Jets at HERA:
New look using NNLO

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BNL, July 23

DESY-17-137 Eur.Phys.J.C77 (2017), 791 [arxiv:1709.07251]
DESY-18-054 Eur.Phys.J.C78 (2018), 538 [arxiv:1804.05663]

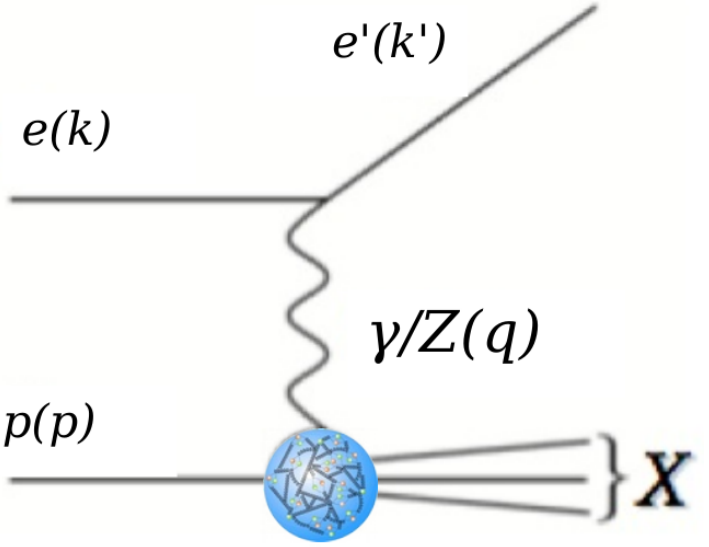
HERA Collider

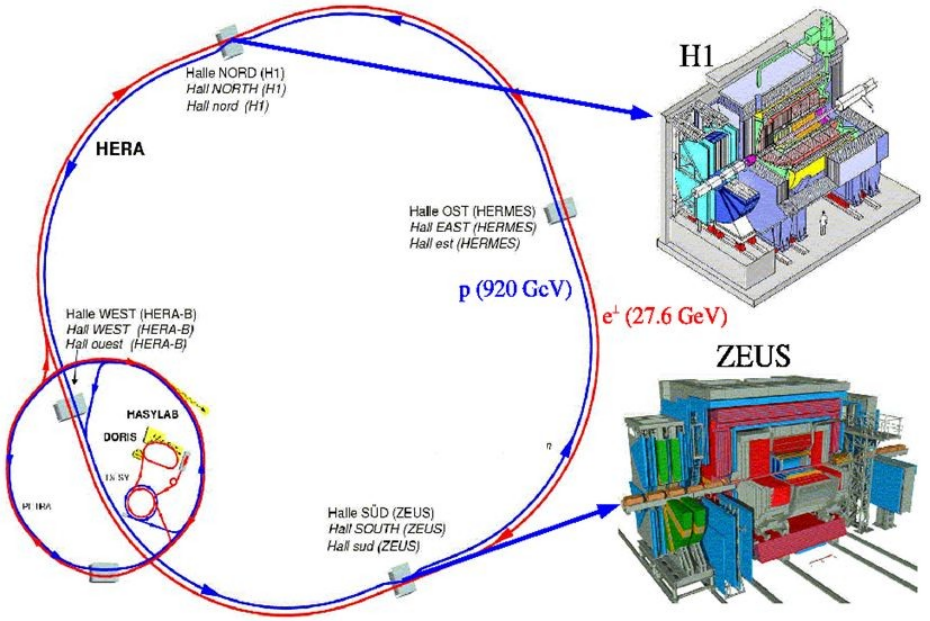
- The only existing ep collider (1992 - 2007)
- About **0.5 fb^{-1}** of data per experiment
- Two multi-purpose detectors (**H1** + **ZEUS**)

$e^{\pm}$ + p

27.6 GeV + 920 GeV

$\sqrt{s} = 319\,\mathrm{GeV}$





Inelasticity

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

Photon virtuality

$$Q^2 = -(k - k')^2$$

$Q^2 \approx 0$ Photoproduction

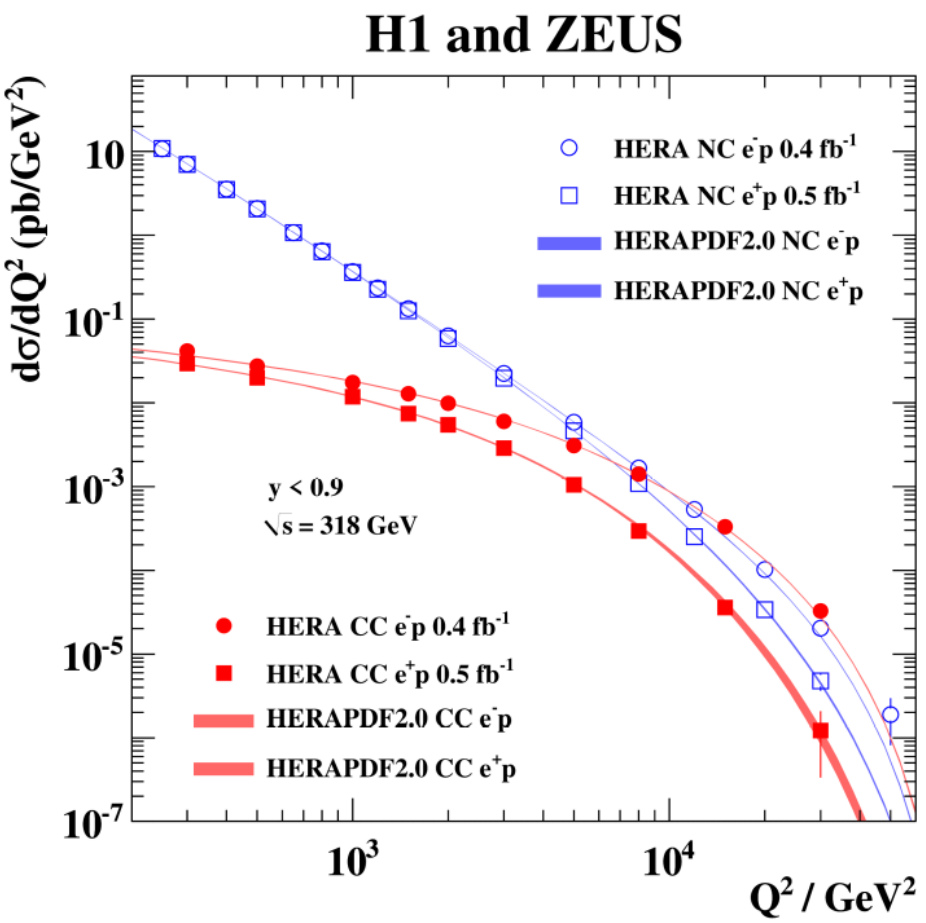
$Q^2 \gg 0$ **Deep-inelastic scattering (DIS)**

HERA Legacy

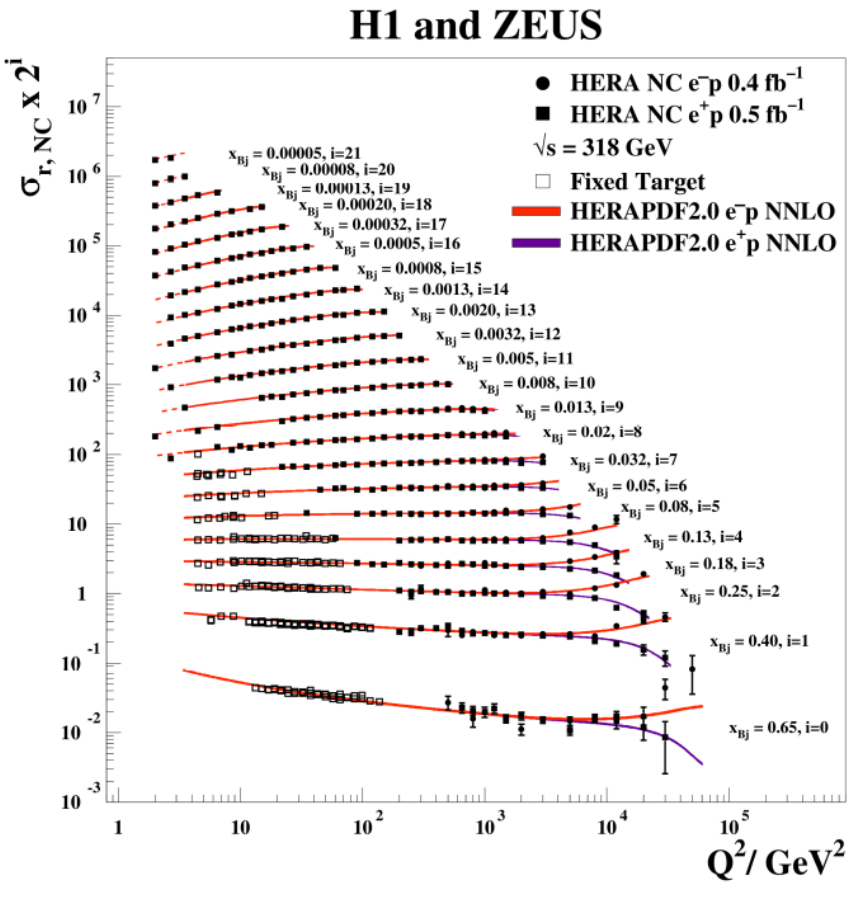
- Combined HERA NC+CC inclusive reduced cross sections (0.5 fb^{-1} per experiment)

[arxiv:1506.06042]

EW Unification



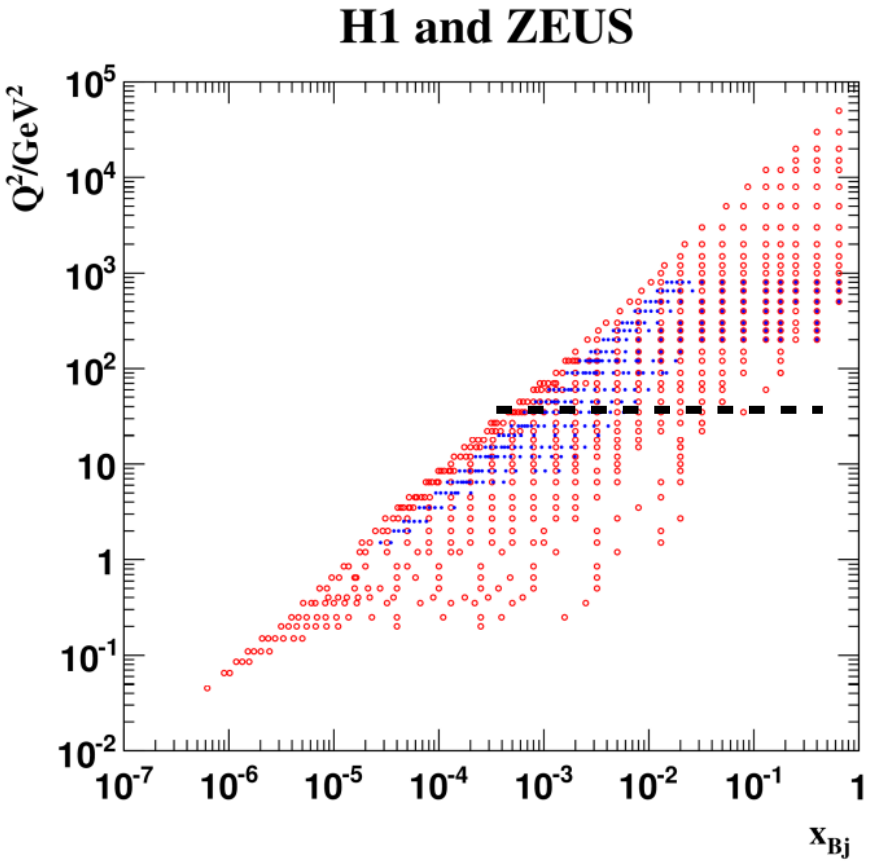
Bjorken Scaling

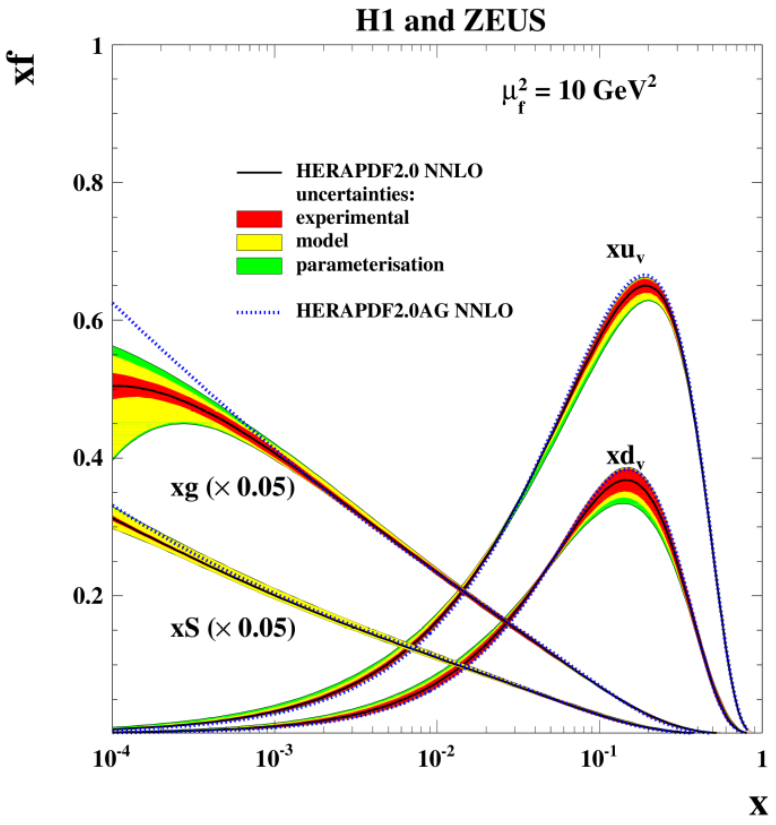


HERA Legacy

[arxiv:1506.06042]

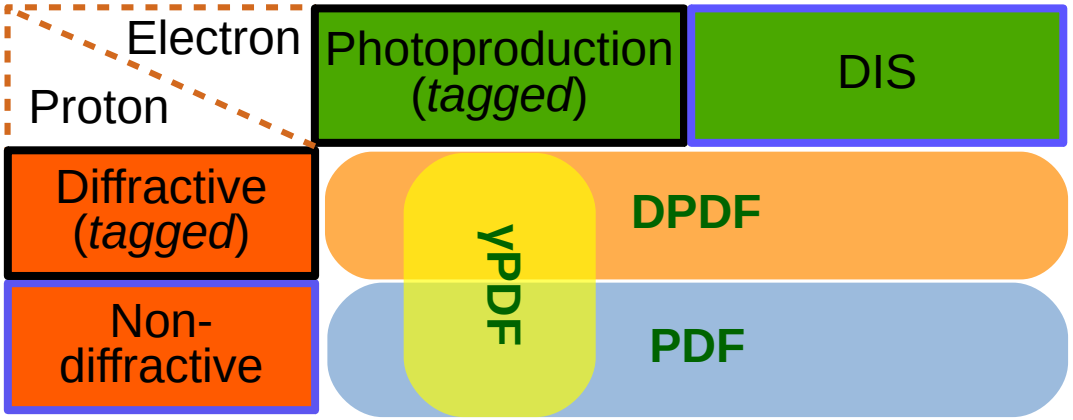
- Large coverage in x, Q^2 limitation due to beam energy and acceptance
- HERAPDF2.0 QCD fit based exclusively on HERA inclusive DIS data



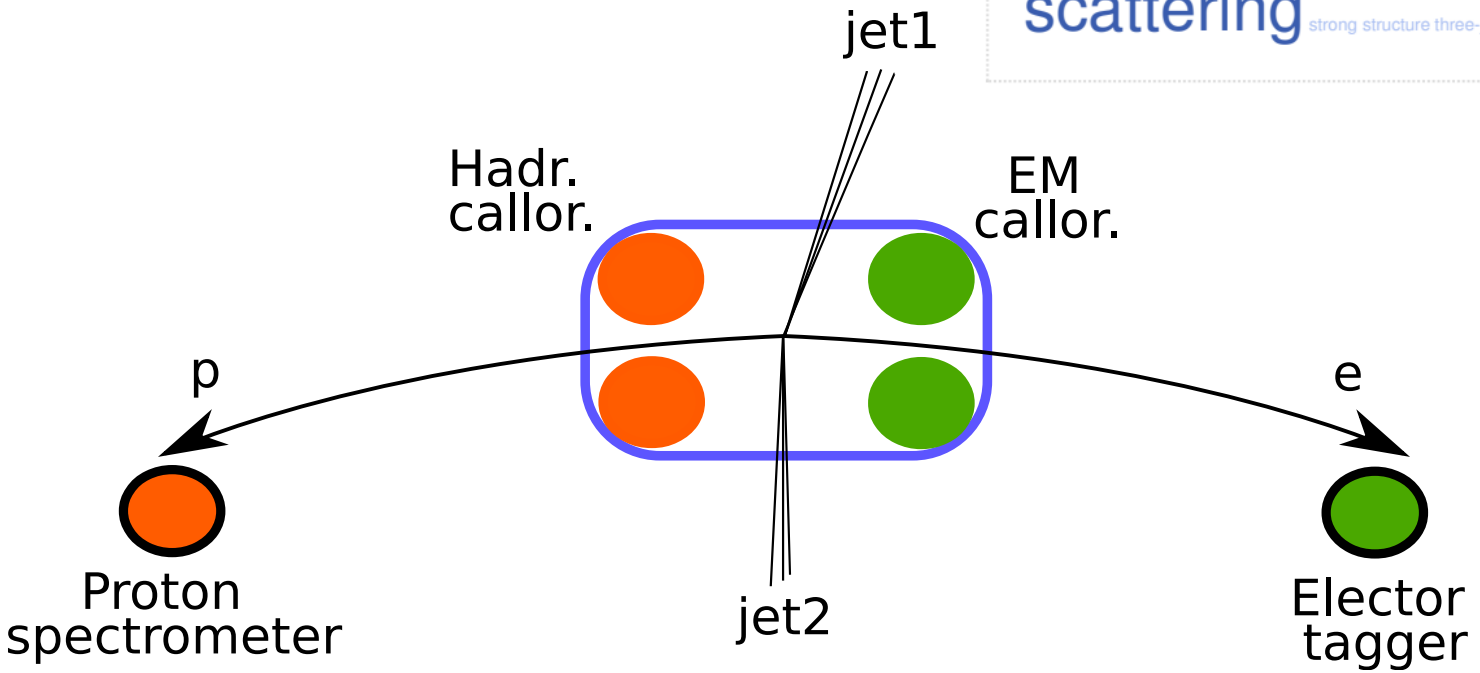


Jet production at HERA

- Basic classification according the state of proton and electron after scattering

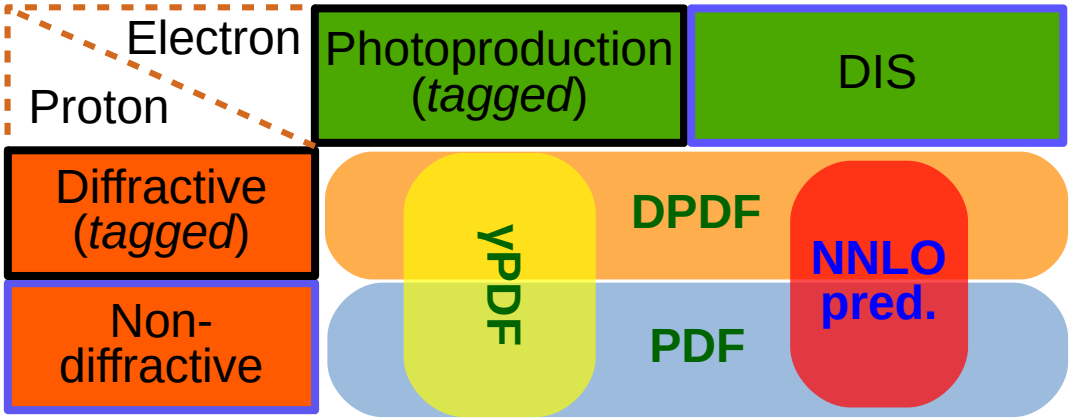


In total 118 Jet analyses from HERA



Jet production at HERA

- Basic classification according the state of proton and electron after scattering



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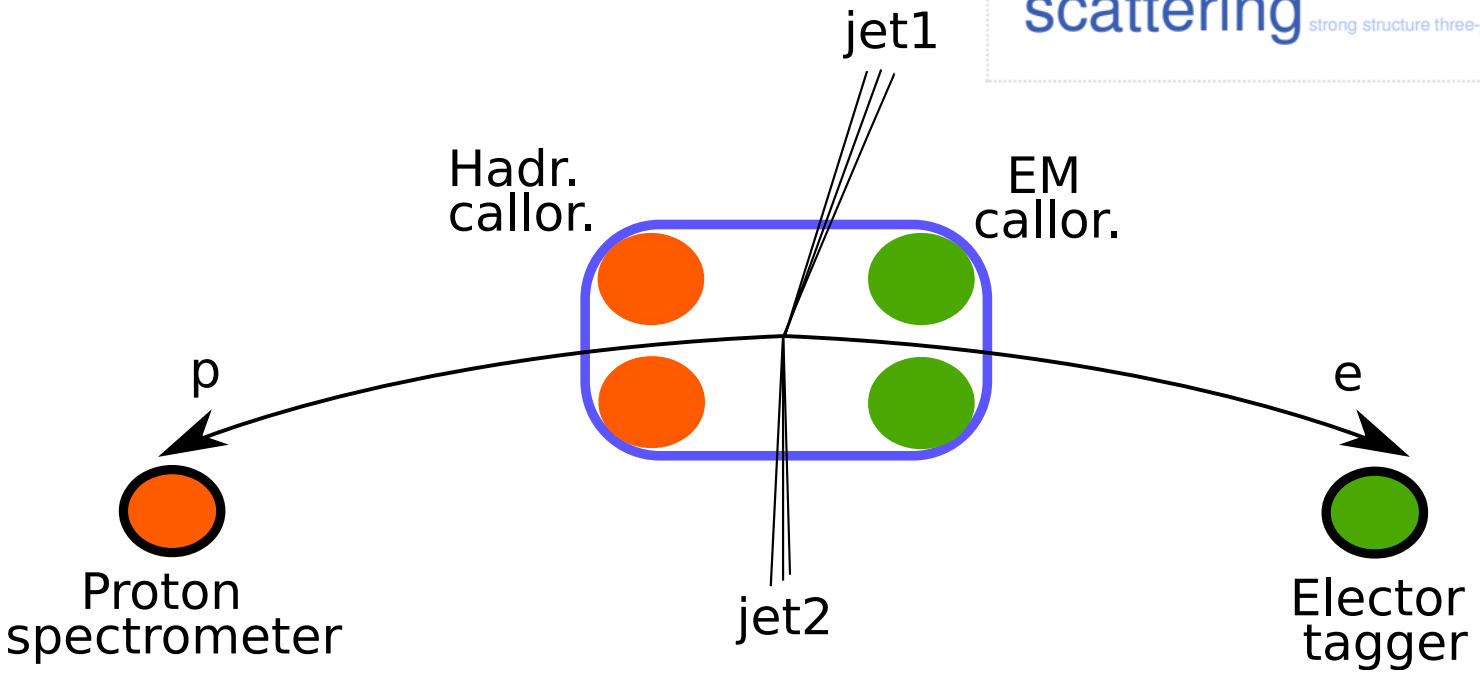
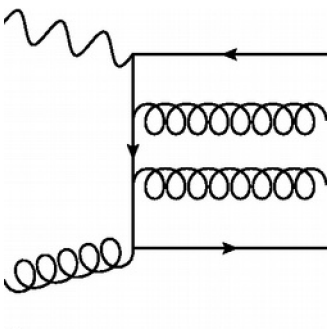


NNLO calculations

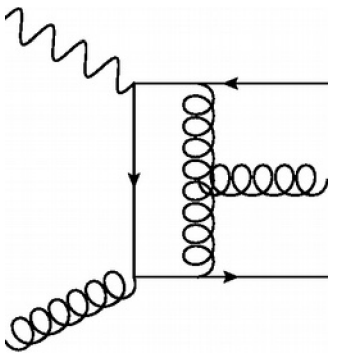
✔ Real-real + real-virtual crosschecked with NLOJET++ & SHERPA

- New NNLO predictions for ep dijets based on **antenna subtraction**
  J. Currie, T. Gehrmann, A. Huss and J. Niehues, JHEP 07 (2017) 018, [1703.05977]
- Matrix element tables precalculated by **NNLOJET** program (~100 CPU years)
- Then convoluted with PDFs and α_S with **fastNLO** using the **APPLfast** interface (<1s)

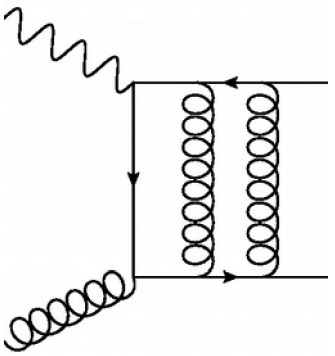
real-real



real-virtual



virtual-virtual



$$\sigma_i = \sum_{k=g,q,\bar{g}} \int dx f_k(x,\mu_F)\, \hat{\sigma}_{i,k}(x,\mu_R,\mu_F) \cdot c_{\mathrm{had},i}$$

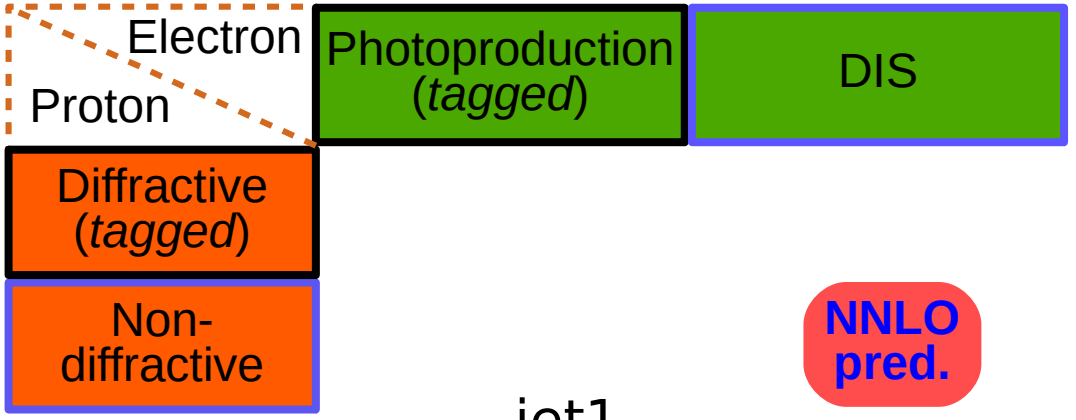
$$\hat{\sigma}_{i,k}(x,\mu_R,\mu_F) = \sum_n \alpha_S^n(\mu_R)\, \hat{\sigma}_{i,k}^{(n)}(x,\mu_R,\mu_F)$$

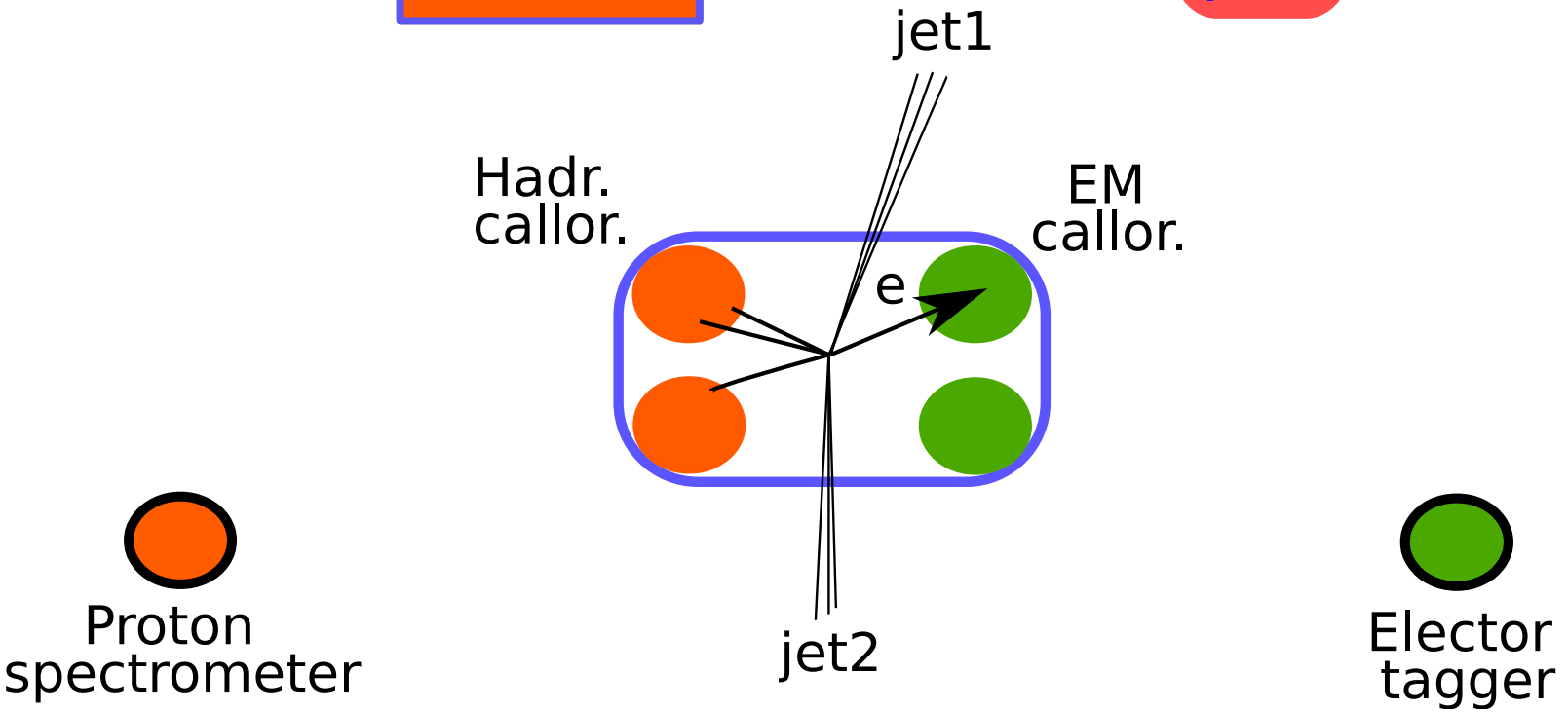
A bit of history

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

Jets in DIS at NNLO

- ✔ Predictions
- ✔ α_s fit
- ✔ PDF fit





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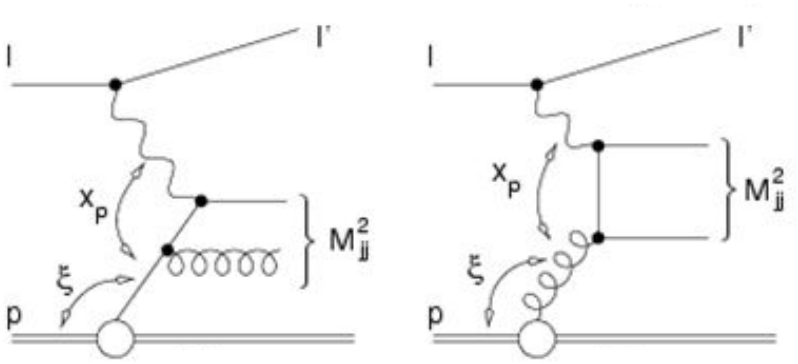
NNLO α_S fit of H1 jets data in DIS

Why α_S ?

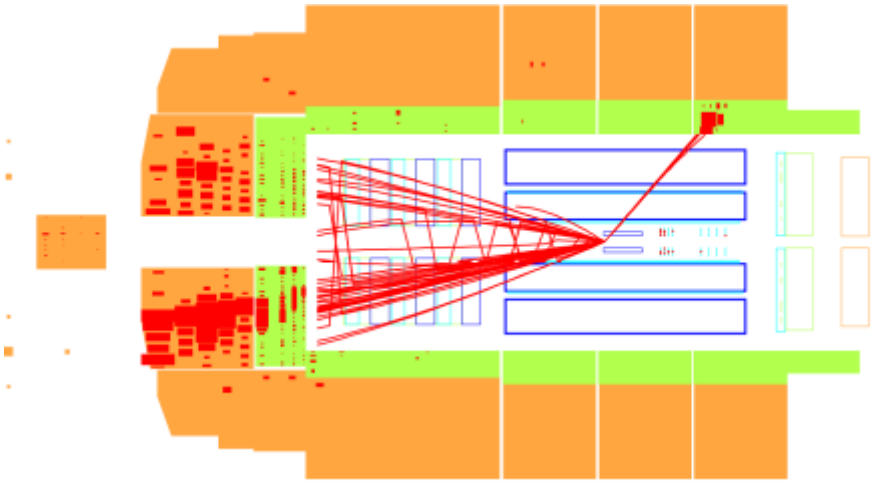
- Among the least known SM parameters
  $G_F = 1.1663787(6) \times 10^{-5}\,\mathrm{GeV}^{-2}$
  $\alpha_S = 1.181(11) \times 10^{-1}$ [PDG16]
- Great importance for LHC physics



Dijet DIS production at H1

Why now?

- NNLO revolution in the last years
- NNLO predictions now available for both *pp* and *ep* dijets
- Complementary to the α_S extraction in *pp* at intermediate scales $7 < \mu < 80\,\mathrm{GeV}$



First NNLO α_S fit of the jet ep data

The data-sets used in NNLO QCD analysis

Data set [ref.]	$\sqrt{s}$ [GeV]	$\mathcal{L}$ [pb^{-1}]	DIS kinematic range	Inclusive jets	Dijets $n_{\text{jets}} \geq 2$
300 GeV [17]	300	33	$150 < Q^2 < 5000\,\text{GeV}^2$ $0.2 < y < 0.6$	$7 < P_{\text{T}}^{\text{jet}} < 50\,\text{GeV}$	$P_{\text{T}}^{\text{jet}} > 7\,\text{GeV}$ $8.5 < \langle P_{\text{T}} \rangle < 35\,\text{GeV}$
HERA-I [23]	319	43.5	$5 < Q^2 < 100\,\text{GeV}^2$ $0.2 < y < 0.7$	$5 < P_{\text{T}}^{\text{jet}} < 80\,\text{GeV}$	$5 < P_{\text{T}}^{\text{jet}} < 50\,\text{GeV}$ $5 < \langle P_{\text{T}} \rangle < 80\,\text{GeV}$ $m_{12} > 18\,\text{GeV}$ $(\langle P_{\text{T}} \rangle > 7\,\text{GeV})^*$
HERA-I [21]	319	65.4	$150 < Q^2 < 15000\,\text{GeV}^2$ $0.2 < y < 0.7$	$5 < P_{\text{T}}^{\text{jet}} < 50\,\text{GeV}$	–
HERA-II [15]	319	290	$5.5 < Q^2 < 80\,\text{GeV}^2$ $0.2 < y < 0.6$	$4.5 < P_{\text{T}}^{\text{jet}} < 50\,\text{GeV}$	$P_{\text{T}}^{\text{jet}} > 4\,\text{GeV}$ $5 < \langle P_{\text{T}} \rangle < 50\,\text{GeV}$
HERA-II [15, 24]	319	351	$150 < Q^2 < 15000\,\text{GeV}^2$ $0.2 < y < 0.7$	$5 < P_{\text{T}}^{\text{jet}} < 50\,\text{GeV}$	$5 < P_{\text{T}}^{\text{jet}} < 50\,\text{GeV}$ $7 < \langle P_{\text{T}} \rangle < 50\,\text{GeV}$ $m_{12} > 16\,\text{GeV}$

Inclusive jets (H1 HERA-II)

Double-diff.

- Q^2 and p_T^{jet}
- Phase space:

$0.2 < y < 0.6$

$-1 < \eta_{\text{lab}}^{\text{jet}} < 2.5$

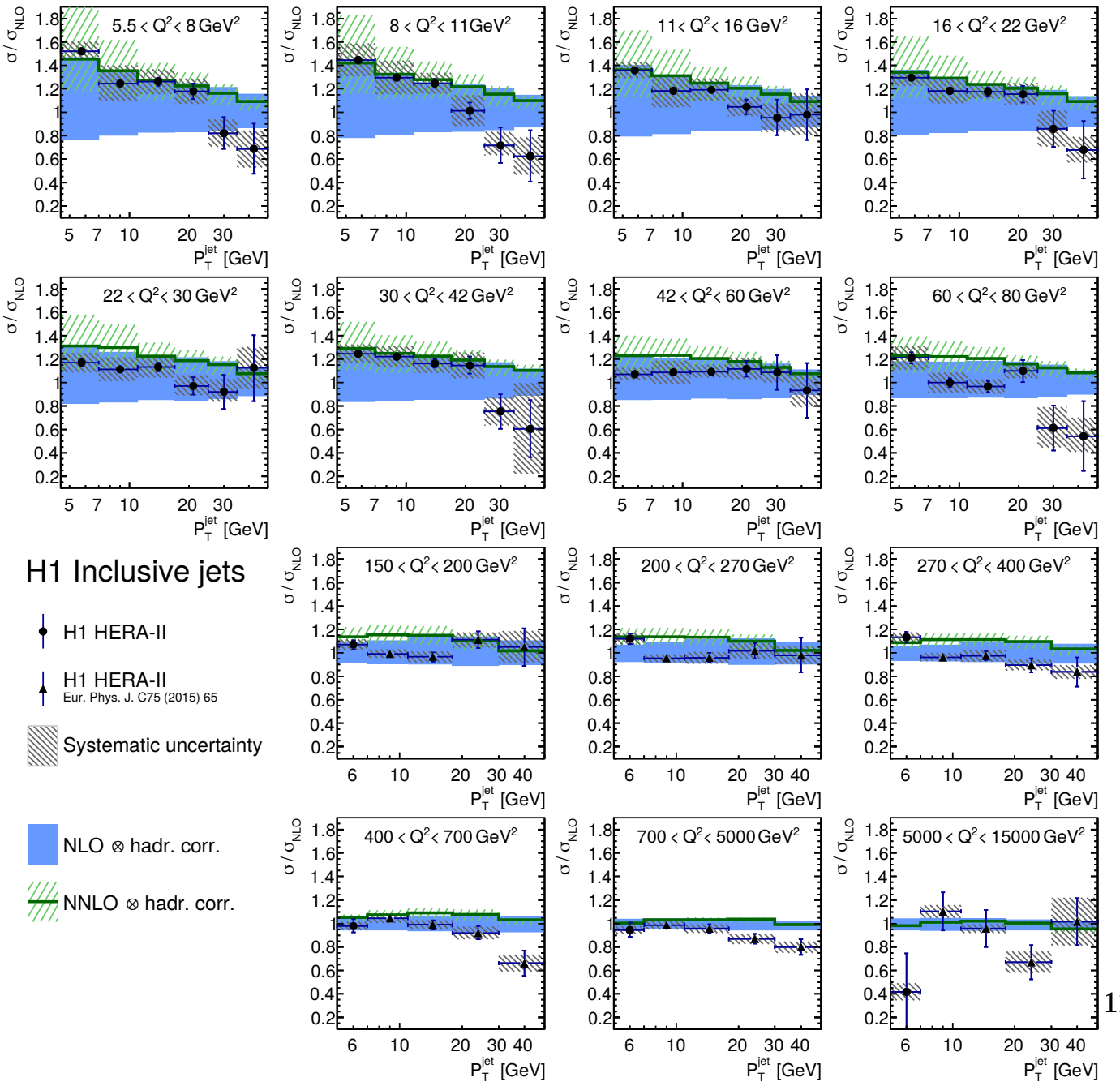
jets found in $\gamma^* p$ with k_T algo (R=1)

NLO predictions

- *NNPDF 3.0 NLO*
- Larger scale unc.
- Chi2/ndf = 1.7

NNLO predictions

- *NNPDF 3.0 NNLO*
- Smaller scale unc.
- Chi2/ndf = 1.3



Dijets (H1 HERA-II)

Double-diff.

- Q^2 and $\langle p_T \rangle_2$
- Mean dijet p_T

$$\langle p_T \rangle_2 = \frac{p_T^{\text{jet1}} + p_T^{\text{jet2}}}{2}$$

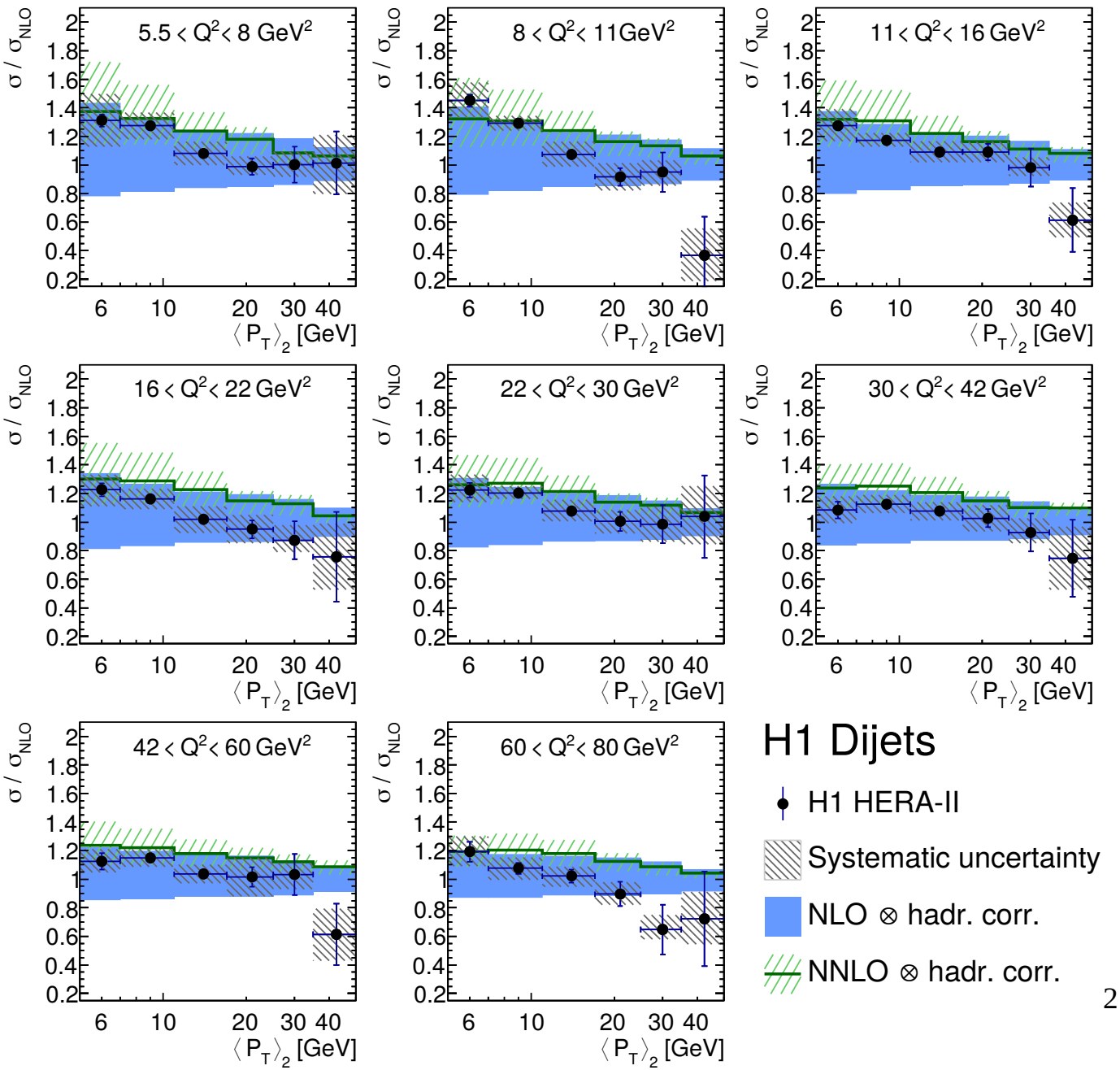
jets found in $\gamma^* p$ with k_T algo (R=1)

NLO predictions

- *NNPDF 3.0 NLO*
- Larger scale unc.
- Chi2/ndf = 1.4

NNLO predictions

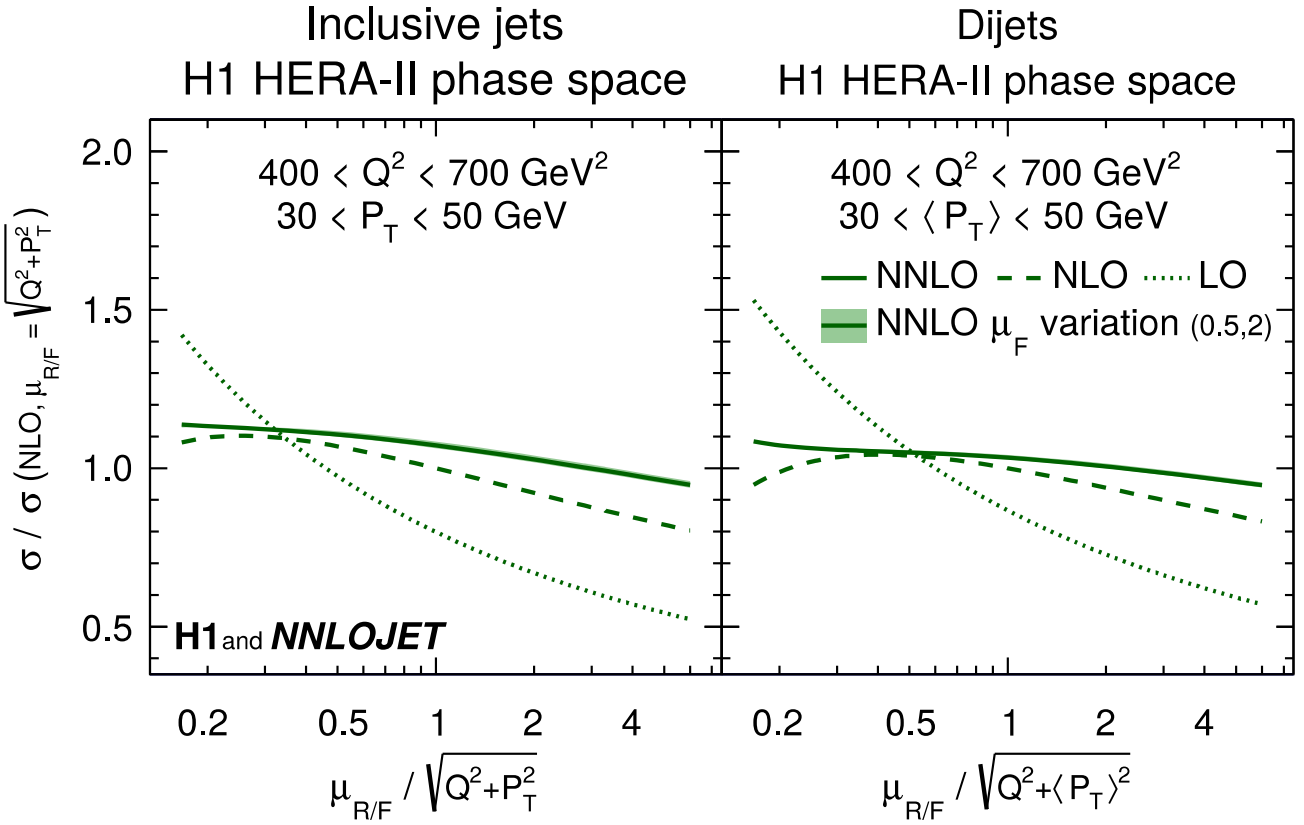
- *NNPDF 3.0 NNLO*
- Smaller scale unc.
- Chi2/ndf = 0.6



Scale dependence

- The NNLO predictions depend **less** on the renormalization scale (=have smaller theor. unc.)
- To estimate the uncertainty the scale varied up and down by the factor of 2
- As a scale we use $\mu_R = \mu_F = \sqrt{Q^2 + p_T^2}$

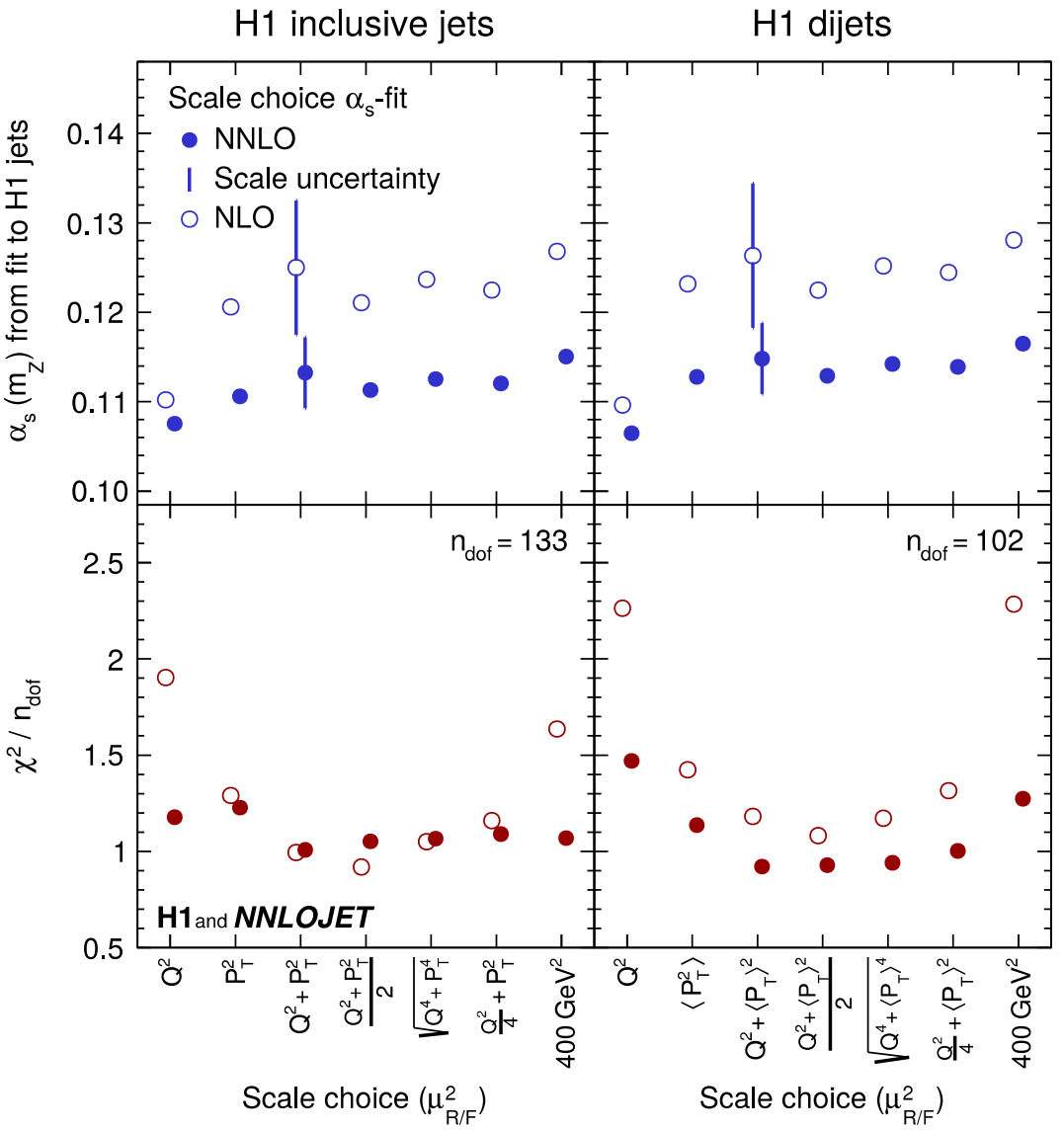
Others functional forms also tested



Functional form of the scale

- 7 possible function studied
- NNLO α_S is typically smaller than the NLO one
- The NNLO χ^2 is typically better
- NNLO scale unc. is smaller

$$
\begin{aligned}
\mu^2 &= Q^2 \\
\mu^2 &= p_T^2 \\
\mu^2 &= Q^2 + p_T^2 \\
\mu^2 &= \frac{Q^2 + p_T^2}{2} \\
\mu^2 &= \sqrt{Q^4 + p_T^4} \\
\mu^2 &= Q^2/4 + p_T^2 \\
\mu^2 &= 400\,\mathrm{GeV}^2
\end{aligned}
$$



All data above m_b threshold used

α_S in PDF and α_S in ME

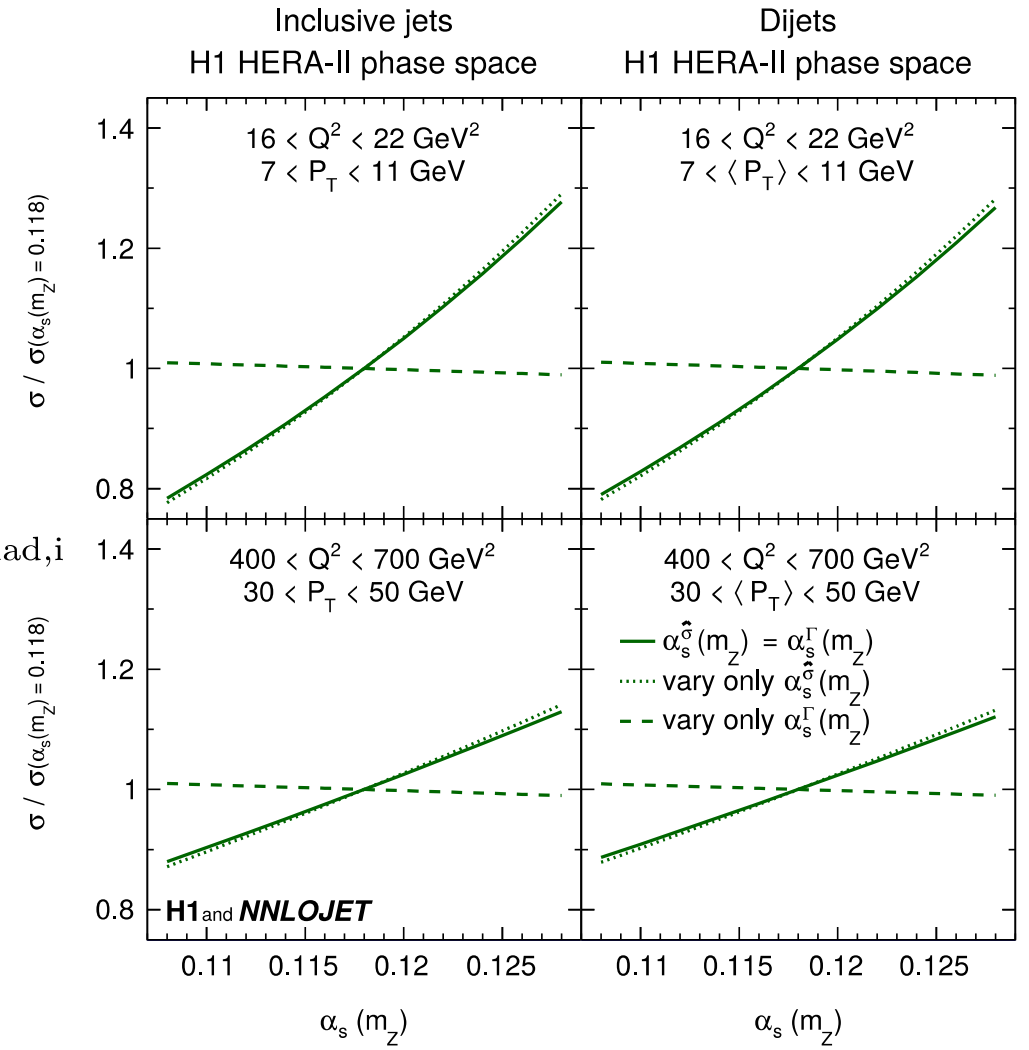
- Alpha strong affects both, PDFs and matrix element
- Both effects considered, α_S in ME more prominent

$$\sigma_i = \sum_{k=g,q,\bar{q}} \int dx \underbrace{f_k(x,\mu_F)}_{\alpha_S \text{ dep.}} \underbrace{\hat{\sigma}_{i,k}(x,\mu_R,\mu_F)}_{\alpha_S \text{ dep.}} \cdot c_{\text{had,i}}$$

$$\hat{\sigma}_{i,k}(x,\mu_R,\mu_F) = \sum_n \alpha_S^n(\mu_R)\, \hat{\sigma}_{i,k}^{(n)}(x,\mu_R,\mu_F)$$

DGLAP equations

$$\mu_F^2 \frac{df}{d\mu_F^2} = P(z,\alpha_s) \otimes f(x,\mu_F^2)$$

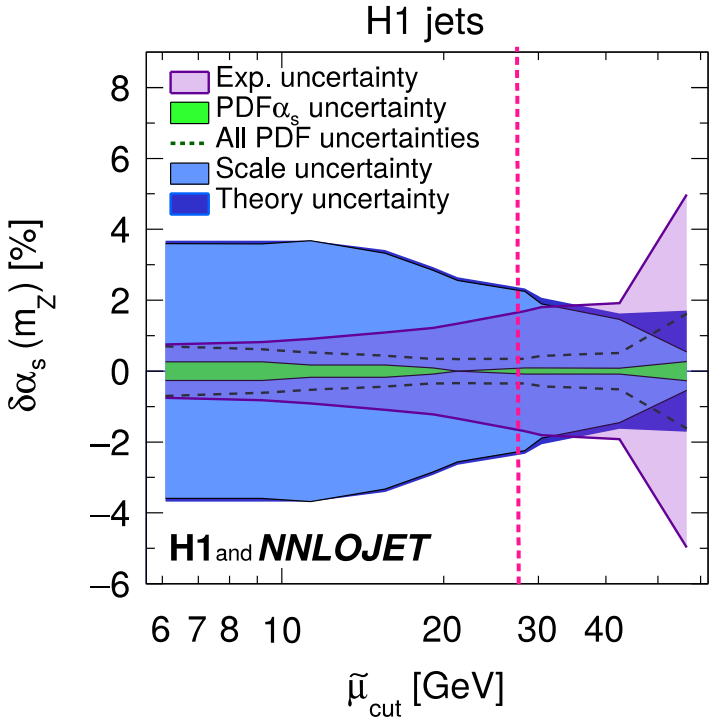


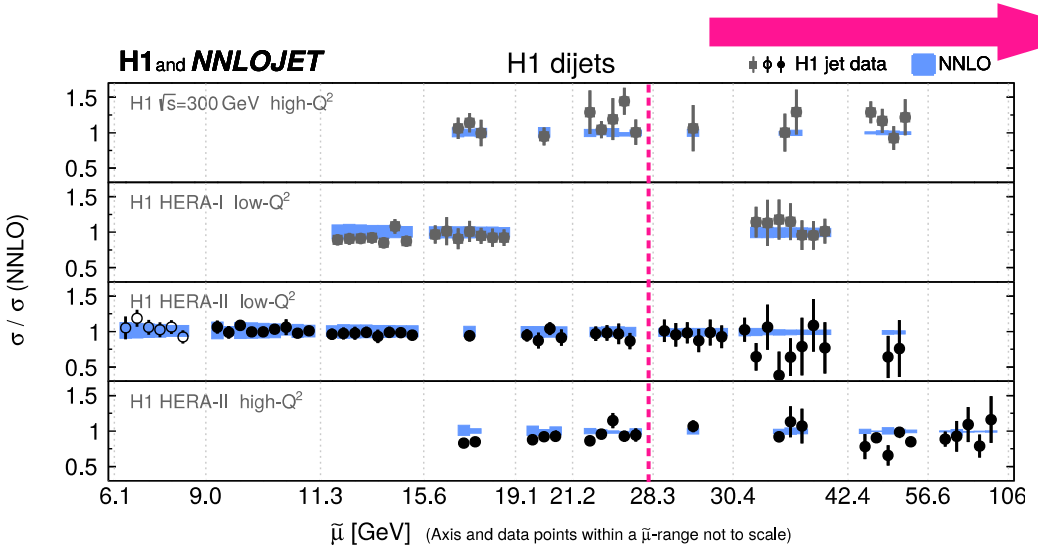
PDFs at scale $\mu_0 = 20\,\text{GeV}$ very well constrained by lot of data
$\longrightarrow$ α_S - "independent"

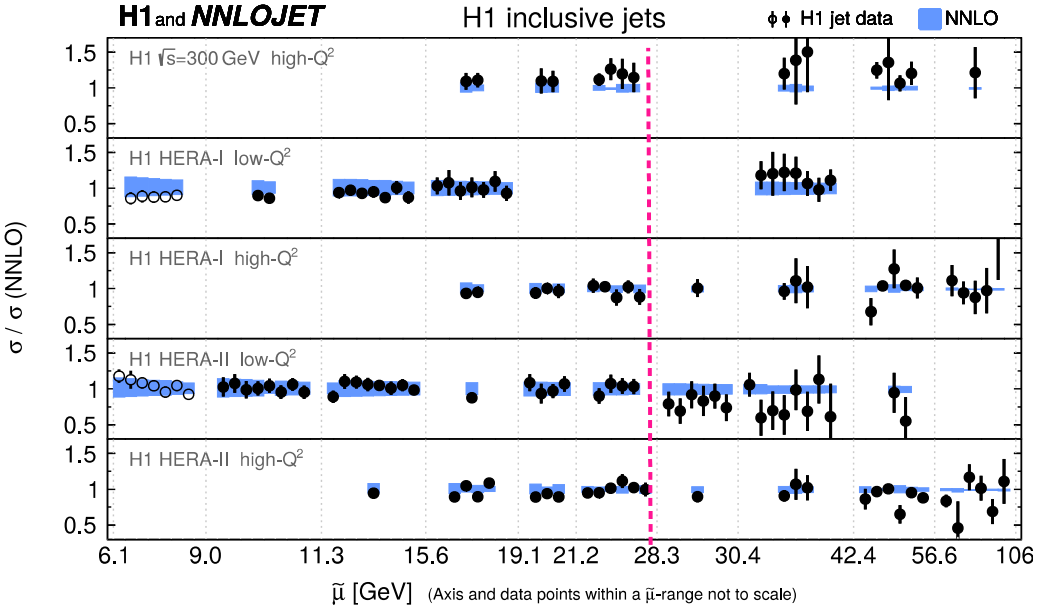
Original PDFs at scale $\mu_0 = 20\,\text{GeV}$ evolved to higher/lower scales by DGLAP with $\alpha_S = \alpha_S(\text{fit par.})$

Which data do we use in the fit?

- The scale uncertainty gets higher with smaller scales ($\mu = \sqrt{p_T^2 + Q^2}$)
- We use only data $\mu > \mu_{\rm cut}$







Small $\mu_{\rm cut}$ $\longrightarrow$ high theor. unc.
Large $\mu_{\rm cut}$ $\longrightarrow$ high exp. unc.

$\Rightarrow$ Compromise $\mu_{\rm cut} = 28\,\text{GeV}$

Alpha strong running and central value

$$\alpha_S(m_Z) = 0.1157$$

Data unc. $(20)_{\mathrm{exp}}$

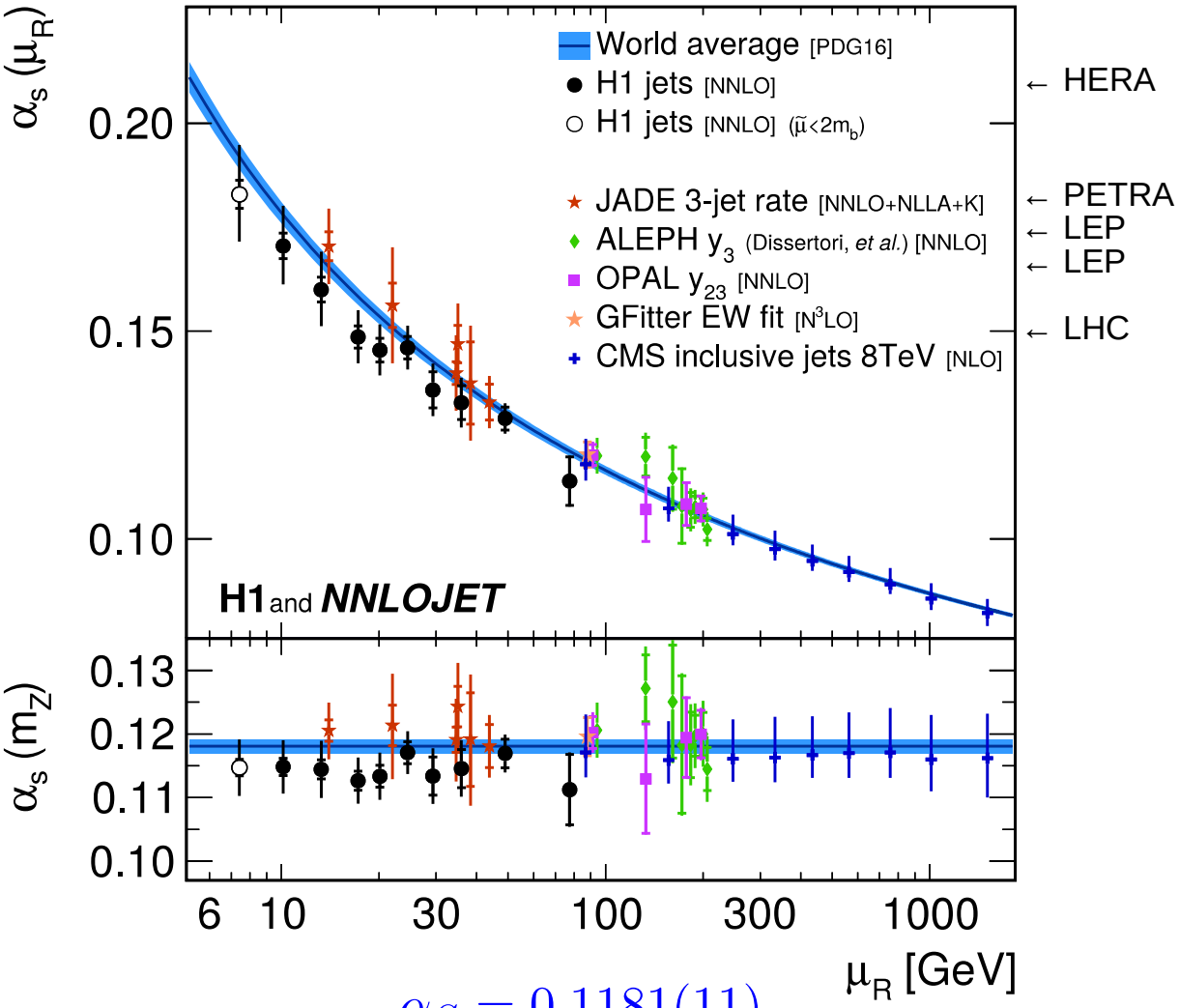
Hadronisation $(6)_{\mathrm{had}}$

NNPDF 3.1 unc. $(3)_{\mathrm{PDF}}$

α_S^{PDF} variants $(2)_{\mathrm{PDF}\alpha_S}$

PDFs from 5 collab. $(3)_{\mathrm{PDFSet}}$

Scale unc. $(27)_{\mathrm{scale}}$



$\alpha_S = 0.1181(11)$

- Scale and experimental unc. dominant
- Consistent with PDG "world average" value

Simultaneous α_S + PDF fit (H1PDF2017)

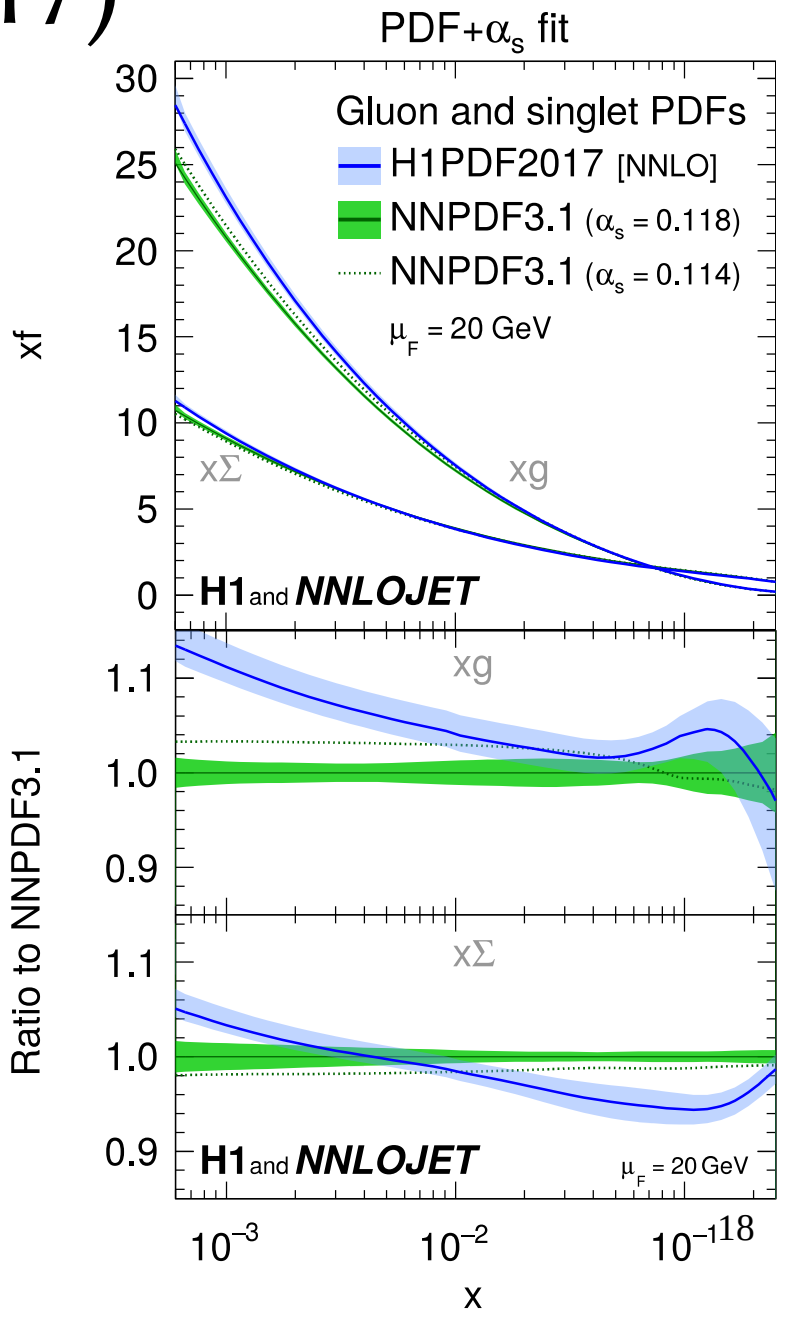
- HERAPDF-like parametrization with 12 parameters at the starting scale $\mu_0^2 = 1.9\,\mathrm{GeV}^2$
- Only data with $Q^2 > 10\,\mathrm{GeV}^2$
- The α_S taken as an additional free parameter of the fit
- Experimental, scale, parametrization and model uncertainty considered

Normalized jet data

Data set [ref.]	Q^2 domain	Inclusive jets	Dijets	Normalised inclusive jets	Normalised dijets	Stat. corr. between samples
300 GeV [17]	high-Q^2	✓	✓	–	–	–
HERA-I [23]	low-Q^2	✓	✓	–	–	–
HERA-I [21]	high-Q^2	✓	–	✓	–	–
HERA-II [15]	low-Q^2	✓	✓	✓	✓	✓
HERA-II [15, 24]	high-Q^2	✓	✓	✓	✓	✓

Inclusive NC+CC

Data set [ref.]	Lepton type	$\sqrt{s}$ [GeV]	Q^2 range [GeV^2]	NC cross sections	CC cross sections	Lepton beam polarisation
Combined low-Q^2 [64]	e^+	301,319	(0.5) 12 – 150	✓	–	–
Combined low-E_p [64]	e^+	225,252	(1.5) 12 – 90	✓	–	–
94 – 97 [61]	e^+	301	150 – 30 000	✓	✓	–
98 – 99 [62, 63]	e^-	319	150 – 30 000	✓	✓	–
99 – 00 [63]	e^+	319	150 – 30 000	✓	✓	–
HERA-II [65]	e^+	319	120 – 30 000	✓	✓	✓
HERA-II [65]	e^-	319	120 – 50 000	✓	✓	✓



Simultaneous PDF + α_S fit

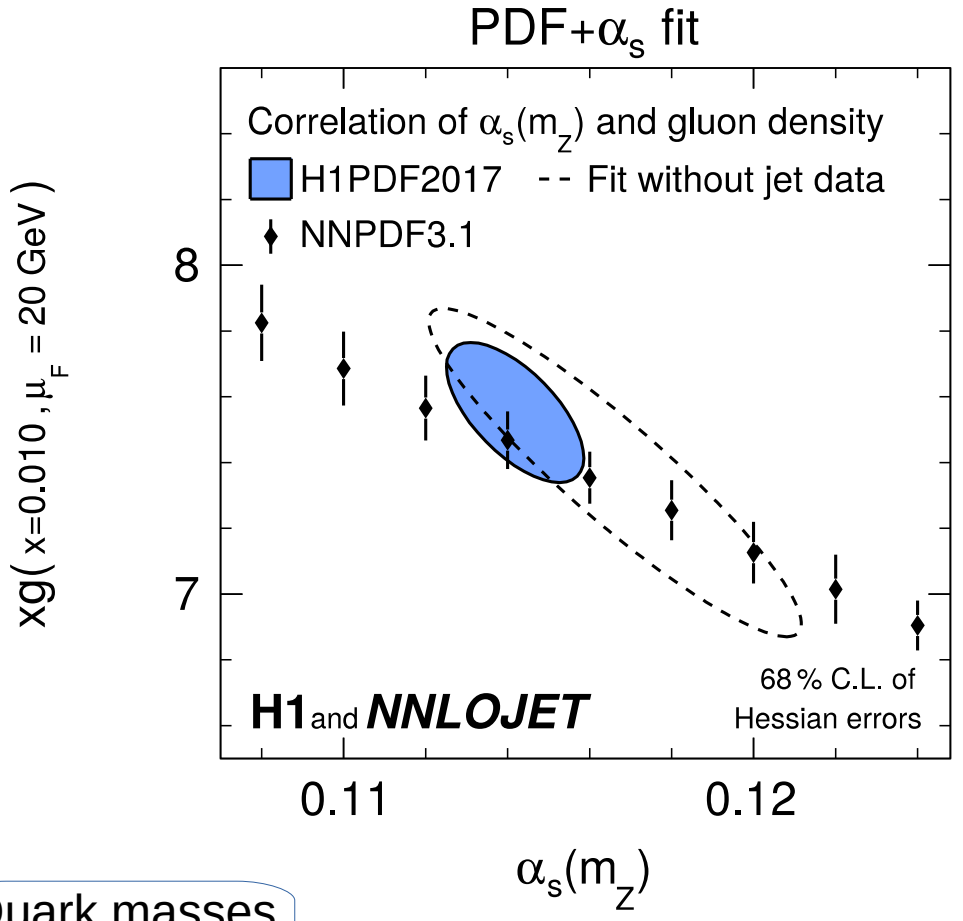
- Resulting fit of inclusive+ jet/inclusive data sets:

  $\chi^2/n_{df} = 1540/(1529-13)$

  (with 141 jet data points)

- Anti-correlation between gluon density and α_S
- Huge precision gain by including jet data

  → **Jet data matter**



$$\alpha_S(m_Z) = 0.1142(11)_{\mathrm{exp,had,PDF}}(2)_{\mathrm{mod}}(2)_{\mathrm{par}}(26)_{\mathrm{scale}}$$

Quark masses unc.

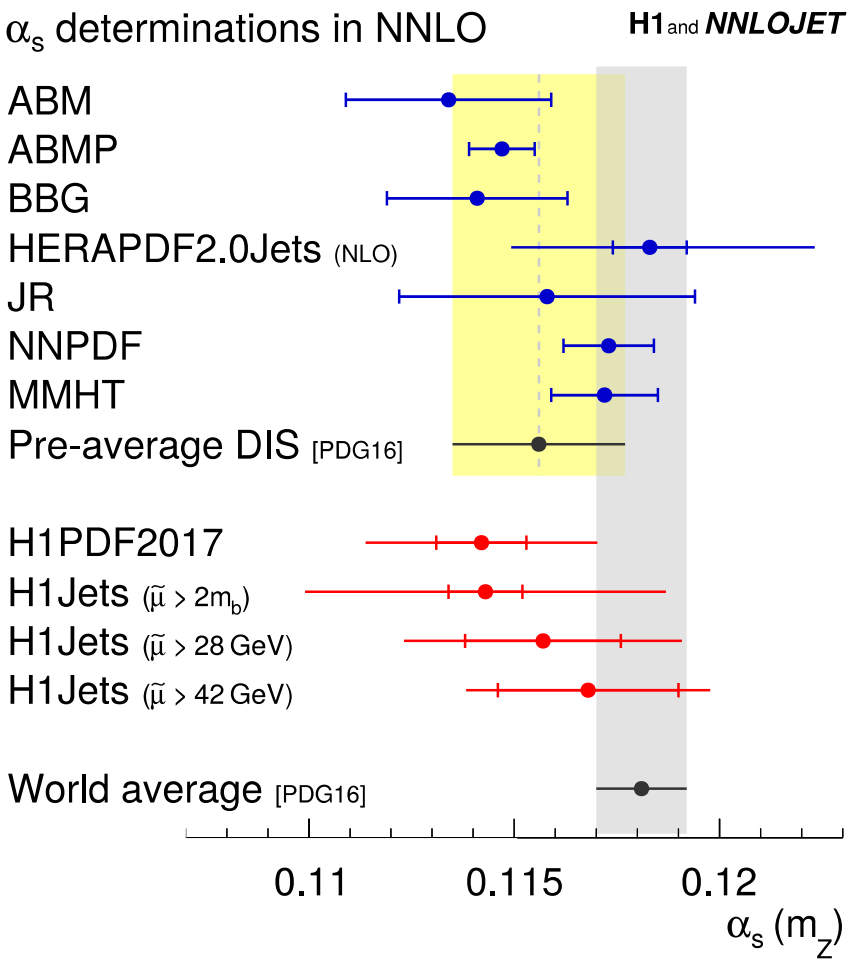
From simultaneous ren.+fact. scale variation

Data+had unc.

Parametrization unc.

Alpha strong values

- Both values of α_S consistent with α_S from global PDF fits
- The NNLO reduces the scale uncertainty **by half**
- The theoretical uncertainty (scale) still dominates
- The indication for lower α_S values when low-scale data included
  $\longrightarrow$ *missing higher orders?*

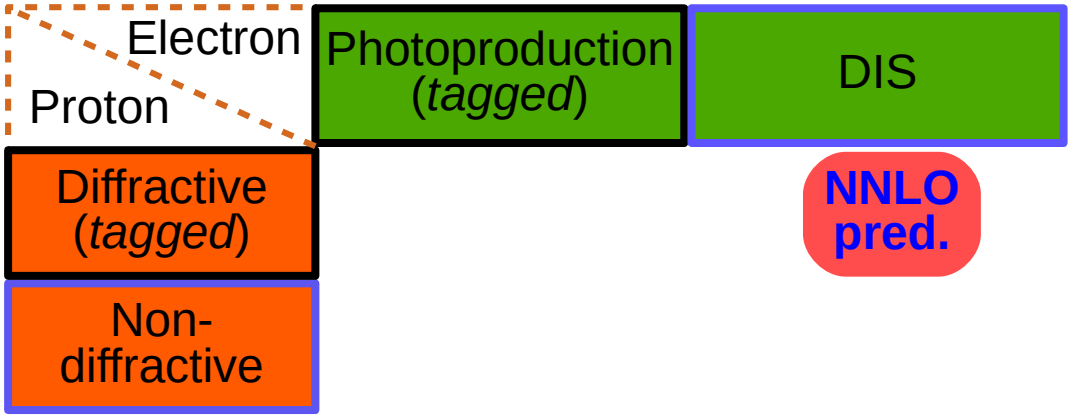


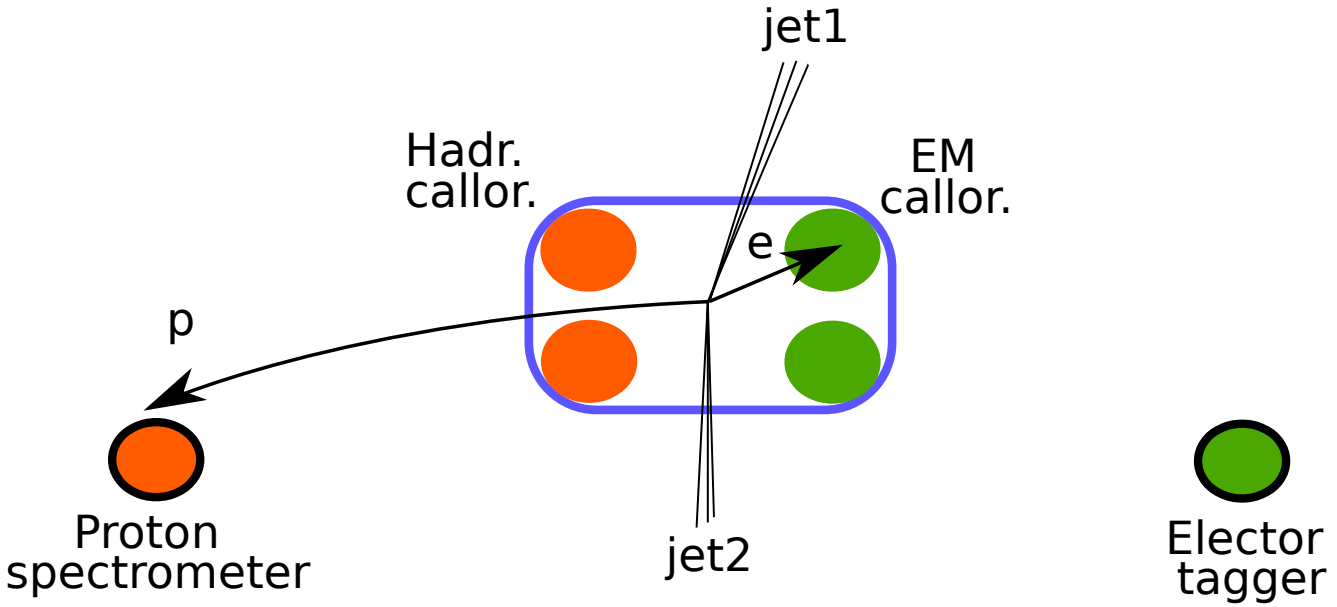
$$\alpha_S^{\mathrm{H1jets},\tilde{\mu}>28\mathrm{GeV}}(m_Z) = 0.1157(20)_{\mathrm{exp}}(28)_{\mathrm{theor.}}$$

$$\alpha_S^{\mathrm{H1PDF2017}}(m_Z) = 0.1142(11)_{\mathrm{exp}}(26)_{\mathrm{theor.}}$$

Jets in DDIS at NNLO

- ✔ **Predictions**
- ✗ α_s fit
- ✗ DPDF fit





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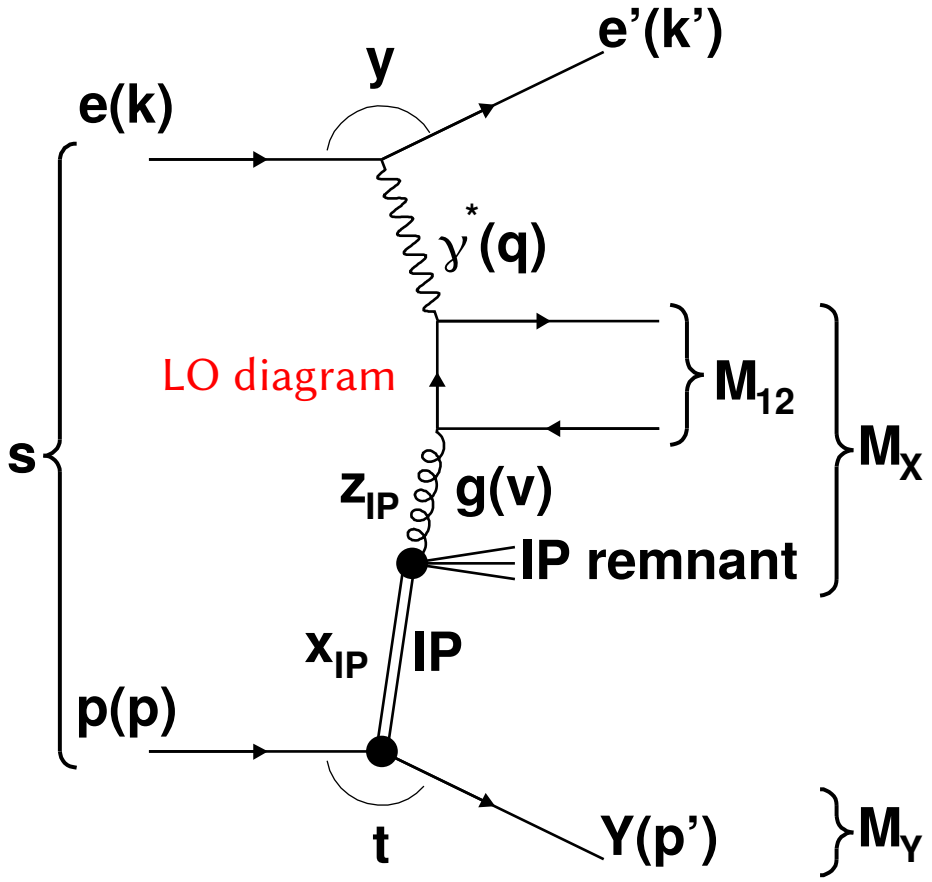
Diffractive Dijet Production in ep

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

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

- For diffractive processes (including dijets) with 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 812 records 500+

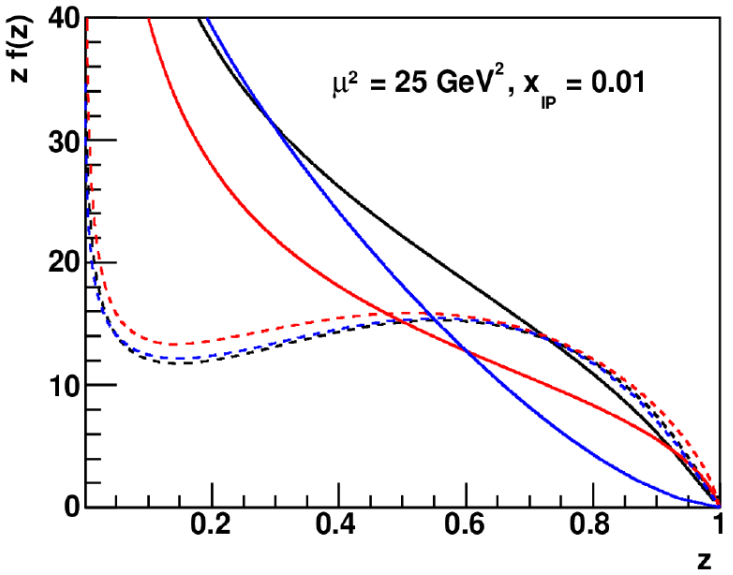
Proof of factorization for diffractive hard scattering
John C. Collins (Penn State U.). Sep 1997. 12 pp.
Published in **Phys.Rev. D57 (1998) 3051-3056,** Erratum: **Phys.Rev. D61 (2000) 019902**
PSU-TH-189
DOI: 10.1103/PhysRevD.57.3051, 10.1103/PhysRevD.61.019902
e-Print: **hep-ph/9709499** | **PDF**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
ADS Abstract Service; OSTI.gov Server
Detailed record - Cited by 404 records 250+

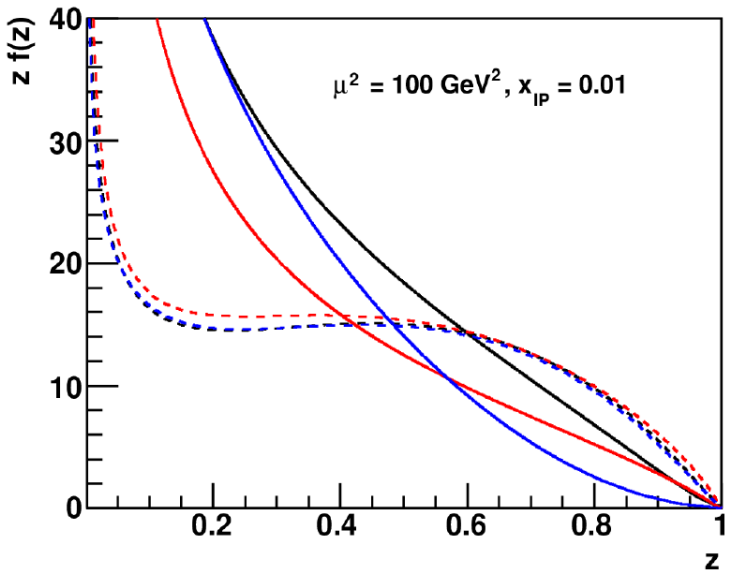
NLO DPDFs

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

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





70% of diffractive exchange momentum carried by gluons

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)

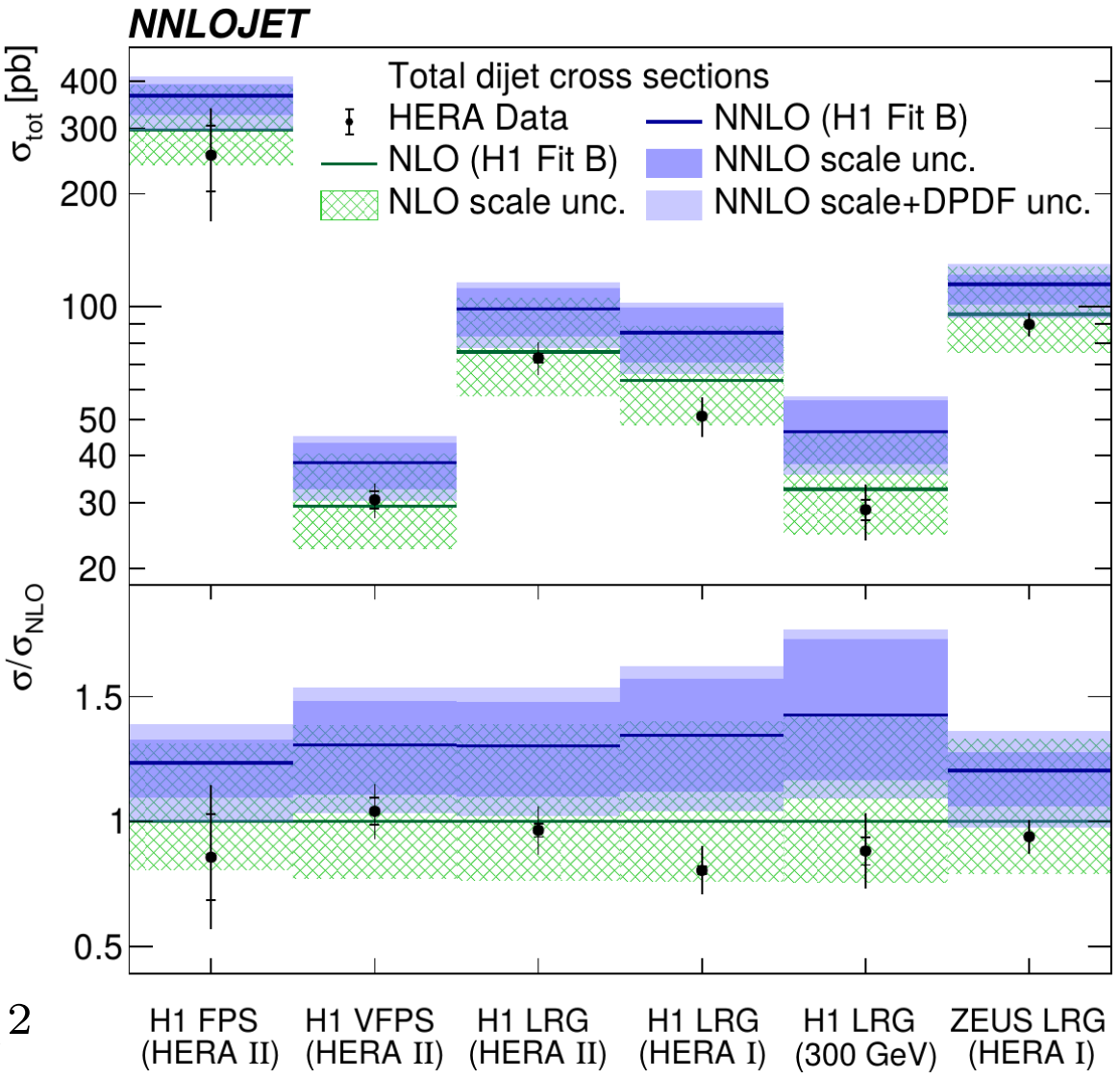
H1 LRG HERA II Phase Space
$4 < Q^2 < 100\ \mathrm{GeV}^2$
$0.1 < y < 0.7$
$x_{I\!P} < 0.03$
$\lvert t\rvert < 1\ \mathrm{GeV}^2$
$M_Y < 1.6\ \mathrm{GeV}$
$p^*_{\mathrm{T},1} > 5.5\ \mathrm{GeV}$
$p^*_{\mathrm{T},2} > 4.0\ \mathrm{GeV}$
$-1 < \eta^{\mathrm{lab}}_{1,2} < 2$

All HERA 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)

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



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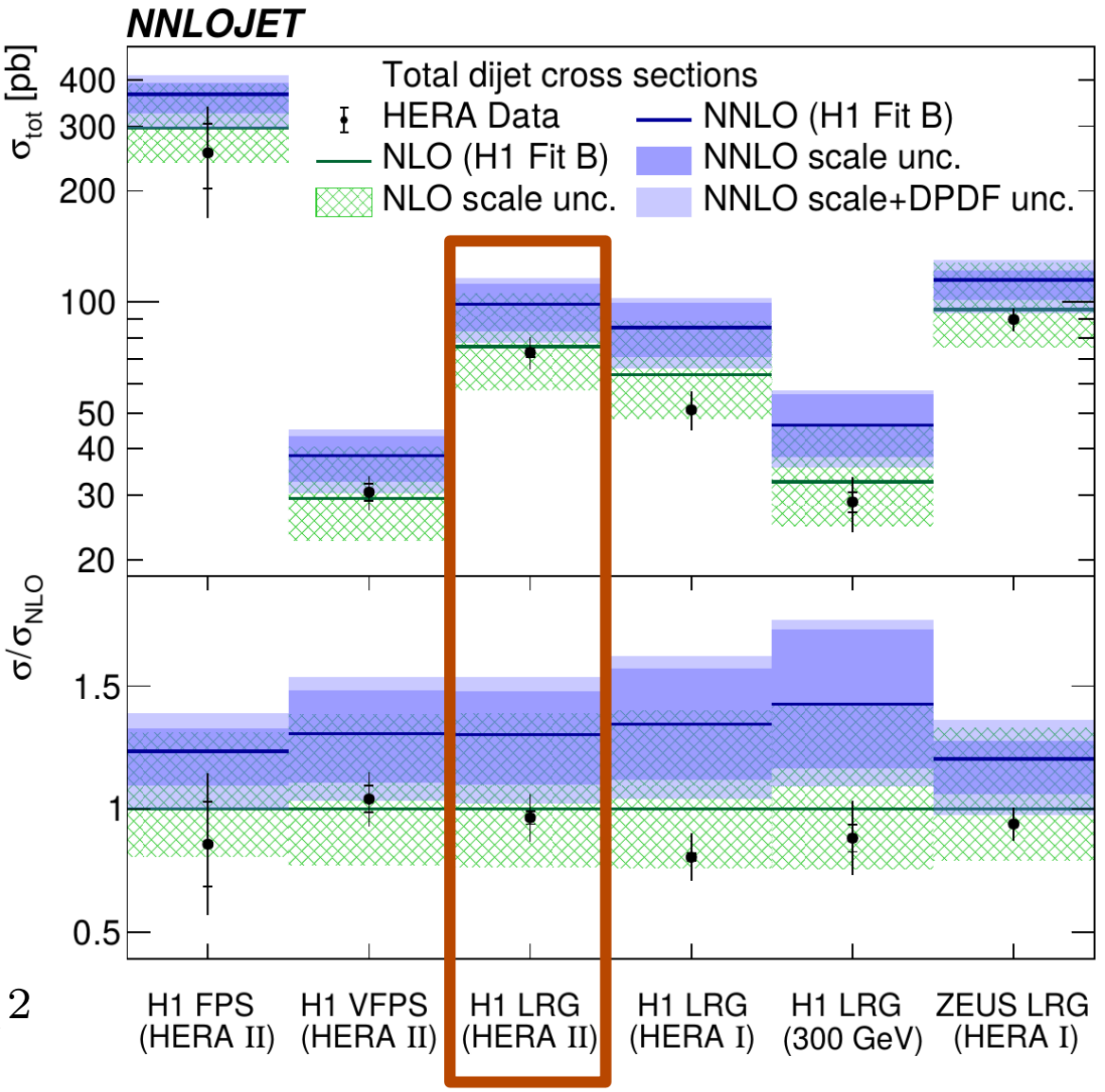
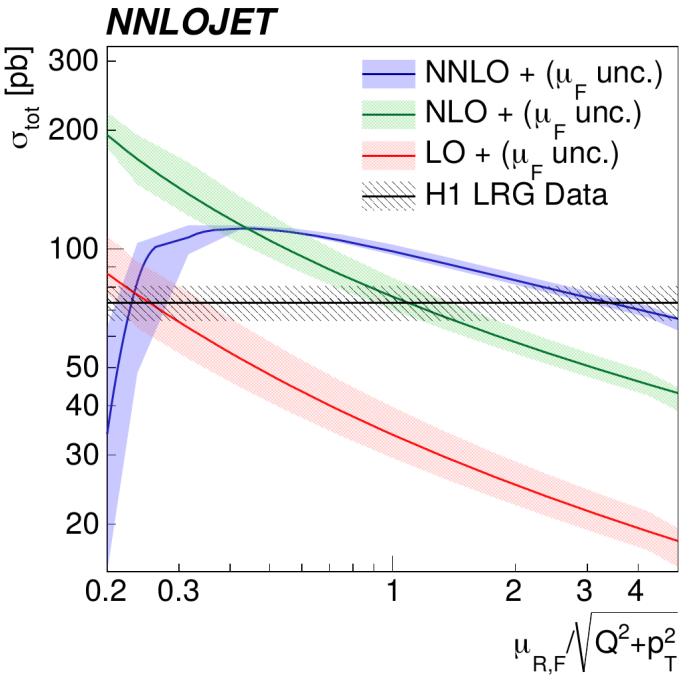


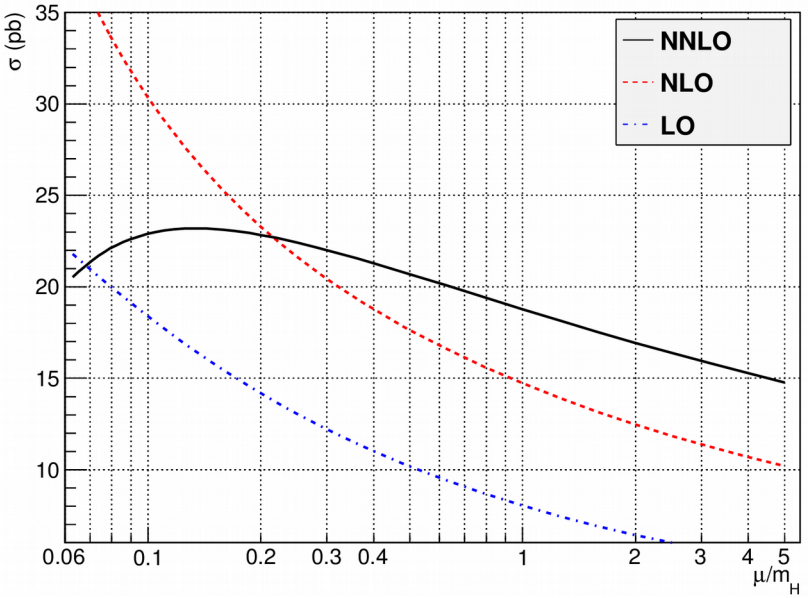
Total Cross Sections - Scale dependence

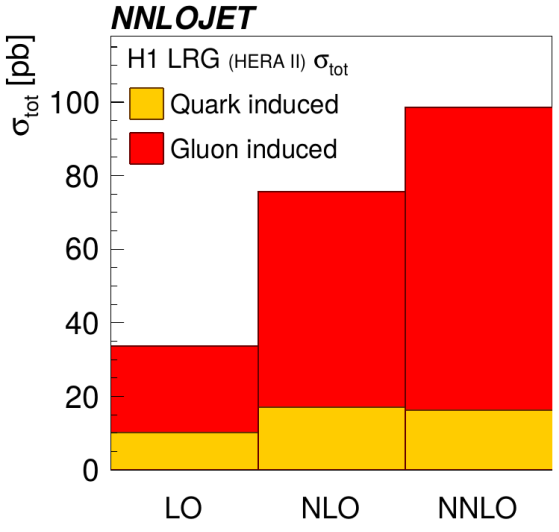
Jets in DDIS ($\sqrt{s}$ = 320 GeV)



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

JHEP 1204 (2012) 004

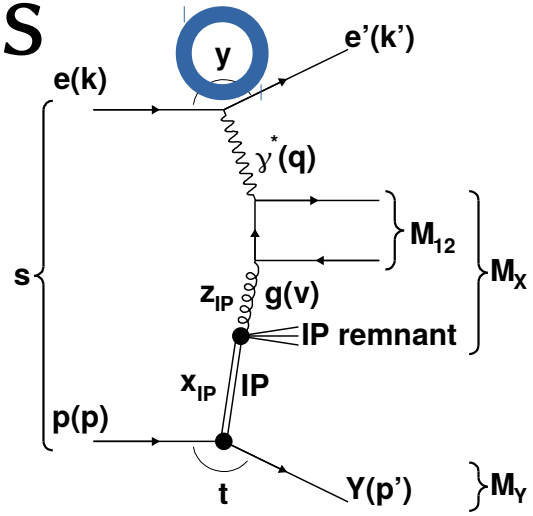


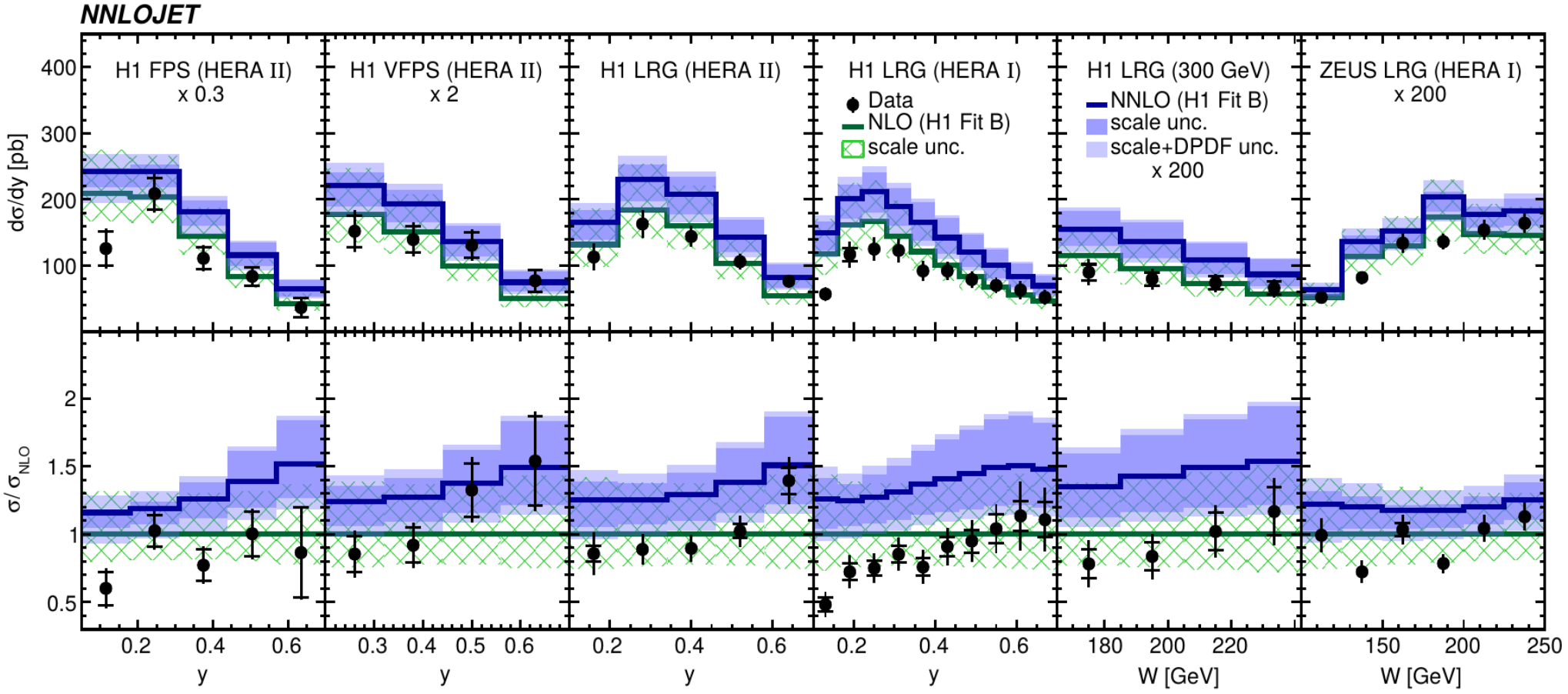


- The gluon-DPDF induced cross section rises gradually with order
- The quark-Induced cross section stagnates at NLO
- At NNLO 84% of the cross section is from gluon DPDF

Differential x-sections

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



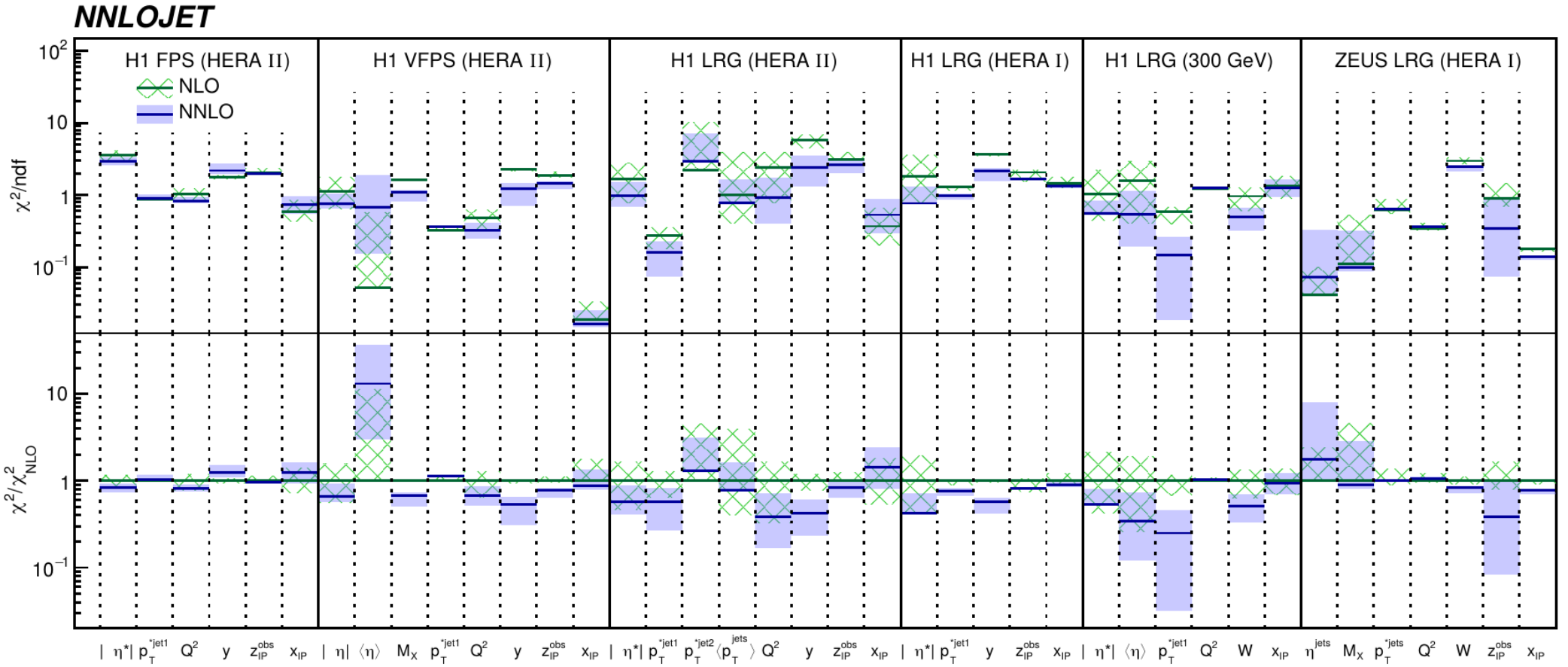


Chi² comparison

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

The normalization-independent definition

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



Conclusion

- The NNLO predictions available for the first time for jets in (D)DIS
- Comparing to NLO the scale uncertainties are smaller and x-sections typically larger

α_S fit of DIS jets

Subclass	$\alpha_s(M_Z^2)$
τ-decays	0.1192 ± 0.0018
lattice QCD	0.1188 ± 0.0011
structure functions	0.1156 ± 0.0021
e^+e^- [jets & shps]	0.1169 ± 0.0034
hadron collider	$0.1151\ ^{+\ 0.0028}_{-\ 0.0027}$
ew precision fits	0.1196 ± 0.0030

H1 NNLO jets 0.1157 ± 0.0034
H1 NNLO jets+PDF 0.1142 ± 0.0028

Pred. for DDIS jets

- Better description of shapes with NNLO, but normalization off
- Only NLO DPDFs available
- Plan for new combined (inclusive+jet) DPDF fit at NNLO

Thank you for your attention

Backup

$\alpha_s(m_Z)$ values from H1 jet cross sections

Data	$\tilde{\mu}_{\mathrm{cut}}$	**$\alpha_s(m_Z)$ with uncertainties**	**th**	**tot**	χ^2/n_{dof}
Inclusive jets					
300 GeV high-Q^2	$2m_b$	$0.1221\,(31)_{\mathrm{exp}}\,(22)_{\mathrm{had}}\,(5)_{\mathrm{PDF}}\,(3)_{\mathrm{PDF}\alpha_s}\,(4)_{\mathrm{PDFset}}\,(36)_{\mathrm{scale}}$	$(43)_{\mathrm{th}}$	$(53)_{\mathrm{tot}}$	6.5/15
HERA-I low-Q^2	$2m_b$	$0.1093\,(17)_{\mathrm{exp}}\,(8)_{\mathrm{had}}\,(5)_{\mathrm{PDF}}\,(5)_{\mathrm{PDF}\alpha_s}\,(7)_{\mathrm{PDFset}}\,(33)_{\mathrm{scale}}$	$(35)_{\mathrm{th}}$	$(39)_{\mathrm{tot}}$	17.5/22
HERA-I high-Q^2	$2m_b$	$0.1136\,(24)_{\mathrm{exp}}\,(9)_{\mathrm{had}}\,(6)_{\mathrm{PDF}}\,(4)_{\mathrm{PDF}\alpha_s}\,(4)_{\mathrm{PDFset}}\,(31)_{\mathrm{scale}}$	$(33)_{\mathrm{th}}$	$(41)_{\mathrm{tot}}$	14.7/23
HERA-II low-Q^2	$2m_b$	$0.1187\,(18)_{\mathrm{exp}}\,(8)_{\mathrm{had}}\,(4)_{\mathrm{PDF}}\,(4)_{\mathrm{PDF}\alpha_s}\,(3)_{\mathrm{PDFset}}\,(45)_{\mathrm{scale}}$	$(46)_{\mathrm{th}}$	$(50)_{\mathrm{tot}}$	29.6/40
HERA-II high-Q^2	$2m_b$	$0.1121\,(18)_{\mathrm{exp}}\,(9)_{\mathrm{had}}\,(5)_{\mathrm{PDF}}\,(4)_{\mathrm{PDF}\alpha_s}\,(2)_{\mathrm{PDFset}}\,(35)_{\mathrm{scale}}$	$(37)_{\mathrm{th}}$	$(41)_{\mathrm{tot}}$	42.5/29
Dijets					
300 GeV high-Q^2	$2m_b$	$0.1213\,(39)_{\mathrm{exp}}\,(17)_{\mathrm{had}}\,(5)_{\mathrm{PDF}}\,(2)_{\mathrm{PDF}\alpha_s}\,(3)_{\mathrm{PDFset}}\,(31)_{\mathrm{scale}}$	$(35)_{\mathrm{th}}$	$(52)_{\mathrm{tot}}$	13.6/15
HERA-I low-Q^2	$2m_b$	$0.1101\,(23)_{\mathrm{exp}}\,(8)_{\mathrm{had}}\,(5)_{\mathrm{PDF}}\,(4)_{\mathrm{PDF}\alpha_s}\,(5)_{\mathrm{PDFset}}\,(36)_{\mathrm{scale}}$	$(38)_{\mathrm{th}}$	$(45)_{\mathrm{tot}}$	10.4/20
HERA-II low-Q^2	$2m_b$	$0.1173\,(14)_{\mathrm{exp}}\,(9)_{\mathrm{had}}\,(5)_{\mathrm{PDF}}\,(5)_{\mathrm{PDF}\alpha_s}\,(3)_{\mathrm{PDFset}}\,(44)_{\mathrm{scale}}$	$(45)_{\mathrm{th}}$	$(47)_{\mathrm{tot}}$	17.4/41
HERA-II high-Q^2	$2m_b$	$0.1089\,(21)_{\mathrm{exp}}\,(7)_{\mathrm{had}}\,(5)_{\mathrm{PDF}}\,(3)_{\mathrm{PDF}\alpha_s}\,(3)_{\mathrm{PDFset}}\,(25)_{\mathrm{scale}}$	$(27)_{\mathrm{th}}$	$(34)_{\mathrm{tot}}$	28.0/23
H1 inclusive jets	$2m_b$	$0.1132\,(10)_{\mathrm{exp}}\,(5)_{\mathrm{had}}\,(4)_{\mathrm{PDF}}\,(4)_{\mathrm{PDF}\alpha_s}\,(2)_{\mathrm{PDFset}}\,(40)_{\mathrm{scale}}$	$(40)_{\mathrm{th}}$	$(42)_{\mathrm{tot}}$	134.0/133
H1 inclusive jets	28 GeV	$0.1152\,(20)_{\mathrm{exp}}\,(6)_{\mathrm{had}}\,(2)_{\mathrm{PDF}}\,(2)_{\mathrm{PDF}\alpha_s}\,(3)_{\mathrm{PDFset}}\,(26)_{\mathrm{scale}}$	$(27)_{\mathrm{th}}$	$(33)_{\mathrm{tot}}$	44.1/60
H1 dijets	$2m_b$	$0.1148\,(11)_{\mathrm{exp}}\,(6)_{\mathrm{had}}\,(5)_{\mathrm{PDF}}\,(4)_{\mathrm{PDF}\alpha_s}\,(4)_{\mathrm{PDFset}}\,(40)_{\mathrm{scale}}$	$(41)_{\mathrm{th}}$	$(42)_{\mathrm{tot}}$	93.9/102
H1 dijets	28 GeV	$0.1147\,(24)_{\mathrm{exp}}\,(5)_{\mathrm{had}}\,(3)_{\mathrm{PDF}}\,(2)_{\mathrm{PDF}\alpha_s}\,(3)_{\mathrm{PDFset}}\,(24)_{\mathrm{scale}}$	$(25)_{\mathrm{th}}$	$(35)_{\mathrm{tot}}$	30.8/43
H1 jets	$2m_b$	$0.1143\,(9)_{\mathrm{exp}}\,(6)_{\mathrm{had}}\,(5)_{\mathrm{PDF}}\,(5)_{\mathrm{PDF}\alpha_s}\,(4)_{\mathrm{PDFset}}\,(42)_{\mathrm{scale}}$	$(43)_{\mathrm{th}}$	$(44)_{\mathrm{tot}}$	195.0/199
H1 jets	28 GeV	$0.1157\,(20)_{\mathrm{exp}}\,(6)_{\mathrm{had}}\,(3)_{\mathrm{PDF}}\,(2)_{\mathrm{PDF}\alpha_s}\,(3)_{\mathrm{PDFset}}\,(27)_{\mathrm{scale}}$	$(28)_{\mathrm{th}}$	$(34)_{\mathrm{tot}}$	63.2/90
H1 jets	42 GeV	$0.1168\,(22)_{\mathrm{exp}}\,(7)_{\mathrm{had}}\,(2)_{\mathrm{PDF}}\,(2)_{\mathrm{PDF}\alpha_s}\,(5)_{\mathrm{PDFset}}\,(17)_{\mathrm{scale}}$	$(20)_{\mathrm{th}}$	$(30)_{\mathrm{tot}}$	37.6/40
H1PDF2017 [NNLO]	$2m_b$	$0.1142\,(11)_{\mathrm{exp,NP,PDF}}\,(2)_{\mathrm{mod}}\,(2)_{\mathrm{par}}\,(26)_{\mathrm{scale}}$		$(28)_{\mathrm{tot}}$	1539.7/1516

Running of the strong coupling

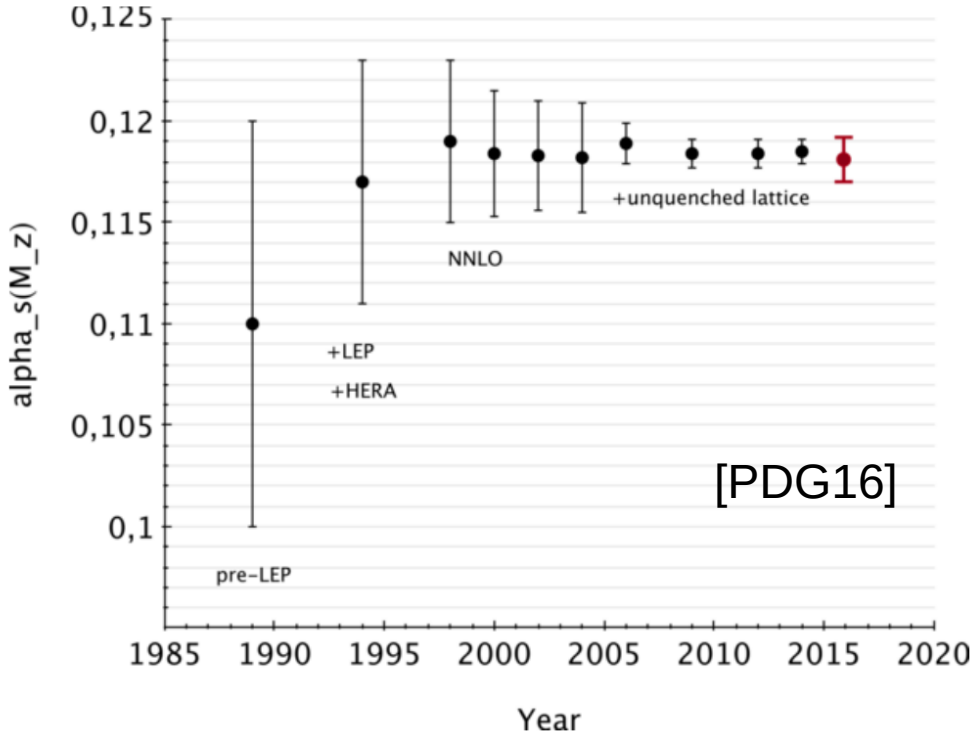
μ_R	Inclusive jets		Dijets		H1 jets	
[GeV]	$\alpha_s(m_Z)$	$\alpha_s(\mu_R)$	$\alpha_s(m_Z)$	$\alpha_s(\mu_R)$	$\alpha_s(m_Z)$	$\alpha_s(\mu_R)$
7.4	0.1148 (13) (42)	0.1830 (34) (114)	0.1182 (28) (41)	0.1923 (77) (116)	0.1147 (13) (43)	0.1829 (34) (114)
10.1	0.1136 (17) (36)	0.1678 (39) (81)	0.1169 (14) (42)	0.1751 (34) (99)	0.1148 (14) (40)	0.1705 (31) (91)
13.3	0.1147 (15) (43)	0.1605 (30) (88)	0.1131 (18) (38)	0.1573 (36) (76)	0.1144 (15) (42)	0.1600 (30) (86)
17.2	0.1130 (15) (33)	0.1492 (26) (59)	0.1104 (19) (30)	0.1445 (33) (53)	0.1127 (15) (33)	0.1486 (27) (59)
20.1	0.1136 (17) (33)	0.1457 (29) (56)	0.1116 (22) (31)	0.1425 (36) (52)	0.1134 (17) (33)	0.1454 (29) (55)
24.5	0.1173 (17) (30)	0.1463 (26) (48)	0.1147 (23) (24)	0.1423 (36) (38)	0.1171 (17) (29)	0.1460 (27) (46)
29.3	0.1084 (36) (29)	0.1287 (51) (41)	0.1163 (34) (34)	0.1401 (50) (50)	0.1134 (30) (32)	0.1358 (44) (46)
36.0	0.1153 (32) (37)	0.1338 (43) (50)	0.1135 (37) (29)	0.1314 (50) (39)	0.1146 (30) (33)	0.1328 (41) (44)
49.0	0.1170 (22) (20)	0.1290 (27) (25)	0.1127 (31) (15)	0.1238 (37) (18)	0.1169 (23) (19)	0.1290 (28) (24)
77.5	0.1111 (55) (19)	0.1137 (58) (20)	0.1074 (84) (19)	0.1099 (88) (20)	0.1113 (55) (19)	0.1139 (58) (20)

Results for the PDF+α_s-fit

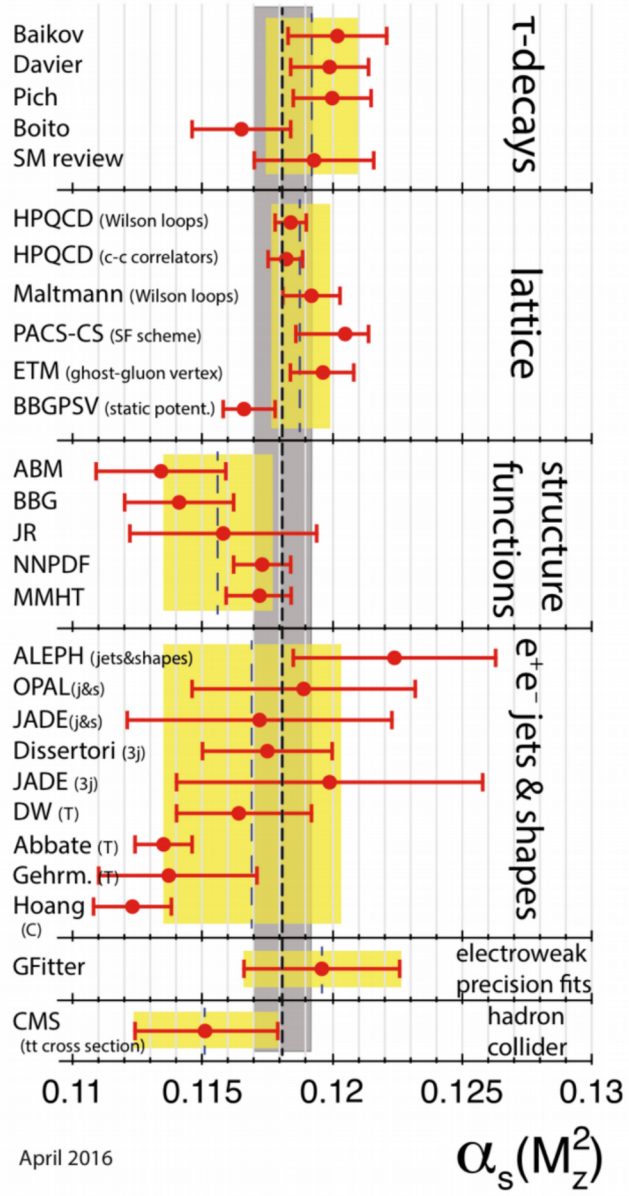
Parameter	Fit result	Correlation coefficients												
		$\alpha_s(m_Z)$	g_B	g_C	g_D	$\tilde{u}_B$	$\tilde{u}_C$	$\tilde{u}_E$	$\tilde{d}_B$	$\tilde{d}_C$	$\bar{U}_C$	$\bar{D}_A$	$\bar{D}_B$	$\bar{D}_C$
$\alpha_s(m_Z)$	0.1142 ± 0.0011	1												
g_B	-0.023 ± 0.035	0.25	1											
g_C	5.69 ± 4.09	-0.08	0.01	1										
g_D	-0.44 ± 4.20	-0.03	-0.10	0.99	1									
$\tilde{u}_B$	0.707 ± 0.036	0.39	0.25	0.05	0.04	1								
$\tilde{u}_C$	4.909 ± 0.096	-0.09	-0.13	0.02	0.03	-0.08	1							
$\tilde{u}_E$	12.7 ± 1.8	-0.03	-0.25	-0.04	-0.01	-0.75	0.57	1						
$\tilde{d}_B$	1.036 ± 0.098	0.24	-0.02	0.06	0.08	0.32	-0.24	-0.24	1					
$\tilde{d}_C$	5.35 ± 0.49	-0.10	-0.07	0.03	0.05	-0.08	-0.24	0.00	0.80	1				
$\bar{U}_C$	4.96 ± 0.86	0.32	-0.28	-0.01	0.05	0.76	0.09	-0.39	0.53	0.11	1			
$\bar{D}_A$	0.299 ± 0.032	0.29	-0.71	-0.04	0.07	0.32	0.01	-0.08	0.38	0.13	0.71	1		
$\bar{D}_B$	-0.091 ± 0.017	0.22	-0.79	-0.05	0.06	0.19	0.03	0.01	0.29	0.09	0.61	0.97	1	
$\bar{D}_C$	16.1 ± 3.8	-0.13	-0.51	-0.01	0.08	-0.15	-0.24	-0.06	0.14	0.24	0.05	0.48	0.46	1
g_A	2.84	constrained by sum-rules												
$\tilde{u}_A$	4.11	constrained by sum-rules												
$\tilde{d}_A$	6.94	constrained by sum-rules												
$\bar{U}_A$	1.80	set equal to $\bar{D}_A(1 - f_s)$												
$\bar{U}_B$	-0.091	set equal to $\bar{D}_B$												

History of Alpha Strong

- The current world average value $\alpha_s(m_Z) = 0.1181(11)$
- Mostly driven by lattice and tau-decays
- From LHC the most precise estimate is from ttbar (NNLO)



At least NNLO fits [PDG16]



Dependence on PDF and α_S^{PDF}

In full H1 jet data sample positive correlation between α_S^{PDF} and α_S

Restricting to $\tilde{\mu} > 28\,\mathrm{GeV}$ makes the α_S-fit uncorrelated to α_S^{PDF}