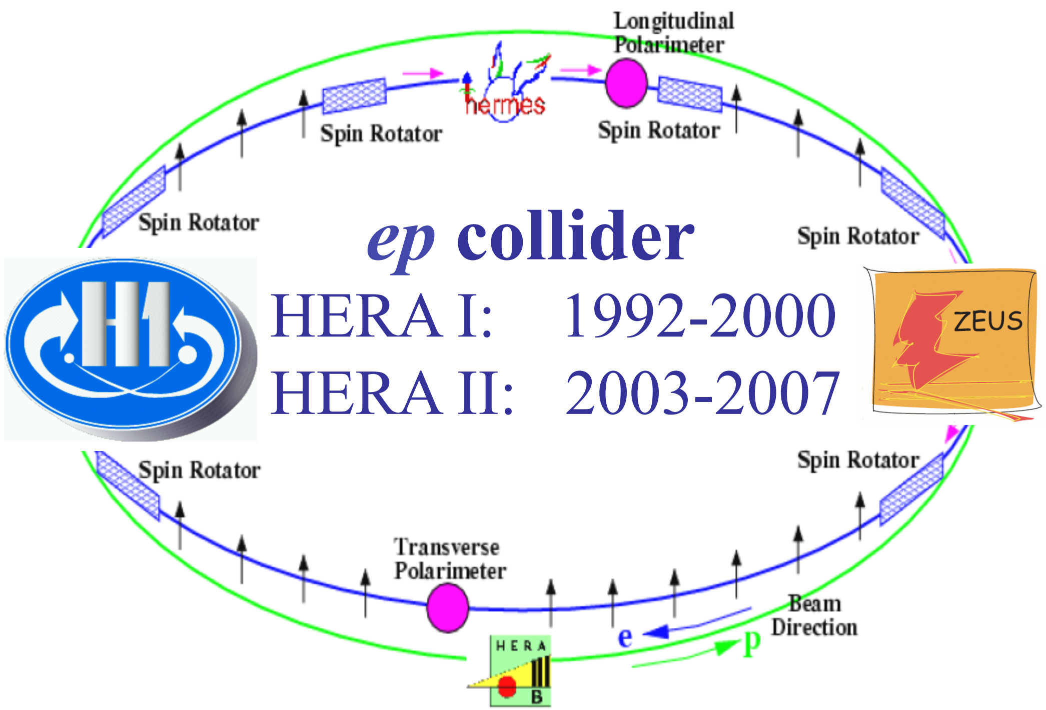
New measurements of jets in DIS and extraction of α_s at NNLO

Vladimir Chekelian (MPI for Physics, Munich)
on behalf of the H1 Collaboration

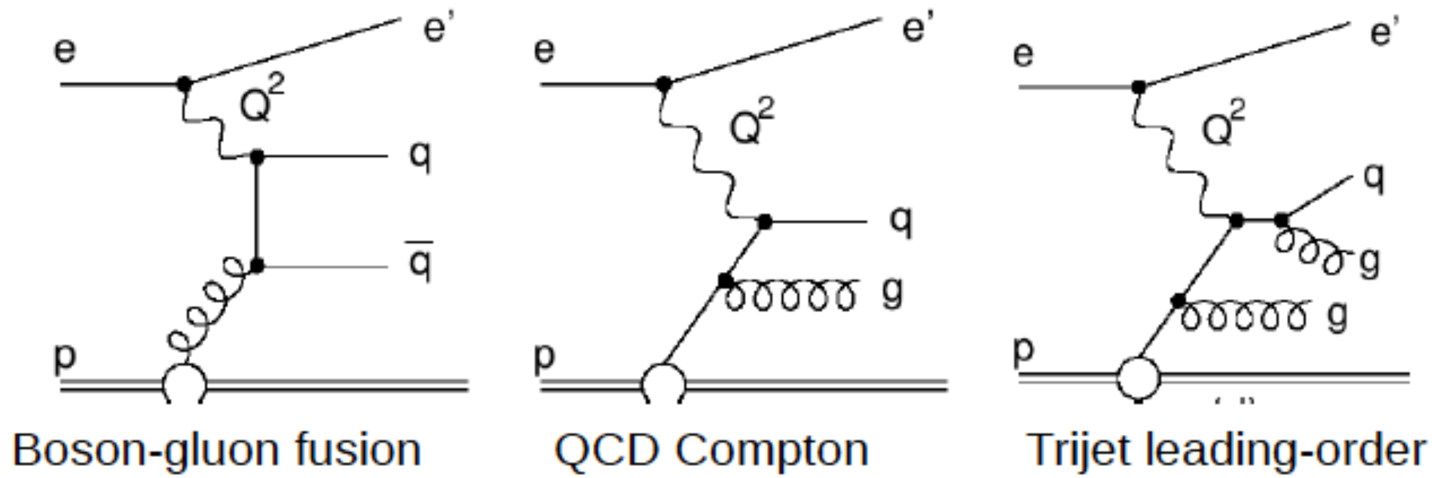


H1: 0.5 fb^{-1} of the *ep* collision data with E_e=27.5 GeV and E_p=920/820/575/460 GeV
$\sqrt{s}$ =319/300/252/225 GeV

Completion of the jet measurements by the H1 collaboration at HERA:

- *new multi-jets cross sections measurements in DIS at low Q^2*
  Eur.Phys.J.C77(2017)4,215
- *α_s determination at NNLO using jet measurements in DIS by H1*
  H1prelim-17-031

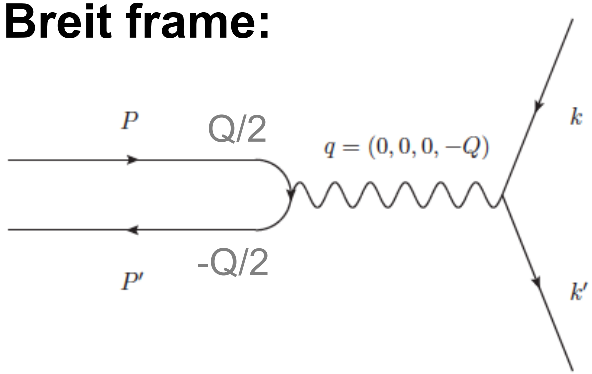
Jets in deep-inelastic *ep* scattering at HERA



DIS kinematics:

$Q^2 = -q^2 = -(e-e')^2$ virtuality
$x = Q^2/2(pq)$ Bjorken x
$y = (pq)/(pe)$ inelastisity

Breit frame:



Jet production in DIS:

- defined in *the Breit frame* (e.g. *k_T algorithm* with R=1)
- sensitive to α_s already at LO
- dominated by boson-gluon fusion and directly sensitive to gluon
- leading order for trijets is $O(\alpha_s^2)$

Eur.Phys.J.C77(2017)4,215

New jet measurements in DIS by H1

Inclusive jet, dijet and trijet production cross sections in ep NC DIS
at low Q^2 ($Q^2 < 100$ GeV^2) with scattered electron in Spacal ($E > 10.5$ GeV)
at high Q^2 ($Q^2 > 150$ GeV^2) – an extension to the low P_T bin: $5 < P_T^{jet} < 7$ GeV
- HERA II data (290 pb^{-1}, $\sqrt{s}$=319 GeV);
- in the Breit frame using k_T algorithm with R=1
- as a function of Q^2 and P_T at the hadron level

→ also jet cross sections normalised to inclusive NC DIS

	Low-Q^2 extended phase space	**Low-Q^2 measurement phase space**	**High-Q^2 measurement phase space extension**
Application	Used for event selection and unfolding	Phase space of jet cross sections	Phase space of jet cross sections
NC DIS phase space	$3 < Q^2 < 120\,\mathrm{GeV}^2$ $0.08 < y < 0.7$	$5.5 < Q^2 < 80\,\mathrm{GeV}^2$ $0.2 < y < 0.6$	$150 < Q^2 < 15\,000\,\mathrm{GeV}^2$ $0.2 < y < 0.7$
Phase space common for all jets	$-1.5 < \eta_{lab}^{jet} < 2.75$ $P_T^{jet} > 3\,\mathrm{GeV}$	$-1.0 < \eta_{lab}^{jet} < 2.5$ $P_T^{jet} > 4\,\mathrm{GeV}$	$-1.0 < \eta_{lab}^{jet} < 2.5$
Inclusive jet	$P_T^{jet} > 3\,\mathrm{GeV}$	$4.5 < P_T^{jet} < 50\,\mathrm{GeV}$	$5 < P_T^{jet} < 7\,\mathrm{GeV}$ ($7 < P_T^{jet} < 50\,\mathrm{GeV}$ published in [26])
Dijet	$N_{jet} \geq 2$ $\langle P_T \rangle_2 > 3\,\mathrm{GeV}$	$N_{jet} \geq 2$ $5 < \langle P_T \rangle_2 < 50\,\mathrm{GeV}$	
Trijet	$N_{jet} \geq 3$ $\langle P_T \rangle_3 > 3\,\mathrm{GeV}$	$N_{jet} \geq 3$ $5.5 < \langle P_T \rangle_3 < 40\,\mathrm{GeV}$	

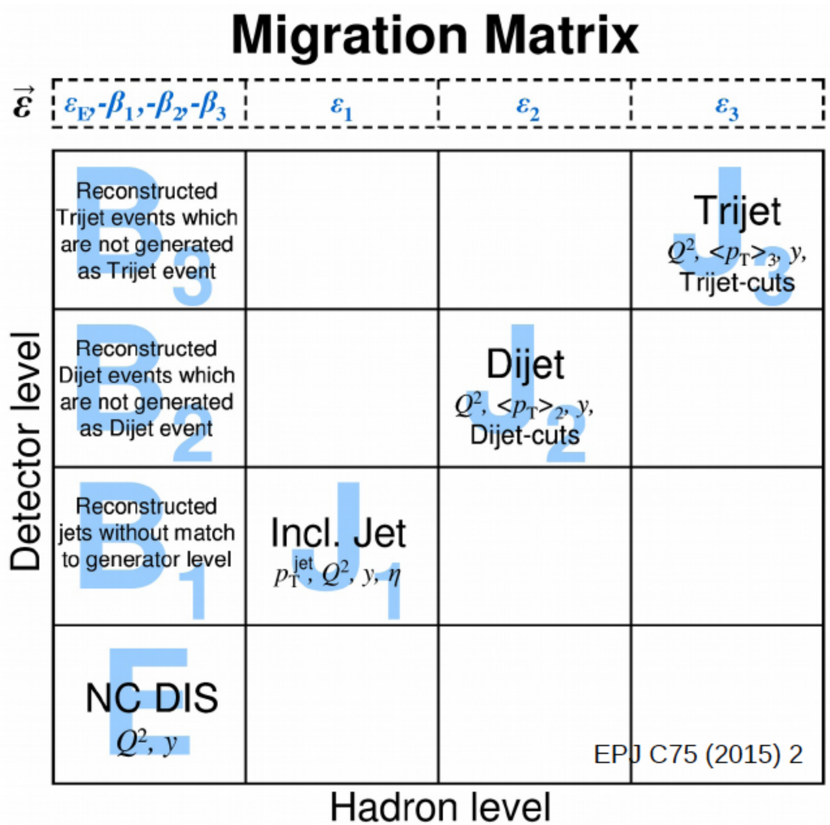
} asymmetric cuts $\langle P_T^j \rangle_{2,3} \gg P_T^{jet}$ to avoid IR sensitive regions in the theory calculations

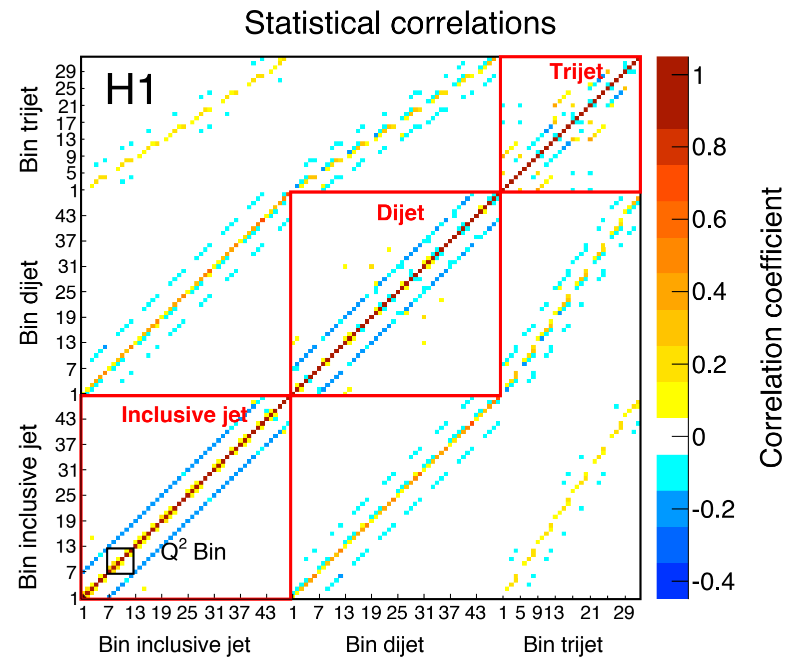
Simultaneous regularised unfolding of **inclusive jets, dijets, trijets and NC DIS**

Detector effects like *migrations, acceptance, effiency* are corrected for in **regularised unfolding** by minimising

$$\chi^2(x,\tau) = (y - Ax)^T V_y^{-1} (y - Ax) + \tau L^T L$$

x	Hadron level
y	Detector level
V_y	Covariance matrix
A	Migration matrix
τL^2	Regularisation term



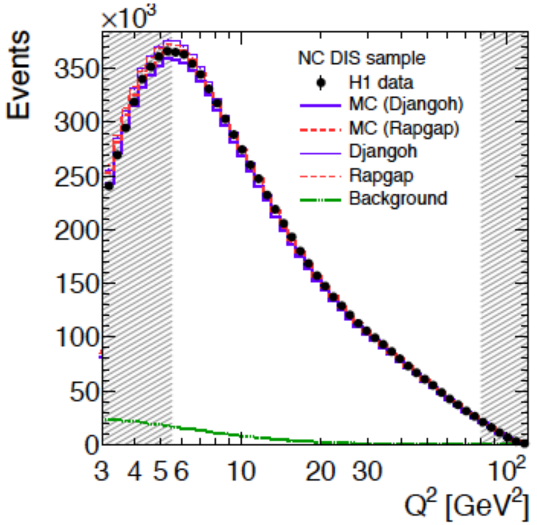


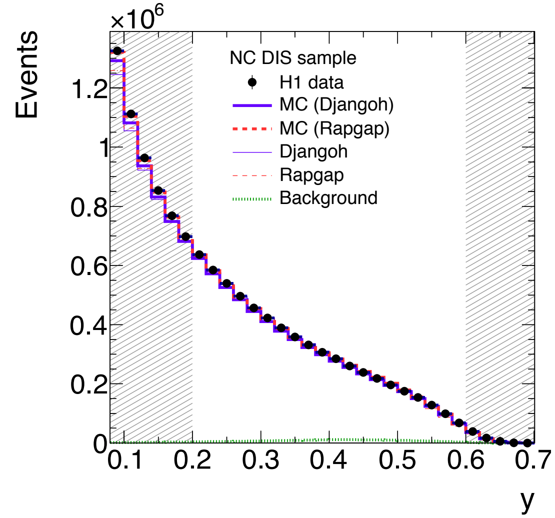
→ two times more bins in P_T - combined later

- *all stat. correlations are provided*
- *systematics: total & eight correlated unc.*
- *normalisation/lumi uncertainty - 2.5%*
- *hadronisation corr. to compare to theory*

Control distributions

Inclusive NC DIS





Extended phase space → *grey areas*

Two NC DIS generators:

Djangoh (blue) / Rapgap (red)

reweighed to describe data well

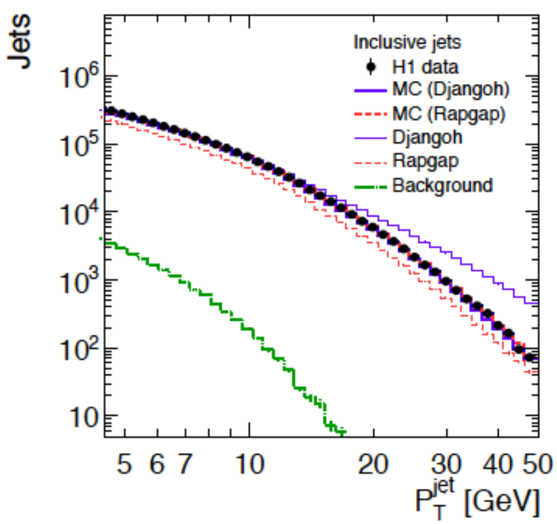
- *half a difference is asigned to syst.*

Background (green): Pythia

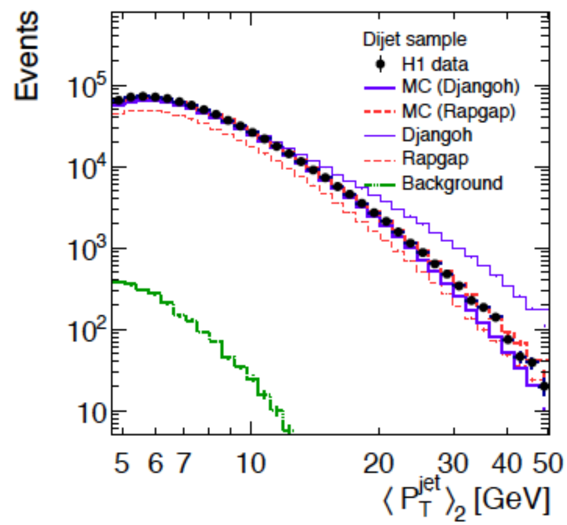
normalised to bkg enriched sample

→ *good overall description of data*

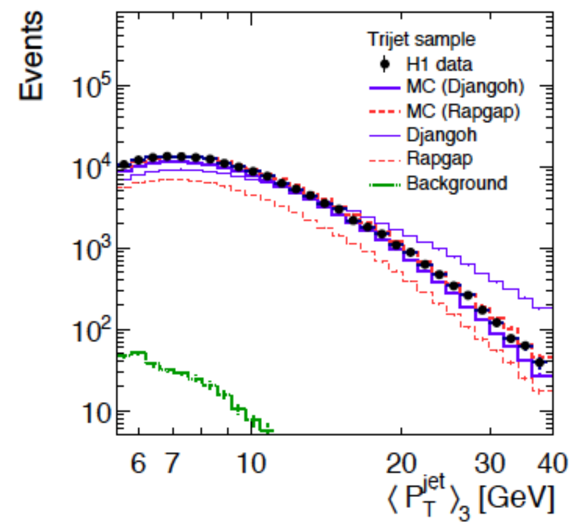
Inclusive jets



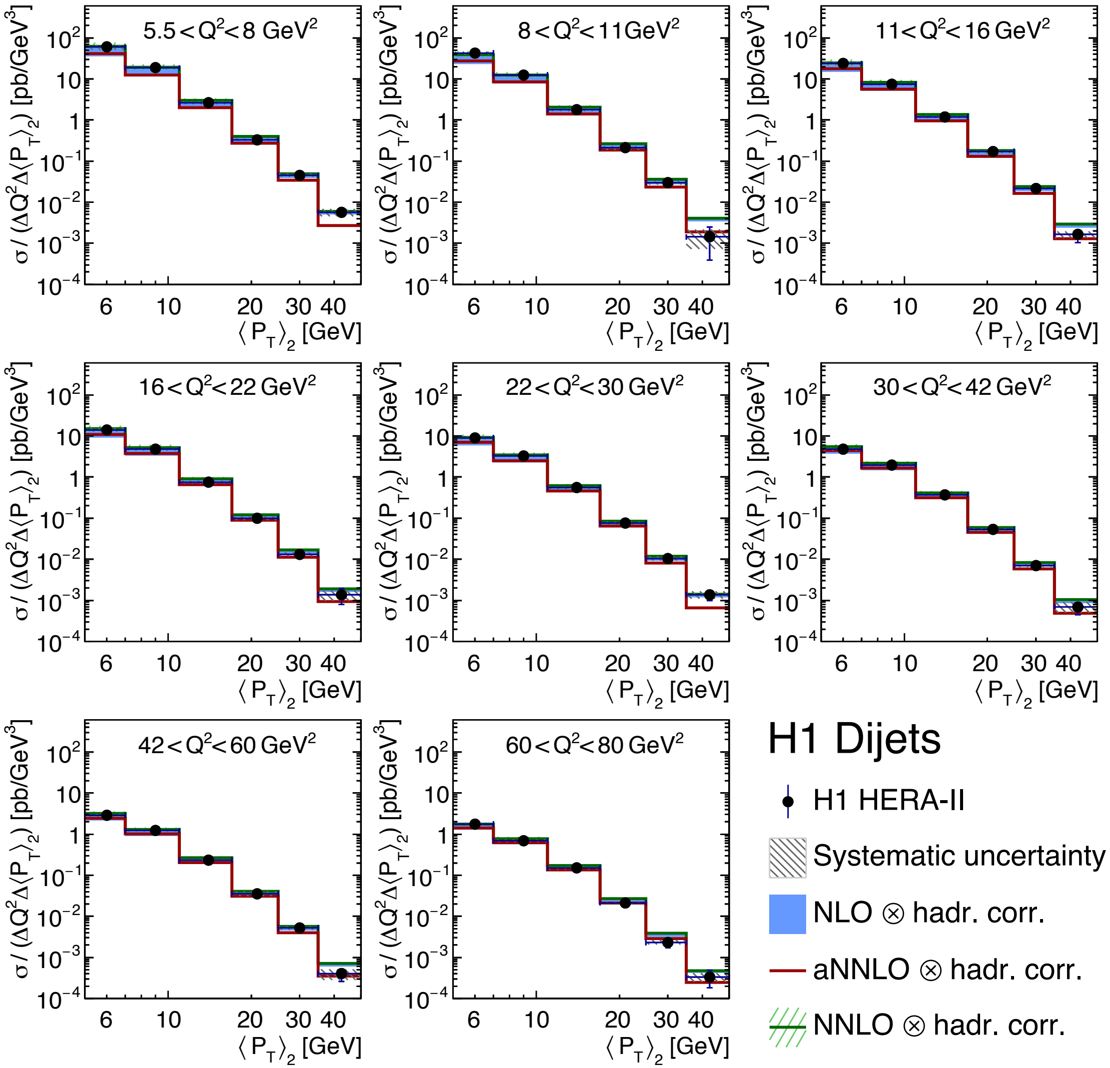
Dijets



Trijets



Doble differential dijets cross sections



σ(bin) / $\Delta Q^2\, \Delta\langle P_T\rangle_2$

- as a function of Q^2 and $\langle P_T\rangle_2 = (P_T^{jet1} + P_T^{jet2})/2$ with $P_T^{jet1,2} > 4$ GeV

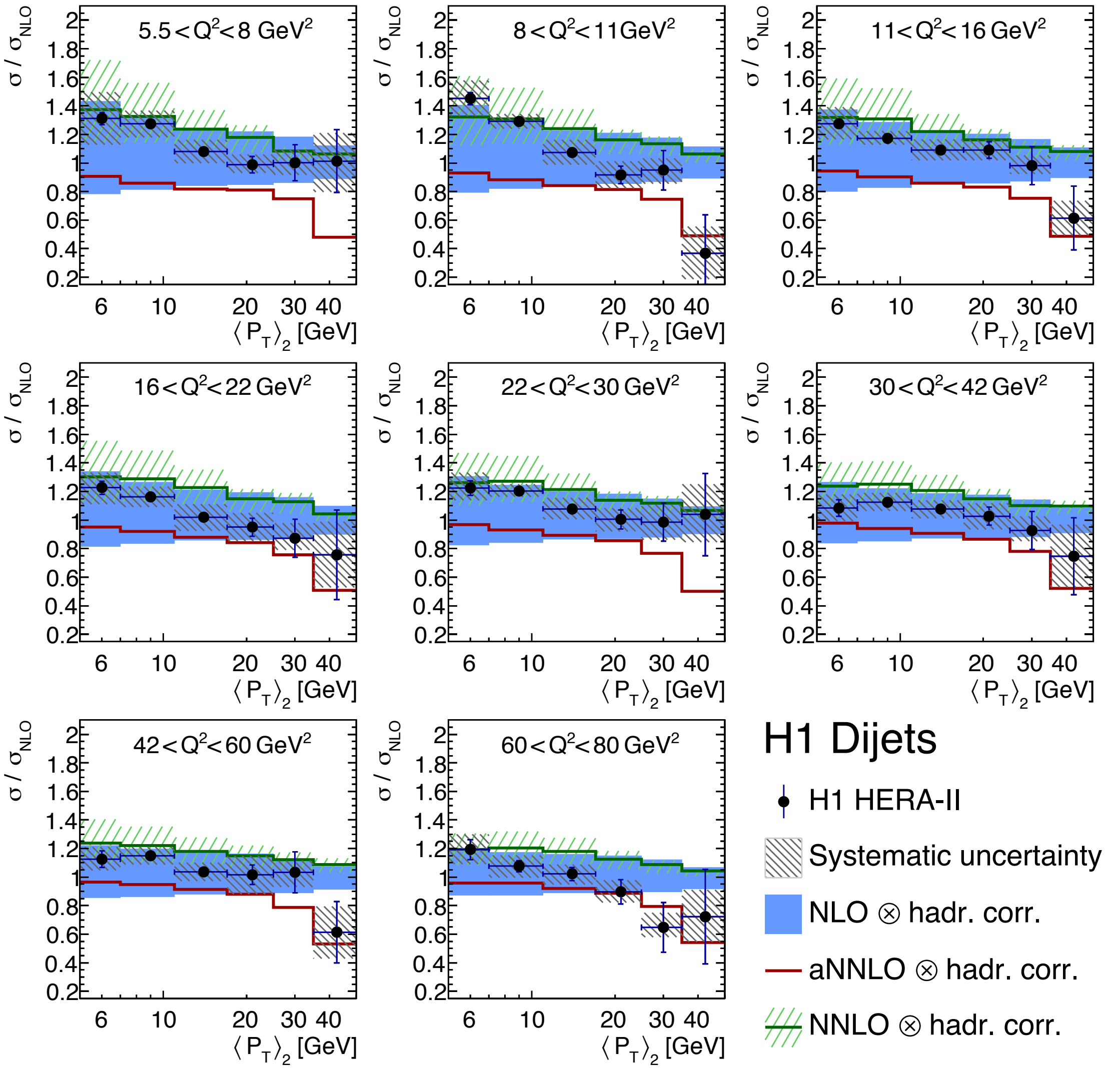
$5.5 < Q^2 < 80$ GeV^2
$5 < \langle P_T\rangle_2 < 50$ GeV

- compared to calculations at NLO, aNNLO, NNLO (NNPDF3.0, $\alpha_s(m_Z) = 0.118$) multiplied by hadronic corr.

→ *reasonable description of the dijet data over 4-5 orders of magnitude*

Dijets: aNNLO & NNLO calculations

divided by σ_{NLO}



aNNLO (approximate NNLO)
Phys.Rev.D92(2015)7,074037

NNLO
Rev.Lett.117(2016)042001

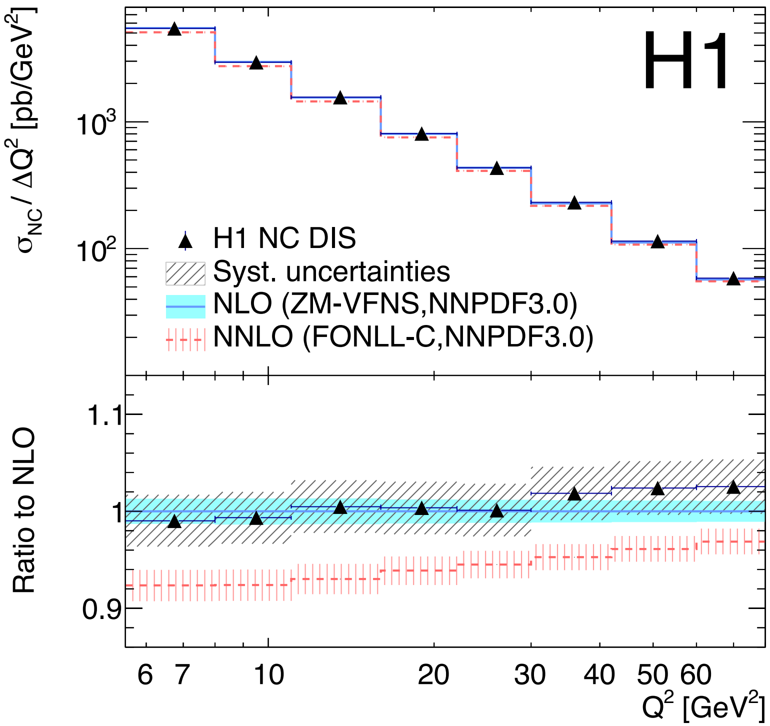
- scale unc. from variation of μ_r and μ_f by factors 0.5/2, excluding (0.5,2) and (2,0.5)

→ aNNLO and NNLO improve P_T shape dependence
→ NNLO reduced scale unc. at high P_T compared to NLO

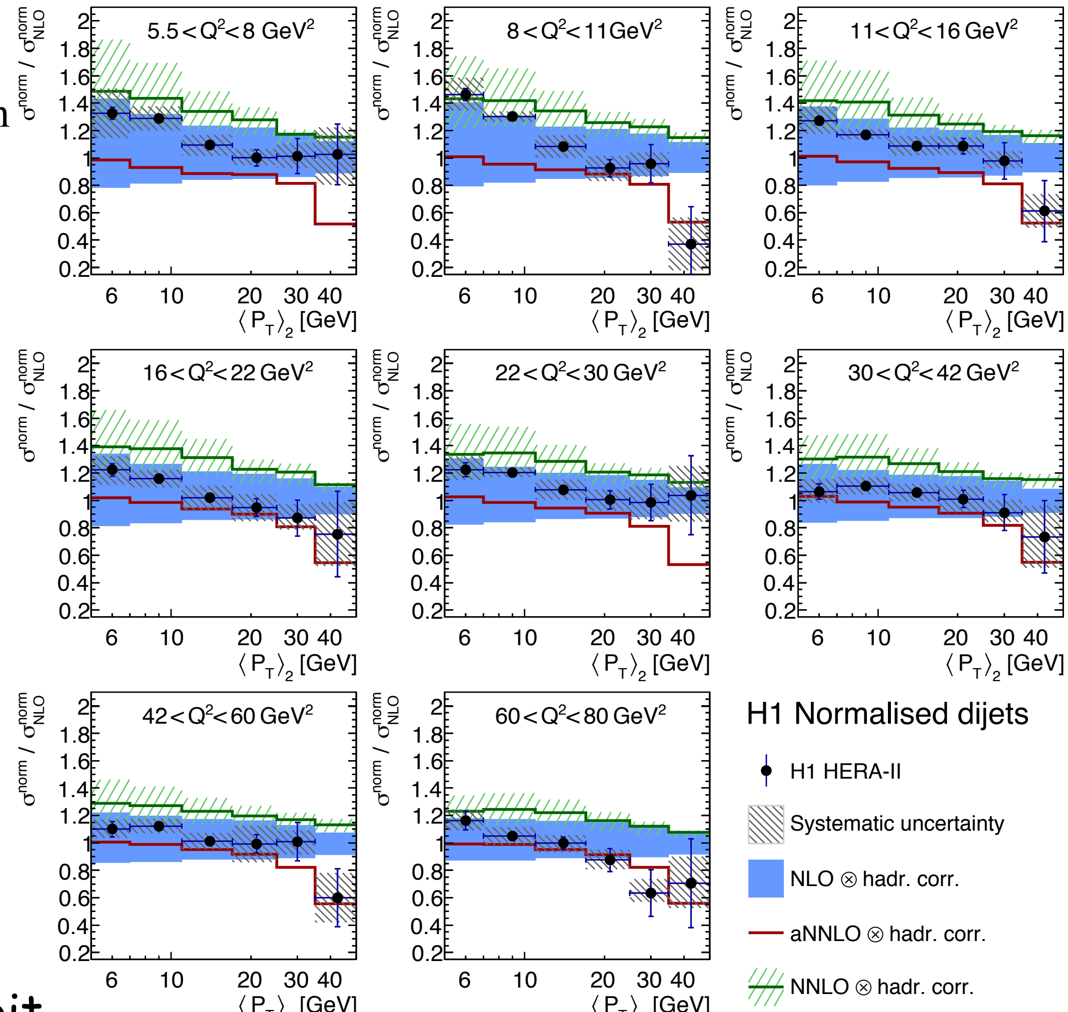
Normalised dijet cross sections

$$\sigma_i^{norm} = \frac{\sigma_i}{\sigma_{i_q}^{NC}}$$

- jet cross sections
- incl. NC DIS in Q^2 bin



divided by σ_{NLO}



- some reduction of exp.unc.
- NNLO overshoots dijet data a bit
- best suited for possible "PDF+α_s" fits together with inclusive NC & CC DIS data

Double diff. inclusive jet cross sections

σ(bin) / $\Delta Q^2 \Delta P_T^{jet}$

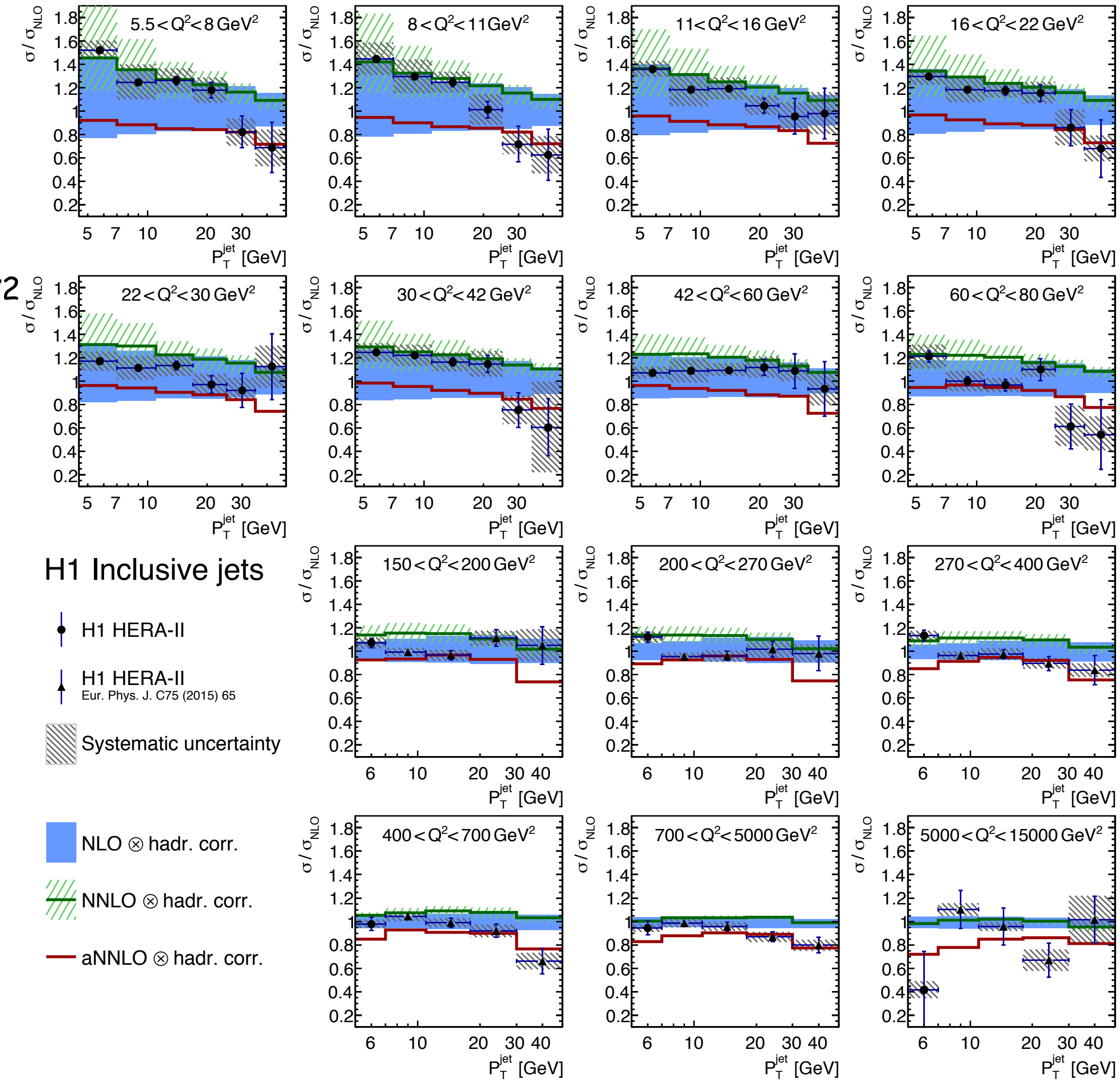
New measurements:
- low Q^2: 5.5 - 80 GeV²
  4.5 < P_T < 50 GeV
- high Q^2: 150 - 15000 GeV²
  5 < P_T < 7 GeV

7 < P_T < 50 GeV published in Eur.Phys.J.C75(2015)2,65

Similar to dijets:
- scale unc. from variation of μ_r and μ_f by factors 0.5/2, excluding (0.5,2) and (2,0.5)

→ aNNLO and NNLO improve P_T shape dependence
→ NNLO reduced scale unc. at high P_T compared to NLO

divided by σ_{NLO}



Normalised inclusive jet cross sections

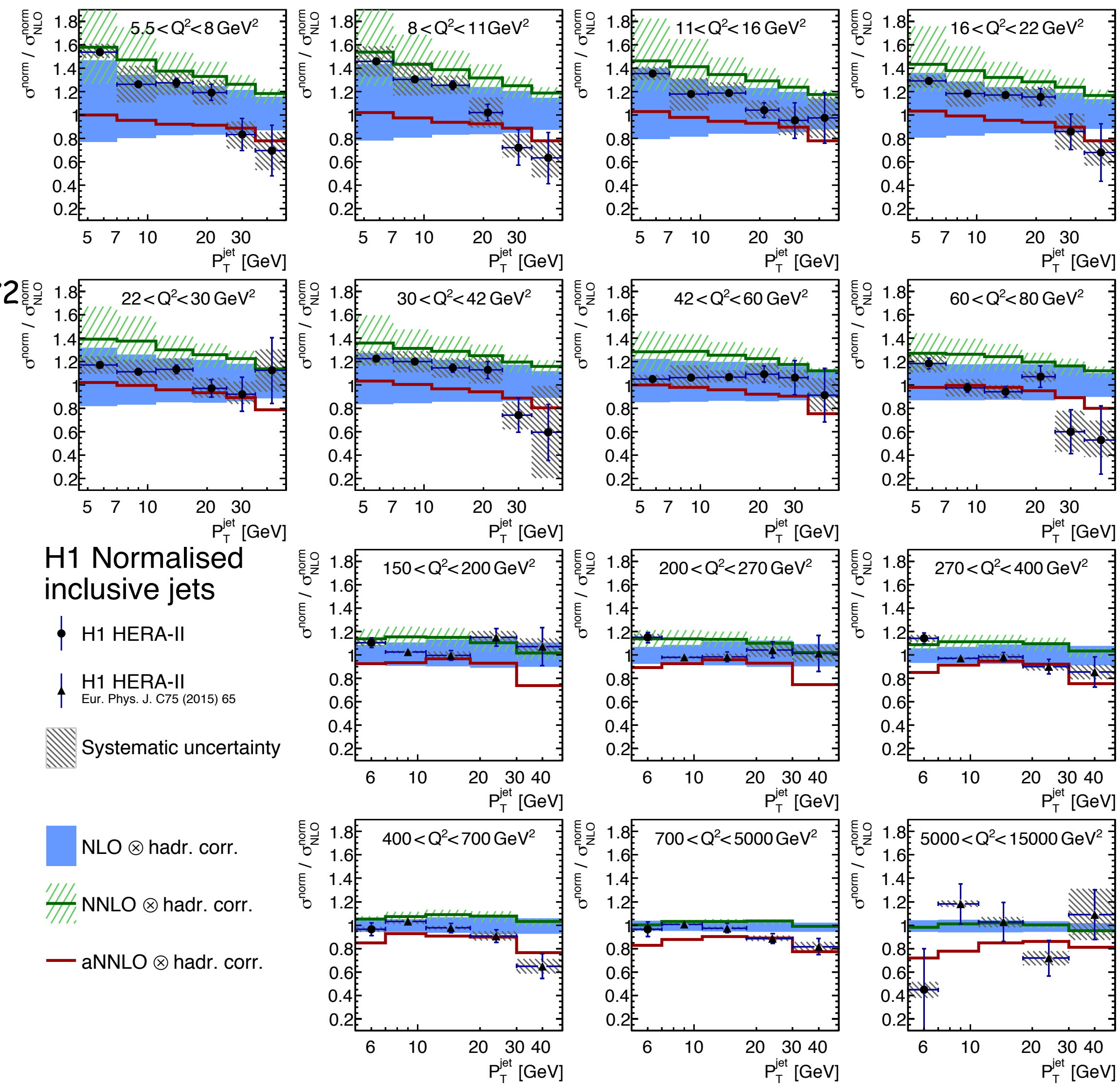
divided by σ_{NLO}

σ/σ_{NC} / ΔP_T^{jet}

New measurements:

- low Q^2: 5.5 - 80 GeV^2
  4.5 < P_T < 50 GeV
- high Q^2: 150 - 15000 GeV^2
  5 < P_T < 7 GeV

7 < P_T < 50 GeV published in Eur.Phys.J.C75(2015)2,65



Similar to dijets:

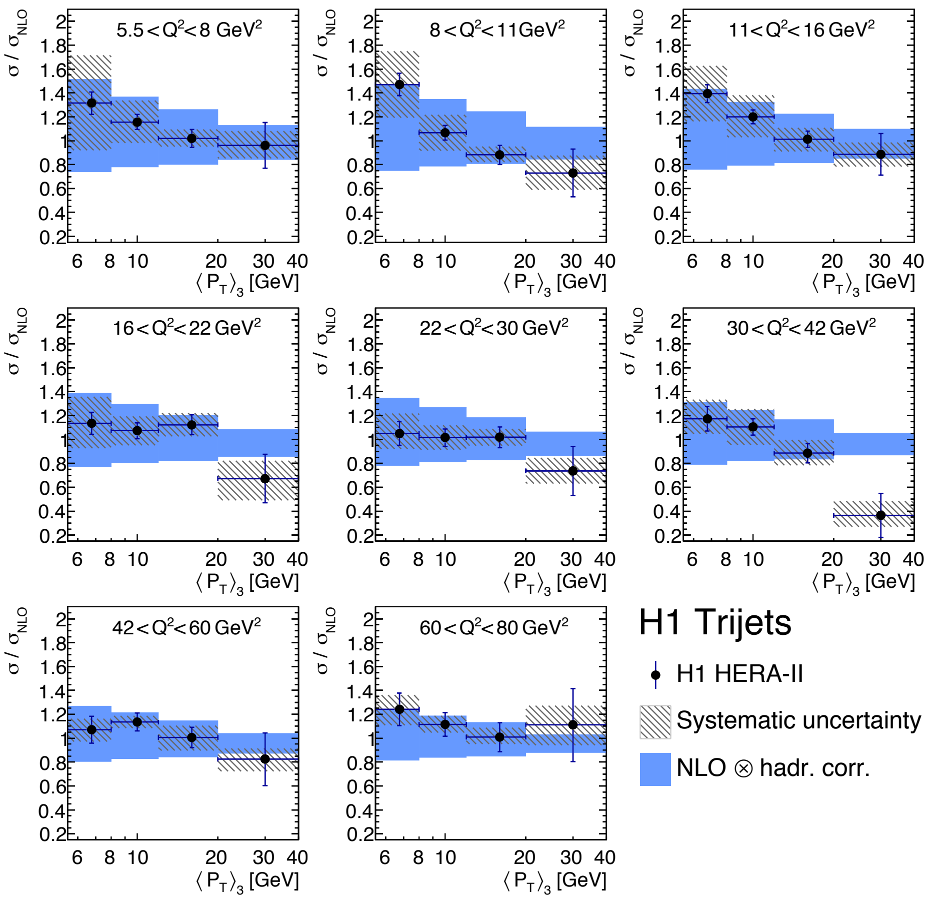
- scale unc. from variation of μ_r and μ_f by factors 0.5/2, excluding (0.5,2) and (2,0.5)

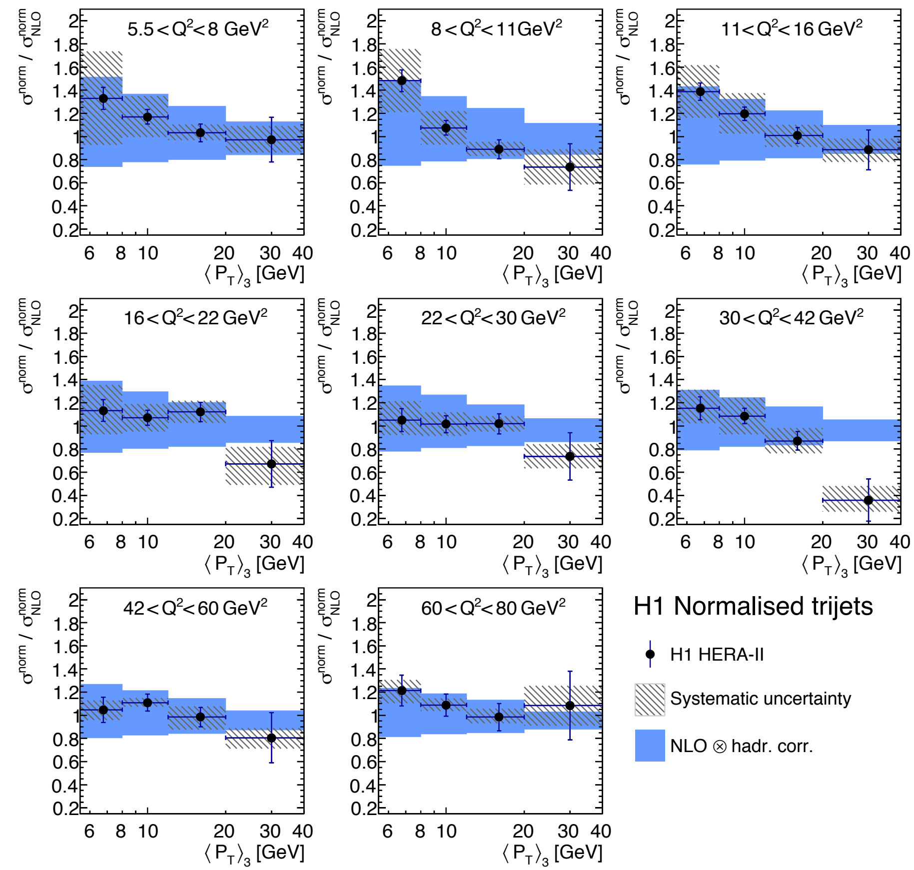
→ aNNLO and NNLO improve P_T shape dependence

→ NNLO reduced scale unc. at high P_T compared to NLO

Trijet cross sections $\langle P_T \rangle_3 = (P_T^{jet1} + P_T^{jet2} + P_T^{jet3})/3$

absolute (divided by σ_{NLO}) normalised





→ *good description of the data by calculations at NLO*

→ *NNLO is not available yet*

Extraction of α_s at NNLO from jet data in DIS

H1prelim-16-031 H1 collaboration and
V.Bertone, J.Currie, T.Gehrmann, C.Gwenlan, A.Huss, J.Niehues, M.Sutton

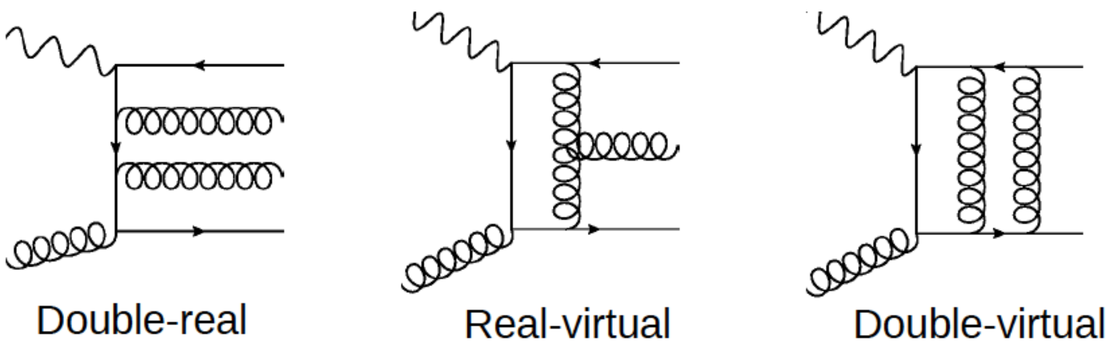
Input jet data in DIS: 5 inclusive jet sets and 4 dijet sets published by H1

Jet cross section & α_s-dependence:

$$\sigma_i = \sum_{n=1}^{\infty} \sum_{k=g,q,\bar{q}} \int dx\, f_k(x,\mu_F)\, \hat{\sigma}_{i,k}^{(n)}(x,\mu_R,\mu_F) \cdot c_{\mathrm{had},i}$$

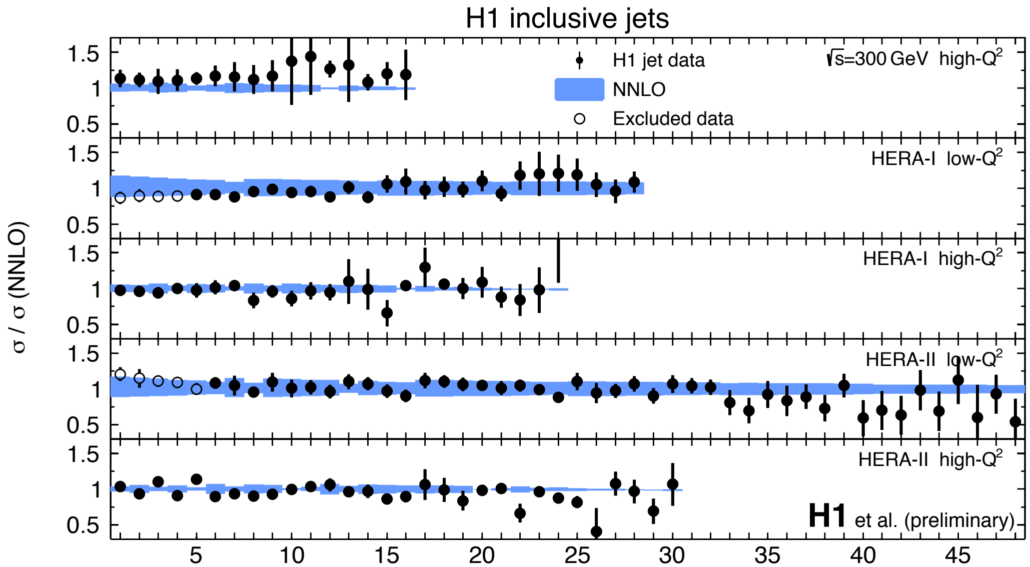
PDFs ME

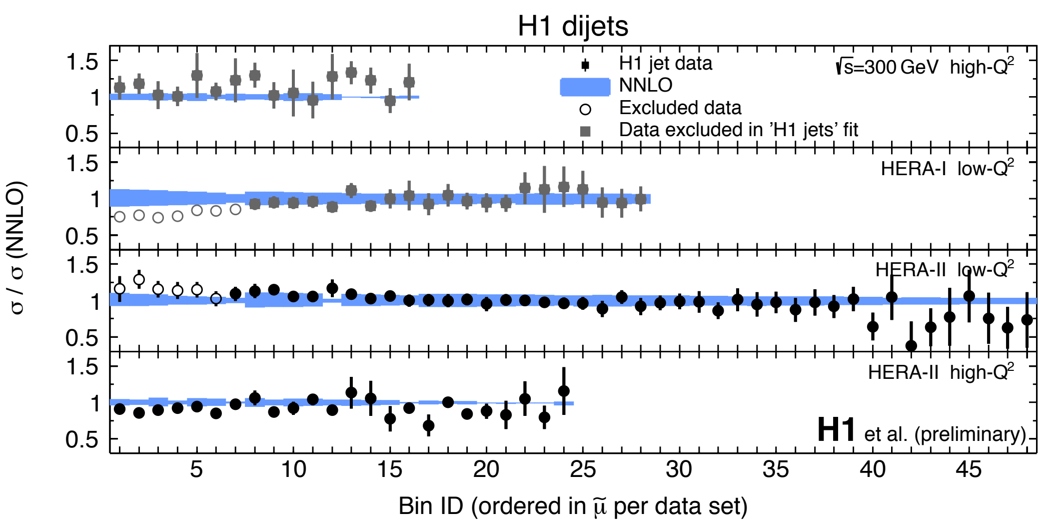
NNLO calculations for ep DIS jet production (2016):



using antenna subtraction technique
J. Currie et al., Rev.Lett.117(2016)042001; arXiv:1703.05977

Input H1 jet data compared to α_s NNLO fit





5 inclusive jet cross section sets

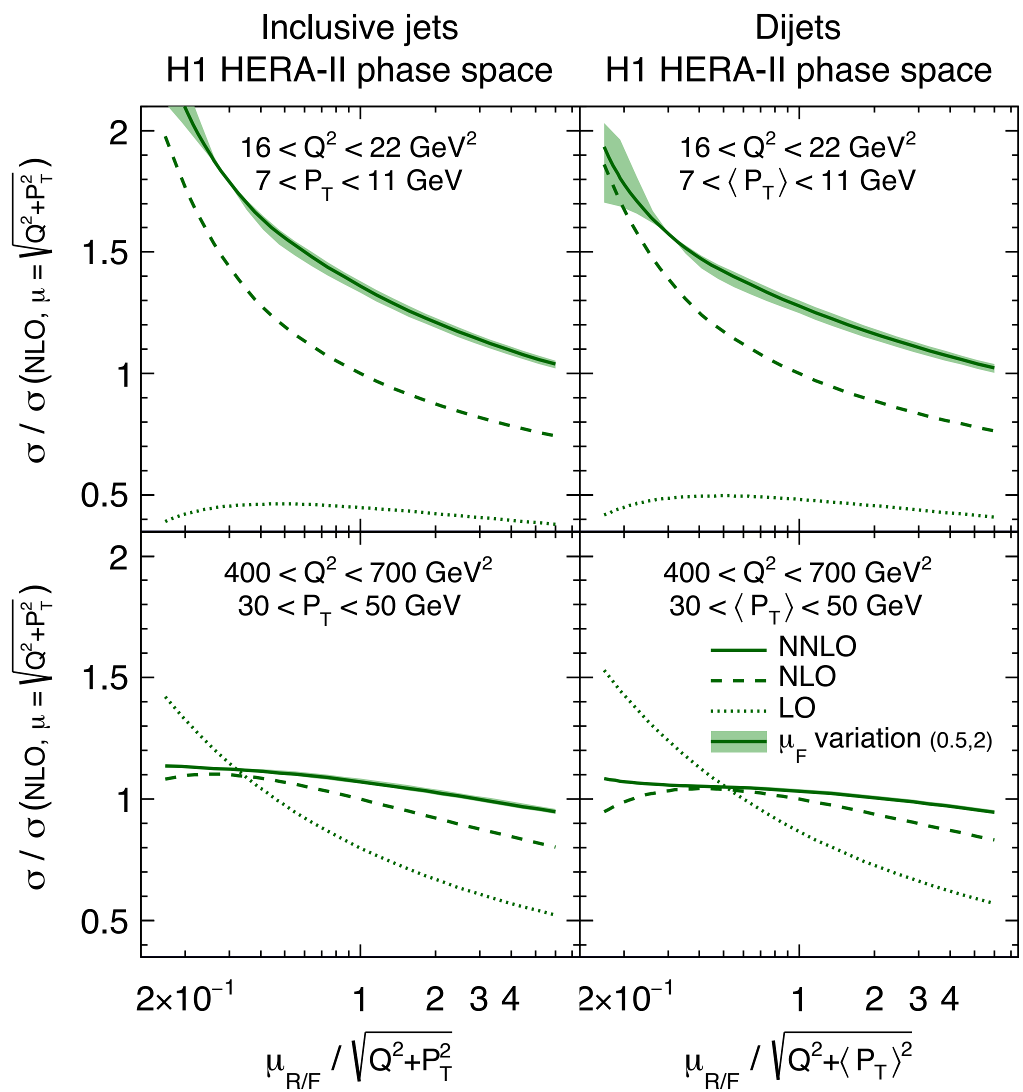
- data period:
  300 GeV / HERA-I / HERA-II
- Q^2 range:
  low-Q^2 (5/5.5-100 GeV^2)
  high-Q^2 (150-15000 GeV^2)
- P_T ranges:
  $4.5/5/7 < P_T < 50$ GeV
- common for all sets:
  $-1 < \eta^{jet}_{lab} < 2.5$, $0.2 < y < 0.7$

4 dijet cross section sets

- $\langle P_T \rangle_2$ ranges
  $5/7 < \langle P_T \rangle_2 < 50$ GeV
  ($m_{12} > 16/18$ GeV)

→ open points with $\mu=\sqrt{Q^2+P_T^2} < 2m_b$ are excluded from α_s NNLO fit

Scale dependence of jet cross sections at NNLO



Scales (renormalisation and factorisation) are chosen to be

$$\mu_R^2 = \mu_F^2 = Q^2 + P_T^2$$

- scale dependence by varying multiplicative factors to μ_R, μ_F in four phase space domains (low & high μ, incl.jets & dijets)

→ *reduction of scale dependency at NNLO compared to NLO*

→ *still relevant scale dependence at NNLO at low scales*

- μ_F dependence small (green band)

Methodology of the $\alpha_s(m_Z)$ determination

The strong coupling constant is determined in a fit of theory to jet data with free parameter $\alpha_s(m_Z)$ by minimizing χ^2 based on log-normal probabilities

$$\chi^2 = \sum_{i,j} \log \frac{\varsigma_i}{\sigma_i} (V_{\text{exp}} + V_{\text{had}} + V_{\text{PDF}})^{-1}_{ij} \log \frac{\varsigma_j}{\sigma_j}$$

ς=Data, σ_i=NNLO, V=covariance matrices

- experimental uncertainties (stat. & syst.)
- scale uncertainty (varying multiplicative factors to $\mu_{R,F}$ by 0.5,2)
- PDF uncertainties (repeating fits without V_{PDF} in χ^2)
- hadronisation unc. (repeating fits without V_{had} in χ^2)

Theory: α_s dependences of the jet cross sections (factorisation theorem)

$$\sigma_i = \sum_{n=1}^{\infty} \sum_{k=g,q,\bar{q}} \int dx\, f_k(x, \mu_F) \hat{\sigma}^{(n)}_{i,k}(x, \mu_R, \mu_F) \cdot c_{\text{had},i}$$

explicit dependence in hard ME:

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

perturbative expansion in orders of α_s

implicit dependence in PDFs:

$$\frac{\partial f}{\partial \alpha_s} = \frac{\mathcal{P} \otimes f}{\beta}$$

splitting kernels $\mathcal{P}$

$$\mu^2 \frac{d\alpha_s}{d\mu^2} = \beta(\alpha_s)$$

ME & PDF dependencies on $\alpha_s^\sigma(m_Z)$, $\alpha_s^f(m_Z)$

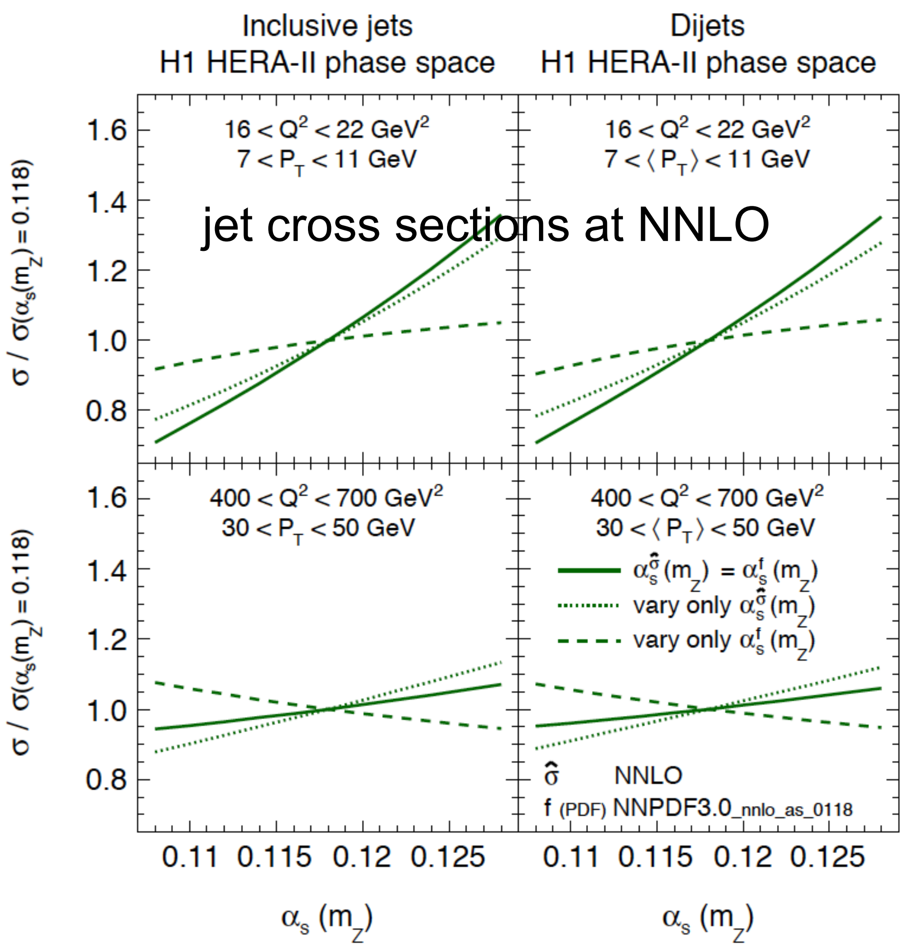
$$\sigma_i = f\left(\alpha_s^f(m_Z)\right) \otimes \hat{\sigma}_i\left(\alpha_s^{\hat{\sigma}}(m_Z)\right) \cdot c_{\mathrm{had},i}$$

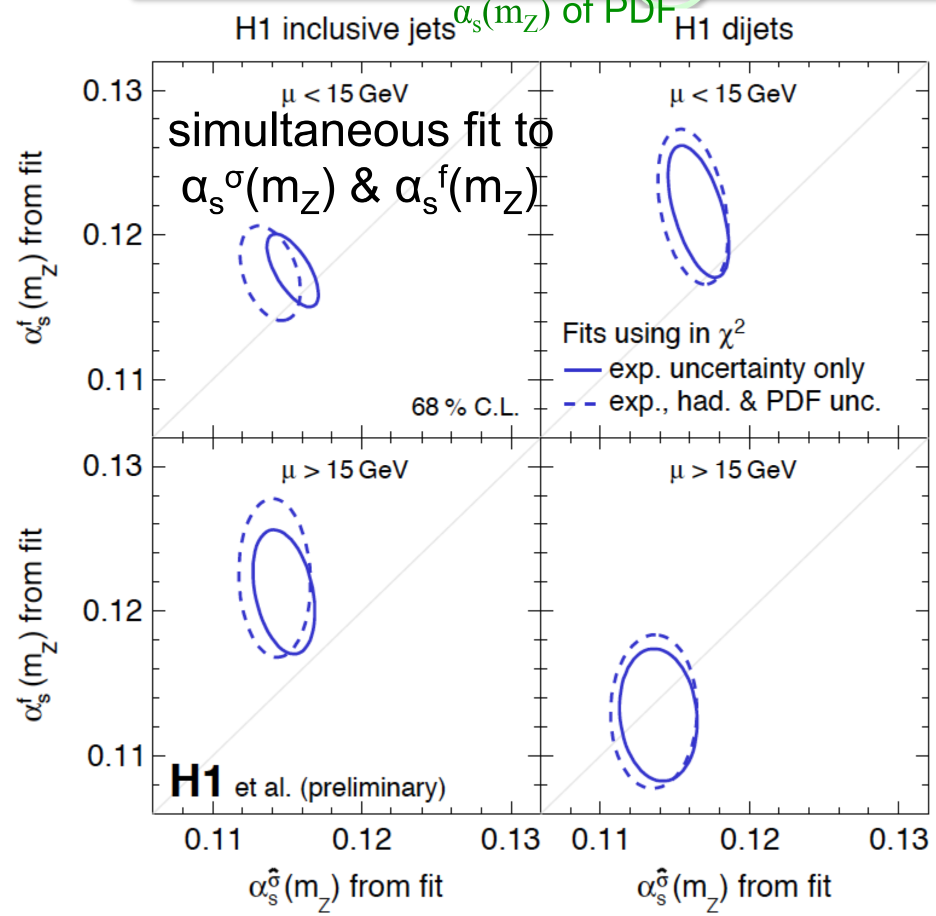
ME: orders of $\alpha_s^{(n)}$

PDF: by integration of $\frac{\partial f}{\partial \alpha_s} = \frac{\mathcal{P} \otimes f}{\beta}$

or $\tilde{f}(\mu) = f(\sqrt{K}\mu)$, $\exp\left[\frac{1}{2}\int_{\alpha_s^{(\mathrm{ref})}}^{\tilde{\alpha}_s^{(\mathrm{ref})}} \frac{d\alpha'_s}{\beta(\alpha'_s)}\right] = \sqrt{K}$

$\alpha_s(m_Z)$ of PDF

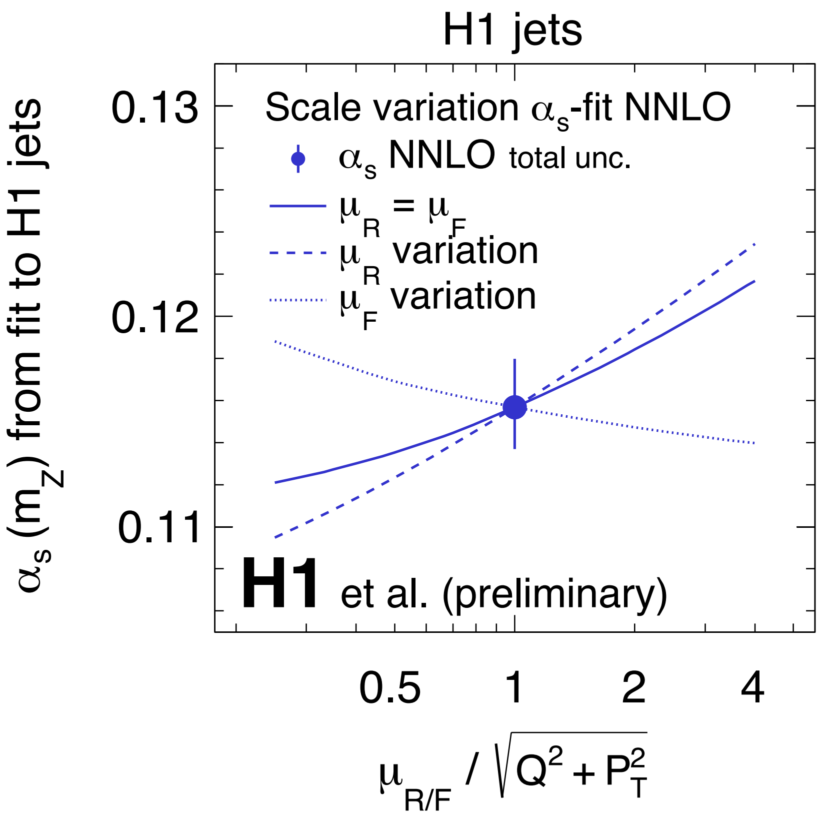


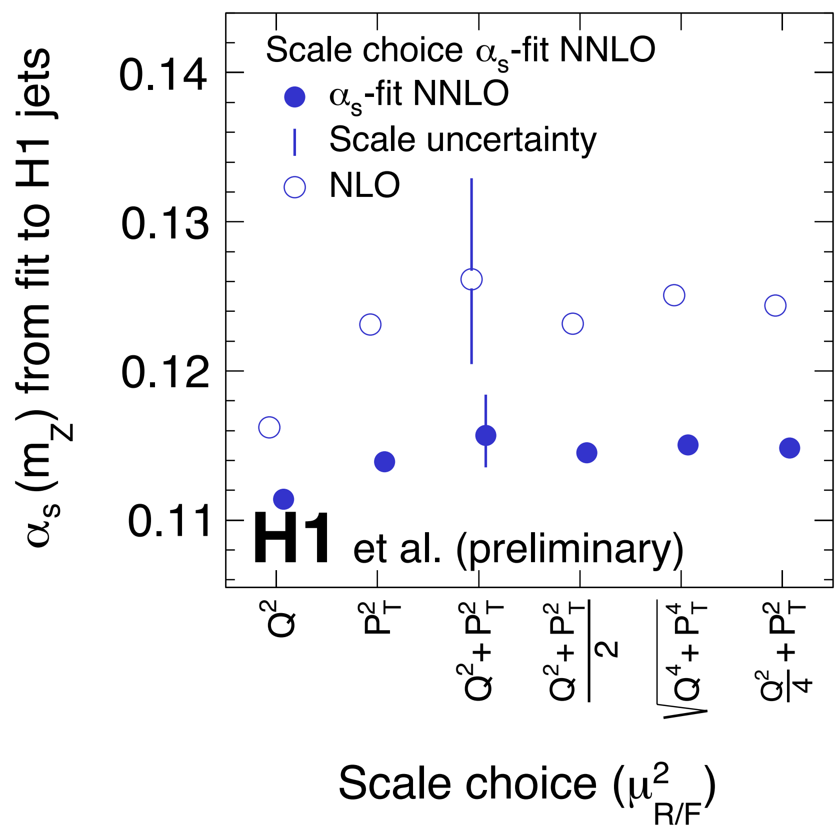


- cross sections are sensitive to both $\alpha_s^{\sigma,f}(m_Z)$

- both $\alpha_s^{\sigma,f}(m_Z)$ from fits are consistent within unc. using NNPDF3.0_nnlo_as_0.118

Variations of the scale and the scale choices



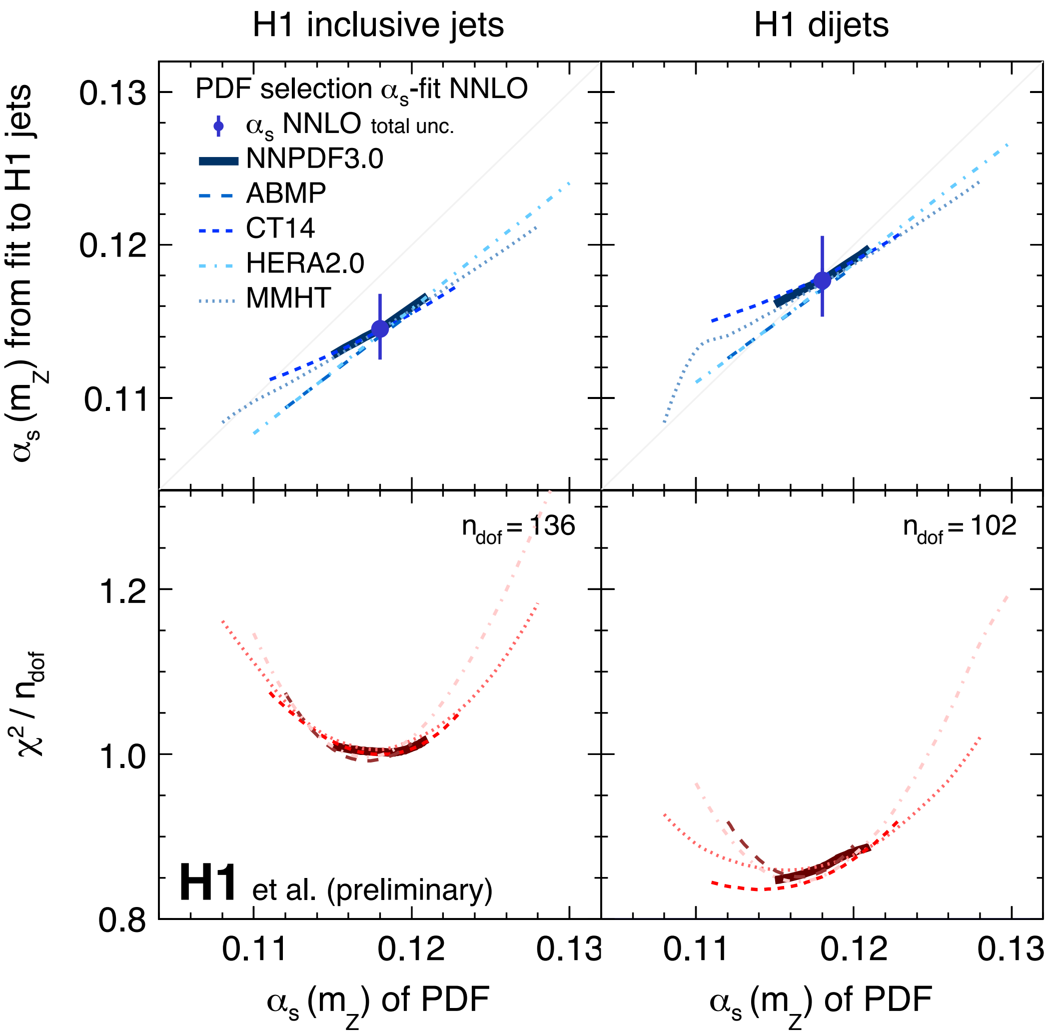


- our choice of scales: $\mu_R^2 = \mu_F^2 = Q^2 + P_T^2$

- μ_R variation has more impact than μ_F
- theory uncertainty related to scale from variation of μ_R, μ_F by 0.5 & 2.0

- Q^2 as scale is disfavored (larger χ^2)
- other choices are within scale unc.
- NNLO has smaller scale uncertainty compared to NLO

Variation of the input PDF sets



$\alpha_s(m_Z)$ $\equiv\alpha_s^\sigma(m_Z)\equiv\alpha_s^f(m_Z)$ and **χ^2/ndf** from repetitive fits with different input PDF sets as a function of "$\alpha_s(m_Z)$ of PDF"

→ different PDF sets obtained for our default $\alpha_s(m_Z)$=0.118 deliver very stable fit results:

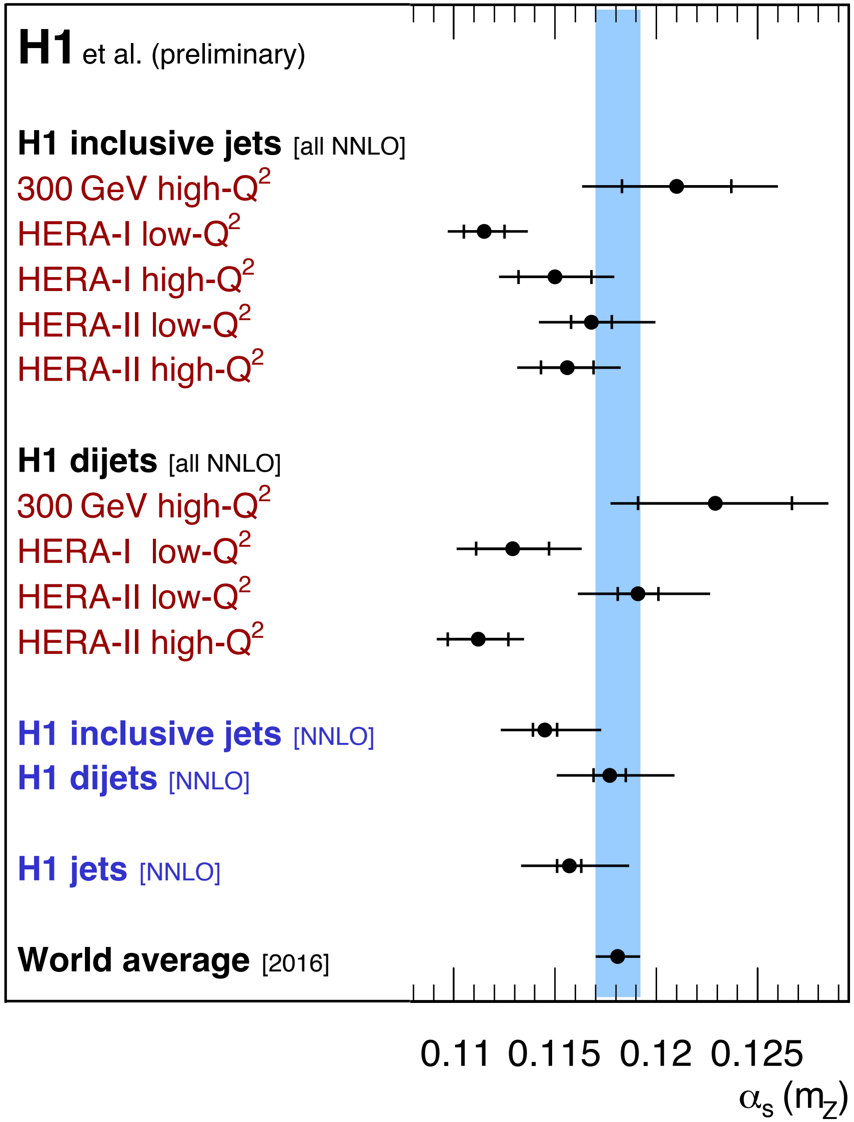
additional PDF unc. "PDFset": ½ max.[Δ(all PDFs at 0.118)]

→ the $\alpha_s(m_Z)$ results are sensitive to input "$\alpha_s(m_Z)$ of PDF"
- minimum of χ^2/ndf is obtained around our default value 0.118

additional PDF unc. "PDFα_s": $\frac{1}{2}$ [$\Delta\alpha_s(m_Z)$=0.004]

(2nd largest unc. after scale unc.)

Strong coupling from jets in DIS at NNLO



Results for $\alpha_s(m_Z)$ at NNLO using
- 9 individual H1 data sets separatly
- all H1 inclusive jets data
- all H1 dijets data
- all H1 jets (excluding dijets HERA-I since no correlations to incl. jets)

all H1 jet data sets are consistent:
- χ^2/ndf is around unity for all fits

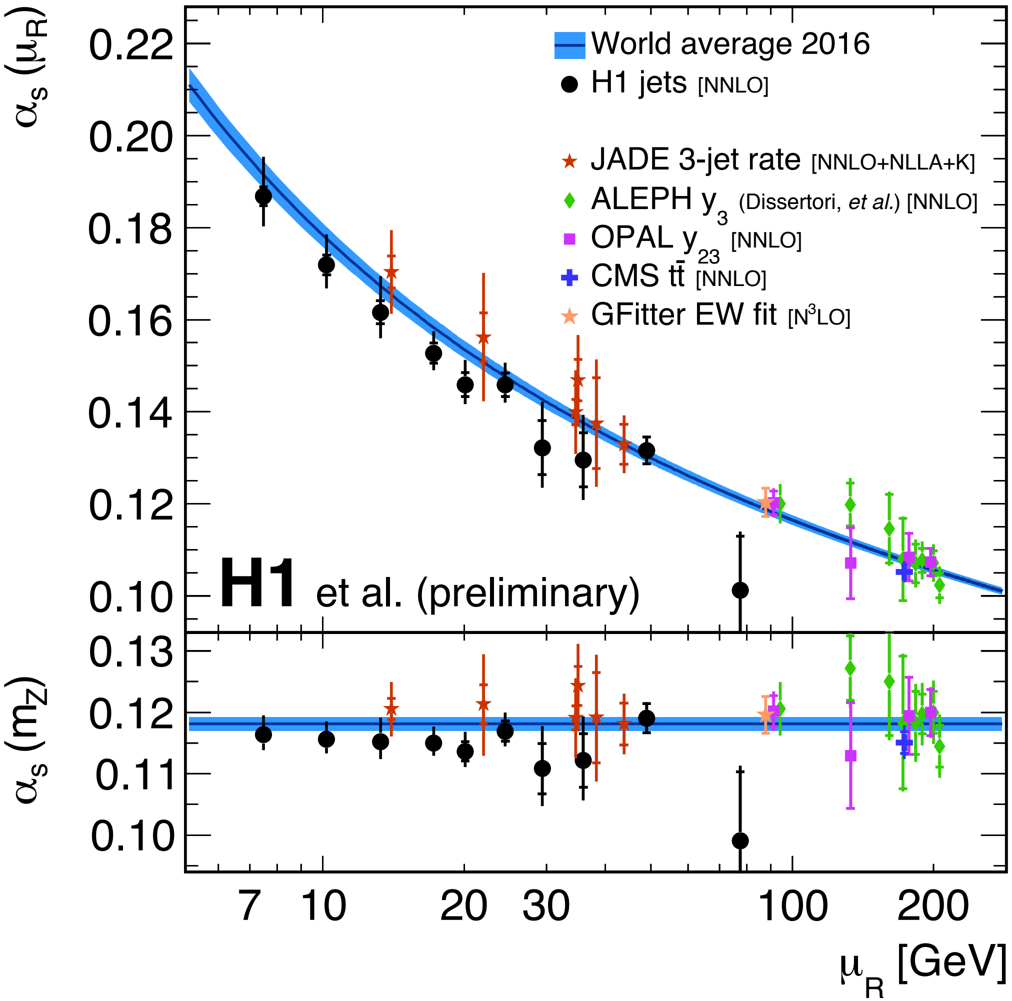
all $\alpha_s(m_Z)$ results are consistent

H1 jets (203 data points, χ^2/ndf=1.03)

$$\alpha_s(m_Z) = 0.1157\,(6)_{\rm exp}\,(3)_{\rm had}\,(6)_{\rm PDF}\,(12)_{{\rm PDF}\alpha_s}\,(2)_{\rm PDFset}\,\left(^{+27}_{-21}\right)_{\rm scale}$$

- excellent experimental precision
- still scale uncertainty is the largest
- in agreement with the world average

Running of strong coupling using jets at NNLO



Fits are performed for groups of jet data points at similar scales and resulting $\alpha_s(m_Z)$ are transported to the average μ_R of the group

- running of α_s in one experiment from 7 to 90 GeV is demonstrated

- in the full range α_s is in agreement with other α_s results at NNLO and the world average with a tendency to be a bit lower

- scale uncertainty is about the same at all μ_R values

Conclusions

The last missing piece in the jet measurements by H1 is on place:

	Process	HERA-I	HERA-II
Low Q^2	Inclusive jets Dijets Trijets	Eur.Phys.J.C67 (2010) 1	Eur.Phys.J.C77 (2017) 4,215
High Q^2	Inclusive jets Dijets Trijets	Eur.Phys.J.C65 (2010) 363	Eur.Phys.J.C75 (2015) 2,65

The first determination of the strong coupling constant $\alpha_s(m_Z)$ at NNLO using ep DIS jet data from H1

$$\alpha_s(m_Z) = 0.1157(6)_{\rm exp}(^{+31}_{-26})_{\rm theo}$$

→ very close and nice cooperation of theoreticians and experimentalists

Jets in DIS: precision QCD phenomenology with NNLO accuracy