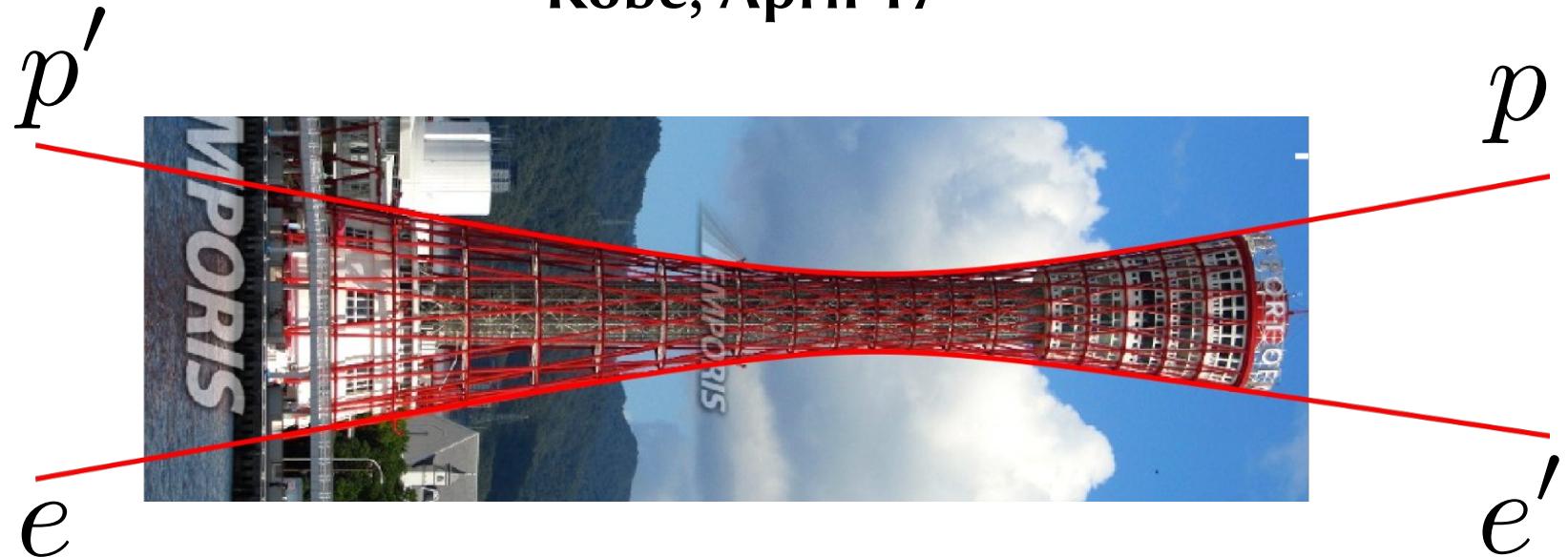


Diffractive dijet production in DIS compared to NNLO QCD predictions

Radek Žlebčík, Daniel Britzger,
Jan Niehues, James Currie,
Thomas Gehrmann, Alexander Huss

DIS 2018

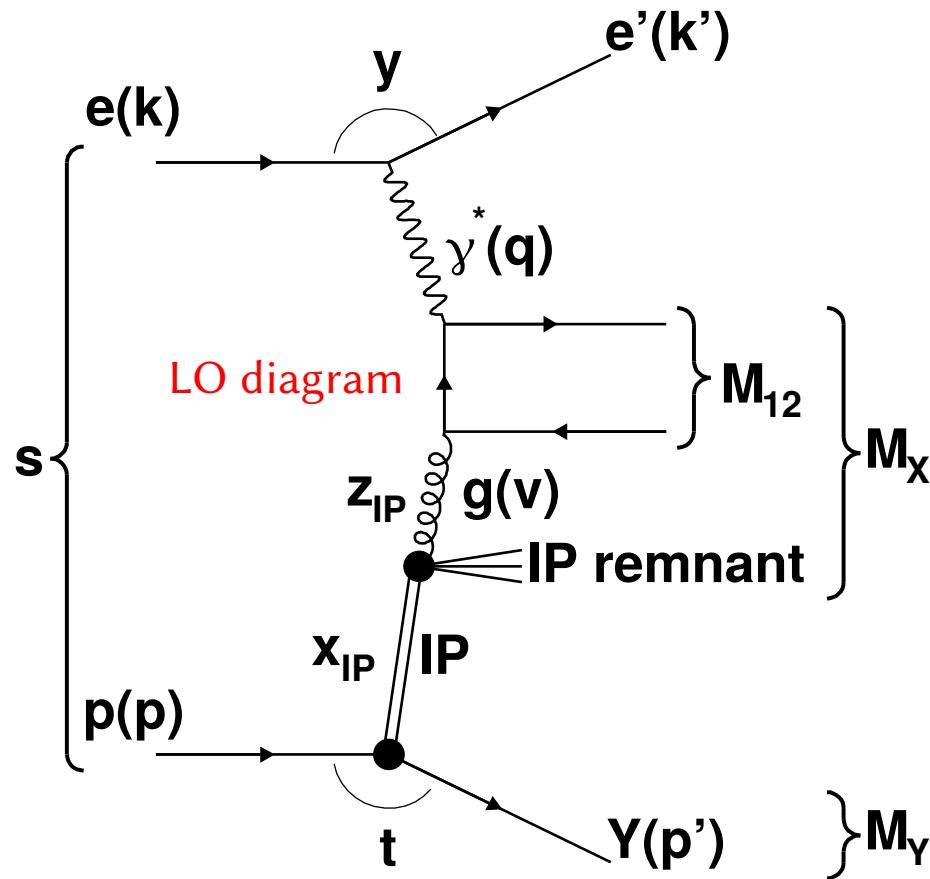
Kobe, April 17



DESY-18-054 submitted to Eur.Phys. J. C, 791 [arxiv:1804.05663]

Diffractive Dijet Production in ep

In diffractive events the beam proton stays intact or dissociates into low mass hadronic system Y



At HERA about 10% of low-x events are diffractive

DIS variables:

$$Q^2 = -(k - k')^2 \quad y = \frac{p \cdot q}{p \cdot k}$$

Dijet mass: M_{12}

Diffractive variables:

$$x_{IP} = 1 - \frac{E'_p}{E_p} \quad t = (p - p')^2$$

At LO: The momentum fraction entering the hard subprocess with respect to the diffractive exchange

$$z_{IP} = \frac{M_{12}^2 + Q^2}{M_X^2 + Q^2}$$

Collinear QCD factorization theorem in hard diffraction

- For diffractive events with a **hard scale** (e.g Q^2 or jets p_T)
- Factorization of the diffractive cross section into **process independent PDFs** and **partonic cross sections**

$$d\sigma(ep \rightarrow epX) = \sum_i f_i^D(x, Q^2, x_{IP}, t) \otimes d\sigma^{ie}(x, Q^2)$$

- For diffractive processes (including dijets) with Q^2 high enough factorization proven by Collins within perturbative QCD, for low Q^2 factorization breaking suggested

Factorization of Hard Processes in QCD

John C. Collins (IIT, Chicago & SUNY, Stony Brook), Davison E. Soper (Oregon U.),

George F. Sterman (SUNY, Stony Brook). May 30, 1989. 91 pp.

Published in **Adv.Ser.Direct.High Energy Phys. 5 (1989) 1-91**

ITP-SB-89-31

DOI: [10.1142/9789814503266_0001](https://doi.org/10.1142/9789814503266_0001)

e-Print: [hep-ph/0409313](https://arxiv.org/abs/hep-ph/0409313) | [PDF](#)

[References](#) | [BibTeX](#) | [LaTeX\(US\)](#) | [LaTeX\(EU\)](#) | [Harvmac](#) | [EndNote](#)

[ADS Abstract Service](#)

[Detailed record](#) - Cited by 812 records 500+

Proof of factorization for diffractive hard scattering

John C. Collins (Penn State U.). Sep 1997. 12 pp.

Published in **Phys.Rev. D57 (1998) 3051-3056**, Erratum: **Phys.Rev. D61 (2000) 019902**

PSU-TH-189

DOI: [10.1103/PhysRevD.57.3051](https://doi.org/10.1103/PhysRevD.57.3051), [10.1103/PhysRevD.61.019902](https://doi.org/10.1103/PhysRevD.61.019902)

e-Print: [hep-ph/9709499](https://arxiv.org/abs/hep-ph/9709499) | [PDF](#)

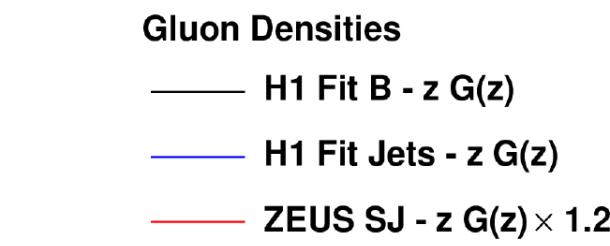
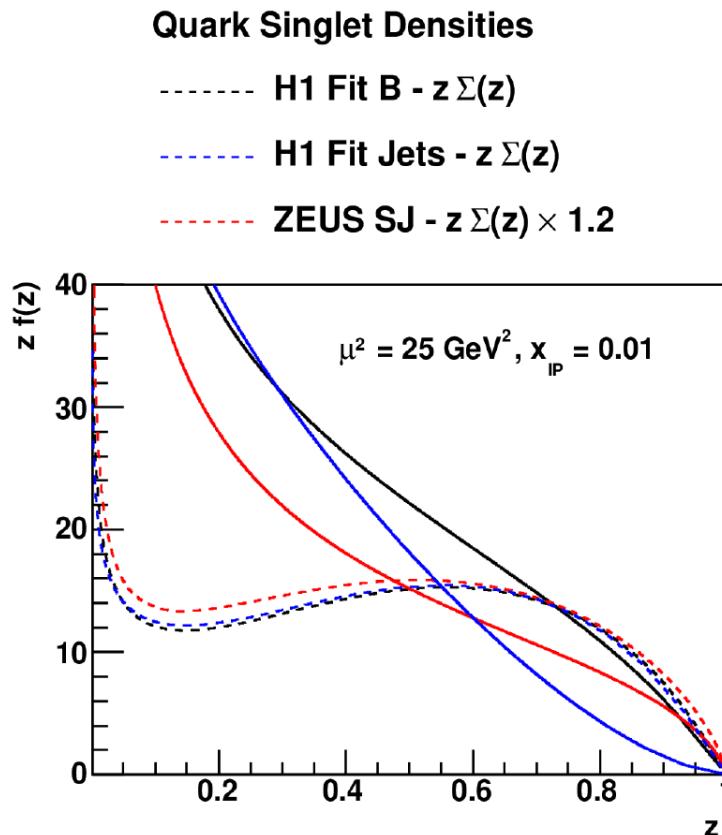
[References](#) | [BibTeX](#) | [LaTeX\(US\)](#) | [LaTeX\(EU\)](#) | [Harvmac](#) | [EndNote](#)

[ADS Abstract Service](#); [OSTI.gov Server](#)

[Detailed record](#) - Cited by 404 records 250+

NLO DPDFs

- DPDF sets differ mainly in gluon component which is weakly constrain from inclusive diffractive data
- For gluon dominated diffractive dijet production we have sizable DPDF uncertainty
- DPDFs obey standard DGLAP evolution equation



Fits of inclusive data
H1 2006 Fit A
H1 2006 Fit B
MRW DPDF

Combined inclusive + dijets data fits
H1 2007 Fit Jets
ZEUS 2009 Fit SJ

70% of
diffractive
exchange
momentum
carried by
gluons

NNLO QCD Predictions

- **NNLOJET** program based on antenna subtraction

*J. Currie, T. Gehrmann, A. Huss and J. Niehues,
JHEP 07 (2017) 018, [1703.05977]*

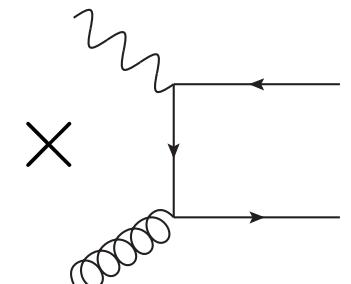
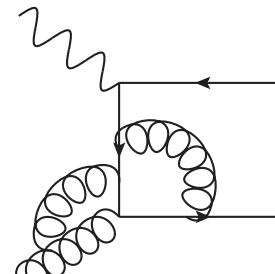
$$d\sigma(ep \rightarrow epX) = \sum_{i,n} d\sigma^{ie(n)}(x, Q^2) \otimes \alpha_S^n \otimes f_i^D(x, Q^2, x_{IP}, t)$$

Cookbook

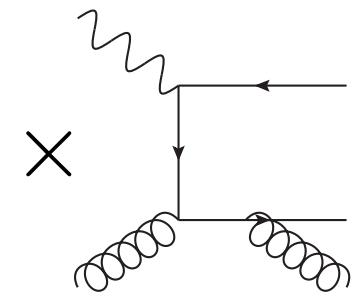
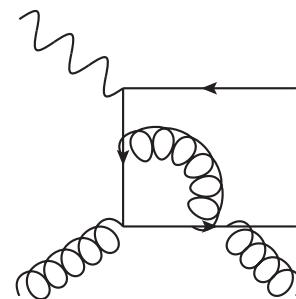
- 1) The **matrix element** tables precalculated by **NNLOJET** program ($\sim 1M$ CPU hours)
- 2) Then convoluted with **DPDFs** and α_S using **fastNLO** ($< 1s$)

✓ The NLO 2jet and 3jet contributions verified against Sherpa and NLOJET++

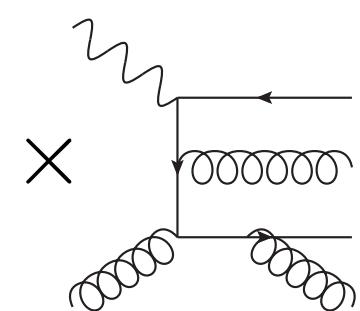
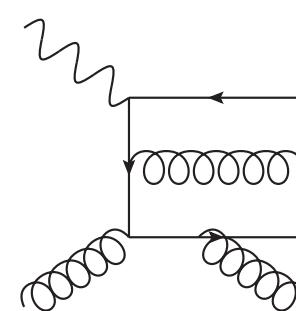
virtual-virtual



real-virtual

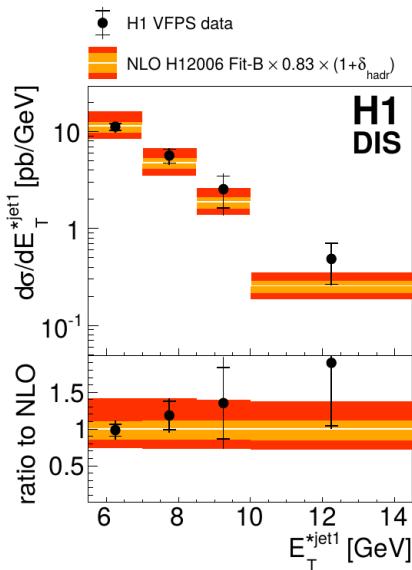


real-real

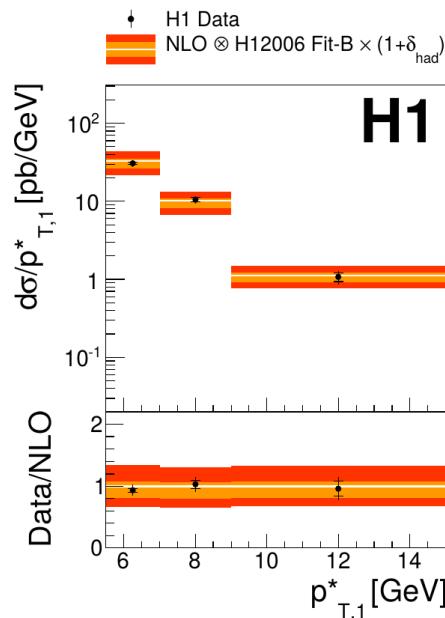


The HERA DDIS jets Legacy

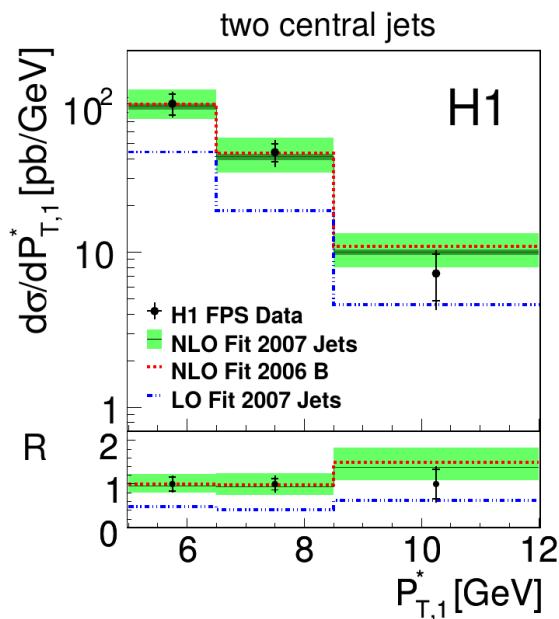
JHEP 1505 (2015) 056



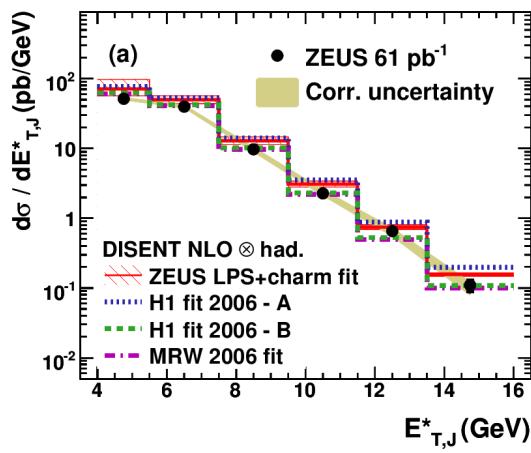
JHEP 1503 (2015) 092



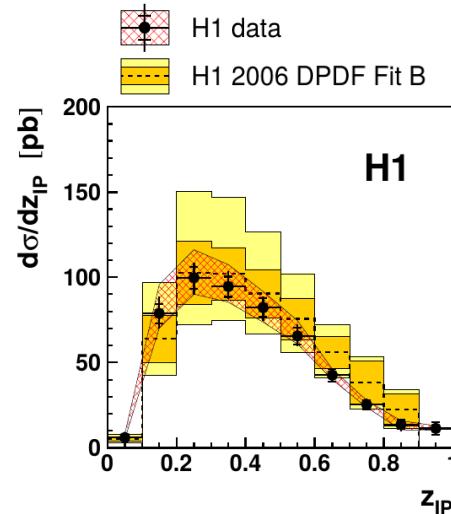
Eur.Phys.J.C72 (2012) 1970



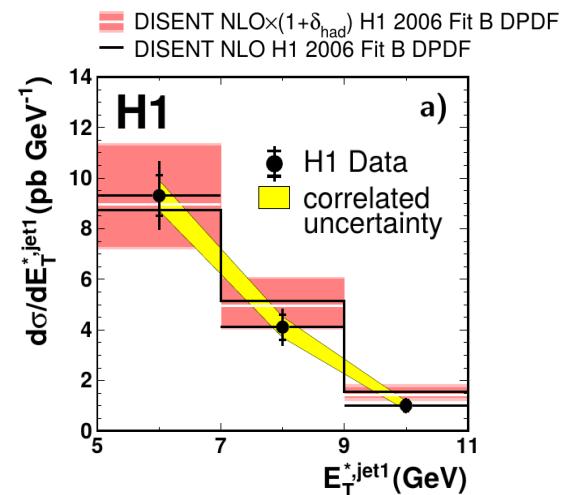
Eur. Phys. J. C 52 (2007) 813-832



JHEP 0710:042,2007



Eur.Phys.J.C 51 (2007) 549



The DIS dijets measurements

- 5times e+p 27.6 GeV + 920 GeV
- 1times e+p 27.5 GeV + 820 GeV
- 4times Large rapidity gap selection (LRG)
- 2times Proton spectrometer (FPS, VFPS)



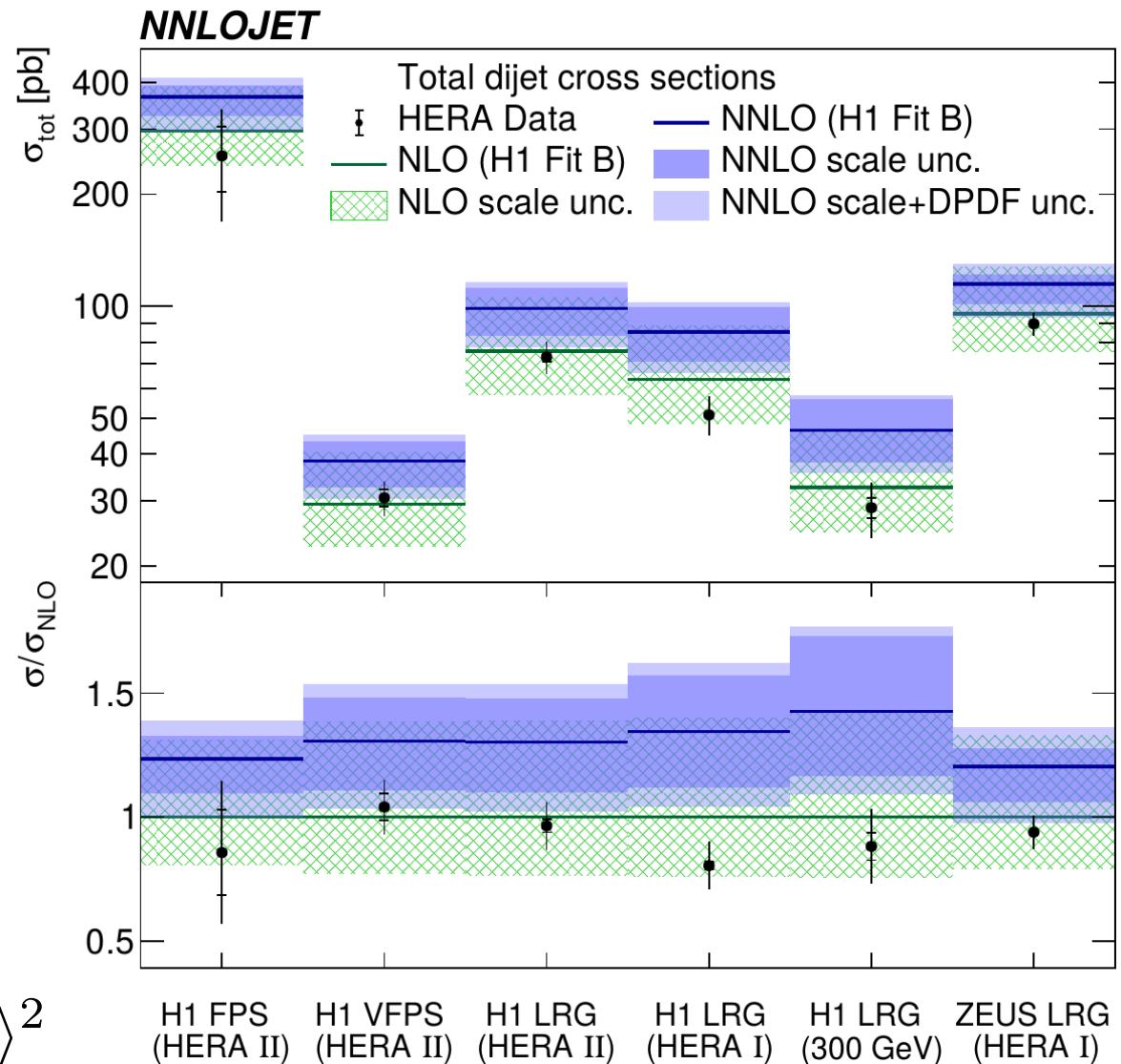
H1 LRG HERA II Phase Space
$4 < Q^2 < 100 \text{ GeV}^2$
$0.1 < y < 0.7$
$x_P < 0.03$
$ t < 1 \text{ GeV}^2$
$M_Y < 1.6 \text{ GeV}$
$p_{T,1}^* > 5.5 \text{ GeV}$
$p_{T,2}^* > 4.0 \text{ GeV}$
$-1 < \eta_{1,2}^{\text{lab}} < 2$

All HERA analyses using k_T -jet algorithm ($R=1$) and asymmetric jet p_T cuts

Total Cross Sections - NLO vs NNLO

- For NNLO the inner bar represents the scale uncertainty, the outer includes DPDF uncertainties
- Total cross sections well described by NLO
- NNLO predictions systematically overestimate the data (NNLO/NLO phase space dependent)

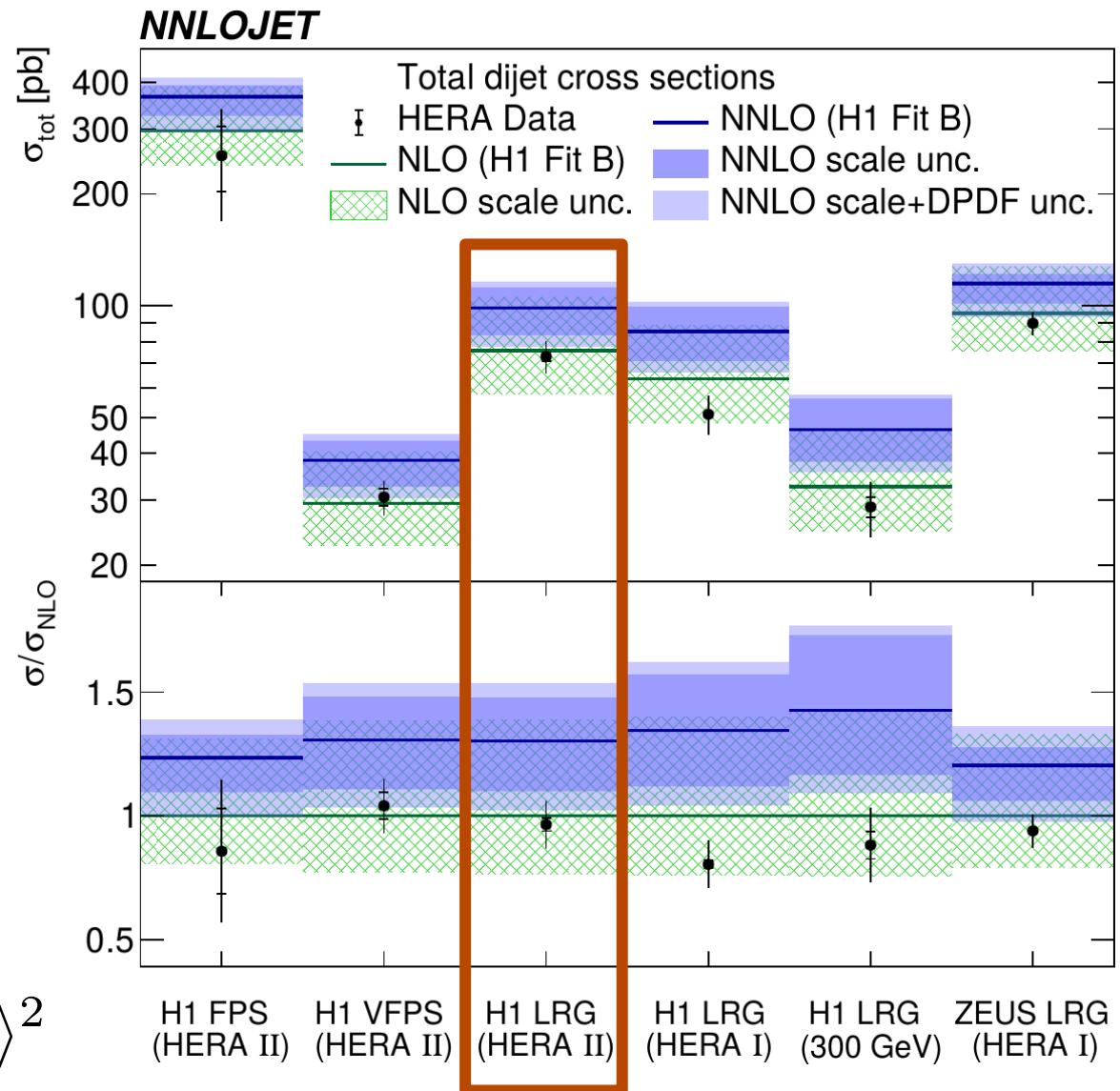
$$\mu_R^2 = \mu_F^2 = Q^2 + \langle p_T^{*\text{jets}} \rangle^2$$



Total Cross Sections - NLO vs NNLO

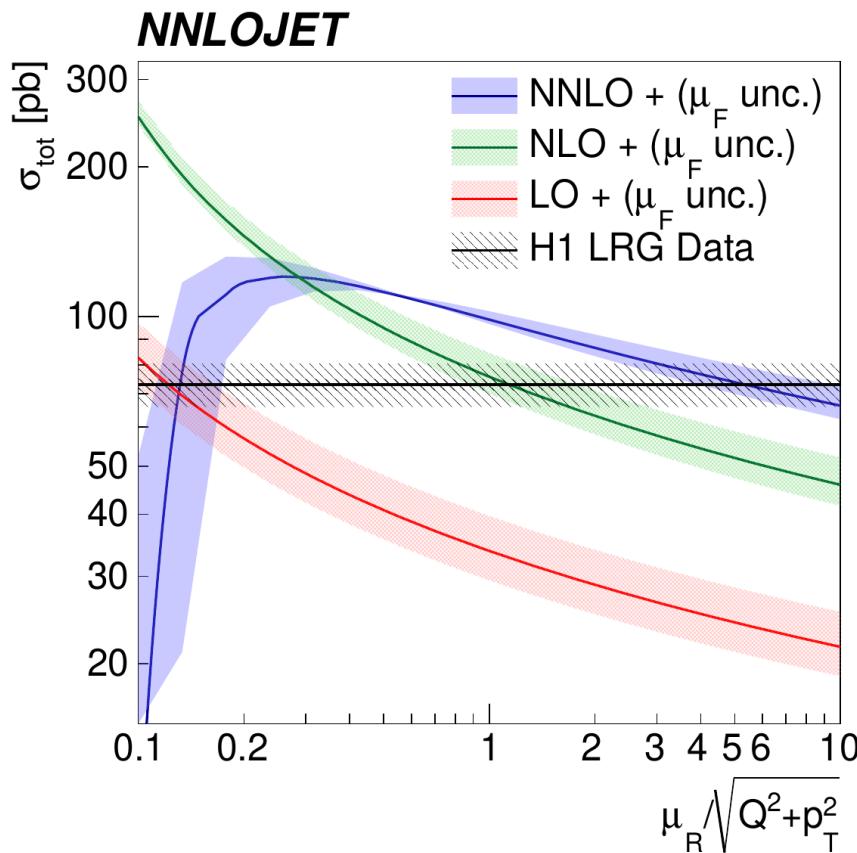
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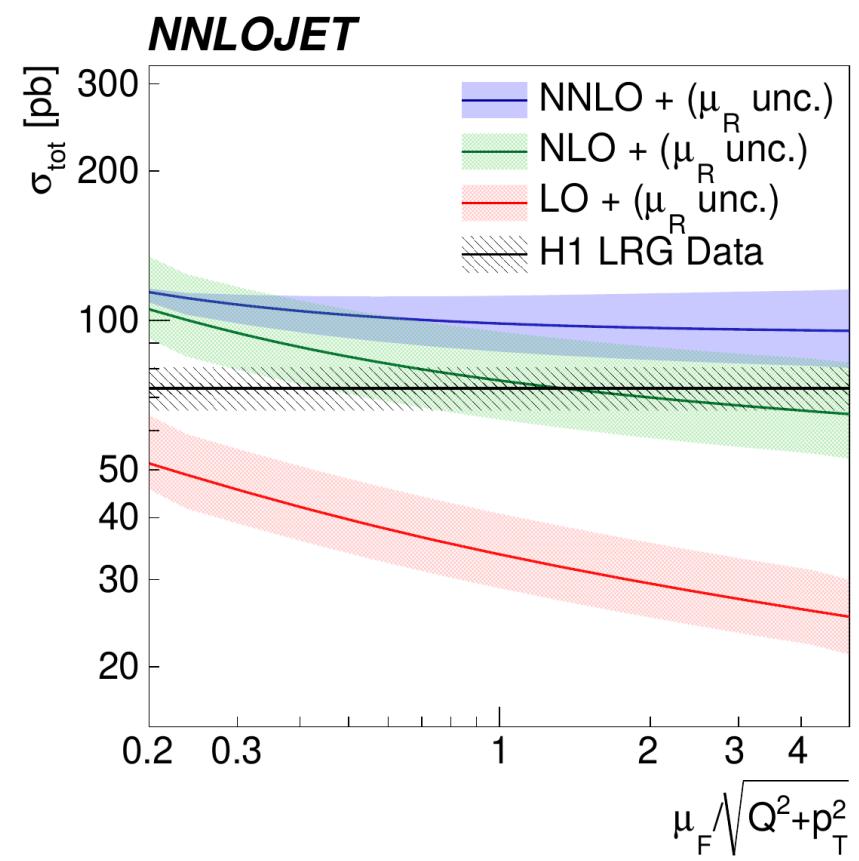


Total Cross Sections - Scale dependence

Renormalization scale dependence



Factorization scale dependence

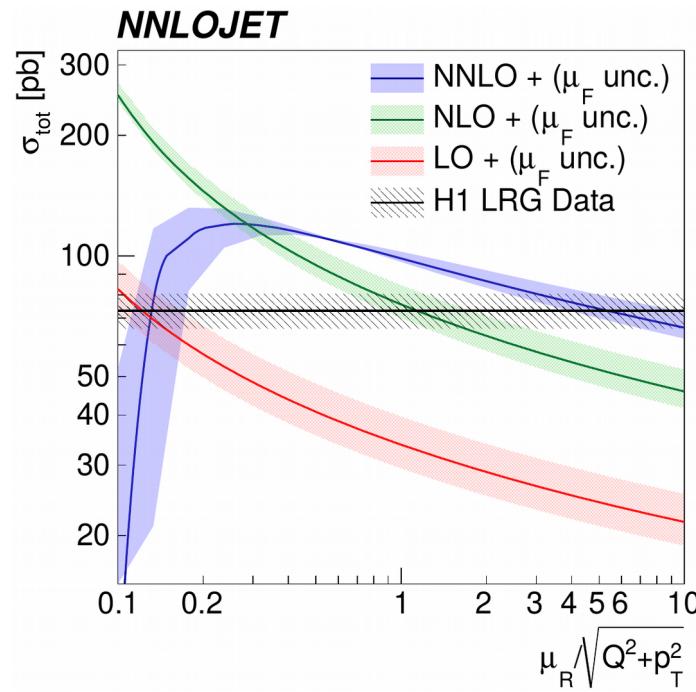


- Comparable NLO and LO renormalization scale dependences (characteristic for gluon-dominated processes)
- NNLO has smaller renormalization scale dependence

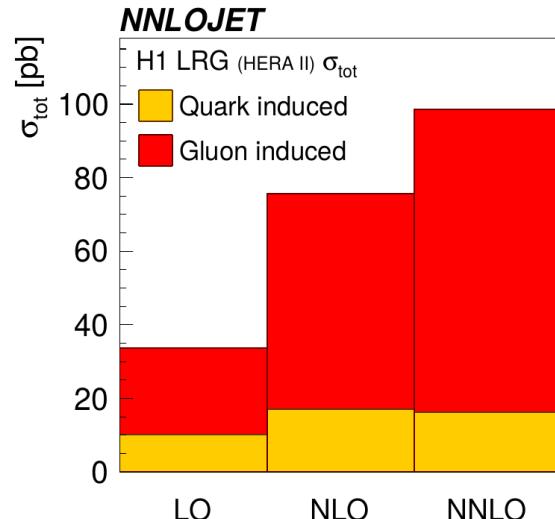
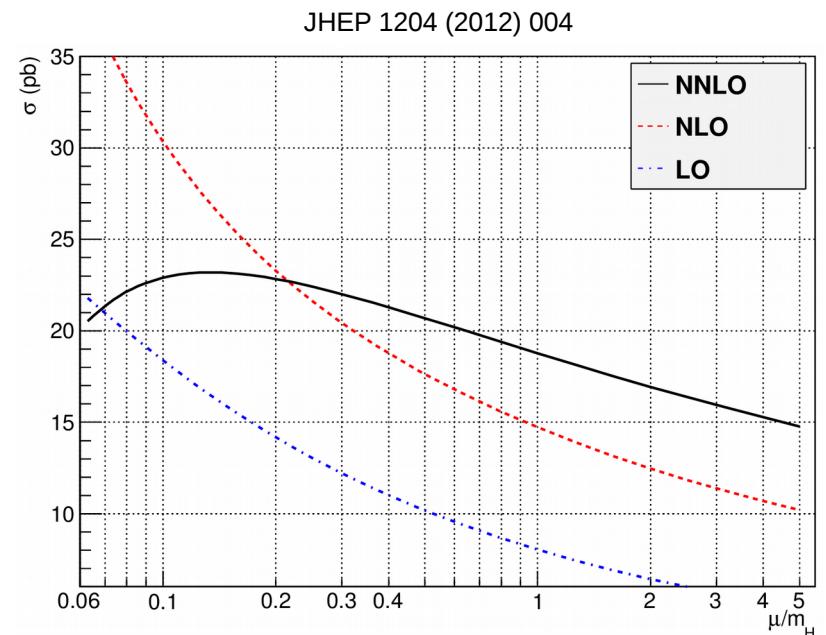
- Factorization scale dependence lower with every order

Total Cross Sections - Scale dependence

Jets in DDIS ($\sqrt{s} = 320$ GeV)



Higgs production in pp ($\sqrt{s} = 8$ TeV)



- The gluon-DPDF induced cross section rises gradually with order
- The quark-Induced cross section stagnates at NLO
- At NNLO 84% of the cross section is from gluon DPDF

Total Cross Sections - Scale dependence

- Four functional form of scales studied, everytime assumed:

$$\mu^2 = \mu_R^2 = \mu_F^2$$

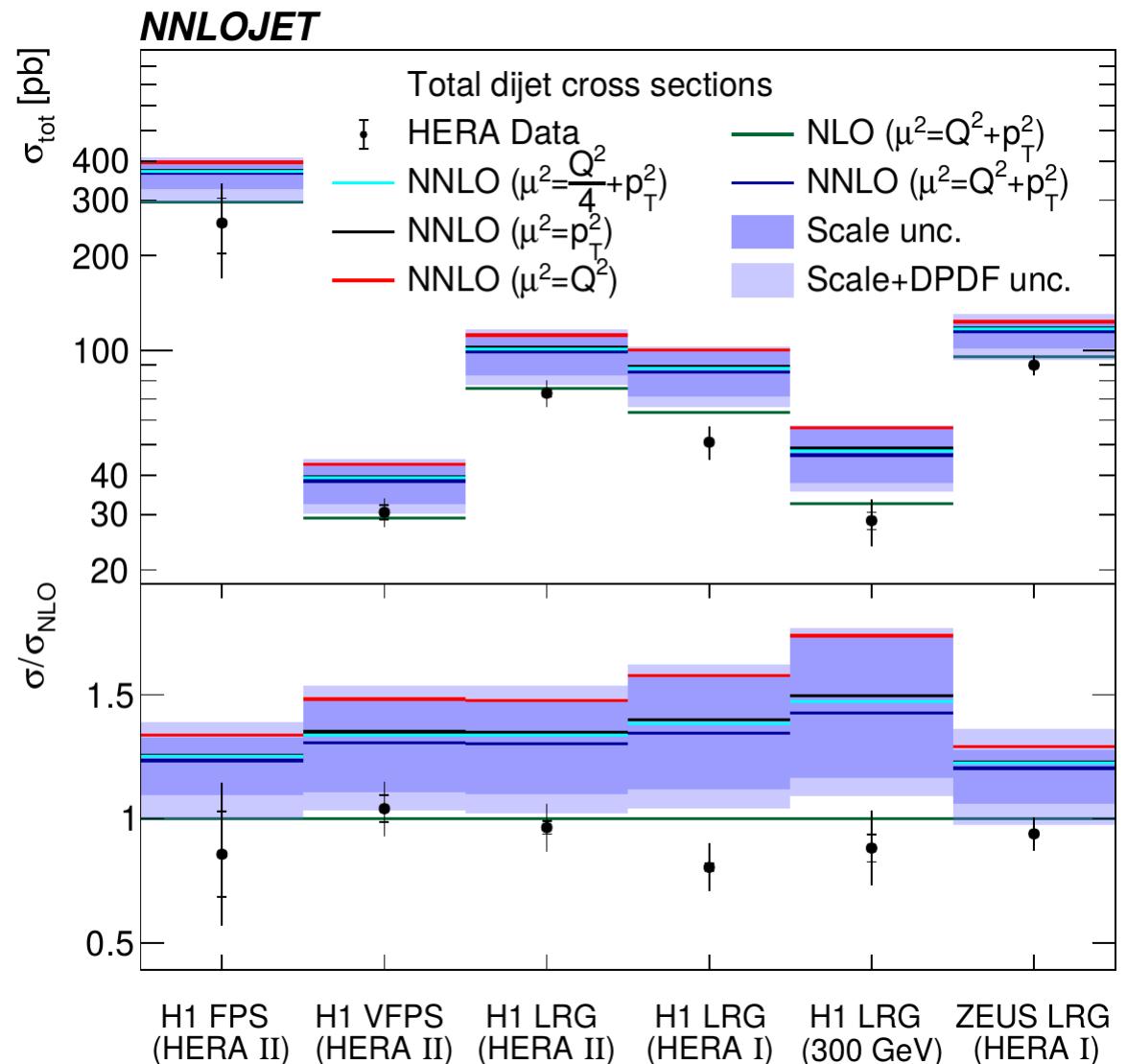
- Alternative parameterizations:

$$\mu^2 = Q^2 + \langle p_T^{*j\text{ets}} \rangle^2$$

$$\mu^2 = \frac{Q^2}{4} + \langle p_T^{*j\text{ets}} \rangle^2$$

$$\mu^2 = \langle p_T^{*j\text{ets}} \rangle^2$$

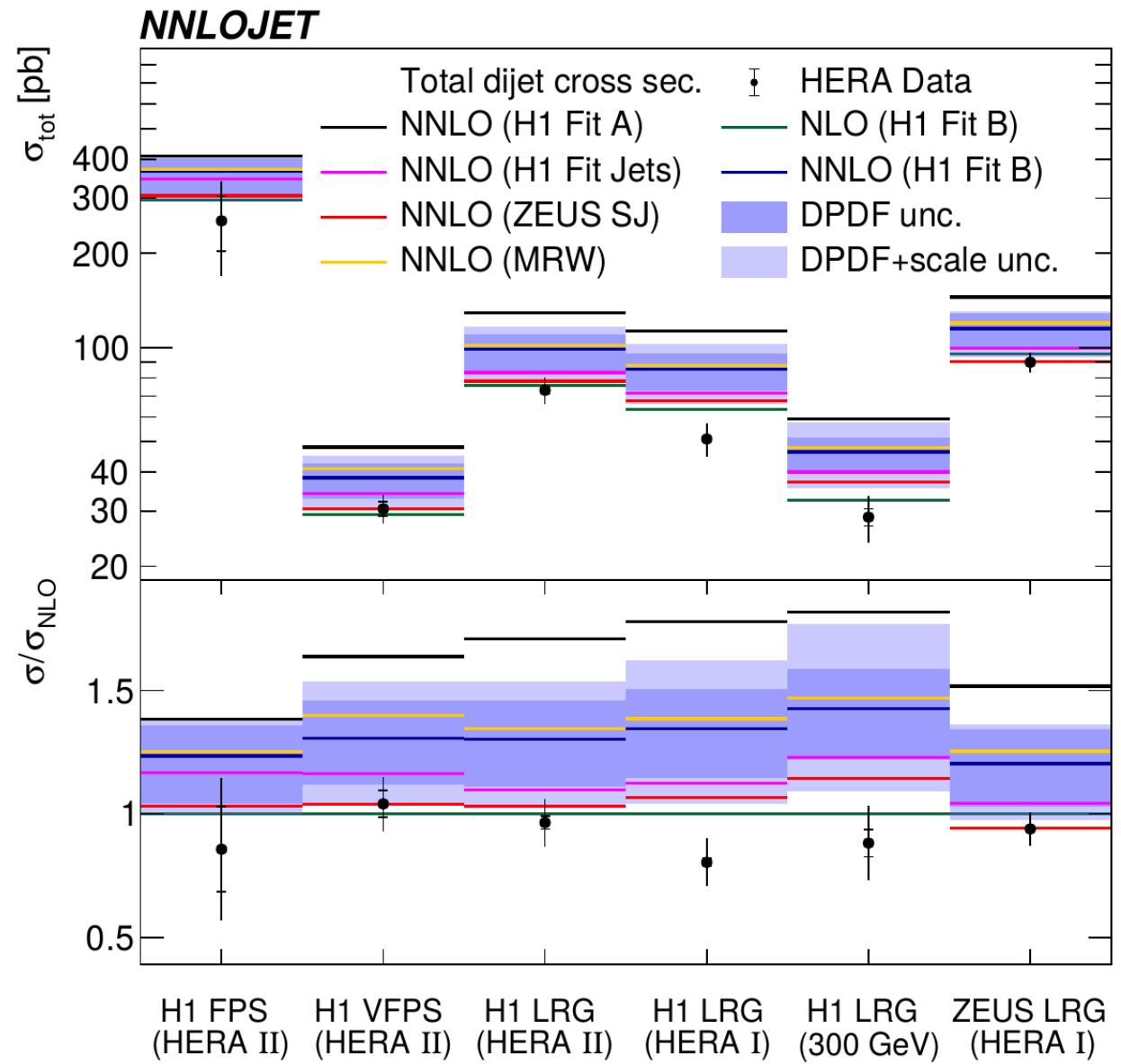
$$\mu^2 = Q^2$$



The p_T is the dominant term, if removed
the cross sections substantially higher

Total Cross Sections - DPDF dependence

- Inner bar represents the DPDF uncertainty, the outer includes scale uncertainties
- Combined fits of inclusive + dijet data
H1 Fitj Jets
ZEUS SJ
- best performance
- Inclusive data fits
H1 Fit A
H1 Fit B
- very different although for inclusive data had similar chi2
MRW – like H1 Fit B



Studied differential distributions

- In total 39 single- and double-differential variables analyses

Histogram	H1 FPS (HERA II)	H1 VFPS (HERA II)	H1 LRG (HERA II)	H1 LRG (HERA I)	H1 LRG (300 GeV)	ZEUS LRG (HERA I)
Q^2	✓	✓	✓		✓	✓
$y [W]^*$	✓	✓	✓	✓	*	*
$p_T^{*,\text{jet}1} [p_T^{*,\text{jet}}]^*$	✓	✓	✓	✓	✓	*
$\langle p_T \rangle$			✓			
$p_T^{*,\text{jet}2}$			✓			
$\langle \eta_{\text{lab}}^{\text{jet}} \rangle [\eta_{\text{jet}}^*]^*$		✓			✓	*
$\Delta\eta_{\text{lab}}^{\text{jet}} [\Delta\eta^*]^*$	*	✓	*	*	*	
M_X		✓				✓
x_{IP}	✓	✓	✓	✓	✓	
z_{IP}^{obs}	✓	✓	✓	✓		✓
$(Q^2; p_T^{*,\text{jet}1})$			✓			
$(Q^2; z_{IP}^{\text{obs}})$			✓			✓
$(p_T^{*,\text{jet}1}; z_{IP}^{\text{obs}})$						✓

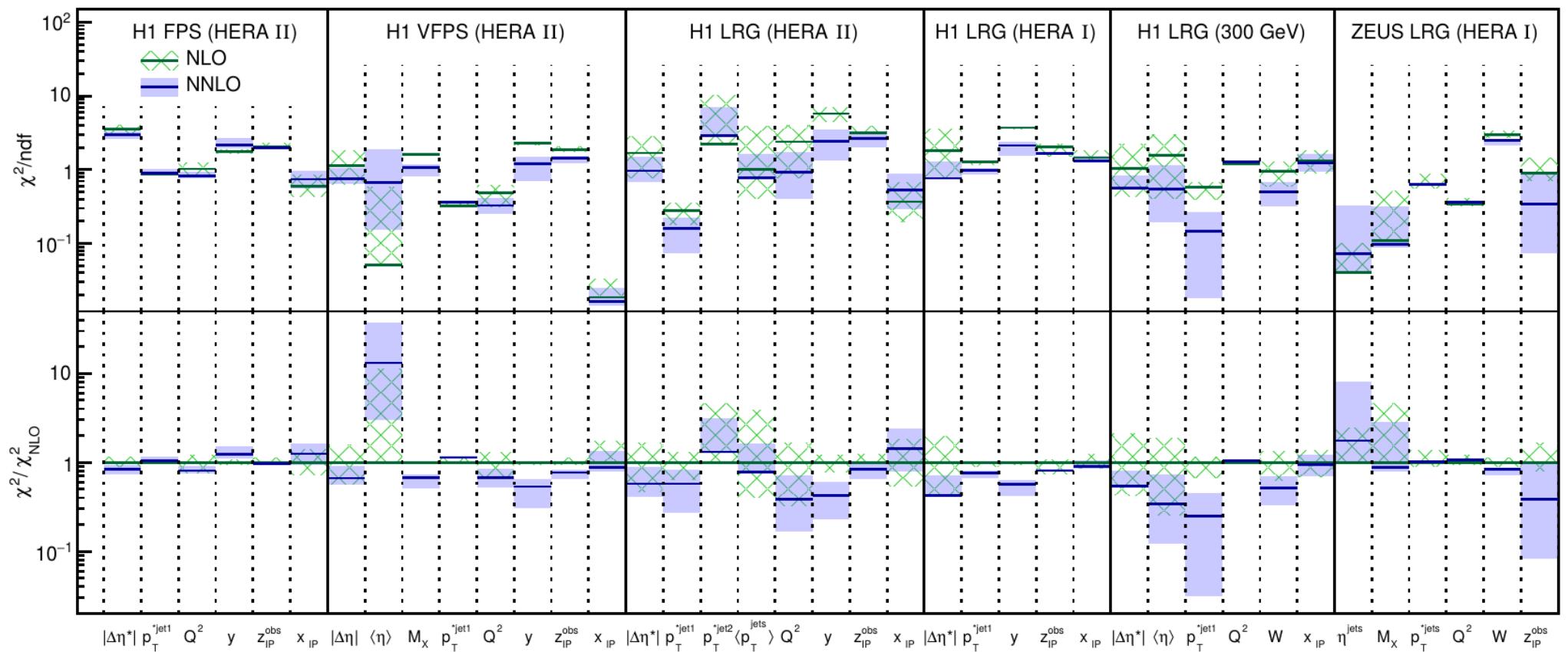
Chi² comparison

- The NNLO typically describe shapes better (improvement seen for all studied DPDFs)

The normalization-independent definition

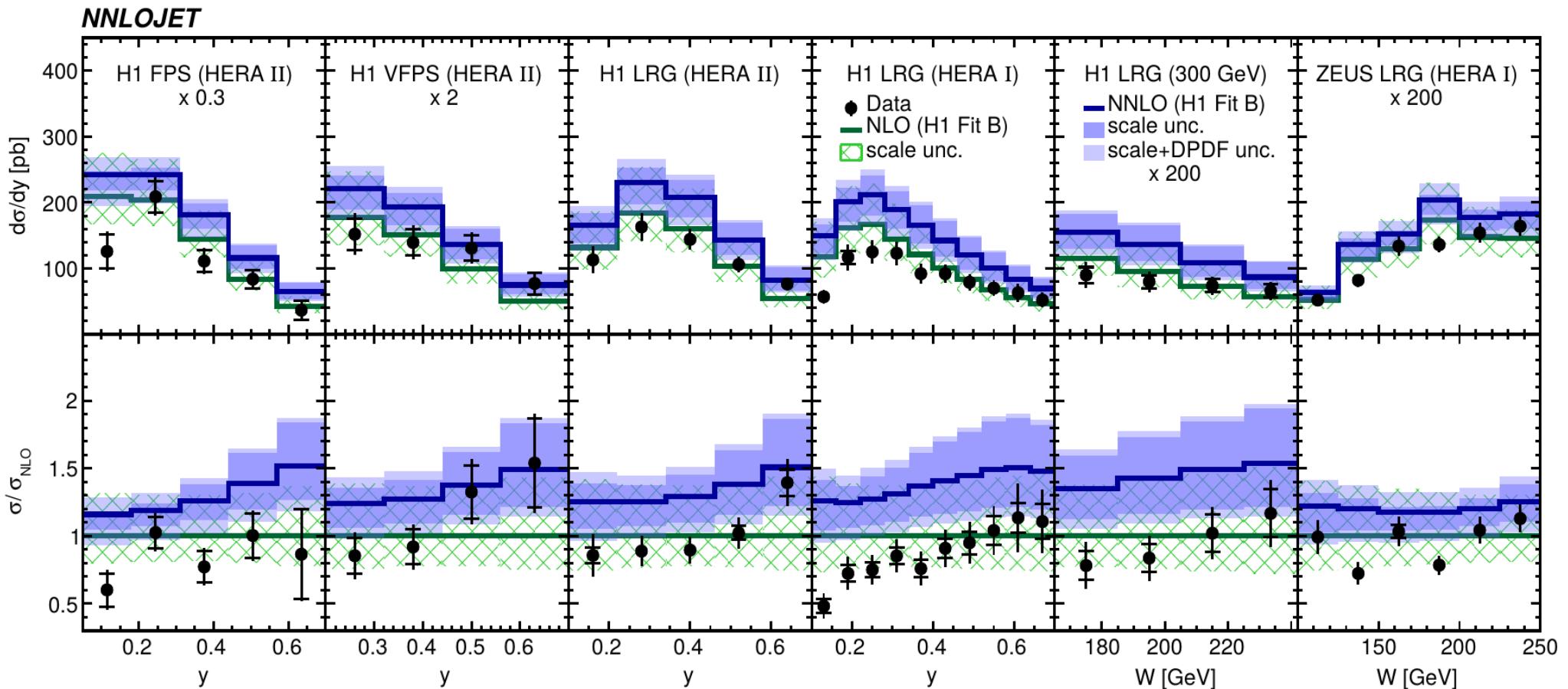
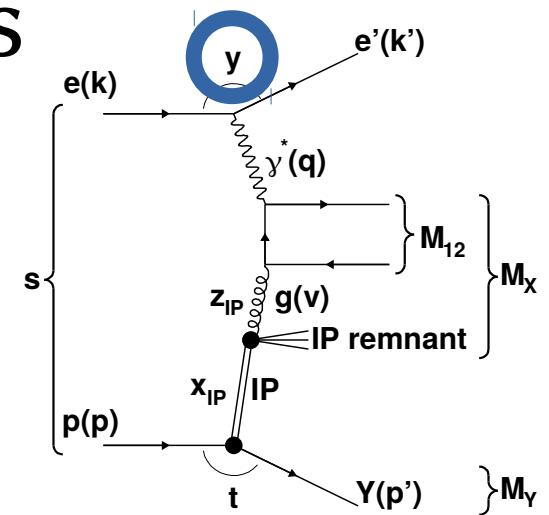
$$\chi^2 = \min_K \sum_{i,j} \log \frac{\sigma_i^{\text{Data}}}{K\sigma_i^{(N)\text{NLO}}} (V^{-1})_{ij} \log \frac{\sigma_j^{\text{Data}}}{K\sigma_j^{(N)\text{NLO}}}$$

NNLOJET



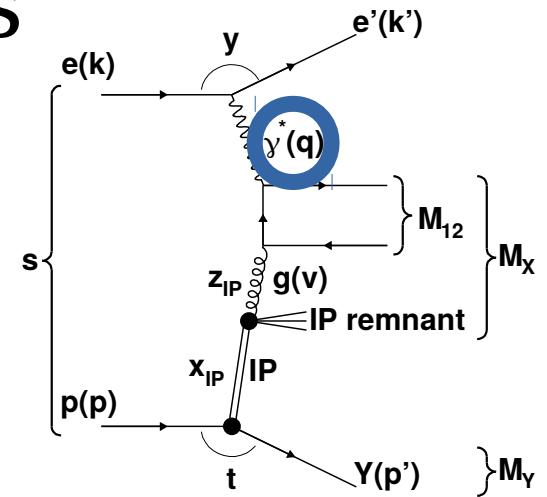
Differential x-sections

- The same or similar distributions from various analyses grouped into one plot, as shown below.
- For inelasticity y NNLO higher for higher y , similar trend in data, note $W = \sqrt{ys}$

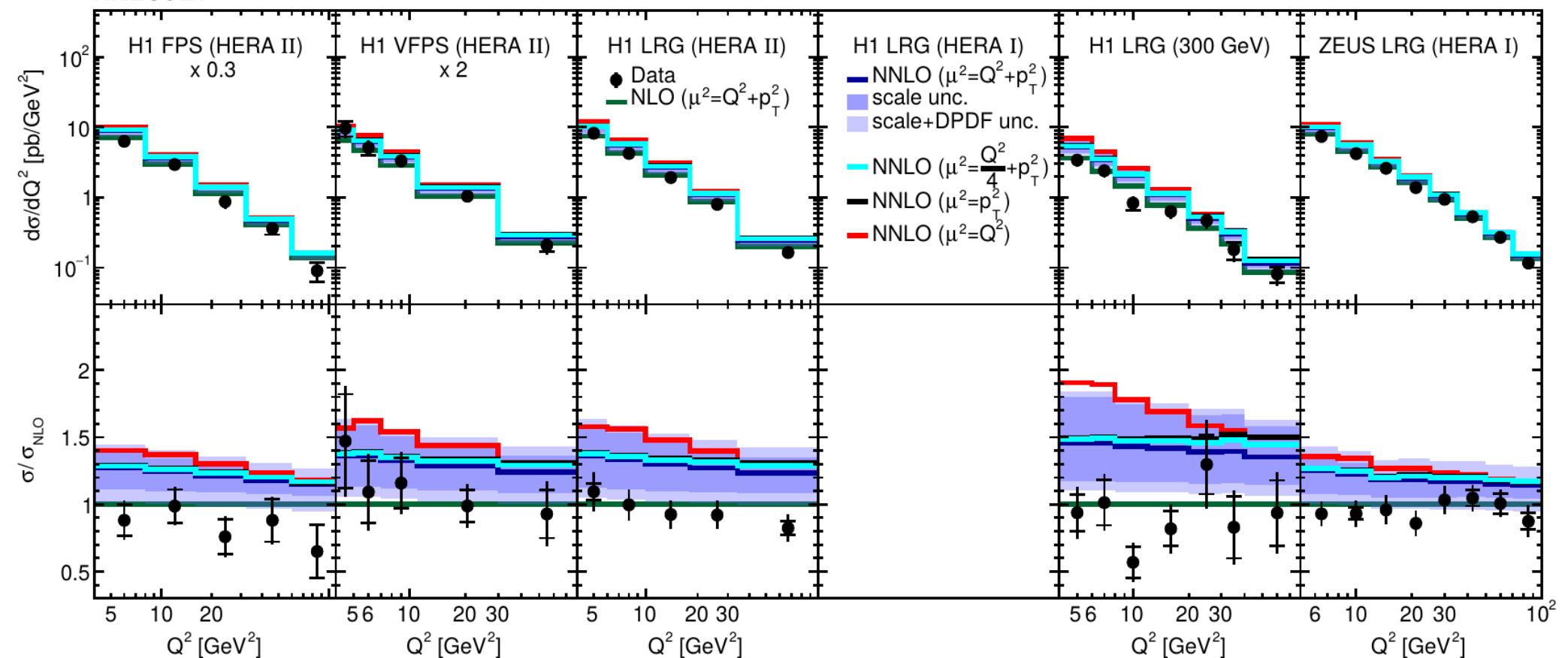


Differential x-sections

- The scale with Q^2 term only predict steeper Q^2 distribution
- Only small difference between other scale prescriptions
- No systematic trend in data



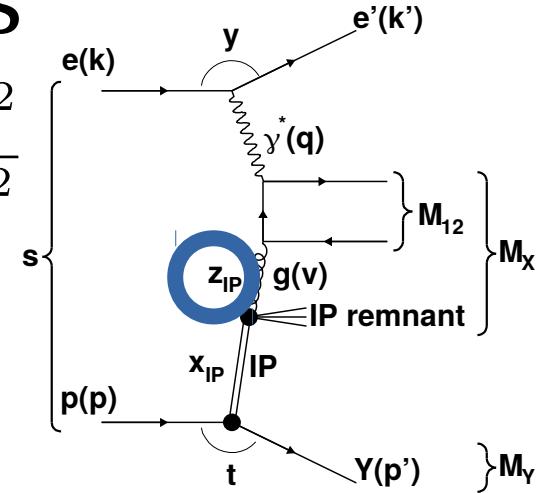
NNLOJET



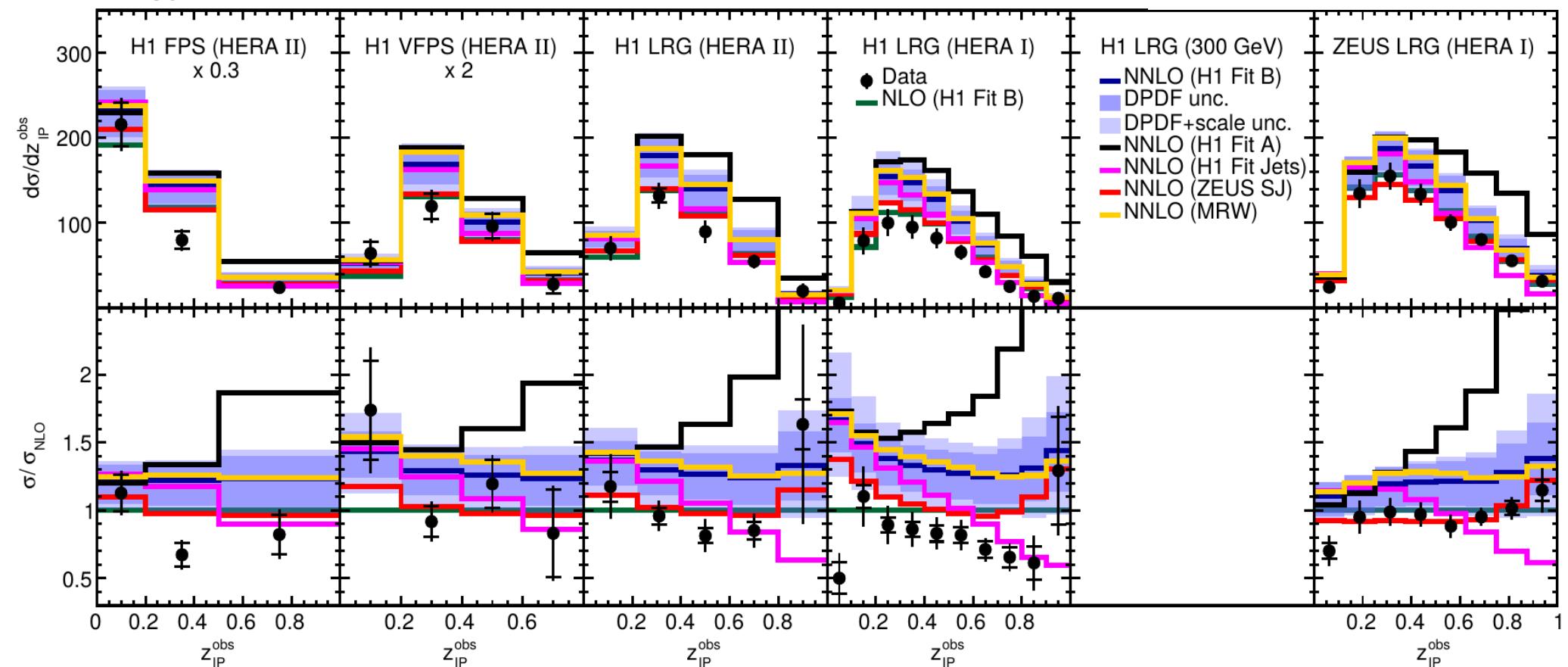
Differential x-sections

- Most sensitive variable to the partonic structure of the diffractive exchange (to DPDFs)
- NNLO predict an increase in the last bin for LRG analyses which is really seen in data

$$z_{IP} = \frac{M_{12}^2 + Q^2}{M_X^2 + Q^2}$$

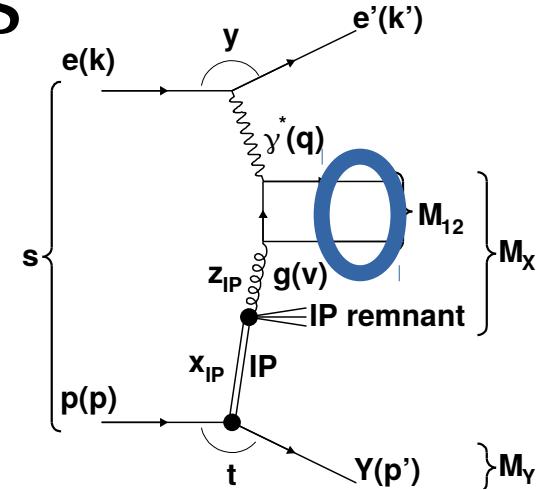


NNLOJET

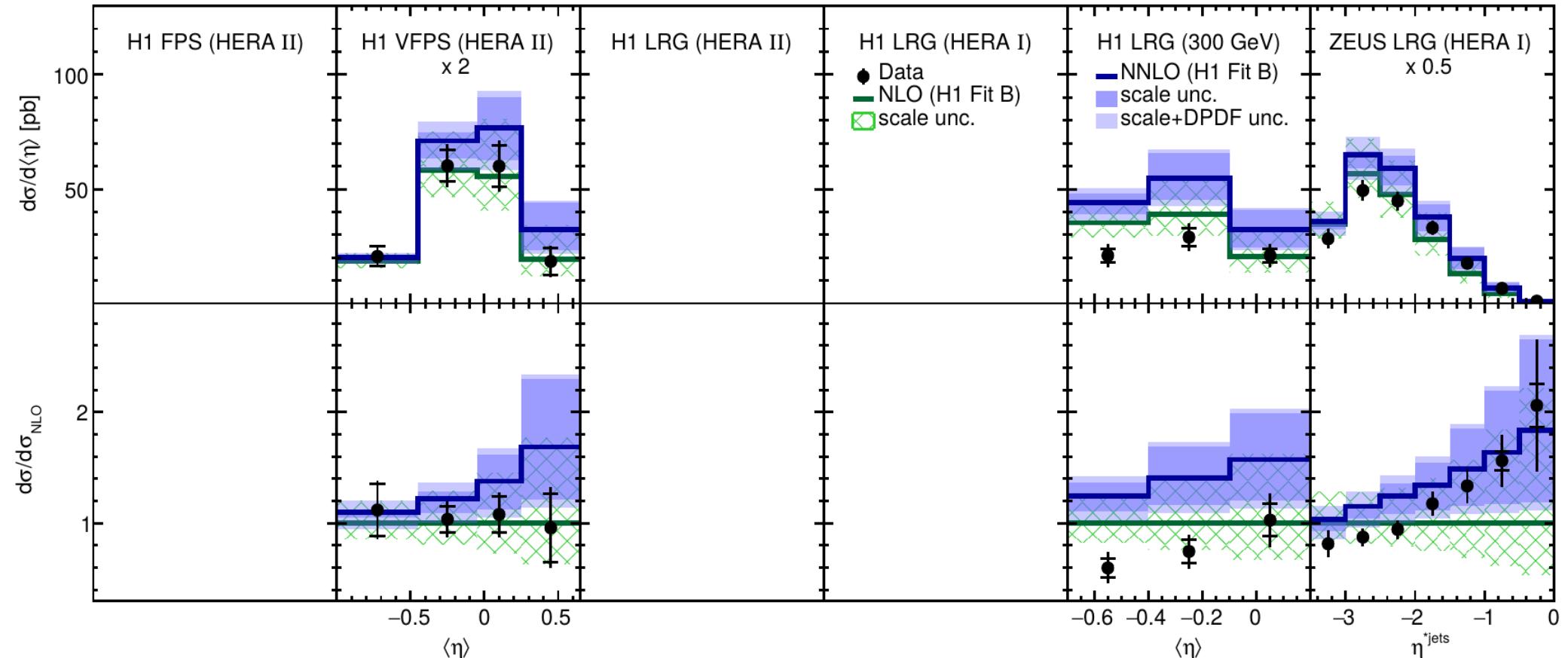


Differential x-sections

- NNLO predicts more jets in the forward (=proton) direction
- The inclusive jet $\eta^{*j\text{ets}}$ shows the biggest observed difference between NLO and NNLO - **factor 2!**



NNLOJET



Summary

- **NNLO QCD** predictions for jets in diffractive DIS
- Differential distributions for 39 single and double-differential observables calculated (from 6 analyses)
- The NNLO cross sections 20%-40% higher than NLO
- Jet based DPDFs provide better agreement with data

Backup

Data Set	\mathcal{L} [pb $^{-1}$]	DIS range	Dijet range	Diffractive range
H1 FPS (HERA II) [53]	156.6 (581ev)	$4 < Q^2 < 110 \text{ GeV}^2$ $0.05 < y < 0.7$	$p_T^{*,\text{jet}1} > 5 \text{ GeV}$ $p_T^{*,\text{jet}2} > 4.0 \text{ GeV}$ $-1 < \eta_{\text{lab}}^{\text{jet}} < 2.5$	$x_{IP} < 0.1$ $ t < 1 \text{ GeV}^2$ $M_Y = m_P$
H1 VFPS (HERA II) [54]	50 (550ev)	$4 < Q^2 < 80 \text{ GeV}^2$ $0.2 < y < 0.7$	$p_T^{*,\text{jet}1} > 5.5 \text{ GeV}$ $p_T^{*,\text{jet}2} > 4.0 \text{ GeV}$ $-1 < \eta_{\text{lab}}^{\text{jet}} < 2.5$	$0.010 < x_{IP} < 0.024$ $ t < 0.6 \text{ GeV}^2$ $M_Y = m_P$
H1 LRG (HERA II) [3]	290 (~15000ev)	$4 < Q^2 < 100 \text{ GeV}^2$ $0.1 < y < 0.7$	$p_T^{*,\text{jet}1} > 5.5 \text{ GeV}$ $p_T^{*,\text{jet}2} > 4.0 \text{ GeV}$ $-1 < \eta_{\text{lab}}^{\text{jet}} < 2$	$x_{IP} < 0.03$ $ t < 1 \text{ GeV}^2$ $M_Y < 1.6 \text{ GeV}$
H1 LRG (HERA I) [37]	51.5 (2723ev)	$4 < Q^2 < 80 \text{ GeV}^2$ $0.1 < y < 0.7$	$p_T^{*,\text{jet}1} > 5.5 \text{ GeV}$ $p_T^{*,\text{jet}2} > 4.0 \text{ GeV}$ $-3 < \eta^{*\text{jet}} < 0$	$x_{IP} < 0.03$ $ t < 1 \text{ GeV}^2$ $M_Y < 1.6 \text{ GeV}$
H1 LRG (300 GeV) [55]	18 (322ev)	$4 < Q^2 < 80 \text{ GeV}^2$ $165 < W < 242 \text{ GeV}$ $(0.30 < y < 0.65)$	$p_T^{*,\text{jet}1} > 5 \text{ GeV}$ $p_T^{*,\text{jet}2} > 4.0 \text{ GeV}$ $-1 < \eta_{\text{lab}}^{\text{jet}} < 2$ $-3 < \eta^{*\text{jet}} < 0$	$x_{IP} < 0.03$ $ t < 1 \text{ GeV}^2$ $M_Y < 1.6 \text{ GeV}$
ZEUS LRG (HERA I) [56]	61 (5539ev)	$5 < Q^2 < 100 \text{ GeV}^2$ $100 < W < 250 \text{ GeV}$ $(0.10 < y < 0.62)$	$p_T^{*,\text{jet}1} > 5 \text{ GeV}$ $p_T^{*,\text{jet}2} > 4.0 \text{ GeV}$ $-3.5 < \eta^{*\text{jet}} < 0$	$x_{IP} < 0.03$ $ t < 1 \text{ GeV}^2$ $M_Y = m_P$