Diffraction at HERA

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On behalf of H1 and ZEUS Collaborations

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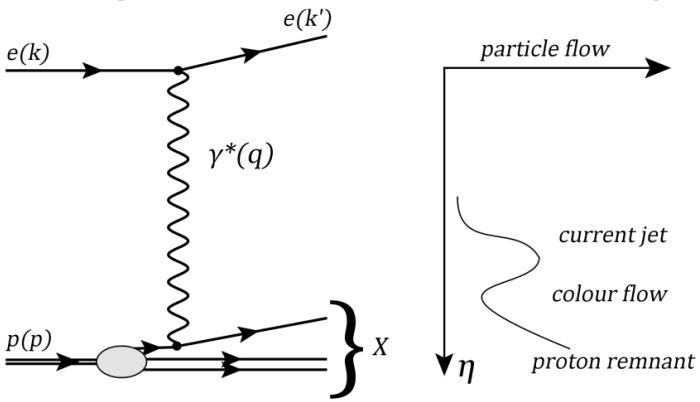
HERA ep collider 1992 – 2007, DESY, Hamburg

- the world's only electron/positron-proton collider
- $E_e = 27.6$ GeV and $E_p = 820(920)$ GeV (575, 460) HE(LE)

- total integrated luminosity 0.5 fb^{-1}

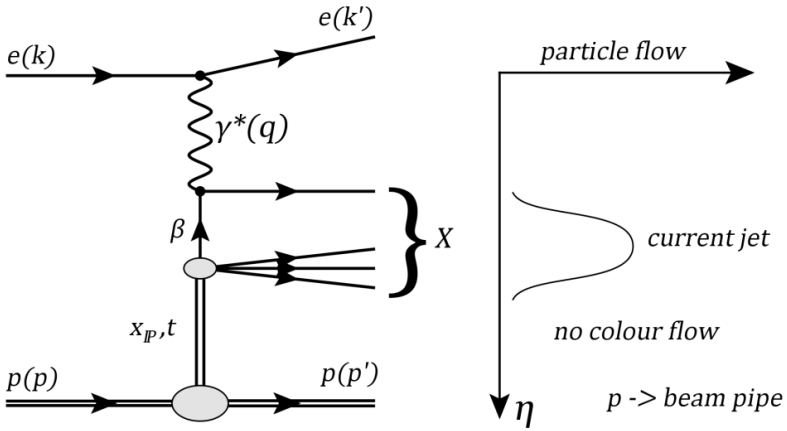
Diffraction in ep collisions

Deep Inelastic Scattering (DIS)



- $Q^2 = -q^2$ - virtuality of the photon
  $Q^2 \approx 0$ - photoproduction,
  $Q^2 \gg 0$ - DIS
- W - photon-proton center-of-mass energy
- x - Bjorken x - fraction of proton's momentum carried by struck quark
- $y = (p \cdot q)/(p \cdot k)$ - inelasticity

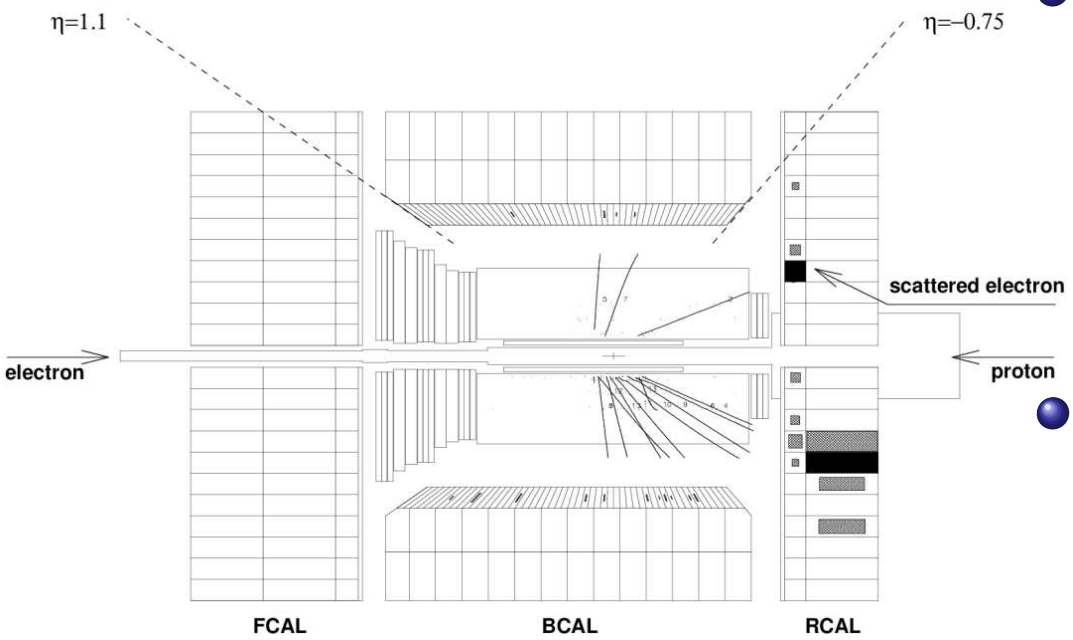
Diffractive Scattering



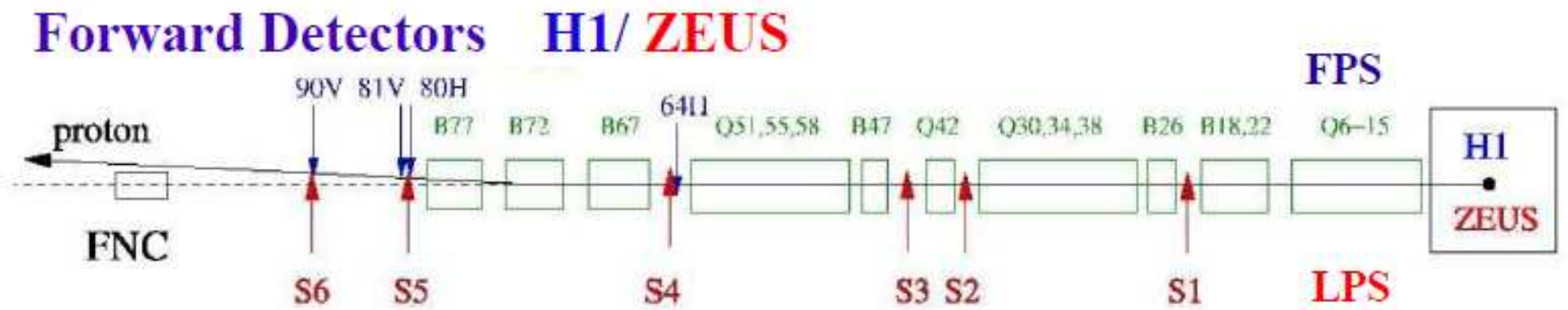
- x_{IP} - fraction of proton's momentum carried by exchanged color singlet
- $t = (p - p')^2$- four momentum transfer squared at proton vertex
- $\beta = x/x_{IP}$ - fraction of Pomeron momentum "seen" by the photon

This talk : $X = jet + jet + X'$; $X = jet + jet$; $X = \gamma + jet + X'$;
$X = D^{\star +} + X'$; $X =$Vector Meson(VM)

Tagging diffractive events in experiment



- Large Rapidity Gap Method:
  - large acceptance
  - elastic and proton dissociative diffractive events are not distinguishable on event-by-event
- Forward Proton Spectrometer:
  - very small acceptance
  - clean proton tagging
  - direct measurement of t and x_{IP}



Factorization in diffractive scattering

- QCD factorization (strictly proven for diffractive DIS)

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

f_i^D - Diffractive PDFs which obey DGLAP
- universal for all diffractive processes

$\sigma^{\gamma^\star i}$ - hard scattering cross section

- proton vertex factorization - experimental fact

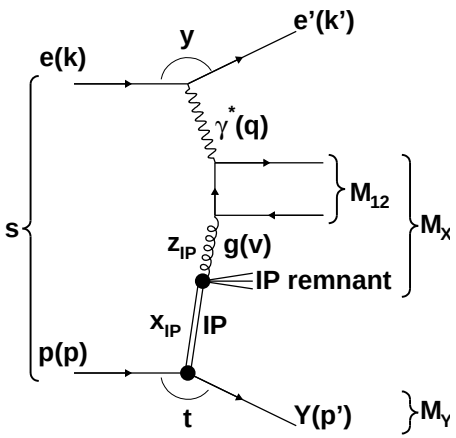
$$f_i^D(x, Q^2, x_{IP}, t) = \underbrace{f_{IP/p}(x_{IP}, t)}_{\text{Pomeron flux}} \cdot \underbrace{f_i^{IP}(\beta = x/x_{IP}, Q^2)}_{\text{Pomeron PDF}}$$

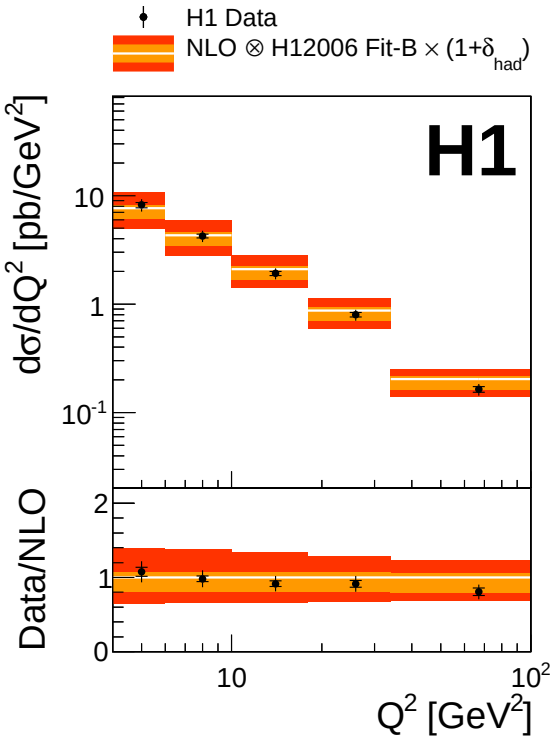
- Test of factorization: use NLO calculations and universal DPDFs to predict and confront with measurement the cross sections for particular diffractive final state. In this talk: diffractive dijet production

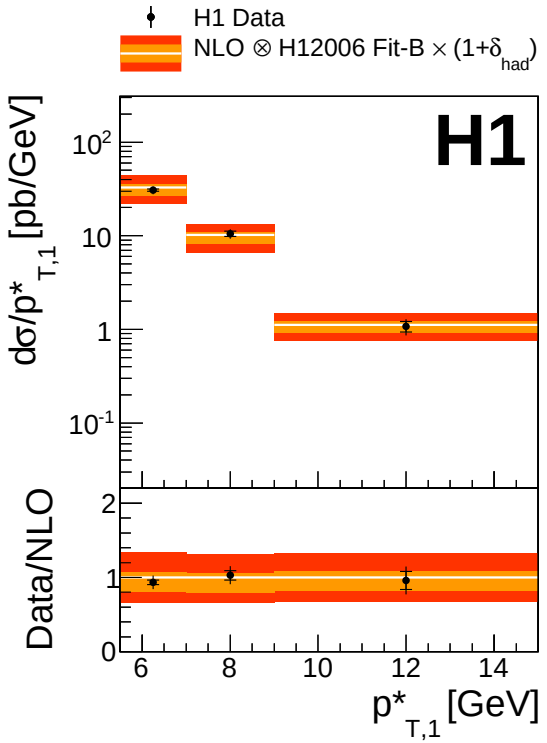
Diffractive dijet production with LRG in DIS

H1 Published 2015

kinematic range: $4 < Q^2 < 100$ GeV^2; $0.1 < y < 0.7$; $p_T^{jet} > 5.5, > 4.0$ GeV





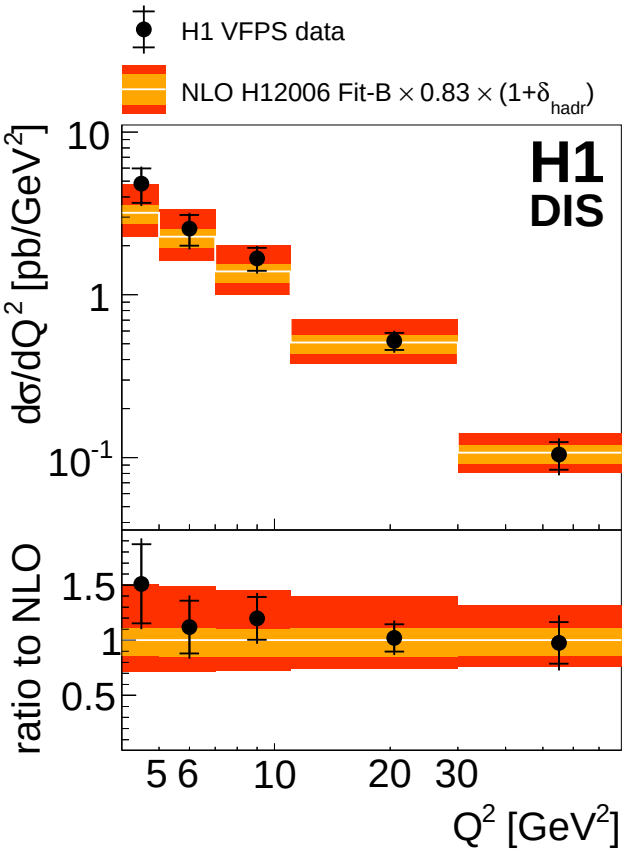


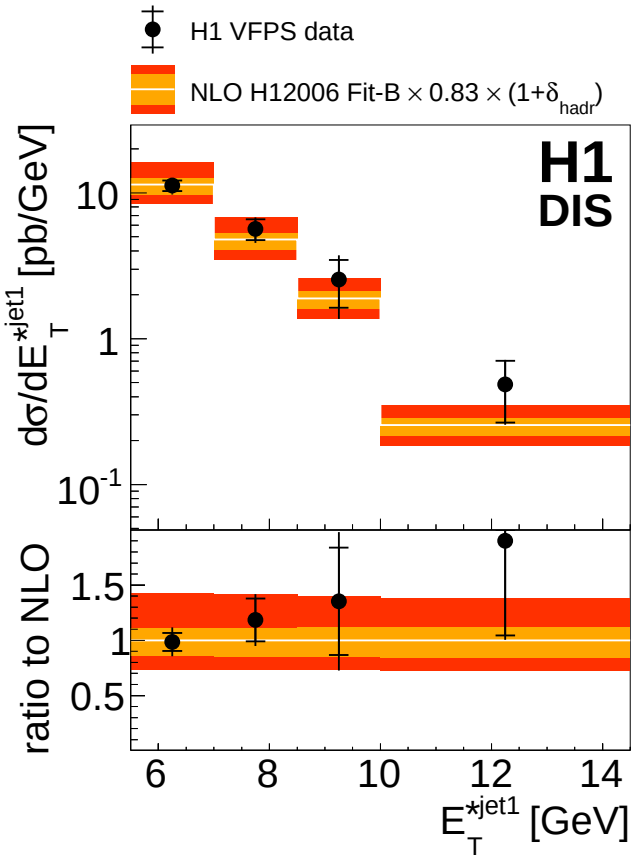
- data compared to NLOJET++ with DPDF H1 2006 fit
- NLO QCD predictions describe data
- factorization theorem holds!

Diffractive dijet in DIS with leading proton in VFPS

H1 Published 2015

kinematic range: $4 < Q^2 < 80$ GeV^2; $0.2 < y < 0.7$; $E_T^{jet} > 5.5, > 4.0$ GeV



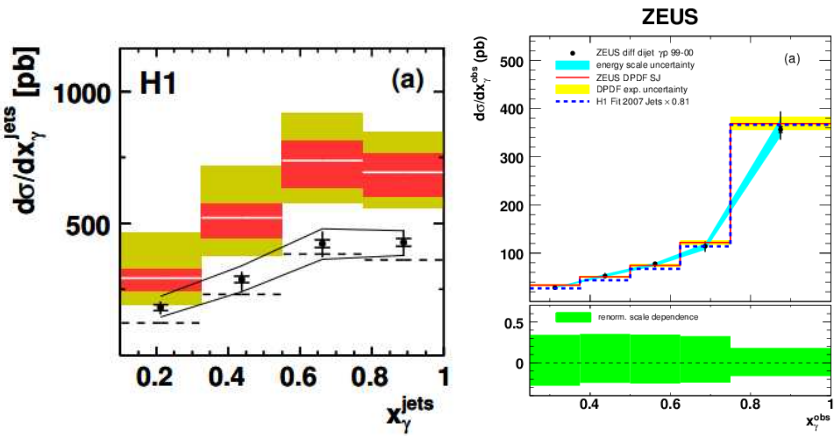


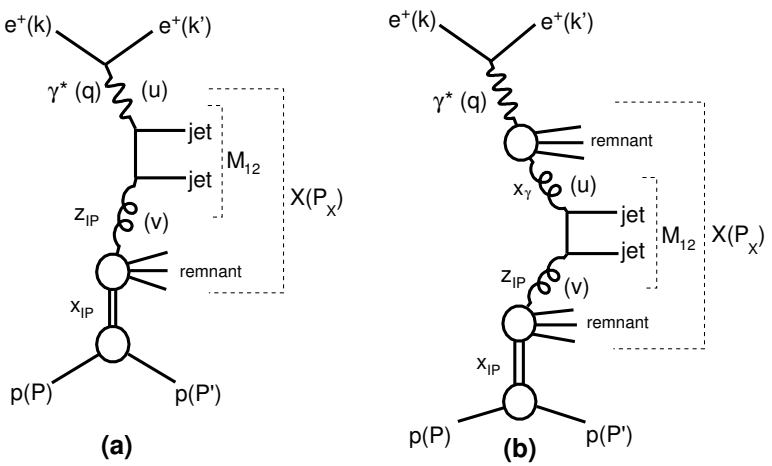
- data compared to NLO with DPDF H1 2006 fit B
- NLO QCD predictions describe data
- factorization theorem holds!

Diffractive dijet in photoproduction

Previous H1 and ZEUS (LRG) analyses

- for dijets in DIS: factorization hold
- for dijet in PHP: HERA results not fully decisive
- factorization breaking observed by H1 but not observed by ZEUS, in slightly different phase space



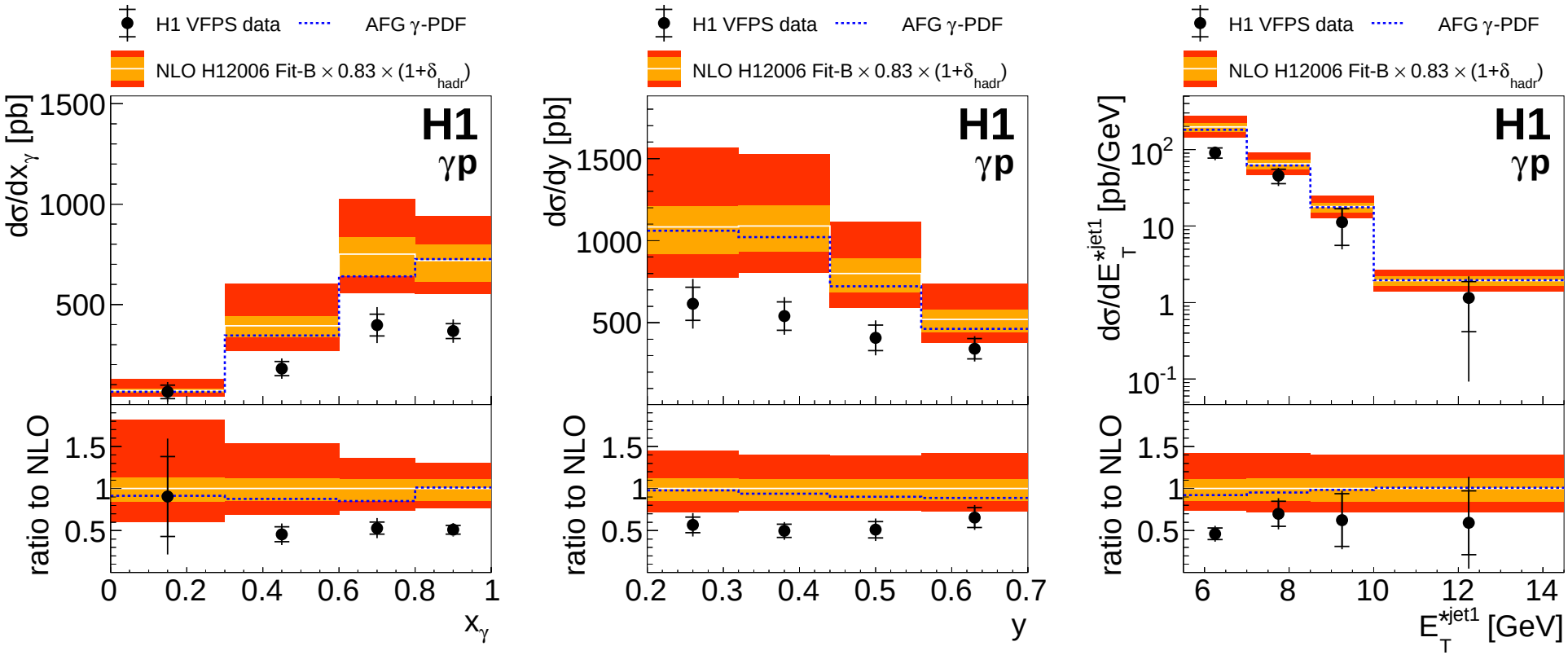


- in pp collisions (TeVatron) the factorization is broken
- quasi-real photon ($Q^2 \approx 0$) can develop a hadronic structure
- resolved photoproduction theory predicts suppression
- the suppression is supposed to be stronger at low scales and low x_γ
- however no dependence of suppression-factor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

Diffractive dijet in PHP with leading proton in VFPS

H1 Published 2015

Kinematic range: $Q^2 < 2$ GeV^2; $0.2 < y < 0.7$; $E_T^{jet} > 5.5, > 4$ GeV

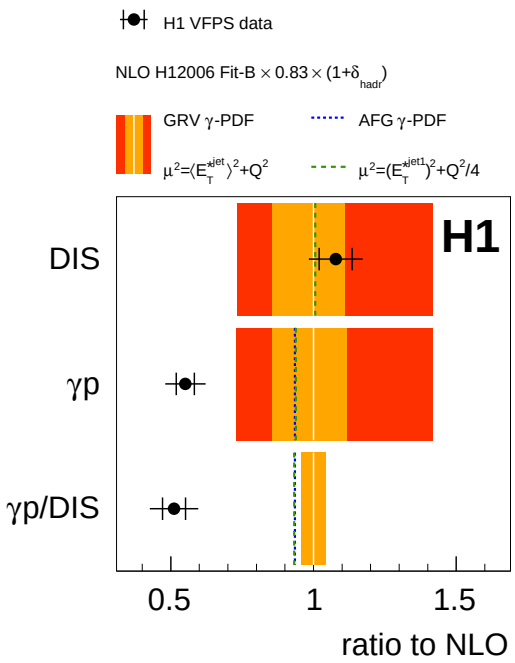


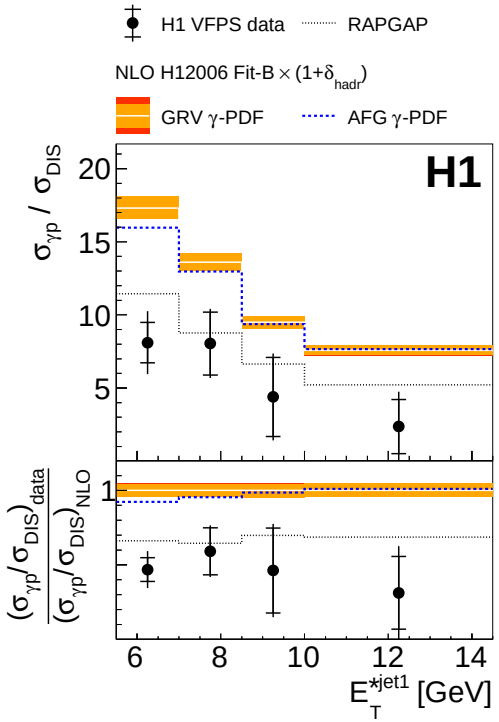
- data compared to NLO with DPDF H1 2006 fit B
- data lower than NLO prediction
- no hints for a higher suppression for low x_γ

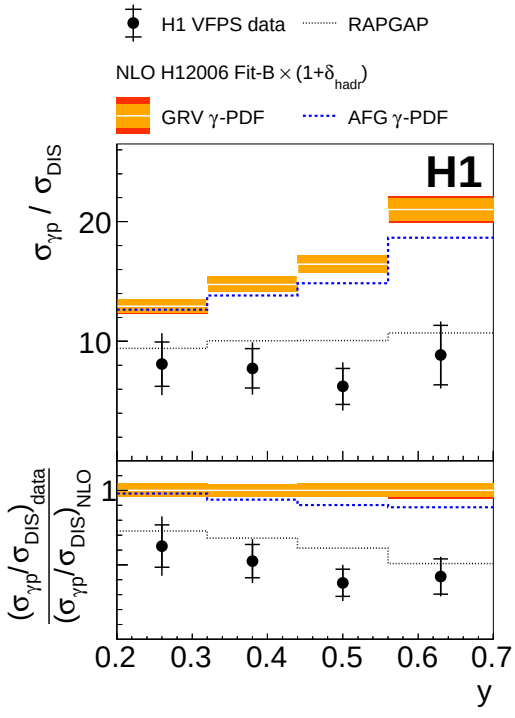
Dijet in PHP and DIS with leading proton in VFPS

H1 Published 2015

- results with VFPS confirm LRG measurement
- double ratio $(DATA/NLO)_{PHP}$ vs $(DATA/NLO)_{DIS}$







- data/NLO: suppression factor in PHP 0.51 ± 0.09
- no hint of a dependence of the E_T of leading jet
- apparent difference between H1 and ZEUS not yet understood

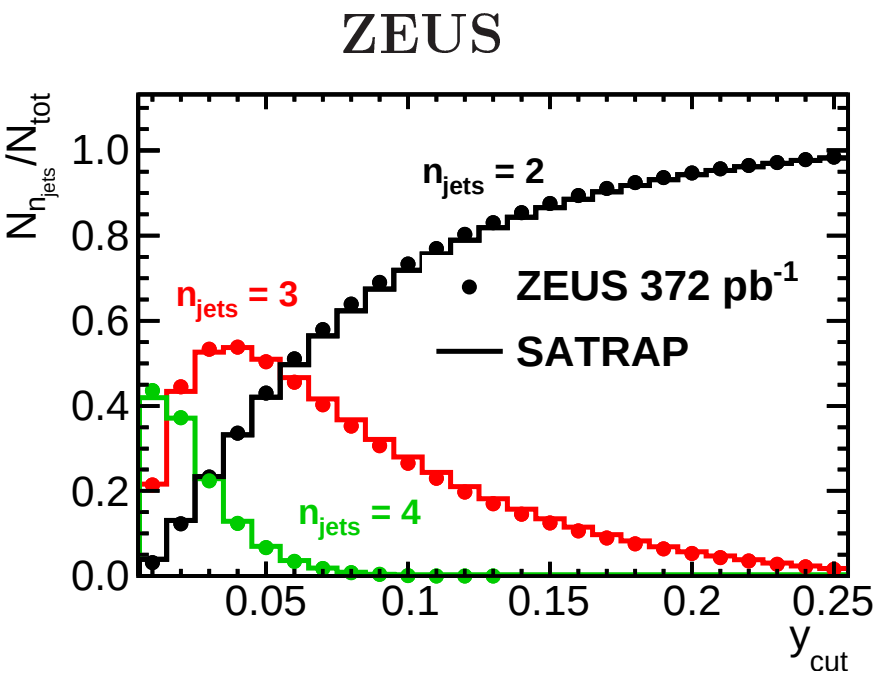
Exclusive dijet production in DIS

ZEUS Published 2015

- Large Rapidity Gap method used to select diffractive events with
  - $Q^2 > 25$ GeV^2
  - $M_X > 5$ GeV
  - $90 < W < 250$ GeV
- exclusive k_t jet algorithm: objects i, j are merged as long as

$$k_t^2 = \min(E_i^2, E_j^2)\sin^2(\theta_{i,j}) < y_{cut} M_x^2$$

- exclusive dijet may originate from: two, three, many partons state
- resolution parameter $y_{cut} = 0.15$ optimizes efficiency vs. purity of dijet sample



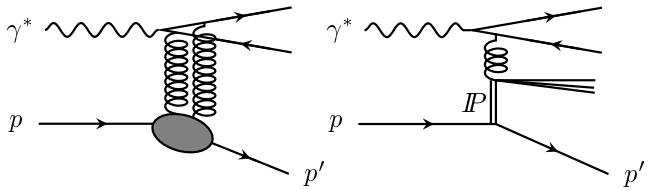
SATRAP:

- color dipole model with saturation
- $q\bar{q}$ and $q\bar{q}g$ in a final state
- good agreement with data
- used for detector level corrections

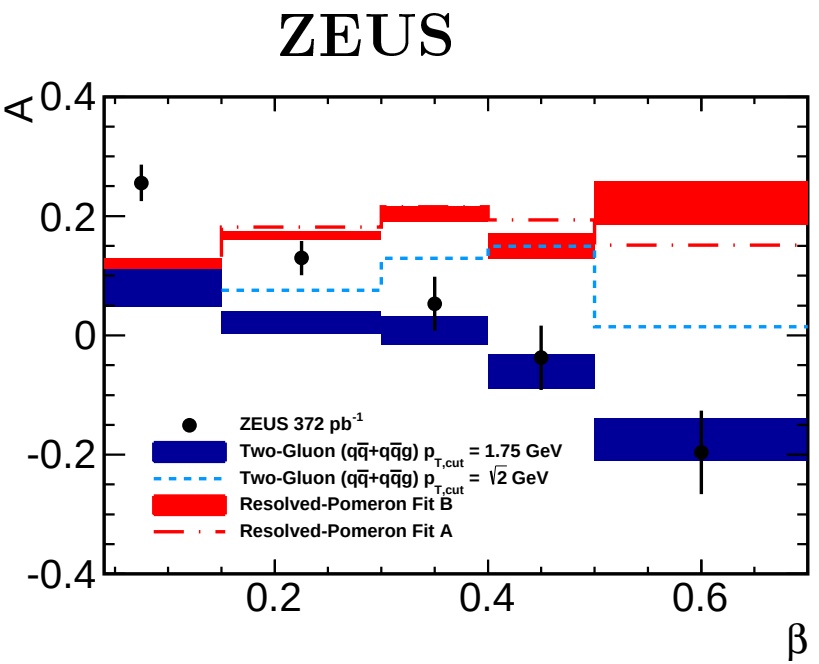
Exclusive dijet production in DIS

ZEUS Published 2015

- select two hard jets $p_t > 2$ GeV to allow comparison to pQCD models



- Two-gluon exchange model (J. Bartels and H. Jung et al.)
- Resolved Pomeron model (G.Ingelman and P.Schlein et al.)
- models predict different shape for dijet azimuthal angular distribution $\mathrm{d}\sigma/\mathrm{d}\phi \propto 1 + A\cos(2\phi)$

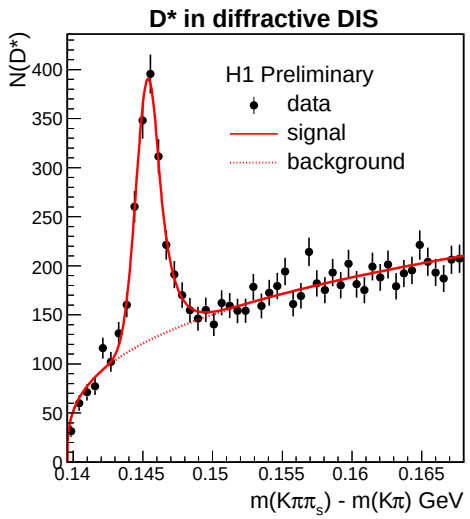


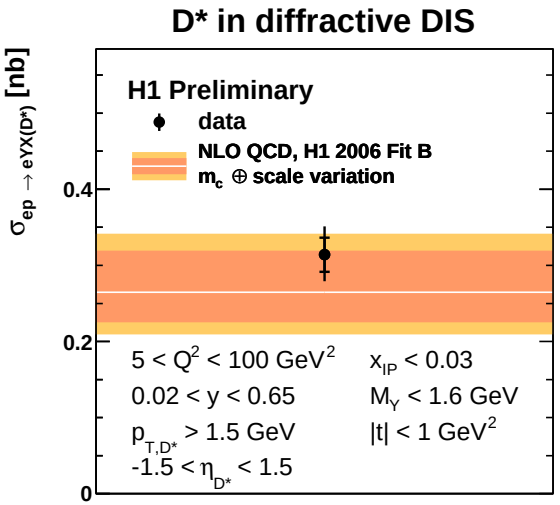
- data favor the two-gluon exchange model prediction
- The Resolved Pomeron model (BGF) does not describe this data

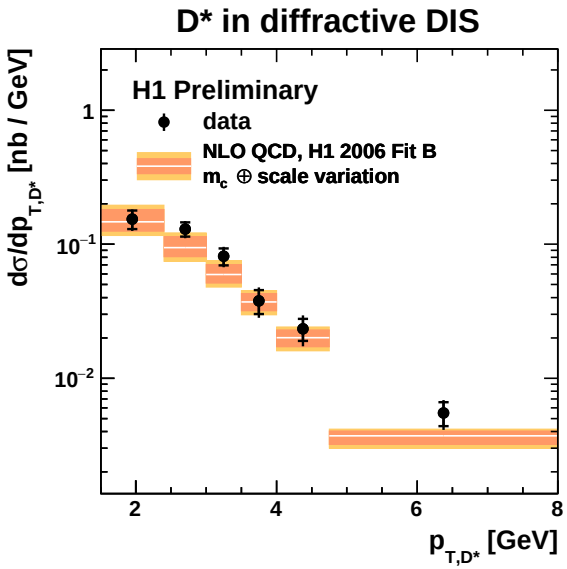
Open charm production in diffarctive DIS

H1 Preliminary 2016

- open charm tagged with $D^{\star}$
- $D^{\star+} \rightarrow D^0 + \pi^+_{slow} \rightarrow (K^-\pi^+)\pi^+_{slow} + C.C.$
- fit of $\Delta m = m(D^{\star}_{cand}) - m(D^0_{cand})$





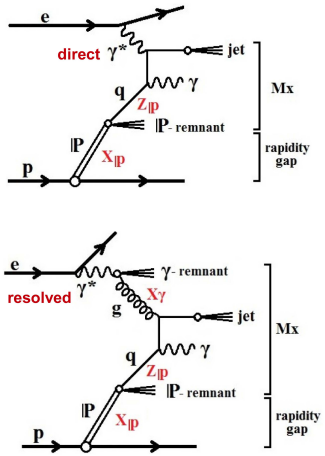


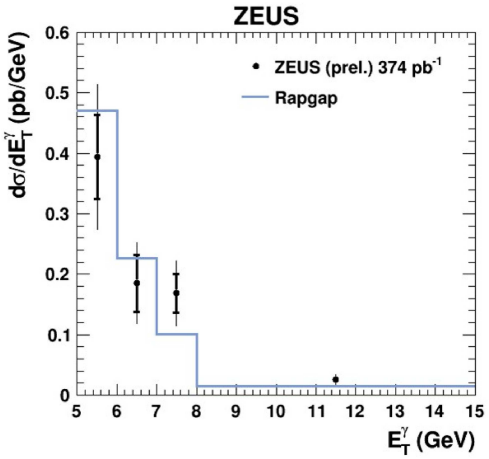
- NLO QCD (HVQDIS in FFNS) using H1 2006 DPDF Fit B
- NLO QCD prediction agree well within errors with measured cross sections
- might serve as an input to DPDF fits and factorization testing

Prompt photons in diffraction and photoproduction

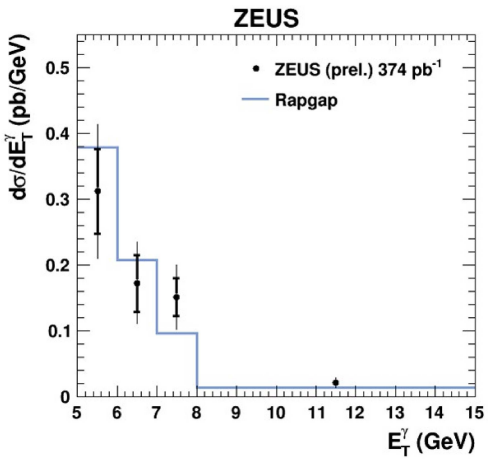
ZEUS Preliminary 2015

- photons directly from hard process
- sensitive to quark content of IP
- inclusive photon and photon+jet measurements performed





Inclusive photon

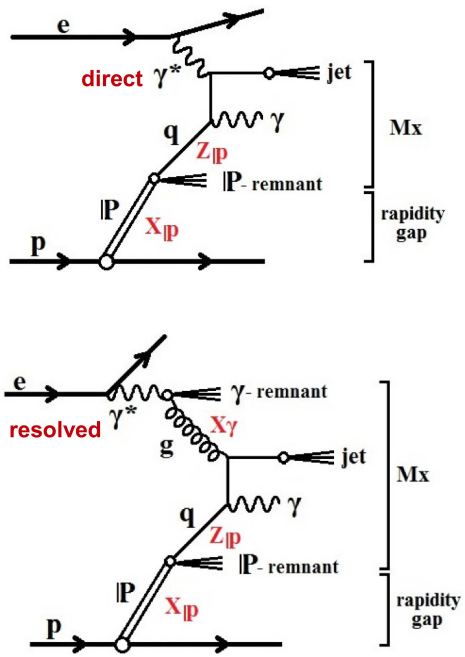


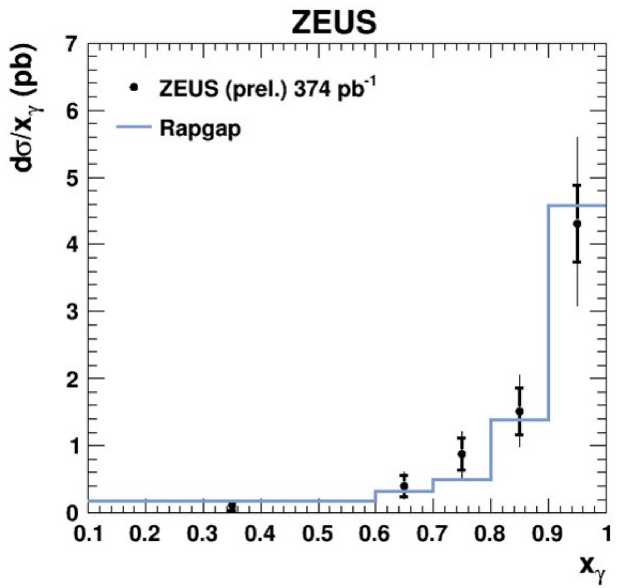
Photon + jet

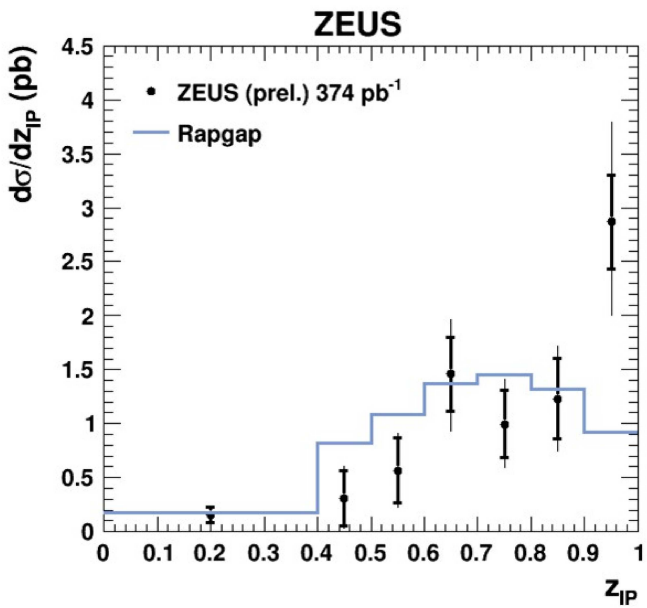
- most photon events accompanied by jet
- reasonable description of shapes MC (RAPGAP)
  - leading order parton-level QCD matrix elements
  - fragmentation using the Lund string model as implemented in PYTHIA
  - H1 2006 Set-B DPDF set is used to describe the parton density in the diffractively scattered proton.
  - for resolved photons, the SaSG 1D LO pdf is used

Prompt photons in diffraction and photoproduction

ZEUS Preliminary 2015







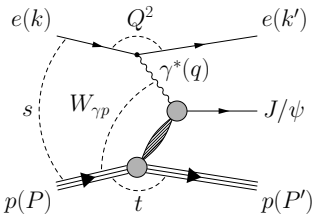
- direct processes dominate
- the variable z_{IP} shows a peak at high values that would imply the presence of processes not currently modeled in RAPGAP

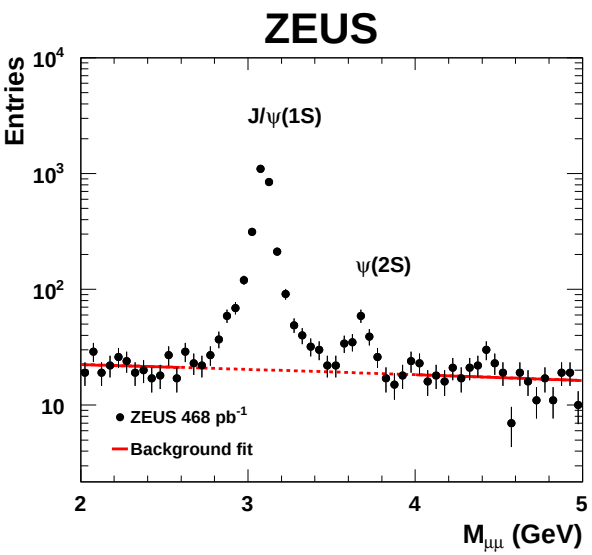
$\sigma_{\psi(2S)}/\sigma_{J/\psi}$ in DIS

ZEUS Published 2016

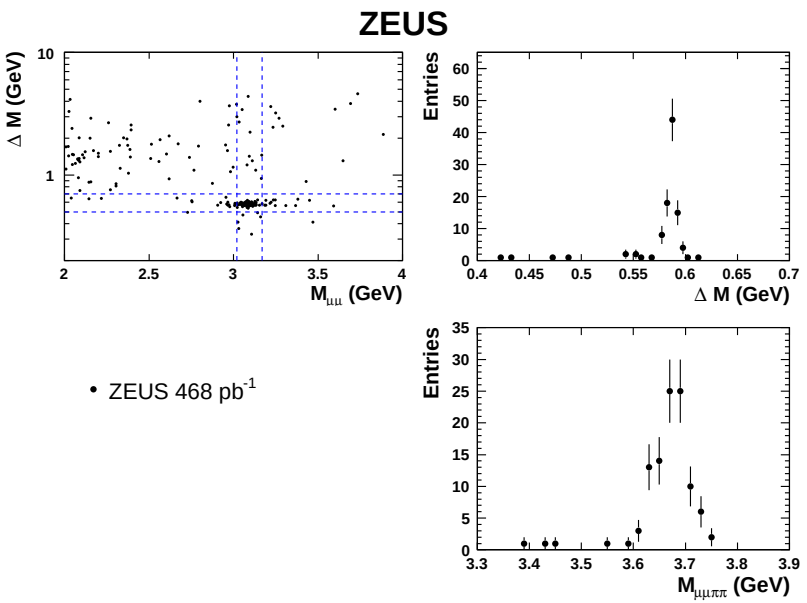
Kinematic range: $5 < Q^2 < 70$ GeV^2; $30 < W < 210$ GeV

$J/\Psi \rightarrow \mu + \mu$
$\Psi(2S) \rightarrow \mu + \mu$





- $\Psi(2S) \rightarrow J/\Psi + \pi^+ + \pi^-$
  $\rightarrow \mu^+ + \mu^- + \pi^+ + \pi^-$

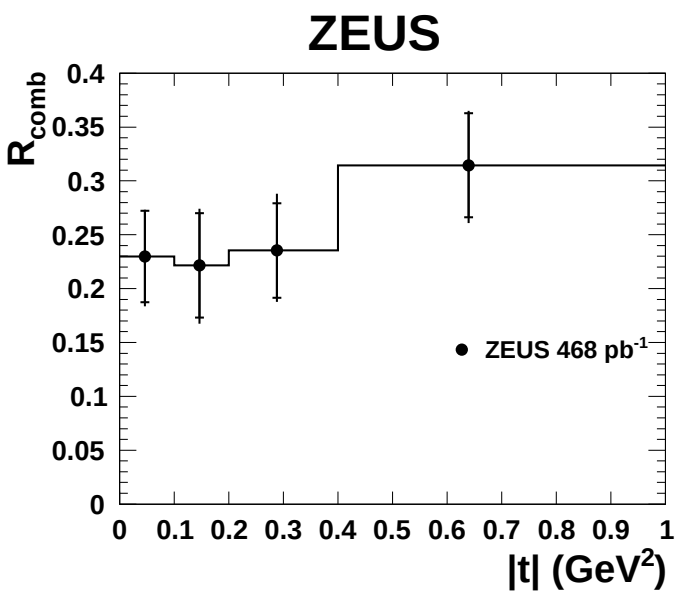


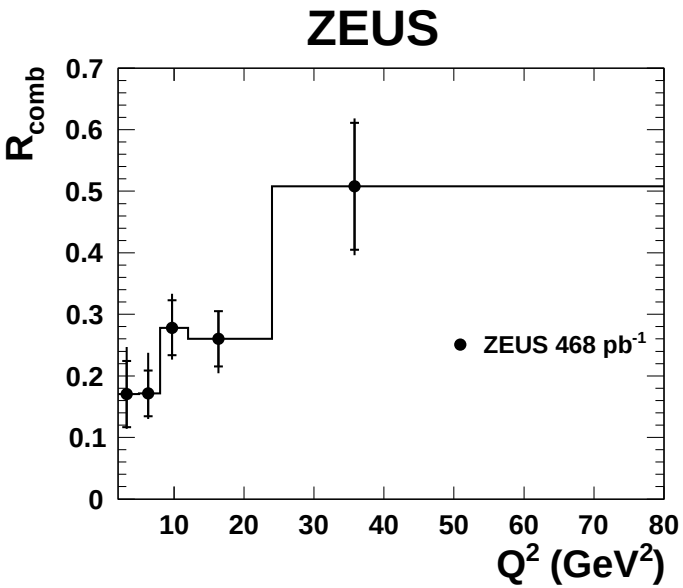
- $\Psi(2S)$: $3.59 < M_{\mu\mu} < 3.79$ GeV
- J/Ψ : $3.02 < M_{\mu\mu} < 3.17$ GeV

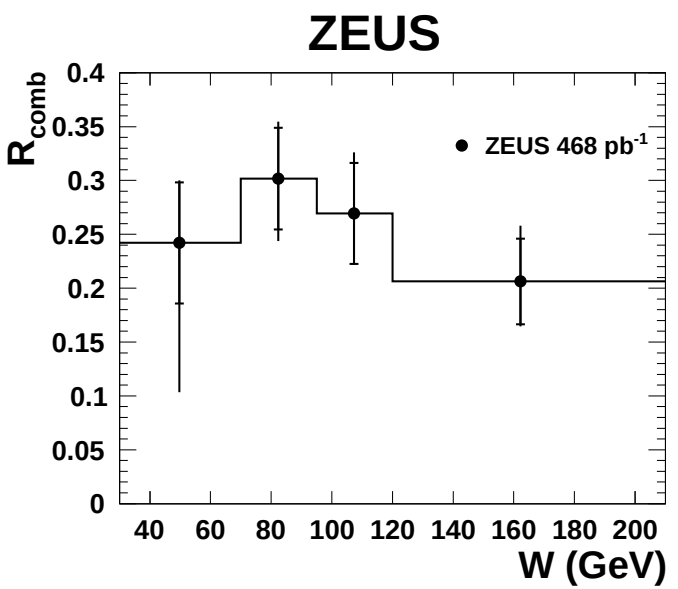
- $\Delta M = M_{\mu\mu\pi\pi} - M_{\mu\mu}$
- $0.5 < \Delta M < 0.7$ GeV
- $3.02 < M_{\mu\mu} < 3.17$ GeV

$\sigma_{\psi(2S)}/\sigma_{J/\psi}$ in DIS

ZEUS Published 2016





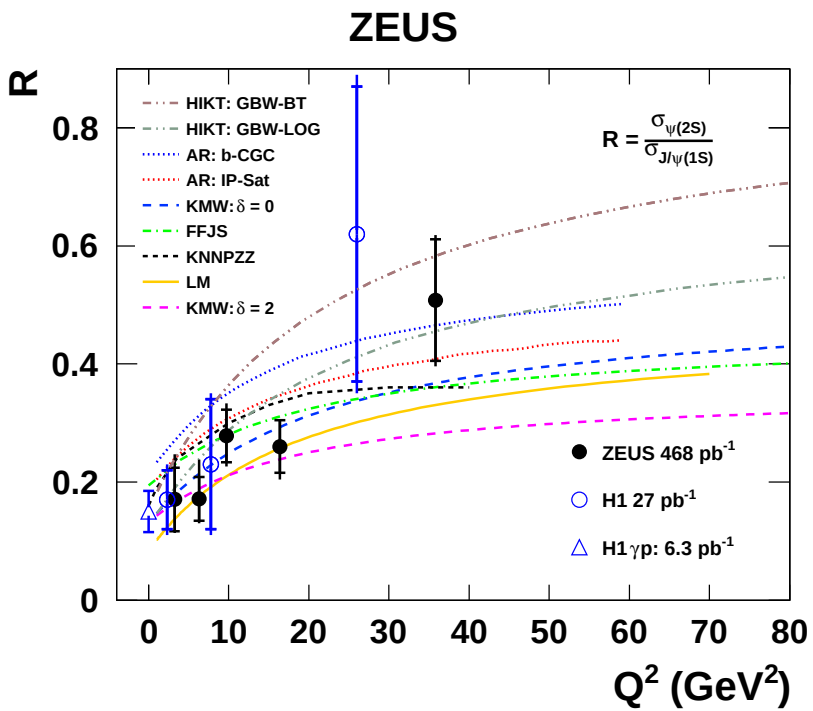


- ratio insensitive to many systematic uncertainties
- ratio gives information about the dynamics of the hard process
- pQCD predicts rise of the ratio with Q^2 reaching plateau at $Q^2 \gg M_\Psi^2$

- indication of an increase with Q^2
- independent on W and $|t|$

$\sigma_{\psi(2S)}/\sigma_{J/\psi}$ in DIS

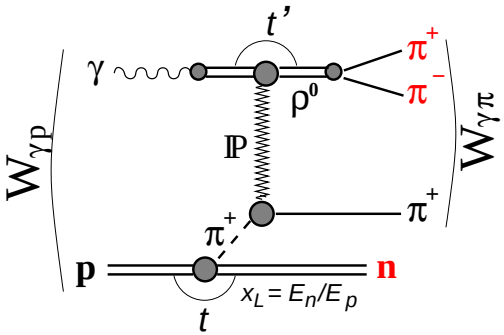
ZEUS Published 2016



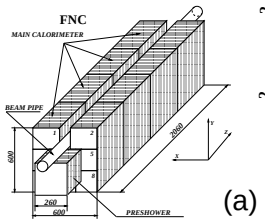
- HIKT, Hüfner et al.: dipole model, dipole-proton constrained by inclusive DIS data
- AR, Armesto and Rezaeian: impact parameter dependent CGC and IP-Sat model
- KMW, Kowalski Motyka Watt: QCD description and universality of quarkonia production
- FFJS, Fazio et al.: two component Pomeron model
- KNNPZZ, Nemchik et al.: color-dipole cross section derived from BFKL generalised eq.
- LM, Lappi and Mäntysaari : dipole picture in IP-Sat model

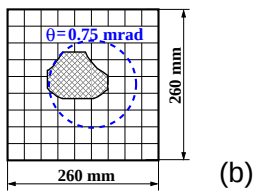
Exclusive ρ^0 photoproduction with a LN

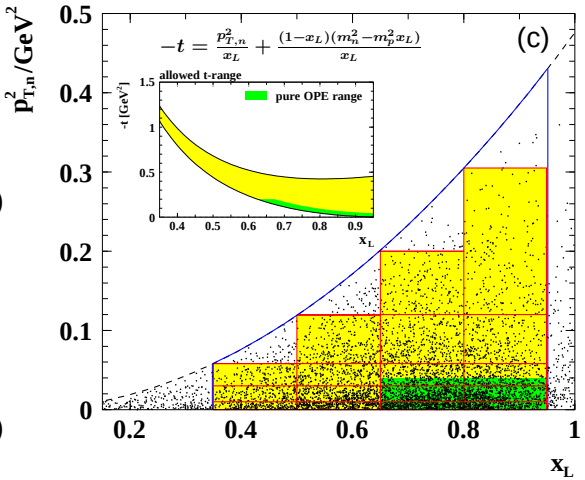
H1 Published 2015



- first measurement of ρ^0 photoproduction with a leading neutron at HERA
- dominated by pion exchange process
- extract $\sigma(\gamma\pi^+ \rightarrow \rho^0 + \pi^+$
- double Peripheral Process (DPP)
- constraints to pion flux models
- study of absorption effects





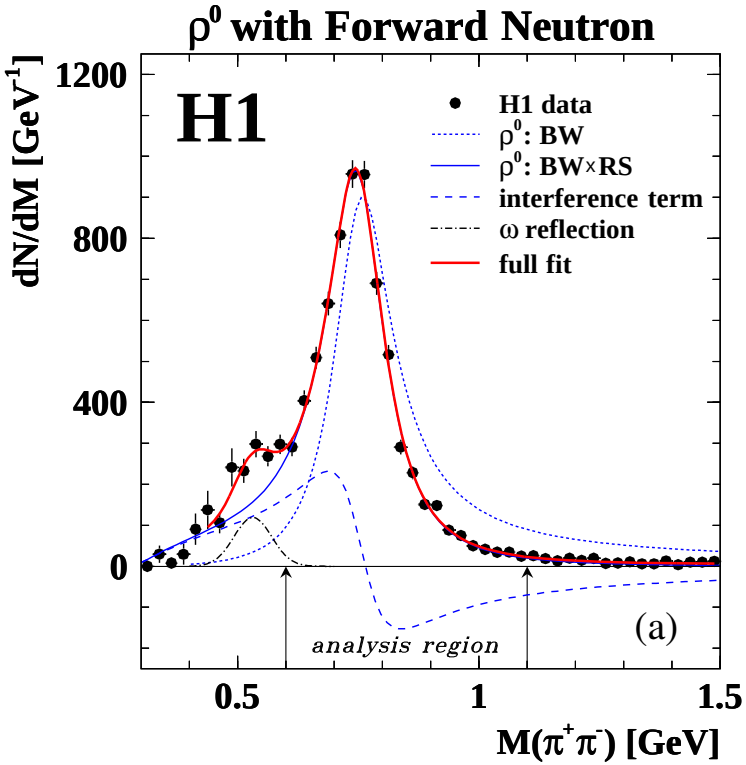


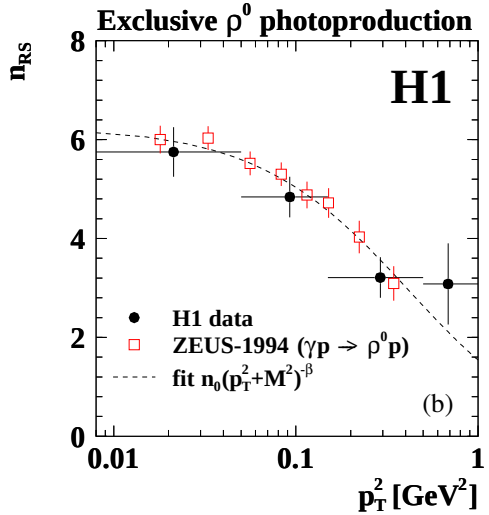
Forward Neutron Calorimeter:

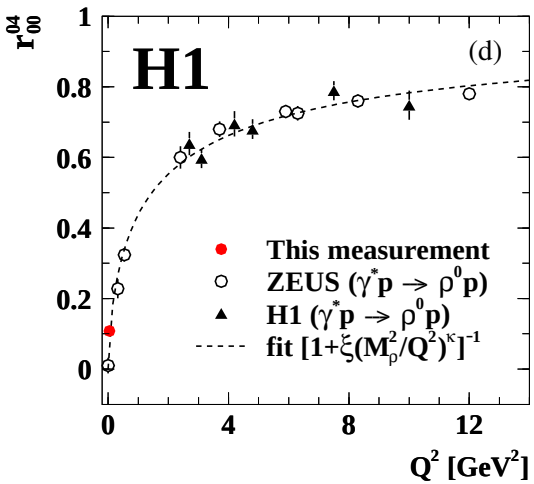
- located at 106 m from the H1 interaction point
- to distinguish and measure *n* and γ/π^0
- select events with hadronic cluster with an energy above 120 GeV
- OPE dominant range with $p_T(n) < 0.2$ GeV

Exclusive ρ^0 photoproduction with a LN

H1 Published 2015







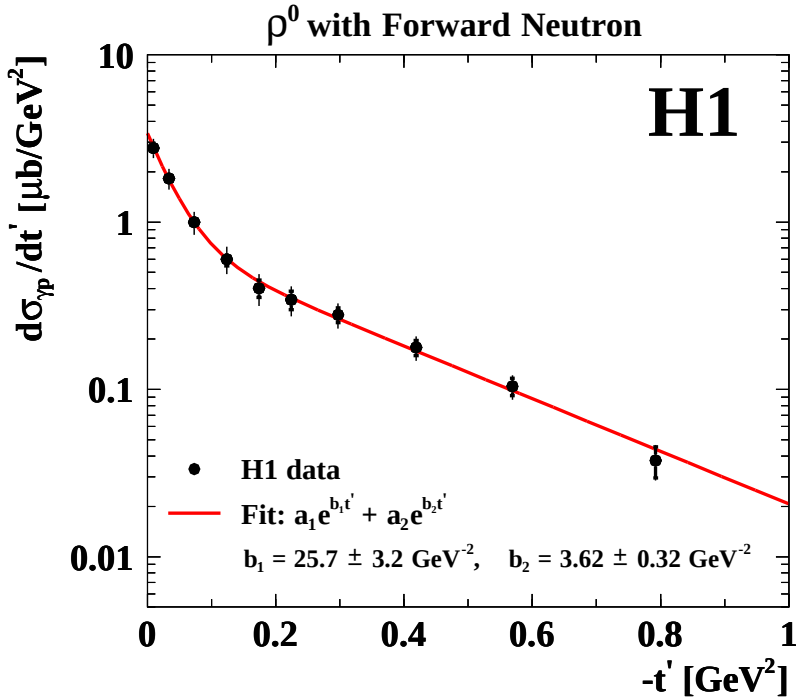
- $n_{RS} = n_0(p_T^2 + M^2)^{-\beta}$

$r_{00}^{04} = 1/(1 + \xi(M^2/Q^2)^{\kappa})$

- $\frac{dN}{dM_{\pi\pi}} \propto BW_{\rho^0}(M_{\pi\pi}) \left(\frac{M_{\pi\pi}}{M_{\rho^0}}\right)^{n_{RS}}$
- $\frac{dN}{dcos\theta_h} \propto 1 - r_{00}^{04} + (3r_{00}^{04} - 1)cos2\theta_h$
- $\theta_h -$ polar angle of the positively charged decay pion in the ρ^0 rest frame with respect to the meson direction in the γp centre-of-mass frame
- properties are consistent with ρ^0 photoproduction

Exclusive ρ^0 photoproduction with a LN

H1 Published 2015



- a strongly changing slope between the low-t' and the high-t' regions
- expected in the DPP interpretation
- large value of b_1 suggests that photons find pions in a cloud which extends far beyond the proton radius

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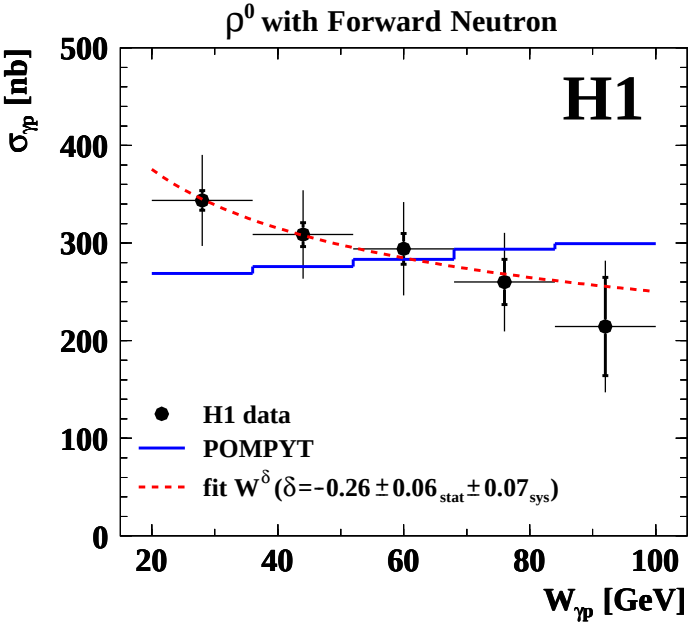

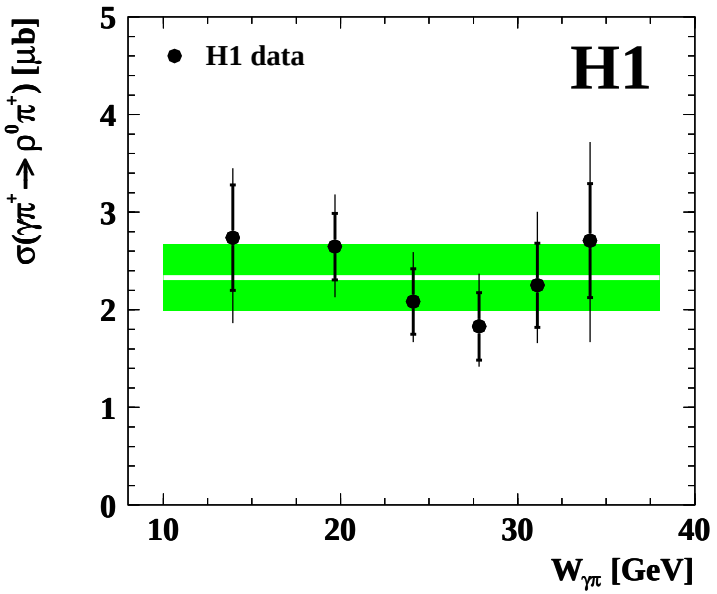

- Regge motivated fit $\sigma_{\gamma p} \propto W^{\delta}$
  $\delta = -0.26$
  ± 0.06 stat. ± 0.07 sys.
- POMPYT MC predicts different trend, typical for Pomeron exchange only

- $\sigma_{\gamma\pi^+ \to \rho^0 \pi^+} = \sigma_{\gamma p \to \rho^0 n \pi^+} / (\text{pion flux})$
- at $\langle W \rangle = 24$ GeV:
  $\sigma_{\gamma\pi^+ \to \rho^0 + \pi^+} / \sigma_{\gamma p \to \rho^0 + p} = 0.25 \pm 0.06$
  significantly lower than expected, suggesting large absorption
  0.44 ± 0.11

Summary

- Diffractive dijets in DIS with LRG confirms factorization in DDIS
- Diffractive dijet production in PHP and DIS with leading proton:
  - in agreement with H1(LRG) (H1 data/theory 0.6, independent of x_γ)
  - not explaining H1/ZEUS results difference (ZEUS data described with NLO QCD)
  - new measurement of double ratios data/NLO in PHP and DIS shows suppression of 0.55 for PHP independent of kinematics
- Exclusive dijet production at DIS, measured by ZEUS, favor model prediction based on a two-gluon exchange
- Recent preliminary result on $D^\star$ production supports validity of collinear factorization
- Prompt photons in diffractive photoproduction measured for the first time indicating reasonable description of cross section shapes with LO prediction
- The cross section ratio $\sigma(\Psi(2S))/\sigma(J/\Psi)$ was measured by ZEUS with improved precision.
  - ratio grows with Q^2 as predicted by pQCD and is constant with W and t
  - ratio is compared with models of VM production, some discrimination of the different models is possible
- Exclusive ρ^0 photoproduction associated with a leading neutron measured by H1 for the first time at HERA:
  - the differential cross section $\mathrm{d}\sigma/\mathrm{d}t'$ for the reaction $\gamma p \to \rho^0 n\pi^+$ shows a behaviour typical for exclusive double peripheral exchange processes
  - the estimated cross section ratio for the elastic photoproduction of ρ^0 mesons on the pion and on the proton equals 0.25 ± 0.06, suggests large absorption corrections