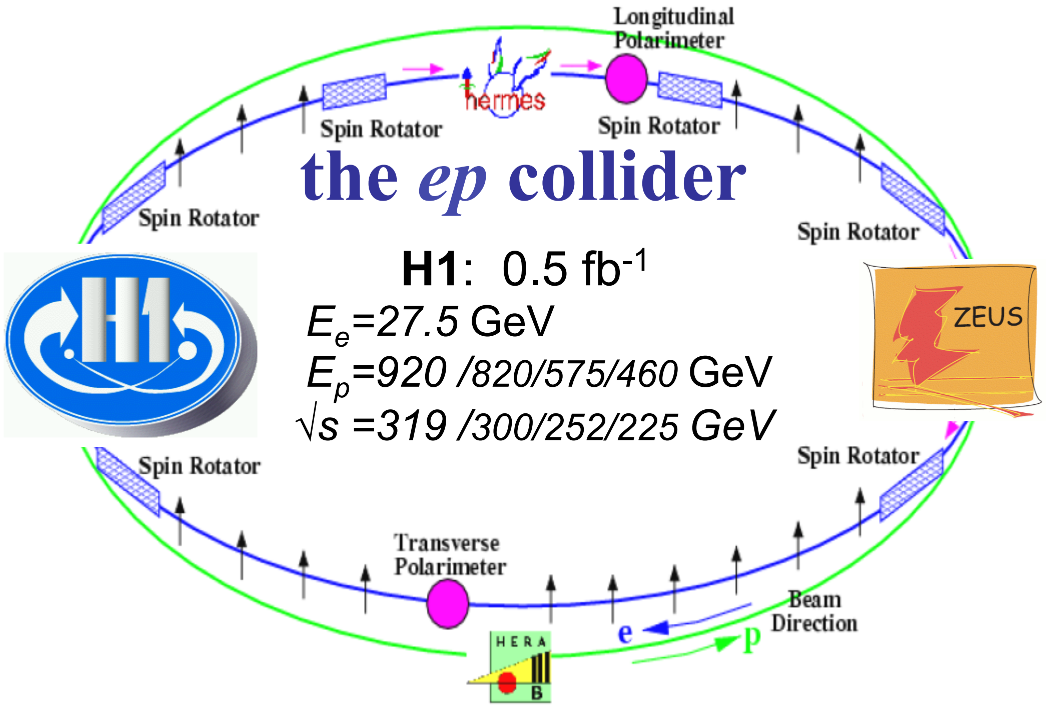
Determination of α_s in NNLO QCD using H1 jet cross section measurements

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



the *ep* collider

H1: 0.5 fb^{-1}

E_e=27.5 GeV

E_p=920 /820/575/460 GeV

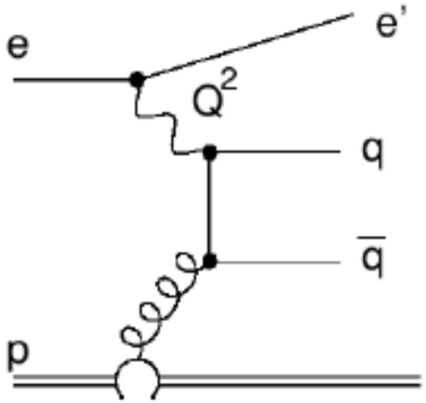
$\sqrt{s}$ =319 /300/252/225 GeV

HERA I: 1992-2000
HERA II: 2003-2007

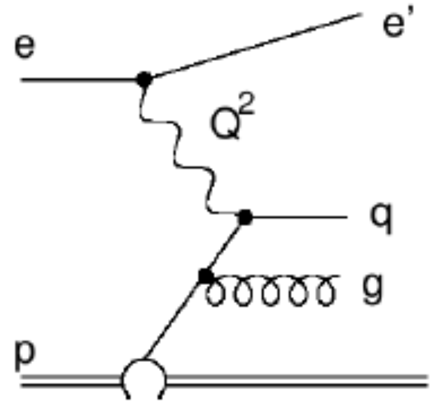
- completion of the jet measurements by the H1 collaboration at HERA
Eur.Phys.J.C77(2017) 215

- $\alpha_s(m_Z)$ determination at NNLO using jet measurements in DIS by H1
Eur.Phys.J.C77(2017) 791

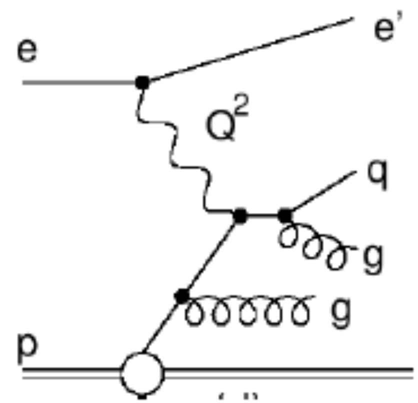
Jets in deep-inelastic *ep* scattering at HERA



Boson-gluon fusion



QCD Compton



Trijet leading-order

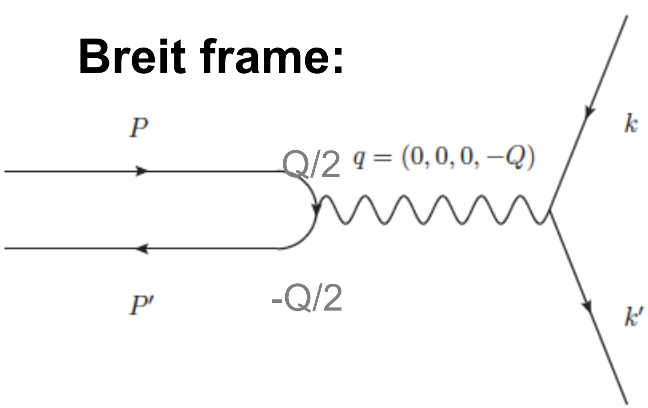
DIS kinematics:

$Q^2 = -q^2 = -(e-e')^2$ virtuality

$x = Q^2/2(pq)$ Bjorken x

$y = (pq)/(pe)$ inelasticity

Breit frame:



Inclusive jet, dijet and trijet production in DIS:

- *determined in Breit frame*
- *sensitive to α_s already at LO*
- *dominated by boson-gluon fusion → sensitive to gluon*
- *leading order for trijets is $O(\alpha_s^2)$*

New jet measurements in DIS by H1

Eur.Phys.J.C77(2017) 215

Inclusive jet, dijet and trijet cross sections in the *ep* NC DIS are measured at low Q^2 as a function of Q^2 and P_T^{jet} at the hadron level

NC DIS	$5.5 < Q^2 < 80$ GeV^2 ;	$0.2 < y < 0.6$
for all jets	$-1.0 < \eta_{lab}^{jet} < 2.5$;	$P_T^{jet} > 4$ GeV

inclusive jets	$4.5 < P_T^{jet} < 50$ GeV	asymmetric cuts $\langle P_T^j\rangle_{2,3} \gg P_T^{jet}$ to avoid IR sensitive regions in theory calculations
dijets	$5.0 < \langle P_T\rangle_2 < 50$ GeV	
trijets	$5.5 < \langle P_T\rangle_3 < 40$ GeV	

extension of the inclusive jet measurements at high Q^2 published in Eur.Phys.J.C75(2015)65 ($Q^2 > 150$ GeV^2, $7 < P_T^{jet} < 50$ GeV) to the low P_T bin: $5 < P_T^{jet} < 7$ GeV

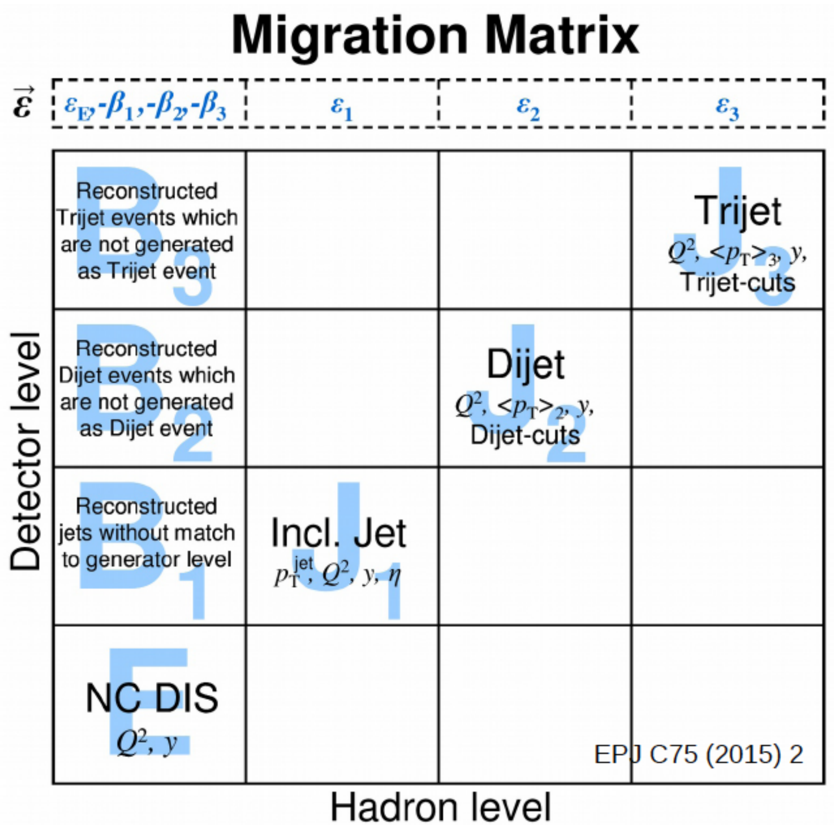
- HERA II data: 290 pb^{-1}, $\sqrt{s}$=319 GeV
- in the Breit frame using k_T algorithm with R=1
- also jet cross sections normalised to inclusive NC DIS are obtained (normalised jet cross sections)

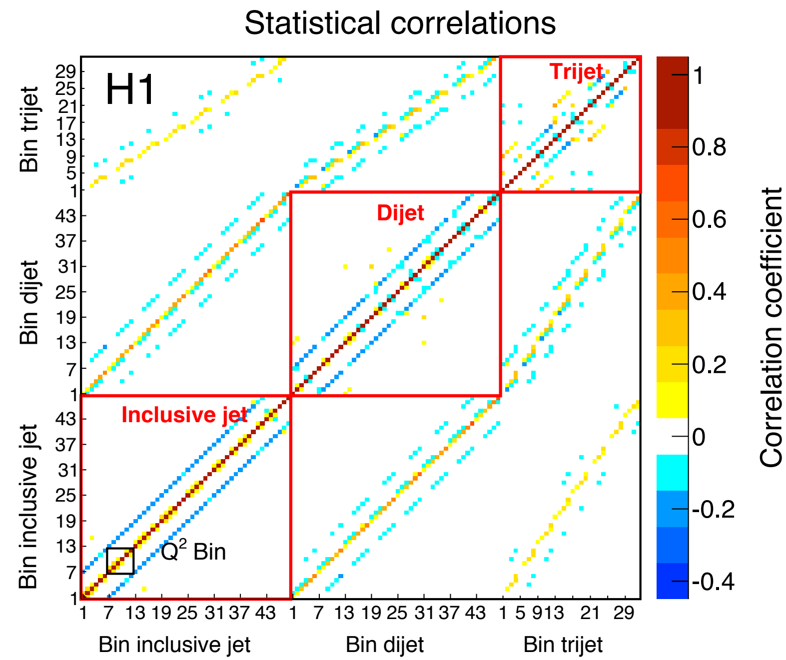
Simultaneous regularised unfolding of **inclusive jets, dijets, trijets and NC DIS**

*Detector effects like migrations, acceptance, efficiency 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

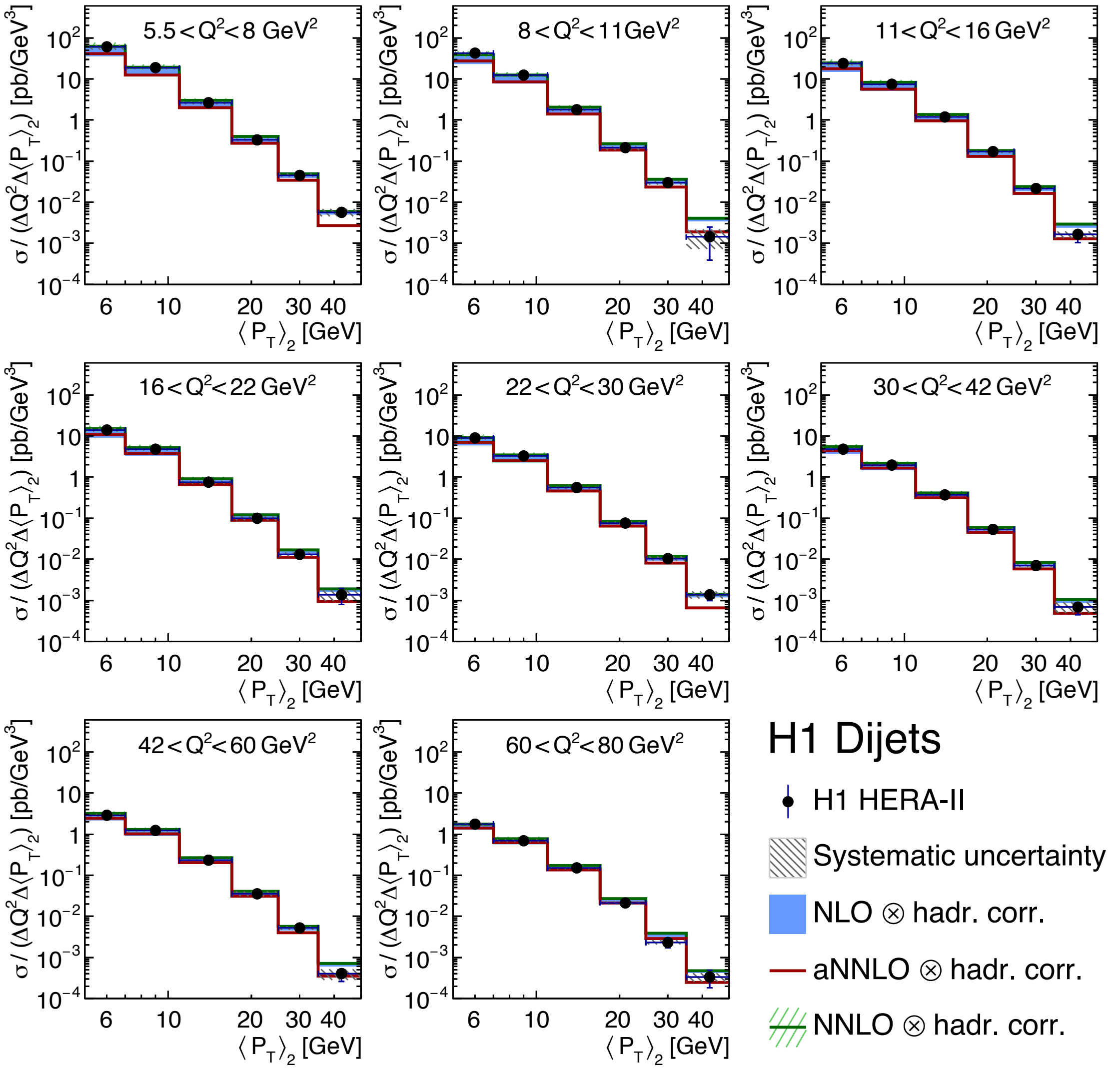




→ two times more bins in P_T (combined later)

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

Double 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

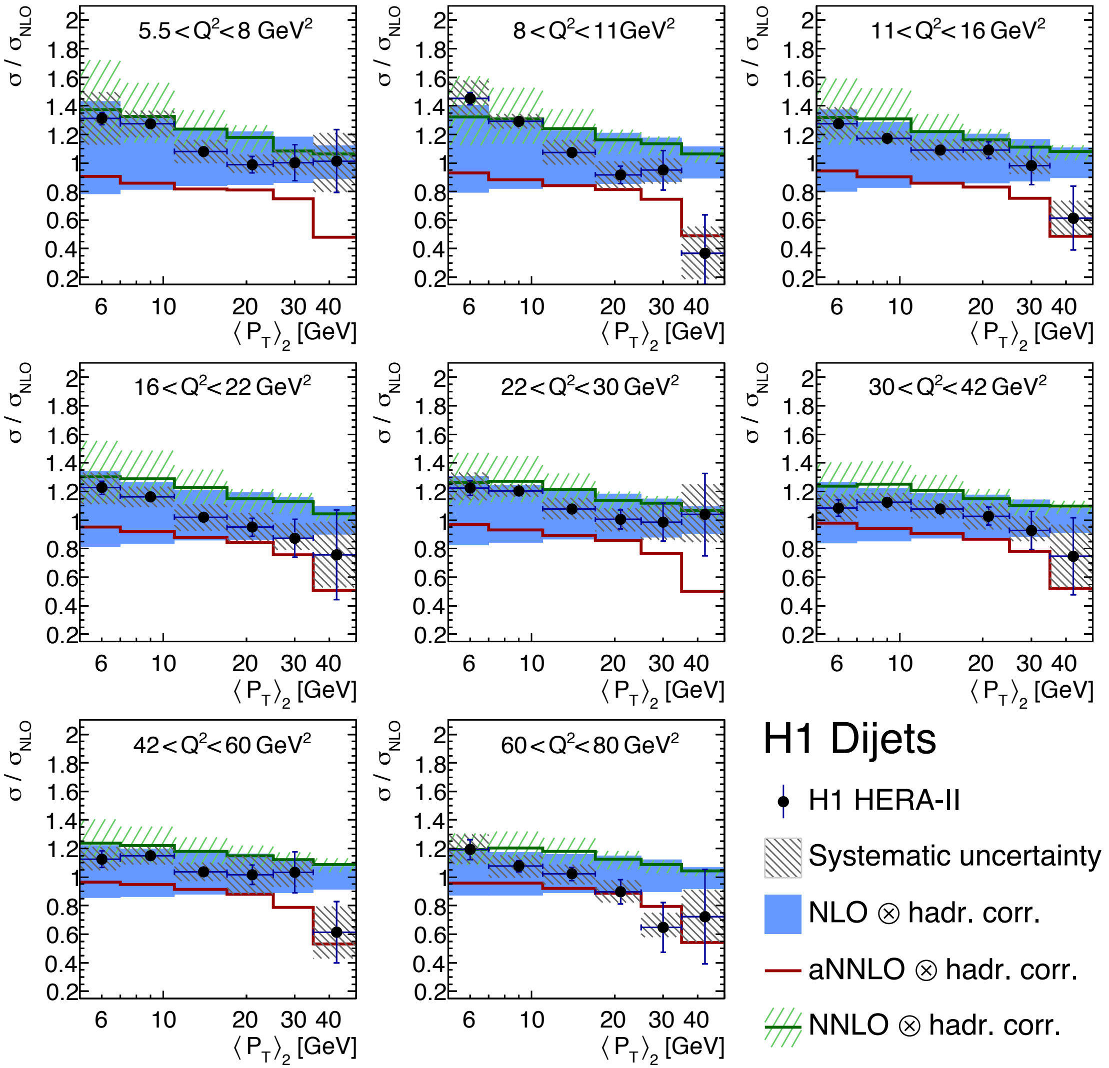
$5.5 < Q^2 < 80$ GeV^2
$5 < \langle P_T \rangle_2 < 50$ GeV

- 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)
- two-loop threshold correction
Phys.Rev.D92(2015)7,074037

NNLO (program NNLOJET)
Rev.Lett.117(2016)042001

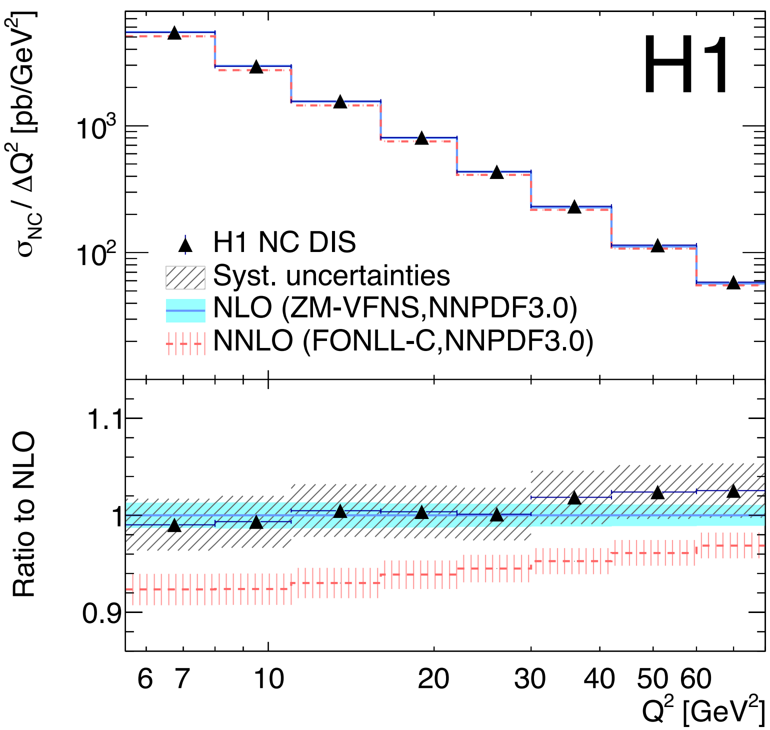
- scale unc. from variation of μ_r and μ_f by factors 0.5/2, excluding (0.5,2) and (2,0.5)

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

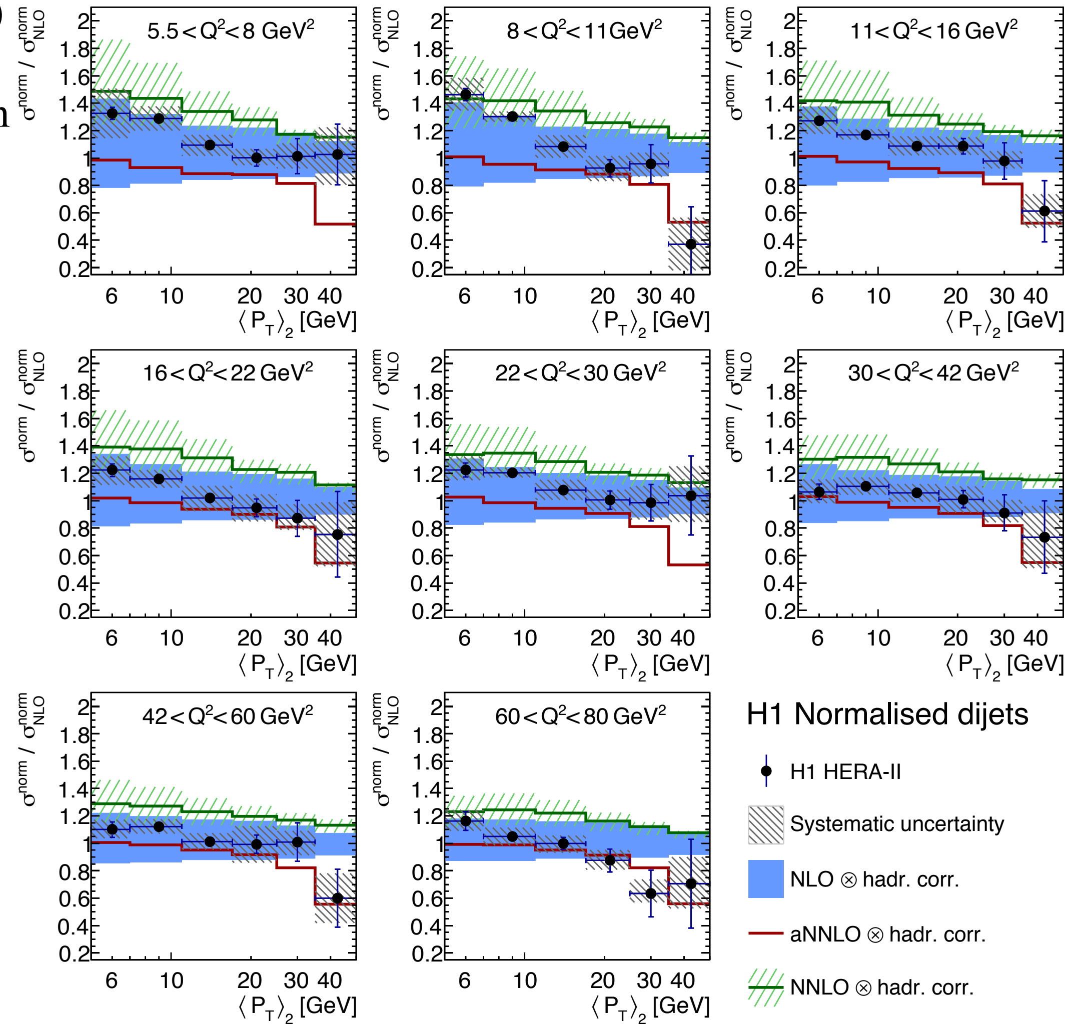
Normalised dijet cross sections

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

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



divided by σ^{norm}_{NLO}



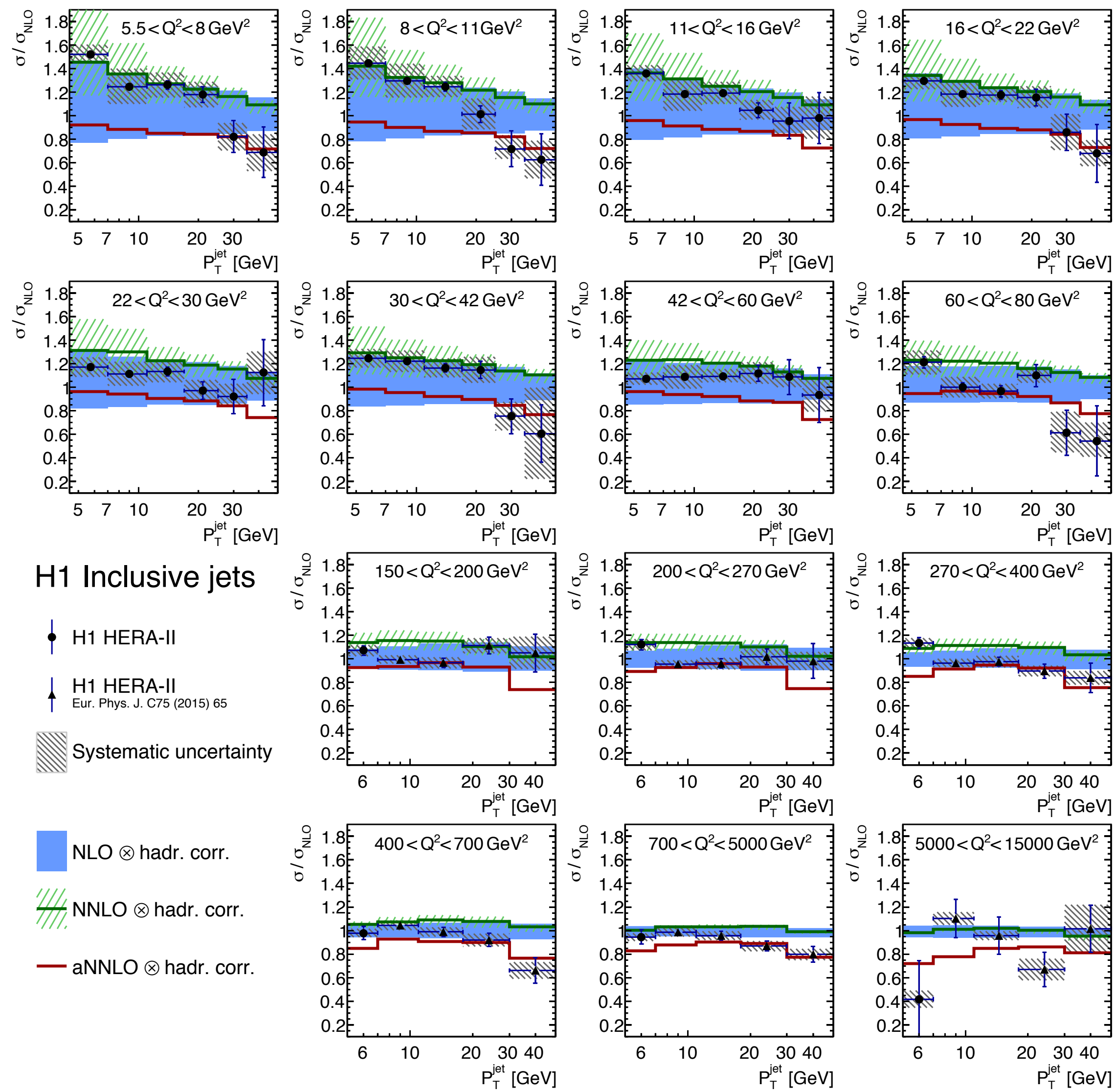
- some reduction of exp.unc.
- best suited for possible "PDF+α_s" fits together with inclusive NC & CC DIS data

Double diff. inclusive jet cross sections

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)65

divided by σ_{NLO}



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

also "normalised" cross sections are provided

Trijet cross sections

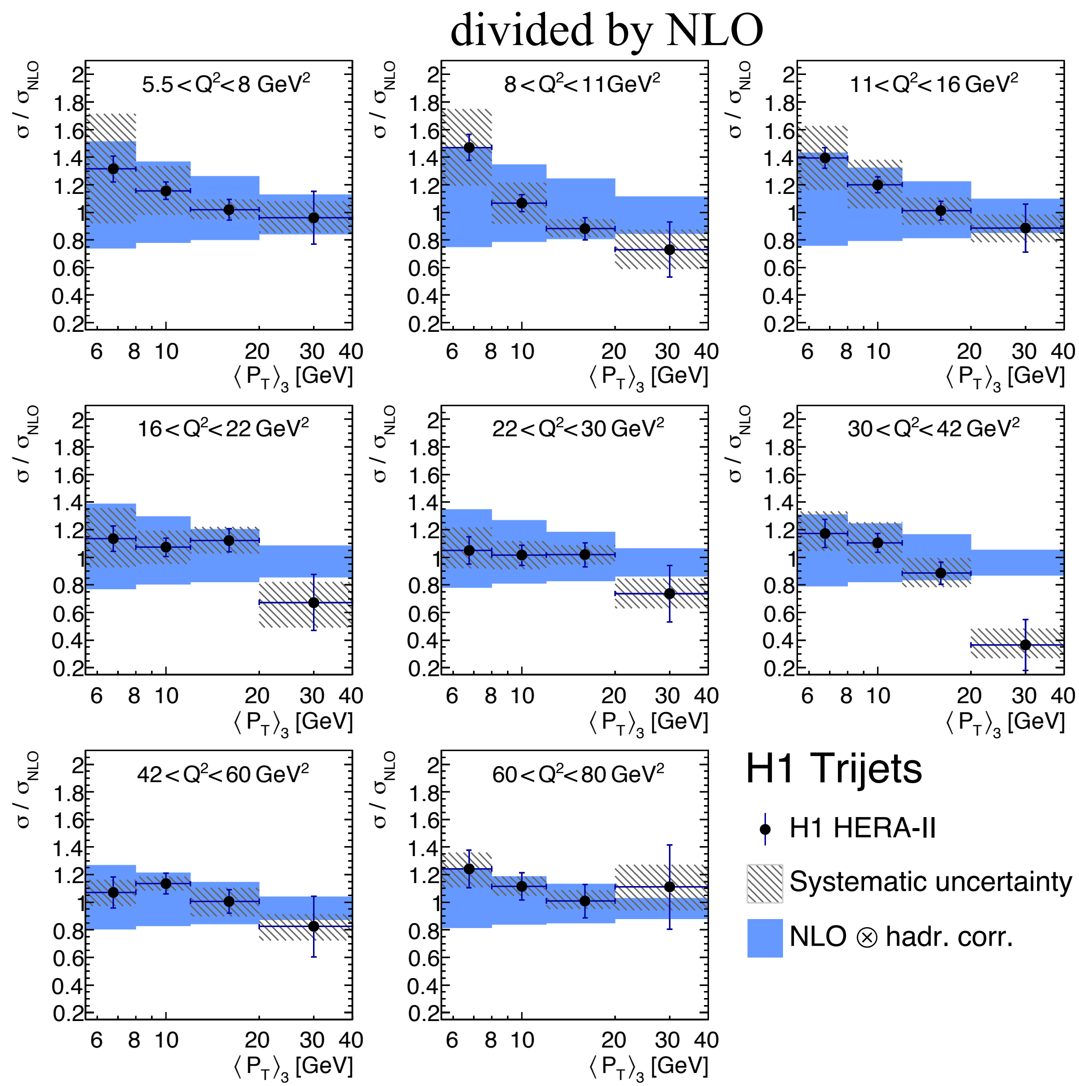
as a function of Q^2 and
$\langle P_T \rangle_3 = (P_T^{jet1}+P_T^{jet2}+P_T^{jet3})/2$
with $P_T^{jet1,2,3} > 4$ GeV

$5.5 < Q^2 < 80$ GeV^2
$5.5 < \langle P_T \rangle_3 < 40$ GeV

→ good description by calculations at NLO

→ NNLO is not available yet

also "normalised" cross sections are provided



Extraction of α_s at NNLO from jet data in DIS

Eur.Phys.J.C77(2017) 791 **H1 collaboration** together with
V.Bertone, J.Currie, T.Gehrmann, C.Gwenlan, A.Huss, J.Niehues, M.Sutton **(NNLOJET)**

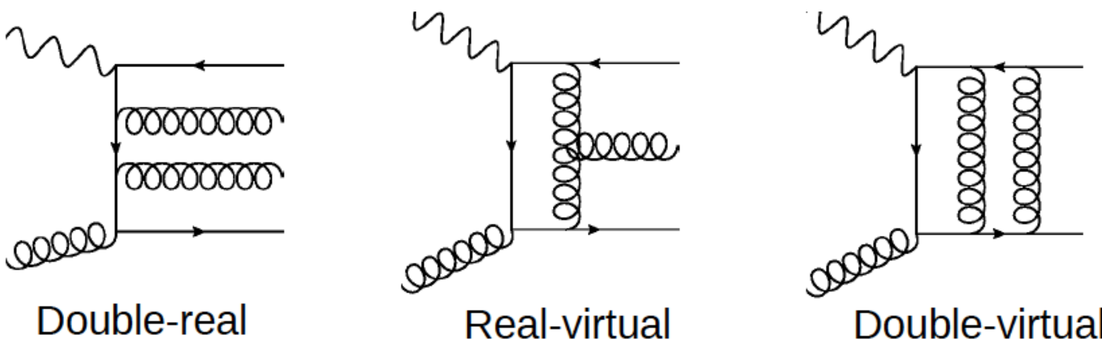
Input jet data in DIS: 5 inclusive jet sets and 4 dijet sets published by H1

Jet cross section:

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

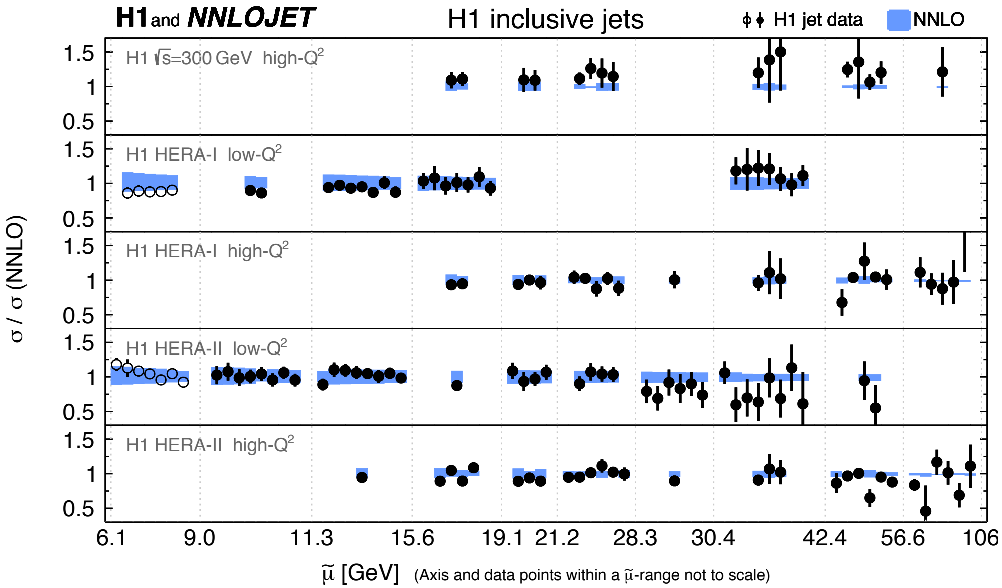
PDFs — ME — hadronisation correction

NNLO calculations for ep DIS jet production (2016/2017):



using antenna subtraction technique
J. Currie et al., Rev.Lett.117(2016)042001; JHEP 1707(2017) 018

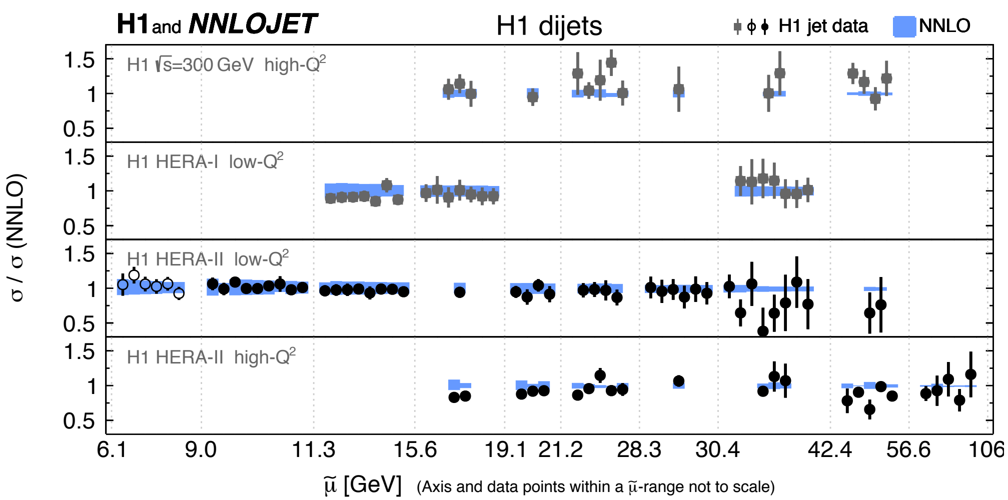
Input H1 jet data compared to α_s NNLO fit



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

→ presented as a function of μ:
$\mu^2 = Q^2_{bin} + P_{T\,bin}^2$



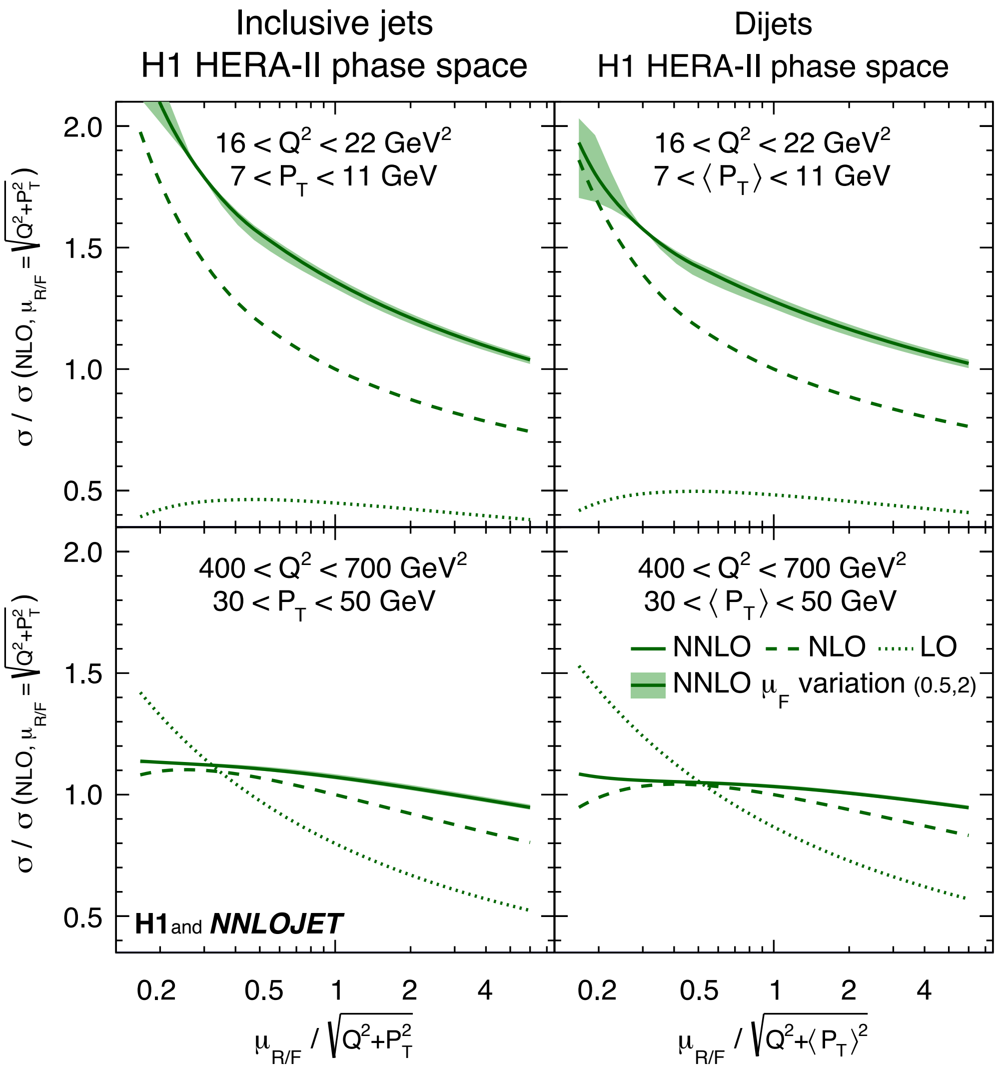
4 dijet cross section sets

- $\langle P_T \rangle_2$ 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 fits (NNLO)*

→ *HERA-II low-Q2: points with $\langle P_T \rangle_2 < 7$ GeV are excluded*

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*

- μ_F dependence small (green band)

Methodology of the $\alpha_s(m_Z)$ determination

NNLO theory: *α_s dependences of the jet cross sections*

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

explicit α_s dep. in hard ME:

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

perturbative expansion in orders of α_s

RGE: running of α_s

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

implicit α_s dependence in PDFs:

$$\mu_F^2 \frac{df}{d\mu_F^2} = \mathcal{P}(\alpha_s)\otimes f \quad \Rightarrow$$

$$f = \Gamma\left(\mu_F,\mu_0,\alpha_s(m_Z)\right)\otimes f_{\mu_0}(x)$$

evolution kernel

Two complementary approaches to determine $\alpha_s(m_Z)$:

α_s-fit (*H1 jet data only*)

- take external PDFs at μ_0=20 GeV (NNPDF3.1 NNLO, $\alpha_s^{PDF}(m_Z)$=0.118)
- propagate those PDFs to any value of μ_F using DGLAP equation in NNLO
- fit theory predictions to H1 jet data with a free parameter $\alpha_s(m_Z)$ by minimizing χ^2

pro: *NNLO theory for jets only* contra: *needs external PDFs*

PDF+α_s-fit (*H1 jet and inclusive NC+CC data*)

- simultaneous fit of PDFs and $\alpha_s(m_Z)$ in NNLO QCD.

pro: *everything in one go* contra: *complicated theory environment*

α_s–fit

- fit jet data with a free parameter $\alpha_s(m_Z)$ by minimizing χ^2 based on log-normal probabilities

$$\chi^2 = \sum_i \sum_j (\log \varsigma_i - \log \sigma_i)\,(V_{\rm exp} + V_{\rm had} + V_{\rm PDF})^{-1}_{ij}\,(\log \varsigma_j - \log \sigma_j)$$

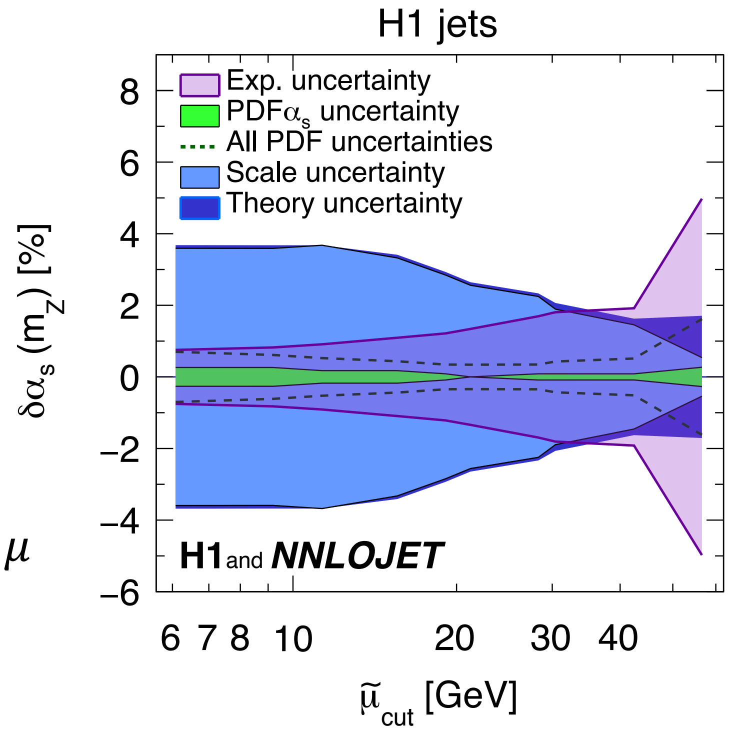
ς=Data, σ_i=NNLO   V=covariance matrices

Uncertainties of the resulting $\alpha_s(m_Z)$ originate from:

exp relative uncertainties of data
had uncertainty of hadronisation correction
PDF uncertainty of PDF (NNPDF3.1 NNLO)
PDFset variation of the PDF sets
PDFas variation of the α_s^{PDF}-value by 0.002
scale variation of the scale by factors 0.5 & 2.0

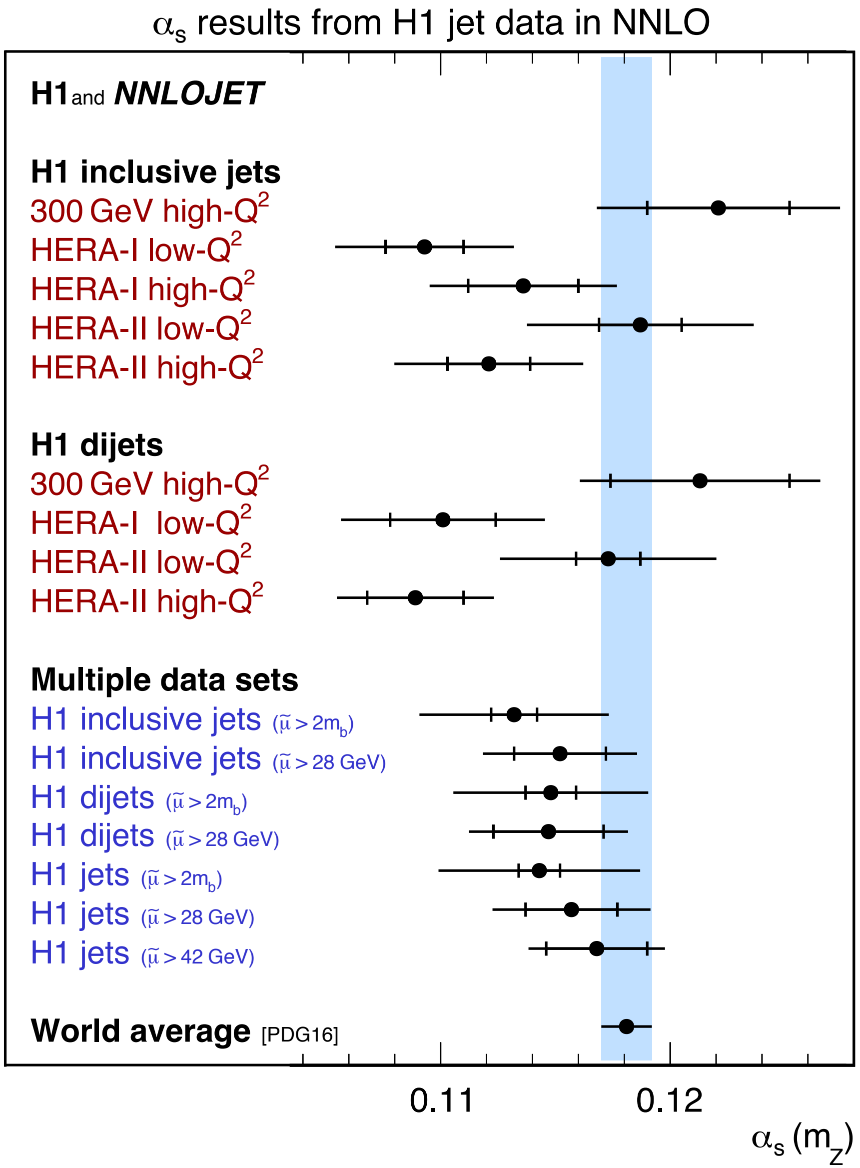
Cut on the scale value of jet data in the fit :

- *exp.* incertainty is increasing with the cut value on μ
- *scale* and *PDFas* are decreasing with the cut on μ



→ **compromise for the main result: μ > 28 GeV**

Strong coupling from H1 jets in DIS at NNLO



Results for $\alpha_s(m_Z)$ at NNLO using H1 jets:

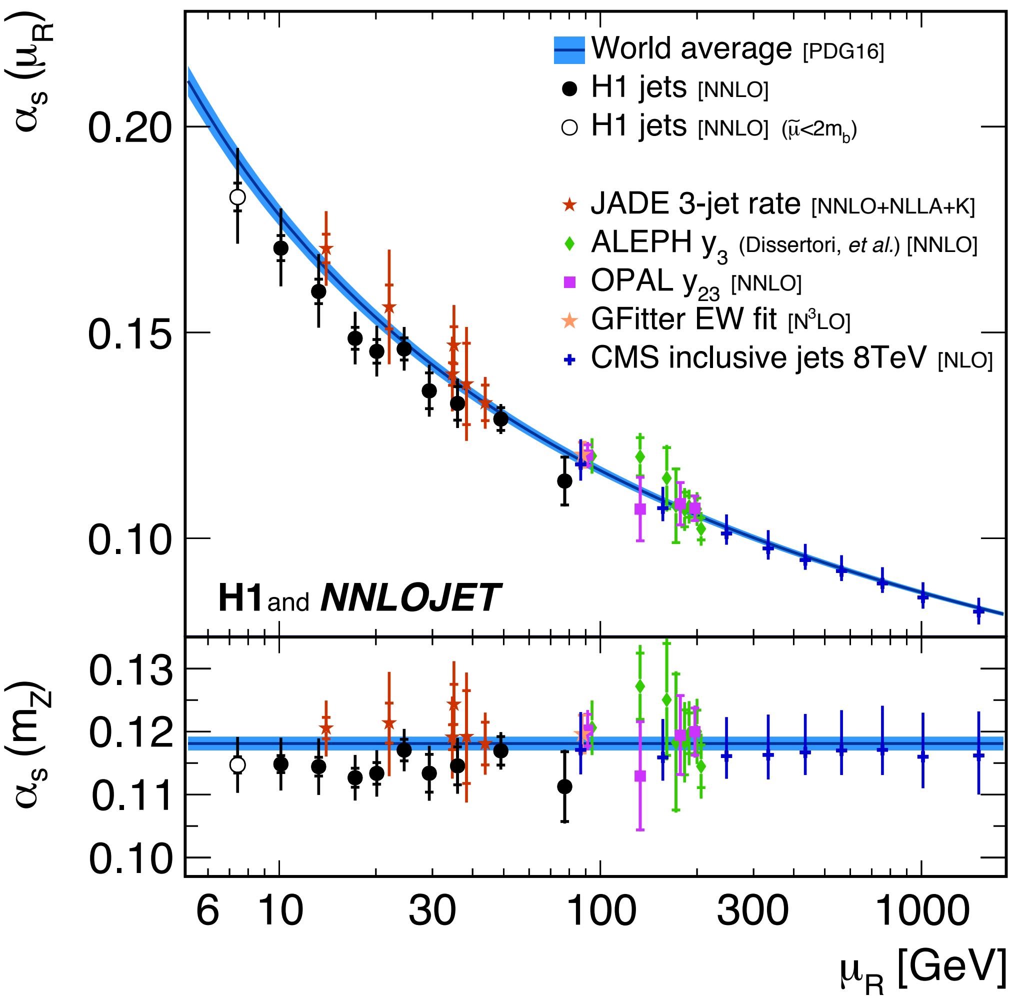
- *input H1 jet data sets (9) are consistent and χ^2/ndf are around unity*
- *all $\alpha_s(m_Z)$ results are consistent*

- main result: H1 jets with $\mu > 28$ GeV ($\chi^2 = 63.2$ for 91 data points)

$$\alpha_s(m_Z) = 0.1157\,(20)_{\rm exp}\,(6)_{\rm had}\,(3)_{\rm PDF}\,(2)_{{\rm PDF}\alpha_s}\,(3)_{\rm PDFset}\,(27)_{\rm scale}$$

- *scale uncertainty is the largest*
- *PDF uncertainties are negligible*
- *in agreement with the world average*

Running of strong coupling at NNLO



α_s-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 is tested from 7 to 90 GeV (in one experiment)

→ consistency with expectation at all scales

→ scale uncertainty dominates at low μ_R values

PDF+α_s-fit in NNLO (H1PDF2017)

The second approach: simultaneous determination of $\alpha_s(m_Z)$ and PDF in the NNLO QCD fit (H1PDF2017)

Input data:
- inclusive NC and CC DIS data from H1 ($Q^2 > 10$ GeV^2)
- normalised incl. jet and dijet cross section data from H1 ($\mu > 2m_b$)

Scales: $\mu_R^2 = Q^2$ for inclusive DIS and $\mu_F^2 = Q^2 + P_T^2$ for jet data

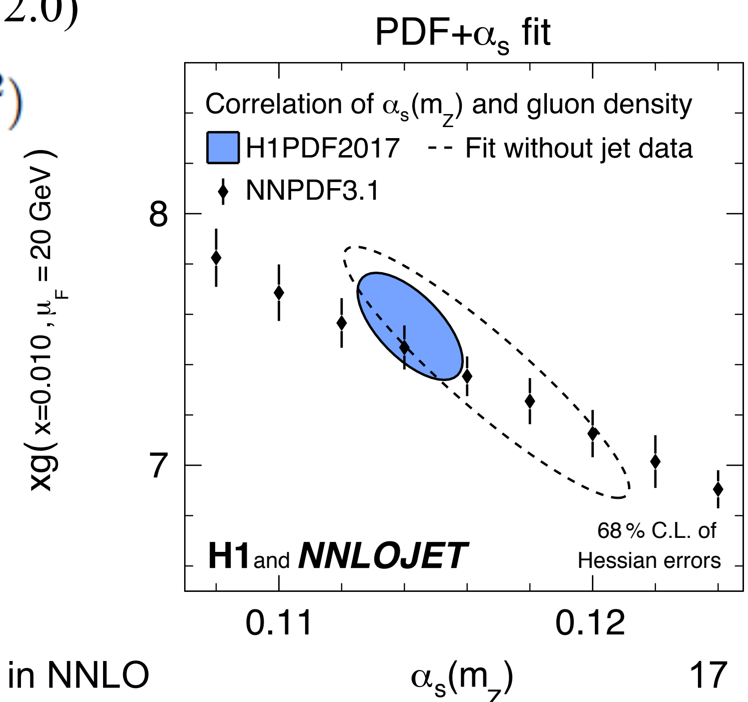
Parameterisation of PDFs: (similar to HERAPDF2.0)

$$xf(x)|_{\mu 0} = f_A x^{f_B} (1-x)^{f_C} (1 + f_D x + f_E x^2)$$

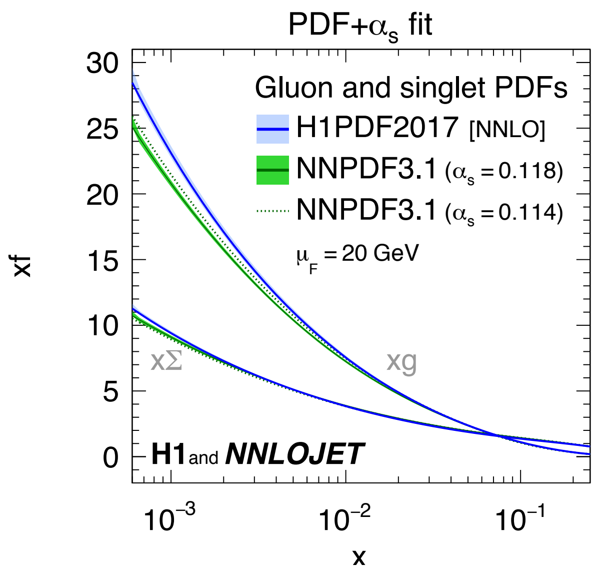
12 parameters in total at $\mu_o = 1.9$ GeV

very different theory and data sets from α_s-fit:
- min μ^{jet}, "normalised jets"; + NC & CC data
- starting at much lower scale μ_o ; + DIS

→ *reduces correlation between gluon and α_s and stabilizes gluon density determination*



PDF+α_s-fit: PDFs & $\alpha_s(m_Z)$ in H1PDF2017



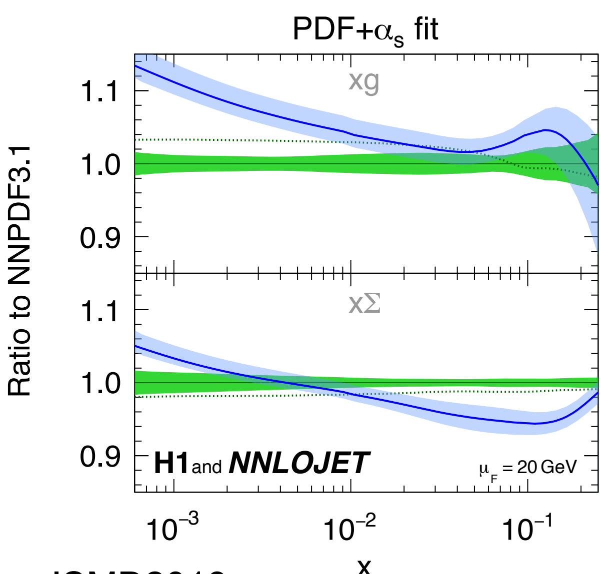
all H1 incl. DIS, incl. jets and dijet data are included into fit

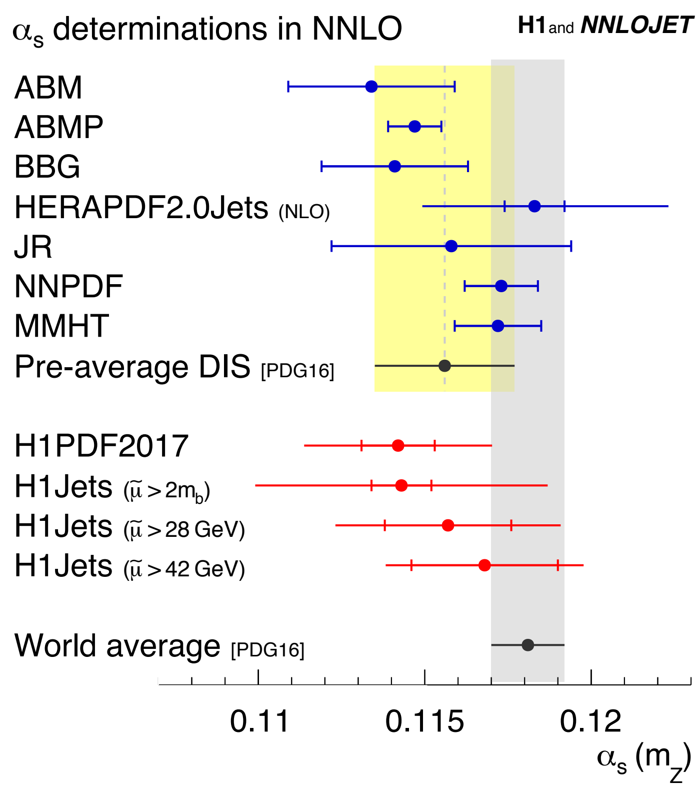
consistency of data sets: χ^2 = 1539.7 for ndf = 1529-13

- PDFs – comparable precision to global fits (with fixed $\alpha_s(m_Z)$)
- $\alpha_s(m_Z)$ – good overall precision of 2.5%

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

consistent with the "H1 jet" fits and other NNLO results





Summary

H1 measurements of jet cross section in NC DIS are accomplished

- HERA I + II (1992-2007)
- inclusive, dijets, trijets
- $5 < Q^2 < 15000$ GeV^2 , $5 < P_T^{jet} < 50$ GeV

Determination of $\alpha_s(m_Z)$ at NNLO using H1 incl. jets, dijets and incl. DIS data

Eur.Phys.J.C77(2017) 791

a_s-fit $\alpha_s(m_Z) = 0.1157\,(20)_{\rm exp}\,(6)_{\rm had}\,(3)_{\rm PDF}\,(2)_{{\rm PDF}\alpha_s}\,(3)_{\rm PDFset}\,(27)_{\rm scale}$

PDF+a_s-fit $\alpha_s(m_Z) = 0.1142\,(11)_{\rm exp,had,PDF}\,(2)_{\rm mod}\,(2)_{\rm par}\,(26)_{\rm scale}$ (H1PDF2017)

- two alternative approaches provide consistent results at NNLO with high experimental and theoretical precision

- fruitful collaboration of theoreticians and experimentalists (H1 & NNLOJET)

Jets in eh/hh collisions → precision QCD phenomenology with NNLO accuracy

α_s–fit: variations of the scale and $\alpha_s^{PDF}(m_Z)$ of PDFs & different scale choices

- *variations of $\mu_{R,F} = Q^2 + P_T^2$ by factors 0.5 & 2.0 are used for theory uncertainty estimation of the resulting $\alpha_s^{fit}(m_Z)$*

- *variation of external PDF sets and $\alpha_s^{PDF}(m_Z)$ of PDF*

different choices of the scale:
- *Q^2 as scale is disfavored (larger χ^2)*
- *other choices are within scale unc.*
- *NNLO scale uncertainty is better than the NLO one*