Diffractive dijet production in DIS compared to NNLO QCD predictions

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QCD – Old Challenges and New Opportunities

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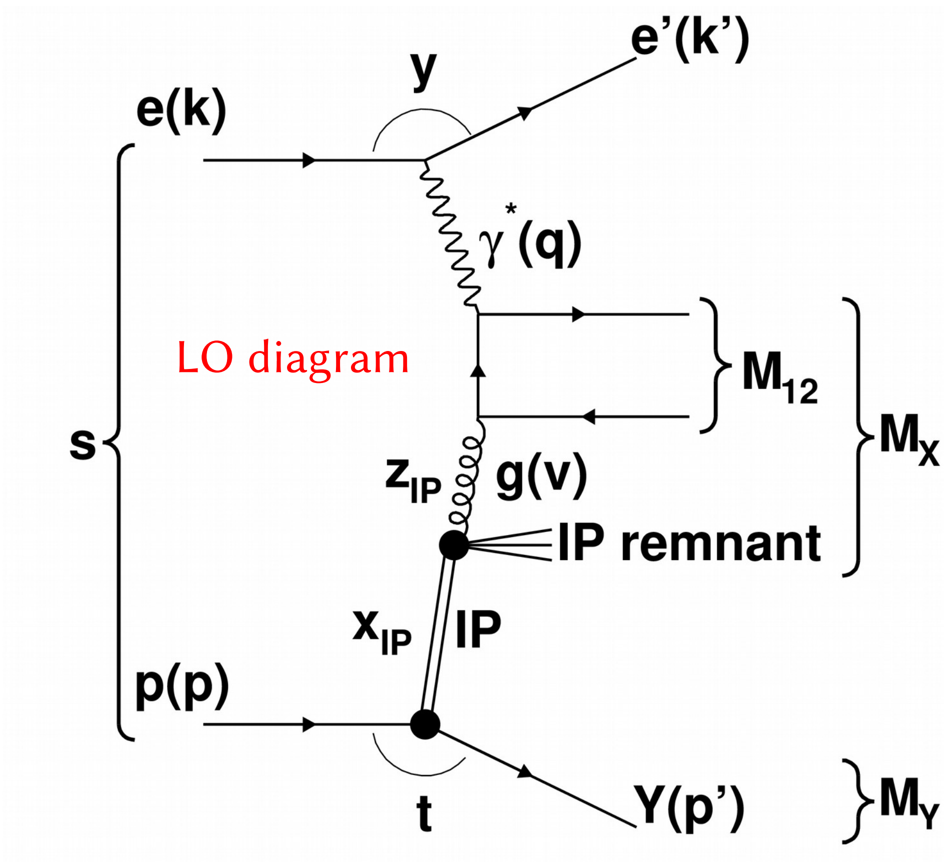
Diffractive Dijet Production in ep

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



DIS variables:

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

Dijet mass: M_{12}

Diffractive variables:

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

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

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

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

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 DPDFs and partonic cross sections

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

- 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
e-Print: hep-ph/0409313 | PDF
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
ADS Abstract Service
Detailed record - Cited by 716 records 500+

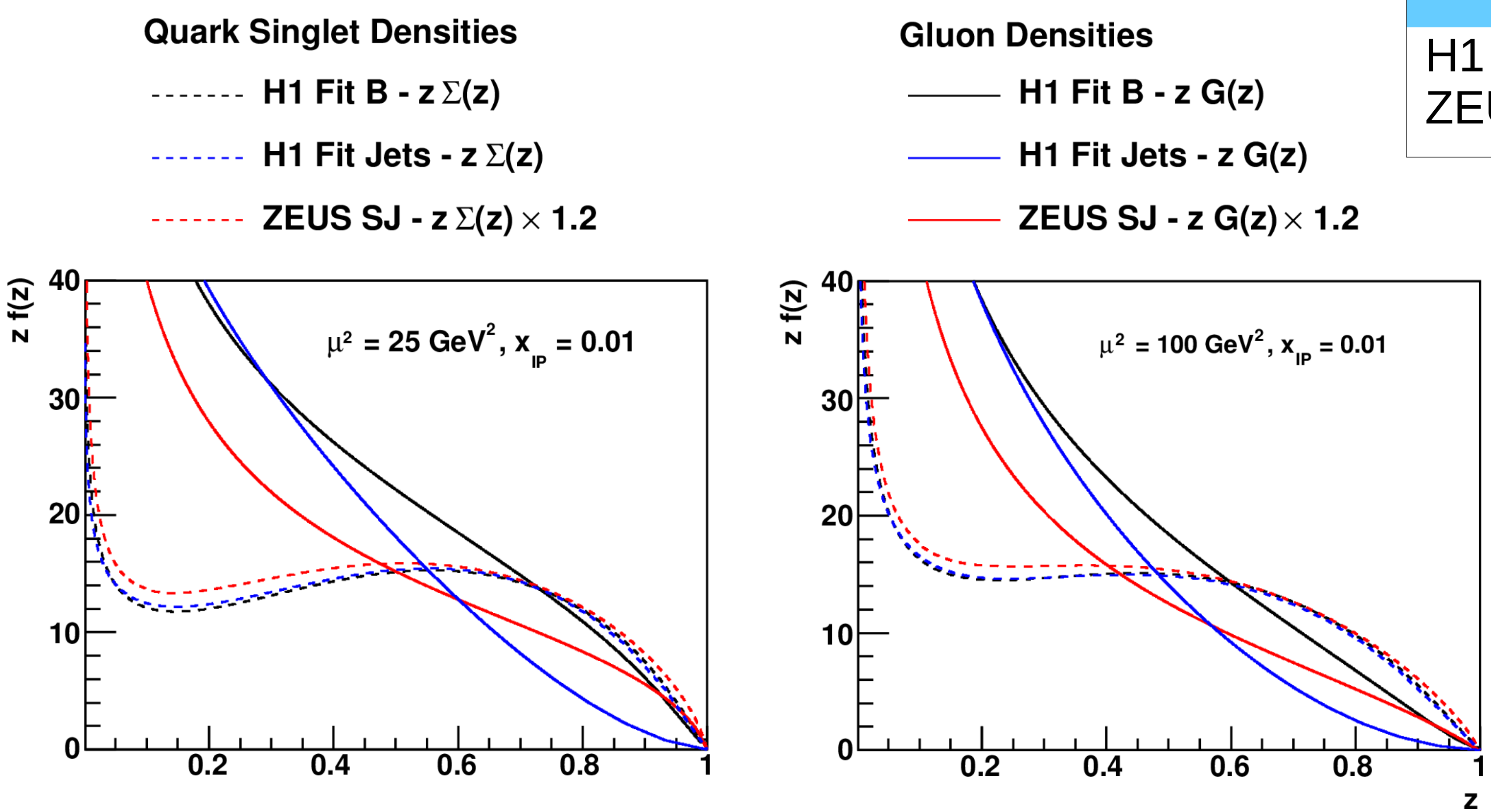
Proof of factorization for diffractive hard scattering
John C. Collins (Penn State U.). Sep 1997. 12 pp.
Published in **Phys.Rev. D57 (1998) 3051-3056**, Erratum: **Phys.Rev. D61 (2000) 019902**
PSU-TH-189
DOI: 10.1103/PhysRevD.61.019902, 10.1103/PhysRevD.57.3051
e-Print: **hep-ph/9709499** | PDF
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
ADS Abstract Service; OSTI Information Bridge Server
Detailed record - Cited by 384 records 250+

NLO DPDFs

- DPDF sets differ mainly in gluon component which is weekly 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**

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]

A bit of history

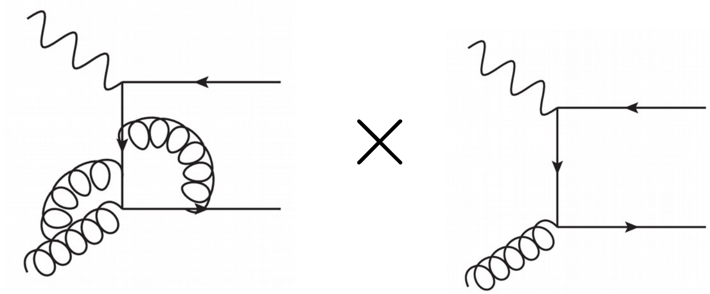
- **1973** Asymptotic freedom of QCD
- **1993** NLO studies of DIS jets
- **2016** NNLO corrections for DIS jets

Cookbook

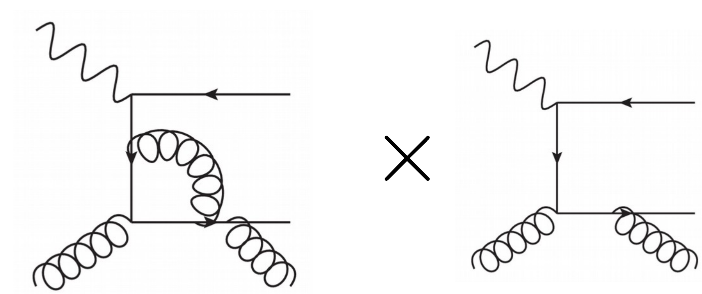
1) The matrix element tables precalculated by **NNLOJET** program (~1M CPU hours)
2) Then convoluted with DPDFs and α_S using **fastNLO** (<1s)

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

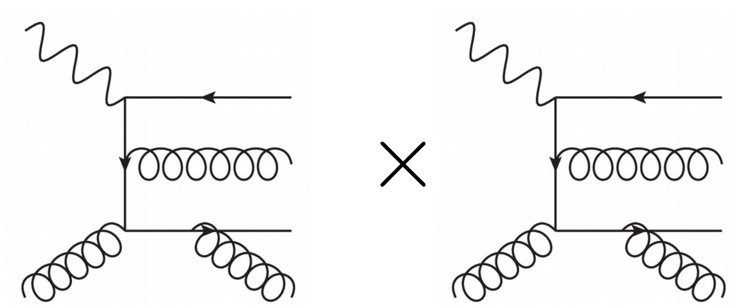
virtual-virtual



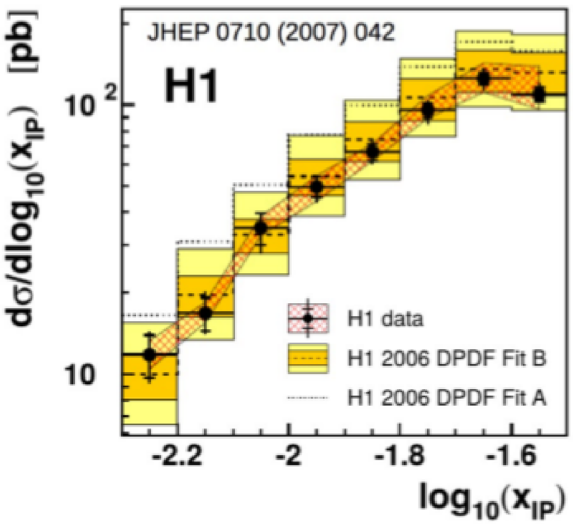
real-virtual

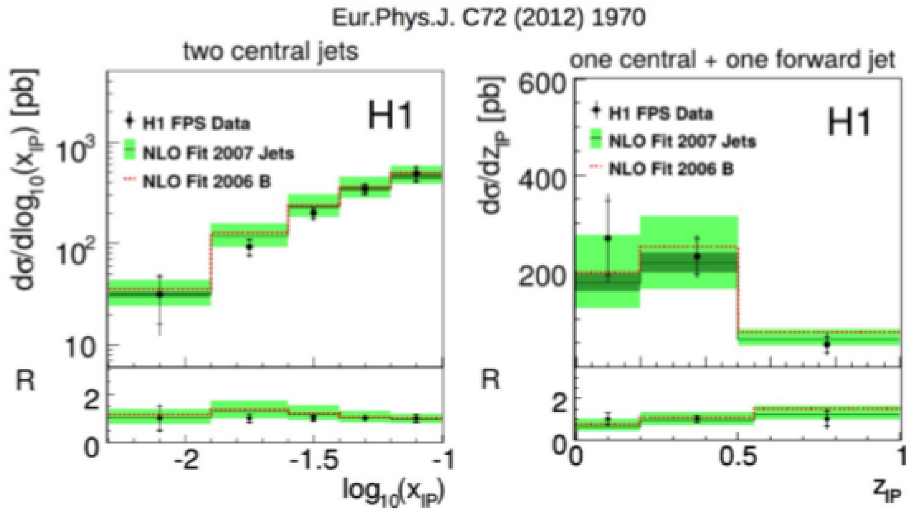


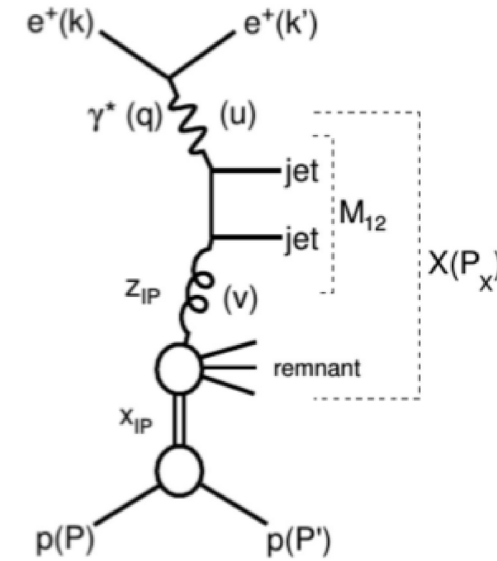
real-real

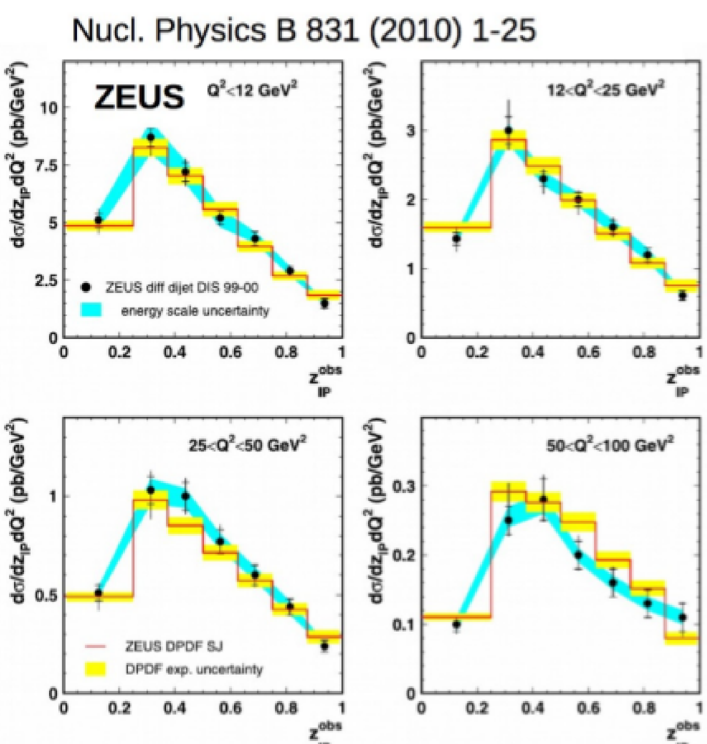


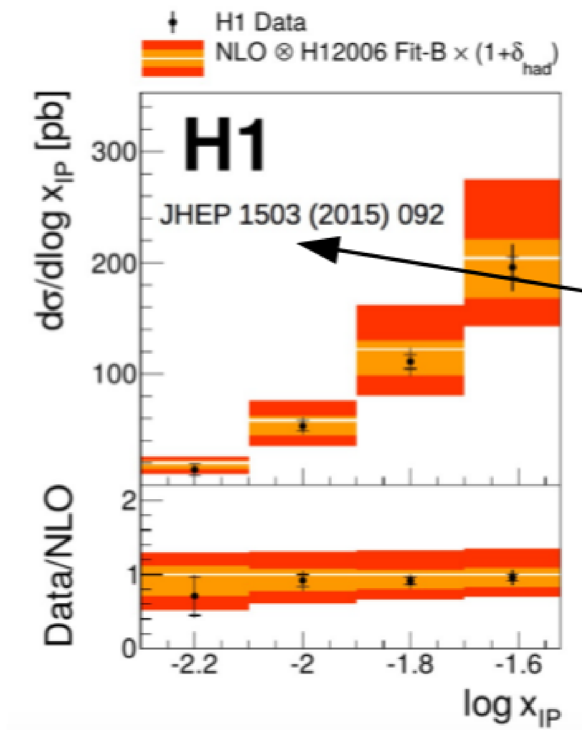
Diffractive di-jets in DDIS











Katarzyna Wichmann:
Soft and hard QCD processes at HERA
Sunday, 24.9.

first measurement of α_s in DDIS

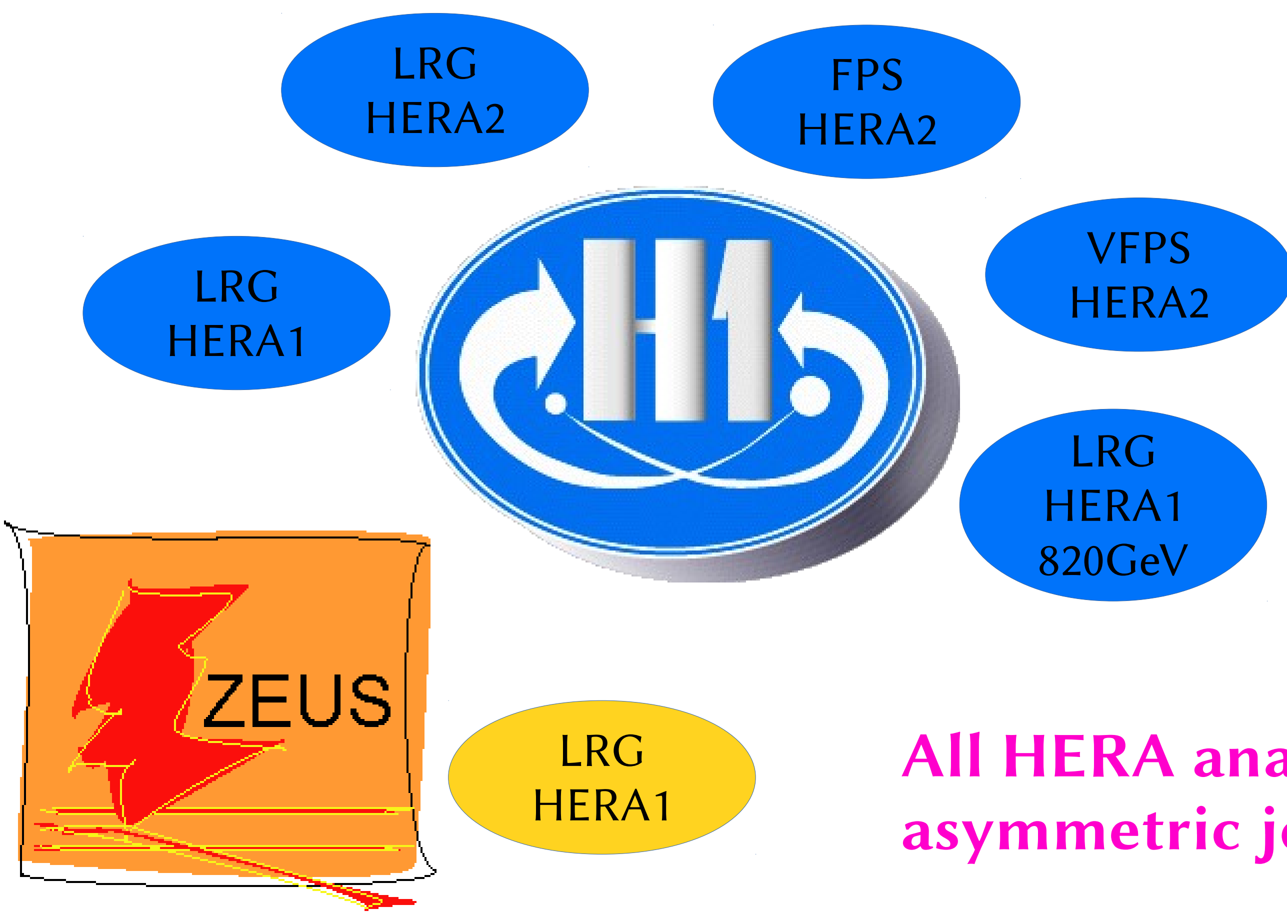
$$\alpha_s(M_Z) = 0.119 \pm 0.004(exp) \pm 0.012(DPDF,\ theo)$$

Factorisation holds in DDIS jets

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 HERA2 Phase Space
$4 < Q^2 < 100\ \mathrm{GeV}^2$
$0.1 < y < 0.7$
$x_{I\!P} < 0.03$
$\|t\| < 1\ \mathrm{GeV}^2$
$M_Y < 1.6\ \mathrm{GeV}$
$p^*_{\mathrm{T},1} > 5.5\ \mathrm{GeV}$
$p^*_{\mathrm{T},2} > 4.0\ \mathrm{GeV}$
$-1 < \eta^{\mathrm{lab}}_{1,2} < 2$

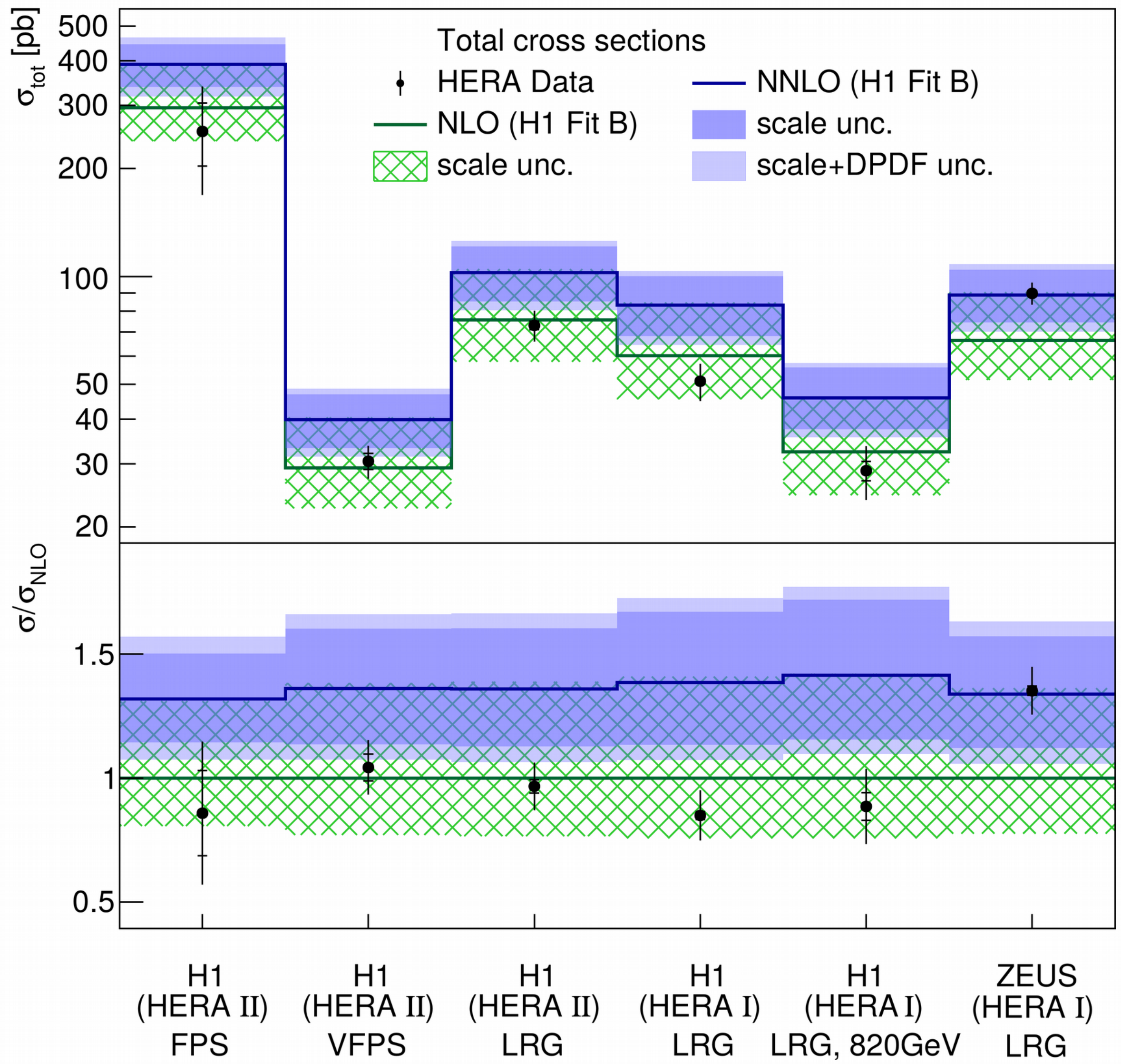


All HERA analyses with asymmetric jet pT cuts included

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 with exception of ZEUS measurement

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



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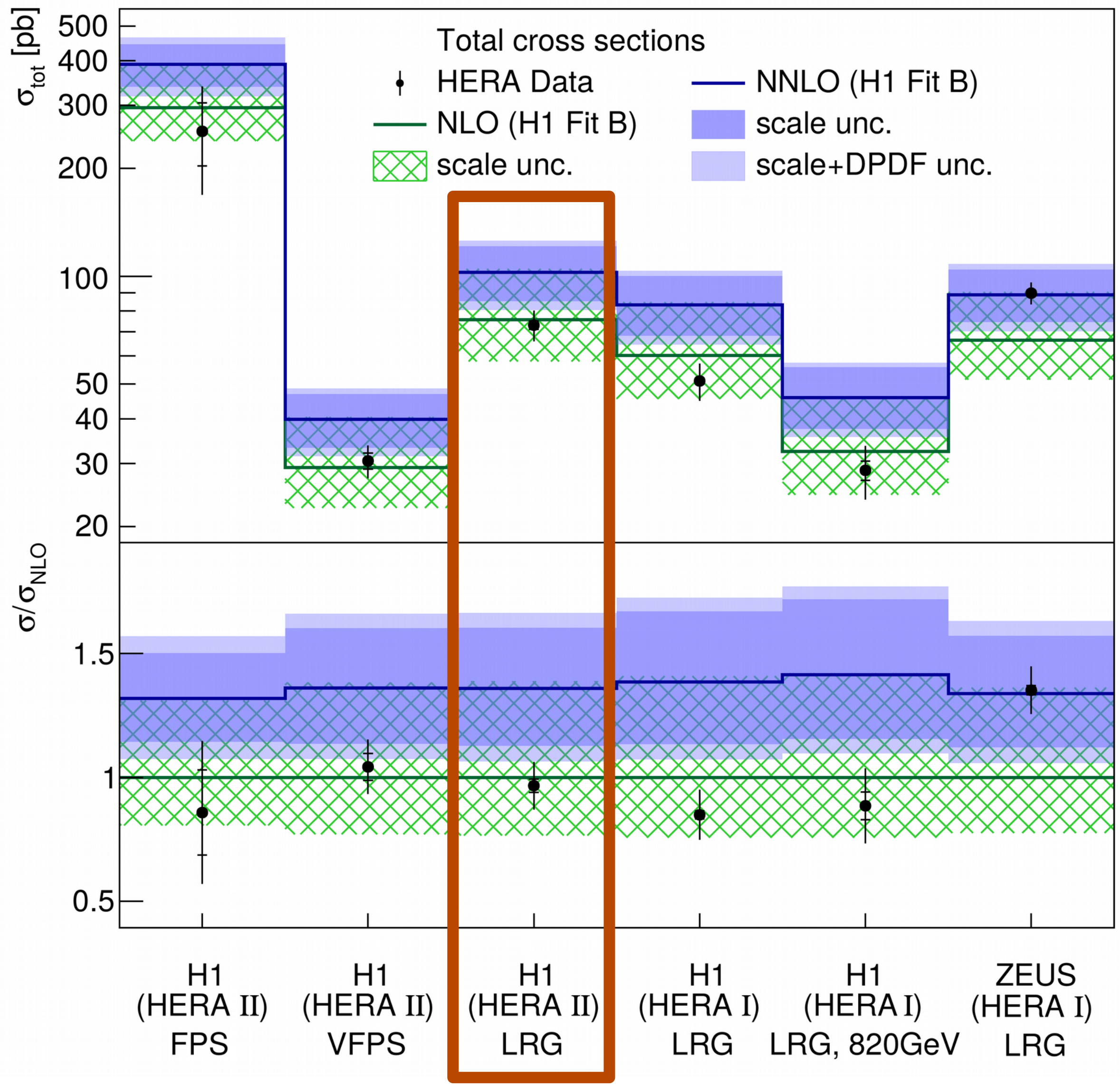
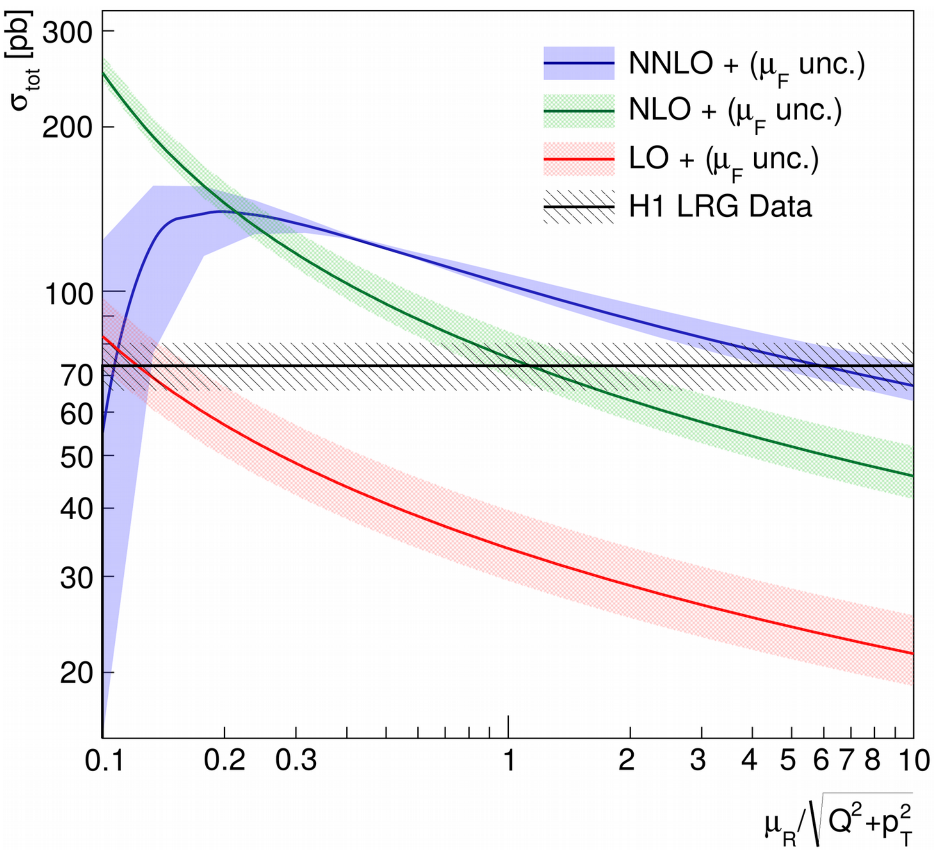
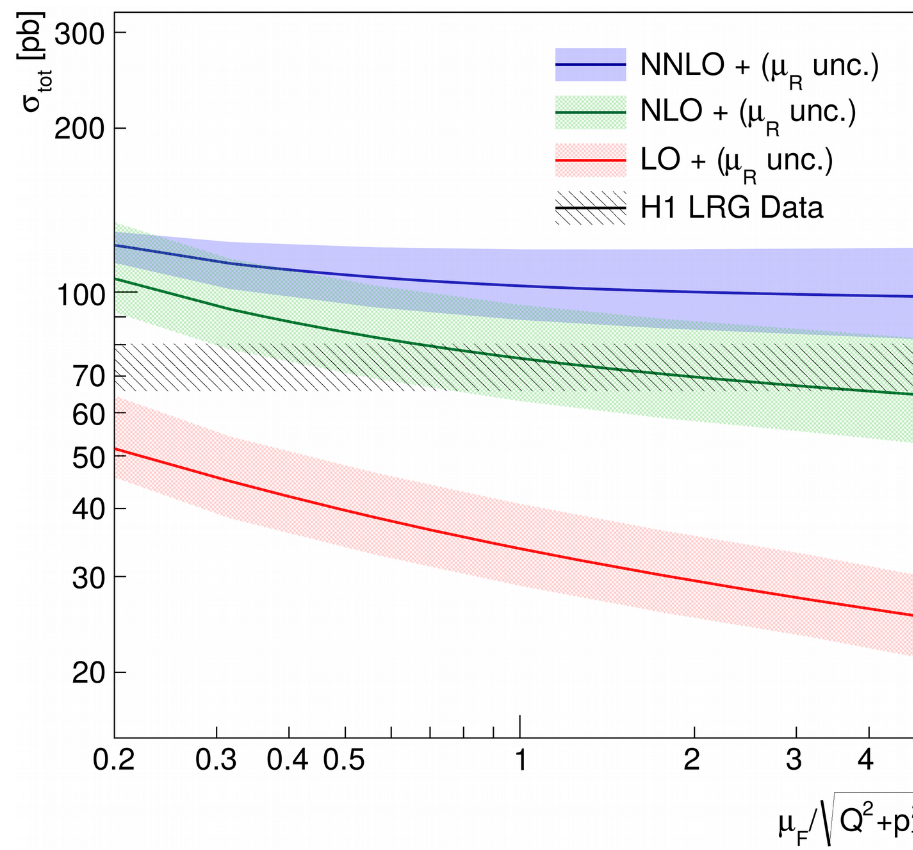


Total Cross Sections - Scale dependence

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

- Four functional form of scales studied, everytime assumed:

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

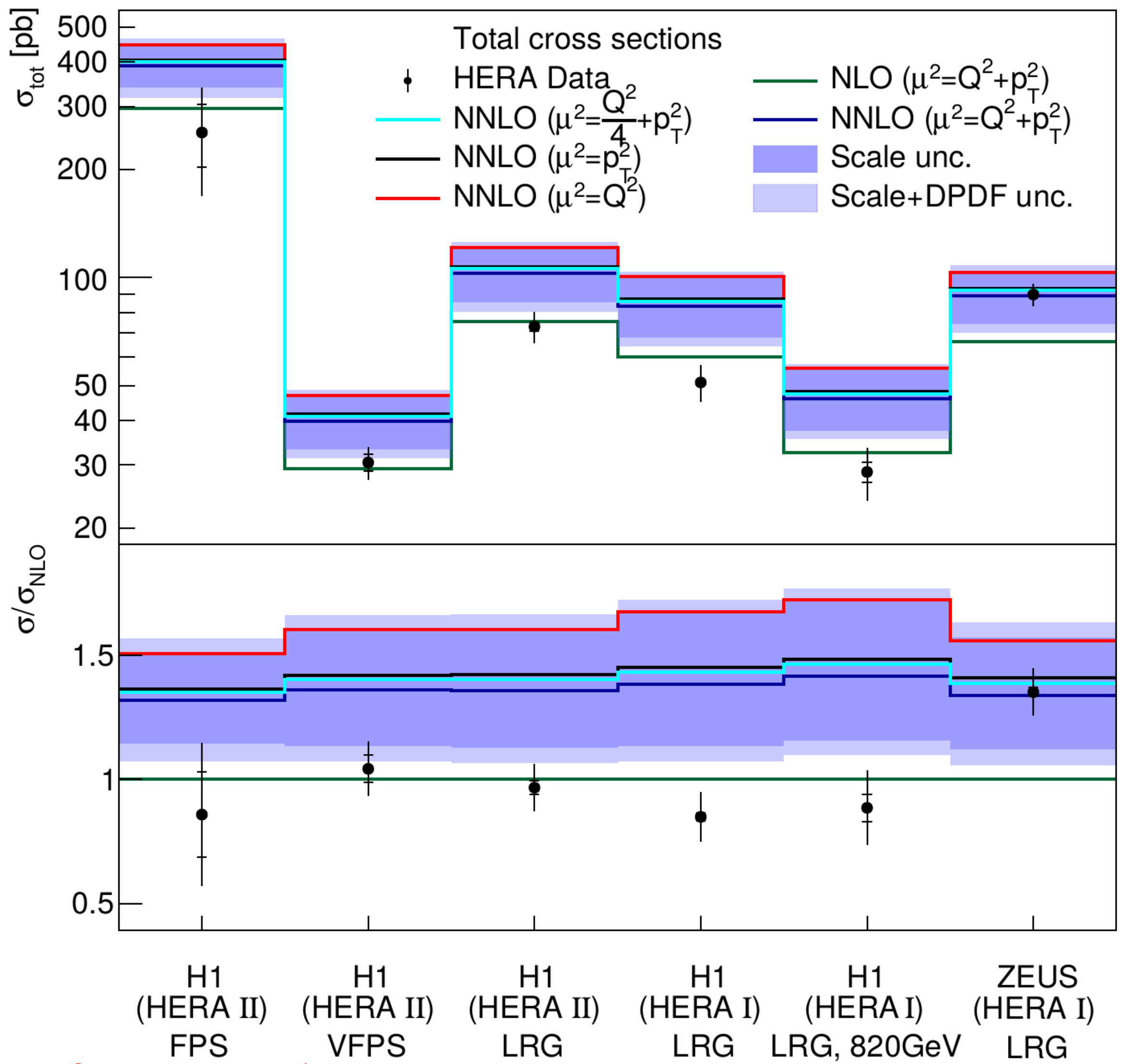
- Alternative parameterizations:

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

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

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

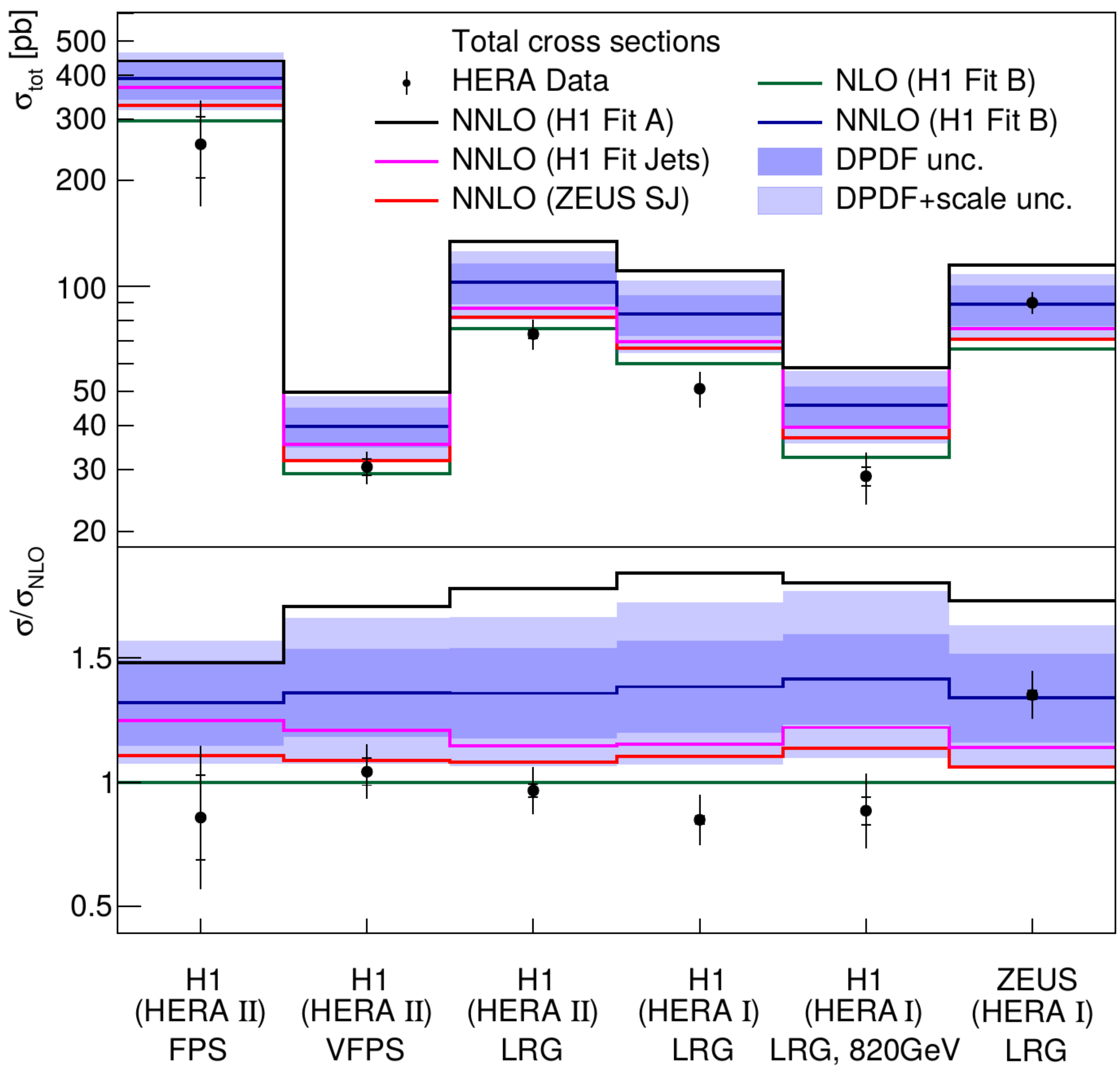
$$\mu^2 = Q^2$$



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
  perform best
- Inclusive data fits
  H1 Fit A
  H1 Fit B
  very different although for inclusive data had similar chi2

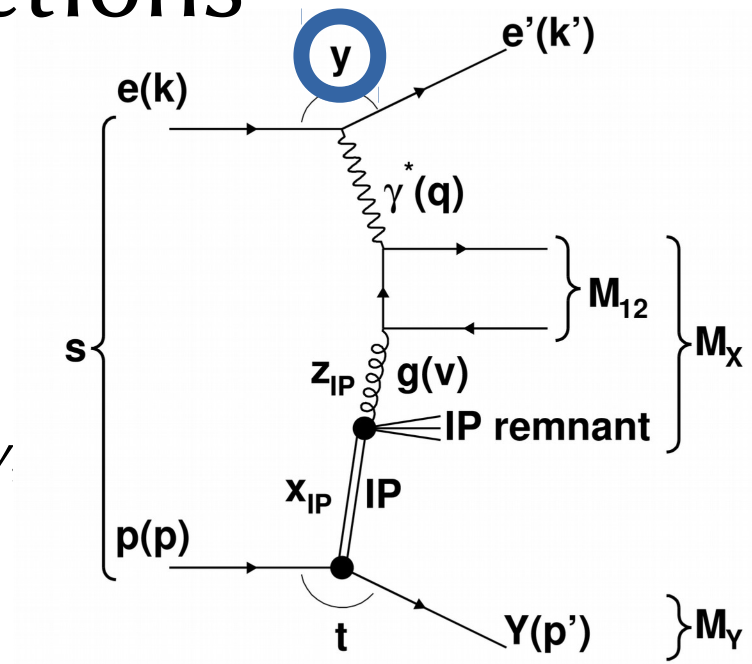


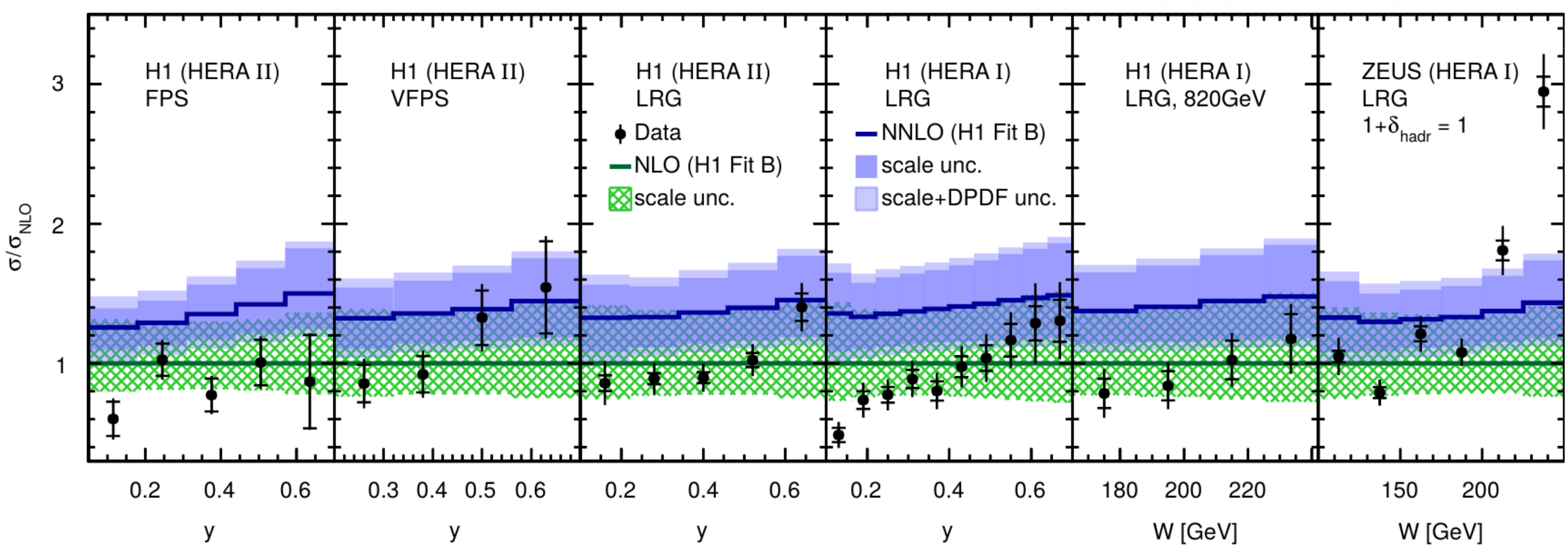
Studied differential distributions

Histogram	H1 HERA-II FPS	H1 HERA-II VFPS	H1 HERA-II LRG	H1 HERA-I LRG	H1 820 GeV LRG	ZEUS HERA-I LRG
Q^2	✓	✓	✓		✓	✓
$y\ [W]^*$	✓	✓	✓	✓	$*$	$*$
$p_T^{*,\mathrm{jet1}}\ [p_T^{*,\mathrm{jet}}]^*$	✓	✓	✓	✓	✓	$*$
$p_T^{*,\mathrm{jet2}}$			✓			
$\langle p_T \rangle$			✓			
$\langle \eta_{\mathrm{lab}}^{\mathrm{jet}} \rangle\ [\eta_{\mathrm{jet}}^*]^*$		✓			✓	$*$
$\Delta\eta_{\mathrm{lab}}^{\mathrm{jet}}\ [\Delta\eta^*]^*$	$*$	✓	$*$	$*$	$*$	
M_X^2		✓				✓
$x_{I\!P}$	✓	✓	✓	✓	✓	✓
$z_{I\!P}$	✓	✓	✓	✓		✓
$\lvert t \rvert\ [\beta)]^*$	✓					$*$
x_γ						$*$
$(Q^2; p_T^{*,\mathrm{jet1}})$			✓			
$(Q^2; z_{I\!P})$			✓			✓
$(Q^2 + (p_T^{*,\mathrm{jet1}})^2; z_{I\!P})$				✓		
$(p_T^{*,\mathrm{jet1}}; z_{I\!P})$						✓

Differential x-sections

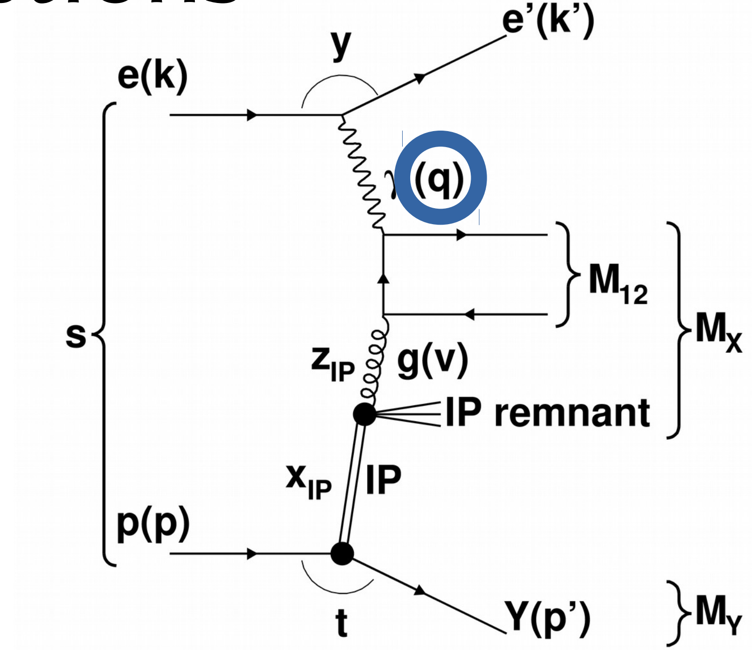
- The same or similar distributions from various analyses grouped into one plot, as shown bellow. In total **57 differential distributions** analyzed
- For inelasticity *y* NNLO higher for higher *y* similar trend in data, note $W = \sqrt{ys}$

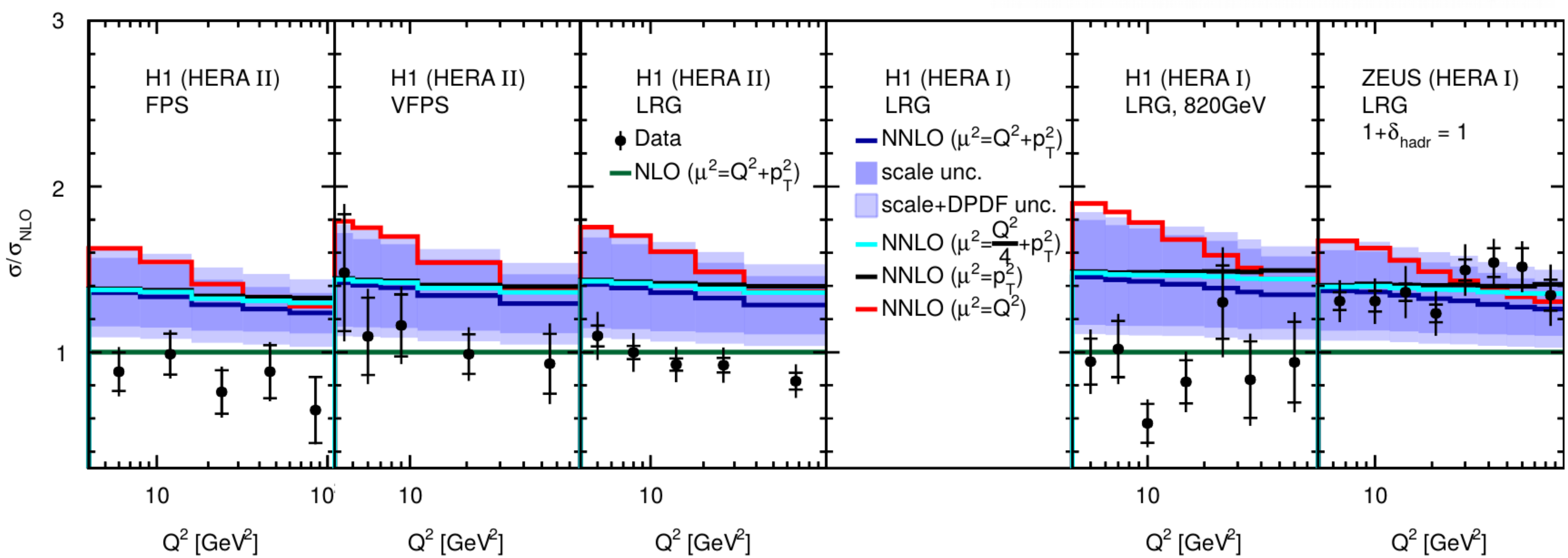




Differential x-sections

- The scale with Q² term only predict steeper Q² distribution
- Only small difference between other scale prescriptions
- No systematic trend in data



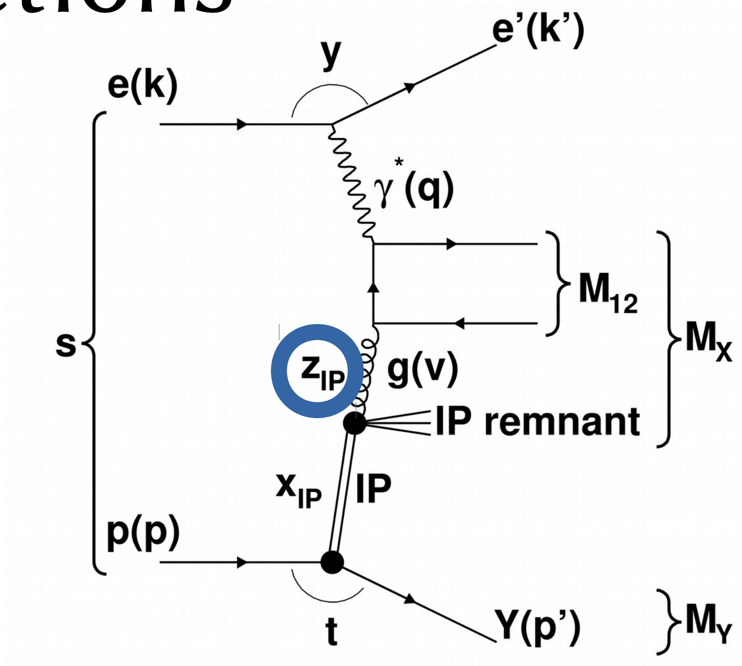


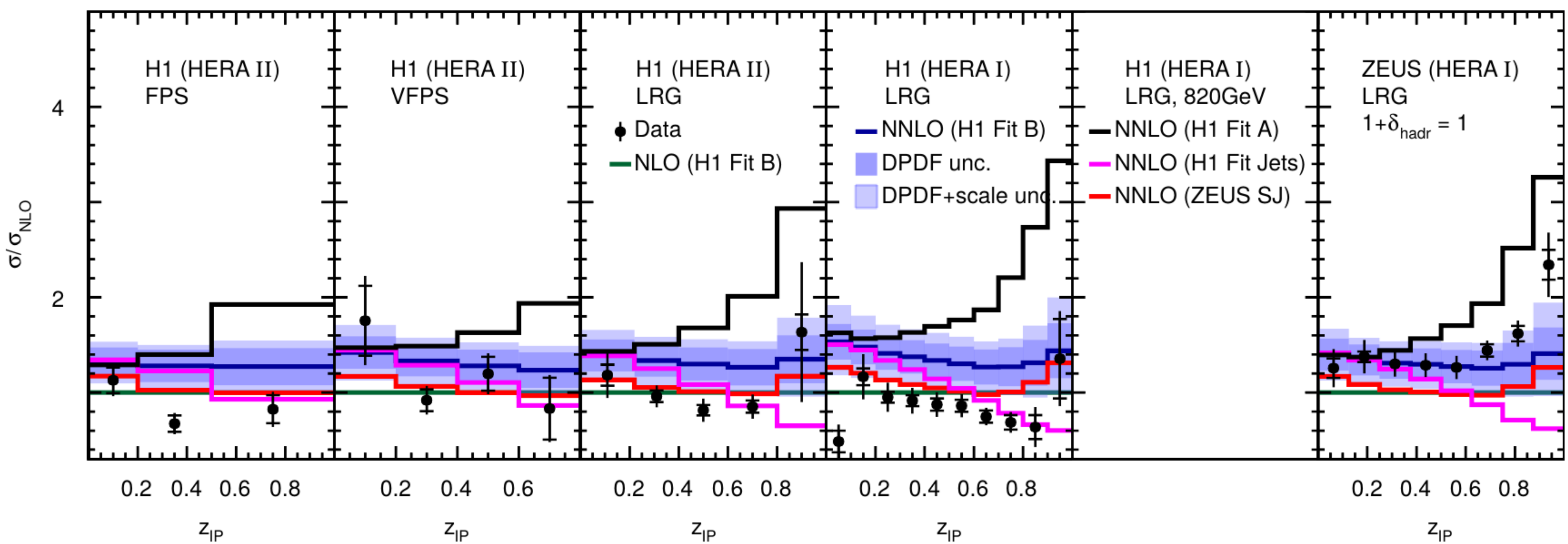
Differential x-sections

- 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

k_T- jet algorithm (R=1)

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

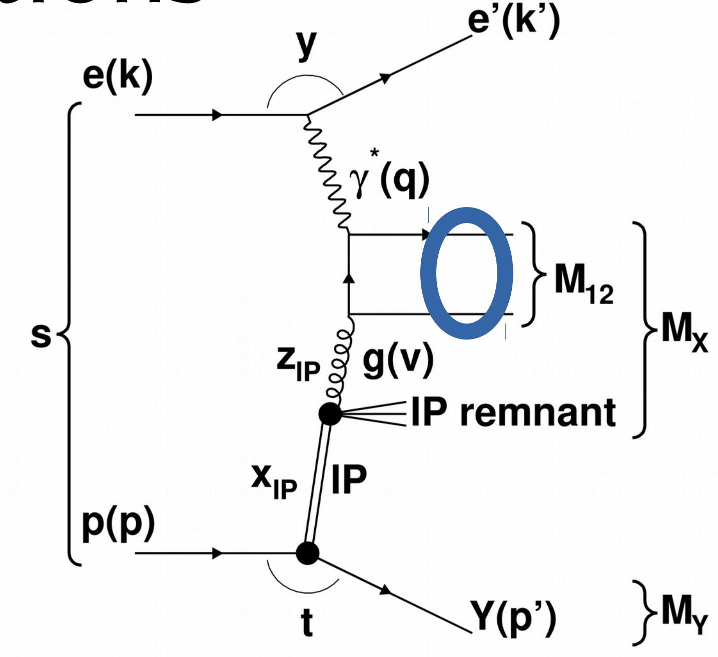


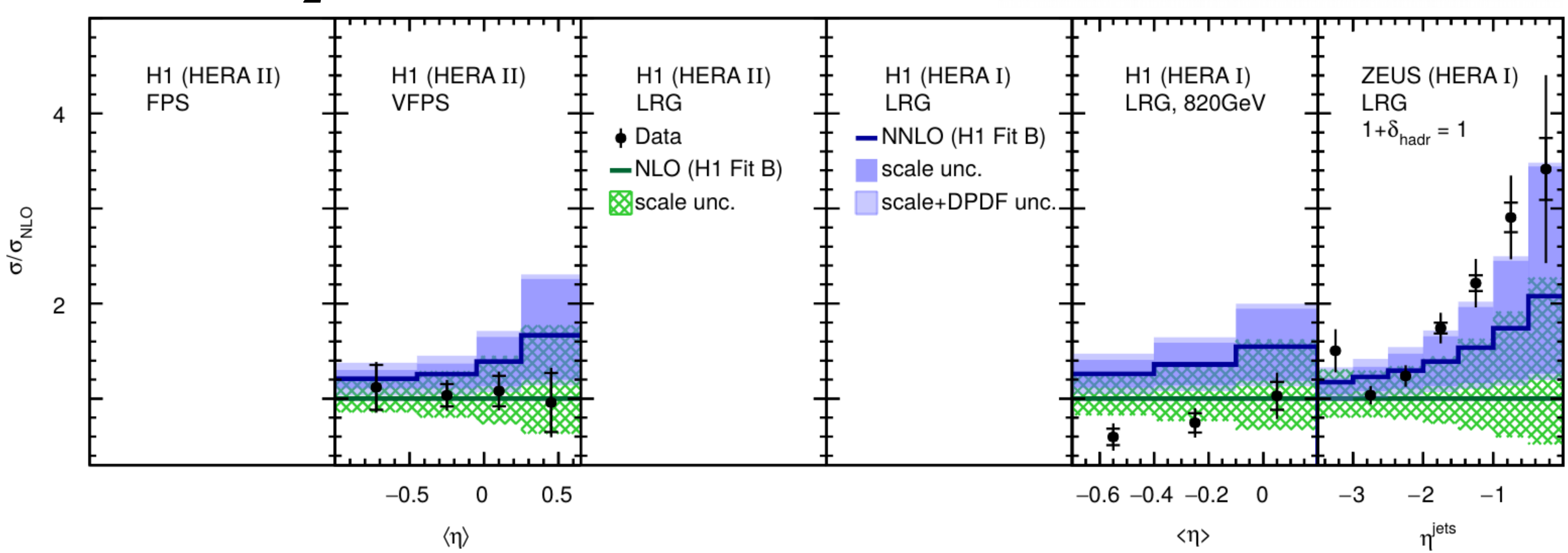


Differential x-sections

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

$$\langle\eta^{\text{jets}}\rangle = \frac{1}{2}\left(\eta^{\text{jet1}} + \eta^{\text{jet2}}\right) \qquad \eta^{*\text{jets}} = \eta^{*\text{jet1,2}}$$





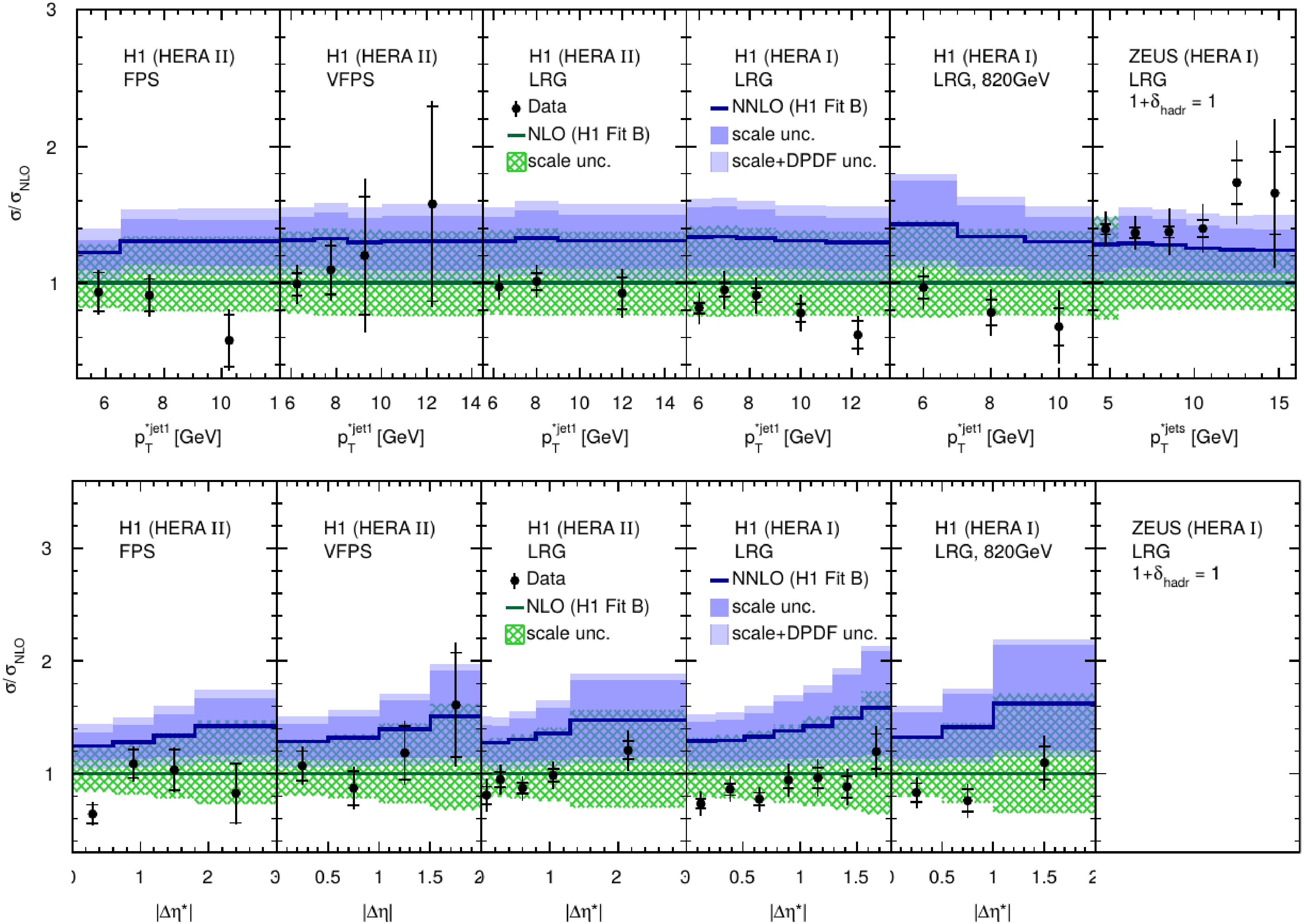
Conclusions

- Dijets in diffractive DIS calculated in **NNLO QCD for the first time**
- Differential distributions for various observables calculated
- The NNLO cross sections about ~40% higher than NLO
- The NNLO predictions overshoot the data for all H1 measurements and all studied DPDFs

Outlook

- Fit the inclusive and dijet diffractive DIS data at NNLO

Backup


H1 (HERA II)
FPS
H1 (HERA II)
VFPS
H1 (HERA II)
LRG
Data
NLO (H1 Fit B)
scale unc.
H1 (HERA I)
LRG
NNLO (H1 Fit B)
scale unc.
scale+DPDF unc.
H1 (HERA I)
LRG, 820GeV
ZEUS (HERA I)
LRG
1+δhadr = 1
σ/σNLO
pT*jet1 [GeV]
pT*jets [GeV]
|Δη*|
|Δη|

Summary of experimental data set

Collab.	Diffr. selection	$\sqrt{s}$ [GeV]	$\mathcal{L}$ [pb^{-1}]	Studied observables	DIS range	Dijet range	Diffractive range
H1 [3]	LRG	319	290 (∼15000ev)		$4 < Q^2 < 100\,\mathrm{GeV}^2$ $0.1 < y < 0.7$	$p_{\mathrm{T}}^{*,\mathrm{jet1}} > 5.5\,\mathrm{GeV}$ $p_{\mathrm{T}}^{*,\mathrm{jet2}} > 4.0\,\mathrm{GeV}$ $n_{\mathrm{jets}} \geq 2$ $-1 < \eta_{\mathrm{lab}}^{\mathrm{jet}} < 2$	$x_{I\!P} < 0.03$ $\lvert t\rvert < 1\,\mathrm{GeV}^2$ $M_{\mathrm{Y}} < 1.6\,\mathrm{GeV}$
H1 [4]	VFPS	319	50 (550ev)		$4 < Q^2 < 80\,\mathrm{GeV}^2$ $0.2 < y < 0.7$	$p_{\mathrm{T}}^{*,\mathrm{jet1}} > 5.5\,\mathrm{GeV}$ $p_{\mathrm{T}}^{*,\mathrm{jet2}} > 4.0\,\mathrm{GeV}$ $n_{\mathrm{jets}} \geq 2$ $-1 < \eta_{\mathrm{lab}}^{\mathrm{jet}} < 2.5$	$0.010 < x_{I\!P} < 0.024$ $\lvert t\rvert < 0.6\,\mathrm{GeV}^2$ $M_{\mathrm{Y}} = m_P$
H1 [5]	FPS	319	156.6 (581ev)		$4 < Q^2 < 110\,\mathrm{GeV}^2$ $0.05 < y < 0.7$	$p_{\mathrm{T}}^{*,\mathrm{jet1}} > 5\,\mathrm{GeV}$ $p_{\mathrm{T}}^{*,\mathrm{jet2}} > 4.0\,\mathrm{GeV}$ $n_{\mathrm{jets}} \geq 2$ $-1 < \eta_{\mathrm{lab}}^{\mathrm{jet}} < 2.5$	$x_{I\!P} < 0.1$ $\lvert t\rvert < 1\,\mathrm{GeV}^2$ $M_{\mathrm{Y}} = m_P$
H1 [6]	LRG	319	51.5 (2723ev)		$4 < Q^2 < 80\,\mathrm{GeV}^2$ $0.1 < y < 0.7$	$p_{\mathrm{T}}^{*,\mathrm{jet1}} > 5.5\,\mathrm{GeV}$ $p_{\mathrm{T}}^{*,\mathrm{jet2}} > 4.0\,\mathrm{GeV}$ $n_{\mathrm{jets}} \geq 2$ $-3 < \eta^{*\mathrm{jets}} < 0$	$x_{I\!P} < 0.03$ $\lvert t\rvert < 1\,\mathrm{GeV}^2$ $M_{\mathrm{Y}} < 1.6\,\mathrm{GeV}$
H1 [7]	LRG	300	18 (322ev)		$4 < Q^2 < 80\,\mathrm{GeV}^2$ $165 < W < 242\,\mathrm{GeV}$	$p_{\mathrm{T}}^{*,\mathrm{jet1}} > 5\,\mathrm{GeV}$ $p_{\mathrm{T}}^{*,\mathrm{jet2}} > 4.0\,\mathrm{GeV}$ $n_{\mathrm{jets}} \geq 2$ $-1 < \eta_{\mathrm{lab}}^{\mathrm{jet}} < 2$ $-3 < \eta^{*\mathrm{jets}} < 0$	$x_{I\!P} < 0.03$ $\lvert t\rvert < 1\,\mathrm{GeV}^2$ $M_{\mathrm{Y}} < 1.6\,\mathrm{GeV}$
ZEUS [8]	LRG	319	61 (5539ev)		$5 < Q^2 < 100\,\mathrm{GeV}^2$ $100 < W < 250\,\mathrm{GeV}$	$p_{\mathrm{T}}^{*,\mathrm{jet1}} > 5\,\mathrm{GeV}$ $p_{\mathrm{T}}^{*,\mathrm{jet2}} > 4.0\,\mathrm{GeV}$ $n_{\mathrm{jets}} \geq 2$	$x_{I\!P} < 0.03$ $\lvert t\rvert < 1\,\mathrm{GeV}^2$ $M_{\mathrm{Y}} = m_P$