MMHT2014 PDFs -- updates

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Introduction
Determination of $\alpha_S$
PDFs and heavy quarks (see, 1510.02332)
Inclusion of combined HERA data
Impact of recent LHC data &
MMHT2016 PDFs (prelim.)
Photon PDF

Diffraction 2016
Sept 2-8\textsuperscript{th}, Acireale
Catania, Sicily
MMHT14 PDFs (successor to MSTW08)

Theoretical updates:
★ Parameterization in terms of Chebyshev polynomials
\[ (1 + \epsilon x^{0.5} + \gamma x) \rightarrow (1 + \sum a_i T_i(y)) \text{ with } y = 1 - 2\sqrt{x} \]
★ Parameterization of deuteron corrections—parameters determined by fit
★ Multiplicative error treatment
★ Updated nuclear corrections
★ Optimal GM-VFNS used
★ Expt value of \( B_\mu \equiv B(D \rightarrow \mu) \) now input (with error) in fit

New data: HERA I combined, Tevatron W,Z updates, LHC data

MSTW08/MMHT14 differences small—an exception is \((u_v-d_v)\) at low x

“MMHT16”: -- HERA I+II, recent LHC data
Further study of $\alpha_s$

see, 1506.05682

PDFs sets in extended range of $\alpha_s$ available. Allows error due to $\alpha_s$ to be added in quadrature
**Impact of final HERA combined data**

**Prediction** of HERA II by MMHT2014 PDFs (which fitted HERA I)

- **NLO** \( \chi^2 = 1611/1185 = 1.36 \) per point
- **NNLO** \( \chi^2 = 1503/1185 = 1.27 \) per point

HERAPDF2.0 (fitting **only** comb.HERA data) with \( Q^2(\text{min})=2 \text{ GeV}^2 \) find \( \chi^2 \sim 1.20 \) per point at NLO and NNLO

**Refitting** with HERA II by MMHT2014 PDFs gives

- **NLO** \( \chi^2 = 1533/1185 = 1.29 \) /pt with \( \Delta \chi^2=29 \) due to other data
- **NNLO** \( \chi^2 = 1457/1185 = 1.23 \) / pt with \( \Delta \chi^2=12 \) due to other data

Also tried fitting **only** HERA II data (**with 4 parameters fixed to avoid spurious PDFs**)

- **NLO** \( \chi^2 = 1416/1185 = 1.19 \) per point
- **NNLO** \( \chi^2 = 1381/1185 = 1.17 \) per point
Fits with data cut fixed at $Q^2 > 2 \text{ GeV}^2$ but with $\chi^2$/d.o.f. calculated for only data with $Q^2 > Q^2(\text{min})$.
PDF uncertainties little improved from MMHT2014

NNLO at $Q^2 = 10^4$ GeV$^2$

Using the plots, the gluon is improved for $x \sim 0.001$. This can be seen in the plots where the gluon distribution has a lower uncertainty band compared to the previous version at this $x$ value.
HERA II effect more obvious when looking at predictions

<table>
<thead>
<tr>
<th></th>
<th>MMHT14</th>
<th>MMHT14 (HERA global)</th>
</tr>
</thead>
<tbody>
<tr>
<td>W Tevatron (1.96 TeV)</td>
<td>2.782±0.056 (±2.0%)</td>
<td>2.789±0.050 (±1.8%)</td>
</tr>
<tr>
<td>Z Tevatron (1.96 TeV)</td>
<td>0.2559±0.0052 (±2.0%)</td>
<td>0.2563±0.0047 (±1.8%)</td>
</tr>
<tr>
<td>W⁺ LHC (7 TeV)</td>
<td>6.197±0.103 (±1.7%)</td>
<td>6.221±0.100 (±1.6%)</td>
</tr>
<tr>
<td>W⁻ LHC (7 TeV)</td>
<td>4.306±0.067 (±1.6%)</td>
<td>4.320±0.064 (±1.6%)</td>
</tr>
<tr>
<td>Z LHC (7 TeV)</td>
<td>0.964±0.014 (±1.5%)</td>
<td>0.966±0.015 (±1.6%)</td>
</tr>
<tr>
<td>W⁺ LHC (14 TeV)</td>
<td>12.48±0.22 (±1.8%)</td>
<td>12.52±0.22 (±1.8%)</td>
</tr>
<tr>
<td>W⁻ LHC (14 TeV)</td>
<td>9.32±0.15 (±1.6%)</td>
<td>9.36±0.14 (±1.5%)</td>
</tr>
<tr>
<td>Z LHC (14 TeV)</td>
<td>2.065±0.035 (±1.7%)</td>
<td>2.073±0.036 (±1.7%)</td>
</tr>
<tr>
<td>Higgs Tevatron</td>
<td>0.874±0.024 (±2.7%)</td>
<td>0.866±0.019 (±2.2%)</td>
</tr>
<tr>
<td>Higgs LHC (7 TeV)</td>
<td>14.56±0.21 (±1.4%)</td>
<td>14.52±0.19 (±1.3%)</td>
</tr>
<tr>
<td>Higgs LHC (14 TeV)</td>
<td>47.69±0.63 (±1.3%)</td>
<td>47.75±0.59 (±1.2%)</td>
</tr>
<tr>
<td>tt Tevatron</td>
<td>7.51±0.21 (±2.8%)</td>
<td>7.57±0.18 (±2.4%)</td>
</tr>
<tr>
<td>tt LHC (7 TeV)</td>
<td>175.9±3.9 (±2.2%)</td>
<td>174.8±3.3 (±1.9%)</td>
</tr>
<tr>
<td>tt LHC (14 TeV)</td>
<td>970±16 (±1.6%)</td>
<td>964±13 (±1.3%)</td>
</tr>
</tbody>
</table>

Up to about 10% reduction in uncertainties.
Very small change in central values.
Impact of LHC data

<table>
<thead>
<tr>
<th>no.pts</th>
<th>MMHT14 $\chi^2$(pred.)</th>
<th>MMHT16 $\chi^2$(fit)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\sigma_{tt}) Tevatron +CMS+ATLAS</td>
<td>18</td>
<td>14.7</td>
</tr>
<tr>
<td>LHCb 7 TeV (W + Z)</td>
<td>33</td>
<td>37.1</td>
</tr>
<tr>
<td>LHCb 8 TeV (W + Z)</td>
<td>34</td>
<td>76.1</td>
</tr>
<tr>
<td>LHCb 8 TeV (e)</td>
<td>17</td>
<td>30.0</td>
</tr>
<tr>
<td>CMS 8 TeV (W)</td>
<td>22</td>
<td>57.6</td>
</tr>
<tr>
<td>CMS 7 TeV (W + c)</td>
<td>10</td>
<td>8.7</td>
</tr>
<tr>
<td>D0 7 (e) asymmetry</td>
<td>13</td>
<td>27.3</td>
</tr>
<tr>
<td>total</td>
<td>3405</td>
<td>3768.0</td>
</tr>
</tbody>
</table>

MMHT14 predictions generally v.good.
MMHT16 fit – no tension – so PDFs v.similar

\[\Delta \chi^2 = 15\] for remainder of data

If coupling free \(\alpha_s(M_Z^2) = 0.118\) (from 0.1172)

look at data in turn →
$W+c$ data and s PDF

Recall need

$B_\mu \equiv B(D \rightarrow \mu)$ for s PDF from $\nu \rightarrow \mu\mu$ evts

$\text{MSTW}$ used fixed $B_\mu = 0.099$ (NuTeV value)

whereas $\text{MMHT}$ fitted $B_\mu = 0.092 \pm 10\%$

and found $B_\mu = (0.085 - 0.091) \pm 15\%$

Uncertainty & value of s increased
\[ \frac{d\sigma_{W+c}}{d|\eta^l|} \]

Data on plot use uncertainties added in quadrature.

Very little change after fit. By eye comparison looks worse, but slightly better when covariance matrix used.
**W⁺, W⁻ production**

very naïve:

\[ u = u_v + q \]
\[ d = d_v + q \]
\[ u(\overline{b}) \sim d(\overline{b}) \sim q \]

\[ A(y=0) = \sigma(W^+) - \sigma(W^-) \]
\[ = u \ d(\overline{b}) - u(\overline{b}) \ d \]
\[ \sim (u_v+q)q - q(d_v+q) \]
\[ = (u_v - d_v)q \]

in practice with y dep.

very rich structure

\[ x_{1,2} = M_W/\sqrt{s} \exp(+/-)y \]

and also Z prod. & D-Y data.
High rapidity $W$ production at LHCb at 7 TeV

\[ \frac{d\sigma_{W^+ \rightarrow \mu\nu}}{d|\eta^{\mu}|} \]

\[ \frac{d\sigma_{W^- \rightarrow \mu\nu}}{d|\eta^{\mu}|} \]

Generally perfectly good agreement using **NNLO**. Uncertainties added in quadrature on plot, but covariance matrix used in fit.
New data on high rapidity $W$ production at LHCb at 8 TeV

Good fit except at lowest $\eta_\mu$ point in each case.
Good agreement with new 8 TeV CMS $W^\pm$rapidity and asymmetry data (shown). (Fit to individual distributions not asymmetry.)

CMS $W$ asym., $\sqrt{s} = 8$ TeV, NNLO

MMHT14(pred.)
MMHT16(fit)

CMS $W^+/W^-$ asym.

Small-$x$ valence quarks require some modification of order the size of uncertainty. Scope for reduced uncertainty with new data inclusion.
Good agreement with new D0 $e$ asymmetry data

Slight undershooting at highest $\eta_e$. Implies slightly smaller down, but other data does not prefer this.
Z production

New data on high rapidity $Z$ production at LHCb at 7 TeV.

Generally perfectly good agreement using NNLO. A little low at low $y_Z$. 
New data on high rapidity $Z$ production at LHCb at 8 TeV.

MMHT14(pred.)  
MMHT16(fit)

$Z \rightarrow \mu^+\mu^-$

Same issue with lowest $y_z$ point. PDFs at moderate $x$ for these points and well constrained by DIS data.
New data on high rapidity $Z$ production at LHCb at 8 TeV with electrons.

No issue at lowest $y_z$ with these data. Relatively large $\chi^2$ only down to fluctuations.
Included some more up-to-date results on $\sigma_{\bar{t}t}$.

Fit very good and with $\alpha_S(M_Z^2) = 0.118$ the fitted $m_t^{\text{pole}} = 173.4$ GeV. At NLO $m_t^{\text{pole}} = 170.2$ GeV.
**Effect on PDFs**

**MMHT16** set (not for distribution) at NNLO with PDF evectors for uncorrelation. 25 PDF parameters with 50 evector directions---9 constrained by one of new LHC data sets.

No significant change in gluon or light sea. (but large $x$)

Small decrease in uncertainty in some small-$x$ regions due to new HERA data.
Large reduction in the $s + \bar{s}$ uncertainty, but little change in central value. Due to $W + c$ jets data.

Some impact on $s - \bar{s}$ uncertainty, from (effective) asymmetry data.
Significant change in $u_v - d_v$ and reduction in uncertainty, from $W^+/W^-$ asymmetry data, including the very accurate CMS asymmetry data.
No major change in $\bar{d} - \bar{u}$, but even less inclination towards a change in sign at high $x$ which was a feature of earlier sets.
Extension of $\bar{d} - \bar{u}$ parameterisation.

Claim of negative values preferred at small $x$ in arXiv:1508.07923 (ABMP), and marginal preference, with large uncertainty, also from CT14 PDFs.

Currently use 3 free parameters, i.e.

$$(\bar{d} - \bar{u})(x, Q_0^2) = A(1 - x)^{n_{sea} + 2}x^\delta(1 + \gamma x + \Delta x^2),$$

Extend to

$$(\bar{d} - \bar{u})(x, Q_0^2) = A(1 - x)^{n_{sea} + 2}x^\delta(1 + \sum_{i=1}^{4} a_i T_i(1 - 2x^{0.5})),$$

where $T_i(1 - 2x^{0.5})$ are Chebyshev polynomials. So 5 free parameters. Easily allows multiple turning points (seen in first fit iteration).

Global fit improves by 6 units, relatively minor given 2 extra parameters and size of tolerance criterion.

Improvement of a couple of units in CMS 8 TeV $W^+, -$ data, newly included LHCb data, E866 total Drell Yan data (not asymmetry) and BCDMS structure function data.
New \((\bar{d} - \bar{u})\) distribution very similar at high \(x\) to previous one.

Now a slightly smaller decrease towards zero at low \(x\) at edge of previous uncertainty band.

No dramatic change but a change to improved parameterisation warranted and small-\(x\) uncertainty likely to increase due to extra freedom.
PDFs with QED corrections

At the level of accuracy we are now approaching it is important to account for electroweak corrections. We need PDFs which incorporate QED into the evolution --- that is we need to include the photon PDF $\gamma(x,Q^2)$ etc.

Sets published recently by NNPDF & CT. ---- large uncertainties

Previous MRST2004 sets assumed $\gamma(x,Q^2)$ generated by photon emission off a model for valence quarks with QED evolution from $m_q \to Q_0$
“New” development -- 
\((1406.2118)\) consider coh. \& non-coh. emission
\[
\gamma(x,Q^2) = \gamma_{\text{coh}} + \gamma_{\text{incoh}}.
\]

Major part of input, especially at low \(x\), comes from coherent which is known to good accuracy. Uncertainty is due to non-coh. part which is calculated from emission from quarks.

\[\text{MRST2004} > \text{NNPDF2.3} \text{ for } x<0.01, \text{ but mainly due to evolution differences not input.}\]
Conclusions

New HERA II combined data well described by MMHT14 PDFs. No significant changes in PDFs in new re-fit. Slight reduction in uncertainties. Low x, low $Q^2$ data accommodated by power corr^n in $F_L$ (none needed in $F_{2}$).

MMHT14 predictions turn out to be very good for (most) LHC data not included in the fit. In re-fit (“MMHT16”) find few changes of significance in central values, but some data reduce uncertainties, mainly in strange and low x valence quarks.

Some new $\sigma(tt(\bar{t}))$ data--fit compatible with world average $m_t^{\text{pole}}$ and there is a small increase in fitted $\alpha_s(M_Z^2)$ to 0.118 at NNLO. Much extended $d(\bar{d}) - u(\bar{u})$ parametrization only leads to very minor changes. No deviation preferred at small x.

Work in progress on updated PDFs with QED corrections
PDFs and Heavy Quarks

Choice of range of heavy quark masses:

Other determinations generally quoted in $\overline{\text{MS}}$ scheme

\[
\begin{align*}
m_c(m_c) &= (1.275 \pm 0.025) \text{ GeV} \\
m_b(m_b) &= (4.18 \pm 0.03) \text{ GeV}
\end{align*}
\]

Might expect \( m_c^{\text{pole}} = 1.5 \pm 0.2 \text{ GeV} \) and \( m_b^{\text{pole}} = 4.9 \pm 0.2 \text{ GeV} \) from conversion of \( m_b \) from $\overline{\text{MS}}$ definition and \( m_b^{\text{pole}} - m_c^{\text{pole}} = 3.4 \text{ GeV} \) with a very small uncertainty (hep-ph/0509195, hep-ph/0408002), where renormalon ambiguity cancels.

MMHT2014 chose \( m_c=1.40 \text{ GeV}, \ m_b=4.75 \) (in pole scheme)

Restrict to pQCD production \( g \rightarrow HH \) with threshold \( Q=m_H \) (\( H=c,b \))

Below we vary \( m_c \) (1.15, 1.55) and \( m_b \) (4.25, 5.25) GeV
**Procedure**

Use GM-VFNS: start at input scale ($Q_0^2=1 \text{ GeV}^2$) with 3 flav. At $Q=m_c$ charm enters evolution, at $Q=m_b$ bottom enters. Use massless evolution & `optimal’ matching at thresholds.

**FFNS:** Heavy quarks kept only in coefficient functions – H quarks generated only in final state – not partons e.g. 3-flavour FFNS neither c or b treated as partons. Fit is **not optimal** -- much data where $m_{c,b}$ relatively small. However, we make available `FFNS’ PDFs using GM-VFNS input but with H quark evolution turned off.

**Note** $\alpha_s(M_Z^2)$ and large $x$ gluon PDF are significantly smaller in FFNS as compared to GM-VFNS
NNLO

fixed $\alpha_s = 0.118$

$\chi^2_{\tilde{\sigma} cc}$ vs $m_c$

$\chi^2_{\text{global}}$

\[ \begin{array}{|c|c|c|c|}
\hline
m_c (GeV) & \chi^2_{\text{global}} & \chi^2_{\tilde{\sigma} cc} & \alpha_s(M_Z^2) \\
\hline
1.15 & 2703 & 78 & 0.1164 \\
1.2 & 2699 & 76 & 0.1166 \\
1.25 & 2698 & 75 & 0.1167 \\
1.3 & 2701 & 76 & 0.1169 \\
1.35 & 2707 & 78 & 0.1171 \\
1.4 & 2717 & 82 & 0.1172 \\
1.45 & 2729 & 88 & 0.1173 \\
1.5 & 2749 & 96 & 0.1173 \\
1.55 & 2769 & 105 & 0.1175 \\
\hline
\end{array} \]

now allow $\alpha_s$ to be parameter--
weak dependence on $\alpha_s$

\leftarrow best global & cc fit - $m_c=1.25\text{GeV}$

\leftarrow MMHT14 ---- fixed $m_c=1.4 \text{ GeV}$

default $m_c=1.4$
% change of PDFs  \( m_c = 1.25 \rightarrow 1.4 \rightarrow 1.55 \text{ GeV} \)

Gluon (NLO), percentage difference at \( Q^2 = 4 \text{ GeV}^2 \)

Light quarks (NLO), percentage difference at \( Q^2 = 4 \text{ GeV}^2 \)

Charm quark (NLO), percentage difference at \( Q^2 = 4 \text{ GeV}^2 \)

Charm quark (NLO), percentage difference at \( Q^2 = 10^4 \text{ GeV}^2 \)

- \( m_c = 1.25 \) 
- \( m_c = 1.4 \) 
- \( m_c = 1.55 \) 

Threshold \( Q = m_c \) 

- charm 
- \( Q^2 = 4 \) 
- \( Q^2 = 10^4 \)
Large fluctuations. Data show some preference for lower $m_b$, $m_b \lesssim 4.5$ GeV.
Uncertainties on some NNLO benchmark LHC cross sections (in nb) due to +/- 10% variation in heavy quark masses

<table>
<thead>
<tr>
<th></th>
<th>$\sigma$</th>
<th>PDF unc.</th>
<th>$m_c$ var.</th>
<th>$m_b$ var.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W^+$ LHC (14 TeV)</td>
<td>12.5</td>
<td>+0.22 (+1.8%)</td>
<td>-0.11 (-0.92%)</td>
<td>-0.035 (-0.28%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-0.18 (-1.4%)</td>
<td>+0.093 (+0.75%)</td>
<td>+0.011 (+0.084%)</td>
</tr>
<tr>
<td>$W^-$ LHC (14 TeV)</td>
<td>9.3</td>
<td>+0.15 (+1.6%)</td>
<td>-0.077 (-0.82%)</td>
<td>-0.030 (-0.32%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-0.14 (-1.5%)</td>
<td>+0.063 (+0.68%)</td>
<td>+0.011 (+0.11%)</td>
</tr>
<tr>
<td>$Z$ LHC (14 TeV)</td>
<td>2.06</td>
<td>+0.035 (+1.7%)</td>
<td>-0.025 (-1.2%)</td>
<td>-0.0017 (-0.08%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-0.030 (-1.5%)</td>
<td>+0.021 (+1.03%)</td>
<td>-0.0035 (-0.17%)</td>
</tr>
<tr>
<td>$t\bar{t}$ LHC (14 TeV)</td>
<td>970</td>
<td>+16 (+1.6%)</td>
<td>-3.0 (-0.31%)</td>
<td>+3.1 (-0.32%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-20 (-2.1%)</td>
<td>+3.1 (+0.32%)</td>
<td>-1.7 (+0.17%)</td>
</tr>
<tr>
<td>Higgs LHC (14 TeV)</td>
<td>47.7</td>
<td>+0.63 (+1.3%)</td>
<td>-0.22 (-0.48%)</td>
<td>-0.16 (-0.33%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-0.88 (-1.8%)</td>
<td>+0.27 (+0.57%)</td>
<td>+0.16 (+0.34%)</td>
</tr>
</tbody>
</table>

Generally uncertainty due to $m_c$ is less than the PDF uncertainty, but is not insignificant; while uncertainty due to $m_b$ is smaller.
\[ \alpha_S(M_Z^2) = 0.1201 \pm 0.0015 \quad \text{NLO} \]

\[ \alpha_S(M_Z^2) = 0.1172 \pm 0.0013 \quad \text{NNLO} \]

default MMHT14 \textbf{NNLO} PDFs take \( \alpha_S = 0.118 \),

\textbf{NLO} PDFs have \( \alpha_S = 0.120 \) (also give a PDF set with 0.118)
For example, differential $\bar{t}t$ production (show CMS below). $y_{\bar{t}t}$ distribution at NLO very good, $p_t$ distribution off in shape ($m_{\bar{t}t}$ somewhere in between).
Full NNLO correction Czakon, Heymes, Mitov improves comparison with $p_{T,t}$ data

Little change in $y_{t\bar{t}}$, some in $m_{t\bar{t}}$. 

$\rightarrow$ NLO
$\rightarrow$ NNLO
$\rightarrow$ CMS data

$\rightarrow$ NLO
$\rightarrow$ NNLO
$\rightarrow$ CMS data
Attempted fit to high luminosity ATLAS 7 TeV inclusive jet data (JHEP 02 (2015) 153)

Prediction at NLO gives $\chi^2/N_{pts} = 411.5/140$.

Refit gives improvement only to $\chi^2/N_{pts} = 398.9/140$.

Deterioration in other data only $\Delta \chi^2 = 5.6$, so failure not due to strong tensions.

Cannot simultaneously fit data in all bins. Mismatch in one rapidity bin different in form to neighbouring bins probing PDFs of similar flavour, $x$ and $Q^2$.

Similar results also seen by other groups.