MMHT Fits and Drell-Yan Precision Measurements at the LHC

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LHC EW meeting, CERN, 13th November

UNIVERSITY OF OXFORD

In memory of James Stirling.
This work and so much else is indebted to him.

Outline/Aim

- Summarise aspects of MMHT fit relevant to DY precision measurements at the LHC. Focus on discussion points from EW precision group:

LHC precision EW working group

PDF issues related to precision Drell-Yan measurements at the LHC

2 Summary of PDF issues to be discussed

The issues discussed within the LHC precision EW working group are summarised below, based on discussions at meetings earlier this year:

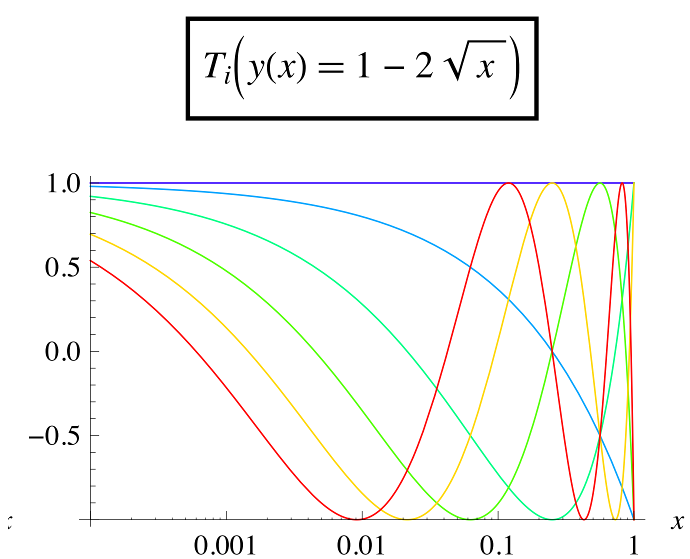
1. Which global PDF sets would wish to be considered in these studies? Hopefully this could start with the most recent sets, namely ABM16, CT14, MMHT14, and NNPDF3.1. Is it worth considering also the PDF4LHC set? From the list of issues raised below, wouldn't it seem more useful to study separately the sets entering this combination, or possibly even their successors?

MMHT Basics - Parameterisation

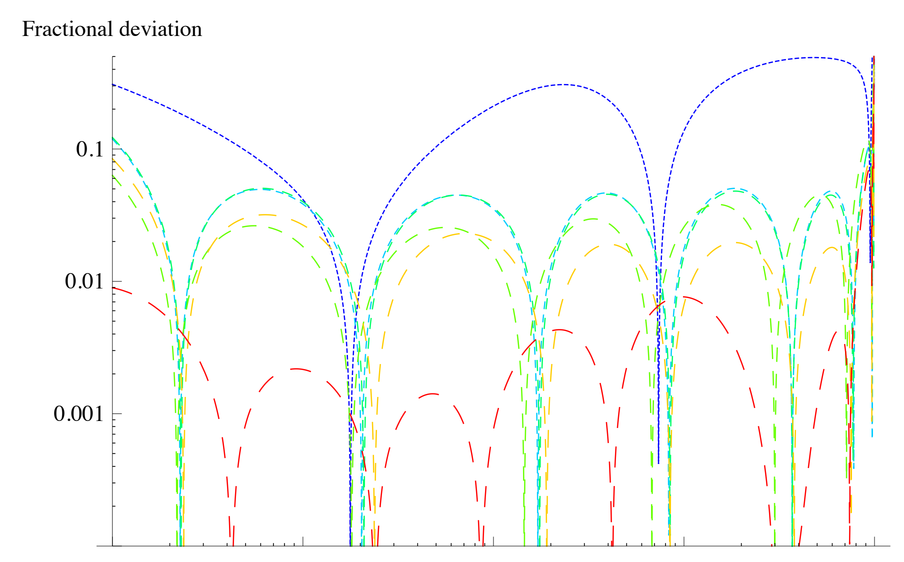
- PDFs parameterised in terms of **Chebyshev** polynomials:

$$xf(x,Q_0^2) \;=\; A(1-x)^{\eta}x^{\delta}\left(1+\sum_{i=1}^{n}a_i T_i^{\rm Ch}(y(x))\right), \qquad y = 1-2\sqrt{x}$$

  - Nature of Chebyshevs - more stable w.r.t. basic polynomial expansion: higher order in $n \Rightarrow$ finer scale in x (avoids large cancellations between terms in ‘standard’ form).
  - Optimum order n explored in fit.
  - Only gluons + light quarks fit: no intrinsic heavy flavour.



A.D. Martin et al., EPJC73 (2013) no.2, 2318



MMHT Basics - Uncertainties

★ **Theory:**

- Strong coupling α_s : left free in fit, dedicated uncertainty studies performed + sets released.
- Quark masses. Pole masses ($m_{c,b} = 1.4, 4.75\,\mathrm{GeV}$) taken, variation in these performed and corresponding PDF sets released.
- Other process-specific uncertainties: $D \to \mu$ branching, deuteron corrections…
- Currently no other theory uncertainty included. Most notably: no uncertainty due to missing higher orders in the theory.

★ **Experimental:**

- Included via Hessian formalism: diagonal variations w.r.t minimum.
- Textbook $\Delta\chi^2 = 1$ not applied.

MMHT - Tolerance

- Uncertainties on parameters a_i given in terms of error (Hessian) matrix:

$$H_{ij} = \frac{1}{2} \frac{\partial^2 \chi^2_{\rm global}}{\partial a_i \partial a_j}\bigg|_{\rm min}.$$

Suitably diagonalised in terms of eigenvectors e_{ij} :

$$H_{ij} e_{jk} = \sqrt{\lambda_k} e_{ik}$$

$$a_i(S_k^{\pm}) = a_i^0 \pm t\, e_{ik},$$

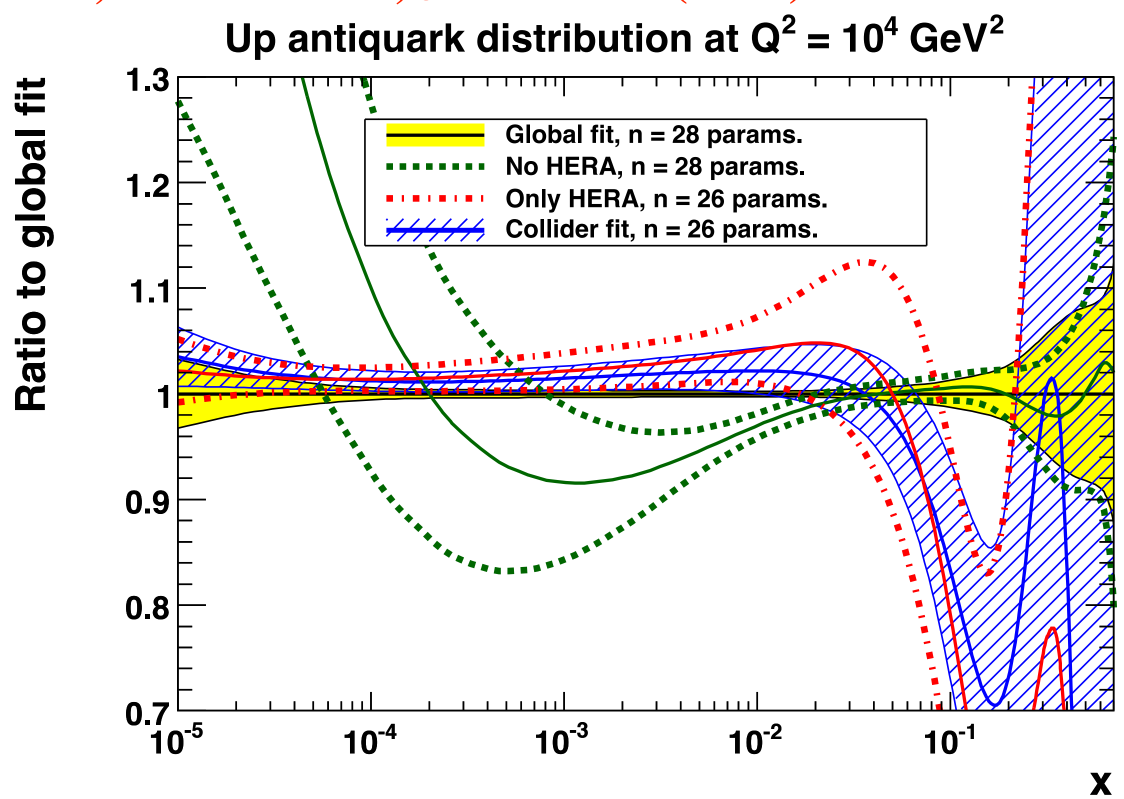
- Where $t = T = (\Delta\chi^2_{\rm global})^{1/2}$ in quadratic approximation.
- 'Tolerance' $T = 1$ in textbook parameter fitting case.
- But, been known for some time that this is not appropriate for global fits…

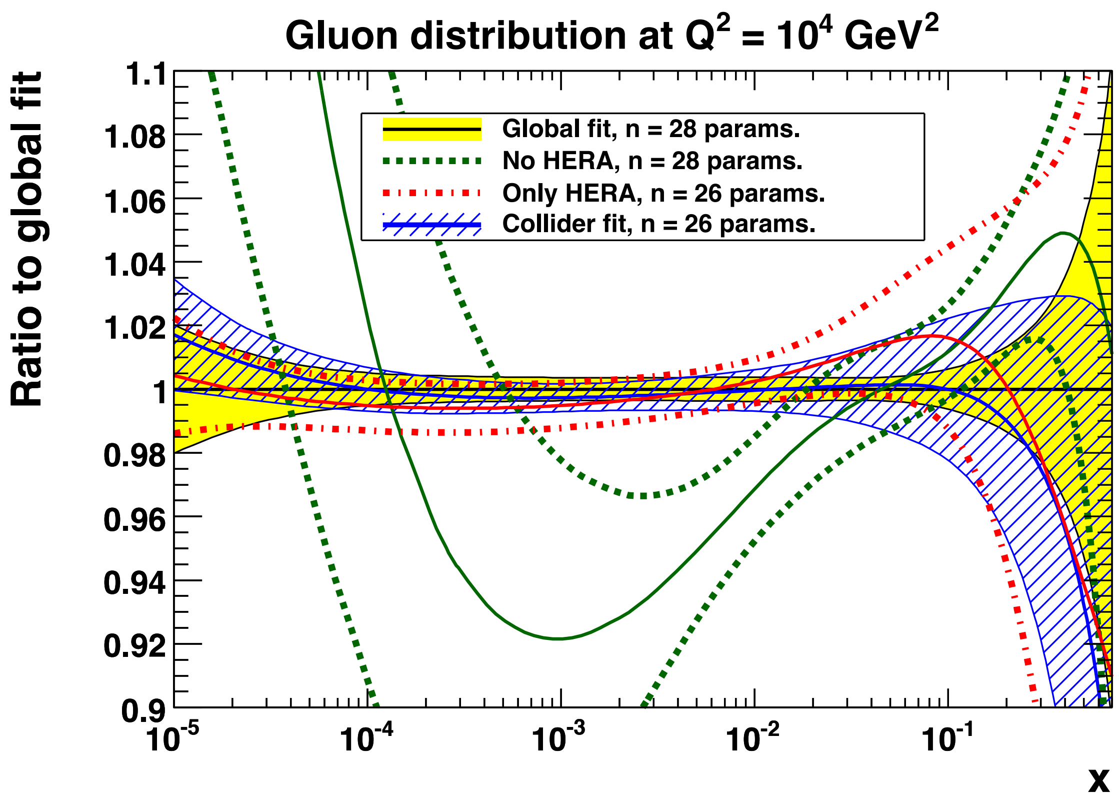
MMHT - (Need For) Tolerance

J. Pumplin, PRD 81 (2010) 074010, 82 (2010) 114020, A.D. Martin et al., EPJC63 (2009) 189-285

- Various studies of this. One nice example - 1205.4024. Fitting to different reduced datasets with $\Delta\chi^2 = 1$ see significant differences between PDFs, beyond nominal error bands:

G. Watt, R. S. Thorne, JHEP 1208 (2012) 052





- Also perform toy study with pseudodata + various inconsistencies injected in. See similar effect, in particular: no automatic increases in PDF errors or significant deterioration in fit quality ($\chi^2/\text{dof} \sim 1$).
- Indicates need for larger tolerance $T > 1$ in global fits.

MMHT - Dynamical Tolerance

- MMHT approach - 'dynamical' tolerance calculation, i.e. tolerance is determined for each eigenvector direction $\Rightarrow$ 50 tolerances for MMHT14 (25 eigenvectors).
- Values calculated using conservative 'hypothesis testing' criteria. Require every dataset n with N points described within $\Delta\chi^2_n < \sqrt{2N}$.

eigen– vector	+ t	T	most constraining data set	− t	T	most constraining data set
1	4.00	3.97	HERA e^+p NC 920 GeV	4.30	4.66	HERA e^+p NC 820 GeV
2	2.50	2.84	HERA e^+p NC 920 GeV	1.80	1.53	NMC μd F_2
3	3.80	4.00	NMC.....HERA F_L	3.70	3.69	NMC μd F_2
4	4.05	4.00	DØ II $W \to \nu e$ asym.	5.00	5.11	DØ II $W \to \nu\mu$ asym.
5	3.40	3.35	DØ II $W \to \nu\mu$ asym.	4.20	4.45	NuTeV $\nu N \to \mu\mu X$
6	1.85	1.88	NuTeV $\nu N \to \mu\mu X$	3.70	3.71	DØ II $W \to \nu\mu$ asym.
7	1.55	1.67	E866/NuSea pd/pp DY	2.15	2.03	E866/NuSea pd/pp DY
8	2.75	2.64	DØ II $W \to \nu\mu$ asym.	1.90	2.01	E866/NuSea pd/pp DY
9	3.40	3.46	E866/NuSea pd/pp DY	3.80	3.78	BCDMS μp F_2
10	3.15	3.47	NuTeV $\nu N \to \mu\mu X$	2.40	2.13	NuTeV νN F_2

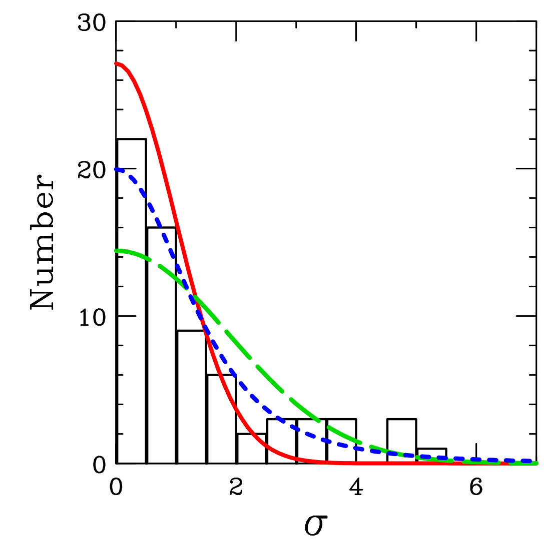
- Find range of $T \sim 1.5 - 5$, with average $T \sim 3$ for e.g. MMHT14NNLO.

Contributions to Tolerance

- Departure from $\Delta\chi^2 = 1$ due to fact that global PDF fit does not correspond to textbook statistical case:

J. Pumplin, PRD 81 (2010) 074010

★ **Dataset incompatibilities:**



- Fits various reduced datasets not consistent within $\Delta\chi^2 = 1$ and follow same trend as toy model.
- Distribution for dataset χ^2_n typically not what you expect from textbook statistics (broader tail etc).
- Note this 'incompatibility' is not purely/necessarily of truly experimental origin- e.g. pQCD theory predictions due to missing higher orders.

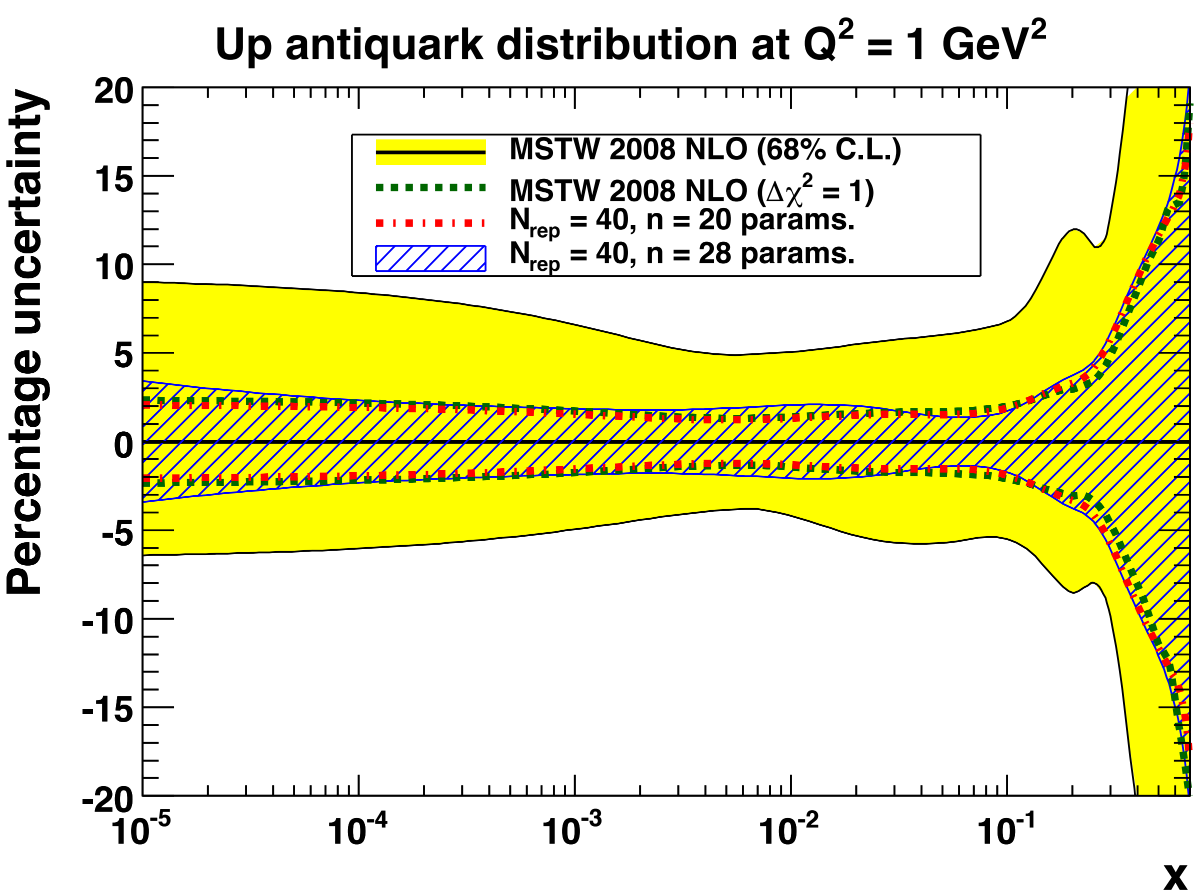
★ **Parameterisation uncertainty:**

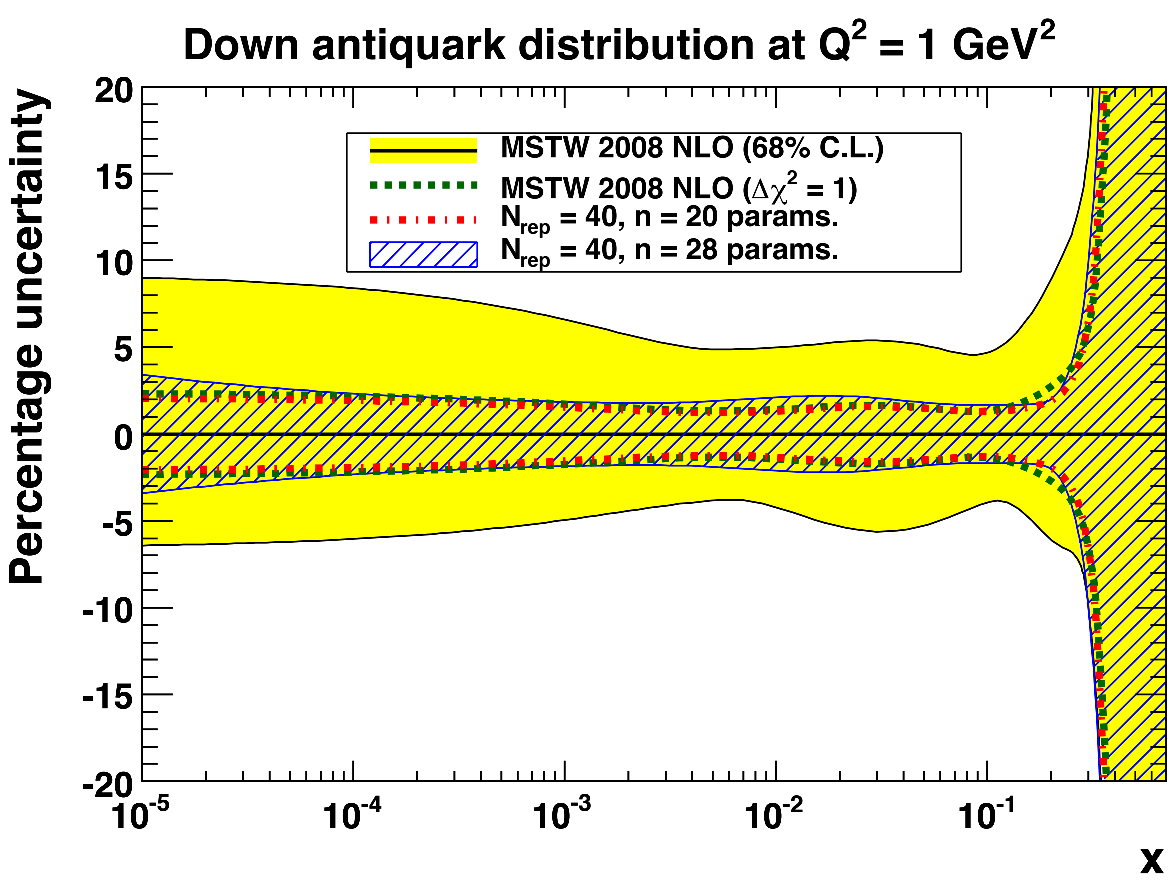
- Restrictions from parameterisations lead to departure from textbook case and underestimated errors.

Contributions to Tolerance

J. Pumplin, PRD 81 (2010) 074010, 82 (2010) 114020

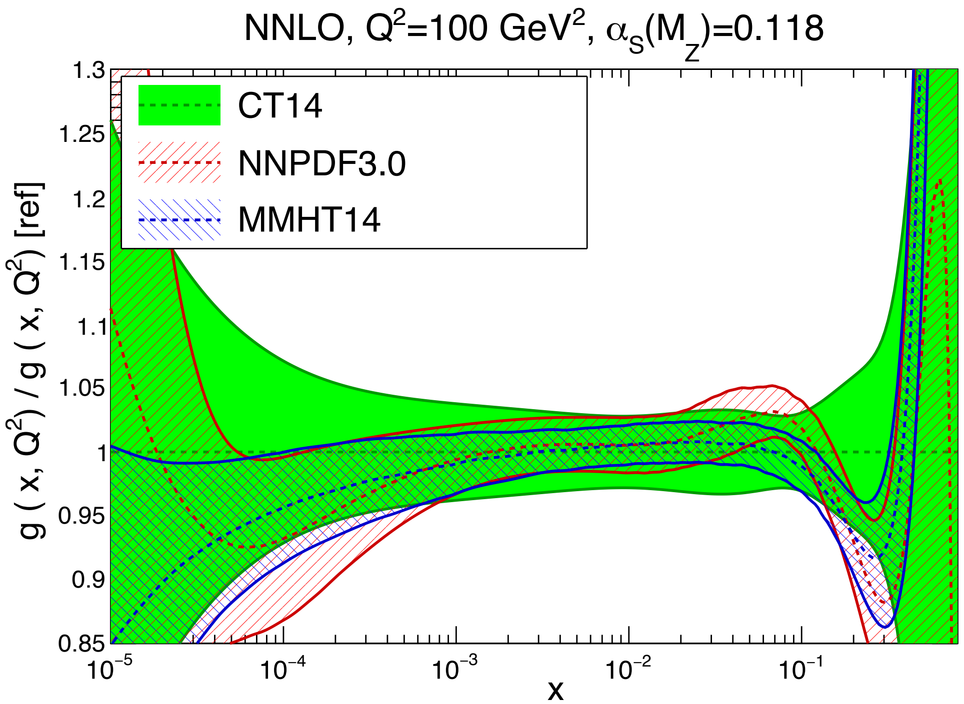
- Relative contributions from these two sources open question: some earlier CT studies indicate $\sim 50/50$ breakdown between two.
- But prior to use of more flexible Chebyshev parameterisation- study of 1205.4024 only saw v. mild differences when using full or somewhat restricted set of eigenvector directions for errors.

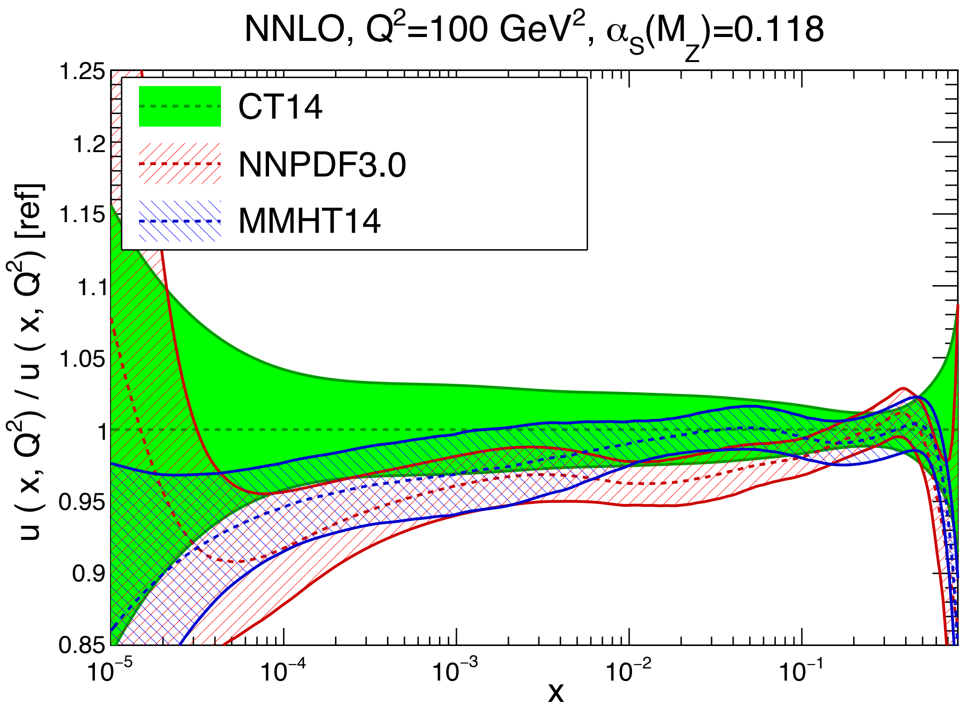




PDF comparisons

N.B. CT14 errors - 90% CL

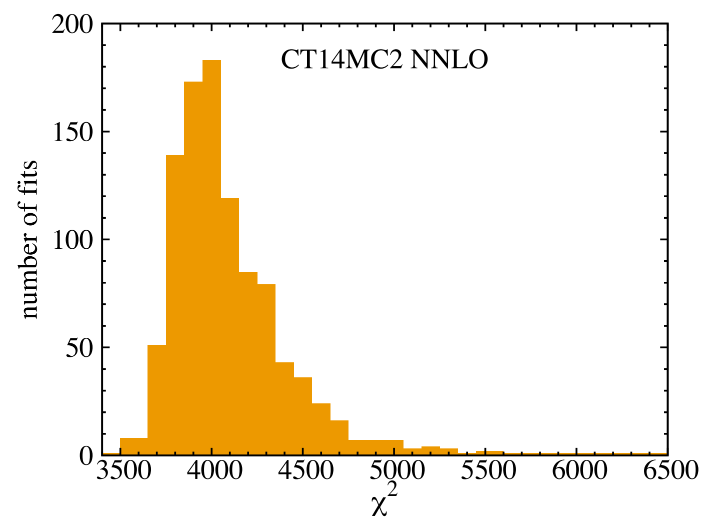


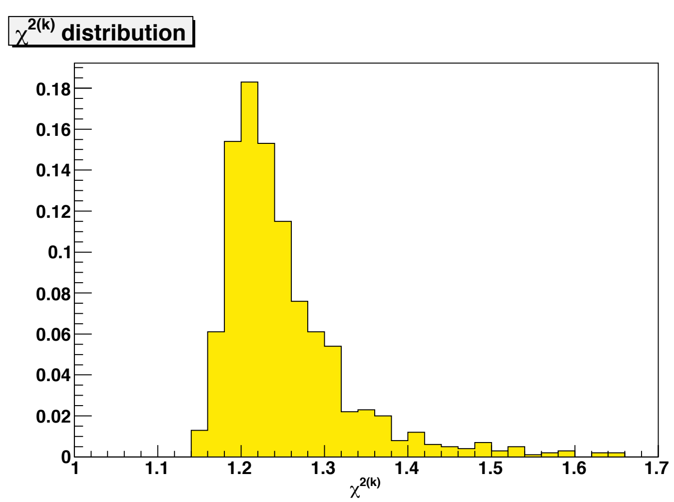


- Despite no explicit tolerance in NNPDF, see broadly similar PDF errors. Explanation somewhat open. Certainly impact from dataset incompatibility present in all cases.

R.D. Ball et al., Nucl. Phys. B849 (2011) 296-363

- Interesting observation - χ^2 distribution for replicas in e.g. CT14MC sets with tolerance rather similar to NNPDF (without - too narrow).

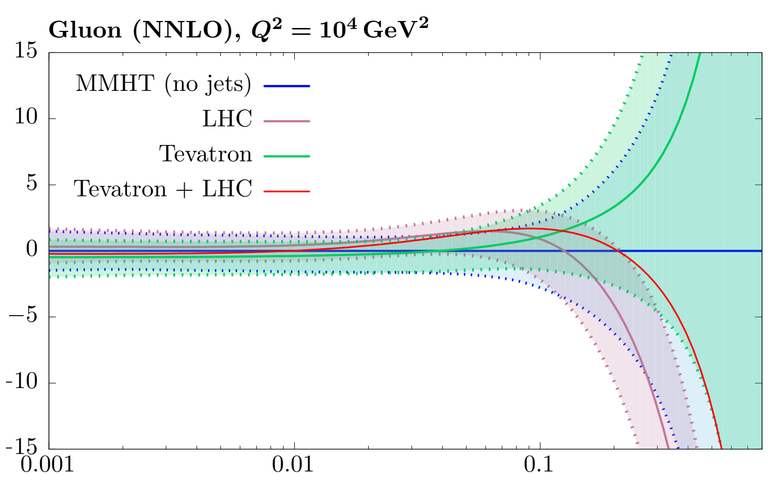


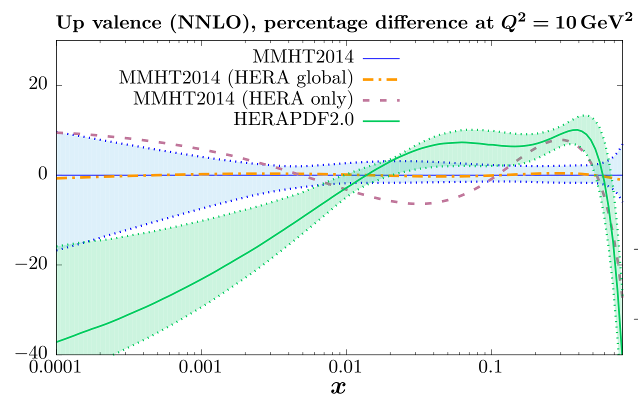


T.J. Hou et al., JHEP 1703 (2017) 099

MMHT Status

- Most recent **public** release MMHT14, but many studies since then/ new data included. Currently working towards updated MMHT set.





Parton distributions in the LHC era: MMHT 2014 PDFs

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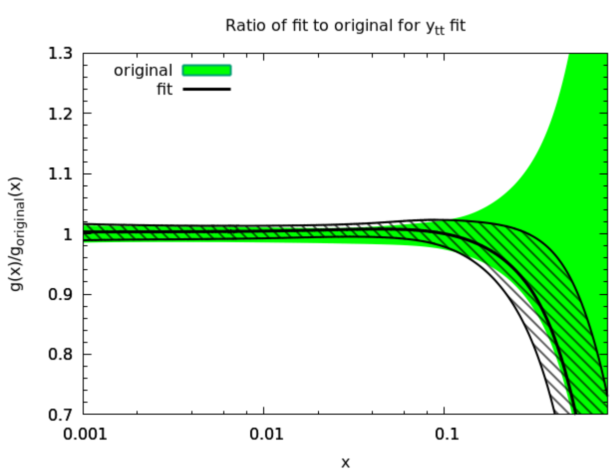
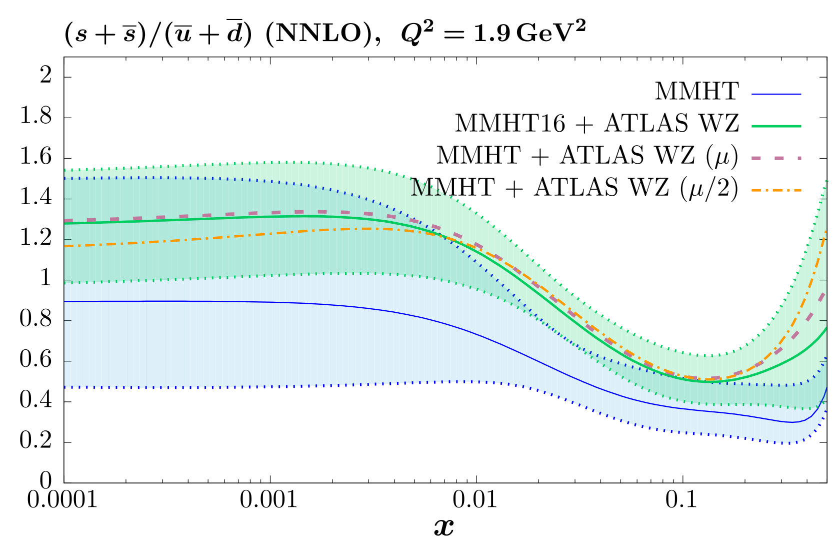
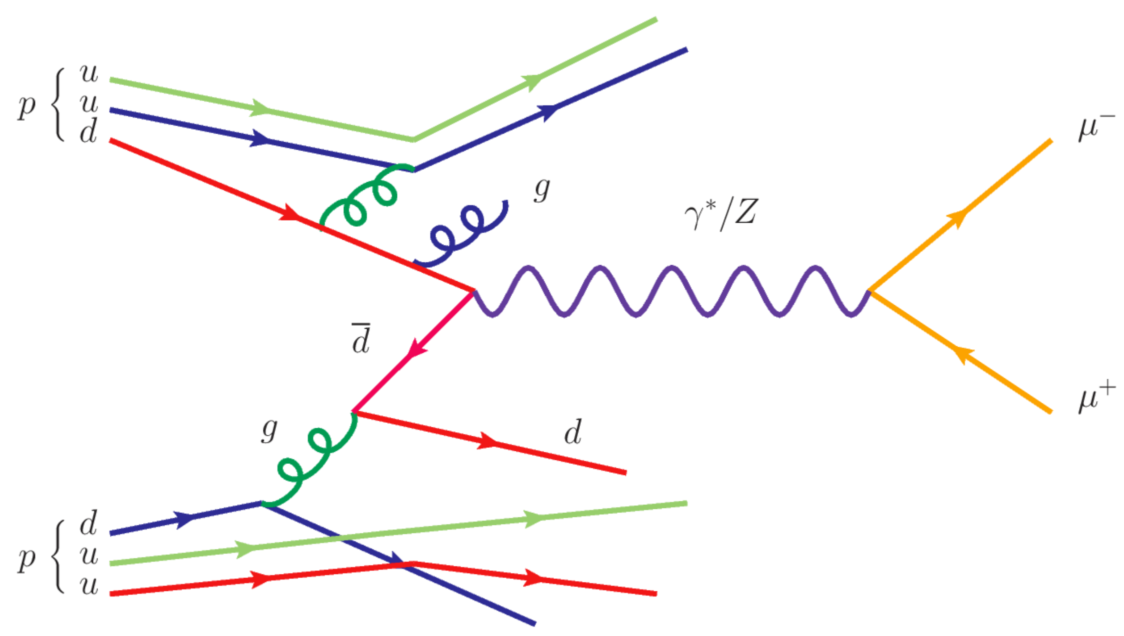




- Highlights with relevance to DY…

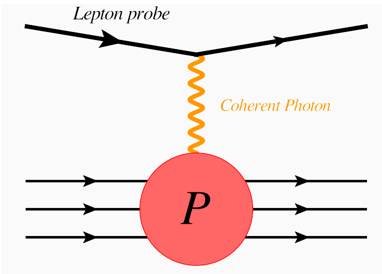
MMHT - Treatment of DY (Theory)

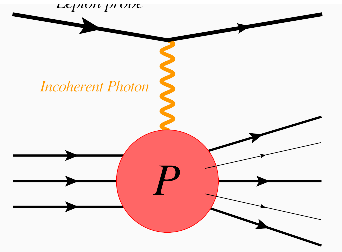
- Drell-Yan theory:
  - NNLO QCD - NLO applgrids (MCFM) combined with NNLO K-factors from FEWZ/DYNNLO.
  - (Currently) no EW corrections.
  - (Currently) no photon-initiated contributions, though in progress…



MMHT - Photon-initiated production

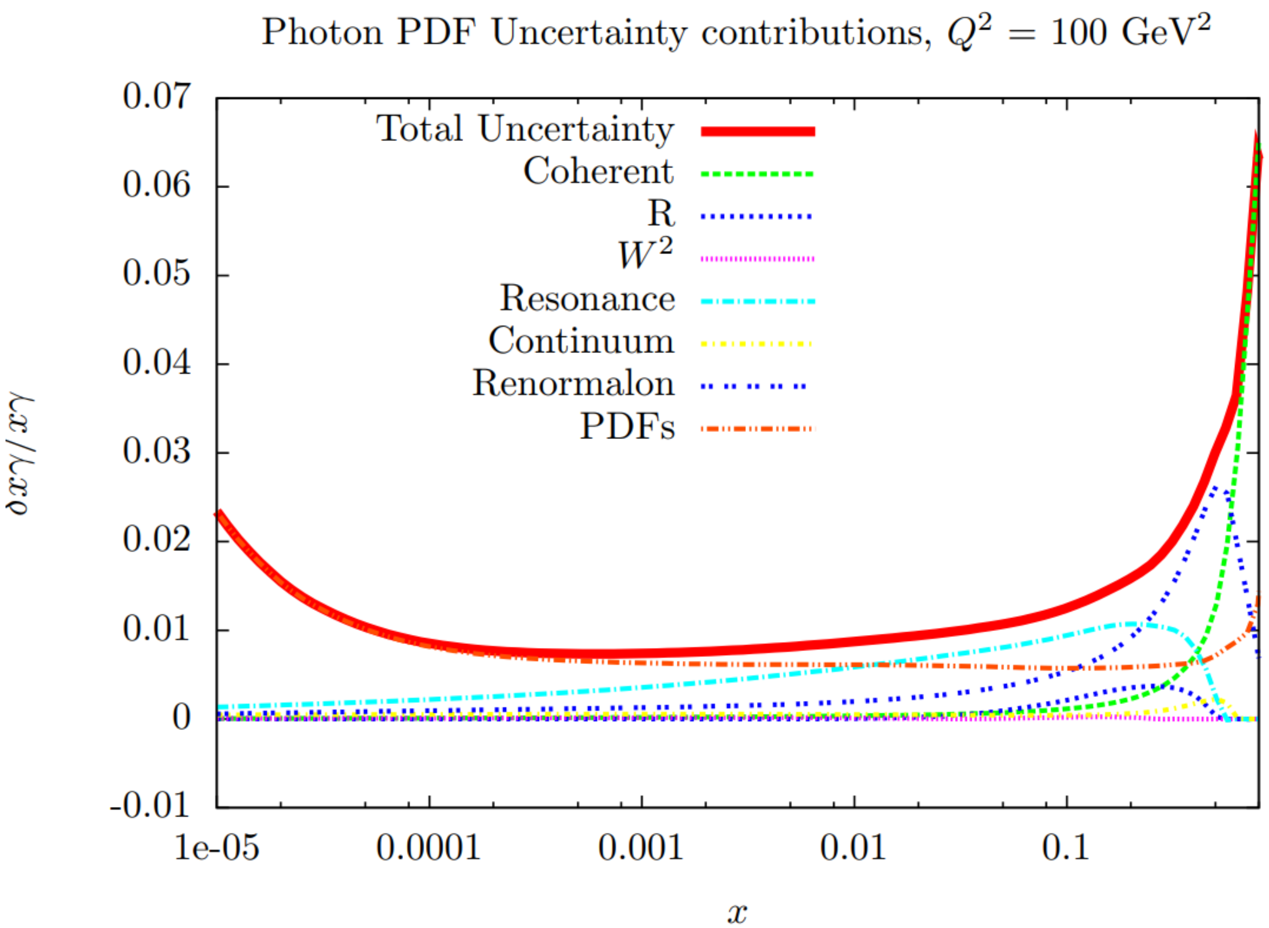
- MMHT photon calculated using (modified) version of LUXqed input - precisely determined in terms of known structure functions:





$$x\gamma(x,Q_0^2) = \frac{1}{2\pi\alpha(Q_0^2)}\int_x^1 \frac{dz}{z}\left\{\int_{\frac{x^2 m_p^2}{1-z}}^{Q_0^2} \frac{dQ^2}{Q^2}\alpha^2(Q^2)\left[\left(z p_{\gamma,q}(z) + \frac{2x^2 m_p^2}{Q^2}\right)F_2(x/z,Q^2) - z^2 F_L(x/z,Q^2)\right] - \alpha^2(Q_0^2) z^2 F_2(x/z,Q_0^2)\right\}$$

- Uncertainties due to experimental determination of structure functions, renormalon contributions…
- Small, at ~ % level even out to high x.

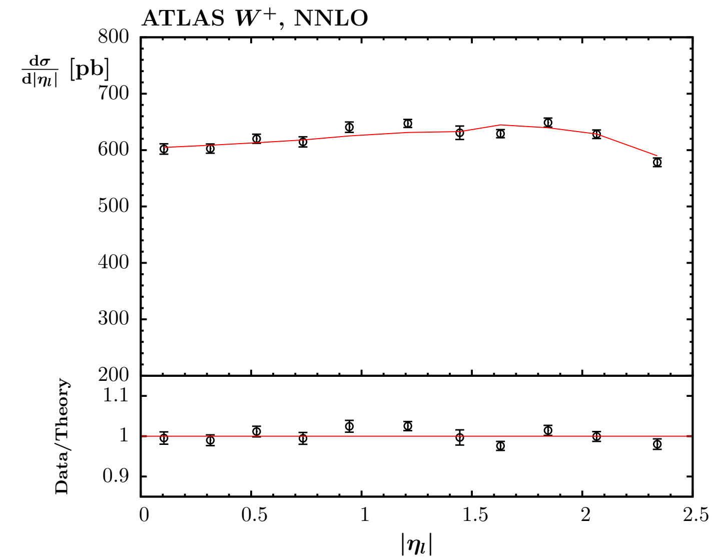


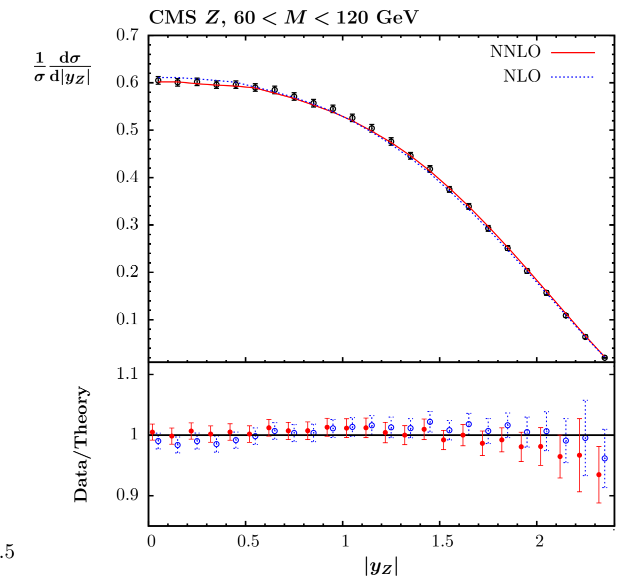
- Will be default in all future releases.

See R. Nathvani, talk at DIS2018, for more details.

MMHT Status: Drell-Yan

- MMHT14 includes reasonable amount of LHC DY @ 7 TeV:
  - ATLAS W, Z rapidity.
  - LHCb W, Z rapidity.
  - CMS W, Z (double diff.).



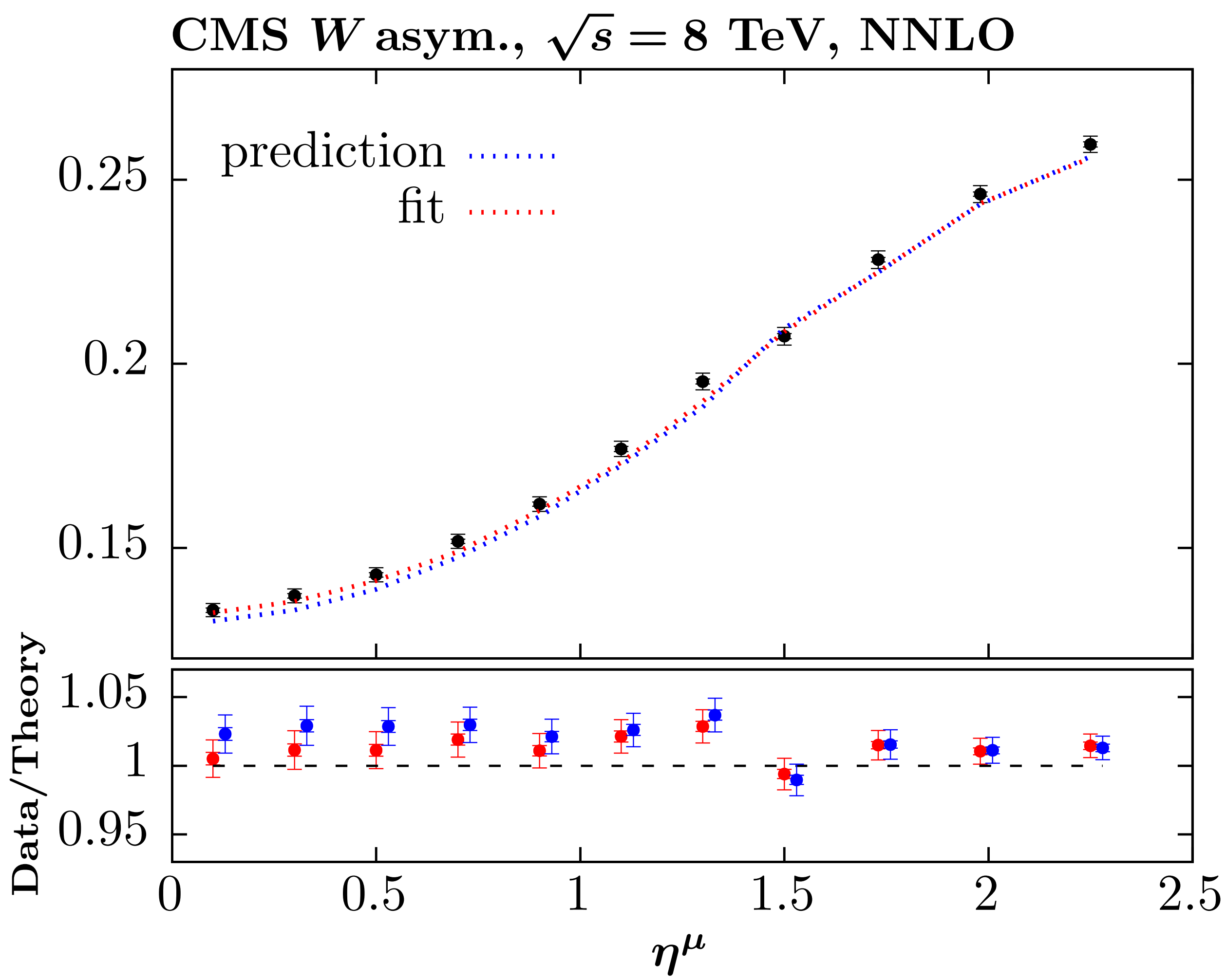


	Points	NLO χ^2	NNLO χ^2
$\sigma_{t\bar{t}}$	18	19.6 (20.5)	14.7 (15.3)
LHCb 7 TeV $W+Z$	33	50.1 (45.4)	46.5 (42.9)
LHCb 8 TeV $W+Z$	34	77.0 (58.9)	62.6 (59.0)
LHCb 8 TeV $Z \to ee$	17	37.4 (33.4)	30.3 (28.9)
CMS 8 TeV W	22	32.6 (18.6)	34.9 (20.5)
CMS 7 TeV $W+c$	10	8.5 (10.0)	8.7 (7.8)
D0 e asymmetry	13	22.2 (21.5)	27.3 (25.8)
Total	3405 (3738)	4375.9 (4336.1)	3741.5 (3723.7)

- LHC W, Z measurements significant element of updated LHC dataset, including various 8 TeV data.
- Most recent MMHT fit - LHC data constrains 21 of 50 eigenvector directions.

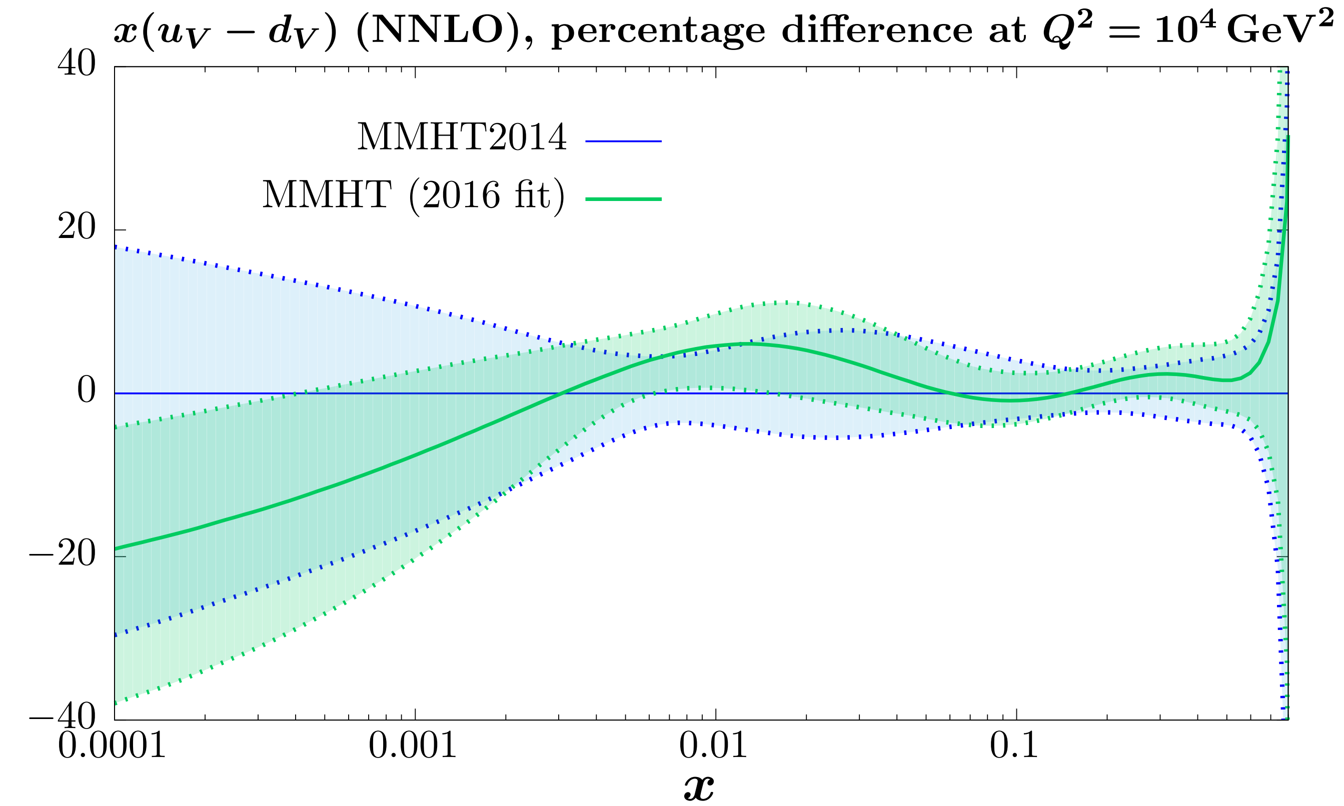
Example 1: CMS 8 TeV W ‘Asymmetry’

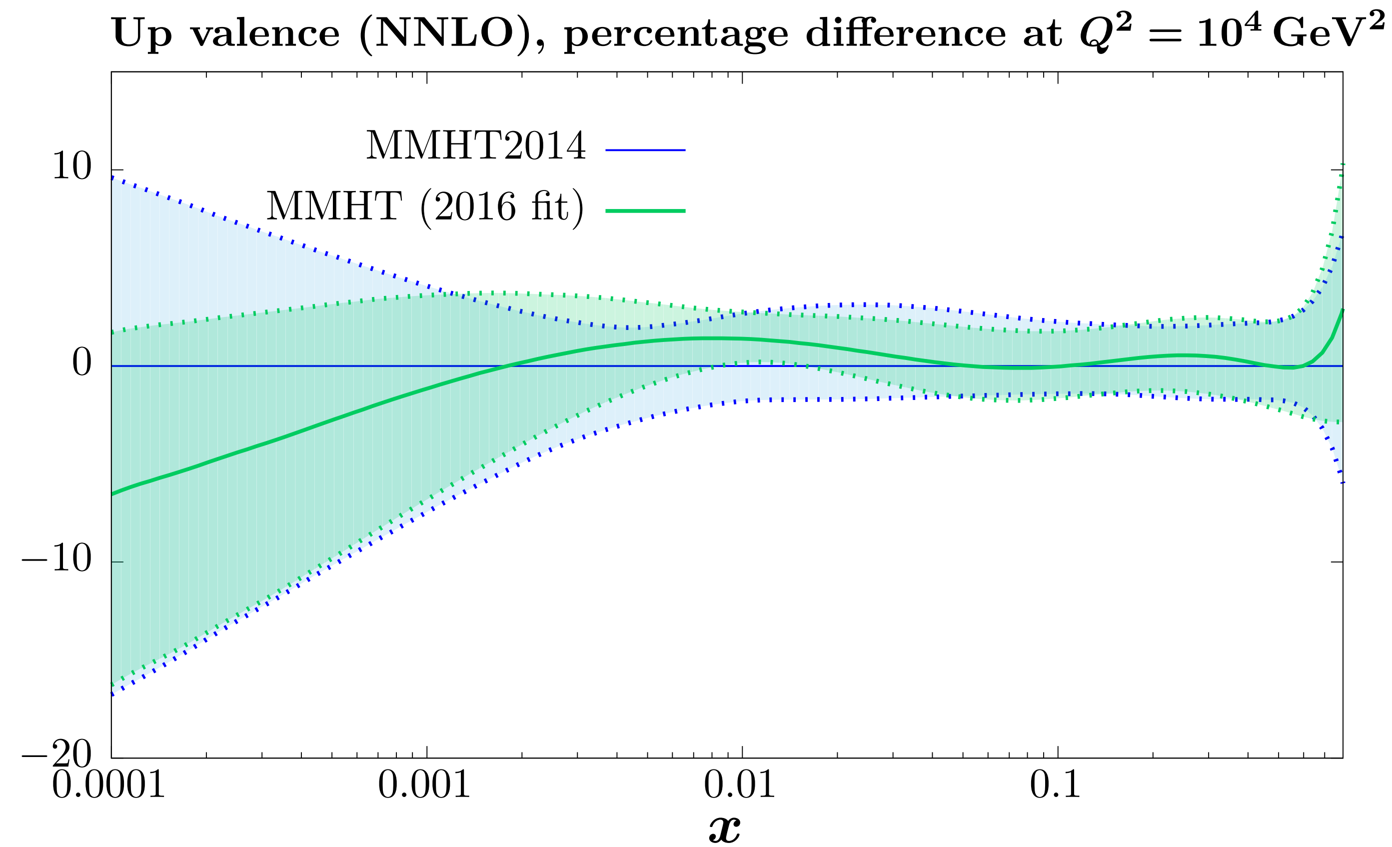
- Include CMS 8 TeV $W^{\pm}$ data (fit individually w. correlations).



- Clear movement with refitting $\Rightarrow$ small x valence quarks modified at level of uncertainty.
- Good fit achieved. Previous issues resolved by extending to more adaptive ‘Chebyshev’ parameterisation.

- Impact on $u_V - d_V$, principally through u_V, from CMS data clear.

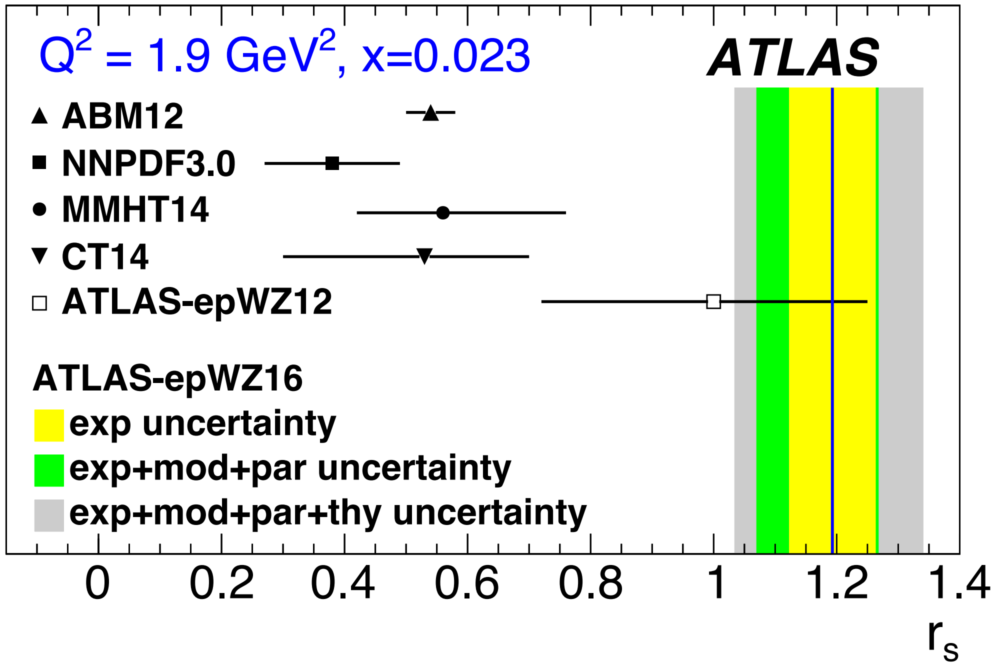




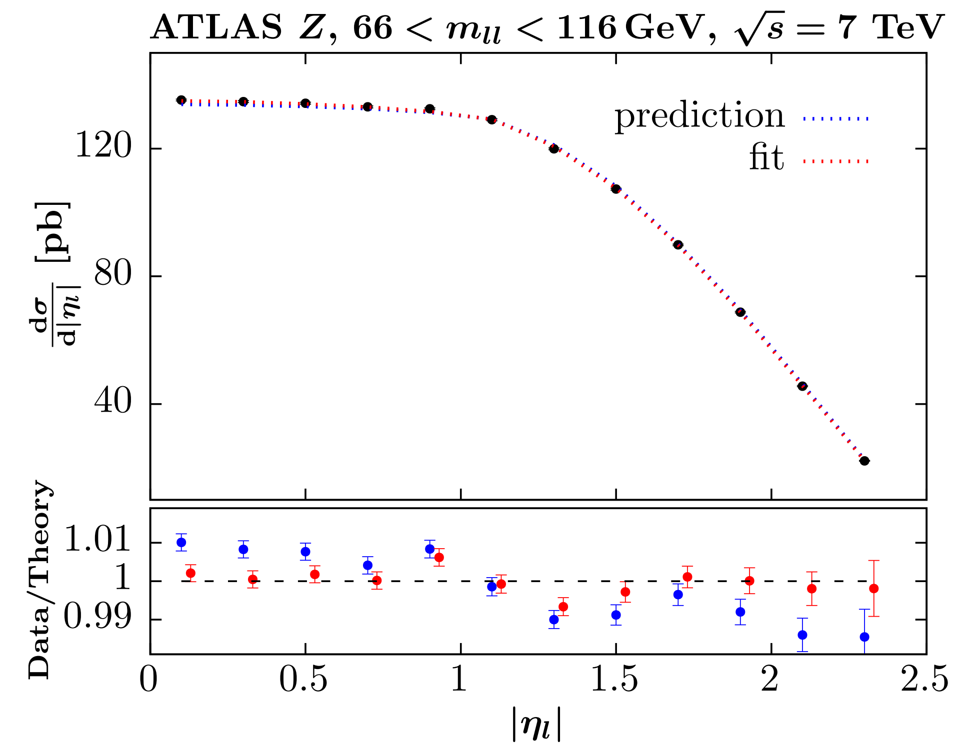
Example 2: ATLAS High Precision W/Z

$$R_s = \frac{s + \bar{s}}{\bar{u} + \bar{d}}$$

- Fit high precision ATLAS W,Z data.
- Recall internal ATLAS study sees higher strangeness (symmetric sea $\bar{s} \sim \bar{u}, \bar{d}$), and tension with global fits.

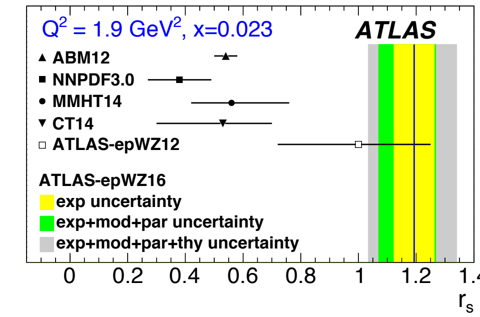


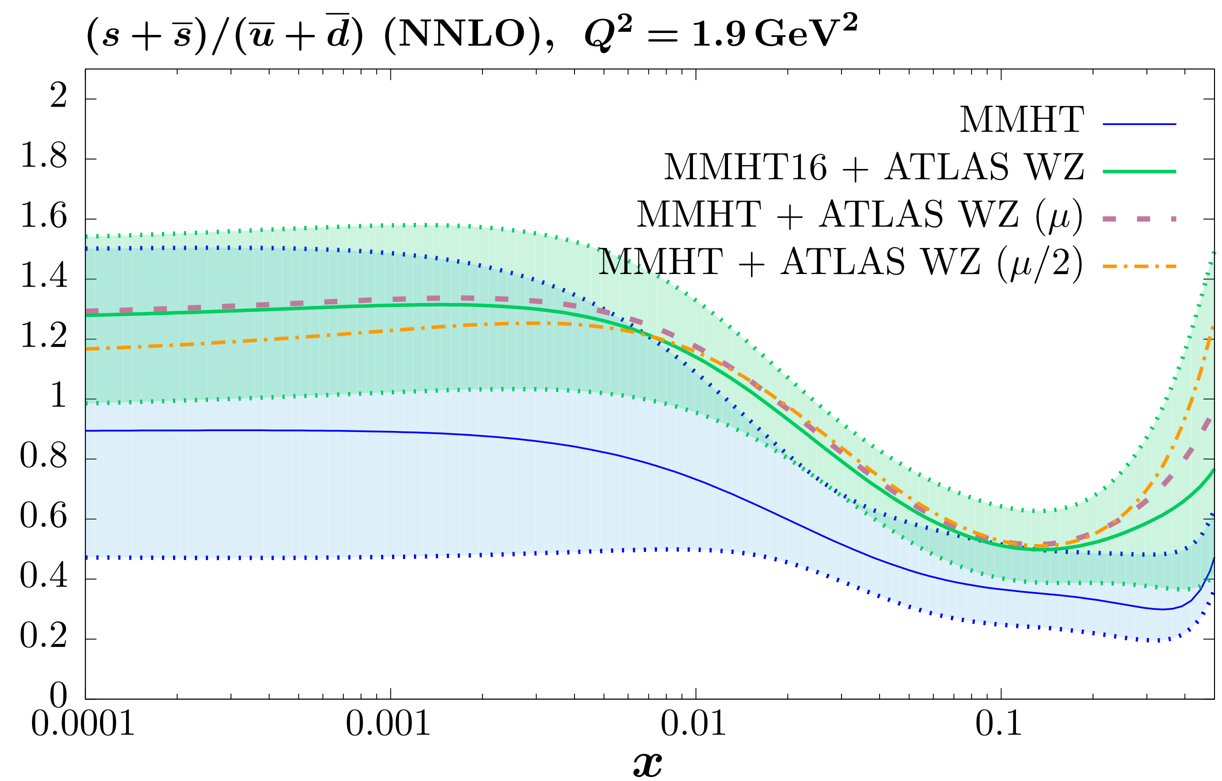
- Adding data into MMHT fit:
  - As expected, significant improvement in description of ATLAS data after refitting.
  - Inclusion improves description of new LHC data (+ D0) by ~ 10 points $\implies$ pull between ATLAS W,Z and other LHC data in **same direction.**
  - Exception - CMS $W + c$, which deteriorates slightly. (CMS 7 TeV DY also)



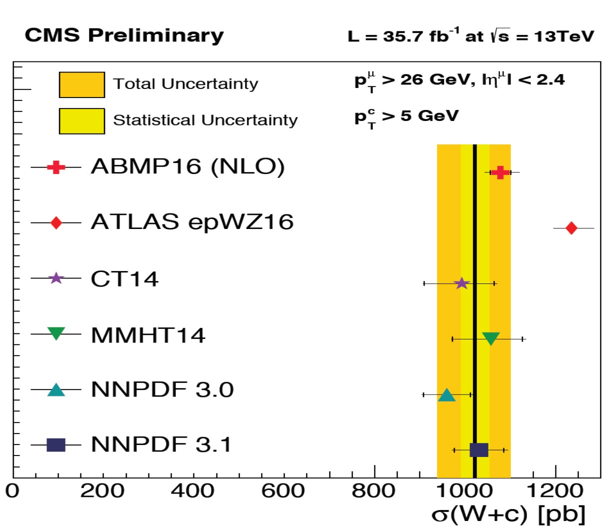
- After refitting, find increased strangeness in line with ATLAS finding, but overall tension with dimuon data relatively mild.

$$R_s \sim 0.85 \pm 0.15$$

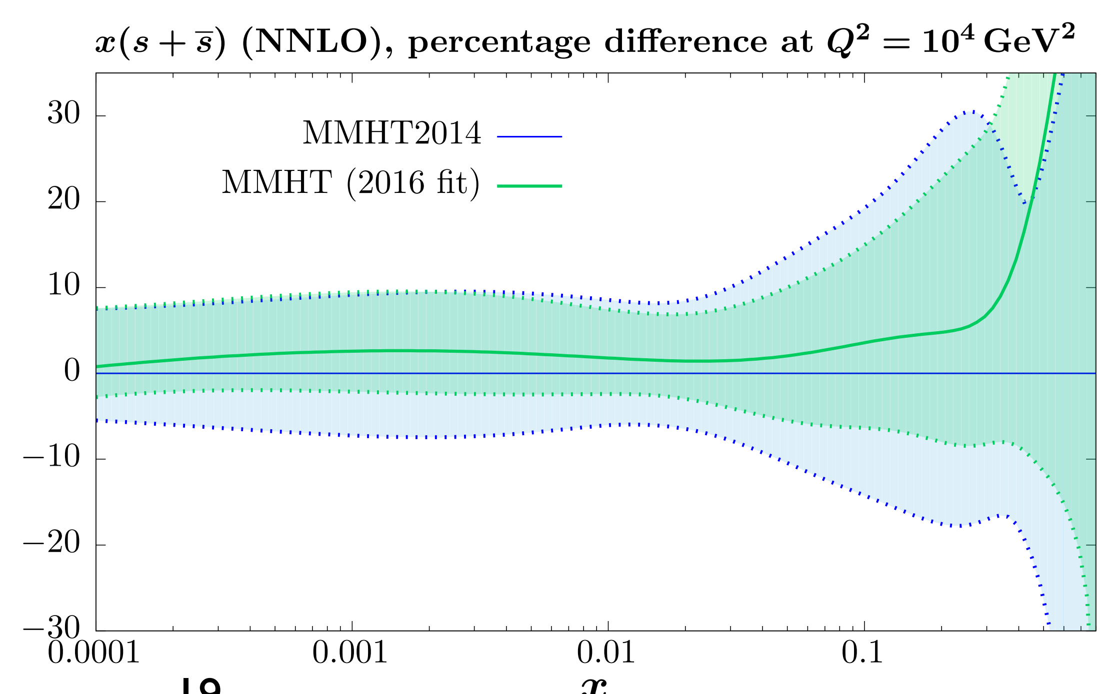


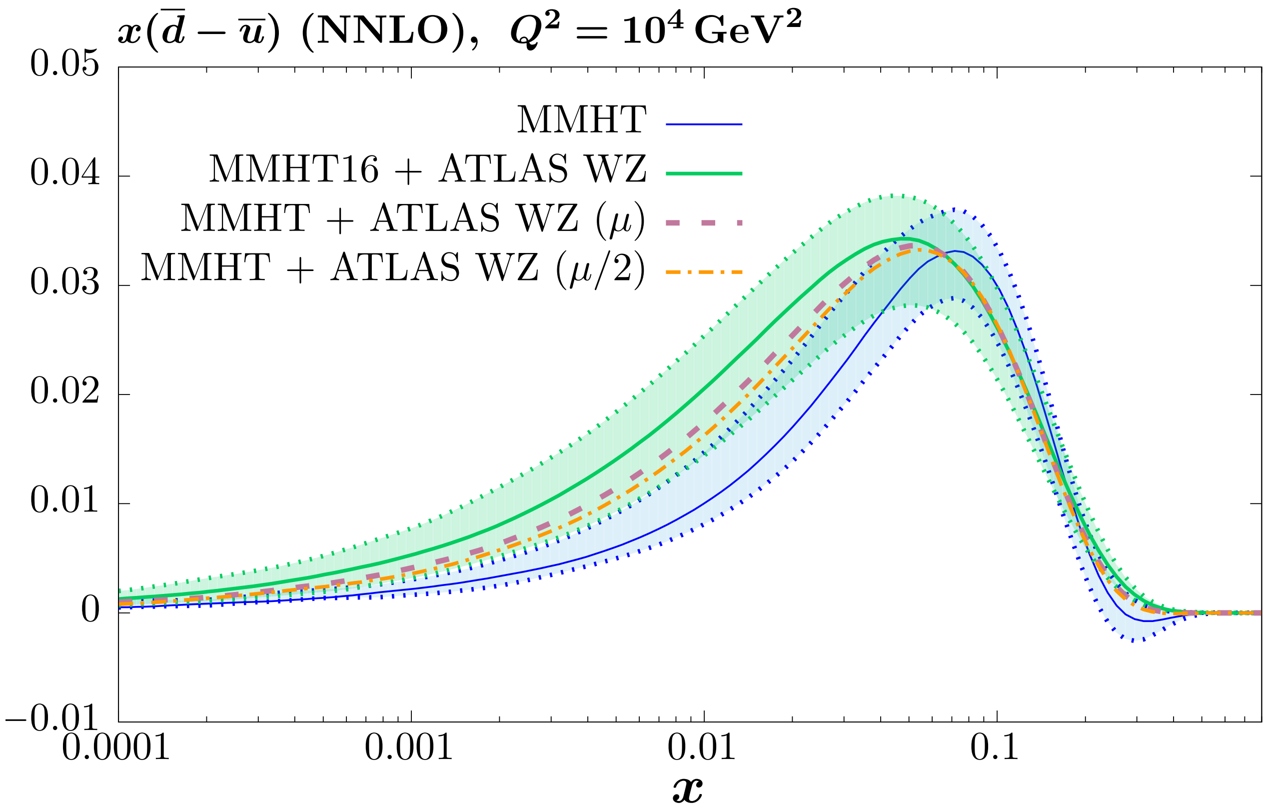


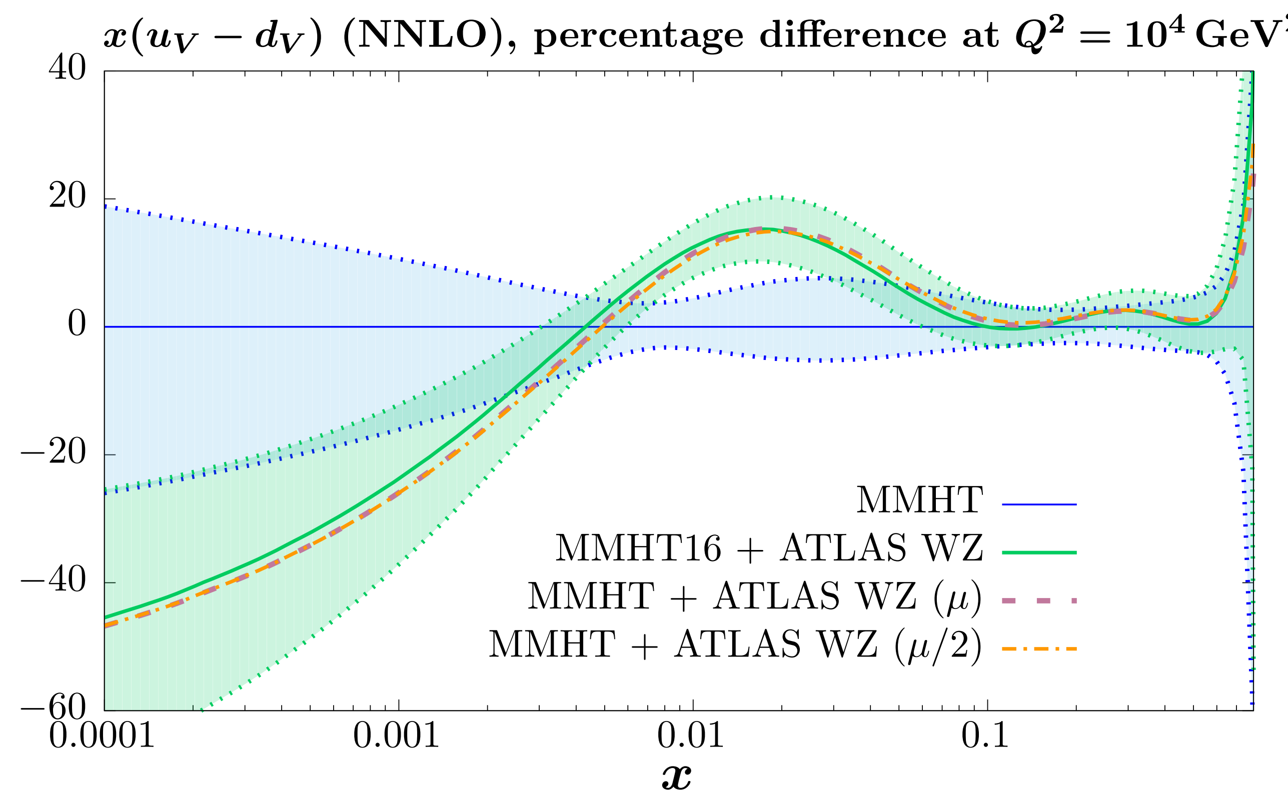
- Fit without ATLAS W,Z but with CMS 7 TeV W + c - mild tendency for strangeness closes to original MMHT14.
- Looks to persist in more recent data - currently looking into. (caveat - NLO theory only).



B. Bilin, DIS18

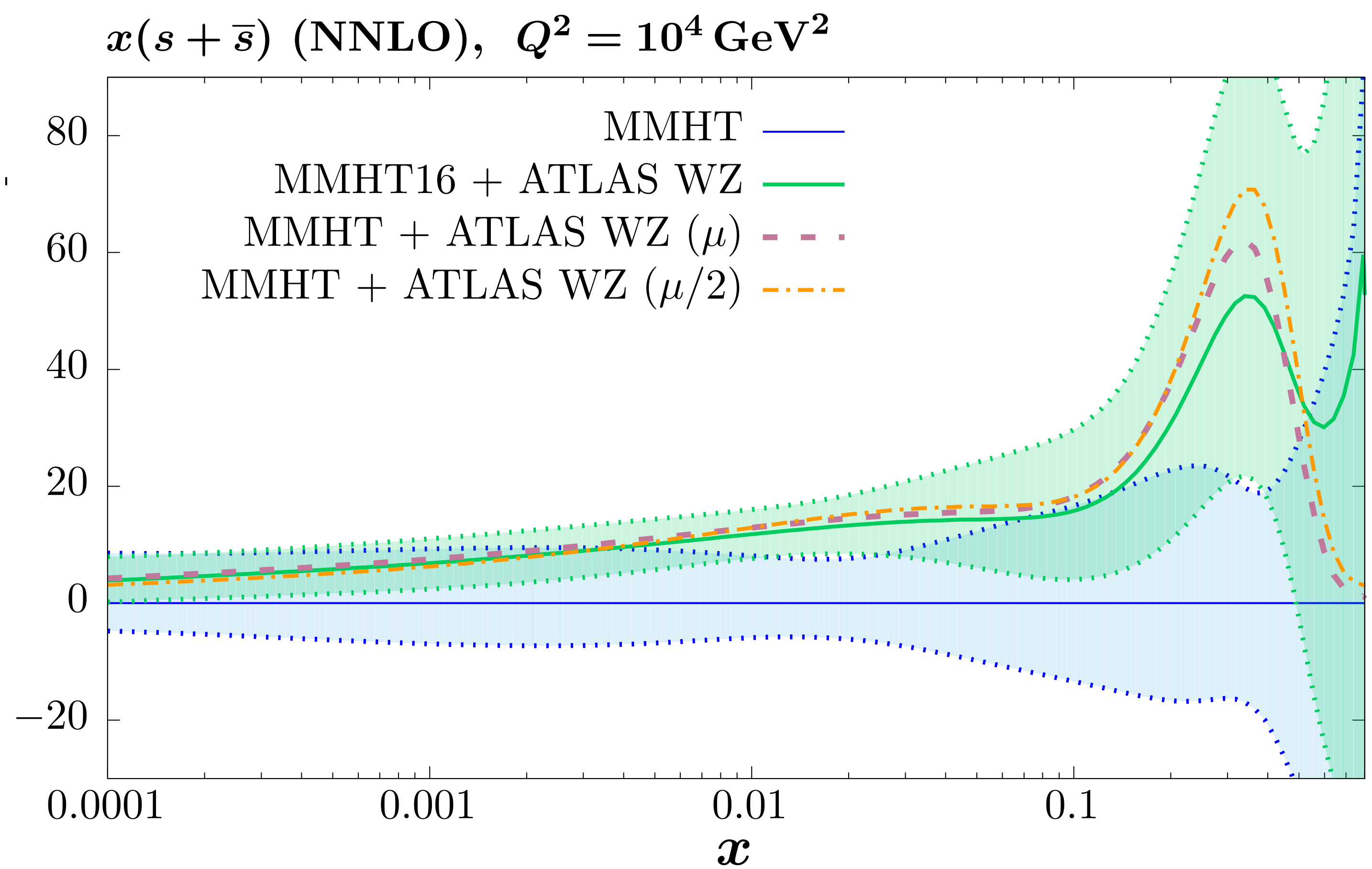


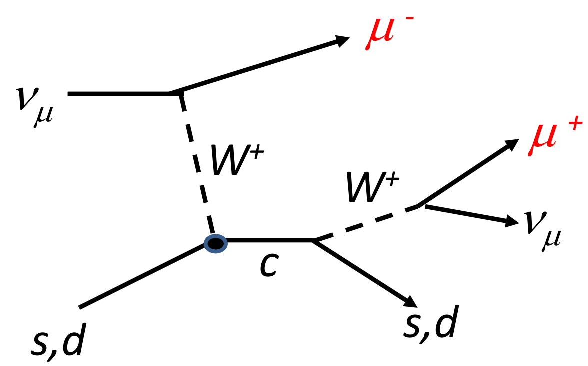




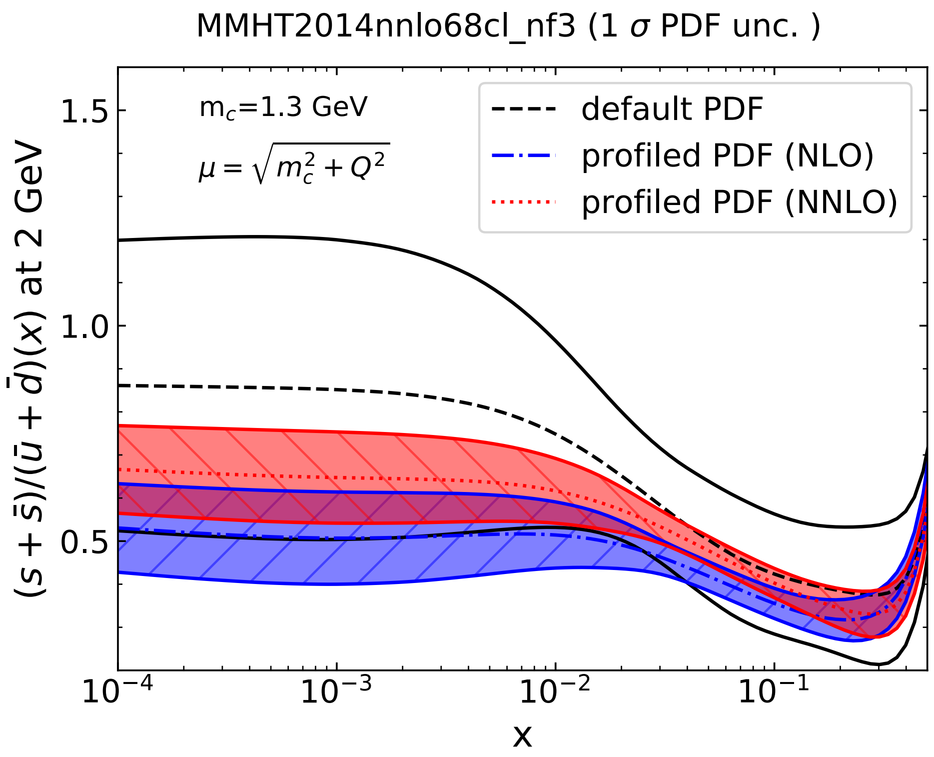
- Impact not just on strange quarks - also other light quark flavour decomposition. Pull in same direction as other LHC data.
- Fit quality to ATLAS relatively poor when considering all mass regions. Not result of tension with other data.
- Some improvement when taking $\mu_{R,F} = \mu_0/2$,with $\chi^2/\text{pts} \sim 2.2 \rightarrow 1.8$, and crucially little significant change in PDFs. More systematic approach needed in future.

Dimuon production - NNLO





J. Gao, JHEP 1802 (2018) 026



- After adding ATLAS W,Z, fit to dimuon data gives large $\sim 2\sigma$ change in $D \to \mu$ branching ratio and extreme change at high x as by product.
- May be improved by inclusion of NNLO corrections. Ongoing work points in this direction

Extended $\overline{d} - \overline{u}$ parameterisation

- MMHT14- use 3 parameters

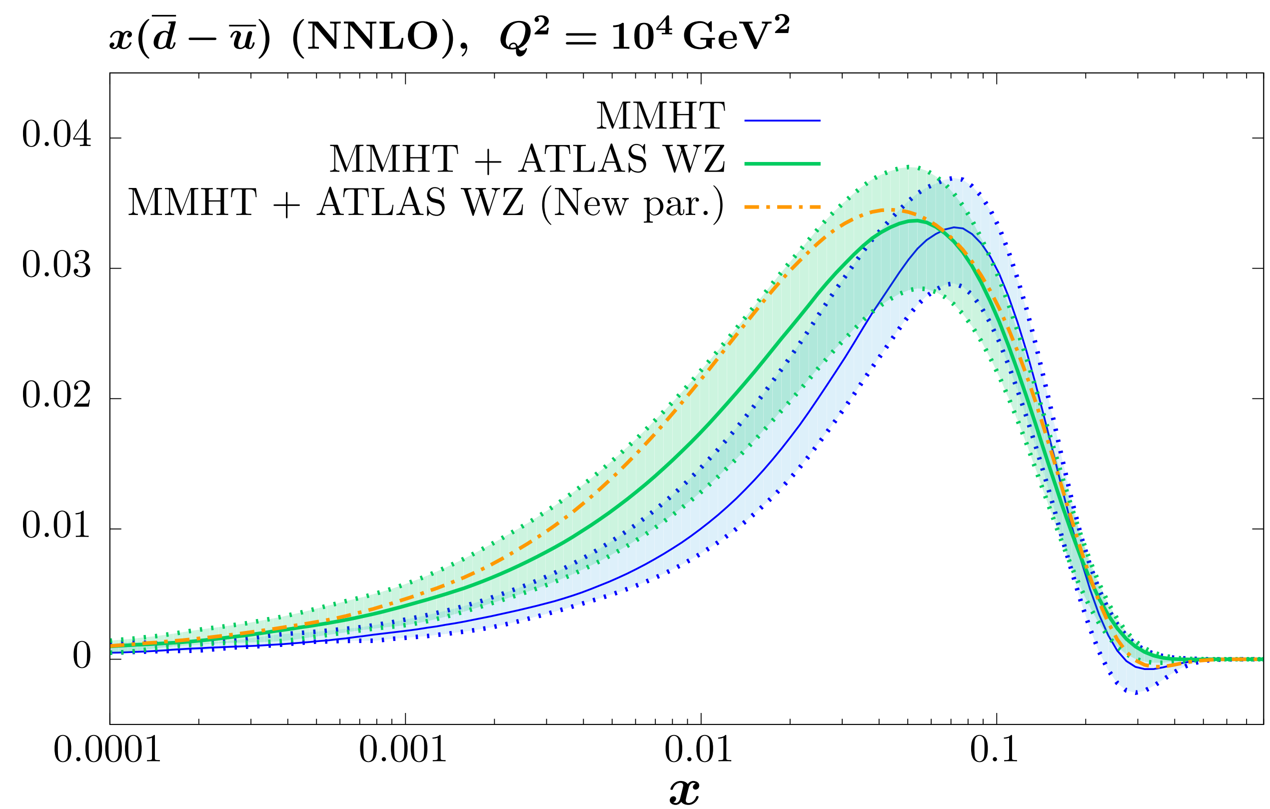
$$(\bar{d} - \bar{u})(x, Q_0^2) = A(1-x)^{\eta_{sea}+2} x^{\delta}(1 + \gamma x + \Delta x^2),$$

- In light of increasingly constraining LHC data, extend to Chebyshev basis:

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

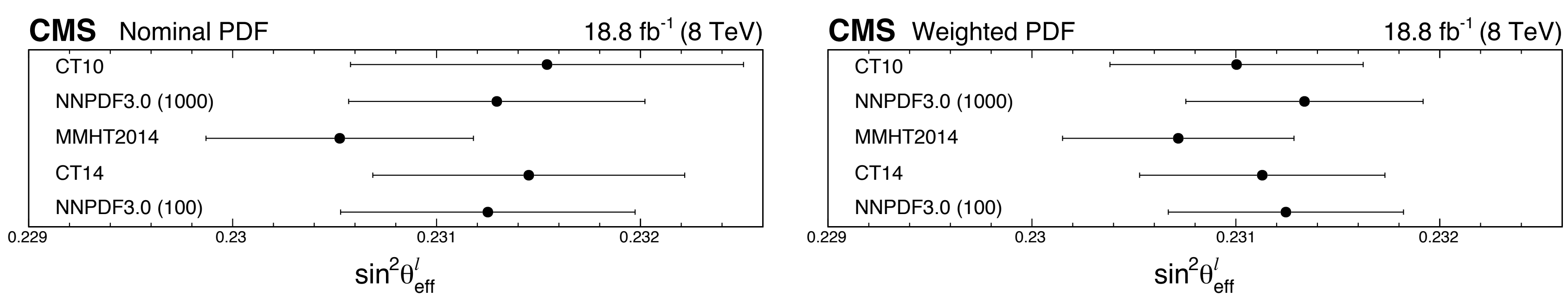
- Global fit (inc. LHC + ATLAS WZ) χ^2 improves by ~ 10 units with ~ 5 in E866 DY asymmetry.

- New $\overline{d} - \overline{u}$ similar to old, though clearly on edge of uncertainty in some regions. Outside at high x .



Summary/Points for Discussion

- Impact on LHC data (W, Z…) on recent MMHT fits clear. Note CMS 8 TeV PDF reweighting gives relatively mild (though not negligible) improvement in uncertainties:
    - How will this look with updated set(s)?
    - And in a full refit?



- Open questions related to breakdown of uncertainties, i.e. tolerance criteria applied by CT/MMHT vs. NNPDF:
    - What is the main driver of the tolerance (inconsistent data/ theory vs. parameterisation)?
    - Why are CT/MMHT & NNPDF errors similar?
- A benchmarking exercise (e.g. HERA + LHC DY + …) well motivated here.

Summary/Points for Discussion

- Impact from photon-initiated production under good control, no longer significant issue.
- Contribution of uncertainty due to missing higher order in pQCD theory not currently included in PDFs. May be increasingly relevant.
- After refitting, ATLAS W,Z and neutrino-induced dimuon data can be ~ accommodated (albeit with some tension). Impact of NNLO corrections to dimuon to be studied. Open question of CMS W + c.
- Other points to unify - quark masses, 68% quoted, question of IC…

Thank you for listening!