Recent HERA results on diffraction and exclusive final states

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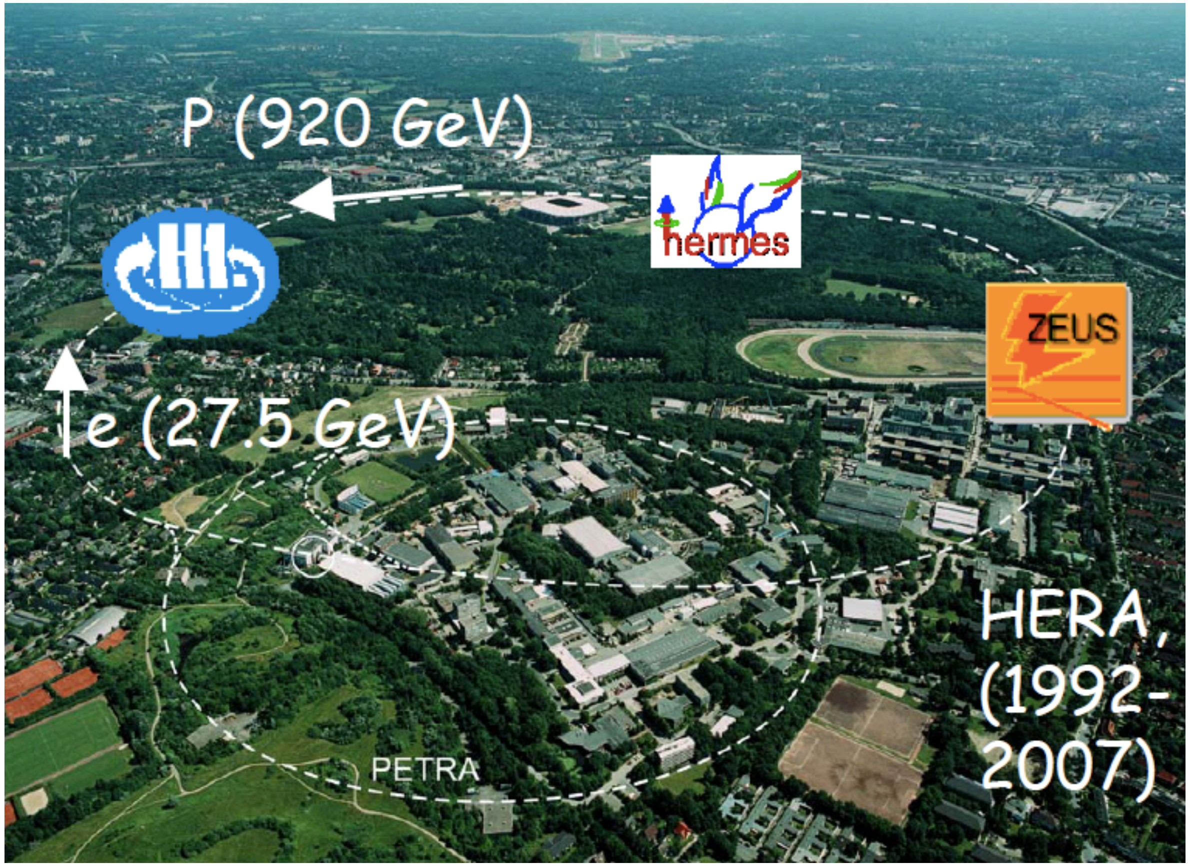
On behalf of the H1 and ZEUS Collaborations

Outline:

- Dijet production in diffractive DIS [H1 – JHEP 03 (2015) 092]
- Diffractive dijets with a leading proton [H1 – JHEP 05 (2015) 056]
- Exclusive dijet production in diffractive DIS [ZEUS – DESY-15-070, sent to EPJC]
- Diffractive photoproduction of isolated ("prompt") photons [ZEUS-prel-15-001]
- Cross section ratio $\Psi'(2S)/J/\Psi(1S)$ in exclusive DIS [ZEUS-prel-15-003]
- Exclusive ρ^0 photoproduction with a leading neutron [H1 – DESY-15-120, sent to EPJC]

ICNFP 2015

HERA experiments



HERA-I : 1992-2000

p : 820 GeV

920 GeV

HERA-II : 2001-2007

p : 920 GeV

575 GeV

460 GeV

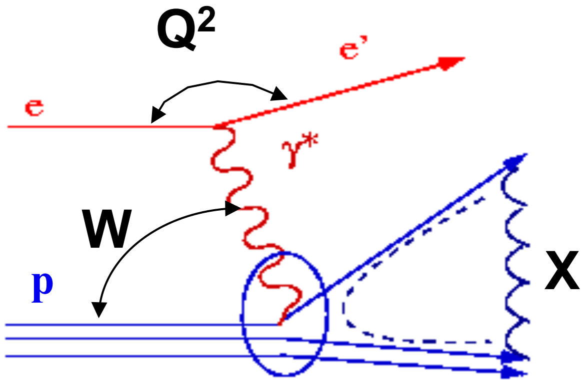
Most of the collected data are at $\sqrt{s}$ = 318 GeV

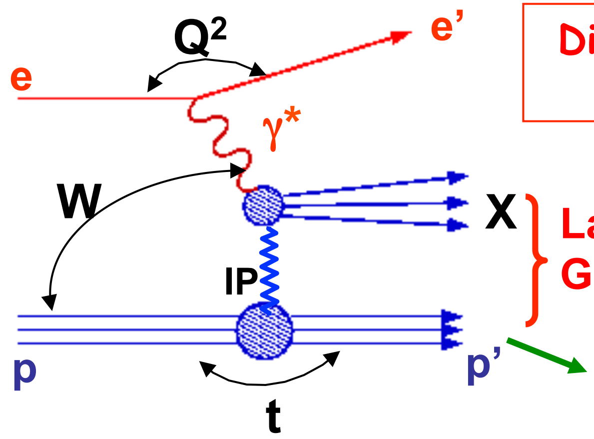
~0.5 fb^{-1} per experiment collected by H1 and ZEUS

Final analyses of HERA data are underway

Diffraction at HERA

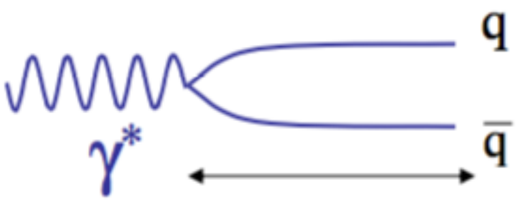
Standard DIS
ep → e'X





Diffractive DIS
ep → e'Xp'

Real and virtual photons can fluctuate in hadronic states ($q\bar{q}$, $q\bar{q}g$, ...)



$$\propto \frac{1}{\sqrt{Q^2 + M^2_{q\bar{q}}}}$$

$$\propto E_\gamma \sim W^2 \sim 1/x$$

(as seen in the proton rest-frame)

Q^2 = photon virtuality
x = Bjorken scaling variable

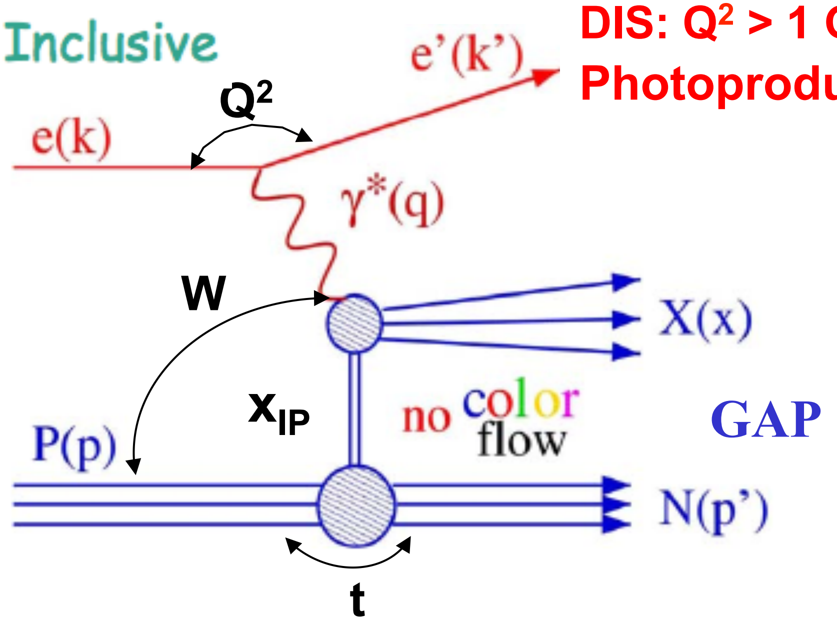
✓ Lifetime of $q\bar{q}$ dipole (hadron!) long because of large Lorentz boost (E_γ ~ 50 TeV at HERA)
→ Dipole interacts hadronically with the proton

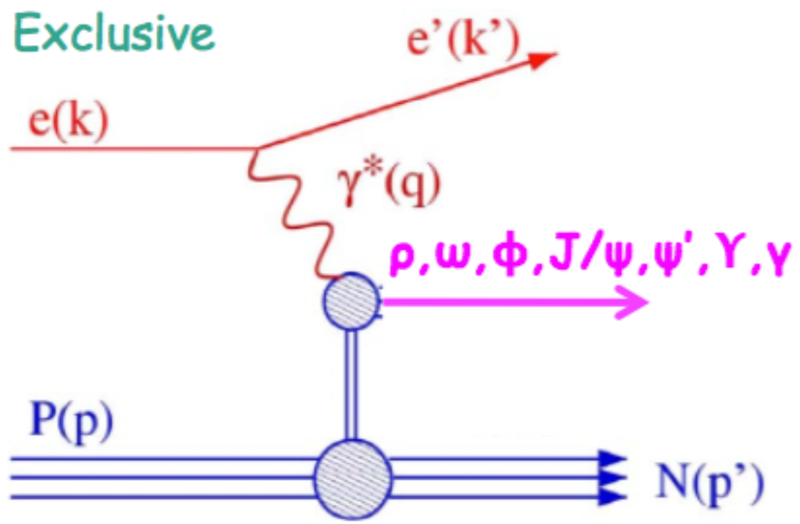
✓ Transverse size proportional to $1/\sqrt{(Q^2+M_{qq}^2)}$
→ If dipole size is small, its interaction with the proton **can be treated perturbatively**

Diffractive events contribute up to 15% of the inclusive DIS cross section

Inclusive and exclusive diffraction

DIS: $Q^2 > 1$ GeV^2
Photoproduction (γp): $Q^2 \sim 0$





Q^2 = virtuality of exchanged photon

x = Bjorken scaling variable

y = inelasticity of virtual photon

W = invariant mass of γ^*-p system

M_X = invariant mass of γ^*-IP system

x_{IP} = fraction of proton momentum carried by IP

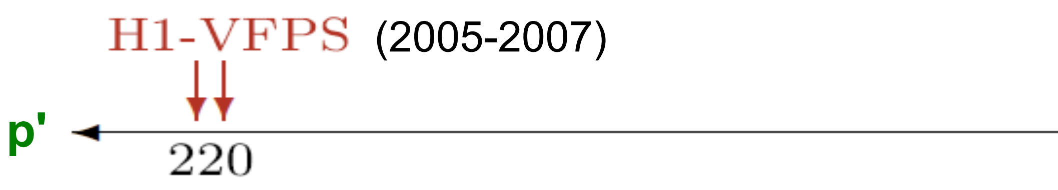
ß = x/x_{IP} = fraction of IP momentum carried by struck parton

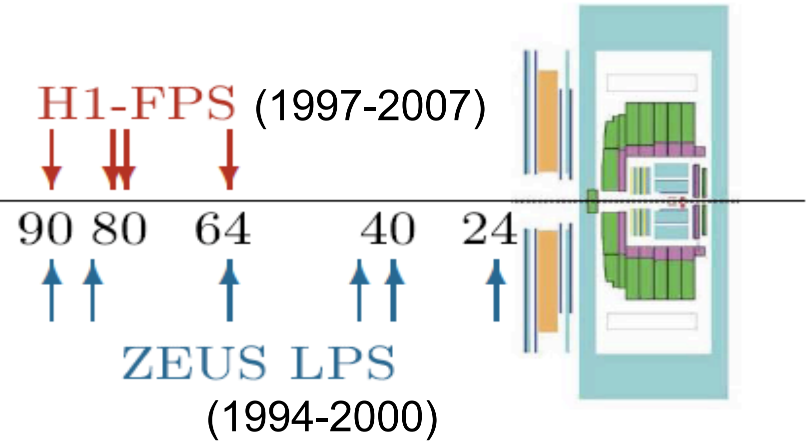
t = (4-momentum exchanged at p vertex)^2
typically: $|t| < 1$ GeV^2

- N = proton
  → Single Diffractive (SD) events
- N = proton dissociative system
  → Double Diffractive (DD) events

Signatures and selection methods

Proton Spectrometer (PS) method





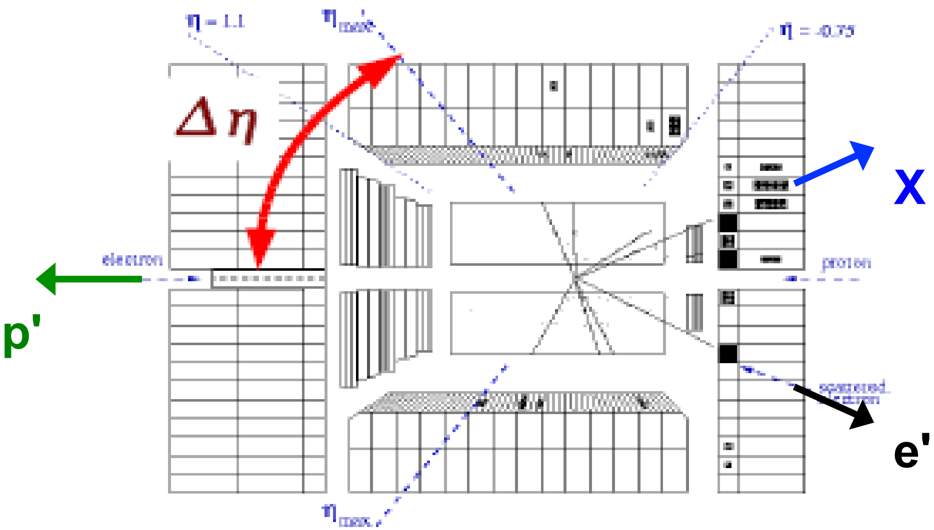
PROS: no DD

direct measurement of t and x_{IP}

high x_{IP} accessible

CONS: low statistics

Large Rapidity Gap (LRG) method



PROS: near perfect acceptance

at low x_{IP}

CONS: DD included

Factorisation properties of diffraction

pQCD framework as long as a hard scale is present:

QCD factorisation theorem, proven for DDIS by **J.Collins [PR D57 (1998) 3051]**

$$\sigma^D(\gamma^* p \to Xp) = \sum_i \hat{\sigma} \otimes f_i^D(x_{IP}, t, z, Q^2)$$

Hard subprocess ME
pQCD calculable

DPDFs = proton PDFs when a fast proton is in the final state,
universal for diffractive DIS processes

Proton-vertex factorisation assumption, supported by H1 and ZEUS data

$$f_i^D(x_{IP}, t, z, Q^2) = f_{IP}(x_{IP}, t) f_i^{IP}(z, Q^2) + f_{IR}(x_{IP}, t) f_i^{IR}(z, Q^2)$$

Flux parametrisation

$$f(x_{IP}, t) = \frac{Ae^{Bt}}{x_{IP}^{2\alpha(t)-1}}$$

with $\alpha(t) = \alpha(0) + \alpha' t$

Pomeron PDFs

Reggeon PDFs taken from pion (GRV)

→ **Use inclusive diffractive data to extract DPDFs via NLO QCD fits,**
fitting z and Q^2 dependence at fixed x_{IP} and t

(z = momentum fraction of the diffr exchange entering the hard scattering)

Factorisation tests in dijet production

Use DPDFs extracted from inclusive DDIS for calculating NLO QCD predictions to semi-inclusive final states → **test universality of DPDFs**

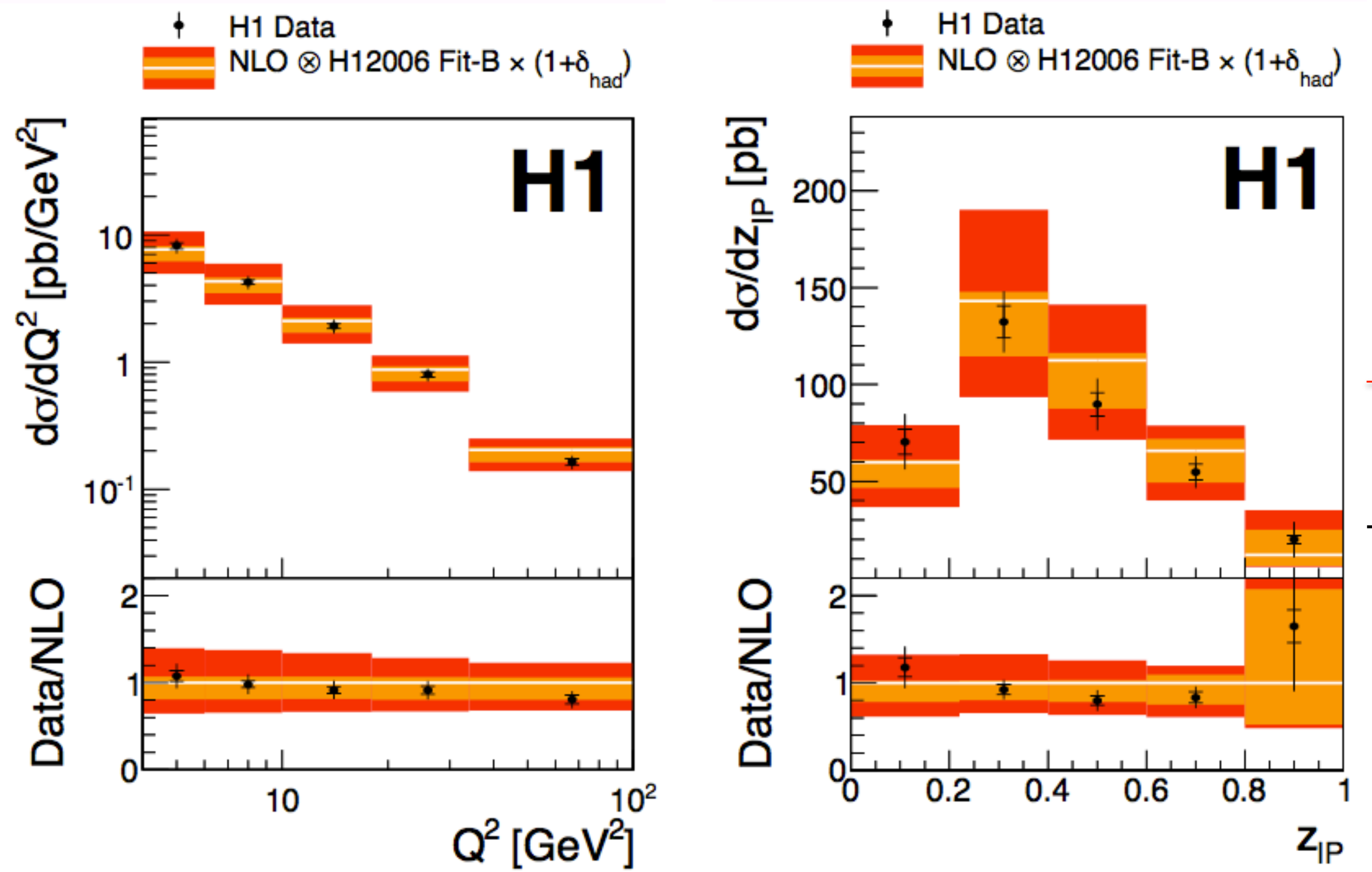
- **DIS regime ($Q^2 > 1$ GeV^2):**

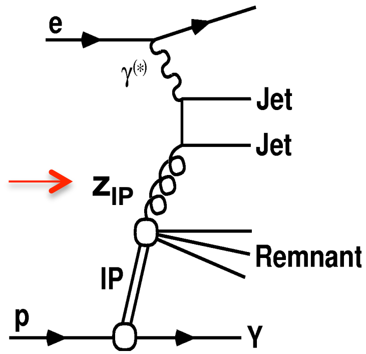
Several H1 and ZEUS measurements of dijet (but also open charm) production in DIS **confirmed factorisation**

New H1 measurement with 6x larger statistics than previous data sets →

Dijets in diffractive DIS

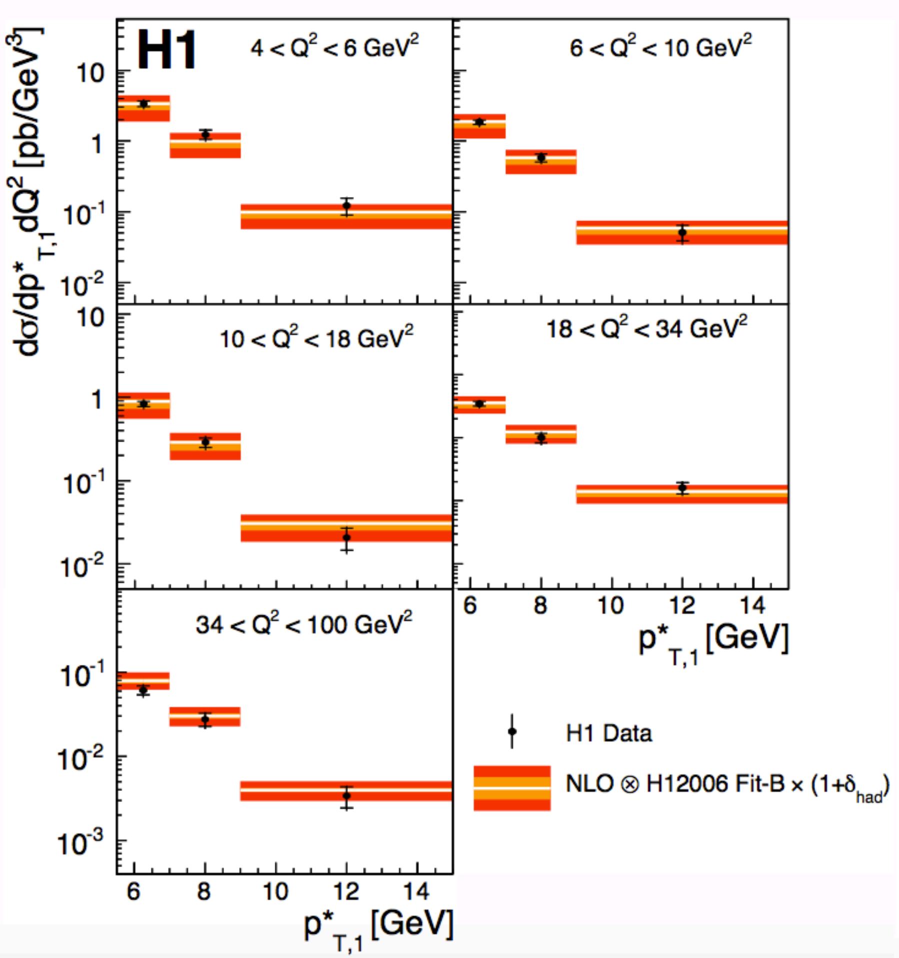
LRG method; $4 < Q^2 < 100$ GeV^2 ; $x_{IP} < 0.03$; $E_T^{jet1(2)} > 5.5$ (4) GeV

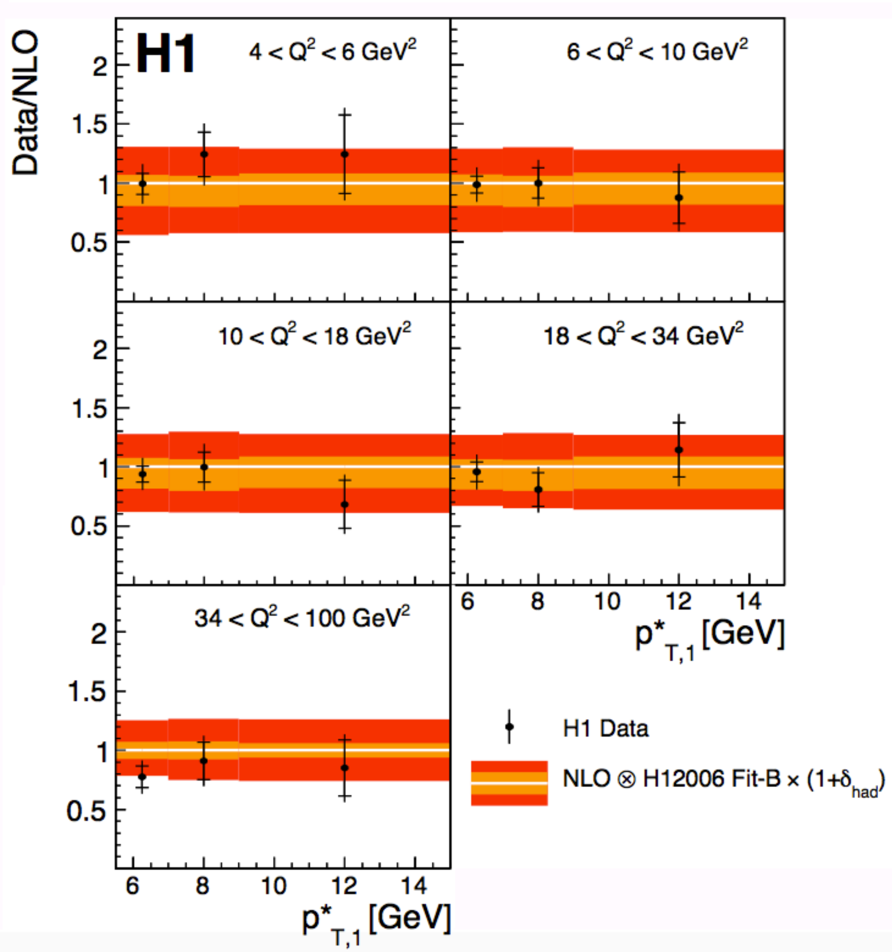




Measurements in agreement with NLO QCD calculations, **factorisation confirmed**

Dijets in diffractive DIS





$\alpha_S(M_Z)$ = 0.119 ± 0.004 (exp) ± 0.012 (DPDF, theo)

Result is consistent within uncertainties with the world average

Factorisation tests in dijet production

Use DPDFs extracted from inclusive DDIS for calculating NLO QCD predictions to semi-inclusive final states → **test universality of DPDFs**

- **DIS regime ($Q^2 > 1$ GeV^2):**

Several H1 and ZEUS measurements of dijet (but also open charm) production in DIS **confirmed factorisation**

New H1 measurement with 6x larger statistics than previous data sets →

- **Photoproduction regime ($Q^2 \sim 0$):**

Factorisation is not expected to hold for diffractive photoproduction, in particular resolved photoproduction where the photon behaves as a hadron
Factorisation was proved to be **broken in hadron-hadron collisions** at **Tevatron** and **LHC** with a "suppression factor" S^2 (= data/NLO) ~ 0.1

Previous measurements gave different results:

H1: LRG method, tagged γp, $E_T^{jet1(2)} > 5(4)$ GeV
$S^2 = 0.58 \pm 0.12(\text{exp}) \pm 0.14(\text{scale}) \pm 0.09(\text{DPDFs})$,
indicating factorisation breaking

H1, EPJ C70 (2010) 15

ZEUS: LRG method, untagged γp, $E_T^{jet1(2)} > 7.5(6.5)$ GeV
$S^2 \sim 1$, compatible with factorisation

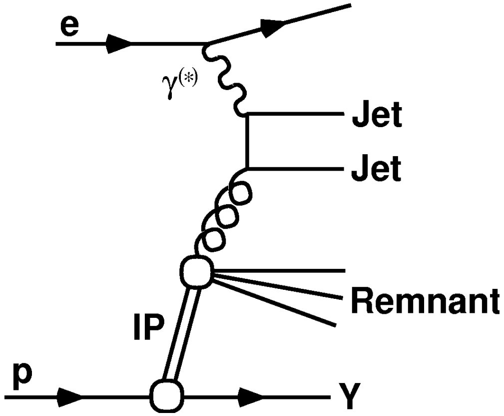
ZEUS, NP B831 (2010) 1

New H1 measurement using data with protons measured in the VFPS →

Hadron-hadron and photoproduction

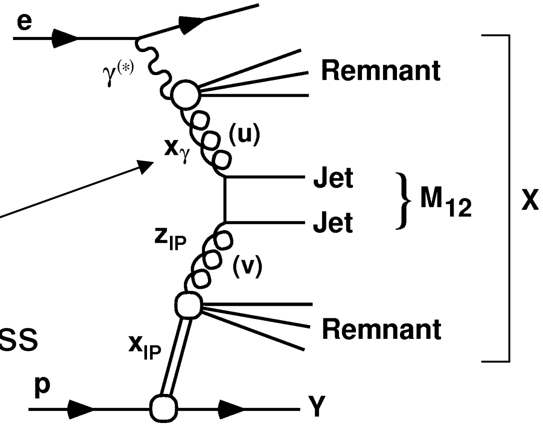
Quasi-real photons ($Q^2 \sim 0$) can develop a **hadronic structure**

Direct photon ($x_\gamma \sim 1$) (at LO) **Resolved photon ($x_\gamma < 1$)**



High E_T of the jets provides the hard scale

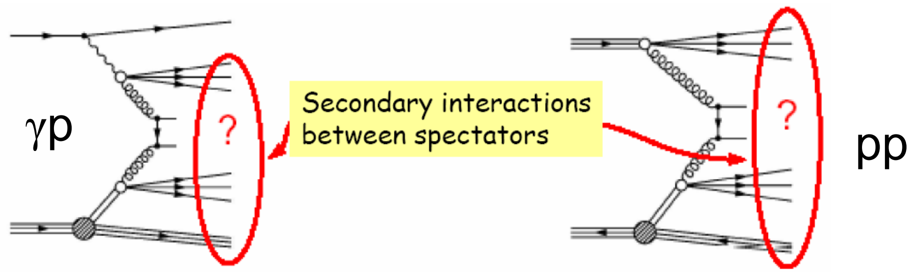
x_γ = fraction of photon's momentum in hard subprocess



QCD factorisation is expected to hold like in DIS

QCD factorisation is expected to break like in hadron-hadron:

Violation of factorisation is understood in terms of (soft) rescattering between spectator partons, in initial and final states, suppressing the large rapidity gap

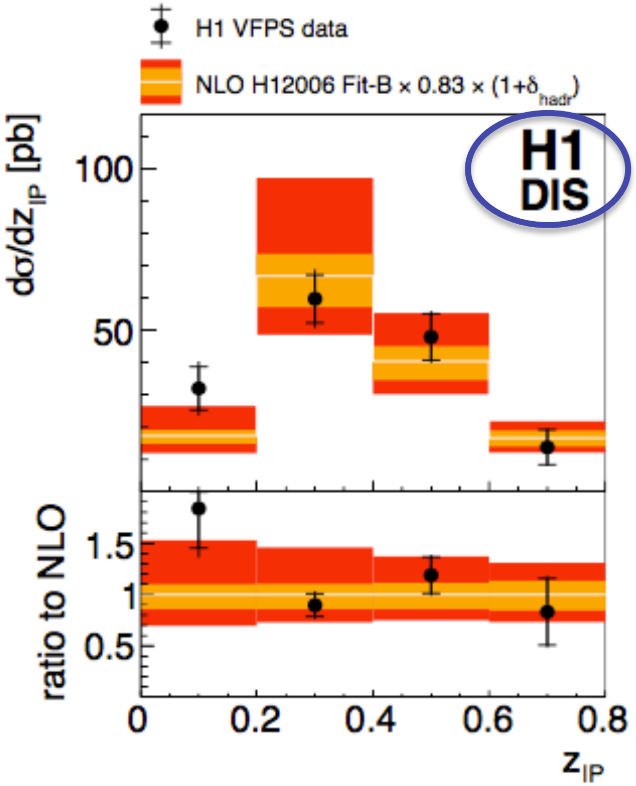


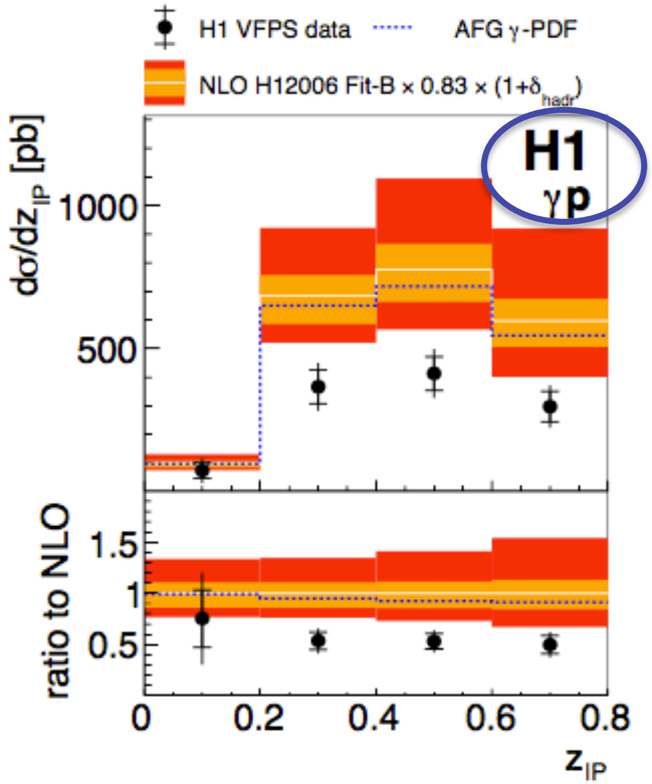
Diffractive dijets with a leading proton

PS method with VFPS; $0.01 < x_{IP} < 0.024$; $|t| < 0.6$ GeV^2 ; $z_{IP} < 0.8$

$E_T^{jet1(2)} > 5.5(4)$ GeV ; $-1 < \eta_{jet\,1(2)} < 2.5$

DIS: $4 < Q^2 < 100$ GeV^2 ; γp: $Q^2 < 2$ GeV^2

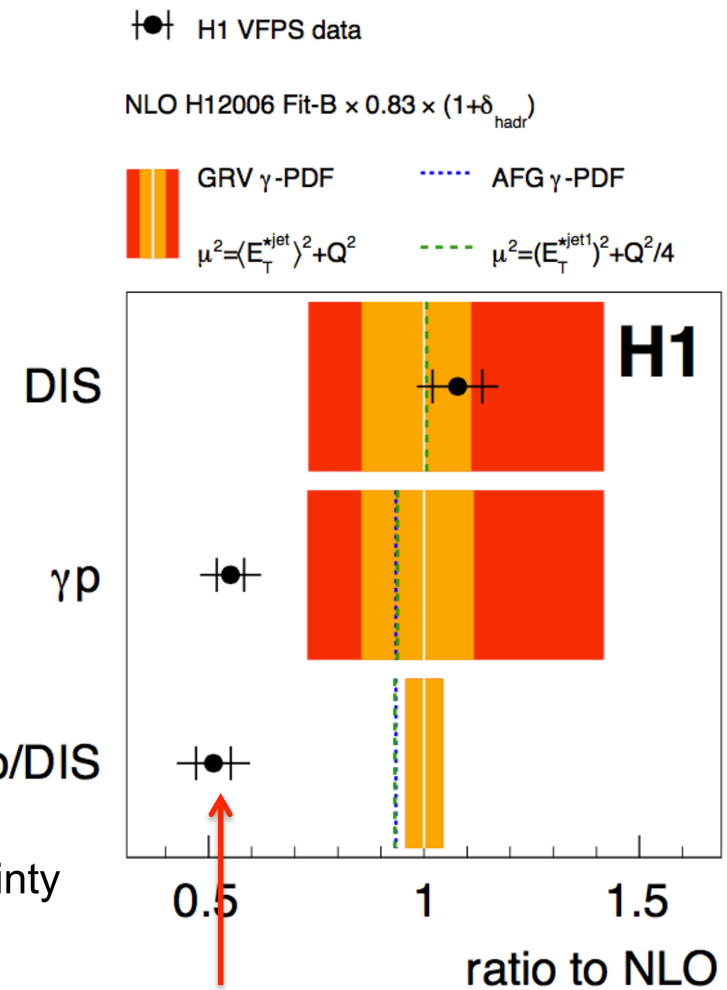




Data in agreement with NLO,
factorisation confirmed in DDIS

Data suppressed with respect to NLO,
factorisation broken in diffractive γp

Dijets in diffractive photoproduction



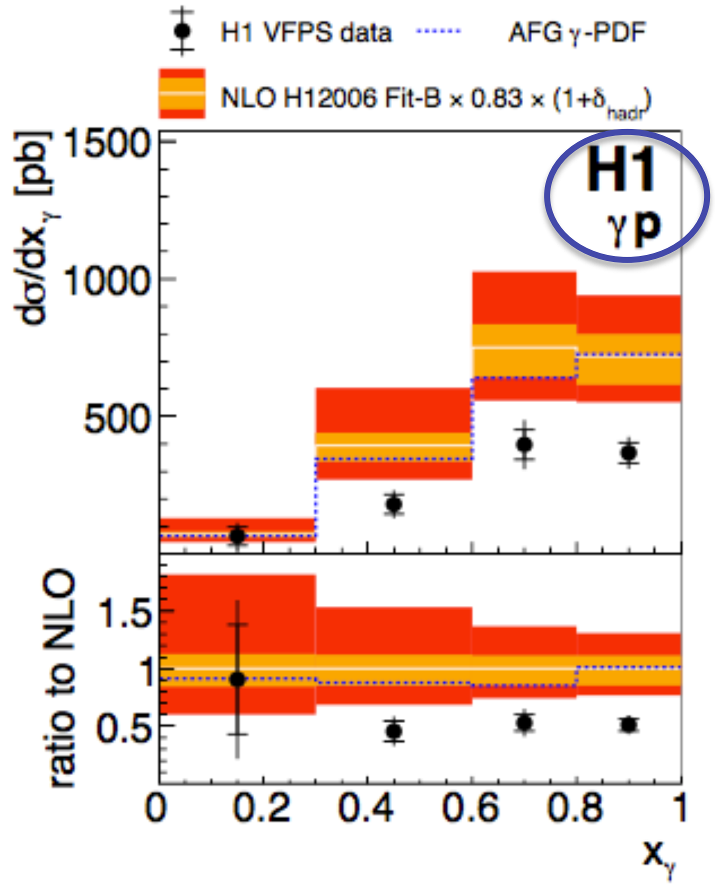
$$\frac{(Data/NLO)_{\gamma p}}{(Data/NLO)_{DIS}} \rightarrow \gamma p/DIS$$

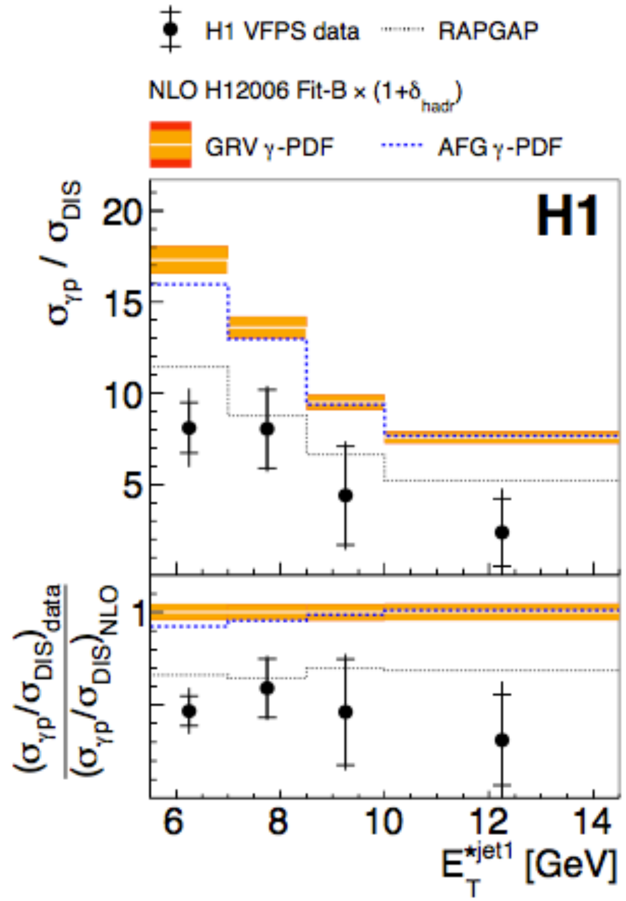
to cancel DPDFs uncertainty

Double ratio photoproduction/DIS: 0.511 ± 0.085(data) ± 0.022/0.021(theo)

→ **previous H1 measurements confirmed**

Dijets in diffractive photoproduction





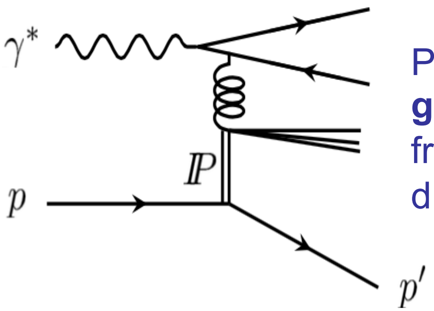
Suppression not dependent on x_γ, in agreement with previous H1 and ZEUS measurements

Within uncertainties, **no dependence of the suppression on E_T** of the leading jet is observed → reason of the difference between H1 and ZEUS results seems not connected with E_T

Exclusive dijets in diffractive DIS

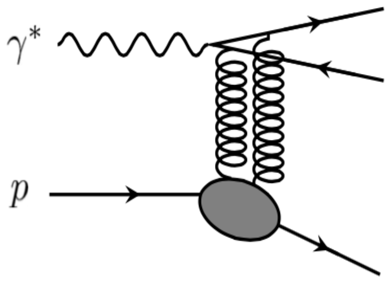
The measurement of **e + p → e' + p' + jet + jet** with only dijet, electron and proton in the final state is sensitive to the **nature of the diffractive exchange** and is a promising reaction to **probe off-diagonal (generalised) gluon distribution**

Resolved pomeron model

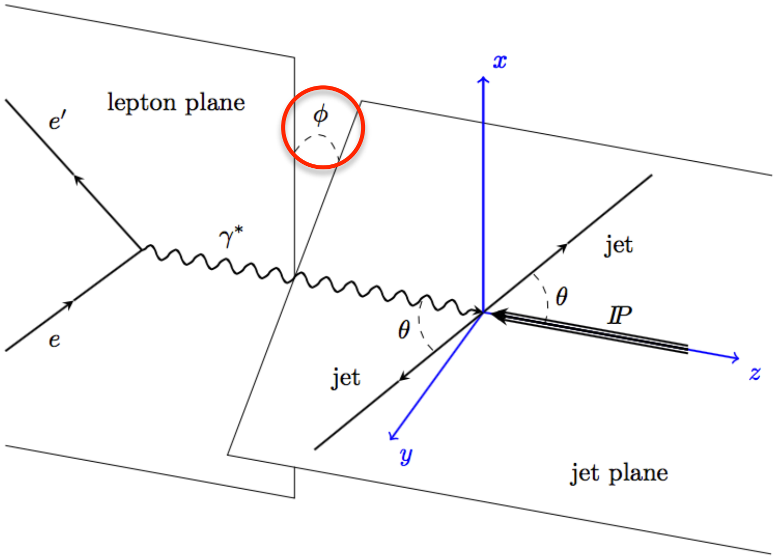


Predictions based on **gluon diffractive PDF** from H1 fits to inclusive diffractive data

Two-gluon exchange model



Cross section proportional to **square of the gluon density of the proton**: predictions based on the GRV parameterisation of the proton gluon density



Models can be distinguished by the theoretical prediction for the distribution of **Φ – angle between lepton and jet planes**

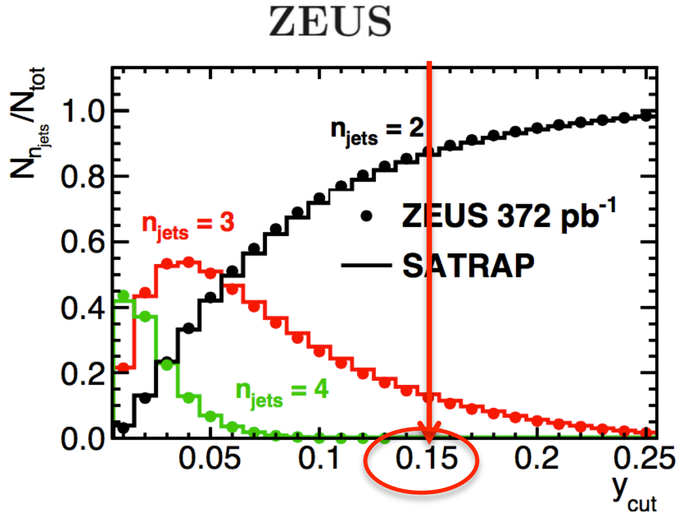
$$d\sigma/d\Phi \propto 1 + A\cos(2\Phi)$$ [Bartels et al., **PLB 386 (1996) 389**]

- Resolved pomeron model – **A positive**
- Two-gluon exchange model – **A negative**

Exclusive dijets in diffractive DIS

e + p → e' + p' + jet + jet with only dijet, electron and proton in the final state

Durham jet algorithm in γ^*IP rest frame in exclusive mode – **all objects in jets**



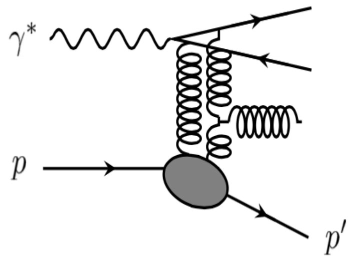
- $Q^2 > 25$ GeV^2
- $90 < W < 250$ GeV
- $x_{IP} < 0.01$
- $M_X > 5$ GeV
- $N_{jets} = 2$ (with $y_{cut} = 0.15$)
- $p_{T,jet} > 2$ GeV.

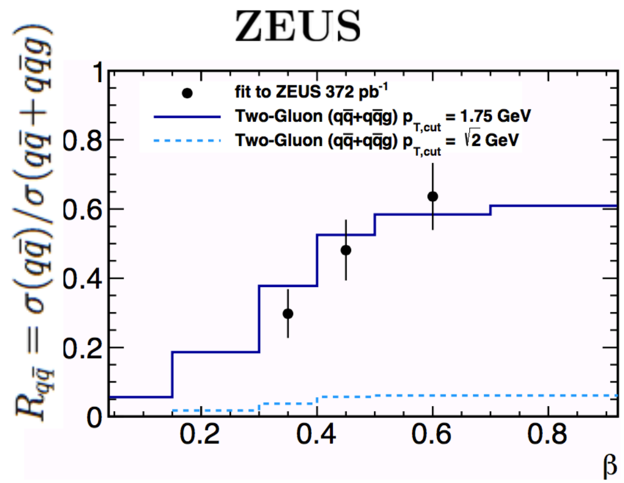
Proton dissociation background:

f_{diss} = 45% ± 4%(stat.) ± 15%(syst.)

Cross section unfolded as a function of β and Φ, reweighted by (1 – f_{diss})

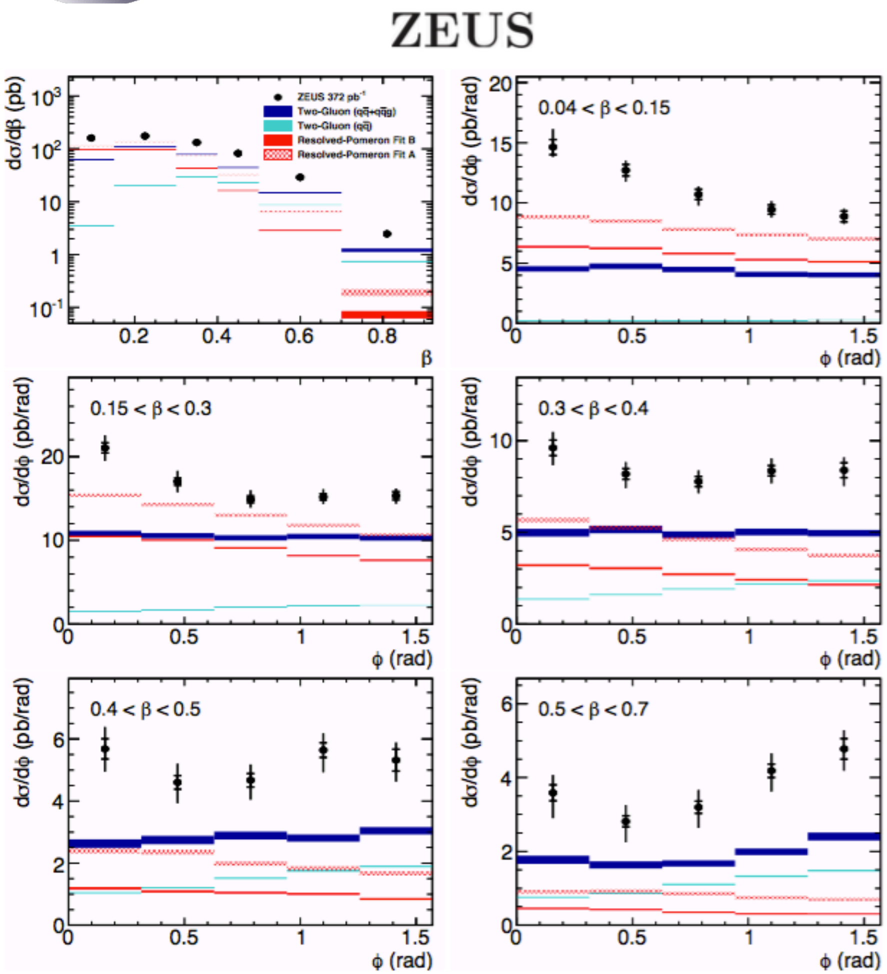
Contribution from the **$q\bar{q}g$ final state at low β**:



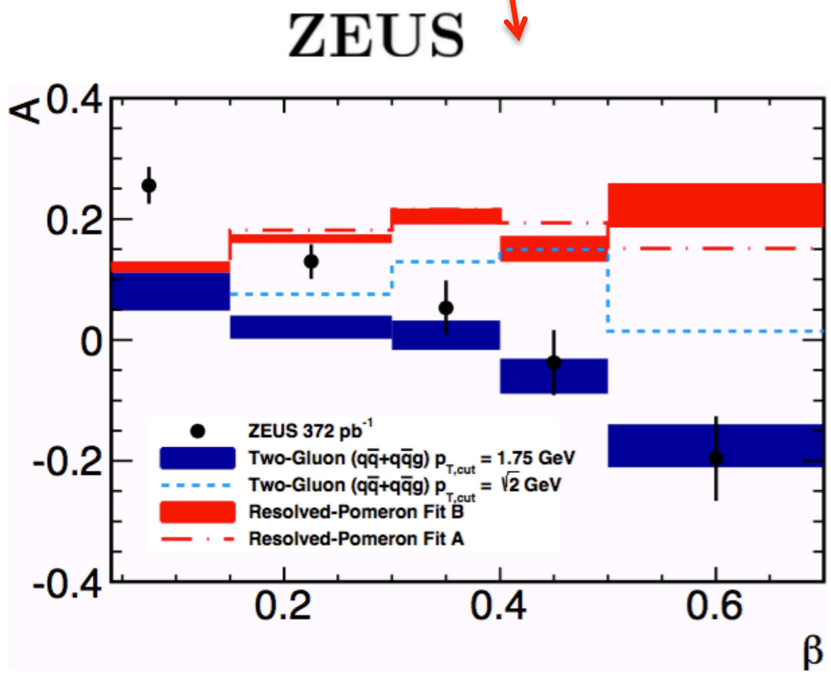


As a result, **A is expected to turn from positive to negative** going **from low to high β values**

Exclusive dijets in diffractive DIS



Fit of dσ/dΦ to 1+**A** cos(2Φ)



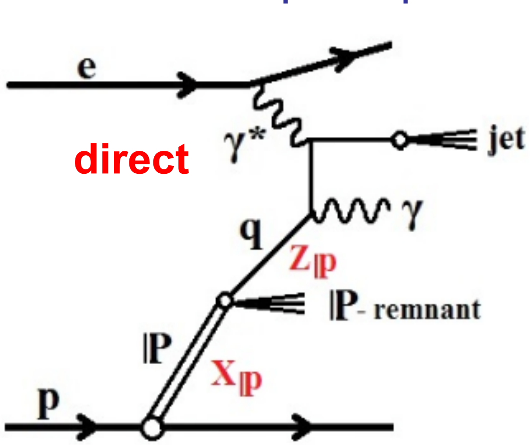
Normalization difference might indicate:
- NLO corrections large ?
- contribution of off-diagonal gluon distribution large ?

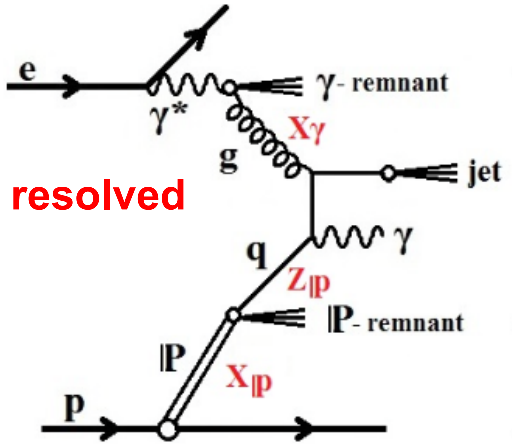
Two-gluon exchange model predicts reasonably well the measured value of A as a function of β for β > 0.3

Diffractive photoproduction of isolated γ's

"**Prompt**": high-p_T photon produced in a hard partonic interaction

In diffractive photoproduction:





Photon must couple to a charged particle ⟹ **explore the non-gluonic nature of the pomeron**

Measure diffractive "prompt" photons **inclusively and with an accompanying jet**, using HERA II (374 pb^{-1}) and HERA I (91 pb^{-1}, only for normalization)

Photons: $E_t^γ > 5$ GeV
$-0.7 < η^γ < 0.9$
"isolated"

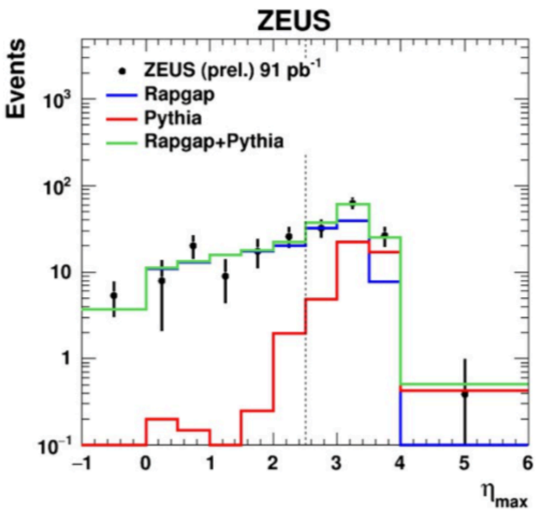
Jets: k_T-cluster algorithm
$E_t^{jet} > 4$ GeV
$-1.5 < η^{jet} < 1.8$

Diffractive selection with **LRG method**: $η_{max} < 2.5$
$x_{IP} < 0.03$

MC: **RAPGAP** with H1 fitB DPDFs and γ−PDF SASG 1D LO (for the resolved photon)

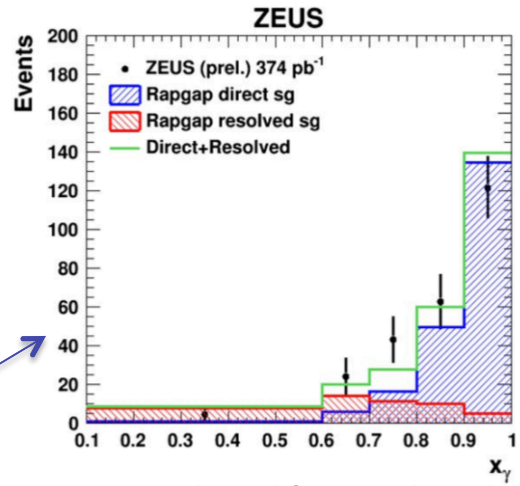
Diffractive photoproduction of isolated γ's

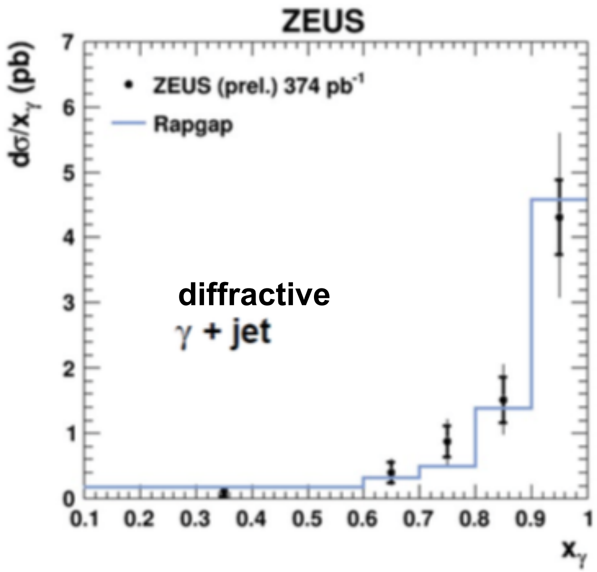
η_{max} well modeled in HERA I data, used to **remove non-diffractive background**



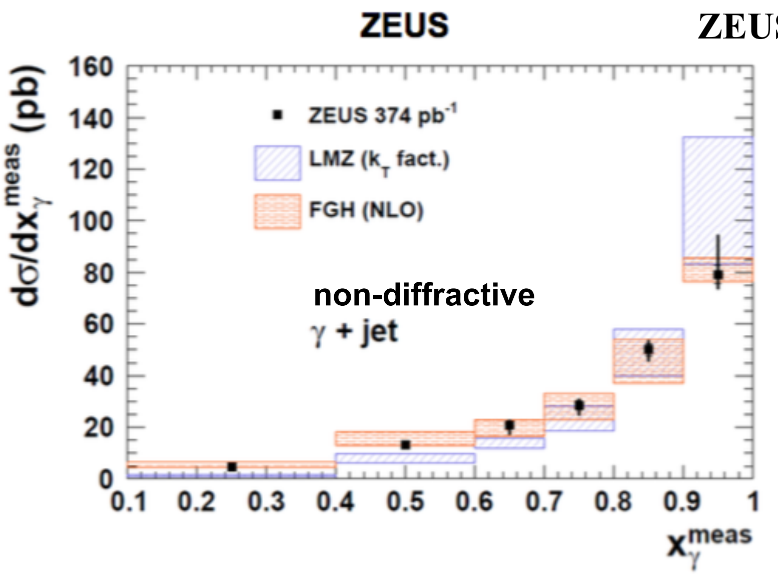
After background removal, **determine direct and resolved mixture**: dir/res = 4

x_γ compared to RAPGAP after reweighting



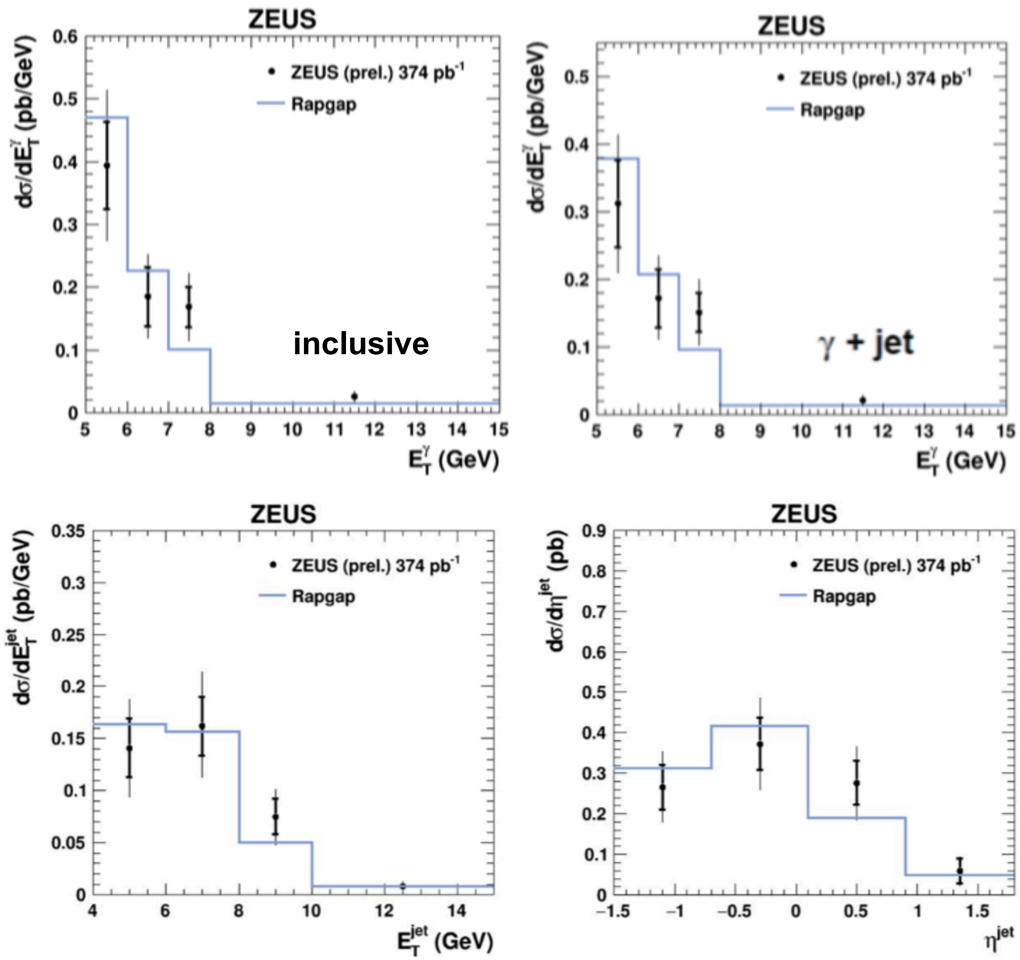


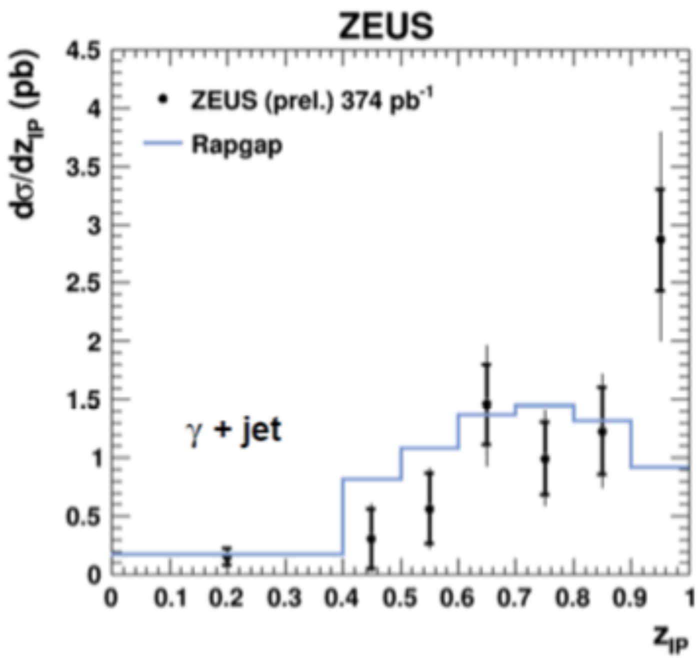
ZEUS, PLB 730 (2014) 293



Diffractive processes seem more strongly **direct-dominated** than non-diffractive ones

Diffractive photoproduction of isolated γ's

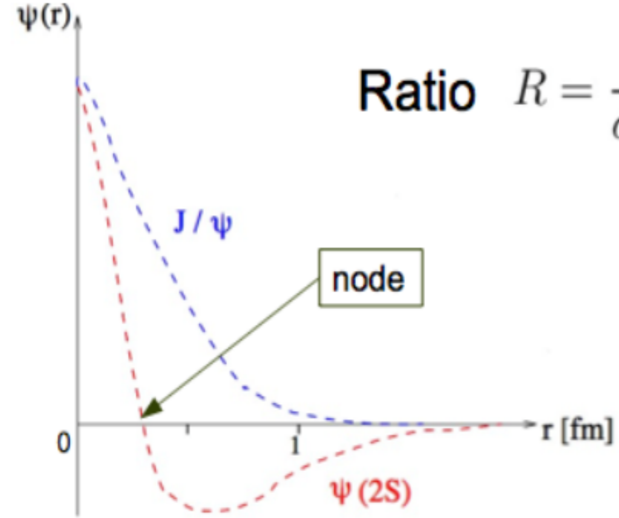




Data show a **sharp peak at z_{IP} ~ 1** which is not described by RAPGAP
[z_{IP} ~ 1 : no activity except jet and γ]

RAPGAP gives a reasonable description of most of the variables
Most photons are accompanied by a jet

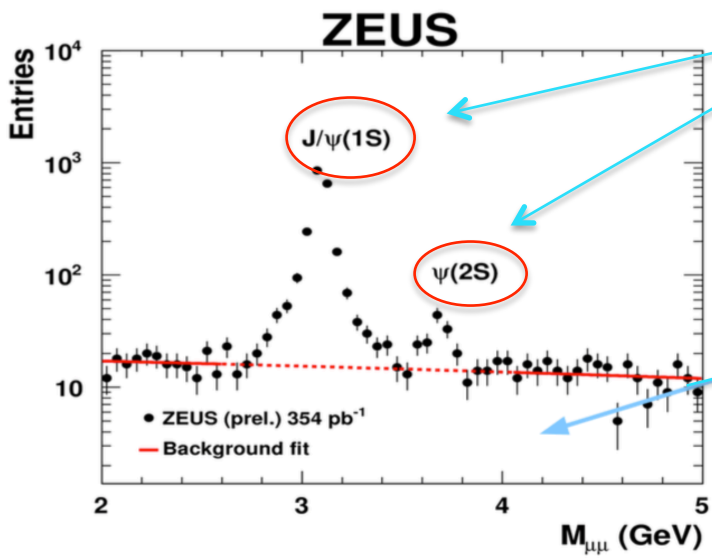
Ψ'(2S)/J/Ψ(1S) in exclusive DIS

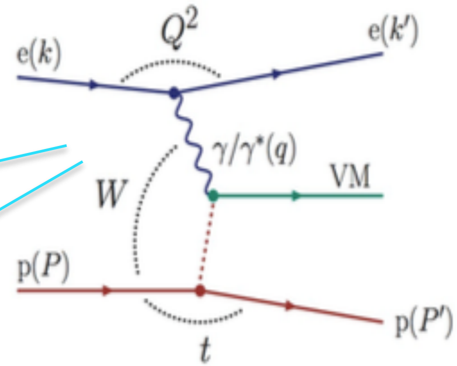


Ratio $R = \frac{\sigma_{\gamma p \to \psi(2S) p}}{\sigma_{\gamma p \to J/\psi p}}$

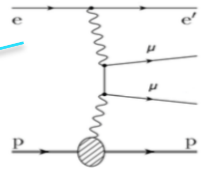
ψ(2S) wave function different from J/ψ wave function: **ratio sensitive to radial wave function of charmonium**

pQCD models predict R ~ 0.17 (γp) and rise of R with Q^2 (DIS)





Bethe-Heither

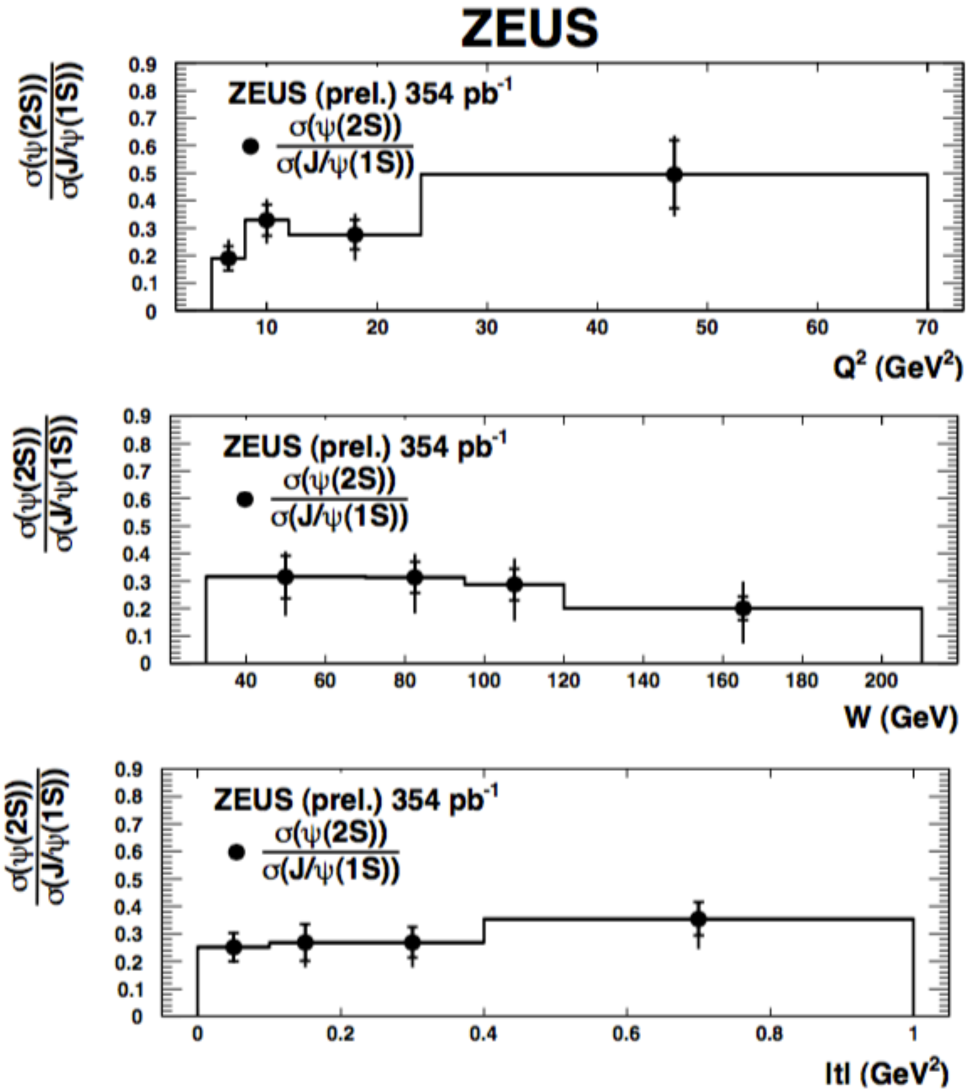


HERA I + HERA II data

ψ(2S) → J/ψ $\pi^+\pi^-$; J/ψ → $\mu^+\mu^-$
ψ(2S) → $\mu^+\mu^-$
J/ψ → $\mu^+\mu^-$

30 < W < 210 GeV
2 < Q^2 < 80 GeV^2
|t| ≤ 1 GeV^2

Ψ'(2S)/J/Ψ(1S) in exclusive DIS



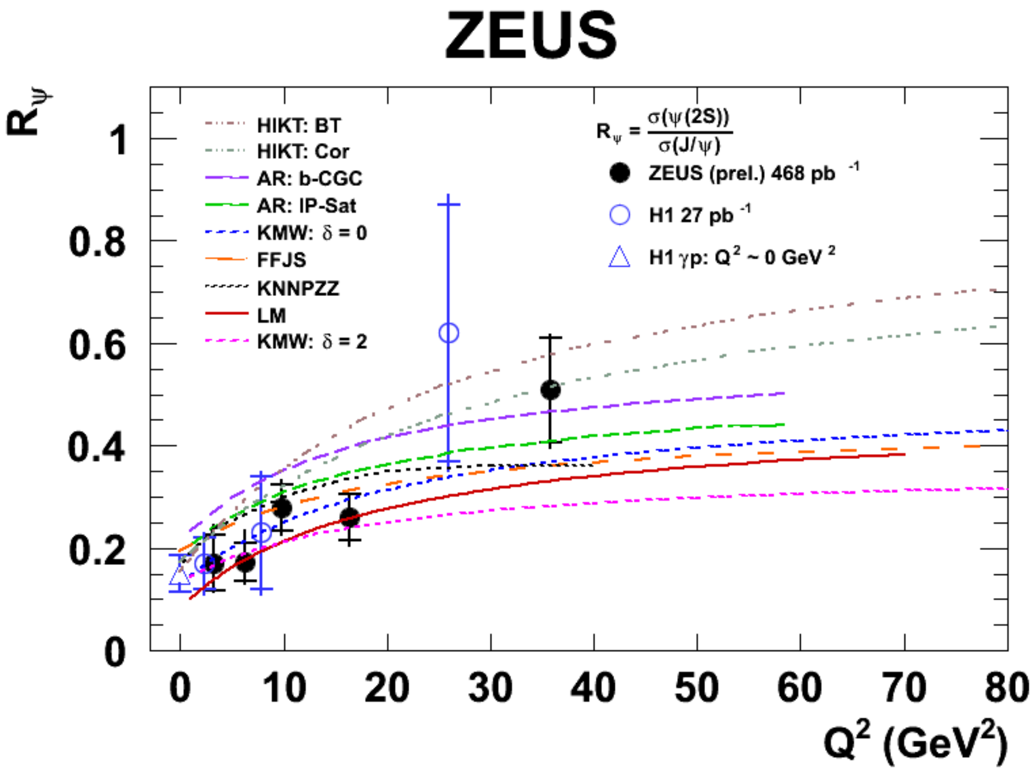
→ Increase with Q^2

→ Independent of W

→ Independent of |t|

Ψ'(2S)/J/Ψ(1S) in exclusive DIS

Comparison with H1 earlier measurement and with models

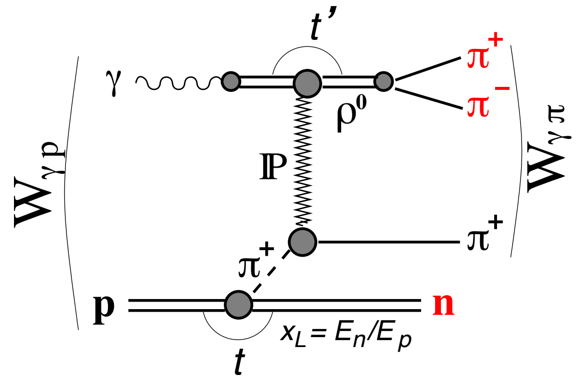


H1, EPJ C10 (1999) 373

HIKT, Hufner 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 photoproduction of ρ^0 mesons with a leading neutron

In **e + p → e' + n + X** the production of neutrons carrying a large fraction of the proton beam momentum is dominated by the **pion exchange process**

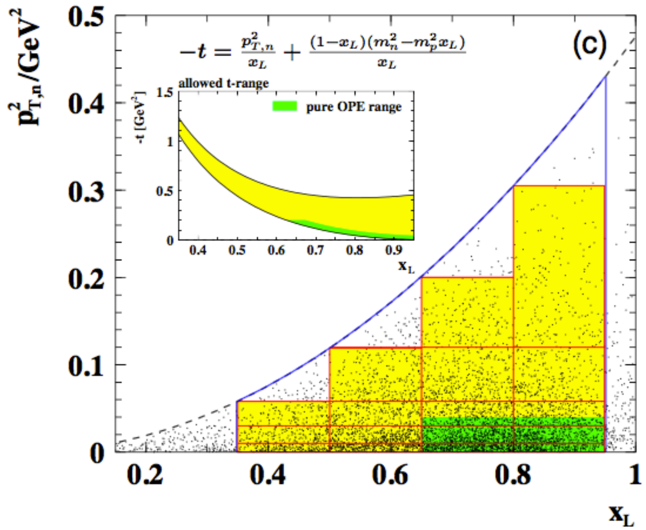


⟹ **Extract $\sigma(\gamma\pi^+ \rightarrow \rho^0\pi^+)$**

Mean W ~ 24 GeV → soft regime

Theoretically: exchange of two Regge trajectories in a Double Peripheral Process (DPP)

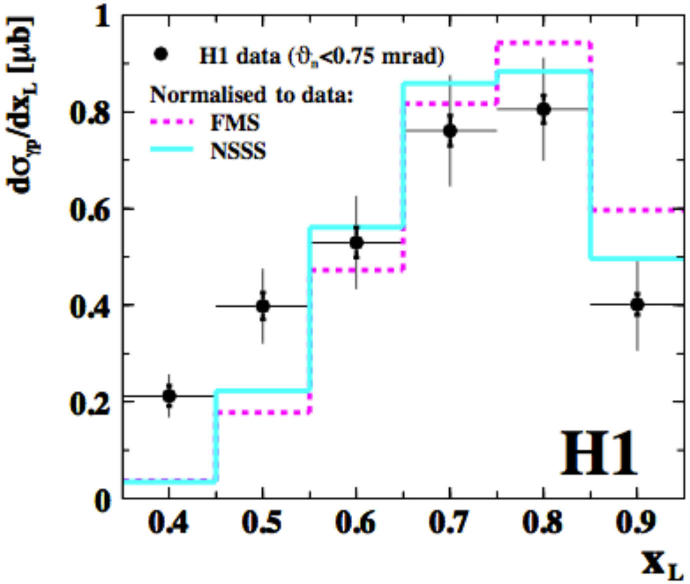
Leading neutron measured in the
Forward Neutron Calorimeter (FNC)

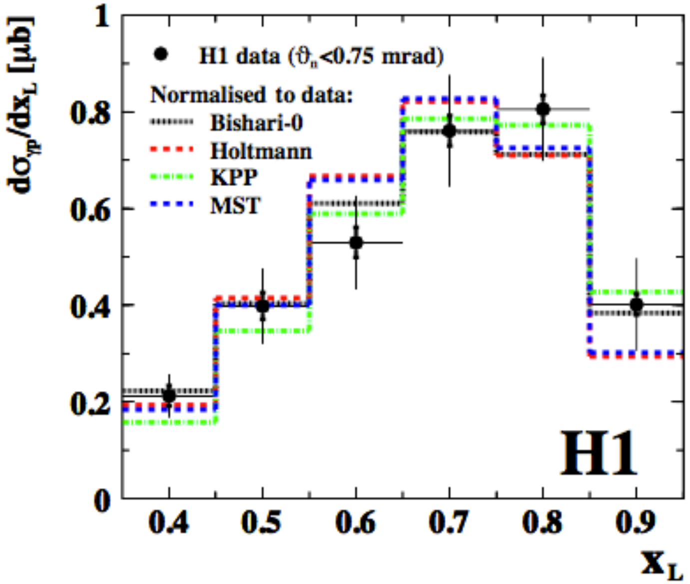


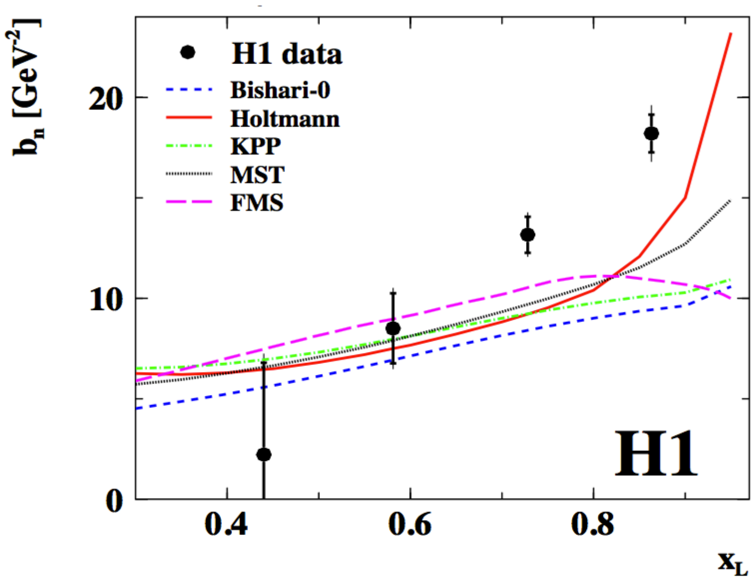
Cross section measurement:

- $20 < W_{\gamma p} < 100$ GeV
- $|t'| < 1$ GeV^2
- $2m_\pi < M_\rho < M_\rho + 5\Gamma_\rho$
- $0.35 < x_L < 0.95$
- $\theta_n < 0.75$ mrad
- Background due to proton dissociation subtracted: $f_{bg} = 0.34 \pm 0.05$

Exclusive photoproduction of ρ^0 mesons with a leading neutron



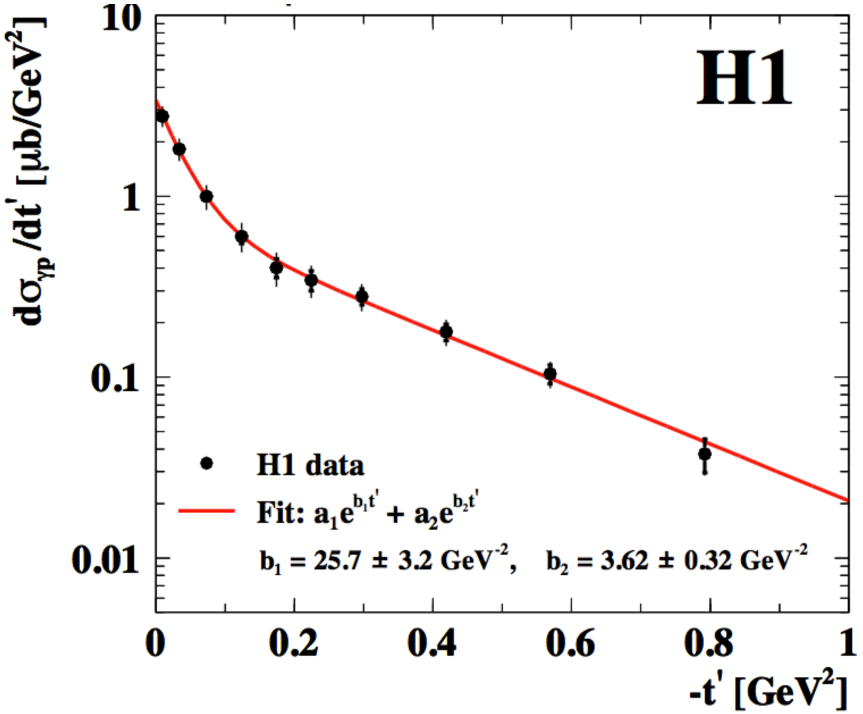


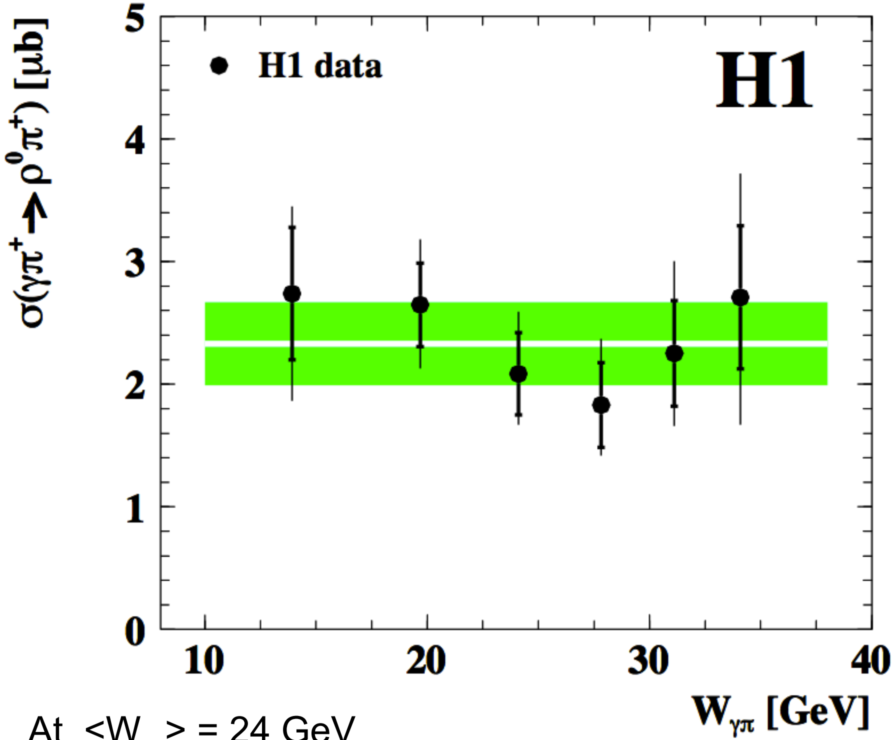


x_L distribution of the leading neutron generally **well described** – some pion fluxes disfavoured

Instead **none of the models can reproduce the t dependence** of the leading neutron – effect of absorptive corrections ?

Exclusive photoproduction of ρ^0 mesons with a leading neutron





Slope of the ρ^0 strongly changing from low-t' to high-t' region, **as expected for a double-peripheral process**

At $\langle W_{\gamma\pi} \rangle$ = 24 GeV

$$\sigma(\gamma\pi^+ \to \rho^0\pi^+) = (2.33 \pm 0.34(\text{exp})^{+0.47}_{-0.40}(\text{model}))\ \mu b$$

$\sigma(\gamma\pi^+)/\sigma(\gamma p) = 0.25 \pm 0.06$

in agreement with a previous ZEUS measurement **[ZEUS, NP B637 (2002) 3]**

Significantly lower than expected, suggesting large absorption corrections

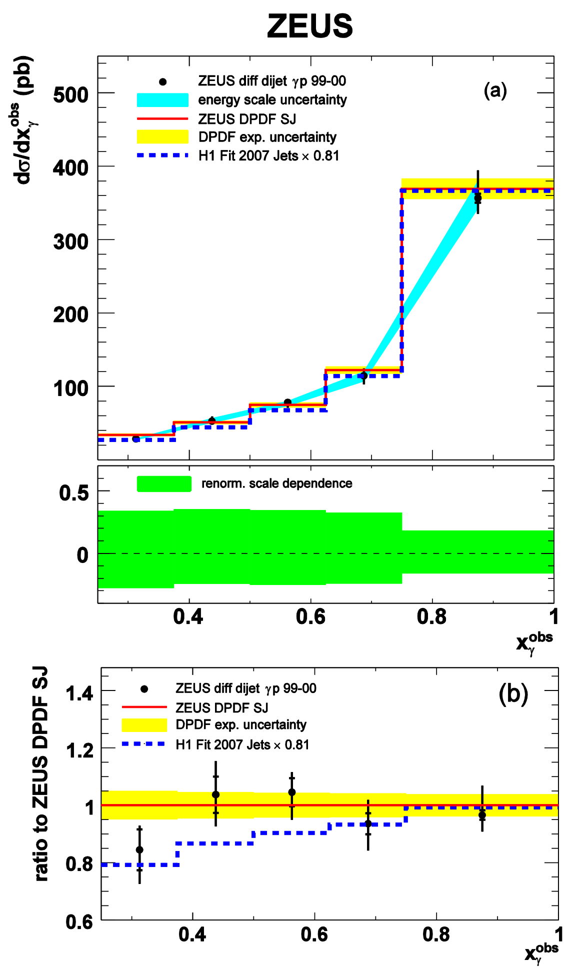
Summary

- New H1 measurement of **diffractive dijet production in DIS** with 6x larger statistics than previous measurements: data in agreement with NLO QCD predictions using H1 DPDFs, confirming factorisation in diffractive DIS; $\alpha_S(M_Z)$ extracted, in agreement with world average
- **Diffractive dijets in photoproduction and DIS** measured by H1 **using the VFPS:** DIS data in agreement with NLO QCD predictions; photoproduction data show a suppression factor ~ 0.5 ± 0.1, consistent with factorisation breaking. Tension with ZEUS measurements, which show no evidence of suppression, persists
- First ZEUS measurement of **exclusive dijets in diffractive DIS:** measured cross sections significantly larger than predicted by models; Two-gluon-Exchange model more successful than the Resolved-Pomeron model in describing the measured value of A as a function of β
- **Diffractive photoproduction of prompt photons**, inclusive and with an accompanying jet, measured by ZEUS: process dominated by direct photons; data show a sharp peak at z_{IP} ~ 1 which is not described by the MC
- **Cross section ratio ψ'/J/ψ** measured by ZEUS with full HERA statistics: ratio grows with Q^2 and is constant with W and t
- **Exclusive ρ^0 photoproduction associated with a leading neutron** measured by H1: used to extract the elastic cross section $\sigma(\gamma\pi^+ \rightarrow \rho^0\pi^+)$ for the first time at HERA, which suggests large absorption corrections

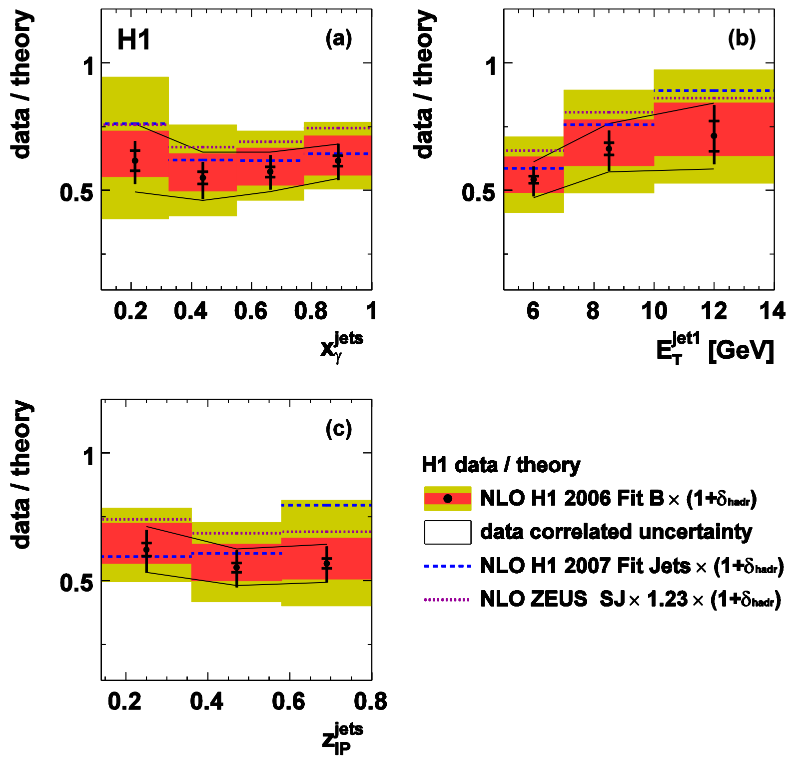
Backup slides

Dijets in diffractive photoproduction

ZEUS, NP B831 (2010) 1



H1, EPJ C70 (2010) 15



Dependence on jet E_T ?

H1: data/NLO = 0.58 ± 0.12(exp) ± 0.14(scale) ± 0.09(DPDF)

Both H1 and ZEUS see **no difference between direct and resolved regions** and prefer a global suppression factor

ZEUS: no evidence for a gap suppression

ZEUS has higher jet-E_T cuts than H1: $E_T^{1(2)} > 7.5(6.5)$ GeV^2