Determination of the strong coupling constant $\alpha_s(m_Z)$ using H1 jet cross section measurements

Daniel Britzger
for the H1 Collaboration and NNLOJET

Eur.Phys.J.C 77 (2017), 791 [arXiv:1709.07251]
Eur.Phys.J.C 77 (2017), 215 [arXiv:1611.03421]

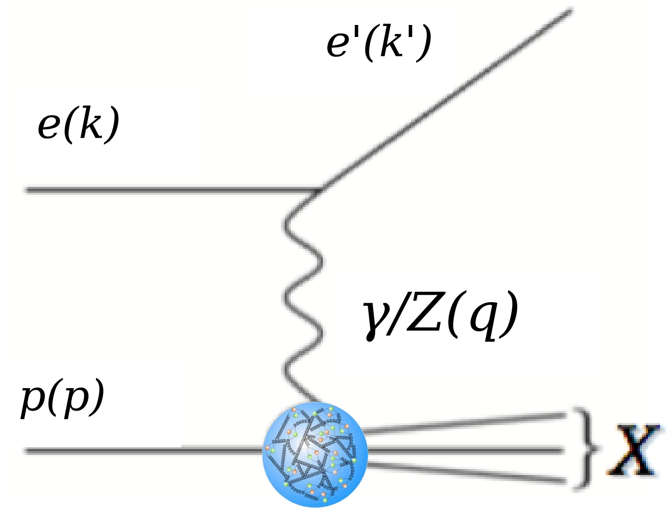
α_s workshop Trento, Italy
12.02.2019

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)
MAX-PLANCK-GESELLSCHAFT

Deep-inelastic *ep* scattering at HERA

Neutral current scattering (NC)

$$ep \rightarrow e'X$$



Photon virtuality

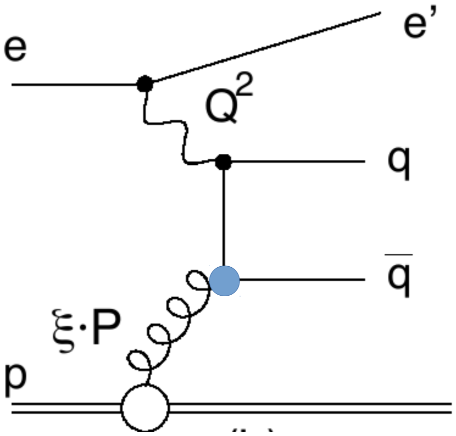
$$Q^2 = -q^2 = -(k - k')^2$$

HERA *ep* collider in Hamburg

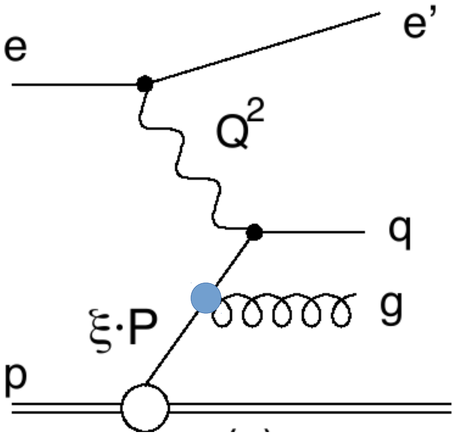
Data taking periods

- HERA I: 1994 – 2000
- HERA II: 2003 – 2007
- $\sqrt{s}$ = 300 or 319 GeV

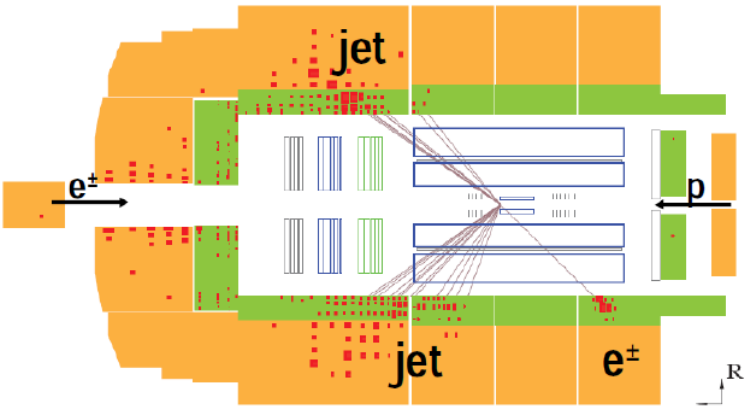
Jet production in DIS



Boson-gluon fusion



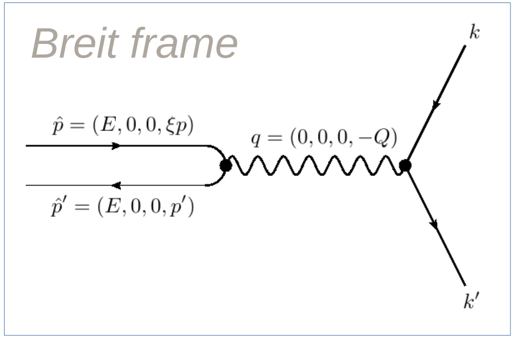
QCD Compton



Exemplary event display

Jets in DIS measured in Breit frame

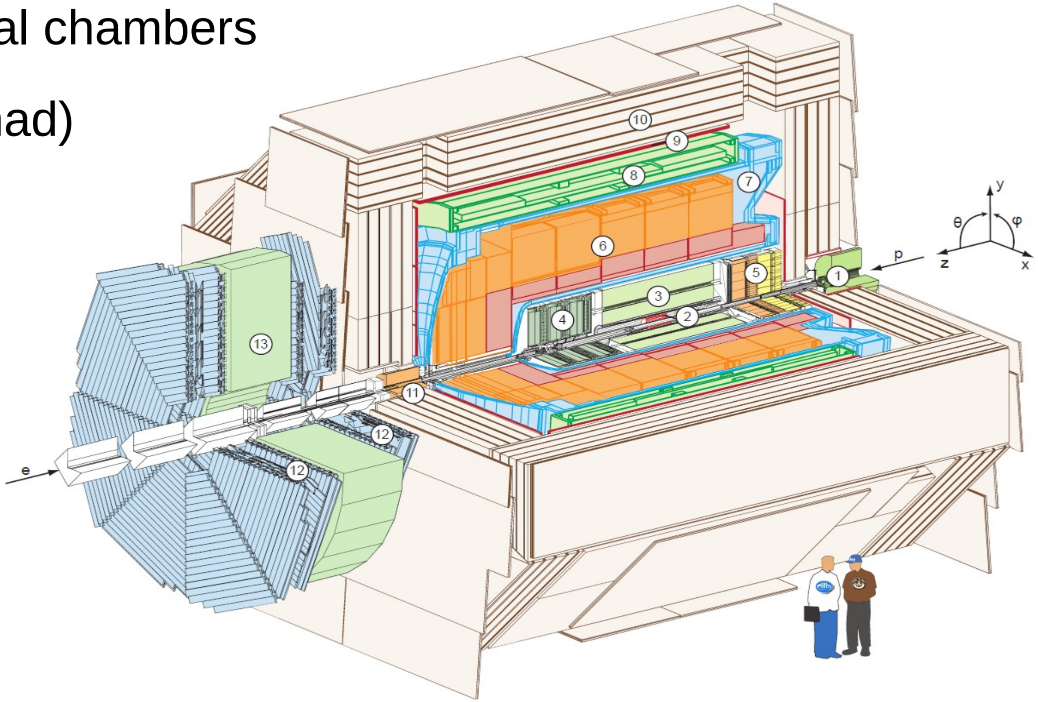
- ep -> 2jets
- Virtual boson collides 'head-on' with parton from proton
- Boson-gluon fusion dominant process
  QCD compton important only for high-p_T jets (high-*x*)



Jet measurement sensitive to α_s and gluon density

H1 Experiment at HERA

- Precise Trackers
  - Silicon tracker; jet chambers; proportional chambers
- Calorimeters
  - Liquid Argon sampling calorimeter (em/had)
  - Scintillating fiber calorimeter



Jet energy scale calibration

- Overconstrained system in NC DIS: Jet calibration using NC DIS events
- Track and calorimeter information exploited ('particle flow')
  → Important for E^{track} < ~25 GeV
- Neural network (cluster classification) based in-situ jet calibration for data and MC

High experimental precision

- Electron measurement: 0.5 – 1% scale uncertainty
- Jet energy scale: 1%

Drawing of the H1 experiment

Inclusive jet cross sections

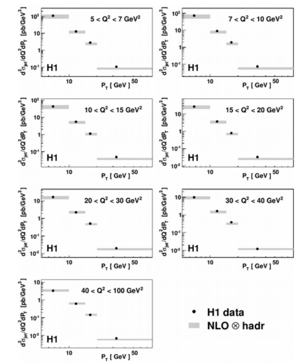
Inclusive jet cross sections

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

Consistency

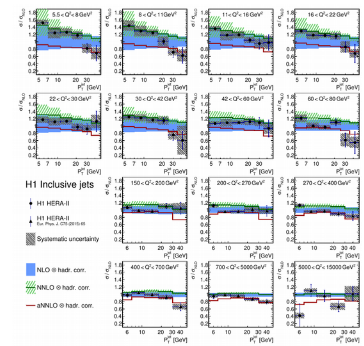
- kt-algorithm, R=1
- $-1.0 < \eta < 2.5$
- P_T ranges from 4.5 to 50 GeV

HERA-I low-Q^2



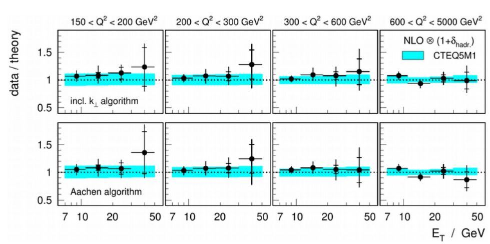
Eur.Phys.J.C67 (2010) 1

HERA-II low-Q^2



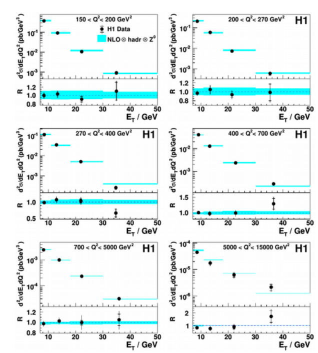
Eur.Phys.J. C77 (2017) 215

300 GeV high-Q^2



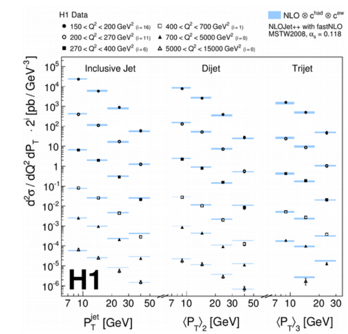
Eur.Phys.J.C19 (2001) 289

HERA-I high-Q^2



Phys.Lett.B653 (2007) 134

HERA-II high-Q^2



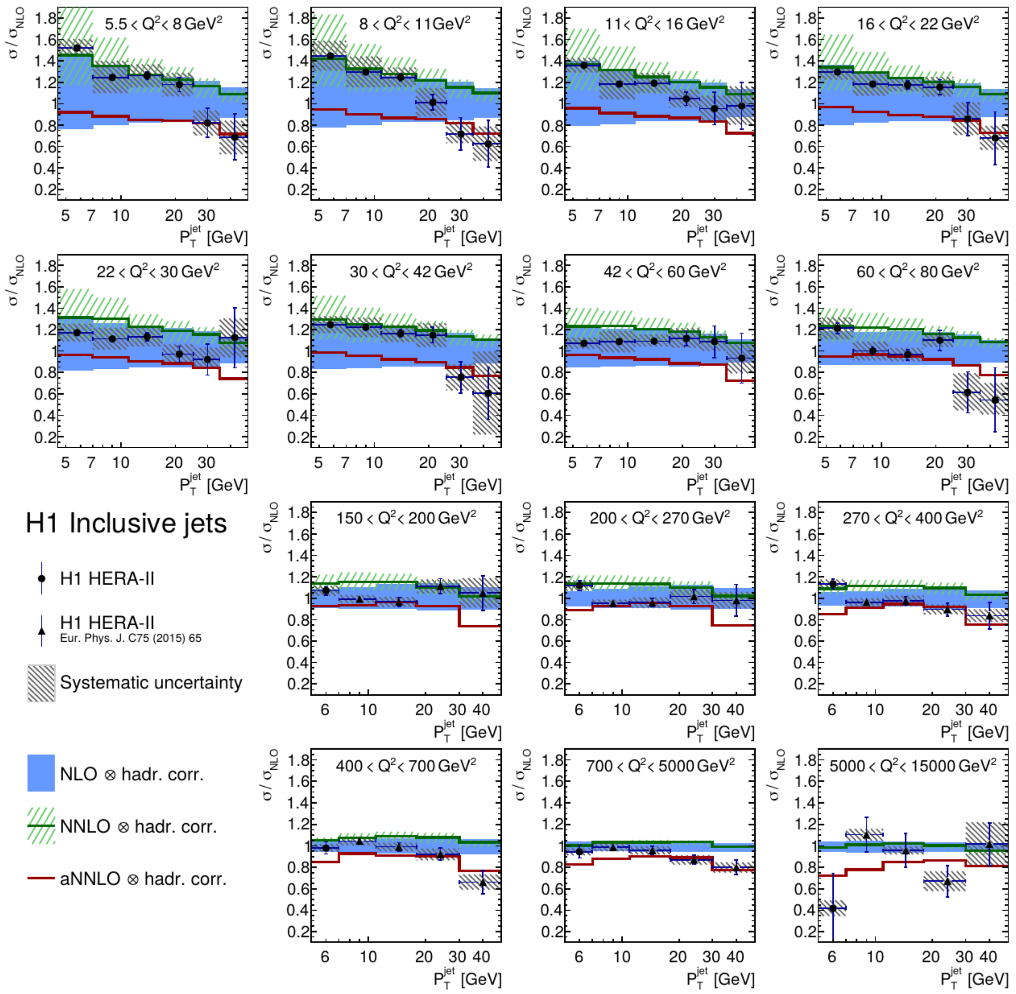
Eur.Phys.J.C75 (2015) 2
arXiv:1611.03421

Inclusive jet cross sections

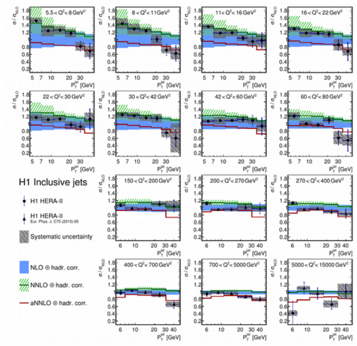
Inclus
- do
- 30
- lov
  hi

Cons
- kt-
- -1
- P_T

HERA-II low- and high-Q^2 inclusive jets

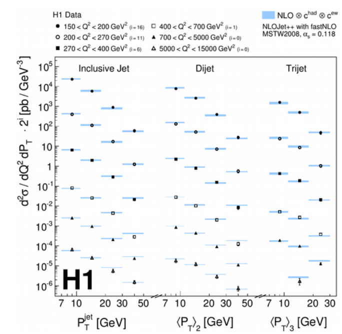


HERA-II low-Q^2



Eur.Phys.J. C77 (2017) 215

HERA-II high-Q^2



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

Dijet cross section

Dijet definitions

- $<p_T>$ greater than 5,7 or 8.5 GeV
- P_T jet greater 4, 5 or 7 GeV
- Asymmetric cuts on p_T^{jet1} and p_T^{jet2}
- M_{12} cut for two data sets

Dijet cross sections

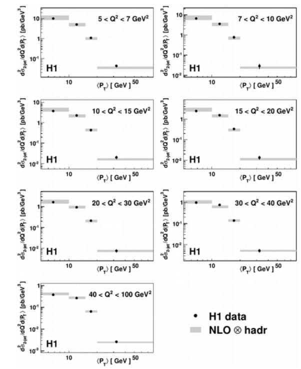
- $d\sigma/dQ^2d<p_T>$
- 300 GeV, HERA-I & HERA-II
- low-Q^2 and high-Q^2

Earlier studies

All inclusive jet and dijet data have been employed for α_s extractions previously

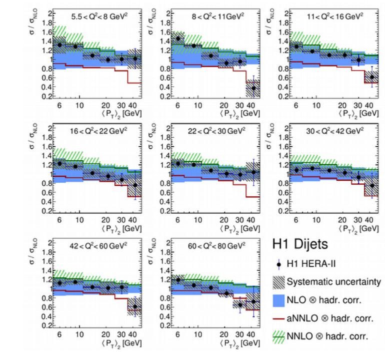
-> Data and uncertainties well-understood
-> NNLO theory is new

HERA-I low-Q^2



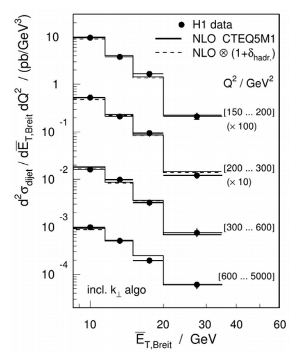
Eur.Phys.J.C67 (2010) 1

HERA-II low-Q^2



Eur.Phys.J. C77 (2017) 215

300 GeV high-Q^2



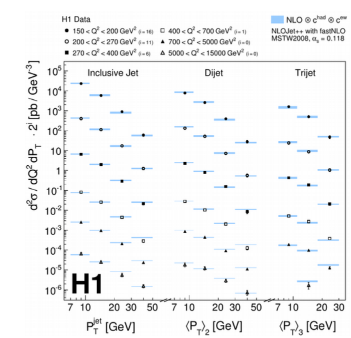
Eur.Phys.J.C19 (2001) 289

HERA-I high-Q^2

Dijet cross sections not statistically independent from HERA-II analysis

Eur.Phys.J.C65 (2010) 363

HERA-II high-Q^2



Eur.Phys.J.C75 (2015) 2

α_s determination in NLO from HERA-II data

→ Highest experimental precision

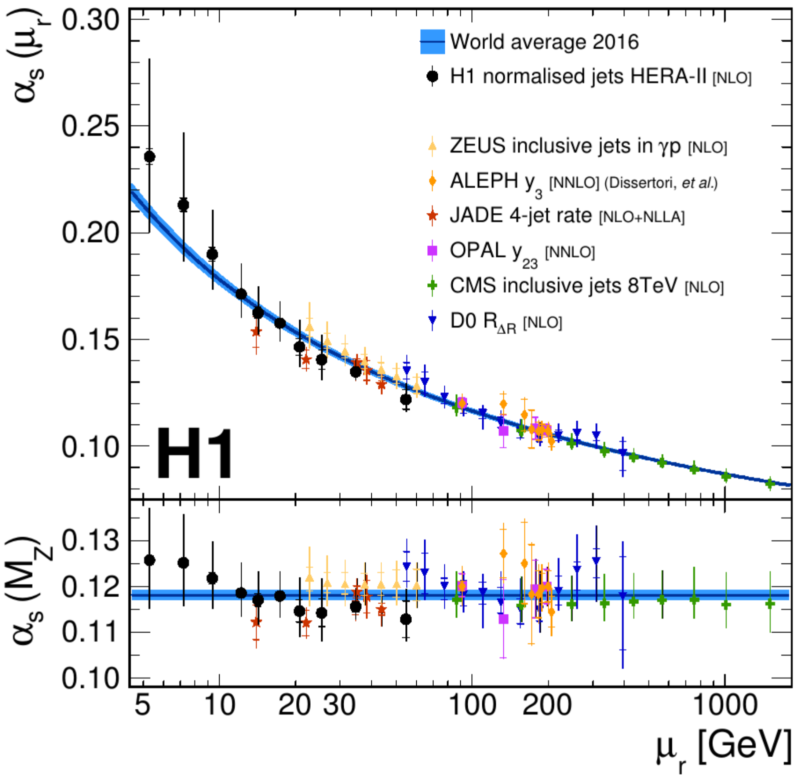
$\alpha_s(M_Z)$ from HERA-II jet data at NLO

H1 HERA-II low- and high-Q² data

- Low-Q² jets (Eur.Phys.J.C 77 (2017) 21)
- high-Q² jets (Eur.Phys.J.C75 (2015) 2)

All normalised jet cross sections

- Normalised inclusive jet
- Normalised dijets
- Normalised three-jets
- Correlations of uncertainties are known
- Fit $\alpha_s(M_Z)$ in χ^2-minimization procedure



Results at NLO

- fit to all HERA-II data points

$$\alpha_s(M_Z) = 0.1173\,(4)_{\rm exp}\,(3)_{\rm PDF}\,(7)_{{\rm PDF}(\alpha_s)}\,(11)_{\rm PDFset}\,(6)_{\rm had}\,(^{+51}_{-43})_{\rm scale}$$

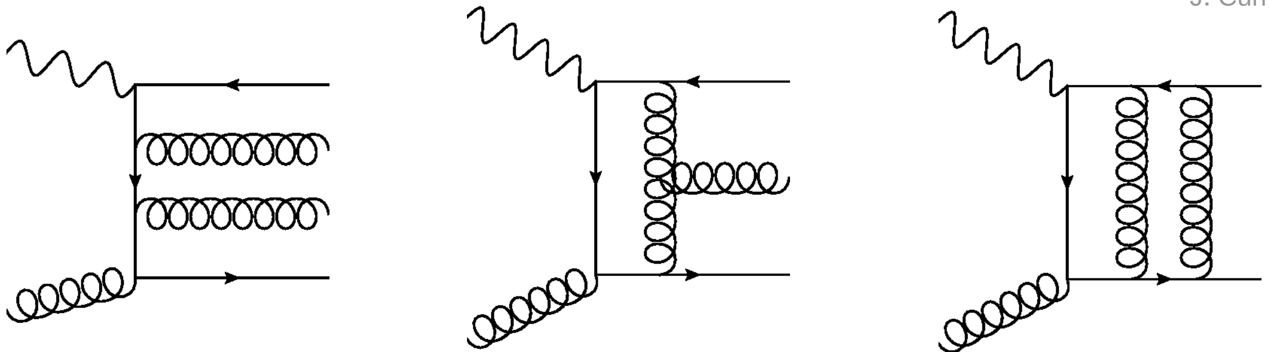
- Very high experimental precision
- α_s determination fully limited by **NLO** scale uncertainites

Eur.Phys.J.C 77 (2017), 215
[arXiv:1611.03421]

α_s determination in NNLO from all H1 inclusive jet and dijet cross section data

DIS jet production in NNLO

J. Curie, et al. [RPL 117 (2016) 042001]
J. Curie, et al. [JHEP 1707 (2017) 018]



Double-real   Real-virtual   Double-virtual

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

A bit of history

- 1973 asymptotic freedom of QCD
  [PRL 30(1973) 1343 & 1346]
- 1993 NLO studies of DIS jet cross sections
  [Phys. Rev. D49 (1994) 3291]
- 2016 NNLO corrections for DIS jets
  [Phys. Rev. Lett. 117 (2016) 042001], [arXiv:1703.05977]

Antenna subtraction

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

α_s-fit methodology

α_s determined in χ_2-minimisation

- $\alpha_s(m_Z)$ is a free parameter to theory prediction σ_i

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

ς_i	H1 jet data
σ_i	NNLO theory
V	covariance matrices

NNLO theory is sensitive to $\alpha_s(m_Z)$

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

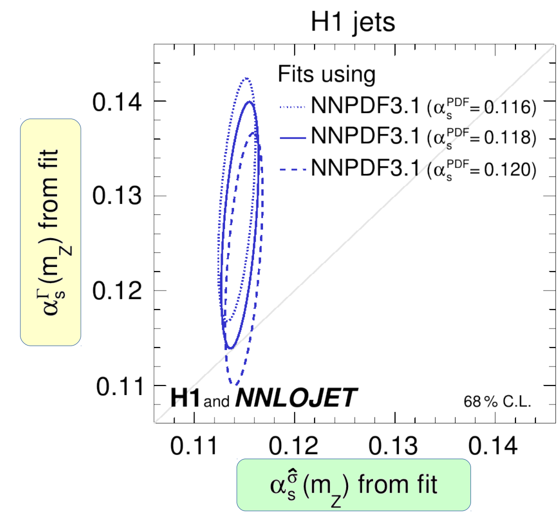
Hard ME's

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

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

- α_s dependence of PDF is accounted for by using PDF at $\mu_{F,0} = 20\text{GeV}$ and applying DGLAP

→ Important for reliable uncertainty estimates!



Separate fits are performed to

- 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')

Inclusive jets

α_s in NNLO from individual data sets

- All fits with good χ^2
- Data sets found to be consistent
- Consistency between low- and high-Q^2

Fit to all inclusive jets data in NNLO

$$0.1132\,(10)_{\rm exp}\,(5)_{\rm had}\,(4)_{\rm PDF}\,(4)_{\rm PDF\alpha_s}\,(2)_{\rm PDFset}\,(40)_{\rm scale}$$

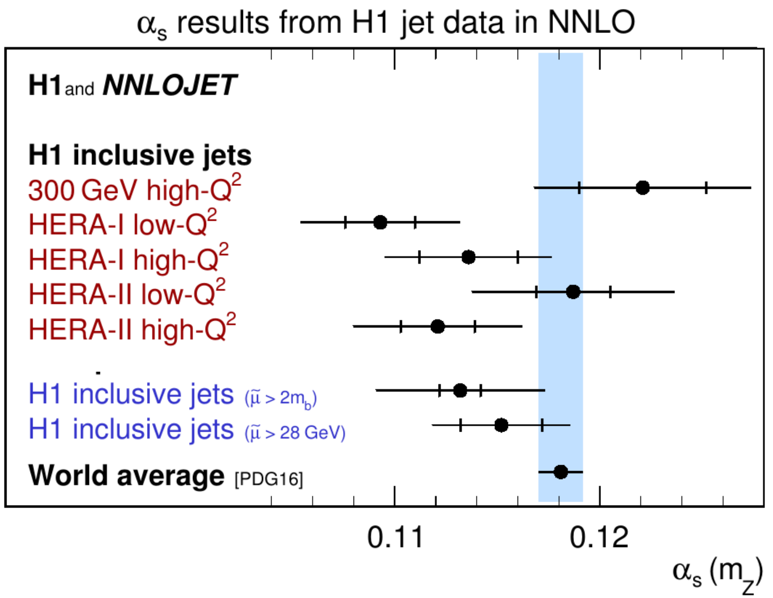
- χ^2/ndf = 134/133
- High experimental precision
- Scale uncertainty is largest (theory) error

Fit with μ > 28GeV

(μ is a characteristic scale assigned to any data point)

$$0.1152\,(20)_{\rm exp}\,(6)_{\rm had}\,(2)_{\rm PDF}\,(2)_{\rm PDF\alpha_s}\,(3)_{\rm PDFset}\,(26)_{\rm scale}$$

- Reduced scale, but increased exp. uncertainty
- No significant dependence on μ cut



See backup slides for a summary of all numerical values

$$\alpha_s(m_Z) = 0.1152\,(20)_{\rm exp}\,(27)_{\rm th}$$

Dijets

Fits to individual dijet data sets

- All data sets with good χ^2
- Reasonable consistency of data sets found

Fit to all dijet data in NNLO

- $\chi^2/\text{ndf} = 93.9/102$:
  consistency of data sets

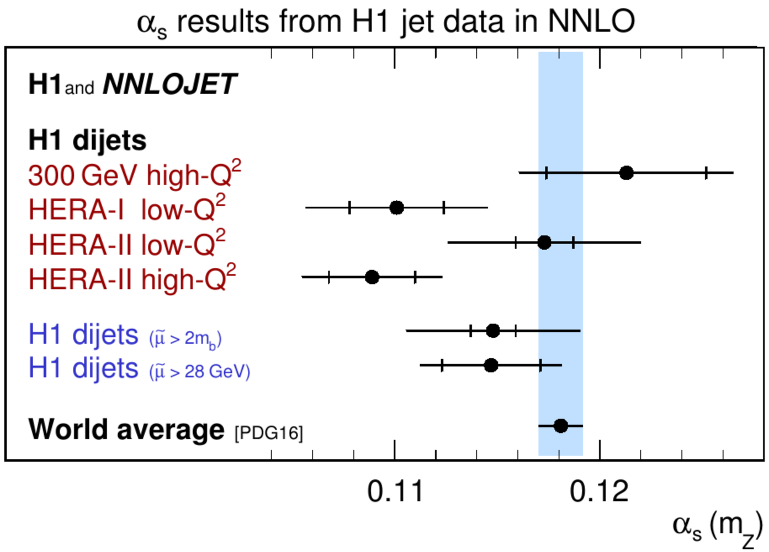
$$0.1148\,(11)_{\rm exp}\,(6)_{\rm had}\,(5)_{\rm PDF}\,(4)_{{\rm PDF}\alpha_s}\,(4)_{\rm PDFset}\,(40)_{\rm scale}$$

- Value consistent with inclusive jets

Fits to all dijets with μ > 28GeV

$$0.1147\,(24)_{\rm exp}\,(5)_{\rm had}\,(3)_{\rm PDF}\,(2)_{{\rm PDF}\alpha_s}\,(3)_{\rm PDFset}\,(24)_{\rm scale}$$

- Reduced scale, but increased exp. uncertainty



$$\alpha_s(m_Z) = 0.1147\,(24)_{\rm exp}\,(25)_{\rm th}$$

Uncertainty budget

$$0.1152\,(20)_{\rm exp}\,(6)_{\rm had}\,(2)_{\rm PDF}\,(2)_{{\rm PDF}\alpha_s}\,(3)_{\rm PDFset}\,(26)_{\rm scale}$$

Experimental uncertianty (exp)

- All exp. uncertainties (incl. all correlations)

hadronsiation uncertainty (had)

- Propagation of hadronisation uncertainties as published with the data: commonly: difference between two MC generators (Django,Rapgap,Sherpa)

PDF uncertainties

- 'PDF' uncertainty
- PDFα_s uncertainty
- PDFset uncertainty
- PDFμ_0 uncertainty

Scale uncertainty

- Scale factors: 0.5 and 2

} Next slides...

PDF related uncertainties

'PDF' uncertainty:
Uncertainties of NNPDF3.1 propagated to the result

PDFset uncertainty
½ max. difference between various PDF sets

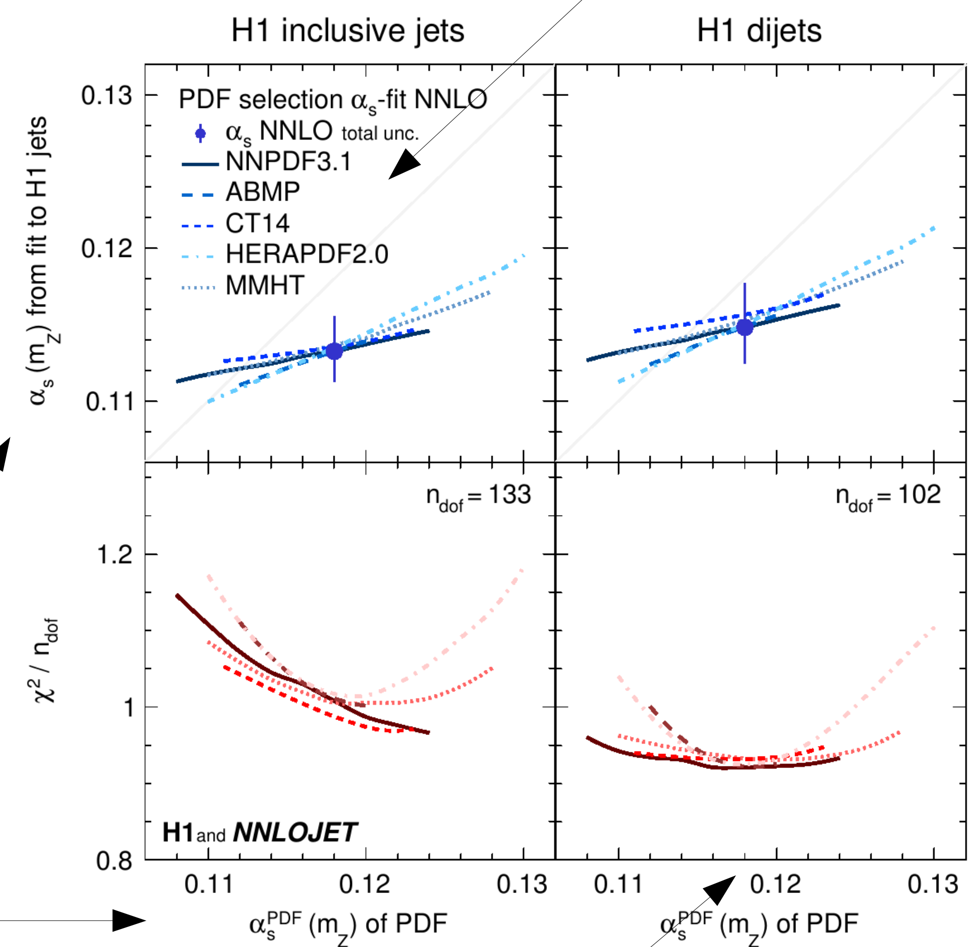
PDFα_s uncertainty
Varyiation of α_s-input to PDF by ±0.002

PDF$\mu_{F,0}$ uncertainty
negligible if $\mu_{F,0}$ varied between 10 to 90GeV

Result of our α_s fit

'Input' value of $\alpha_s(m_Z)$ to the PDF determination

PDFset

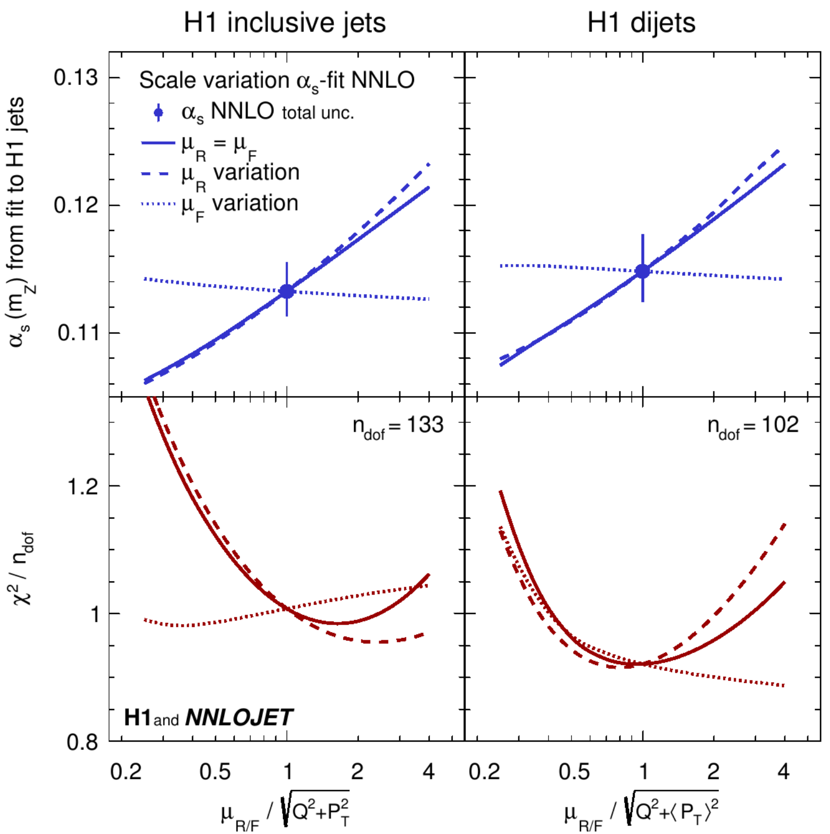


PDFα_s

Scale uncertainty

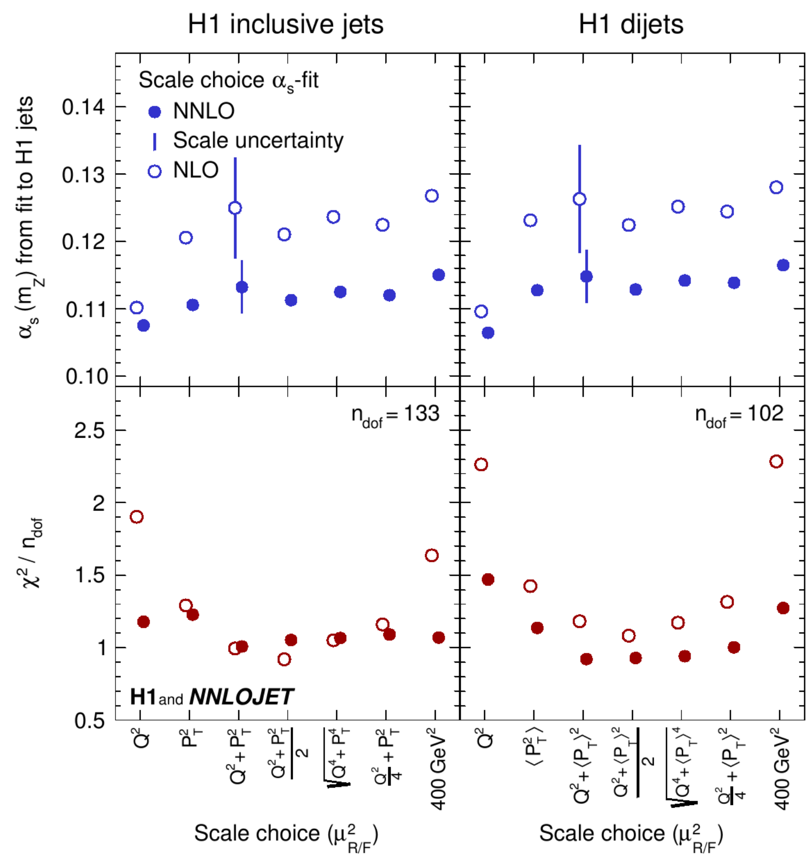
Scale variations

- μ_R variation dominates
- Large scale factor cause large χ^2 values



Scale choices

- Scale uncertainty also covers different scale choices
- μ = 20GeV: fixed scale!
  → no running, no DGLAP → consistent results



H1jets
fit to inclusive jet and dijet cross sections

H1 jets

Fit to inclusive jet and dijet together

- Stat. and experimental correlations are known
- χ^2/ndf = 0.98 for 200 data points

-> Inclusive jet and dijet data are consistent

$$0.1143\,(9)_{\rm exp}\,(6)_{\rm had}\,(5)_{\rm PDF}\,(5)_{{\rm PDF}\alpha_s}\,(4)_{\rm PDFset}\,(42)_{\rm scale}$$

H1 jets with μ > 28GeV

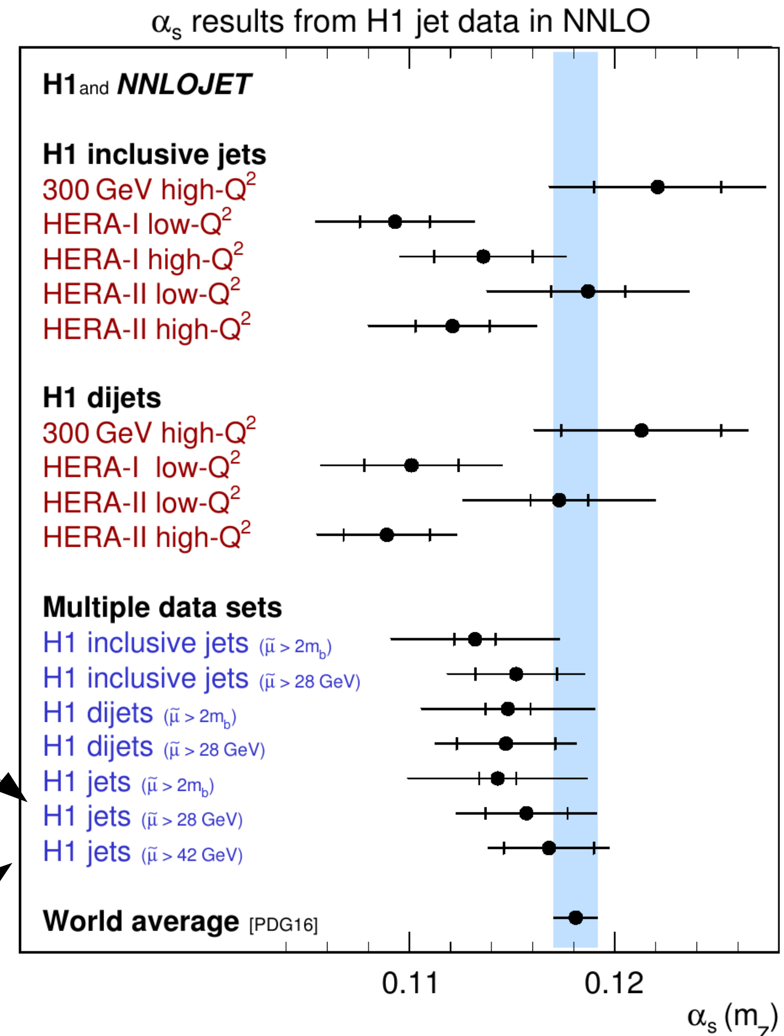
- 91 data points

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

- Moderate exp. precision (due to μ>28GeV)
- Scale uncertainty dominates
- PDF uncertainties negligible

Smallest theo. uncertainty for: μ > 42GeV

$$0.1168\,(22)_{\rm exp}\,(7)_{\rm had}\,(2)_{\rm PDF}\,(2)_{{\rm PDF}\alpha_s}\,(5)_{\rm PDFset}\,(17)_{\rm scale}$$



Main result with: μ > 28GeV

$$\alpha_s(m_Z) = 0.1157\,(20)_{\rm exp}\,(29)_{\rm th}$$

Study of total uncertainty

Scale uncertainties at various scales μ

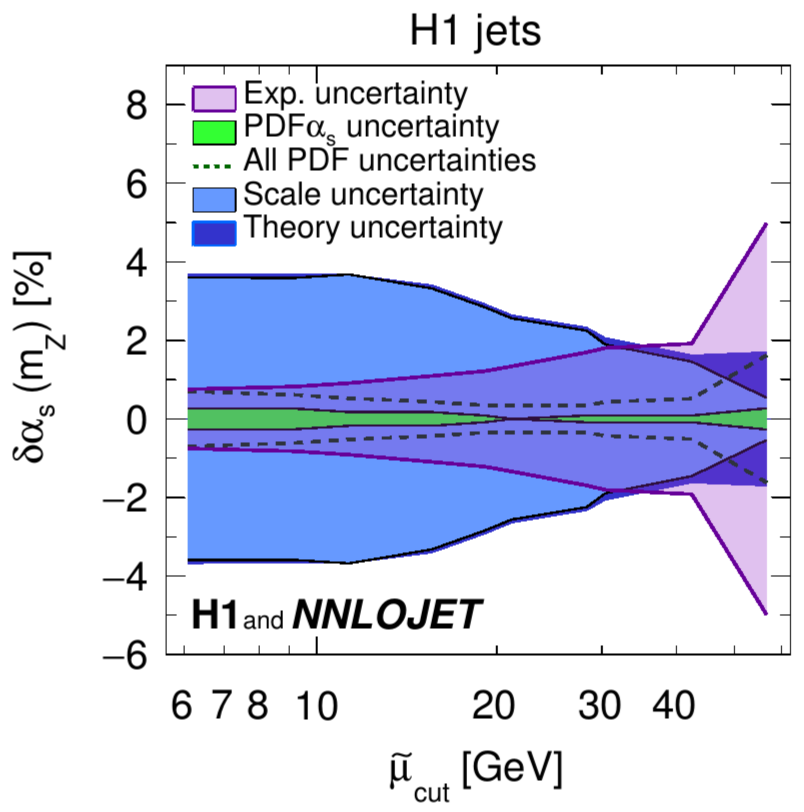
- At low-μ: large scale uncertainties...
- ... but also high sensitivity to $\alpha_s(m_Z)$

Fits imposing a cut on scale μ

- Repeat α_s fits:
  successively cut away data below μ_{cut}

Cut on μ

- Scale uncertainty decreases with μ_{cut}
- Exp. uncertainty increases with μ_{cut}



Comparison of NNLO predictions with data

All H1 jet cross section data compared to NNLO predictions

- Inclusive jets
- Dijets

Overall good agreement

- NNLO describes all data very well
- Also justified by good χ² values of the fits

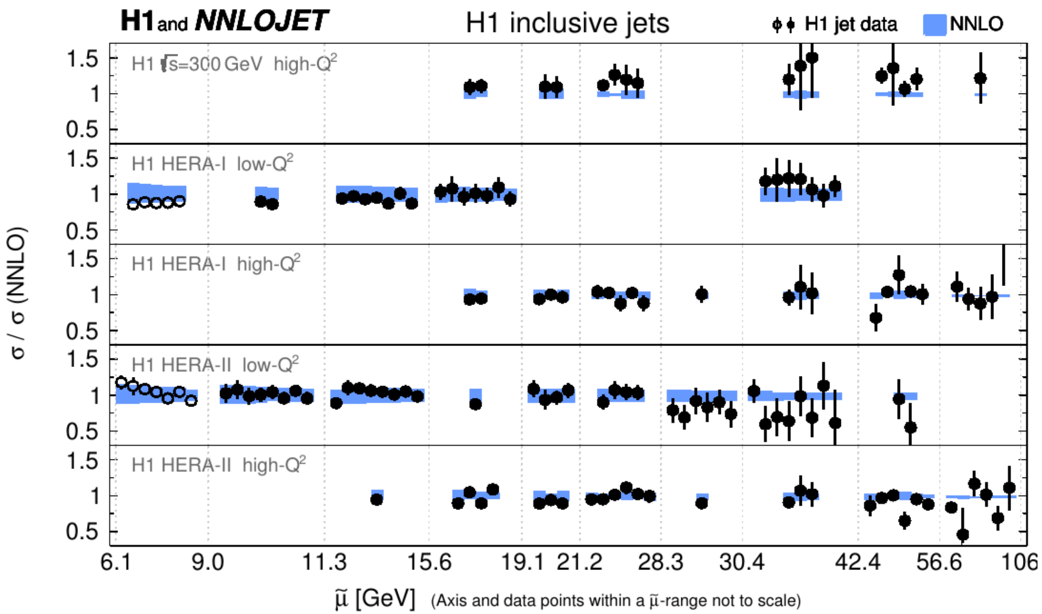
Data points displayed vs. μ

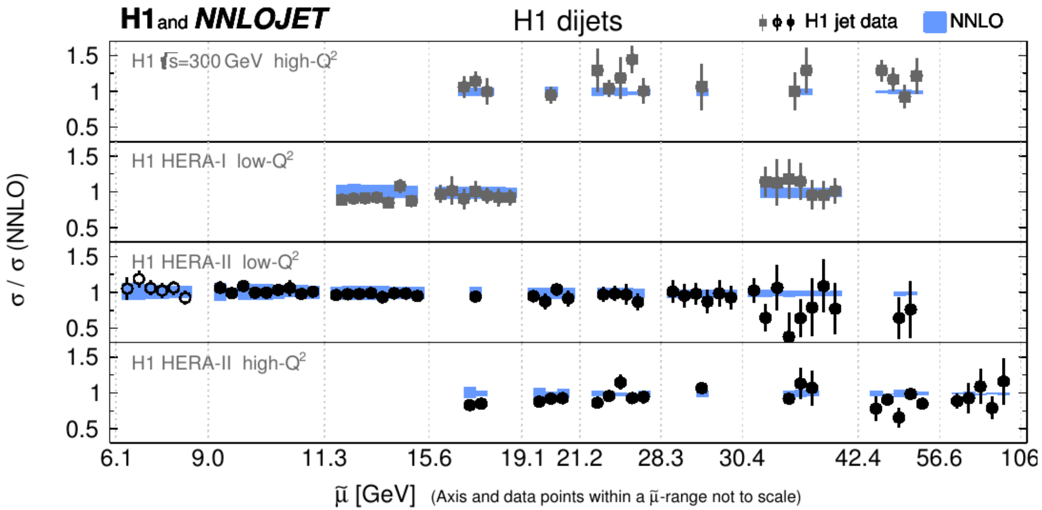
- apply grouping/binning

→ use for scale-dependent studies

Reminder: our scale choice

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





Scale dependence

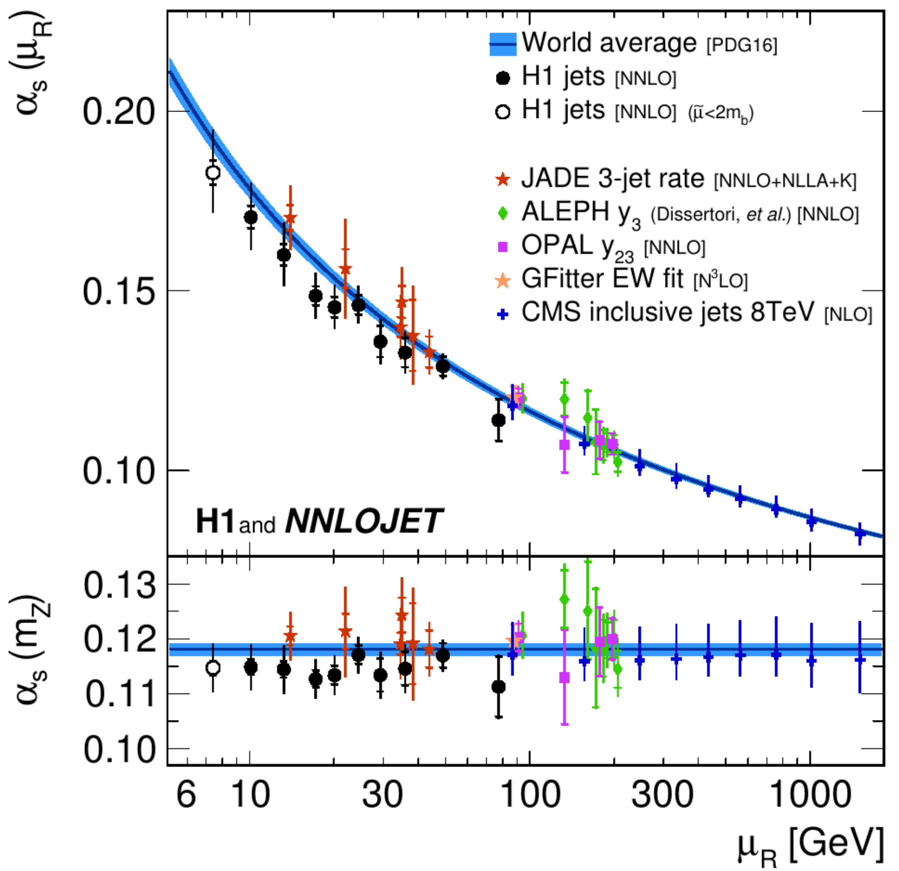
- Perform fits to groups of data points at similar scale
- Assume running to be valid within the limited range covered by interval

H1 jets

- Good consistency with other data
- First determination using jet data in NNLO

Most precise determination of $\alpha_s(\mu_R)$ in range between 7 and 90 GeV

- Measurement bridges the gap between low-scale α_s determinations and LEP/LHC determinations



Alternative α_s fitting approach

'PDF+α_s-fit'
H1PDF2017

Alternative α_s fit approach: 'PDF+α_s-fit'

Perform H1 alone PDF fit: H1PDF2017

- Use (all) H1 inclusive DIS data (Q^2>10GeV^2)
- 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

PDFs are parameterised as

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

- Similar to HERAPDF/H1PDF2012

Mind: all PDFs are commonly determined predominantly from (H1) inclusive DIS data

Cross section: ~ PDF ⊗σ

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

Inclusive NC & CC DIS

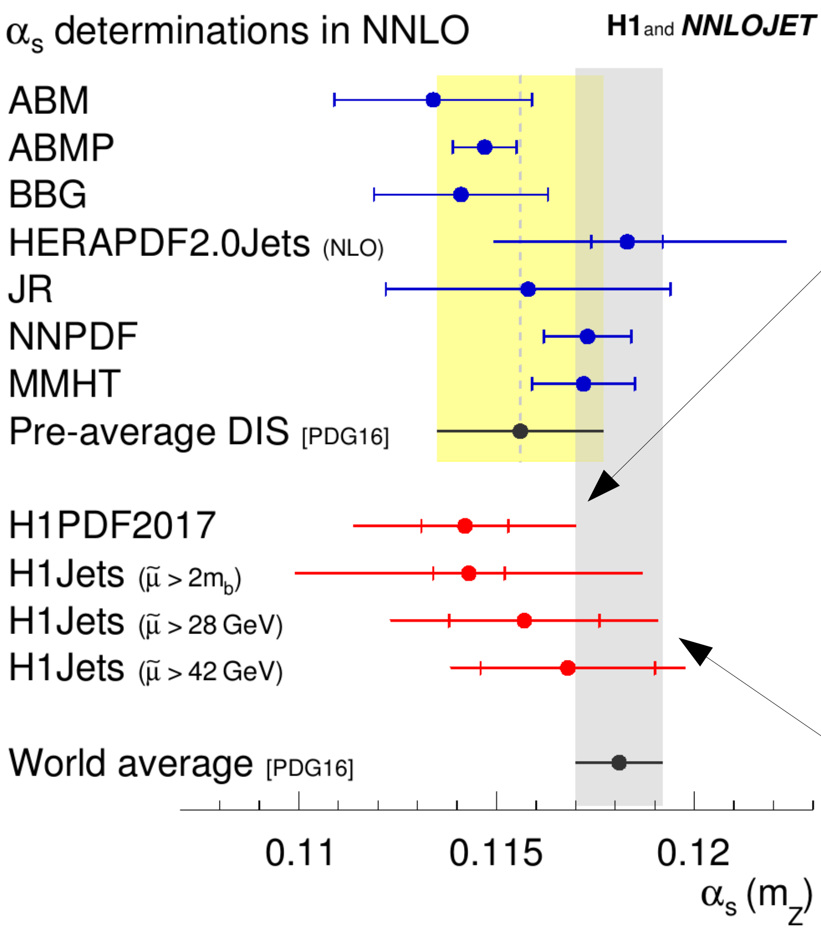
Data set [ref.]	Lepton type	$\sqrt{s}$ [GeV]	Q^2 range [GeV^2]	NC cross sections	CC cross sections	Lepton beam polarisation
Combined low-Q^2 [64]	e^+	301,319	(0.5) 12 – 150	✓	–	–
Combined low-E_p [64]	e^+	225,252	(1.5) 12 – 90	✓	–	–
94 – 97 [61]	e^+	301	150 – 30 000	✓	✓	–
98 – 99 [62, 63]	e^-	319	150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

Normalised jets

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	✓	✓	✓	✓	✓

Results

Inner errors: exp. uncertainty
Outer errors: total uncertainty



α_s determined in PDF+α_s-fit

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

- χ^2/ndf ~ 1.01
- High experimental precision
- Scale uncertainty dominates:
  determined from simultaneous variation of all scales involved in calculation

Discussion / comparison

- Result consistent with our other determination

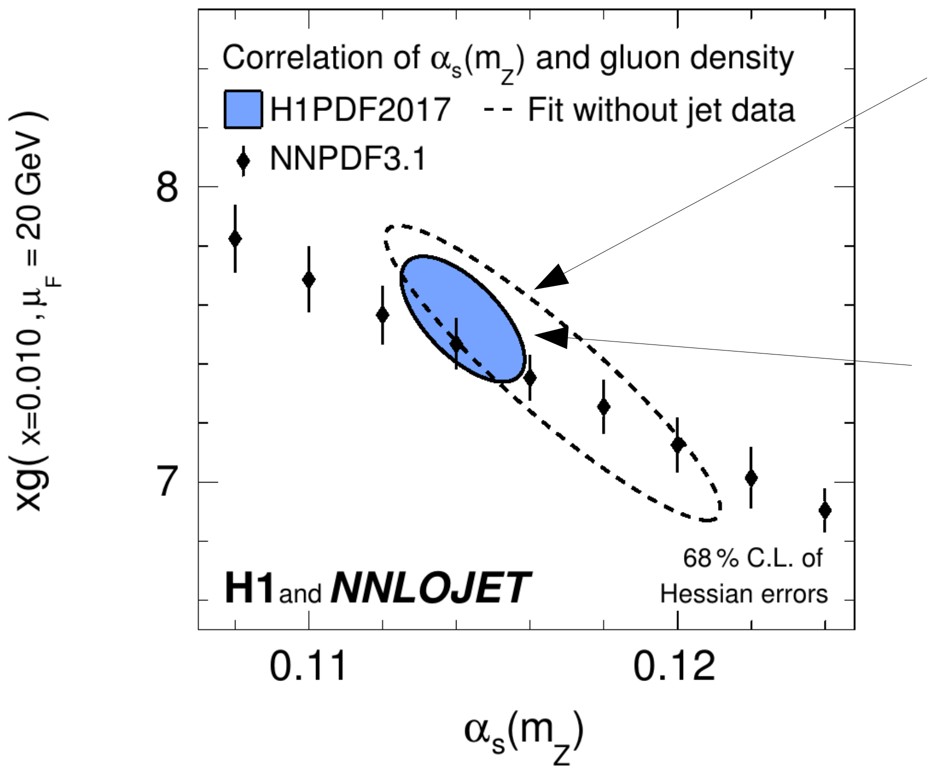
Our two main results are fairly distinct:

- PDF+α_s-fit mostly sensitive to jets at lower scale
- H1jets: μ>28 GeV

$$\alpha_s(m_Z) = 0.1142\,(28)_{\text{tot}}$$

α_s and the gluon-PDF

Correlation of α_s and g



H1PDF2017: PDF+α_s-fit

- Simultaneous determination of the gluon and α_s

Fit to inclusive DIS data alone

- no jet data
- Large correlation:
  α_s and gluon **cannot** be determined simultaenously from inclusive DIS data alone

Including jet data

- determination of α_s and gluon feasible

Comparison with NNPDF3.1

- Error ellipses with similar correlation as individual NNPDF3.1 fits
- Uncertainty of gluon in H1PDF2017 somewhat competitive to NNPDF3.1…
- …. but alpha_s is a free parameter !

PDF+α_s-fit – H1PDF2017 [NNLO]

Result for PDFs

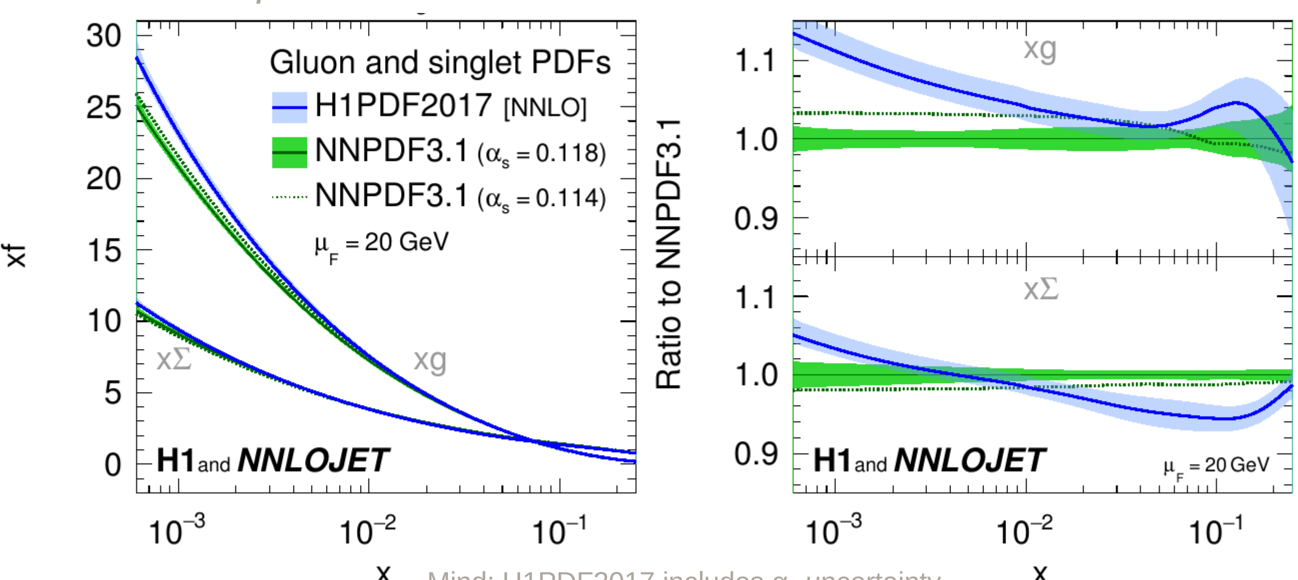
- Set of PDFs determined with high precision
- Precision is competitive with global PDF fitters

...despite α_s is a <u>free parameter</u> to the fit:

H1PDF2017

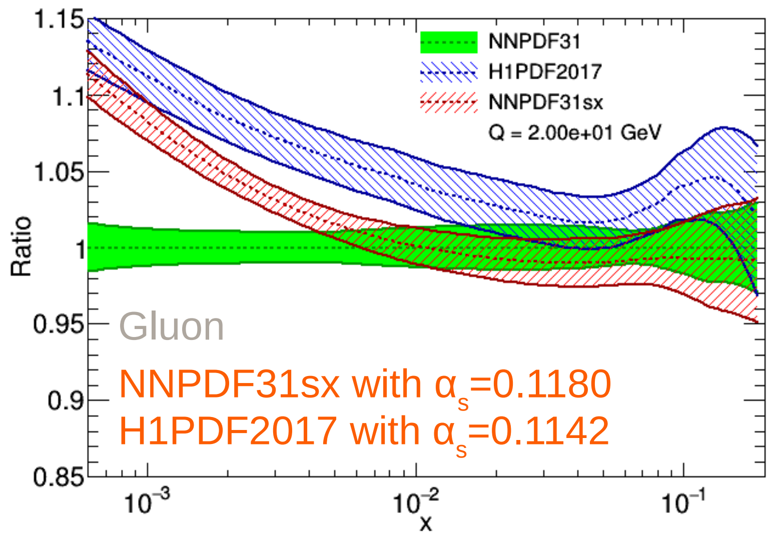
- Gluon at lower *x*-values tends to be higher (than e.g. NNPDF3.1)
- Gluon very similar to NNPDF3.1sx, which includes low-x resummation (no low-Q² data included in our H1 fit)

Comparison of H1PDF2017 and NNPDF3.1



Mind: H1PDF2017 includes α_s-uncertainty, whereas NNPDF does not

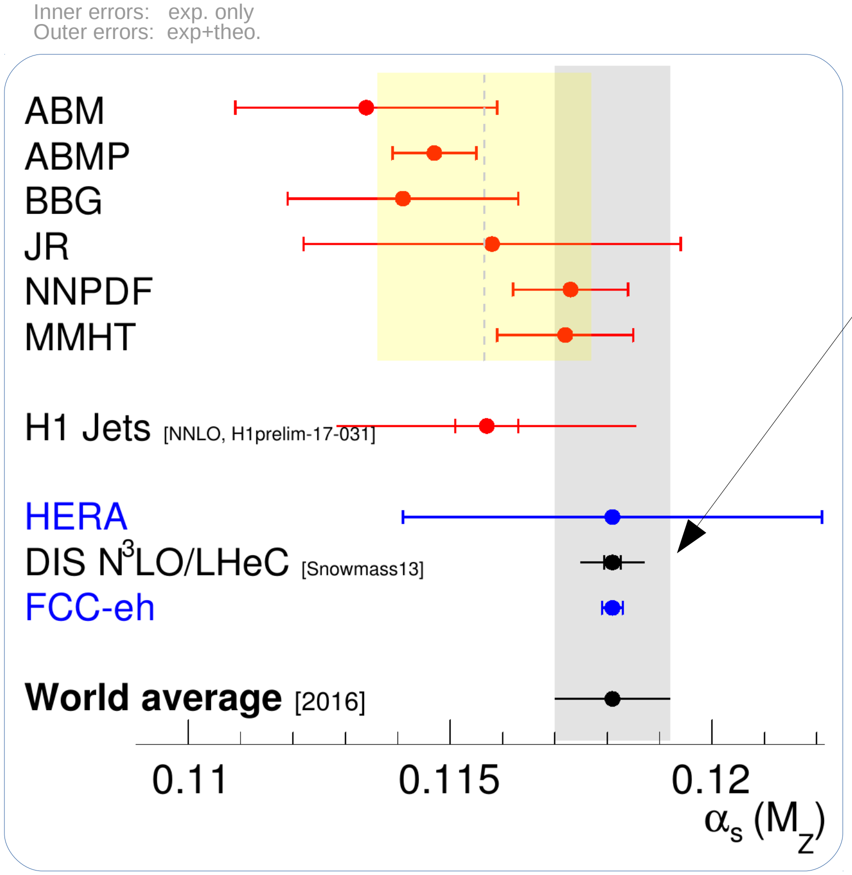
Comparison with NNPDF3.1sx



Apfelweb. Thanks to S. Carraza

Possible future improvements

Possible future improvements in DIS



DB, M. Klein, FCC Week '17 Berlin

New experiments: LHeC, FCC-eh

- incl. DIS:
  - LHeC: 0.1-0.2% (exp) + 0.4%(N3LO)
  - FCC-eh: 0.1% (exp)

  LHeC Study Group [arXiv:1206.2913]
  See also: M. Klein in 'Memory of G. Altarelli', Appendix 1 [arXiv:1802.04317]
- jets, jet shapes, … O(‰)

Old experiments (HERA)

- H1&ZEUS combination: w.i.p.
- Jets in photoproduction
- Jet shapes
  - Analysis of HERA-II data (H1,ZEUS)
  - new jet-shape observables
- F_2 measurement at high-x–low-Q^2

Theory: present

- Incl. DIS: N3LO
- Event shapes: N3LO (J Currie et al, JHEP 1805 (2018) 209)
- Event shapes: N3LL (Kang et al. PoS DIS2015 (2015) 142)
- NNLO+PS (Hoeche et al. Phys.Rev. D98 (2018), 114013)

Theory: future

- N3LO DGLAP (4-loop) (A Vogt et al., PoS LL2018 (2018) 050)
- three-jets in NNLO
- Jets: NNLO + approx.

Summary

All H1 jet data confronted with NNLO predictions

- NNLO provides improved description w.r.t. NLO
- Quantitative comparison of all data
- NNLO predictions studied in great detail

NNLO used for determination of $\alpha_s(m_Z)$

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

NNLO predictions for jets are used for α_s (and PDF) fits for the first time

- Successful determination of gluon-density and $\alpha_s(m_Z)$ simultaneously
- Competitive precision for $\alpha_s(m_Z)$ and PDFs
- H1PDF2017 available at LHAPDF

Fruitful collaboration of theoreticians and experimentalists (H1 & NNLOJET)

Scale dependence of NNLO cross sections

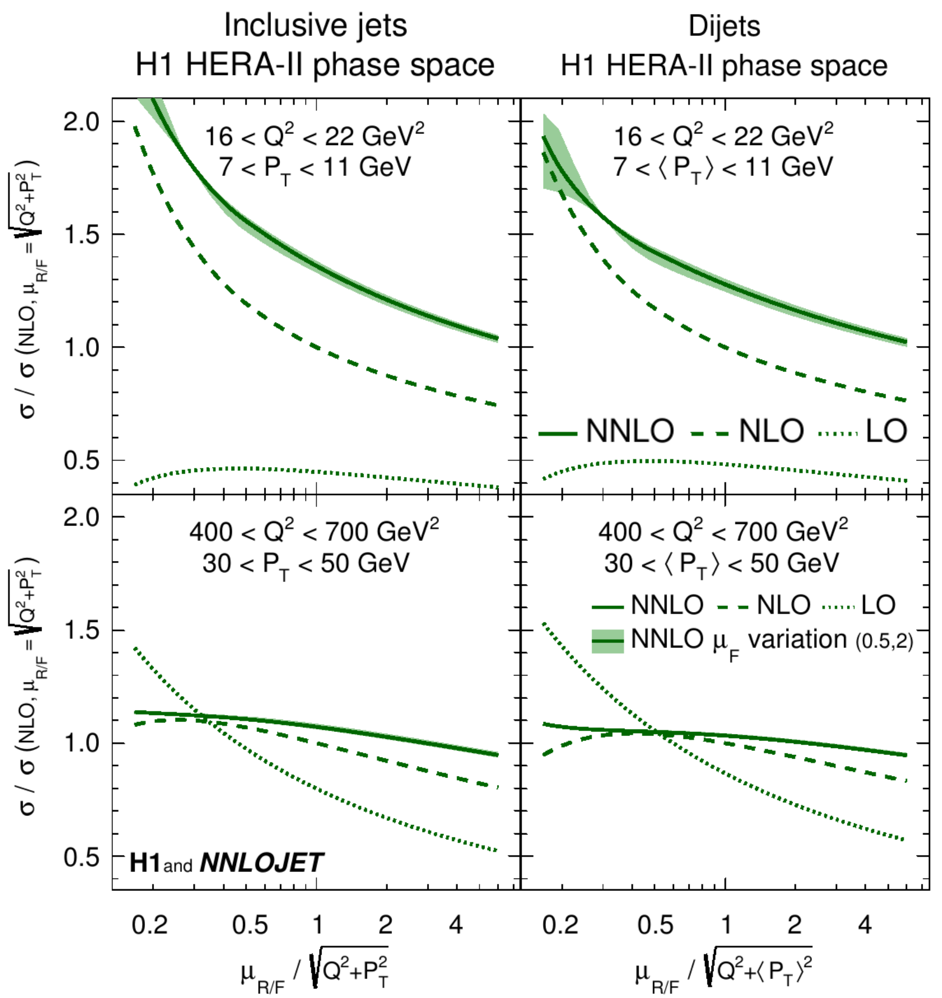
Simultaneous variation of μ_R and μ_F

At lower scales

- Significant NNLO k-factors
- NNLO with reduced scale dependence
- Inclusive jets with higher scale dependence than dijets

At higher scales

- NNLO with reduced scale dependence
- μ_F dependence very small



$\alpha_s(m_Z)$ dependence of cross sections

Jet cross sections directly sensitive to α_s

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

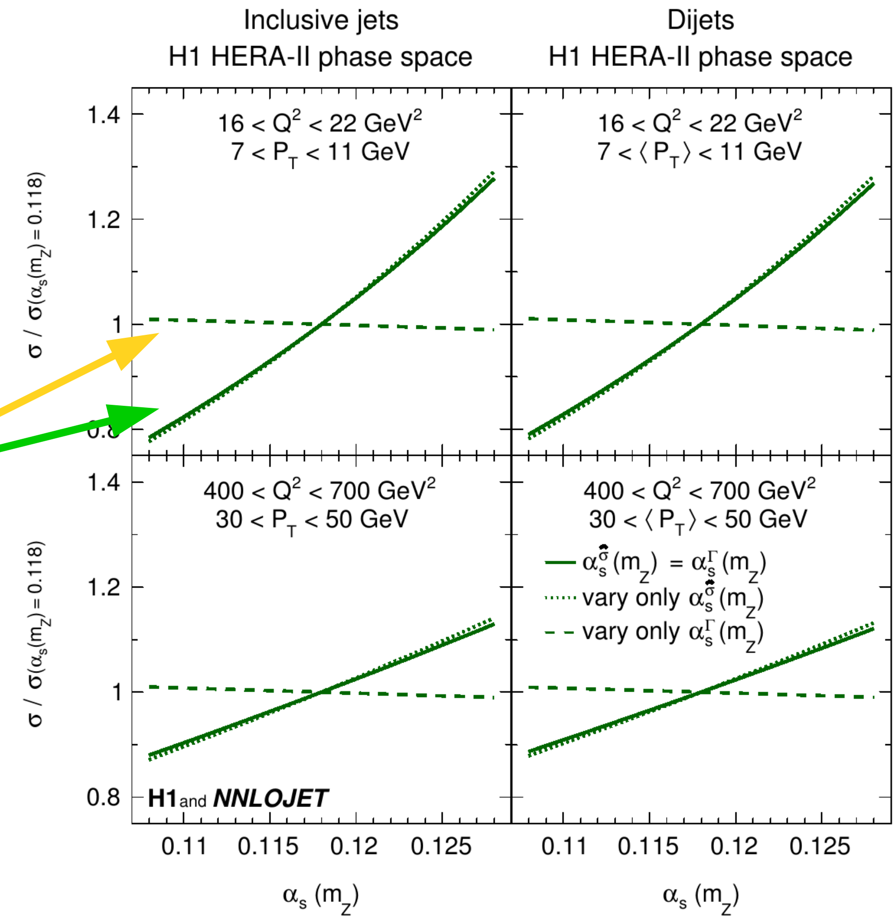
Two α_s-dependencies

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

Hard ME's

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

- *Predominant α_s-sensitivity from ME's*
- *PDF's with almost negligible sensitivity*



α_s dependencies separately fitted

Fits to

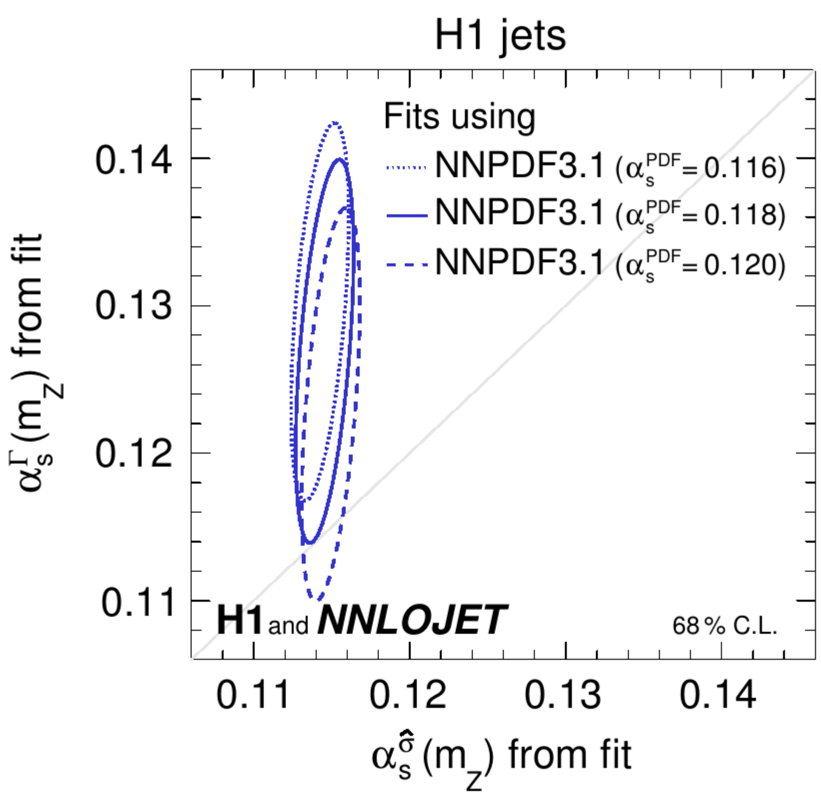
- Inclusive jet and dijet data fitted together
- Fits performed for different PDFs

Fits with two free α_s parameters

$$\sigma_i = f(\alpha_s^f(m_Z)) \otimes \hat{\sigma}_k(\alpha_s^{\hat{\sigma}}(m_Z)) \cdot c_{\text{had}}$$

Results

- Most sensitivity arises from matrix elements
- Best-fit α_s-values in PDF's and ME's are consistent
- Anti-correlation between $\alpha_s^{PDF}(m_Z)$ and $\alpha_s^{\Gamma}(m_Z)$



Summary of all α_s results

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

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

Table 5: Values of the strong coupling constant $\alpha_s(\mu_R)$ and at the Z-boson mass, $\alpha_s(m_Z)$, obtained from fits to groups of data points with comparable values of μ_R. The first (second) uncertainty of each point corresponds to the experimental (theory) uncertainty. The theory uncertainties include PDF related uncertainties and the dominating scale uncertainty.

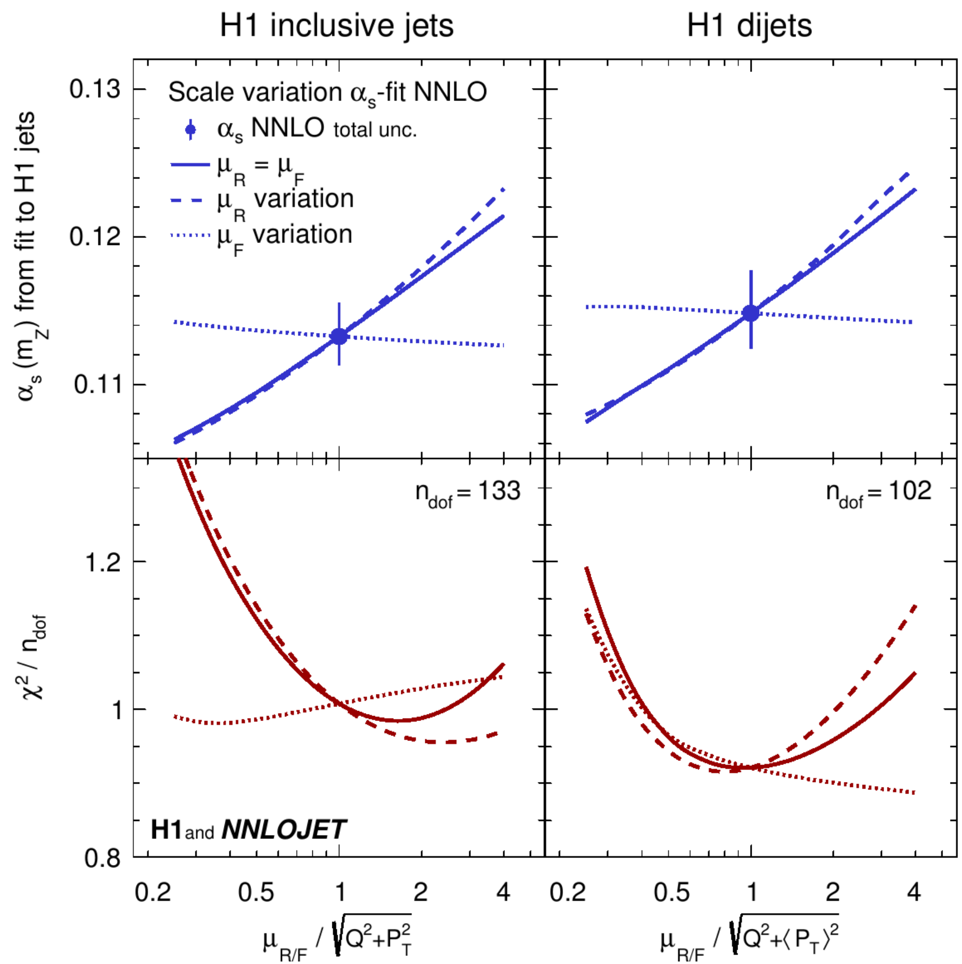
Scale dependence of α_s fit

α_s results as a function of scale factors

- Smooth results for studied scale variations
- μ_R variation with more impact than μ_F

χ^2 values

- somewhat a 'technical parameter'
  -> not intended to be a parabolas
- χ^2 values increase for large scale factors
  -> large scale factors disvafored



Scale choice for α_s fit

Study scales calculated from Q^2 and p_T

'p_T' refers to: p_T^{jet} or $\langle p_T \rangle$

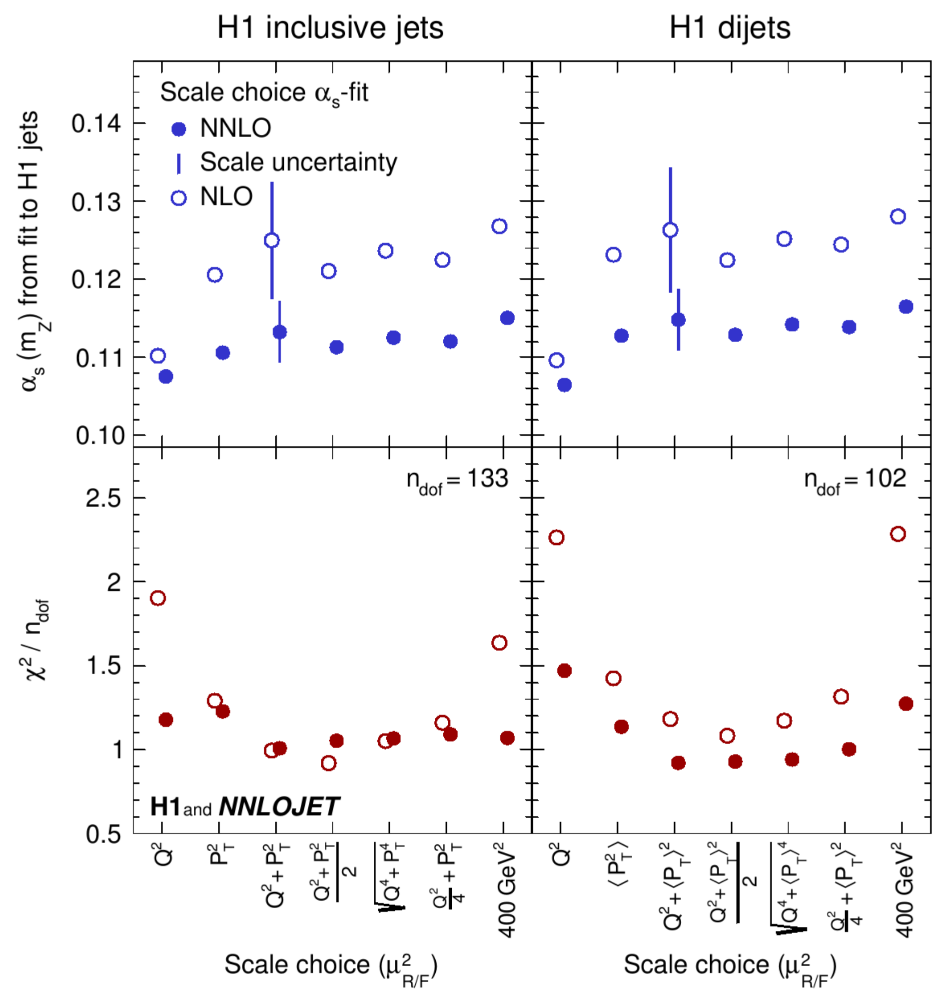
α_s results and χ^2 values

- 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

NNLO with reduced scale dependence



Dependence on the PDF

PDF is an external input to NNLO calculation

PDF fitting groups differ

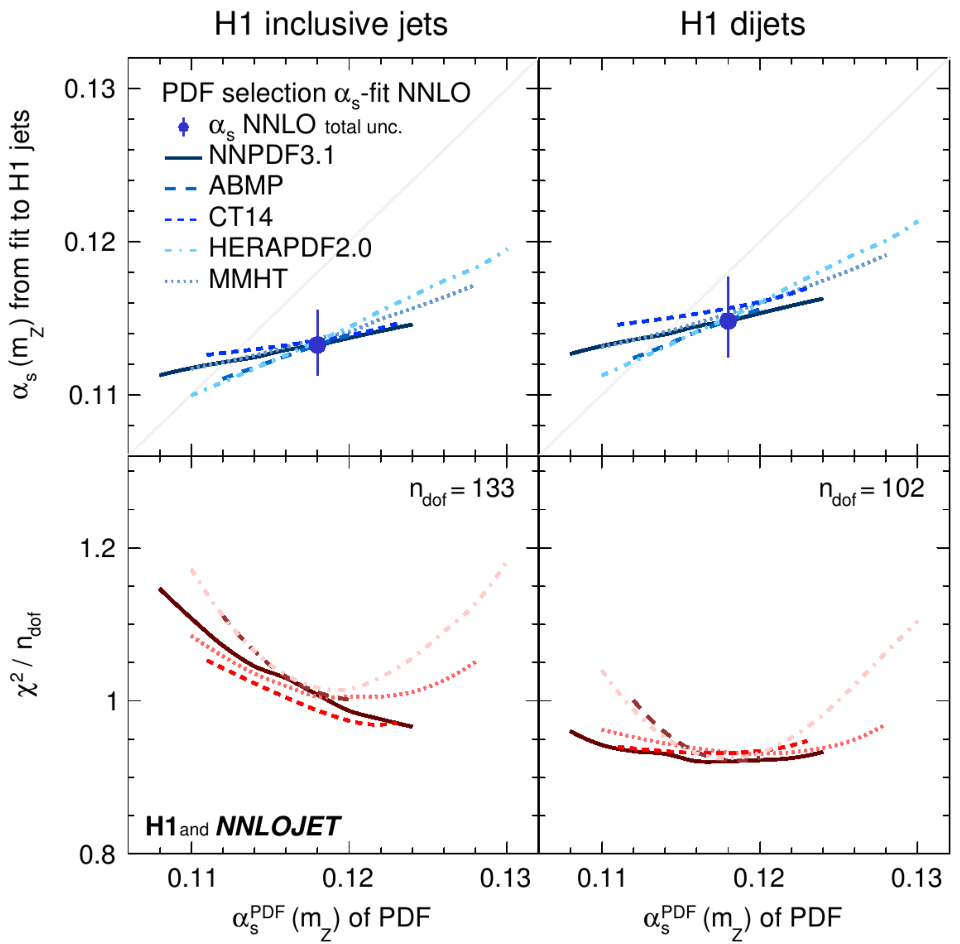
- choice of input data sets,
  PDF parameterisations, model parameters, fit methodology, etc...
- Though:
  different PDFs appear to be quite consistent

Choice of α_s for PDF determination

- $\alpha^{PDF}_s(m_Z)$ important input parameter to PDF fit
- Small correlation with fitted results

Our (main) α_s result

- almost independent on PDF assumptions



Scale dependence

Test running of strong coupling

- Perform fits to <u>groups of data points</u> at similar scale
- Assume running to be valid within the limited range covered by interval

Results

- All fits have good χ^2
- Consistency of inclusive jets and dijets
- Consistency with expectation at all scales
- Scale uncertainty dominates at lower μ