Diffraction at HERA

Vladimir Spaskov (JINR)
on behalf of the H1 and ZEUS Collaborations

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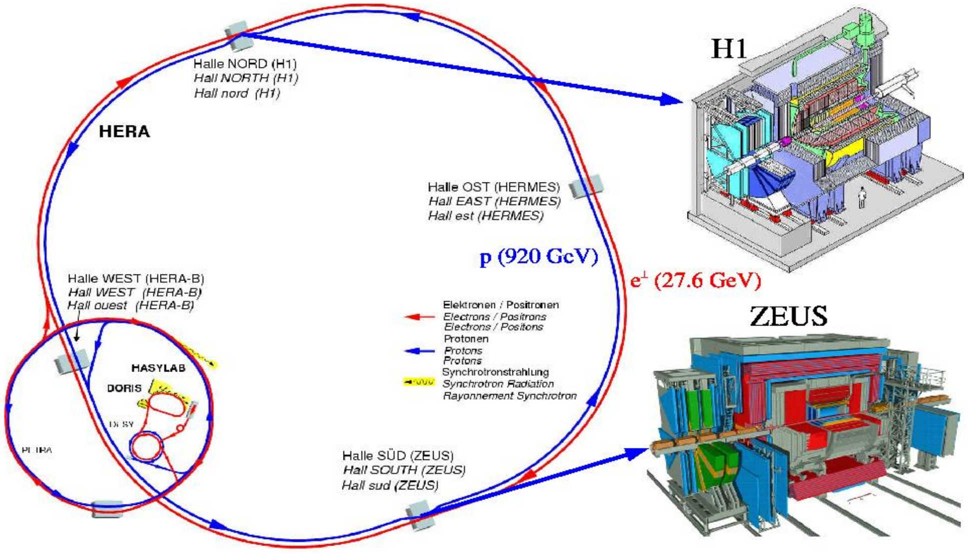
Outline:
- Introduction – HERA and diffractive scattering
- Inclusive diffraction (LP + LRG)
- Diffractive dijets in DIS and PhP
- Vector meson production
- Summary

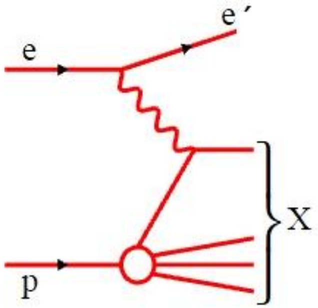
HERA *ep* collider

- **The world's only electron/positron-proton** collider at DESY, Hamburg
- **E_e = 27.6 GeV, E_p = 920 GeV** (also 820, 460, 575 GeV)
- **centre-of-mass energy up to $\sqrt{s}$ ≈320 GeV**

- Two collider experiments: **H1** and **ZEUS**

• data taken:
HERA-1 (1992-2000)
HERA-2 (2003-2007)
• total lumi ~ 0.5 fb^{-1} per experiment





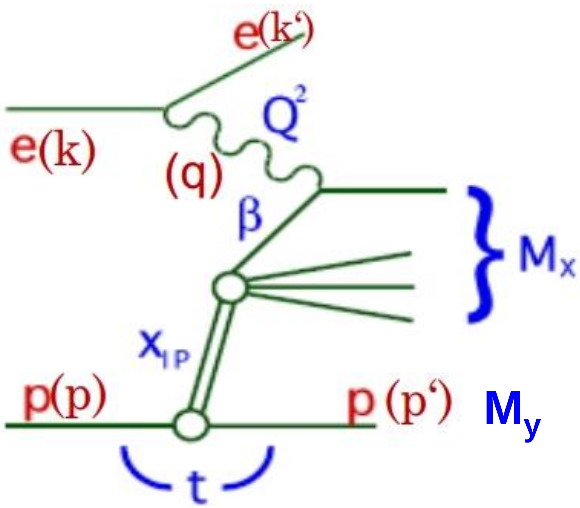
DIS: Probe structure of proton → F_2

One of first HERA surprises:
~10% of DIS events have no activity in proton region → diffractive interactions

HERA: ~10% of low-x DIS events diffractive

Probe structure of color singlet exchange → F_2^D

$Q^2 = -q^2$ Virtuality of the photon
$Q^2 \approx 0$ → photoproduction
$Q^2 >> 0$ → DIS



Momentum fraction of proton carried by color singlet exchange
$$x_{IP} = \frac{q\cdot(p-p')}{q\cdot p} \approx \frac{Q^2+M_x^2}{Q^2+W^2}$$

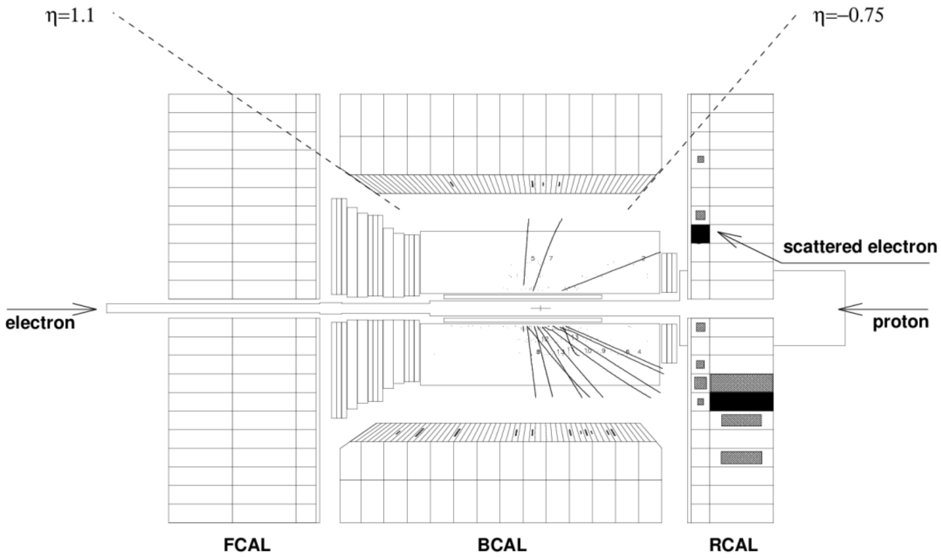
Momentum fraction of color singlet carried by struck quark
$$\beta = \frac{x}{x_{IP}} \approx \frac{Q^2}{Q^2+M_x^2}$$

4-momentum transfer squared $t = (p-p')^2$

Inelasticity $y = \frac{p\cdot q}{p\cdot k}$ $(0 \le y \le 1)$

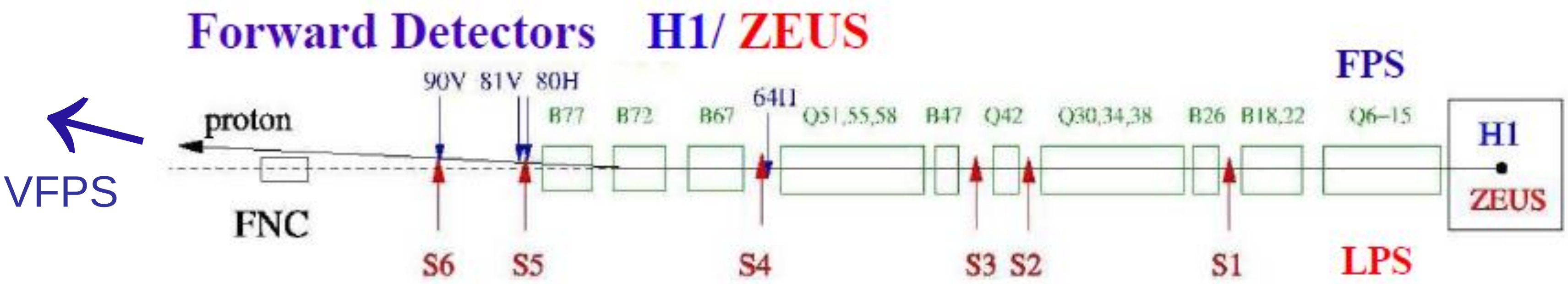
Large Rapidity Gap:

+ high statistics
- contains proton dissociative background
  $M_y < 1.6$ GeV
- limited by systematic uncertainties related to unmeasured proton



Proton Spectrometer:

+ no proton dissociative background $M_y = m_p$
+ x_{IP} and t-measurements
+ access to high x_{IP} range (IP+IR)
- low geometrical acceptance



Factorization

Inclusive diffractive cross section:

$$\frac{d^4\sigma^{ep\to e'Xp'}}{d\beta dQ^2 dx_{IP}dt} = \frac{4\pi\alpha_{em}^2}{\beta Q^4}(1-y+\frac{y^2}{2})\sigma_r^{D(4)}(\beta,Q^2,x_{IP},t)$$

Relation to F_2^D and F_L^D:

$$\sigma_r^{D(4)}(\beta,Q^2,x_{IP},t) = F_2^{D(4)} - \frac{y^2}{1+(1-y)^2}F_L^{D(4)}$$

$\sigma_r^{D(4)} \approx F_2^{D(4)}$ at low and medium **y**

- **QCD factorization** (proven for DDIS by Collins et al.)

$$\sigma^D(\gamma^* p \to Xp) = \sum_{parton\_i} f_i^D(x,Q^2,x_{IP},t)\cdot\sigma^{\gamma^* i}(x,Q^2)$$

$\sigma^{\gamma^* i}$ - universal hard scattering cross section (same as in inclusive DIS)

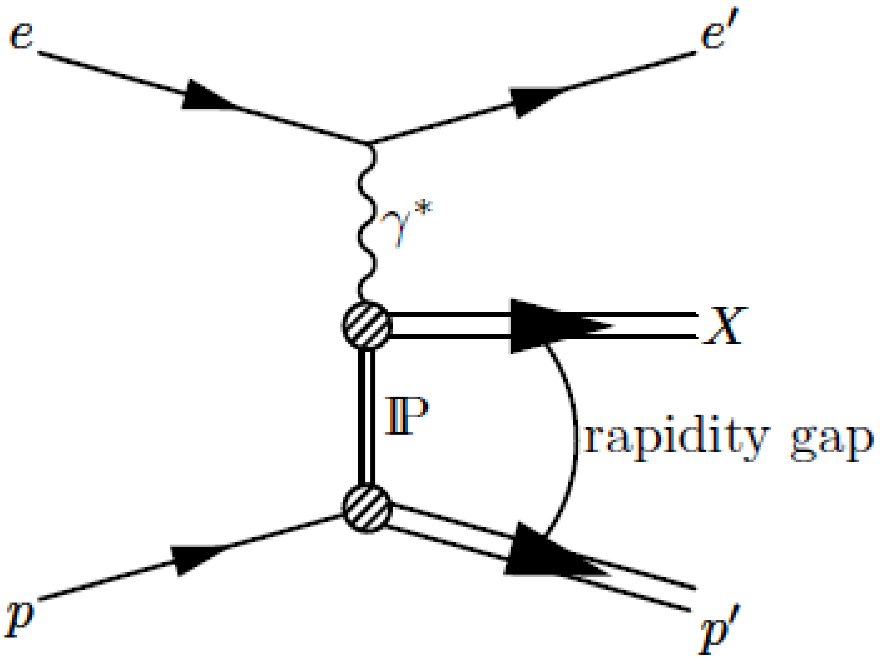
f_i^D - DPDFs, valid at fixed x_{IP},t which obey DGLAP universal for diffractive ep DIS (inclusive, dijets, charm)

- **Regge factorization** (e.g. Resolved Pomeron Model by Ingelman & Schlein)

$$f_i^D(x,Q^2,x_{IP},t) = \underbrace{f_{IP/p}(x_{IP},t)}_{\text{pomeron flux factor}}\cdot \underbrace{f_i^{IP}(\beta = x/x_{IP},Q^2)}_{\text{pomeron PDF}}$$

- shape of diffractive PDFs is independent of x_{IP},t while normalization is controlled by pomeron flux $f_{IP/p}(x_{IP},t)$

Inclusive diffraction

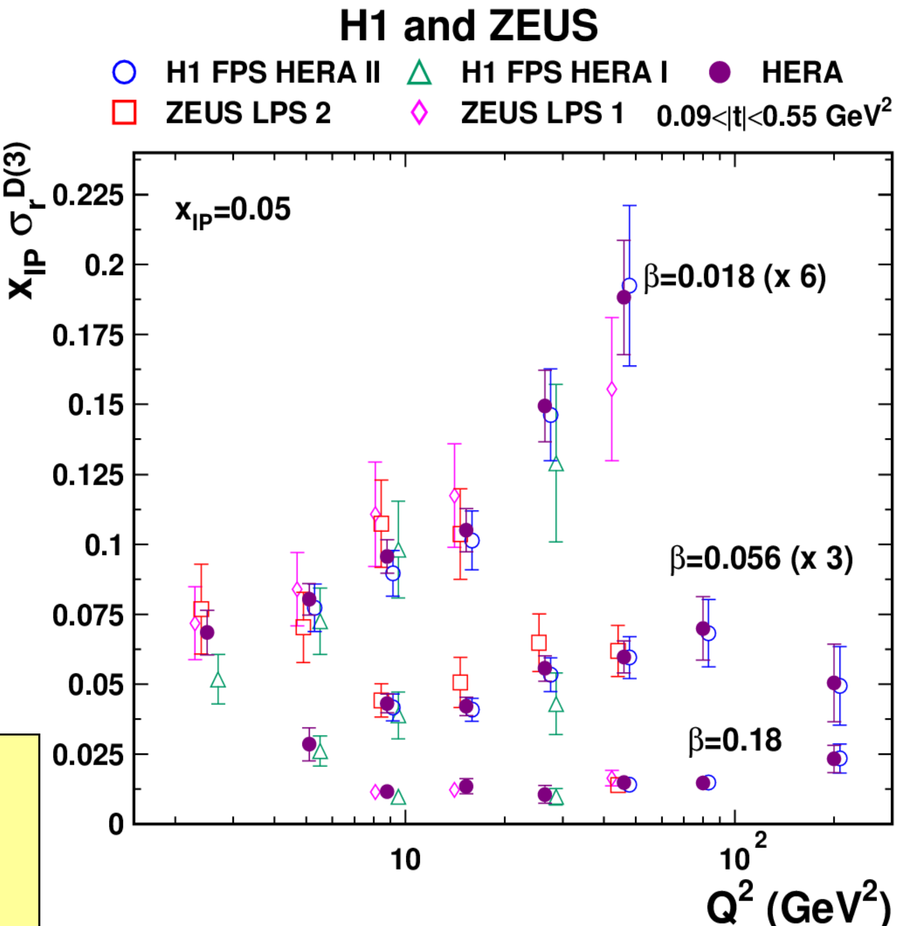


Eur. Phys. J. C72 (2012) 2175

- Proton spectrometers data in $0.09<|t|<0.55$ GeV^2
- Combination method uses iterative χ^2 minimization and includes full error correlations
- First combined inclusive diffractive cross sections:
  - H1: EPJ C71 (2011) 1578
  - H1: EPJ C48 (2006) 749
  - ZEUS: Nucl. Phys B816 (2009) 1
  - ZEUS: EPJ C38 (2004) 43

➔ Different exp. data are consistent each other χ^2_{min}/ndof = 133/161

➔ Total uncertainty on cross section is 6% for the most precise points



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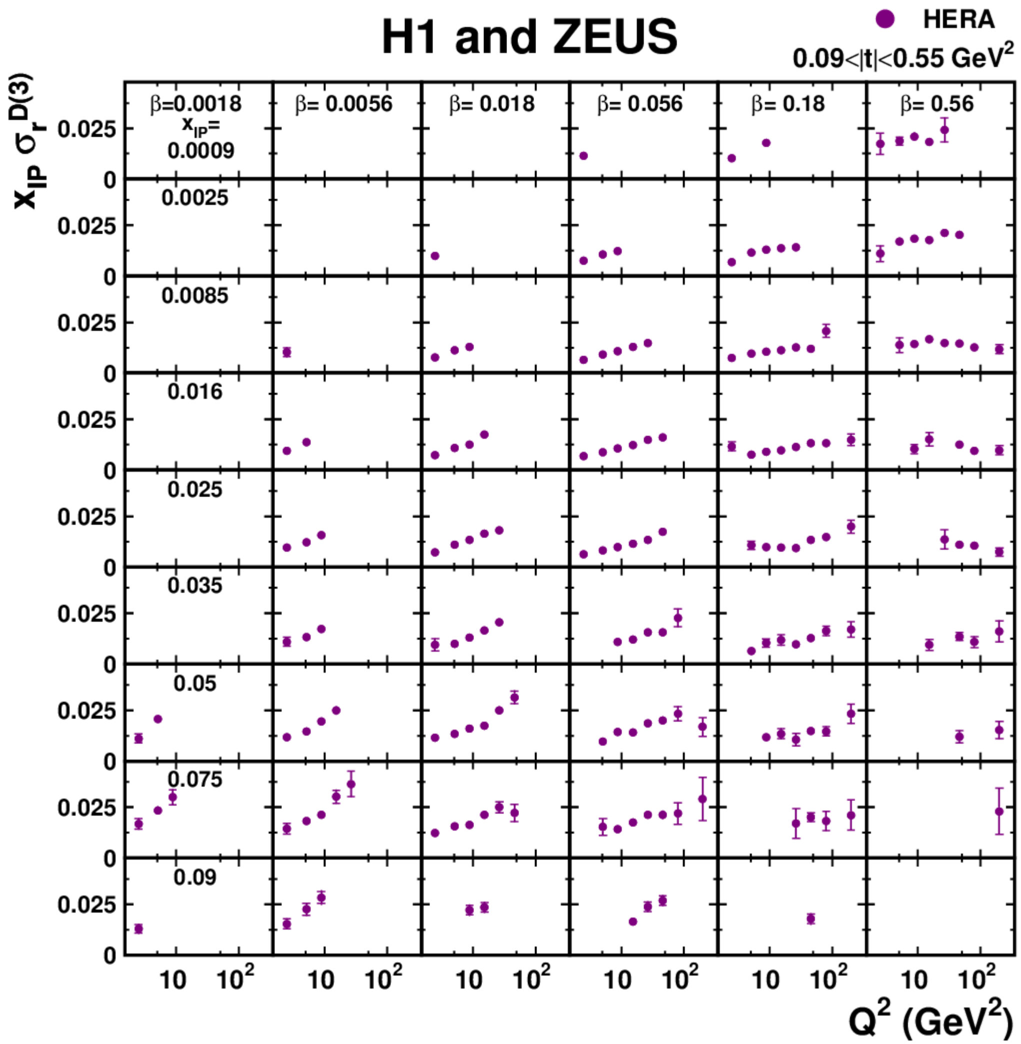
- The combination results is more precise results and
- wide kinematic range:
  - $2.5 \leq Q^2 \leq 200\ \mathrm{GeV}^2$
  - $0.0018 \leq \beta \leq 0.816$
  - $0.00035 \leq x_{IP} \leq 0.09$
  - $0.09 < |t| < 0.55\ \mathrm{GeV}^2$
- The results provide the most precise determination of the absolute normalization of $ep \rightarrow eXp$ cross section



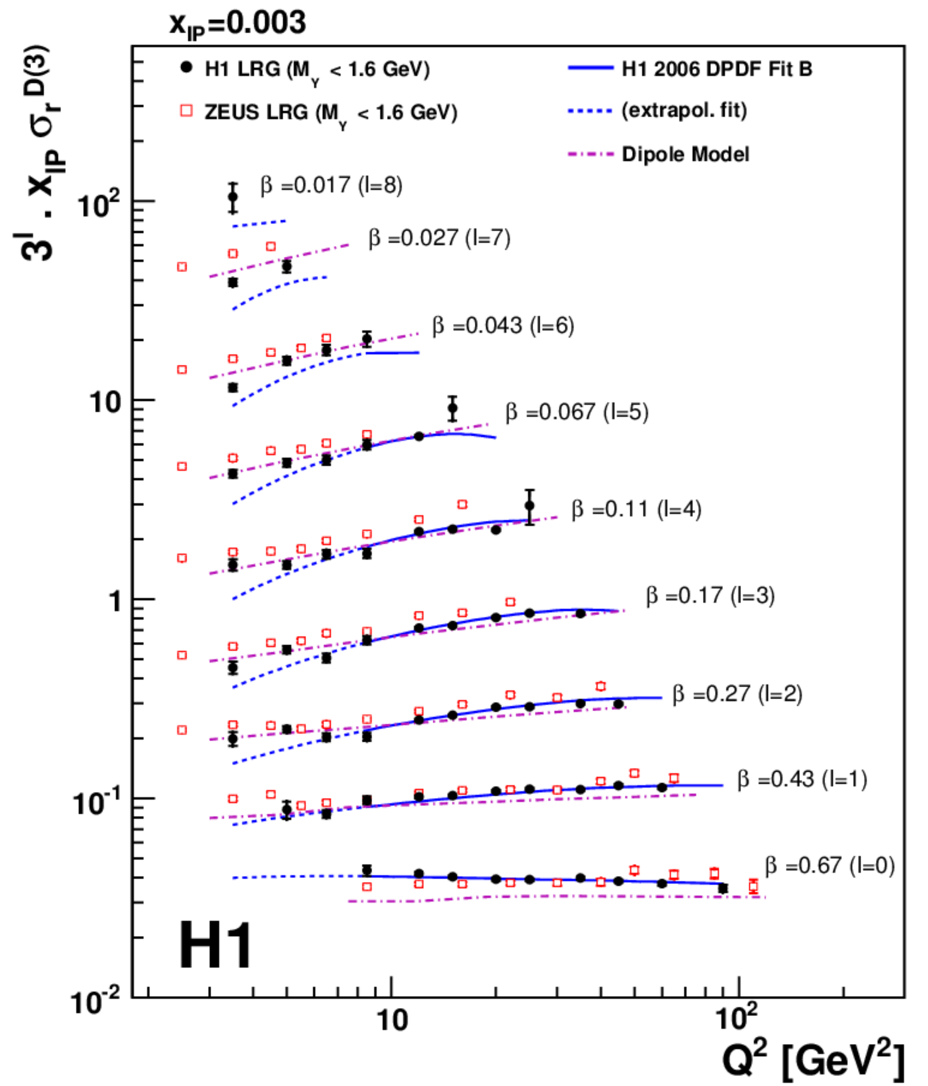
Large Rapidity Gap

EPJ C72 (2012) 2074

- Combined all H1 measurements
- LRG method
- Increase in statistics
- reduction of uncertainties

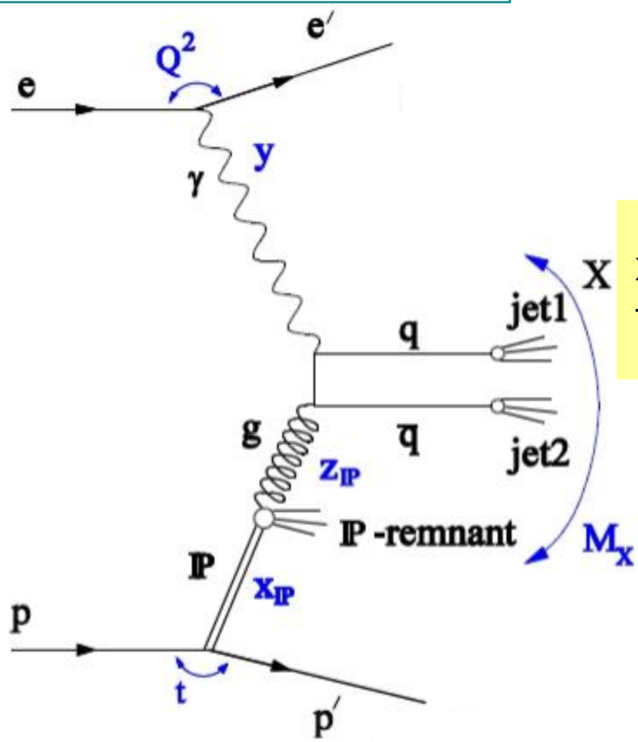
➔the dipole model can describe the low Q^2 kinematic domain

➔DPDF fits are more successful to describe the region of high Q^2



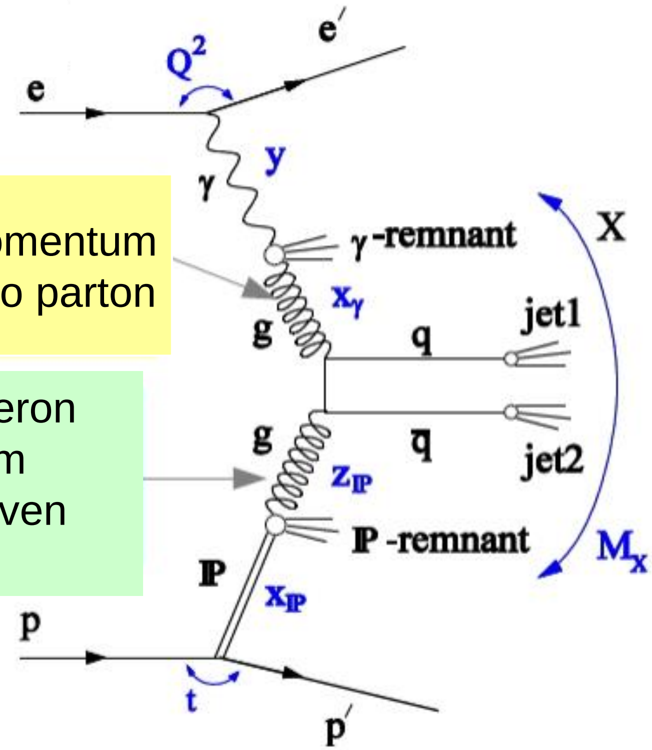
Direct photon:
No photon remnant
$X_\gamma = 1$ (at parton level)
Dominant for high Q^2 (DIS)

Resolved photon:
Photon remnant $x_\gamma < 1$
Dominant for low Q^2 (PhP)



x_γ – photon momentum fraction given to parton

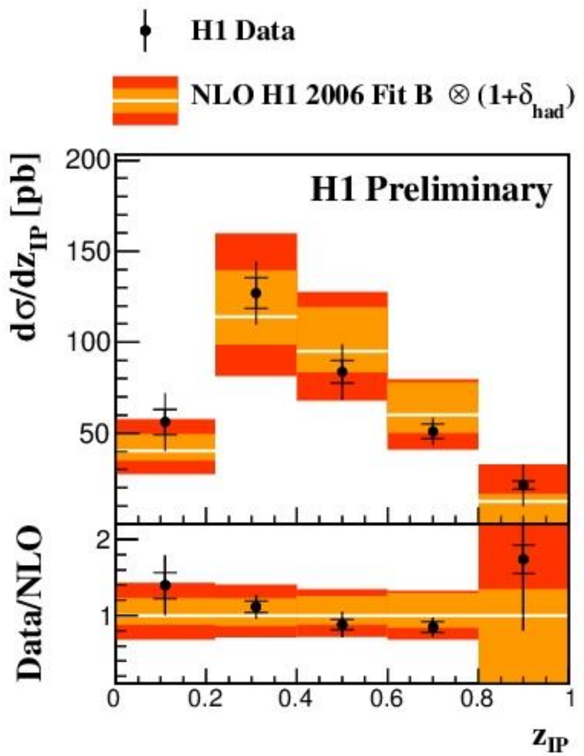
z_{IP} – pomeron momentum fraction given to parton

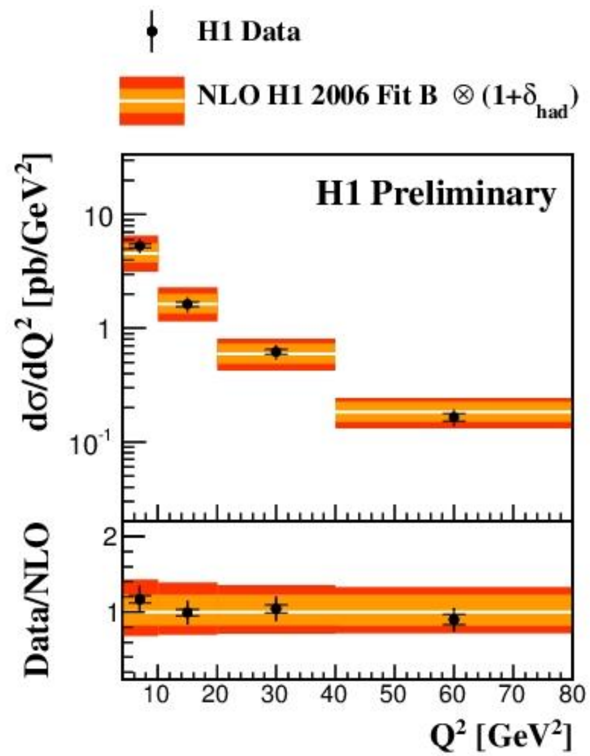


LO diagrams!

- High stat. and wide kin. range: $4 < Q^2 < 80$ GeV^2, $0.1<y<0.7$, $E_T > 5.5, 4.0$ GeV
- Data compared to NLOJET++ with DPDF H1 2006 Fit

H1 prel 14-014

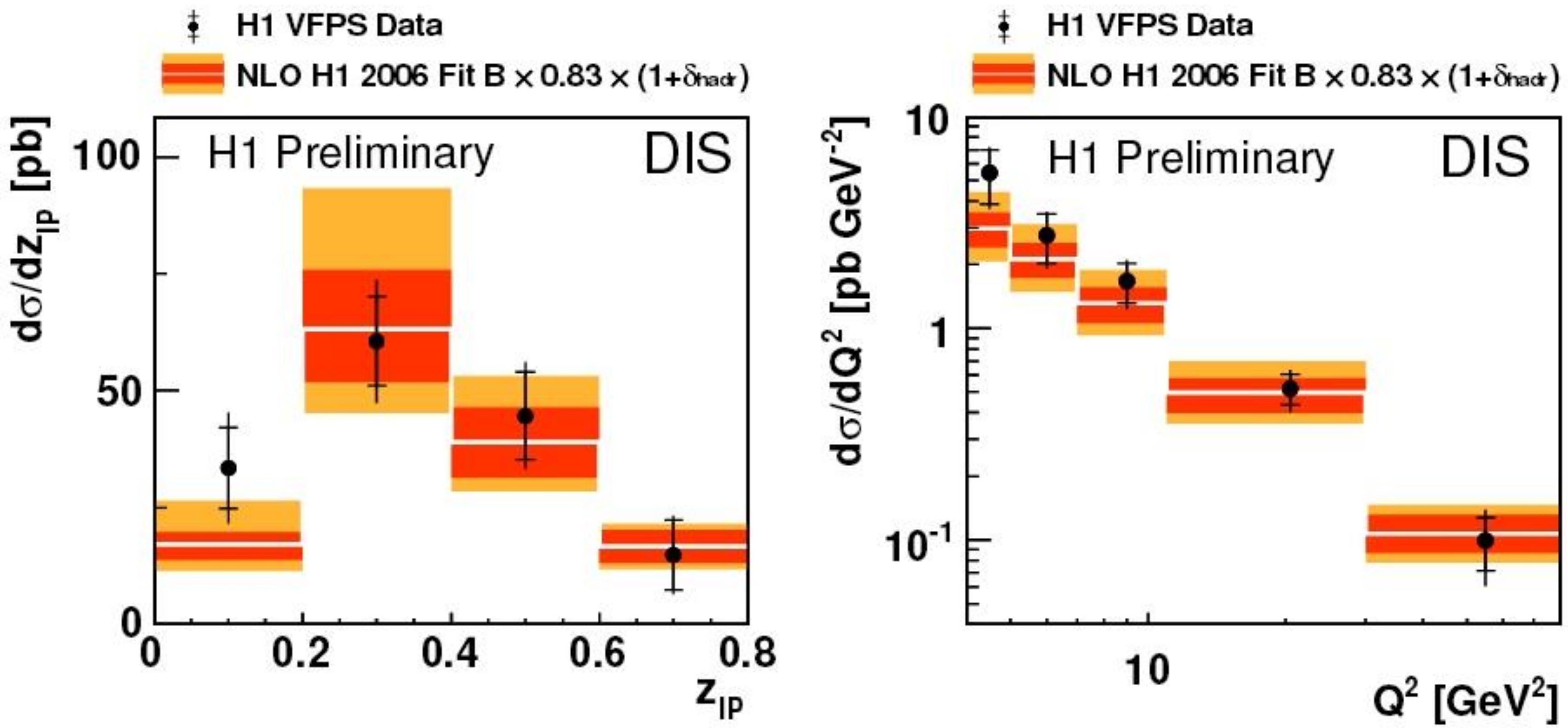




➔ NLO QCD predictions describe data
➔ Factorization theorem holds!

- Leading proton measured in Very Forward Proton Spectrometer
- Kinematic range: $4 < Q^2 < 80$ GeV^2, $0.2<y<0.7$, $E_T > 5.5, 4.0$ GeV

H1 prel 14-011

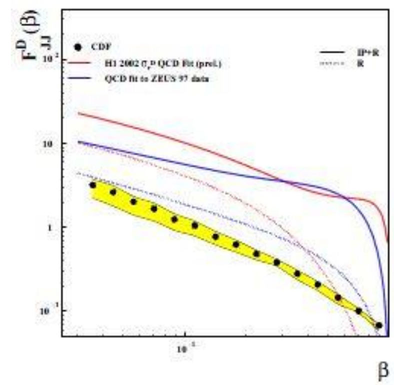


→NLO QCD predictions describe data

Diffractive dijets in PhP

- In diffractive DIS factorization experimentally confirmed by H1 and ZEUS
- in p − p collisions (Tevatron) the factorization is broken

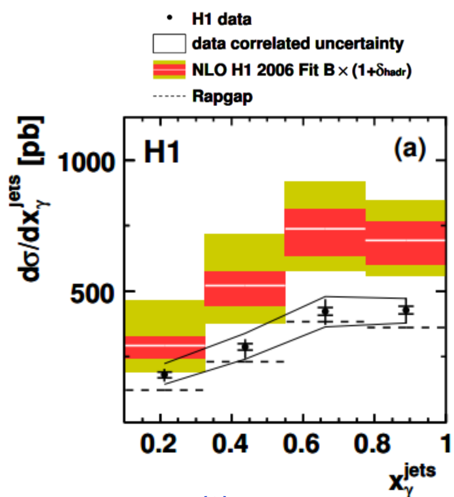
Tevatron vs HERA



S ≈ 0.1

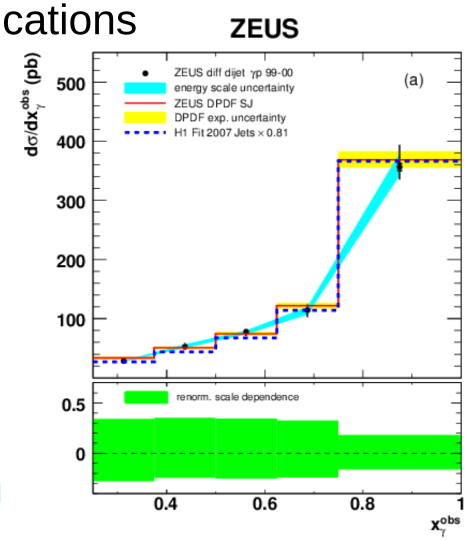
- factorization breaking observed by H1 in PhP, but not observed by ZEUS
- theory predicts suppression of resolved photoproduction
- the suppression is supposed to be stronger at low E_T scales and low x_γ
- however no x_γ dependence of suppression-factor visible

2010 publications



$E_T^{J1(2)} > 5(4)$ GeV

S ≈ 0.6



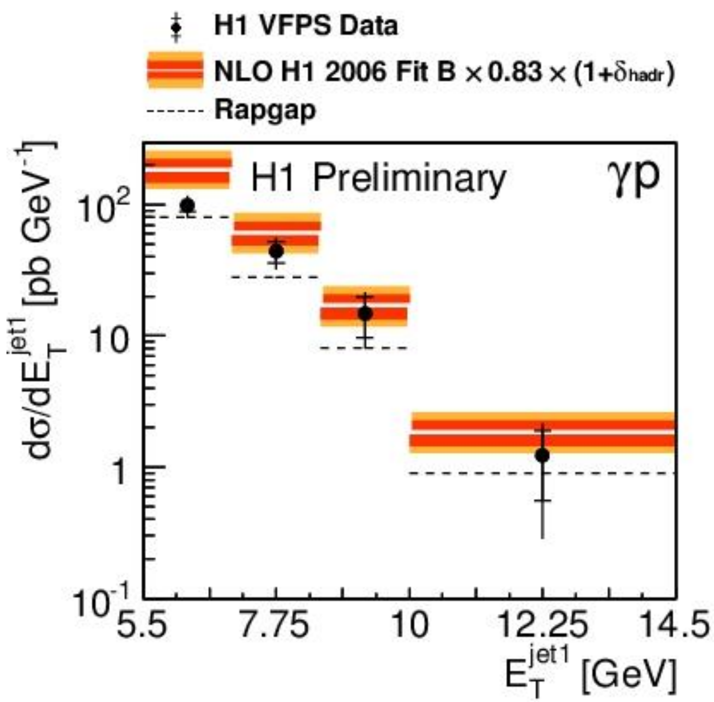
$E_T^{J1(2)} > 7.5(6.5)$ GeV

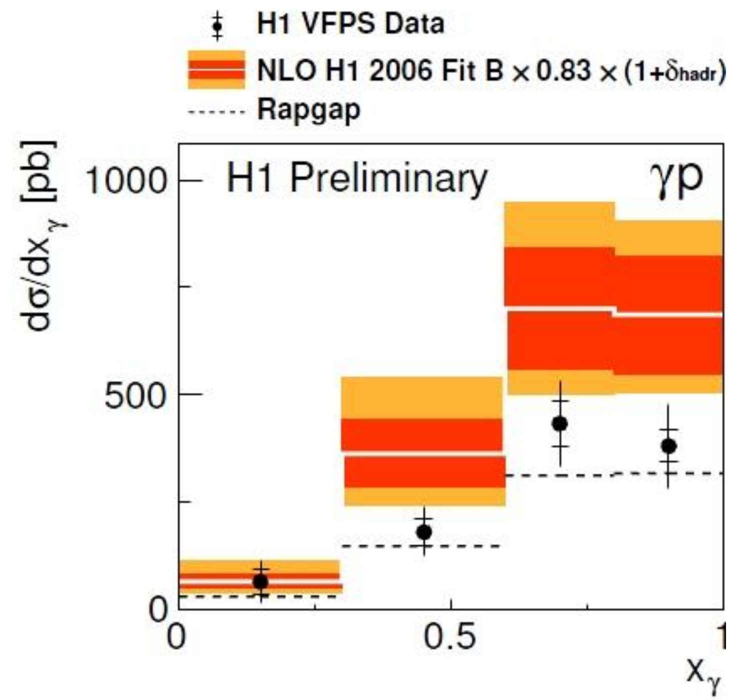
S ≈ 1.0

Diffractive dijets in PhP Leading Proton

- Leading proton measured in Very Forward Proton Spectrometer
- Kin. range: $Q^2 < 2$ GeV^2, $0.2<y<0.7$, E_T >5.5,4.0 GeV

H1 prel 14-011



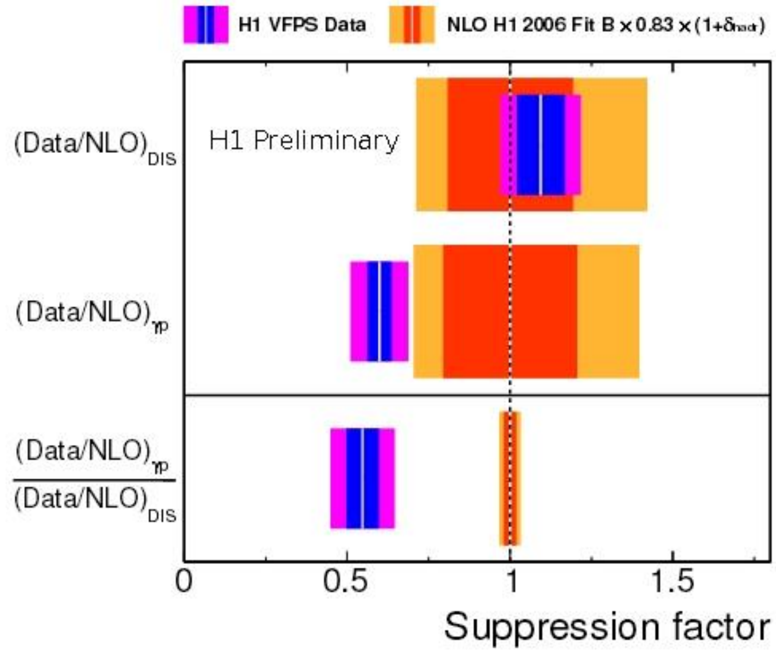


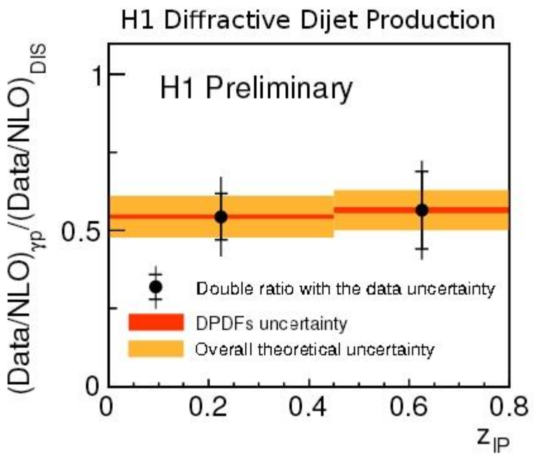
➔ Data lower than NLO prediction,
➔ No hints for a higher suppression for x_γ <1

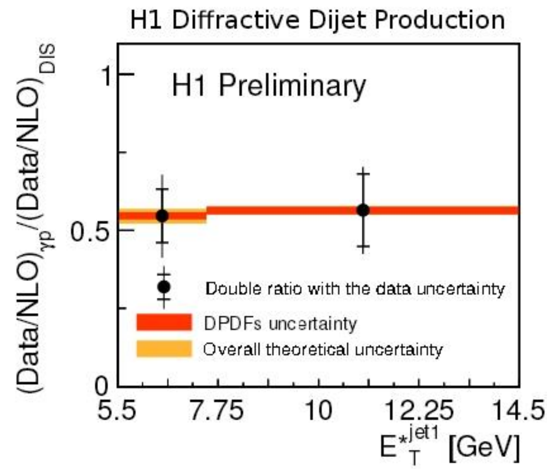
Diffractive dijets with leading proton, DIS and PhP

H1 prel 14-011

- Measurement with VFPS confirms LRG measurement
- Suppression factor in PHP
  S = 0.55 ± 0.10(data) ± 0.02(theor.)
- No hint of a dependence of the suppression on z_{IP} and E_T of leading jet







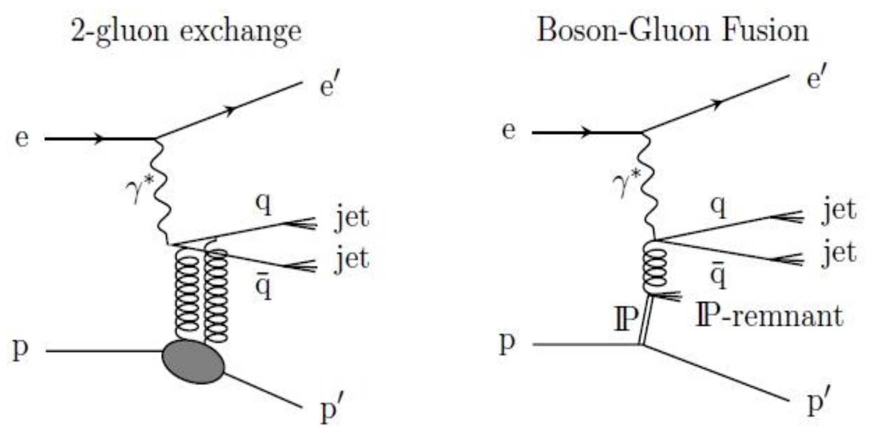
Diffractive dijets in DIS — Exclusive production

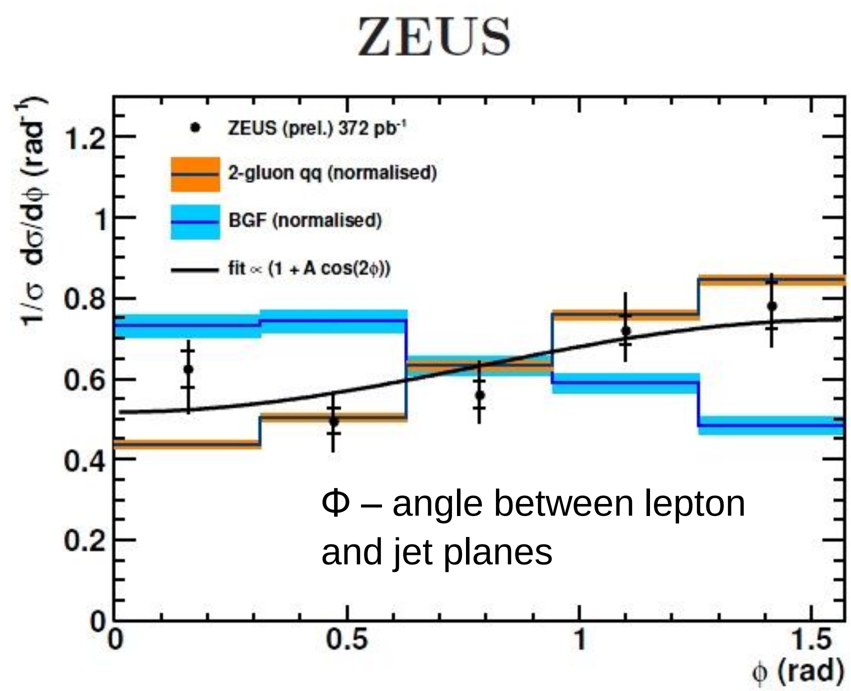
ZEUS prel 14-004

$e + p \rightarrow e' + p' + jet + jet$

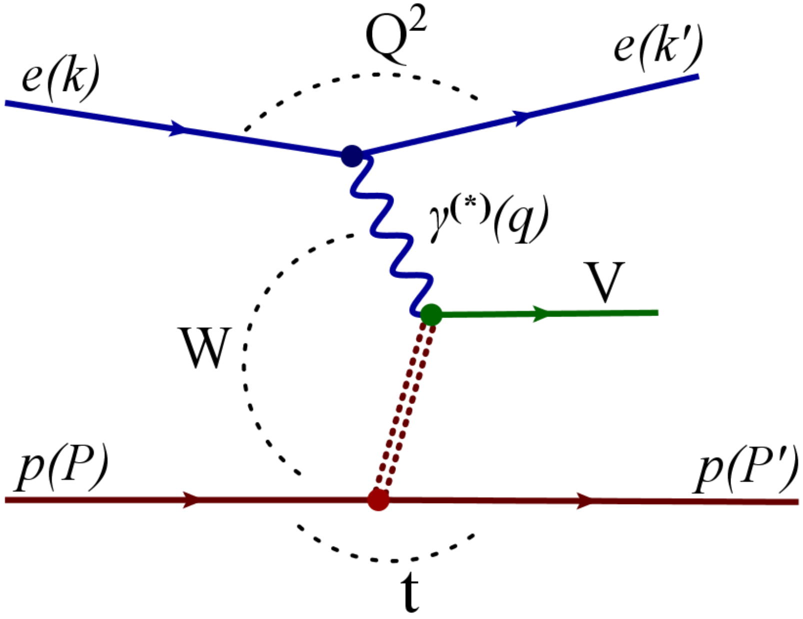
- High stat and wide kin. range: $Q^2 > 25$ GeV^2, 90<W<250 GeV, $P_T > 2$ GeV
- Measure of shape of the azimuthal angular distribution of exclusive dijets in DDIS
- Dijet reconstructed with k_t jet algorithm
- Data compared to
  - 2 gluon exchange model (perturbative calculations based on proton PDF)
  - BGF (calculations based on pomeron structure functions)

Data favour 2-gluon exchange model of $q\bar{q}$ production over BGF



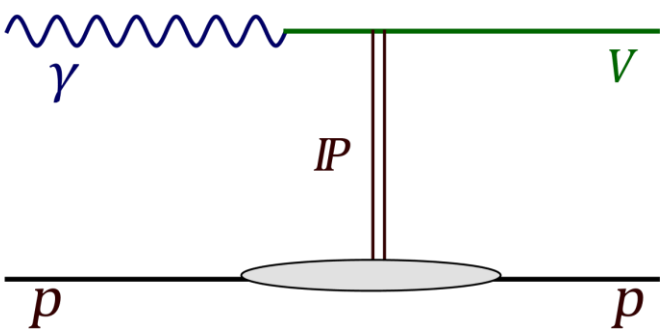


Vector meson production



Vector meson production

- Soft physics: Vector Dominace Model, Regge theory



$$\sigma \propto W_{\gamma p}^{\delta}$$

- Weak energy dependence, δ ~ 0.2

$$\delta = 4(\alpha_{IP}(t) - 1)$$

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

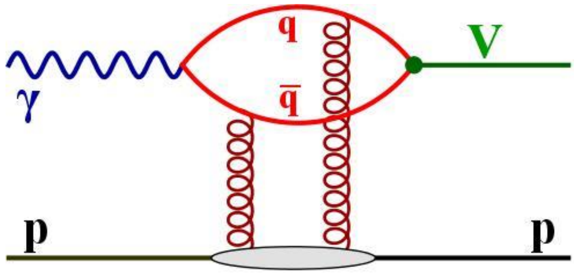
$$\frac{d\sigma}{dt} \propto e^{-bt}$$

- Shrinkage of diffractive peak

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

b_0 ~ 10 GeV^{-2}

- In presence of a hard scale (M_{VM}, Q^2, t) calculations in pQCD are possible



pQCD description (exchange of ≥ 2 gluons)

Fast increase of the cross section with energy due to the gluon density in proton

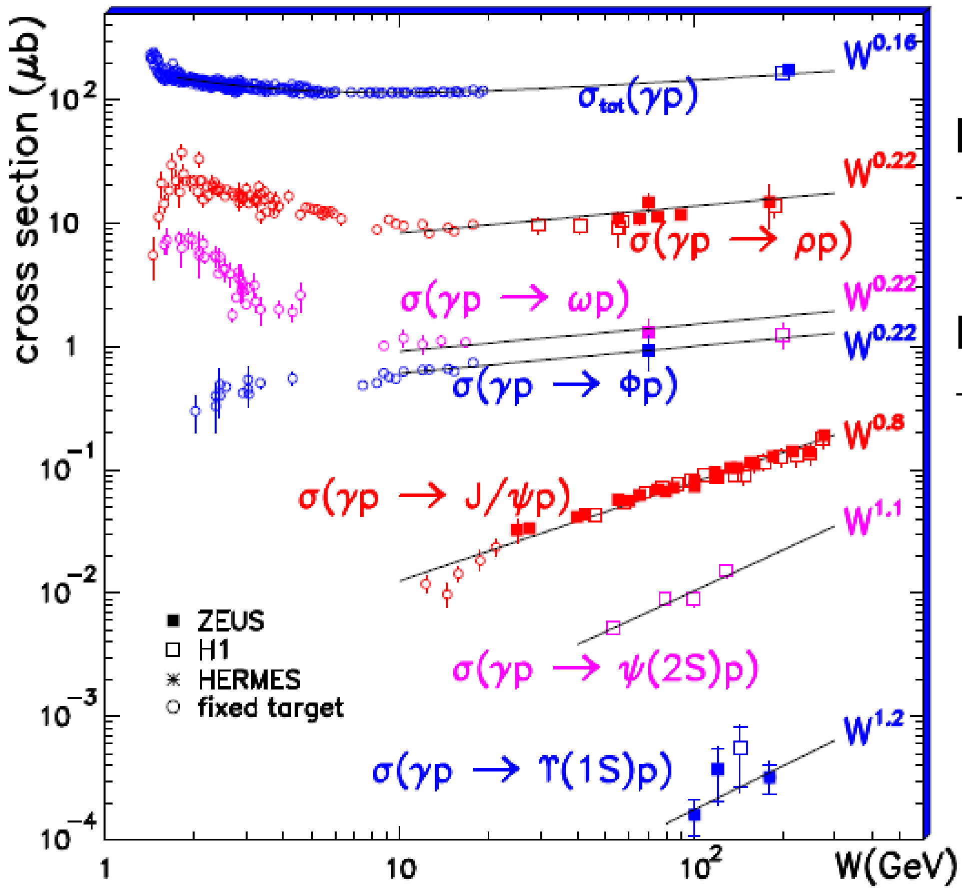
$$\sigma \sim |\, x\, g(x, Q^2)\,|^2$$

Large W corresponds to small x

$$W^2 \propto \frac{1}{x}$$

measurement of VM production cross section → test the transition between soft and hard processes

➢ The cross section dependence on W can be parameterized as: $\sigma \propto W_{\gamma p}{}^{\delta}$

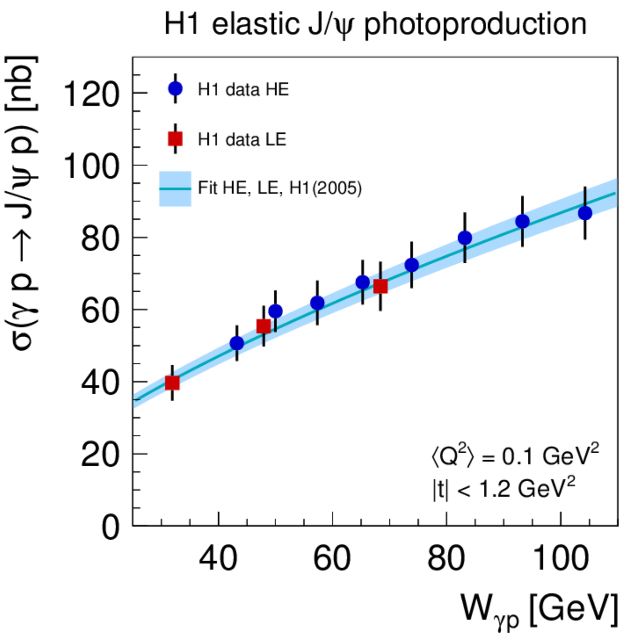


Low mass (ρ, ω, φ) – no perturbative scale → weak energy dependence

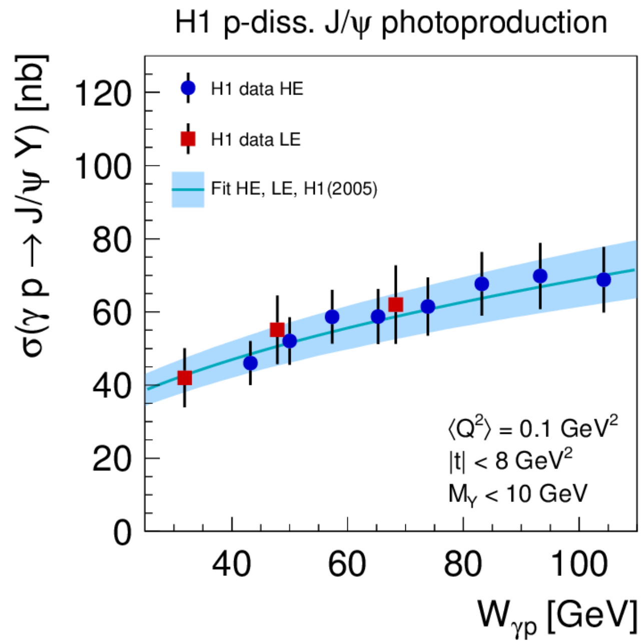
High mass (J/ψ, ψ',ϒ) – perturbative scale → strong energy dependence

J/Ψ photoproduction   Elastic and p-diss. vs $W_{\gamma p}$

Phys. J. C73 (2013) 2466



Kin. range:
$25 < W_{\gamma p} < 110$ GeV
$|t| < 1.2$ GeV^2 – elastic
$|t| < 8$ GeV^2 – p-diss



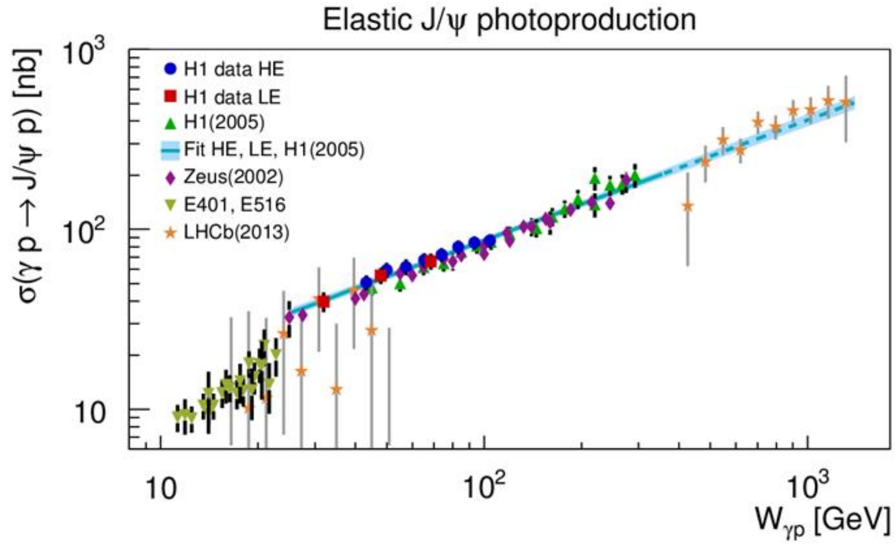
- Parameterization (for elastic and p-diss.): $\sigma = N (W_{\gamma p} / W_0)^{\delta}$ with $W_0 = 90$GeV
- Simultaneous fit of elastic and p-diss cross sections, including correlations, including previous H1 (EPJ C46(2006)585)
- Results: $\gamma p \rightarrow J/\psi p$: $\delta_{el} = 0.67 \pm 0.03$

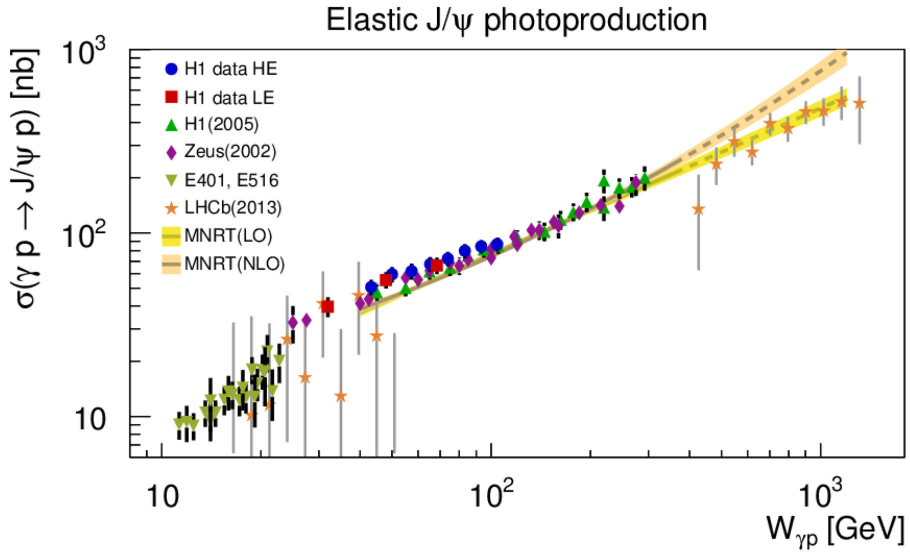
  $\gamma p \rightarrow J/\psi Y$: $\delta_{pd} = 0.42 \pm 0.05$
- The results is typical for the hard processes

Comparison to other experiments

Phys. J. C73 (2013) 2466

- H1 measurement in the transition region from fixed target to previous HERA data
- Good agreement with previous HERA measurements
- Fixed target data: steeper slope, lower normalization
- Fit to H1 data extrapolated to higher Wγp describes the LHCb data
- LO and NLO fit to previous J/ψ data and extrapolated to higher Wγp.





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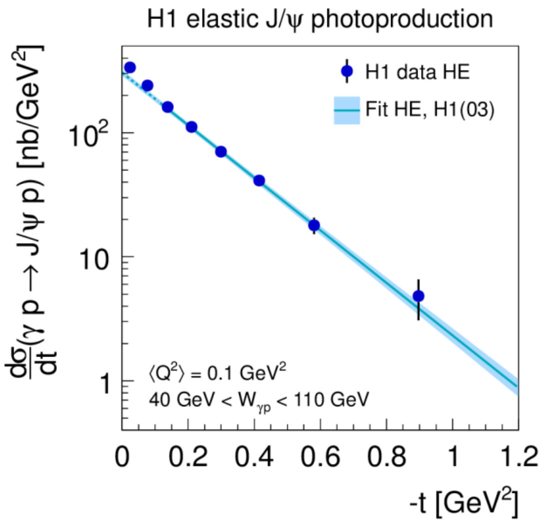
- The t-dependence of elastic cross section carries information about the transverse size of the interaction region
  - elastic: $d\sigma/dt = N_{el}\, e^{-b_{el}|t|}$
- p-diss cross section dominant for | t | > 1 GeV^2
  - p-diss: $d\sigma/dt = N_{pd}\,(1 + (b_{pd}/n)|t|)^{-n}$
- Results:

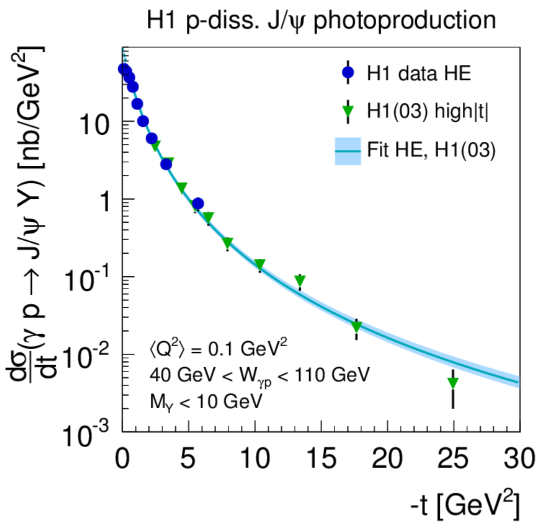
$\gamma p \to J/\psi p$: b_{el} = (4.88 ± 0.15) GeV^{-2}

$\gamma p \to J/\psi Y$: b_{pd} = (1.79 ± 0.12) GeV^{-2}

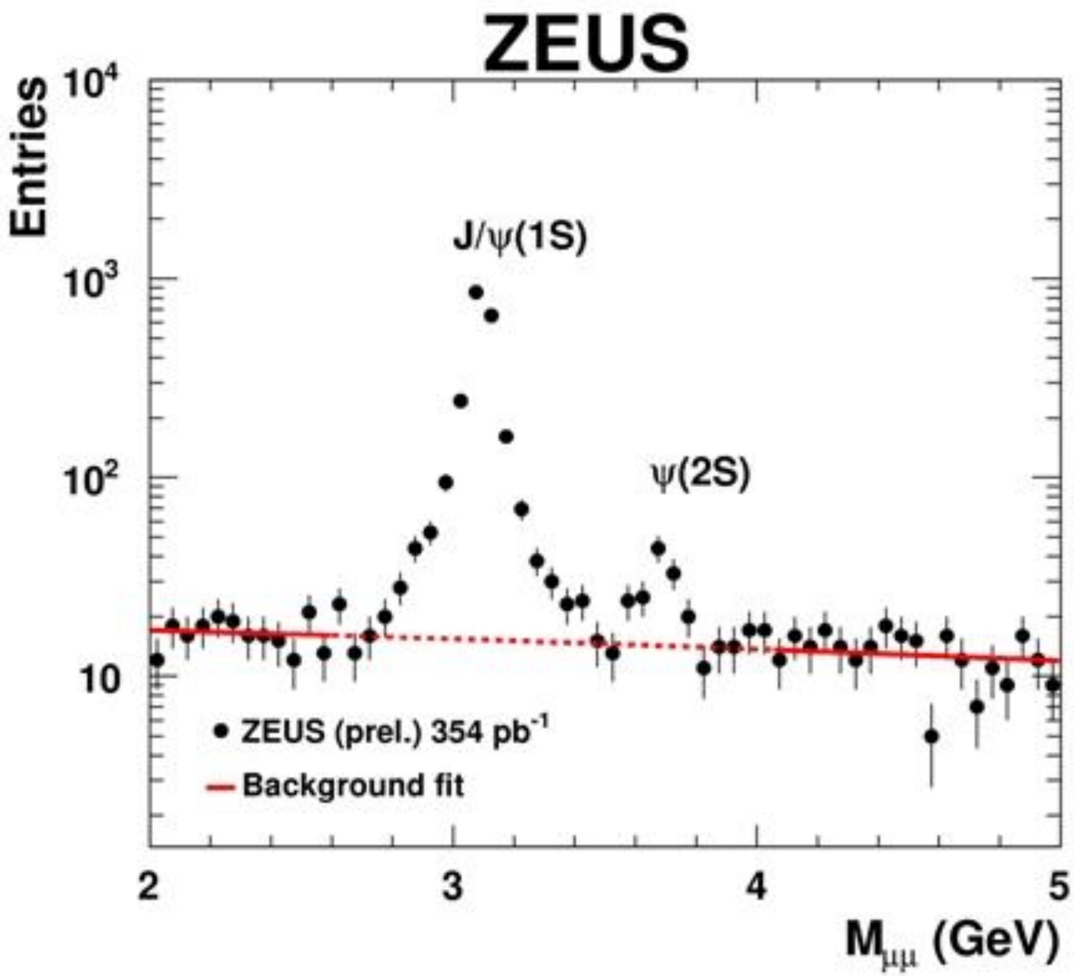
n = 3.58± 0.15

- The new data extend the reach to small values of |t|
- Slope parameter b_{el} is typical for the hard processes





Charmonium production in DIS $\sigma_{\Psi(2S)}/\sigma_{J/\Psi(1S)}$ ratio



$J/\psi(1S) \rightarrow \mu+\mu-$

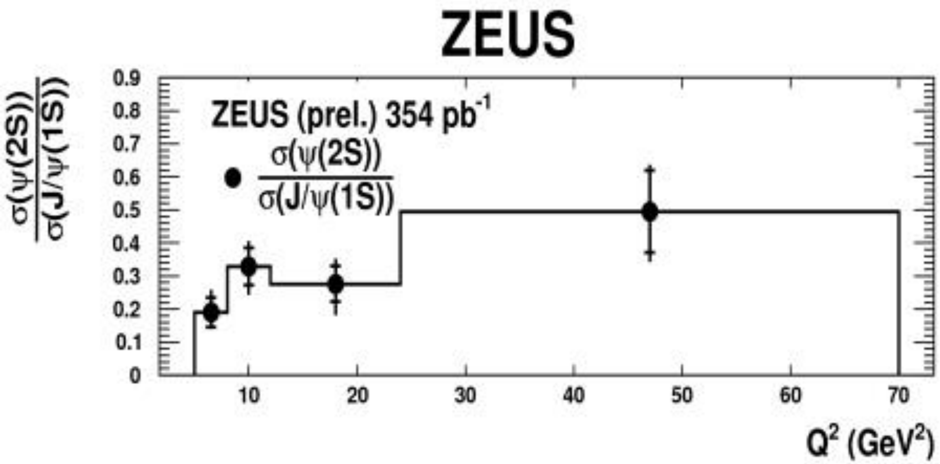
$\psi(2S) \rightarrow \mu+\mu-$

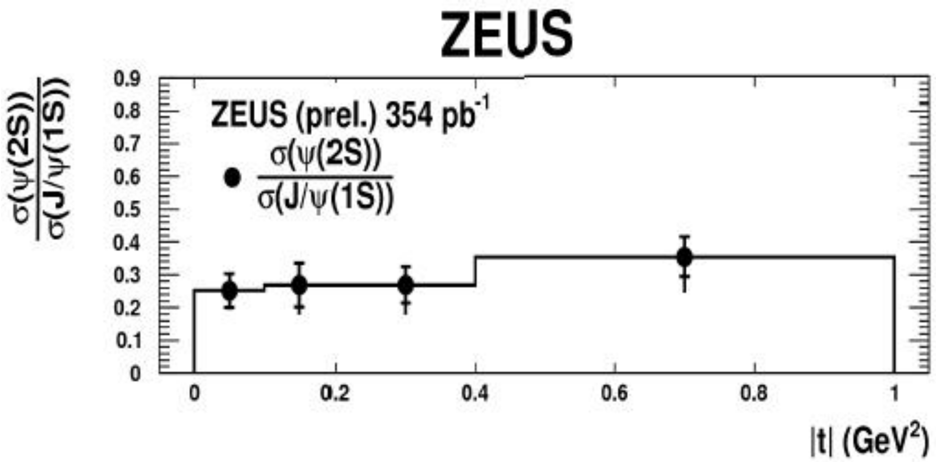
Kinematic range:

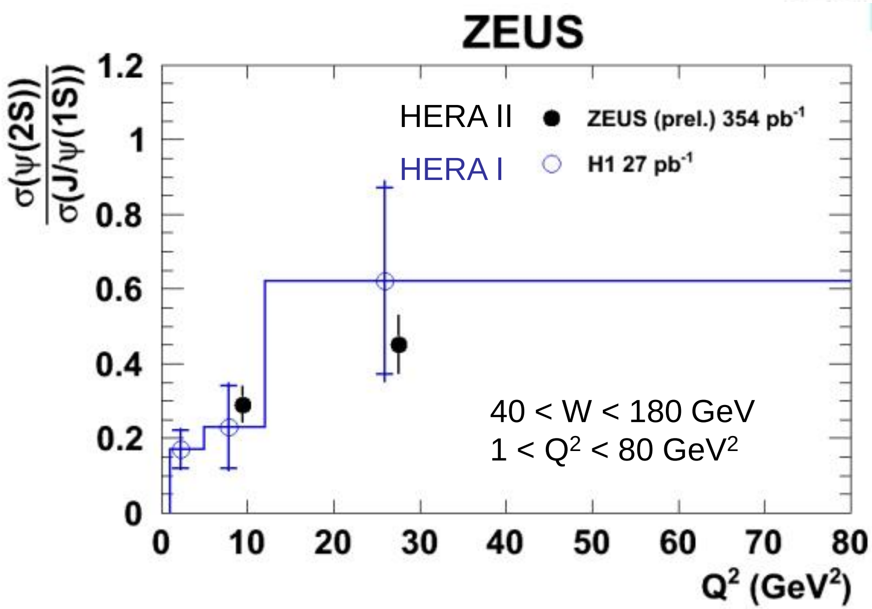
$30 \le W \le 210$ GeV
$5 \le Q^2 \le 70$ GeV^2
$|t| \le 1$ GeV^2

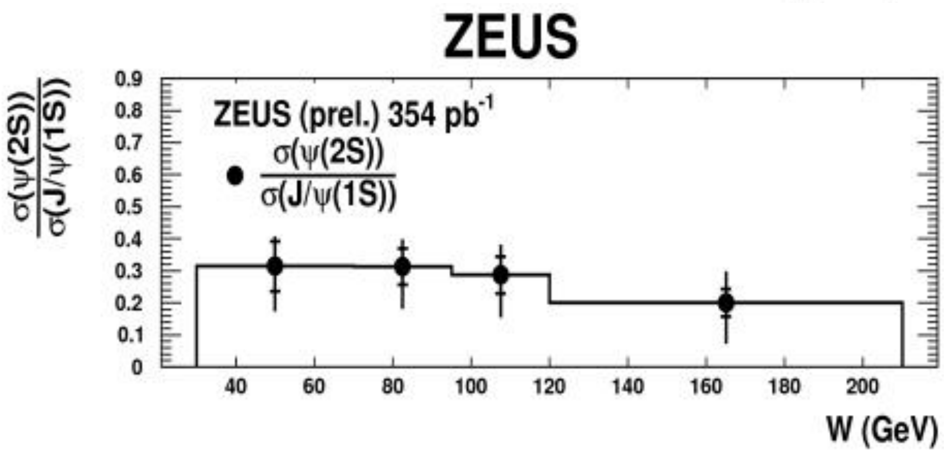
➔ $\sigma_{\Psi(2S)}/\sigma_{J/\Psi(1S)}$ ratio gives information about the dynamics of the hard process
➔ pQCD predicts rise of ratio with Q^2

Ratio σ(ψ(2S))/σ(J/ψ(1S)) vs Q^2, W and |t|







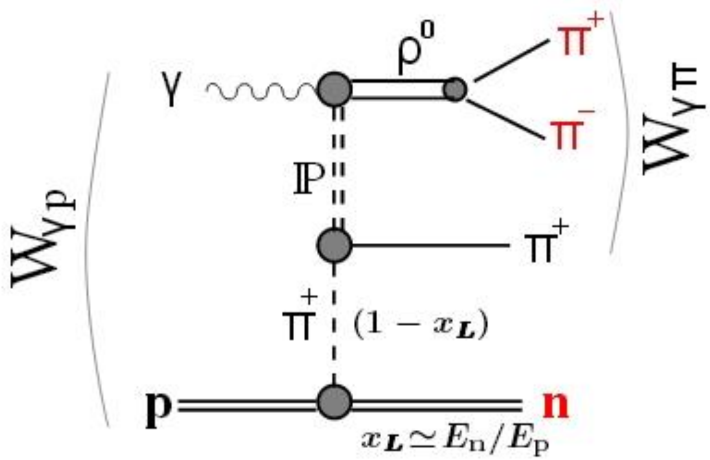


- Indication of an increase with Q^2
- Independent of W
- Independent of |t|

- Significantly improved accuracy → Lumi ↑ for HERA II

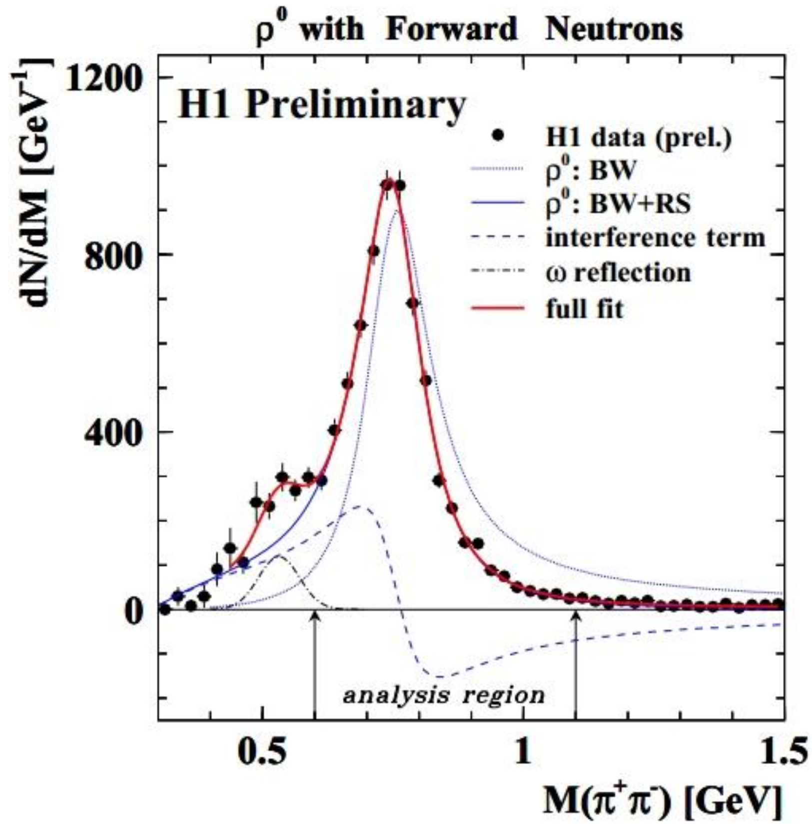
Exclusive PhP of ρ^0 meson with forward neutron

H1 prel 14-013



- double peripheral process (DPP), involving π-exchange at the proton vertex

Kinematic range: $Q^2 < 2$ GeV^2, $|t| < 1$ GeV^2,
$20 < W_{\gamma p} < 100$ GeV, $E_n > 120$ GeV

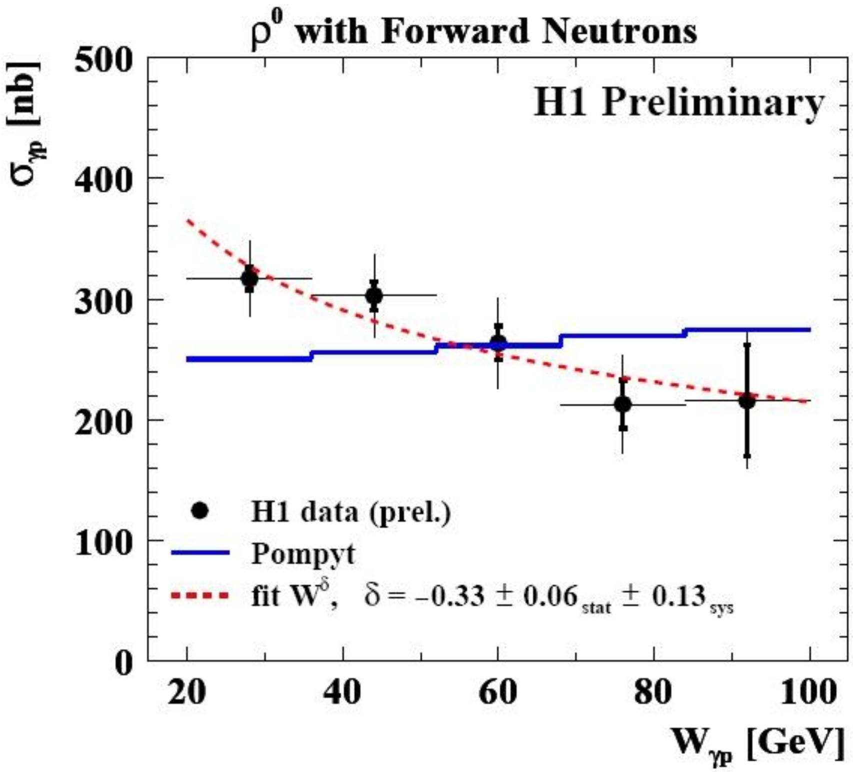


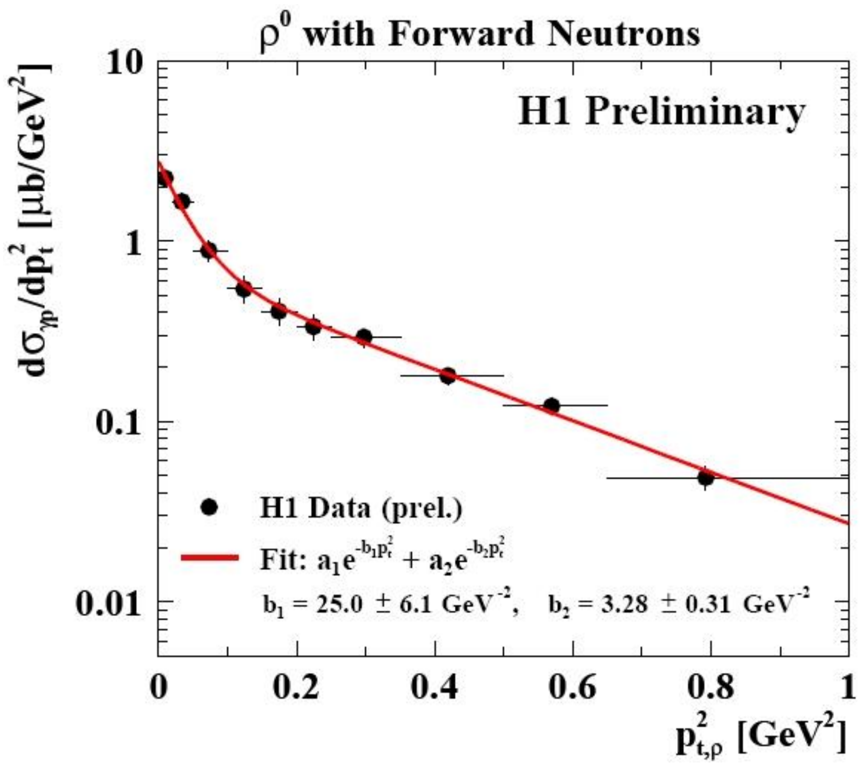
No hard scale present ⇒ Regge framework is most appropriate

Process measured for the first time at HERA

Exclusive PhP of ρ^0 meson with forward neutron

H1 prel 14-013





- Regge motivated fit W^δ yields $\delta < 0$
  (in qualitative agreement with DPP and in contrast to MC, $\delta_{MC} = 0.08 \pm 0.02$, which is expected from purely IP exchange)

- DPP explanation:
  low mass $\pi^+ n$ state → large slope
  high masses → less steep slope

Differential cross sections $d\sigma/dp^2_{t,p}$ show the behaviour typical for exclusive DPP

Summary

- Combined proton spectrometer data provide better precision
- LRG Inclusive Diffraction is measured with improved precision
- QCD factorization is confirmed by diffractive dijet measurements in DIS; Data described by NLO QCD calculations
- H1: suppression of diffractive dijet photoproduction ZEUS: no suppression; difference between measurements is not understood
- The cross section of p-diss. diffractive J/ψ production is measured precisely at small $|t|$ for the first time at HERA.
- Photoproduction cross section for exclusive ρ^0 production associated with leading neutron is measured for the first time at HERA.

Thank you for your attention!