Review of Diffraction at HERA

+ recent results

Alessia Bruni

INFN Istituto Nazionale di Fisica Nucleare

on behalf of H1 and ZEUS Collaborations

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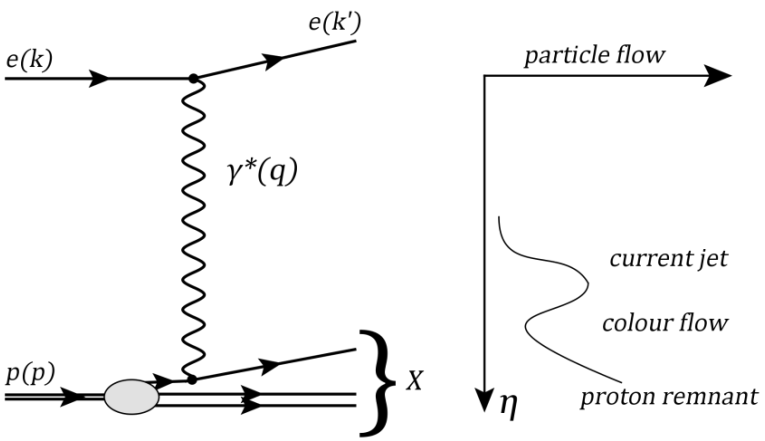
HERA ep collider 1992 – 2007, DESY, Hamburg

- **The world's only electron/positron-proton** collider
- **E_e = 27.6 GeV, E_p = 920 GeV** (820, 460, 575 GeV)

- **total luminosity ~ 0.5 fb^{-1} per experiment**

Diffractive scattering

Deep Inelastic Scattering (DIS)



Q^2 = $-q^2$ - virtuality of the photon

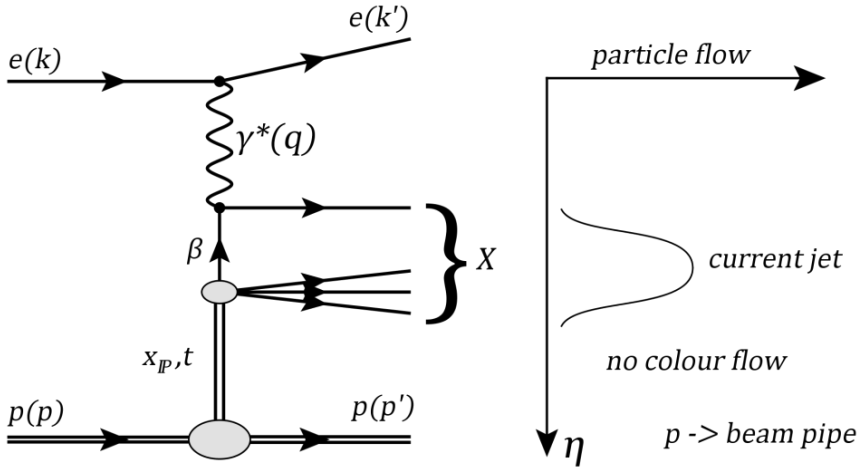
$Q^2 \approx 0$ photoproduction, $Q^2 > 0$ DIS

W photon-proton CME

x Bjorken-x: fraction of proton's momentum carried by struck quark

y = Pq/Pk inelasticity

Diffractive Scattering (DDIS)



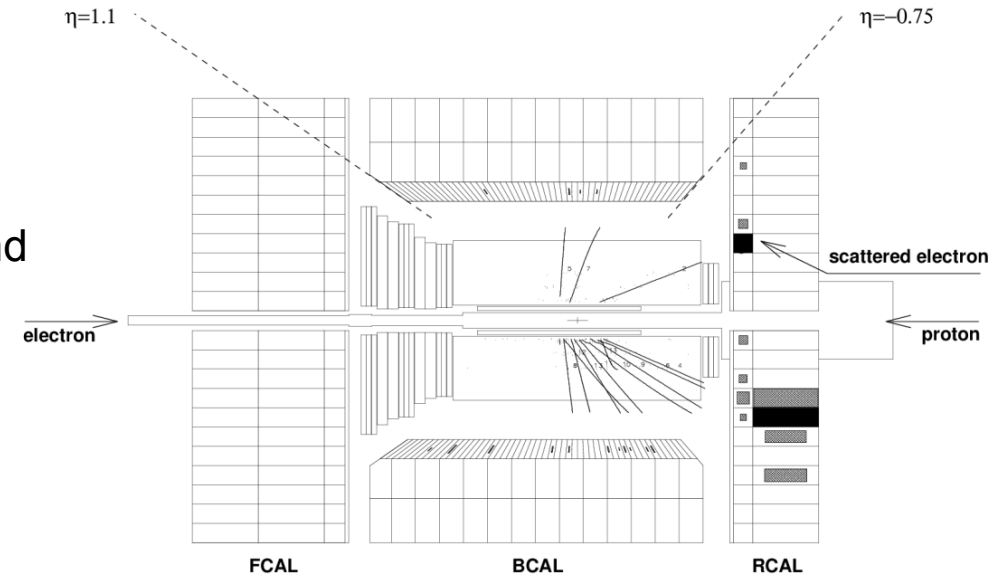
x_{IP} fraction of proton's momentum of the colour singlet system

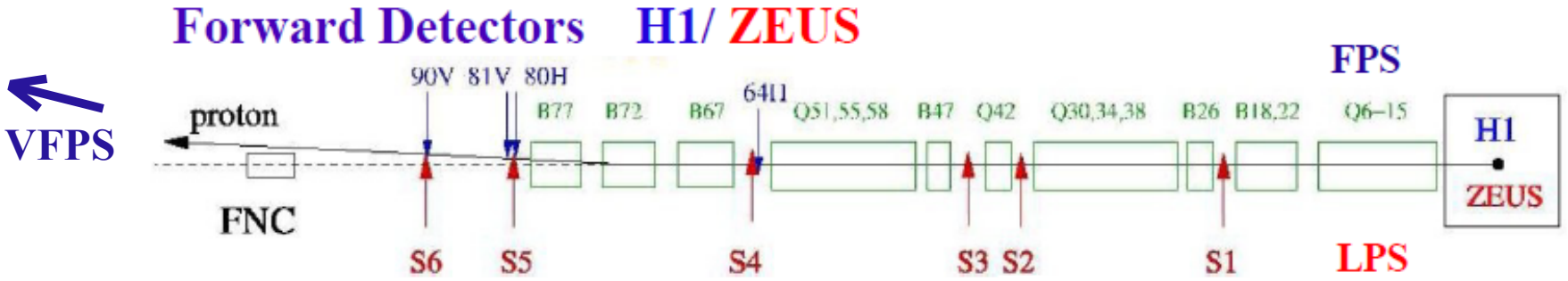
t = $(p-p')^2$ 4-momentum transfer squared at proton vertex

β = x/x_{IP} fraction of IP carried by the quark "seen" by photon

Experimental Methods

- Large Rapidity Gap:
  - high statistics
  - contains proton dissociative background
- Proton spectrometer:
  - low statistics
  - no proton dissociative background
  - Measurement of t variable





Diffractive cross section

- Inclusive diffractive cross section (analogy to inclusive DIS):

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

- reduced diffractive cross section is:

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

- Integrate over t when proton is not tagged → $\sigma_r^{D(4)}(\beta, Q^2, x_{IP})$
- $\sigma_r^{D(4)} \approx F_2^{D(4)}$ at low and medium y
- $\sigma_r^{D(4)} = F_2^{D(4)}$ if $F_L^{D(4)} = 0$

Factorisation

- QCD factorisation - rigorously proven

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

DPDFs – obey DGLAP, universal for diff. ep DIS

hard scattering cross section

- proton vertex factorisation – experimentally proven

$$f_i^D(x, Q^2, x_{IP}, t) \sim f_{IP/p}(x_{IP}, t) f_{i/IP}^D(\beta, Q^2)$$

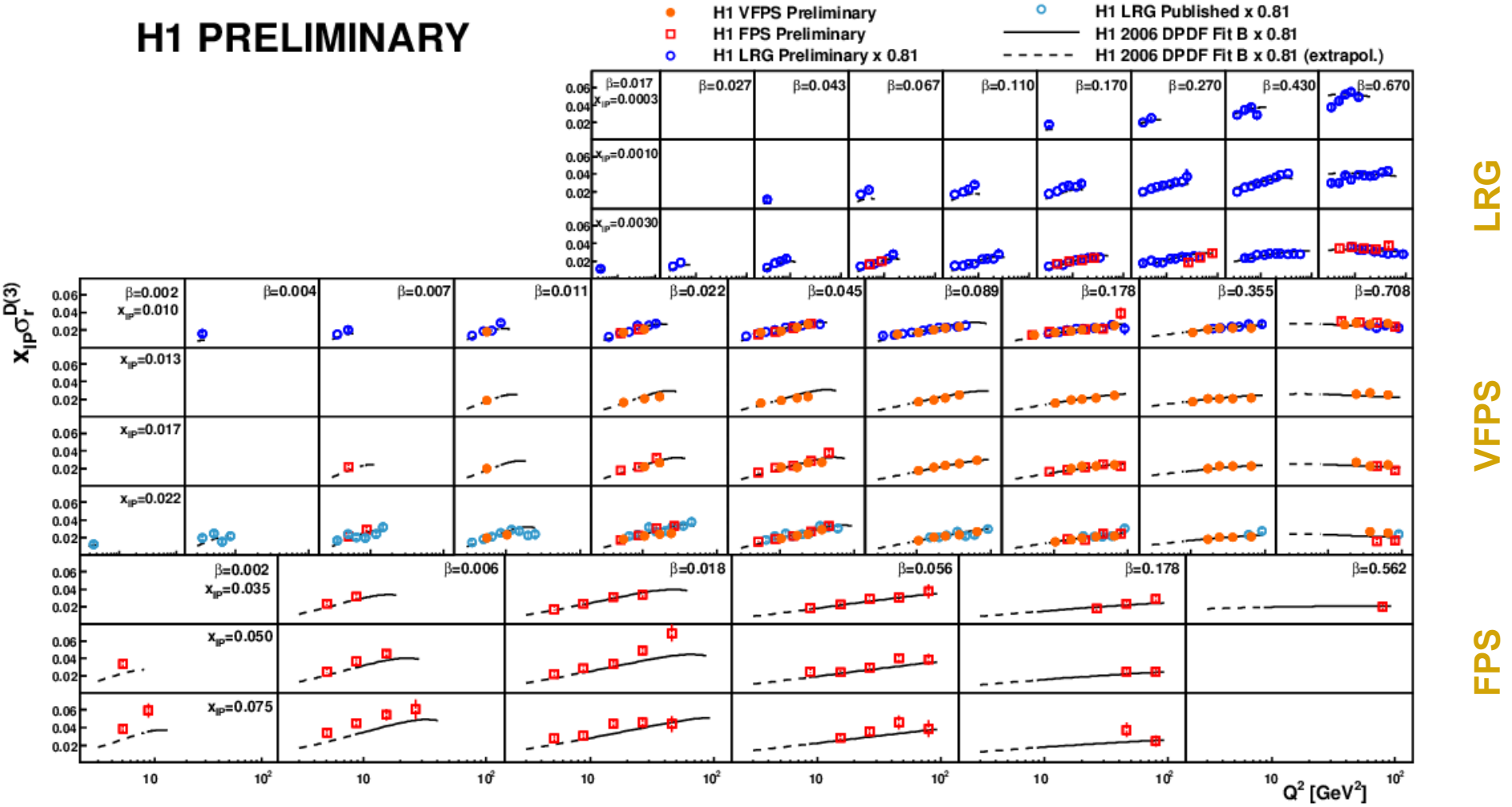
Pomeron flux factor

Pomeron PDF

- Goal: extract DPDFS from inclusive diffr. data and use them together with NLO calculations to predict diffractive charm and jet production

Diffractive Structure Function Measurements

- Experimental summary of H1 σ^D measurements

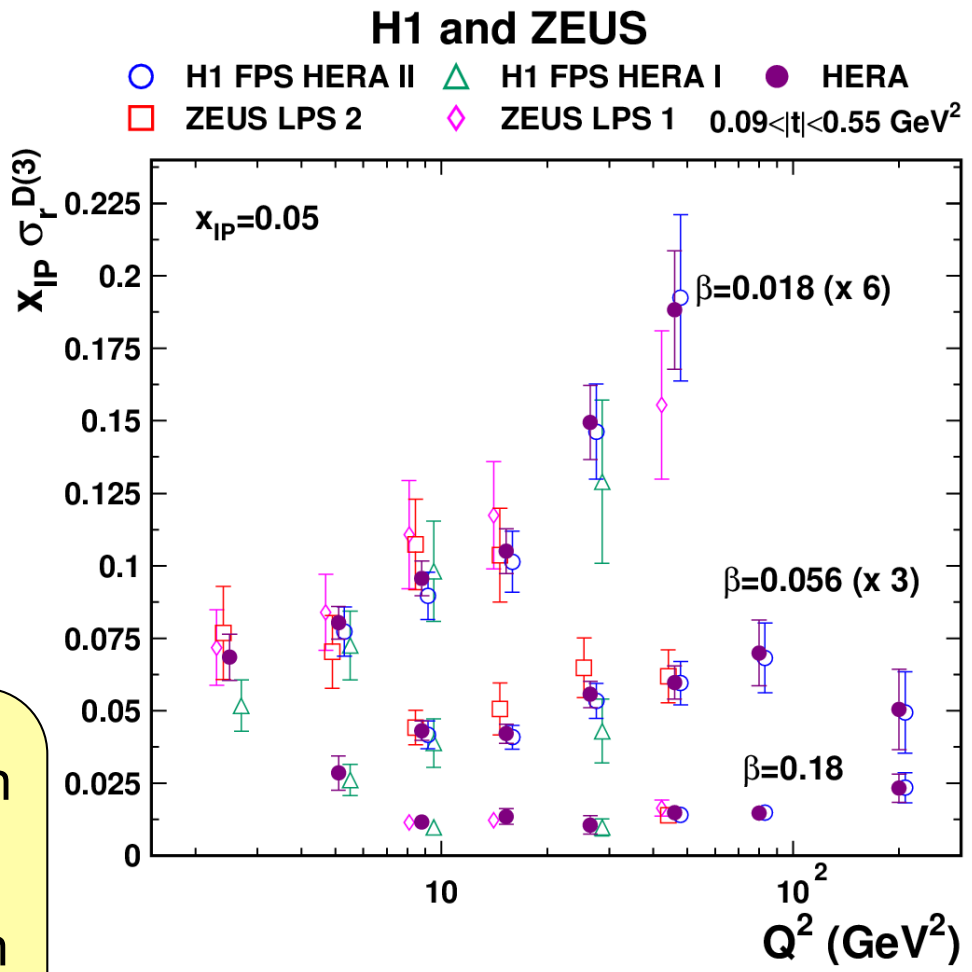


- Data consistent in the region of overlap of the different techiques
- The data compare well with DPDF fits

HERA combined inclusive diffractive cross sections -LP

Eur. Phys. J. C72 (2012) 2175

- Proton spectrometers to detect the leading protons
- 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



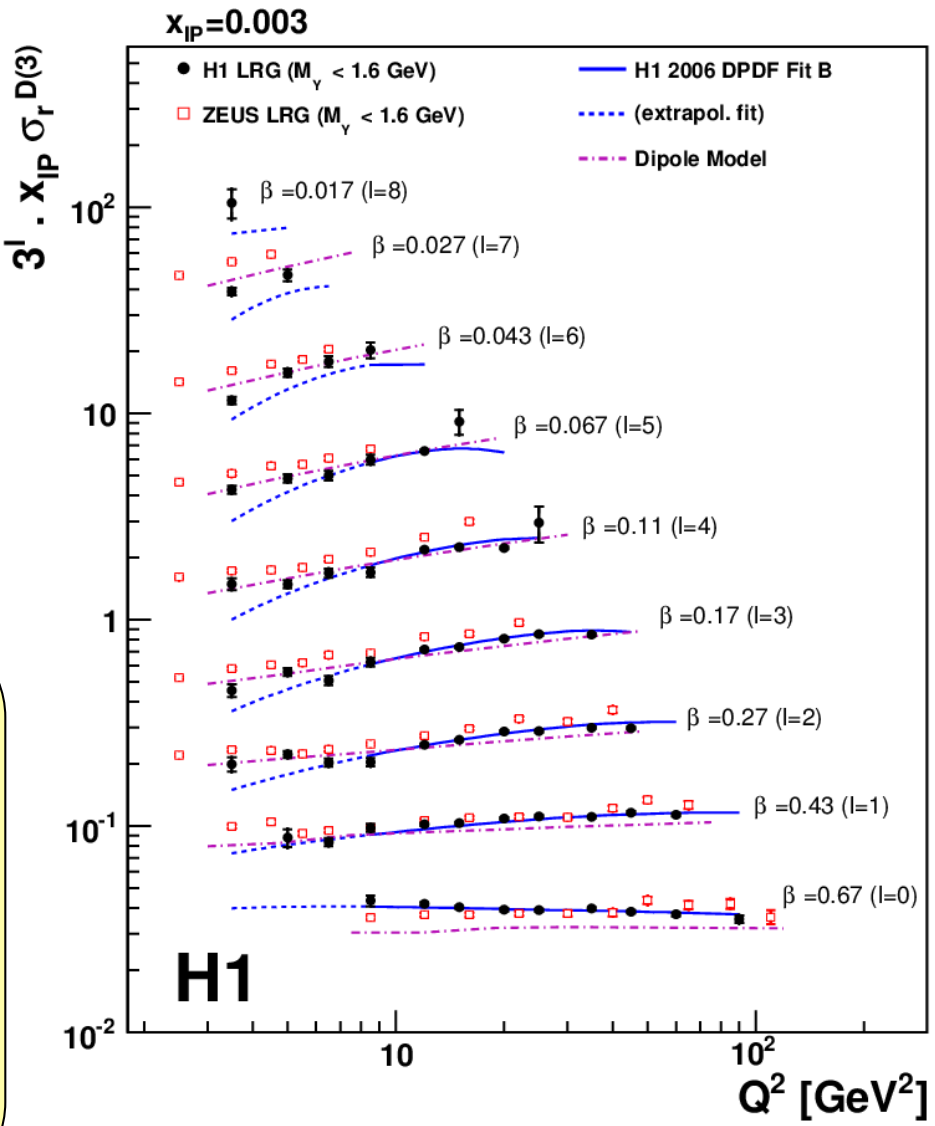
- The input data are consistent with χ^2_{min}/ndof = 133/161
- Total uncertainty on cross section is 6% for the most precise points

Inclusive Diffractive DIS at HERA, Large Rapidity Gap

EPJ C72 (2012) 2074

- Combined H1 measurements
- Increase in statistics, reduction of uncertainties
- Data compared to DGLAP and dipole models

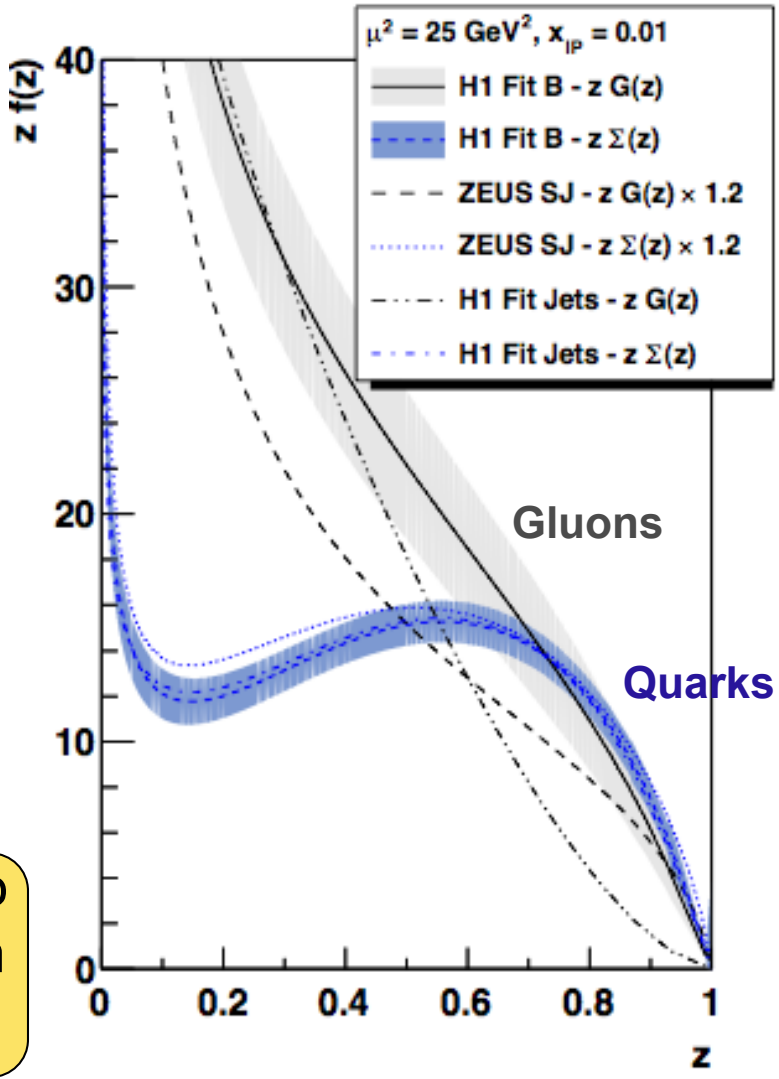
- the dipole model can describe the low Q^2 kinematic domain better than H1 DPDF fits
- DPDF fits are more successful to describe the region of high Q^2
- No unique picture for describing data



Diffractive PDFs

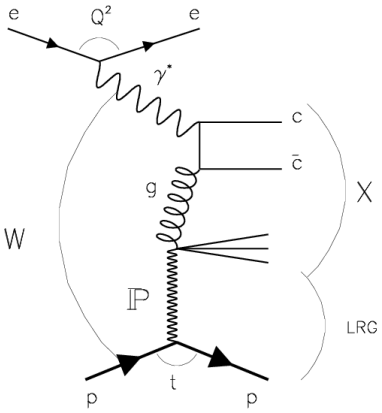
R.Zlebcik,K.Cerny,A.Valkarova,EPJ C71, (2011) 1741

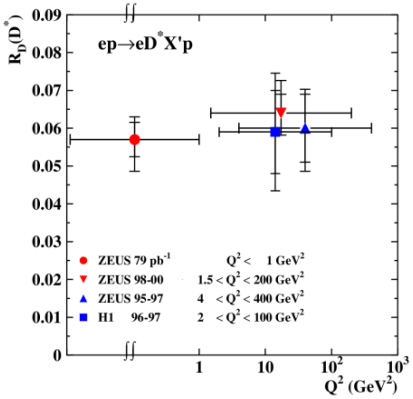
- DPDFs obtained by H1 and ZEUS from inclusive, dijet
- z - the longitudinal four-momentum fraction of the parton entering the hard sub-process with respect to Pomeron
- Gluon exchange dominates
- DPDF fits used in NLO calculations to predict diffractive production of charm and jets



Diffractive production of $D^{*\pm}(2010)$ at HERA

- Charm provides a hard scale, ensuring the applicability of pQCD even for low Q^2
- is sensitive to the gluon content of the diffractive exchange
- R_D=fraction of charm production diffractive/ inclusive is approximately independent of Q^2

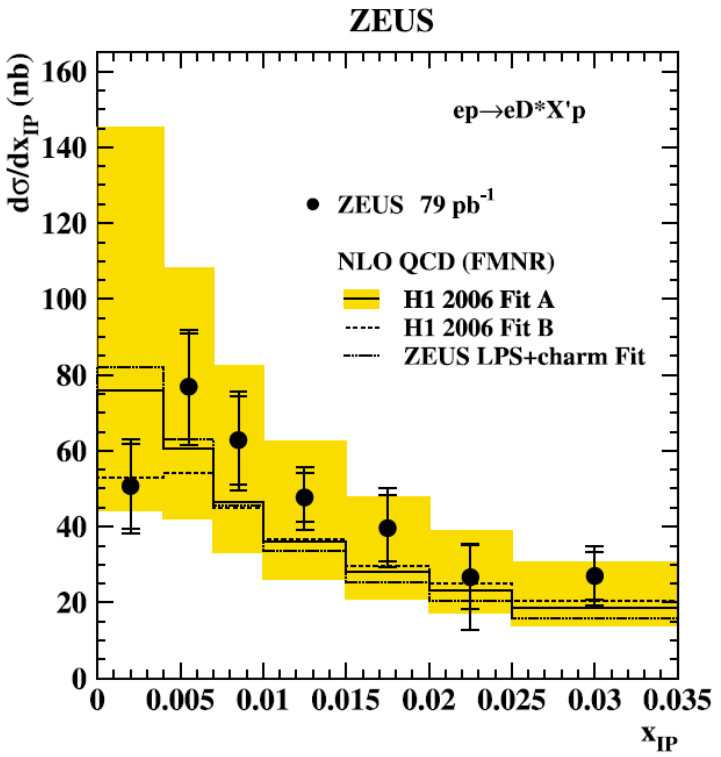




Eur. Phys. J. C 51 (2007) 301-315

D^* diffractive photoproduction:

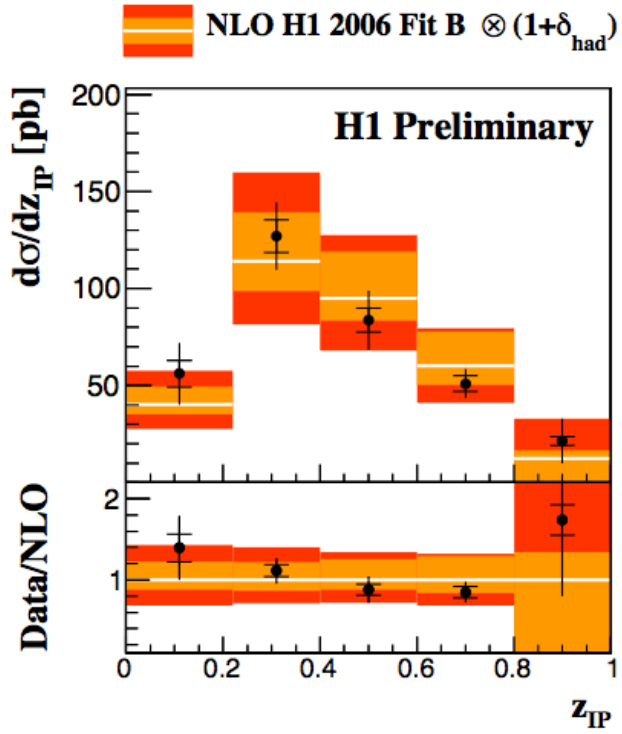
- The NLO QCD calculations reproduce the x_{IP} differential cross section in both shape and normalization.
- Supports the QCD factorisation theorem in diffraction, implying the universality of diffractive PDFs

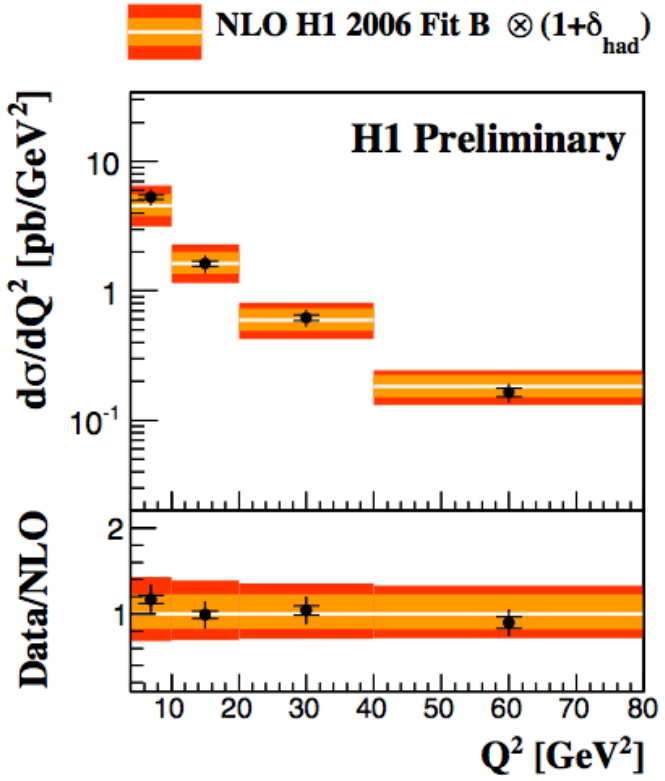


NEW! Diffractive dijets in DIS, Large Rapidity Gap

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

H1 prel 14-014



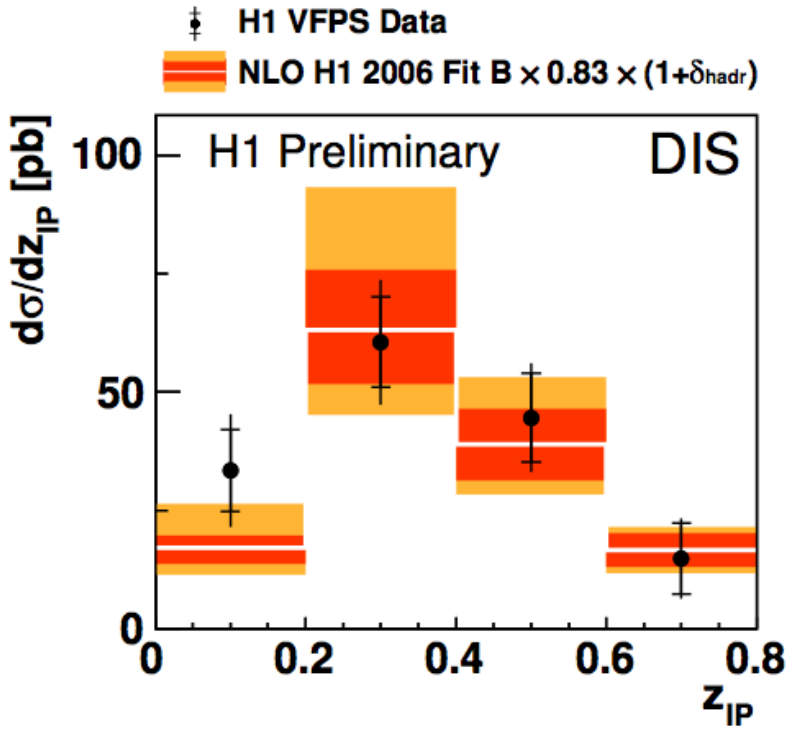


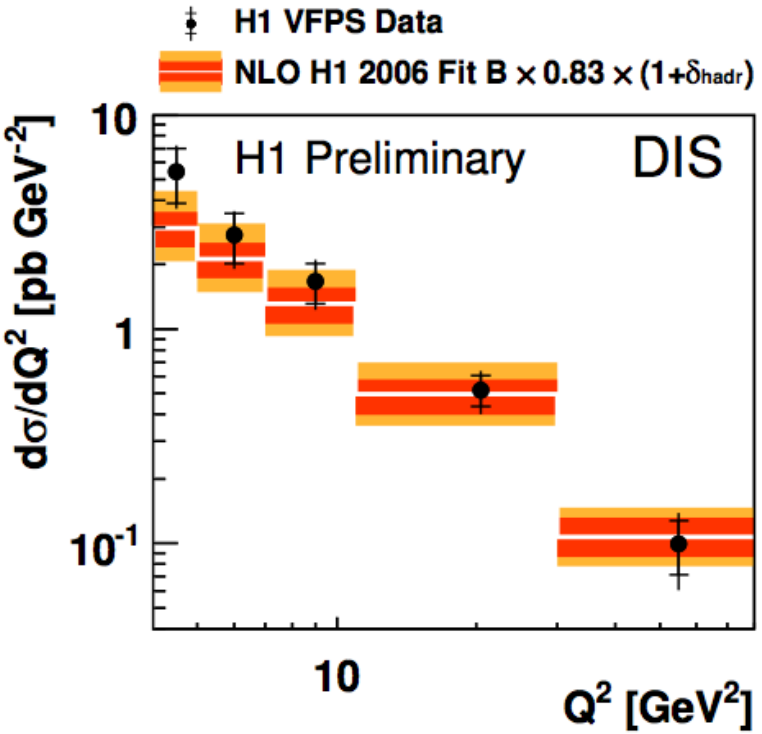
- NLO QCD predictions describe data
- Factorization theorem holds!

NEW! Diffractive dijets in DIS, leading proton

- Leading proton measured in Very Forward Proton Spectrometer
- Kin. range: $4 \le Q^2 \le 80$ GeV^2 $0.2<y<0.7$ $E_T>4.0$ GeV

H1 prel 14-011

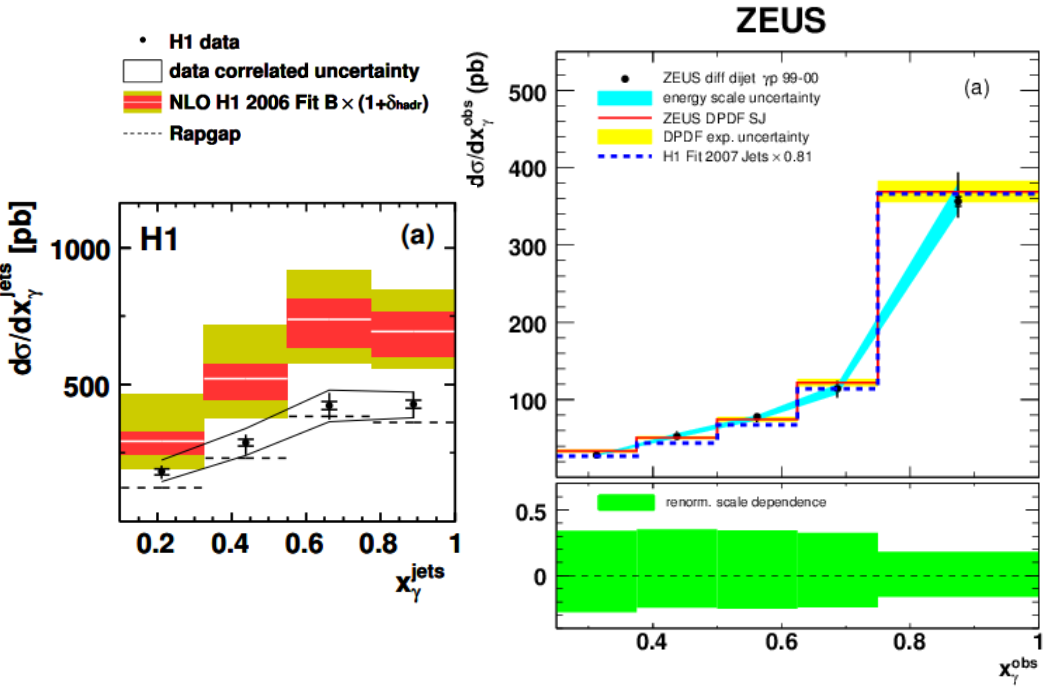


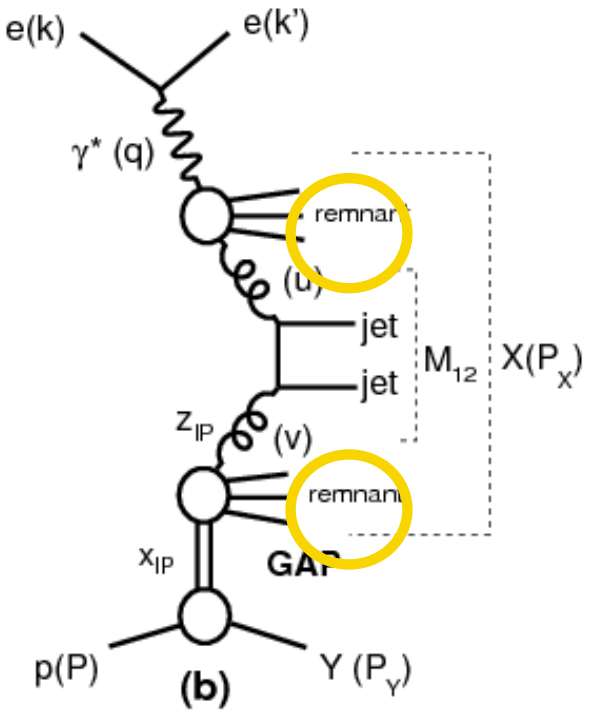


- NLO QCD predictions describe data
- Factorization theorem holds!

Diffractive dijets in PhP

- For dijet in DIS: the factorisation holds
- For dijets in PhP HERA results not fully decisive
- factorisation breaking observed by H1 but not observed by ZEUS, in slightly different phase space



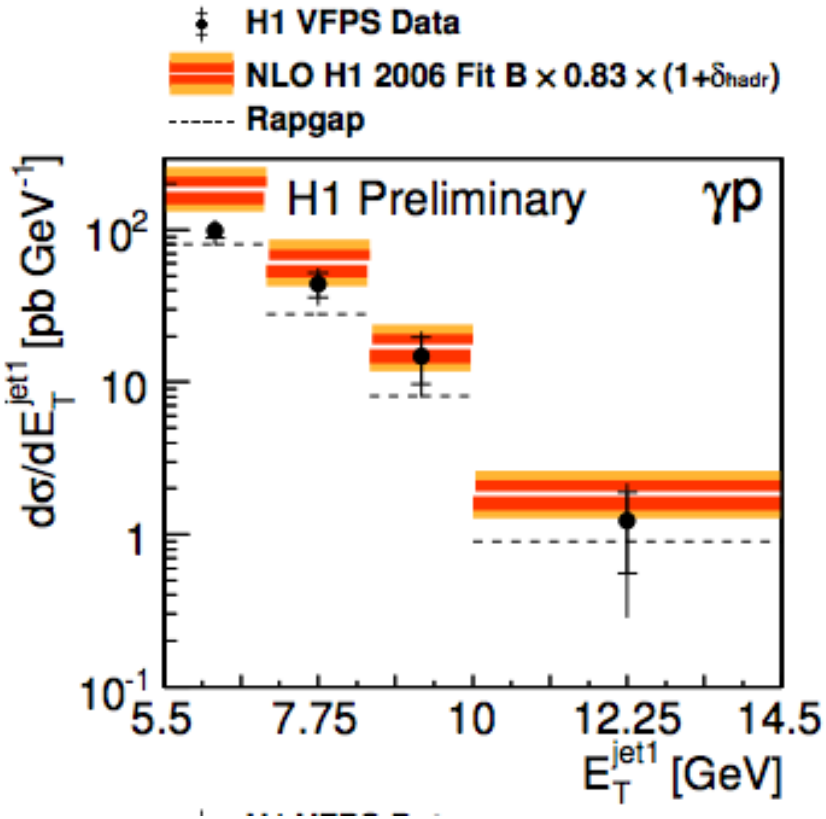


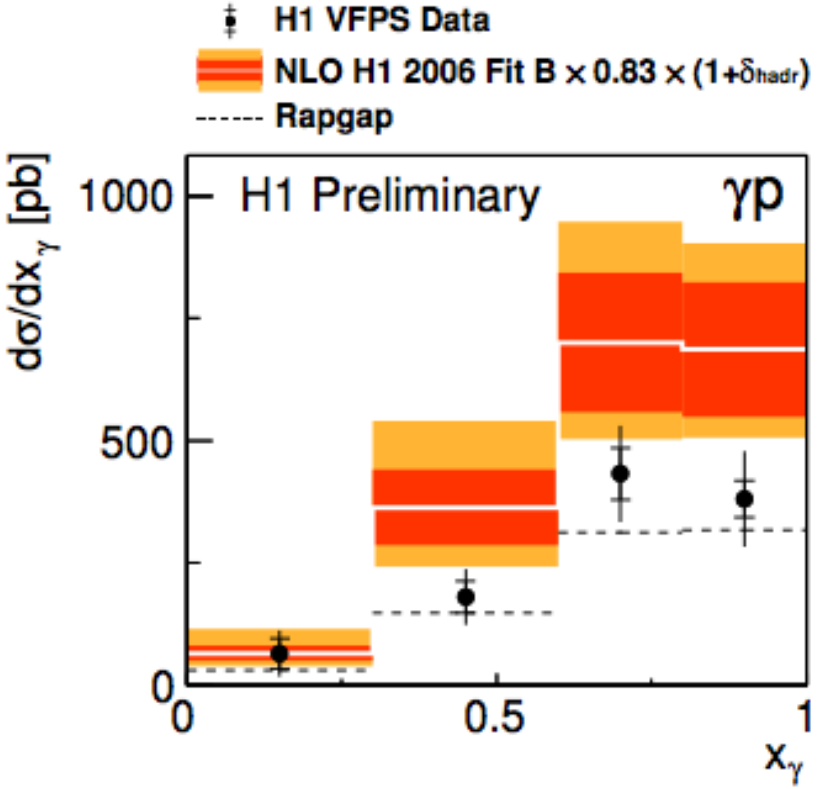
- in p − p collisions (TeVatron) the factorisation is broken
- real photon ($Q^2 \simeq 0$) can develop a hadronic structure
- resolved photoproduction theory predicts suppression
- the suppression is supposed to be stronger at low scales and **low x_γ**,
- however no dependence of suppression-factor visible

NEW! Diffractive dijets in PHP, leading proton

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

H1 prel 14-011



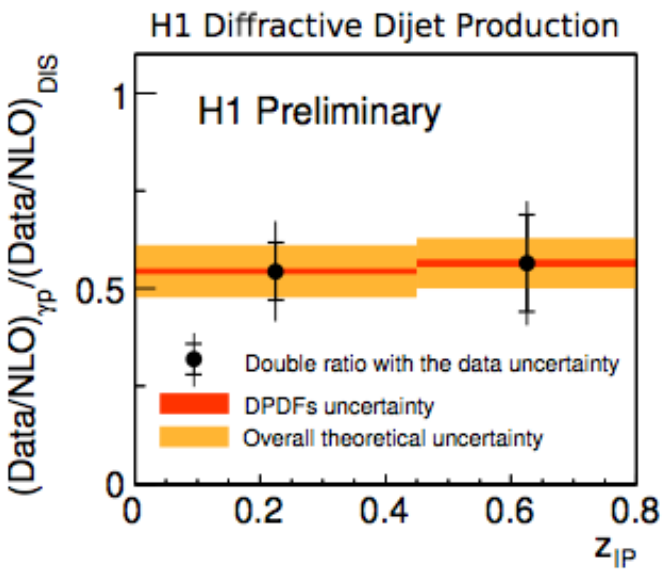


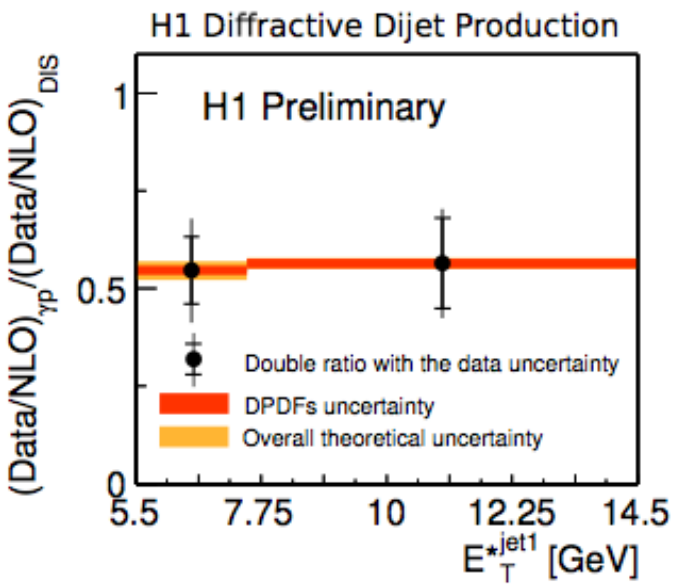
- Data lower than NLO prediction,
- No hints for a higher suppression for $x_\gamma \sim 1$

NEW! Diffractive dijets whith leading proton, DIS and PHP

- Measurement with VFPS confirms LRG measurement

H1 prel 14-011



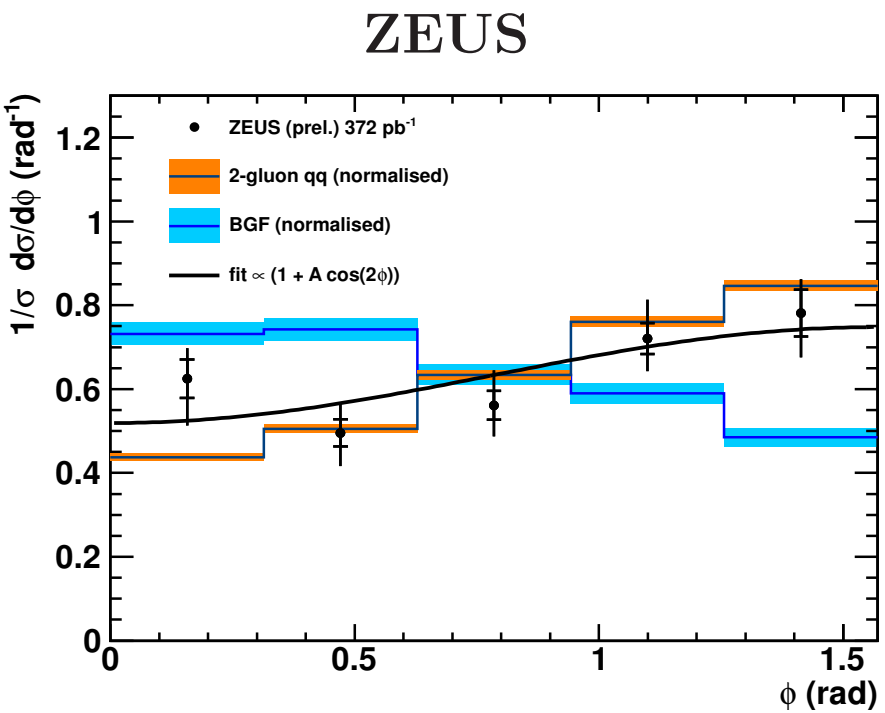


- Data/NLO: suppression factor in PHP ~0.55
- No hint of a dependence of the suppression on z_{IP} and E_T of leading jet
- Apparent difference between H1 and ZEUS not yet understood

NEW! Diffractive dijets in DIS

ZEUS prel 14-004

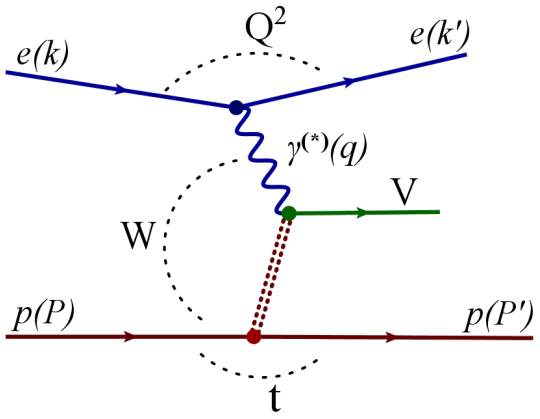
- High stat and wide kin. range: $Q^2 \leq 25$ GeV^2 $90<W<150$ $P_{T\ jet}>2$ GeV
- Measure of shape of the azimuthal angular distribution of exclusive dijets in DDIS
- Dijets reconstructed with Durham Exclusive kt jet algorithm
- Data compared to
  - 2 gluon exchange model
  - BGF (resolved Pomeron Model



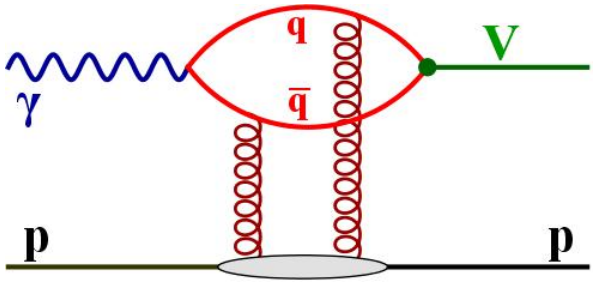
Data favours 2-gluon exchange model of qq production over BGF

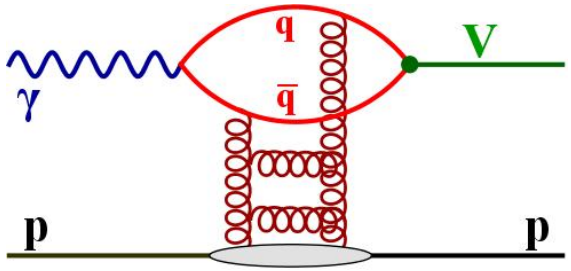
Vector Meson production

- Soft physics: Vector Dominace Model, Regge theory



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

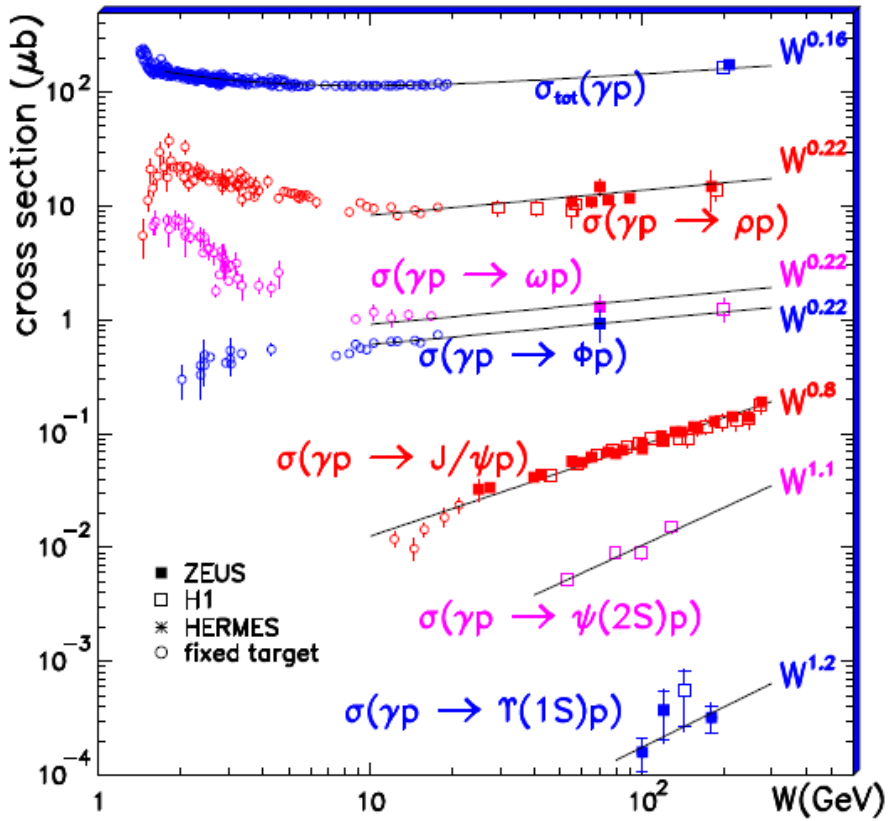




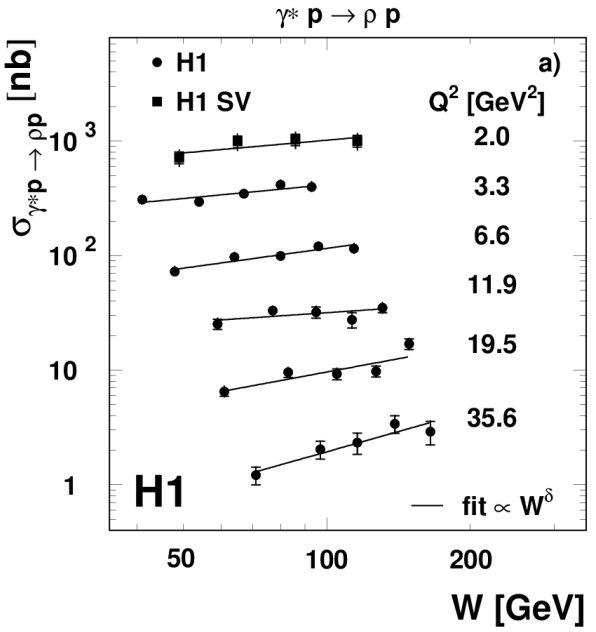
Vector Meson production: W-dependence

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

photoproduction

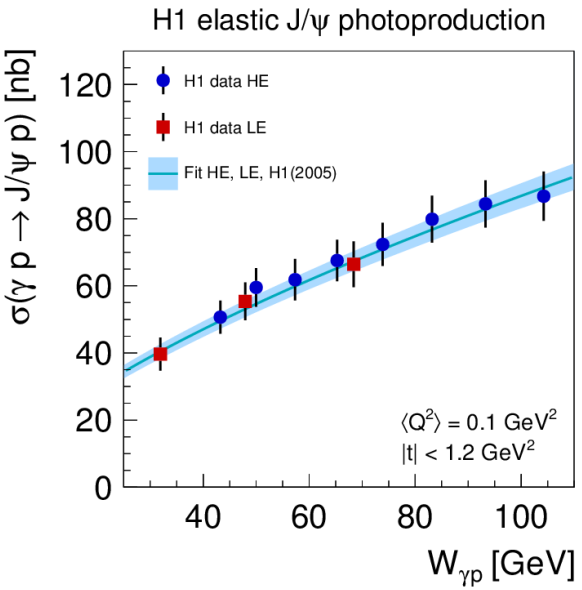


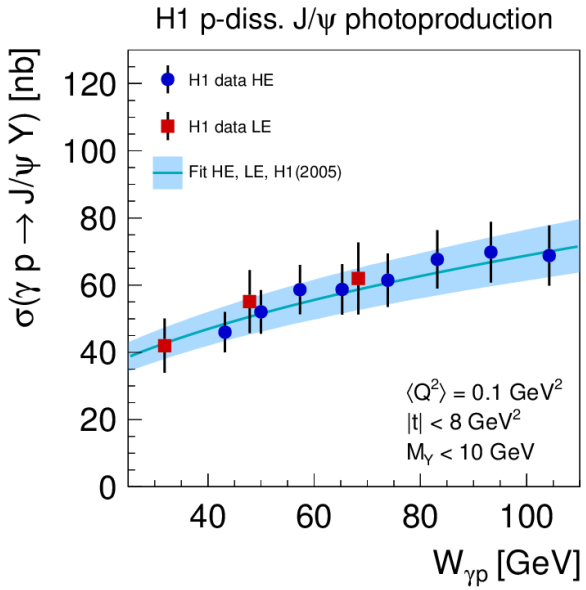
electroproduction (DIS)



- The rapid rise of cross section with $W\gamma p$, is related to the increasing gluon density with decreasing of fractional momentum $x \propto 1/W_{\gamma p}^{\ 2}$

Elastic and p-diss cross sections as a function of Wγp





Phys. J. C73 (2013) 2466

- Fit model:
  - Parametrisation (for elastic and p-diss.):

$$\sigma = N\,(W_{\gamma p} / W_0)^{\delta} \text{ with } W_0 = 90\text{GeV}$$

- Simultaneous fit of elastic and p-diss cross sections:
  - including correlations, including previous H1 hep-ex/0510016
- Results:

$\gamma p \to J/\psi p$: $\quad \delta_{el} = 0.67 \pm 0.03$

$\gamma p \to J/\psi Y$: $\quad \delta_{pd} = 0.42 \pm 0.05$

$\delta_{el} = \delta_{pd} - \delta_{el}$: $\quad -0.25 \pm 0.06$

- Cross section ratio shows a $W_{\gamma p}$ dependence

Exclusive γp → J/ψp, comparison to other experiments

- Exclusive γp → J/ψp
- Fit to HERA data extrapolated to higher Wγp describes the LHCb data
- LO and NLO fits to HERA data extrapolated to higher Wγp, LO in better agreement than NLO

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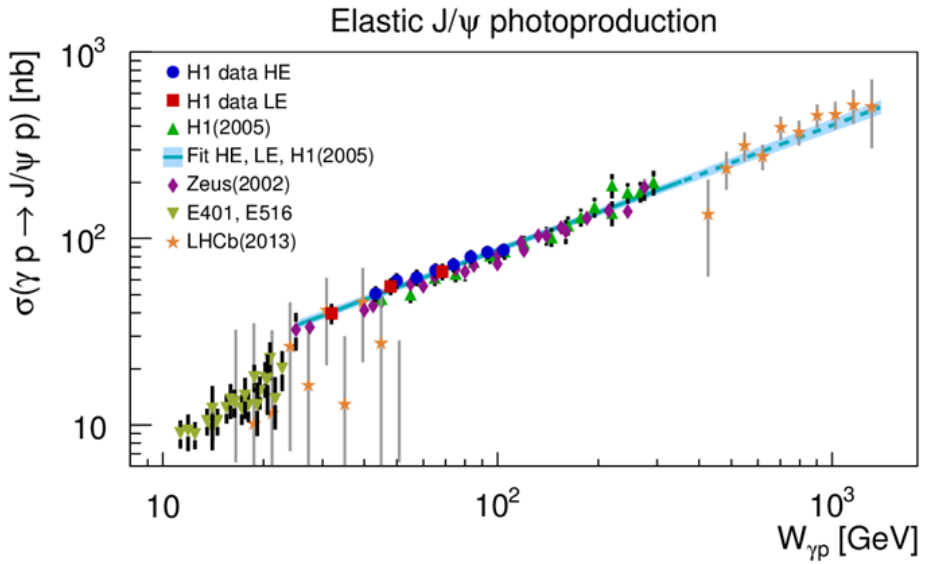
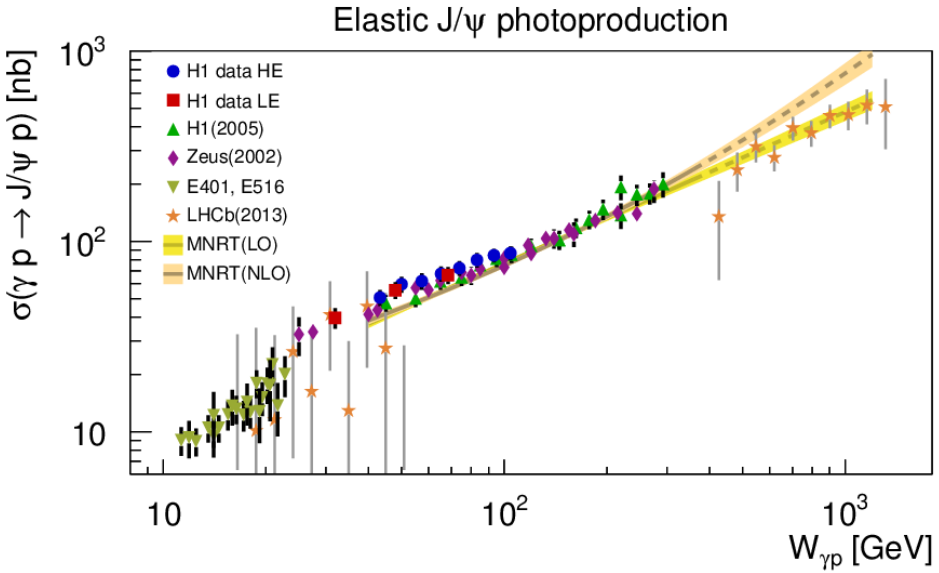
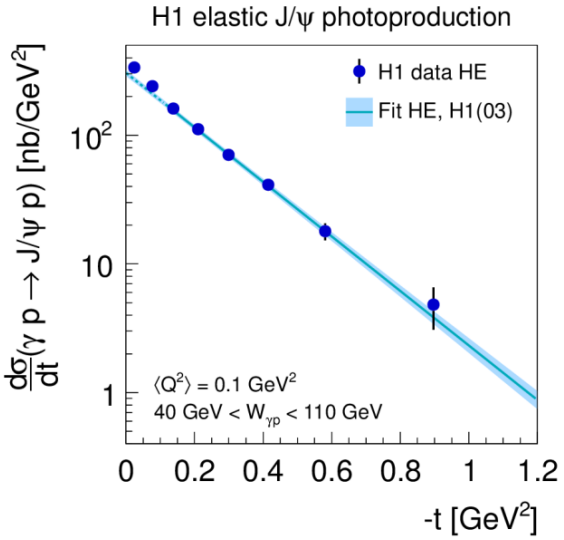




p-diss cross sections as a function of t

Phys. J. C73 (2013) 2466

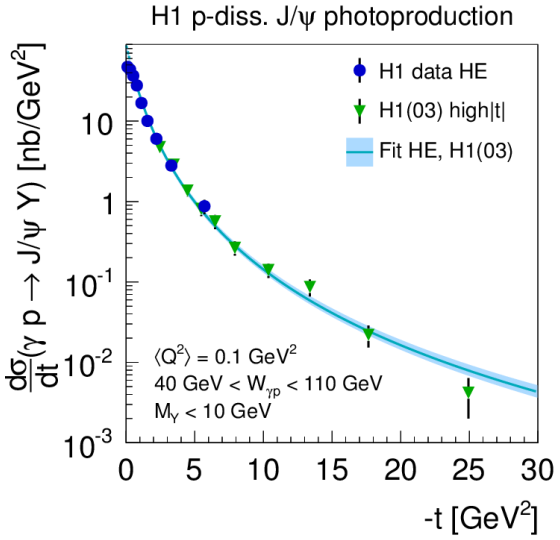
- The t-dependence of elastic cross section carries information about the transverse size of the interaction region
  - elastic: $d\sigma/dt = N_{el}\, e^{-b_{el}|t|}$
- p-diss cross section dominant for | t | > 1 GeV^2
  - p-diss: $d\sigma/dt = N_{pd}\,(1 + (b_{pd}/n)|t|)^{-n}$



- Results:

HE: $\gamma p \to J/\psi p$: 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



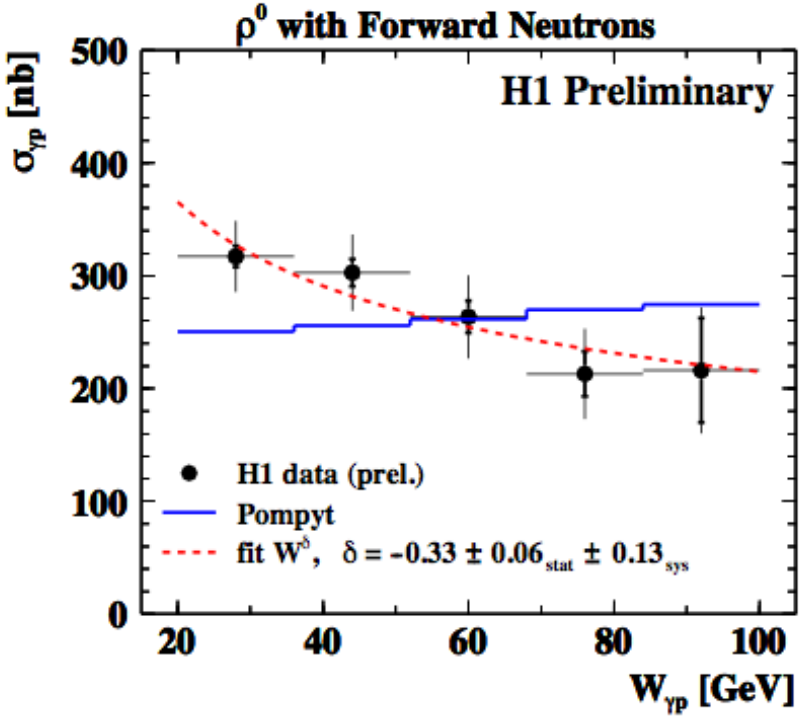
Eur. J. C 24 (2002) 345

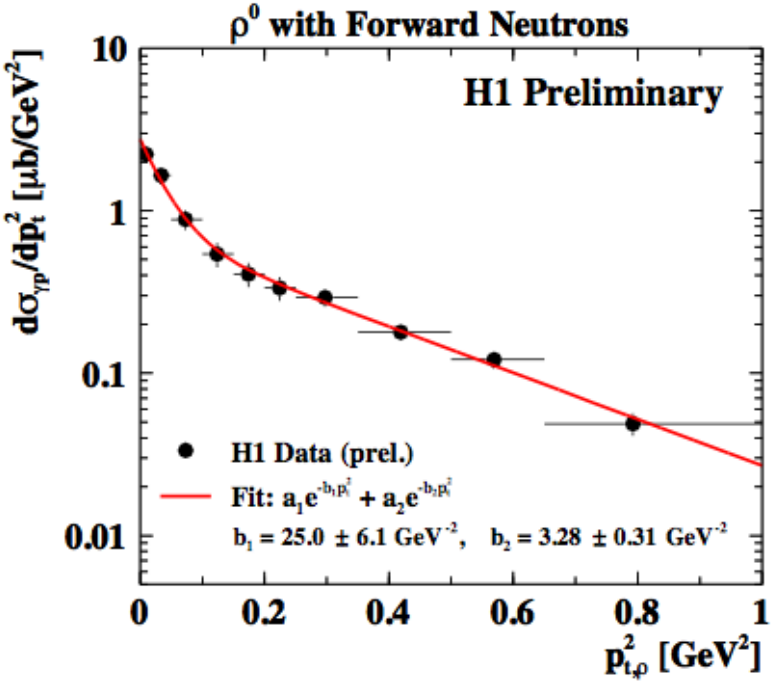
- ZEUS meas. (2002)
- $\gamma p \to J/\psi p$: b_{el} = (4.15 ± 0.05 ± 0.20) GeV^{-2} W=90 GeV
- $\gamma p \to J/\psi Y$: b_{pd} = 6.5 GeV^{-2} resonant +

  b_{pd} = 0.65 GeV^{-2} non resonant

NEW! Exclusive PHP of rho mesons with forward neutron

H1 prel 14 - 013





- Kin. Range: $Q^2<1GeV^2$ $|t|<1\ GeV^{-2}$, $E_n>120$ GeV
- Process measured for the first time at HERA
- Differential cross section $\gamma p \rightarrow \rho^0 \pi^+ n$ as in exclusive double peripheral process

Summary

- Events with a Large Rapidity Gap in DIS observed at HERA since 1993
- Diffraction investigated both with LRG and proton spectrometer
- Hard diffraction is present, dominated by gluons
- Diffractive factorisation confirmed by dijet measurements in DIS and open charm
- Data described by NLO QCD calculations with impressive agreement
- Apparent difference between ZEUS and H1 in dijet diffractive photoproduction not yet understood
- Vector meson production provides opportunity to test the property of diffraction and proton structure

- This talk is dedicated to the memory of Sasha Proskuryakov, author of many diffractive analysis: rho and phi VM, inclusive DDIS with LPS and LRG, QCD fits.

- We sady missed him one month ago. We remember the colleague and the friend