Unpolarized PDFs: MMHT perspective

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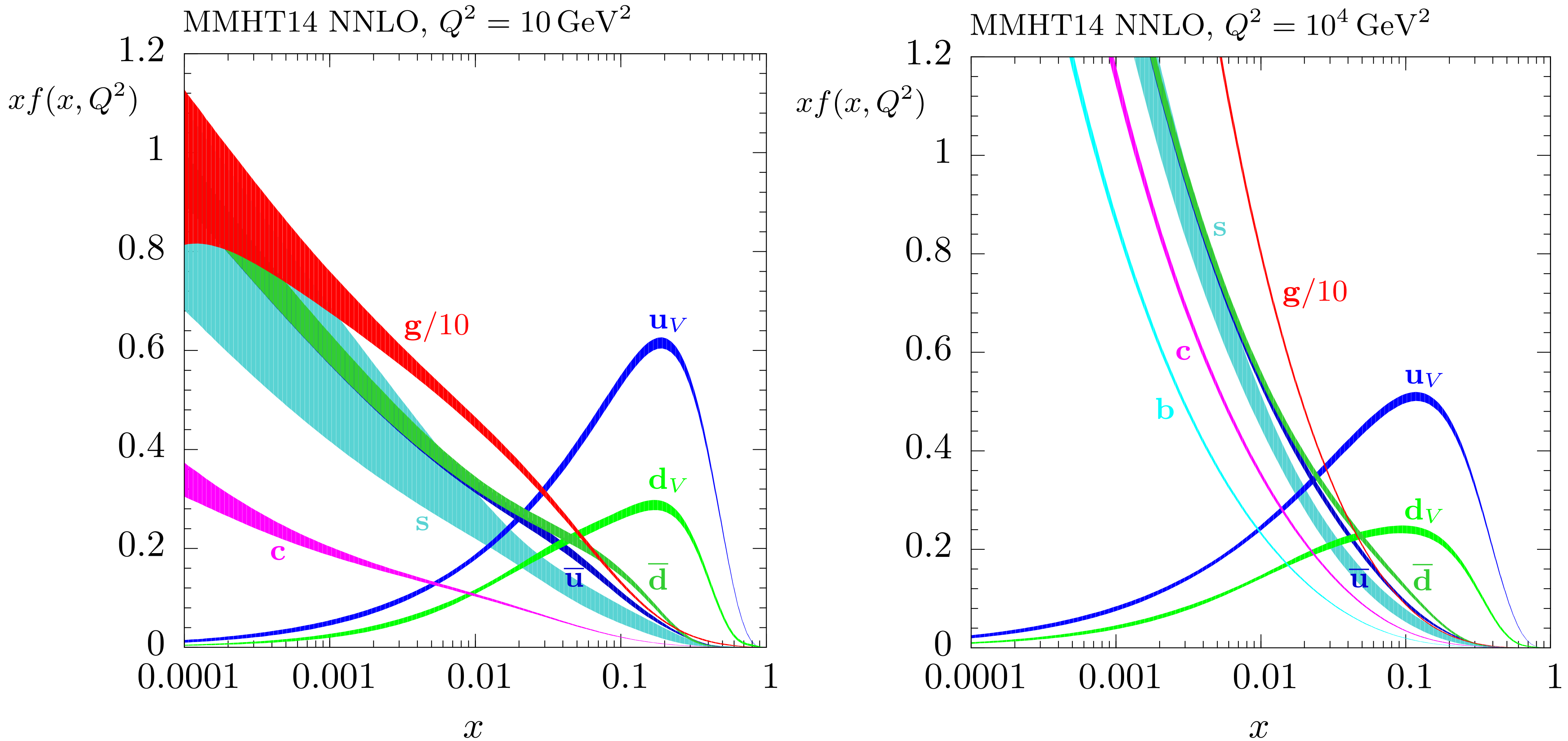
In collaboration with Alan Martin, Ricky Nathvani, and Robert Thorne

and thanks to Patrick Motylinski, Ben Watt, Graeme Watt and James Stirling

Outline

- MMHT PDFs, a (brief) introduction:
    - Parameterisation.
    - Data sets.
    - Theory input, error treatment…
- PDF sets and current uncertainties.
- PDF moments and Gottfried sum rule violation.
- Outlook.

MMHT PDFs



- Global PDF set building on earlier MSTW framework.
- MMHT14: latest version, available up to NNLO, for different flavour schemes and heavy quark masses.
- Subsequent unofficial fits performed with e.g. final HERA data set, and further LHC data.

MMHT: parameterisation

- The 6 light $q/\overline{q}$ flavour and gluon are parametrised in terms of the combinations $u_V, \, d_V, \, S = 2(\overline{u} + \overline{d}) + s + \overline{s}, \, s + \overline{s}, \, s - \overline{s}, \, \overline{d} - \overline{u}, \, g$
- 'Standard' historical form for PDF at $Q_0 = 1\,\text{GeV}$:

$$xf(x, Q_0^2) = A(1-x)^\eta x^\delta (1 + \epsilon x^{0.5} + \gamma x).$$

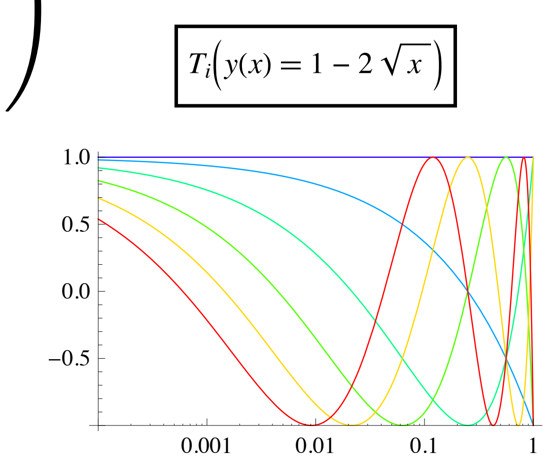
- $\delta(\eta)$ - low(high) x. Classic form due to general theory expectations.
- Complete freedom in intermediate $(\ldots)$ terms. In light of LHC data, earlier form not sufficiently flexible.

A.D. Martin et al., Eur.Phys.J. C73 (2013) no.2, 2318. arXiv:1211.1215

- Now parameterised in terms of Chebyshev Polynomials:

$$xf(x, Q_0^2) = A(1-x)^\eta x^\delta \left(1 + \sum_{i=1}^{4} a_i T_i(1-\sqrt{x})\right)$$

i.e. 7 free parameters.



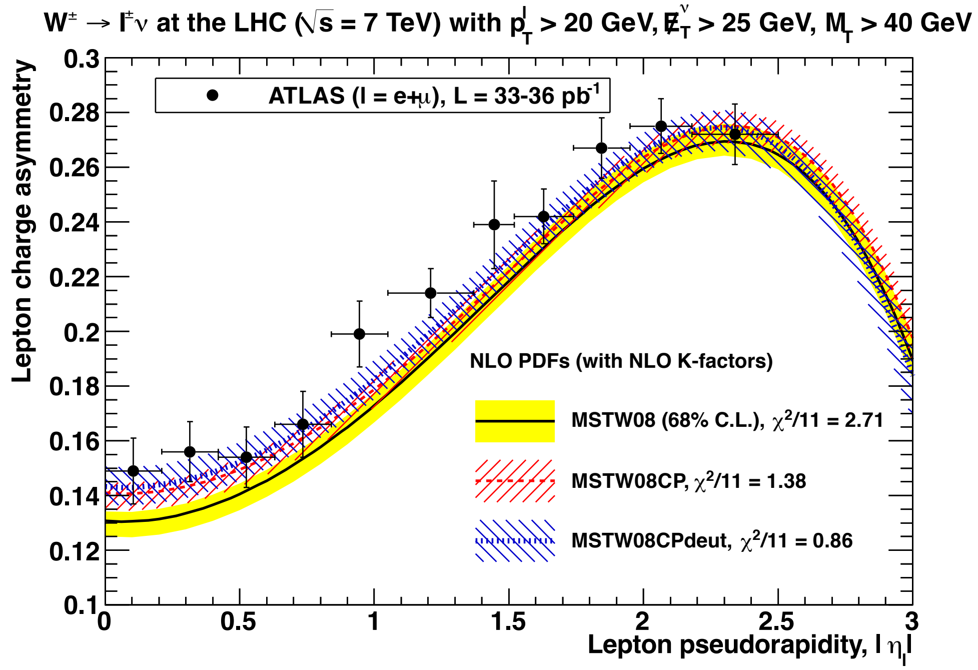
MMHT: parameterisation

- Number of parameters driven by data considerations, e.g. Chebyshev form first taken for $u_V - d_V$ due to difficulty describing LHC W data.

- Less constrained PDFs - simpler forms:

$$s_- \equiv x(s - \bar{s}) = A_-(1-x)^{\eta_-}x^{\delta_-}(1 - x/x_0)$$

  - $s - \bar{s}$ / $\bar{d} - \bar{u}$: 'historical-type' forms with 3/4 free parameters.
  - $s + \bar{s}$: low x power fixed assuming $\bar{s} \sim \bar{u}, \bar{d}$
  - g : increased flexibility demanded by e.g. DIS data. 8 free parameters.

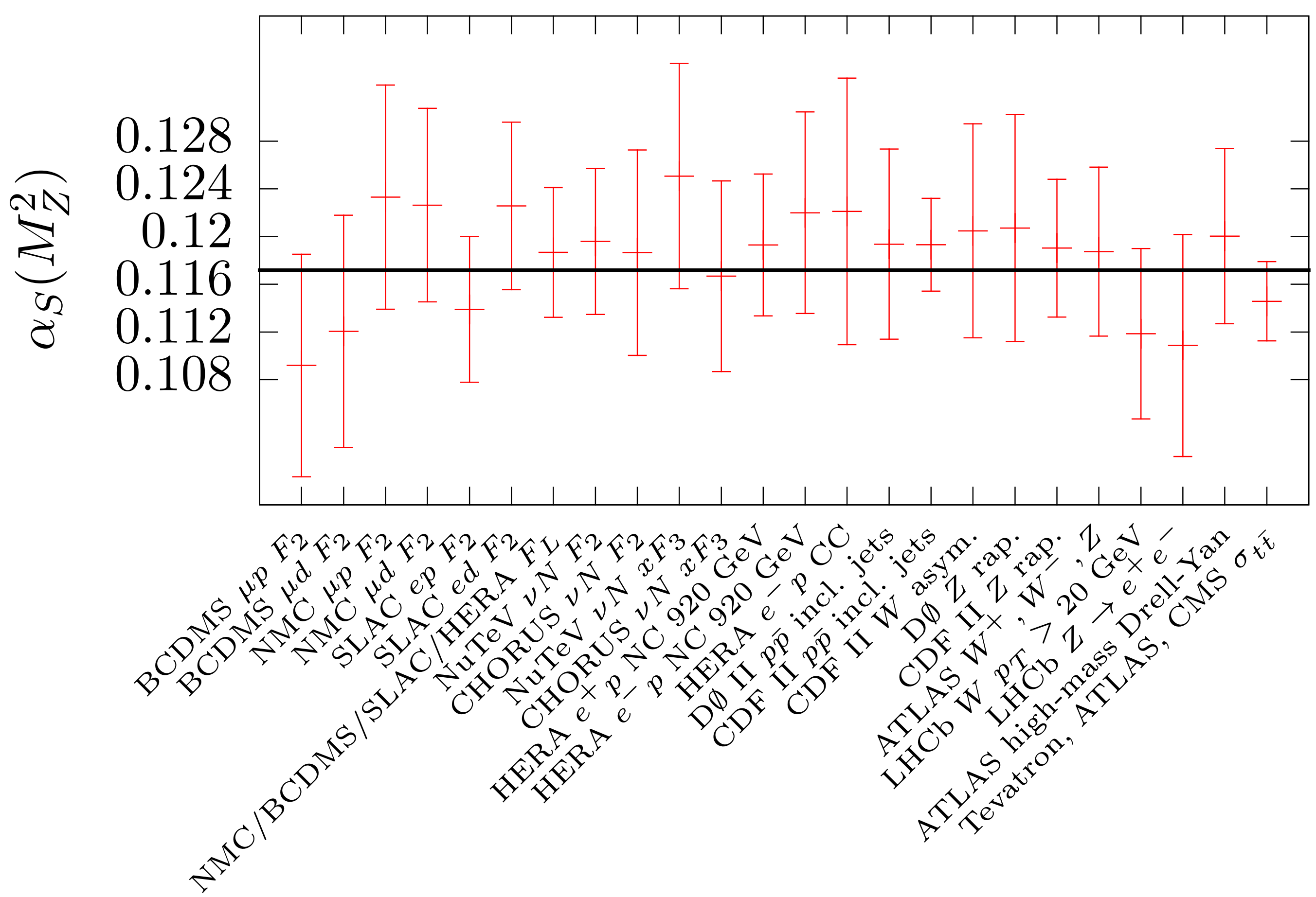


- 4 constraints from sum rules $\Rightarrow$ 37 free PDF parameters in total.

- Heavy (c, b) quark PDFs generated entirely from DGLAP evolution ($g \to q\bar{q}$ emission). No intrinsic charm.

MMHT: uncertainties

- Use Hessian method. Standard $\Delta\chi^2 + 1$ error setting appropriate when fitting consistent data sets, with gaussian errors and well-defined theory.
- Not the case here $\Rightarrow$ use weaker hypothesis testing criteria.
- ‘Dynamical Tolerance’: set uncertainties on each parameter by requiring that every data set is described within its (suitably rescaled) 68% CL.



MMHT: strong coupling

- By default, allow α_S (+ uncertainty) to be determined by fit alone.

Find result consistent with world average, e.g. for MMHT14:

$$\alpha_S^{w.a.}(M_Z^2) = 0.1181 \pm 0.0011$$

$$\text{NNLO:} \qquad \alpha_S(M_Z^2) = 0.1172 \pm 0.0013 \ (68\% \text{ C.L.}),$$

- More recent HERA + LHC data tends to pull this up towards 0.118.
- Also try adding in world average as data point. Impact on PDFs small.

LCTS/2015-17
IPPP/15/33
DCPT/15/66
October 20, 2015

arXiv:1506.05682

Uncertainties on α_S in the MMHT2014 global PDF analysis and implications for SM predictions

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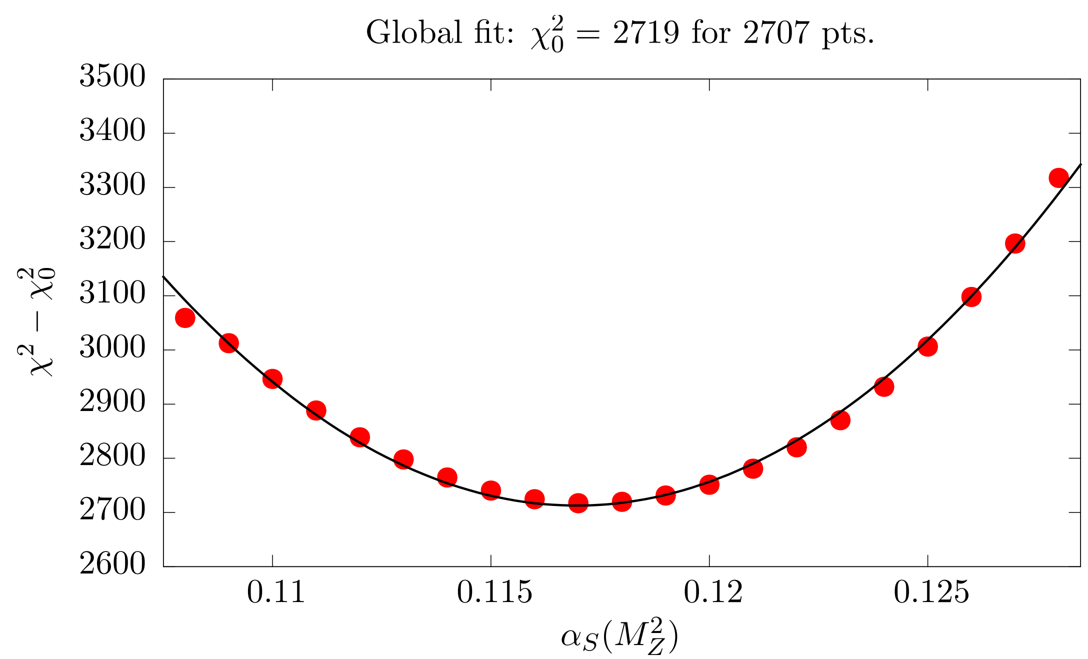

MMHT: data sets

- Global fit $\Rightarrow$ range of (pp, $p\bar{p}$, ep) collider and fixed-target data included. Aim to constrain PDFs as much as possible.

- MMHT14 - range of data sets, including:
  - Hera charged and neutral current, heavy quark structure functions.
  - Fixed nuclear target with neutrino beams.
  - Fixed proton/deuteron target structure function data.
  - Tevatron collider - jets, W, Z production.
  - First LHC data - W, Z, $t\bar{t}$.

Post-MMHT14 fits

- In 2015 final HERA combined Run-I + II data set released. Study of 1601.03413: lead to some reduction in MMHT14 uncertainties. Not enough to justify new release.

LCTS/2015-45
IPPP/15/81
DCPT/15/162
May 12, 2016

The impact of the final HERA combined data on PDFs obtained from a global fit

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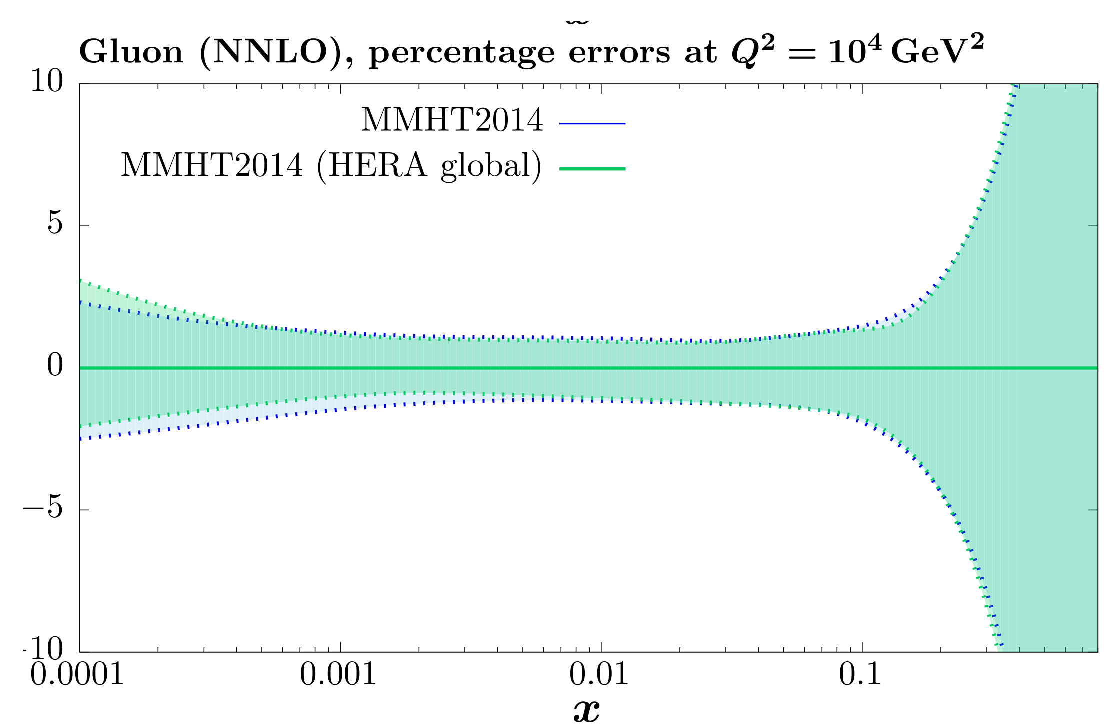
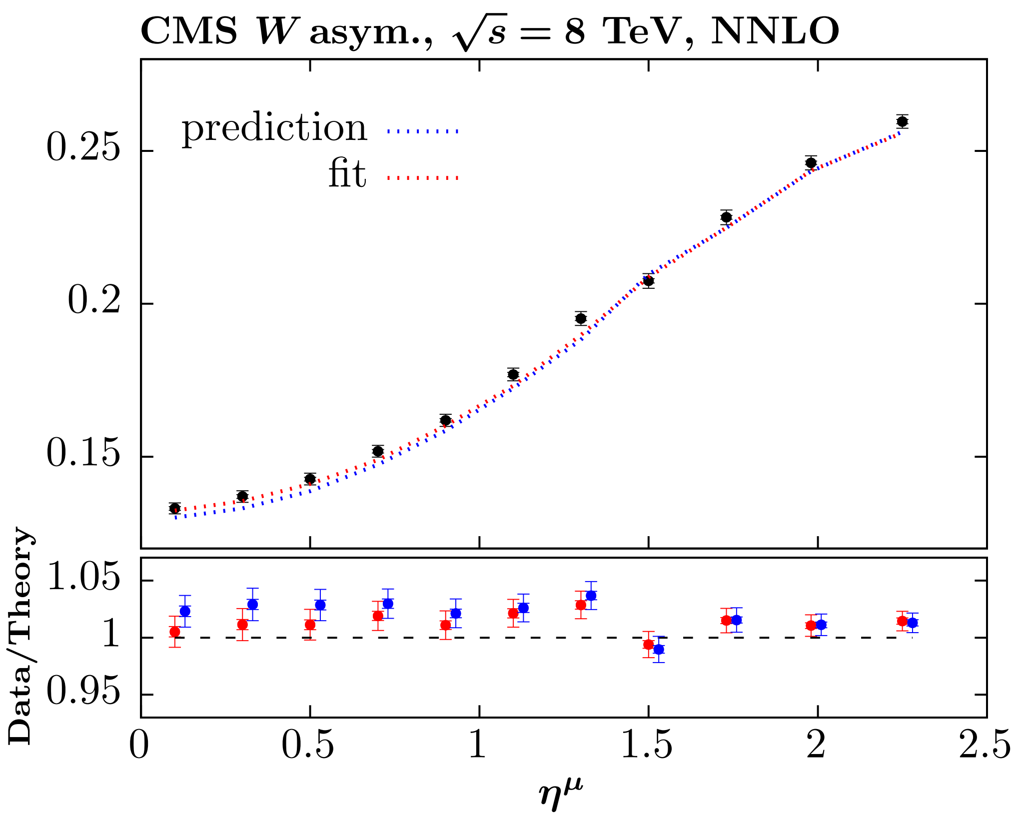
Abstract

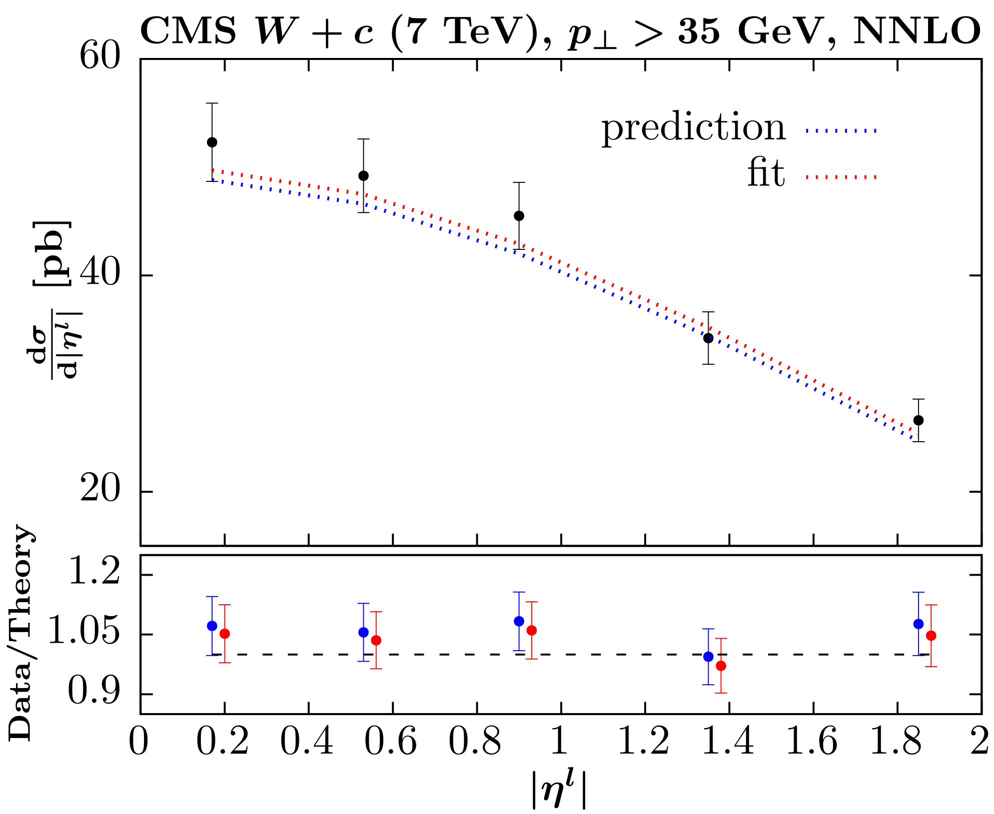
We investigate the effect of including the HERA run I + II combined cross section data on the MMHT2014 PDFs. We present the fit quality within the context of the global



Post-MMHT14 fits

• Much experimental progress from the LHC: increasingly precise data available (W, Z over wide range of x, jet production…). Unofficial **MMHT (2016 fit)** performed to range of new such data.

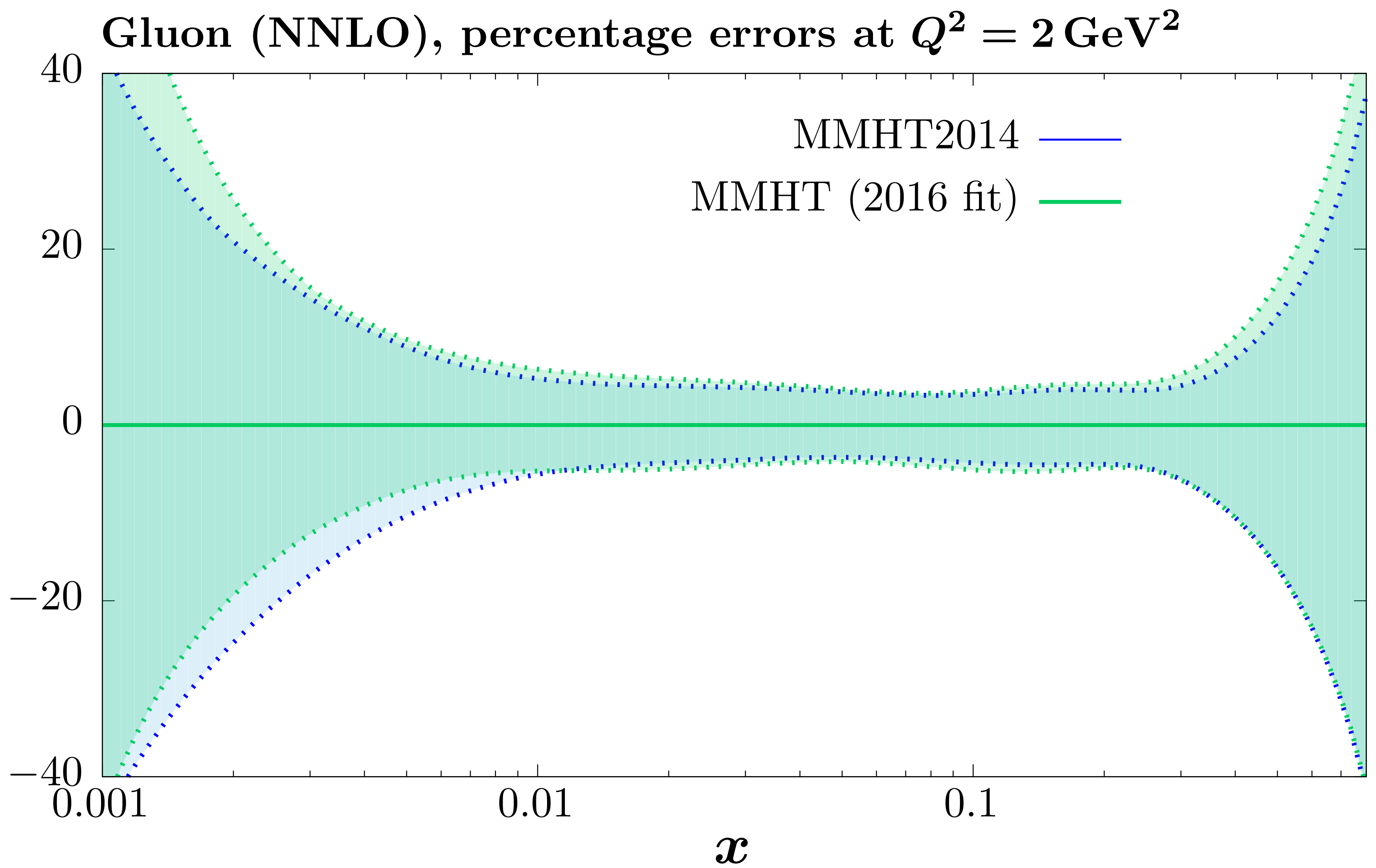




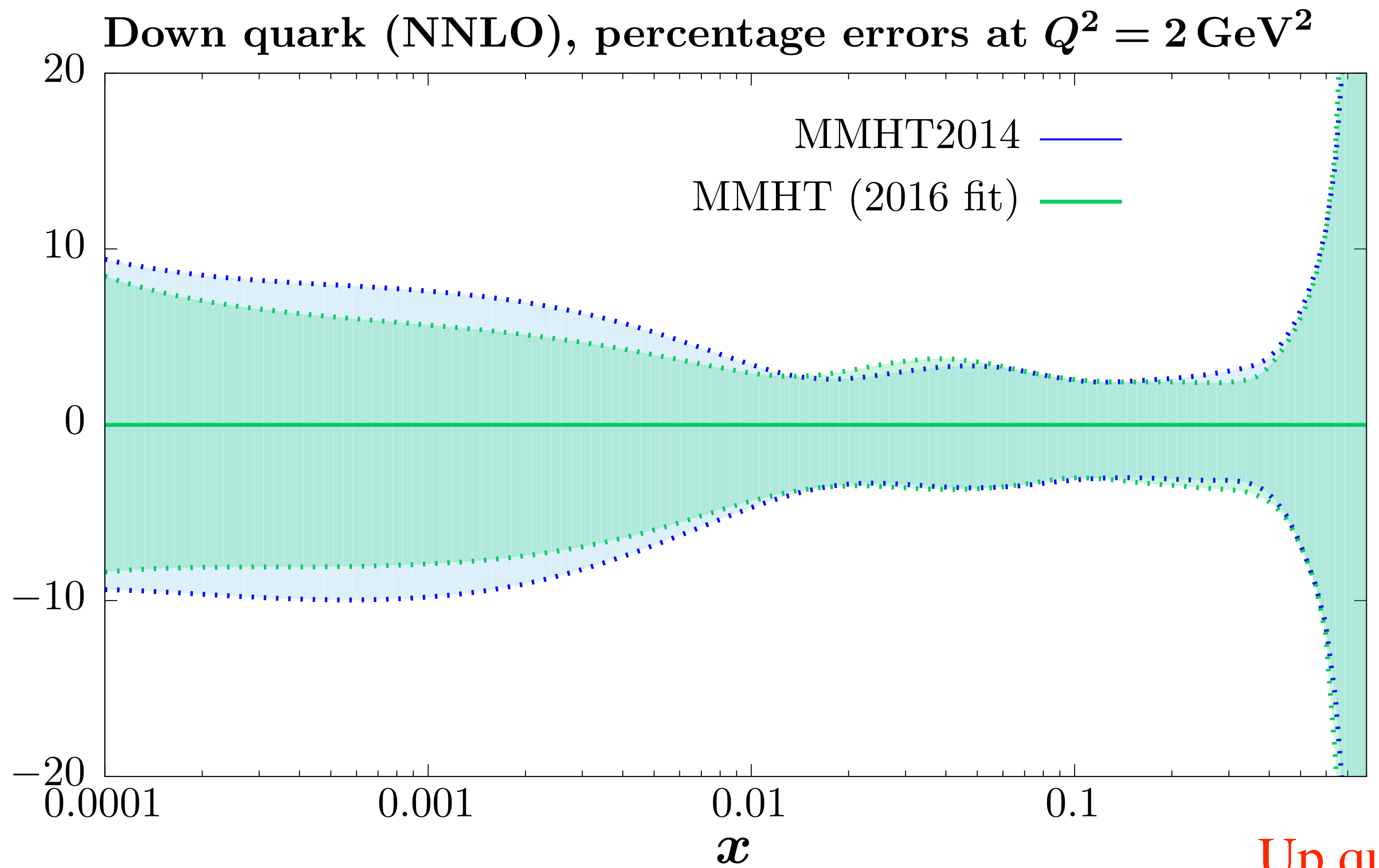
• LHC data precision keeps improving, e.g. new ATLAS W, Z data. First look: impact dramatic (see later).

• All to be included in updated fit in intermediate future.

PDFs: current uncertainties



- Low x : $\lesssim 10^{-3}$
  - Uncertainties large. Little constraint.
  - Future: Possibilities with heavy meson production.
- Mid x: $10^{-3} \lesssim x \lesssim 10^{-1}$
  - Uncertainties low as $\sim 5\%$. Constraints from HERA.
  - Future: LHC jets, $t\bar{t}$ (differential), $Z\, p_\perp$, isolated photon…
- High x: $\gtrsim 0.1$
  - Currently uncertainties $\uparrow$ as $x \uparrow$. Constraints from Tevatron jets, fixed target DIS, LHC $t\bar{t}$, sum rule.
  - Future: LHC jets, $t\bar{t}$ (differential), $Z\, p_\perp$, isolated photon…



Up quark: similar picture

- Low x : $\lesssim 10^{-3}$

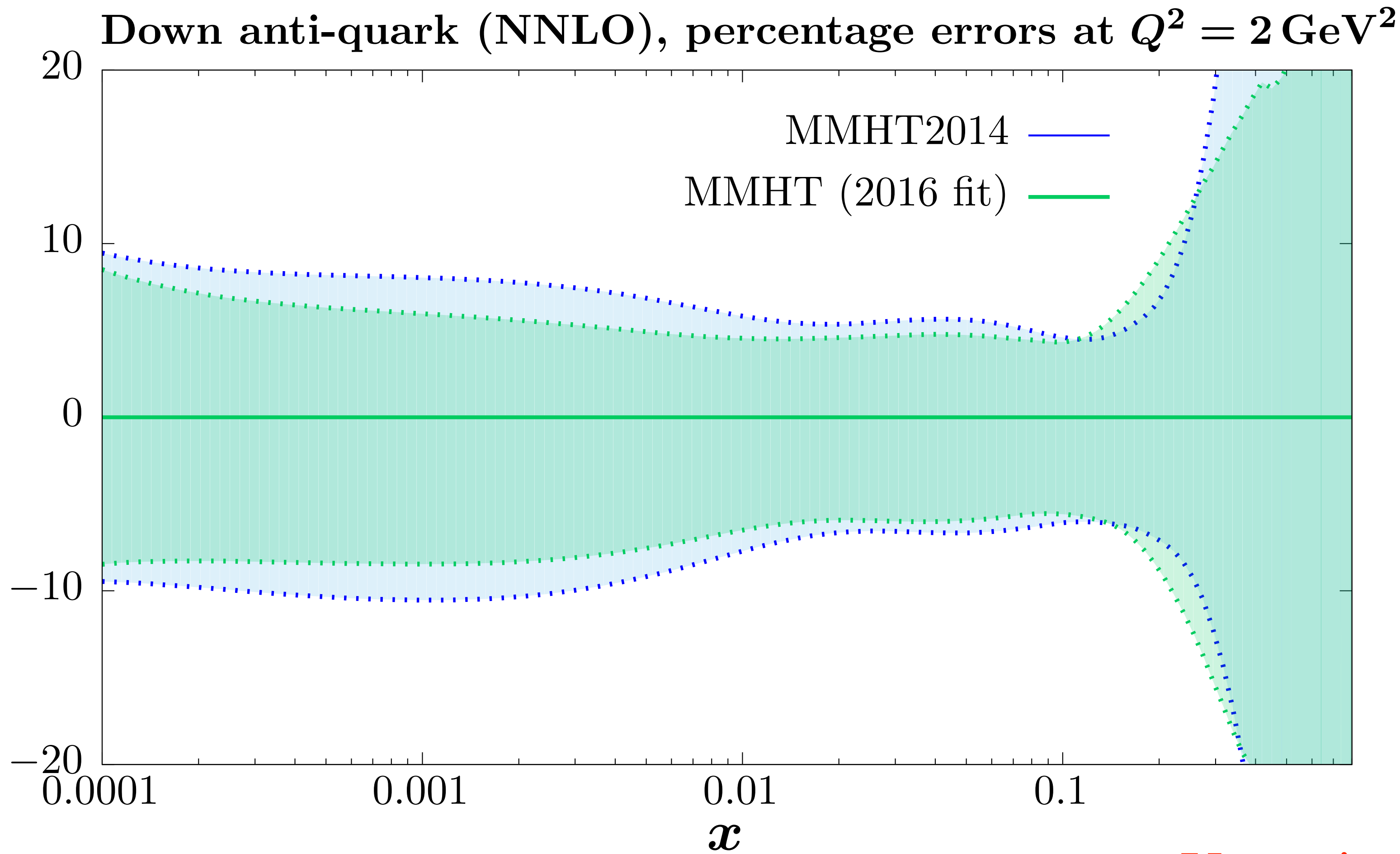
  ‣ Uncertainties $\sim 10\%$. Constraint from HERA.

- Mid x: $10^{-3} \lesssim x \lesssim 10^{-1}$

  ‣ Uncertainties low as $\sim 5\%$. Constraints from HERA, LHC DY.

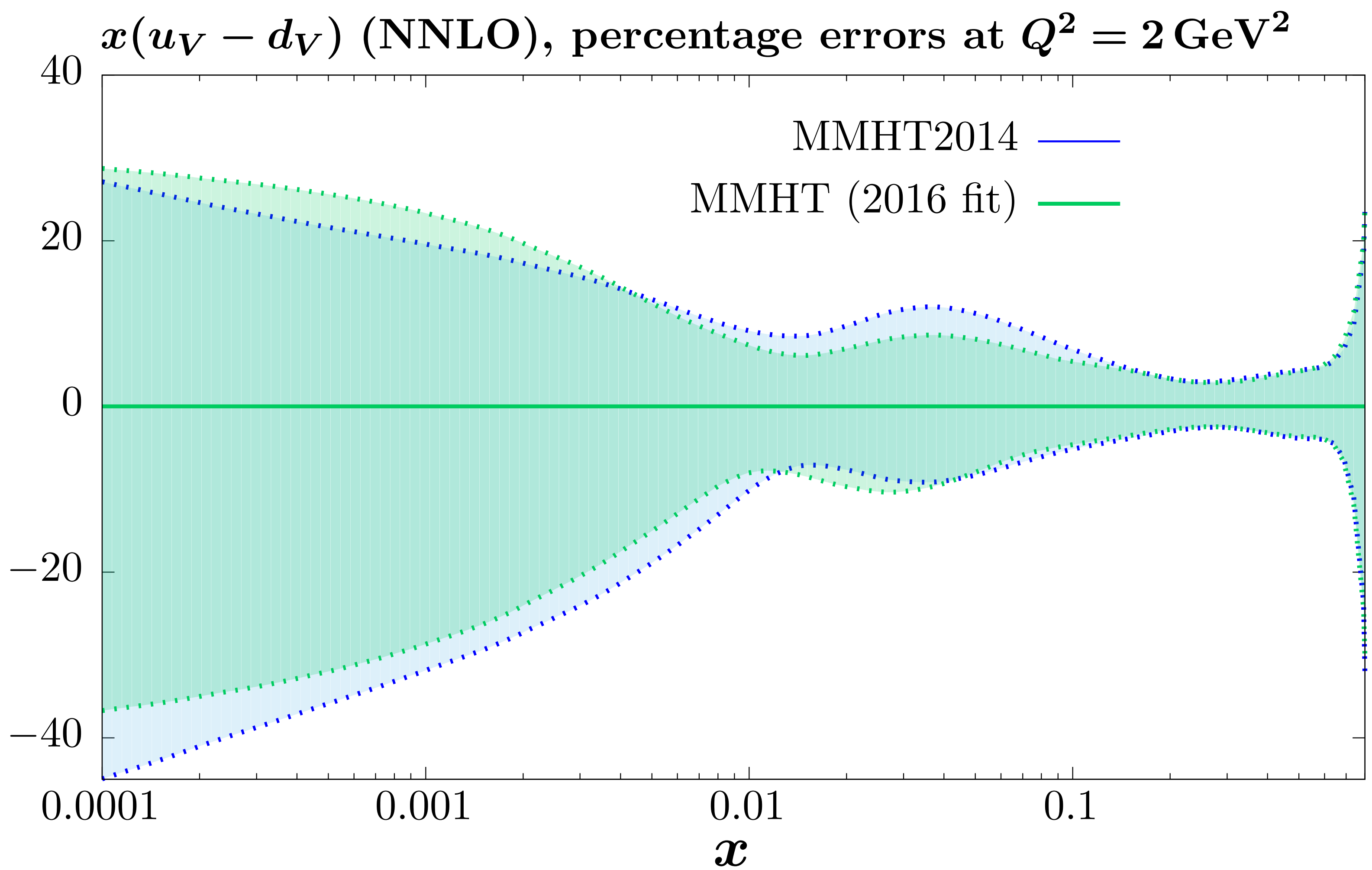
- High x: $\gtrsim 0.1$

  ‣ Currently uncertainties $\sim 5\%$ until $x \sim 0.4$. Constraints from HERA, fixed (deuterium) target, LHC W, Z.

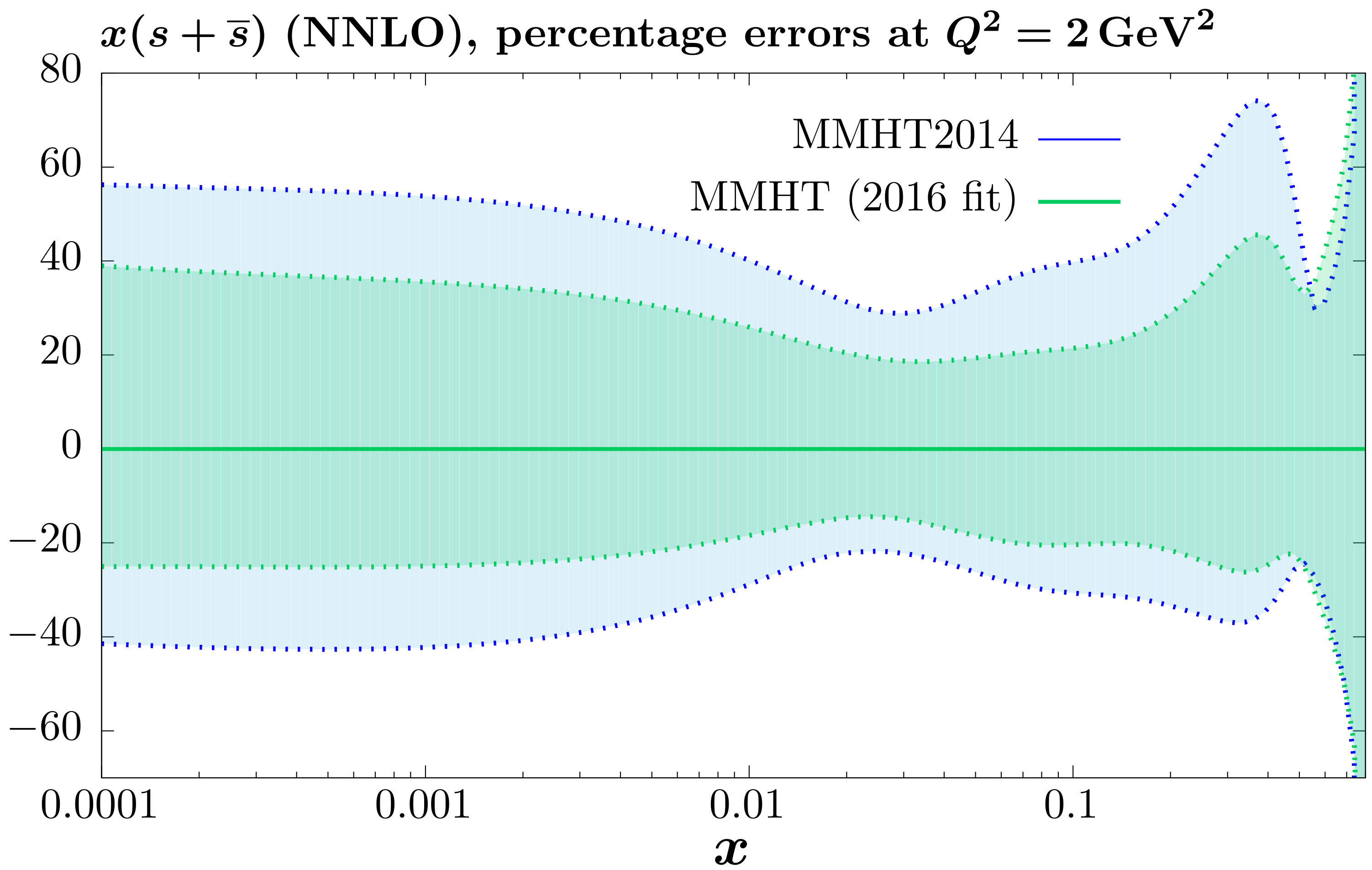


Up anti-quark: similar picture

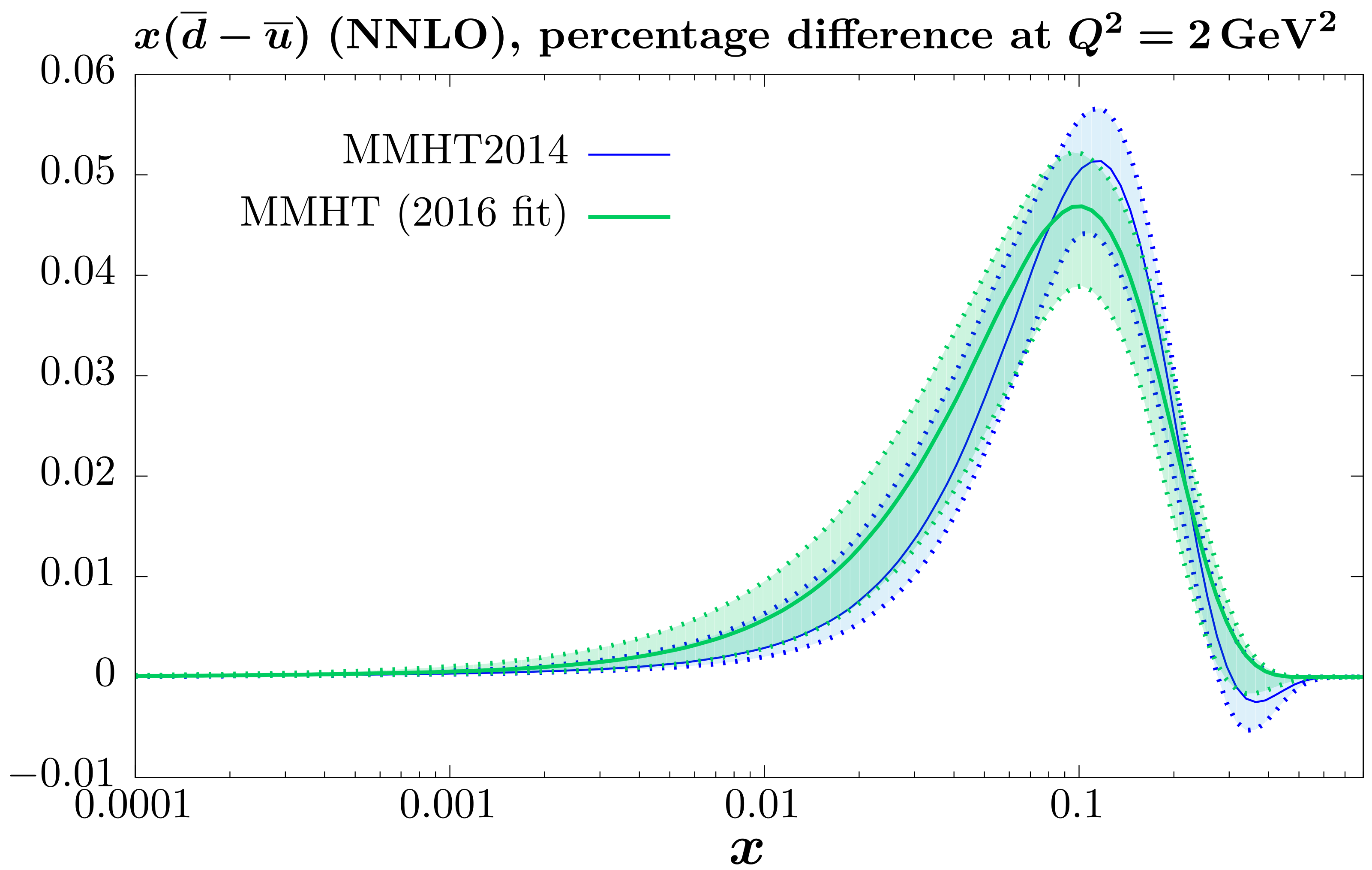
- Low x : $\lesssim 10^{-3}$
  - Uncertainties $\sim 10\%$. Constraint from HERA, LHC DY.
- Mid x: $10^{-3} \lesssim x \lesssim 10^{-1}$
  - Uncertainties low as $\sim 5\%$. Constraints from HERA, LHC DY.
- High x: $\gtrsim 0.1$
  - Currently uncertainties $\sim 5\%$ until $x \sim 0.4$. Constraints from fixed target DY, LHC $W,\ Z$.



- Low x : $\lesssim 10^{-3}$
  - Uncertainties $\sim 30 - 40\%$. Constraint largely from number sum rule.
- Mid x: $10^{-3} \lesssim x \lesssim 10^{-1}$
  - Uncertainties $\sim 5 - 30\%$. Constraints from LHC W asymmetry.
- High x: $\gtrsim 0.1$
  - Currently uncertainties $\sim 5\%$ until $x \sim 0.7$. Constraints from Tevatron/LHC W asymmetry, fixed target, neutrino DIS.



- Low x : $\lesssim 10^{-3}$
  - Uncertainties $\sim 30-40\%$. Constraints from HERA and $\bar{s} \sim \bar{u}, \bar{d}$ assumption.
  - Future: LHC low mass DY.
- Mid, High x: $10^{-3} \lesssim x \lesssim 10^{-1}$ $\gtrsim 0.1$
  - Uncertainties $\sim 30-40\%$. Constraints from neutrino beam charm production, LHC $W+c$ and $W,\ Z$.
  - Future: LHC $W+c$ and $W,\ Z$.



- Mid, High x: $10^{-3} \lesssim x \lesssim 10^{-1}$ $\gtrsim 0.1$
  - Uncertainties $\sim 10\%$. Constraints from fixed target DY, Tevatron and LHC W, Z.
- Low x : $\lesssim 10^{-3}$
  - Uncertainties driven to large extent by parameterisation constraints (Regge behaviour).

- Recent work on more adaptive parameterisation show qualitatively similar results. Potential for more realistic uncertainties as $x\downarrow$, but no big changes found.

PDFs: moments

MMHT: moments (1)

- Common observable: $$\langle x^n \rangle_f (\mu^2) = \int \mathrm{d}x\, f(x,\mu^2) \cdot x^n$$

in particular isovector momentum fraction $\langle x \rangle_{u-d}$. What do we find?

$\mu = 2\,\mathrm{GeV}$	MSTW08	MMHT14	MMHT (2016)	$\langle x \rangle$
$\langle x \rangle_{u-d}$	$0.1533^{+2.9\%}_{-2.1\%}$	$0.1509^{+3.5\%}_{-2.6\%}$	$0.1522^{+3.4\%}_{-2.7\%}$	0.1

- The average x contributing to this moment is ~ 0.1: $\langle x \rangle_{u-d} \sim \langle x \rangle_{u_V - d_V}$
- Uncertainties fairly stable. Some increase from MSTW, due to more flexible $u_V - d_V$ parameterisation.
- Earlier constraints from fixed (p/d) target data and neutrino DIS on nuclear targets. But increasingly collider data places constraint - W asymmetry at Tevatron/LHC sensitive to flavour decomposition.

MMHT: moments (2)

- Fot higher $u - d$ moments and gluon momentum fraction:

$\mu = 2\,\mathrm{GeV}$	MSTW08	MMHT14	MMHT (2016)	$\langle x \rangle$
$\langle x^2 \rangle_{u-d}$	$0.0534^{+3.2\%}_{-2.2\%}$	$0.0510^{+3.7\%}_{-2.9\%}$	$0.0517^{+3.7\%}_{-2.9\%}$	0.4
$\langle x^3 \rangle_{u-d}$	$0.0229^{+3.2\%}_{-2.7\%}$	$0.0215^{+4.2\%}_{-3.5\%}$	$0.0219^{+4.2\%}_{-3.5\%}$	0.5
$\langle x \rangle_g$	$0.4192^{+2.4\%}_{-2.0\%}$	$0.4116^{+2.0\%}_{-2.5\%}$	$0.4130^{+2.4\%}_{-2.2\%}$	0.1

find similar level of precision.

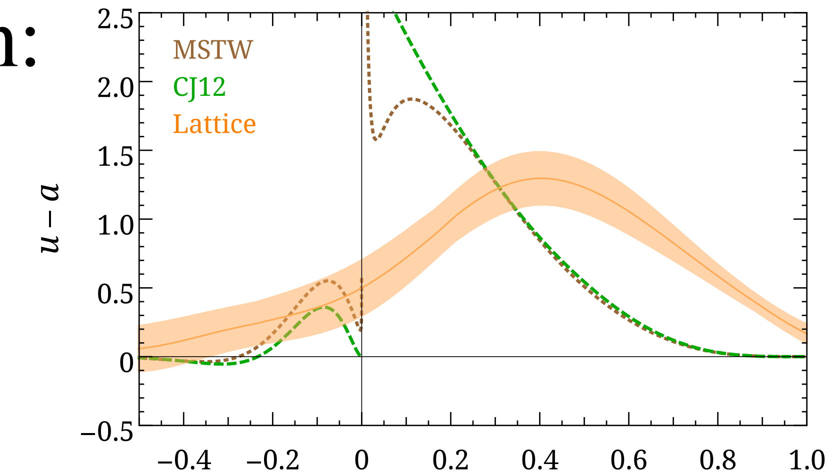
- $u - d$: slightly larger than first moment due to higher x probed.
- Gluon: LHC data (jets, $t\bar{t}$, $Z\,p_\perp$, isolated photon) will play increasing role in constraining this region of x .

Gottfried Sum Rule Violation

see Jiunn-Wei Chen's talk

- More recent efforts to reconstruct the $u - d$, $\overline{u} - \overline{d}$ PDFs directly.

Potential observable - Gottfried Sum rule Violation:



$$\langle x^0 \rangle_{\overline{d}-\overline{u}} = \int \mathrm{d}x \, (\overline{d} - \overline{u}) \neq 0$$

$\mu = 2\,\mathrm{GeV}$	MSTW08	MMHT14	MMHT (2016)	$\langle x \rangle^x$
$\langle x^0 \rangle_{\overline{d}-\overline{u}}$	$0.080^{+15\%}_{-12\%}$	$0.084^{+20\%}_{-13\%}$	$0.094^{+16\%}_{-20\%}$	0.05

- Uncertainties larger. Result from arXiv:1402.1462: 0.14 ± 0.5 in agreement, but on the high side.
- Earlier constraints from fixed p/d target Drell-Yan and DIS. More recently LHC W, Z playing increasing role.
- Aside: behaviour as $x \to 0$?

High precision data: an example

ATLAS W, Z data

- Recently ATLAS have released the final 7 TeV data on W, Z production, over range of m_{ll}, y_{ll}, η_l. For some kinematics, precision well below % level.

- They find potentially sizeable impact on PDFs, which in general struggle to describe data.

EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

ATLAS EXPERIMENT

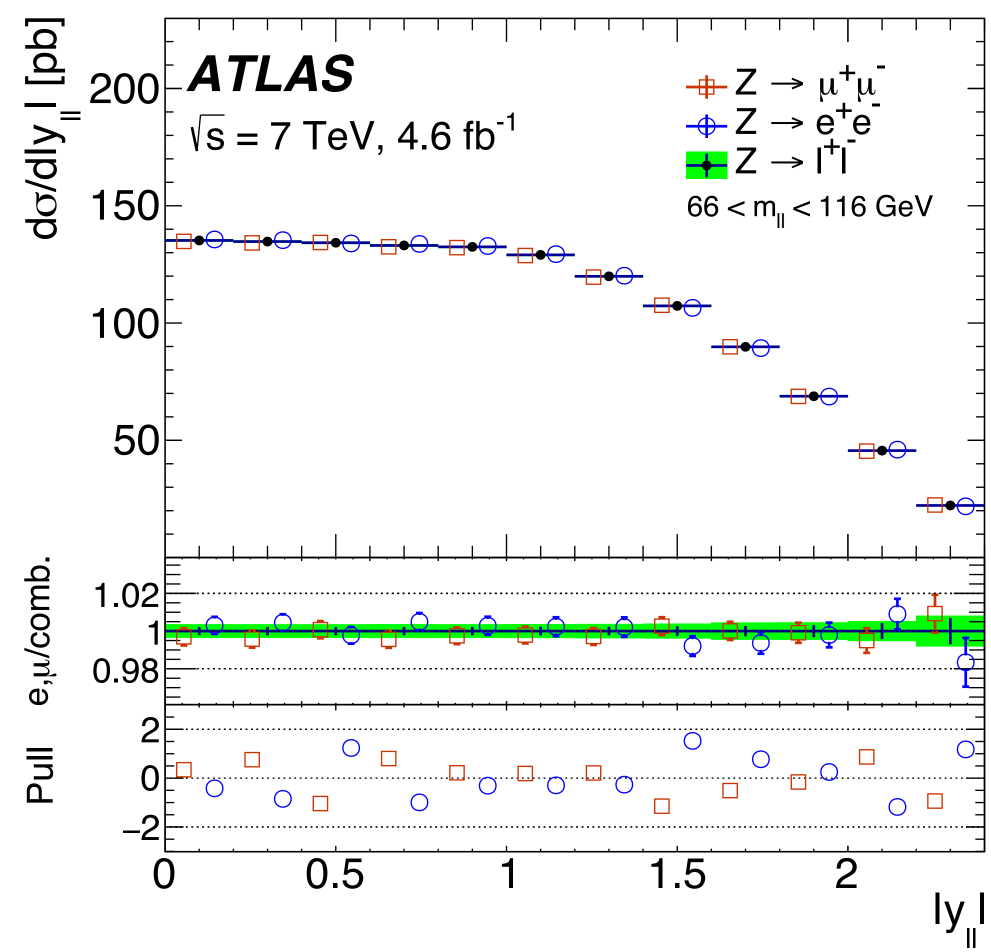
arXiv:1612.03016

Submitted to: EPJC

CERN-EP-2016-272
12th December 2016

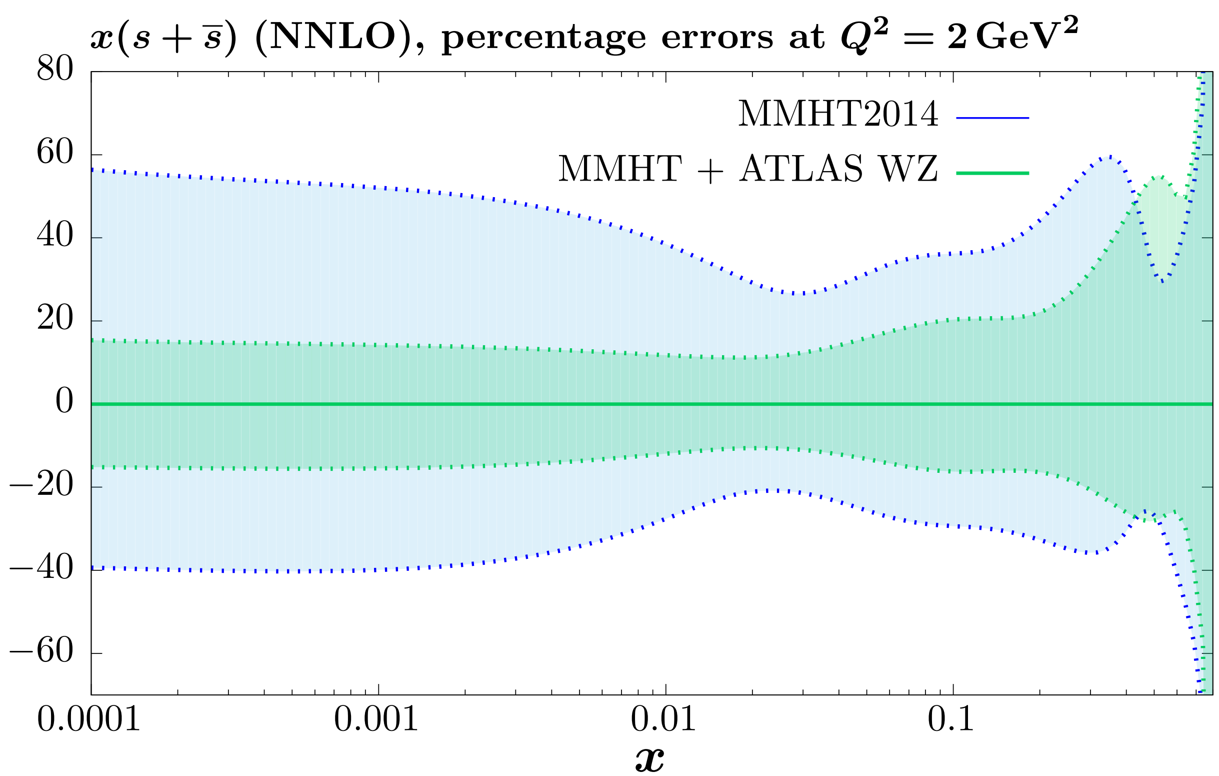
Precision measurement and interpretation of inclusive W^+, W^- and Z/γ^* production cross sections with the ATLAS detector

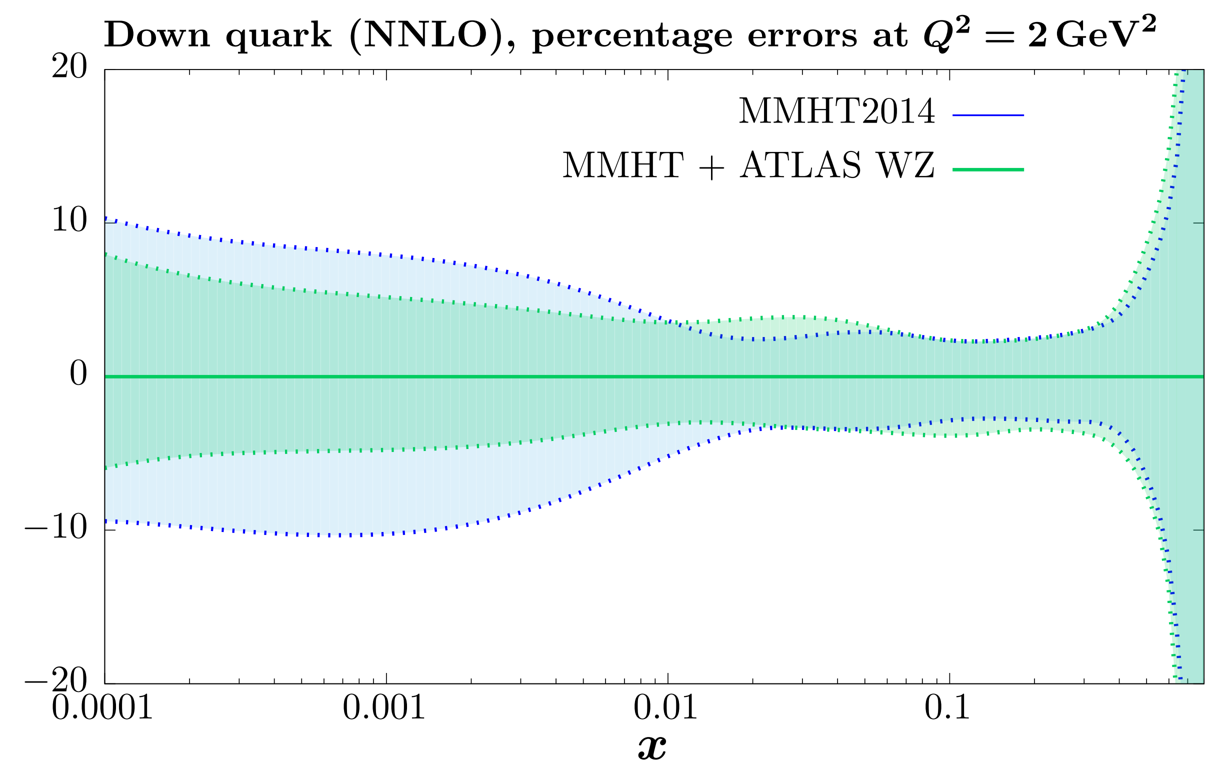
The ATLAS Collaboration



First comparison

- Including this data in fit, we find impressive improvements in PDFs…





$\longrightarrow$ High precision PDF determination. However, not without issues.

- Comparison to ATLAS data with baseline MMHT PDF very poor indeed- $\chi^2/N_{\mathrm{pts.}} = 400/61$. Improves after fitting, but only to still fairly poor $130/61$.
- Raises questions about e.g. theoretical uncertainties in fixed-order fit (choice of μ_R, μ_F?) at this level of precision. Additional handles helpful.

Outlook

- MMHT PDFs: result of global fit range of data types.
- MMHT14 last public release. Impact of later HERA and LHC data studied. New fit to come in intermediate future.
- PDF uncertainties low as $O(5-10\%)$, but vary greatly between partons and with x (can be larger!) . Much room for improvement in e.g. strange, $u_V - d_V$, gluon at low/high x .
- Moments:
  - Isovector $u-d$ momentum fraction (and higher moments) known to few $\%$.
  - Gluon momentum fraction known to $\sim 2\%$. Expect improvements with more LHC (jet, $t\bar{t}$ ...) data.
  - Gottfried sum rule violation known to $\sim 20\%$. Input from lattice?
- LHC impressive source of high precision PDF constraints, but not issue-free. Input from lattice?