Recent developments in QCD global analyses of proton’s PDFs

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in collaboration with the CTEQ-TEA (CT) group

“XLV International Symposium on Multiparticle Dynamics”
Investigation of the structure of the nucleon crucial for a multitude of high-energy physics programs.

Interpretation of experimental measurements at hadron colliders relies on the precise knowledge of fundamental QCD parameters and Parton Distribution Functions (PDFs) of the proton.

- Discrimination of New Physics signals at the LHC crucially depends on precise knowledge of PDFs

- Global QCD analysis of PDFs is a vast topic, I'll focus on:
  - basic facts,
  - brief overview of the current status of modern PDFs,
  - aspects of the CT14 analysis.
  - selected CT14 recent results.
Making a long story short…

Parton distribution functions (PDFs) of the proton are essential ingredients of factorization theorems in QCD:

The general structure of the inclusive cross section for high-energy collisions involving hadron-hadron, lepton-hadron beams, or hadron targets, is a convolution product of long-distance non-perturbative contributions (PDFs) and short-distance infrared-safe perturbatively calculable quantities (hard scatterings cross sections). For Drell-Yan process in the collinear limit we have (Collins Soper Sterman (1984), (1985))

\[
\sigma(h_1 h_2 \to l^+ l^- + \text{X}) = \\
\sum_{a,b} \int_{x_1}^1 d\xi_1 \int_{x_2}^1 d\xi_2 f_{h_1 \to a}(\xi_1, \alpha_s(\mu_R), \mu_R, \mu_F) f_{h_2 \to b}(\xi_2, \alpha_s(\mu_R), \mu_R, \mu_F) \\
\times \hat{\sigma}^{ab}(\frac{x_1}{\xi_1}, \frac{x_2}{\xi_2}; \alpha_s(\mu_R), Q, \mu_F, \mu_R) + \mathcal{O}\left(\frac{\Lambda^2}{Q^2}\right),
\]

(1)

\(\mathcal{O}\left(\frac{\Lambda^2}{Q^2}\right)\) are subleading terms: higher twists, target corrections,…
Complicated objects

The formal definition of PDFs in QCD, contains all the complications of “real life”: UV regulator in DR, gauge invariance.

Collins (2011)

\[ f_{(0)j/h}(\xi) = \int \frac{dw^-}{2\pi} e^{-i\xi P^+ w^-} \langle P|\bar{\psi}_j^{(0)}(0, w^-, 0_T) W(w^-, 0) \frac{\gamma^+}{2} \psi_j^{(0)}(0)|P\rangle_c, \]

(2)

that is for quarks, where the Wilson-line factor is

\[ W(w^-, 0) = P \left[ e^{-ig_0 \int_0^{w^-} dy^- A^+_{(0)\alpha}(0, y^-, 0_T) t_{\alpha}} \right]. \]

(3)

Similarly to the case of renormalization scheme, a set of rules has to be provided in order to define the PDFs when a cross section calculation is performed, e.g. \( \overline{\text{MS}} \) scheme.
In the collinear picture, the use of RG invariance tells us how to predict scale dependence or “evolution” of PDFs by renormalization group equations (RGE’s) once the “initial conditions” are given. Parton evolution is obtained in terms of integro-differential equations known as DGLAP (Dokshitzer-Gribov-Lipatov-Altarelli-Parisi) equations

\[
\frac{d}{d \log \mu_F} f_i(x, \mu_R, \mu_F) = \sum_{j=q, g} \int_x^1 \frac{dy}{y} P_{ij} \left( \frac{x}{y}; \alpha_s, \mu_R, \mu_F \right) f_j(y, \mu_R, \mu_F),
\]

The evolution kernels or “splitting functions” \( P_{ij} \) are known at 3-loop for the unpolarized case. Moch, Vermaseren, Vogt (2004)
Universal objects

Gluons, quarks and antiquarks are the known constituents of the proton. Their distributions as a function of $x$ and generic scale $\mu$, at which partons are probed, are universal quantities that do not depend on the specific hard process under consideration.

Differently from hard-scattering cross sections, the analytic structure of the PDFs cannot be predicted by perturbative QCD, but has to be determined by comparing standard sets of cross sections, such as Eq. 1, to experimental measurements by using a variety of analytical and statistical methods.

For this reason PDFs are “data-driven” quantities.
PDFs for the LHC in the NNLO QCD era

The increasing accuracy of the current data and LHC run I unprecedented energies, pushed the high-energy physics community towards a new realm of precision calculations:

- Enormous progress in perturbative NNLO QCD calculations (e.g. unitarity based methods ),
- semi-automated calculations of multi-leg NLO processes,
- NLO calculation of complex multi-leg processes such as for the production of vector boson plus 5 jets (e.g. $W + 5$ jets; $H + 3$ jets),
- Understanding of jets substructure
- theoretical progress in the combination of the fixed-order results with a parton shower codes,
- rapid developments of very sophisticated tools for phenomenology such as: HERAFITTER platform, (see H. Pirumov talk), META and MC-H PDFs (see A. Buckley talk),
- **LHC run II: next challenge for precision**
STATUS
Unpolarized collinear PDFs at NLO, NNLO in QCD:

Recent (2014-2015) determinations including LHC run I data:

- CTEQ TEA $\rightarrow$ CT10, CT14 (Hessian method)
- MMHT $\rightarrow$ MSTW, MMHT14 (Hessian method)
- NNPDF $\rightarrow$ NNPDF3.0 (MC sampling and neural networks)
- ABM $\rightarrow$ ABM12LHC (Hessian method)

Other recent determinations not including LHC data

- HERA2.0 (Hessian method)
- CTEQ-Jlab $\rightarrow$ CJ12 fit (Hessian method)
- JR (Hessian method)

In the past years, a lot of efforts have been put in organizing a systematic library to access all PDFs with an organic C++ interface:

https://lhapdf.hepforge.org/

Extremely important tool for hadron collider phenomenology.
Different methodologies

Methodologies for PDF determination vary among recent PDF analyses:

- smaller/larger/different data sets considered,
- heavy-flavor treatment (GMVFN, FFN,),
- different values/treatment of $\alpha_s(M_Z)$,
- different parametrizations for input PDFs at $Q_0$,
- ...

⇒ differences in central predictions and error estimate

A couple of examples with pre LHC PDFs:
Results for $F_2^c(x, Q^2)$ in DIS at NLO/NNLO

At NNLO and $Q \approx m_c$:

- S-ACOT-χ ≃ FFN($N_f = 3$) without tuning

- It is close to other NNLO schemes

- S-ACOT-χ predictions are for a physically motivated rescaling variable
  $\zeta = x(1 + 4m_c^2/Q^2)$. Dependence on the form of $\zeta$ is also reduced

From: M.G., Nadolsky, Lai, Yuan, PRD (2012)
Other examples of pre LHC determinations

Gluon luminosity at the LHC 13 TeV.
From PDF4LHC 1507.00556, JPG (2015)

Z-boson production: $p_T$ spectrum LHC 8 TeV.
From Malik and Watt JHEP (2014)
PDF4LHC: Comparisons and Benchmarking

The PDF4LHC Working Group:

- performing thorough benchmark studies of PDFs and of predictions at the LHC
- making recommendations for a standard method of estimating $\text{PDFs} + \alpha_s(M_Z^2)$ uncertainties at the LHC through a combination of the results from different individual groups.
- Forthcoming PDF4LHC LHC run II PDF recommendations arXiv:xxxx.xxxxx with more recent extensive comparisons between CT14, NNPDF3.0, MMHT14, ABM12LHC, HERA2.0 ...

http://www.hep.ucl.ac.uk/pdf4lhc/
Recent efforts in comparisons/benchmarking

Comparison of PDFs at $Q^2 = 10^2 \text{ GeV}^2$
between the NNPDF3.0, CT14 and MMHT14 sets
at NNLO,
with $\alpha_s(M^2_Z) = 0.118$.

From PDF4LHC
1507.00556 (July 2015)
SOME RECENT ANALYSES
Constraints on the gluon at low $x$ from LHCb

“Impact of heavy-flavour production cross sections measured by the LHCb experiment on parton distribution functions at low $x$”

Zenaiev et al., PROSA Collaboration
EPJC 2015
(More in Achim Geiser’s talk)

“Charm production in the forward region: constraints on the small-$x$ gluon and backgrounds for neutrino astronomy”

Gauld, Rojo, Rottoli, Talbert, 1506.08025 (2015)
Procedures for the combination of the PDFs into the future PDF4LHC ensemble

Possible methods for the construction of the combined PDF4LHC ensemble:

- Meta-parametrizations + MC replicas + Hessian data set diagonalization
  J. Gao, P. Nadolsky JHEP (2014)
  http://metapdf.hepforge.org (Gao, Huston, Nadolsky)

- Unweighting/compression of Monte-Carlo replicas
  G. Watt, R. Thorne, 1205.4024; R. Ball et al., 1108.1758; S. Forte, G. Watt, 1301.6754

- A compression algorithm for the combination of PDF sets
  (more in Andy Buckley’s talk)
PDF’s backbone: new high precision HERA data

Measurements of lepton-proton deep-inelastic-scattering (DIS) reaction data from H1 and ZEUS coll. at HERA are the most important data sets in PDFs determination.

H1 and ZEUS

- HERA NC e+p 0.4 fb^{-1}
- HERA NC e+p 0.5 fb^{-1}
- √s = 318 GeV
- Fixed Target
- HERAPDF2.0 e+p NLO

Recent: New combined data and HERA2.0 PDFs released

arxiv:1506.06042 (More in Iris Abt’s talk)
The need for precision


- Significantly reduced the scale dependence of the Higgs cross section
- PDF and $\alpha_s$ uncertainties become the dominant remaining theoretical uncertainty.
The CT14 global QCD analysis

New results from the CTEQ-TEA group:


arXiv:1506.07443
What’s new in CT14 NNLO PDFs

CT14 differs from CT10 PDFs in several respects:

**new HERA data:**

- Combined HERA charm production measurements \( (F_2^{(c)}) \)
- Measurements of the longitudinal \( F_L(x, Q^2) \) in DIS neutral currents

**new Tevatron data:**

- Tevatron Run 1 CDF and D0 inclusive jet data are dropped,
- Old D0 data (0.75 fb\(^{-1}\)) superseded by the new D0 (9.7 fb\(^{-1}\)) \( W \)-electron rapidity asymmetry data.

**LHC 7 TeV run I data included**

- ATLAS and LHCb \( W \) and \( Z \) production,
- ATLAS, CMS and LHCb \( W \)-lepton charge asymmetry,
- ATLAS and CMS inclusive jet data.

CT14 has 2995 data points
## CT14 Data sets ensemble I

<table>
<thead>
<tr>
<th>ID#</th>
<th>Experimental data set</th>
<th>$N_{pt}$</th>
<th>$\chi^2_e$</th>
<th>$\chi^2_e/N_{pt}$</th>
<th>$S_n$</th>
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<tr>
<td>101</td>
<td>BCDMS $F_2^p$</td>
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<td>H1 $\sigma^b_r$</td>
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<td>Combined HERA charm production</td>
<td>47</td>
<td>59</td>
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<td>HERA1 Combined NC and CC DIS</td>
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<td>591</td>
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<td>H1 $F_L$</td>
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<td>1.92</td>
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### CT14 Data sets ensemble II

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<tr>
<th>ID#</th>
<th>Experimental data set</th>
<th>$N_{pt}$</th>
<th>$\chi^2_{e}$</th>
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<th>$S_n$</th>
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<td>201</td>
<td>E605 Drell-Yan process</td>
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<td>E866 Drell-Yan process, $\sigma_{pd}/(2\sigma_{pp})$</td>
<td>15</td>
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<td>204</td>
<td>E866 Drell-Yan process, $Q^3 d^2\sigma_{pp}/(dQdx_F)$</td>
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<td>252</td>
<td>1.37</td>
<td>3.19</td>
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<td>225</td>
<td>CDF Run-1 electron $A_{ch}$, $p_{T\ell} &gt; 25$ GeV</td>
<td>11</td>
<td>8.9</td>
<td>0.81</td>
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<td>227</td>
<td>CDF Run-2 electron $A_{ch}$, $p_{T\ell} &gt; 25$ GeV</td>
<td>11</td>
<td>14</td>
<td>1.24</td>
<td>0.67</td>
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<td>DØ Run-2 muon $A_{ch}$, $p_{T\ell} &gt; 20$ GeV</td>
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<td>8.3</td>
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<td>-0.02</td>
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<td>240</td>
<td>LHCb 7 TeV 35 pb$^{-1}$, $W/Z$ $d\sigma/dy_\ell$</td>
<td>14</td>
<td>9.9</td>
<td>0.71</td>
<td>-0.73</td>
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<td>LHCb 7 TeV 35 pb$^{-1}$, $A_{ch}$, $p_{T\ell} &gt; 20$ GeV</td>
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<td>5.3</td>
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<td>260</td>
<td>DØ Run-2 $Z$ rapidity</td>
<td>28</td>
<td>17</td>
<td>0.59</td>
<td>-1.71</td>
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<td>261</td>
<td>CDF Run-2 $Z$ rapidity</td>
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<td>48</td>
<td>1.64</td>
<td>2.13</td>
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<td>CMS 7 TeV 4.7 fb$^{-1}$, muon $A_{ch}$, $p_{T\ell} &gt; 35$ GeV</td>
<td>11</td>
<td>12.1</td>
<td>1.10</td>
<td>0.37</td>
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<td>CMS 7 TeV 840 pb$^{-1}$, elec. $A_{ch}$, $p_{T\ell} &gt; 35$ GeV</td>
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<td>10.1</td>
<td>0.92</td>
<td>-0.06</td>
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<td>268</td>
<td>ATLAS 7 TeV 35 pb$^{-1}$, $W/Z$ cross sec., $A_{ch}$</td>
<td>41</td>
<td>51</td>
<td>1.25</td>
<td>1.11</td>
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<td>DØ Run-2 9.7 fb$^{-1}$ elec. $A_{ch}$, $p_{T\ell} &gt; 25$ GeV</td>
<td>13</td>
<td>35</td>
<td>2.67</td>
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<td>504</td>
<td>CDF Run-2 inclusive jet production</td>
<td>72</td>
<td>105</td>
<td>1.45</td>
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<td>514</td>
<td>DØ Run-2 inclusive jet production</td>
<td>110</td>
<td>120</td>
<td>1.09</td>
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<td>535</td>
<td>ATLAS 7 TeV 35 pb$^{-1}$ incl. jet production</td>
<td>90</td>
<td>50</td>
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<td>538</td>
<td>CMS 7 TeV 5 fb$^{-1}$ incl. jet production</td>
<td>133</td>
<td>177</td>
<td>1.33</td>
<td>2.51</td>
</tr>
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</table>
Aspects of the CT14 analysis

- PDFs are parametrized at init scale $Q_0 = 1.3$ GeV.
- Large-$x$ data not included to avoid large non-perturbative contributions ($W > 3.5$ GeV).
- More flexible parametrizations for gluon, $d/u$ at large $x$, both $d/u$ and $\bar{d}/\bar{u}$ at small $x$, and strange ($\bar{s} = s$) PDFs.
- Non-perturbative parametrization employing Bernstein polynomials $P_a(x)$: $x f_a(x) = x^{a_1} (1 - x)^{a_2} P_a(x)$

This reduces the correlation among its coefficients.

- CT14: 28 shape parameters, while CT10 has 25.
- S-ACOT-$\chi$ NNLO for the heavy flavor treatment.
- NNLO calculations for $DIS$, $DY$, $W$, $Z$ cross sections, for the jet cross sections and DIS charged currents we only use the NLO calculation but with NNLO PDF.
Aspects of the CT14 analysis: $\alpha_s(M_Z)$

- Central value of $\alpha_s(M_Z) = 0.118$ has been assumed in the global fits at NLO and NNLO, but
- PDF sets at alternative values of $\alpha_s(M_Z)$ are provided.
- CT14 prefers $\alpha_s(M_Z) = 0.115^{+0.006}_{-0.004}$ at NNLO (0.117 ± 0.005 at NLO) at 90 % confidence level (C.L.).

Uncertainties from the global QCD fits are larger than those of the data from LEP and other experiments included into the world average *Chin.Phys.C* (2014).

CT14 $\alpha_s(M_Z)$ central is consistent with the world average value.
The CT14 PDFs $u, \bar{u}, d, \bar{d}, s = \bar{s}$, and $g$, evolved up to $Q = 2$ GeV and $Q = 100$ GeV.
CT14 vs CT10 at NNLO 90% C.L.

- **g(x,Q)**, $Q = 100$ GeV, 90% c.l.
  - CT14NNLO
  - CT10NNLO/CT14NNLO

- **u(x,Q)**, $Q = 100$ GeV, 90% c.l.
  - CT14NNLO
  - CT10NNLO/CT14NNLO

- **d(x,Q)**, $Q = 100$ GeV, 90% c.l.
  - CT14NNLO
  - CT10NNLO/CT14NNLO

- **\(\bar{u}(x,Q)\)**, $Q = 100$ GeV, 90% c.l.
  - CT14NNLO
  - CT10NNLO/CT14NNLO

- **ATLAS, CMS 7 TeV W/Z prod.** ⇒ $d$-quark increased by 5% at $x \approx 0.05$.

- **D0 ele charge asy data** ⇒ $d$ highly reduced at $x \geq 0.1$ and $u$ moderately increased.
CT14 $d(x, Q)/u(x, Q)$ ratios

$Q = 10 \text{ GeV}, 90\% \text{ c.l.}$
- $d(x, Q)/u(x, Q)$
- $x$-axis: $0.0 \leq x \leq 0.9$
- $y$-axis: $0.0 \leq d(x, Q)/u(x, Q) \leq 1.0$

$Q = 2 \text{ GeV}, 90\% \text{ c.l.}$
- $d(x, Q)/u(x, Q)$
- $x$-axis: $10^{-4} \leq x \leq 0.8$
- $y$-axis: $0.0 \leq d(x, Q)/u(x, Q) \leq 2.0$

- $d/u$ at $Q = 2 \text{ GeV}, 90\% \text{ c.l.}$
- $x$-axis: $10^{-4} \leq x \leq 0.8$
- $y$-axis: $0.0 \leq d/u \leq 2.0$

$\uparrow 9.7 \text{ fb}^{-1}$ D0 charge asy $\Rightarrow$ reduction of the central ratio at $x > 0.1$,

$\uparrow$ new parametrization form $\Rightarrow$ increased uncertainty at $x < 0.05$

$\uparrow$ $s$ reduction at $x > 0.01$ $\Rightarrow$ smaller ratio $(s + \bar{s})/({\bar{u}} + {\bar{d}})$. The $SU(3)$-symmetric asymptotic solution at $x \to 0$ is still allowed in CT14: bigger unc. $x \approx 10^{-5}$. 

$\downarrow$ CT14 NNLO
$\downarrow$ CT10 NNLO
$\downarrow$ CJ12 NLO
$\downarrow$ CT14 NNLO
$\downarrow$ CT10 NNLO
$\downarrow$ Ratio to reference fit CT14NNLO

- $d(x, Q)/u(x, Q)$
- $x$-axis: $0.0 \leq x \leq 0.9$
- $y$-axis: $0.0 \leq d(x, Q)/u(x, Q) \leq 1.0$

- $(s + \bar{s})/({\bar{u}} + {\bar{d}})$
- $x$-axis: $10^{-4} \leq x \leq 0.5$
- $y$-axis: $0.0 \leq (s + \bar{s})/({\bar{u}} + {\bar{d}}) \leq 2.0$
CT14 NNLO: agreement with data

Total of 2947 data points from 33 experiments
\( \chi^2 = 3252 \) at the best fit CT14 NNLO, \( \chi^2/N_{pt} = 1.10 \).

Data and theory are in reasonable good agreement for most experiments (next slides)

\( W/Z \) Correlations plots CT14 vs CT10 @ NNLO
CT14 NNLO: agreement with data

Inclusive jet production and $W$ lepton charge asymmetry at the LHC 7 TeV
CT14 NNLO: agreement with data

$LHCb, \sqrt{s}=7$ TeV, $35 \text{ [pb]}^{-1}$

Electron charge asymmetry

$P_T > 20$ GeV

$C0, L=9.7 \text{ fb}^{-1}$

$E_T, \text{miss} > 25$ GeV

CMS 7 TeV, cross section of $W^\pm + c$

$\rho_T, > 25$ GeV

$W + c$ is not included in the fit (theory available only at NLO).
CT14 NNLO: agreement with data

Total inclusive $t\bar{t}$ cross section at NNLO in QCD with Top++, (Czakon, Mitov, CPC 2014)

<table>
<thead>
<tr>
<th>$pp \rightarrow t\bar{t}$ (pb), PDF unc., $\alpha_s = 0.118$</th>
<th>$7$ TeV</th>
<th>$8$ TeV</th>
<th>$13$ TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$68%$ C.L. (Hessian)</td>
<td>$177 + 4.8% - 3.9%$</td>
<td>$250 + 3.9% - 3.5%$</td>
<td>$820 + 2.6% - 2.7%$</td>
</tr>
<tr>
<td>$68%$ C.L. (LM)</td>
<td>$+4.8% - 4.6%$</td>
<td>$+2.9% - 2.9%$</td>
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<table>
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<tr>
<th>$pp \rightarrow t\bar{t}$ (pb), PDF+$\alpha_s$</th>
<th>$7$ TeV</th>
<th>$8$ TeV</th>
<th>$13$ TeV</th>
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<td>$68%$ C.L. (Hessian)</td>
<td>$+5.5% - 4.6%$</td>
<td>$+5.2% - 4.4%$</td>
<td>$+3.6% - 3.5%$</td>
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<tr>
<td>$68%$ C.L. (LM)</td>
<td>$+5.1% - 4.7%$</td>
<td>$+3.6% - 3.5%$</td>
<td></td>
</tr>
</tbody>
</table>

Approx NNLO $p_T$ spectrum for the final state top-quark with DiffTop (M.G., Lipka, Moch, JHEP 2015)
Post CT14 analysis: ongoing/future work

- impact of the new HERA II recent combined DIS measurements
- impact of $t\bar{t}$ inclusive and differential cross section on
- ....
Conclusions

- LHC unprecedented energies brought us in a new precision era
- A lot of efforts are ongoing to pin down PDFs uncertainties which still remain among the major sources of systematical theory uncertainties
- Things will be very interesting when many missing NNLO Xsecs will be consistently included in the next PDF iteration.
- Several future LHC programs for discovery of new physics interactions strongly depend on our knowledge of proton structure.

THANK YOU!
Backup
In global PDF fits a large number of iterations of the theory calculation programs (NLO, NNLO) is required to evaluate cross sections:

some of these computations are CPU time consuming!

Advanced tools have been developed to have theory calculations on grids: extremely fast!

⇒ **FastNLO** and **APPLgrid**
CT14 vs CT10 at NNLO 90% C.L.

\[ \bar{d}(x,Q) \quad Q = 100 \text{ GeV, 90\% c.l.} \]

\[ s(x,Q) \quad Q = 100 \text{ GeV, 90\% c.l.} \]
Definitions of the covariance matrix

\[ \chi^2 = \sum_{\{\text{exp.}\}} \left[ \frac{1}{\sum_{k=1}^{N_{\text{pts}}} s_k^2} \left( D_k - T_k(\{a\}) - \sum_{\alpha=1}^{N_\lambda} \lambda_\alpha \beta_{k\alpha} \right)^2 + \sum_{\alpha=1}^{K_e} \lambda_\alpha^2 \right] \]

The experimental correlated systematic errors \( \beta_{k\alpha} \) are often published as percentages. It can be taken to be a percentage of the theoretical prediction \( T_k \) ("truth") or the experimental datum \( D_k \).

1. **Experimental \((D)\) prescription:** normalize all \( \beta_{k\alpha} \) to \( D_k \)

2. **\( T \) \((T_0)\) prescription:** normalize luminosity & other multiplicative errors to (fixed) \( T_k \), additive errors to \( D_k \)

3. **Extended \( T \) \((T_0)\) prescription:** normalize all errors to (fixed) \( T_k \)

The methods are numerically equivalent if \( T_k \) is close to \( D_k \). Additive (multiplicative) errors are to be normalized to \( T_k \) \((D_k)\) to avoid/reduce biases. The available experimental data usually do not specify if the errors are additive or multiplicative.
Kinematics: LHC 7 TeV

7 TeV LHC parton kinematics

\[ x_{1,2} = (\frac{M}{7 \text{ TeV}}) \exp(\pm y) \]
\[ Q = M \]

- \( M = 10 \text{ GeV} \)
- \( M = 100 \text{ GeV} \)
- \( M = 1 \text{ TeV} \)
- \( M = 7 \text{ TeV} \)

\( Q^2 \) (GeV²) vs. \( x \)
Kinematics: LHC 14 TeV

LHC parton kinematics

\[ x_{1,2} = (M/14 \text{ TeV}) \exp(\pm y) \]

\[ Q = M \]

\[ y = \frac{4}{2} \]

\[ M = 10 \text{ TeV} \]

\[ M = 1 \text{ TeV} \]

\[ M = 100 \text{ GeV} \]

\[ M = 10 \text{ GeV} \]

HERA

fixed target

WJS2008