LISHEP 2006

International School on High Energy Physics

Workshop on Collider Physics, April 2-7

Semi-exclusive and exclusive diffraction in ep scattering

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on behalf of the H1 and ZEUS Collaborations

OUTLINE

- **Hard diffraction in QCD**
- **Diffractive final states (jets, charm)**
- **Exclusive processes, Vector Mesons and Deeply Virtual Compton Scattering**

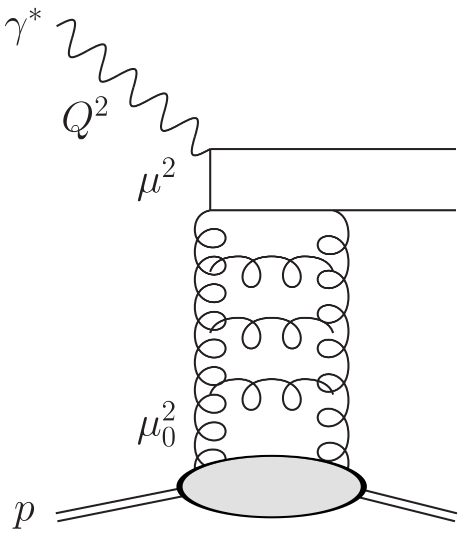
Hard diffraction in QCD

Diffr. processes with one or several large scales are called hard

Hard diffraction is the interplay of systems with small size configurations (quark and gluons) and large size configurations (set by the size of the protons)

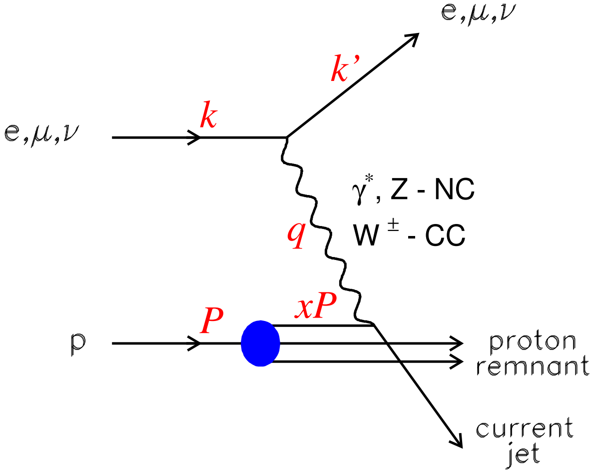
Application of pQCD relies on the ability to separate small (hard) from large configurations (soft)

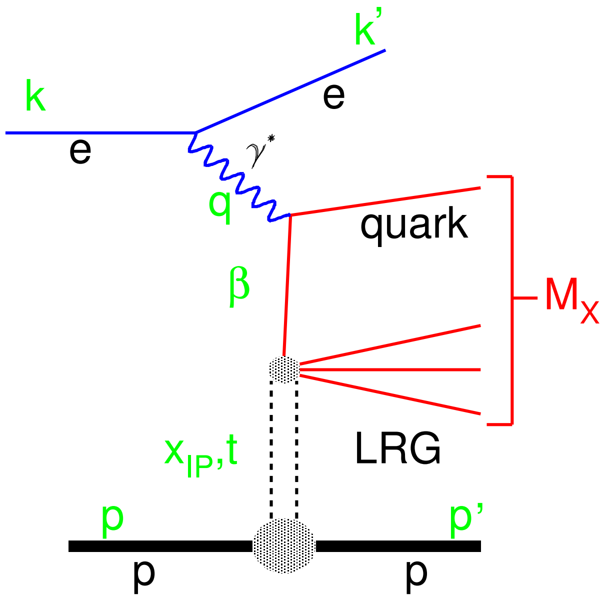
Hard diffraction is a laboratory for QCD studies:



- dynamics of hard processes
- wave function of hadrons, i.e. VM
- evolution equations in gluon ladders, i.e. look for violation of DGLAP
- the structure of the proton, Generalized Parton Distributions

Kinematic variables





DIS

Q^2	virtuality of exchanged boson
W	photon-proton centre of mass energy
x	Bjorken variable
	fraction of proton's momentum carried by struck quark
y	γ inelasticity $= Q^2/sx$

Diffractive DIS

$x_{I\!P}$	fraction of proton's momentum of colour singlet exchange
	$= \frac{q\cdot(p-p')}{q\cdot p} \simeq \frac{Q^2+M_X^2}{Q^2+W^2}$
β	fraction of Pomeron's momentum carried by quark coupling
	to $\gamma^* = \frac{Q^2}{2q\cdot(p-p')} \simeq \frac{Q^2}{Q^2+M_X^2} = x/x_{I\!P}$
t	$= (p-p')^2$, 4-momentum transfer squared at p-vertex

QCD Factorization theorem

Breit rest frame (fast proton)

DIS

$$F_2(x,Q^2) = \sum_i \int dz\, f_i(z,Q^2) \quad \hat{F}_i(x,Q^2)$$

parton density (universal, DGLAP)

hard scattering (pQCD)

Diffractive DIS

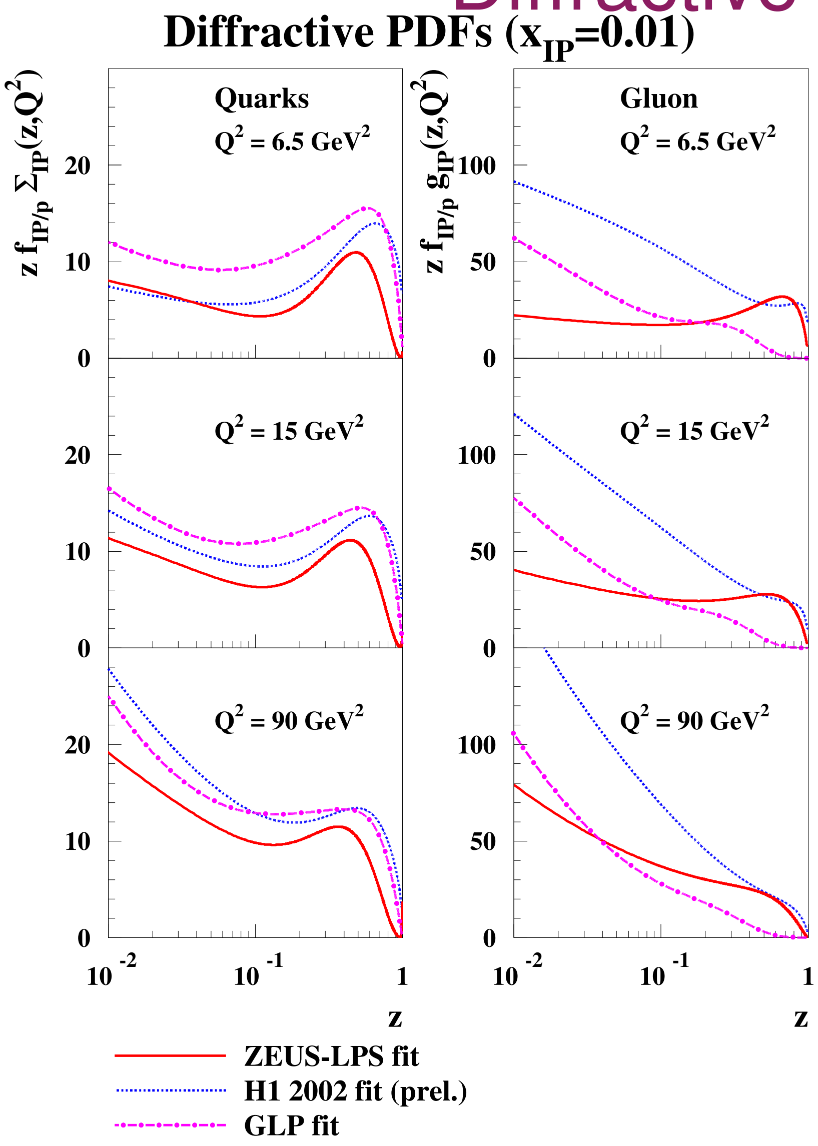
$$F_2^{D(4)} = \frac{d^2F_2^D(x_{\mathbb{P}},t,x,Q^2)}{dx_{\mathbb{P}}\,dt} = \sum_i \int dz \frac{d^2 f^D_{i/p}(x_{\mathbb{P}},t,z,\mu^2)}{dx_{\mathbb{P}}\,dt} \quad \hat{F}_i(\frac{x}{z},\frac{Q^2}{\mu^2})$$

Diffractive PDF

same as F_2

- Factorization proved for DDIS and exclusive hard diffraction (Collins, Berera &Soper, Trentadue & Veneziano)
- Not true for diffr. hadron-hadron collisions

Diffractive parton distributions



- Additional assumption: Regge factorization (Ingelman & Schlein)

$$\frac{d^2 F_2^D(x_{I\!P},t,x,Q^2)}{dx_{I\!P}\,dt} = f_{I\!P/p}(x_{I\!P},t) F_2^{I\!P}(\beta,Q^2)$$

- NLO DGLAP fits:

Parametrise Flavour Singlet (q, $\bar{q}$) and Gluons at $Q^2 = 3\ \mathrm{GeV}^{-2}$

Evolve with NLO DGLAP and fit

- Gluon dominated

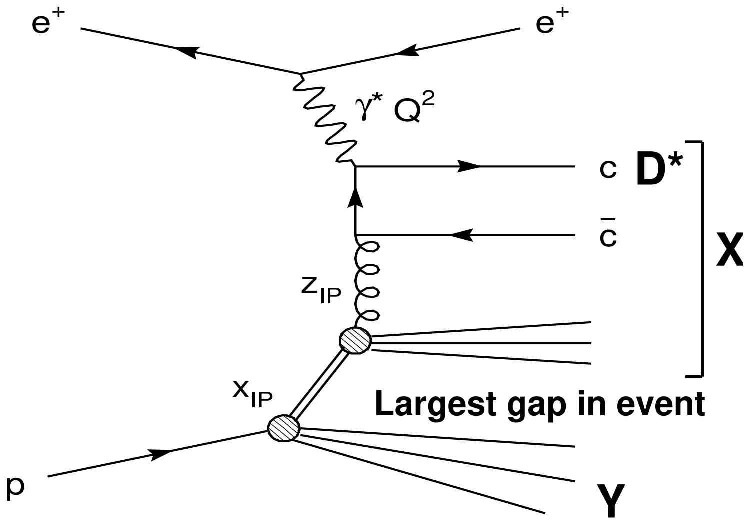
- Large discrepancy between different diffractive PDFs, due to different Q^2 distributions of data sets, $\rightarrow$ careful comparison of data ongoing

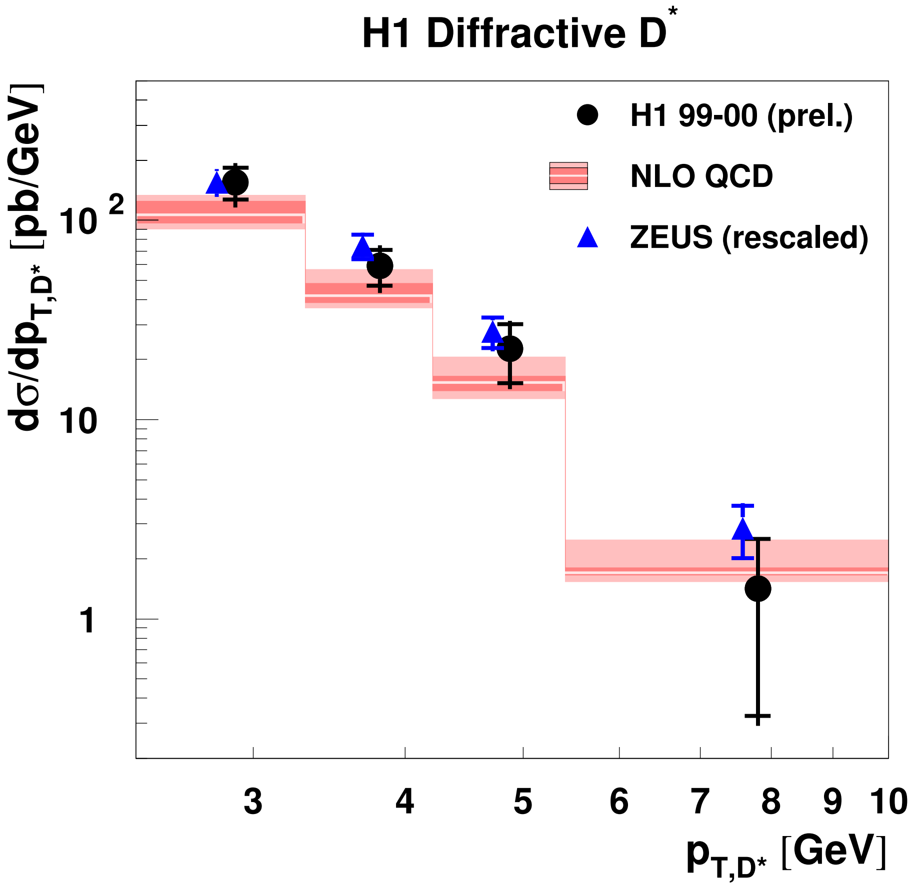
- In the following slides, H1 2002 diffractive PDFs will be used as reference

z = fractional momentum of parton

Factorization tests: D* in DIS

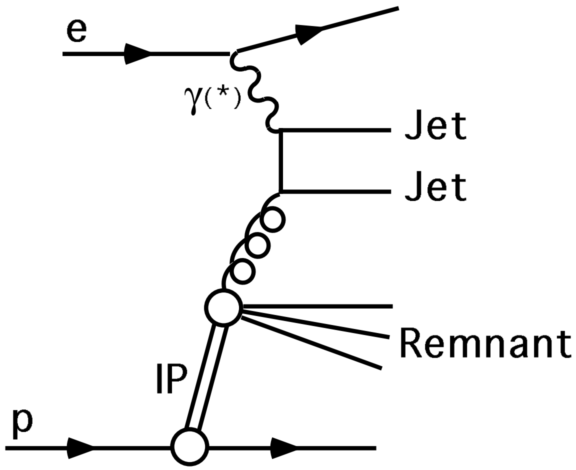
• Use Diffractive PDFs from NLO DGLAP fits of F_2^D to predict rate of charm production, ie. use H1 2002 fit as reference

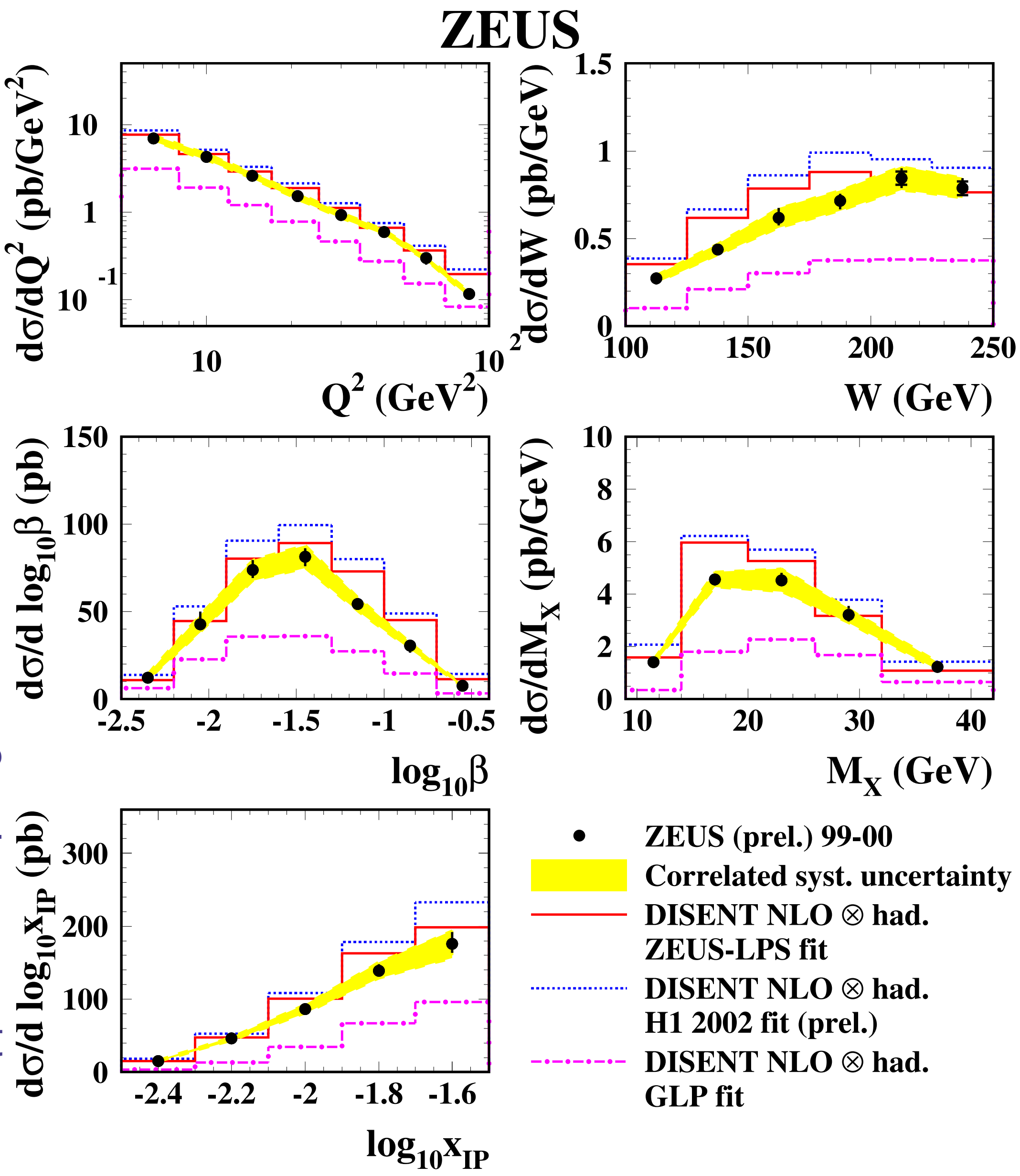




• NLO calc. + diffractive PDFs H1 2002 describe data
$\Rightarrow$ Assuming this dPDFs, QCD factorization works

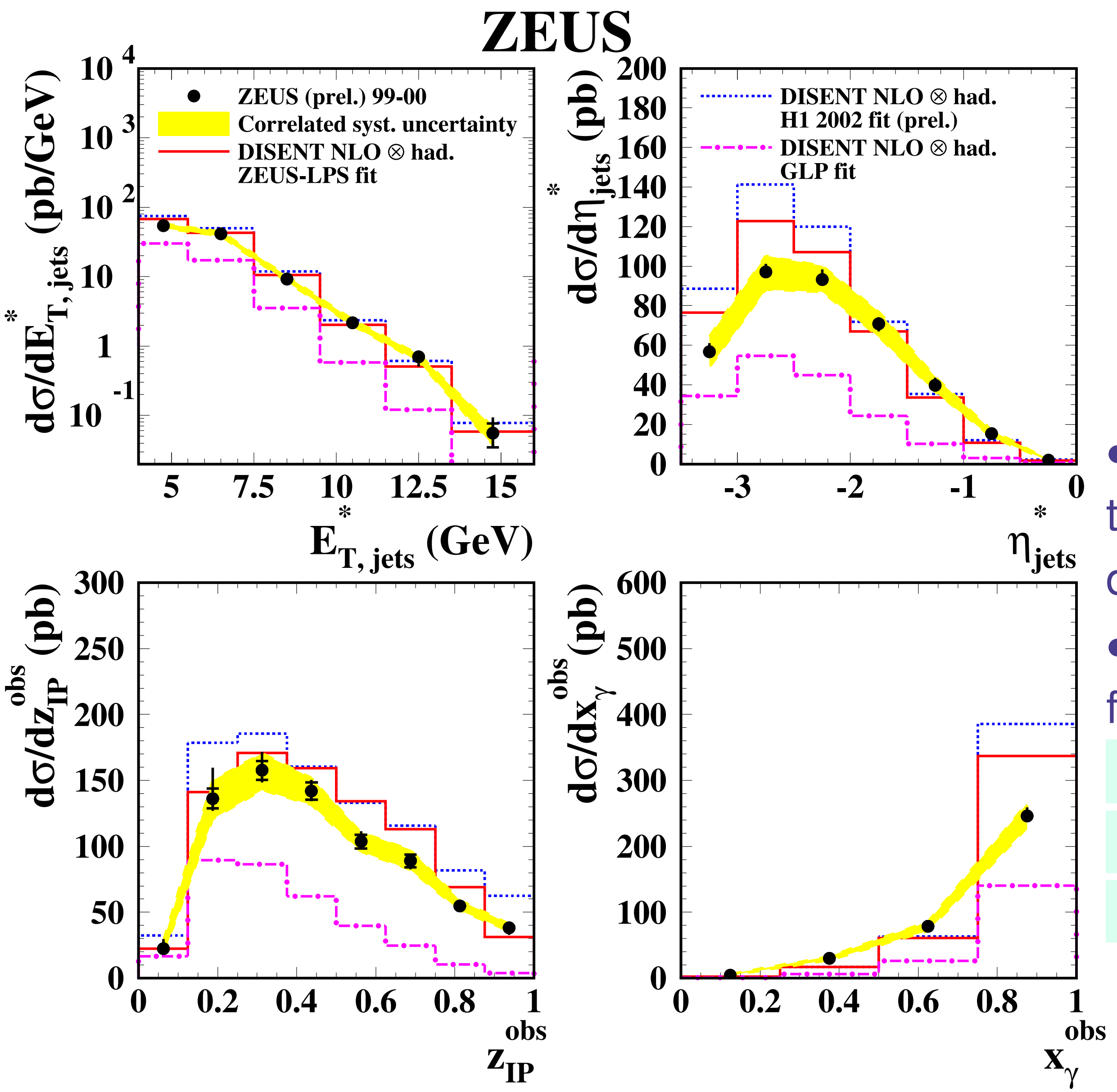
Factorization tests: dijet in DIS





Use diffractive PDFs from NLO DGLAP fits of F_2^D to predict rate of dijet production

- Shape reproduced by NLO
- Large discrepancy between different diffractive PDFs



Factorization tests: dijet in DIS

- NLO predictions using diffractive PDFs H1 fit 2002 are above data
- Large discrepancy between different diffractive PDFs

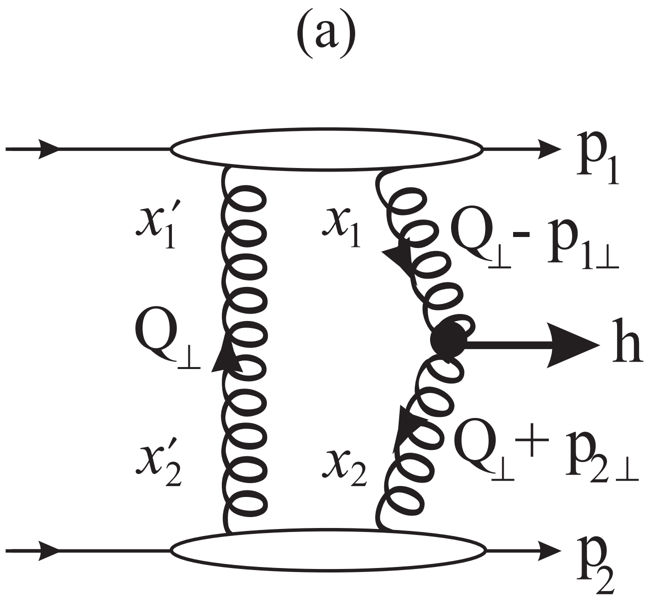
Fact. holds in DIS?

Need more work on DPDFs

to make conclusions

Factorization not expected to hold for pp

- Interest for light Higgs at LHC

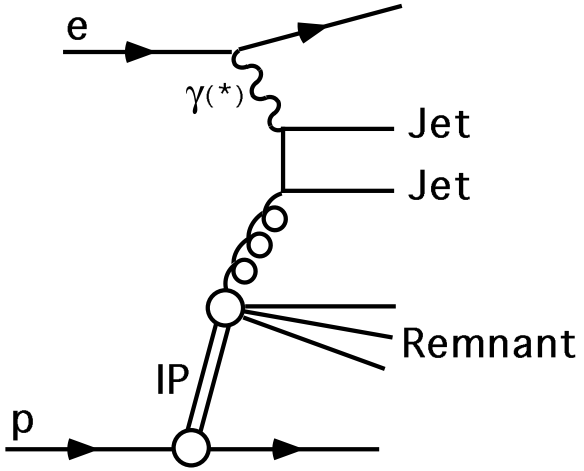


- Violation of factorization understood in terms of (soft) rescattering corrections of the spectator partons (Kaidalov, Khoze, Martin, Ryskin)
- Input from Tevatron essential, Run II data expected

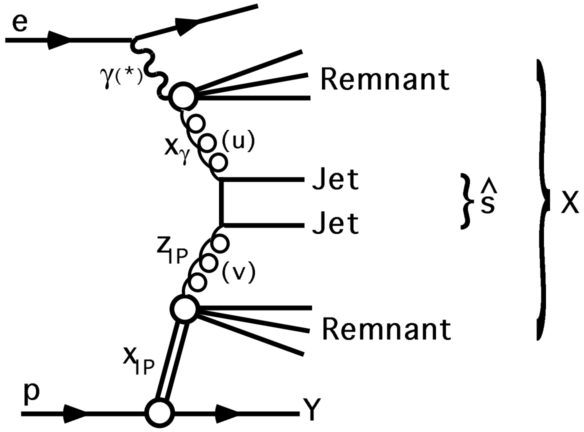
Factorization tests in γp

Real photon ($Q^2 \simeq 0$) can develop hadronic structure
$\Rightarrow$ study fact. breaking at HERA

direct γ ($x_\gamma \simeq 1$) unsuppressed



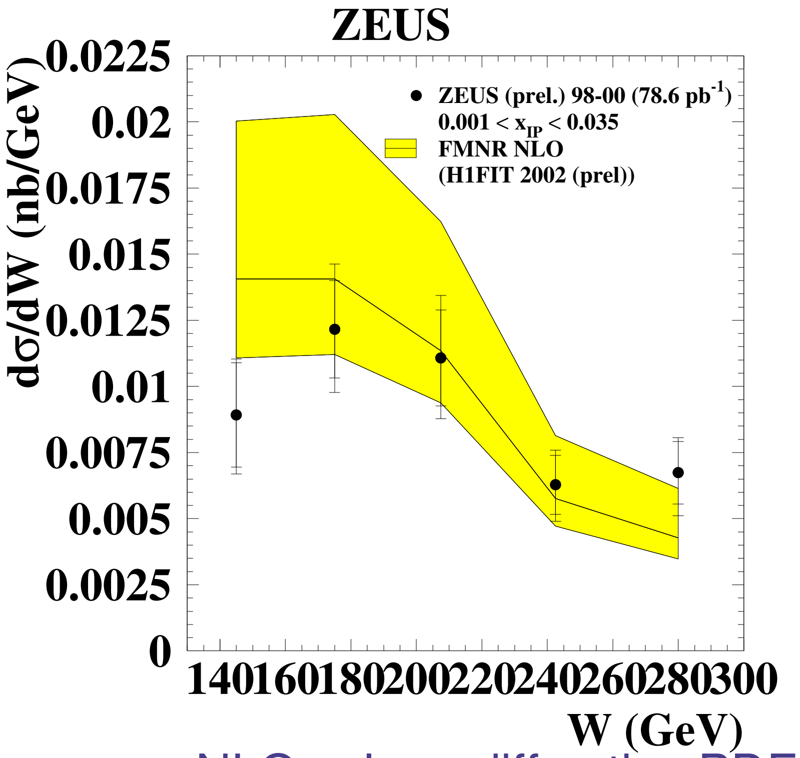
resolved γ (hadron like, at low x_γ) suppressed)

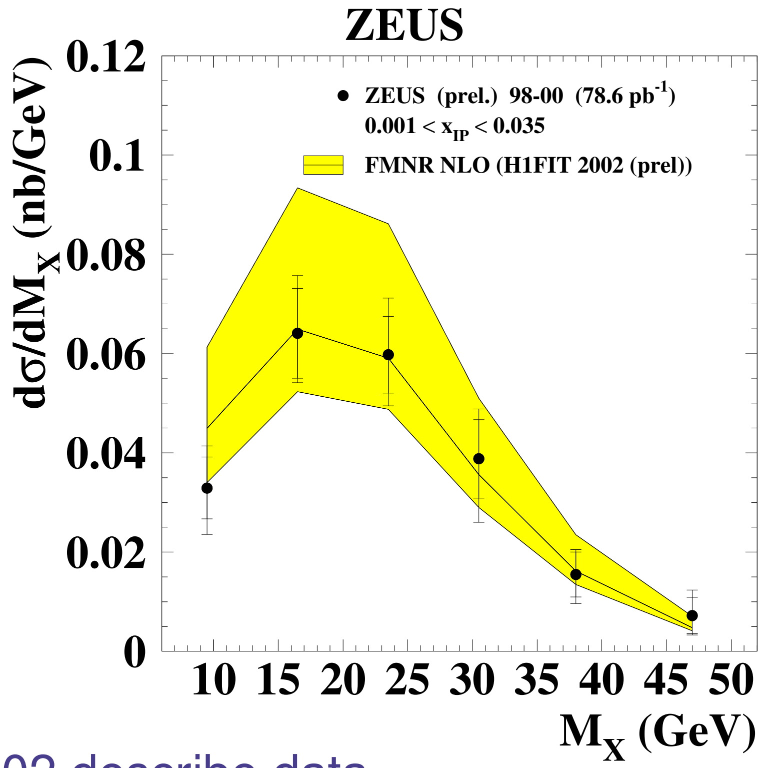


- x_γ reconstructed by jets, $x_\gamma = x_\gamma^{OBS} = \frac{\sum (E-p_z)_{jets}}{\sum (E-p_z)_{hadrons}}$
- in NLO, suppression of resolved contribution by a factor 3 expected (Kaidalov et al.)

Factorization tests: D* in γp

In the kin. region of the measurement, D^* production mainly produced in direct photon processes $\rightarrow$ no suppression expected

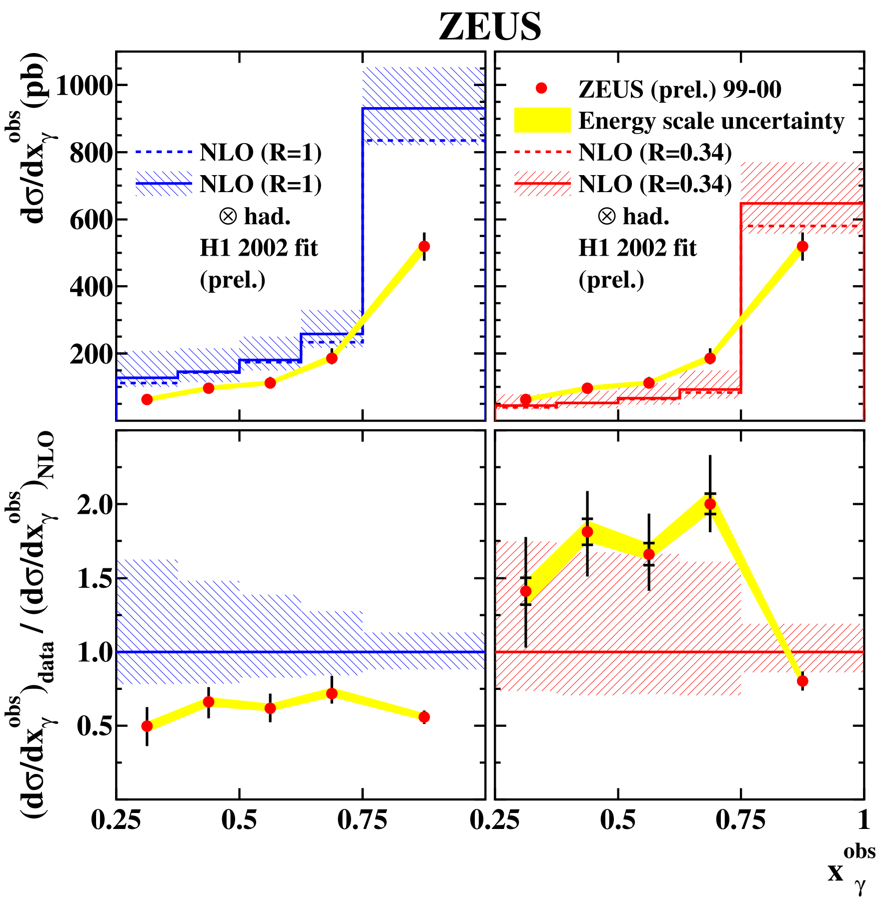


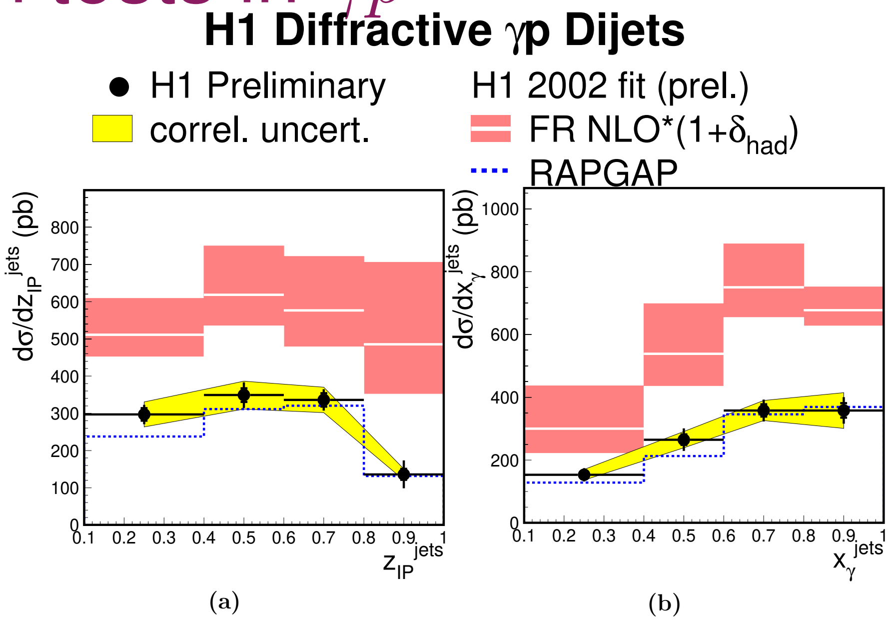


- NLO calc. + diffractive PDFs H1 2002 describe data

$\Rightarrow$ Assuming this dPDFs, QCD factorization works

Factorization tests in γp





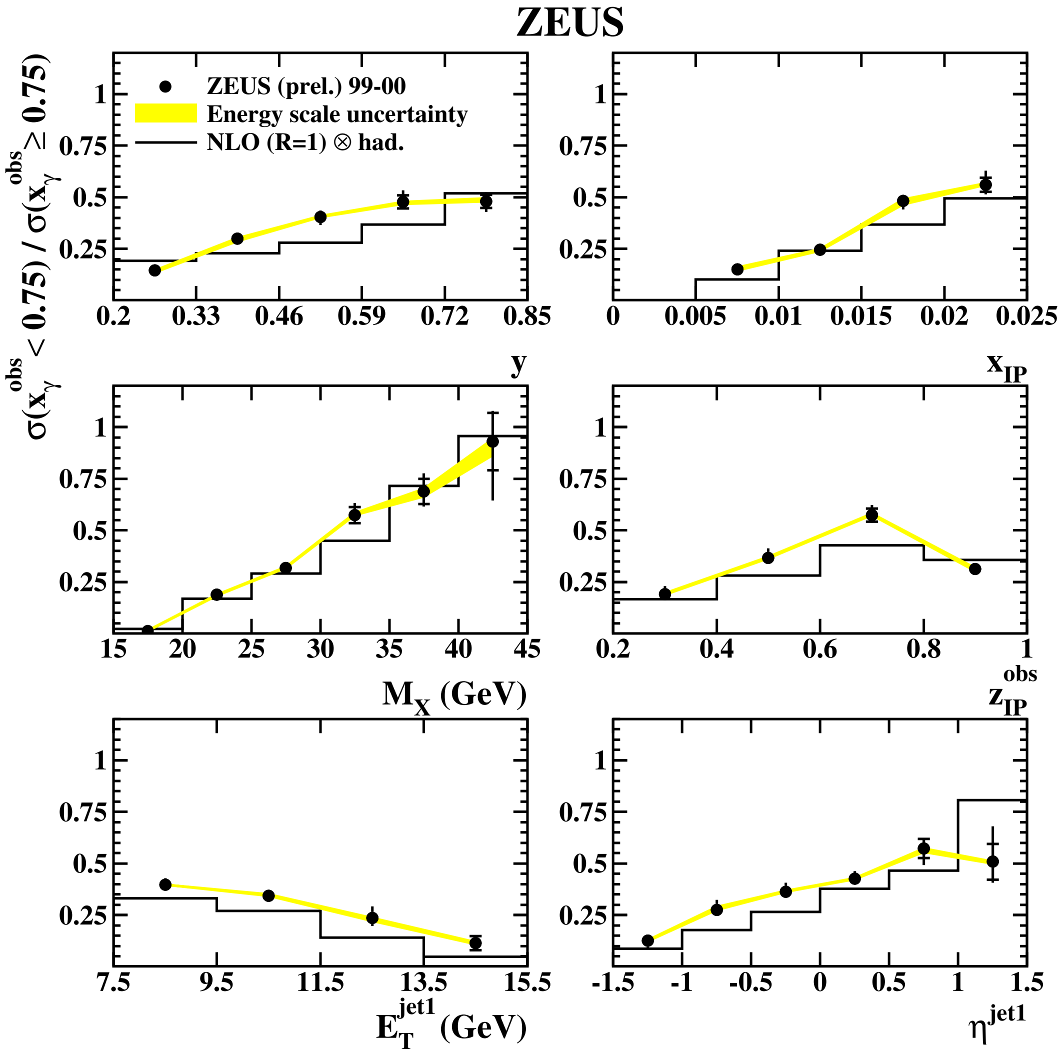
- NLO predictions using diffractive PDFs H1 2002 are above data
- no suppression of resolved contribution only
- large uncertainty in diffr. PDFs

$\rightarrow$ difficult to estimate the suppression factor

Is factorization broken in γp?

Need better understanding of DPDFs to make conclusions

Factorization tests in γp



Ratio resolved ($x_\gamma < 1$)/ direct ($x_\gamma \simeq 1$) compared to NLO

- measurement independent from diffractive PDFs

$\Rightarrow$ theory in agreement with data

QCD factorization tests summary

Diffractive charm (DIS and photoproduction):

- Data agree with NLO predictions with H1 2002 diffr. PDFs
- Factorization hold (assuming PDFs are correct)

Diffractive dijets in DIS:

- Data reasonably described by NLO predictions with H1 2002 diffr. PDFs
- Factorization hold (assuming PDFs are correct)

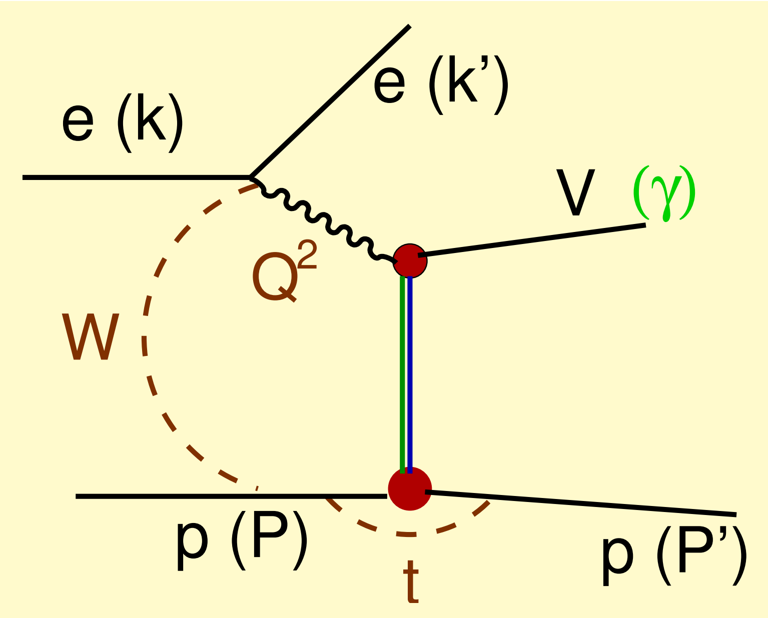
Diffractive dijets in Photoproduction:

- Data described by LO and NLO in shape
- NLO QCD is above the data if assuming H1 2002 PFDs
- data favor a global suppression of NLO QCD rather than a suppression of only the resolved component
- Theory investigating factorization scheme and scale dependence between direct and resolved contribution

Description progressing (both data and theory), but picture still unclear

Vector meson production and DVCS in $\gamma^* p$

HERA regime: collisions of 27.5 GeV e with 920 GeV p



- Q^2 - virtuality of exchanged γ^*
  $Q^2 = -q^2 = -(k - k')^2$
- W - $\gamma^* p$ centre of mass energy
  $W = (q + p)^2$
- 4-momentum transfer squared at the p vertex $t = (P - P')^2$
- x - Bjorken variable $x = \frac{Q^2}{P \cdot q} = \frac{Q^2}{Q^2 + W^2}$

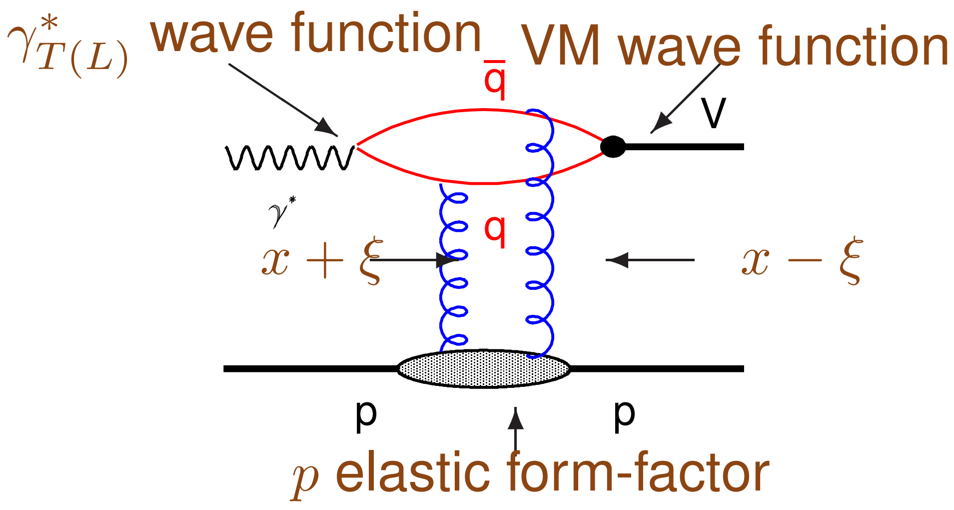
$0 < Q^2 < 100\ \mathrm{GeV}^2$, $20 < W < 300\,\mathrm{GeV}$, $-t < 30\ \mathrm{GeV}^{-2}$,
$10^{-4} < x < 10^{-2}$

Real photon or Vector Meson (ρ, ω, ϕ, J/ψ, $\psi(2s)$, Υ)

hard scale provided by Q^2, M or t

QCD factorization - two approaches

QCD - Breit frame



NLO calculation available for

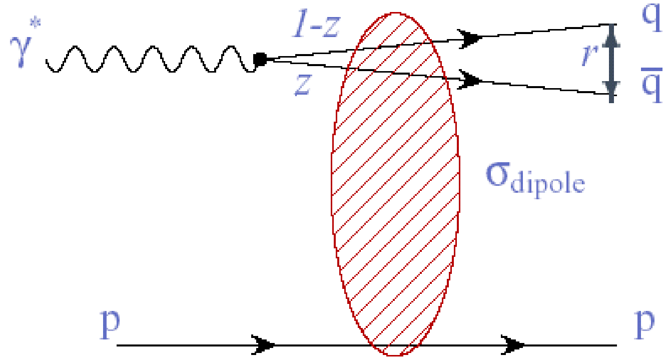
J/ψ (γp, DIS) and ρ (DIS)

$\sigma_L \simeq \frac{\alpha_S^2}{Q^6}|xG(x,Q^2)|^2 \Rightarrow$

$\sigma_L \propto \frac{\alpha_S^2}{Q^6}|H(x_1,x_2,t,Q^2)|^2$

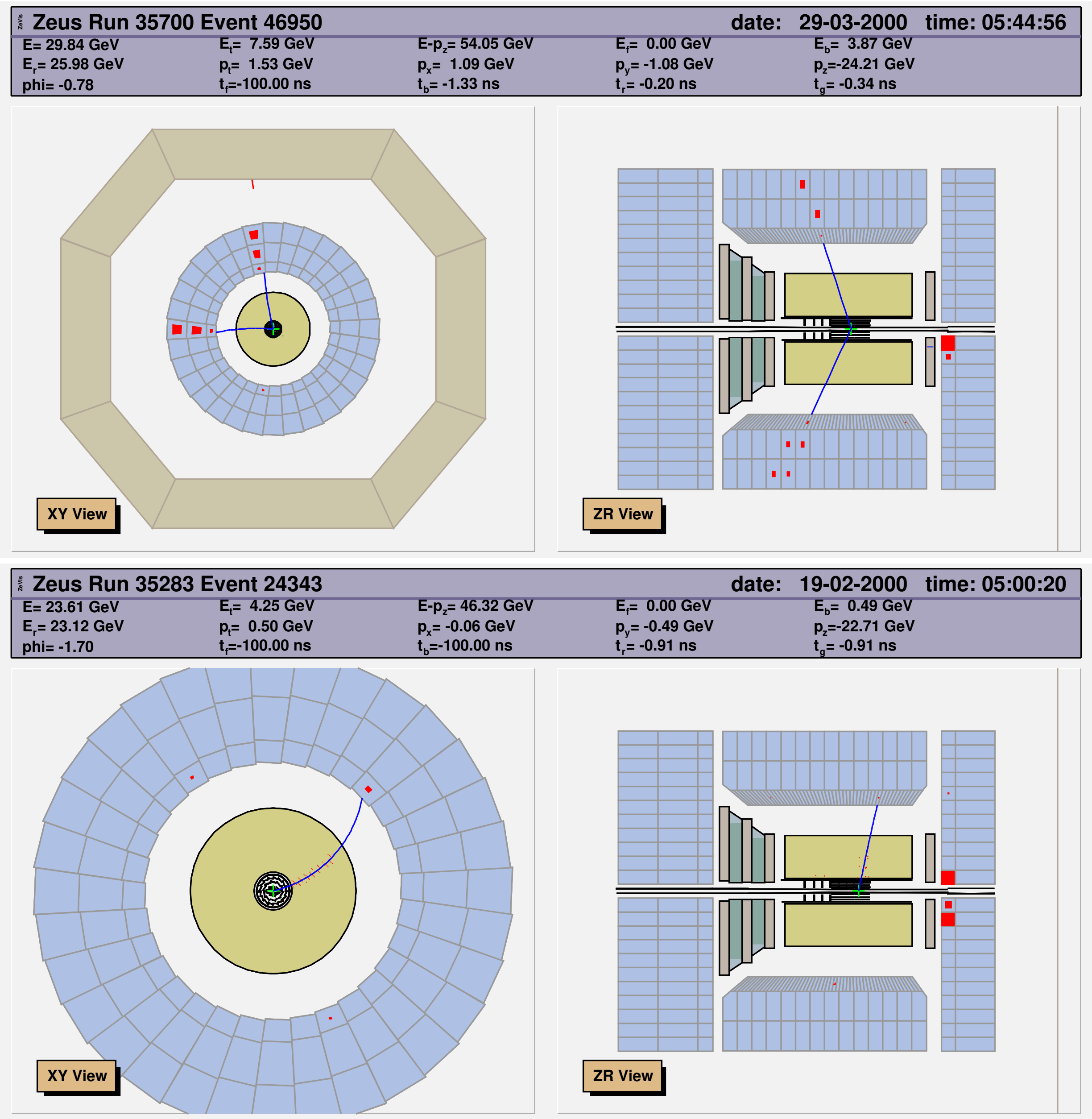
Generalised PDFs approximated from PDFs

Colour dipole - target frame



- γ^* fluctuates in $q\bar{q}$ + $q\bar{q}g$ + ..
- Lifetime of dipole very long because of large γ boost
- Transverse size $\propto 1/(Q^2+M^2_{q\bar{q}})$

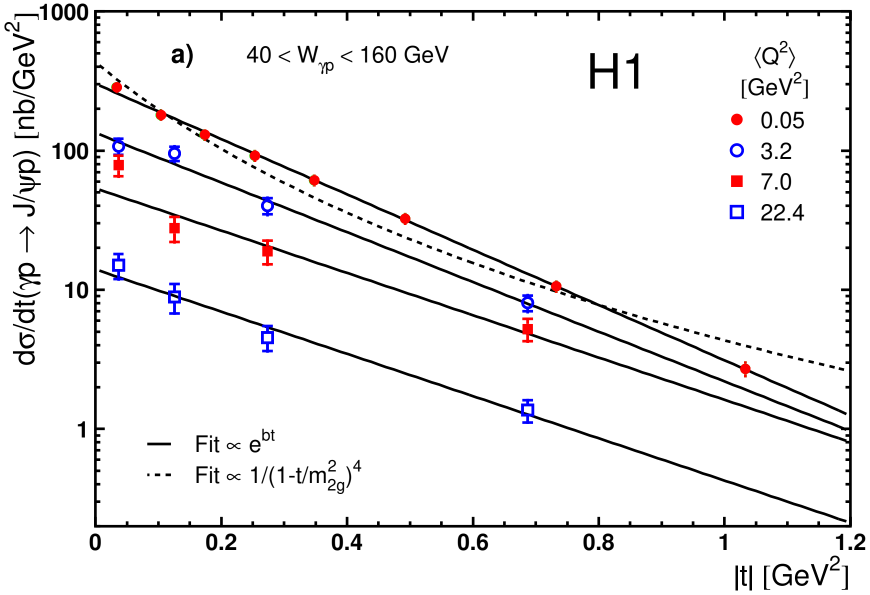
  $\sigma_{\gamma^* p}(x,Q^2)$ = $\int dr^2 dz \psi^{in}(r,z,Q^2)\sigma^2_{dipole}(x,r)\psi^{ou}$
- σ_{dipole} from models (2-gluons, ..)

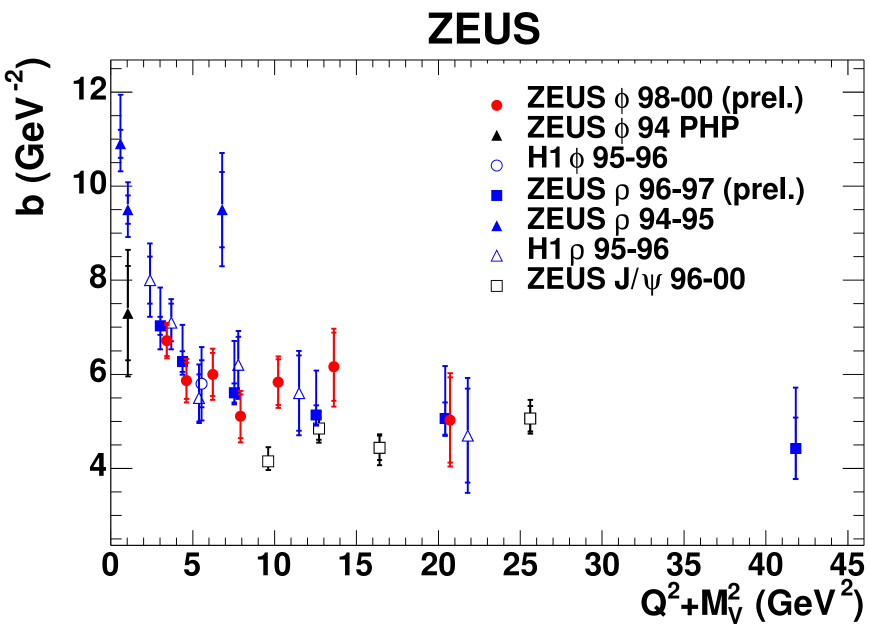


Clean experimental signature

- scattered e reconstructed in CAL or beam pipe calorimeter (DIS) or undetected (γp)
- scattered p undetected
- $\rho \to \pi^+\pi^-$,
  $J/\psi \to l^+l^-$ (BR 6%)
  γ reconstructed in CAL or 2 particles in central chamber identified as pions, electrons or muons (γ and electrons can be reconstructed in CAL, outside tracking acceptance)
- nothing else in the detector

Exclusive VM production - t dependence

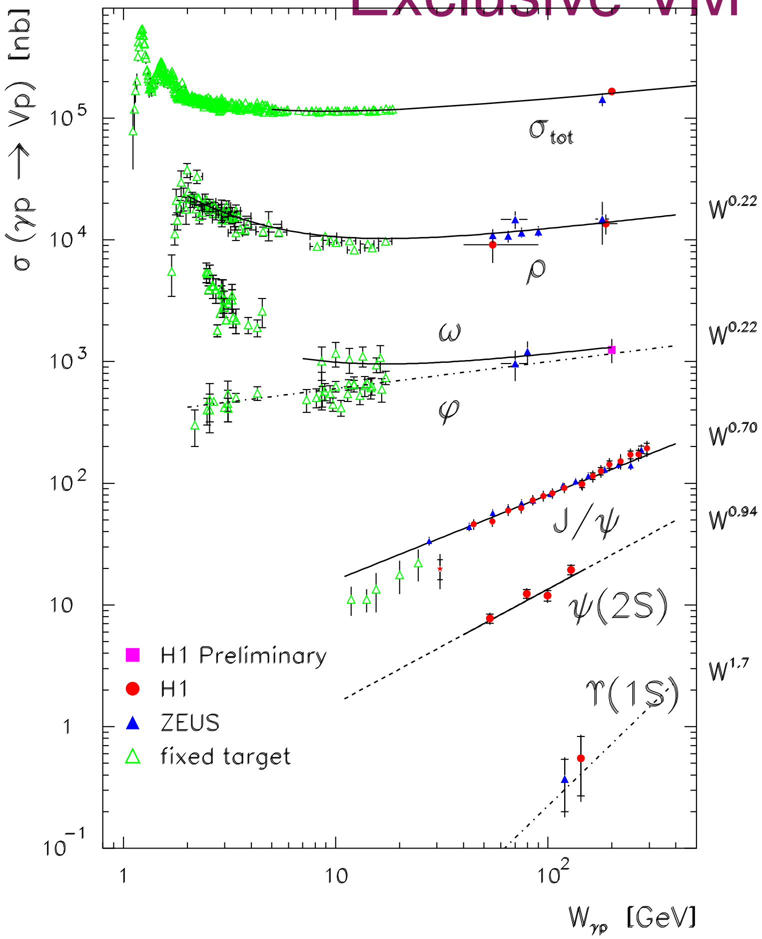


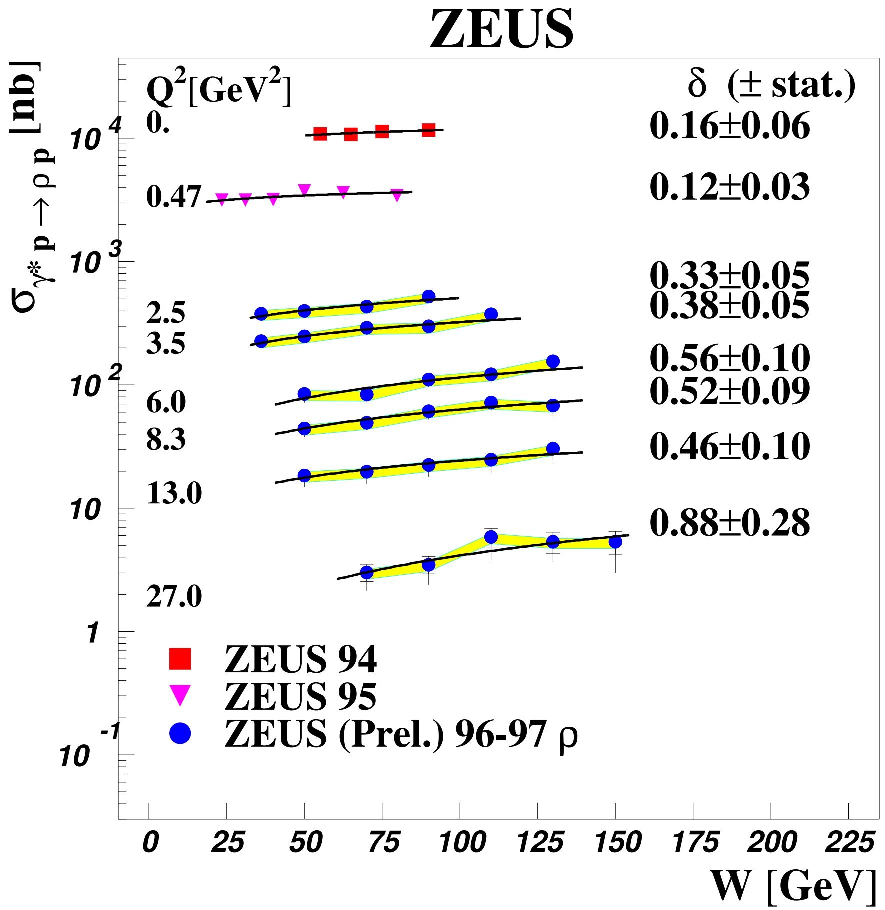


- $d\sigma/dt \propto e^{bt}$, for $|t| < 1$ GeV^2
- b reflects the transverse size of the interaction $c\bar{c}$-p
- no dependence of b on Q^2, interaction dominated by size of p

- General transition from large to small configuration at increasing values of $Q^2 + M^2$

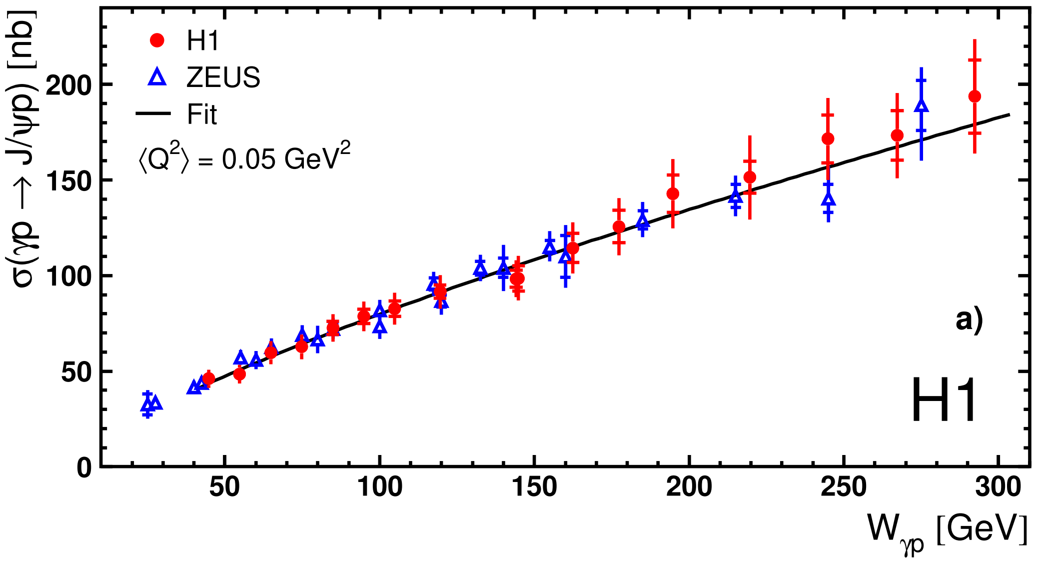
Exclusive VM production - W dependence

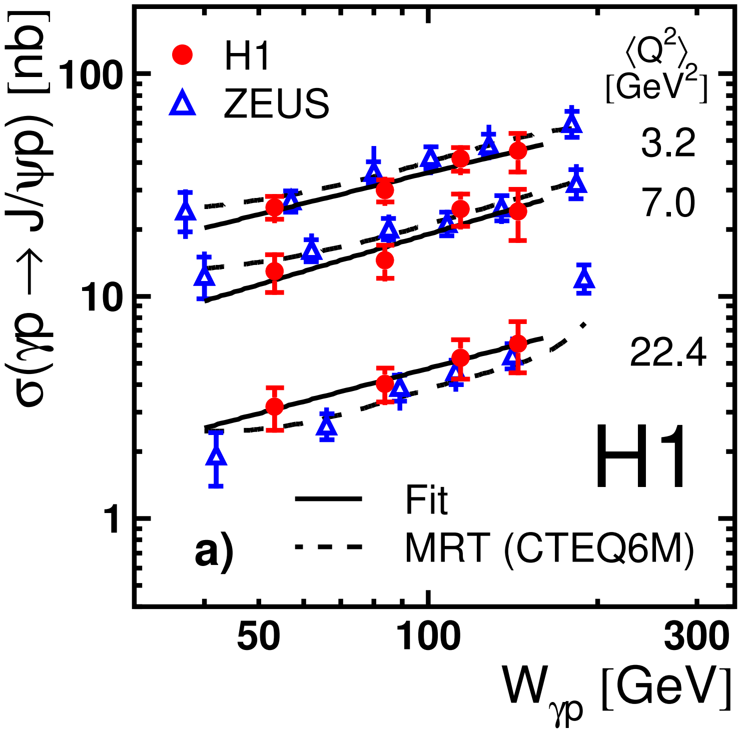


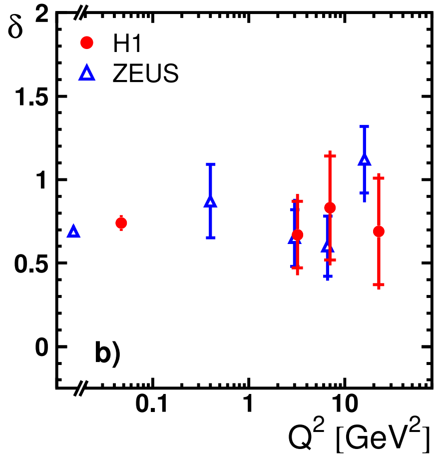


- Decreasing of cross section with increasing size
- Decrease partially compensated by increase of gluon density at small $x \propto 1/W^2$
- Transition to small size configuration reflects in hard behaviour

Exclusive J/ψ production - W dependence

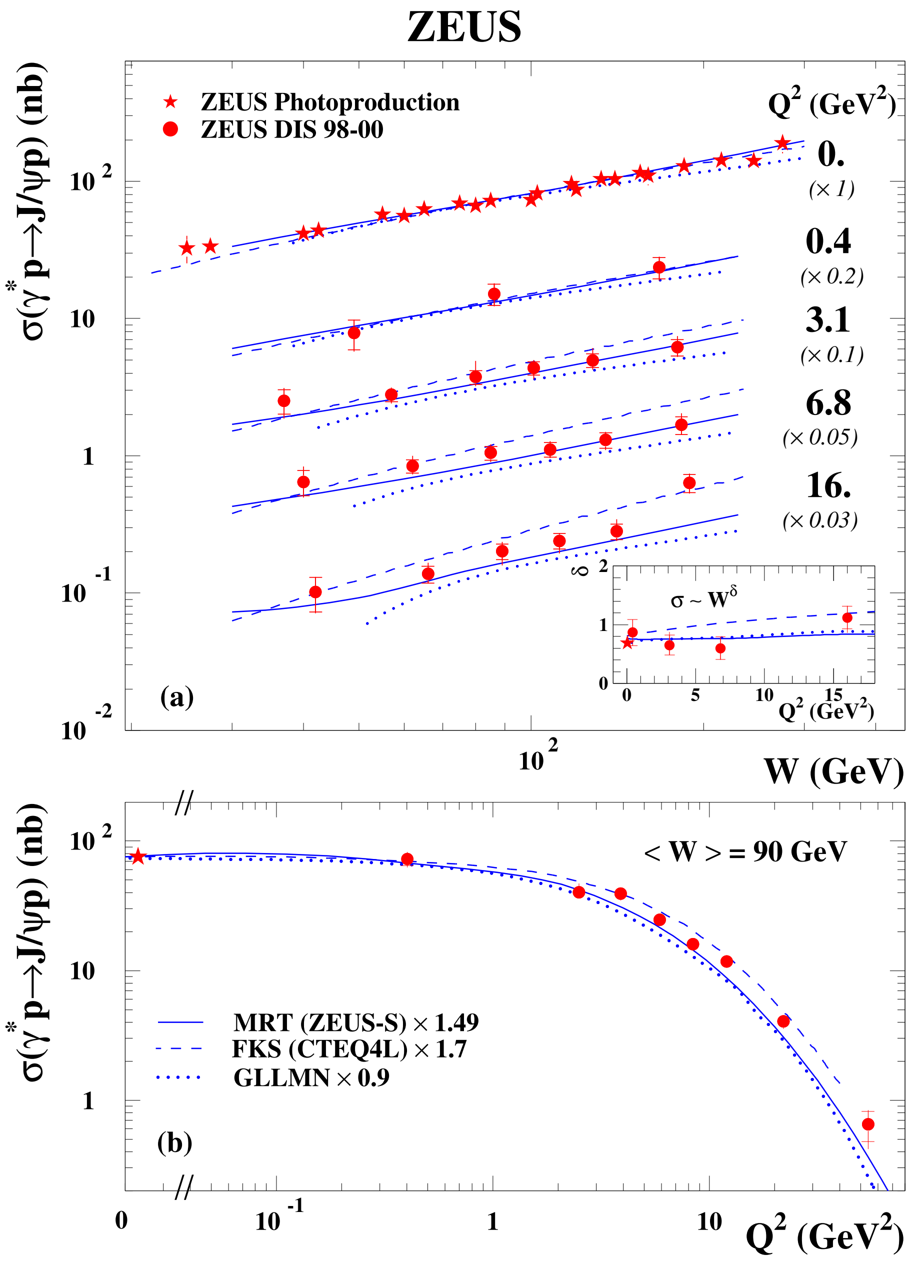






σ vs W in bins of Q^2

- $\sigma \propto W^{\delta}$, with $\delta = 0.7$
- no dependence on δ from Q^2,
  J/ψ mass already provides hard scale



Exclusive J/ψ production

comparison with QCD models

Martin, Ryskin Teubner

Frankfurt, Koepf, Strikman

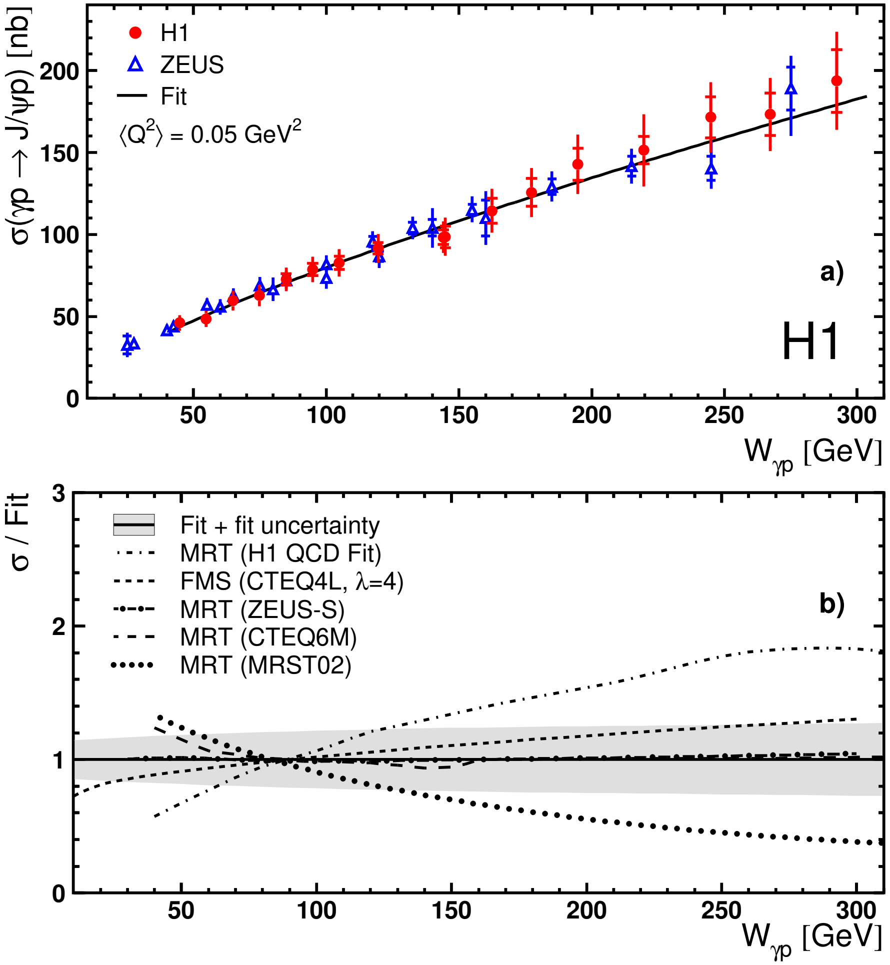
Gotsman, Levin, Lublisky, Maor, Naftali

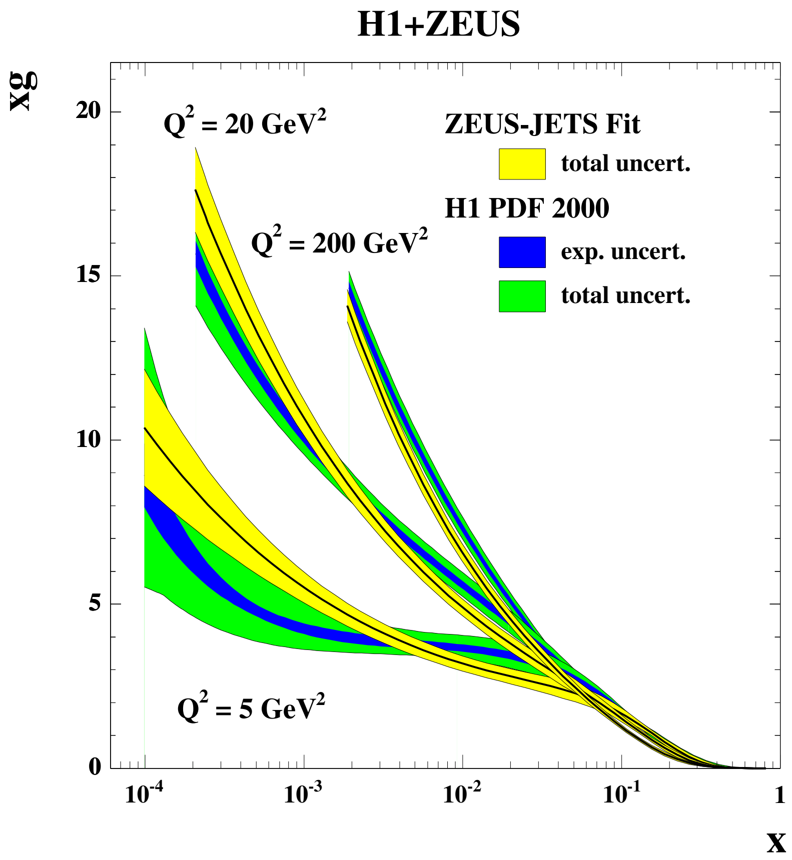
Models differ for:

- assumptions on $c\bar{c}$ wave function
- corrections applied to LO calculations
- assumptions on GPDFs

- large uncertainty in normalisation
- models describe qualitatively data
- rise of σ with W related to increase in gluon density at low x

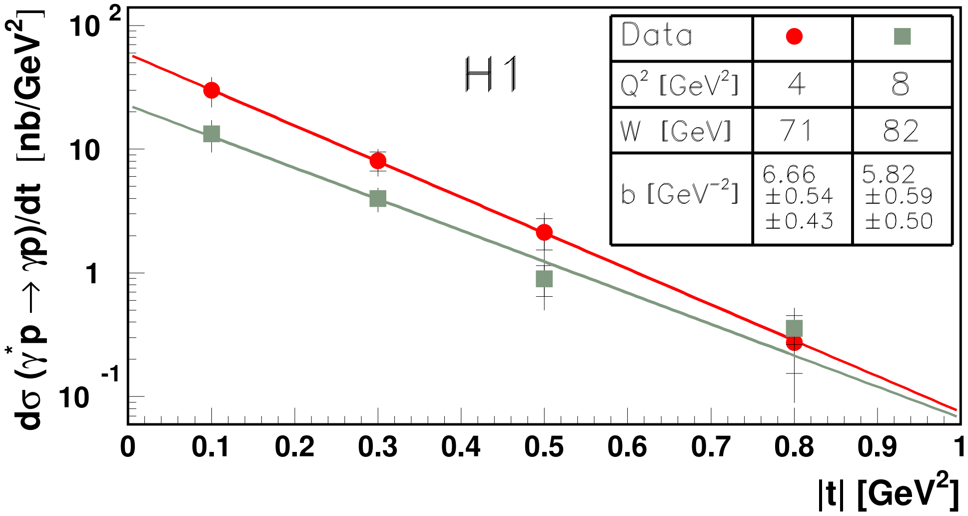
Exclusive J/ψ production - comparison to different PDFs

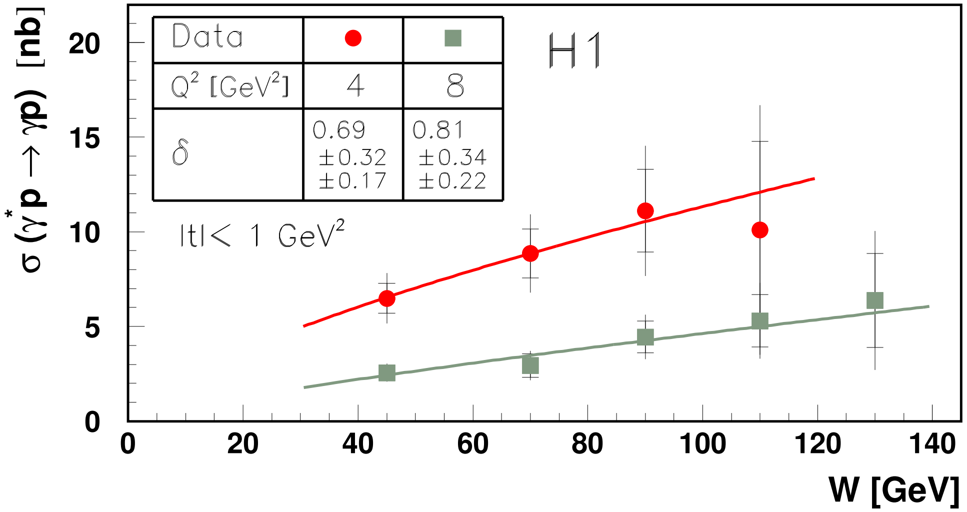


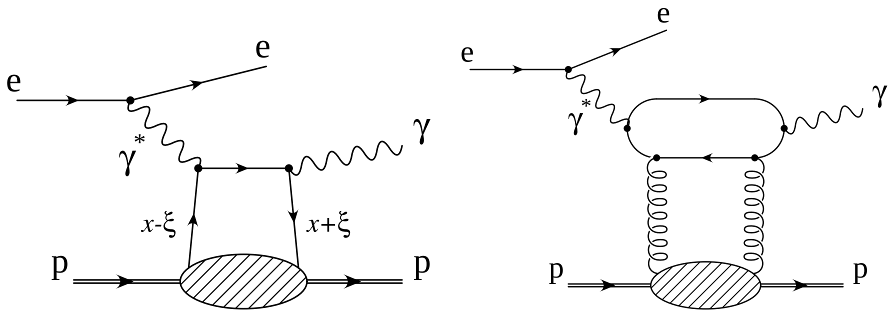


- strong sensitivity to generalised gluon distribution
- could the data be used to constrain gluon density?

Deeply Virtual Compton Scattering







$ep \longrightarrow ep\gamma$ at high Q^2, low |t|

- Skewedness ξ = non-zero

$\longrightarrow$ sensitive to Generalised Parton Distributions (GPDs)

- GPDs generalise PDFs $\rightarrow$ info on parton correlation + transverse motion

equal to usual PDFs as $\xi \to 0$, $t \to 0$

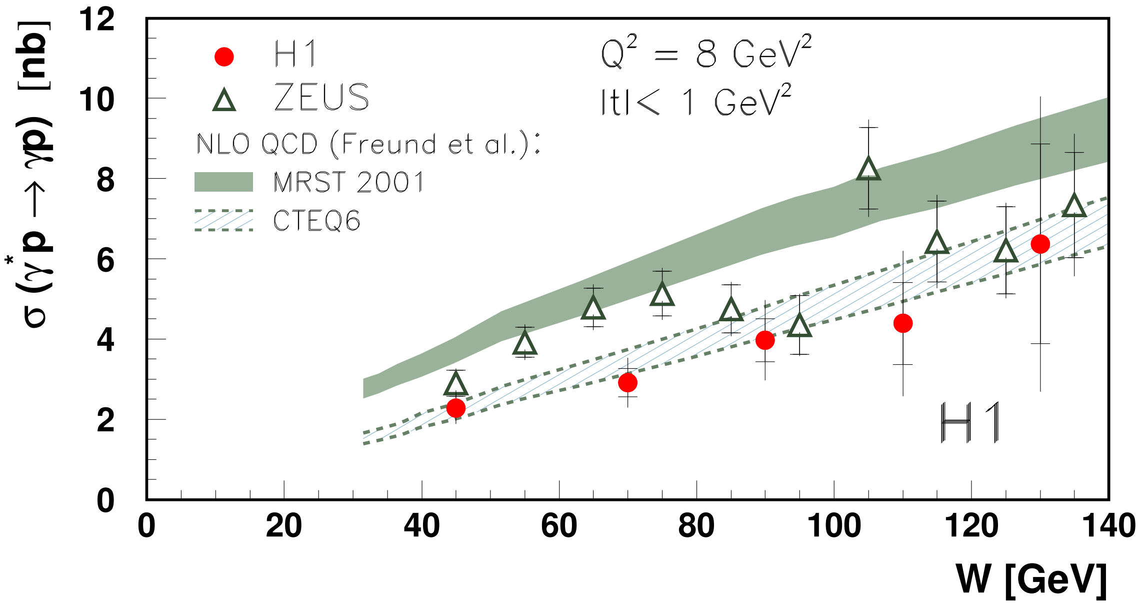
First measurement of the t-slope

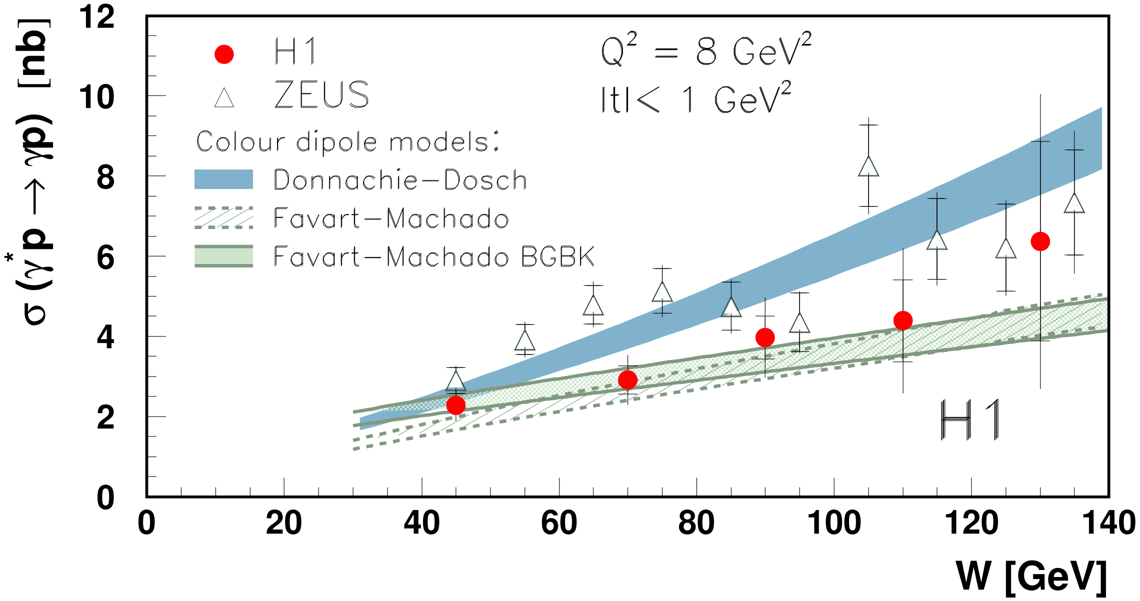
$b = 6.02 \pm 0.35 \pm 0.39\ \mathrm{GeV}^{-2}$

W dependence: $\sigma \propto W^{\delta}$

indication of a hard regime

Deeply Virtual Compton Scattering





Fully calculable in Q. NLO by A. Freund and M. McDermott

Input: GPDs

$|x| < \xi$ (DGLAP region)

$H^q(x;\xi;t;\mu^2) = q(x;\mu^2)e^{-b|t|}$

$H^g(x;\xi;t;\mu^2) = g(x;\mu^2)e^{-b|t|}$

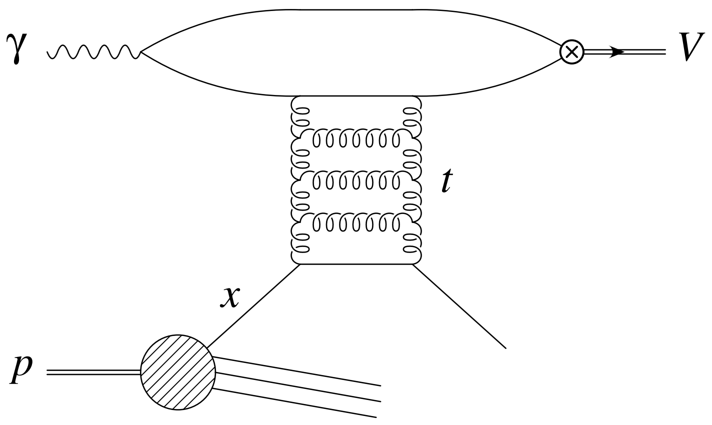
$|x| < \xi$ (ERBL region), single analytic function

b from data, Q^2 and ξ generated dynamically

Error band assuming b as measured

Good description by QCD-NLO calculations

DGLAP vs BFKL dynamics - VM at large t

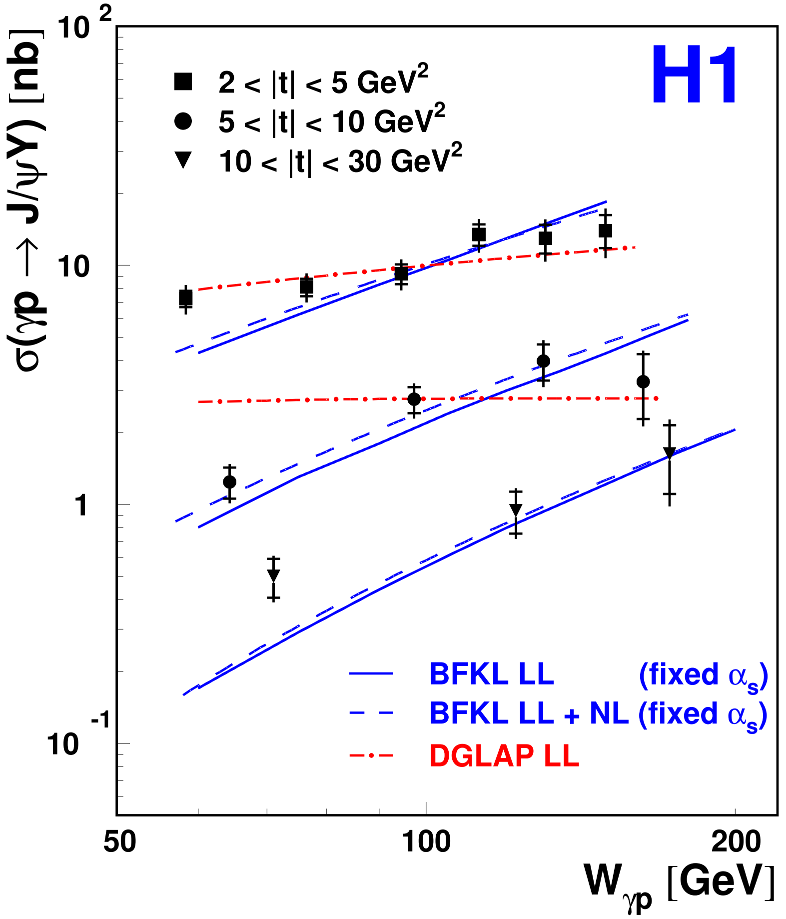


At high t, proton mostly dissociates

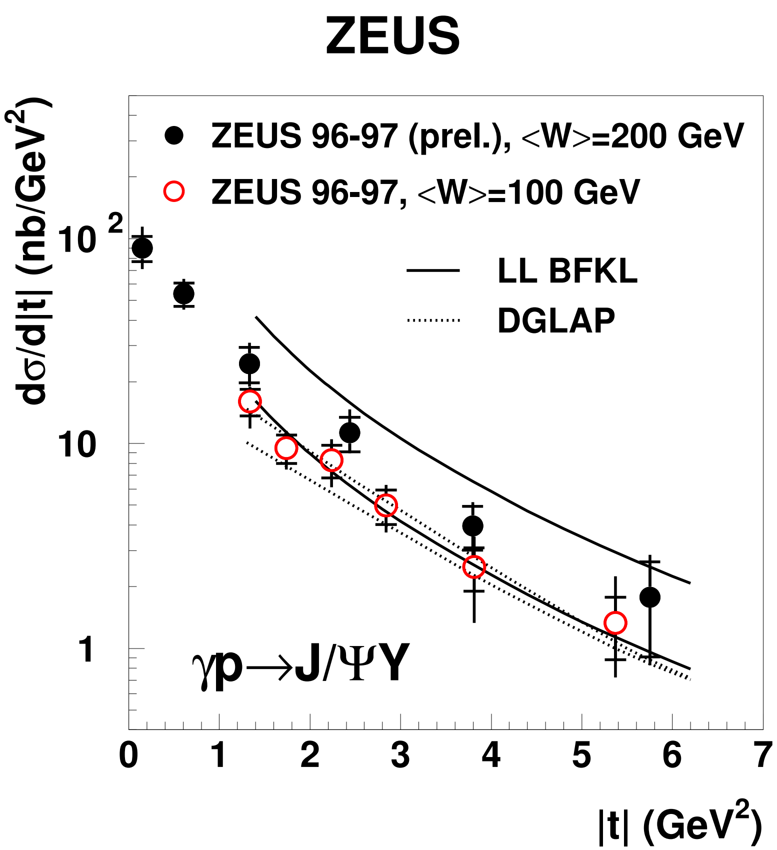
$\gamma p \to V\ Y$

- BFKL evolution driven by terms $\alpha_S^n \ln^n(W^2/|t|)$
- BFKL model by Enberg, Forshaw, Motyka, Poludnioski
  Free parameters of the model:
  - α_s^{IF} coupling of the 2-gluons to each impact factor
  - α_s^{BFKL} gluon coupling inside the ladder
  - Λ^2 undefined energy scale
- challenge is to provide simultaneous description of kin. variables

DGLAP vs BFKL dynamics - W dependence

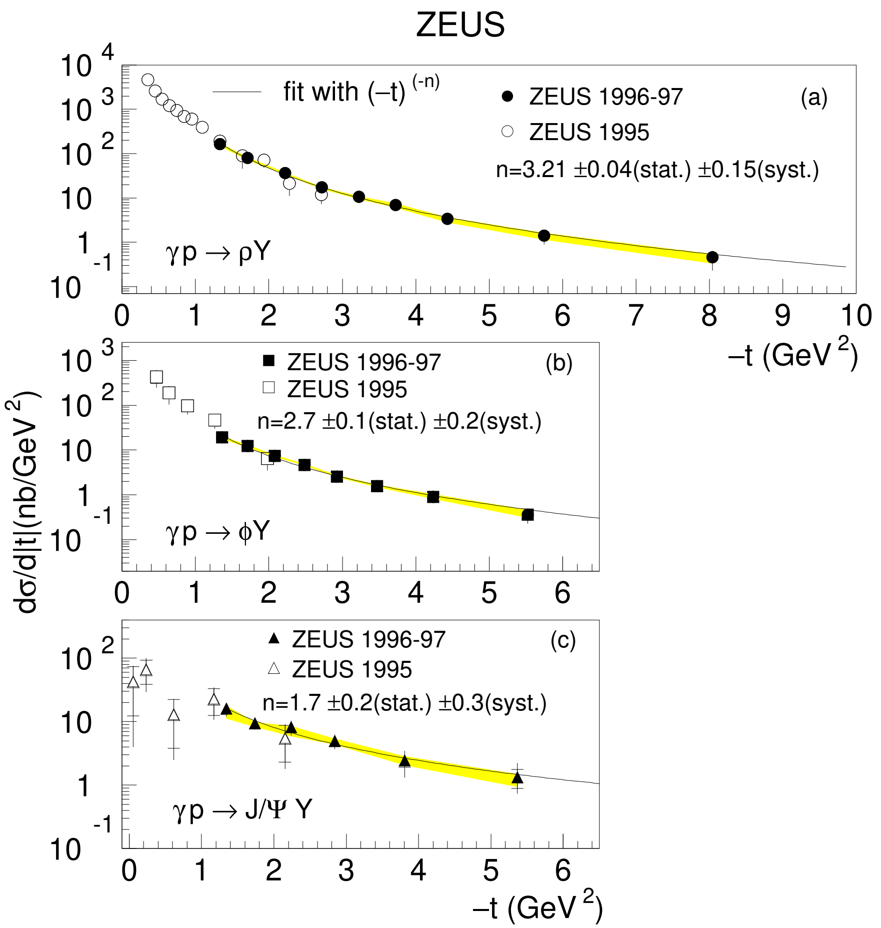


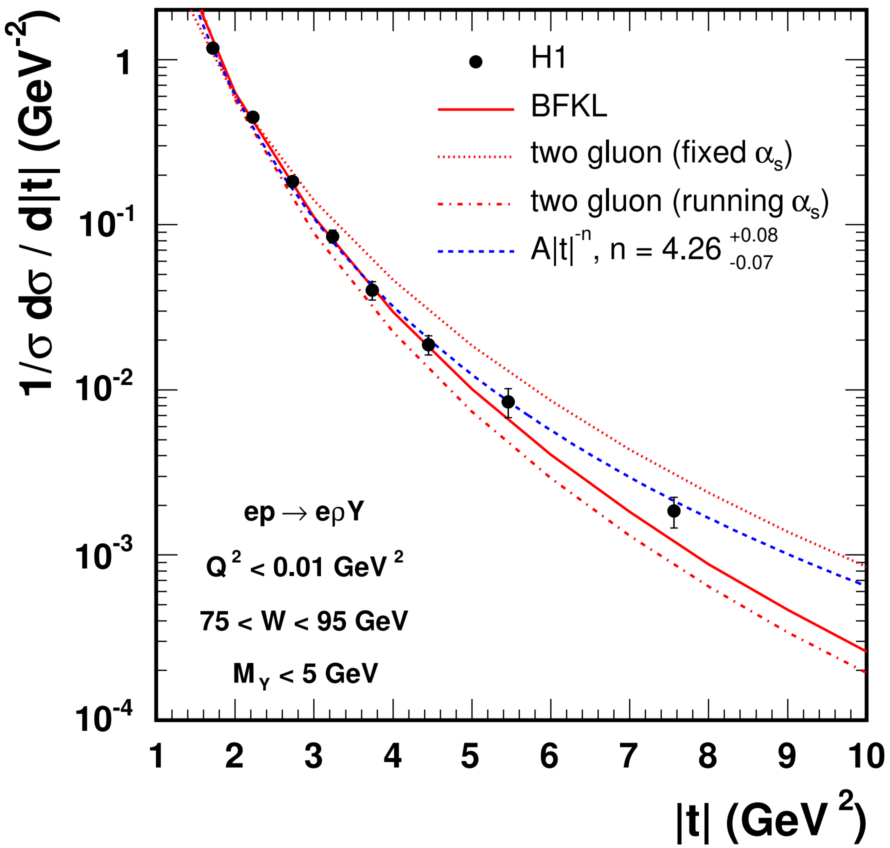
$\gamma p \to J/\psi\, Y$



- DGLAP fails to descrive evolution at large $|t|$
- BFKL describes data

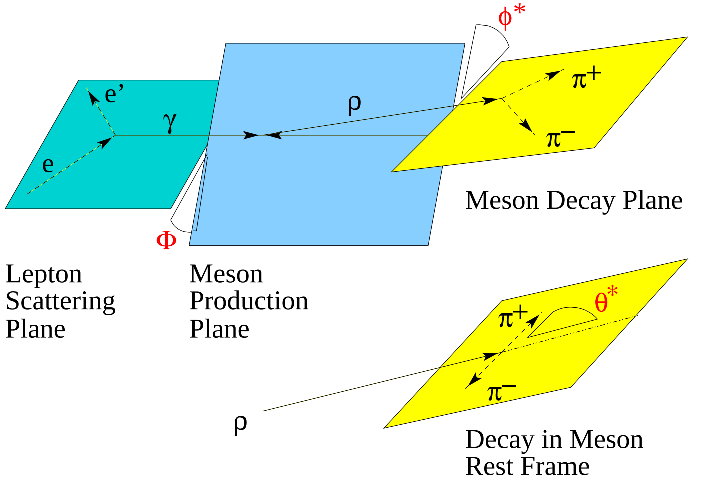
DGLAP vs BFKL dynamics - t dependence





- $d\sigma/dt \propto |t|^{-n}$ at large $|t|$, as predicted
- BFKL describes data

Decay angular distributions



Helicity angles

θ_h, ϕ_h - angles of decay particle in the meson rest frame

Φ - angle between scattering and production plane

Angular distributions are related to the spin of γ^* and meson

Angular distr. $\rightarrow$ spin density matrix elements r_{ij}^{kl} $\rightarrow$ helicity amplitudes $T_{\lambda_{VM}\lambda_\gamma}$

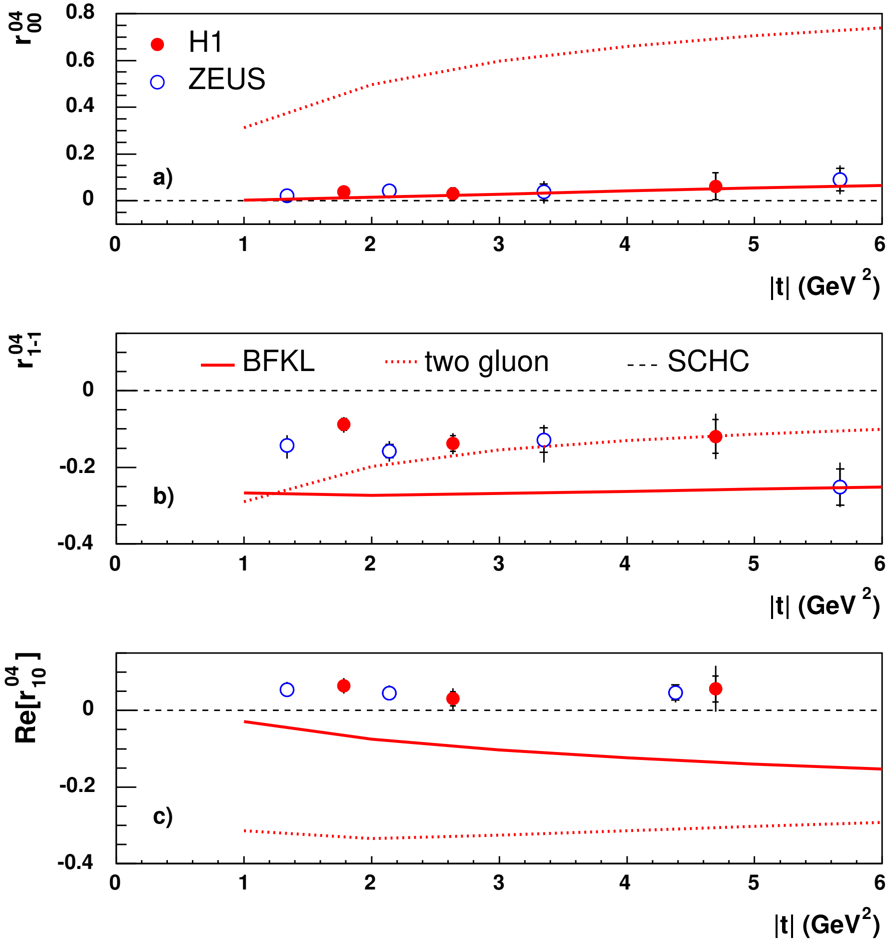
s-channel helicity conservation (SCHC):

- the VM retains the γ^* helicity. $R = \sigma_L/\sigma_T$ is related to the spin density matrix elements r_{00}^{04} (good approximation).

pQCD:

- during the interaction, the orbital angular momentum of the $q\bar{q}$ can be modified through the transfer of transverse momentum carried by gluons;
- the helicity of the outgoing vector meson can be different from that of the incoming photon, helicity flip between photon and meson is possible.

DGLAP vs BFKL dynamics - decay angular distributions



$\gamma p \rightarrow \rho\, Y$

- W and t dependence well described by BFKL models
- but BFKL models unable to describe r^{04}_{10} (production of longitudinal ρ mesons from transverse γ)
- progress in theory expected

Summary

- Experimentally much progress has been achieved,
  - high precision in wide kinematic region
  - increased statistics at high Q^2 will help (700 pb^{-1} expected at HERA II)
- Theoretically chance to investigate the QCD dynamics in the semi-hard regime,
  - the overall picture looks correct
  - large uncertainties
  - full NLO calculations are missing