fast rise with W}}$$

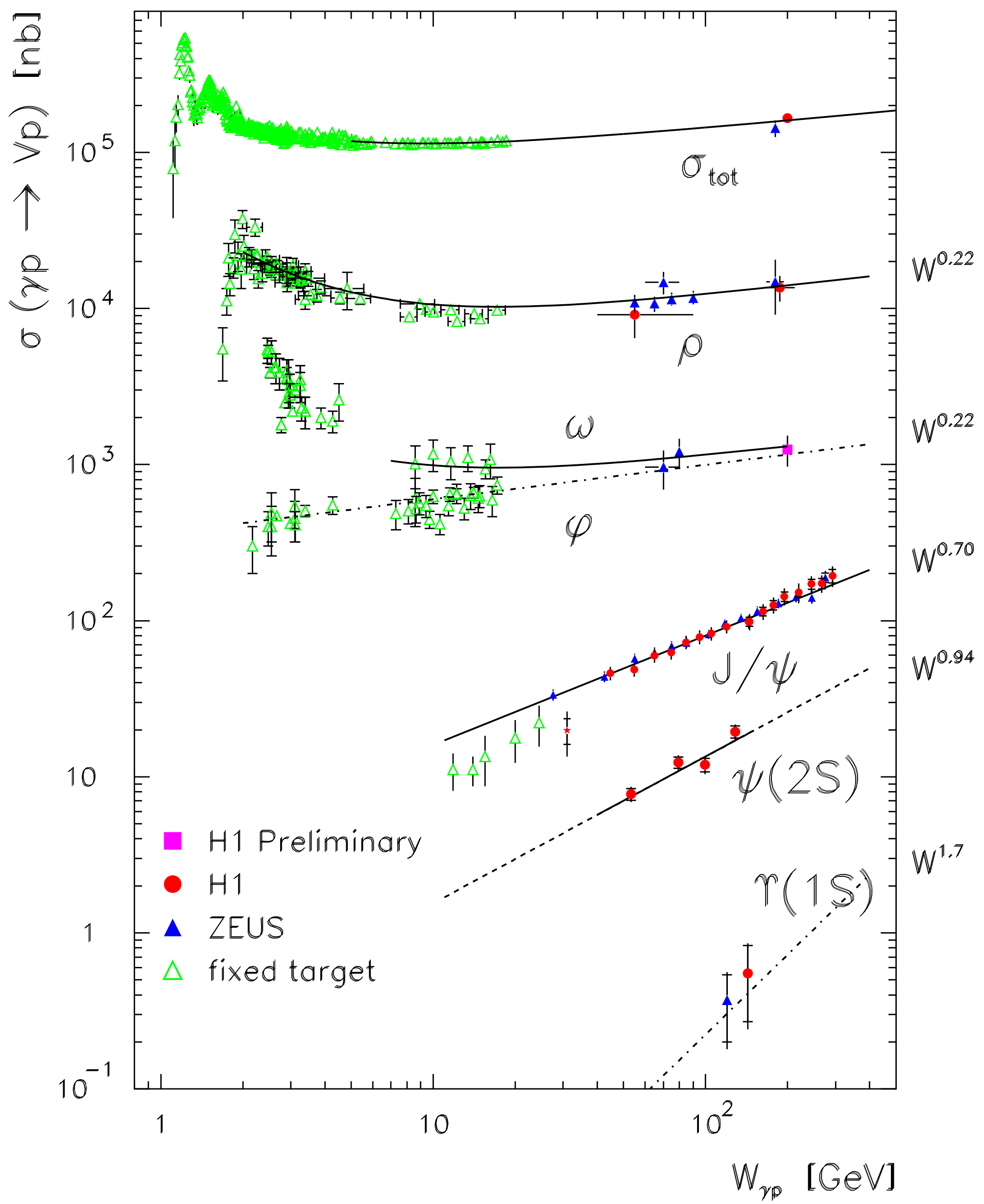
Do pQCD models describe the data ?

Which variables can provide a hard scales ?

$$\boxed{b \approx 4\,\text{GeV}^{-2} \text{ and } \text{á}' \approx 0 \text{ no or little shrinkage}}$$

Can the Vectormeson Mass be a Hard Scale ? I

Photoproduction ; $Q^2=0$



ñ, ù , ö, ø , ø (2s), ϒ

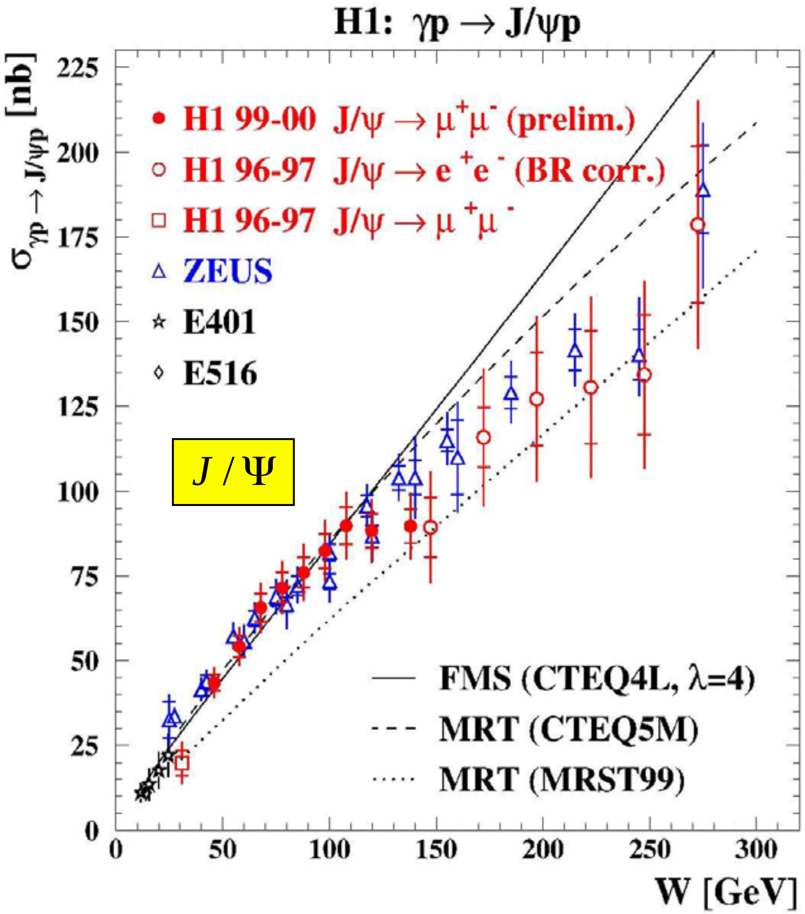
The w-dependence of the "light" vector-meson (ρ, ω, φ) production is described by Regge phenomenology

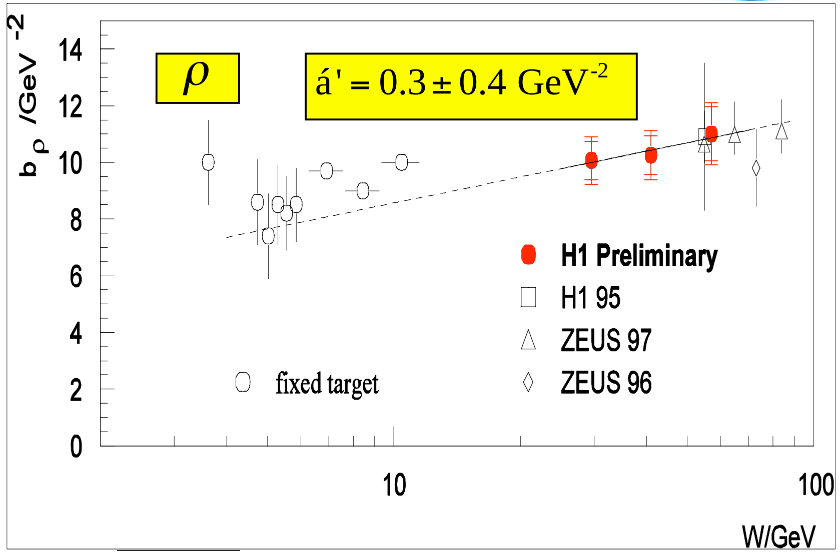
ä ≈ 0.22

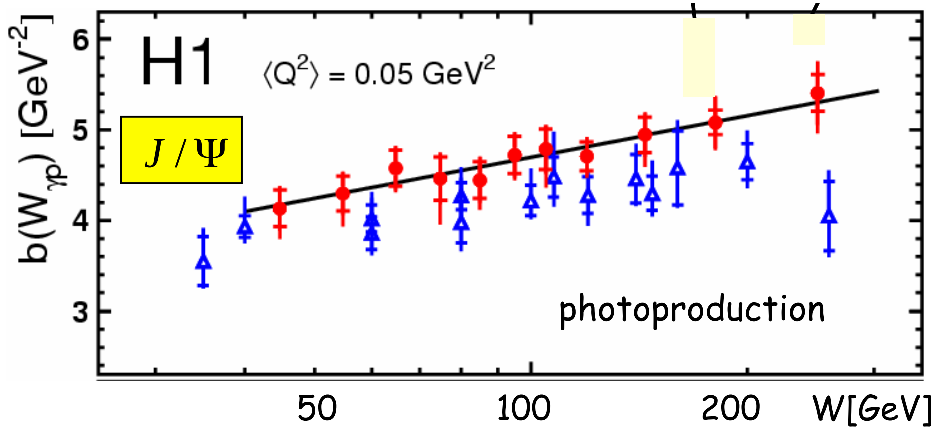
For higher mass vector mesons the rise of the production cross section with W gets steeper.

This indicates the onset of hard diffractive scattering

Photoproduction : $Q^2=0$





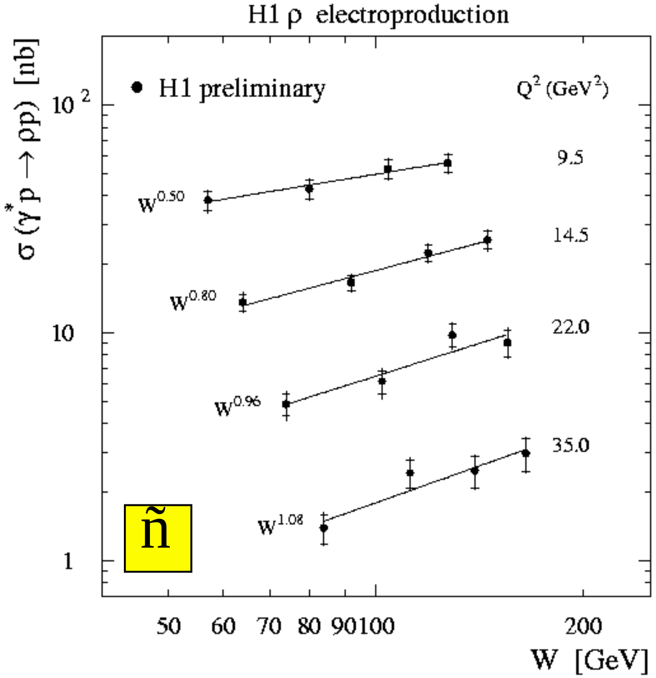


$\alpha' = (0.164 \pm 0.028 \pm 0.030)$ GeV^{-2}

pQCD models can describe the data.

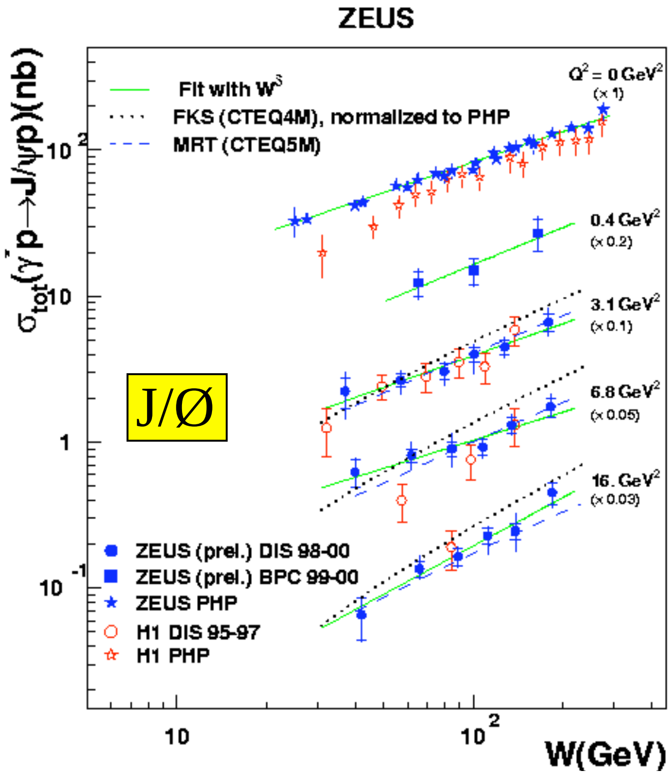
Still some shrinkage seen in J/Ψ photoproduction but compatible with pQCD models.

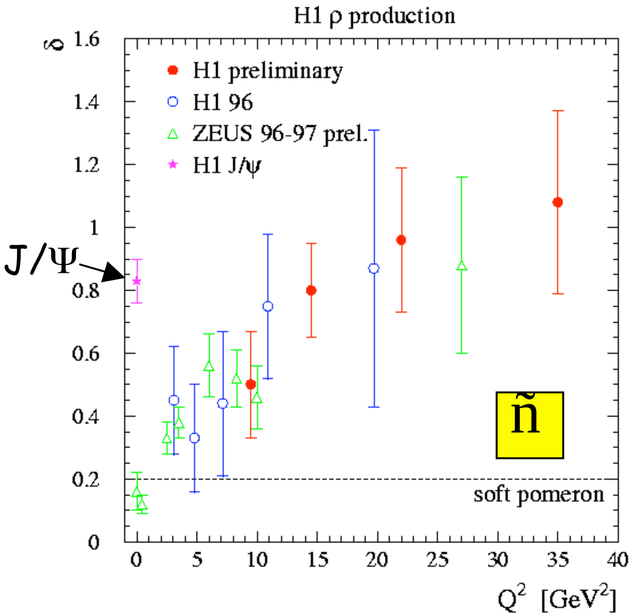
Can Q^2 be a Hard Scale ? I



ρ-electroproduction

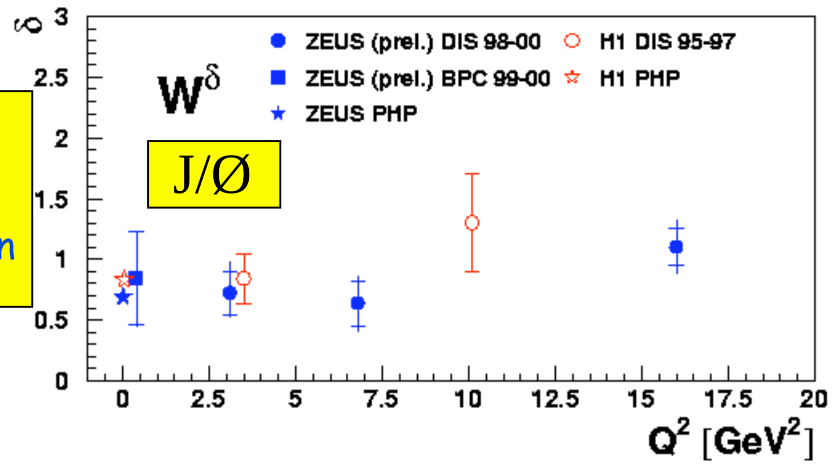
For ρ -production the W-dependence gets steeper with Q^2.





J/Ψ -electroproduction

The rise with W is essentially independent of Q^2 for J/Ψ production

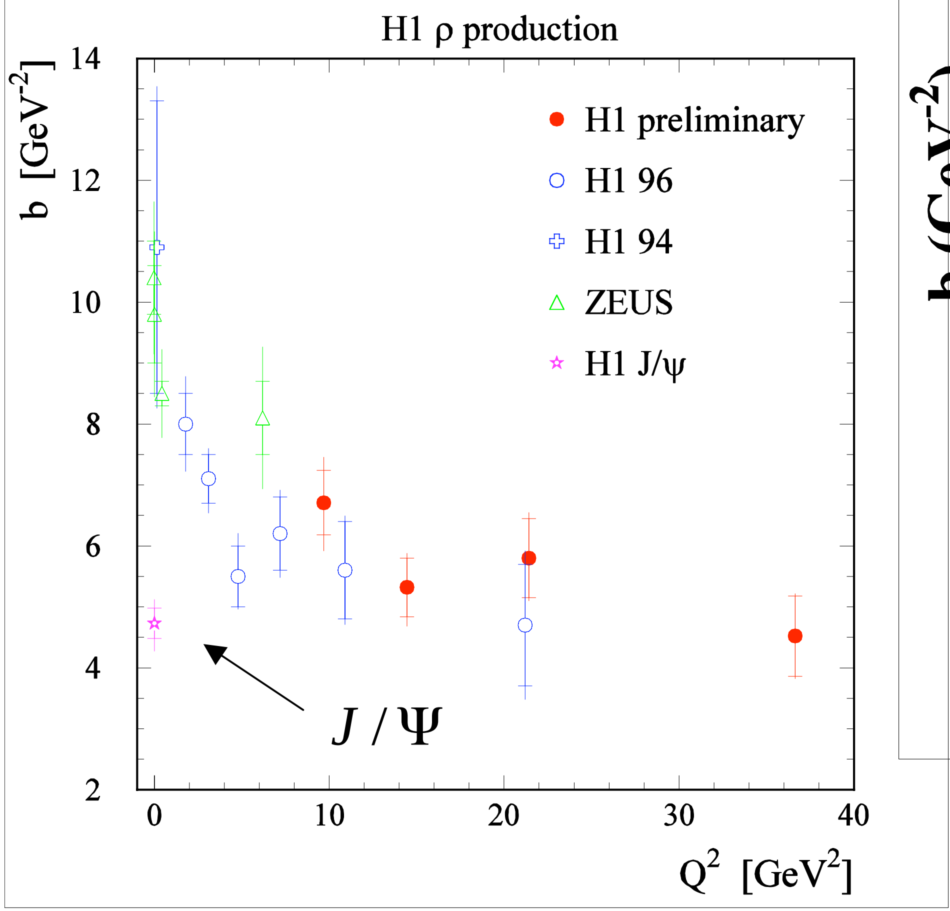


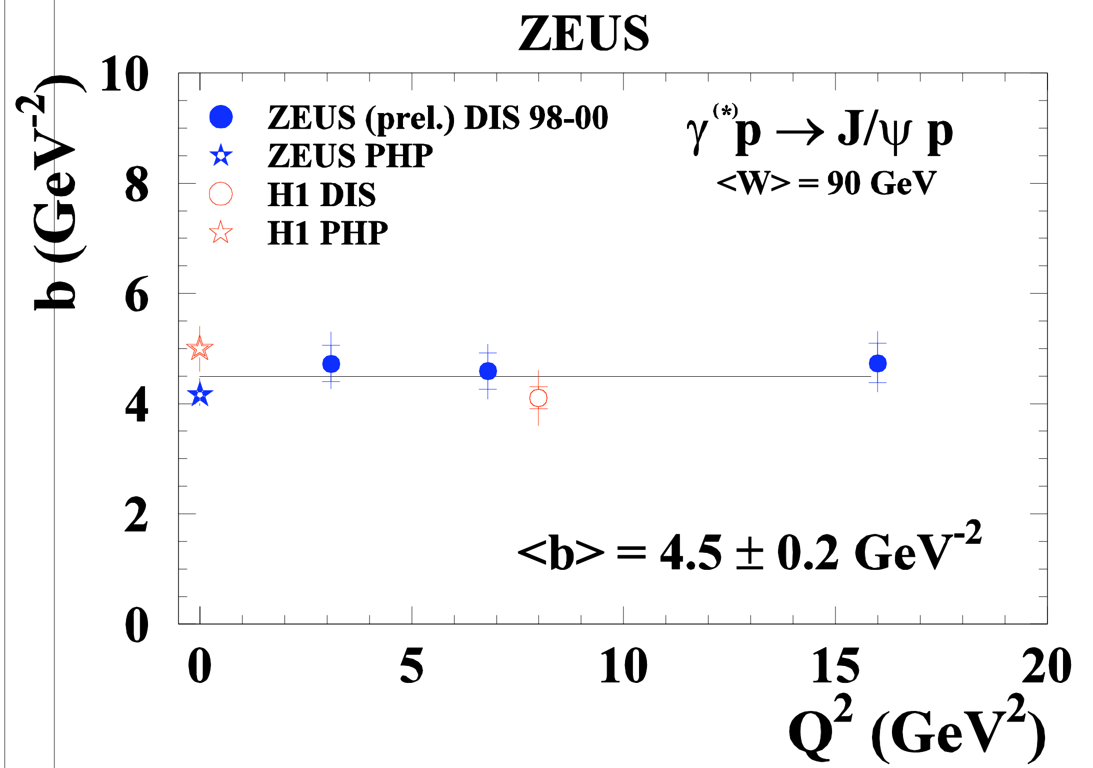
Can Q^2 be a Hard Scale ? II

ñ

Slopes of the t-distributions

J/Ø



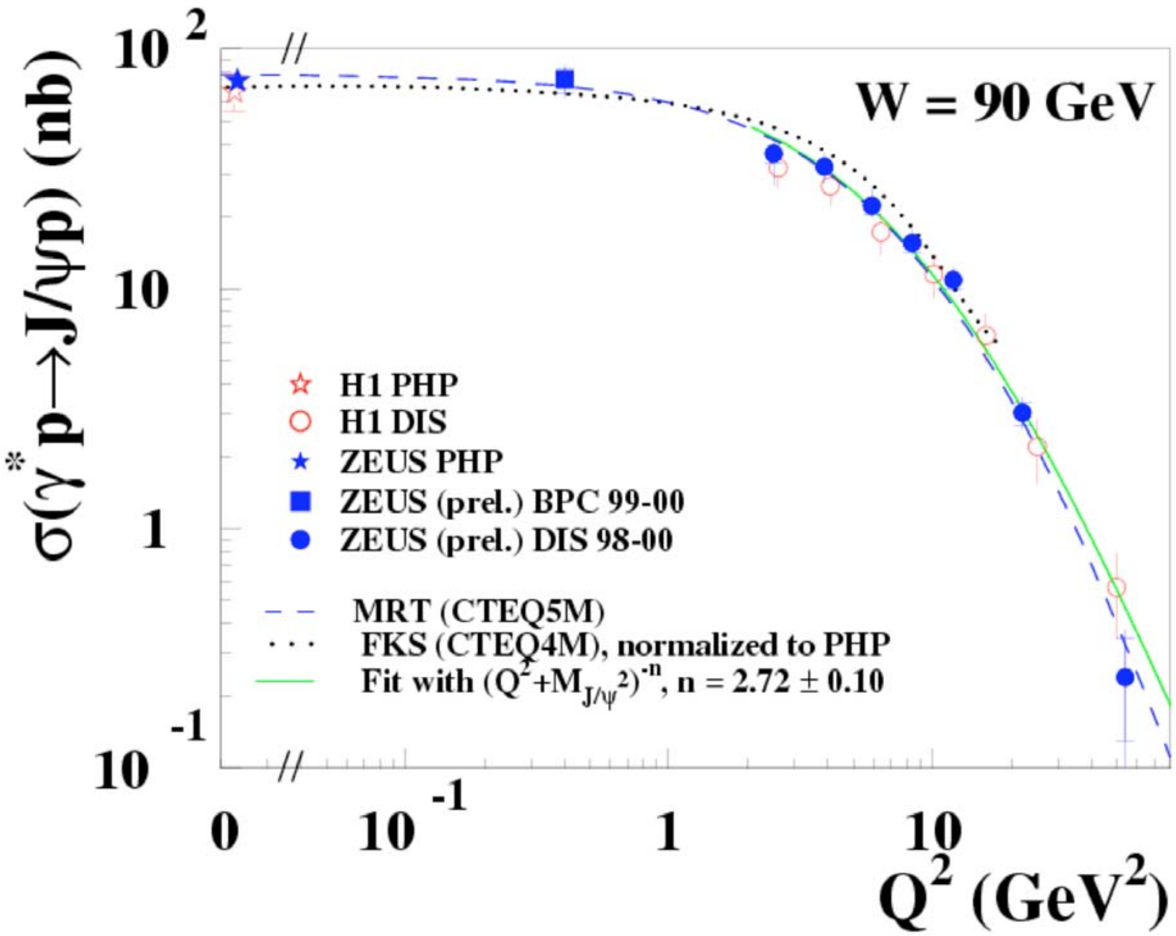


The b-slope of J/Ψ-production is independent of Q^2. It is a hard process already at Q^2 =0.

The b-slope of ρ-production decreases with Q^2. At high Q^2 it reaches the value of J/Ψ-production.

Can Q^2 be a Hard Scale ? III

J/Ψ -production as a function of Q^2



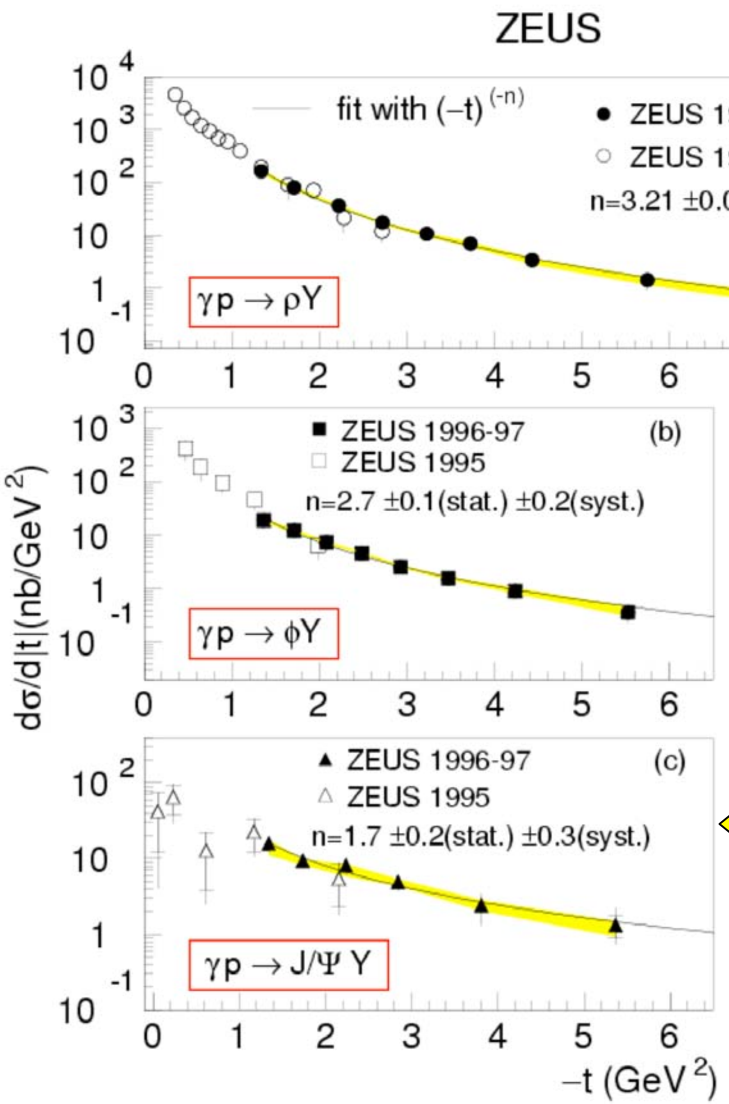
pQCD based models

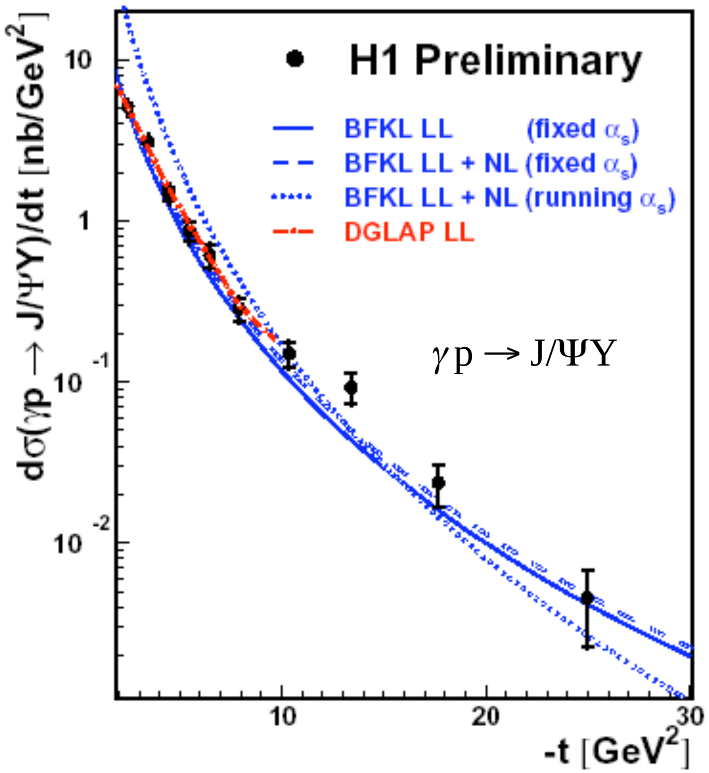
describe the Q^2 dependence

and the magnitude of

J/Ψ -electroproduction

Can |t| be a Hard Scale ?





Ivanov et al.

pQCD models

Bartels et al.

$$\frac{d\sigma_{\gamma p \to VY}}{d|t|} \propto |t|^{-n}$$

not exponential at high |t|, predicted by pQCD models.

t-dependence of p-dissociative vectormeson production can be described by pQCD models.

Large |t| may provide a hard scale to apply pQCD.

Summary of Exclusive Vectormeson Production

1.) A high vector meson mass provides a hard scale.
Photoproduction of ρ, ω, ϕ is described by soft Pomeron exchange,
whereas J/Ψ photoproduction is a hard process, it can be described by pQCD models.

2.) Vectormeson production at high Q^2 is a hard process, pQCD can be applied.

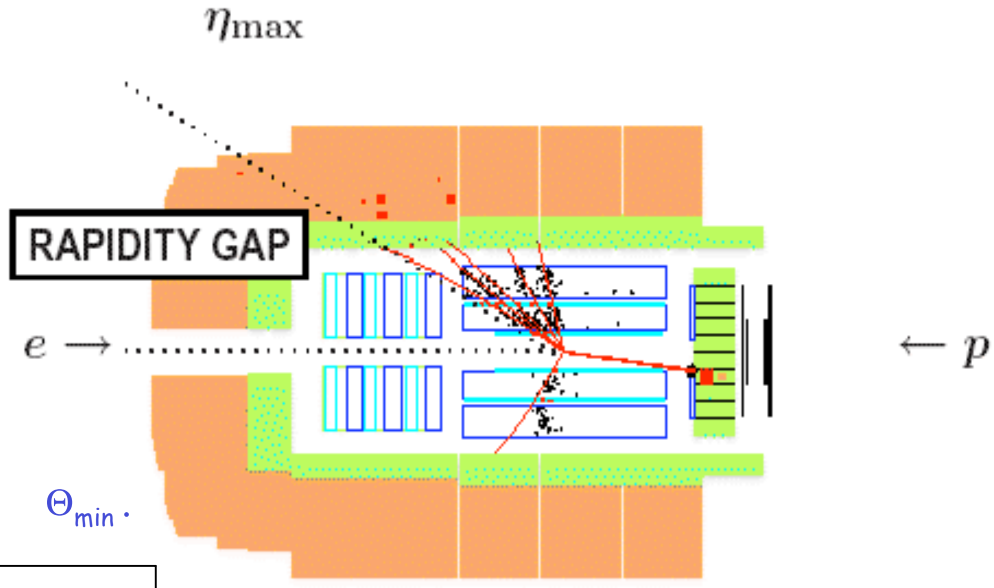
3.) Vectormeson production at high $|t|$ is a hard process.
The $|t|^{-n}$ dependence is in agreement with pQCD expectations.

Inclusive Diffraction I

1.) The large rapidity gap (LRG) method

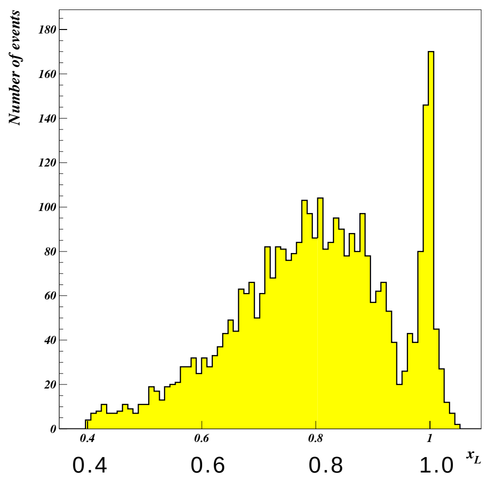
ς$_{max}$ = -ln tan(È$_{min}$/2)

No tracks or energy deposits in calorimeter for rapidities greater than η_{max} or at angles less than Θ_{min}.

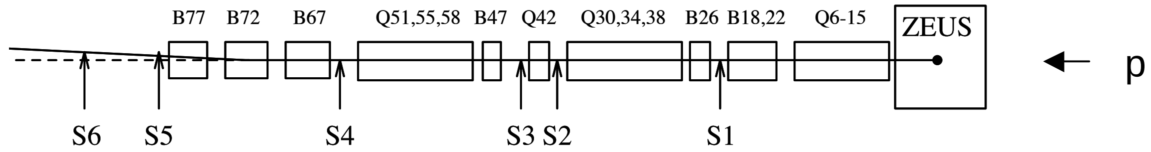


$ep \rightarrow eXp$

2.) Detection of outgoing proton (H1,ZEUS)



$x_L = 1 - x_{IP}$



$x_L \approx 1$ -> diffractively scattered proton

$$t = -\frac{p_T^2}{x_L} - \frac{(1-x_L)^2}{x_L} M_p^2$$

the only method to measure the t-distribution

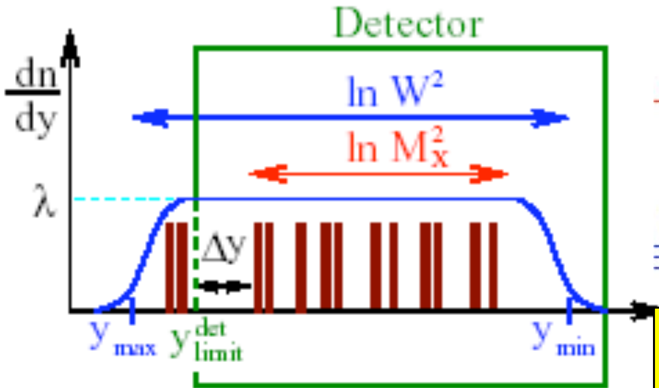
3.) The M_x-method (H1,ZEUS)

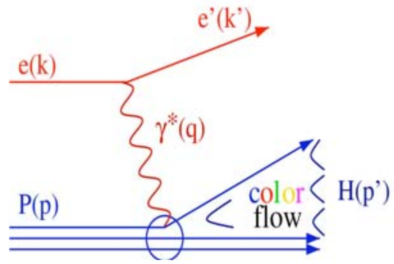
(i) Nondiffractive events :

Rapidity $y = \frac{1}{2} \ln \frac{E+p_z}{E-p_z}$

Property of a produced particle

Uncorrelated particle emission between incoming p-direction and scattered quark.





$$\frac{dN_{part}}{dy} = ë = \text{const.}$$

$$W^2 = c_0 e^{y_{max} - y_{min}}$$

$$M_X^2 = c_0 e^{y_{limit} - y_{min}}$$

Poisson distr. for Δy in nondiffractive events

$$P(0) = e^{-ëÄy}$$

$$\Rightarrow \frac{dN_{nondiff}}{d \ln M_X^2} = c \cdot e^{b \cdot \ln M_X^2}$$

(ii) Diffractive events :

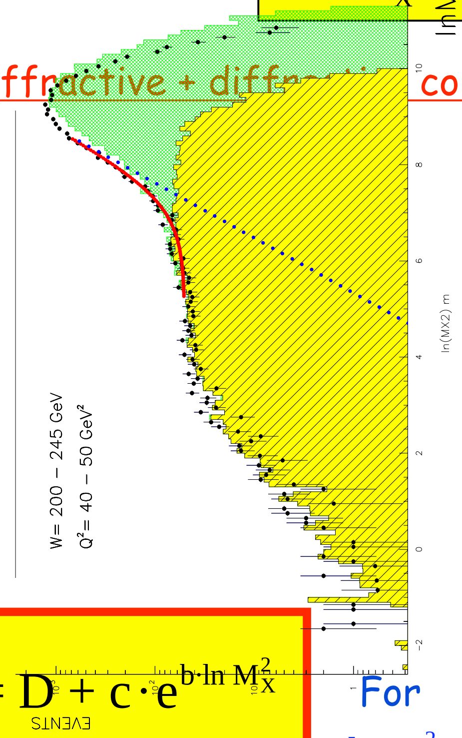
$$\frac{dN_{diff}}{dM_X^2} \propto \frac{1}{(M_X^2)^n}$$

At high energies and not too low M_X

$n \approx 1$

$$\Rightarrow \frac{dN_{diff}}{d \ln M_X^2} \approx \text{const.}$$

(iii) Nondiffractive + diffractive contributions



$$\frac{dN}{d \ln M_X^2} = D + c \cdot e^{b \cdot \ln M_X^2}$$

For $\ln M_X^2 \le \ln W^2 - \eta_0$

Fit slope b and c -> subtract nondiffractive events.

Diffractive Cross-Section and Diffractive Structure Functions

$$\frac{d^4\sigma}{dQ^2\,dt\,dx_{IP}\,d\beta} = \frac{2\pi\alpha_{em}}{\beta Q^2}[1-(1-y)^2]\cdot F_2^{D(4)}(Q^2,t,x_{IP},\beta)$$

Contribution from longitudinal structure function neglected by ZEUS

sizable only at high y

H1 defines : $\sigma_r^D = F_2^D - \underbrace{\frac{y^2}{1+(1-y)^2}}_{\text{sizable only at high } y} F_L^D$

If t is not measured :

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

analogously : $\sigma_r^{D(3)}(\beta,x_{IP},Q^2)$

QCD factorization for diffractive DIS processes :

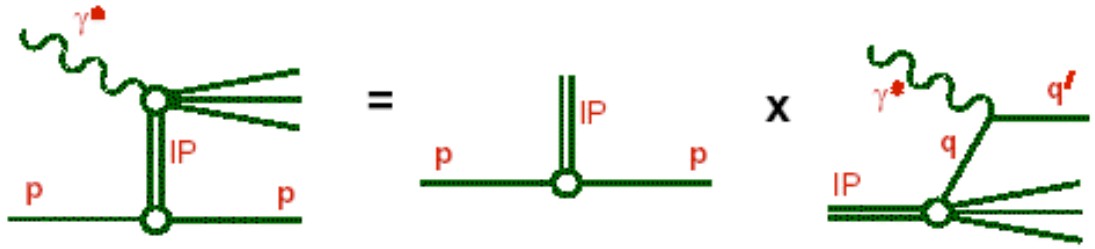
$$\sigma^{diff} \propto f_q^{diff}(Q^2,t,x_{IP},\beta)\cdot\hat{\sigma}_{pQCD}$$

(proven for ep-scattering, Collins et al.)

f_q^{diff} are universal diffractive parton densities which evolve according to DGLAP .

Regge-Factorization and Reggeon-Contributions

Regge factorization for Pomeron with partonic structure : (assumption, no proof)



Pomeron flux factor from Regge theory :

$$\sigma^{diff} \propto f_{IP/p}(t, x_{IP}) \cdot F_2^{IP}(Q^2, \beta)$$

$$f_{IP/p}(t, x_{IP}) = \frac{e^{B \cdot t}}{x_{IP}^{2\alpha(t)-1}}$$

Separating diffractive (Pomeron) from nondiffractive (Reggeon) contributions :

$$\mathbf{F_2^{D(4)}(x_{IP}, t, \beta, Q^2) = f_{IP}(x_{IP}, t) \cdot F_2^{IP}(\beta, Q^2) + n_{IR} f_{IR}(x_{IP}, t) \cdot F_2^{IR}(\beta, Q^2)}$$

Parameters B_{IP}, α'_{IP} follow from fit to the t-dependence,
the Reggeon structure function is taken as the π structure function.

All other parameters are derived from fits to the data.

QCD DGLAP Fits

H1 QCD-fit to LRG data (DGLAP fit):

QCD factorization :

$$F_2^{D(3)}(x_{IP},\beta,Q^2) = f_{IP/p}(x_{IP})F_2^{IP}(\beta,Q^2) + f_{IR/p}(x_{IP})F_2^{IR}(\beta,Q^2)$$

$$f_{IP/p}(x_{IP}),\ F_2^{IP}(\beta,Q^2),\ f_{IR/p}(x_{IP}),\ F_2^{IR}(\beta,Q^2)$$

Follow from fit to data and
assumption of pion trajectory for Reggeon exchange

$$F_2^{IP}(\beta,Q^2) = \sum_i f_i^D(\beta,Q^2)$$

i = parton species ; $u, d, s, \bar{u}, \bar{d}, \bar{s}$, gluon   light flavour singlet

$$f_i^D(\beta,Q^2)$$

universal diffractive parton distribution functions (DPDF)

DPDFs parametrised at a starting value Q_0^2 as :

$$zf_i(z,Q_0^2) = A_i z^{B_i}(1-z)^{C_i} \cdot e^{-\frac{0.01}{1-z}}$$

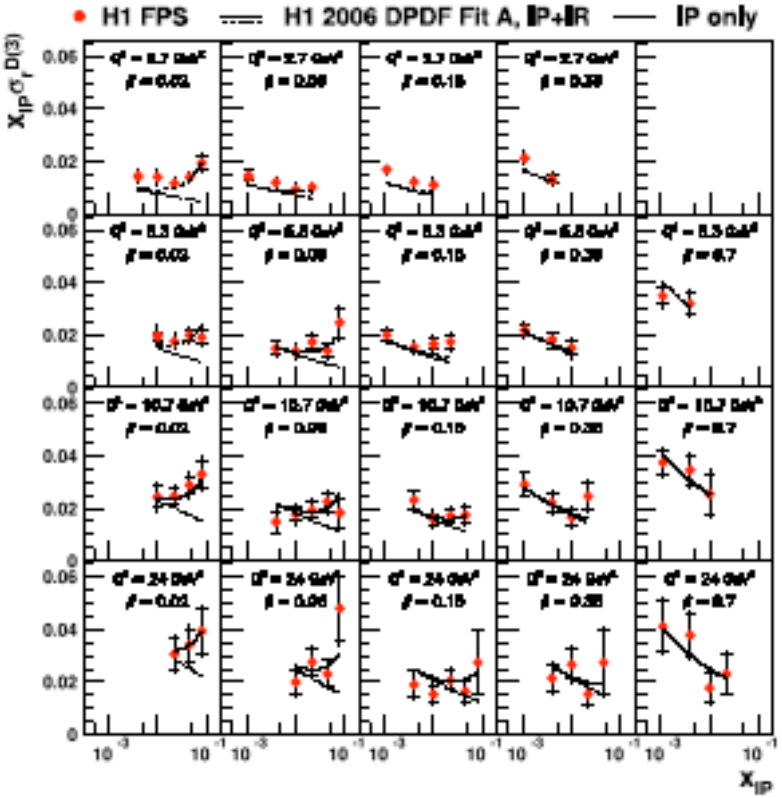
z is the longitudinal momentum fraction of the parton
entering the hard sub-process.

$z = \beta$ for lowest order quark-parton modell process,
$0 < \beta < z$ for higher order processes.

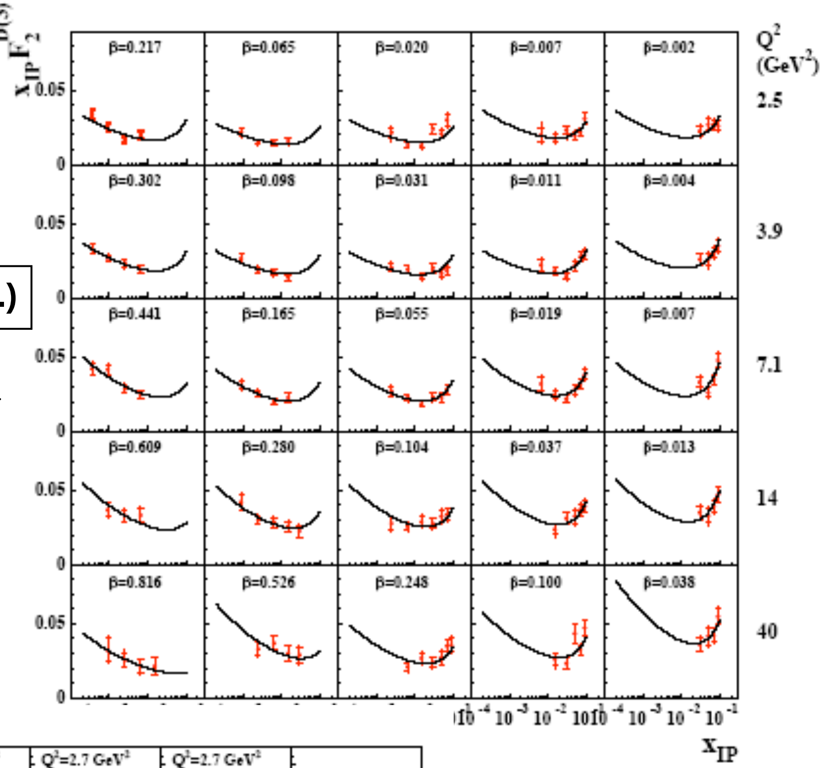
DPDFs evolved according to DGLAP to higher Q^2

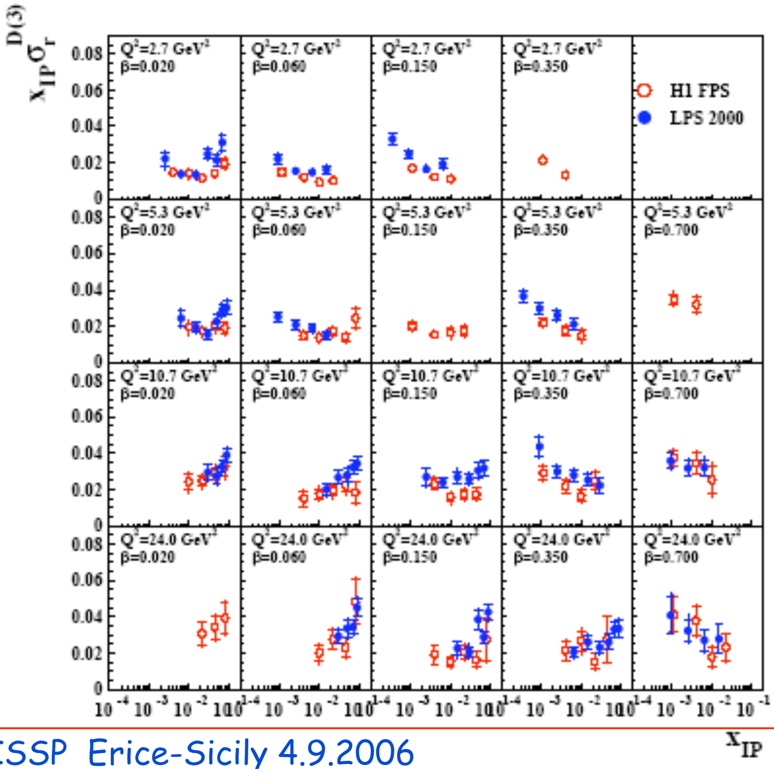
Results from proton detection method

H1 FPS 2006 data



ZEUS LPS 00 (prel.)



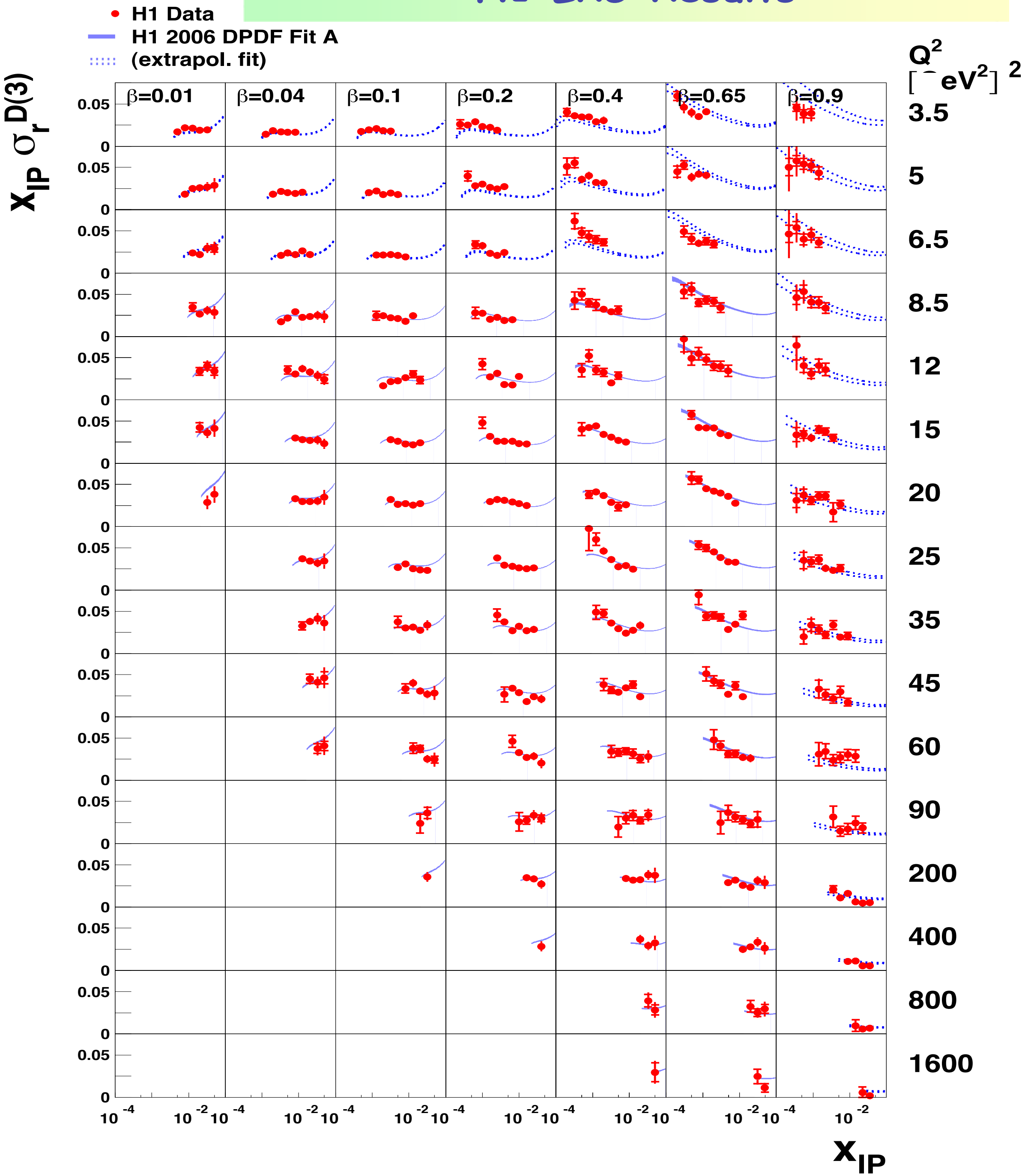


ZEUS LPS 00 (prel.), H1 FPS 06

Comparison of H1-FPS and ZEUS-LPS data.

Good agreement considering the normalization uncertainties of about +/- 10% for each of the datasets

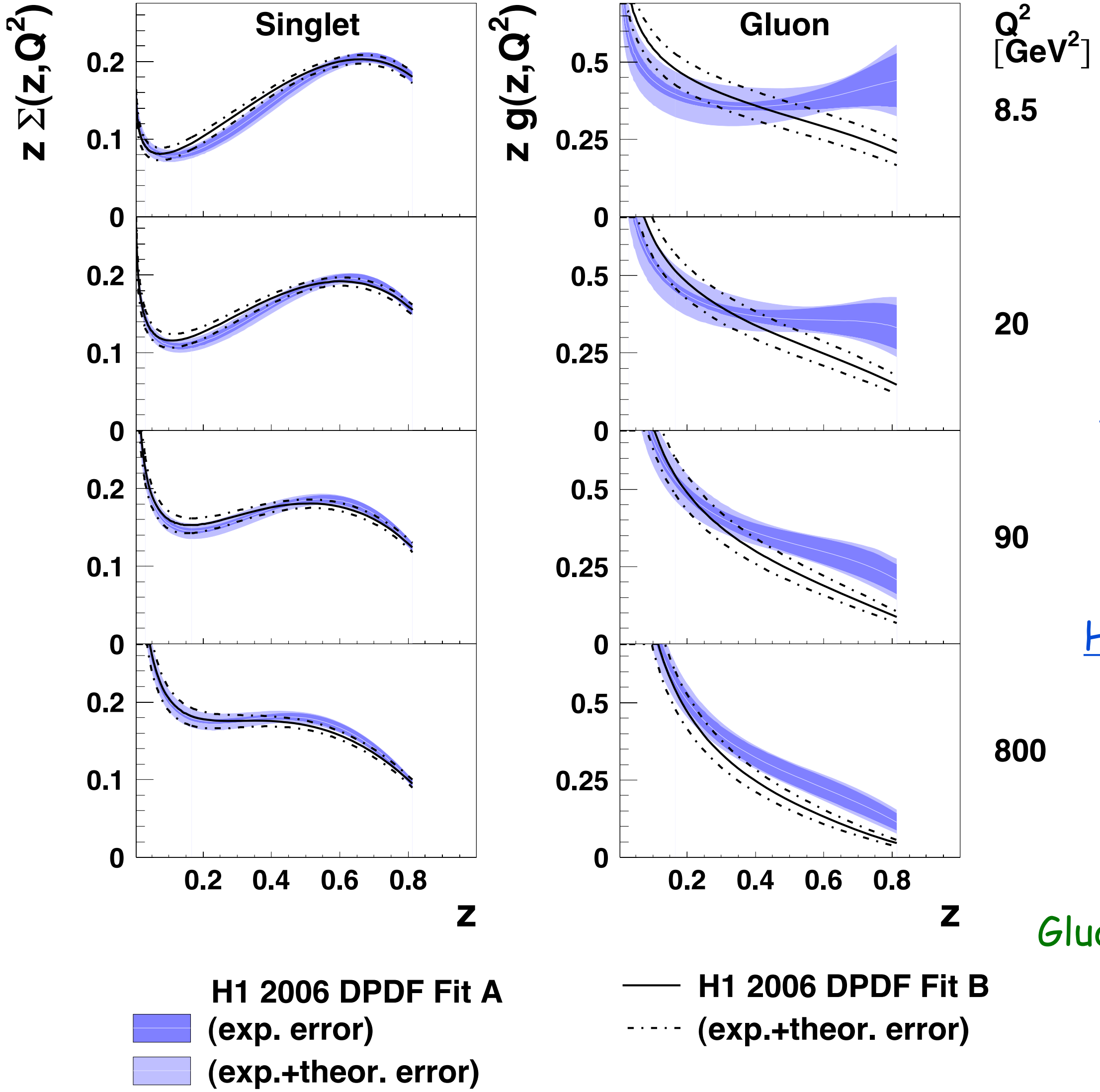
H1 LRG Results



Comparison of reduced cross-section with H1 QCD-fit

H1 DPDF Fits

H1 DPDFs



Singlet Structure function

$$\Sigma(z) = u(z) + d(z) + s(z) + \bar{u}(z) + \bar{d}(z) + \bar{s}(z)$$

H1 2006 DPDF Fit A :

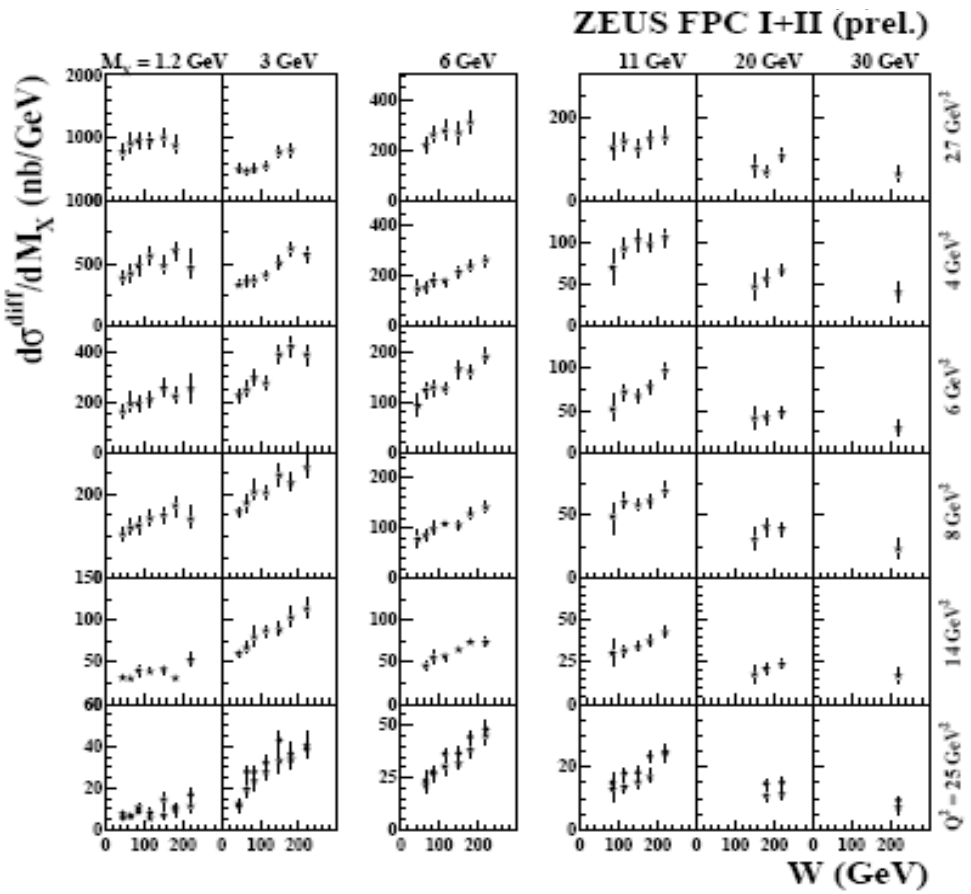
In gluon density set parameter B to zero

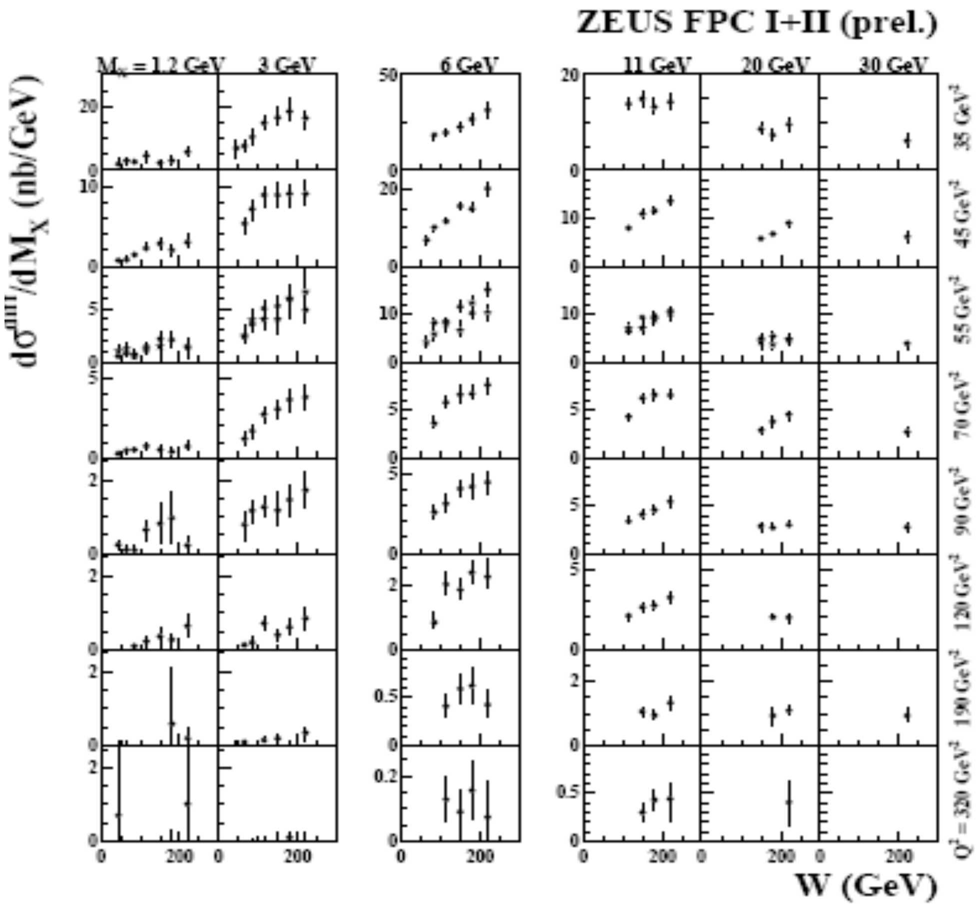
H1 2006 DPDF Fit B :

In gluon density set parameter C to zero

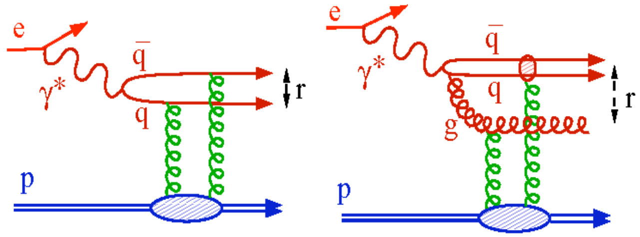
Gluon density only weakly constraint by the data

ZEUS M_X-Method Results





ZEUS BEKW(mod) Fit



Fit with BEKW model

(Bartels, Ellis, Kowalski and Wüsthoff, 1998)

- $$x_{IP} F_2^{D(3)} = c_T \cdot F^T_{q\bar{q}} + c_L \cdot F^L_{q\bar{q}} + c_g \cdot F^T_{q\bar{q}g}$$

$$F^T_{q\bar{q}} = \left(\frac{x_0}{x_{IP}}\right)^{n_T(Q^2)} \cdot \beta(1-\beta)\,,$$

$$F^L_{q\bar{q}} = \left(\frac{x_0}{x_{IP}}\right)^{n_L(Q^2)} \cdot \frac{Q_0^2}{Q^2+Q_0^2} \cdot \left[\ln\left(\frac{7}{4} + \frac{Q^2}{4\beta Q_0^2}\right)\right]^2 \cdot \beta^3(1-2\beta)^2\,,$$

$$F^T_{q\bar{q}g} = \left(\frac{x_0}{x_{IP}}\right)^{n_g(Q^2)} \cdot \ln\left(1+\frac{Q^2}{Q_0^2}\right) \cdot (1-\beta)^{\gamma}$$

assume $n_T(Q^2) = c_4 + c_7 \ln\left(1+\frac{Q^2}{Q_0^2}\right)\,,\ n_L(Q^2) = c_5 + c_8 \ln\left(1+\frac{Q^2}{Q_0^2}\right)\,,$

$$n_g(Q^2) = c_6 + c_9 \ln\left(1+\frac{Q^2}{Q_0^2}\right)$$

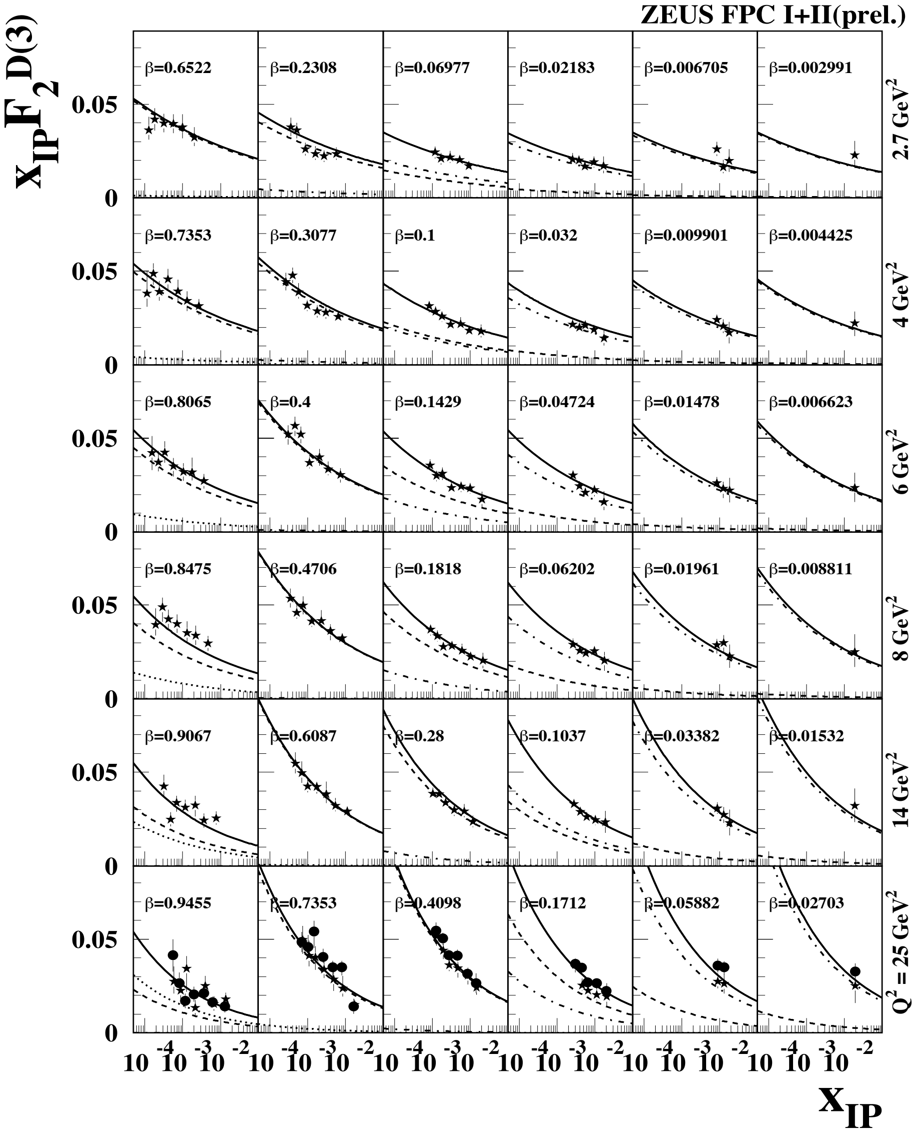
The ZEUS data support taking $n_T(Q^2)=n_g(Q^2)=n_1 \cdot \ln(1+Q^2/Q^2_0)$ and $n_L = 0$

Taking $x_0 = 0.01$ and $Q^2_0 = 0.4$ GeV^2 results in the modified BEKW model with the 5 free papameters :

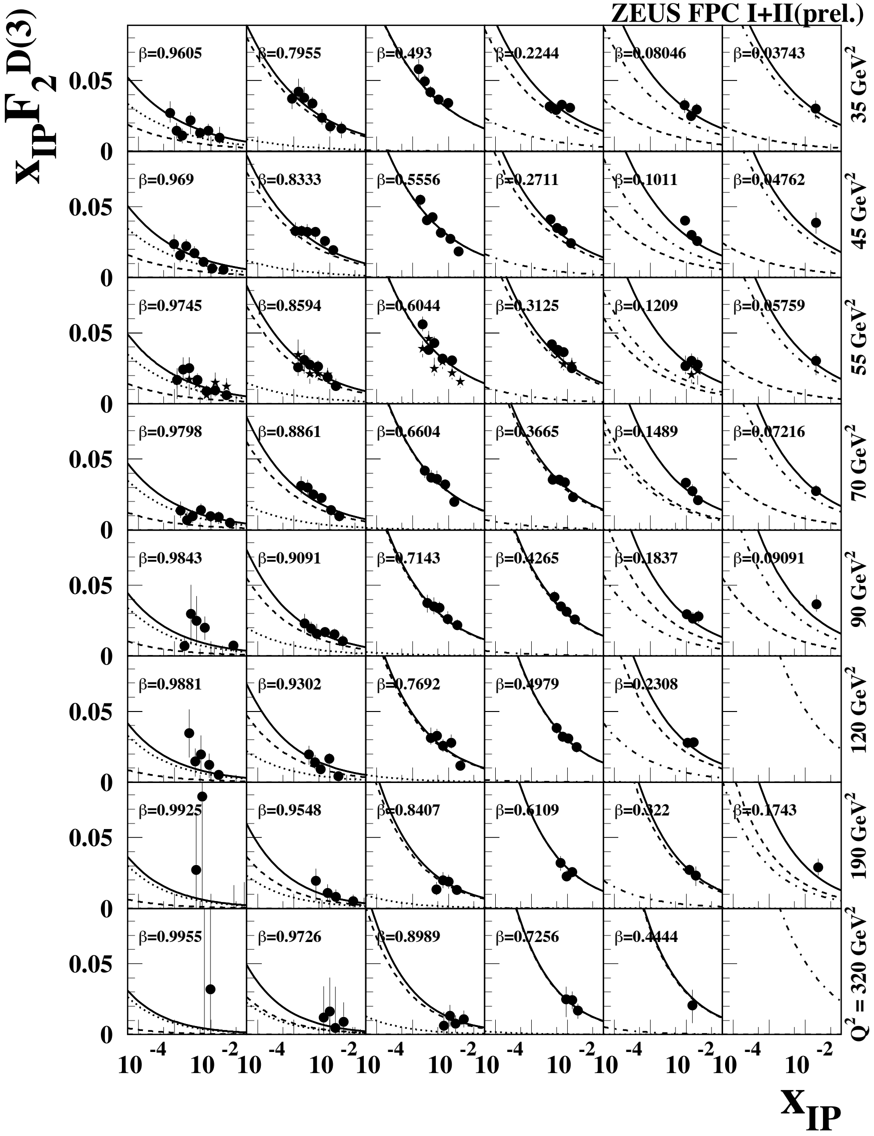
$$\boxed{c_T\,,\ c_L\,,\ c_g\,,\ n_1^{T,g}\,,\ \gamma}$$

ZEUS-M_X Diffractive Structure Functions with BEKW(mod.) Fit

★ FPC I   2006/06/21 16.36



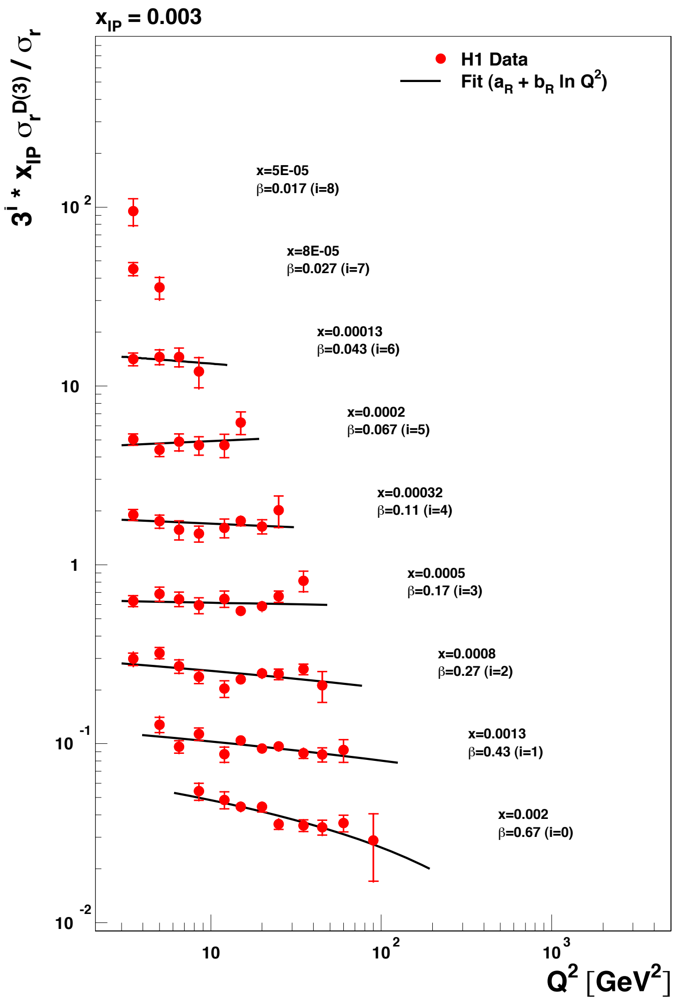
● FPC II   2006/06/21 16.26

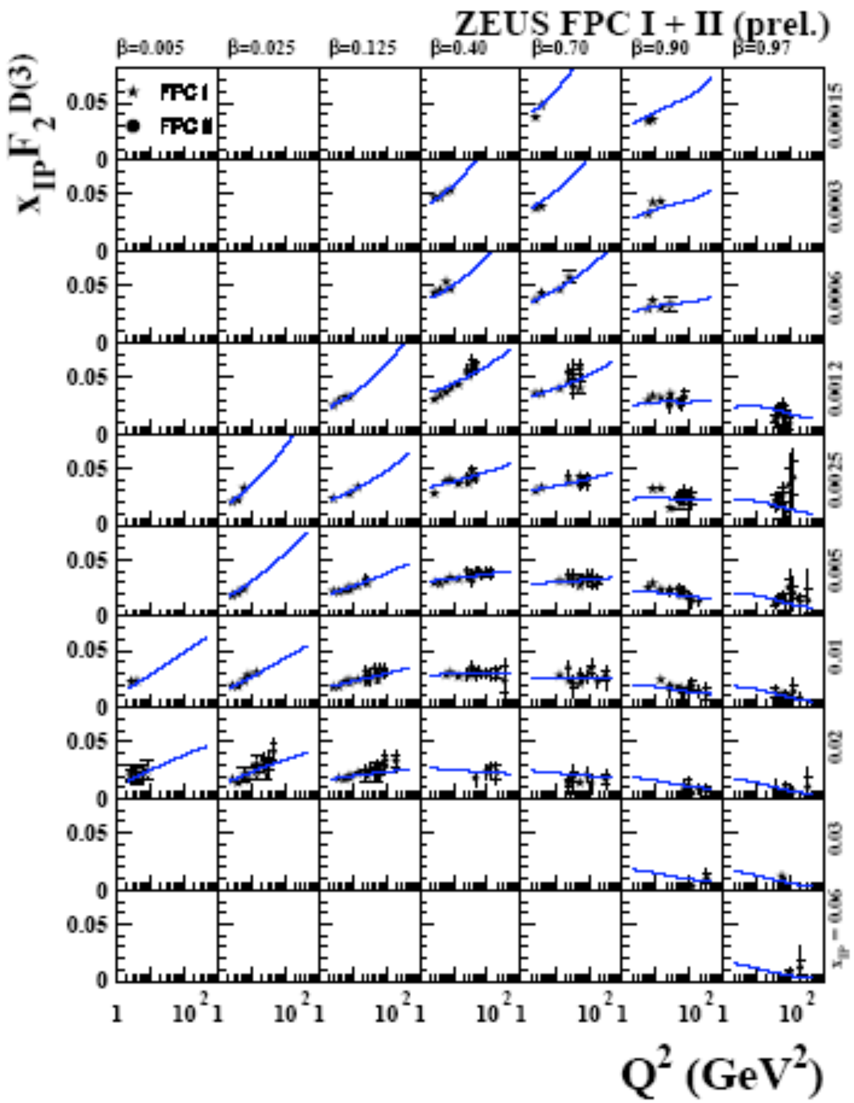


BEKW-fit : > 400 points, 5 parameters, $\chi^2/n_D = 0.71$

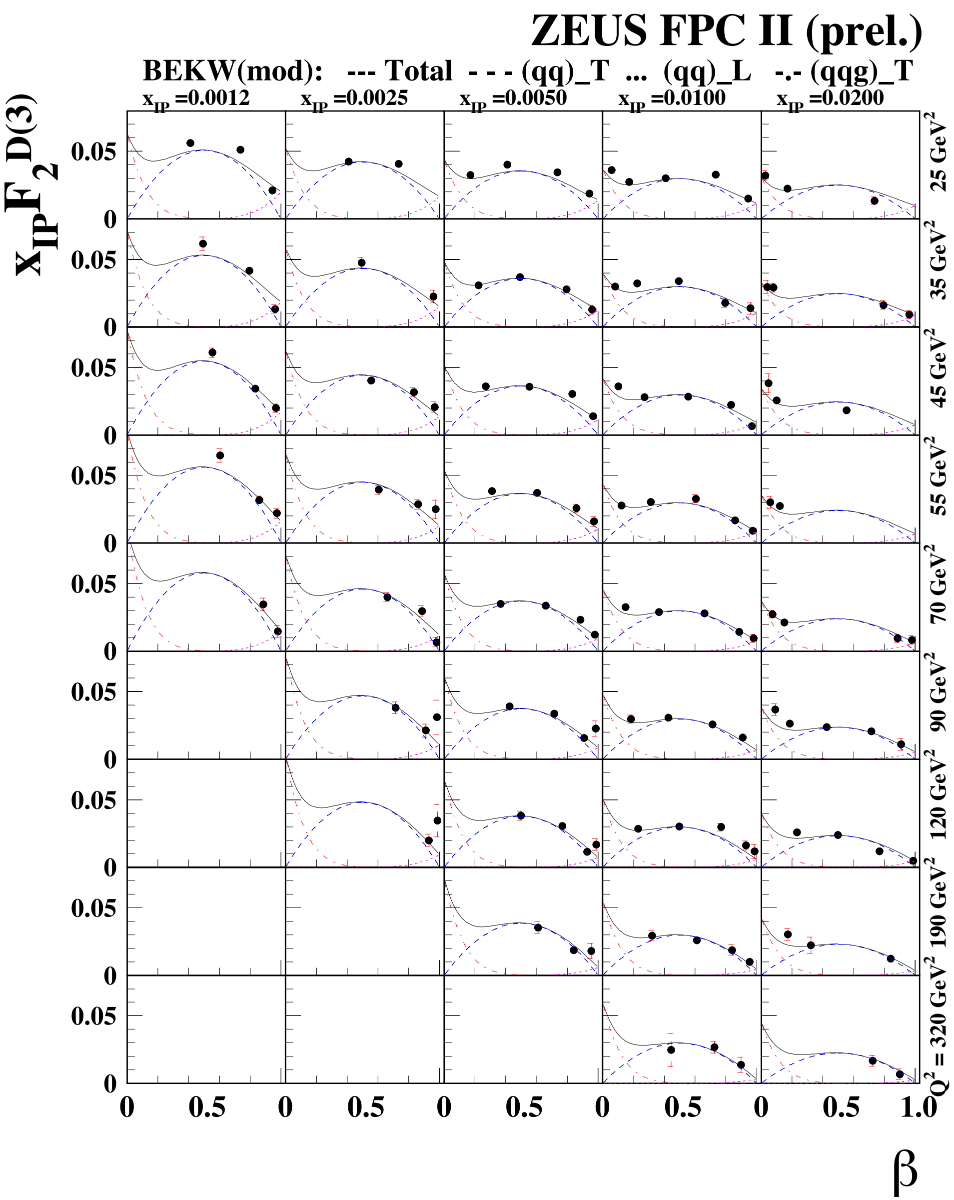
- ——— sum of all contributions
- ········ longitudinal $q\bar{q}$ contribution
- – – – transverse $q\bar{q}$ contribution
- – · – · transverse $q\bar{q}g$ contribution

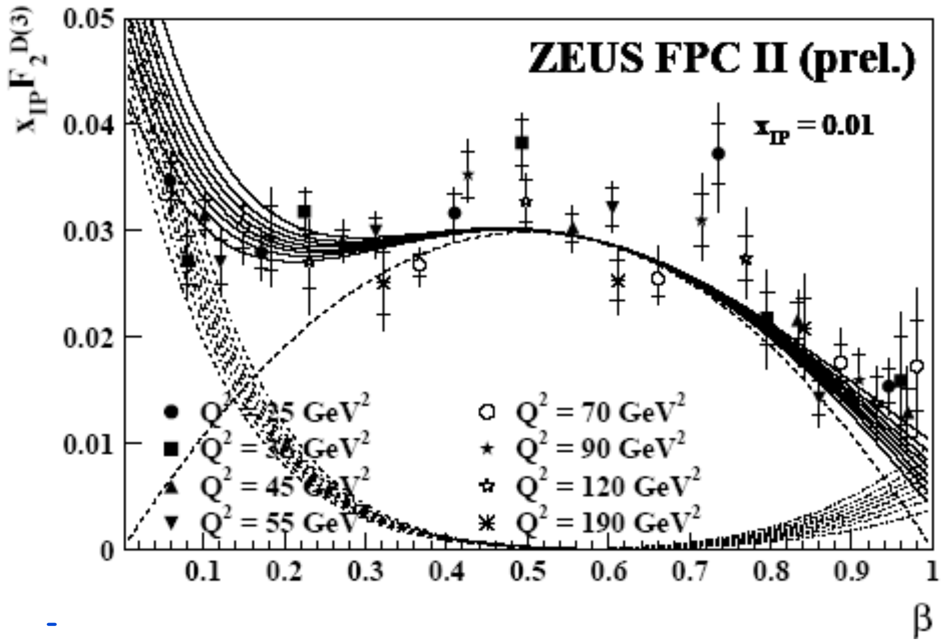
QCD Scaling Violations





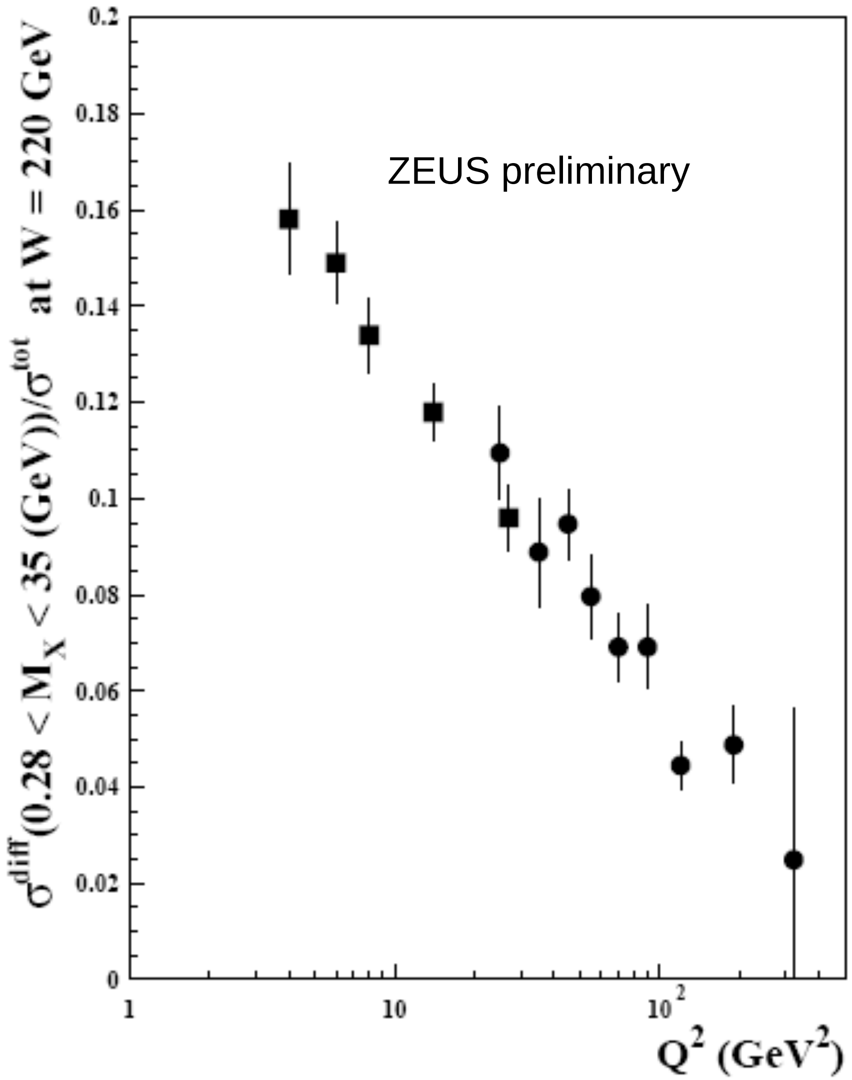
H1 and ZEUS see considerable QCD scaling violations





- for fixed Q^2 and x_{IP} the data show a broad maximum around β=0.5 which is due to the $q\bar{q}_T$ contribution ,
- towards low β values the $q\bar{q}g$ contribution rises
- strongly ,
- the longitudinal $q\bar{q}_L$ contribution is sizable only at very high β and is responsible for a finite value of the diffractive structure function at β –> 1.

Ratio of diffractive DIS to Total DIS Cross-Section



$\sigma^{diff}(0.28 < M_X < 35$ GeV) at W=220 GeV from ZEUS M_X data.

σ^{tot} derived in the same analysis from the Same data.

$r = \sigma^{diff}(0.28 < M_X < 35 \text{ GeV})/\sigma^{tot}$

$$\boxed{r = a - b \cdot \ln(1 + Q^2)}$$

with

$a = 0.22$, $b = 0.034$

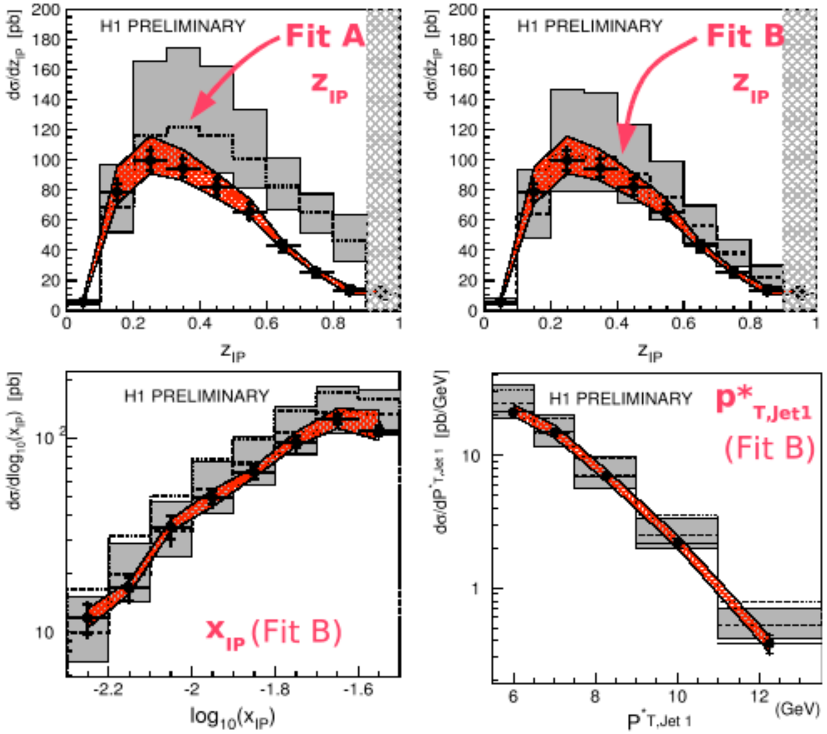
r varies only logarithmically

→ inclusive diffraction is a leading twist process

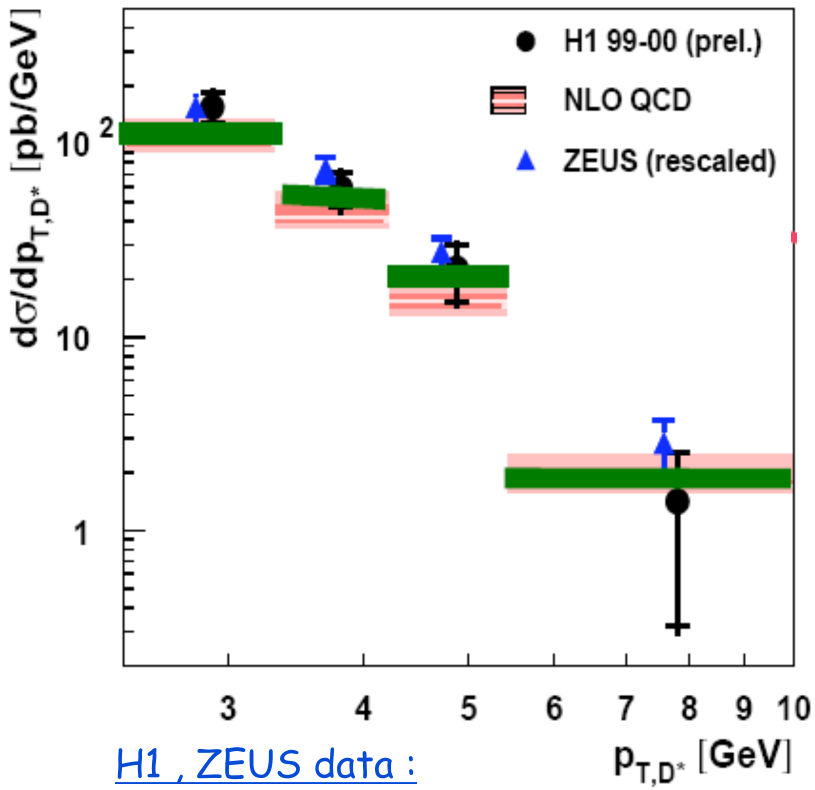
Are DPDFs Universal ?

Can one use DPDFs to calculate exclusive diffractive reactions ?

Diffractive dijet production



Diffractive D^* production



H1 dijet data : $4 < Q^2 < 80$ GeV^2

NLO prediction : Nagy et al.
DPDFs : H1 2006 fits A,B

H1 , ZEUS data :

NLO prediction : Collins et al.
DPDFs : H1 2002 fit

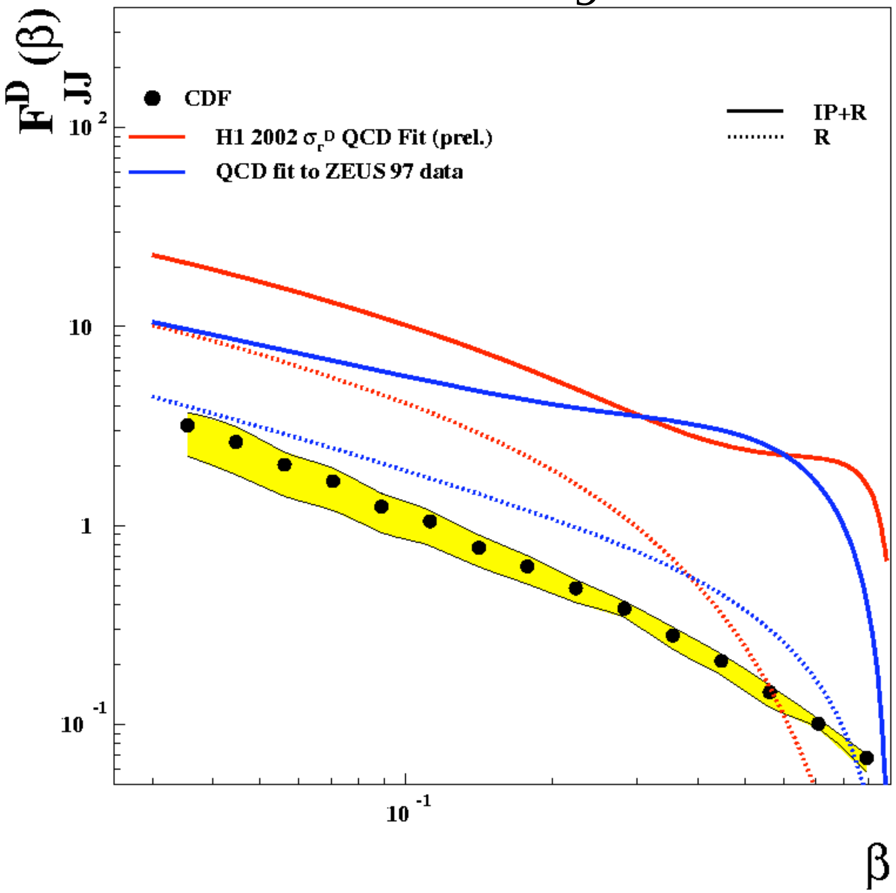
Perturbative QCD calculations with diffractive parton density functions from inclusive diffraction can describe exclusive diffractive reactions.

QCD factorization concept is validated by experiments

QCD factorization in hadron-hadron scattering: (not proven, not expected to hold)

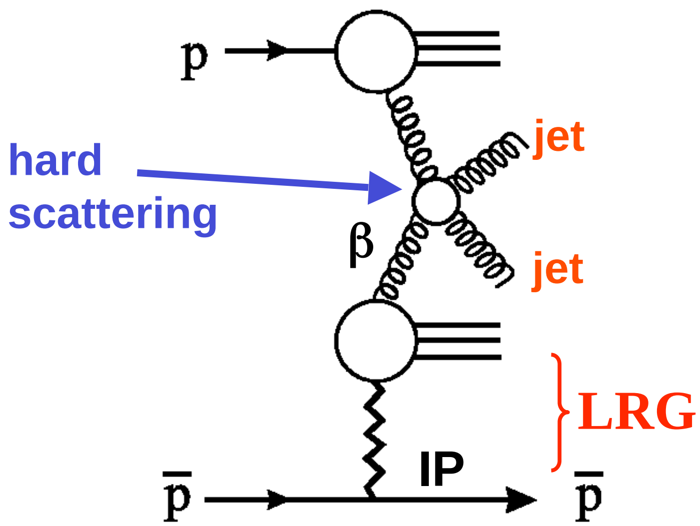
CDF dijet production

$$F^{i}_{jj}(\beta) = \beta[g(\beta) + \frac{4}{9}q(\beta)]$$



Use DPDFs from HERA to predict dijet production at the Tevatron

QCD factorization broken by factor 5-7



Survival probability < 1 due to multiple Pomeron exchange and final state interactions.

Summary of Inclusive Diffraction

1.) Three experimental methods to measure inclusive diffraction at HERA : FPS/LPS, LRG, and M_X. All include contributions from proton dissociation or from Reggeon exchange or from both.

2.) The diffractive cross-section can be expressed in terms of diffractive structure functions.

3.) The QCD factorization scheme in DIS is proven and experimentally verified in diffractive DIS.

4.) Assuming Regge factorization H1 extracted DPDFs from the LRG data.

5.) Although theoretically not expected, Regge factorization seems to hold in practice.

6.) There are experimental indications that DPDFs might be universal in DIS.

7.) QCD inspired dipole models can describe inclusive diffraction as well. The ZEUS M_X data are described rather precisely over the whole kinematic range by the BEKW(mod) parametrization.

8.) The BEKW modell explains the diffractive structure function $F_2D(3)$ in terms transverse and longitudinal quark-antiquark and quark-antiquark-gluon contributions.

9.) The diffractive structure function $F_2D(3)$ shows large scaling violations. This points to a large gluon fraction in the colourless exchange.

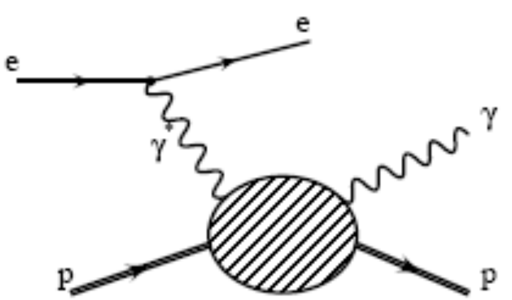
10.) Inclusive diffraction is a leading twist reaction.

11.) QCD factorization does not hold for diffractive hadron-hadron interactions. Using HERA DPDFs leads to a gross overestimation of dijet production at the Tevatron.

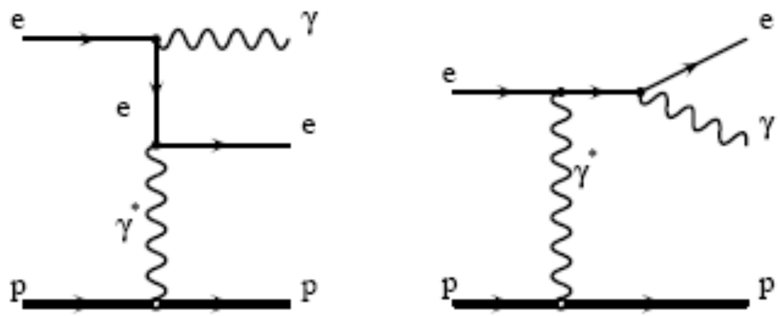
Additional Material

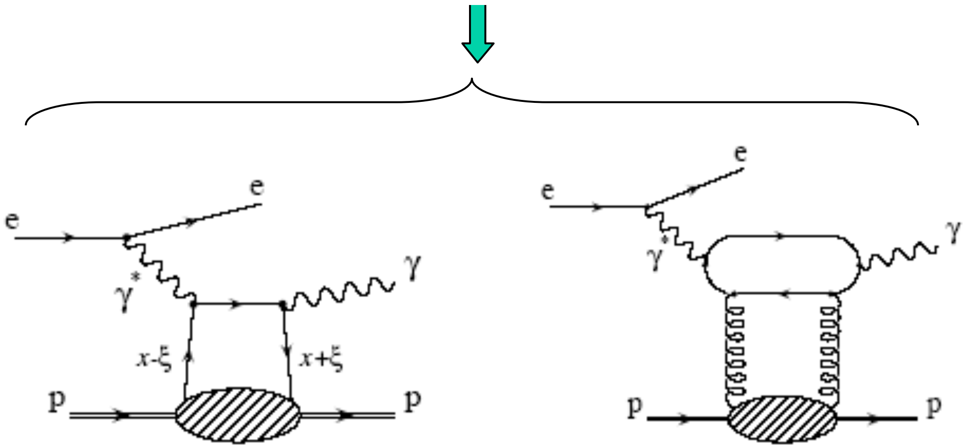
Deeply Virtual Compton Scattering I

DVCS



Bethe-Heitler





Bethe-Heitler processes lead to the same final state

Difficult to disentangle experimentally

Interference between QCD and QED gives access to DVCS-QCD amplitude :

$$\sigma \propto |A_{BH}|^2 + (A^*_{DVCS} A_{BH} + A_{DVCS} A^*_{BH}) + |A_{DVCS}|^2$$

ξ – skewedness

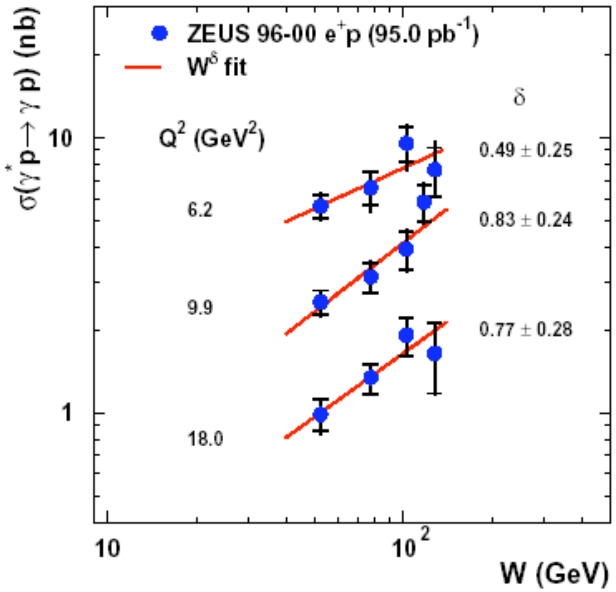
Probably cleanest test of pQCD , no hadrons in the final state.

Interference term can be derived from asymmetries, e.g.

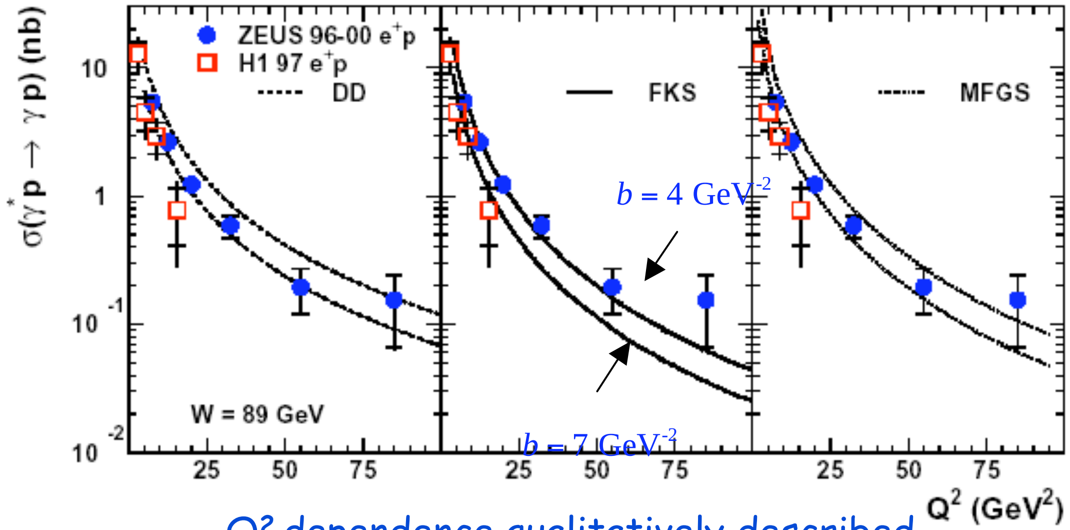
Beam-Spin-Asymmetry: $\boxed{d\sigma(\vec{e}p) - d\sigma(\overleftarrow{e}p)}$

Generalized parton distributions GPD -> information on transverse distribution of partons

Deeply Virtual Compton Scattering II

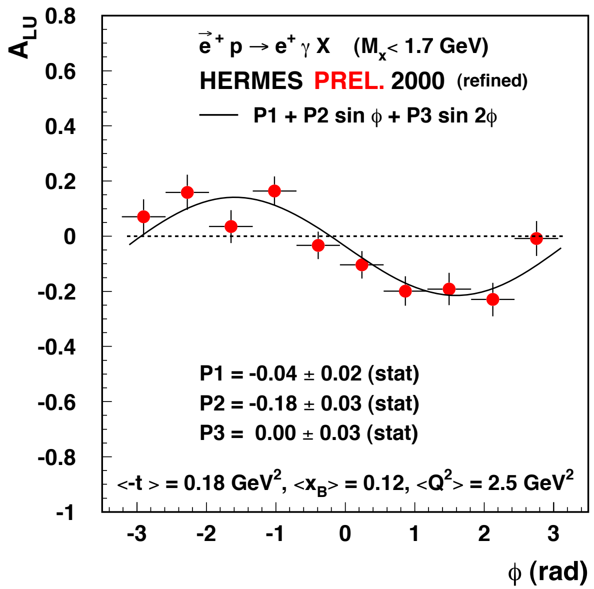


W dependence stronger than for soft Pomeron and increasing with Q^2



Q^2 dependence qualitatively described by pQCD based models

HERMES result on beam-spin-asymmetry A_{LU}



Φ is angle between scattering plane and production plane.

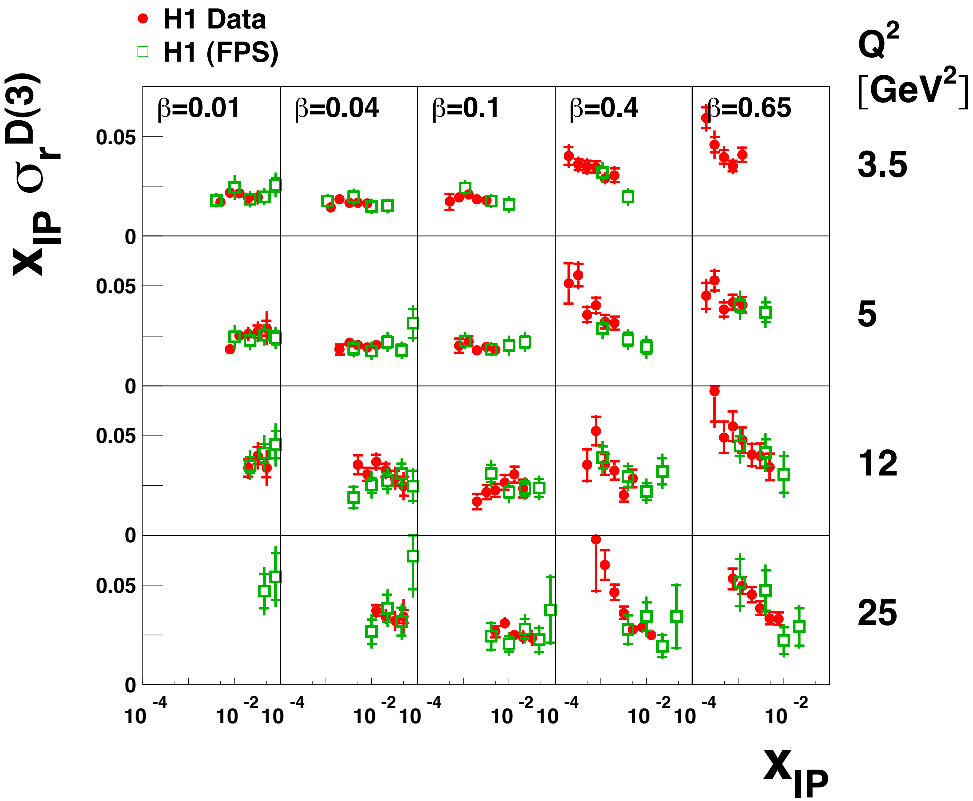
Note: HERMES is a fixed target experiment using the HERA e^+/e^- beam and a polarizable target.

Maybe not yet a hard process at Q^2 = 2.5 GeV²

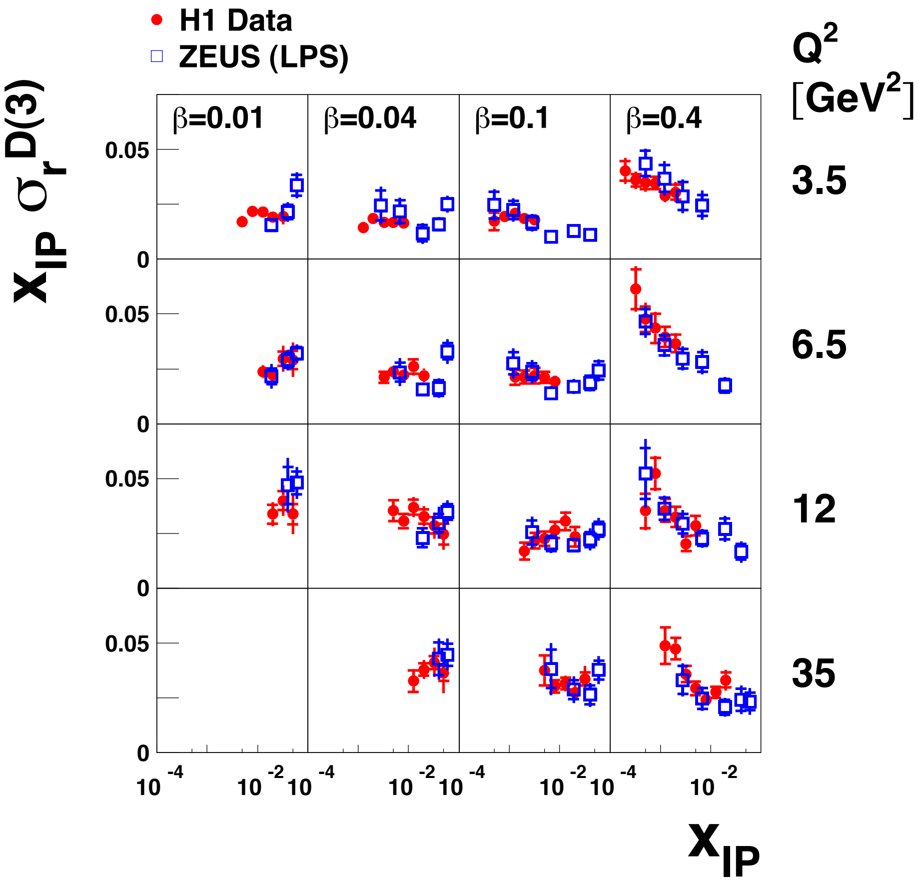
No extraction of GPDs yet.

Comparison of H1 LRG with H1 FPS and ZEUS LPS

Comparison of H1 LRG with H1 FPS

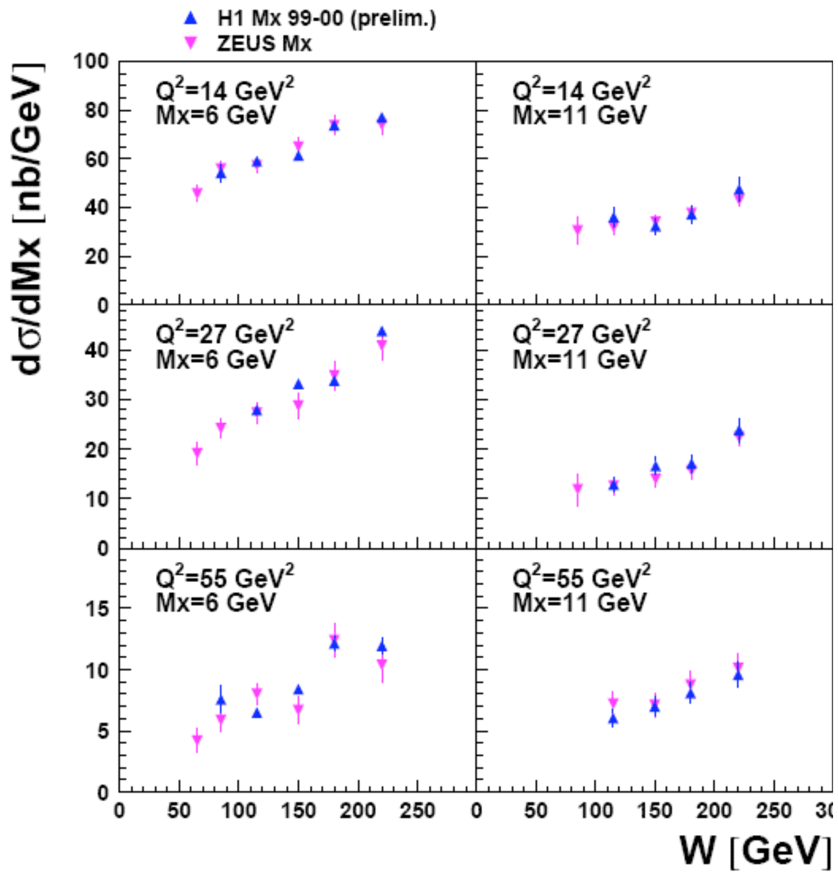


Comparison of H1 LRG with ZEUS LPS



Comparison of H1 and ZEUS Results

$d\sigma/dM_X$ from H1 and ZEUS



$x_{IP}\sigma_r^{D(3)}$ from H1 and ZEUS