Diffractive Dijet Production in *ep* Collisions at HERA

- JHEP 1503 (2015) 092 [arXiv:1412.0928]
- JHEP 1505 (2015) 056 [arXiv:1502.01683]

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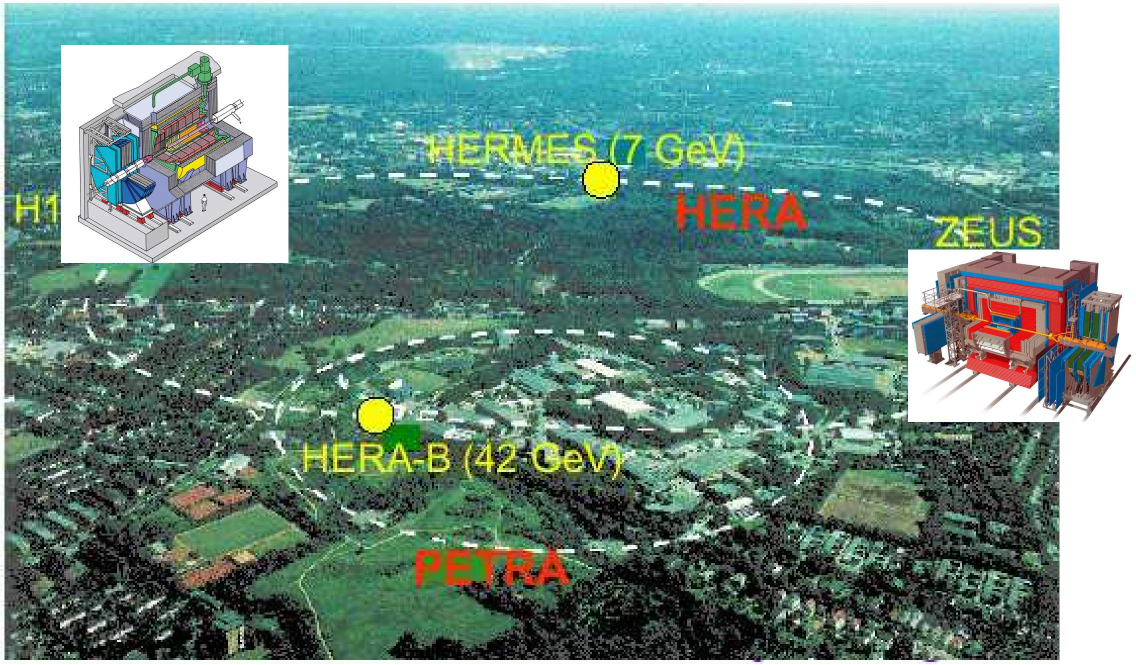
On behalf of H1 Collaboration

HERA: The World's Only ep Collider

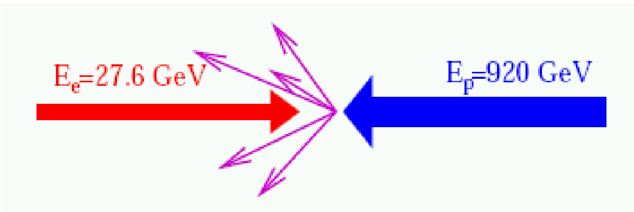


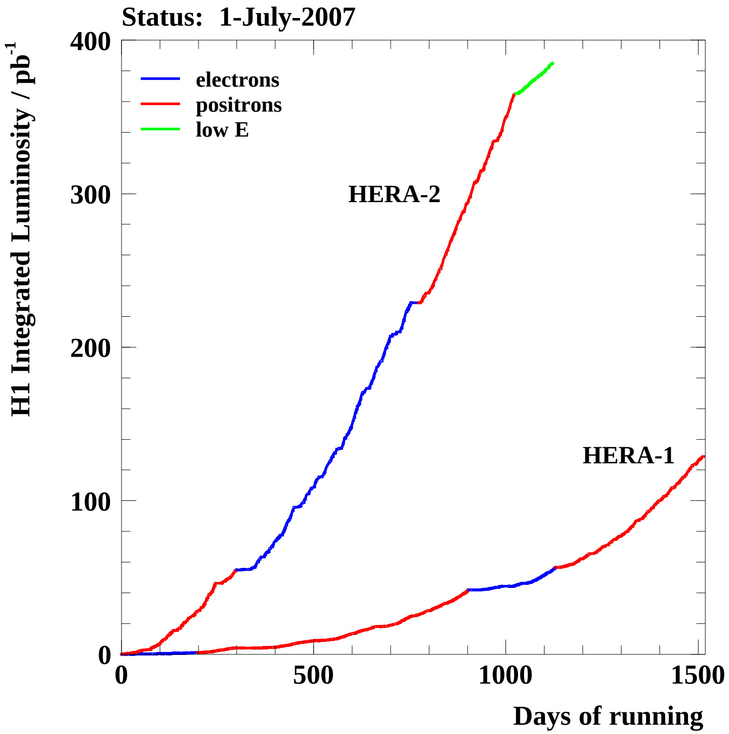
HERA-1 (1993-2000) $\simeq 120$ pb^{-1}

HERA-2 (2003-2007) $\simeq 380$ pb^{-1}

Final Data samples

H1+ZEUS: 2×0.5 fb^{-1}

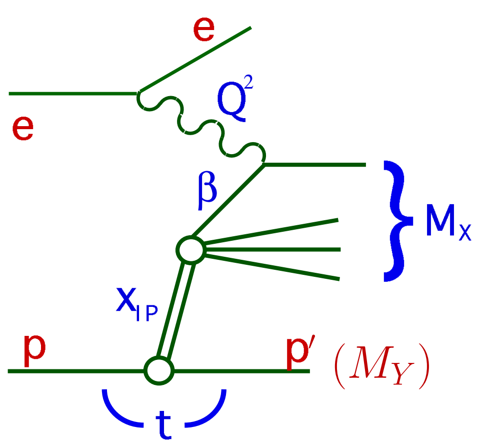




- 1998 E_p upgrade: $820 \Rightarrow 920$ GeV
  ($\sqrt{s}$: $301 \Rightarrow 319$ GeV)
- 2001 HERA-2 upgrade: $\mathcal{L} \times 3$, Polarised e^+/e^-
  ($\langle P \rangle = 40\%$)

Diffraction at HERA

- Fundamental aim: understand high energy limit of QCD (gluodynamics; CGC ?)
- Novelty: for the first time probe partonic structure of diffractive exchange
- Practical motivations: study factorisation properties of diffraction; try to transport to hh scattering (e.g. predict diffractive Higgs production at LHC)



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

(momentum fraction of colour singlet exchange)

$$\beta = \frac{Q^2}{Q^2+M_X^2} = x_{q/I\!P} = \frac{x}{x_{I\!P}}$$

(fraction of exchange momentum, coupling to γ^*)

$$t = (p - p')^2$$

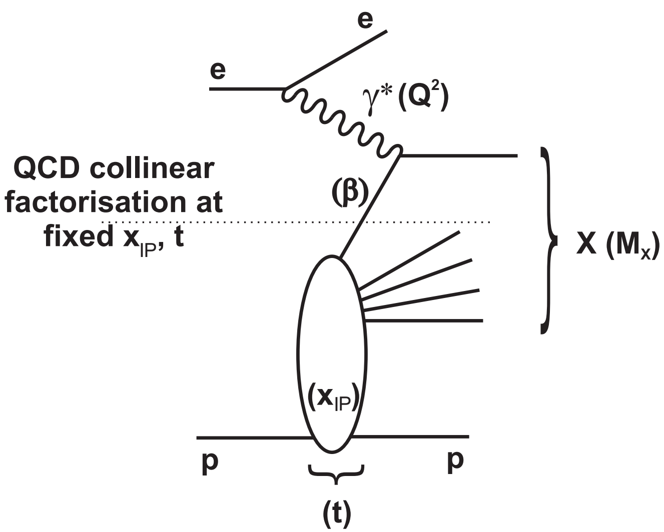
(4-momentum transfer squared)

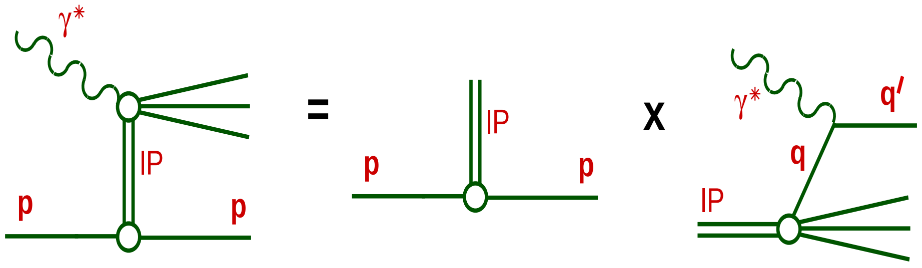
Experimental methods:

1) selecting LRG events

2) detecting p in Roman Pots
($60 - 220$ m from IP)

Factorisation properties in diffraction





QCD versus Regge factorisation

QCD factorisation

(rigorously proven for DDIS by Collins et al.):

$$\sigma_r^{D(4)} \propto \sum_i \hat{\sigma}^{\gamma^* i}(x, Q^2) \otimes f_i^D(x, Q^2; x_{I\!P}, t)$$

- $\hat{\sigma}^{\gamma^* i}$ – hard scattering part, same as in inclusive DIS
- f_i^D – diffractive PDF's, valid at fixed $x_{I\!P}, t$ which obey (NLO) DGLAP

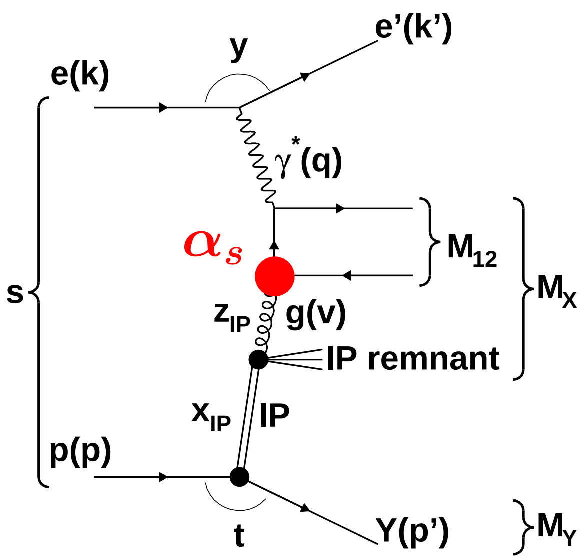
Regge factorisation

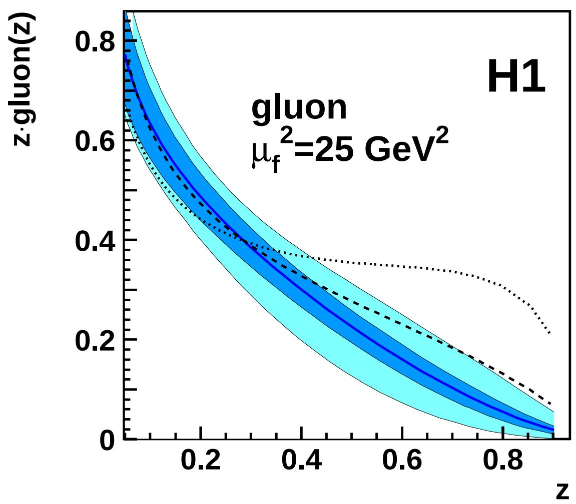
(conjecture, e.g. RPM by Ingelman,Schlein):

$$F_2^{D(4)}(x_{I\!P}, t, \beta, Q^2) = \Phi(x_{I\!P}, t) \cdot F_2^{I\!P}(\beta, Q^2)$$

- In this case shape of diffractive PDF's is independent of $x_{I\!P}, t$ while normalization is controlled by Regge flux $\Phi(x_{I\!P}, t)$

Diffractive dijet production





From HERA-I data

Jets are fundamentable observables in HE scattering, used to test and verify several important concepts.

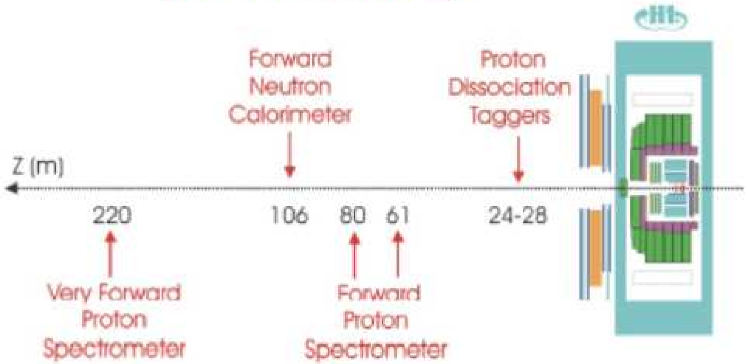
In diffraction:

- Factorization properties
  - – QCD factorization and universality of DPDFs
  - – proton vertex factorization
  - – Regge factorization and the concept of (resolved) Pomeron
- DPDF fits
  - – direct sensitivity to gluon content of diff.exchange
  - – improved DPDF precision especially at high $z_{I\!P}$
- QCD studies
  - – try to distinguish different evolution schemes
  - – test MC models (e.g. $2g$ vs Colour Dipoles vs SCI)
  - – eventually extract α_s and check overal consistency

Selection of Diffractive Events

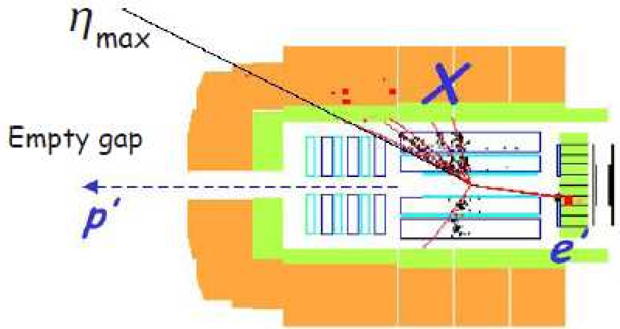
Measure the leading proton

➔ Forward spectrometers (H1 FPS/VFPS)



- x_{IP} and t measurements
- Less statistics
- p-tagging systematics

Measure a Large Rapidity Gap



- Data integrated over |t| < 1 GeV^2
- High statistics
- Contamination from proton dissociation events

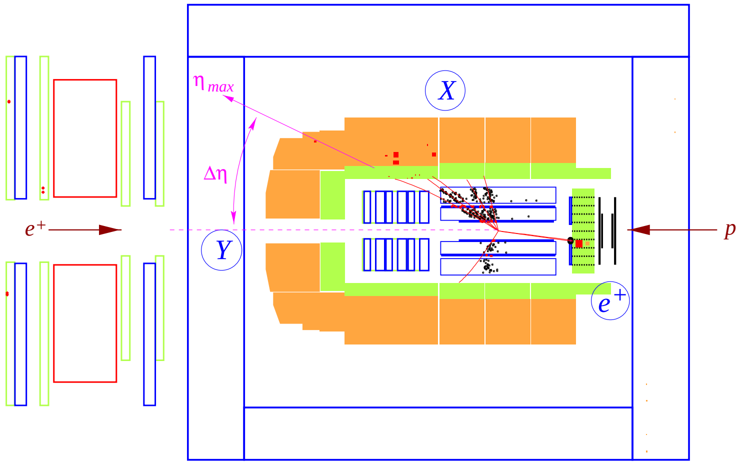
  ➔ Needs to be controlled

↘ Different systematics

↘ Different kinematic coverage

Diffractive dijets in DIS using LRG method

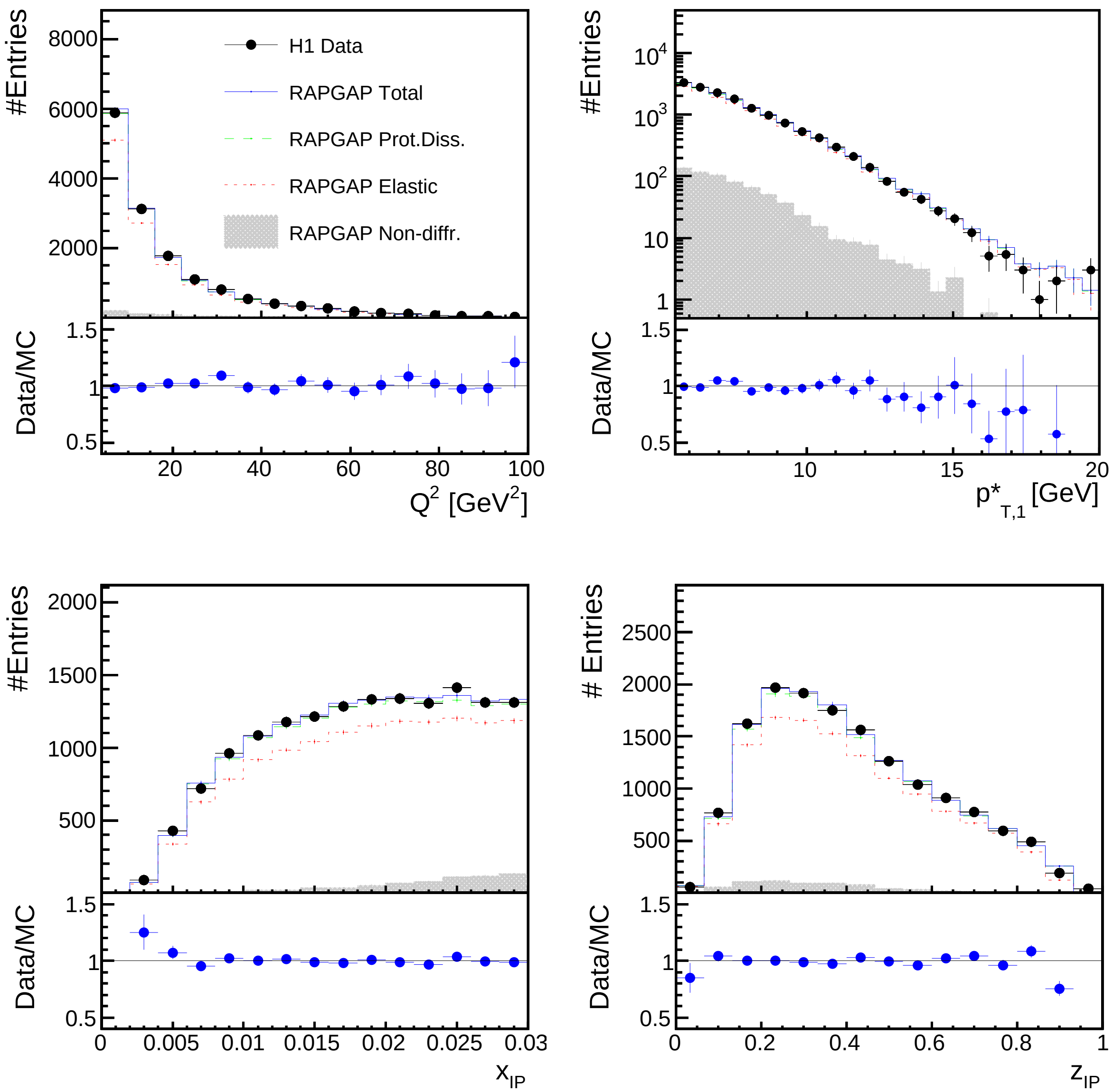
Diffractive dijet data sample



- High statistics: $\mathcal{L} = 290$ pb^{-1}, 15000 dijet events
- Improvement in systematics: jet E-scale 1%; unfolding
- Precision ⇒ stringent test of QCD at NLO in DDIS
- New: first determination of α_s in diffraction

	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	$x_{I\!P} < 0.04$ LRG requirements	$x_{I\!P} < 0.03$ $\lvert t\rvert < 1$ 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 $-1 < \eta^{lab}_{1,2} < 2$

LRG dijets: Control distributions



- Simulations: LO MC Rapgap ($I\!P$, $I\!R$ and p-diss contrib.)
- MC reweighted in $x_{I\!P}$, $z_{I\!P}$ and x_γ to describe data in extended PS
- All reconstructed quantities are well descibed $\Rightarrow$ LO MC can be used to correct for detector effects (acceptance, efficiency)
- Regularized unfolding (TUnfold) corrects for resolution, migrations

Integrated cross section: Data vs NLO QCD

Experimental uncertainties:

Electron angle	1%
Electron energy	1%
Hadronic energy	4%
Model uncertainty	5%
Normalisation	8%
Total	10%

- NLOJET++ with 5 active flavours
  (adopted to DDIS using $x_{\mathbb{P}}$ slicing method)
- 2-loop RGE; $\alpha_s(M_Z) = 0.118$
- scale $\mu_R^2 = \mu_F^2 = \langle P_T^{*jet} \rangle^2 + Q^2$
  (scale is varied by factor of 2 up and down)
- H1-2006 Fit-B DPDFs are used
  (DPDF uncertainties are propagated
  to predicted cross sections)

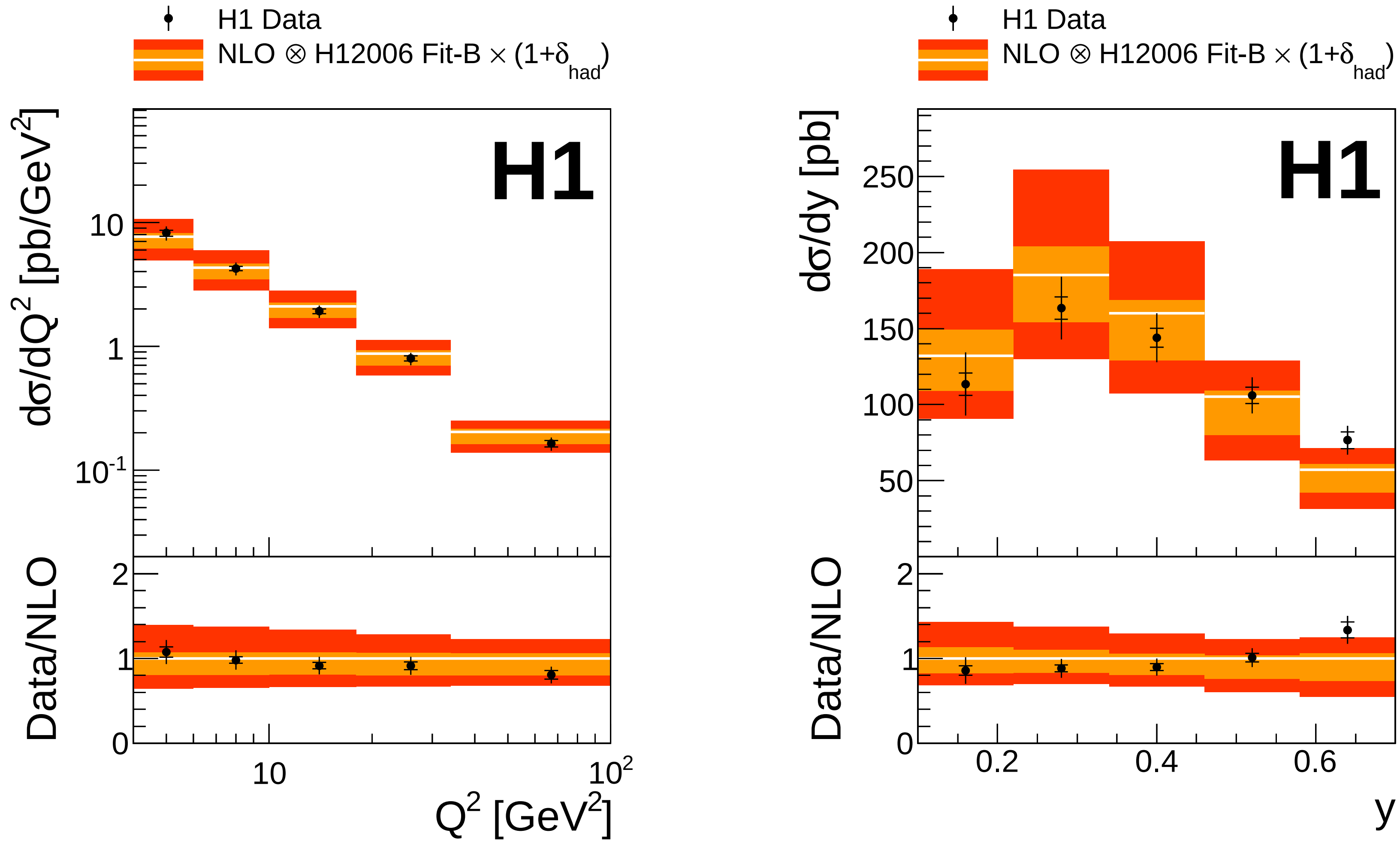
Measured cross section:

$$\sigma_{meas}^{dijet}(ep \to eXY) = 73 \pm 2(stat) \pm 7(syst)\ \mathbf{pb}$$

Predicted at NLO:

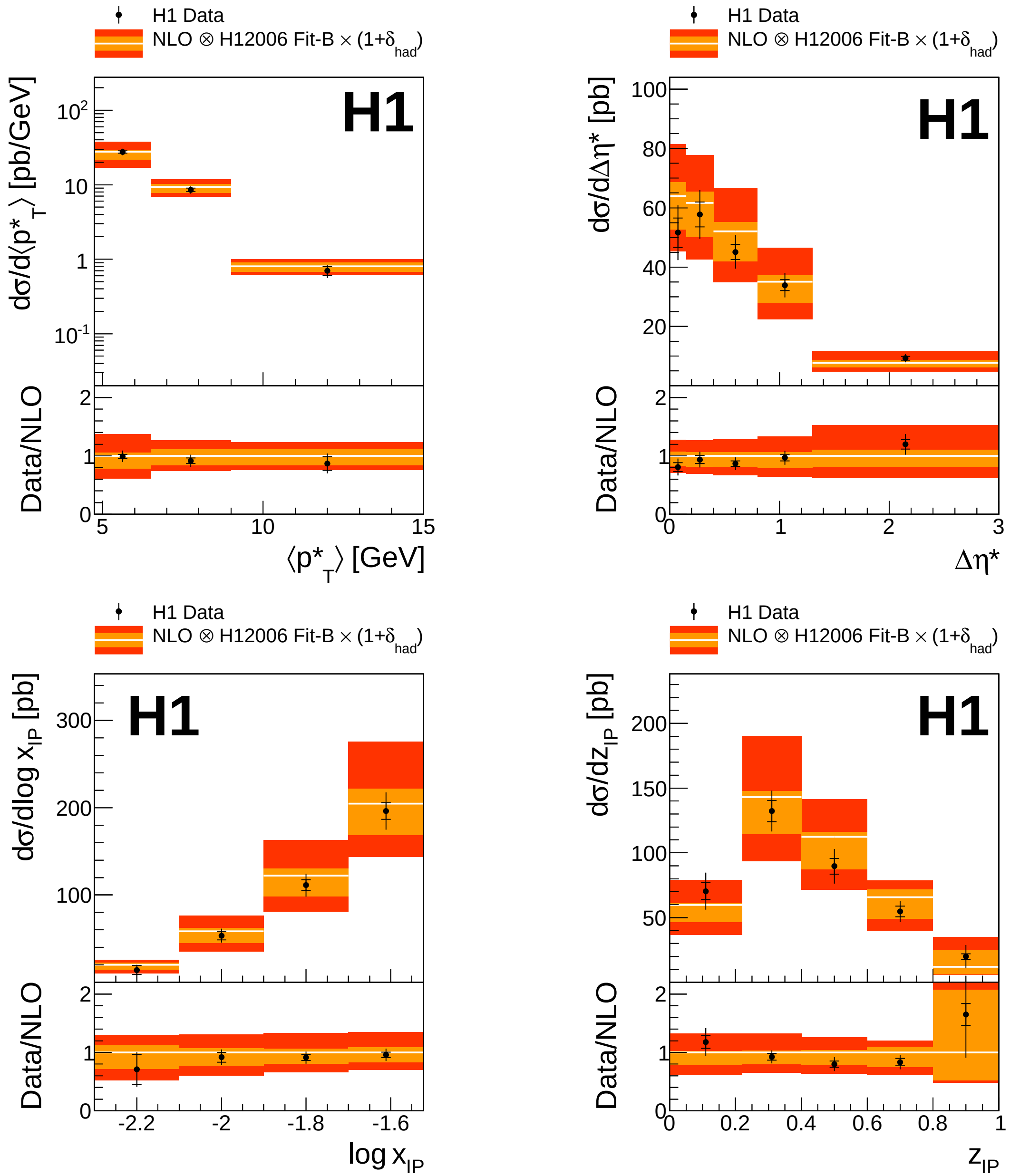
$$\sigma_{theo}^{dijet}(ep \to eXY) = 77^{+25}_{-20}(scale)^{+4}_{-14}(DPDF) \pm 3(had)\ \mathbf{pb}$$

Single-differential cross sections (1)



- QCD: Yellow band – uncertainty due to DPDF and hadr., red band – total uncertainty
- DIS kinematics is well described. Data are more precise than NLO prediction

Single-differential cross sections (2)

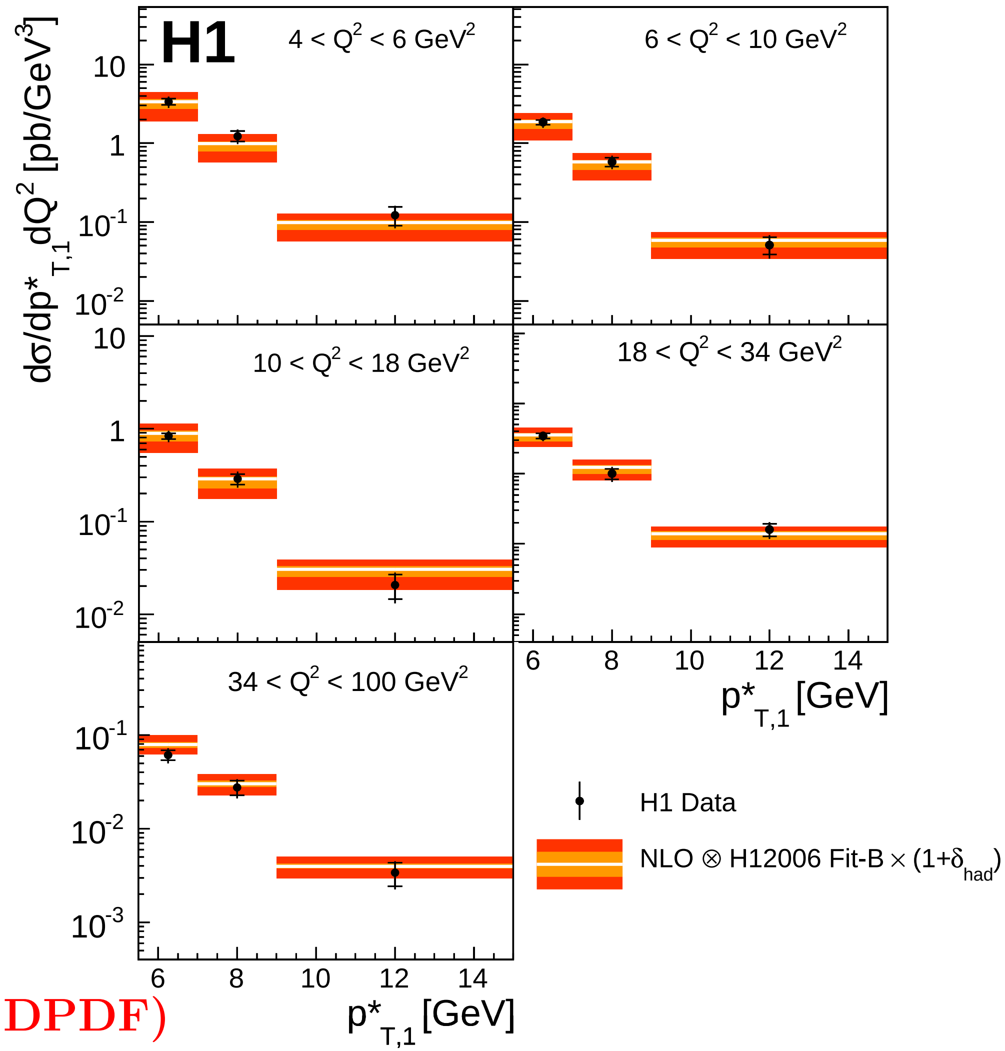


- Jet variables are described ⇒ NLO QCD is applicable in studied phase space

- Diffractive variables described. Data have the potential to further constrain DPDFs

Double-differential cross sections

- NLO QCD in agreement with high precision LRG data. QCD factorization holds
- Possible input for new DPDF extraction
- Used here for $\alpha_s(M_Z)$ fit keeping DPDF fixed
- NLO predictions for fit obtained with FastNLO
- Fit result $\chi^2/\mathrm{ndf} = 16.7/14$



$$\alpha_s(M_z) = 0.119 \pm 0.004(\mathrm{exp}) \pm 0.012(\mathrm{th, DPDF})$$

First extraction of α_s in diffraction. Important consistency check for full concept

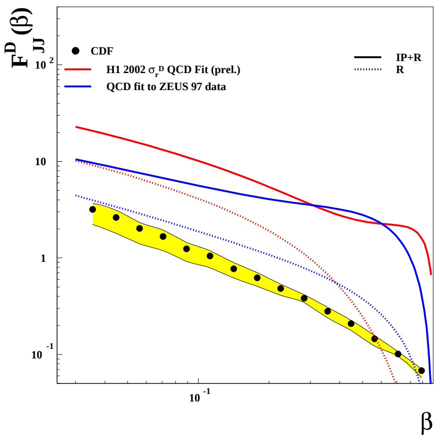
Diffractive dijet production with Leading Proton

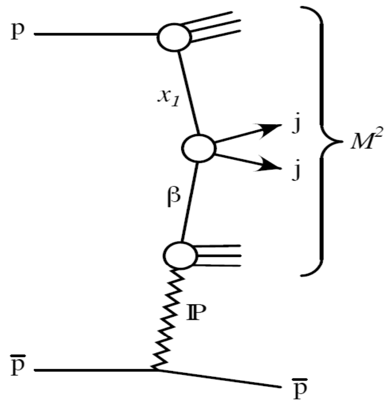
QCD Factorisation Tests in Diffraction: History

QCD Factorisation holds in DIS regime (H1, ZEUS)

However, it breaks down at Tevatron ...

Tevatron vs HERA





QCD Factorisation Tests in Diffraction at HERA

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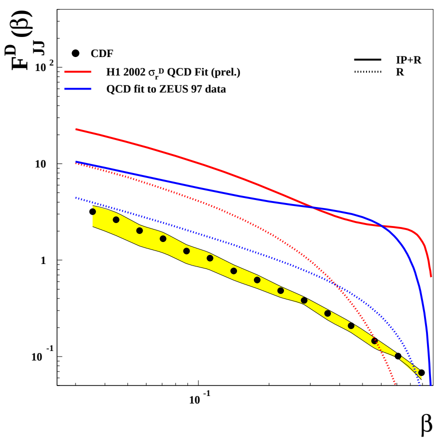

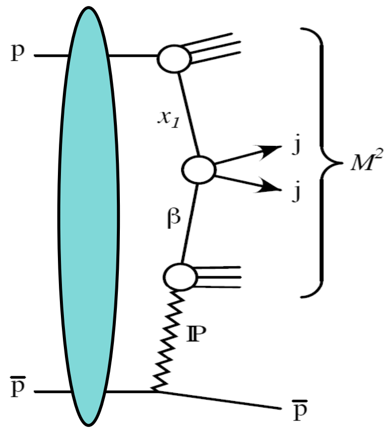

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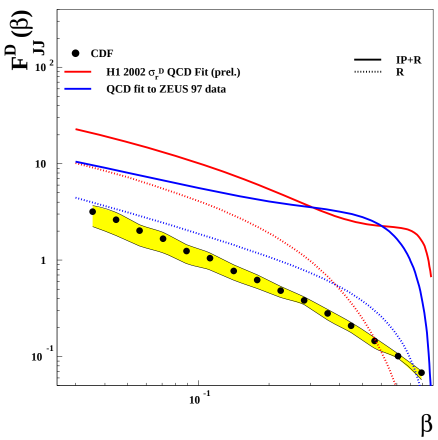
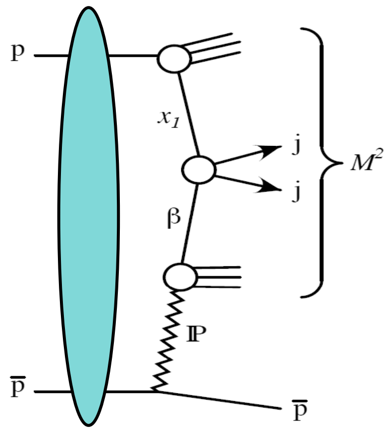
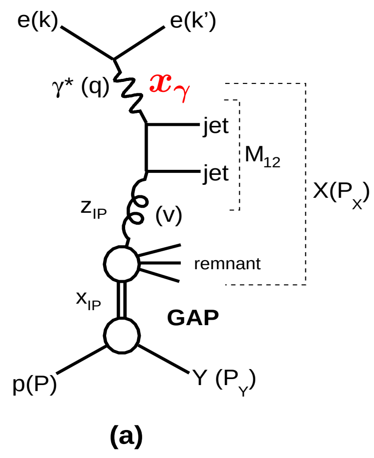
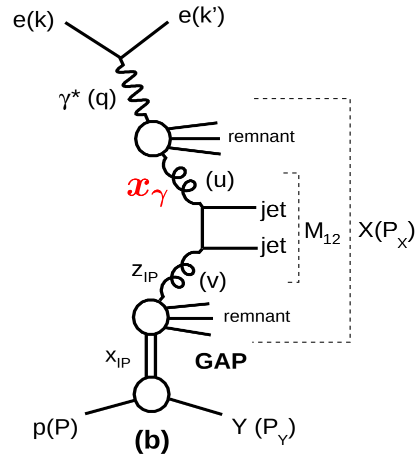




$\Rightarrow$ Test it in photoproduction:





direct, $x_\gamma = 1$ (DIS-like) resolved, $x_\gamma < 1$ (hadron-like)

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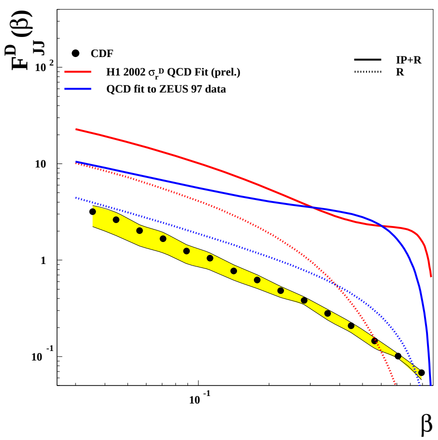

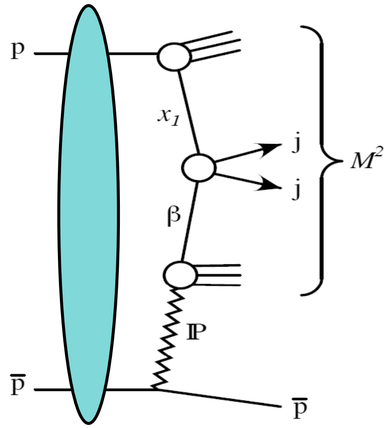

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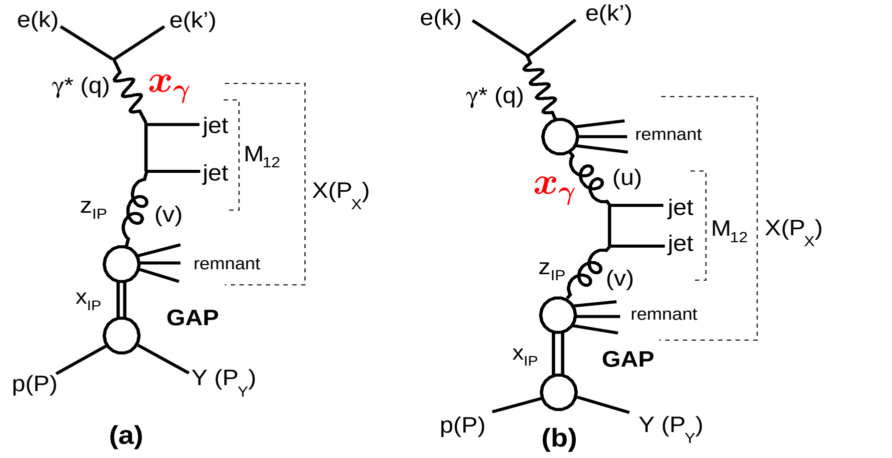

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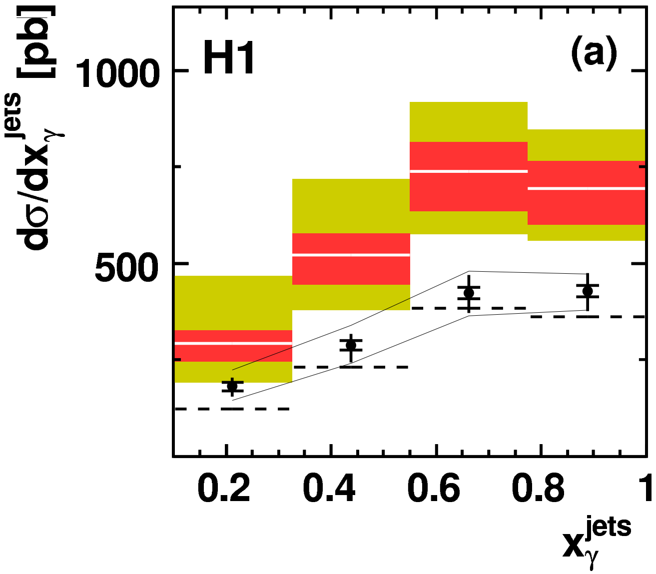


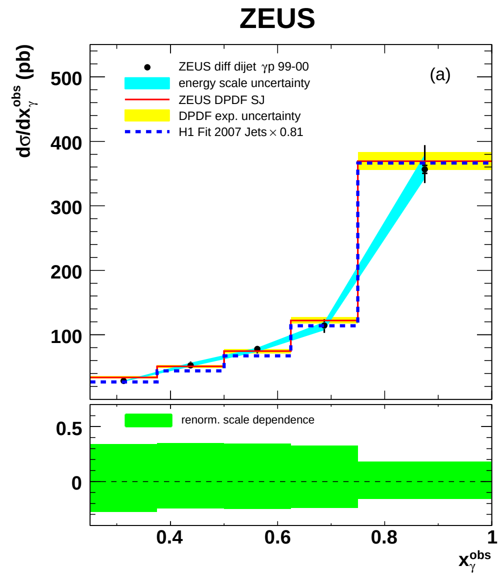
LRG ($\sim 20\%$ p-diss)

tagged γp **untagged**

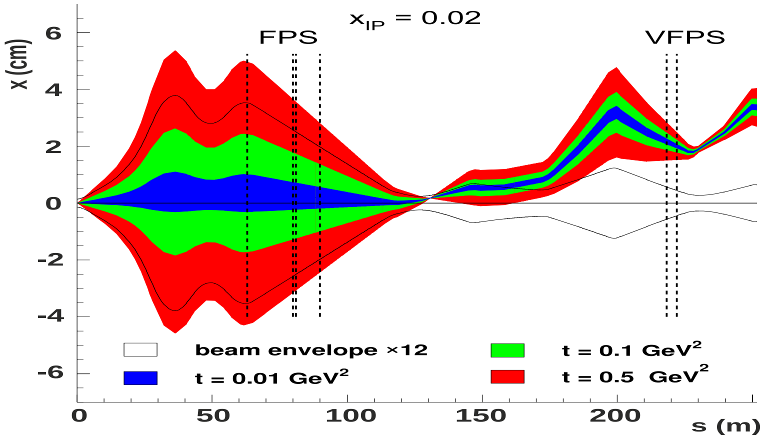
$5(4)\ \mathrm{GeV} < E_T^{j_{1(2)}} > 7.5(6.5)\ \mathrm{GeV}$

$S^2 \approx 0.6$ $S^2 \approx 1.0$

No x_γ dependence



New analysis: VFPS Dijets in DIS and PHP



- 2006/07 e$^+$p data, $\mathcal{L} \approx 30(50)$ pb^{-1}
- Leading proton measured by VFPS
- Untagged photoproduction (e$^+$ escapes in the beampipe)

Statistics: 3800 dijet events in PHP
550 dijet events in DIS

Data unfolded to the level of stable hadrons using *TUnfold* program

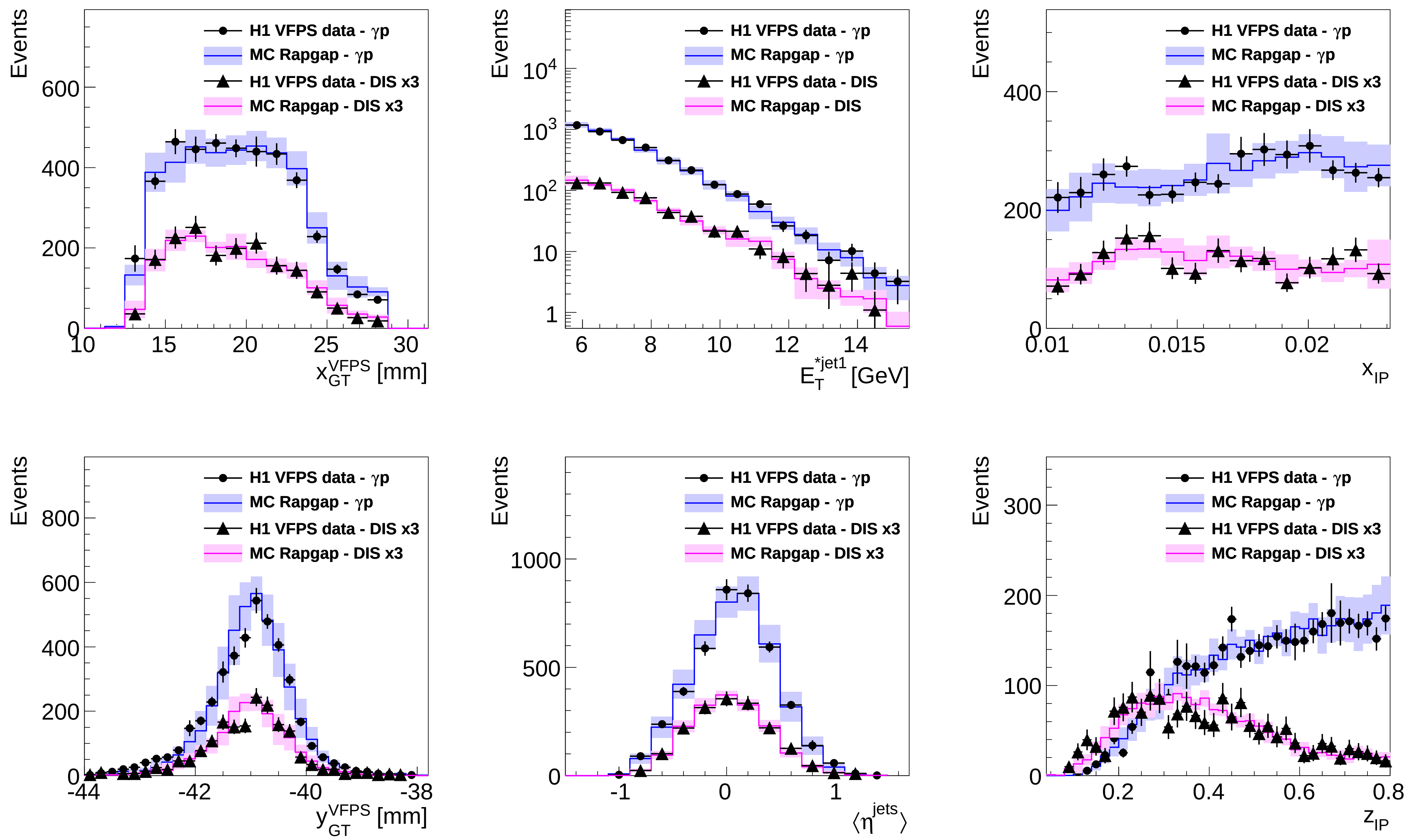
Results are compared to NLO QCD

- Scales: $\mu_r^2 = \mu_f^2 = \langle E^2_{T,\mathrm{jet}} \rangle + Q^2$
- DPDF H1 2006 Fit B and GRV-HO γ-PDF used
- Different scale choices and γ-PDF studied

	Photoproduction	DIS
Event kinematics	$Q^2 < 2\,\mathrm{GeV}^2$	$4 < Q^2 < 100\,\mathrm{GeV}^2$
	$0.2 < y < 0.7$	
Leading proton	$0.01 < x_{IP} < 0.024$	
	$\lvert t \rvert < 0.6\,\mathrm{GeV}^2$	
		$z_{IP} < 0.8$
Dijets	$E_T^{*jet1} > 5.5\,\mathrm{GeV}$	
	$E_T^{*jet2} > 4\,\mathrm{GeV}$	
	$-1 < \eta^{\mathrm{jet1,2}} < 2.5$	

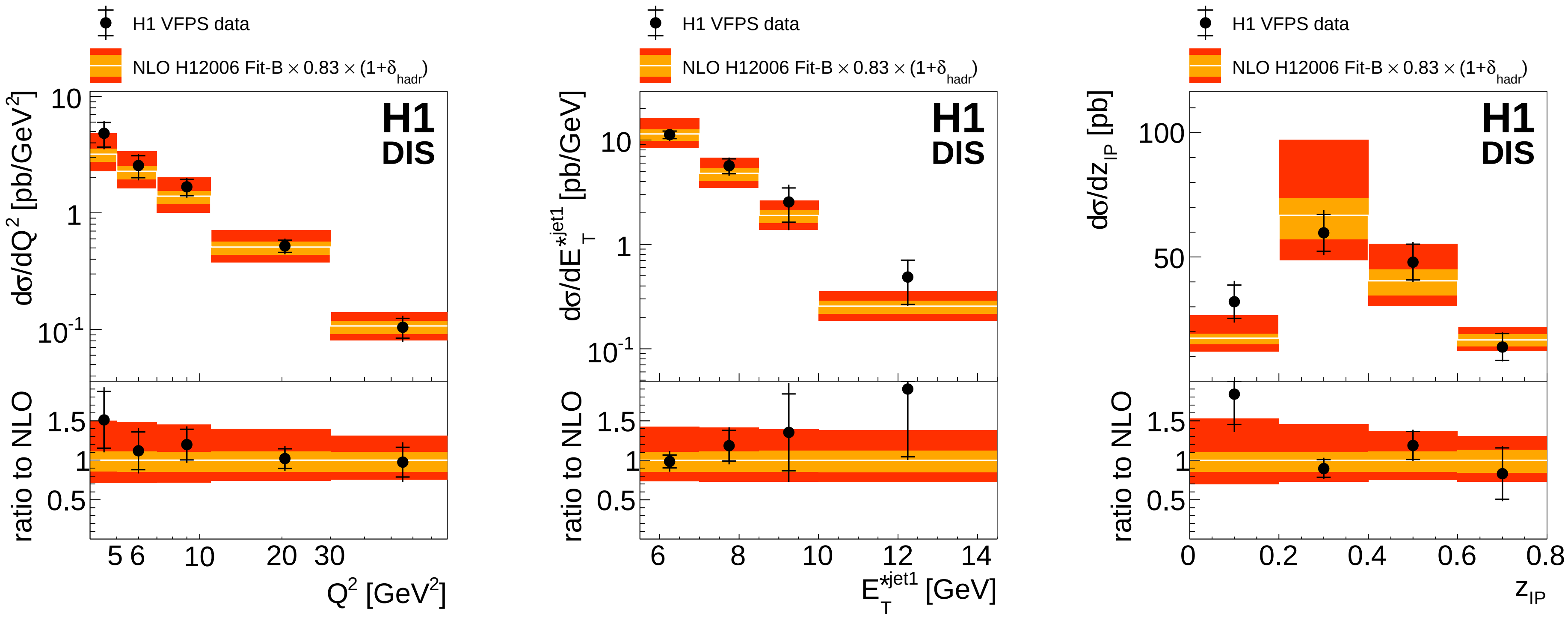
Table 1: Analysis phase space.

VFPS dijets: Control distributions



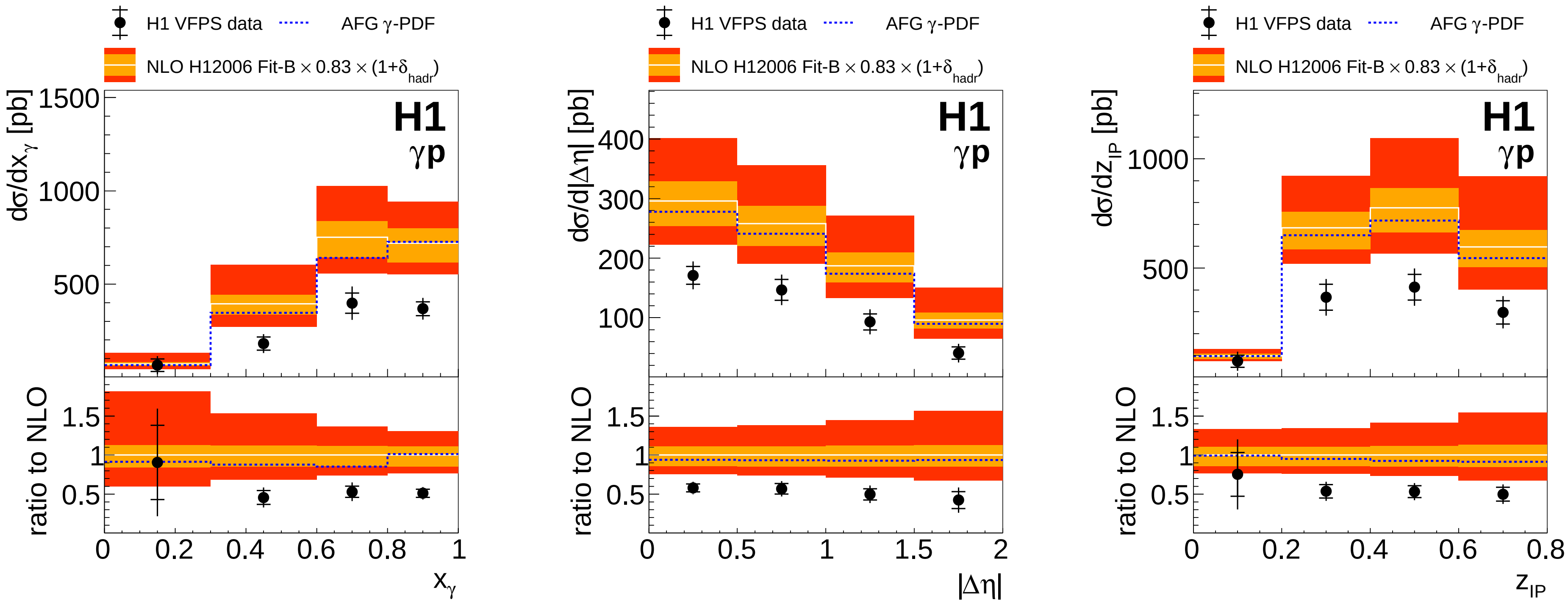
VFPS **Jets** **Pomeron**

Data vs NLO: DIS cross sections



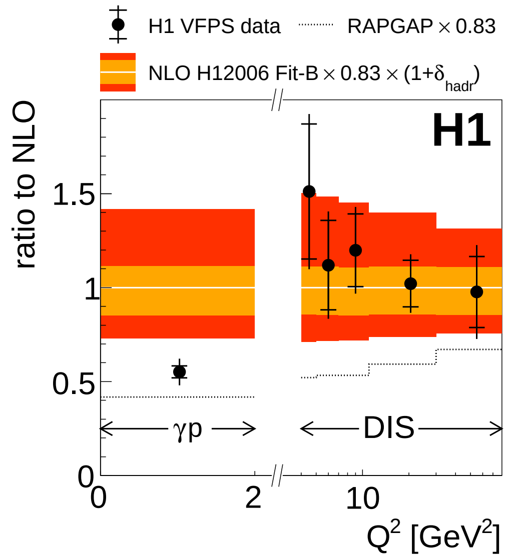
- NLOJET++ (verified against DISENT NLO)
- Data compatible with NLO predictions both in shape and normalisation
- Jet E_T slightly harder than predicted

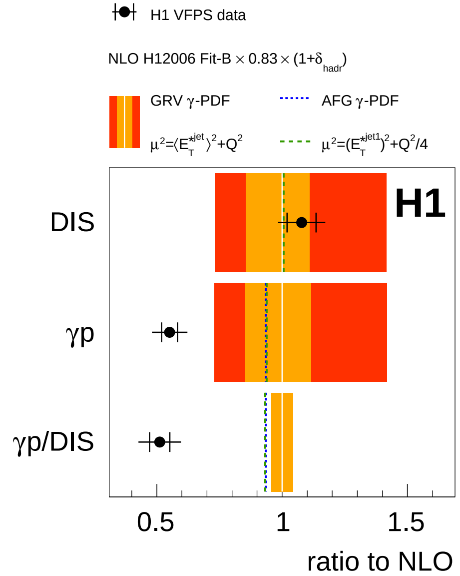
Data vs NLO: PHP cross sections

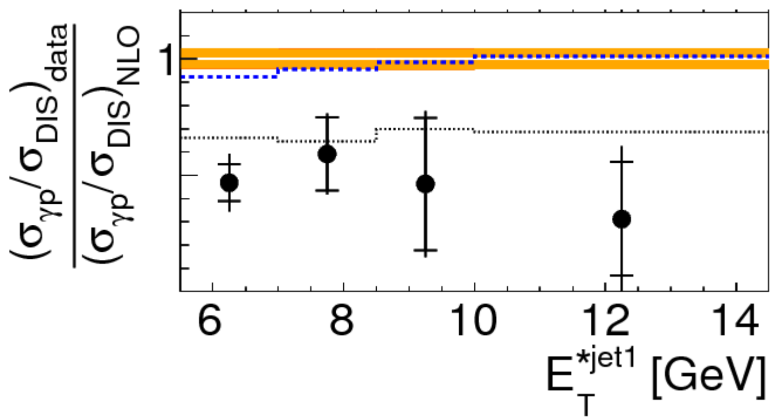


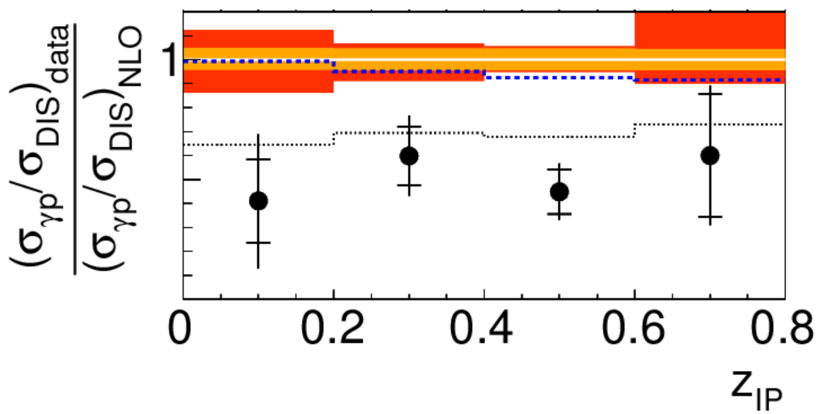
- FKS (Frixione *et al.*, verified against Klasen & Kramer)
- Data compatible with NLO predictions in shape (in particular no x_γ dep.)
- Normalisation is off by factor of ~ 2 (albeit large theory uncertainty)

VFPS Dijets: Ratio PHP to DIS









- Factorisation is broken in photoproduction: $\langle S^2 \rangle = 0.51 \pm 0.09$
- Independence on x_γ confirmed. No jet E_T dependence is observed.

Summary

- Diffractive dijet production in DIS studied with high statistics LRG sample.
- Single and double differential cross sections are measured. Good agreement with NLO calculation is observed.
- Extracted α_s provides important consistency test of pQCD picture for diffractive dijets in DIS.
- New measurement of diffractive dijets with a leading proton detected in H1 VFPS is performed simultaneously in DIS and PHP.
- DIS data well described by NLO QCD, while photoproduction is suppressed by a factor of $\langle S^2 \rangle \simeq 0.5$
- Earlier determinations of $\langle S^2 \rangle$ by H1 with LRG technique are confirmed. Suppression is not related to p dissociation. It is x_γ and E_T^{jet} independent.