Progress on CTEQ-TEA PDFs

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On behalf of CTEQ-TEA collaboration

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CTEQ-TEA working group

- **CTEQ-Tung et al. (TEA)**, in memory of Prof. Wu-Ki Tung, who established CTEQ Collaboration in early 90’s

- **Michigan State University**: J. Huston, J. Pumplin, D. Stump, C. Schmidt, **J. Winter**, C.-P. Yuan
- **Southern Methodist University**: T.-J. Hou, P. Nadolsky, **B. T. Wang, K. P. Xie**
- **Xinjiang University**: S. Dulat
- **Shanghai Jiao Tong University**: J. Gao
- **University of Manchester/Kennesaw State**: M. Guzzi


**CT14 parton distribution functions**

This page provides numerical table files for the computation of CT14 leading order (LO), next-to-leading order (NLO) and next-to-next-to-leading order (NNLO) parton distribution functions. They can be interpolated with the help of a NEW standalone Fortran interface and demonstration program, as well as the tables with interpolated values of the QCD coupling \( \alpha_s \) and PDFs.
CT14 Parton distributions

- Last major release on general-purpose PDFs, CT14 NNLO/NLO sets including alternative $\alpha_s$ series and $n_f=3, 4, 6$ [1506.07443]

- D0 W-electron asymmetry data superseded by the new one with full luminosity; combined HERA charm production, H1 FL data in NC DIS

- early LHC Run I data on W/Z charged lepton rapidity and asymmetry; inclusive jet production from ATLAS and CMS

- more flexible parametrization for gluon, $d/u$ at large-$x$, both $d/u$ and $\bar{d}/\bar{u}$ at small-$x$, 28 eigenvectors comparing to 25 for CT10

CT14 remains as our official sets for general purpose use
Beyond CT14 nominal sets

- Progress have been made on studies of specialized sets, effects of new HERA data with CT14 setups, and towards the new CT17 family

- **CT14 QEDinc PDFs**, models and constraints on photon PDFs, [1509.02905]

- **CT14 MC PDFs**, replicas for certain applications (talk by J. Gao), [1607.06066]

- **CT14 HERA2 PDFs**, effects of combined HERA1+2 data, [1609.07968]

- **CT14 IC PDFs**, fitted charm component (talk by M. Guzzi), [1704.xxxx]

- **CT17 preliminary fits and related**, [17xx.xxxx]
CT17p — data to be included

- Previous LHC and HERA 1 data included in CT14 will be superseded by updated Run 1 and HERA 1+2 data; adding new LHC data, especially on Z boson $p_T$ and top quark differential distributions

- Combined HERA1+2 DIS [1506.06042] update
- LHCb 7 TeV Z, W muon rapidity dist. [1505.07024] update
- LHCb 8 TeV Z rapidity dist. [1503.00963] update
- ATLAS 7 TeV inclusive jet [1410.8857] update
- CMS 7 TeV inclusive jet (extended $y$ range) [1406.0324] update
- ATLAS 7 TeV Z $p_T$ dist. [1406.3660] new
- LHCb 13 TeV Z rapidity dist. [1607.06495] update
- CMS 8 TeV Z $p_T$ and rapidity dist. (double diff.) [1504.03511] new
- CMS 8 TeV W, muon asymmetry dist. [1603.01803] update
- ATLAS 7 TeV W/Z, lepton(s) rapidity dist. [1612.03016] update
- CMS 7,8 TeV $t\bar{t}$ differential distributions new
- ATLAS 7,8 TeV $t\bar{t}$ differential distributions new
CT14 HERA2 PDFs

- CT14-like fits with HERA1 data replaced by HERA2 data (Run I and II combined)

### HERA1 data in CT14 NNLO

<table>
<thead>
<tr>
<th>$Q_{cut}$ [GeV]</th>
<th>no cut</th>
<th>2.00</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\chi^2/N_{pts}(N_{pts})$</td>
<td>(647)</td>
<td>1.02 (579)</td>
</tr>
<tr>
<td>NC $e^+p$</td>
<td>(434)</td>
<td>1.05 (366)</td>
</tr>
<tr>
<td>NC $e^-p$</td>
<td>(145)</td>
<td>0.74 (145)</td>
</tr>
<tr>
<td>CC $e^+p$</td>
<td>(34)</td>
<td>0.97 (34)</td>
</tr>
<tr>
<td>CC $e^-p$</td>
<td>(34)</td>
<td>0.53 (34)</td>
</tr>
</tbody>
</table>

### HERA2 data in CT14 HERA2 NNLO

<table>
<thead>
<tr>
<th>$Q_{cut}$ [GeV]</th>
<th>no cut</th>
<th>2.00</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\chi^2/N_{pts}(N_{pts})$</td>
<td>(1306)</td>
<td>1.25 (1120)</td>
</tr>
<tr>
<td>NC $e^+p$</td>
<td>(1066)</td>
<td>1.11 (880)</td>
</tr>
<tr>
<td>NC $e^-p$</td>
<td>(159)</td>
<td>1.45 (159)</td>
</tr>
<tr>
<td>CC $e^+p$</td>
<td>(39)</td>
<td>1.10 (39)</td>
</tr>
<tr>
<td>CC $e^-p$</td>
<td>(42)</td>
<td>1.52 (42)</td>
</tr>
</tbody>
</table>

#### $\chi^2/N_{pts}$ as increasing weight

- NMC $F_2^p$ data dropped; CMS 7 TeV inclusive jet data updated
- freeing one more parameter for strangeness parametrization
- overall HERA2 data fit reasonably well, except for the e-p data
CT14 HERA2 PDFs

- CT14-like fits with HERA1 data replaced by HERA2 data (Run I and II combined)

residuals on kinematic plane

data points with large residuals spread over the entire region

change of selection cuts does not show systematic effects

no clear indication of deviation from DGLAP evolution

varying $Q$ cut

$A_{gs} = x^\lambda Q^2$

varying $A_{gs}$ cut
CT14 HERA2 PDFs

- CT14-like fits with HERA1 data replaced by HERA2 data (Run I and II combined)

![CT14HERA2 (red) vs. CT14 PDFs (blue)](image)

- effects due to new data and freeing one parameter; all changes well within CT14 uncertainties; continue to recommend CT14 nominal set for LHC Run2
CT17p — theory for LHC data

* FastNLO/APPLgrid NLO fast interface with tabulated NNLO/NLO K-factors; several issues arise given the percent-level precision required
  * Local generation of APPLgrid tables from MCFM and aMCFast
  * MC errors in the K-factors; dependence of the K-factors on the PDFs
  * MC errors in APPLgrid tables especially for fiducial cross sections at tail region

Inclusion of the theoretical error through scale variations with certain assumptions on correlations, e.g.,

\[ \sigma_{bin}^{NLO}(\mu_F,0, \mu_R,0, i) \left\{ 1 + \alpha_s^2(\mu_R,0) \sum_{j=1}^{5} e_j(i) x_j \right\} \]

FastNLO tables generated from DiffTop for top-quark pair production
CT17p — agreement with and between data

- Preliminary studies on agreement with the new LHC data also on possible tension between different data

- Method: from the nominal fit (with all data sets included) start a scan with increasing weight for one data set (weight 10 for extreme case)

- LHC data studied: LHCb 7 TeV W,Z rapidity, 8 TeV Z rapidity; ATLAS 7 TeV Z pT, 7 TeV inc. jet; CMS 7 TeV inc. jet

- All results are PRELIMINARY; currently theo. predictions used for LHC jet and Z p_T data are at NLO only; still working on the NNLO K-factors

<table>
<thead>
<tr>
<th>Data</th>
<th>$\chi^2/\text{N}_{\text{pt}}$ (nom.)</th>
<th>$\chi^2/\text{N}_{\text{pt}}$ (extr.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHCb 7</td>
<td>44/33</td>
<td>28/33</td>
</tr>
<tr>
<td>LHCb 8</td>
<td>38/17</td>
<td>22/17</td>
</tr>
<tr>
<td>ATL. 7 Z pT</td>
<td>48/8</td>
<td>21/8</td>
</tr>
<tr>
<td>ATL. 7 Jet</td>
<td>305/140</td>
<td>284/140</td>
</tr>
<tr>
<td>CMS 7 Jet</td>
<td>233/158</td>
<td>213/158</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$\Delta\chi^2/\text{N}_{\text{pt}}$</th>
<th>LHCb7(extr.)</th>
<th>ATL. Jet(extr.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHCb 7</td>
<td>-15/33 ↓</td>
<td>+1/33</td>
</tr>
<tr>
<td>LHCb 8</td>
<td>-8/17 ↓</td>
<td>-3/17</td>
</tr>
<tr>
<td>ATL. 7 Z pT</td>
<td>-3/8</td>
<td>+16/8 ↑</td>
</tr>
<tr>
<td>ATL. 7 Jet</td>
<td>+4/140</td>
<td>-20/140 ↓</td>
</tr>
<tr>
<td>CMS 7 Jet</td>
<td>+6/158</td>
<td>+13/158 ↑</td>
</tr>
</tbody>
</table>
CT17p — LHCb 7 and 8 TeV W/Z data

CT14 already show good agreement with the data; consistency of 7 and 8 TeV; refitting further bring CT17p close to central of the data predictions vs. data, CT14 (blue), CT10(dotted), CT17p(red solid)

Figure 16: Prediction of CT10 and CT17p for ATLAS 7 TeV W and Z rap.
CT17p — LHCb 7 and 8 TeV W/Z data

- LHCb data prefer smaller $u$bar and $d$bar both for 7 and 8 TeV, and larger strangeness; negligible impact on gluon PDF

PDF correlation

CT17p best-fit vs. CT14 HERA2

- red curve represents CT17p fit with weight=1 for all data set, dark green/blue lines for fits with increasing weight (up to 10) for the specified set
- large spread indicating strong effects from that data in direction from red to blue
**CT17p — ATLAS 7 TeV Z p_T**

- Fitting 8 data points in range [40, 150] GeV, poor fit if w/o K-factors; prefer harder gluon \( \sim 0.02 \), softer gluon \( x > 0.1 \); impact small on quarks
CT17p — ATLAS 7 TeV inc. jet

- Hard to get a good fit with all rapidity intervals; data prefer harder gluon $x > 0.1$, softer gluon $~0.02$, smaller d-quark $x > 0.5$

predictions vs. data, CT17p(red), CT17p+w10(blue dashed)

- different trends of theory vs. unshifted data in low and high rapidity bins; refitting failed to adjust theory in the same manner

- small statistical and uncorrelated sys. errors; most likely large chi2 is due to fluctuation of data itself
CT17p — ATLAS 7 TeV inc. jet

- Hard to get a good fit with all rapidity intervals; data prefer harder gluon $x>0.1$, softer gluon $\sim0.02$, smaller d-quark $x>0.5$

CT17p best-fit vs. CT14 HERA2

![Figure 1](image1.png)

- Gluon, ATLAS 7 jet
- D-quark, ATLAS 7 jet
- S-quark, ATLAS 7 jet

![Figure 2](image2.png)

- CDF Run 2 jet $Z_{pt}$
- ATLAS jet

![Figure 3](image3.png)
CT14 QEDinc PDFs

- CT14 set including photon PDF (NLO QCD+LO QED) based on radiative ansatz and with constraints from photon production in DIS

- Elastic part: equivalent photon approach, momentum frac. \( \sim 0.15\% \)

- Inelastic part: radiative ansatz with one free parameter (momentum frac.), similar to MRST QED

PDFs with photon (inelastic)

\[ \mu_F = 3.2 \text{ GeV} \]

68\% CL limit on photon carried mom. frac. of proton, 0.11\% at \( Q = 1.3 \) GeV
CT14 MC replicas

Two ensembles of CT14 MC replicas, Linear sampling (MC1), Log sampling (MC2), both with 1000 replicas

Hessian, MC1, MC2: solid, short-dashed, long-dashed

g (x,Q) at Q=1.3 GeV, CT14 NNLO, asym. std. dev.  
d (x,Q) at Q=1.3 GeV, CT14 NNLO, asym. std. dev.

reproducing statistical measures given by Hessian sets with small numbers of replicas; maintain positivity conditions as imposed in CT14
CT14 fitted charm

- Update on studies of the intrinsic charm models, BHPS and SEA-like, based on CT14 setups

χ² change vs. mom. fraction

charm PDF

For each model the 90% C.L. limit on the momentum fraction carried by charm are determined

allow much larger charm PDF than in perturbative case; changes on other flavors small in general
Summary

- We are working towards a major update of the CTEQ-TEA PDFs with the new combined HERA data and new LHC Run 1 and Run 2 data, especially the Z boson pT data and top-quark pair distributions.

- Percent-level precision of the LHC data requires careful examination of both the theoretical predictions used, e.g., MC uncertainties in NNLO predictions, remaining theoretical errors, and the agreement/tension between different data, e.g., if tension exists then may lose the constraining power and may even get larger uncertainties on the PDFs.

- We use FastNLO or local generated APPLgrid tables for all the new LHC data, K-factors either can be calculated locally or from public.

- After we better understand new constraints from the experiments, we plan to release the CT17 PDFs later this year.

Thanks for your attention!
Backup

Top-quark pair differential distributions

- Several distributions measured by ATLAS and CMS that have information on the high-x gluon:
  \( m_{TT}, y_{TT}, p_T, y_t, p_T \); double, triple differential dist.

- Only one distribution should be used, unless a correlation model can be developed
  which one?

- We are currently doing exploratory studies at NLO using MCFM and DiffTop and at aNNLO using DiffTop
  starting with rapidity and pT of the top quark

- ATLAS and CMS have different trends; in this case, ATLAS favors harder gluon (than NNPDF3.0) at high x, CMS weaker gluon

- In general, the ATLAS and CMS top results are in tension internally, and with each other (the latter more so in the case of normalized distributions where the experimental errors are smaller)

- If tension, then gluon PDF uncertainty may not decrease and may even increase
LHCb data prefer smaller $u\bar{u}$ and $d\bar{d}$ both for 7 and 8 TeV, and larger strangeness; negligible impact on gluon PDF.

CT17p best-fit vs. CT14 HERA2

- Red curve represents CT17p fit with weight=1 for all data set, dark green/blue lines for fits with increasing weight (up to 10) for the specified set.
- Large spread indicating strong effects from that data in direction from red to blue.