Diffractive processes at HERA
Recent results from H1 and ZEUS experiments

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On Behalf of H1 and ZEUS Collaborations

World's only $e \rightarrow \leftarrow p$ collider

$\sqrt{s_{max}}$= 318 GeV

$\mathcal{L}$~0.5 fb^{-1}/ experiment

- HERA I : 1992-2000
- HERA II: 2003-2007

e^-p :~ 200 pb^{-1}
e^+p :~ 300 pb^{-1}

Analyses Ongoing!

XVII Lomonosov Conference on Elementary Particle Physics

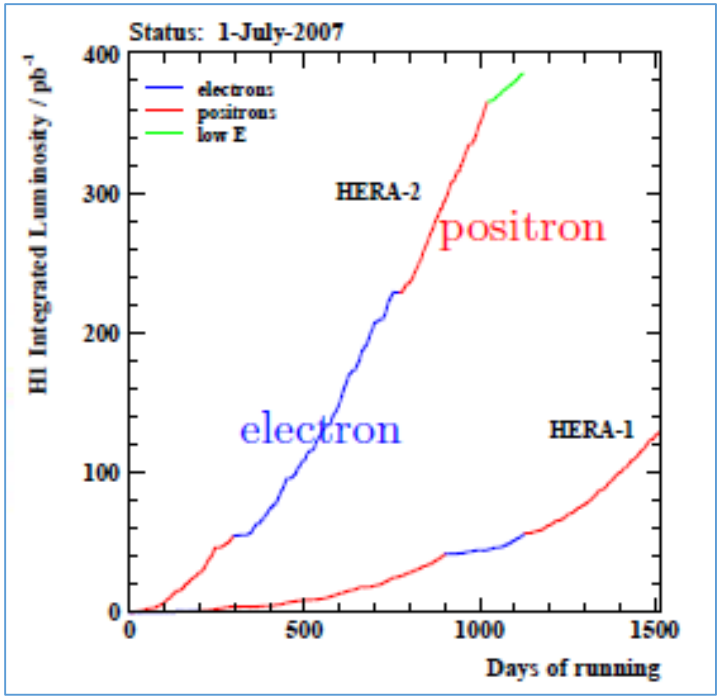
20 – 26 august 2015 **Moscow**

Diffraction at HERA $ep \longrightarrow eXp$ since 1993

H1 and ZEUS collected ~*0.5 fb*$^{-1}$ data:

- good measurement accuracy
- new detailed results → test QCD assumptions and expectations

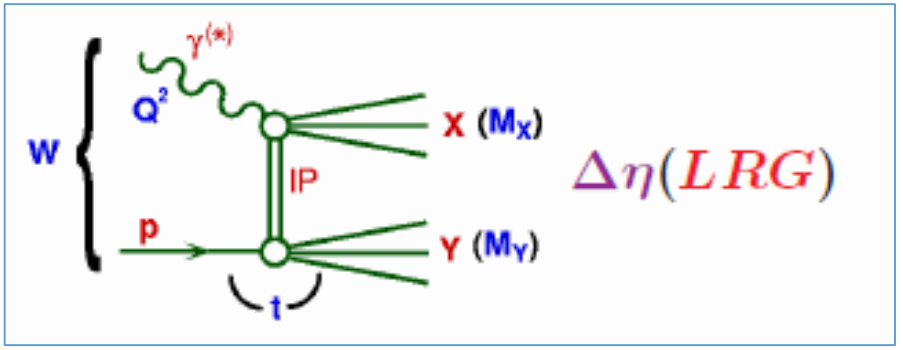
H1[JHEP 1505 (2015) 056], H1[JHEP 1503 (2015) 092], ZEUS[DESY 15-070], ZEUS-prel-15-001



Diffractive dissociation: $\mathcal{R}_{DD} = \frac{\sigma_{DD}}{\sigma_{Incl}} \simeq 10 - 15\%$

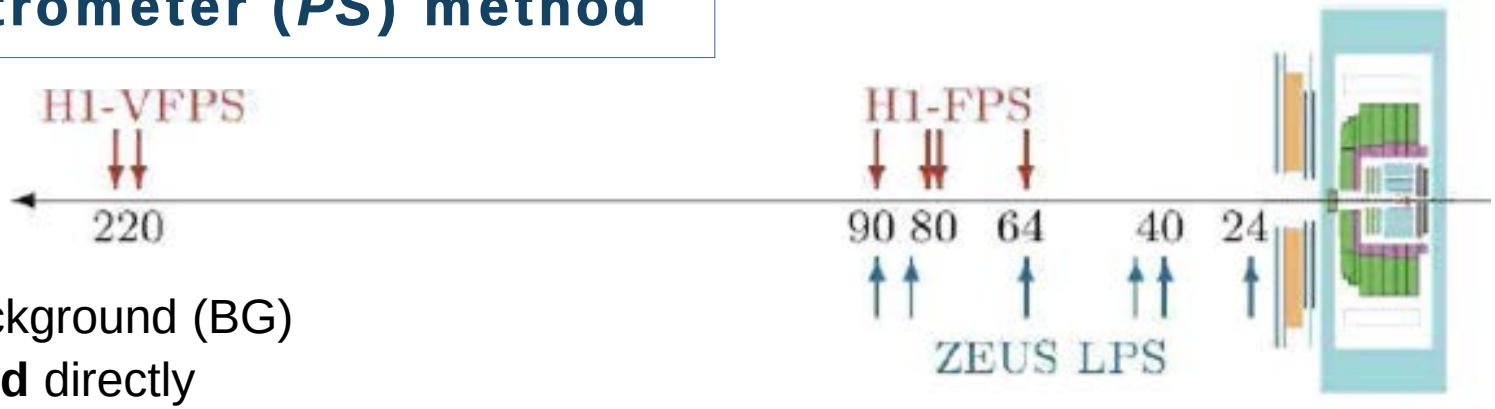
t-channel exchange (*IP*):

- vacuum quantum numbers colour singlet
- small momentum transfer t
- $M_Y = m_p \rightarrow$ elastic diffraction
  $M_Y > m_p \rightarrow$ proton dissociation (BG)



Signatures and Selection Methods

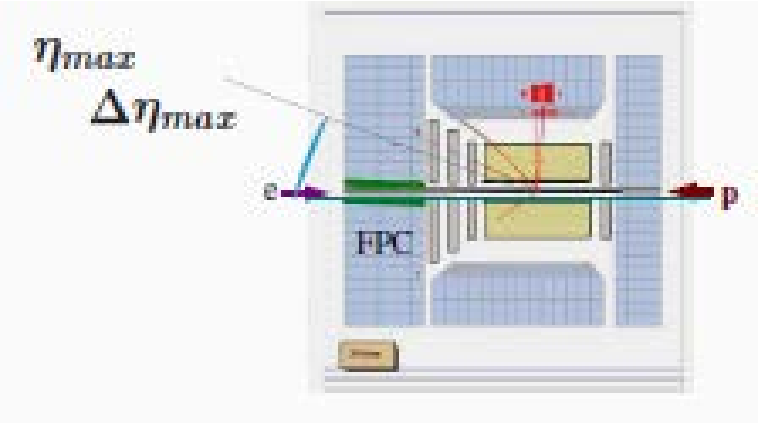
Proton Spectrometer (*PS*) method



- ***no p_diss*** background (BG)
- ***t, x_{IP}* measured** directly
- ***larger x_{IP}*** (< 0.1) accessible
- ***low Acc*** (~ 2%)

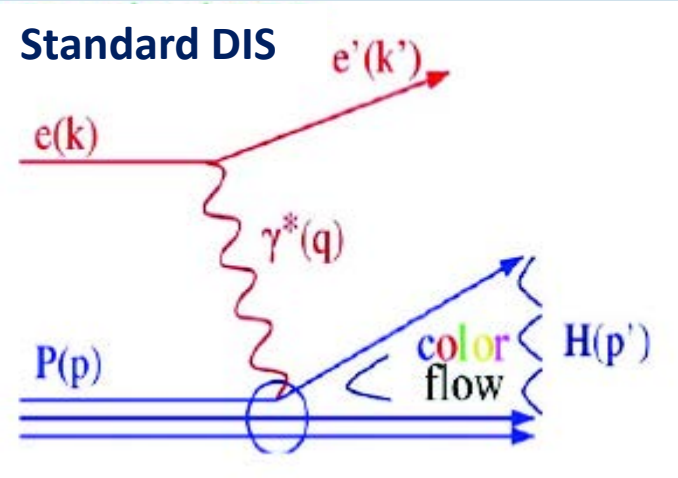
H1 FPS	$x_{IP} < 0.1$	- 156 pb^{-1} HERA I+II
ZEUS LPS	$x_{IP} < 0.1$	- 33 pb^{-1} HERA I
H1 VFPS	$0.009 < x_{IP} < 0.03$	- 87 pb^{-1} HERA II (e+p)

Large Rapidity Gap (*LRG*) method



- ***p_diss*** background (~ 15 − 20%)
- ***t* not measured**
- ***smaller x_{IP}*** (< 0.03) accessible
- ***higher Acc*** (~ 10%)

Kinematics of (virtual) Photon Diffractive Dissociation



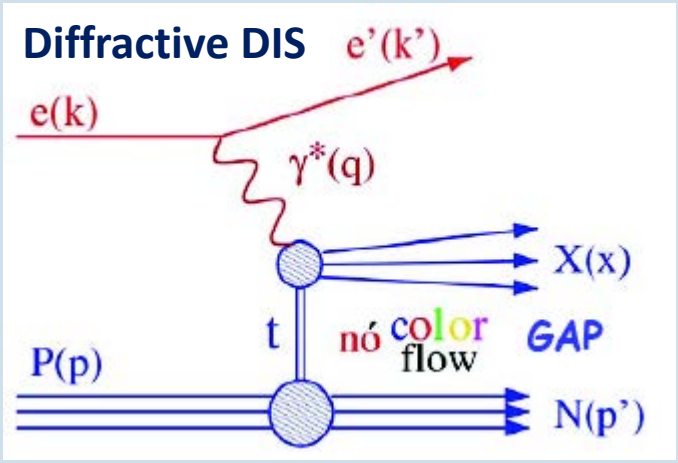
$Q^2 = -q^2$ – virtuality of the exchanged γ^*

$Q^2 \approx 0$ – $\gamma^* p$ $Q^2 >> 0$ – DIS

W – γ^*p center-of-mass energy

x – struck quark fractional momentum -Bjorken-x

$y = Q^2/(sx)$ – γ^* inelasticity



$X_{IP} \simeq (Q^2+M_X^2)/(Q^2+W^2)$ — colour singlet exchange fractional momentum (wrt to proton)

$\beta = x/x_{IP}$ — fractional momentum (wrt to *IP*) of a parton scattering off the γ^*

$t = (p - p')^2$ — 4-momentum transfer squared at the *p* vtx

M_x — invariant mass of diffractively produced system *X*

N=proton: Single Diffractive Dissociation / Elastic Scattering

N=proton-dissociative system: Double Diffractive Dissociation (BG)

QCD Factorisation

QCD factorization theorem: Cross-sections in hadron-hadron or electron-proton collisions are the convolution of universal (process independent) parton distribution functions (PDFs) and (perturbatively calculable) partonic cross-sections:

$$\sigma^D(\gamma^* p \to X p) = \sum_{parton\ i} f_i^D(x, Q^2, x_{I\!P}, t) \otimes \sigma^{\gamma^* i}(x, Q^2)$$

$f_i^D(x, Q^2, x_{I\!P}, t)$ — ***Universal*** diffractive parton distribution functions (***DPDFs***)
Calculated with evolution equations from initial phenomenological parametrization

$\sigma^{\gamma^* i}(x, Q^2)$ — ***Universal*** partonic cross-sections (perturbatively calculable if a hard scale found)

Factorisation of dependences on variables $(x_{I\!P}, t)$ describing the proton vertex has been empirically found to apply to a good approximation. This factorisation is parameterised using Regge formalism (Regge factorisation):

$$f_i^D(\beta, Q^2, x_{I\!P}, t) = f_{I\!P,I\!R}(x_{I\!P}, t) \cdot f_{i/I\!P}(\beta, Q^2) + f_{I\!R}(x_{I\!P}, t) \cdot f_{i/I\!R}(\beta, Q^2)$$

IP and *IR* fluxes: $f_{I\!P,I\!R}(x_{I\!P}, t) = \frac{A_{I\!P,I\!R} e^{B_{I\!P,I\!R} t}}{x_{I\!P}^{2\alpha_{I\!P,I\!R}(t)-1}}$

$$\alpha_{I\!P,I\!R}(t) = \alpha_{I\!P,I\!R}(0) + \alpha'_{I\!P,I\!R} t$$

QCD factorisation suggests tests: calculations with DPDFs measured in incslusive DDIS would describe other hard (hard scale present) diffractive processes.

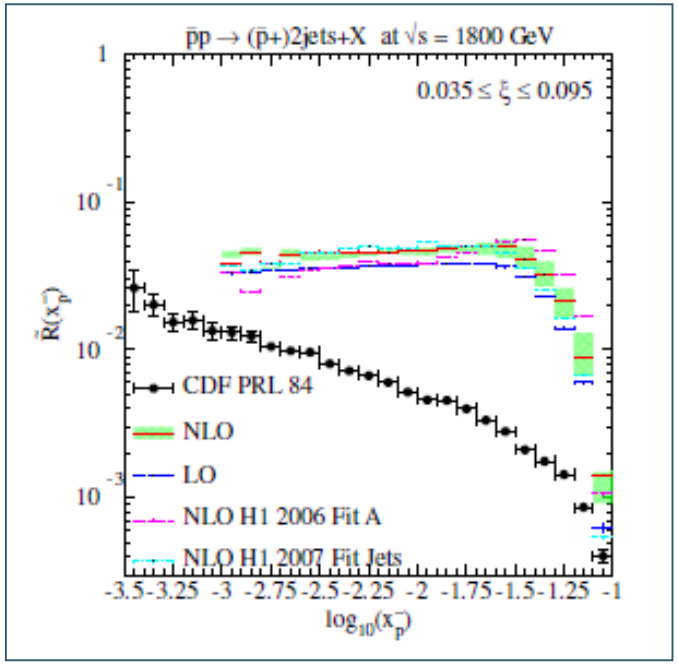
QCD Factorisation Tests

HERA DPDFs fail to describe hadron-hadron diffractive scattering

Diffractive Dijet Production: calculations overestimate data by factor of ~10 !

Tevatron $p\bar{p}$ $\sqrt{s}=1800$ GeV: CDF

[PoS DIS2010 (2010) 073]



$S^2=0.1$-0.2

Suppression factor

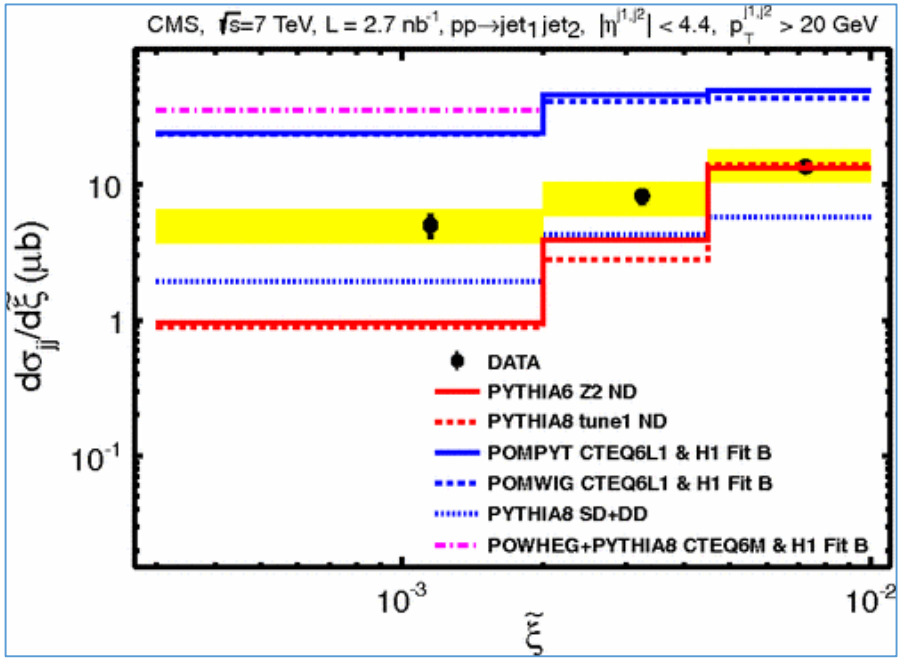
$S^2 = \sigma^{DATA} / \sigma^{QCD}$

Why ?

QCD factorisation violation

LHC pp $\sqrt{s}=7$ TeV: CMS

[Phys. Rev. D 87 (2013) 012006]



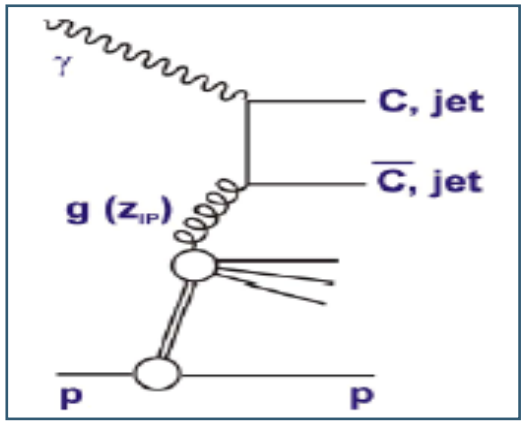
$S^2=0.08 \pm 0.04$

What about HERA (virtual) photon dissociation?

Diffractive production of dijets at HERA

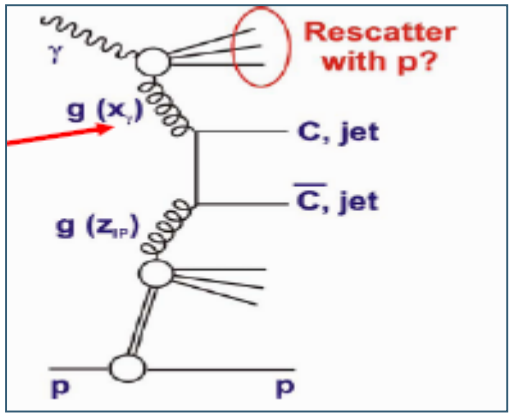
$$ep \longrightarrow e+jet1+jet2+X+p$$

Pointlike photon *LO QCD* **Resolved photon**



$$x_\gamma = x_\gamma^{OBS} = \frac{\sum (E - p_z)_{jets}}{(E - p_z)_{hadrons}}$$

x_γ - fraction of γ's momentum in hard subprocess



DIS, direct γp

resolved γp

γ^* directly involved in hard scattering: $x_\gamma = 1$ (parton level)
Measured $x_\gamma \approx 1$
(due to hadronisation & resolution)

γ^* fluctuates into hadronic system
which takes part in hadronic scattering,
dominant at $Q^2 \simeq 0$: $x_\gamma < 1$

Not Expected QCD Factorisation Break Possible

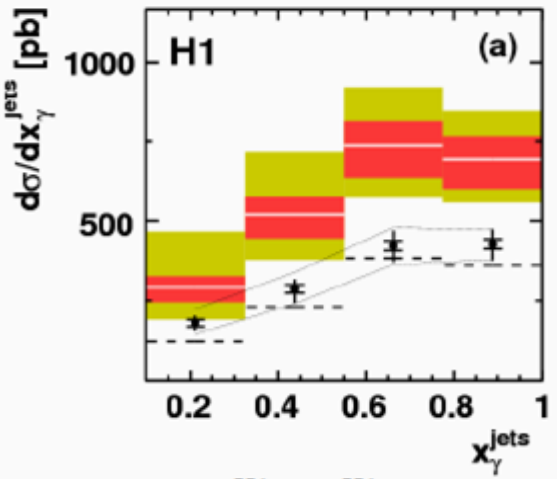
Diffractive Dijet Photoproduction

- Factorization break observed by H1 and not observed by ZEUS
- The suppression is supposed to be larger at low scales and low x_γ

But there are no x_γ dependence of suppression factor visible

Eur. Phys. J. C70 (2010) 15

X_γ $E_T^{jet1(2)}>5(4)\,\mathrm{GeV}$



$\sigma_{data}^{H1}/\sigma_{NLO}^{H1}\approx 0.6$

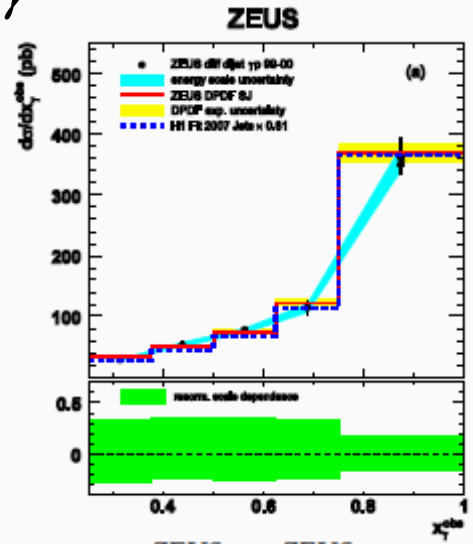
LRG + electron tagger

~3600 γp events

M_Y < 1.6 GeV

Nucl. Phys. B381 (2010)

X_γ $E_T^{jet1(2)}>7.5(6.5)\,\mathrm{GeV}$



$\sigma_{data}^{ZEUS}/\sigma_{NLO}^{ZEUS}\approx 1.0$

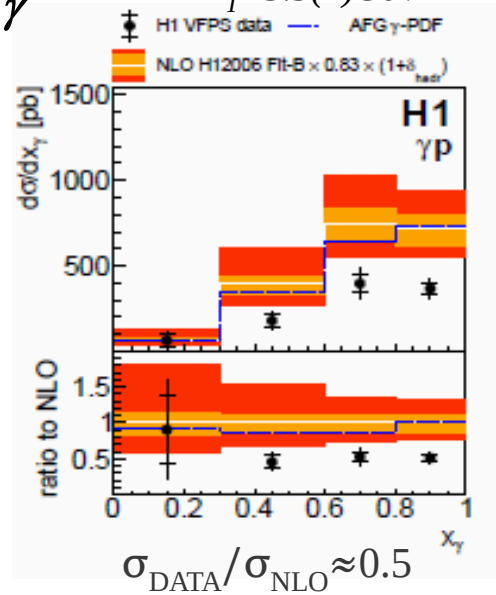
LRG + electron VETO

~ 6990 γp events

M_Y ~ m_p

JHEP 1505 (2015) 056

X_γ $E^{jet1(2)}{}_T>5.5(4)\,\mathrm{GeV}$



$\sigma_{DATA}/\sigma_{NLO}\approx 0.5$

VFPS + electron VETO

~ 3768 γp events

M_Y = m_p

Diffractive Dijets in DIS

JHEP 1503 (2015) 092

$\mathcal{L} = 290\ pb^{-1}$ DIS LRG data 2005-2007

$N_{ev} \sim 15000$

$4 < Q^2 < 100\ GeV^2$ $0.1 < y < 0.7$ $|t| < 1\ GeV^2$

$X_{IP} < 0.03$ $M_Y < 1.6\ GeV$

JHEP 1505 (2015) 056

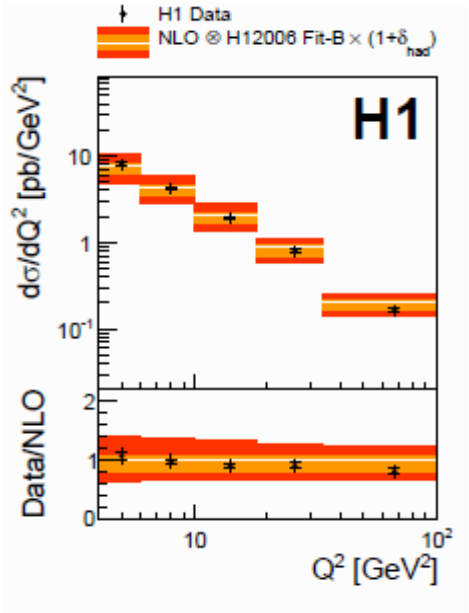
2006-2007 data VFPS DIS $\mathcal{L} = 50\ pb^{-1}$

$N_{ev} = 500$

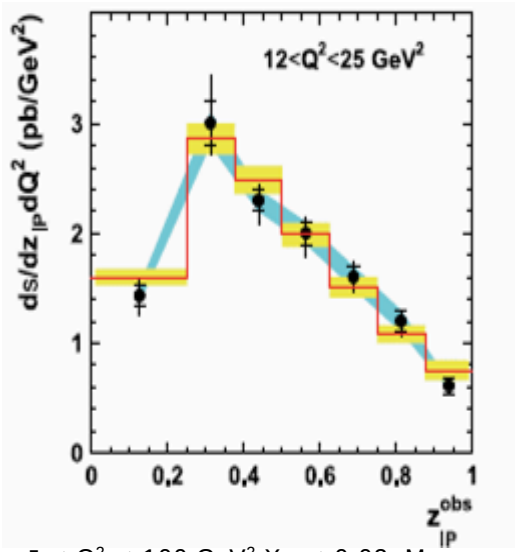
$4 < Q^2 < 80\ GeV^2$ $0.2 < y < 0.7$ $|t| < 0.6\ GeV^2$

$0.01 < x_{IP} < 0.03$ $z_{IP} < 0.8$

$-1 < \eta_{jet,1,2} < 2$ $E_T^*(jet1,2) > 5.5, 4.0\ GeV$ $-1 < \eta_{jet,1,2} < 2.5$

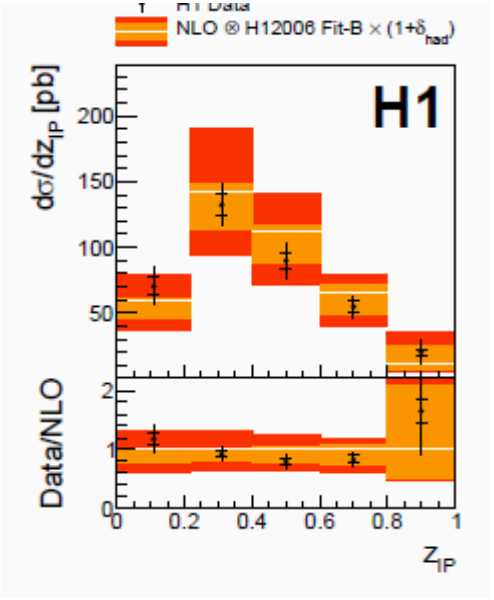


ZEUS



$5 < Q^2 < 100\ GeV^2$ $X_{IP} < 0.03$ $M_Y \sim m_p$

$-2 < \eta_{jet,1,2} < 2$ $E^*T(jet1,2) > 5.0, 4.0\ GeV$



NLO calculations with DPDFs H1 2006 Fit B (H1) and ZEUS fit SJ (ZEUS) describe measured cross sections both in shape and normalization.

QCD factorisation in DIS - HOLDS

Diffractive Dijets in DIS

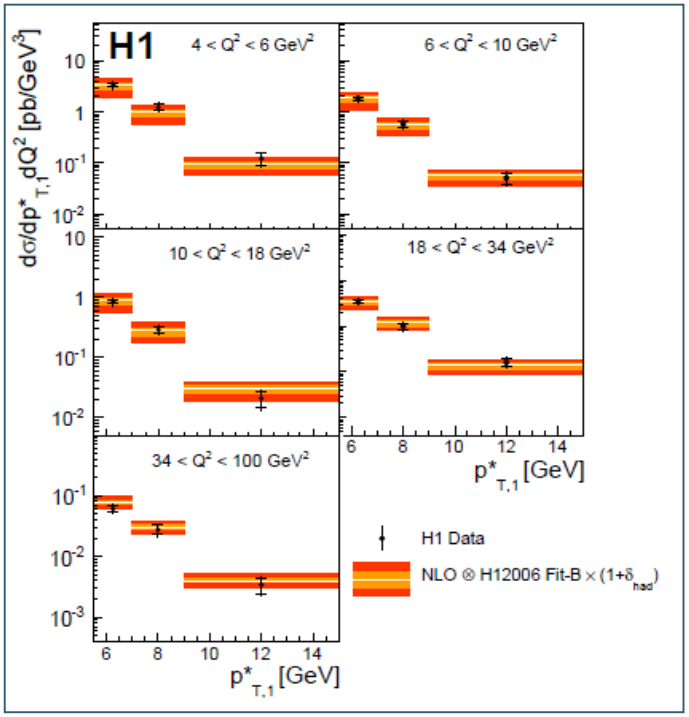
JHEP 1503 (2015) 092 (new measurements)

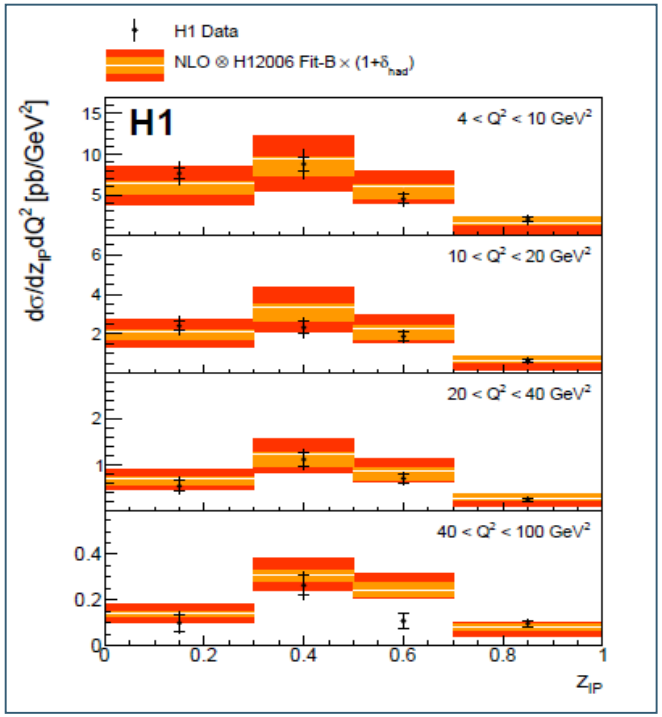
2005-2007 data LRG DIS $\mathcal{L} = 290\ \mathrm{pb}^{-1}$

$4 < Q^2 < 100\ \mathrm{GeV}^2$ $0. < y < 0.7$ $|t| < 1\ \mathrm{GeV}^2$ $X_{IP} < 0.03$ $M_Y < 1.6\ \mathrm{GeV}$

E_T^* (jet1,2) $> 5.5, 4.0\ \mathrm{GeV}$ $-1 < \eta_{jet,1,2} < 2$

Double differential cross sections measured for the 1st time





NLO calculations - in agreement with new measurements

QCD factorisation in DIS - HOLDS

high precision of data $\Rightarrow$ α_s determined:

$\alpha_S(M_Z) = 0.119 \pm 0.004(exp) \pm 0.012(PDF, th)$ -consistent with world average

Diffractive Dijets in γp

JHEP 1505 (2015) 056

$\mathcal{L}$= 50 pb^{-1} DIS VFPS data 2006-2007

2006-2007 data VFPS γp $\mathcal{L}$= 30 pb^{-1}

N_{ev}=500

$4 < Q^2 < 80$ GeV^2

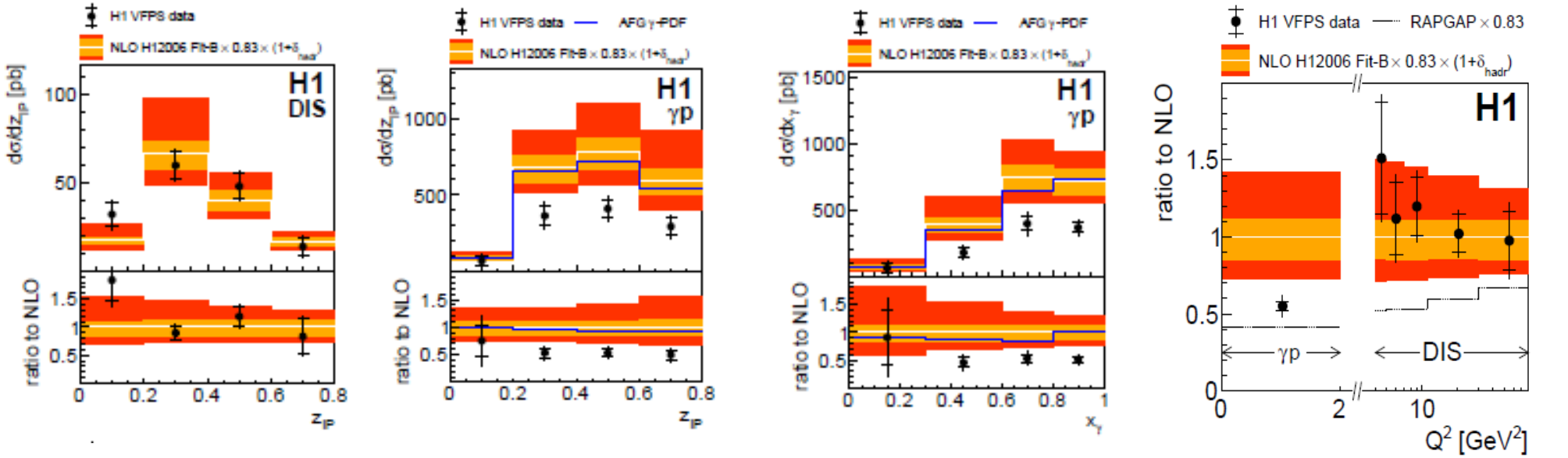
$0.2<y<0.7$ $|t|<0.6$ GeV^2

$0.01<x_{IP}<0.03$ $z_{IP}<0.8$

$E_T^*(jet1,2)>5.5,4.0$ GeV $-1<\eta_{jet,1,2}<2.5$

N_{ev}=3768

$Q^2 < 2$ GeV^2

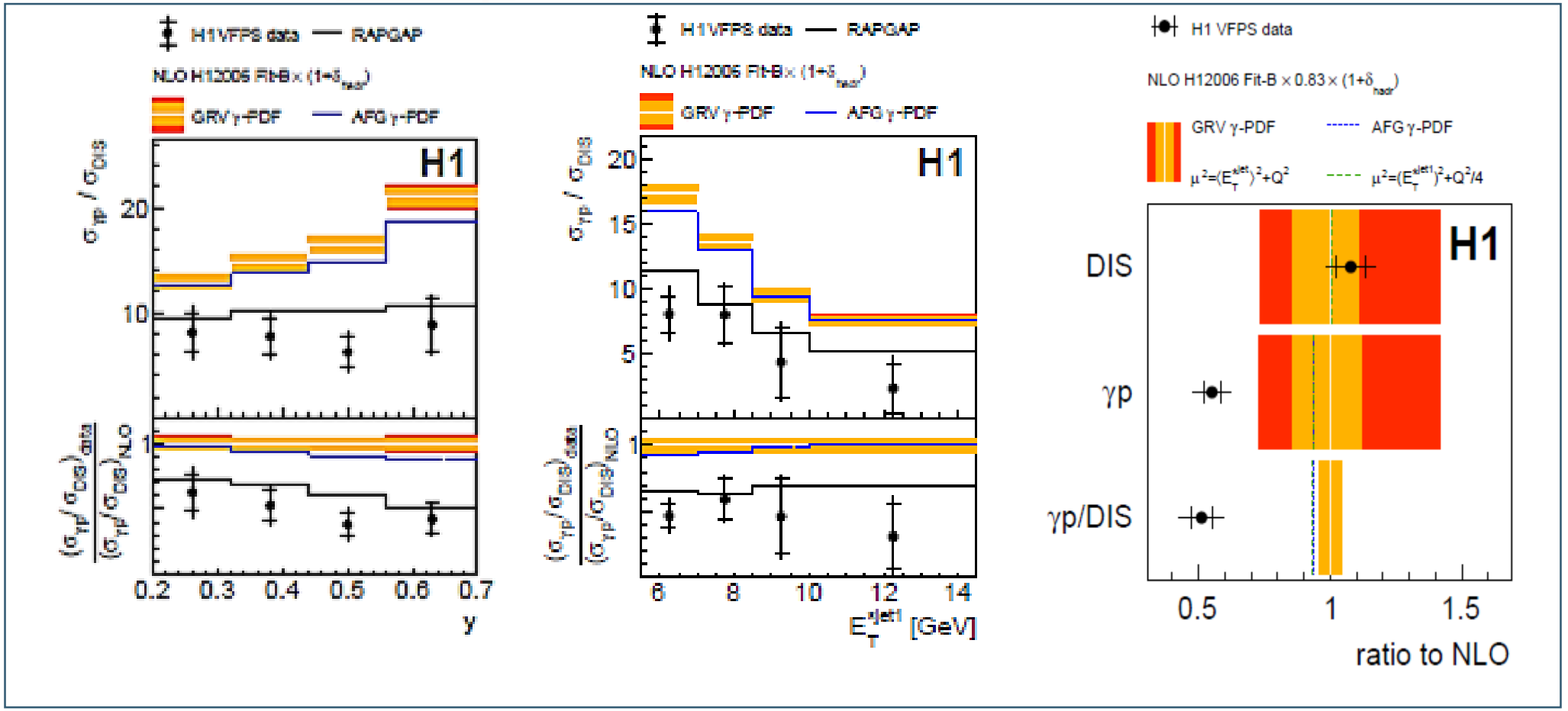


- DIS in agreement with QCD factorisation: Data/NLO(DIS) =1.080±0.11 (data)±0.45/0.29(th)
- Factorisation break in γp (as earlier H1 LRG): Data/NLO(γp)=0.551±0.078(data)±0.230/0.149(th)
  - not related to X_γ (H1 and ZEUS)
- VFPS (no *p* dissociation) compare to LRG (*p* dissociation included)

Diffractive Dijets in γp

JHEP 1505 (2015) 056

Double ratio $\frac{(\sigma_{\gamma p}/\sigma_{DIS})_{data}}{(\sigma_{\gamma p}/\sigma_{DIS})_{NLO}}$ ⟶ cancellations of large theoretical uncertainties



- *y* dependence of double ratio not described by NLO
  - Double ratio shows no dependence on $E_{T,jet1}$

Exclusive dijet production in diffractive DIS

arXive:1505.05783

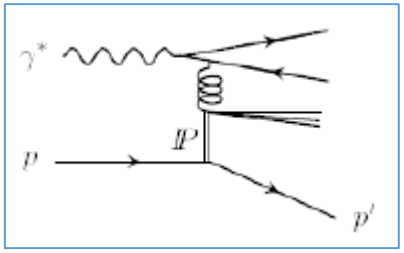
$ep \longrightarrow e + Jet + Jet + p$

- $Q^2 > 25\ GeV^2$ $90 < W < 250\ GeV$ $\mathcal{L}$~$372\ fb^{-1}$
- $x_{IP} < 0.01$ $\eta_{max} < 2$ (LRG) $M_X > 5\ GeV$
- $N_{jets}=2$ $p_{T,jets}>2GeV$

k_T -cluster with FastJet

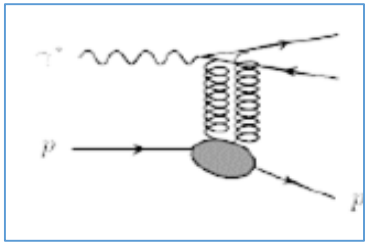
- hard process calculable in pQCD:

Resolved Pomeron model

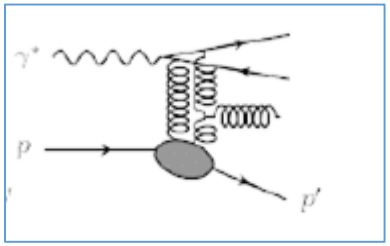


BGF: $\sigma \sim G^D(x)$
gluon dPDF
(H1 2006 A or B)

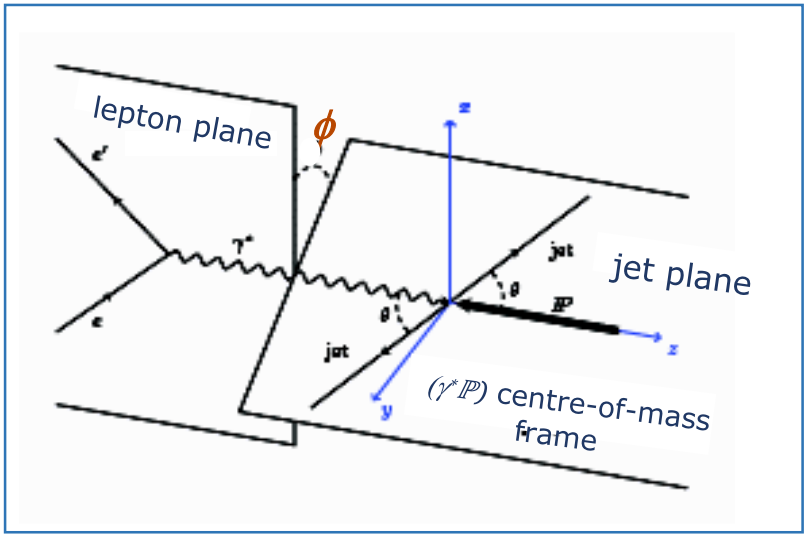
Two Gluon Exchange model



$\sigma \sim G_p(x)^2$
gluon PDF
(GRV)



- theory: $d\sigma/d\phi \sim 1 + \boldsymbol{A} \cos 2\phi$,
- ***A*** sensitive to the nature of an object interacting with γ^*
- J. Bartels et al.,Phys. Lett. B 386 (1996) 389:
  $A > 0$ for BGF & $A < 0$ for two gluon exchange



Exclusive dijet production in diffractive DIS

arXive:1505.05783

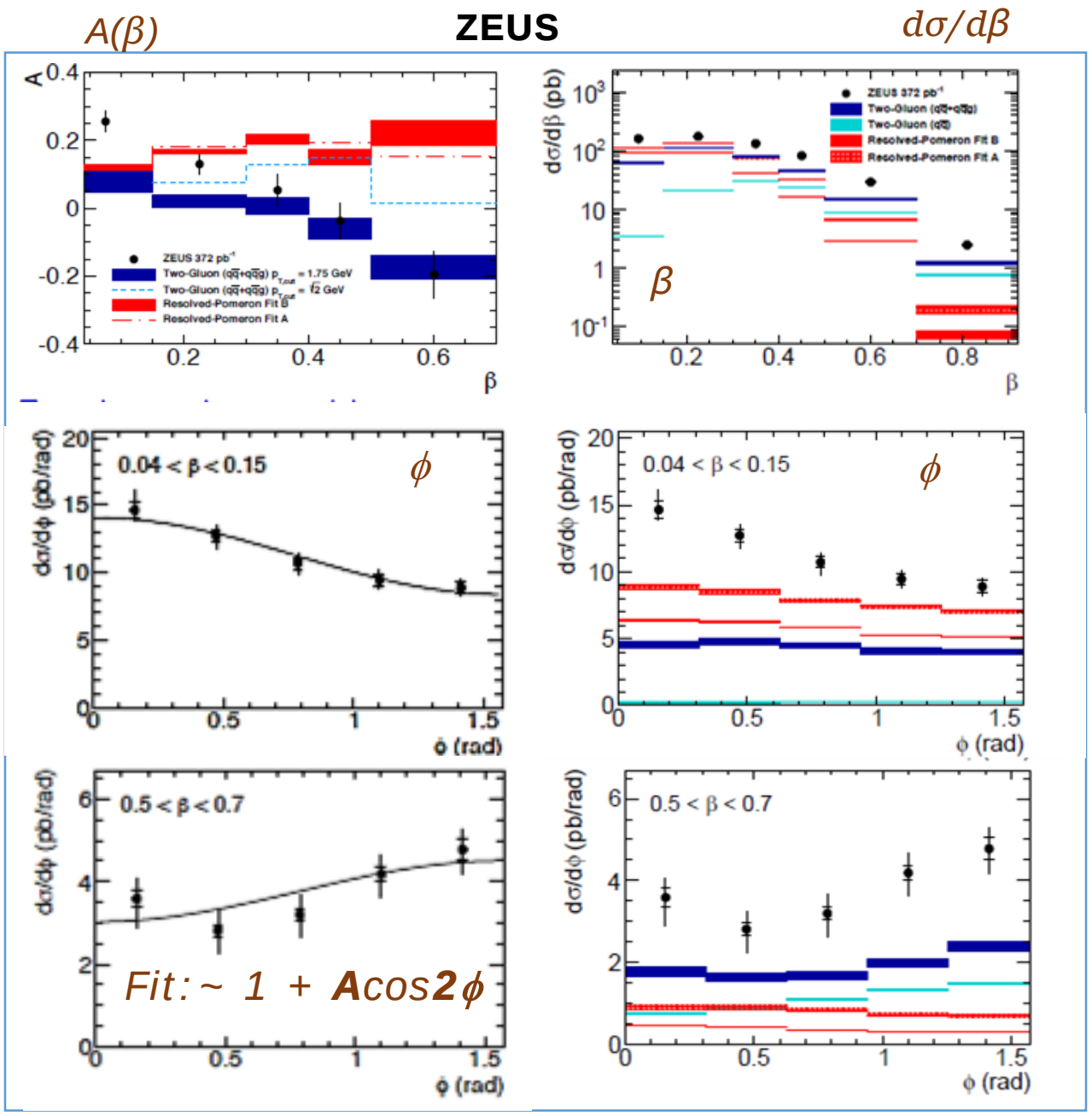
Resolved-Pomeron model:

A~ constant(β) > 0 in full *β* range
Calculated σ underestimate data by a factor of ~2 for *β<0.2* and by a factor of ~10 for *β>0.7*

Two Gluon Exchange model:

A>0 @ β<0.4 due to $q\bar{q}g$
A<0 @ β>0.4
*1 + **A**cos**2**ϕ* fits to $d\sigma/d\phi$

Calculations underestimate data

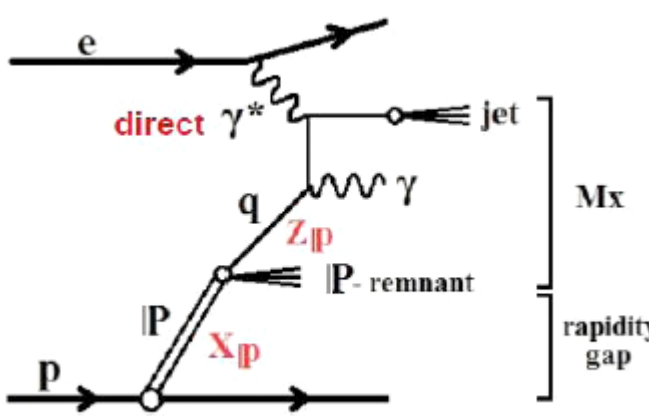


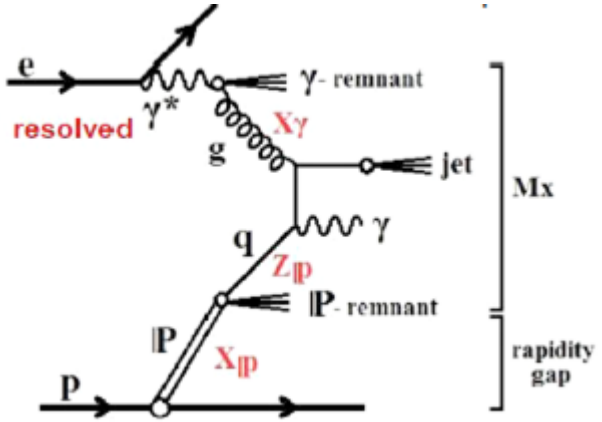
Diffractive Photoproduction of Isolated Photons

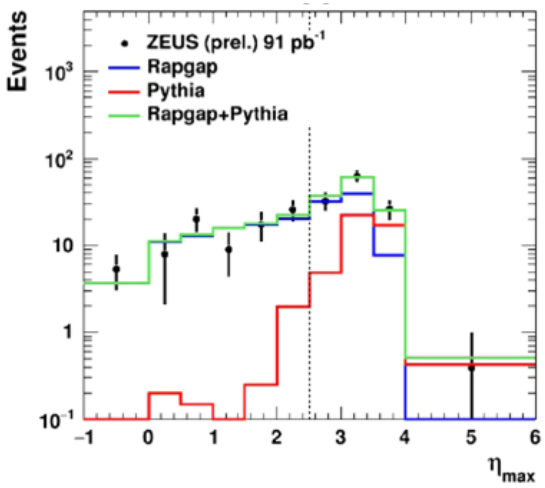
ZEUS-prel-15-001

"Isolated/prompt" photons — high- p_T photons, produced in a hard partonic subprocess of ep scattering

LO diagrams for diffractive processes with a prompt photon in a final state







These processes, while rare, are interesting for several reasons.

Prompt γ must be radiated from a charged partonic object (q): may reveal q content of $\mathbb{P}$

or of higher-order processes in which both $\mathbb{P}$ & γ^* couple to q. Specific models of the hard diffractive process may be tested.

$\mathcal{L}$ = 374 pb^{-1} of HERA II data $\mathcal{L}$ = 91 pb^{-1} of HERA I data

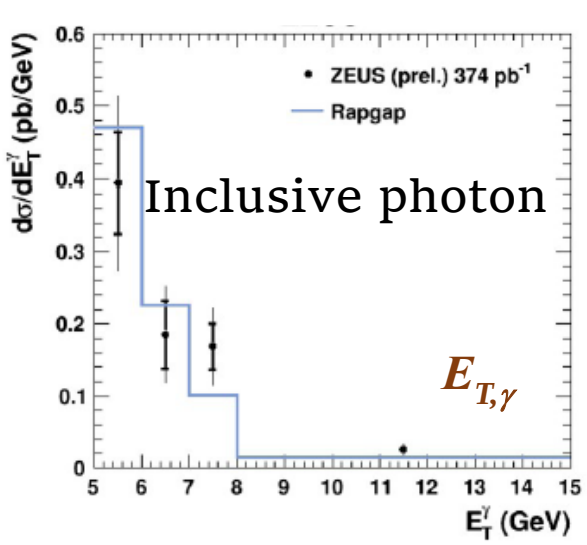
$Q^2<1$ GeV^2 $0.2<y<0.7$

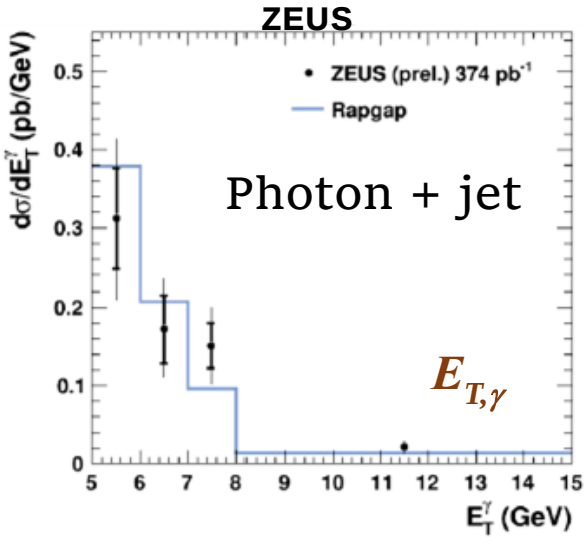
LRG: $\eta_{max} < 2.5$ and $x_{IP} < 0.03$

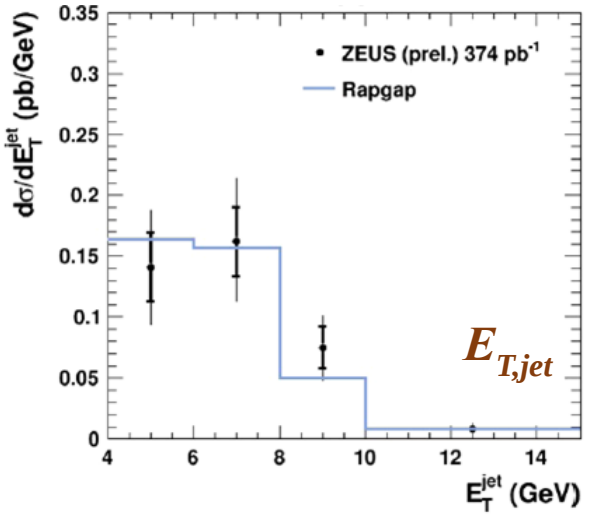
$5< E_T^{\gamma}<15$ GeV and $-0.7< \eta_{\gamma}<0.9$ $4< E_T^{jet}<35$ GeV and $-1.5< \eta^{jet}<1.8$

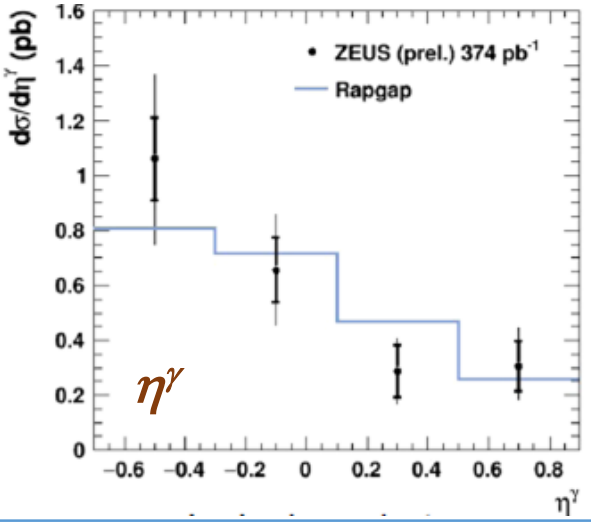
Diffractive Photoproduction of Isolated Photons

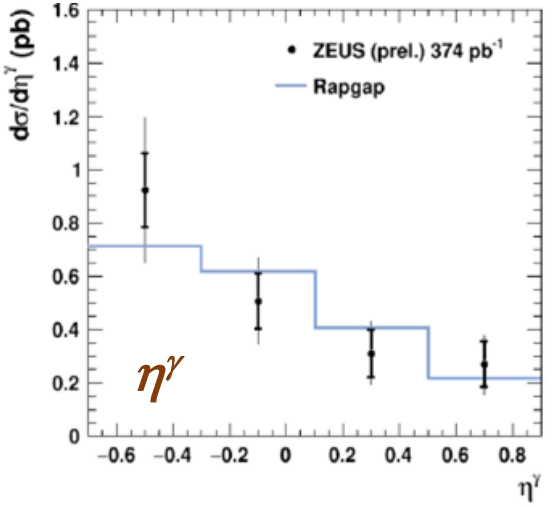
ZEUS-prel-15-001

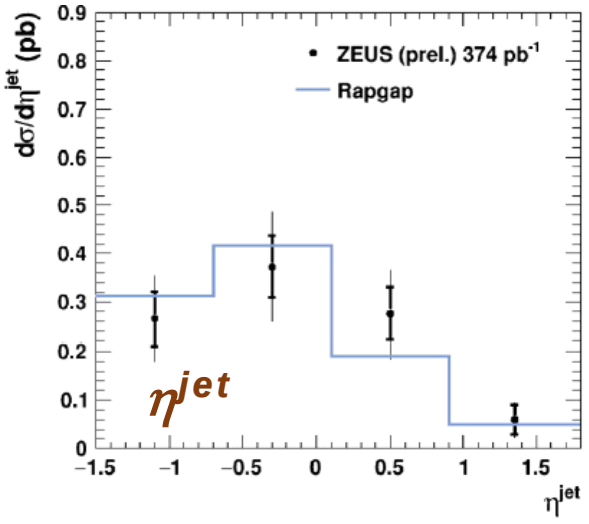












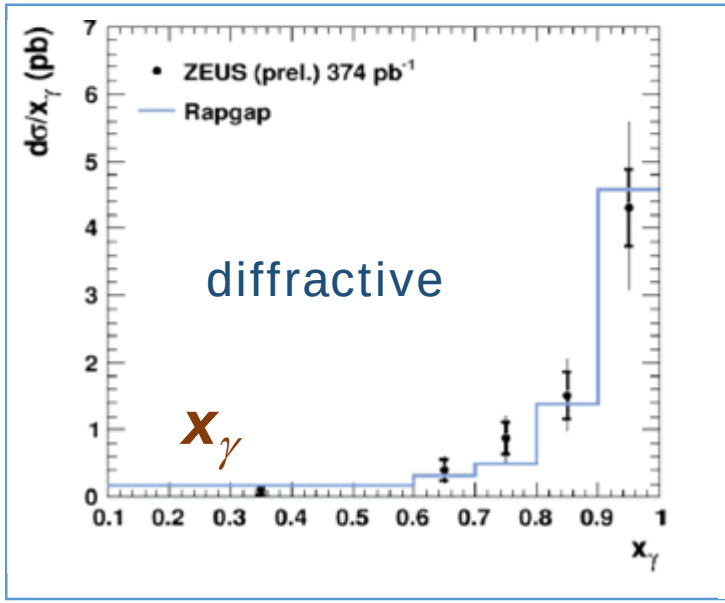
Shapes fairly well described by RAPGAP (DPDF-p H1-2006-B, PDF-γ SASG 1D LO) normalized to data.

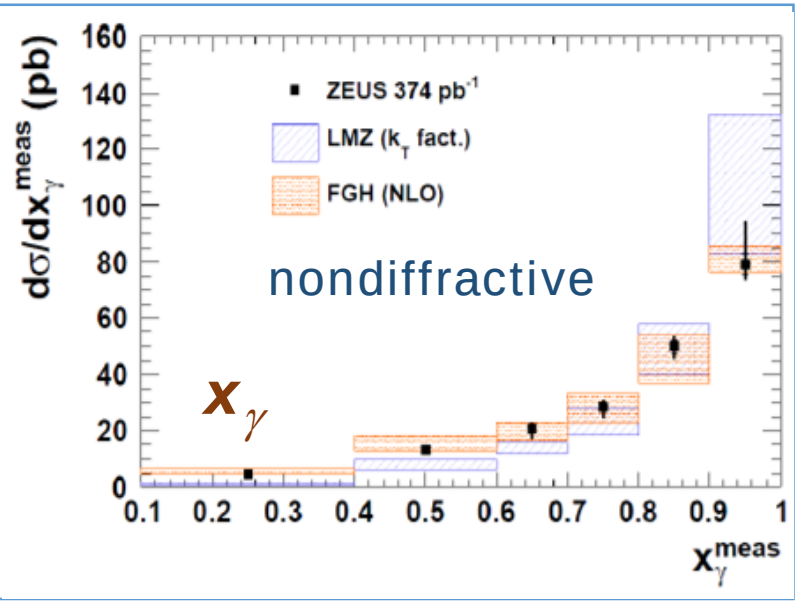
Most photons (~0.8) are accompanied by a jet.

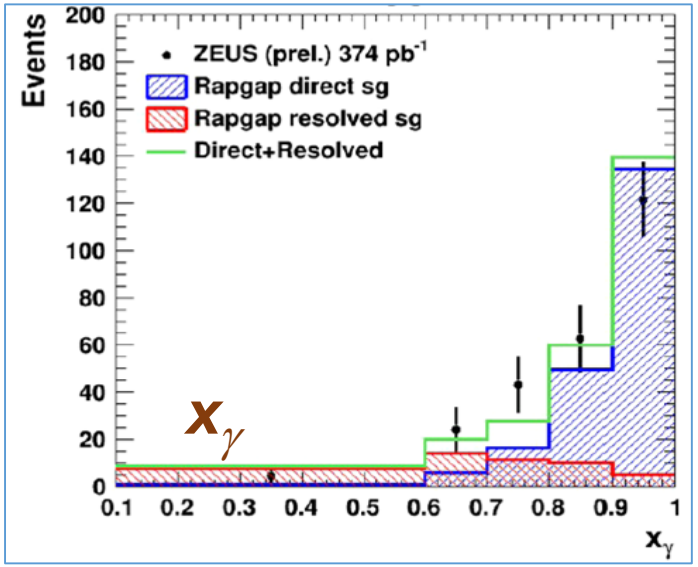
Diffractive Photoproduction of Isolated Photons

ZEUS-prel-15-001

Diffractive process is more direct-dominated than non-diffractive one







x_γ distribution fitted to RAPGAP direct + resolved sample:
Ratio = direct/resolved = 4/1 obtained

$$x_\gamma = \Sigma_{\gamma\,+jet}(E - p_z) \,/\, \Sigma_{all\ EFOs}(E - p_z)$$

Diffractive Photoproduction of Isolated Photons

ZEUS-prel-15-001

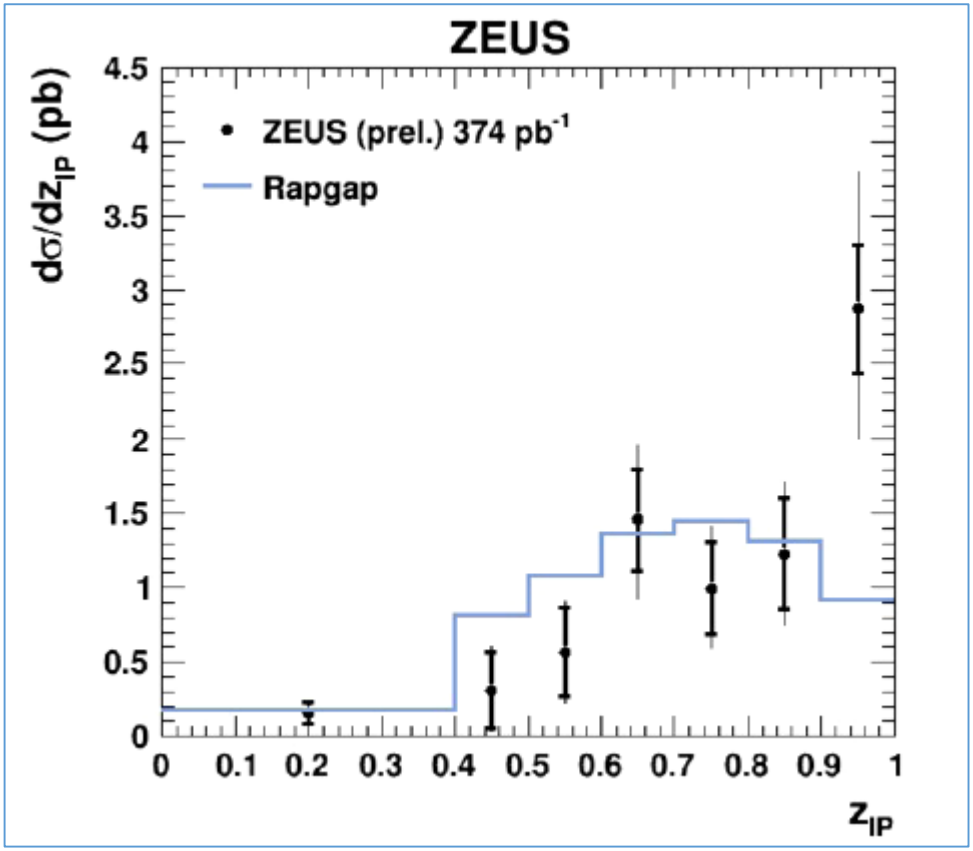
The distribution in $z_{IP} = \Sigma_{\gamma+jet}(E + pz) / \Sigma_{all\ EFOs}(E + pz)$ shows a prominent peak near $z_{IP} = 1$ not described by RAPGAP.

Checks performed to find peaks' origin:

Non-diffractive contribution, smooth in this region does not account for the peak.

The reweighting does not account for it.

A few percent of the 100 peak events could come from an initial-state radiative DIS process.



Would z_{IP} peak at high values imply contribution of processes not currently modelled with RAPGAP?

Further studies required

No new data but new results on diffraction studies

New data on dijets in diffractive DIS and γp with higher precision

- For dDIS regime QCD factorisation is confirmed to hold by H1 and ZEUS
- For γp dijets are in favor of QCD factorisation break, not confirmed by ZEUS
- γp suppression factor shows independence w.r.t. *p-dissociation*, x_γ & $E_{T,jet}$
- For the 1st time double differential cross sections & α_s measured in dDIS

Exclusive dijets in diffractive DIS measured for the 1st time

- Cross sections are underestimated by Resolved-Pomeron and Two Gluon Exchange models
- Shapes of the ϕ distributions are described with $1 + A\cos 2\phi$ as motivated by theory, A *as a function of* β being closer to Two Gluon Exchange model

"Prompt" photons in diffractive γp studied for the 1st time

- Calculations using RAPGAP reasonably describe shapes of kinematic variable distributions except for high value z_{IP} peak
- Data are strongly dominated by the direct γp process & most of the detected photons are accompanied by a jet.

Studies of HERA data are ongoing: new results are expected