Determination of the strong coupling constant $\alpha_s(m_Z)$ in next-to-next-to-leading order QCD using H1 jet cross section measurements

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**Why $\alpha_s$?**

**Strong coupling $\alpha_s$ enters in the calculation of every process that involves the strong interaction**

**World average value**

$\alpha_s(m_Z) = 0.1181 \pm 0.0011$ [PDG2016]

~0.9% relative uncertainty

**Uncertainty on $\alpha_s$**

- non-negligible uncertainties on many observables: e.g. Higgs production cross sections, branching ratios, ...

**Jet measurements**

- Direct constraint on $\alpha_s$
- So far no NNLO results available
Deep-inelastic $ep$ scattering

**Neutral current scattering (NC)**

$ep \rightarrow e'X$

- $e(k)$
- $e'(k')$
- $p(p)$
- $\gamma/Z(q)$
- $x$ (virtual photon)
- $Q^2 = -q^2 = -(k - k')^2$
- $y = \frac{p \cdot q}{p \cdot k}$

**Kinematic variables**

**HERA $ep$ collider in Hamburg**

- Data taking periods:
  - HERA I: 1994 – 2000
  - HERA II: 2003 – 2007
- $\sqrt{s} = 300$ or $319$ GeV
H1 Experiment at HERA

**H1 multi-purpose detector**
Asymmetric design
Trackers
- Silicon tracker,
- Jet chambers
- Proportional chambers
Calorimeters
- Liquid Argon sampling calorimeter
- SpaCal: scintillating fiber calorimeter
Superconducting solenoid, 1.15T
Muon detectors

**High experimental precision**
- Overconstrained system in NC DIS
- Electron measurement: 0.5 – 1% scale uncertainty
- Jet energy scale: 1%
Jet production in DIS

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 $\alpha_s$ and gluon density
Inclusive jet cross sections by H1

**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-$Q^2$**

**HERA-II low-$Q^2$**

**300 GeV high-$Q^2$**

**HERA-I high-$Q^2$**

**HERA-II high-$Q^2$**

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**Dijet cross section by H1**

**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**
- $d\sigma/dQ^2dp_T$
- 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 $\alpha_s$ extractions previously

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

**HERA-I low-$Q^2$**

**HERA-II low-$Q^2$**

**300 GeV high-$Q^2$**

**HERA-I high-$Q^2$**

**HERA-II high-$Q^2$**


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DIS jet production in NNLO

A bit of history

- 1973 asymptotic freedom of QCD
  [PRL 30(1973) 1343 & 1346]
- 1993 NLO studies of DIS jet cross sections
- 2016 NNLO corrections for DIS jets

Antenna subtraction

- Cancellation of IR divergences with local subtraction terms
- Construction of (local) counter terms
- Move IR divergences across different phase space multiplicities
Scale dependence of NNLO cross sections

Simultaneous variation of $\mu_R$ and $\mu_F$

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
- $\mu_F$ dependence very small
\( \alpha_s \)-fit methodology

\( \alpha_s \) determined in \( \chi^2 \)-minimisation

- \( \alpha_s(m_Z) \) is a free parameter to NNLO theory prediction \( \sigma_i \)

\[
\chi^2 = \sum_{i,j} \log \frac{S_i}{\sigma_i} (V_{\text{exp}} + V_{\text{had}} + V_{\text{PDF}})_{ij}^{-1} \log \frac{S_j}{\sigma_j}
\]

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

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

- \( \alpha_s \) dependence of PDF is accounted for by using \( \mu_{F,0}=20\text{GeV} \) and applying DGLAP

Perform fits 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')
  (exclude HERA-I dijet data as correlations to inclusive jets are not known)
**Strong coupling in NNLO from jets**

**$\alpha_s$ from individual data sets**
- High experimental precision
- Scale uncertainty is largest (theory) error
- All fits with good $\chi^2$
  - $\rightarrow$ consistency of data

**Main result**
- Inclusive jets & dijets $\mu>28$GeV, 91 data points

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

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

**Smallest exp. uncertainty**
- Fit to all data: $\Delta\alpha_s = (9)_{\text{exp}}$
Scale dependence of $\alpha_s$ fit

$\alpha_s$ results as a function of scale factors
- Smooth results for studied scale variations
- $\mu_R$ variation with more impact than $\mu_F$

$\chi^2$ values
- somewhat a 'technical parameter'
  -> not intended to be a parabolas
- $\chi^2$ values increase for large scale factors
  -> large scale factors disfavoured
Study scales calculated from $Q^2$ and $p_T$

'\(p_T\)' refers to: $p_T^{\text{jet}}$ or $<p_T>$

\(\alpha_s\) results and \(\chi^2\) values
- Spread of results covered by scale uncertainty
- \(\chi^2\) values are similar for different choices
  \(\rightarrow\) NNLO with small 'scale dependence'

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

NNLO with reduced scale dependence
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 $\alpha_s$ for PDF determination

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

Our (main) $\alpha_s$ result

- almost independent on PDF assumptions
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 of course by good $\chi^2$ values of the fits

Great success of pQCD
Tests of running of strong coupling

**Test running of strong coupling**

- Perform fits to **groups of data points** at similar scale
- Assumes running to be valid within the limited range covered by interval
- All fits have good $\chi^2$

**Results**

- Consistency with expectation at all scales
- Scale uncertainty dominates at lower $\mu$
- Consistency of inclusive jets and dijets **(backup)**

Most precise test in range $7 < \mu < 90$ GeV
Alternative $\alpha_s$ fitting approach

'PDF+$\alpha_s$ -fit'
H1PDF2017
Alternative $\alpha_s$ fitting approach: 'PDF+$\alpha_s$-fit'

**Simultaneous fit PDFs and $\alpha_s$**
- PDFs are predominantly 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

**PDFs are parameterised as**

$$xf(x)\big|_{\mu_0} = f_Ax^f_B(1-x)^f_C(1+f_Dx+f_Ex^2)$$

**Cross section: $\sim$ PDF $\otimes \sigma$**

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

**Normalised jets**

<table>
<thead>
<tr>
<th>Data set</th>
<th>$Q^2$ domain</th>
<th>Inclusive jets</th>
<th>Dijets</th>
<th>Normalised inclusive jets</th>
<th>Normalised dijets</th>
<th>Stat. corr. between samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>300 GeV [17]</td>
<td>high-$Q^2$</td>
<td>✓</td>
<td>✓</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>HERA-I [23]</td>
<td>low-$Q^2$</td>
<td>✓</td>
<td>✓</td>
<td>–</td>
<td>–</td>
<td>–</td>
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<tr>
<td>HERA-I [21]</td>
<td>high-$Q^2$</td>
<td>✓</td>
<td>–</td>
<td>✓</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>HERA-II [15]</td>
<td>low-$Q^2$</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
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<tr>
<td>HERA-II [15, 24]</td>
<td>high-$Q^2$</td>
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<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

**Inclusive NC & CC DIS**

<table>
<thead>
<tr>
<th>Data set</th>
<th>Lepton type</th>
<th>$\sqrt{s}$</th>
<th>$Q^2$ range</th>
<th>NC cross sections</th>
<th>CC cross sections</th>
<th>Lepton beam polarisation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Combined low-$Q^2$ [64]</td>
<td>$e^+$</td>
<td>301,319</td>
<td>(0.5) 12 – 150</td>
<td>✓</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Combined low-$E_T$ [64]</td>
<td>$e^+$</td>
<td>225,252</td>
<td>(1.5) 12 – 90</td>
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<td>–</td>
<td>–</td>
</tr>
<tr>
<td>94 – 97 [61]</td>
<td>$e^+$</td>
<td>301</td>
<td>150 – 30,000</td>
<td>✓</td>
<td>✓</td>
<td>–</td>
</tr>
<tr>
<td>98 – 99 [62, 63]</td>
<td>$e^-$</td>
<td>319</td>
<td>150 – 30,000</td>
<td>✓</td>
<td>✓</td>
<td>–</td>
</tr>
<tr>
<td>99 – 00 [63]</td>
<td>$e^+$</td>
<td>319</td>
<td>150 – 30,000</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>HERA-II [65]</td>
<td>$e^+$</td>
<td>319</td>
<td>120 – 30,000</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>HERA-II [65]</td>
<td>$e^-$</td>
<td>319</td>
<td>120 – 50,000</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>
PDF+$\alpha_s$-fit – H1PDF2017 [NNLO]

Result for PDFs
- Set of PDFs determined with high precision
- Despite $\alpha_s$ is a free parameter to the fit: precision is competitive with global PDF fitters
- Gluon at lower $x$-values tends to be higher
  -> nowadays: also favored by small-$x$ resummed PDFs

PDF+$\alpha_s$-fit
- Using H1 jet data allows a precise determination of the gluon PDF and $\alpha_s$
- $\chi^2/\text{ndf} \sim 1.01$

Comparison of H1PDF2017 and NNPDF3.1

Correlation of $\alpha_s$ and $g$
Results

$\alpha_s$ determined in PDF+$\alpha_s$-fit

$\alpha_s(m_Z) = 0.1142 \pm 0.0011_{\text{exp., had., PDF}} \pm 0.0002_{\text{mod}} \pm 0.0006_{\text{par}} \pm 0.0016_{\text{scale}}$

- High experimental precision
- Moderate theory uncertainty from NNLO

Comparison

- Higher precision than most of other (comparable) determinations
  - $\Rightarrow$ PDF groups commonly determine exp. uncertainties (only)
  - $\Rightarrow$ We further estimate scale uncertainties

- All H1 results consistent
- Results competitive with world average

- All results from DIS data tend to be lower than world average value
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 $\alpha_s(m_Z)$
- $\alpha_s$-fit
  $$\alpha_s(m_Z) = 0.1157 (20)_{\text{exp}} (6)_{\text{had}} (3)_{\text{PDF}} (2)_{\text{PDF}} \alpha_s (3)_{\text{PDFset}} (27)_{\text{scale}}$$
- $\alpha_s$+PDF-fit
  $$\alpha_s(m_Z) = 0.1142 (11)_{\text{exp, had, PDF}} (2)_{\text{mod}} (2)_{\text{par}} (26)_{\text{scale}}$$
- High experimental and theoretical precision

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 at LHAPDF

Fruitful collaboration of theoreticians and experimentalists (H1 & NNLOJET)
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Study of total uncertainty

Scale uncertainties at various scales $\mu$
- At low-$\mu$: large scale uncertainties...
- ... but also high sensitivity to $\alpha_s(m_Z)$

Fits imposing a cut on scale $\mu$
- Repeat $\alpha_s$ fits: successively cut away data below $\mu_{\text{cut}}$

Results
- Scale uncertainty decreases with $\mu_{\text{cut}}$
- Exp. uncertainty increases with $\mu_{\text{cut}}$

Cut on $\mu$ can balance between exp. and theoretical uncertainties at constant total precision
$\alpha_s(m_Z)$ dependence of cross sections

**Jet cross sections directly sensitive to $\alpha_s$**

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

**Two $\alpha_s$-dependencies**

- Predominant $\alpha_s$-sensitivity from ME's
- PDF's with almost negligible sensitivity

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**Graphs**

Inclusive jets

- H1 HERA-II phase space
- $16 < Q^2 < 22$ GeV$^2$
- $7 < P_T < 11$ GeV

Dijets

- H1 HERA-II phase space
- $16 < Q^2 < 22$ GeV$^2$
- $7 < \langle P_T \rangle < 11$ GeV

- $400 < Q^2 < 700$ GeV$^2$
- $30 < P_T < 50$ GeV

- $400 < Q^2 < 700$ GeV$^2$
- $30 < \langle P_T \rangle < 50$ GeV

Graphs showing $\sigma / \sigma(\alpha_s(m_Z))$ for different $\alpha_s(m_Z)$ values.
$\alpha_s$ dependencies separately fitted

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

**Fits with two free $\alpha_s$ 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 $\alpha_s$-values in PDF's and ME's are consistent
- Anti-correlation between $\alpha_s^{\text{PDF}}(m_Z)$ and $\alpha_s^{\Gamma}(m_Z)$
<table>
<thead>
<tr>
<th>Data</th>
<th>$\mu_{\text{cut}}$</th>
<th>$\alpha_s(m_Z)$ with uncertainties</th>
<th>th</th>
<th>tot</th>
<th>$\chi^2 / n_{\text{dof}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Inclusive jets</strong></td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>300 GeV high-$Q^2$</td>
<td>$2m_b$</td>
<td>0.1221 (31)<em>{\text{exp}} (22)</em>{\text{had}} (5)<em>{\text{PDF}} (3)</em>{\text{PDF}<em>{\alpha_s}} (4)</em>{\text{PDFset}} (36)_{\text{scale}}</td>
<td>(43)_{\text{th}}</td>
<td>(53)_{\text{tot}}</td>
<td>6.5/15</td>
</tr>
<tr>
<td>HERA-I low-$Q^2$</td>
<td>$2m_b$</td>
<td>0.1093 (17)<em>{\text{exp}} (8)</em>{\text{had}} (5)<em>{\text{PDF}} (5)</em>{\text{PDF}<em>{\alpha_s}} (7)</em>{\text{PDFset}} (33)_{\text{scale}}</td>
<td>(35)_{\text{th}}</td>
<td>(39)_{\text{tot}}</td>
<td>17.5/22</td>
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<tr>
<td>HERA-I high-$Q^2$</td>
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<td>0.1136 (24)<em>{\text{exp}} (9)</em>{\text{had}} (6)<em>{\text{PDF}} (4)</em>{\text{PDF}<em>{\alpha_s}} (4)</em>{\text{PDFset}} (31)_{\text{scale}}</td>
<td>(33)_{\text{th}}</td>
<td>(41)_{\text{tot}}</td>
<td>14.7/23</td>
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<td>HERA-II low-$Q^2$</td>
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<td>0.1187 (18)<em>{\text{exp}} (8)</em>{\text{had}} (4)<em>{\text{PDF}} (4)</em>{\text{PDF}<em>{\alpha_s}} (3)</em>{\text{PDFset}} (45)_{\text{scale}}</td>
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<td>(37)_{\text{th}}</td>
<td>(41)_{\text{tot}}</td>
<td>42.5/29</td>
</tr>
<tr>
<td><strong>Dijets</strong></td>
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<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>300 GeV high-$Q^2$</td>
<td>$2m_b$</td>
<td>0.1213 (39)<em>{\text{exp}} (17)</em>{\text{had}} (5)<em>{\text{PDF}} (2)</em>{\text{PDF}<em>{\alpha_s}} (3)</em>{\text{PDFset}} (31)_{\text{scale}}</td>
<td>(35)_{\text{th}}</td>
<td>(52)_{\text{tot}}</td>
<td>13.6/15</td>
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<tr>
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<td>0.1101 (23)<em>{\text{exp}} (8)</em>{\text{had}} (5)<em>{\text{PDF}} (4)</em>{\text{PDF}<em>{\alpha_s}} (5)</em>{\text{PDFset}} (36)_{\text{scale}}</td>
<td>(38)_{\text{th}}</td>
<td>(45)_{\text{tot}}</td>
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<td>HERA-II low-$Q^2$</td>
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<td>0.1173 (14)<em>{\text{exp}} (9)</em>{\text{had}} (5)<em>{\text{PDF}} (5)</em>{\text{PDF}<em>{\alpha_s}} (3)</em>{\text{PDFset}} (44)_{\text{scale}}</td>
<td>(45)_{\text{th}}</td>
<td>(47)_{\text{tot}}</td>
<td>17.4/41</td>
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<td>HERA-II high-$Q^2$</td>
<td>$2m_b$</td>
<td>0.1089 (21)<em>{\text{exp}} (7)</em>{\text{had}} (5)<em>{\text{PDF}} (3)</em>{\text{PDF}<em>{\alpha_s}} (3)</em>{\text{PDFset}} (25)_{\text{scale}}</td>
<td>(27)_{\text{th}}</td>
<td>(34)_{\text{tot}}</td>
<td>28.0/23</td>
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<tr>
<td>H1 inclusive jets</td>
<td>$2m_b$</td>
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<td>(40)_{\text{th}}</td>
<td>(42)_{\text{tot}}</td>
<td>134.0/133</td>
</tr>
<tr>
<td>H1 inclusive jets</td>
<td>28 GeV</td>
<td>0.1152 (20)<em>{\text{exp}} (6)</em>{\text{had}} (2)<em>{\text{PDF}} (2)</em>{\text{PDF}<em>{\alpha_s}} (3)</em>{\text{PDFset}} (26)_{\text{scale}}</td>
<td>(27)_{\text{th}}</td>
<td>(33)_{\text{tot}}</td>
<td>44.1/60</td>
</tr>
<tr>
<td>H1 dijets</td>
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<td>(42)_{\text{tot}}</td>
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<td>H1 dijets</td>
<td>28 GeV</td>
<td>0.1147 (24)<em>{\text{exp}} (5)</em>{\text{had}} (3)<em>{\text{PDF}} (2)</em>{\text{PDF}<em>{\alpha_s}} (3)</em>{\text{PDFset}} (24)_{\text{scale}}</td>
<td>(25)_{\text{th}}</td>
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<td>H1 jets</td>
<td>$2m_b$</td>
<td>0.1143 (9)<em>{\text{exp}} (6)</em>{\text{had}} (5)<em>{\text{PDF}} (5)</em>{\text{PDF}<em>{\alpha_s}} (4)</em>{\text{PDFset}} (42)_{\text{scale}}</td>
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<td>(44)_{\text{tot}}</td>
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<td>H1 jets</td>
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<td>0.1157 (20)<em>{\text{exp}} (6)</em>{\text{had}} (3)<em>{\text{PDF}} (2)</em>{\text{PDF}<em>{\alpha_s}} (3)</em>{\text{PDFset}} (27)_{\text{scale}}</td>
<td>(28)_{\text{th}}</td>
<td>(34)_{\text{tot}}</td>
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<td>H1 jets</td>
<td>42 GeV</td>
<td>0.1168 (22)<em>{\text{exp}} (7)</em>{\text{had}} (2)<em>{\text{PDF}} (2)</em>{\text{PDF}<em>{\alpha_s}} (5)</em>{\text{PDFset}} (17)_{\text{scale}}</td>
<td>(20)_{\text{th}}</td>
<td>(30)_{\text{tot}}</td>
<td>37.6/40</td>
</tr>
<tr>
<td>H1PDF2017 [NNLO]</td>
<td>$2m_b$</td>
<td>0.1142 (11)<em>{\text{exp, NP, PDF}} (2)</em>{\text{mod}} (2)<em>{\text{par}} (26)</em>{\text{scale}}</td>
<td>(28)_{\text{tot}}</td>
<td></td>
<td>1539.7/1516</td>
</tr>
</tbody>
</table>
Daniel Britzger – $\alpha_s(m_Z)$ in NNLO using H1 jets

ICHEP2018, Seoul
<table>
<thead>
<tr>
<th>Data set</th>
<th>$\sqrt{s}$ [GeV]</th>
<th>$\mathcal{L}$ [pb$^{-1}$]</th>
<th>DIS kinematic range</th>
<th>Inclusive jets ( P_T^{\text{jet}} &lt; 50 \text{ GeV} )</th>
<th>Dijets ( n_{\text{jets}} \geq 2 ), ( P_T^{\text{jet}} &gt; 7 \text{ GeV} )</th>
<th>( 8.5 &lt; \langle P_T \rangle &lt; 35 \text{ GeV} )</th>
<th>( 5 &lt; P_T^{\text{jet}} &lt; 50 \text{ GeV} )</th>
<th>( 5 &lt; \langle P_T \rangle &lt; 80 \text{ GeV} )</th>
<th>( m_{12} &gt; 18 \text{ GeV} )</th>
<th>( \langle P_T \rangle &gt; 7 \text{ GeV} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>300 GeV</td>
<td>300</td>
<td>33</td>
<td>150 &lt; ( Q^2 &lt; 5000 \text{ GeV}^2 ) ( 0.2 &lt; y &lt; 0.6 )</td>
<td>7 &lt; ( P_T^{\text{jet}} &lt; 50 \text{ GeV} )</td>
<td>( P_T^{\text{jet}} &gt; 7 \text{ GeV} )</td>
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<td>( \langle P_T \rangle &gt; 7 \text{ GeV} )</td>
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<tr>
<td>HERA-I</td>
<td>319</td>
<td>43.5</td>
<td>5 &lt; ( Q^2 &lt; 100 \text{ GeV}^2 ) ( 0.2 &lt; y &lt; 0.7 )</td>
<td>5 &lt; ( P_T^{\text{jet}} &lt; 80 \text{ GeV} )</td>
<td>( P_T^{\text{jet}} &gt; 7 \text{ GeV} )</td>
<td>( 8.5 &lt; \langle P_T \rangle &lt; 35 \text{ GeV} )</td>
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<td>( \langle P_T \rangle &gt; 7 \text{ GeV} )</td>
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<tr>
<td>HERA-I</td>
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<td>65.4</td>
<td>150 &lt; ( Q^2 &lt; 15000 \text{ GeV}^2 ) ( 0.2 &lt; y &lt; 0.7 )</td>
<td>5 &lt; ( P_T^{\text{jet}} &lt; 50 \text{ GeV} )</td>
<td>( P_T^{\text{jet}} &gt; 7 \text{ GeV} )</td>
<td>( 8.5 &lt; \langle P_T \rangle &lt; 35 \text{ GeV} )</td>
<td>( 5 &lt; P_T^{\text{jet}} &lt; 50 \text{ GeV} )</td>
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<td>( m_{12} &gt; 18 \text{ GeV} )</td>
<td>( \langle P_T \rangle &gt; 7 \text{ GeV} )</td>
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<tr>
<td>HERA-II</td>
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<td>290</td>
<td>5.5 &lt; ( Q^2 &lt; 80 \text{ GeV}^2 ) ( 0.2 &lt; y &lt; 0.6 )</td>
<td>4.5 &lt; ( P_T^{\text{jet}} &lt; 50 \text{ GeV} )</td>
<td>( P_T^{\text{jet}} &gt; 4 \text{ GeV} )</td>
<td>( 5 &lt; \langle P_T \rangle &lt; 50 \text{ GeV} )</td>
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<td>( 5 &lt; \langle P_T \rangle &lt; 80 \text{ GeV} )</td>
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<td>351</td>
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<td>( m_{12} &gt; 16 \text{ GeV} )</td>
<td>( \langle P_T \rangle &gt; 7 \text{ GeV} )</td>
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</tbody>
</table>
Inclusive jet cross sections

- Low $Q^2$: $4.5 < P_T < 50$ GeV
- High $Q^2$: $5 < P_T < 50$ GeV

Predictions

- NLO, aNNLO & NNLO

NLO

- Data well described within uncertainties

aNNLO

- Somewhat improved shape description

NNLO

- Improved shape and normalisation
- Reduced scale uncertainties for larger values of $\mu_r$

Also measured

- Normalised inclusive jet cross sections
Ratio of dijet cross sections to NLO

**Scale uncertainty**
- So-called '7-point scale variation':
  Vary $\mu_r$ and $\mu_f$ independently by factors of 2 and 0.5, but exclude variations in 'opposite' directions

**Ratio to NLO prediction**
- NLO give reasonable descriptions within large scale uncertainties
- aNNLO improves shape
  - aNNLO expected to improve description at high $<p_T>$
- NNLO improves shape dependence
  - NNLO predictions have smaller scale uncertainties than NLO at high-$<p_T>$