NNLO predictions for dijet production in diffractive DIS

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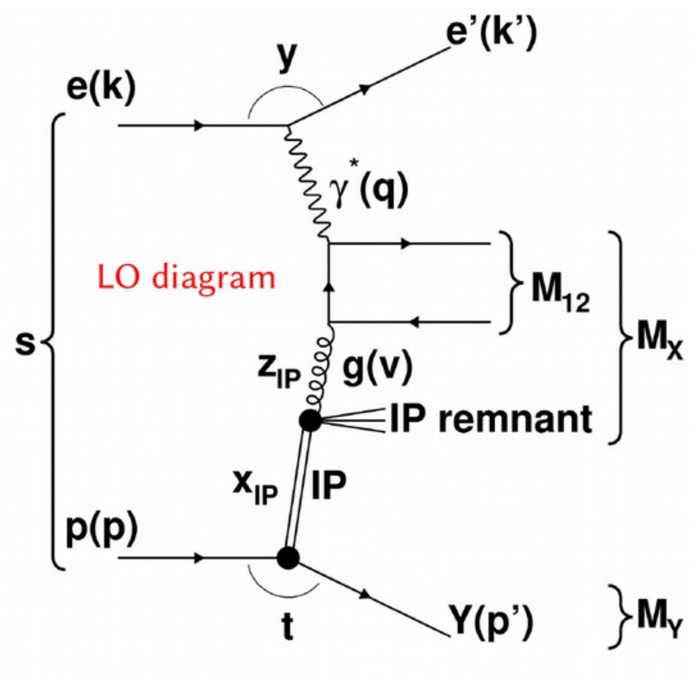
Diffractive Dijet Production in ep

In diffractive events the beam proton stays intact
or dissociates into a 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 7% of low-x events are diffractive

Collinear QCD factorization theorem in hard diffraction

Collinear factorization in hard diffraction

- For diffractive events with hard scale
  e.g. Q^2 or p_T of jets

- Factorization of the diffractive cross section into
  \+ partonic cross sections (NNLO)
  \+ process independent DPDFs (currently determined only in NLO)

J. Collins, Phys.Rev. D57 (1998) 3051

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

- For diffractive processes (including dijets) with scale high enough,
  -> factorization proven by Collins within perturbative QCD

Diffractive parton densities (DPDFs)

DPDFs

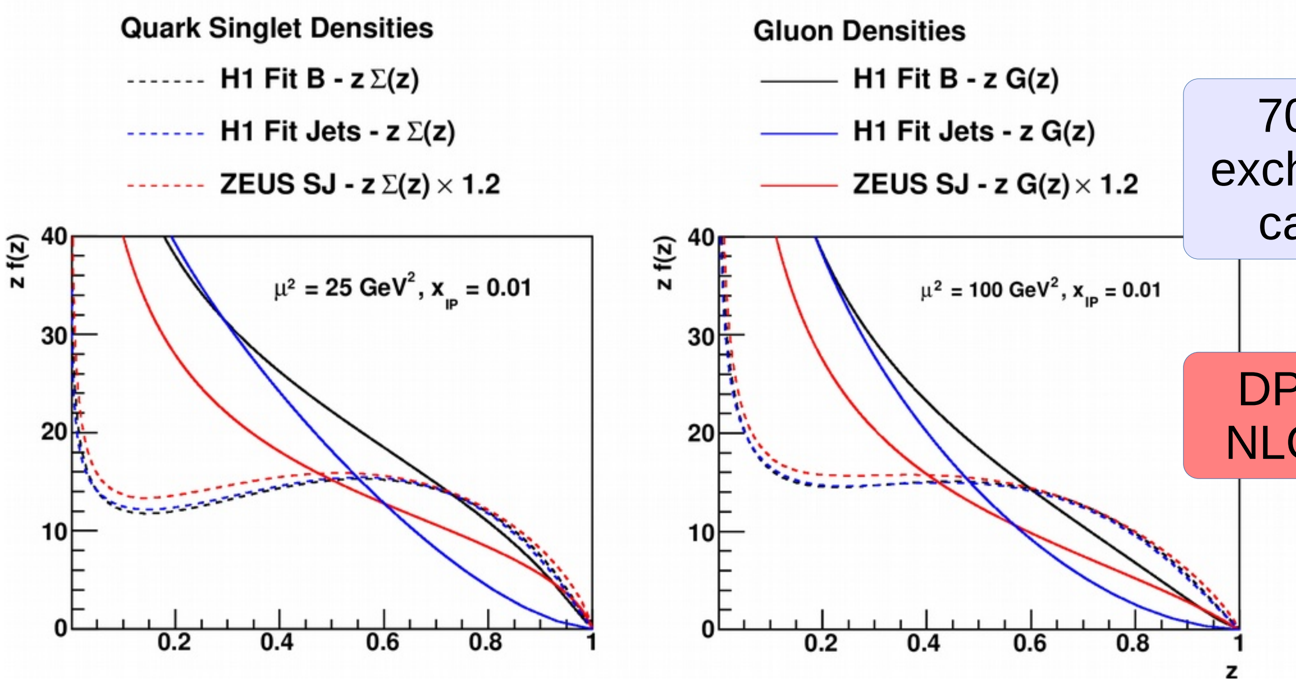
- DPDFs commonly determined from inclusive DDIS data
- DPDFs differ mainly in gluon component
  -> gluon weekly constrained by inclusive DDIS data
- DPDFs obey standard DGLAP evolution equation
- For gluon dominated diffractive dijet production -> sizable DPDF uncertainty

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

DPDFs available in NLO accuracy only !

NNLO QCD predictions

NNLO QCD predictions

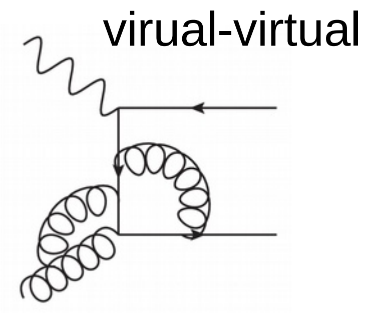
- NNLOJET program based on antenna subtraction
  J. Currie, T. Gehrmann, A. Huss, J. Niehues [arXiv:1606.03991], [arXiv:1703.05977]

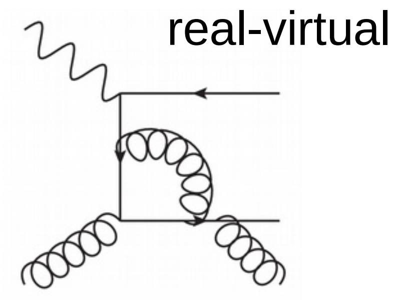
- NNLO proven to be successful for non-diff. jets in DIS
  [arXiv:1703.05977], [arXiv:1611.03421]

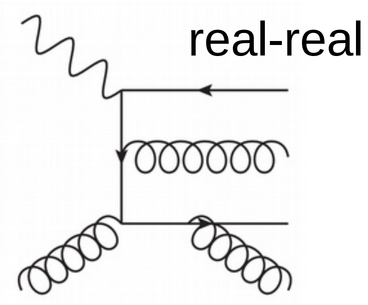
- Cancellation of IR divergences with local subtraction terms: moved across different phase space multiplicities

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

- The non-perturbative corrections taken from published measurements
  (ZEUS did not published any hadronization corrections -> not included here!)







Calculations for dijets in diffractive DIS

Two steps of calculations

- NNLOJET together with fastNLO

Matrix element calculations

- Perform phase space integration
- Calculate hard coefficients independent of PDFs and α_s
- Run calculation at nominal center-of-mass energy with E_p=920 GeV
- O(100-500k) CPU hours

- Store 'x'-dependence of ME's w.r.t. 920 GeV hadron in fastNLO format (and Q^2 and $\langle p_T \rangle$ dependence)

Convolutions with DPDFs

- x_{IP} and z_{IP} integration performed using '*x*'-dependent pre-calculated ME's
- Calculations for E_p=820 GeV performed using 920 GeV ME's
- Calculation equivalent to commonly used 'slicing' method

DDIS dijet measurements

6 'analysis' of inclusive dijets in DDIS at HERA

- 5x *ep* @ 27.6 GeV + 920 GeV
- 1x *ep* @ 27.5 GeV + 820 GeV

- 4x Large rapidity gap (LRG)
- 2x Proton spectrometers (FPS, VFPS)

H1 LRG HERA2 Phase Space
$4 < Q^2 < 100\ \mathrm{GeV}^2$
$0.1 < y < 0.7$
$x_{I\!P} < 0.03$
$\lvert t\rvert < 1\ \mathrm{GeV}^2$
$M_Y < 1.6\ \mathrm{GeV}$
$p^*_{\mathrm{T},1} > 5.5\ \mathrm{GeV}$
$p^*_{\mathrm{T},2} > 4.0\ \mathrm{GeV}$
$-1 < \eta^{\mathrm{lab}}_{1,2} < 2$

All HERA measurements with asymmetric p_T^{jet} cuts

k_T-jets with R=1

LRG HERA-II

FPS HERA-II

LRG HERA-I

VFPS HERA-II

LRG HERA-I 820GeV

LRG HERA-I

ZEUS

Total cross section – NLO vs. NNLO

Total cross sections

- inner band represents scale uncertainty
  outer bands include DPDF uncertainties
- DPDF: H1PDF20016 FitB
- Scale choice

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

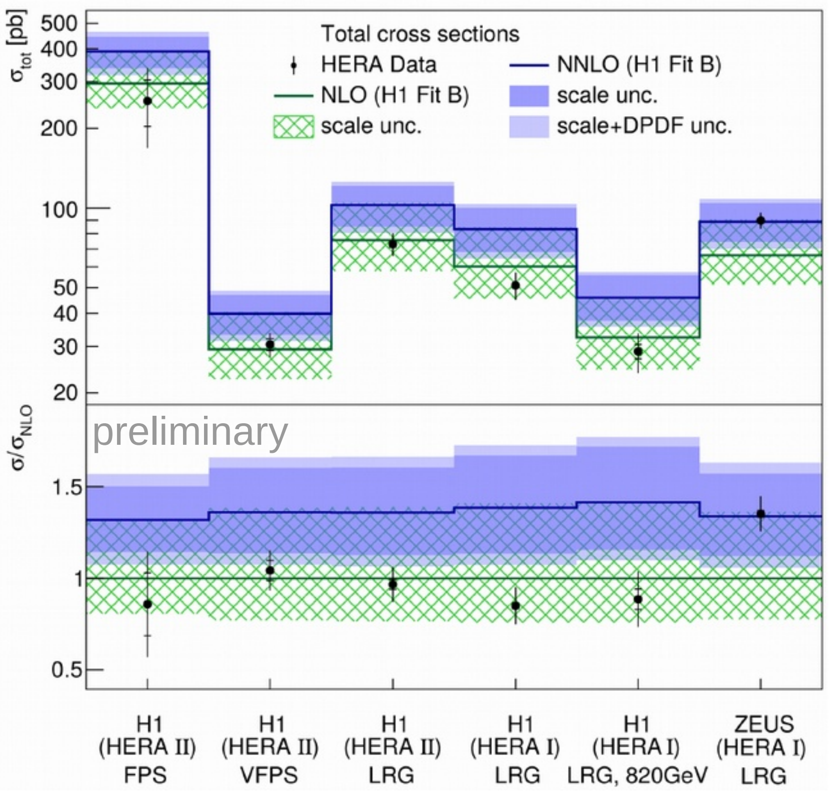
NLO

- Good agreeement with data
- Consistency with published calculations

NNLO

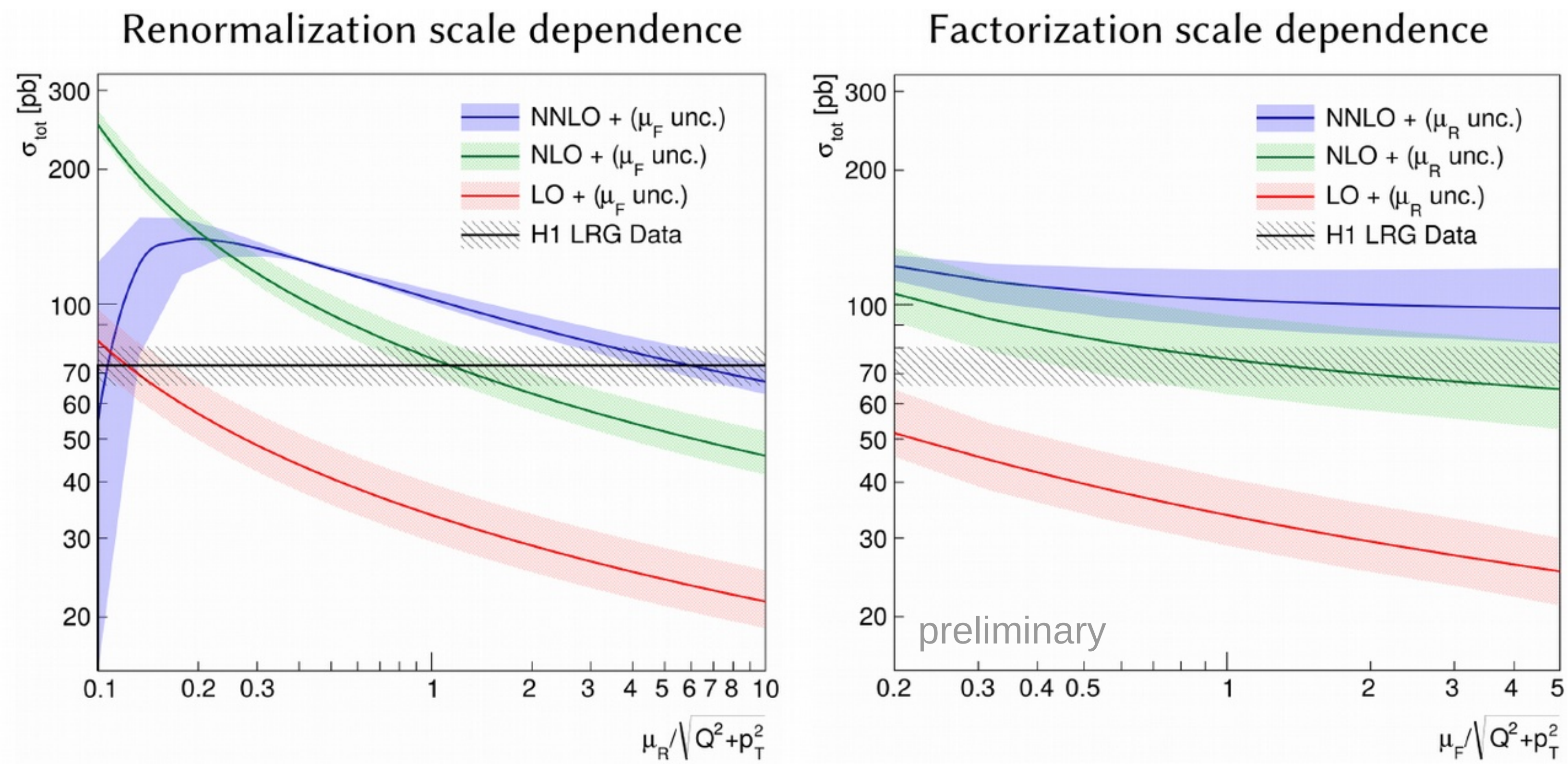
- predictions systematically
  overestimate data
- with exception of ZEUS measurement

NNLO about 30% higher than NLO



Reminder: DPDFs in NLO accuracy only
No NNLO DPDFs available

Scale dependence: total cross section



- Comparable renormalization scale dependences in NLO and LO
- Factorization scale dependence lower with every order

NNLO with reduced scale dependence compared to NLO

Total cross section – Scale dependence

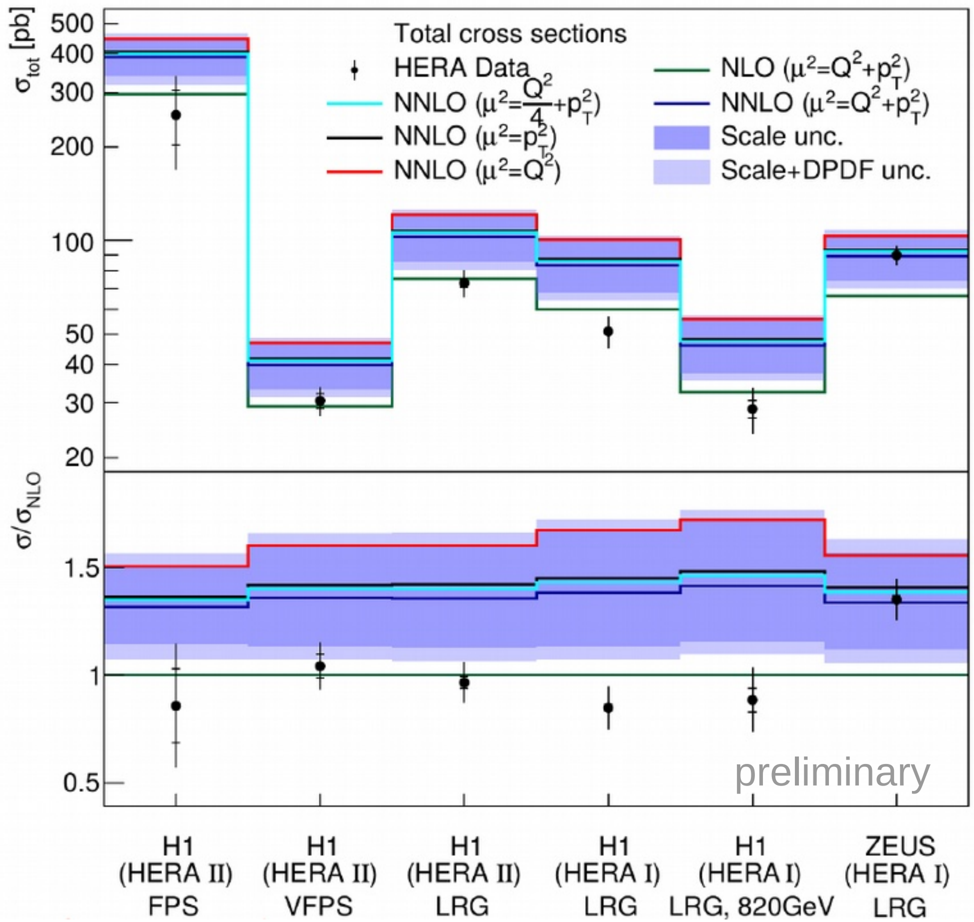
Functional definition for scales

- Four choices studied, assuming

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

- Alternative definitions

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



- p_T is characteristic for dijets
  if not considered for scale, the cross section is substantially higher

Total cross section – DPDF dependence

Study different (NLO) DPDF sets

Total cross sections

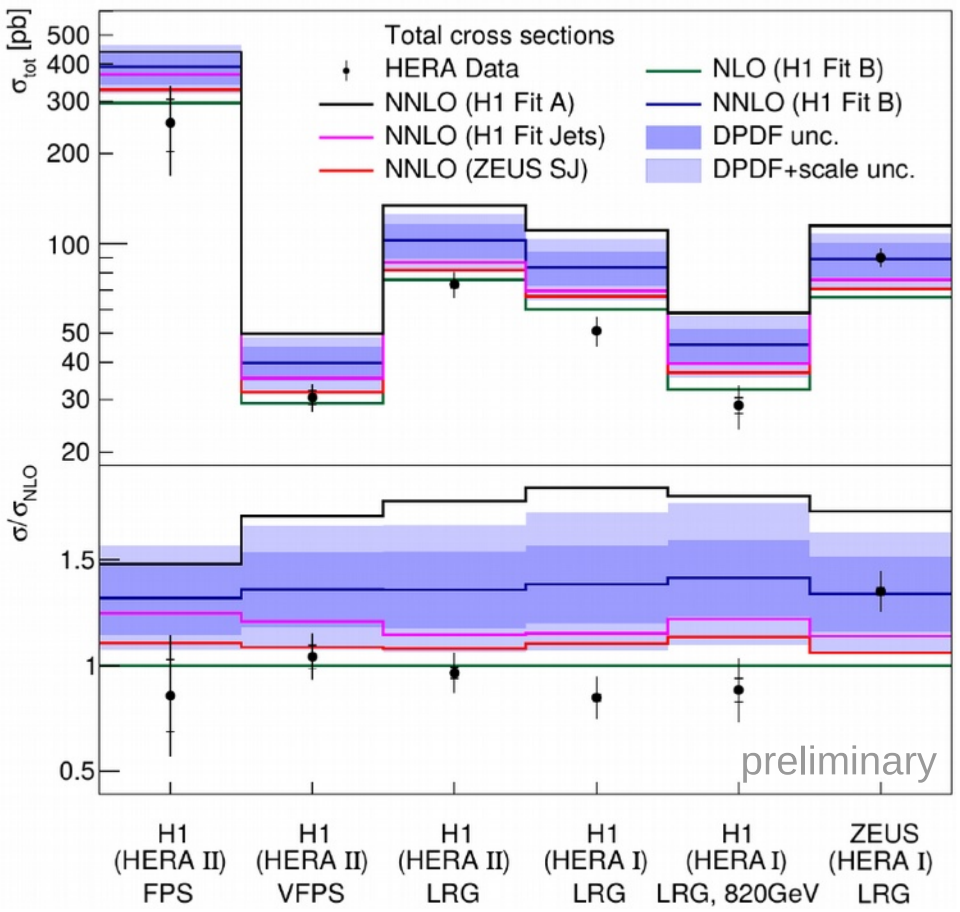
- Inner bars represent DPDF uncertainty outer bars include scale uncertainty

H1 FitA & FitB (2006)

- Fits to inclusive data alone
- FitA and FitB very different although for inclusive data had similar chi2

H1 Fit-Jets & ZEUS SJ

- Both: fits of inclusive + dijet data
- H1 Fit-Jets & ZEUS SJ perform best

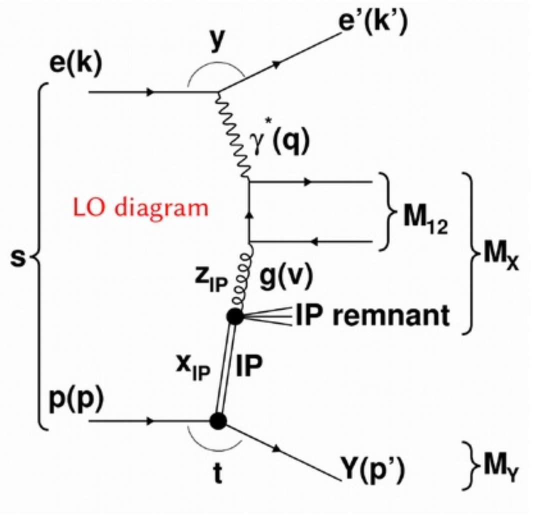


No DPDFs in NNLO accuracy available

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 $[W]^*$	✓	✓	✓	✓	*	*
$p_T^{*,\text{jet1}}$ $[p_T^{*,\text{jet}}]^*$	✓	✓	✓	✓	✓	*
$p_T^{*,\text{jet2}}$			✓			
$\langle p_T \rangle$			✓			
$\langle \eta_{\text{lab}}^{\text{jet}} \rangle$ $[\eta_{\text{jet}}^*]^*$		✓			✓	*
$\Delta\eta_{\text{lab}}^{\text{jet}}$ $[\Delta\eta^*]^*$	*	✓	*	*	*	
M_X^2		✓				✓
$x_{I\!P}$	✓	✓	✓	✓	✓	✓
$z_{I\!P}$	✓	✓	✓	✓		✓
$\lvert t \rvert$ $[\beta)]^*$	✓					*
x_γ						*
$(Q^2; p_T^{*,\text{jet1}})$			✓			
$(Q^2; z_{I\!P})$			✓			✓
$(Q^2 + (p_T^{*,\text{jet1}})^2; z_{I\!P})$				✓		
$(p_T^{*,\text{jet1}}; z_{I\!P})$						✓

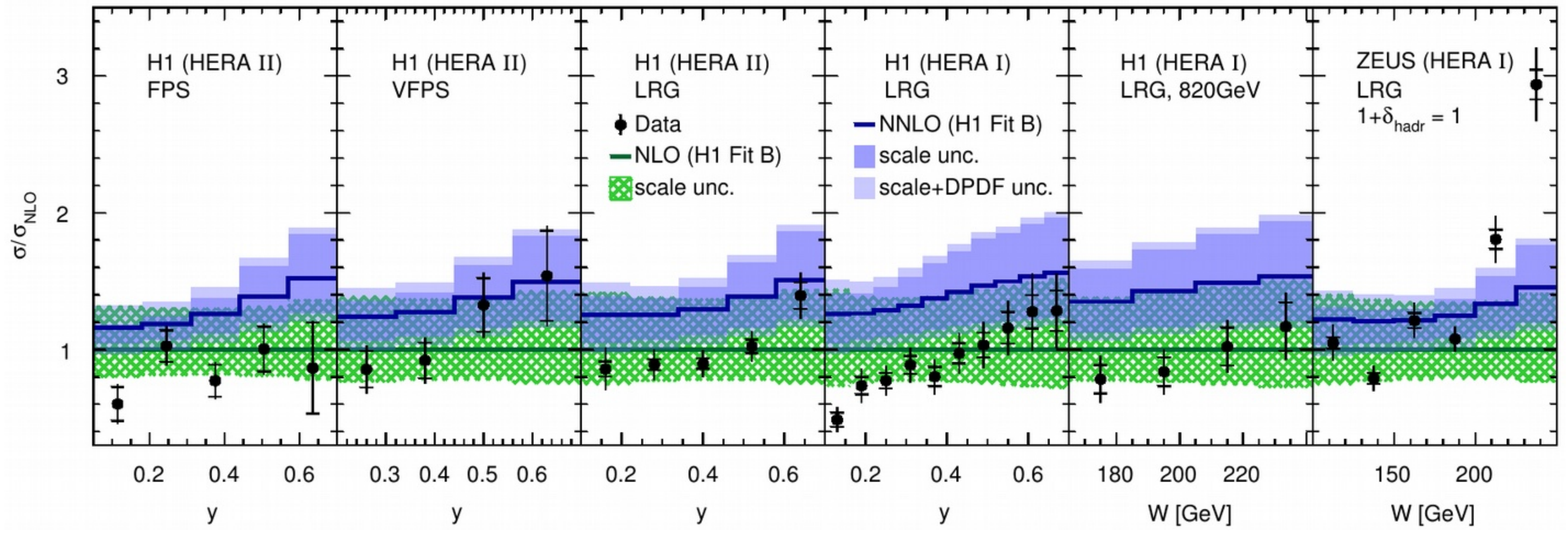
Differential cross section



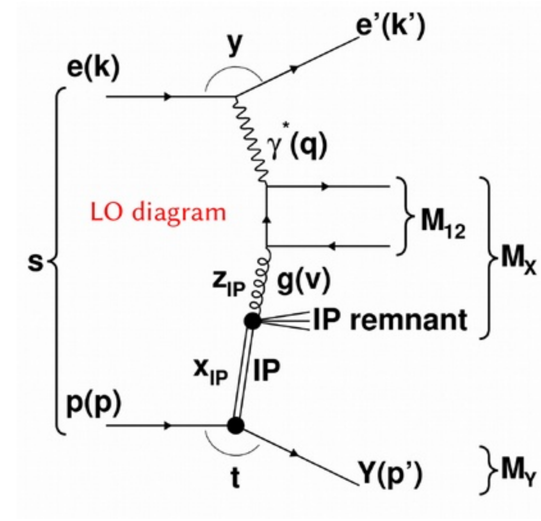
- In total 57 differential distributions analyzed
- Different analyses grouped for corresponding observables into a single plot

Inelasticity y

- note: $W = \sqrt{ys}$
- NNLO higher for higher y, similar trend in data

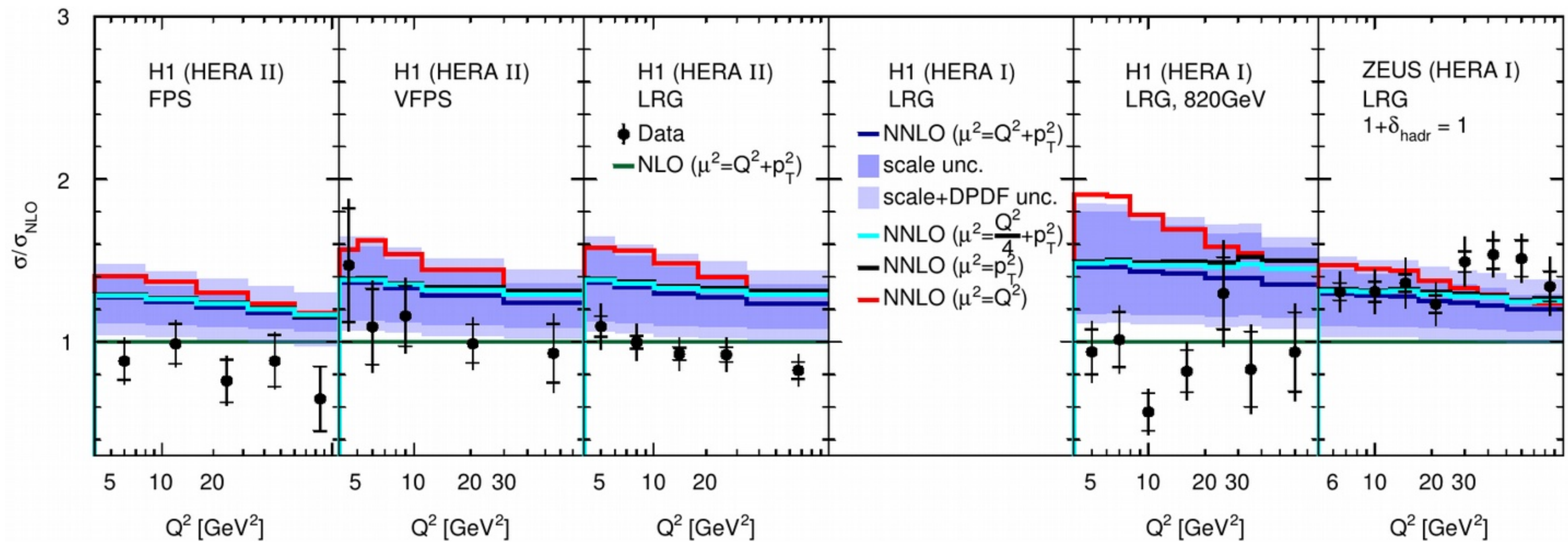


Differential cross section



- Different definitions for renorm. and factorization scales

- NNLO tends to improve the shape description of the data
- The scale choice μ^2=Q^2 predicts steeper Q^2 distribution
- Only small difference between studied scales
  All choices covered (mainly) by scale uncertainty

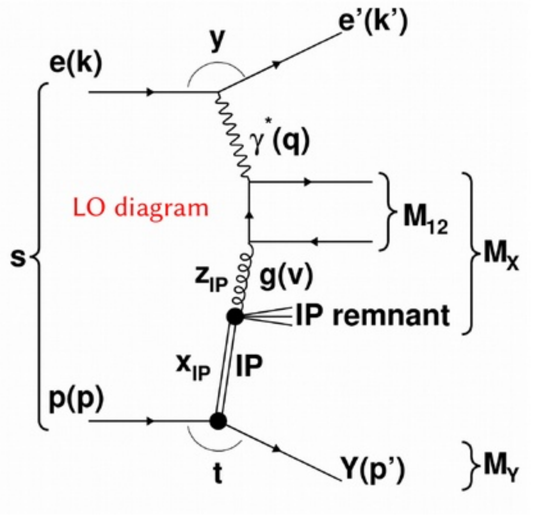


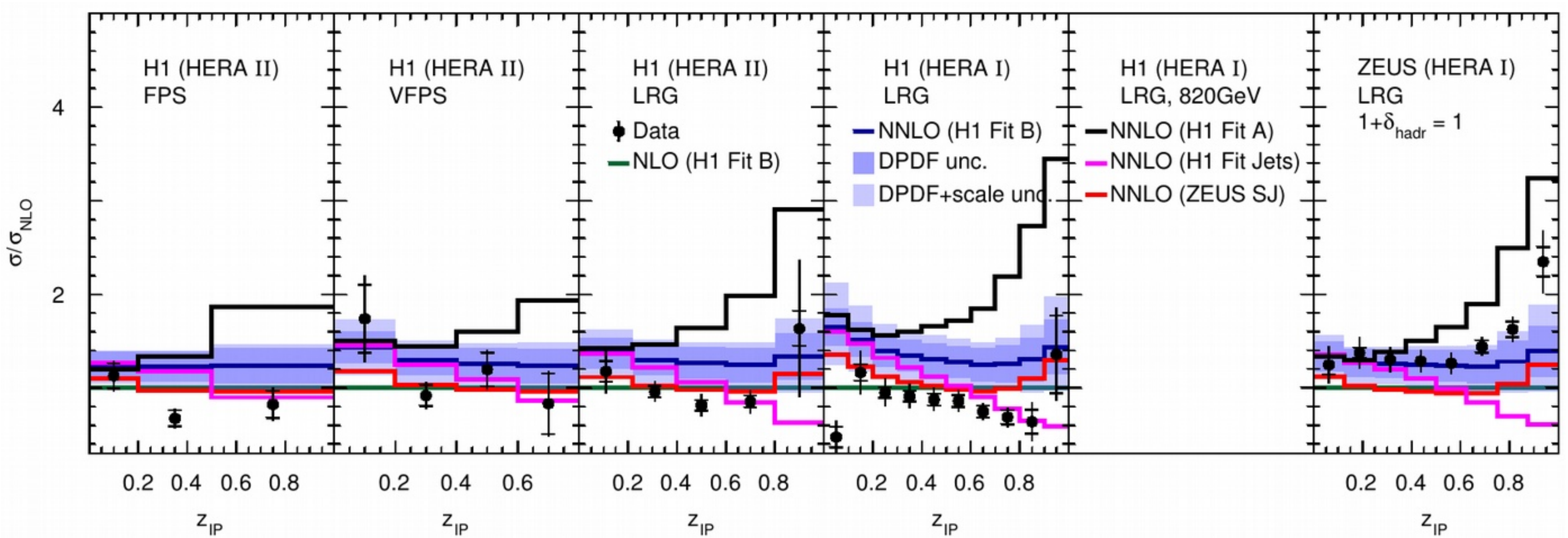
Differential cross section

- z_{IP}: fractional longitudinal momentum of the pomeron transferred to the dijet system

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

- z_{IP} sensitive to partonic structure of the diffractive exchange -> and thus to the DPDFs
- NNLO predicts an increase for higher z_{IP} for LRG analyses -> trend also seen in data ($z_{IP} > 0.8$)
  DPDFs are extrapolated to that region

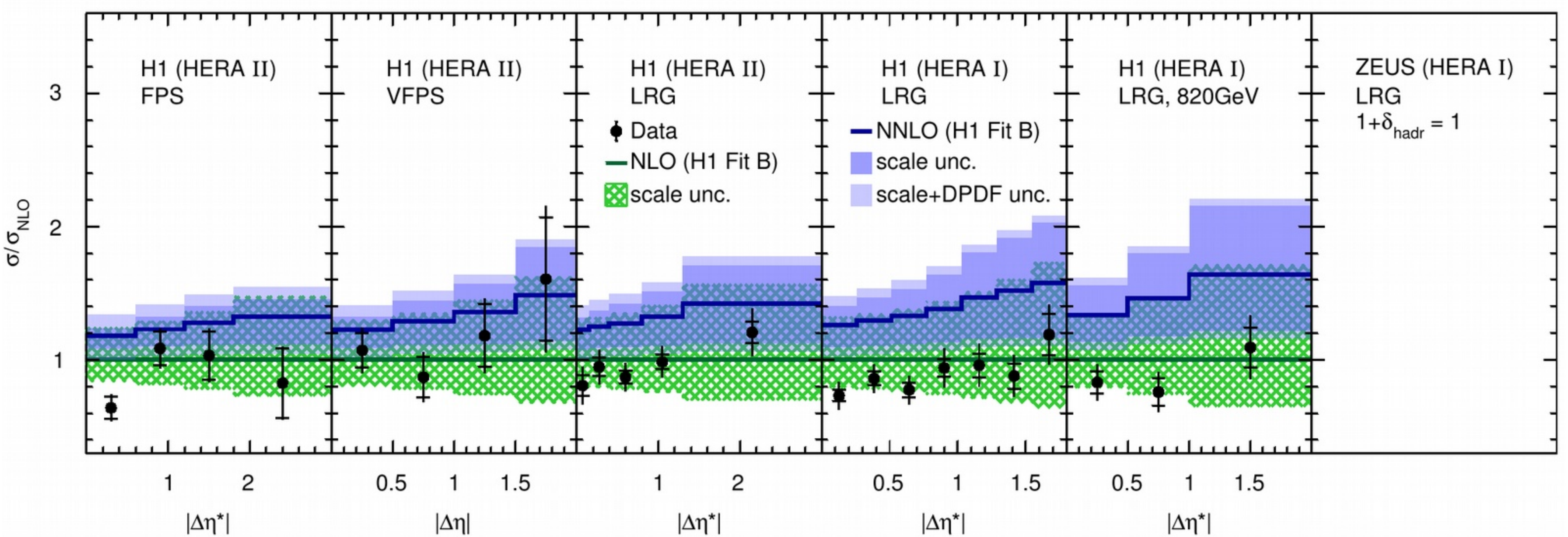




Differential cross section

- Rapidity separation of the two leading jets *Δη*
- Mind: laboratory frame or *γ*p* frame for different analyses
- Observable sensitive to higher order radiation

- NNLO improves shape-description of distributions



Double-differential distributions

For example: H1 HERA-II LRG: $d\sigma/dQ^2dp_T^{jet1}$

- Similar conclusions than from single-differential distributions

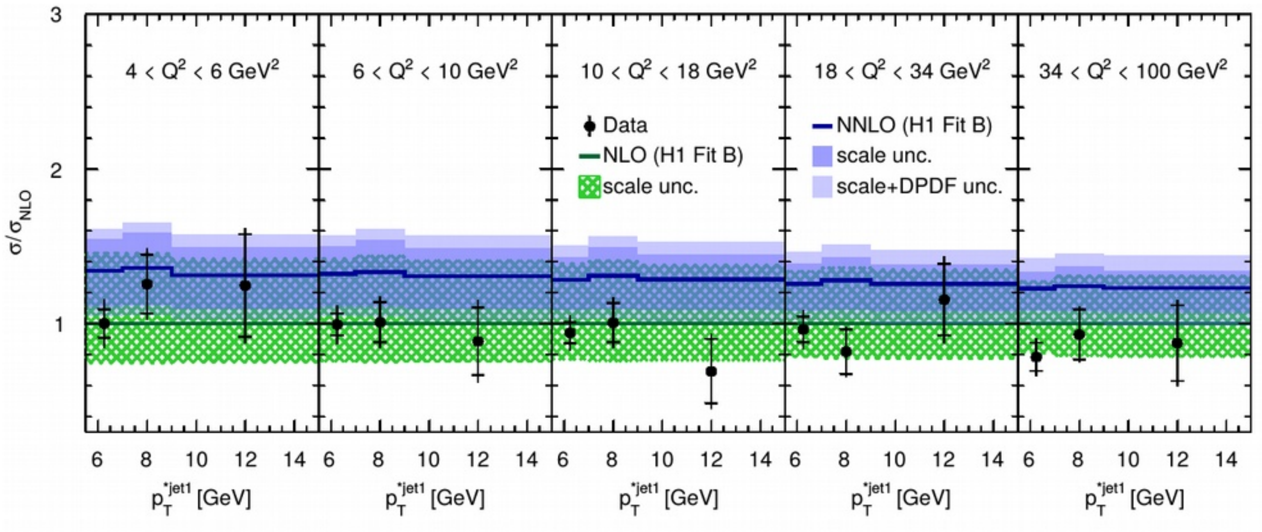
Extraction of α_s performed in NNLO (as H1 did)

- χ^2 improves in NNLO by 2 units for 14 d.o.f. in comparison to NLO
- Value of $\alpha_s(m_Z)$ is unreasonably low, because of 'normalisation issue' (DPDFs!?)

$$\Delta\alpha_s(m_Z) = 4\% \text{ (exp,had)} + 4.5\% \text{ (DPDF)} + {}^{+4}_{-5.5\%} \text{ (scale)}$$

- Scale uncertainty decreases by factor 2.5 – 3 in comparison to NLO
- Scale uncertainty of similar size than α_s-uncertainty from inclusive jets by CMS @ 8TeV

JHEP 03 (2017) 156



Summary

- Dijets in diffractive DIS calculated in NNLO QCD (preliminary!)
- Differential distributions for various observables calculated and comparison to numerous measurements
- The NNLO cross sections are about ~30% higher than NLO
- The NNLO predictions overshoot the data for all H1 measurements and all studied (NLO) DPDFs
- Quantitative tests confirm the improved shape description of data in NNLO compared to NLO
- First(!) NNLO study of a diffractive process...
  more studies are needed for a better understanding of diffractive DIS
  (NNLO DPDFs, hadronization corrections...)
- NNLO ME's are stored in fastNLO format and can be made available

Summary of experimental data set

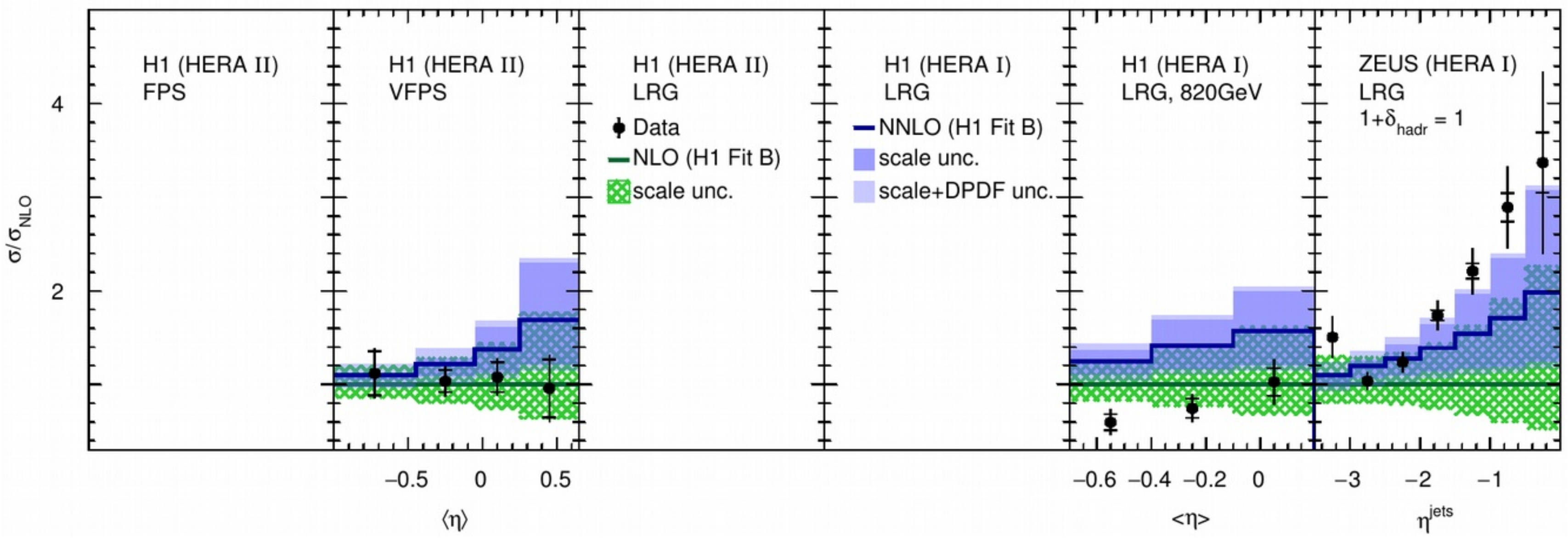
Collab.	Diffr. selection	$\sqrt{s}$ [GeV]	$\mathcal{L}$ [pb^{-1}]	Studied observables	DIS range	Dijet range	Diffractive range
H1 [3]	LRG	319	290 (∼15000ev)		$4 < Q^2 < 100\,\text{GeV}^2$ $0.1 < y < 0.7$	$p_T^{*,\text{jet1}} > 5.5\,\text{GeV}$ $p_T^{*,\text{jet2}} > 4.0\,\text{GeV}$ $n_{\text{jets}} \geq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

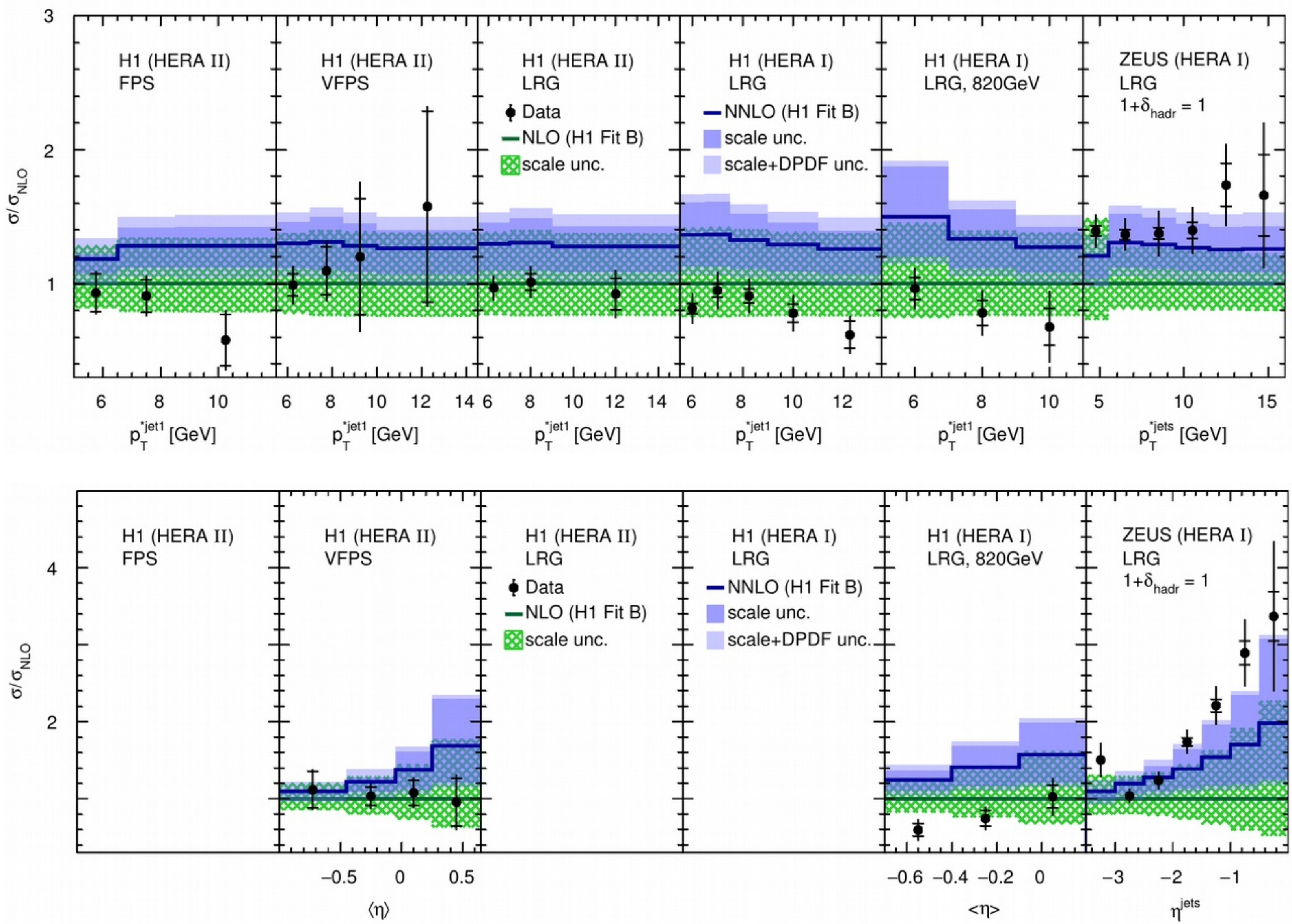
Differential cross sections

- NNLO predicts more jets in the forward (=proton) direction

- The inclusive jet variable filled for each jet in the event shows the biggest observed difference between NLO and NNLO - factor 2!

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




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
$1+\delta_{hadr} = 1$
σ/σ_{NLO}
p_T^{*jet1} [GeV]
p_T^{*jets} [GeV]
⟨η⟩
<η>
η^{jets}