Extraction of α_S at NNLO from HERA Jet DIS data

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developer team

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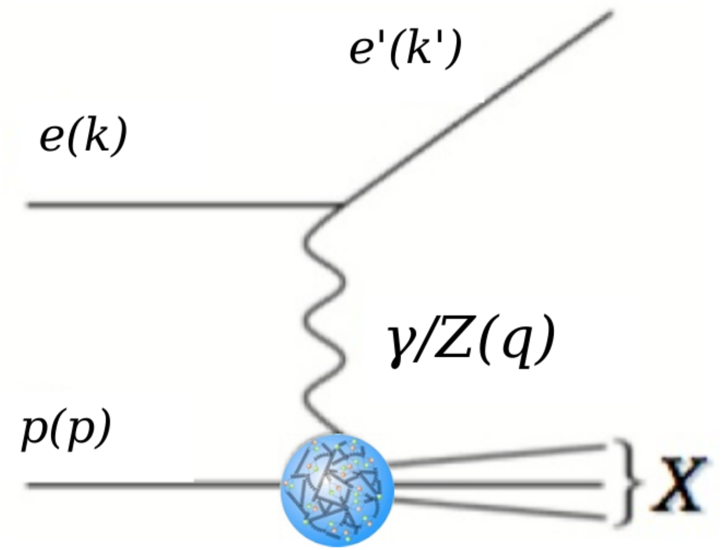
DESY-17-137 Eur.Phys.J.C77 (2017), 791 [arxiv:1709.07251]

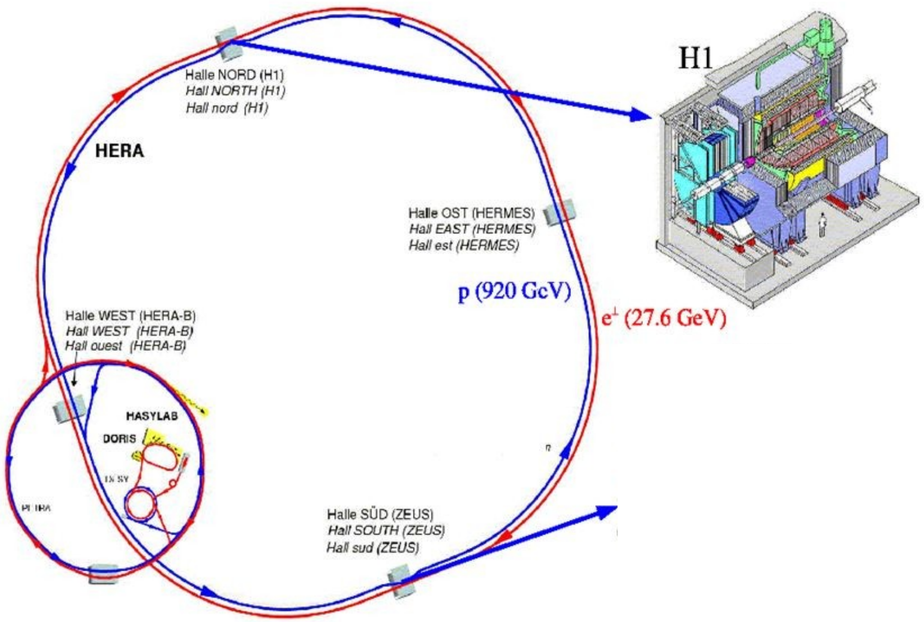
HERA Collider

- 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

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

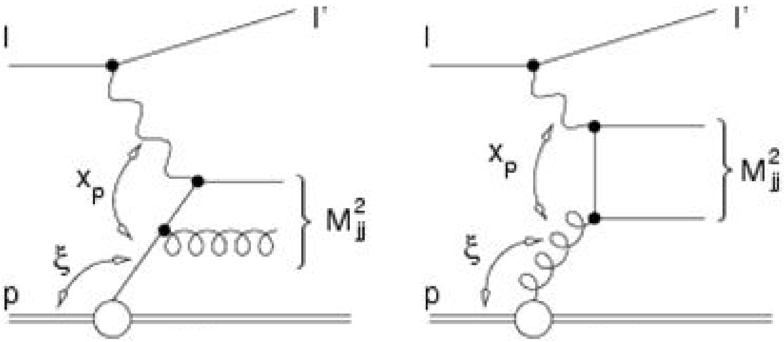
$Q^2 \approx 0$ Photoproduction

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

NNLO α_S fit of H1 jets data in DIS

Why α_S ?

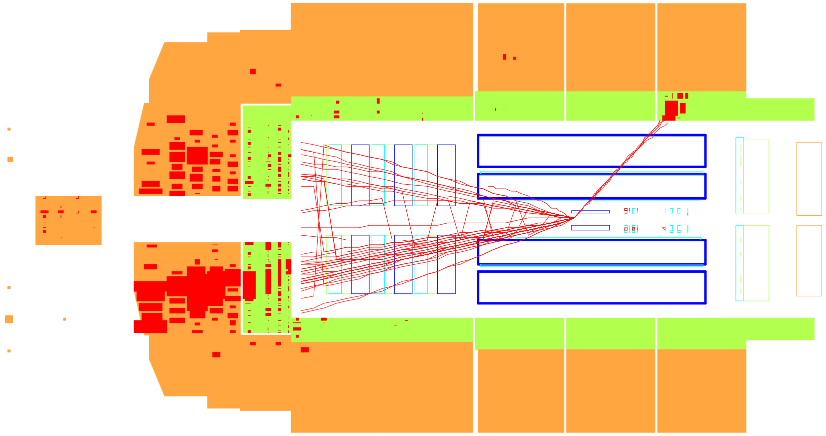
- Among the least known SM parameters
  $G_F = 1.1663787(6) \times 10^{-5}\,\mathrm{GeV}^{-2}$
  $\alpha_S = 1.181(11) \times 10^{-1}$ [PDG16]
- Great importance for LHC physics



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 $7 < \mu < 80\,\mathrm{GeV}$

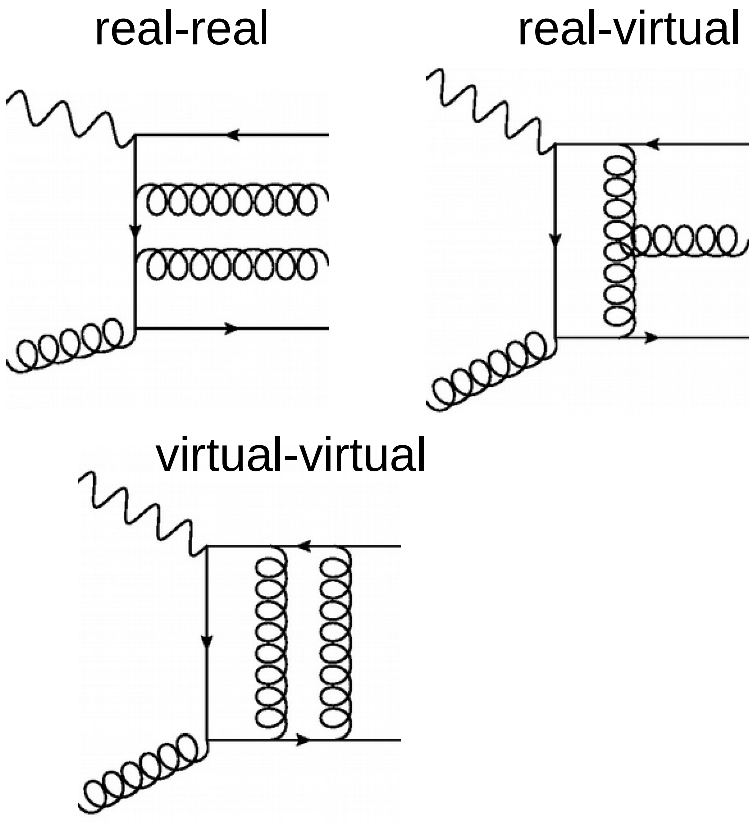


First NNLO α_S fit of the jet ep data

NNLO calculations

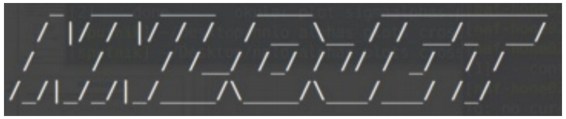
✔ Real-real + real-virtual crosschecked with NLOJET++ & SHERPA

- 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 (~1M CPU hours)
- Then convoluted with PDFs and α_S with **fastNLO** using the **APPLfast** interface (<1s)



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

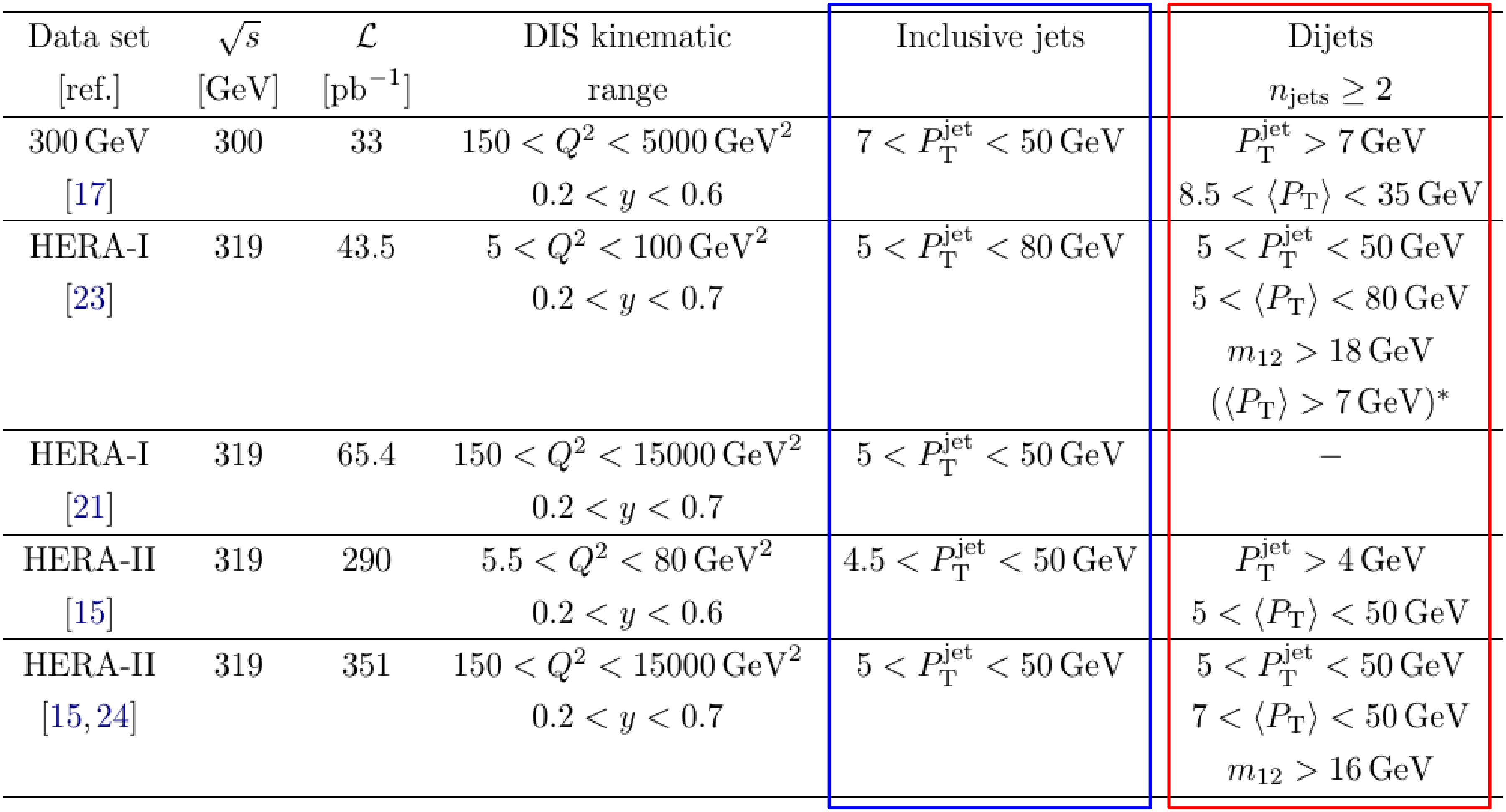
$$\hat{\sigma}_{i,k}(x,\mu_R,\mu_F) = \sum_n \alpha_S^n(\mu_R)\, \hat{\sigma}^{(n)}_{i,k}(x,\mu_R,\mu_F)$$



A bit of history

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

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:

$0.2 < y < 0.6$

$-1 < \eta^{\mathrm{jet}}_{\mathrm{lab}} < 2.5$

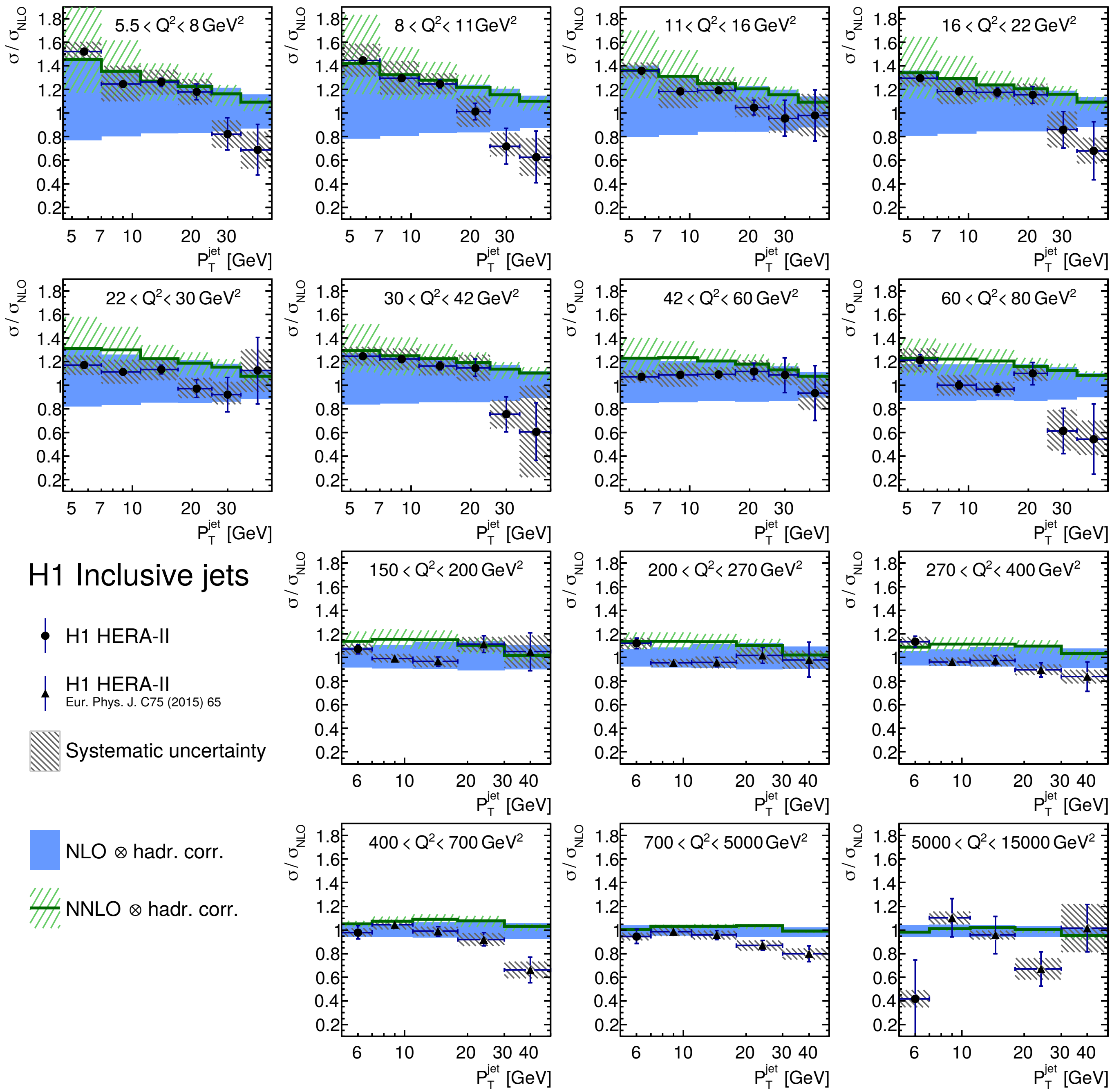
jets found in $\gamma^* p$
with $\mathrm{k_T}$ algo (R=1)

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

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

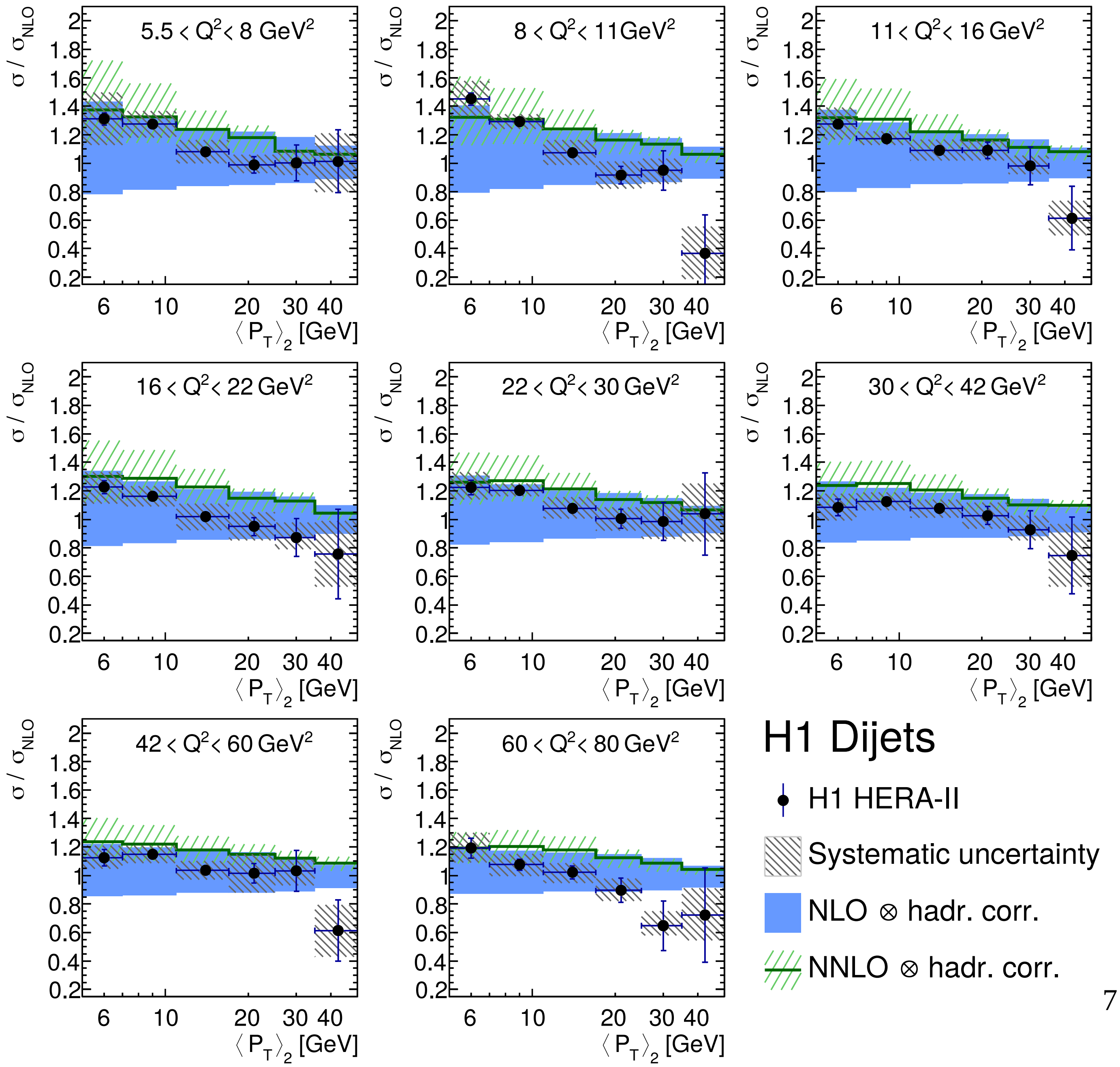
jets found in $\gamma^* p$ with k_T algo (R=1)

NLO predictions

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

NNLO predictions

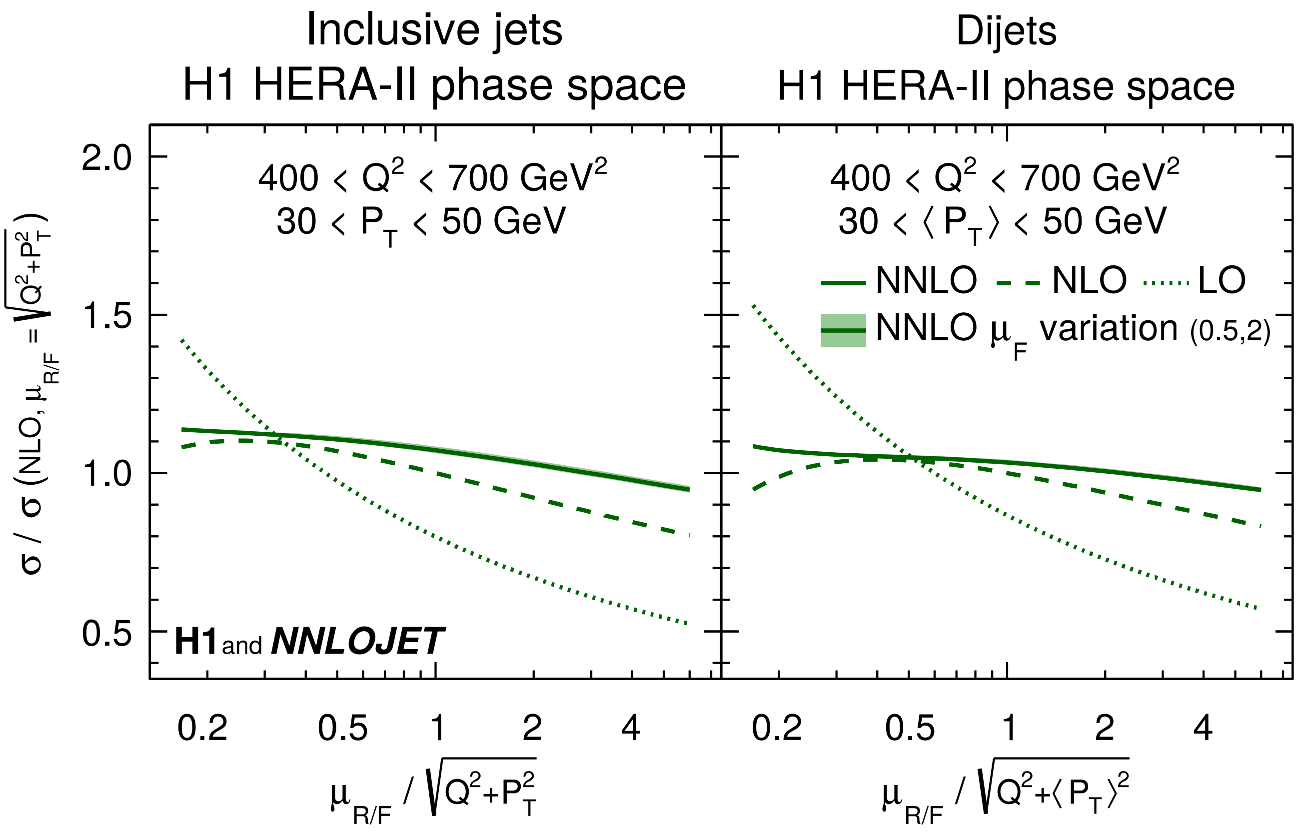
- *NNPDF 3.0 NNLO*
- Smaller scale unc.
- Chi2/ndf = 0.6



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

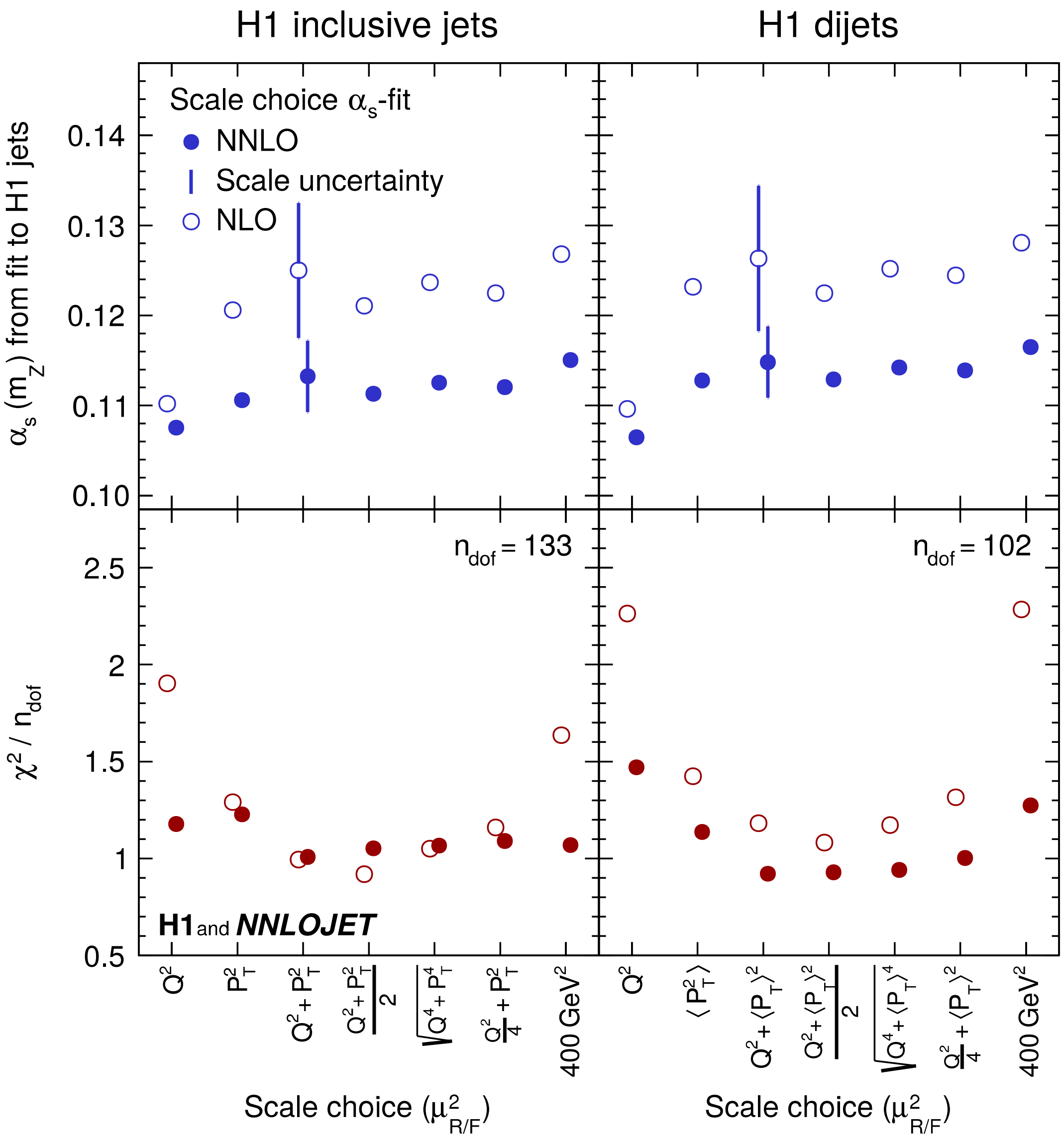
Others functional forms also tested



Functional form of the scale

- 7 possible function studied
- NNLO α_S is typically smaller than the NLO one
- The NNLO χ^2 is usually 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

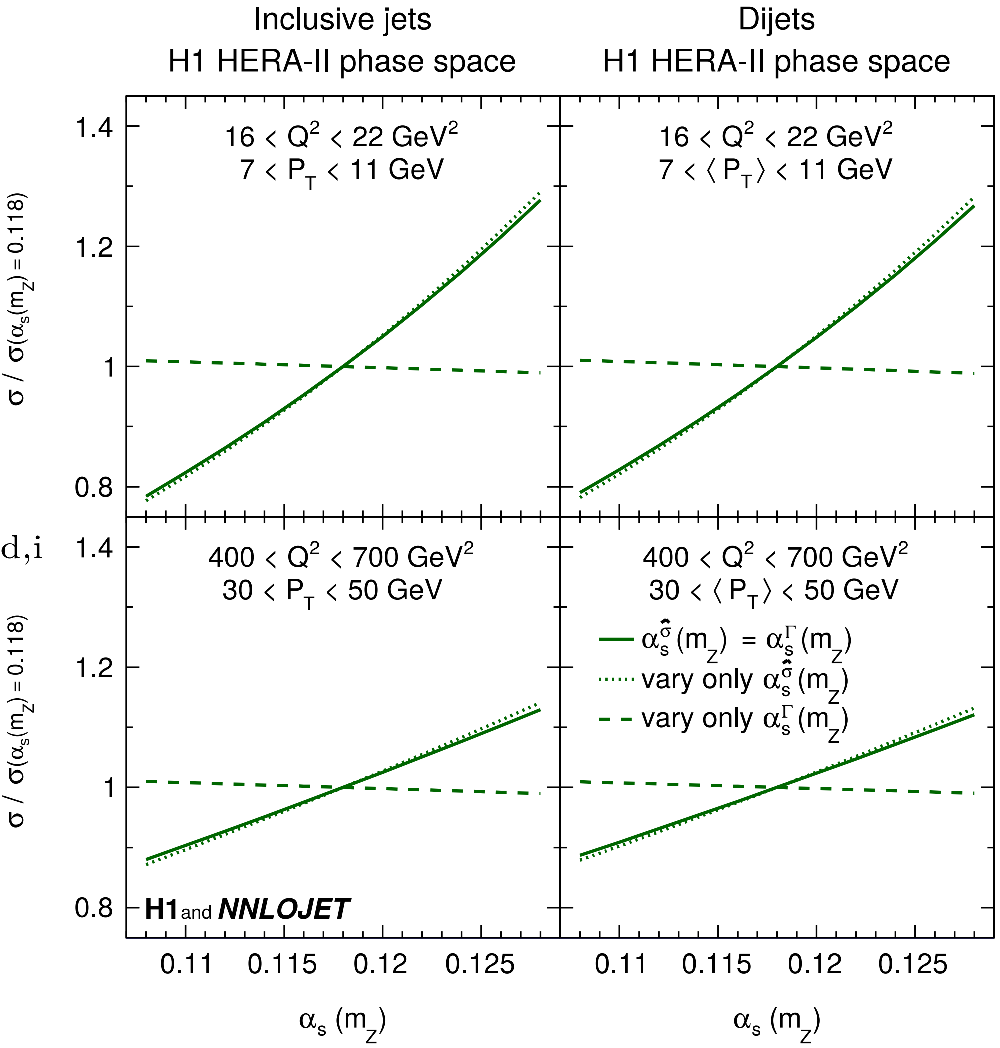
- Alpha strong affects both, PDFs and matrix element
- Both effects considered, α_S in ME more prominent

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

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

DGLAP equations

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



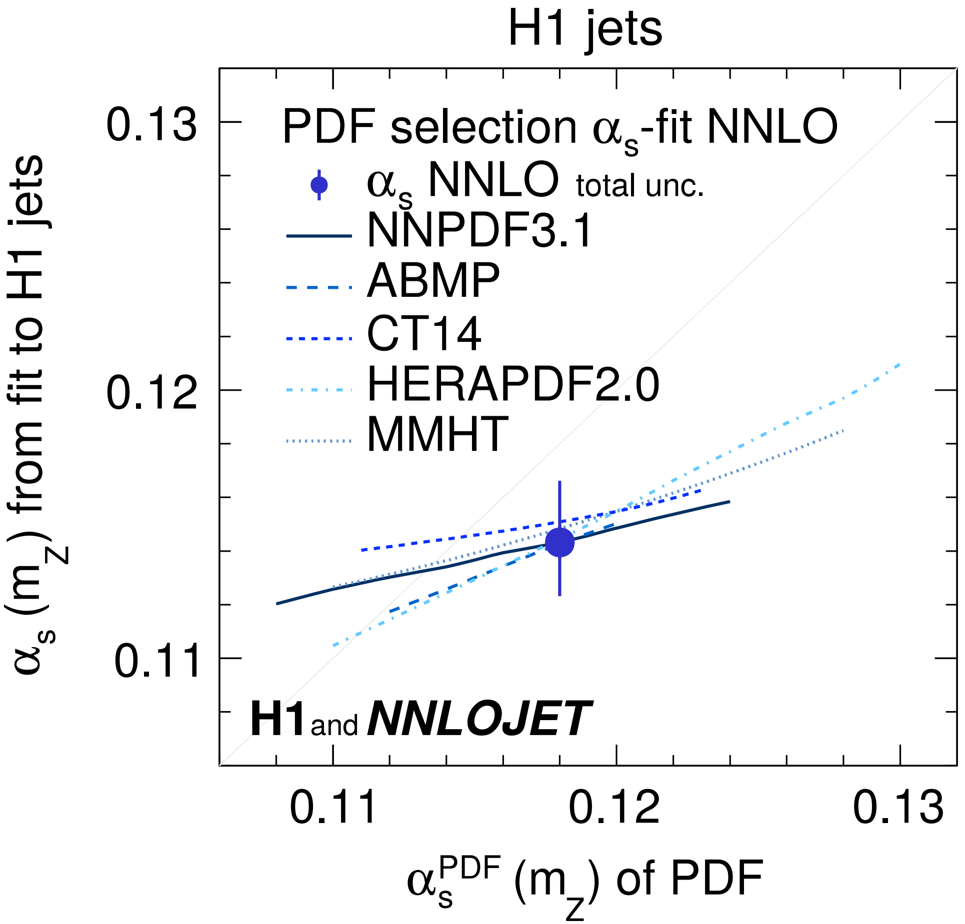
PDFs at scale $\mu_0 = 20\,\text{GeV}$ very well constrained by lot of data $\longrightarrow$ α_S - “independent”

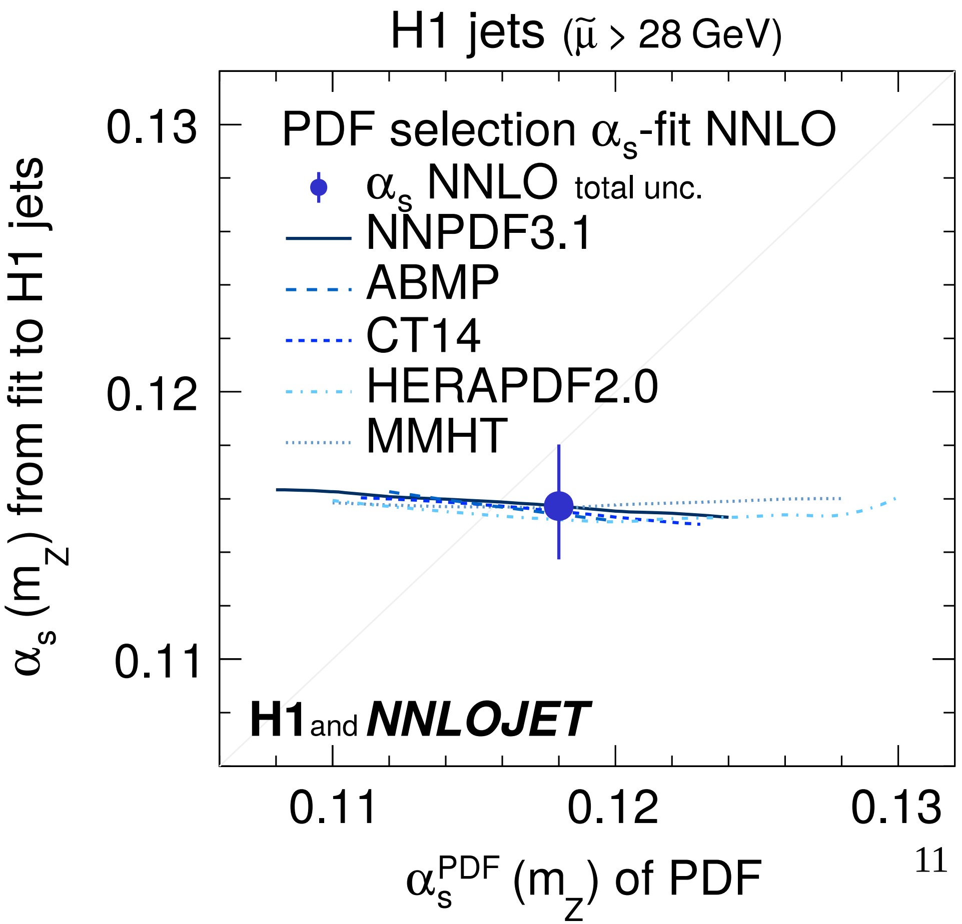
Original PDFs at scale $\mu_0 = 20\,\text{GeV}$ evolved to higher/lower scales by DGLAP with $\alpha_S = \alpha_S(\text{fit par.})$

Dependence on PDF and α_S^{PDF}

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

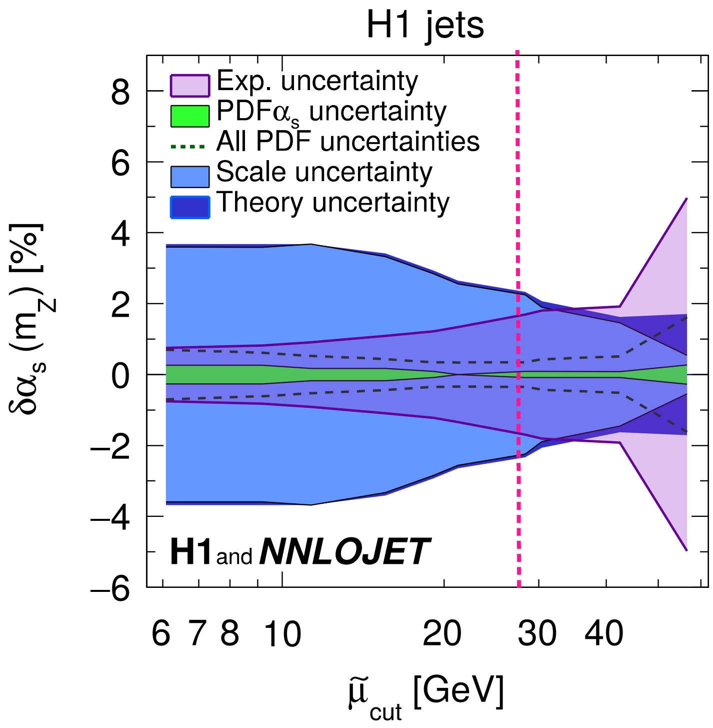
Restricting to $\tilde{\mu} > 28\,\mathrm{GeV}$ makes the α_S-fit uncorrelated to α_S^{PDF}

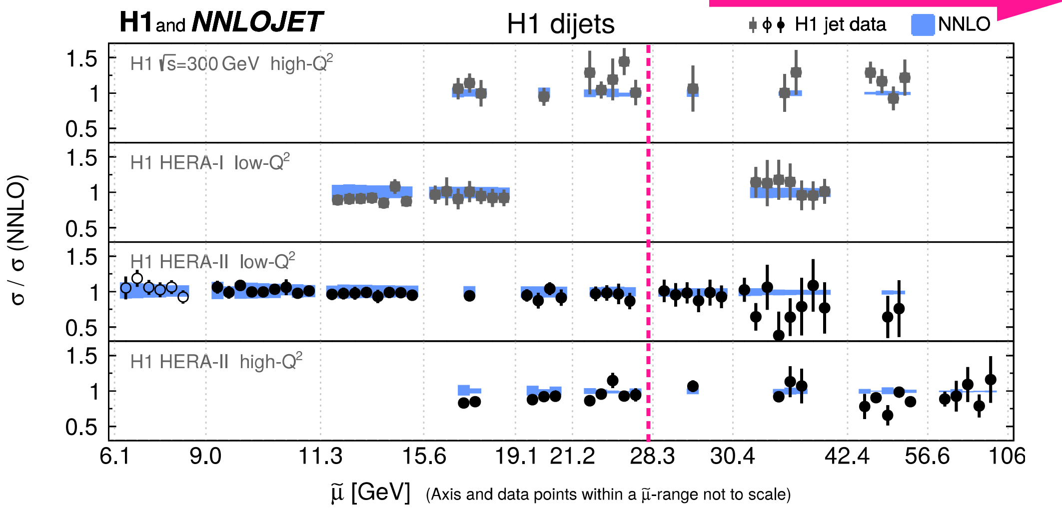


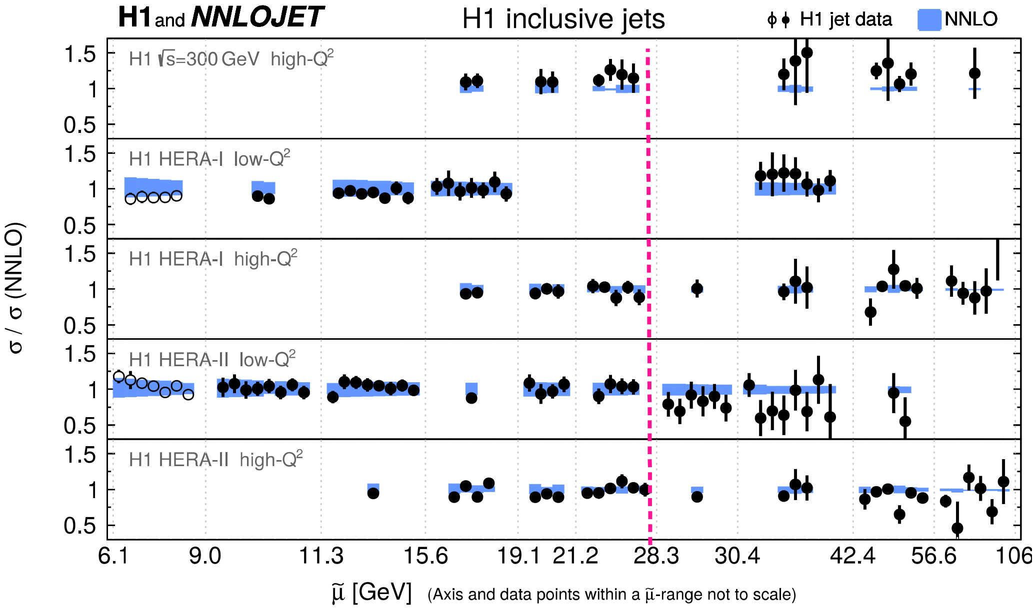


Which data do we use in the fit?

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







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

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

Alpha strong running and central value

$$\alpha_S(m_Z) = 0.1157$$

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

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

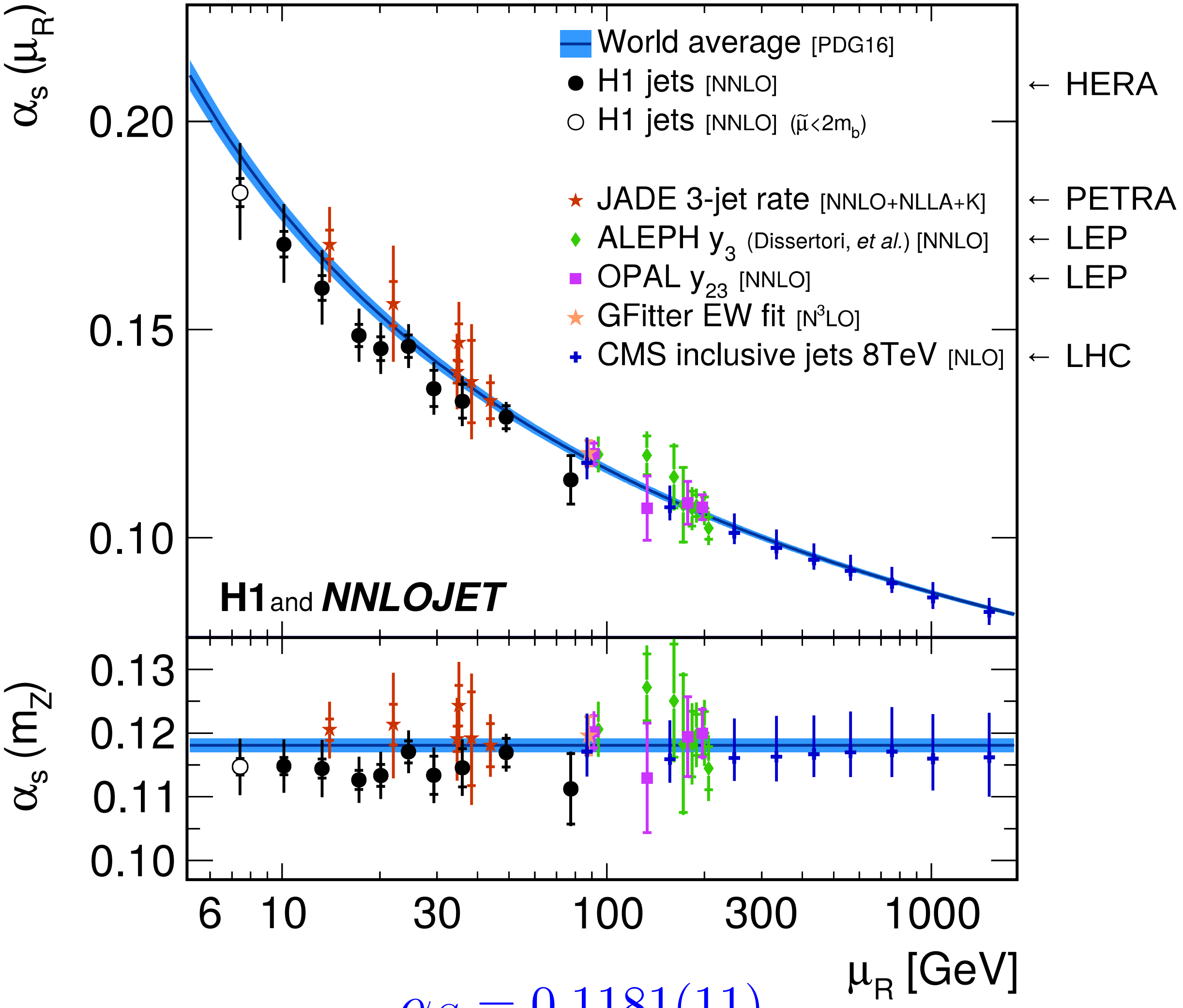
NNPDF 3.1 unc. $(3)_{\mathrm{PDF}}$

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

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

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

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

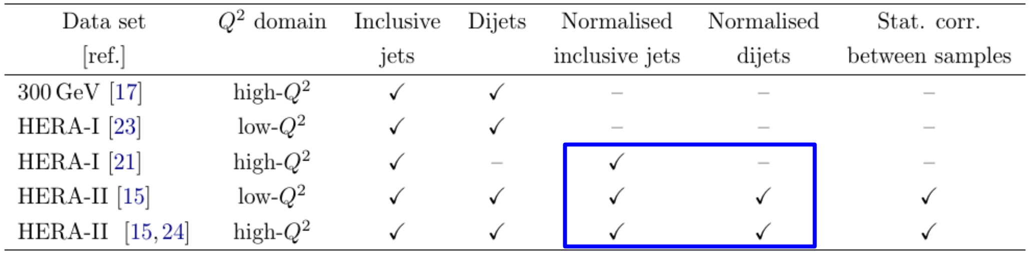


$$\alpha_S = 0.1181(11)$$

Simultaneous α_S + PDF fit (H1PDF2017)

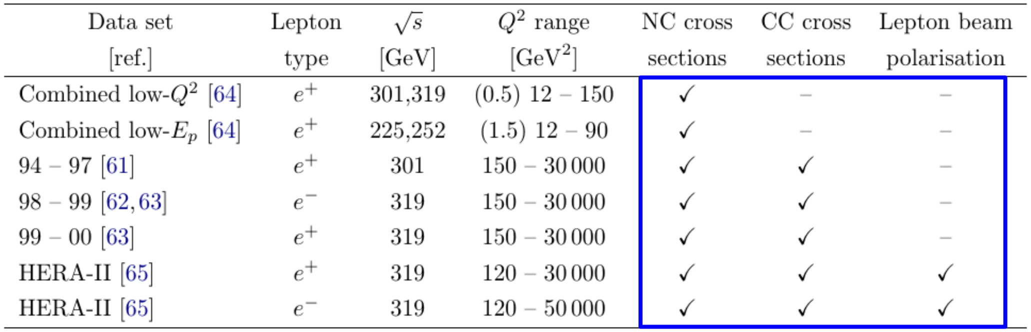
- HERAPDF-like parametrization with 12 parameters at the starting scale $\mu_0^2 = 1.9\,\mathrm{GeV}^2$
- Only data with $Q^2 > 10\,\mathrm{GeV}^2$
- The α_S taken as an additional free parameter of the fit
- Experimental, scale, parametrization and model uncertainty considered

Normalized jet data

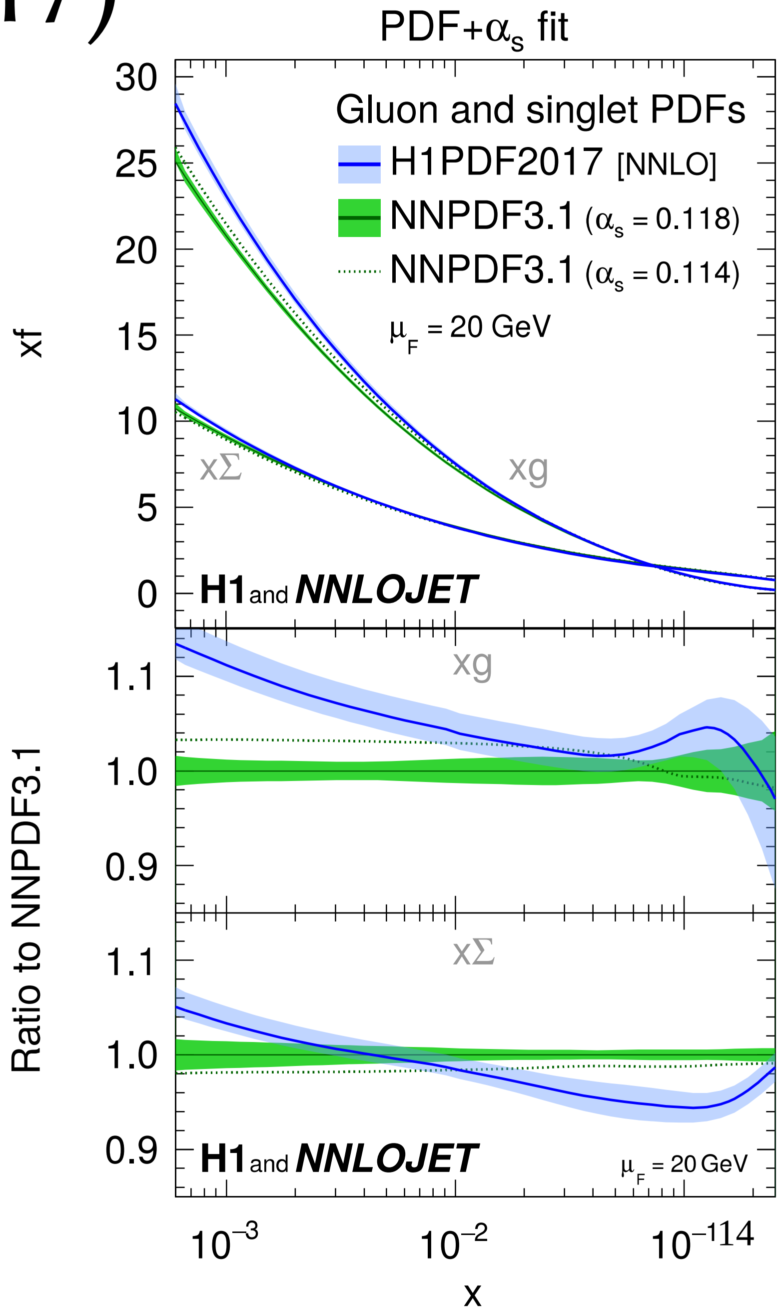


Data set [ref.]	Q^2 domain	Inclusive jets	Dijets	Normalised inclusive jets	Normalised dijets	Stat. corr. between samples
300 GeV [17]	high-Q^2	✓	✓	–	–	–
HERA-I [23]	low-Q^2	✓	✓	–	–	–
HERA-I [21]	high-Q^2	✓	–	✓	–	–
HERA-II [15]	low-Q^2	✓	✓	✓	✓	✓
HERA-II [15, 24]	high-Q^2	✓	✓	✓	✓	✓

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:

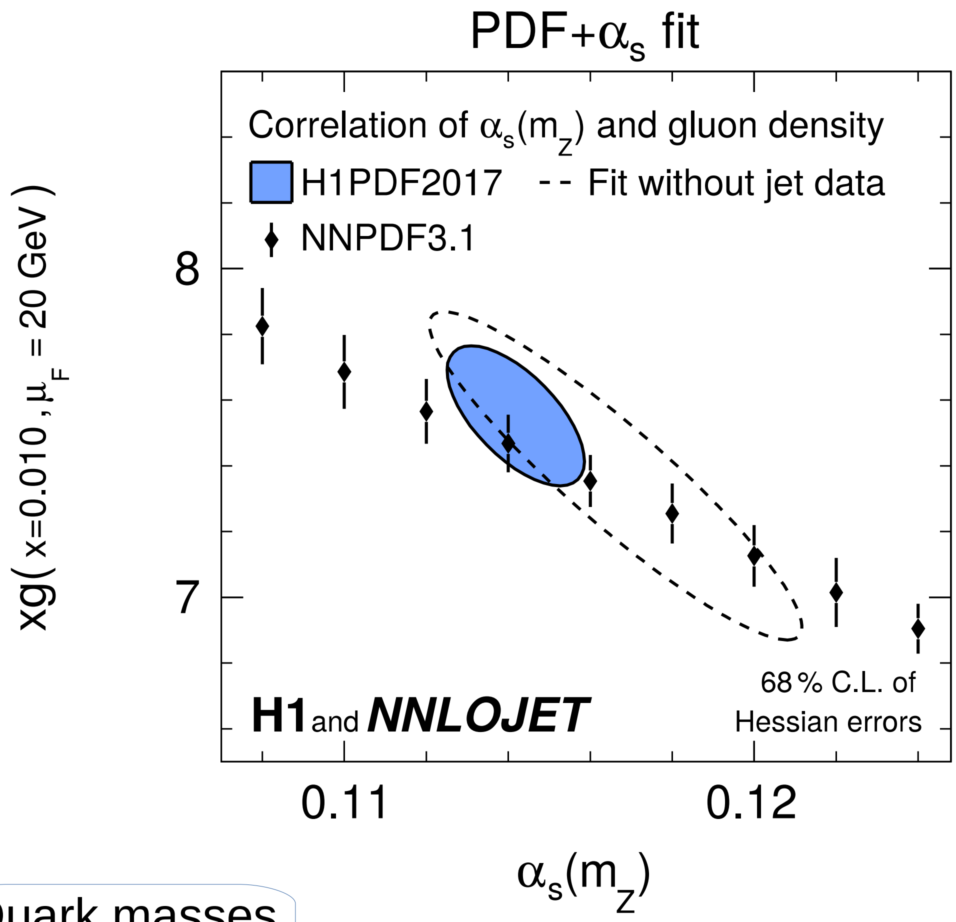
  $$\chi^2/n_{df} = 1540/(1529 - 13)$$

  (with 141 jet data points)

- Anti-correlation between gluon density and α_S

- Huge precision gain by including jet data

  → Jet data matter



Quark masses unc.

From simultaneous ren.+fact. scale variation

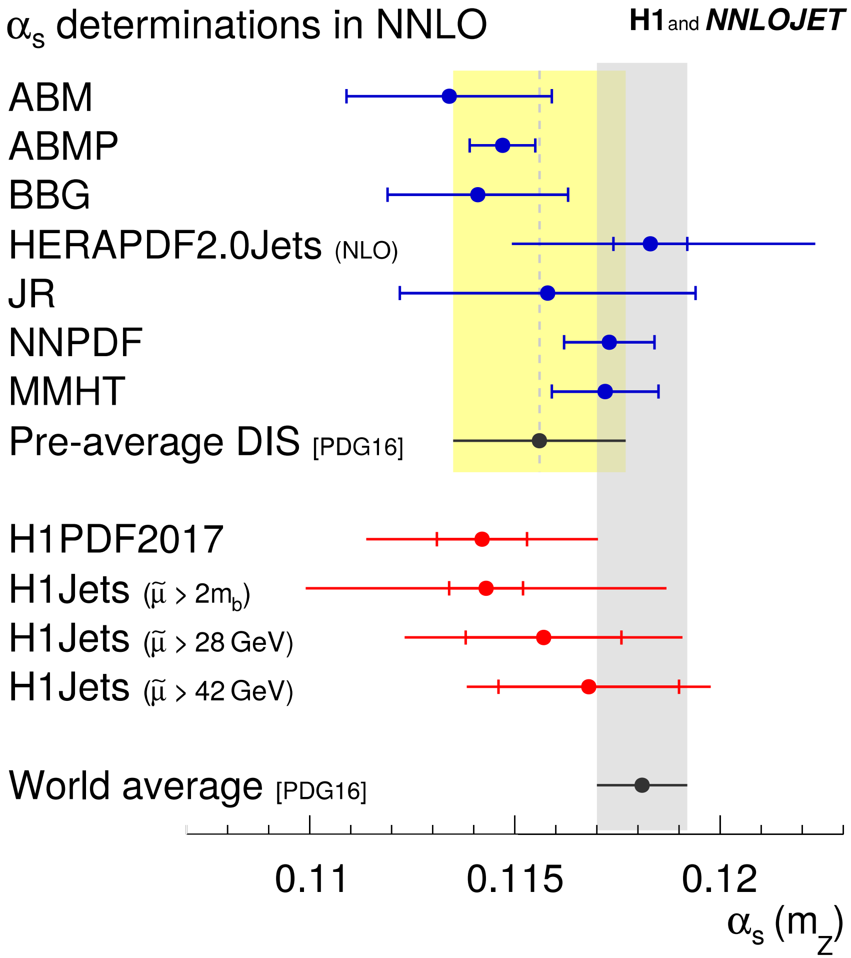
$$\alpha_S(m_Z) = 0.1142(11)_{\mathrm{exp,had,PDF}}(2)_{\mathrm{mod}}(2)_{\mathrm{par}}(26)_{\mathrm{scale}}$$

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?*



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

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

Conclusion

- The α_S from the jet DIS data estimated with NNLO precision for the first time
- The obtained value competitive with LHC and LEP measurements but at unique scale 7-80GeV
- Simultaneous determination of α_S and PDFs possible with high precision using H1 jet data

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	$0.1151 \begin{smallmatrix} + 0.0028 \\ - 0.0027 \end{smallmatrix}$
ew precision fits	0.1196 ± 0.0030

S. Bethke, Nucl.Part.Phys.Proc. 282-284 (2017) 149-152

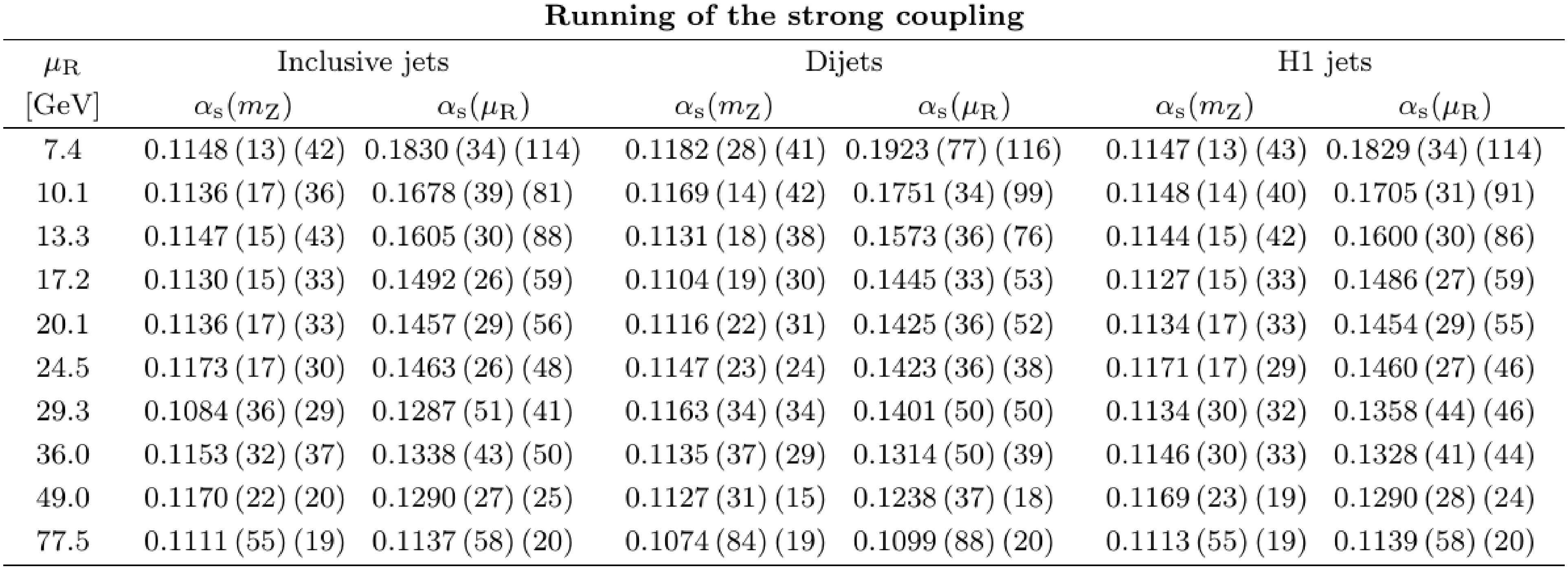
H1 NNLO jets 0.1157 ± 0.0034

H1 NNLO jets+PDF 0.1142 ± 0.0028

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

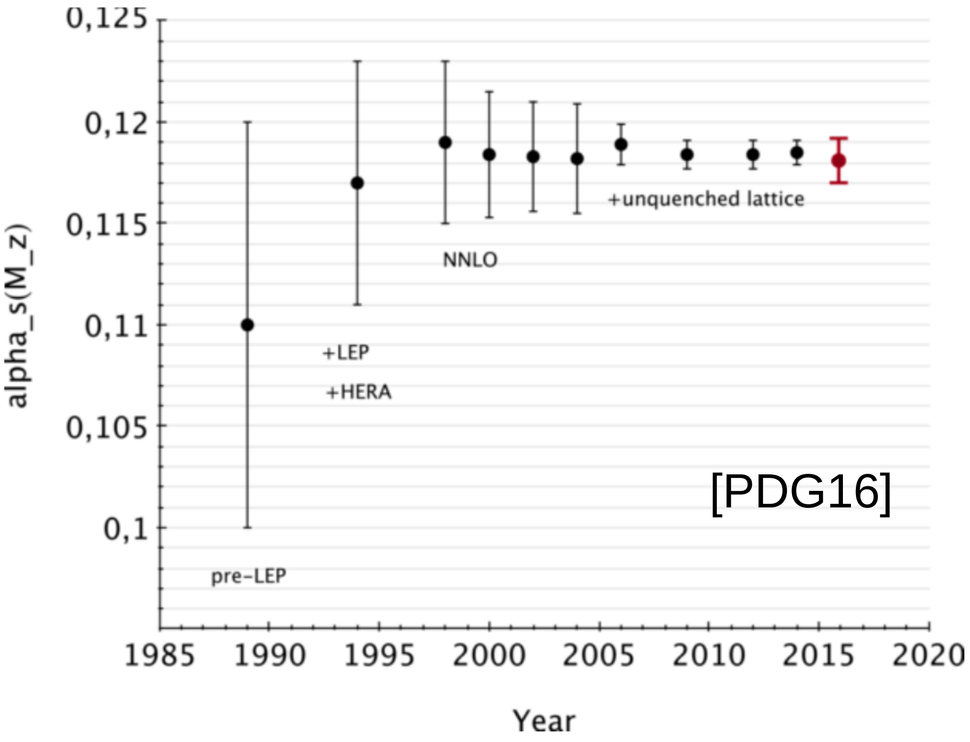
μ_{R}	Inclusive jets		Dijets		H1 jets	
[GeV]	$\alpha_s(m_Z)$	$\alpha_s(\mu_R)$	$\alpha_s(m_Z)$	$\alpha_s(\mu_R)$	$\alpha_s(m_Z)$	$\alpha_s(\mu_R)$
7.4	0.1148 (13) (42)	0.1830 (34) (114)	0.1182 (28) (41)	0.1923 (77) (116)	0.1147 (13) (43)	0.1829 (34) (114)
10.1	0.1136 (17) (36)	0.1678 (39) (81)	0.1169 (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)



[PDG16]

At least NNLO fits [PDG16]