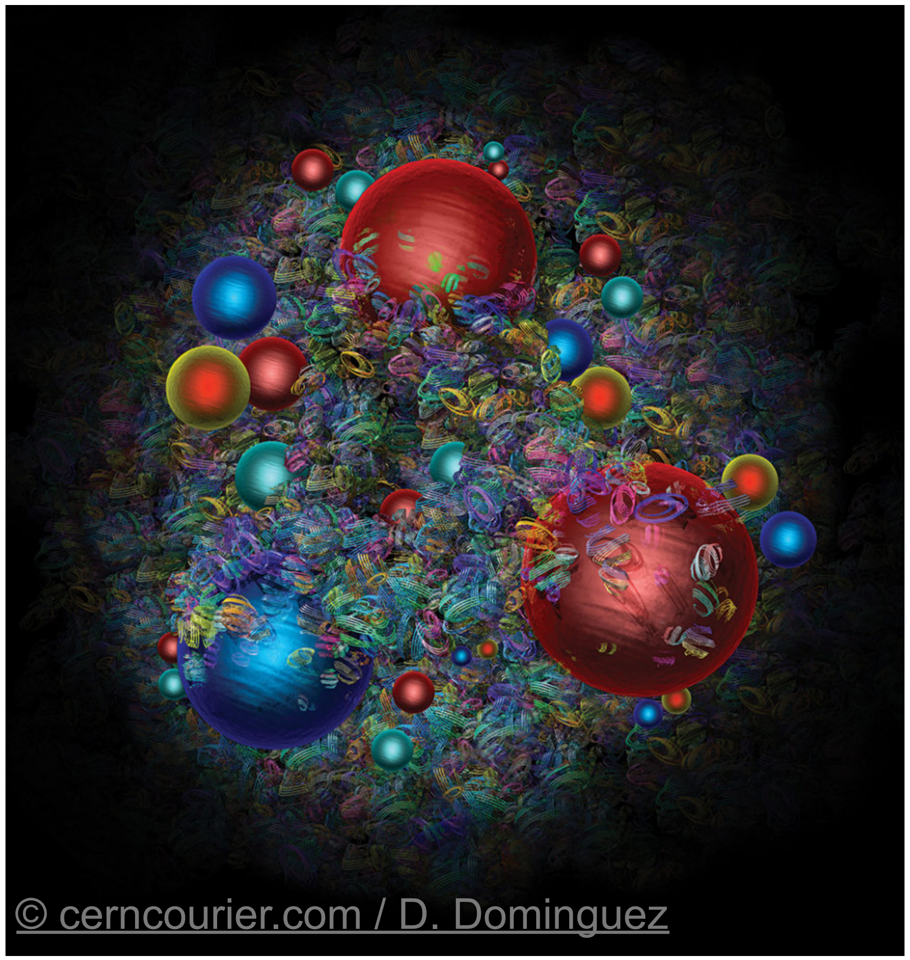
Determination of α_S at NNLO QCD Using H1 Jet Cross Section Measurements



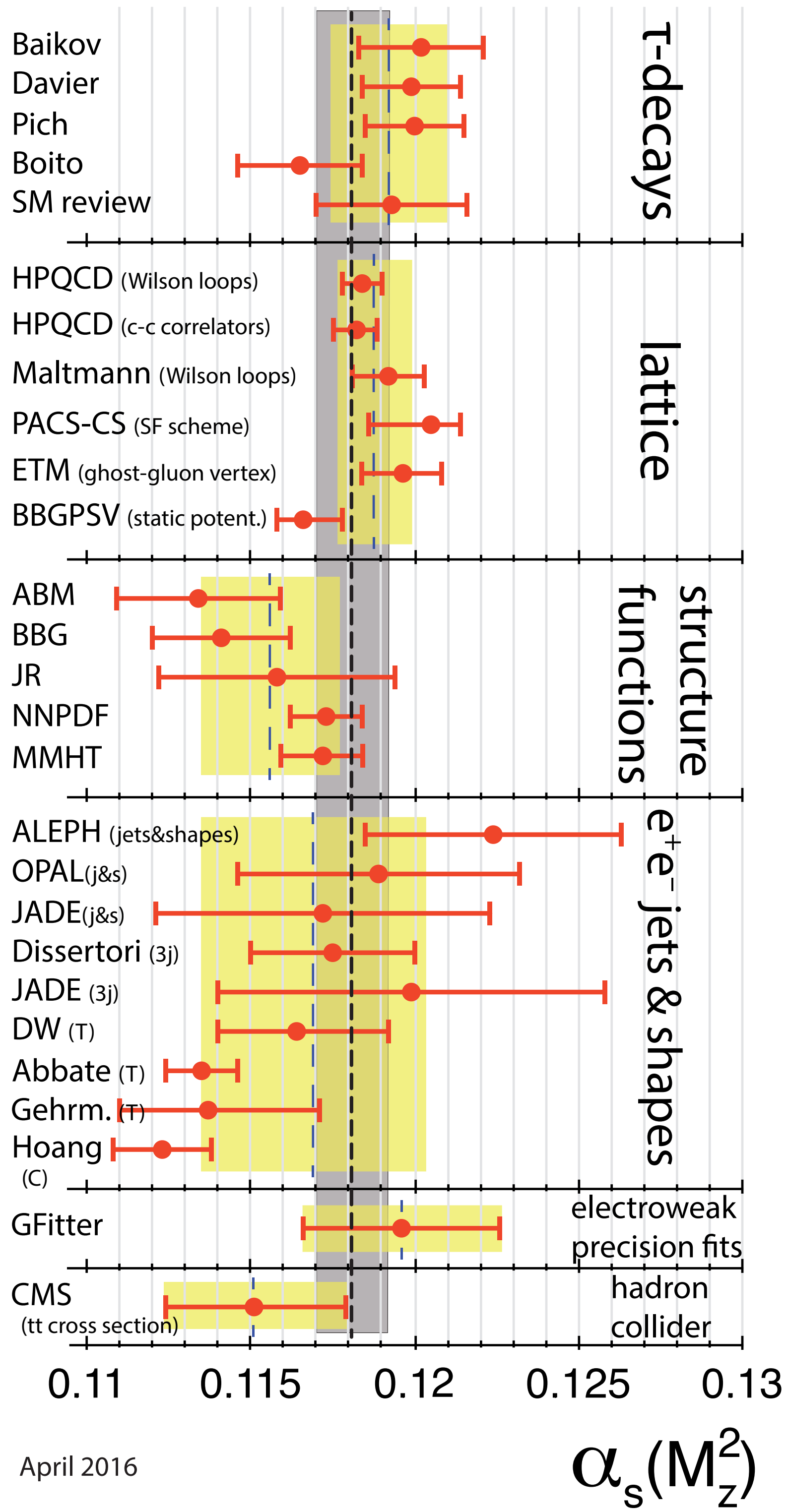
- Motivation – QCD, α_S and the RGE
- H1 jet cross section measurements in DIS
- Methodology
- Extraction of the strong coupling constant α_S

  Eur.Phys.J.C 77 (2017), 791

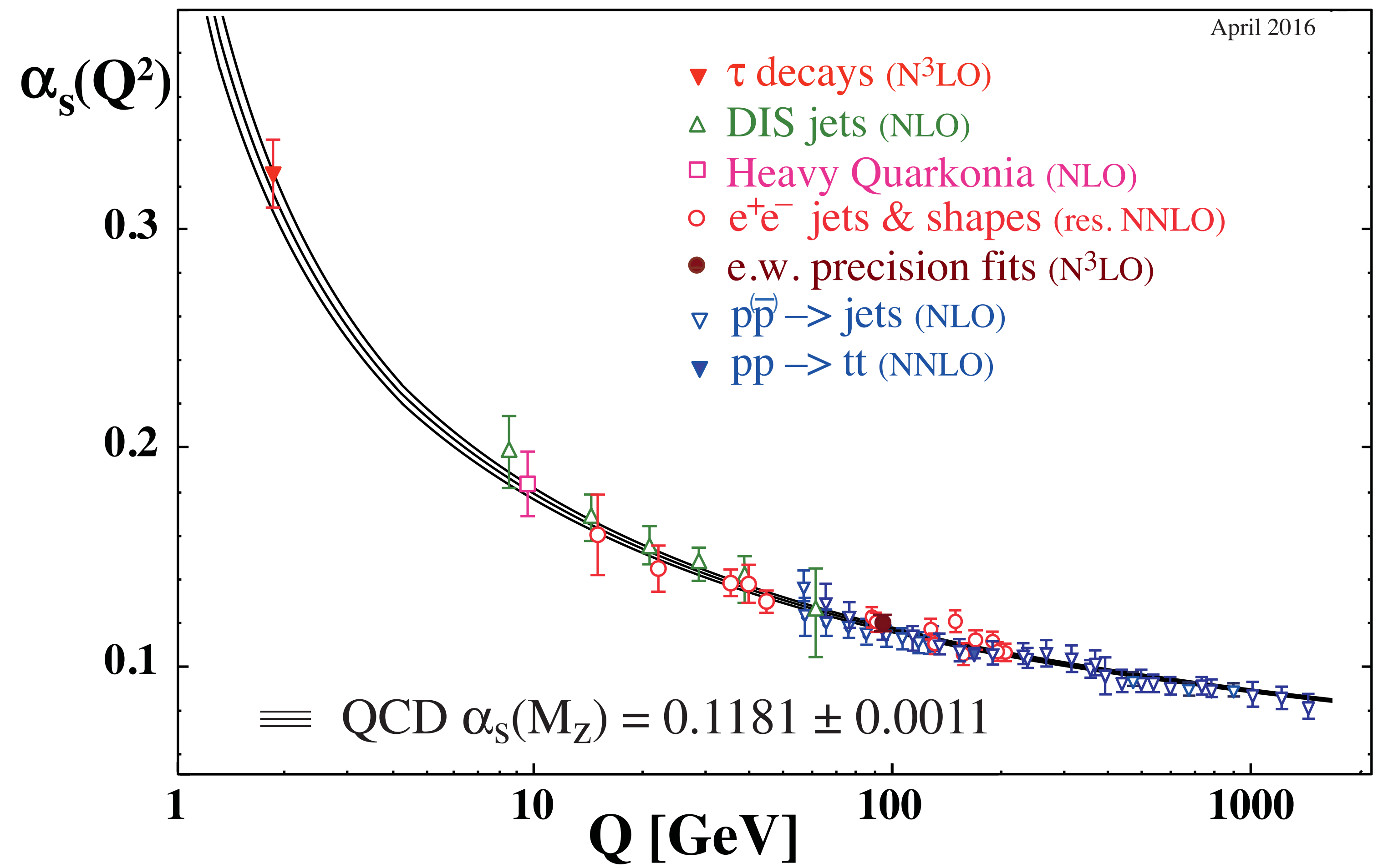
Eram Rizvi

Queen Mary
University of London

EPS 2019
Ghent, Belgium
12th July 2019



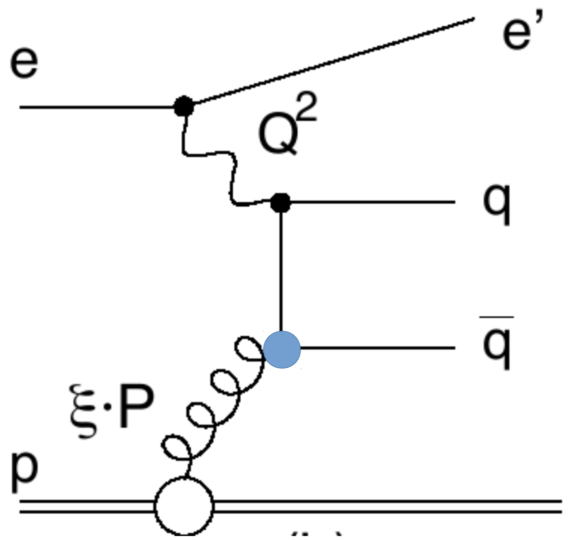
- Quantum Chromodynamics (QCD) is the theory of the strong interaction
- Renormalization group equation (RGE) encodes the dependence of the coupling parameter on the energy scale μ (=running)
- Values of $\alpha_S(\mu)$ are not predicted



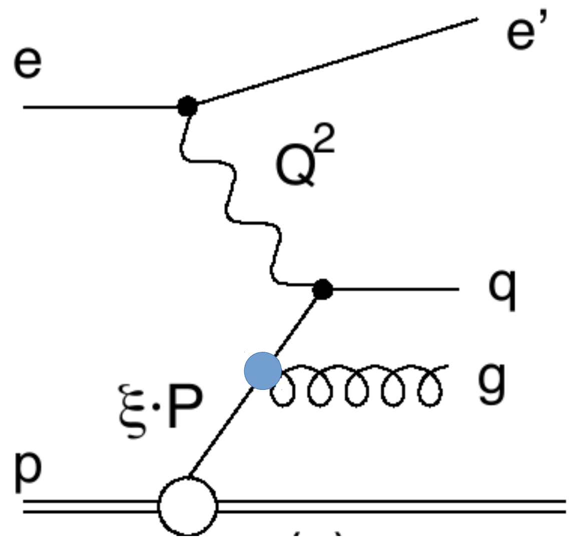
M. Tanabashi et al. (Particle Data Group), Phys. Rev. D **98**, 030001 (2018)

QCD Tests probe two aspects:

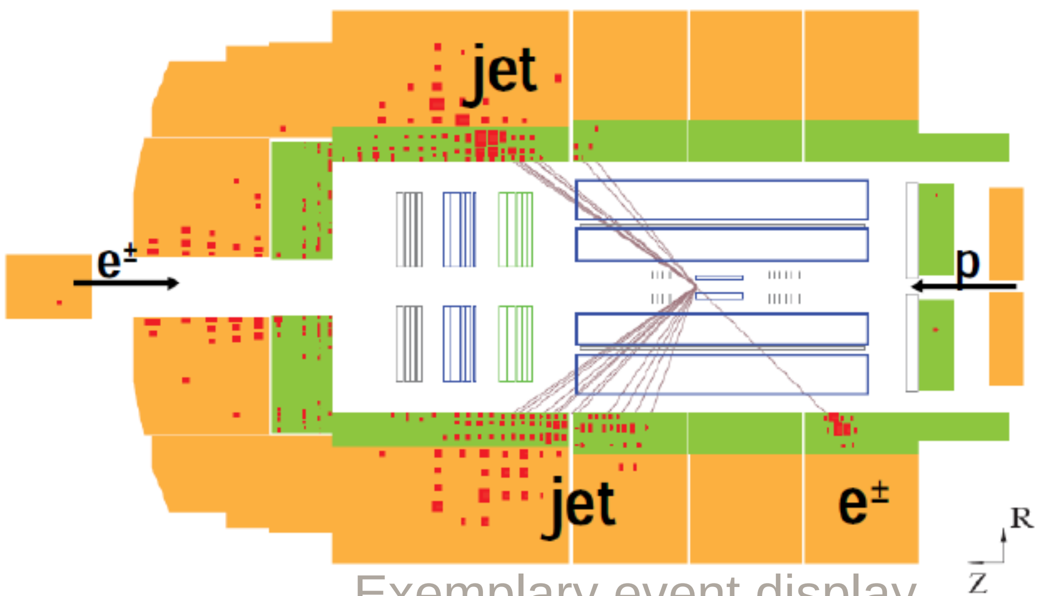
- determination of the value at some fixed scale $\alpha_S(\mu = M_Z)$
- scale dependence of $\alpha_S(\mu)$



Boson-gluon fusion



QCD Compton

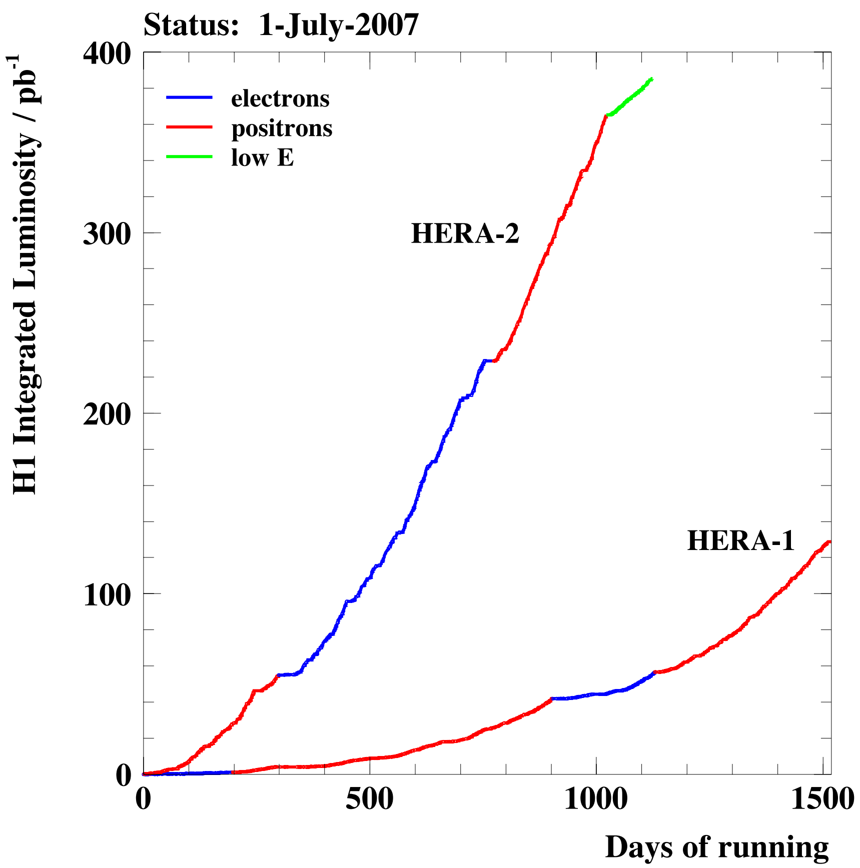


Exemplary event display

- Dependence of α_s in matrix element and in PDFs
- Dominant sensitivity is from matrix element

<u>HERA-I operation 1993-2000</u>
Ee = 27.6 GeV
Ep = 820 / 920 GeV
√s=301 GeV & √s=318 GeV
$\int\mathcal{L}$ ~ 110 pb^{-1} per experiment

<u>HERA-II operation 2003-2007</u>
Ee = 27.6 GeV
Ep = 920 GeV
√s=318 GeV
$\int\mathcal{L}$ ~ 330 pb^{-1} per experiment
Longitudinally polarised leptons



H1 Inclusive Jet & Dijet Cross Sections

Inclusive jet cross sections

- $d\sigma/dQ^2dP_{T,jet}$
- HERA-I & HERA-II
- low-Q^2 (<100 GeV^2) and
- high-Q^2 (>150 GeV^2) regions

Selections

- kt-algorithm, R=1
- -1.0 < η_{lab} < 2.5
- P_T ranges from 4.5 to 50 GeV (Breit frame)

Dijet cross sections

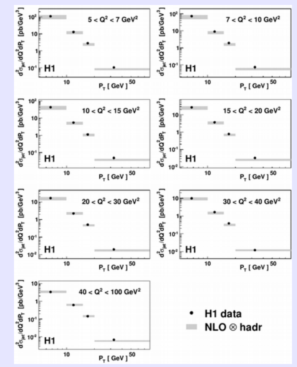
- $d\sigma/dQ^2d\langle P_T\rangle$
- HERA-I & HERA-II
- low-Q^2 (<100 GeV^2) and
- high-Q^2 (>150 GeV^2) regions

Selections

- $\langle P_T\rangle$ greater than 5, 7, or 8.5 GeV (Breit frame)
- $P_{T,Jet}$ greater than 4, 5, 7 GeV
- asymmetric jet P_T cuts
- M_{12} cut applied in two cases

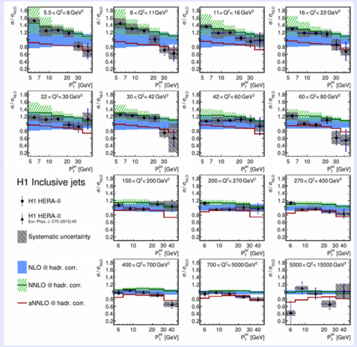
- All data sets used in α_S extractions
- Well understood data & exptl. uncertainties
- New NNLO theory now available

HERA-I low-Q^2



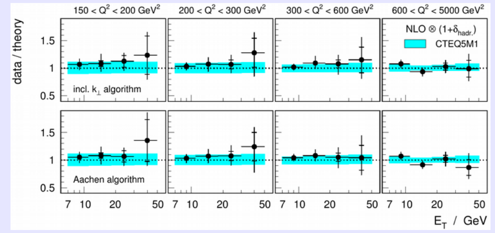
Eur.Phys.J.C67 (2010) 1

HERA-II low-Q^2



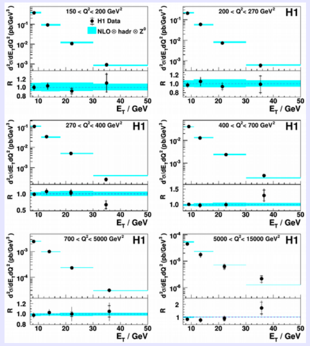
arXiv:1611.03421

300 GeV high-Q^2



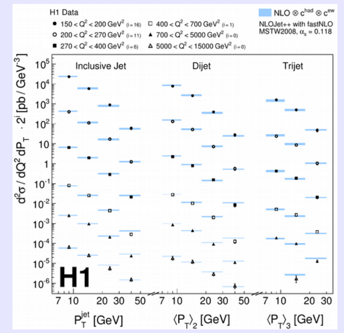
Eur.Phys.J.C19 (2001) 289

HERA-I high-Q^2



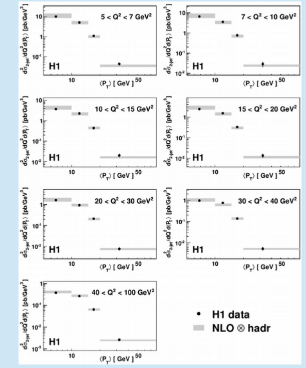
Phys.Lett.B653 (2007) 134

HERA-II high-Q^2



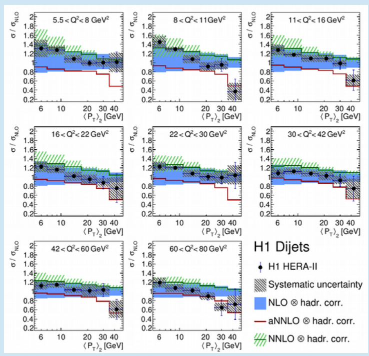
Eur.Phys.J.C75 (2015) 2
arXiv:1611.03421

HERA-I low-Q^2



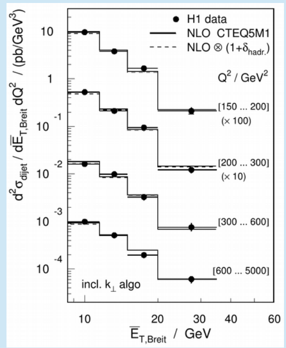
Eur.Phys.J.C67 (2010) 1

HERA-II low-Q^2



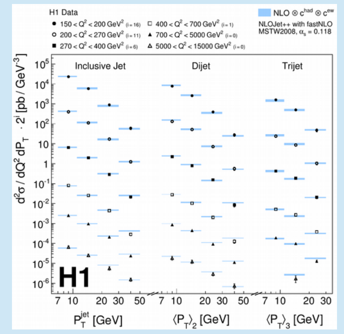
Eur.Phys.J. C77 (2017) 215

300 GeV high-Q^2



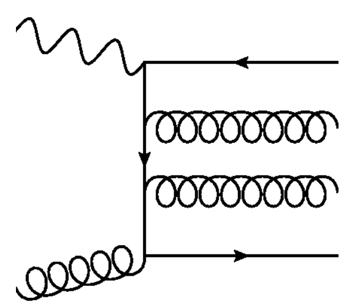
Eur.Phys.J.C19 (2001) 289

HERA-II high-Q^2



Eur.Phys.J.C75 (2015) 2

NNLO Jet Production in DIS

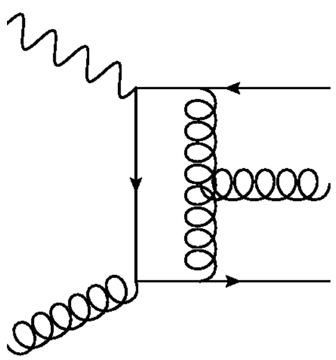


Double-real

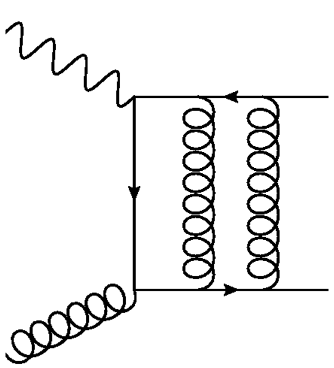
$$d\sigma^{RR,S}_{NNLO} \approx \underbrace{X(\{p_X\})}_{\text{antenna}} \overbrace{d\Phi_3(\{p_X\})}^{\text{Antenna PS}} \times \underbrace{|\mathcal{M}(\{\widetilde{p_m}\})|^2}_{\text{reduced ME}} \overbrace{d\Phi_m(\{\widetilde{p_m}\})}^{\text{reduced PS}} \times \underbrace{\mathcal{J}(\{\widetilde{p_m}\})}_{\text{jet function}}$$

Antenna subtraction

- Cancellation of IR divergences with local subtraction terms
- Construction of (local) counter terms
- Move IR divergences across different phase space multiplicities



Real-virtual



Double-virtual

Take $\mu_R = \mu_F = \sqrt{Q^2 + P_T^2}$

simple form & non-zero as Q or $P_T \rightarrow 0$

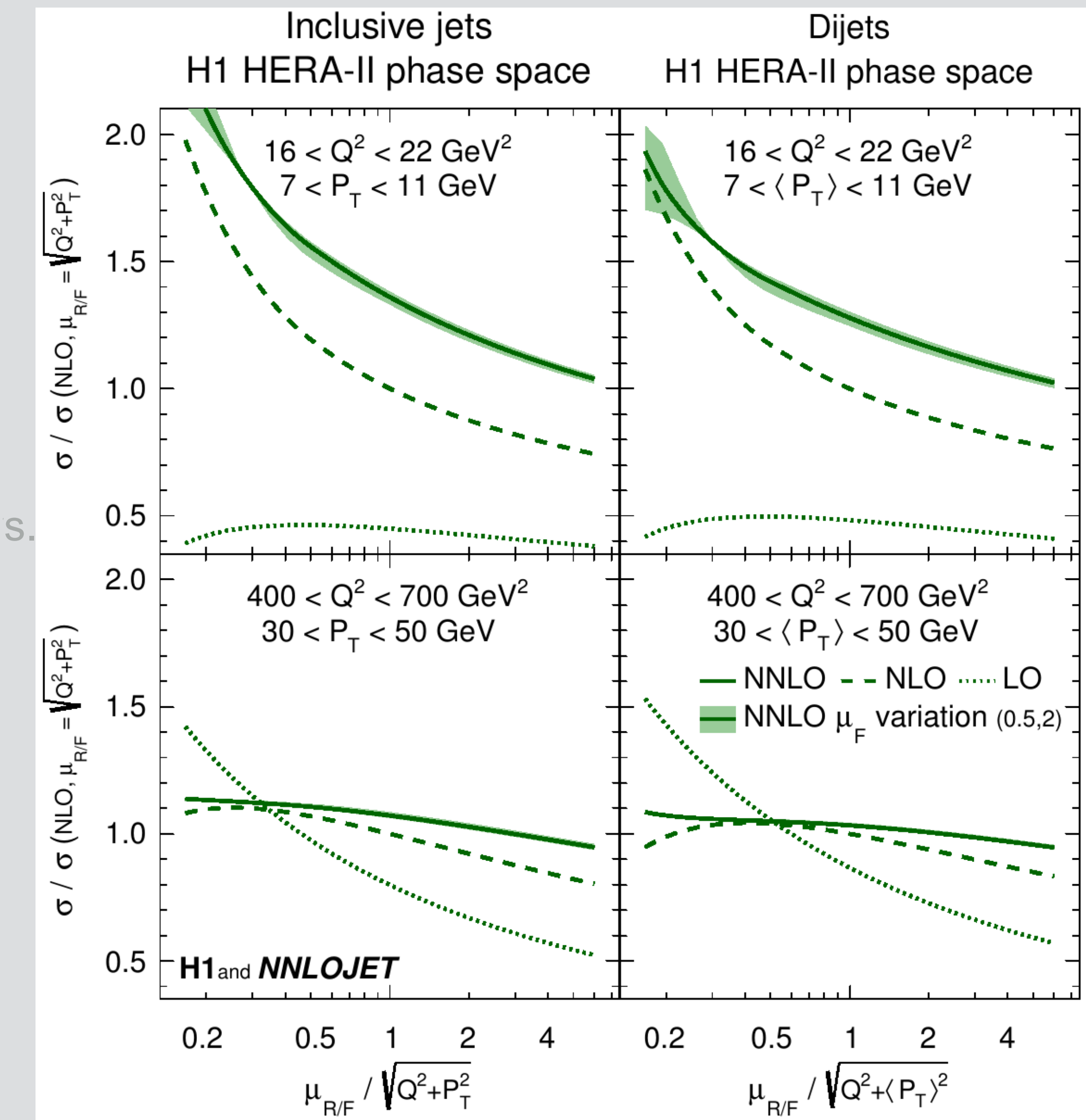
Simultaneous variation of μ_R and μ_F

At low scales:

- Significant NNLO k-factors
- Incl. jets with higher scale dependence than dijets

At higher scales

- NNLO with reduced scale dependence
- μ_F dependence very small



Methodology

α_s determined in χ^2 minimisation method

Take experimental & theoretical uncertainties into account

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

σ = predictions
ς = measurements
V = Covariance matrices → rel unc.
- V_{had} = hadronisation corrections
- V_{PDF} = PDFs
- V_{exp} = Experimental uncertainties

NNLO theory has α_s dependence in PDFs and hard M.E.
PDF piece accounted for in DGLAP evolution using μ_F = 20 GeV
μ_F = 20 GeV is typical μ_F of data

Perform fit to all H1 data:

- All inclusive jet data sets (137 data points)
- All dijet data sets (103 data points)
- All H1 jet data taken together (denoted as 'H1 jets')
  (exclude HERA-I dijet data as correlations to inclusive jets are not known)

Comparison of Data to NNLO

All H1 Inclusive jets & Dijets data compared to NNLO predictions

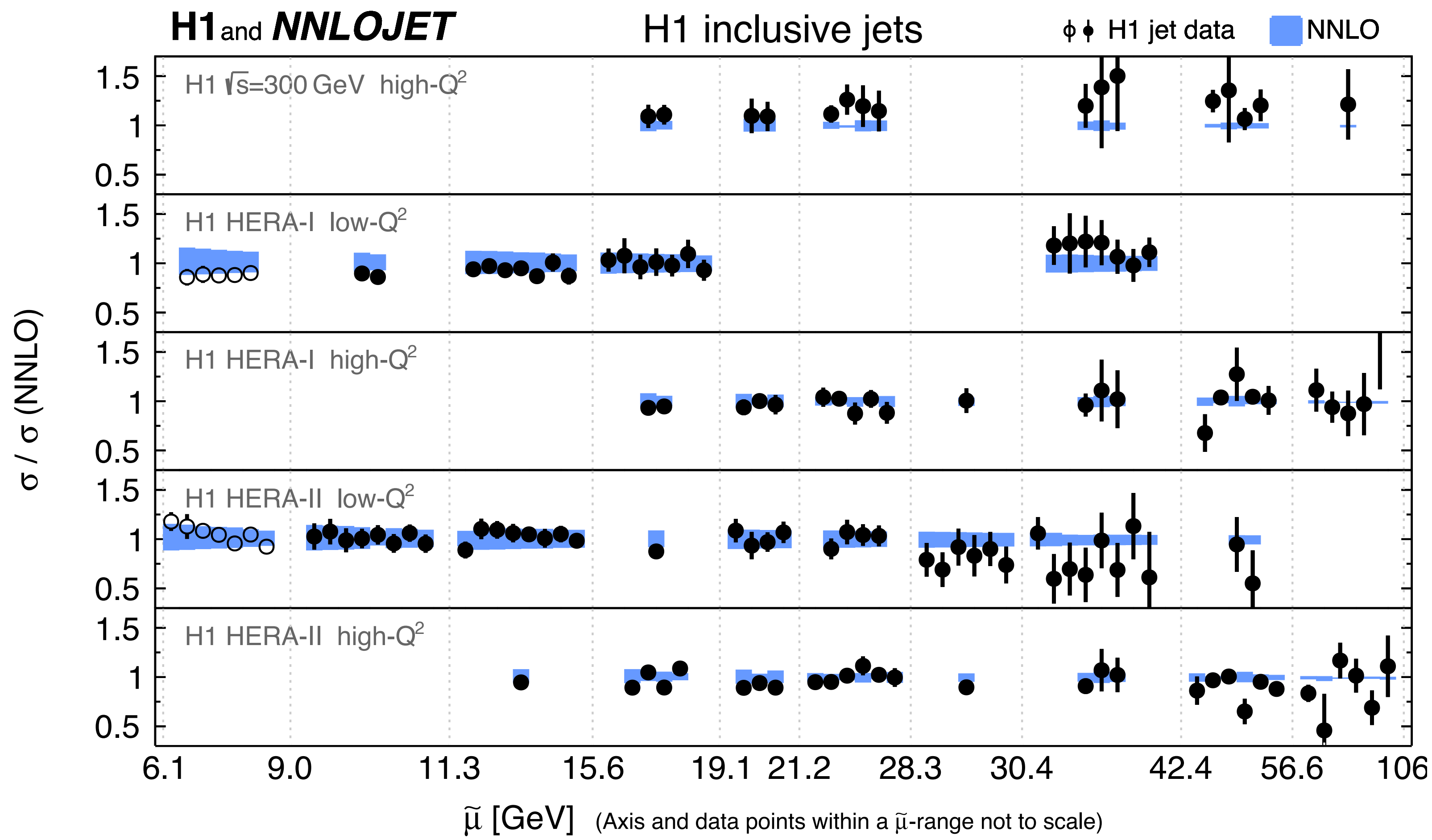
Define for each measurement bin

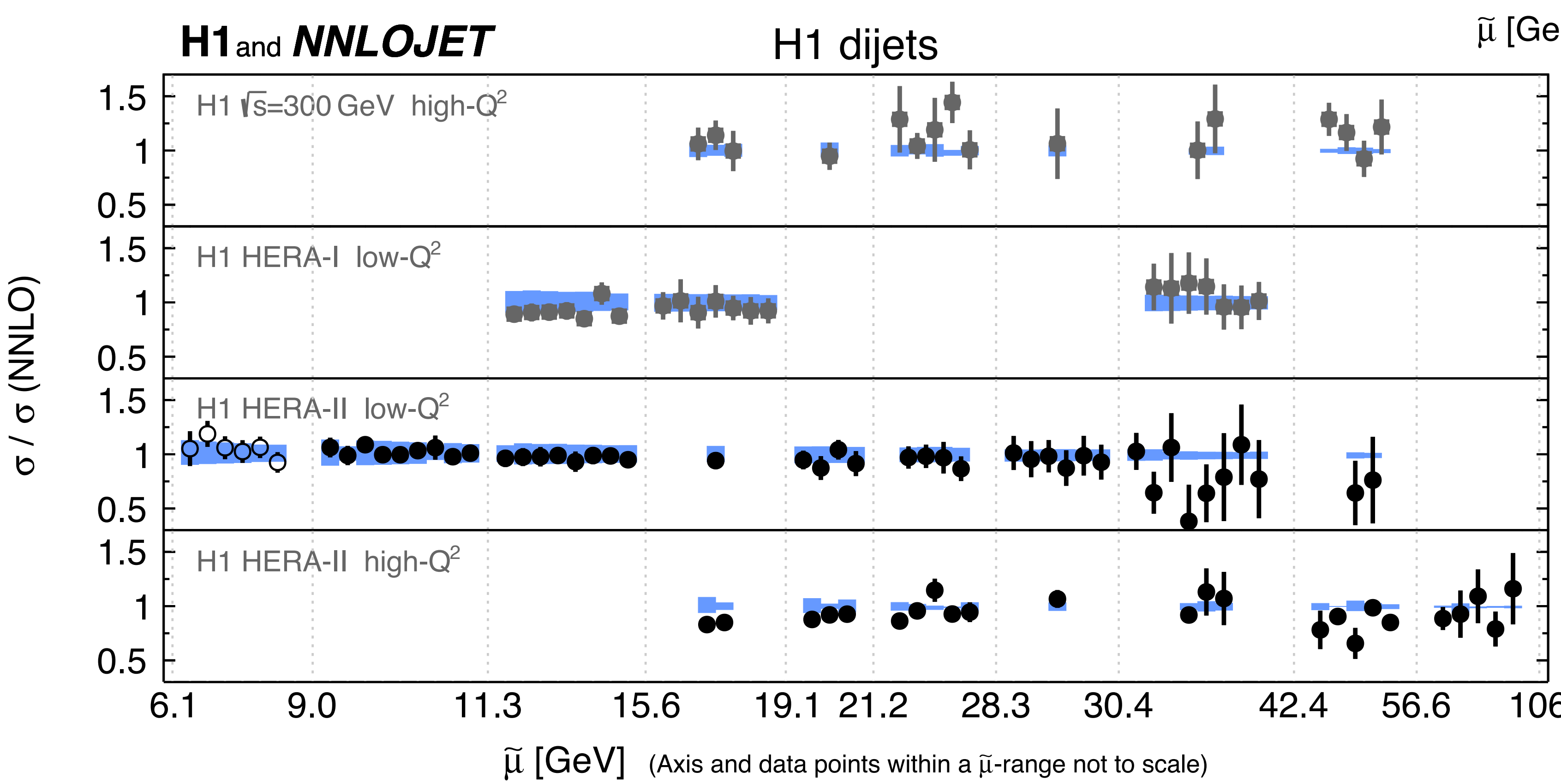
$$\tilde{\mu} = \sqrt{Q^2_{ave} + P^2_{T,ave}}$$

Average of upper and lower bin edge

Data with $\tilde{\mu}$ > 28 GeV :

- independent of α_s used in PDF
- reduced scale dependence



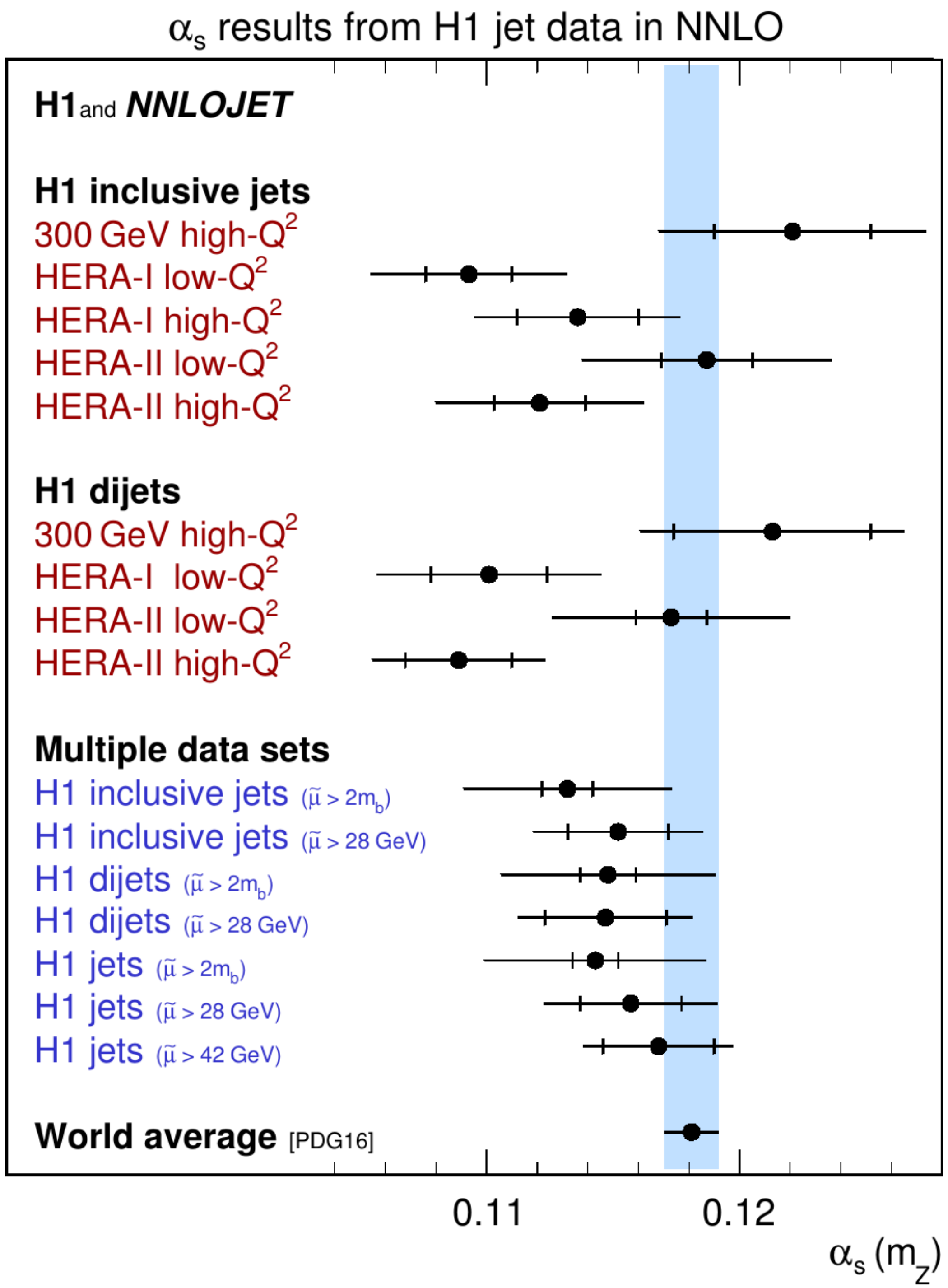


- NNLO describes data very well
- Also justified by good χ^2 values
- Great success of pQCD

α_S From DIS Jets at NNLO

α_s from individual data sets
- High experimental precision
- Scale uncertainty is largest error
- All fits have good χ^2 → consistency of data

Combined α_s from all data sets
- Inclusive & dijet data
- $\tilde{\mu}$ > 28 GeV → 91 data points
- All fits have good χ^2 → consistency of data
- Moderate exptl. precision
- Dominated by scale uncertainty
- Small PDF uncertainties

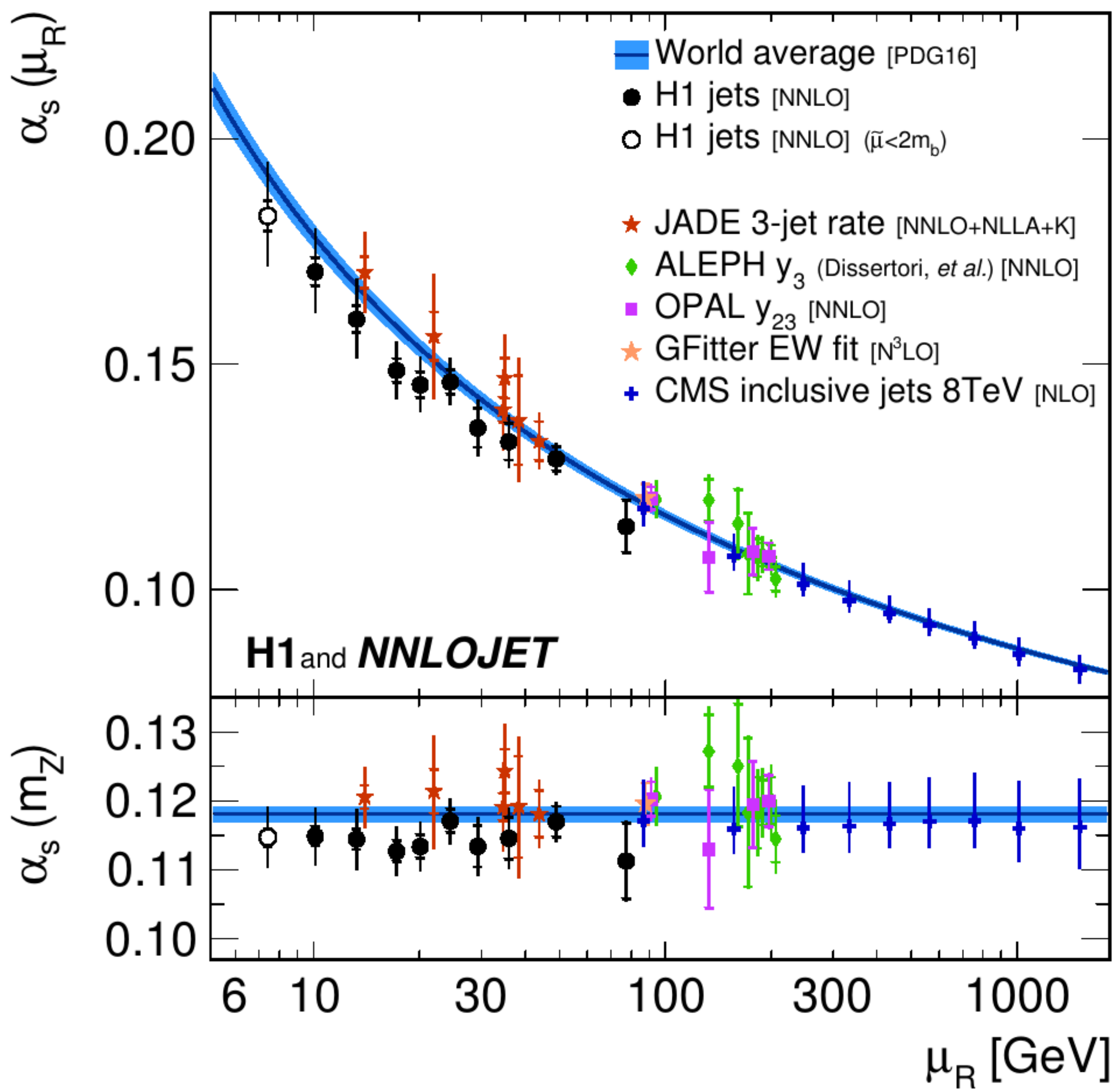


$$\alpha_s(m_Z) = 0.1157\,(20)_{\rm exp}\,(6)_{\rm had}\,(3)_{\rm PDF}\,(2)_{{\rm PDF}\alpha_s}\,(3)_{\rm PDFset}\,(27)_{\rm scale}$$

Running of α_S

Test running of strong coupling
- Perform fits to data at similar scale
- Assumes running valid in limited interval range
- All fits have good χ^2

Results
- Consistency with expectation at all scales
- Scale uncertainty dominates at lower μ
- Consistency of inclusive jets and dijets



Alternative Approach: PDF + α_s fit

Simultaneous PDF and α_s fit
PDFs mostly determined from
H1 inclusive DIS data

Perform H1 alone PDF fit: H1PDF2017
Use all H1 inclusive DIS data
Use all H1 normalised jet cross section data
→ 1529 data points

Normalised jet cross sections
Jet cross sections normalised to inclusive DIS
Correlations of jets and inclusive DIS cancel

Inclusive Neutral and Charged Current DIS data

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	✓	✓	✓

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

$\hat{\sigma}_{i,j}$ = partonic cross section
$c_{\mathrm{had,i}}$ = hadronisation corrections

PDFs are parameterised as

$$xf(x)|_{\mu_0} = f_A x^{f_B}(1-x)^{f_C}(1+f_D x + f_E x^2)$$

Inclusive Jets and Dijets 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	✓	✓	✓	✓	✓

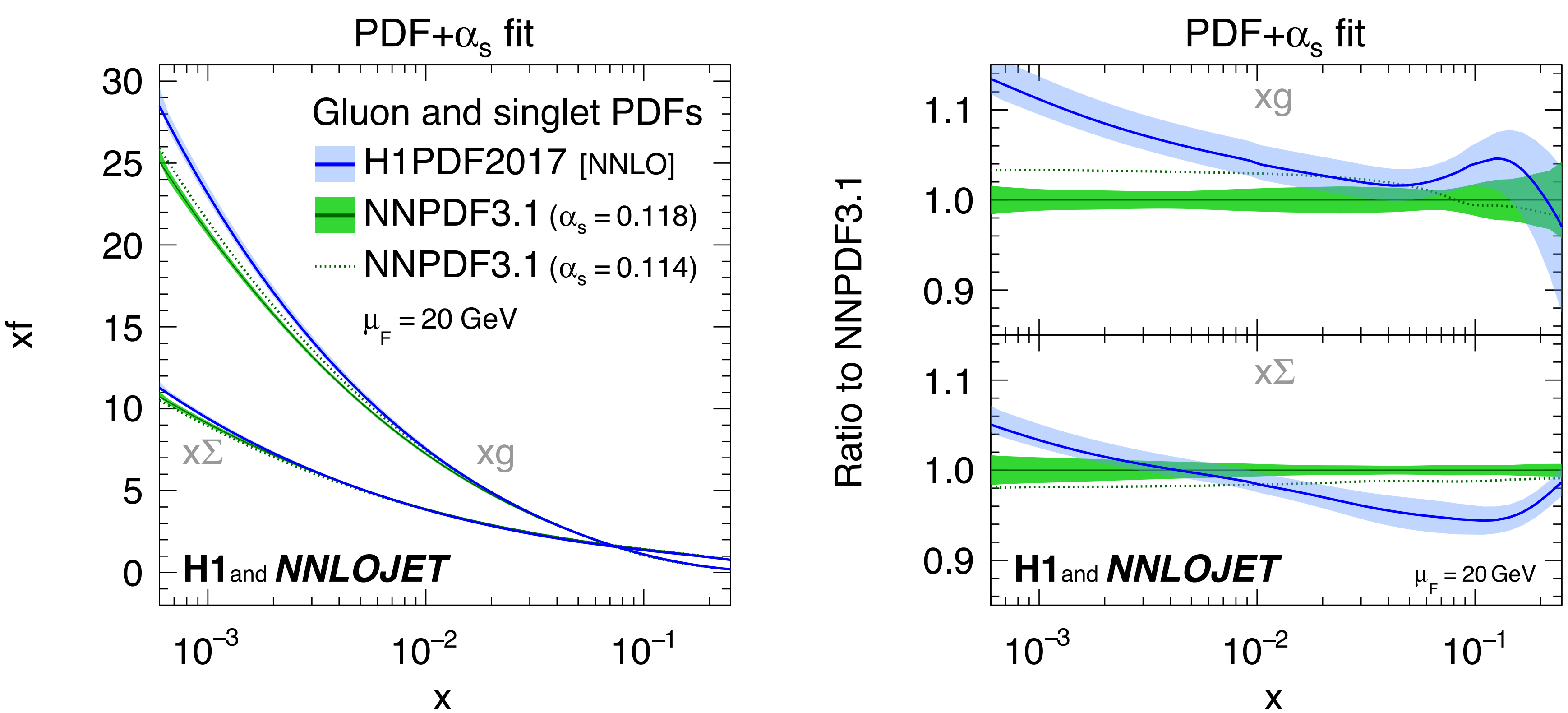
Alternative Approach: PDF + α_s fit

Result for PDFs
Set of PDFs determined with high precision
(even with α_s a free fit parameter)
→ precision is competitive with global PDF fitters

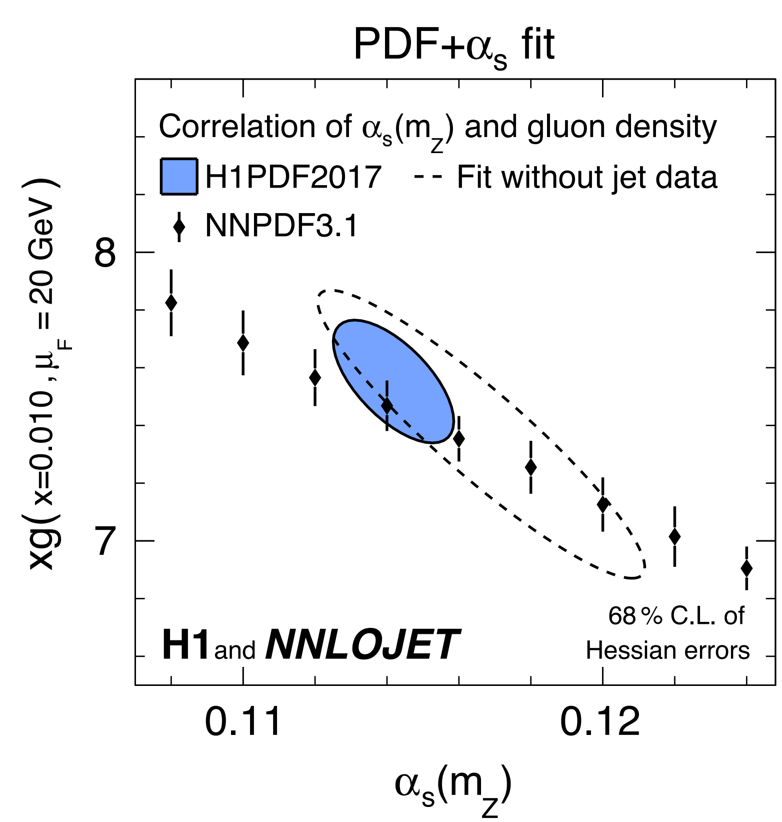
Gluon at lower x-values tends to be higher
→ now typically favoured by small-x resummed PDFs

PDF + α_s fit
χ^2/ndf = 1.01
Simultaneous fit with H1 jet data
→ precise determination of the gluon PDF and α_s

Comparison of H1PDF2017 with NNPDF3.1



Correlation of α_s with gluon

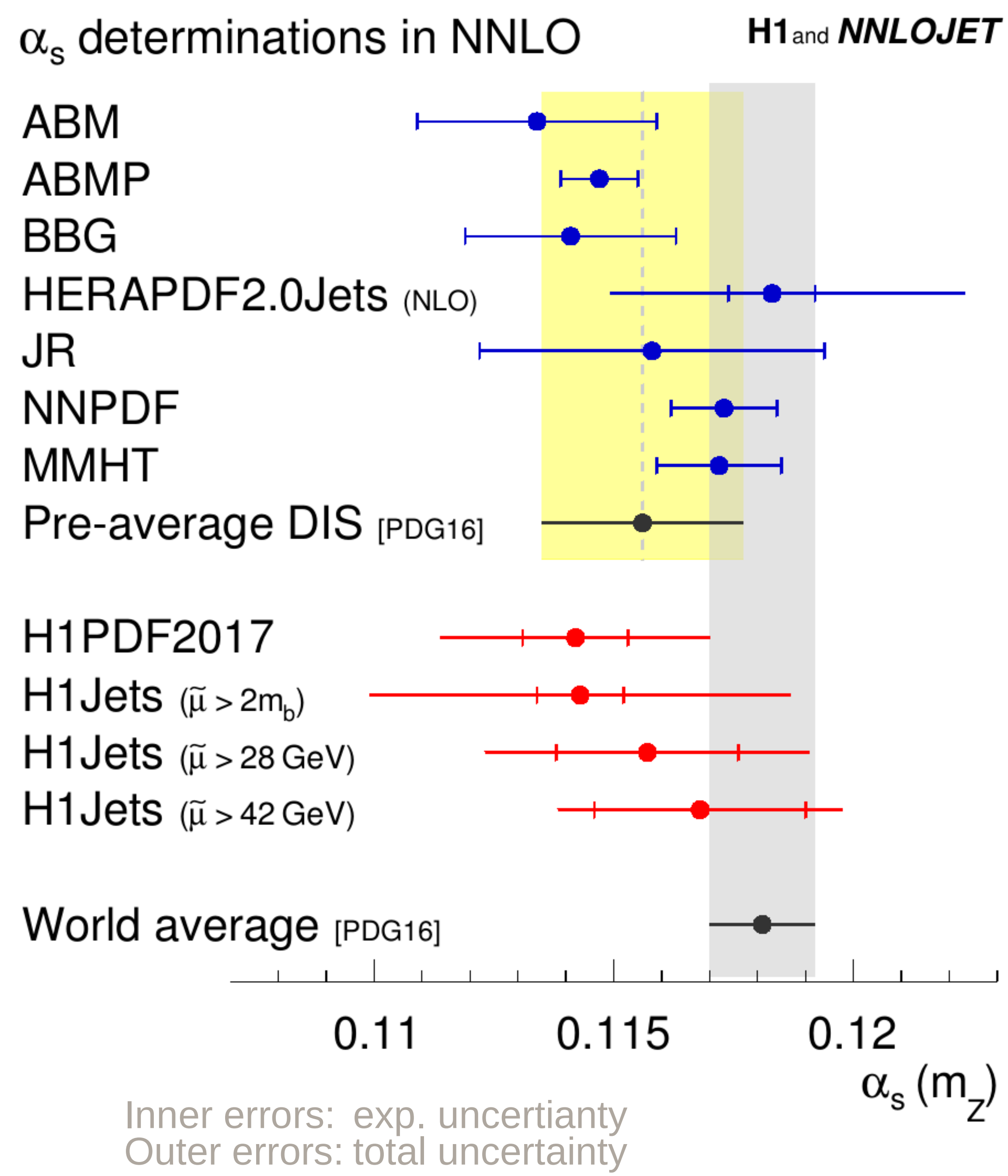


Results: PDF + α_s fit

Simultaneous PDF and α_s fit

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

- High experimental precision
- Moderate theory uncertainty from NNLO



Comparison

- Higher precision than most comparable determinations
  → PDF groups commonly determine exp. uncertainties only
  → We further estimate scale uncertainties
- All H1 results consistent
- Results competitive with world average
- All results from DIS data typically lower than world average

Summary

- All H1 jet data compared with NNLO predictions
- NNLO theory provides improved description w.r.t. NLO
- Quantitative comparisons of all data
- NNLO predictions studied in great detail

NNLO used for determination of $\alpha_s(m_Z)$ in two methods:

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

High experimental and theoretical precision achieved

- NNLO predictions for jets are used for PDF fits for the first time
- Successful determination of gluon-density and $\alpha_s(m_Z)$ simultaneously
- Competitive precision of PDFs and $\alpha_s(m_Z)$
- H1PDF2017 available in LHAPDF

Special thanks to ***NNLOJET*** team for fruitful collaboration of theoreticians and experimentalists

Backup

Extracted α_S values

Scale Choice for α_S fit

Study scales calculated from Q^2 and P_T
'P_T' refers to: P_{Tjet} or $<P_T>$

α_s results and χ^2 values
- Spread of results covered by scale uncertainty
- χ^2 values are similar for different choices
  → NNLO with small 'scale dependence'

NLO matrix elements
Large scale uncertainty
Relevant dependence of result on scale choice
- Mainly larger χ^2 values than NNLO
- Larger fluctuation of χ^2 values than NNLO