Hard Diffraction at HERA

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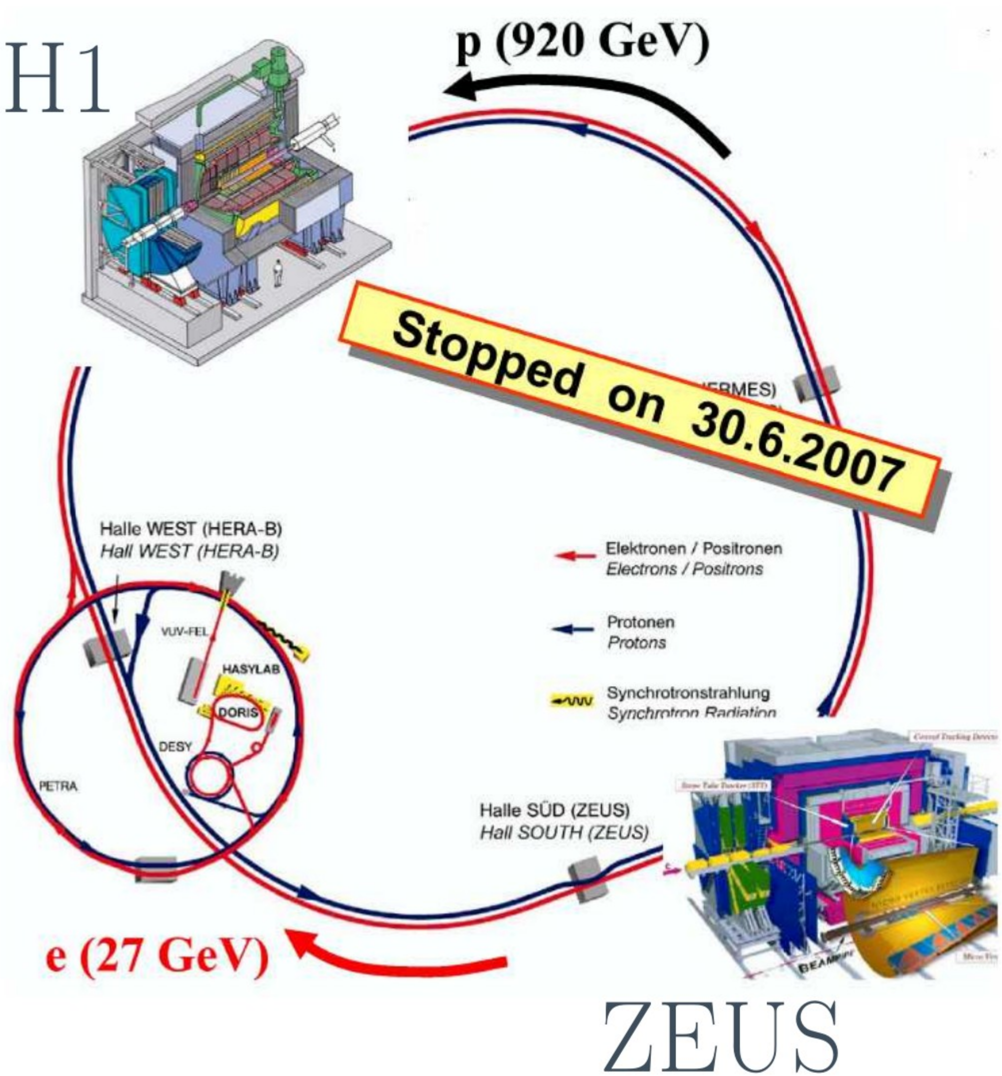
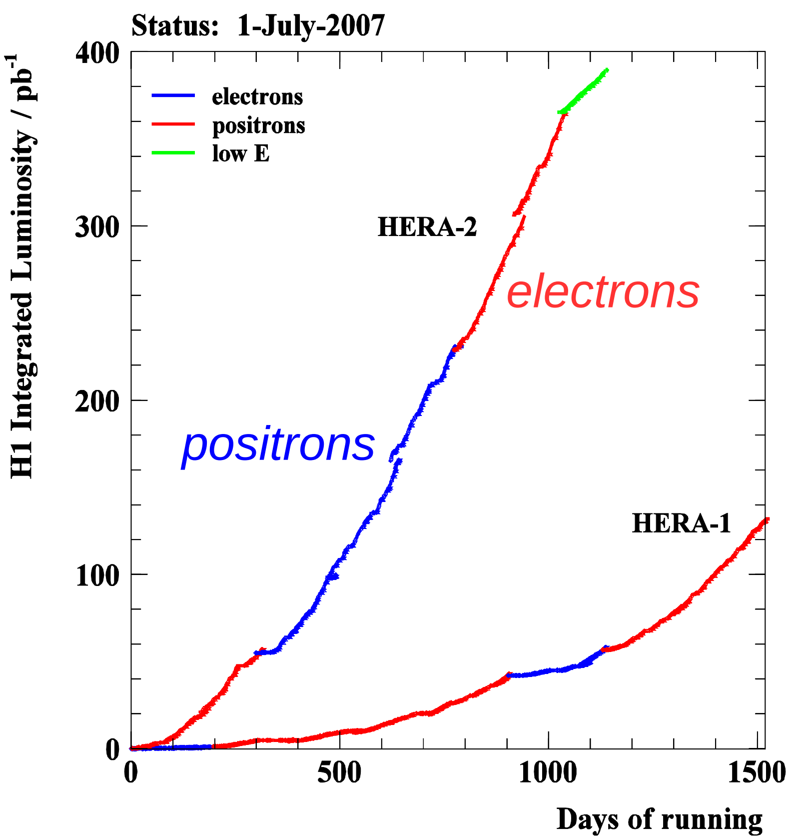
JDK

HERA *ep* collider



HERA e±p collider

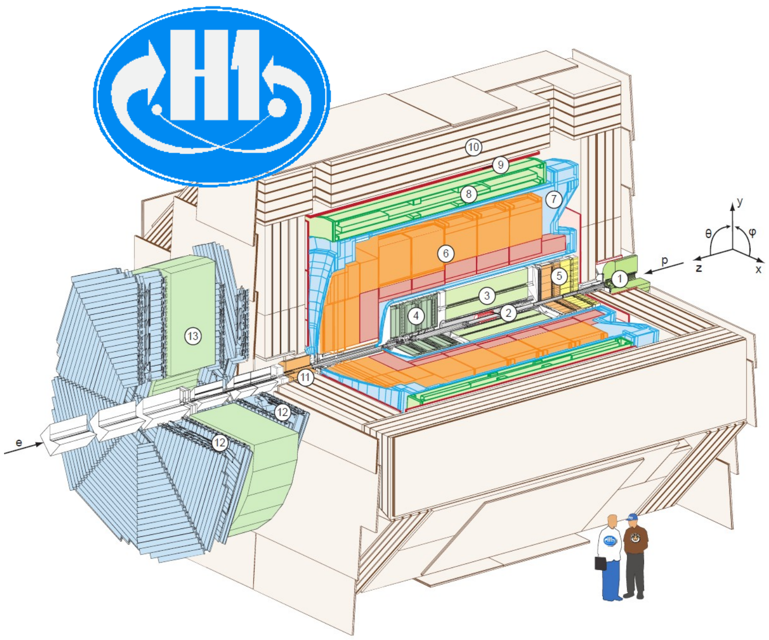
- E_e = 27.6 GeV
- E_p = 920 GeV
- √s = 319 GeV
- Operational until 2007

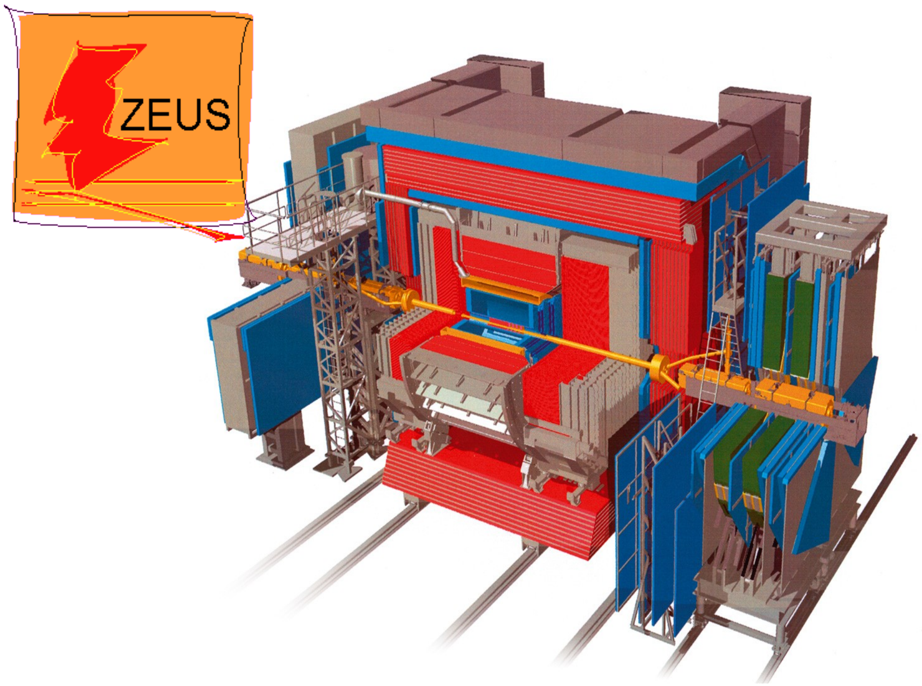


The H1 and ZEUS Detectors

Two multi-purpose experiments: H1 and ZEUS

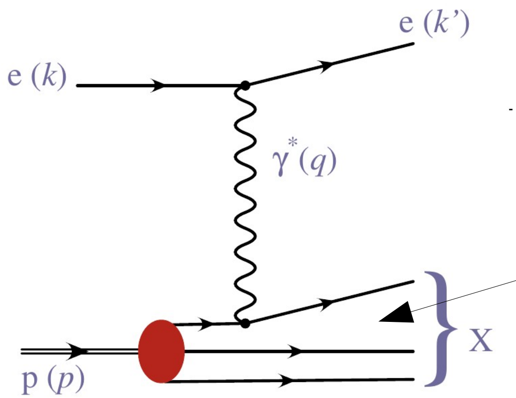
- Recorded integrated luminosity: ~0.5 fb^{-1} per experiment
- Excellent control over experimental uncertainties
  - Over-constrained system in DIS
  - Electron measurement: 0.5 – 1% scale uncertainty
  - Jet energy scale: 1%
  - Trigger and normalisation uncertainties: 1-2 %
  - Luminosity: 1.8 – 2.5%





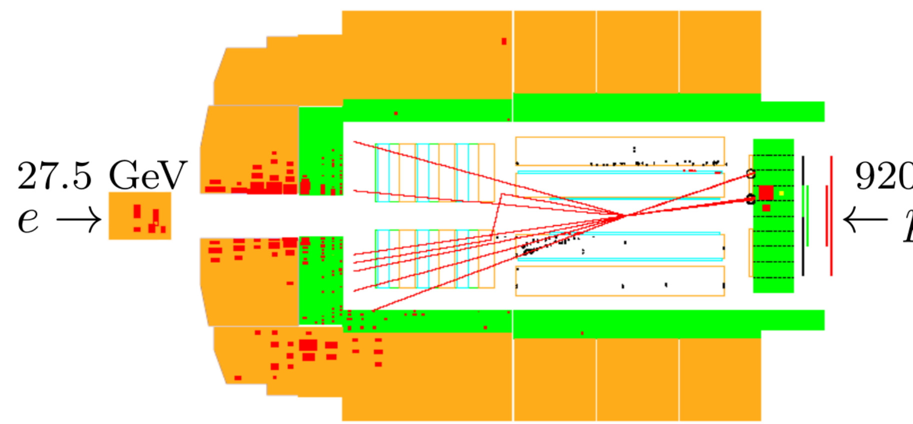
Diffractive Scattering in DIS

Deep-inelastic scattering (DIS): ep → eX

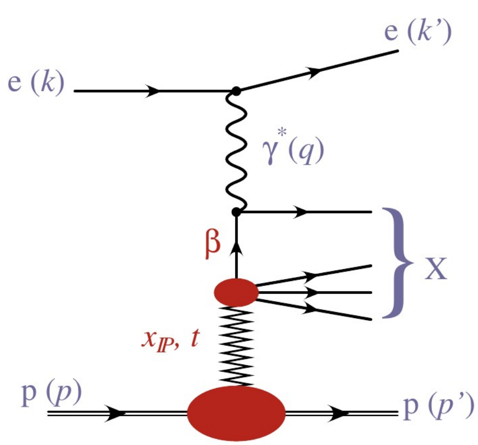


Particle flow in 'forward' direction:

- proton remnant
- *color* flow

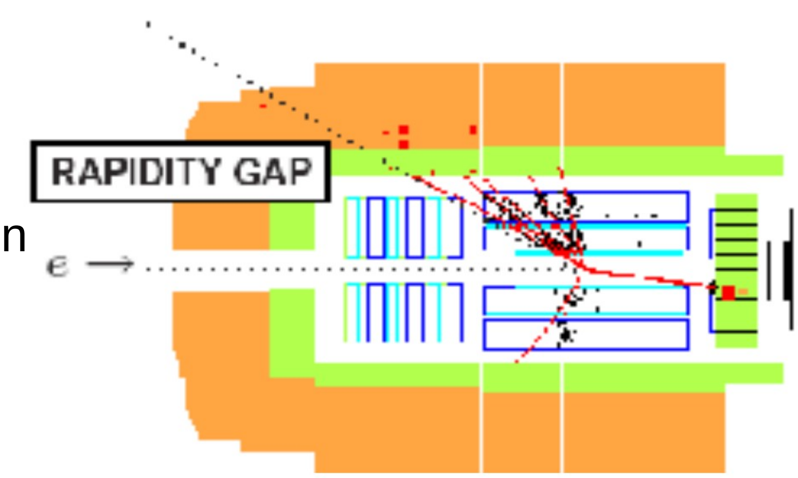


Diffractive scattering (DDIS): ep → eXp



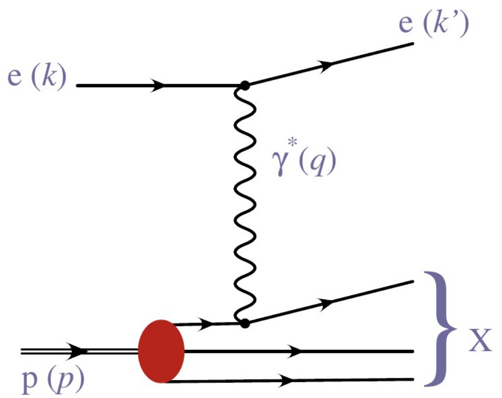
No activity in 'forward' region:

- rapidity gap
- proton → beam pipe
- no color flow between final state *X* and outgoing proton



Kinematics of DIS and diffractive DIS

Deep-inelastic scattering (DIS): ep → eX



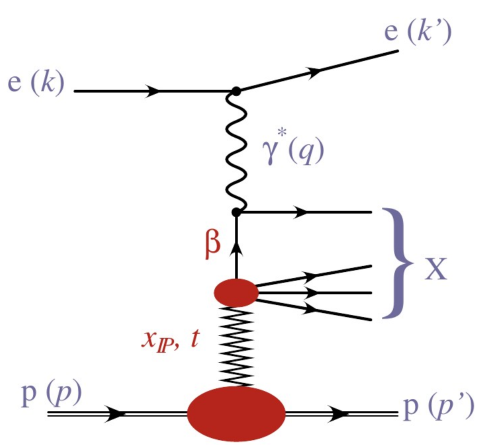
Q^2 $= -q^2$ - virtuality of the exchanged photon

W $\gamma^* - p$ system energy

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

y γ^* inelasticity : $y = Q^2/s\,x$

Diffractive scattering (DDIS): ep → eXp



$x_{I\!P}$ fraction of proton's momentum of the colour singlet exchange

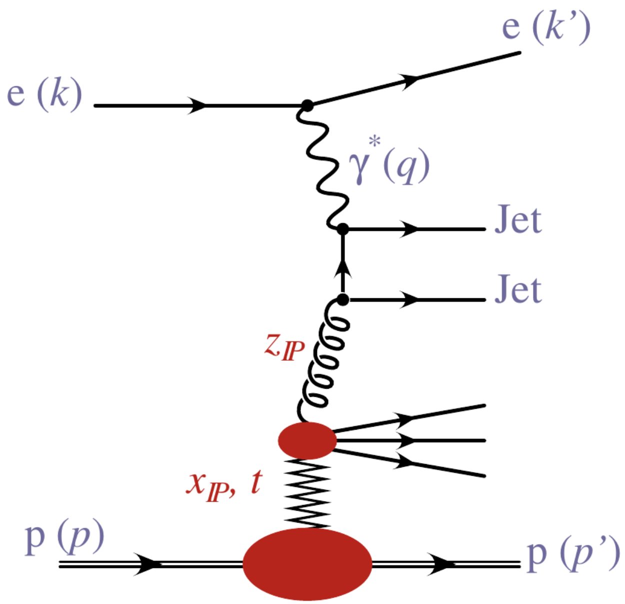
$x_{I\!P} \simeq \frac{Q^2+M_X^2}{Q^2+W^2}$

β fraction of $I\!P$ carried by the quark "seen" by the γ^* $\beta = x/x_{I\!P}$

t $= (p-p')^2$, 4-momentum squared at the p vertex

Dijets in diffractive DIS (LRG) (H1)

Inclusive dijet production in diffractive DIS



- HERA-II data: $L = 290\ pb^{-1}$
- 6 times more data than previous analysis
- Diffractive events identified by 'large rapidity gap' (LRG) ($\eta_{max} > 3.2$)
- Jets identified using k_T jet algorithm
- Regularised unfolding in extended phase space using TUnfold

	Extended Analysis Phase Space	Measurement Cross Section Phase Space
DIS	$3 < Q^2 < 100$ GeV^2 $y < 0.7$	$4 < Q^2 < 100$ GeV^2 $0.1 < y < 0.7$
Diffraction	$x_P < 0.04$ LRG requirements	$x_P < 0.03$ $\|t\| < 1$ GeV^2 $M_Y < 1.6$ GeV
Dijets	$p^*_{T,1} > 3.0$ GeV $p^*_{T,2} > 3.0$ GeV $-2 < \eta^{lab}_{1,2} < 2$	$p^*_{T,1} > 5.5$ GeV $p^*_{T,2} > 4.0$ GeV $-1 < \eta^{lab}_{1,2} < 2$

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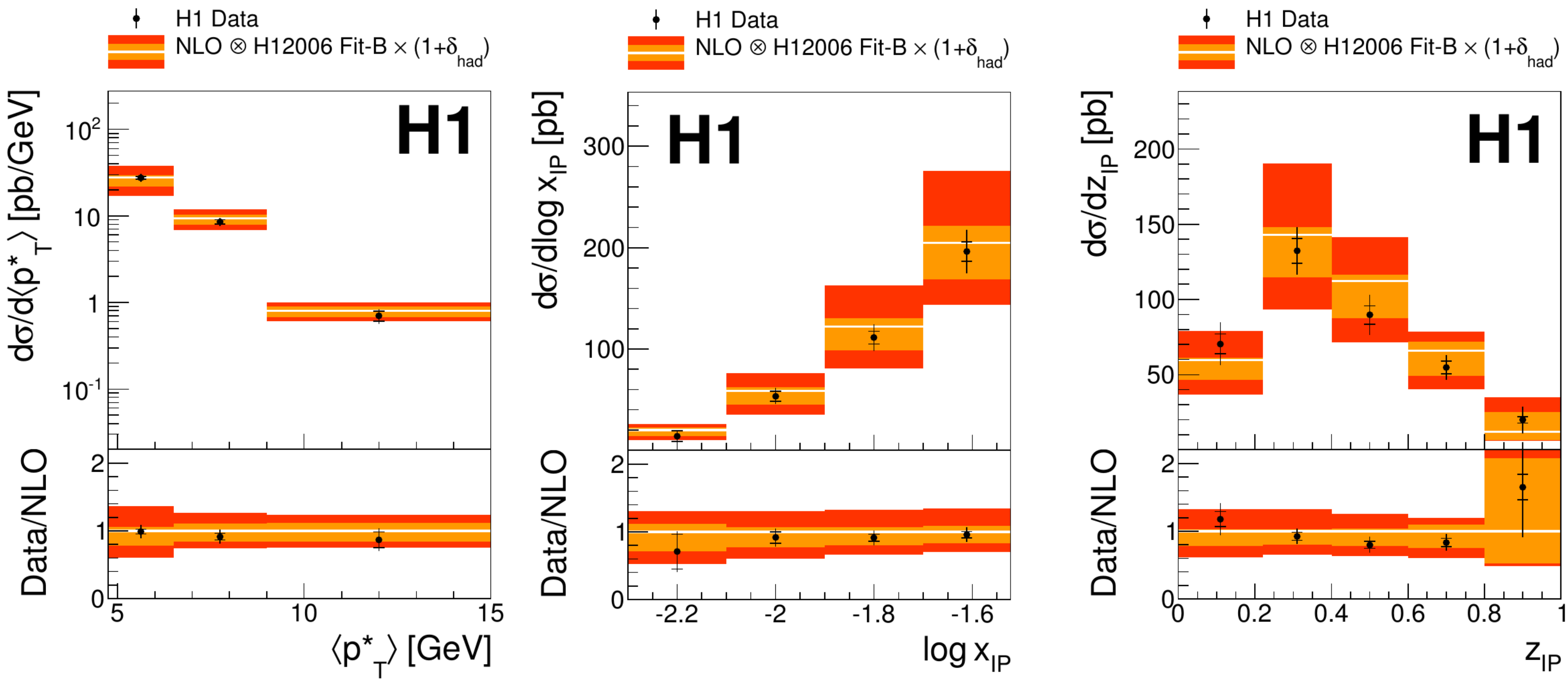
Dijets in diffractive DIS (LRG) (H1)

Measurement of single and double-differential contributions



NLO predictions using nlojet++ (adapted to DDIS) and H1PDF2006-FitB

Data well described by NLO predictions

Data precision overshoots theory

- Large PDF and theory uncertainties

Data precision mostly limited by systematic effects

- 7% normalisation uncertainty

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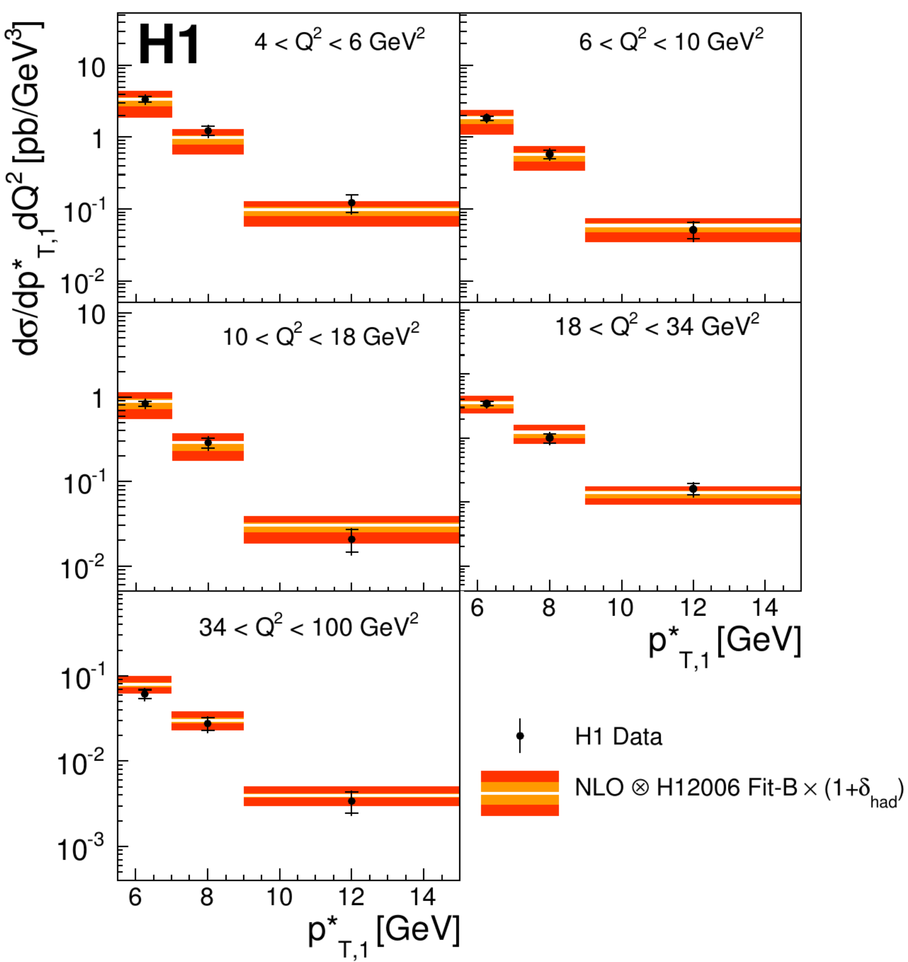
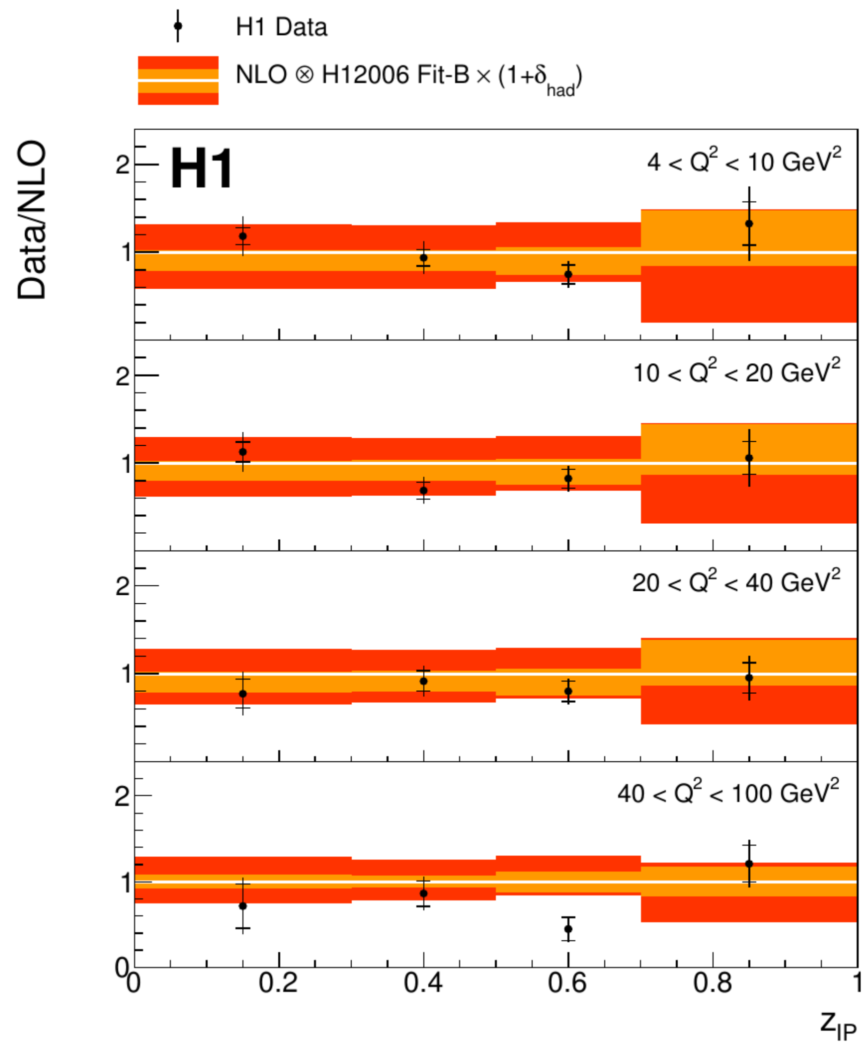
Dijets in diffractive DIS (LRG) (H1)

Double differential measurements
$d\sigma/d(Q^2, p^*_{T1})$ and $d\sigma/d(Q^2, z_{IP})$

Data precision overshoots theory precision
→ Also at $z_{IP} > 0.5$ for all Q^2 values

Data precision limited mostly by statistics
Data well described by NLO predictions



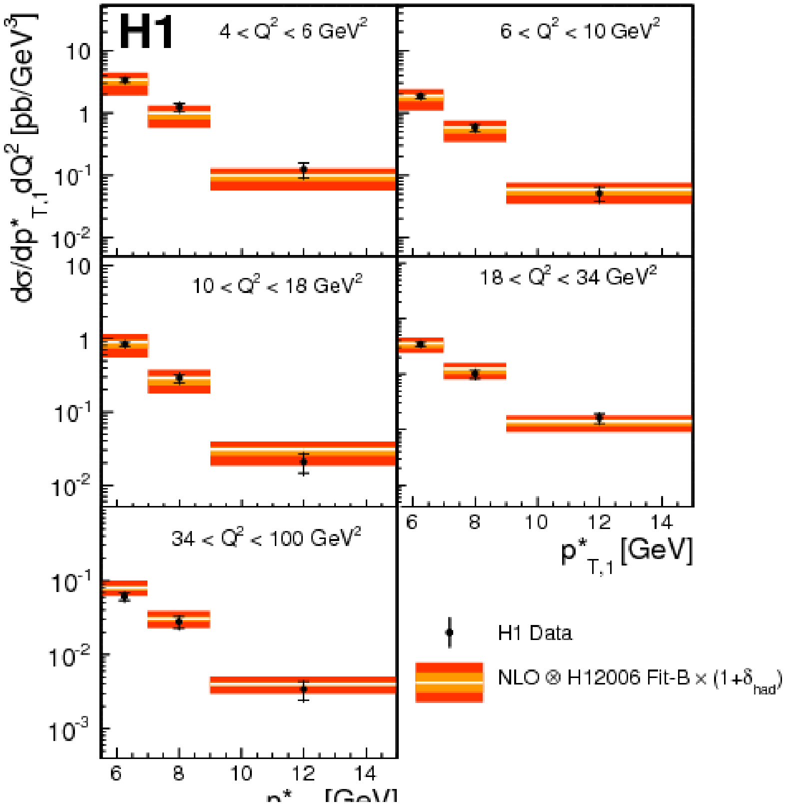


Dijets in diffractive DIS (LRG) (H1)

Double differential measurement (p^*_{T1}, Q^2)
→ use for extraction of strong coupling constant $\alpha_s(M_Z)$

$$\alpha_s(M_Z) = 0.119 \pm 0.004\,(\text{exp}) \pm 0.002\,(\text{had}) \pm 0.005\,(\text{DPDF}) \pm 0.010\,(\mu_r) \pm 0.004\,(\mu_f)$$
$$= 0.119 \pm 0.004\,(\text{exp}) \pm 0.012\,(\text{DPDF, theo})$$

- fastNLO adapted for DDIS
- Fit yields good χ^2/ndf = 16.7/14
- Precision limited by *theoretical* precision
- *Experimenal* precision limited by normalisation uncertainty (including LRG selection)



First determination of α_s in hard diffraction at HERA

Although uncertainty is not competitive with other determinations:
→ Extraction supports the concept of dijet calculations in pQCD
→ Possible impact of dijets for future DPDFs

Factorisation in Diffraction

pQCD framework as long as hard scale is present
→ *Factorisation theorem*: proven for DDIS by J. Collins [PRD 57 (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

Pomeron PDFs

Reggeon PDFs taken from pion (GRV)

DPDFs are extracted from inclusive DDIS data via NLO QCD fits
→ No firm basis in QCD
→ Test DPDFs with semi-inclusive states to *test universality of DPDFs*

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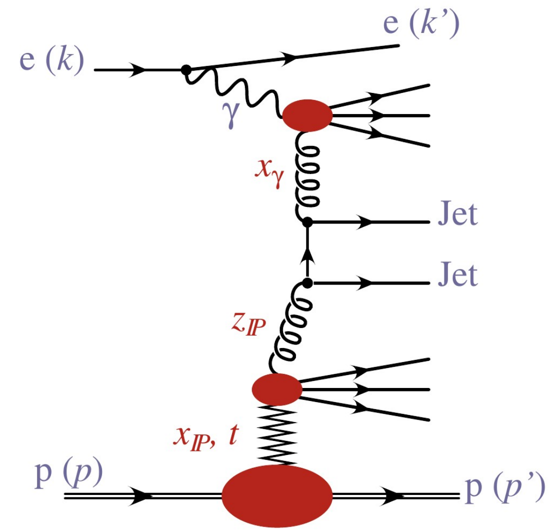
Diffractive Dijets in Photoproduction and DIS (VFPS) (H1)

Factorisation properties of diffractive dijets

- Factorisation holds for dijets in DDIS
- in *p-p* collisions, factorisation is broken
  → $S^2 \sim 0.1$ at Tevatron/LHC using HERA DPDFs

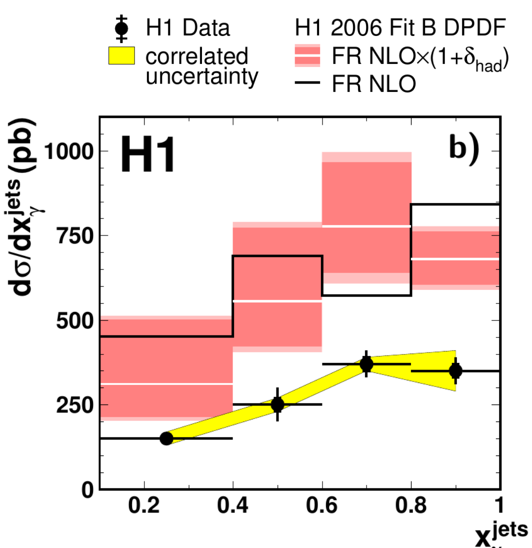
$$S^2 = \frac{\sigma(data)}{\sigma(NLO)}$$



Dijets in photoproduction

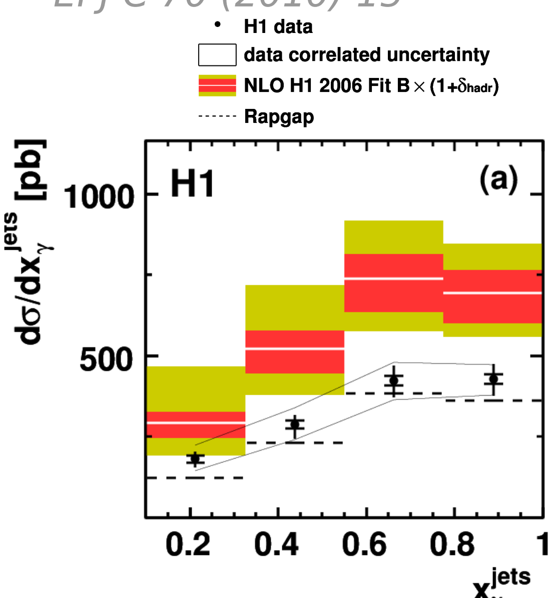
- Real photon develops a hadronic structure ($Q^2 \rightarrow 0\ GeV^2$)
- 'Suppression' w.r.t. to NLO observed by H1
- No indication observed by ZEUS in QCD analysis

Phys. J. C 51 (2007) 549



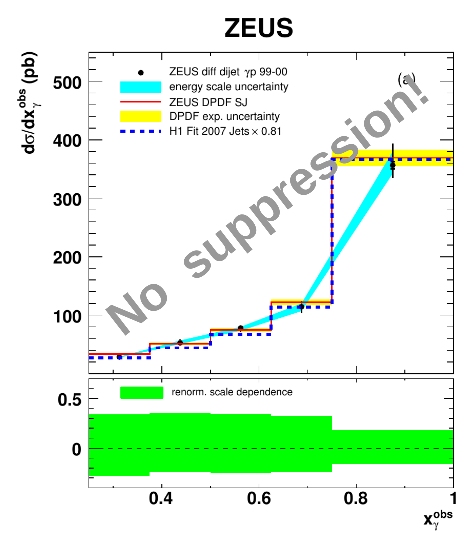
H1 *analysis with LRG method and γ-veto*

EPJ C 70 (2010) 15



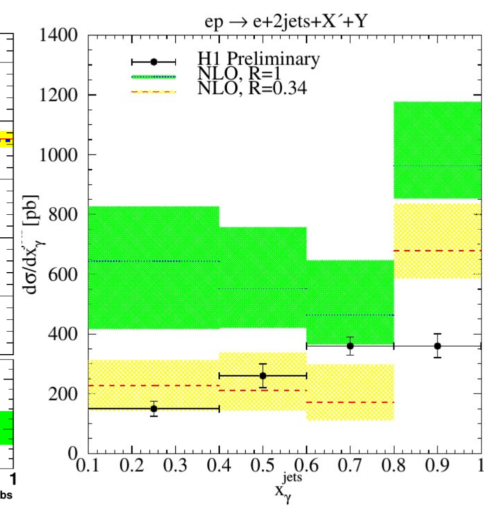
H1 *analysis with LRG method and γ-tag*

Nucl. Phys. B 831 (2010) 1



ZEUS *QCD analysis in NLO*

Klasen, Kramer [EPJ C 38 (2004) 93]

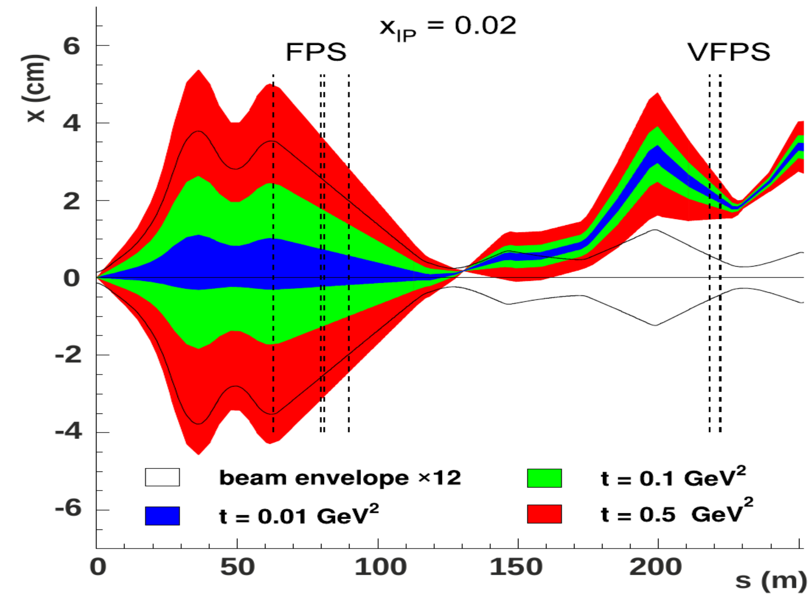


KK *alternative NLO calculations*

Diffractive Dijets in Photoproduction and DIS (VFPS) (H1)

Measure final state proton in VFPS (Very Forward Spectrometer)

- VFPS is 220m from interaction point
  - 2 stations at 218 and 220m
  - high acceptance (90%) and efficiency (96%)
  - low background (<1%)
- direct measure of the scattered proton:
  - giving x_{IP} and t measurements
- Complementary method to LRG method



Simultaneous measurement of dijets

- in ***Photoproduction*** (γp)
- in ***DIS***

→ Counter analysis performed

Data fully unfolded to hadron level using TUnfold
→ Extended phase space to control migrations

→ Could contribution of p-dissociation be the reason ?

DIS	$\gamma - p$
$4 < Q^2 < 80$ GeV^2	$Q^2 < 2$ GeV^2
$0.2 < y < 0.8$	
$E_T^{jet1(2)} > 5.5(4)$ GeV	
$-1 < \eta_{jet1,2} < 2.5$	
$0.010 < x_{I\!P} < 0.024$	
$\lvert t \rvert < 0.6$ GeV^2	
$M_Y = M_p$	

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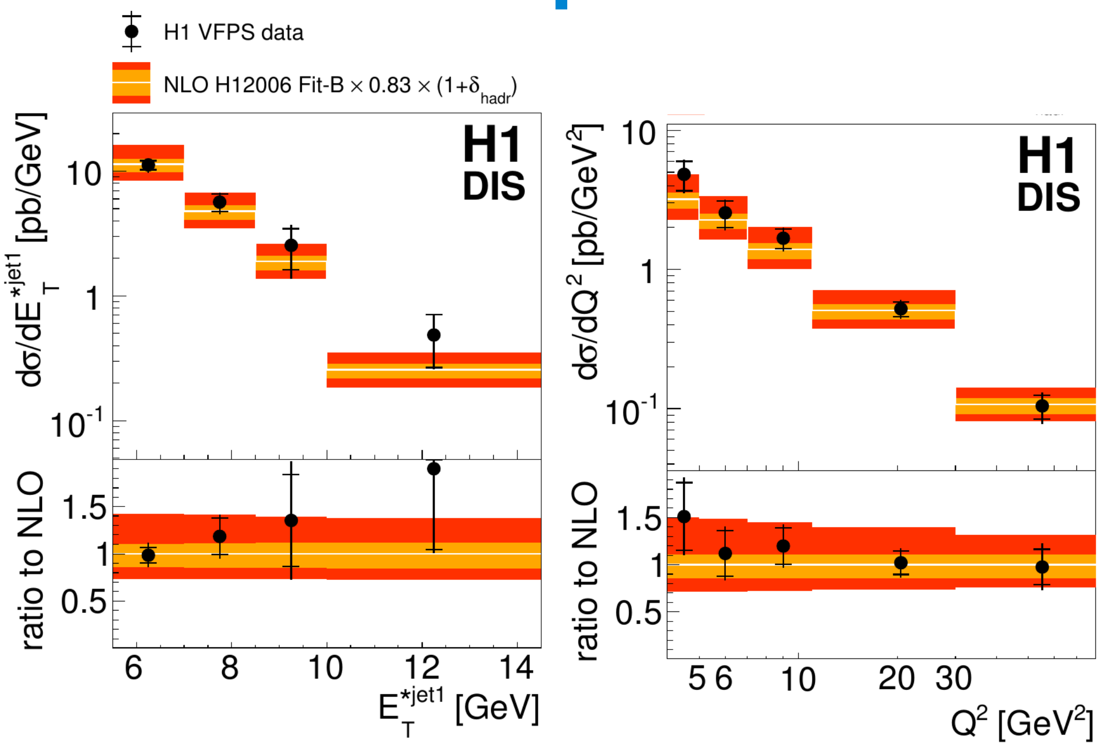
Diffractive Dijets in Photoproduction and DIS (VFPS) (H1)



Dijets in *γp*

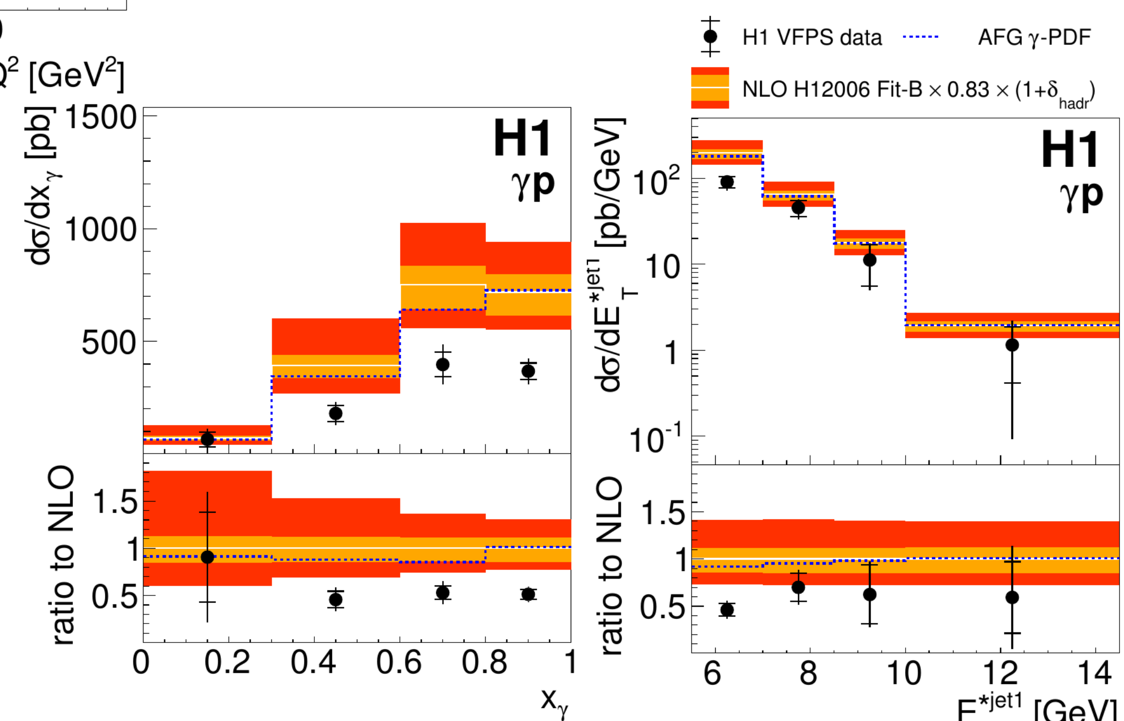
- Luminosity: $L \sim 30\ pb^{-1}$
- NLO by FKS (Frixione et al.)
- H12006 Fit-B
- GRV and AFG γ-PDF

γp: Shape well described by NLO, but normalisation is overestimated

Dijets in *DIS*

- Luminosity: $L \sim 50\ pb^{-1}$
- NLO by nlojet++ with H12006 Fit-B

DIS: Shape and normalisation well described by NLO



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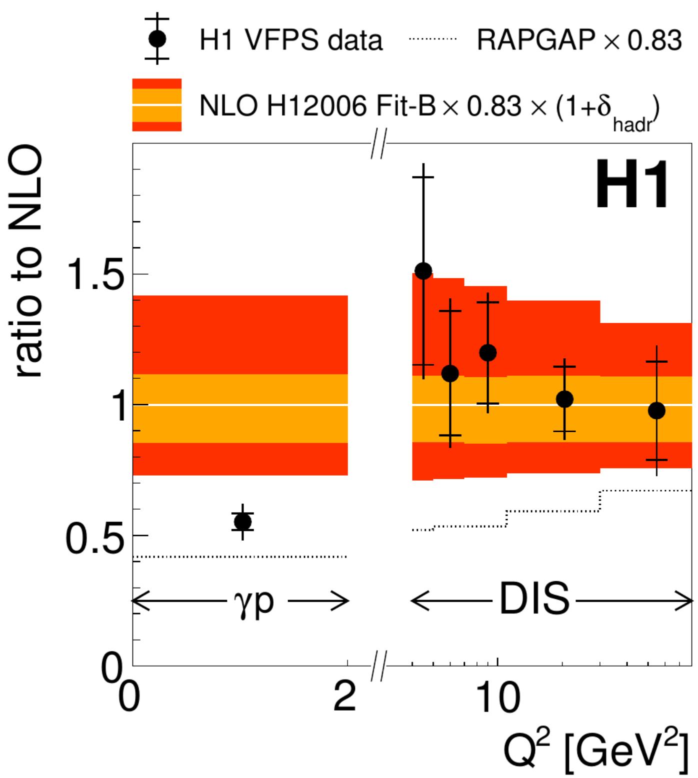
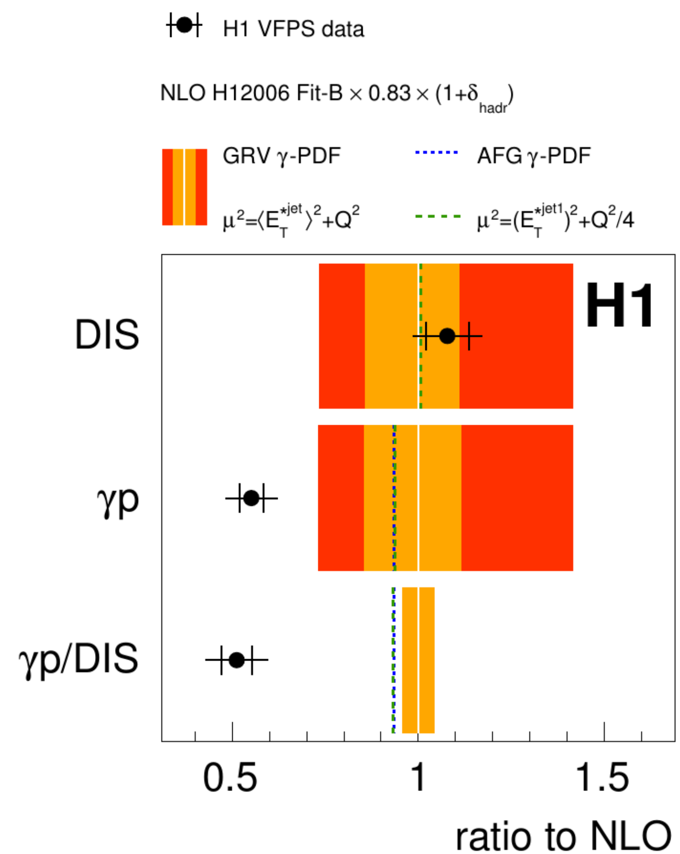
Diffractive Dijets in Photoproduction and DIS (VFPS) (H1)

Direct comparison of DIS and γp data with NLO and RAPGAP



New analysis confirms previous results from H1 with complementary experimental method

Double-ratio γp/DIS of total cross sections

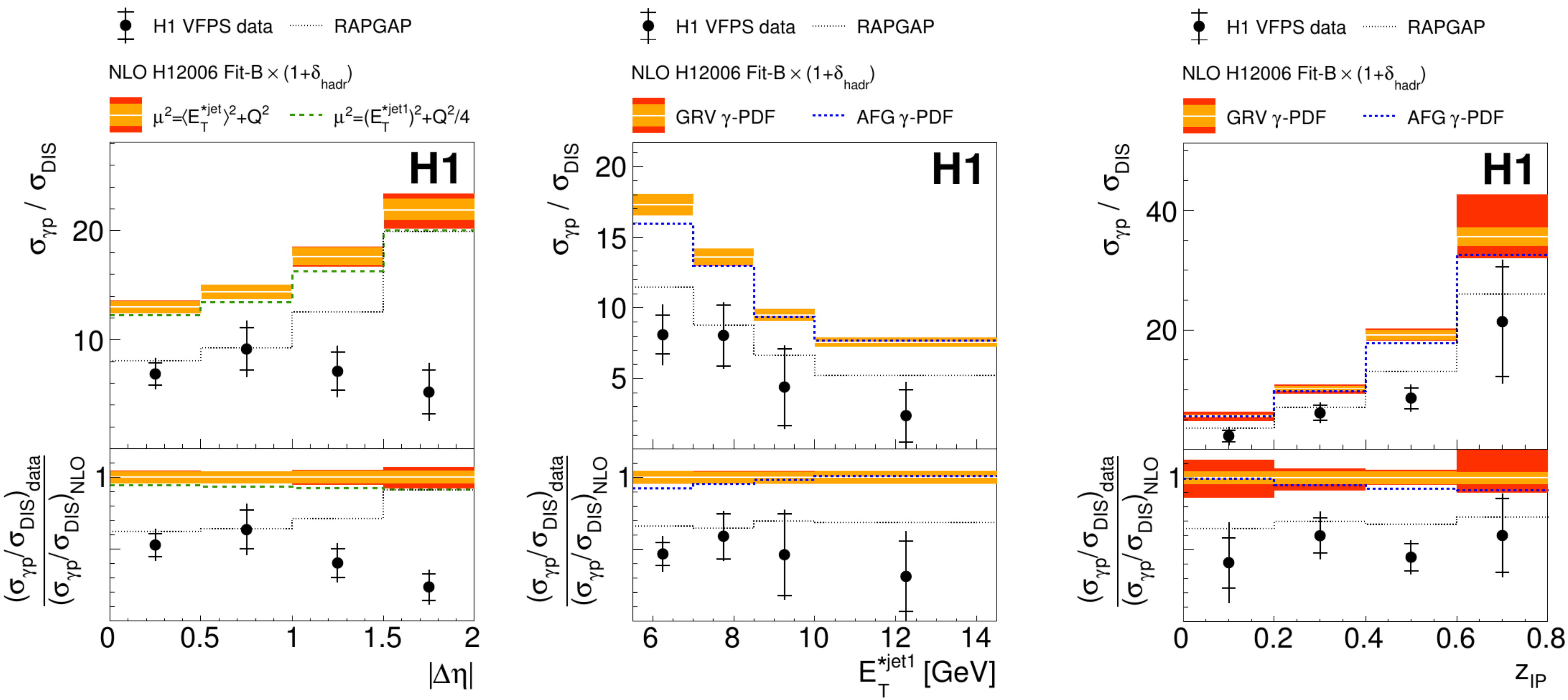


$$\frac{(\sigma_{\gamma p}/\sigma_{DIS})_{data}}{(\sigma_{\gamma p}/\sigma_{DIS})_{NLO}}$$

Suppression factor:
$S^2 = 0.511 \pm 0.085$ (data) ± 0.022 (th.)

Diffractive Dijets in Photoproduction and DIS (VFPS) (H1)

Double-ratio $(\text{data/NLO})_{\gamma p}$ / $(\text{data/NLO})_{DIS}$ of single-differential cross sections



No hint for 'suppression' as function of z_{IP}, x_γ or E_T^{jet1}

Largest deviation from constant for |Δη|

Diffractive photoproduction of isolated photons

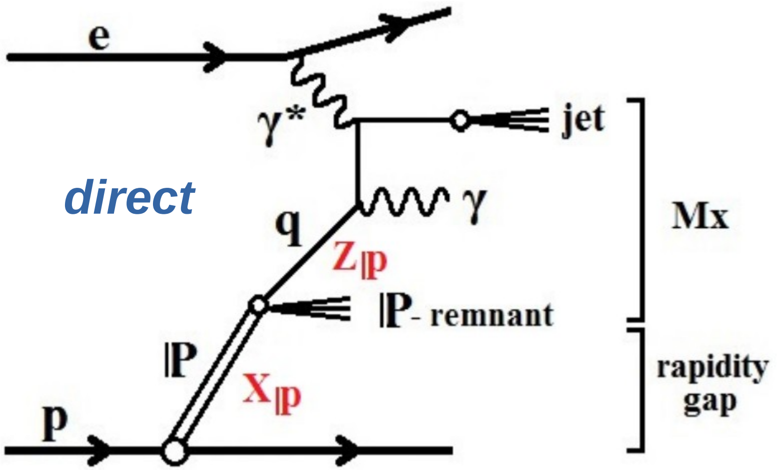
Measure *prompt photons* with and without accompanying jet

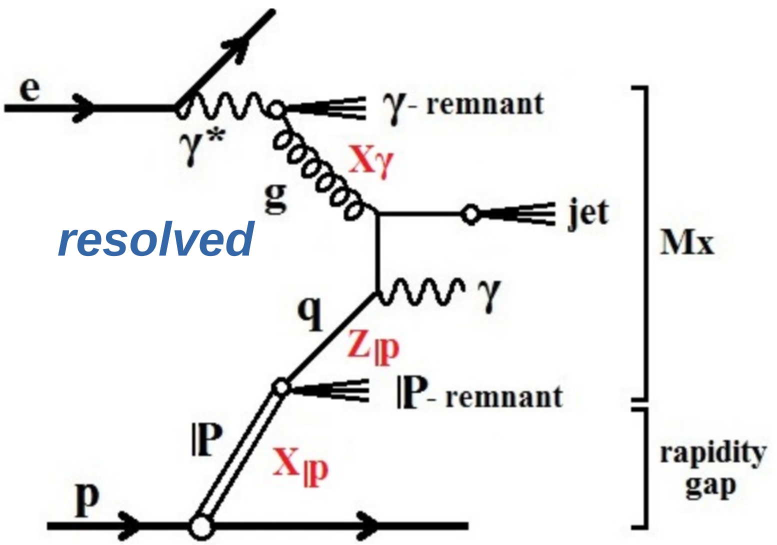
Photon must couple to a charged particle
→ explore non-gluonic nature of pomeron

LRG method for diffractive final state

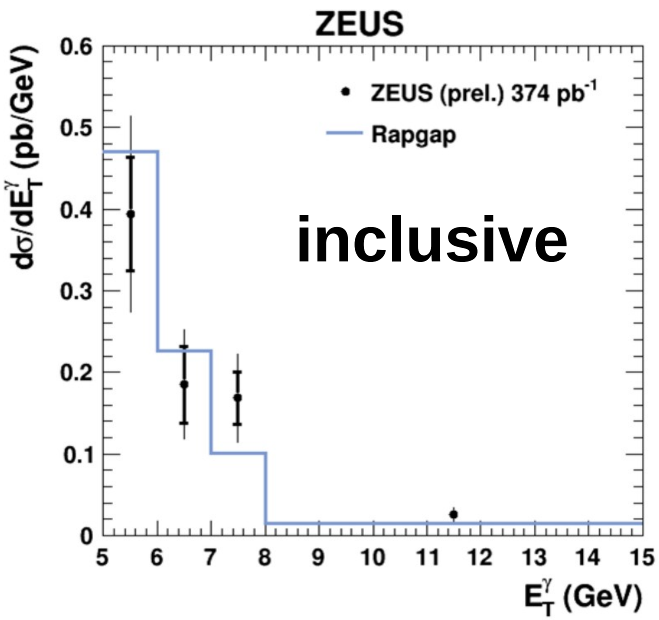
$Q^2 < 1\ GeV^2$
$x_{IP} < 0.03$
$E_{T\gamma} > 5\ GeV$
$-0.7 < \eta_\gamma < 0.9$
$-1.5 < \eta_{jet} < 1.8$
$E_{Tjet} > 4\ GeV$

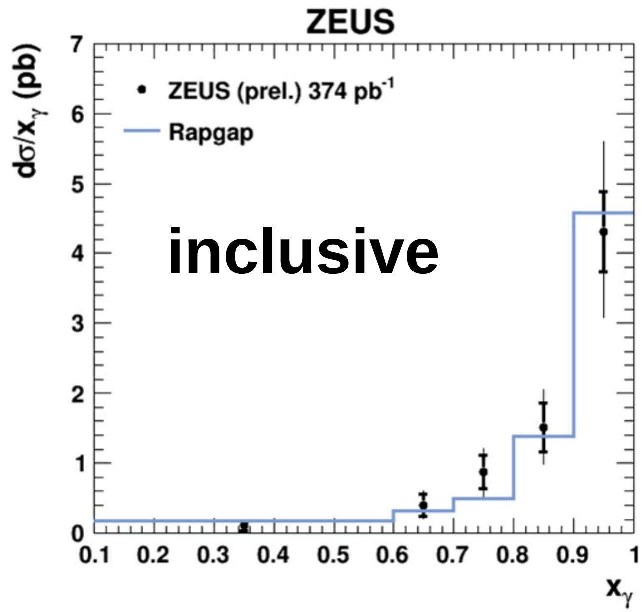
Comparison to:
Rapgap with H12006-FitB normalised to data

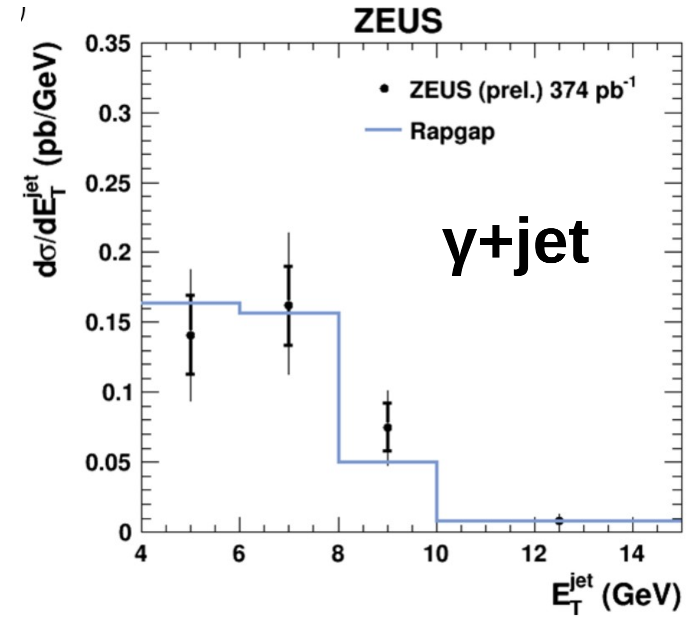




Diffractive photoproduction of isolated photons





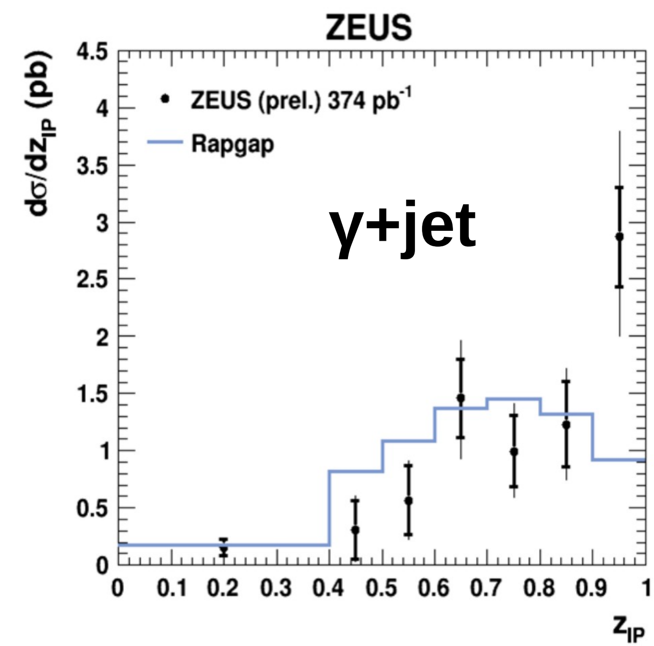


Normalised Rapgap prediction give reasonable description of most variables

Only at z_{IP}, where H12006-FitB was not fitted

Most photons are accompanied by a jet

Further studies will continue



Summary

Inclusive dijets in diffractive DIS

Data well described in NLO
Data precision overshoots theory precision
α_s extraction feasible ($\Delta^{theo} > \Delta^{data}$)

Inclusive dijets in γp (and DIS)

Complementary measurements using VFPS proton spectrometer
DIS: NLO well describes VFPS cross sections
γp: NLO overshoots VFPS cross sections

Prompt photons in diffractive γp

Measurement of another hard process to investigate factorisation breaking
Shapes mostly well described by RAPGAP
η^{max} and z_{IP} not well described

Exclusive dijets in diffractive DIS

see talk by A. Bruni

JDK

Inclusive deep-inelastic *ep* scattering (DIS)

ep scattering: $e^{\pm}p = e^{\pm} + X$

- Centre-of-mass energy

$$\sqrt{s} = \frac{p}{(k+p)^2}$$

- Virtuality of exchanged boson

$$Q^2 = -q^2 = -(k \cdot k')^2$$

- Bjorken scaling variable

$$x_{\mathrm{Bj}} = \frac{Q^2}{2p \cdot q}$$

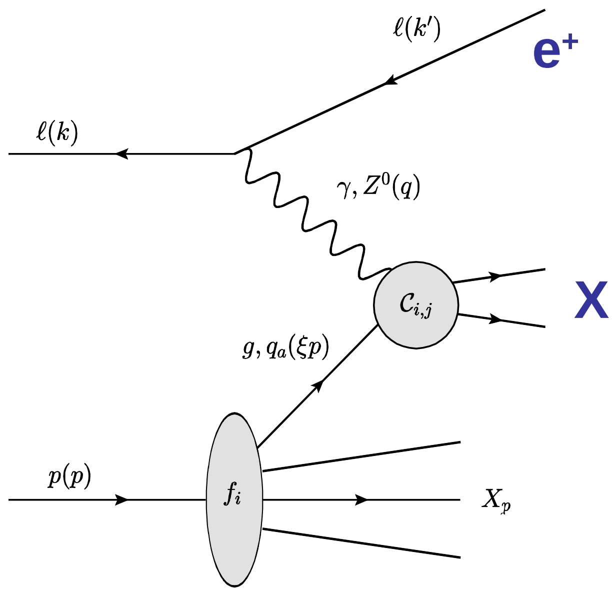
- Inealsticity

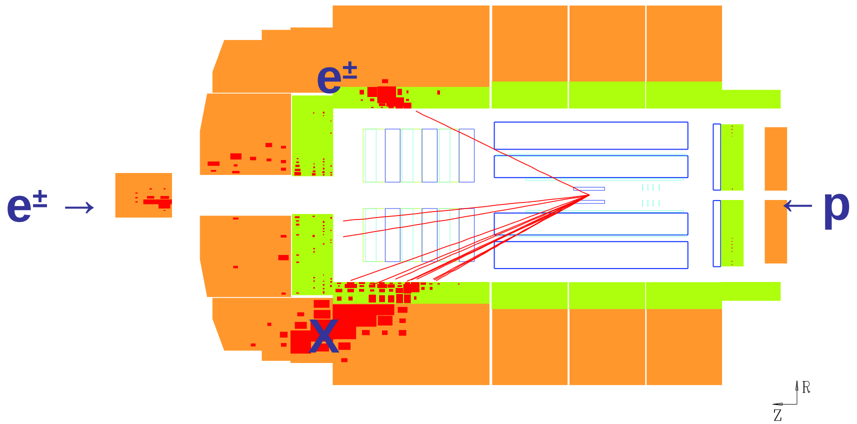
$$y = \frac{p \cdot q}{p \cdot k}$$

Cross section calculation

- Collinear factorisation
- Hard scattering calculable in pQCD
- PDFs have to be determined from experiment

Neutral current DIS

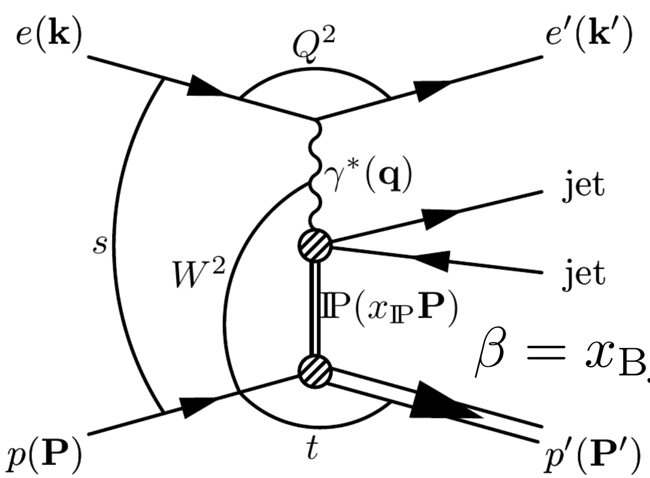




Exlusive dijets in diffractive DIS (ZEUS)

Exclusive dijets sensitive to the nature of exchanged object:

- Single or double gluon exchange ?

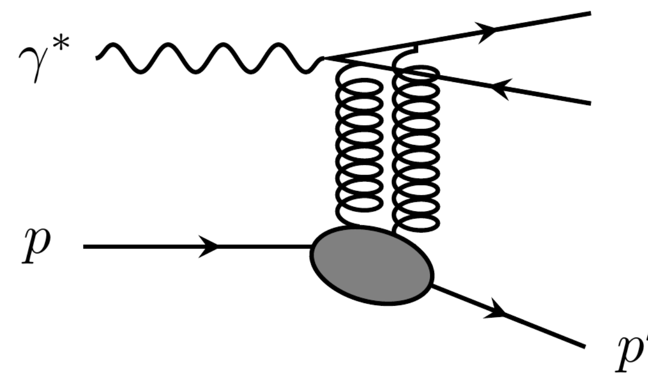


$$\beta = x_{\mathrm{Bj}}/x_{IP}$$

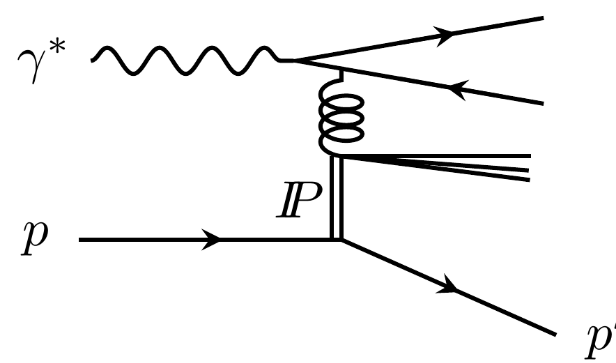
Dijet events identified using 'large rapidity gap'
Exclusive Durham jet algorithm in phase space

$$\mathrm{Q}^2 > 25\mathrm{GeV}^2$$
$$90 < W < 250\mathrm{GeV}$$
$$\mathrm{x}_{IP} < 0.01$$
$$\mathrm{M}_X > 5\mathrm{GeV}$$
$$\mathrm{p}_T^{\mathrm{jet}} > 2GeV$$

Two-gluon exchange model



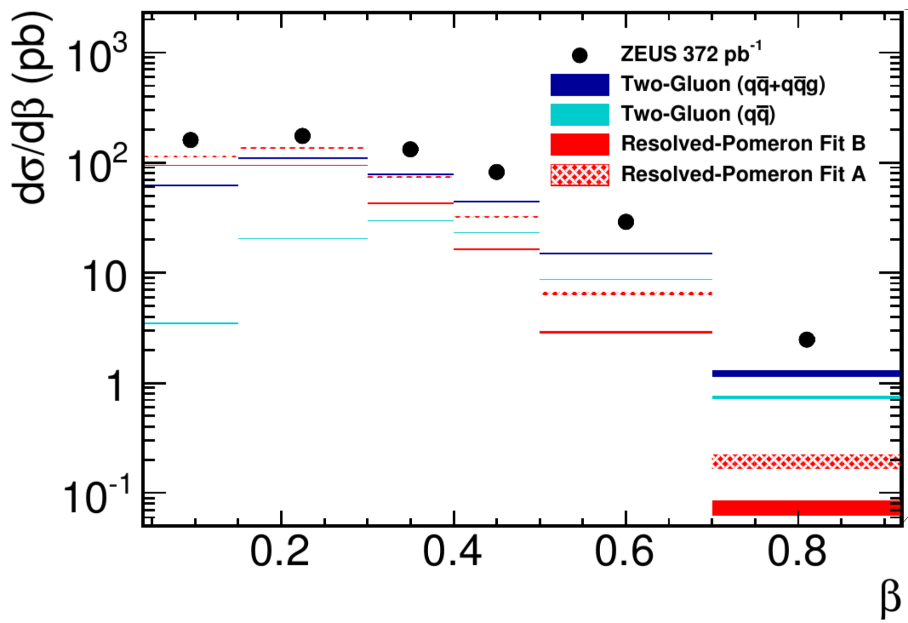
Resolved Pomeron model

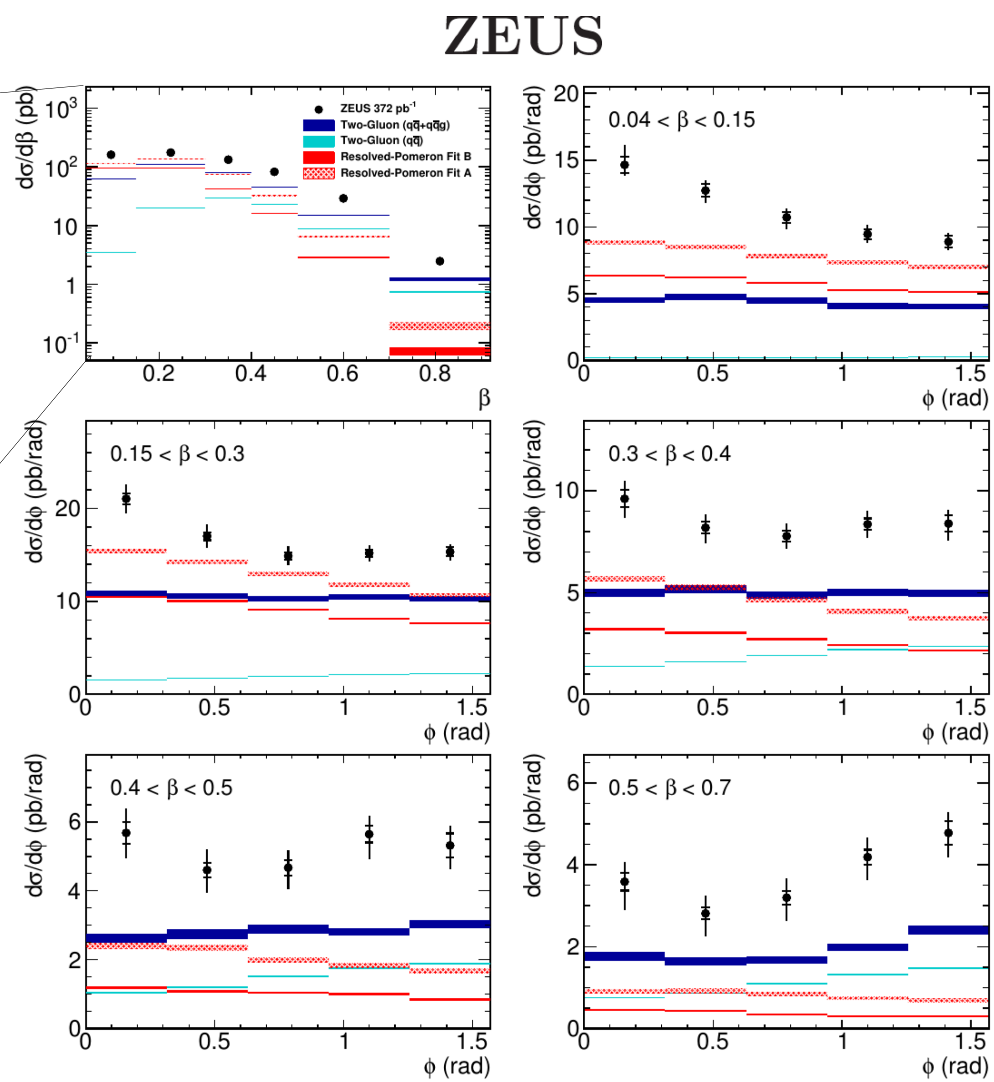


→ Study nature of diffractive exchange

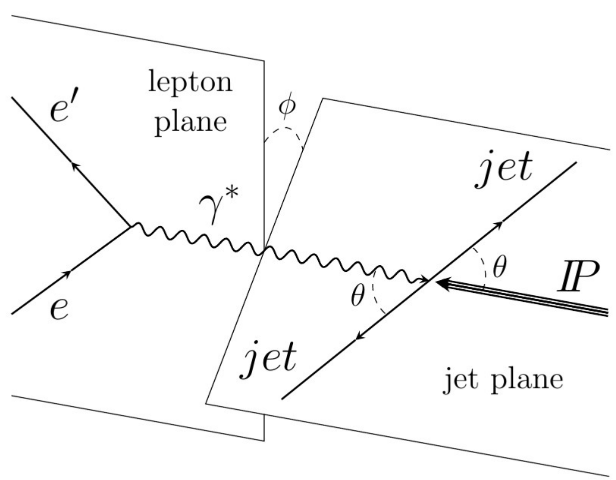
Exlusive dijets in diffractive DIS (ZEUS)

Differential cross sections in β and φ





Angle φ between lepton and jet planes



Normalisation discrepancy:
Large NLO corrections?

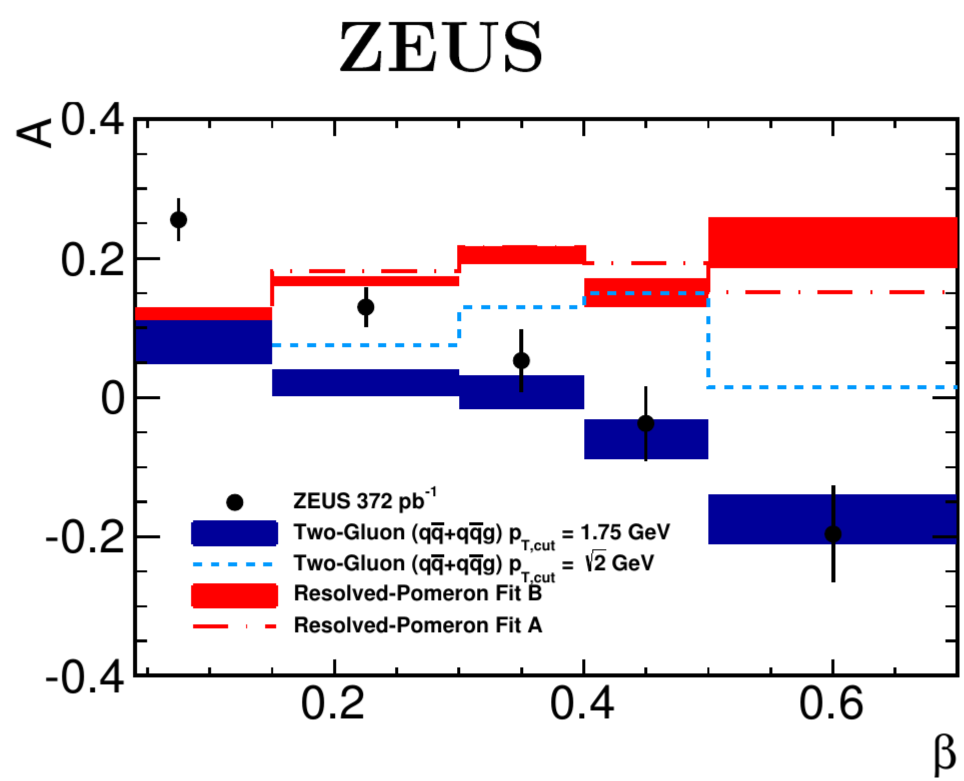
Exlusive dijets in diffractive DIS (ZEUS)

dσ/dφ fitted in each β bin using fit function

$$\frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}\phi} \propto 1 + A\cos 2\phi$$

Parameter *A* distiguishes between the two models

- Positive A for single gluon exchange
- Negative A for two gluon exchange



A vs φ: good descripton by two gluon model for β > 0.3

H1 and ZEUS Roman pots