ABM update

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(in collaboration with J.Blümlein and S.Moch)
PDF fit framework

QCD evolution
massless NNLO, massive NLO OMEs
(OPENQCDRAD)

3-flavour PDFs

- DIS inclusive
  - NNLO (OPENQCDRAD)
    - Power corr. (TMC+higher-twist)

- DIS heavy quark
  - NNLO (approx.) (OPENQCDRAD)

5-flavour PDFs

- Drell-Yan (W,Z,γ)
  - NNLO (DYrap,FEWZ-grids)

- t-quark
  - (Hathor, fasttop)
Higher twists: generalities

Operator product expansion:

\[ F_{2,T} = F_{2,T}^{(\text{leading twist})} + H_{2,T}(x)/Q^2 + \ldots \quad \text{– additive} \]

\[ F_{2,T} = F_{2,T}^{(\text{leading twist})} (1 + h_{2,T}(x)/Q^2 + \ldots) \quad \text{– multiplicative} \]

- The only one in accordance with QCD
- For multiplicative form the LT anomalous dimensions strongly affect the HT terms at small \( x \)

High twists appear in the DIS data at large \( x \) (equiv. \( W \)) and/or small \( Q^2 \)

Virchaux, Milsztajn PLB 274, 221 (1992)
Higher twists: small and moderate $x$

$$F_{2,T} = F_{2,T}^{(\text{leading twist})} + \frac{H_{2,T}(x)}{Q^2} \quad \text{H}(x) = x^{h_T}P(x)$$

- $H_{T}(x)$ continues a trend observed at larger $x$; $H_2(x)$ is comparable to 0 at small $x$
- $h_T = 0.05\pm 0.07 \rightarrow$ slow vanishing at $x \to 0$

- No dramatic increase of $F_L$ at small $x$: different from the study with multiplicative form of HTs
  
  Abt et. al. hep-ph/1604.02229

- Alternative explanations are available in literature: resummation, saturation, etc.
Higher twists: correlation with $\alpha_s$

- The value of $\alpha_s$ and twist-4 terms are strongly correlated

- With HT=0 the errors are reduced → no uncertainty due to HTs

- With account of the HT terms the value of $\alpha_s$ is stable with respect to the cuts

<table>
<thead>
<tr>
<th>fit ansatz</th>
<th>cuts on DIS data</th>
<th>$\alpha_s(M_Z)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>higher twist modeling</td>
<td></td>
<td>NLO</td>
</tr>
<tr>
<td>higher twist fitted</td>
<td>$Q^2 &gt; 2.5 \text{ GeV}^2$, $W &gt; 1.8 \text{ GeV}$</td>
<td>0.1191(11)</td>
</tr>
<tr>
<td>higher twist fixed at 0</td>
<td>$Q^2 &gt; 10 \text{ GeV}^2$, $W^2 &gt; 12.5 \text{ GeV}^2$</td>
<td>0.1212(9)</td>
</tr>
<tr>
<td></td>
<td>$Q^2 &gt; 15 \text{ GeV}^2$, $W^2 &gt; 12.5 \text{ GeV}^2$</td>
<td>0.1201(11)</td>
</tr>
<tr>
<td></td>
<td>$Q^2 &gt; 25 \text{ GeV}^2$, $W^2 &gt; 12.5 \text{ GeV}^2$</td>
<td>0.1208(13)</td>
</tr>
</tbody>
</table>

$\alpha_s(M_Z) = 0.1153(20)$ (NNLO)  
($W^2 > 15 \text{ GeV}^2$, $Q^2 > 10 \text{ GeV}^2$)

**A stringent cut on $Q$ is necessary for the fit with HT=0**

Moch et al. hep-ph/1405.4781
Higher twists: fit with stringent cut on $Q,W$

$\chi^2$/NDP

<table>
<thead>
<tr>
<th></th>
<th>HT fitted $Q^2&gt;2.5 \text{ GeV}^2$, $W&gt;1.8 \text{ GeV}$</th>
<th>HT=0, $Q^2&gt;10 \text{ GeV}^2$, $W^2&gt;12.5 \text{ GeV}^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>HERA</td>
<td>1510/1168</td>
<td>1220/1007</td>
</tr>
<tr>
<td>Fixed target: SLAC, NMC, BCDMS</td>
<td>1145/1008</td>
<td>498/444</td>
</tr>
</tbody>
</table>

Value of $\chi^2$ is stable w.r.t. to cuts

Stringent cut affects high-$x$ data, however, the large-$x$ PDF uncertainties remain stable
HERA charm data and $m_c$

H1, ZEUS EPJC 78, 473 (2018)

Theory: FFN scheme, running mass definition (cf. talk afternoon)

$m_c (m_c) = 1.245 \pm 0.019 \text{(exp.)} \text{ GeV}$

present analysis

$m_c (m_c) = 1.252 \pm 0.018 \text{(exp.)} \text{ GeV}$

ABMP16

$m_c (\text{pole}) \sim 1.9 \text{ GeV (NNLO)}$

Marquard et al. PRL 114, 142002 (2015)

$m_c (m_c) = 1.246 \pm 0.023 \text{ (h.o.)} \text{ GeV} \text{ NNLO}$

Kiyo, Mishima, Sumino PLB 752, 122 (2016)

$m_c (m_c) = 1.279 \pm 0.008 \text{ GeV}$

Kühn, LoopsLegs2018

Good consistency with the earlier results and other determinations → further confirmation of the FFN scheme relevance for the HERA kinematics
HERA beauty data and $m_b$

\[ m_b(m_b) = 3.96 \pm 0.10 \text{(exp.) GeV} \]

present analysis

\[ m_b(m_b) = 3.84 \pm 0.13 \text{(exp.) GeV} \]

ABMP16

\[ m_b(m_b) = 4.18 \pm 0.04 - 0.03 \text{ GeV} \]

PDG 2018

Improved agreement with other determinations, evidently due to data purification

$X^2/\text{NDP} = 36/27$
Impact of stringent cut on PDFs at small $x$

Gluon goes higher, consistent with the constraint from charm/beauty

Strange sea goes lower at small $x$, consistent with 1 within errors → SU(3) symmetry
Running t-quark mass can be determined simultaneously**

\[ m_t(m_t) = 160.8 \pm 1.1 \text{ GeV} \]

\[ m_t(\text{pole}) = 170.4 \pm 1.2 \text{ GeV} \]

\[ m_t(\text{MC}) \approx 172.5 \text{ GeV from LHC} \]

(Hoang et al. try to quantify the difference)

** Running-mass definition provides better perturbative stability ( Extras)
t-quark: single production (mass determination)

$m_t(m_t) = 161.1 \pm 3.8 \text{GeV}$ (single-top only)

<table>
<thead>
<tr>
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</tr>
</thead>
<tbody>
<tr>
<td>$t\bar{t}$</td>
<td>158.6 ± 0.6</td>
<td>158.4 ± 0.6</td>
<td>164.7 ± 0.6</td>
<td>164.6 ± 0.6</td>
<td>164.3 ± 0.6</td>
</tr>
<tr>
<td>$t$-channel</td>
<td>158.7 ± 3.7</td>
<td>158.0 ± 3.7</td>
<td>160.1 ± 3.8</td>
<td>160.5 ± 3.8</td>
<td>164.0 ± 3.8</td>
</tr>
<tr>
<td>$s$- &amp; $t$-channel</td>
<td>158.4 ± 3.3</td>
<td>157.7 ± 3.3</td>
<td>159.1 ± 3.4</td>
<td>159.6 ± 3.4</td>
<td>162.4 ± 3.5</td>
</tr>
</tbody>
</table>
Small errors due to cancellation of theor. unc. in case the MC version is fixed; they are much larger if different MCs are considered.

The single-top data are sensitive to the u/d ratio, however in general they are not competitive with the DY constraints.

The only window opens when the hadronization MC is fixed and the modeling errors cancel in the ratio → model dependent result.

The comparison can be also inverted in order to discriminate hadronization models.
**Data set used for study of impact PDF shape on $\alpha_s$**

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Process</th>
<th>NPDP</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>DIS</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HERA I+II</td>
<td>$e^\pm p \rightarrow e^\pm X$</td>
<td>1168</td>
</tr>
<tr>
<td></td>
<td>$e^\pm p \rightarrow (\nu) X$</td>
<td></td>
</tr>
<tr>
<td>Fixed-target (BCDMS, NMC, SLAC)</td>
<td>$t^\pm p \rightarrow t^\pm X$</td>
<td>1935</td>
</tr>
</tbody>
</table>

| **DIS heavy-quark production**  |                  |      |
| HERA I+II                       | $e^\pm p \rightarrow e^\pm cX$ | 52   |
| H1, ZEUS                        | $e^\pm p \rightarrow e^\pm bX$ | 29   |
| Fixed-target (CCFR, CHORUS, NOMAD, NuTeV) | $(\nu) N \rightarrow \mu^\pm cX$ | 232  |

| **DY**                          |                  |      |
| Fixed-target (FNAL-605, FNAL-866) | $pN \rightarrow \mu^+\mu^- X$ | 158  |

**The ABMP16 framework with:**

- DY data replaced by the deuteron ones $\Rightarrow$ comparable quark disentangling at moderate and large $x$

- t-quark data excluded (no relevance for the first round of estimates)
## Checking styles of PDF shape

<table>
<thead>
<tr>
<th></th>
<th>ABMP16</th>
<th>CJ15</th>
<th>CT10</th>
<th>CT14</th>
<th>epWZ16</th>
<th>MMHT14</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{PDF}$</td>
<td>28</td>
<td>21</td>
<td>26</td>
<td>26</td>
<td>14</td>
<td>31</td>
</tr>
<tr>
<td>$\mu_0^2$ (GeV$^2$)</td>
<td>9</td>
<td>1.69</td>
<td>1.69</td>
<td>1.69</td>
<td>1.9</td>
<td>1</td>
</tr>
<tr>
<td>$\chi^2$</td>
<td>4065</td>
<td>4108</td>
<td>4148</td>
<td>4153</td>
<td>4336</td>
<td>4048</td>
</tr>
<tr>
<td>PDF shape</td>
<td>$x^a(1-x)^b \exp[P(x,\ln(x))]$</td>
<td>$x^a(1-x)^b \exp[P(x,\sqrt{x})]$</td>
<td>$x^a(1-x)^b \exp[P(x,\sqrt{x})]$</td>
<td>$x^a(1-x)^b \exp[P(x,\sqrt{x})]$</td>
<td>$x^a(1-x)^b \exp[P(x,\sqrt{x})]$</td>
<td>$x^a(1-x)^b \exp[P(x,\sqrt{x})]$</td>
</tr>
<tr>
<td>Constraints</td>
<td>$\bar{u} = \bar{d}$ ($x \to 0$)</td>
<td>$\alpha_{uv} = \alpha_{dv}$</td>
<td>$\alpha_{u} = \alpha_{d}$</td>
<td>$\alpha_{u} = \alpha_{d}$</td>
<td>$\alpha_{u} = \alpha_{d}$</td>
<td>$\alpha_{u} = \alpha_{d} = \alpha_{s}$</td>
</tr>
<tr>
<td>$\alpha_s(M_Z)$</td>
<td>0.1153</td>
<td>0.1147</td>
<td>0.1150</td>
<td>0.1160</td>
<td>0.1162</td>
<td>0.1158</td>
</tr>
</tbody>
</table>

- Various PDF-shape modifications provide comparable description with $N_{PDF} \sim 30$

- Some deterioration, which happens in cases is apparently due to constraints on large(small)-$x$ exponents

**Conservative estimate of uncertainty in $\alpha_s(M_Z)$: 0.0007, more optimistic: 0.0003**
# DY: data used in the ABMP16 fit

<table>
<thead>
<tr>
<th>Experiment</th>
<th>ATLAS</th>
<th>CMS</th>
<th>DØ</th>
<th>LHCb</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sqrt{s}$ (TeV)</td>
<td>7</td>
<td>13</td>
<td>7</td>
<td>8</td>
</tr>
<tr>
<td>Final states</td>
<td>$W^+ \to l^+\nu$</td>
<td>$W^+ \to l^+\nu$</td>
<td>$W^+ \to l^+\nu$</td>
<td>$W^+ \to l^+\nu$</td>
</tr>
<tr>
<td>Luminosity (1/fb)</td>
<td>0.035</td>
<td>0.081</td>
<td>4.7</td>
<td>18.8</td>
</tr>
<tr>
<td>$N_{DP}$</td>
<td>30</td>
<td>6</td>
<td>11</td>
<td>22</td>
</tr>
<tr>
<td>ABMP16</td>
<td>31.0</td>
<td>9.2</td>
<td>22.4</td>
<td>16.5</td>
</tr>
<tr>
<td>CJ15</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>CT14</td>
<td>42</td>
<td>–</td>
<td>– $^b$</td>
<td>–</td>
</tr>
<tr>
<td>HERAFitter</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>MMHT16</td>
<td>39 $^c$</td>
<td>–</td>
<td>–</td>
<td>21</td>
</tr>
<tr>
<td>NNPDF3.1</td>
<td>29</td>
<td>–</td>
<td>–</td>
<td>19</td>
</tr>
</tbody>
</table>

$^a$ The values of NDP and $\chi^2$ correspond to the unfiltered samples.

$^b$ For the statistically less significant data with the cut of $p_T^{l^+} > 35$ GeV the value of $\chi^2 = 12.1$ was obtained.

$^c$ The value obtained in MMHT14 fit.

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**Good overall agreement in NNLO with some tension between DØ and LHCb data**

<table>
<thead>
<tr>
<th>Experiment</th>
<th>NDP</th>
<th>$\chi^2$ after the data sets excluded</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>– ATLAS CMS DØ LHCb</td>
</tr>
<tr>
<td>ATLAS</td>
<td>36</td>
<td>37.7 – 37.0 38.3 39.6</td>
</tr>
<tr>
<td>CMS</td>
<td>33</td>
<td>26.6 25.6 – 26.0 23.5</td>
</tr>
<tr>
<td>DØ</td>
<td>23</td>
<td>48.5 48.1 47.7 – 44.2</td>
</tr>
<tr>
<td>LHCb</td>
<td>80</td>
<td>98.2 100.2 97.4 78.8 –</td>
</tr>
</tbody>
</table>
New input: ATLAS at 7 TeV

**Good agreement with W data**

**Undershooting Z-boson data**

**Different trends for the central and forward Z-boson data**

<table>
<thead>
<tr>
<th>ATLAS data set</th>
<th>$\chi^2$/NDP</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W^\pm$, $Z$(central)</td>
<td>43/34</td>
</tr>
<tr>
<td>$W^\pm$, $Z$(central), $Z$(forward)</td>
<td>84/43</td>
</tr>
</tbody>
</table>
DY: impact of the recent data (ATLAS, 5 TeV)

PRELIMINARY: Uncertainty correlations are not taken into account (still unpublished); smaller impact on fit is expected when they are included.
DY: towards double differential distributions

- Reasonable agreement with the ABMP16 predictions
- Complimentary constraint on PDFs → improved quark disentangling
- Other CMS and ATLAS data in progress; the bottleneck is NNLO computations with the fiducial-volume cuts
Summary

- The fit with stringent cuts, $W^2 > 12.5 \text{ GeV}^2$, $Q^2 > 10 \text{ GeV}^2$, on the DIS data is considered
  
  - impact of the higher-twist terms is minimized
  
  - small-x gluon goes higher, consistent with the constraint from charm/beauty; small-x strange sea goes lower at small $x$, consistent with 1 within errors; valence quarks stable
  
  - reasonable description of the recent charm/beauty HERA data with
    
    $m_c(m_c) = 1.245 \pm 0.019(\text{exp.}) \text{ GeV}$
    
    $m_b(m_b) = 3.96 \pm 0.10(\text{exp.}) \text{ GeV}$
  
- Update of the pair- and single-top production with
  
  $m_t(m_t) = 160.8 \pm 1.1 \text{ GeV}$
  
  $m_t(m_t) = 161.1 \pm 3.8 \text{GeV}$ \hspace{1cm} (single-top only)

- potential impact on the $d/u$ ratio form $t/t\overline{t}$, however validation of MC tools is still needed

- Steady progress with accommodating more DY data into the fit
  
  - recent ATLAS data at 5 and 7 Tev
  
  - double differential data on $Z$-boson production from CMS and ATLAS
EXTRAS
Impact of high twists on SLAC data

Power-like terms affect comparison even with a cut $W^2 \geq 12.5 \text{ GeV}^2$
Impact of the t-quark data on the ABMP16 fit

HATHOR (NNLO terms are checked with TOP++)

Running mass definition provides nice perturbative stability

Langenfeld, Moch, Uwer PRD 80, 054009 (2009)

Czakon, Fiedler, Mitov PRL 110, 252004 (2013)
DYNNLO-FEWZ difference not fully understood; further benchmarking is needed
Closure test of the NNPDF3.1 fit

Different trend for W and Z data ⇒ χ²/NDP= 400/34; problems with the flavor disentangling

● Suppressed (fitted) charm distribution requires corresponding enhancement of strangeness sur to constraint from W data

Thorne QCD@LHC2018
DY: ATLAS versus CMS

Different trends for ATLAS and CMS Z-production data: ATLAS seems to go higher than CMS with a different trend w.r.t. rapidity; however the errors are still large
NNLO DY corrections in the fit

The existing NNLO codes (DYNNLO, FEWZ) are quite time-consuming → fast tools are employed (FASTNLO, Applgrid,.....)

– the corrections for certain basis of PDFs are stored in the grid
– the fitted PDFs are expanded over the basis
– the NNLO c.s. in the PDF fit is calculated as a combination of
  expansion coefficients with the pre-prepared grids

The general PDF basis is not necessary since the PDFs are already constrained by the data, which do not require involved computations → use as a PDF basis the eigenvalue PDF sets obtained in the earlier version of the fit

\[ \mathbf{P}_0 \pm \Delta \mathbf{P}_0 \] – vector of PDF parameters with errors obtained in the earlier fit
\[ \mathbf{E} \] – error matrix
\[ \mathbf{P} \] – current value of the PDF parameters in the fit

– store the DY NNLO c.s. for all PDF sets defined by the eigenvectors of \( \mathbf{E} \)
– the variation of the fitted PDF parameters \((\mathbf{P} - \mathbf{P}_0)\) is transformed into this eigenvector basis
– the NNLO c.s. in the PDF fit is calculated as a combination of transformed \((\mathbf{P} - \mathbf{P}_0)\) with the stored eigenvector values
DY: tool benchmarking

A variety of tools/methods employed in the PDF fits: DYNNO/FEWZ/ResBos, NLO combined with NNLO K-factors, etc. → a consolidation is required for using potential of the existing data.
Test fit with the neural network shape

Valence u-quark is modeled by $x^\alpha (1-x)^\beta \text{NN}(x)$, where NN is neural network with 37 parameters (NNPDF3.0 ansatz), other PDFs use MMHT14 shape

Result is in quite agreement with the MMHT14 shape $x^\alpha (1-x)^\beta \text{P}(x)$ with 4 parameters in $\text{P}(x) \Rightarrow$ no particular flexibility is provided by neural network

Study of sea and gluon distribution in progress, the same behaviour expected