Diffraction at HERA

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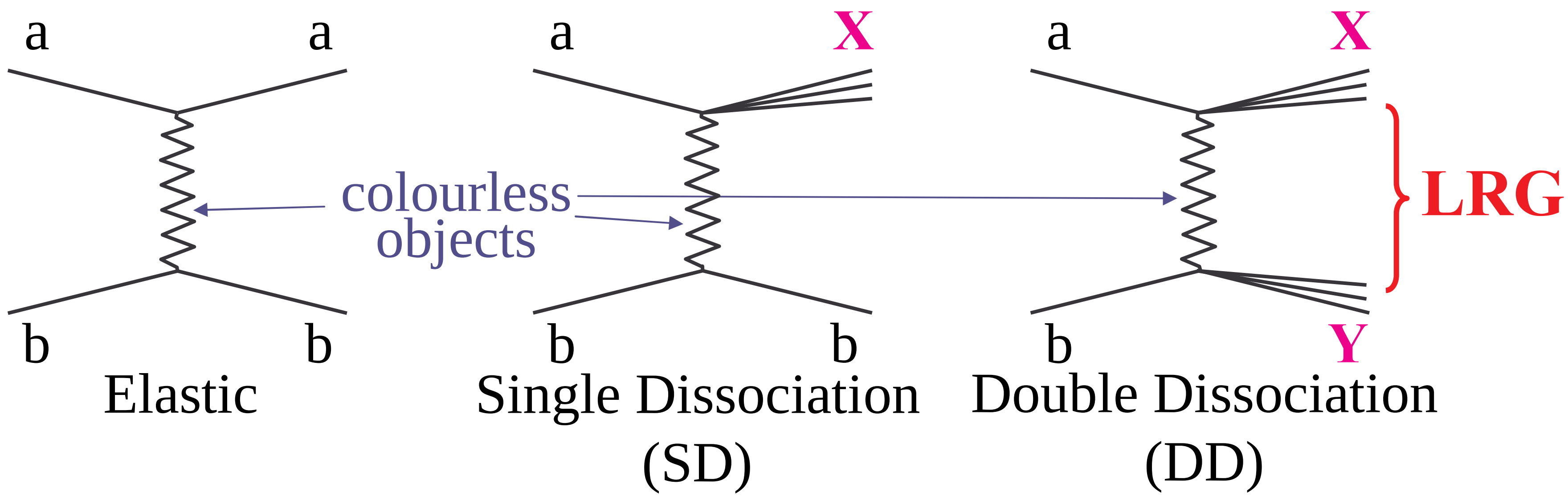
- ❑ inclusive reaction ($\gamma^*p \rightarrow Xp$)
- ❑ vector mesons ($\gamma^*p \rightarrow VM\ p$)
- ❑ deep virtual Compton scattering ($\gamma^*p \rightarrow \gamma p$)

Diffractive scattering



Large fraction of events (~30% of σ_{tot}) in which:

- beam particles emerge intact (elastic) or dissociate into low mass states **X**,**Y** (M_X, M_Y « s)
- there is a *t*-channel exchange of a colourless object
- emerging systems hadronize independently
  $\Rightarrow$ Large Rapidity Gap (**LRG**) if s large enough: $y \approx \frac{1}{2} \ln s/M_X^2$

The Hadronic level: Regge Theory

Experimental observations in diffractive scattering (soft process):

- **weak energy dependence** of cross sect. $\Rightarrow \boldsymbol{\sigma \propto s^{\sim 0.16}}$ $\boldsymbol{= s^{2(\alpha_{\mathbb{P}}(0)-1)}}$
- **very small scattering angles** $\Rightarrow$ exponential dep. : $d\sigma/d|t| \propto e^{-b\cdot|t|}$
- **b slope increases with energy**: $b(s) = b_0 + 2 \cdot \alpha'_{\mathbb{P}} \cdot \ln(s/s_0)$

successfully parameterized by the **Regge theory**,

$\Rightarrow$ exchange of trajectories, $\alpha_j(t) = \alpha_j(0) + \alpha'_j \cdot t$ $(j = \pi, \mathbb{P}, \mathbb{R})$.

$\alpha_{\mathbb{P}}(0)$ **= 1 + ε = "intercept", determines the energy dependence** of σ^{tot} $(\propto s^{\alpha_{\mathbb{P}}(0)-1} = \varepsilon)$ and σ^{el}, σ^{diffr} $(\propto s^{2\varepsilon})$

$\alpha'_{\mathbb{P}}$ = "**slope**", determines the growth with energy of the transverse extension of the scattering system ($\Rightarrow$ colour radiation cloud), $\Rightarrow$ **characterizes the confinement forces in QCD**

Access to $\alpha'_{\mathbb{P}}$ only in diffraction

From Hadrons to Partons

Since 1988: **UA8, Tevatron, HERA:** hard diffraction
from hadronic degrees of freedom to **hadronic subcomponents**
and **quantum field theories**, i.e. in terms of **QCD**

HERA: QCD machine. Several advantages:

- diffraction in DIS is **much simpler** than in hadron-hadron, since only one large (~ 1 fm) non-pert. object (hadron) is present
- **excellent acceptance** for diffractive dissociated system: asymmetric beams ($E_{e^\pm}$ = 27.5, E_p = 820(920) GeV) open up the γ^*-hemisphere
- virtual-γ provides **varying resolution power**: $Q^2 : 10^{-8} \rightarrow 10^5\ \mathrm{GeV}^2$
  (corresponding to probing distances $\Delta r : 10^3 \rightarrow 10^{-3}$ fm)
  $\Rightarrow$ study the transition between soft and hard regimes
- small-x $\Rightarrow$ **high parton densities** $\Rightarrow$ saturation

About 10% of the DIS events at HERA at small-x **are diffractive.**

Hard Diffraction in QCD

$$\frac{d^4\sigma(x,Q^2,\xi,t)}{d\xi dt} = \sum_i \int_x^{\xi} dy \cdot \hat{\sigma}(x,Q^2,y) \cdot \frac{df_i^D(y,\xi,t)}{d\xi dt} \quad \text{(for large enough } Q^2\text{)}$$

hard-process cross section

DPD's

- **Hard QCD factorization in diffractive DIS proven** (Collins, 1998) which validates the concept of:

- **Diffractive Parton Distributions** (Veneziano et al., Berera et al., 1994)

DPD's are **conditional probabilities** of finding, in a fast proton, a parton i with momentum fraction y, while the proton (intact) is scattered with mom. transfer t and losing $\xi \equiv x_P$

DPD's **obey the usual DGLAP evolution equations**.

$\Rightarrow$ **diffractive DIS is firmly rooted in QCD, like inclusive DIS.**

The diffractive cross section in DIS

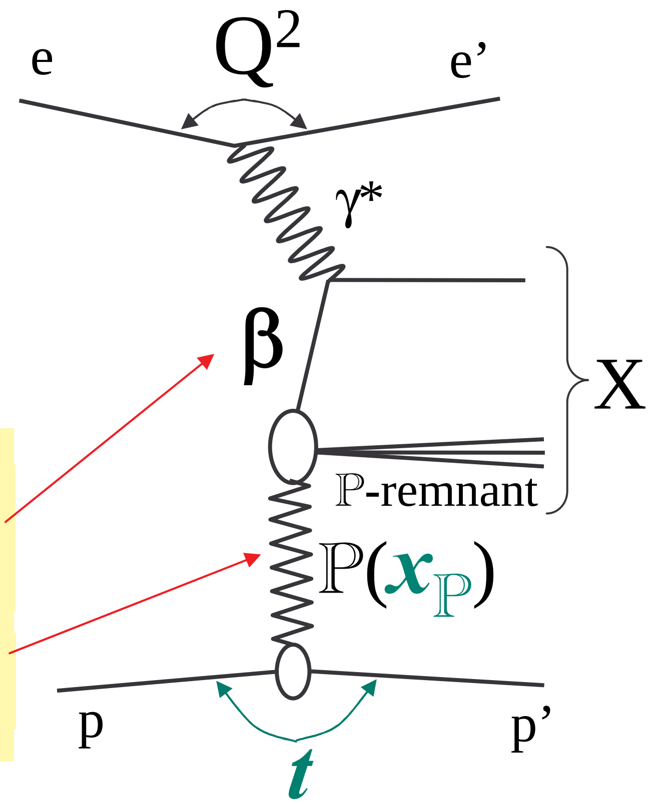
Two more variables ($x_{\mathbb{P}}$ and t) to describe the proton vertex:

$$\frac{d^4\sigma_{ep}}{d\beta dQ^2 dx_{\mathbb{P}} dt} = \frac{4\pi\alpha^2}{\beta Q^4} \cdot \left(1 - y + \frac{y^2}{2}\right) \cdot F_2^{D(4)}(\beta, Q^2, x_{\mathbb{P}}, t)$$

where $\mathbf{F_2^{D(4)}}$ **(β,Q^2,$x_{\mathbb{P}}$,t)** is the diffractive structure function and:

$\beta = \dfrac{Q^2}{M_X^2 + Q^2} = \dfrac{x}{x_{\mathbb{P}}}$ = fraction of $\mathbb{P}$-momentum carried by the quark coupling to the γ^*

$x_{\mathbb{P}} = \dfrac{M_X^2 + Q^2}{W^2 + Q^2}$ = fraction of proton mom. carried by $\mathbb{P}$



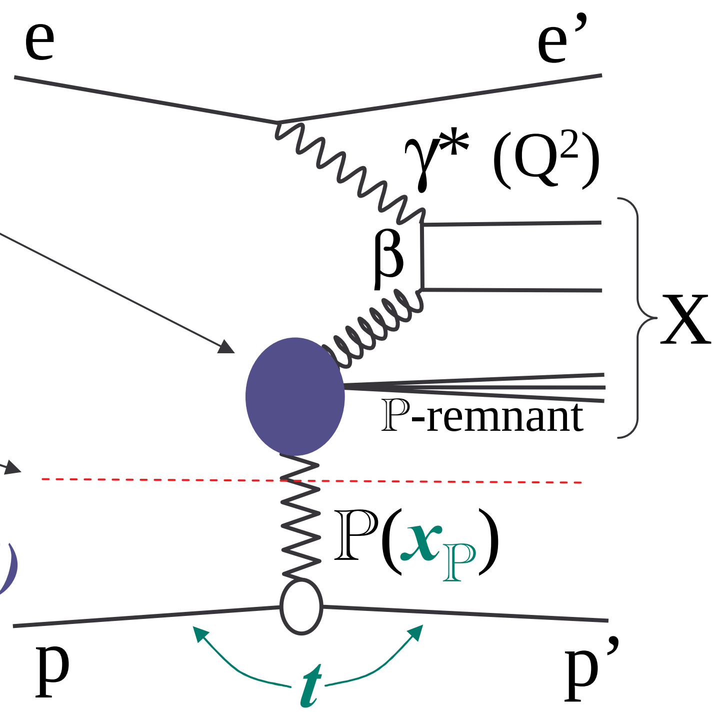
Integration over t gives $\mathbf{F_2^{D(3)}}$ **(β,Q^2,$x_{\mathbb{P}}$)**, which is often measured.

Models for Hard Diffraction: the DIS Frame

Ingelman-Schlein model (born for hadron-hadron, 1984)
Apply concept of soft-pomeron to hard scattering, **assuming:**

1) **$\mathbb{P}$ has a partonic structure,**
   like for real hadrons

2) **Regge factorisation,**
   $\mathbb{P}$ structure function
   factorizes from $\mathbb{P}$-flux:



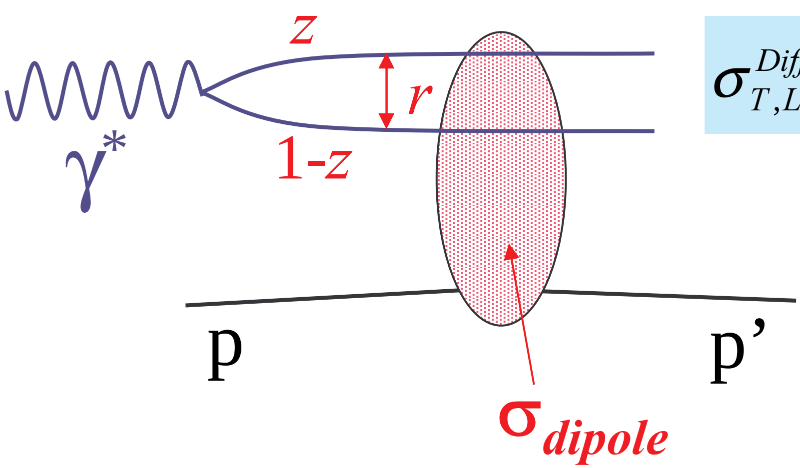
$$F_2^{D(4)}(\beta,Q^2,x_{\mathbb{P}},t) = \Phi_{\mathbb{P}/p}(x_{\mathbb{P}},t)\cdot F_2^{D(2)}(\beta,Q^2)$$

$\mathbb{P}$-flux factor: $(1/x_{\mathbb{P}})^{2\alpha_{\mathbb{P}}(t)-1}$ in Regge approach

diffractive structure function

Models for Hard Diffraction: the target frame

Physical picture of DIS most easily seen **in the proton rest frame:**
$\gamma^* \to q\bar{q}$ fluctuations (+$q\bar{q}g$, …).
At small-x, the lifetime $\tau_{osc} \approx 1/(xM_p)$ large, up to 1000 fm at HERA,
$\Rightarrow$**interaction between a colour-dipole** (the $q\bar{q}$ state) **and the proton:**



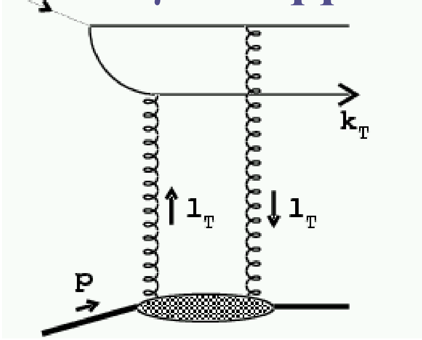
process indep.

$$\sigma_{T,L}^{Diffr}(x,Q^2) = \int d^2r dz \left|\Psi_{T,L}(r,z,Q^2)\right|^2 \cdot \sigma_{dipole}^2(x,r)$$

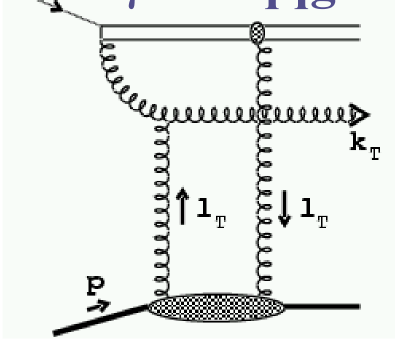
- $\Psi_{T,L}$ = $\gamma^*_{T,L} \to q\bar{q}$ wave function
- σ_{dipole} = dipole-proton cross-section
- $z = E_q/E_{\gamma^*}$
- r = transverse separation of $q\bar{q}$.

Diffraction: colour-singlet exchange
$\Rightarrow$ σ_{dipole} modelled at lowest order in pQCD by two gluon exchange.

$\gamma^* \to q\bar{q}$



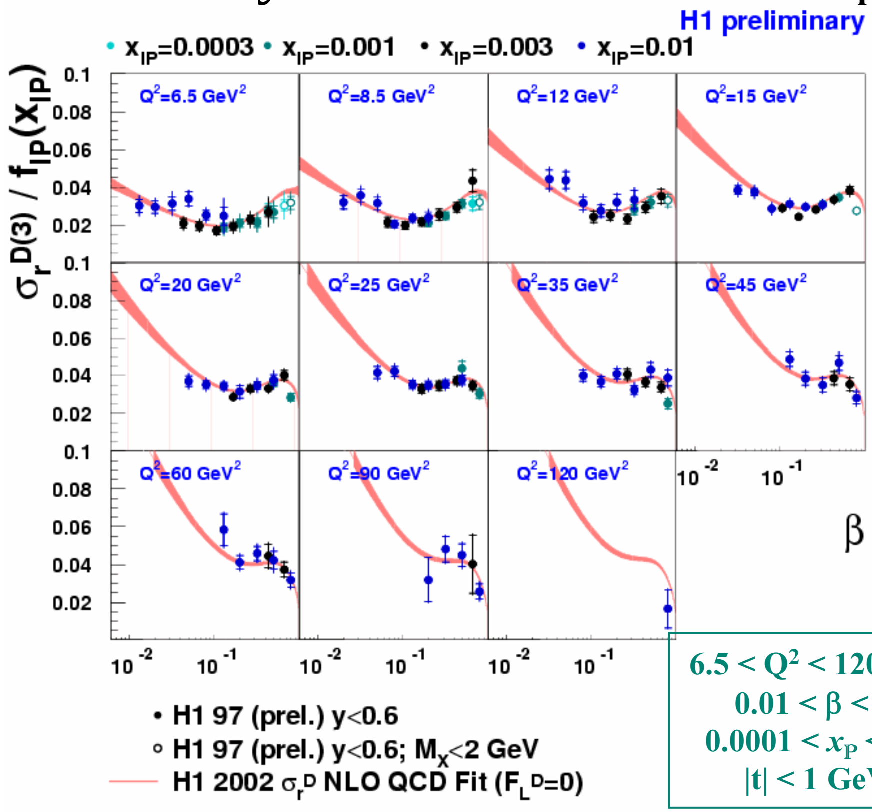
$\gamma^* \to q\bar{q}g$



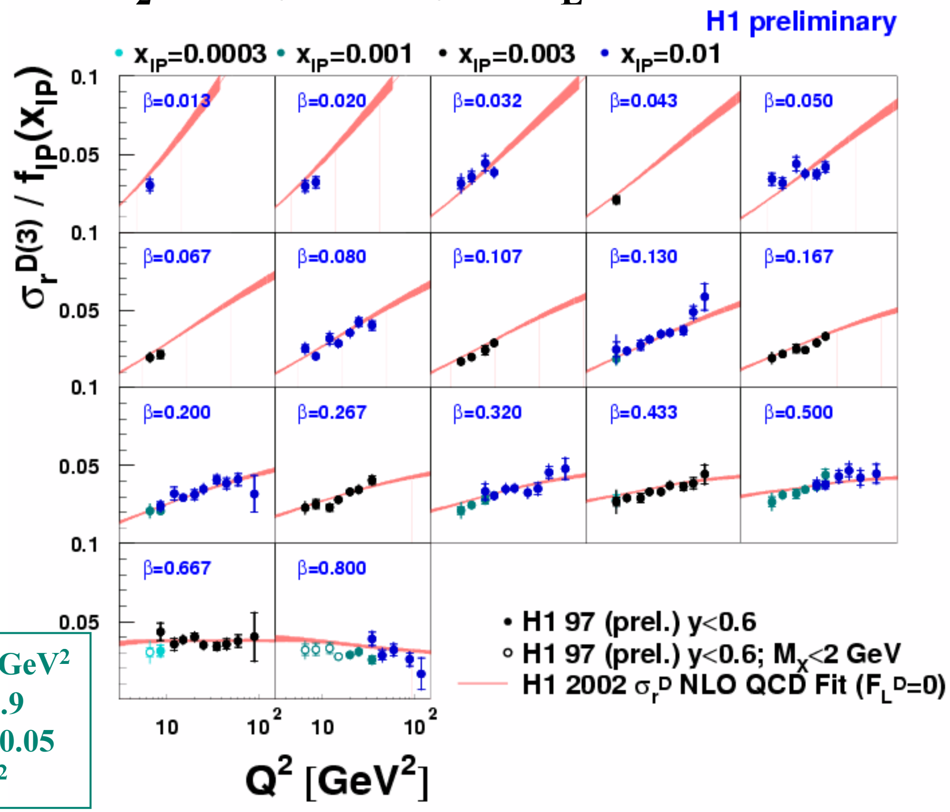
Inclusive measurements:
the diffractive
Structure Functions

Reduced diffractive cross section: $\sigma_r^{D(3)}$

Preliminary H1 measurement of $\boldsymbol{\sigma_r^{D(3)} = F_2^{D(3)}} - [y^2/(1+(1-y)^2)]\cdot \boldsymbol{F_L^{D(3)}}$:



$6.5 < Q^2 < 120$ GeV^2
$0.01 < \beta < 0.9$
$0.0001 < x_{\mathbb{P}} < 0.05$
$|t| < 1$ GeV^2

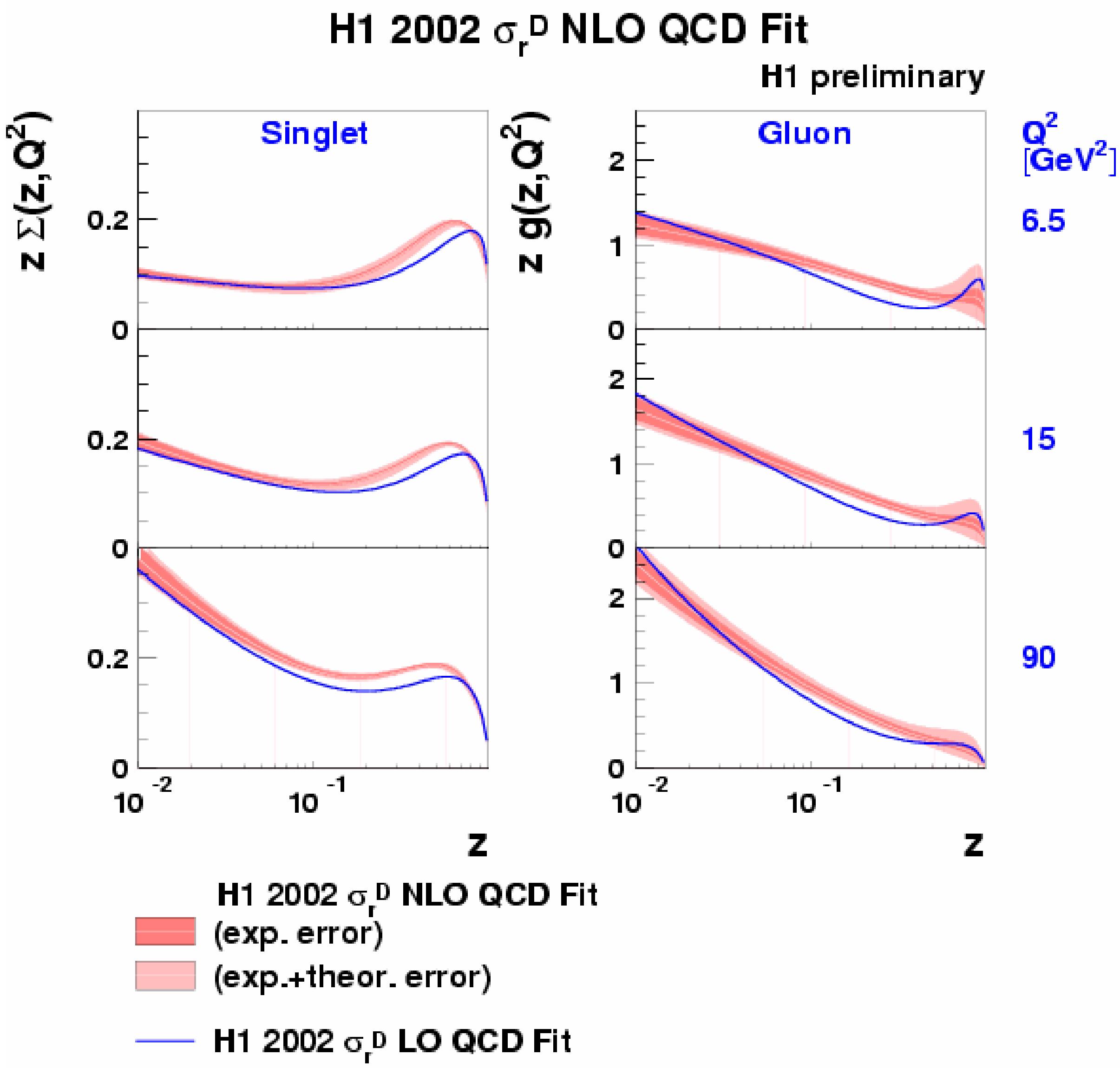


- data at different $x_{\mathbb{P}}$ show that factorising the $x_{\mathbb{P}}$ dependence is a good approximation.
- striking feature of data: strong scaling violations up to $\beta = 0.5$ ($x = 0.1$, for F_2) $\Rightarrow$ gluons!

Diffr. parton densities from NLO QCD fit

NLO QCD fit to σ_r^D
assuming
Regge factorization:

gluon density
much bigger than
quark density,
$\Downarrow$
diffractive exchange
mediated dominantly
by gluons

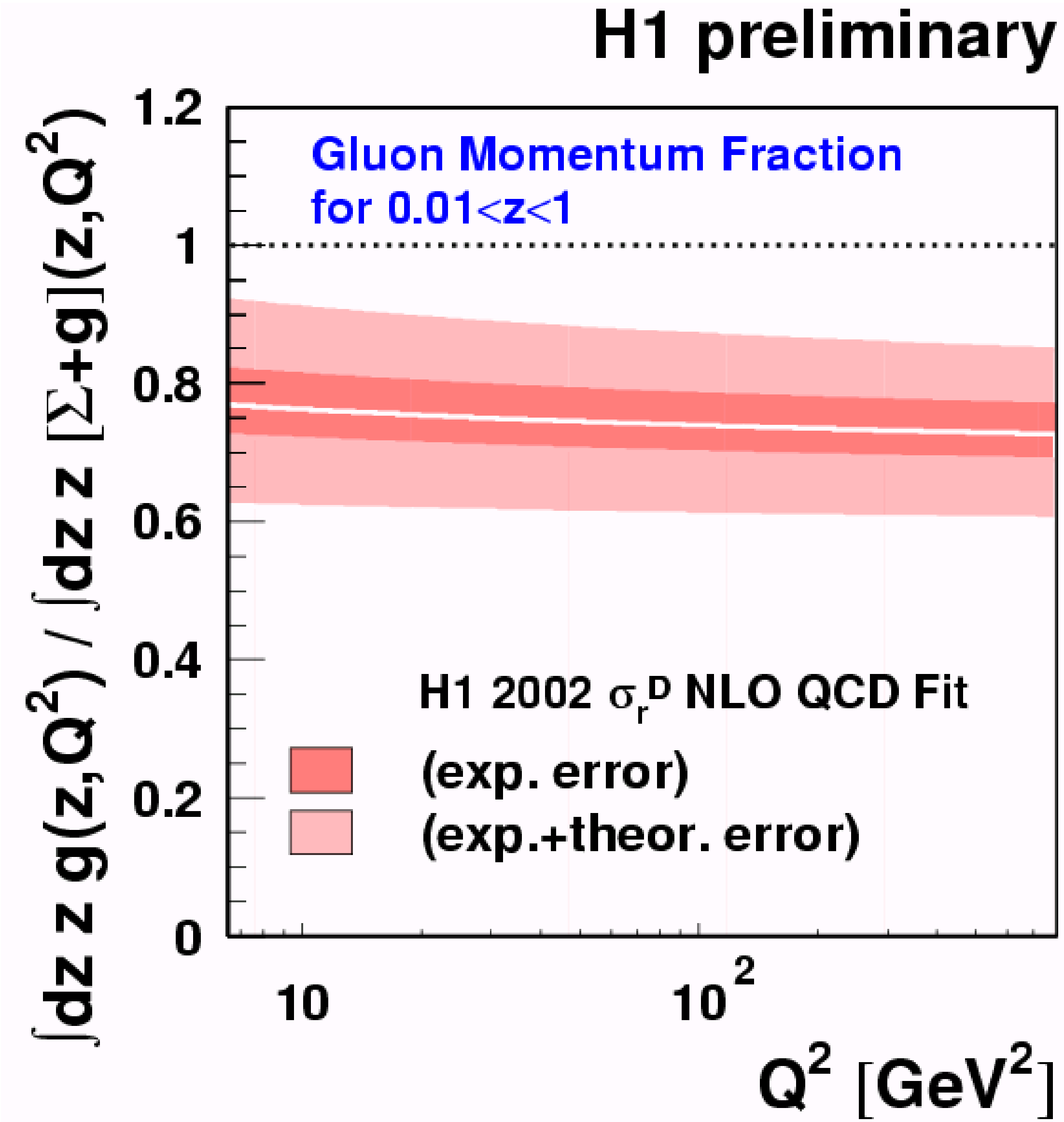


Gluon momentum fraction

Probability that
a gluon initiates the
diffractive scattering

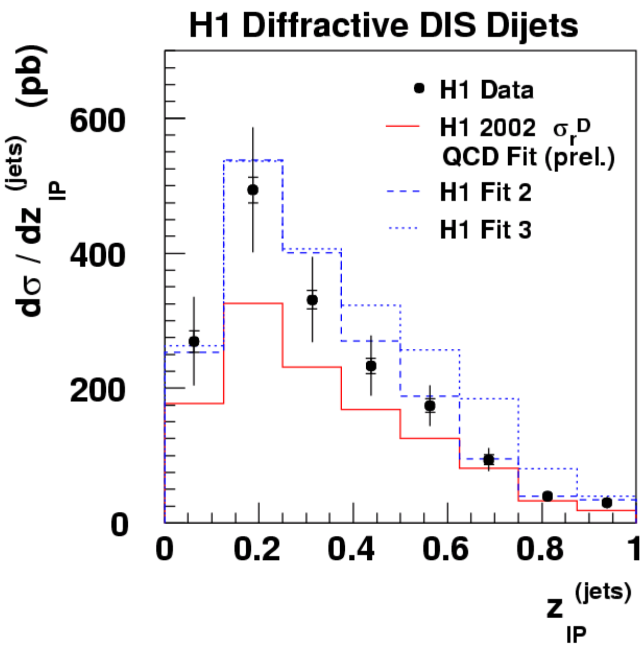
The diffractive exchange
is dominated by the
diffractive gluon density

which carries an integrated
fraction 75 ± 15 % of the
exchanged momentum



Diffractive PDF's applied to jets and charm

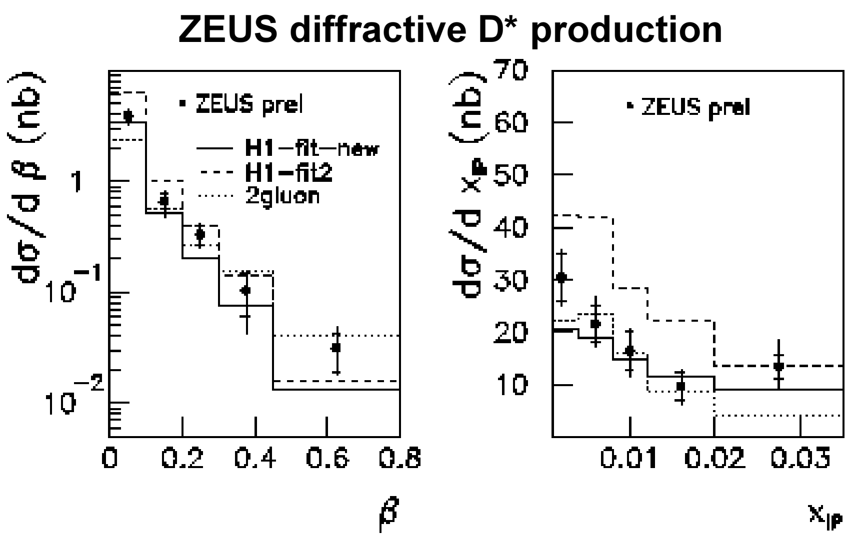
Test of QCD factorisation
(not Regge factorisation!):
apply DPD's to other processes.



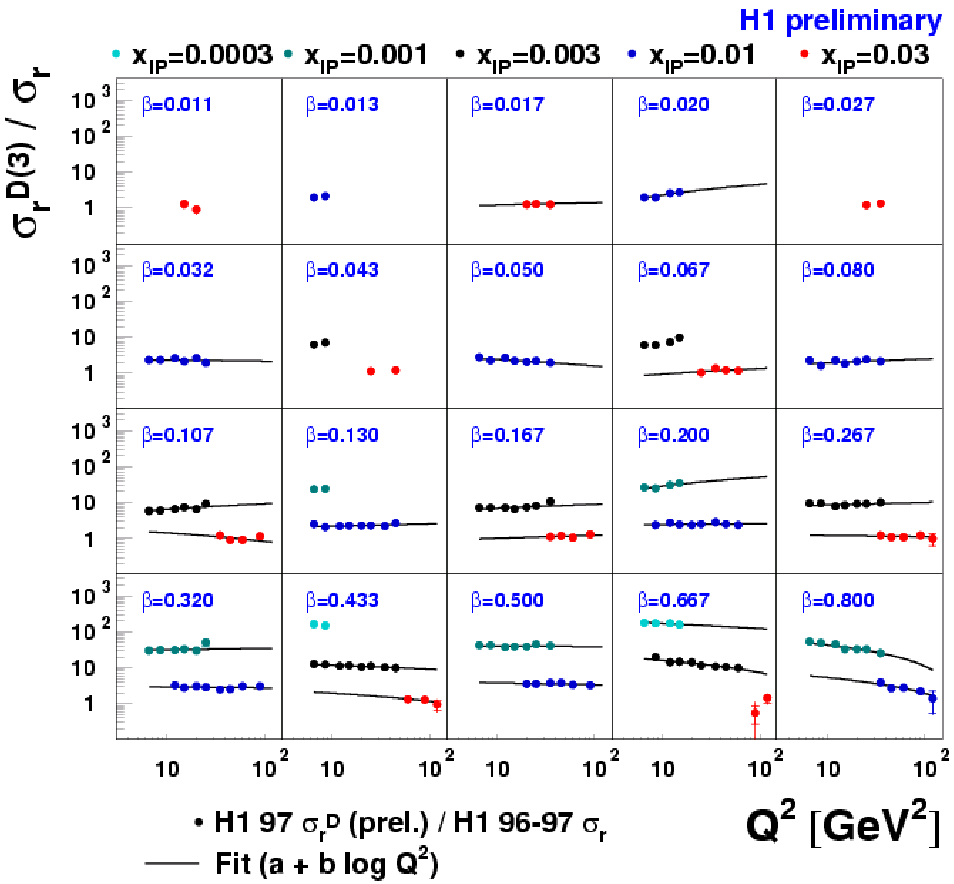
Dijets and **D*** production in diffractive DIS at HERA
(syst. errors on DPD's
not yet propagated):

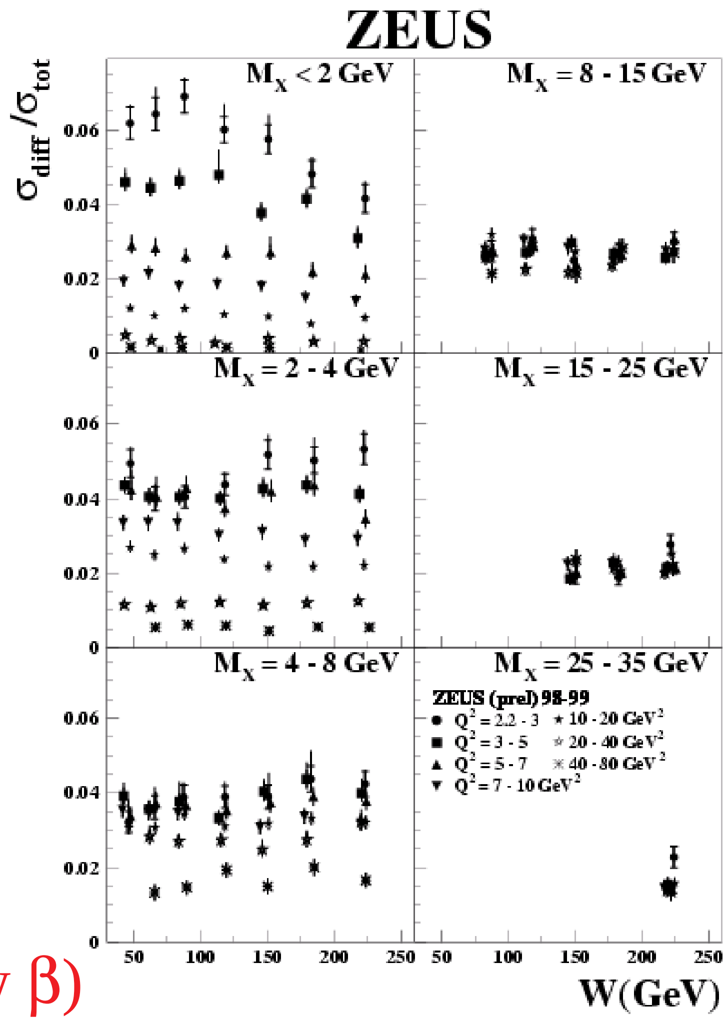
- shapes of distributions well described by predictions obtained with DPD's
- normalisations: ≈ ok

⇒ no evidence for breakdown of hard QCD factorisation



Cross section ratio: diffractive/total





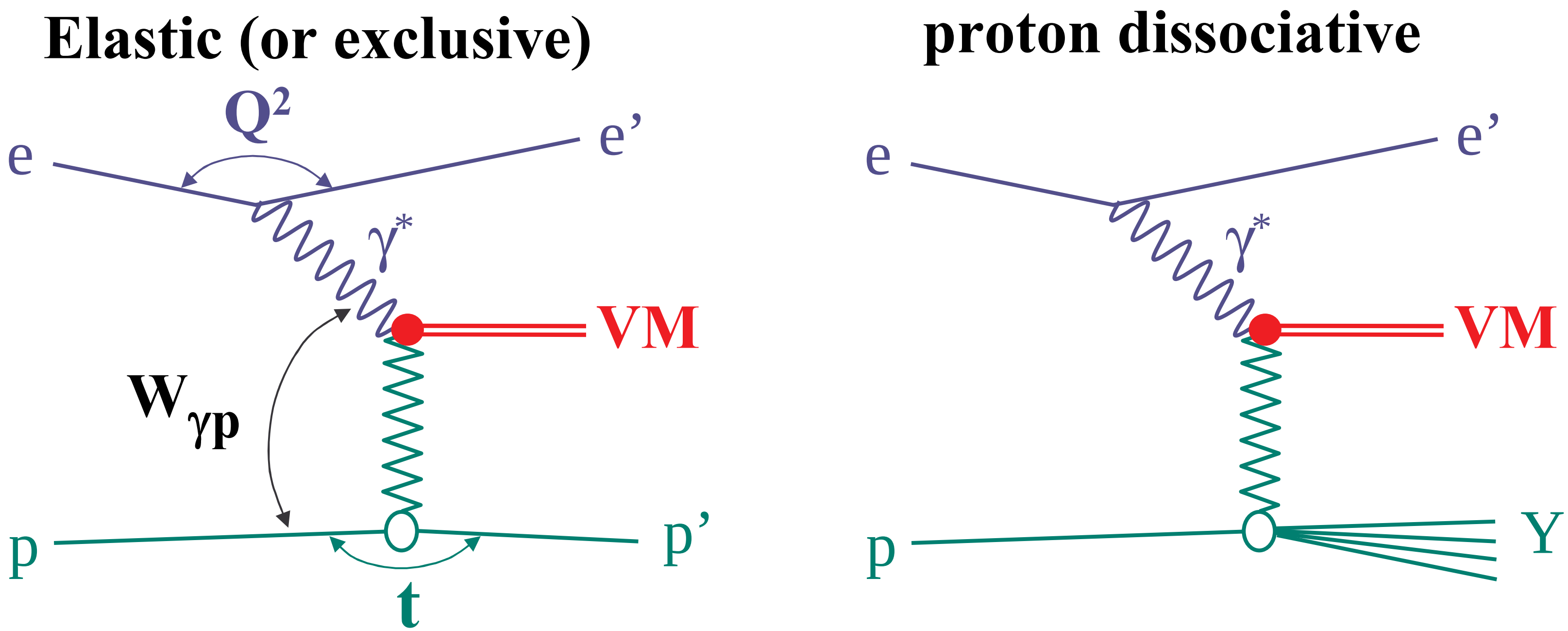
- little Q^2 dependence at high M_X (low β)
- flat in W

⇒ dynamics of diffractive DIS remarkably similar to inclusive DIS

Exclusive (or Elastic) production of Vector mesons

$$\gamma^{*}p \rightarrow VM\ p$$

Vector Mesons production at HERA



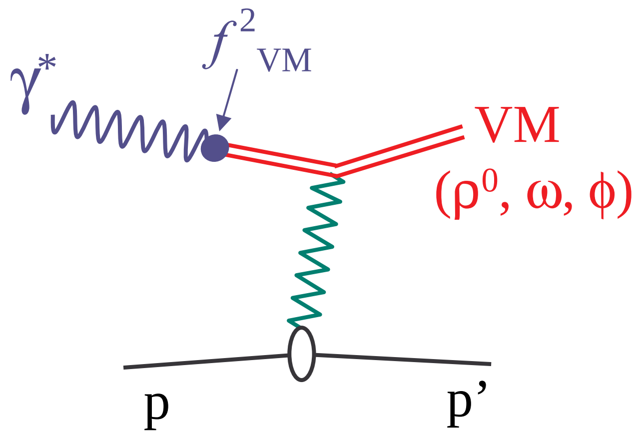
Experimentally: very clean processes in wide kinematic range

Q^2	γ^* virtuality	$0 < Q^2 < 100$ GeV^2
$W_{\gamma p}$	c.m. energy of γ^*p system	$20 < W_{\gamma p} < 290$ GeV
t	4-mom. transfer squared at p-vertex	$0 < \lvert t \rvert < 20$ GeV^2
VM	Vector Meson	$\rho^0, \omega, \phi, J/\psi, \psi', \Upsilon$

HERA ⇒ simultaneous control of different scales: Q^2, $|t|$, M^2_{VM}

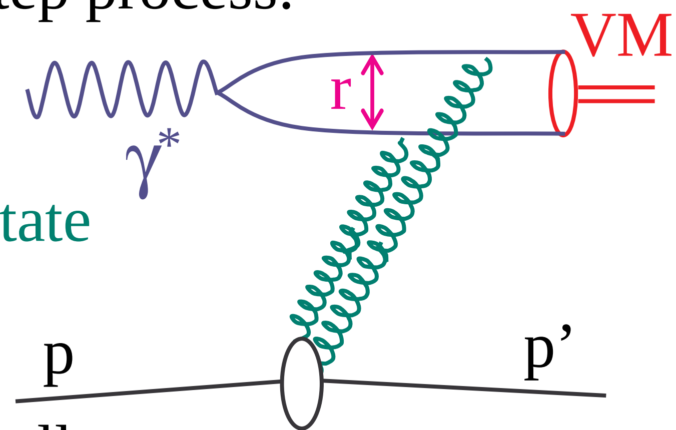
Models for Elastic VM production

Elastic Photoproduction ($Q^2 \sim 0$) of light Vector Mesons (VM) is a soft process.
No hard scale $\Rightarrow$
Vector Dominance Model × Regge theory:
γ^* fluctuates into VM before the interaction



A hard scale is often present at HERA $\Rightarrow$ perturbative QCD applicable
In the target frame, VM production is a 3-step process:

1. $\gamma^* \rightarrow q\bar{q}$ oscillation
2. $q\bar{q}$ scatters off the proton by two-gluon exchange (at lowest order) in colour singlet state
3. VM is formed (well after the interaction)



If dipole size: $\mathbf{r = 1/[z(1\text{-}z)Q^2 + m_q^2]^{1/2}}$ is small
(large m_q or γ^*_L at high Q^2) $\Rightarrow$ qq pair resolves gluons $\Rightarrow$ **pQCD**

Elastic VM: pQCD predictions

1. **Fast rise with energy, $W^{2(\alpha_{\mathbb{P}}(<t>)-1)}$:**

Gluon from F_2 scaling violations

$$\sigma_L \propto [{}^1/_{Q^6}] \cdot \alpha_s^2 (Q_{eff}^2) \cdot [xg(x,Q_{eff}^2)]^2 \approx [x^{-0.2}]^2 \approx W^{0.8} \quad (x \approx 1/W^2)$$

2. **Universality of t-dependence: $e^{-b_{2g}|t|}$,**

$$\Rightarrow b_{2g} \sim 4\ \mathrm{GeV}^{-2} \text{ independent of W} \Rightarrow \alpha'_{\mathbb{P}} = 0$$

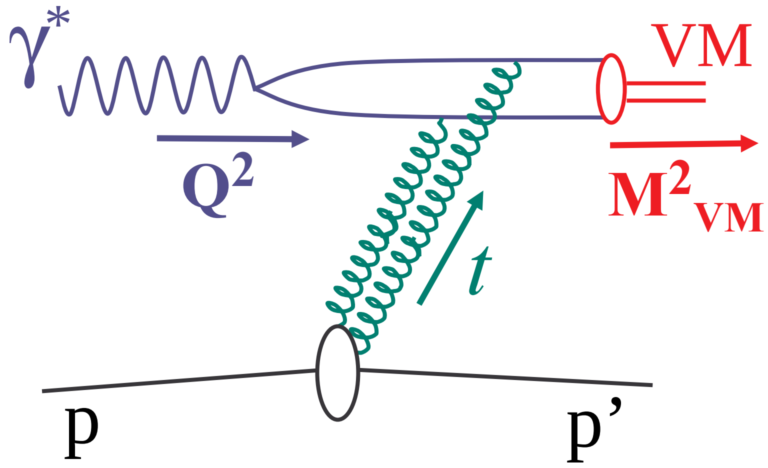
Questions:

- **Do these pQCD-based models describe HERA VM data?**
- **At which scale Q_{eff}^2 should xg be evaluated?**

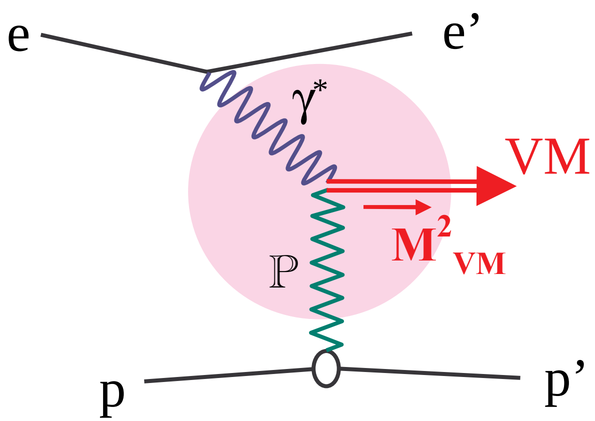
  i.e. which (or which combination) of Q^2, M_{VM}^2 and $|t|$ is the scale of the process?

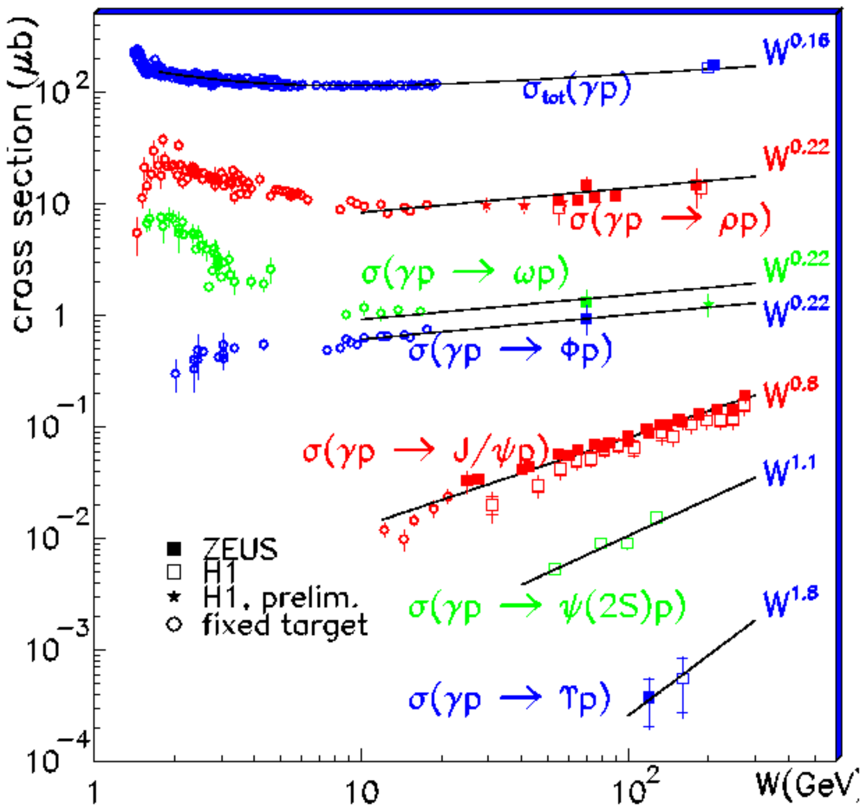
  For example, in Ryskin model

  $$Q^2_{eff} = ¼ \cdot (Q^2 + M_{VM}^2 + |t|)$$



Elastic VM in photoproduction ($Q^2 = 0$)





Fit $\sigma^{el} \propto W^{\delta}$ $(\delta \approx 2(\alpha_{\mathbb{P}}(<t>))$ gives:

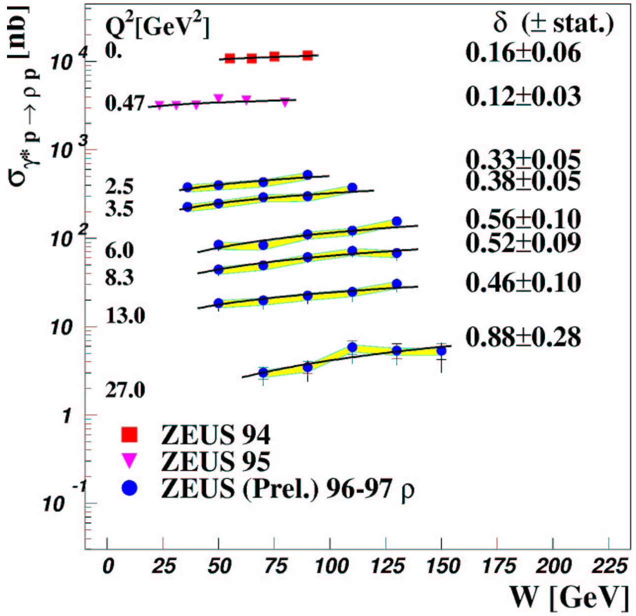
$\delta \approx 0.22$ **"soft" W-dep. for ρ^0, ω, ϕ**

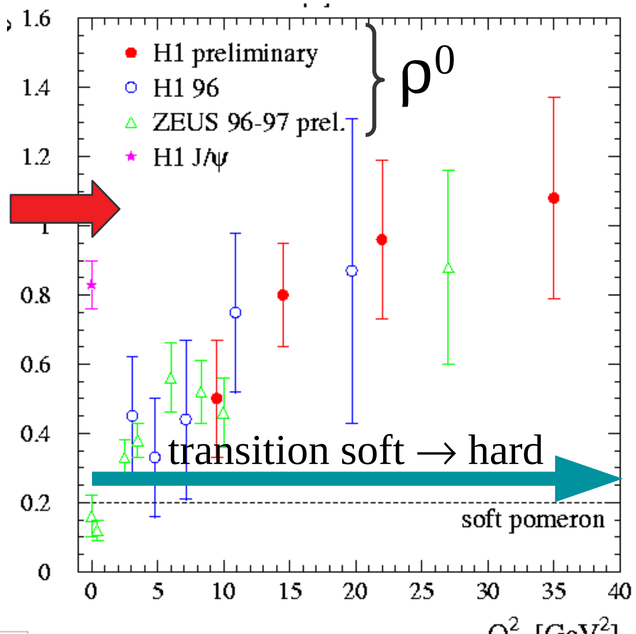
$\delta \approx 0.8$ **"hard" W-dep. for J/Ψ**

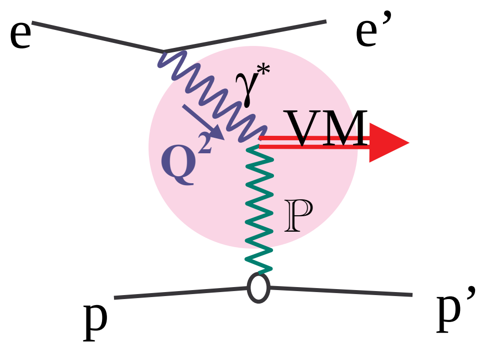
J/Ψ described by pQCD models
if steep gluon from fits to
F_2 scaling violations are used:

⇒the VM mass is a
scale for the hard process

W-dependence of elastic VM in bins of Q^2



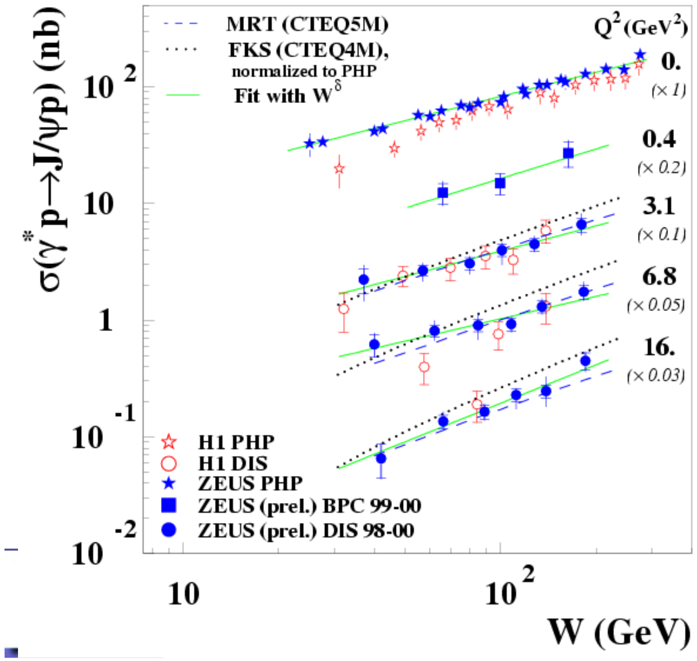


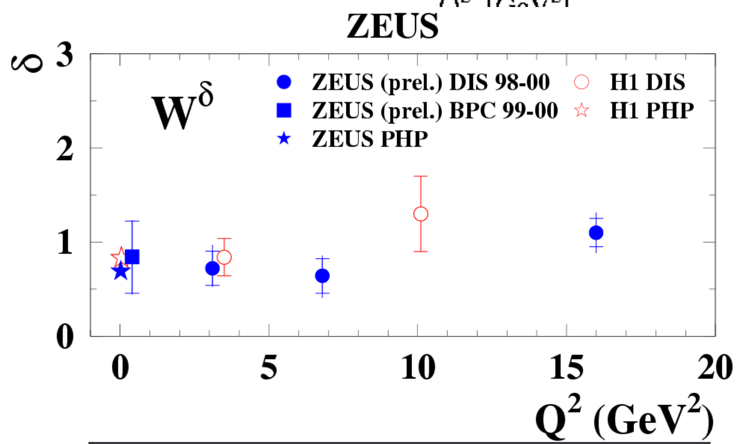


W dep. steepens vs. Q^2

$\Rightarrow$ soft $\rightarrow$ hard regime

(like for $M_{J/\psi}$)



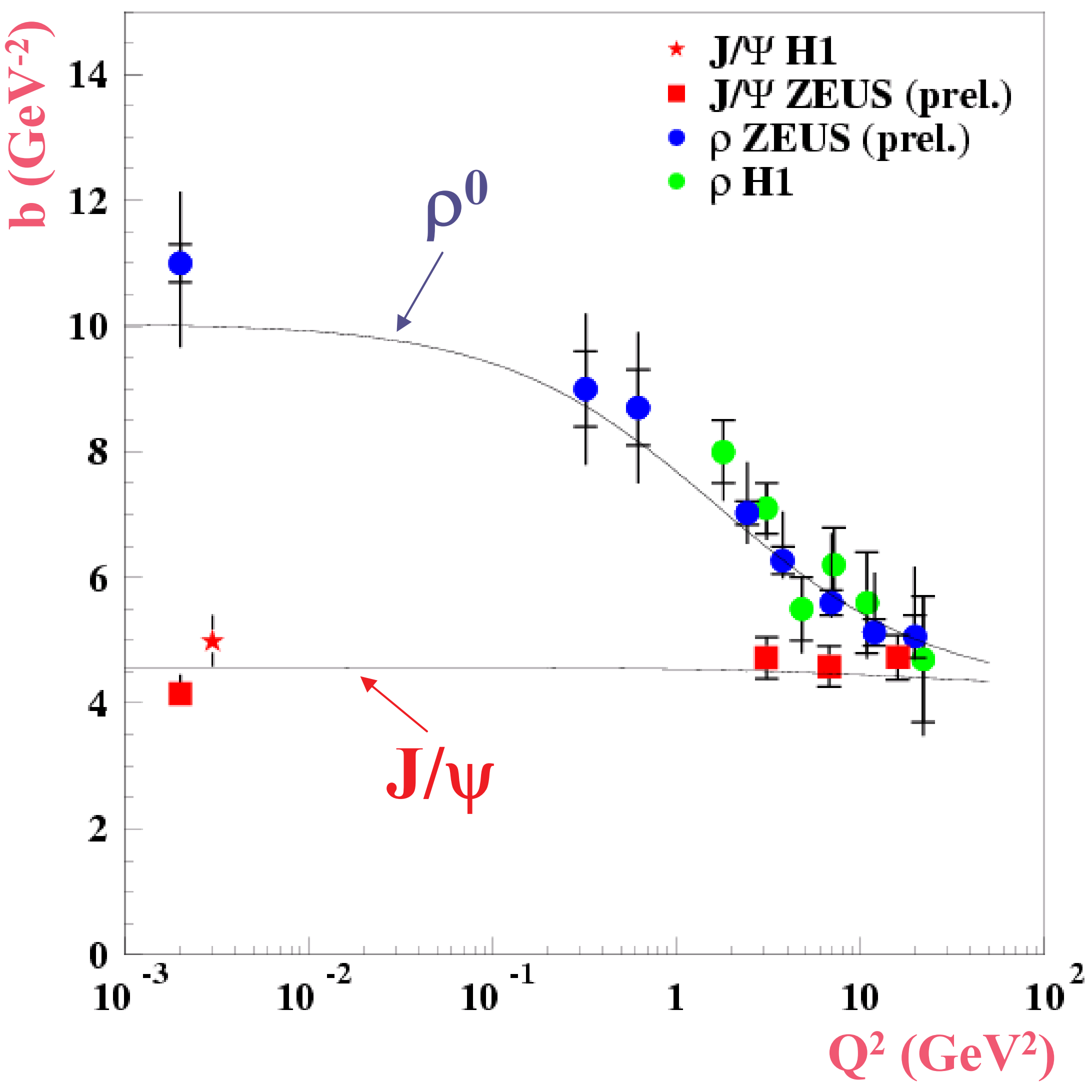


J/ψ already steep at $Q^2 = 0$

Fit ρ^0 and J/ψ elastic cross sections with W^δ:

$\Rightarrow Q^2$ is a scale for the hard process

Size of ρ^0 and J/Ψ mesons



$d\sigma/d|t| \propto e^{-\mathbf{b}\cdot|t|}$

the |t| distribution slope, b, is the Fourier transform of the spatial extension of the VM

Size of ρ^0 shrinks with Q^2, while J/ψ is small already at small Q^2

$\Downarrow$

universal |t| depencence

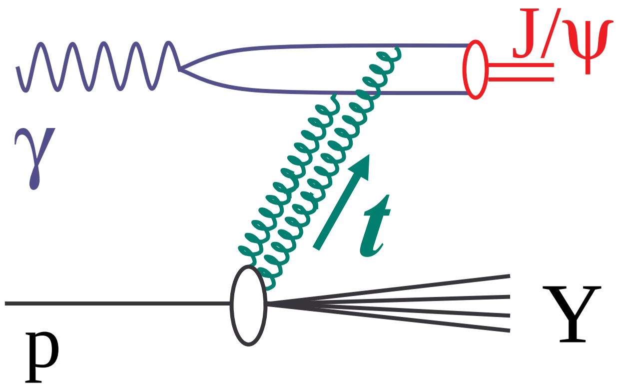
if the scale (Q^2 or M^2) is large

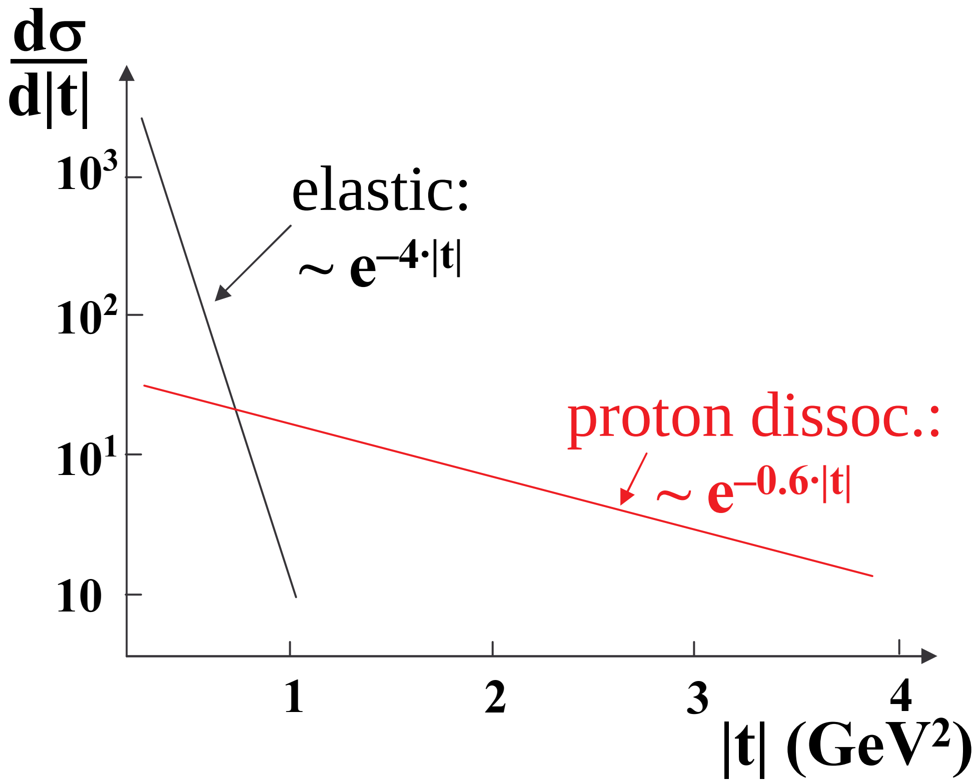
Photoprod. of proton-dissoc. VM at high |t|

High-|t| domain: little explored so far.

At high-|t|, proton dissociative production dominates. Example:

$\gamma^* p \rightarrow J/\psi Y$ at $Q^2 \sim 0$





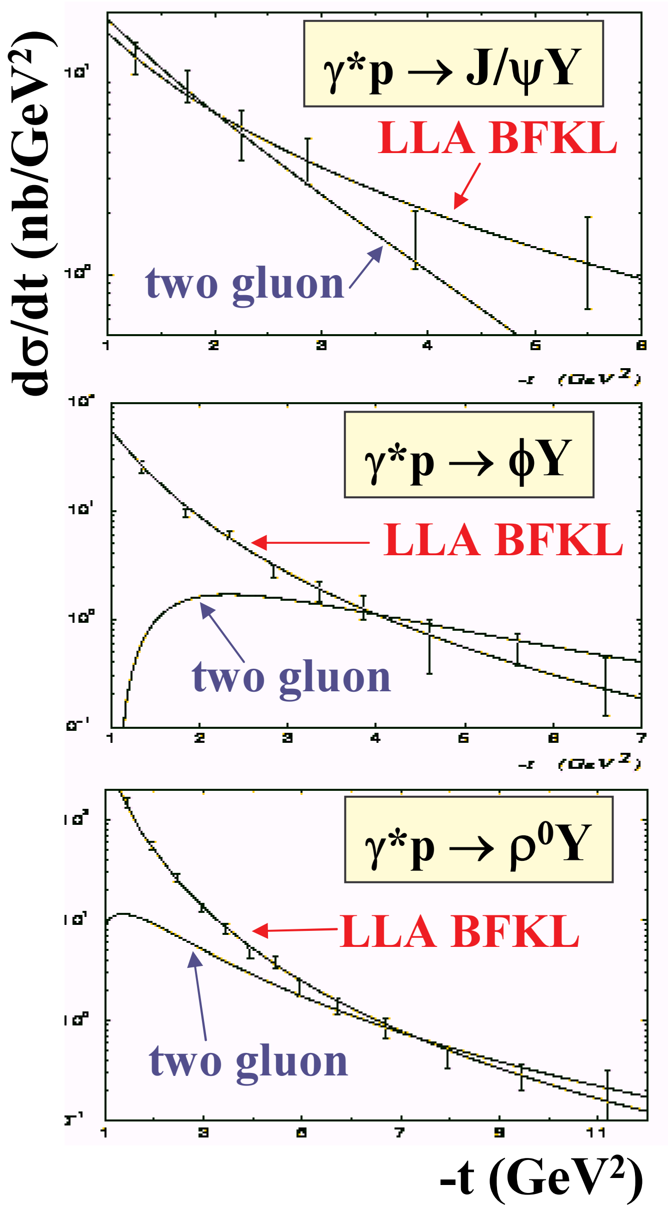
⇒ study proton dissociation to investigate high-|t| dynamics

Photoprod. of proton-dissoc. VM at high |t|

Dependence at large |t|:

- $d\sigma_{\gamma p \to VY} / d|t| \propto |t|^{-n}$ (not exponential)

$\Rightarrow$ indication that **large |t| may provide a hard scale to apply perturbative QCD**



Recently, Forshaw and Poludniowski fitted the ZEUS data for p-dissociative photoproduction of ρ^0, ϕ and J/ψ mesons:

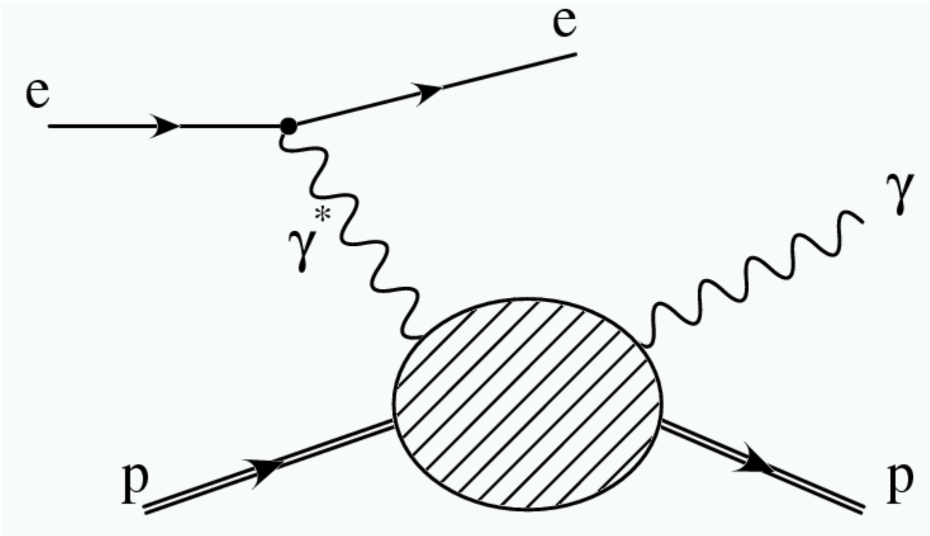
- BFKL LLA approach: consistent with data
- two-gluon-exchange approach at LO: inadequate

"Smoking gun for BFKL?"

Deeply Virtual Compton Scattering (DVCS)

Deeply Virtual Compton Scattering (DVCS)

is the diffractive production of real-γ in DIS: $ep \to ep\gamma$ ($\gamma^*p \to \gamma p$)

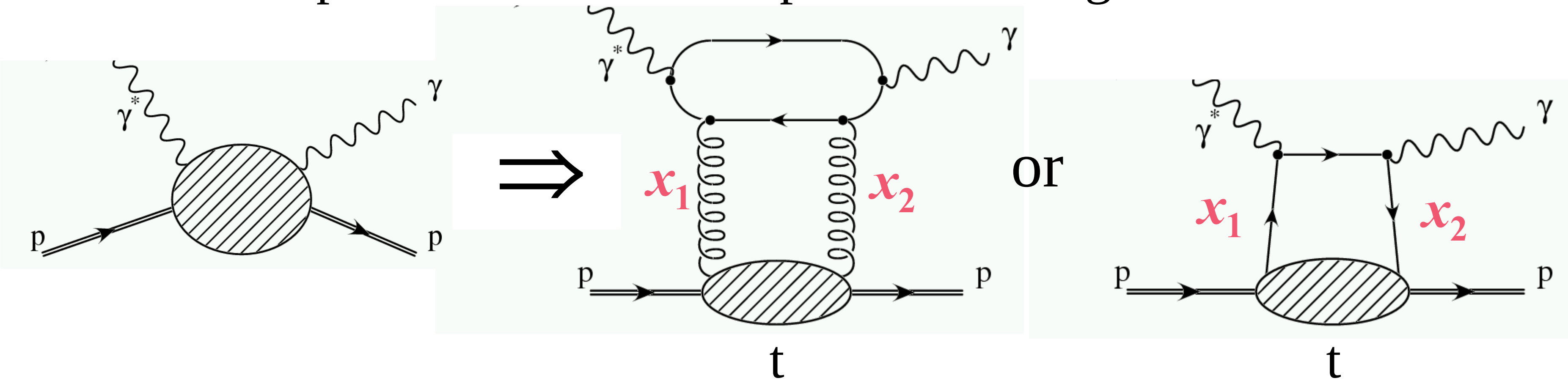


Similar to elastic VM production, but γ, instead of VM, in final state

- theoretically pure: no VM wave-function (non-pert.) involved
- particularly interesting, since it gives access to:
  - $\mathrm{Re}(\mathcal{M}_{\gamma^*p \to \gamma p})$
  - **Skewed Parton Distributions (SPD)** which are fundamental quantities for <u>exclusive processes</u> in QCD

Skewed Parton Distributions

The DVCS process is also a two-parton exchange



- usual parton distributions are diagonal: $x_1 \equiv x_2 \Rightarrow \mathrm{p} = \mathrm{p}' \Rightarrow \mathbf{t = 0}$
- Skewed Parton Distributions are <u>non-diagonal</u>:

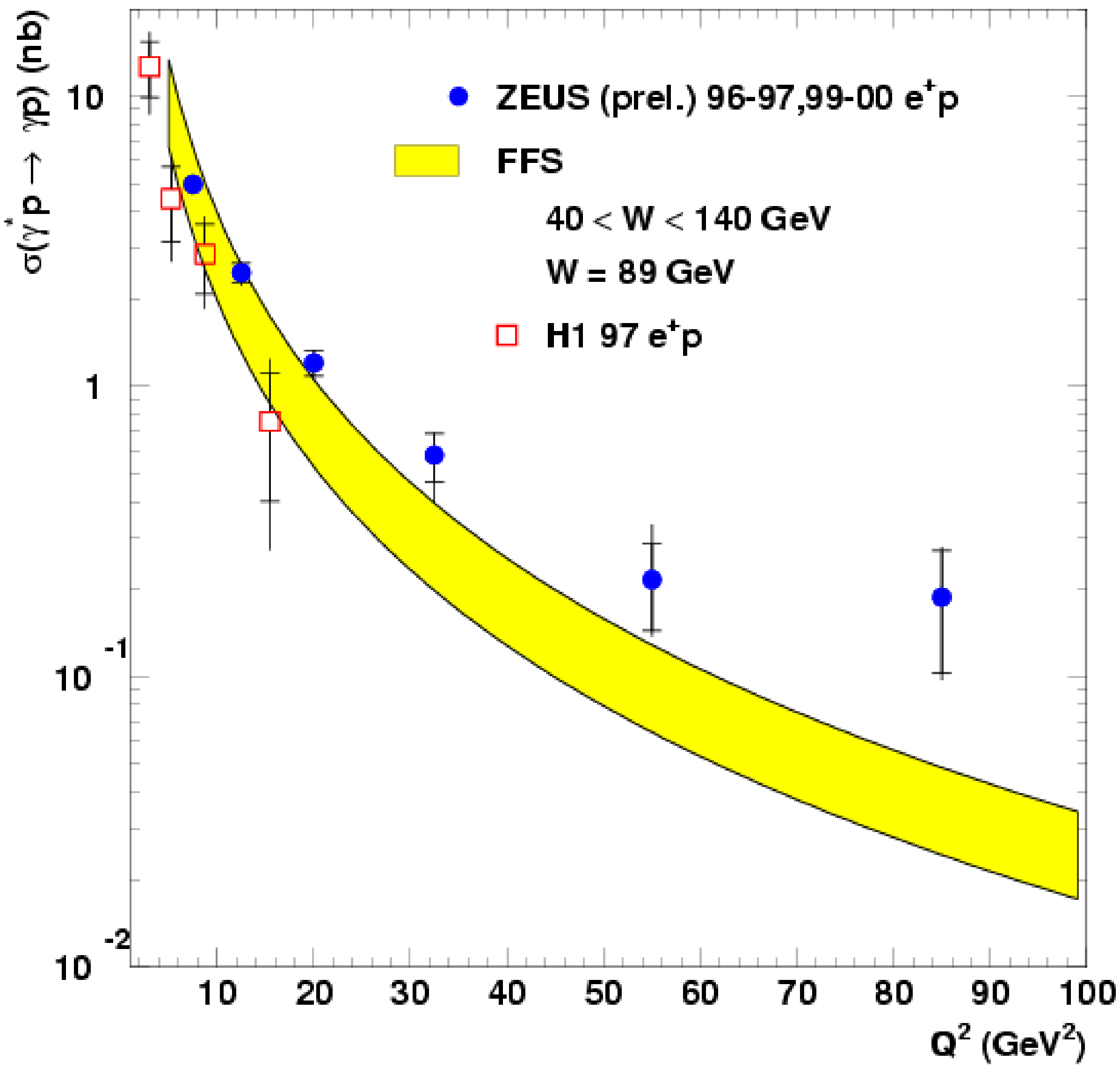
$$x_1 \neq x_2 \; (x_1 - x_2 = x) \Rightarrow \mathrm{p} \neq \mathrm{p}' \Rightarrow \textbf{allow } \mathbf{t \neq 0}$$

Very useful concept since they account for:

- parton k_T (in addition to long. momenta)
- two-particle correlations in the proton

Notice: most of the data shown above are at small-|t|, where the SPD can be approximated by the conventional parton distributions

Q^2 dependence of DVCS

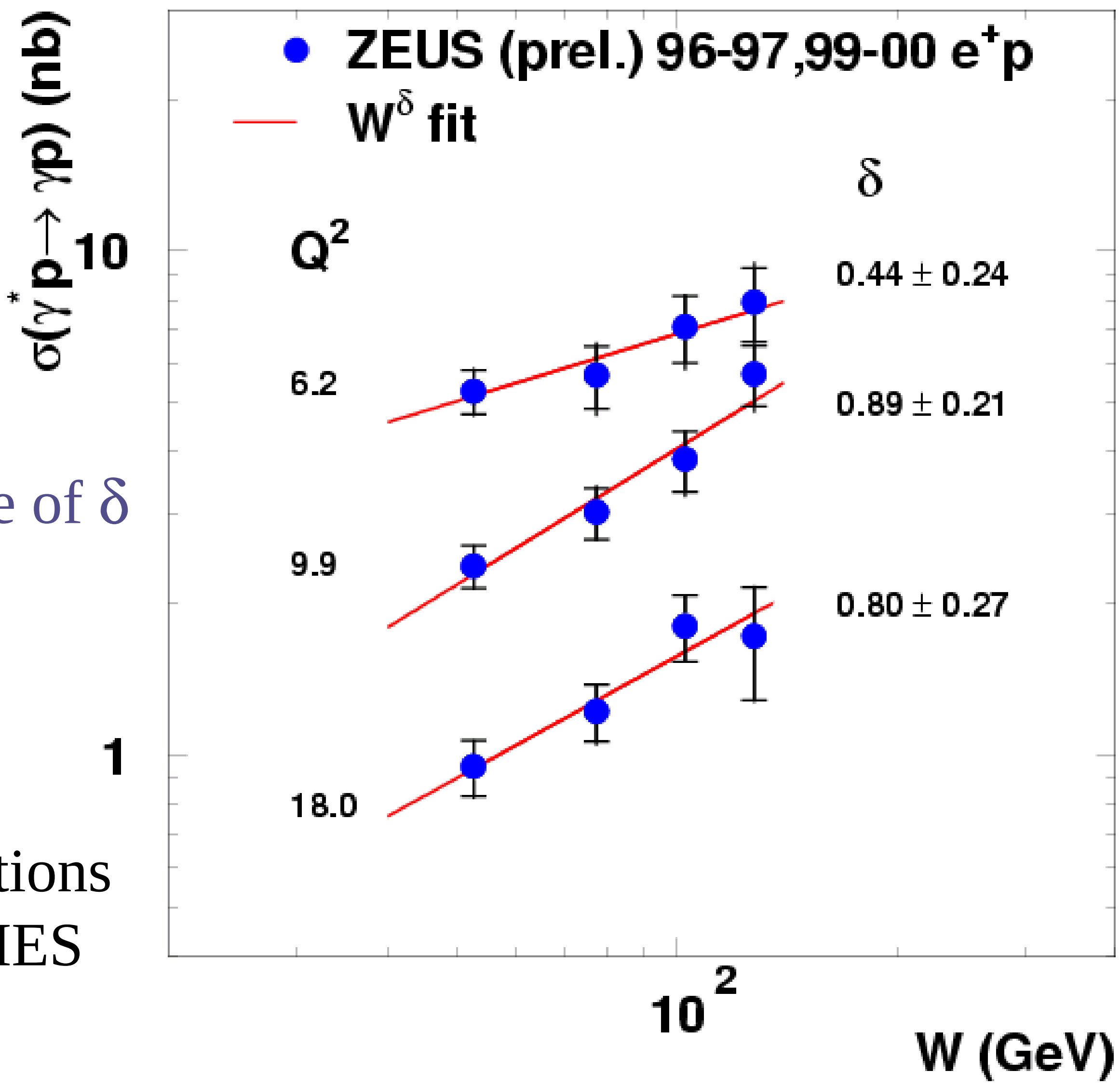


W dependence of DVCS

δ larger than ~ 0.2
$\Rightarrow$ hard process

Hint for a Q^2 dependence of δ

Promising for future extraction of generalised (skewed) parton distributions in H1, ZEUS and HERMES



Conclusions

- **Inclusive diffraction:**
  - scaling violations up to $\beta = 0.5 \Rightarrow$ gluons initiate (75 ± 15) % of diffraction
  - DPD's extracted in inclusive diffr. can be applied to dijets and charm
  - **dynamics of diffraction remarkably similar to that of inclusive DIS**

- **Vector mesons:**
  - Q^2, the VM mass and $|t|$ provide a hard scale to apply pQCD
  - size of ρ^0 meson at large Q^2 similar to $J/\psi \Rightarrow$ **universal $|t|$ depencence**

- **Deeply virtual Compton scattering:**
  - **reaction measured**; described by pQCD
  - promising for extraction of generalised (skewed) parton densities

In general, **pQCD does a good job**