MMHT PDFs: plans and ongoing work

Lucian Harland-Lang, University College London

Parton distributions for the LHC
Benasque, Spain, 15 Feb 2015

In collaboration with Alan Martin, Patrick Motylinski and Robert Thorne

and thanks to Ben Watt, Graeme Watt and James Stirling

MMHT14 PDFs

Parton distributions in the LHC era: MMHT 2014 PDFs

L. A. Harland-Lang[a,b], A. D. Martin[b], P. Motylinski[a] and R.S. Thorne[a]

[a] Department of Physics and Astronomy, University College London, WC1E 6BT, UK
[b] Institute for Particle Physics Phenomenology, Durham University, DH1 3LE, UK

Abstract

We present LO, NLO and NNLO sets of parton distribution functions (PDFs) of the proton determined from global analyses of the available hard scattering data. These MMHT2014 PDFs supersede the 'MSTW2008' parton sets, but are obtained within the same basic framework. We include a variety of new data sets, from the LHC, updated Tevatron data and the HERA combined H1 and ZEUS data on the total and charm structure functions. We also improve the theoretical framework of the previous analysis. These new PDFs are compared to the 'MSTW2008' parton sets. Almost always the PDFs, and the predictions, are within one standard deviation of those of MSTW2008. The major changes are the $u-d$ valence quark difference at small x due to an improved parameterisation and, to a lesser extent, the strange quark PDF due to the effect of some LHC data and a better treatment of the $D \to \mu$ branching ratio. We compare our MMHT PDF sets with those of other collaborations; in particular with the NNPDF3.0 sets, which are contemporary with the present analysis.

MMHT14 PDFs

- New LO, NLO and NNLO PDF sets released - successor to MSTW08.
- Theoretical updates:

arXiv:1211.1215

  - Extended parameterization in terms of Chebyshev polynomials (c.f. MSTWCPdeut).
  - Parameterization of deuteron corrections, parameters determined from fit.
  - Multiplicative error treatment.
  - Updated nuclear corrections.
  - "Optimal" GM-VFNS used.
  - Various other changes, e.g. $B_\mu \equiv B(D \to \mu)$ now input (with error) in fit.
- New data: Cutoff: data published before 2014
  - HERA Run-I updates, not Run-II (wait until combination published).
  - Tevatron updates (W and Z data).
  - Range of LHC data (W, Z, $t\bar{t}$, jets) now included.
- MSTW08/MMHT14 differences generally small, with some exceptions (mainly from updated theory updates).

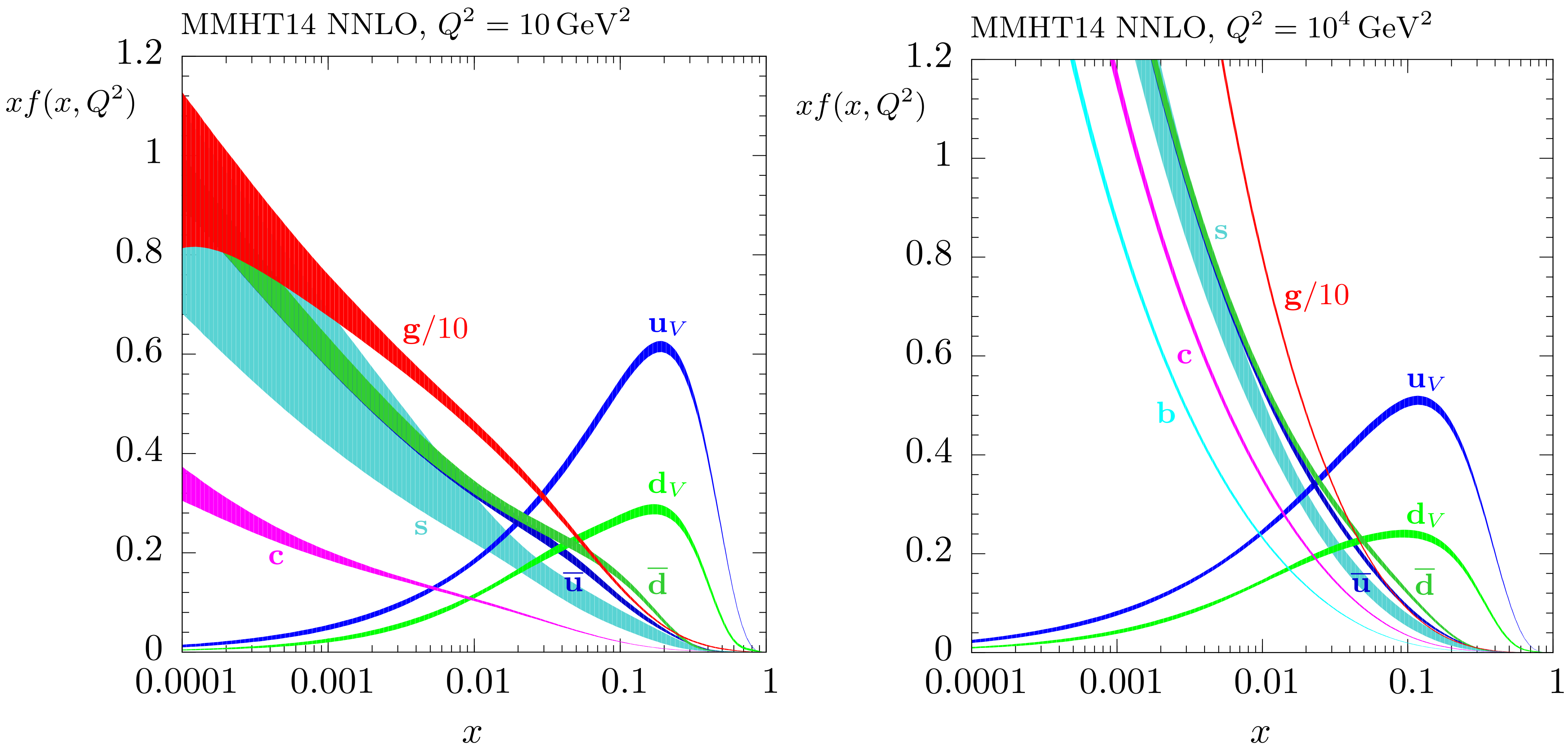
MMHT14 PDFs

- Error sets with 25 eigenvector pairs available for (close to) best fit $\alpha_S(M_Z^2) = 0.135, 0.120, 0.118$ at LO, NLO and NNLO respectively. In addition, NLO error set available at $\alpha_S(M_Z^2) = 0.118$.

- In addition, central fits for short range of α_S values available:
  - LO : $\alpha_S(M_Z^2) = 0.134, 0.135, 0.136$
  - NLO: $\alpha_S(M_Z^2) = 0.117, 0.118, 0.119, 0.120, 0.121$
  - NNLO: $\alpha_S(M_Z^2) = 0.117, 0.118, 0.119$

- Allows α_S variation in vicinity of default to be examined, and error to be calculated by adding in quadrature.
- Full study of relationship between α_S and PDFs will be a subject of follow-up publication.

MMHT14 PDFs



- Available in LHAPDF 5 and 6 and at

http://www.hep.ucl.ac.uk/mmht

where standalone code Fortran code, C++ wrapper, and mathematica implementations are also available.

MMHT14: plans

- Immediate plans:
  - Detailed study of α_S variation, globally and for different data sets.
  - Release of fixed flavour PDFs, study of $m_{c,b}$ dependence.
- Longer term:
  - Already published LHC data not included in MMHT14 fit, and more to come.
  - HERA Run-II combination to be published.
  - NNLO calculations for differential $t\bar{t}$ (public) and for jets anticipated quite soon.

$\longrightarrow$ Can expect a new PDF release on a $O(1\,\text{year})$ timescale.

- Other studies in earlier stages:
  - QED contributions: an update to MRST2004QED.
  - PDFs at high x: a phenomenological study.

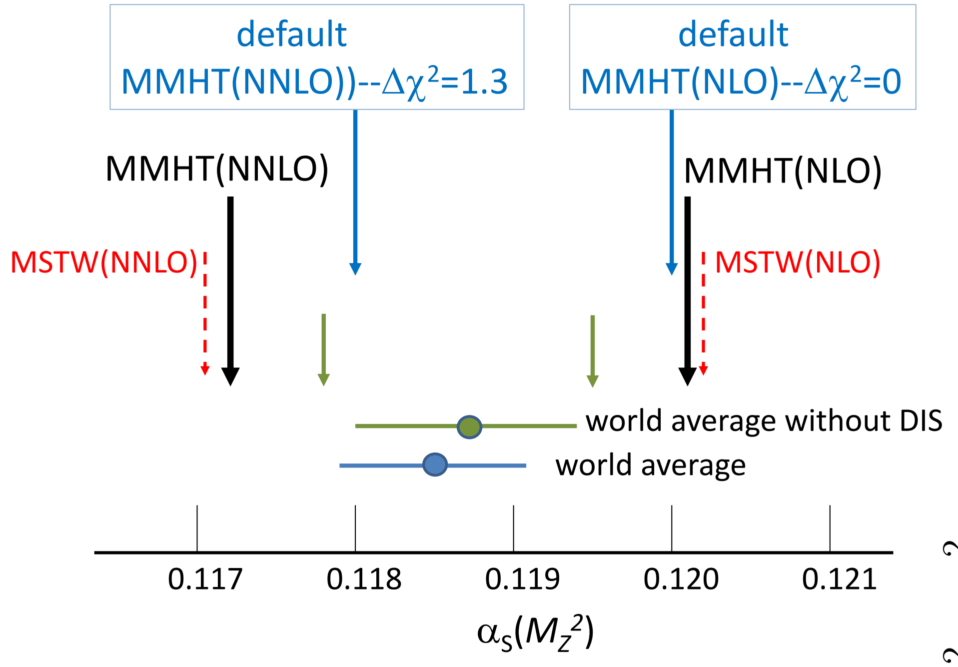
α_S uncertainty: follow-up study

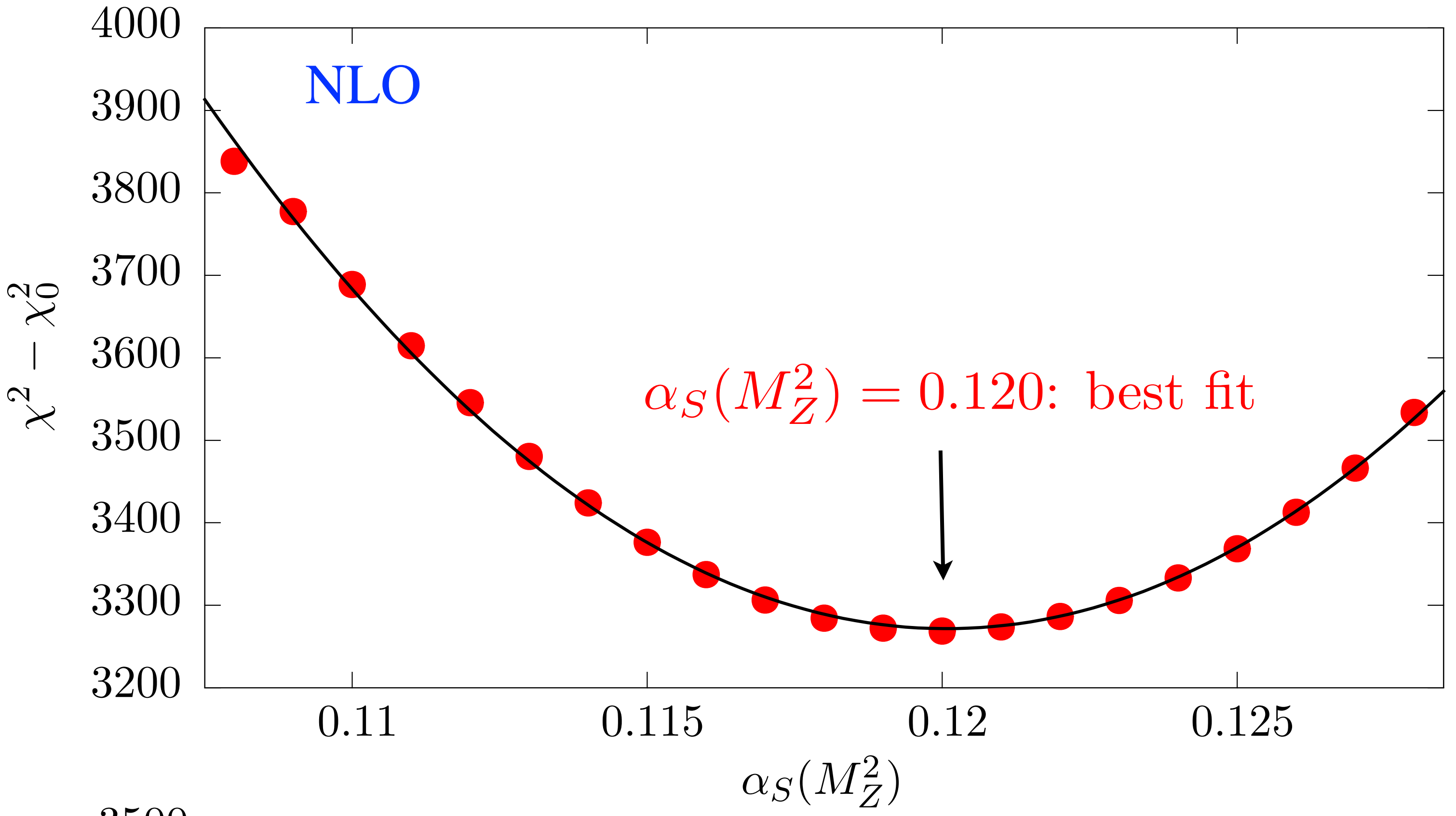
- In current release, central PDF sets given for short range of values (increments of 0.001). Allows α_S variation in vicinity of best first to be examined for a given observable and for uncertainty to be calculated by adding in quadrature. c.f. CTEQ study - arXiv:1004.4624

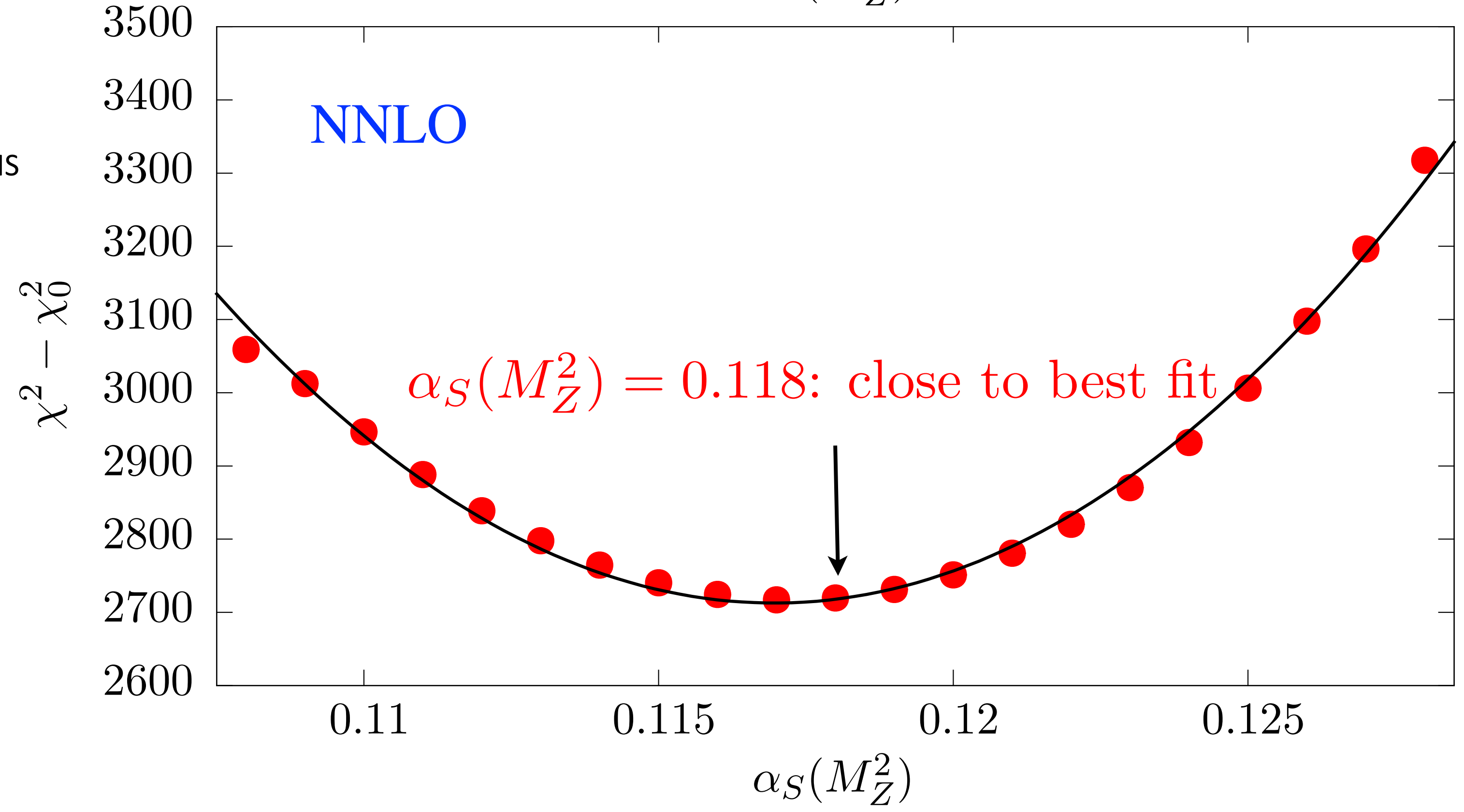
- Study in preparation: detailed analysis of α_S variation for individual data sets and determination of uncertainty according to dynamical tolerance criteria.

α_S : global variation

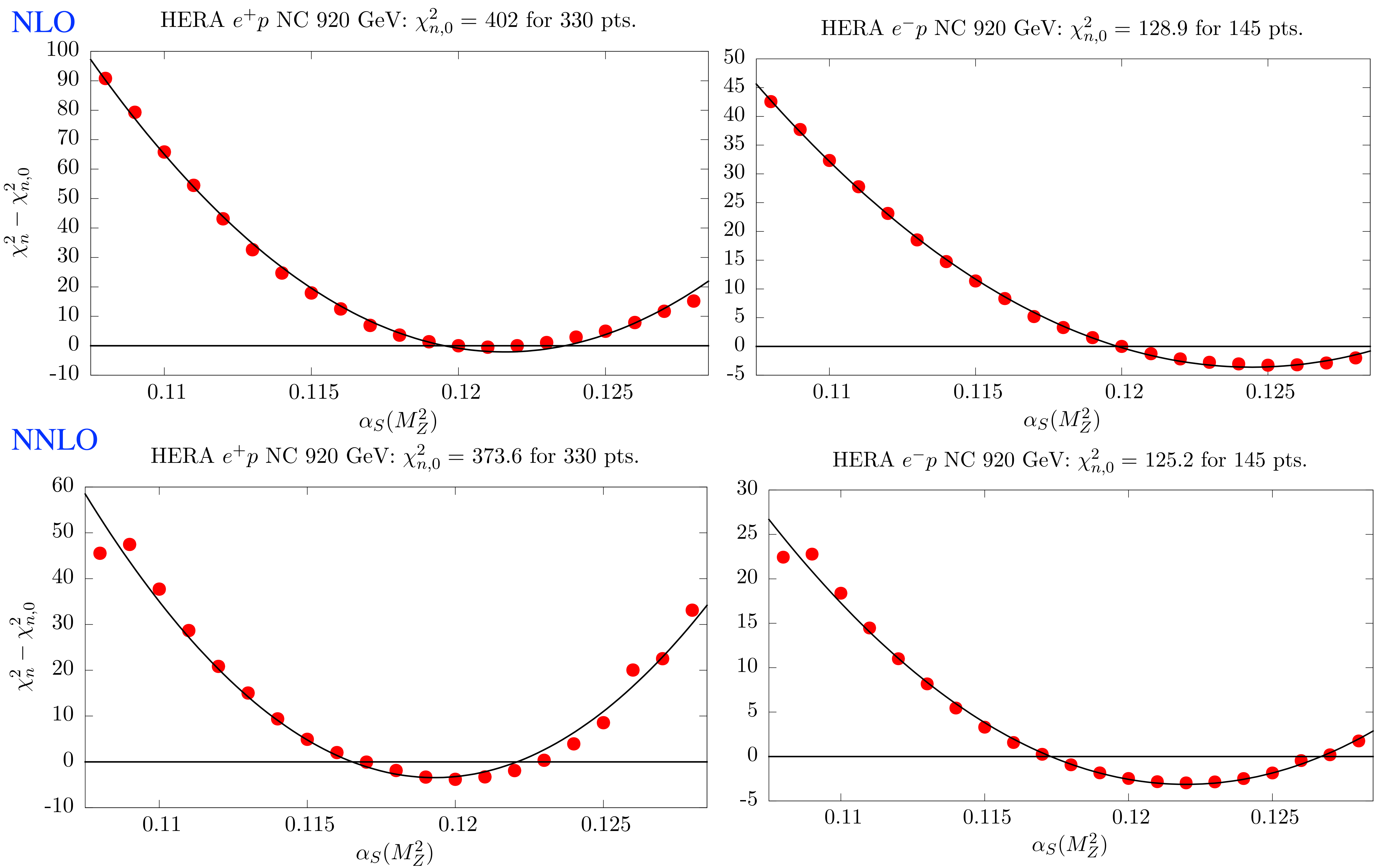
Consider *global* χ^2 variation with α_S ...







Individual data sets

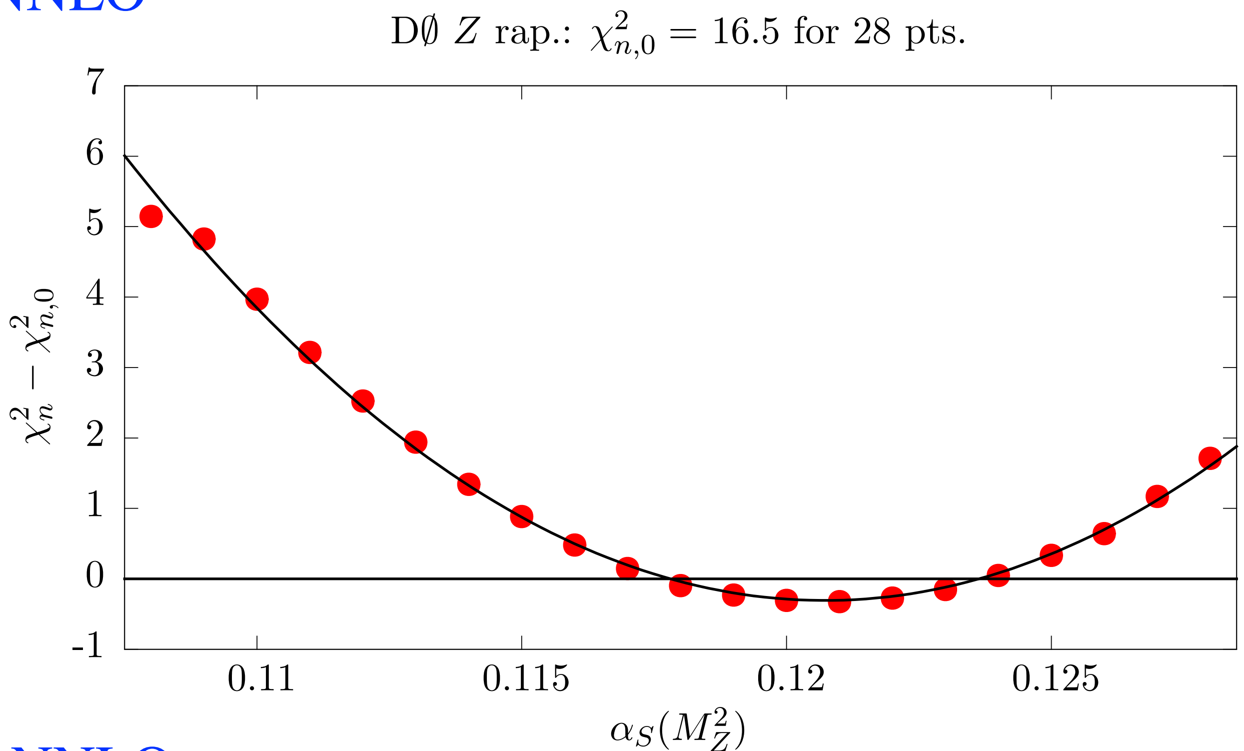


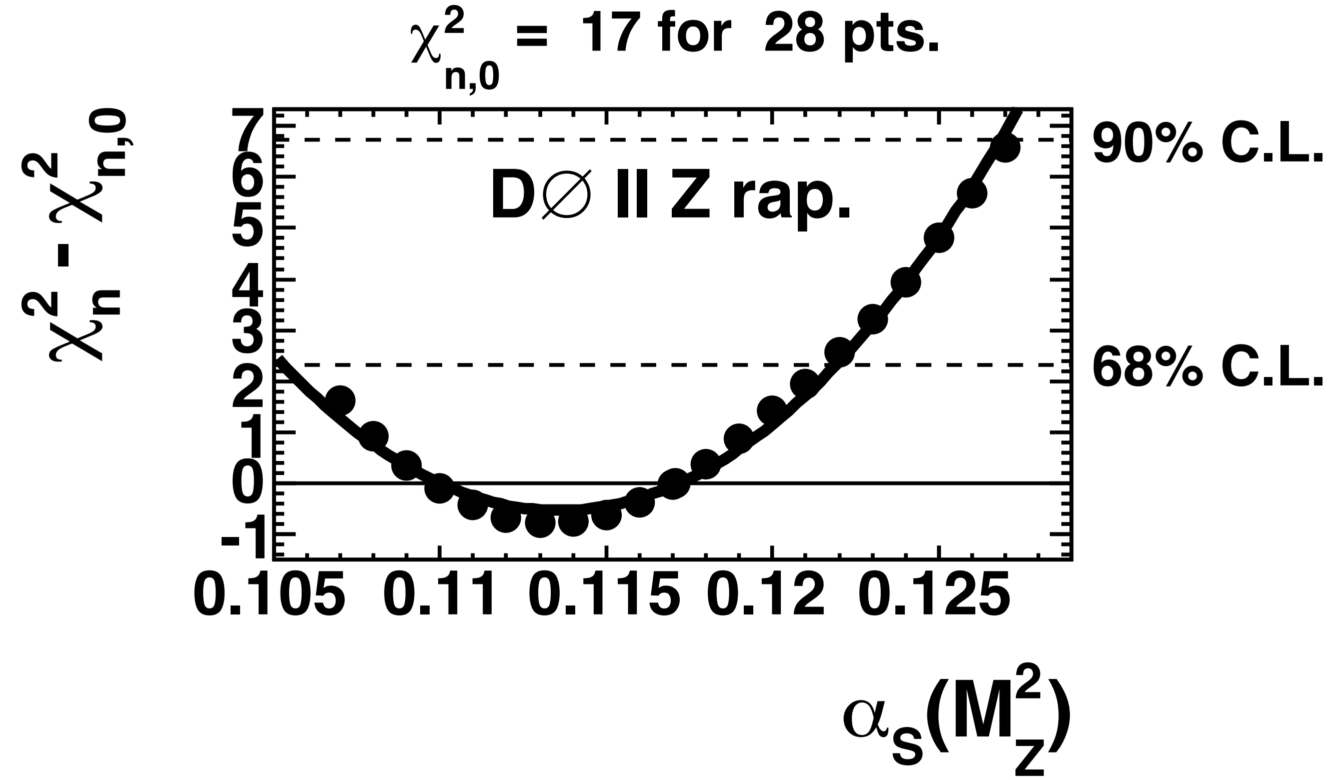
HERA Run-I combined NC: e^+p min. similar to global min., e^-p a bit higher.

Comparison with MSTW08. Generally similar, but some differences.

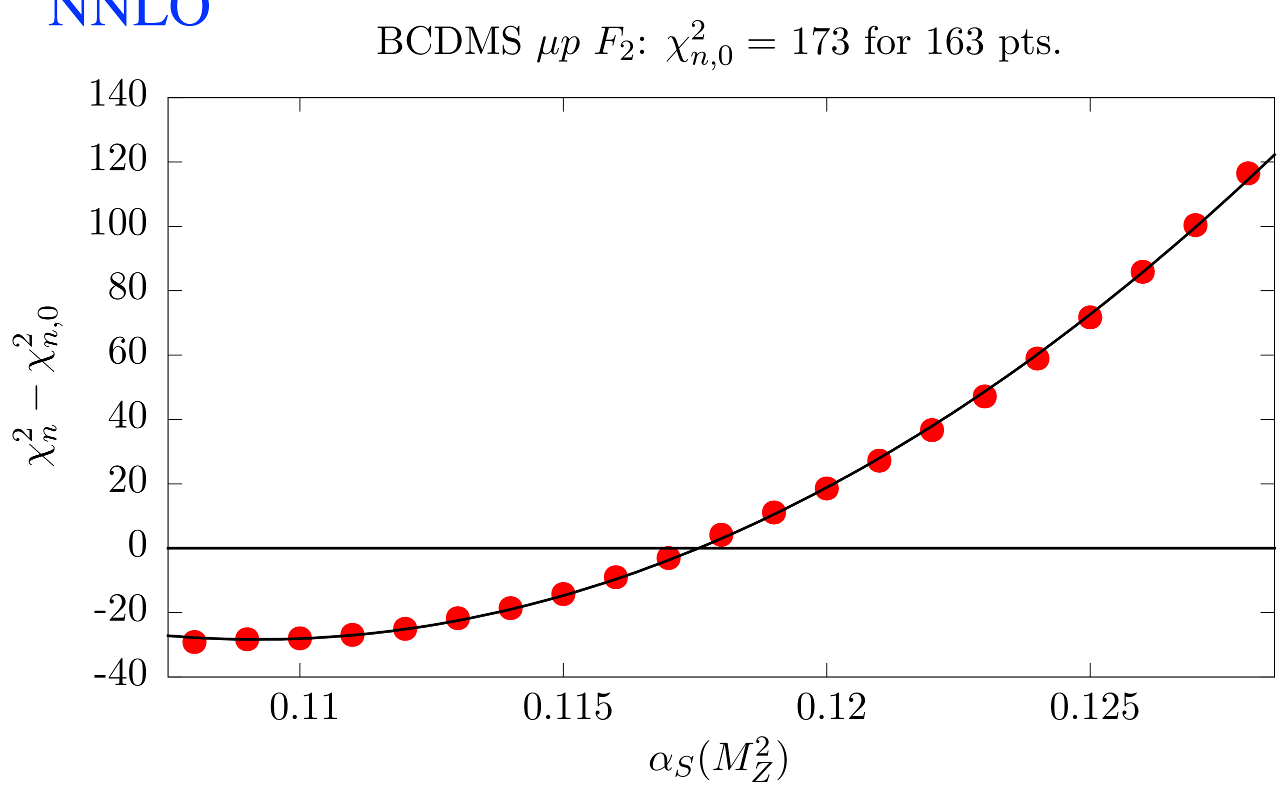
arXiv:0905.3531

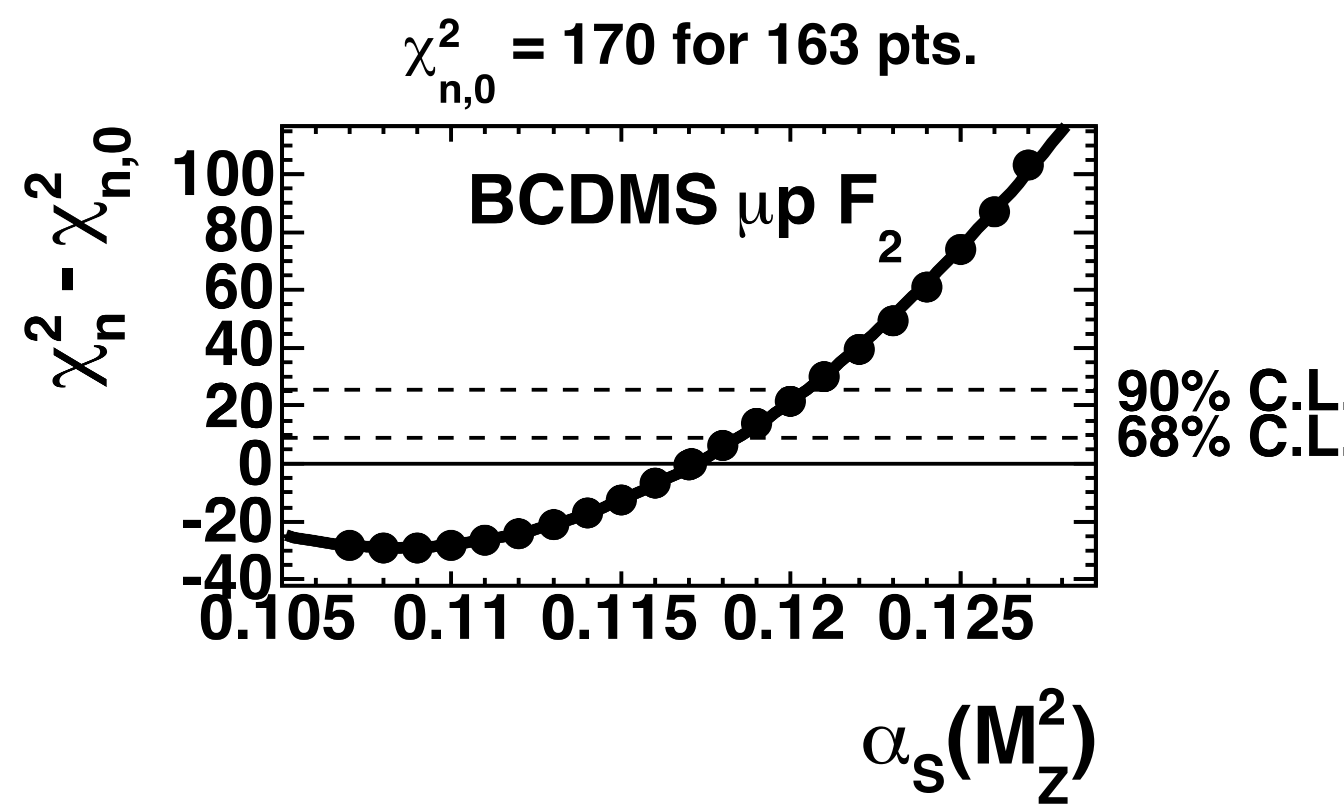
NNLO





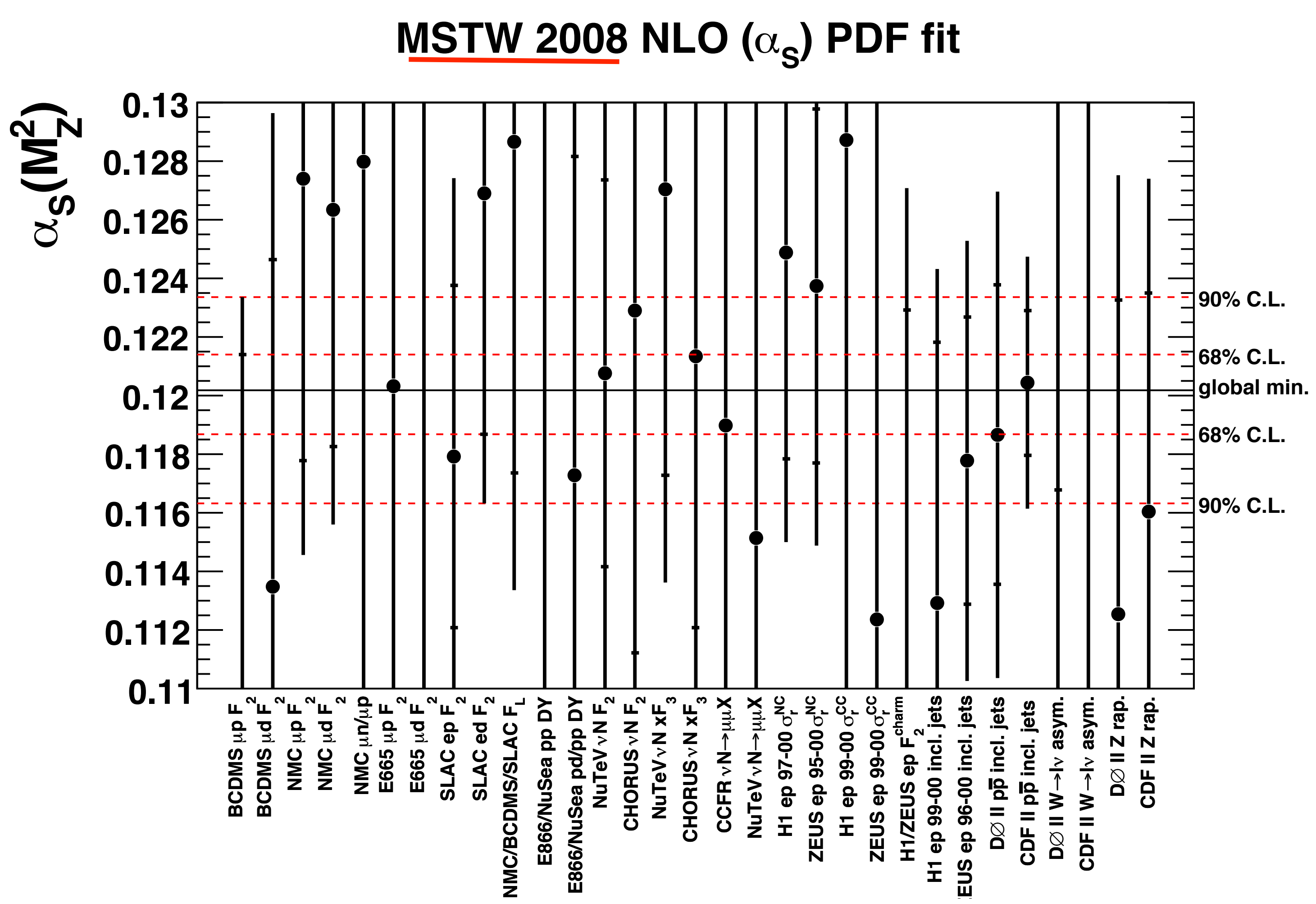
NNLO



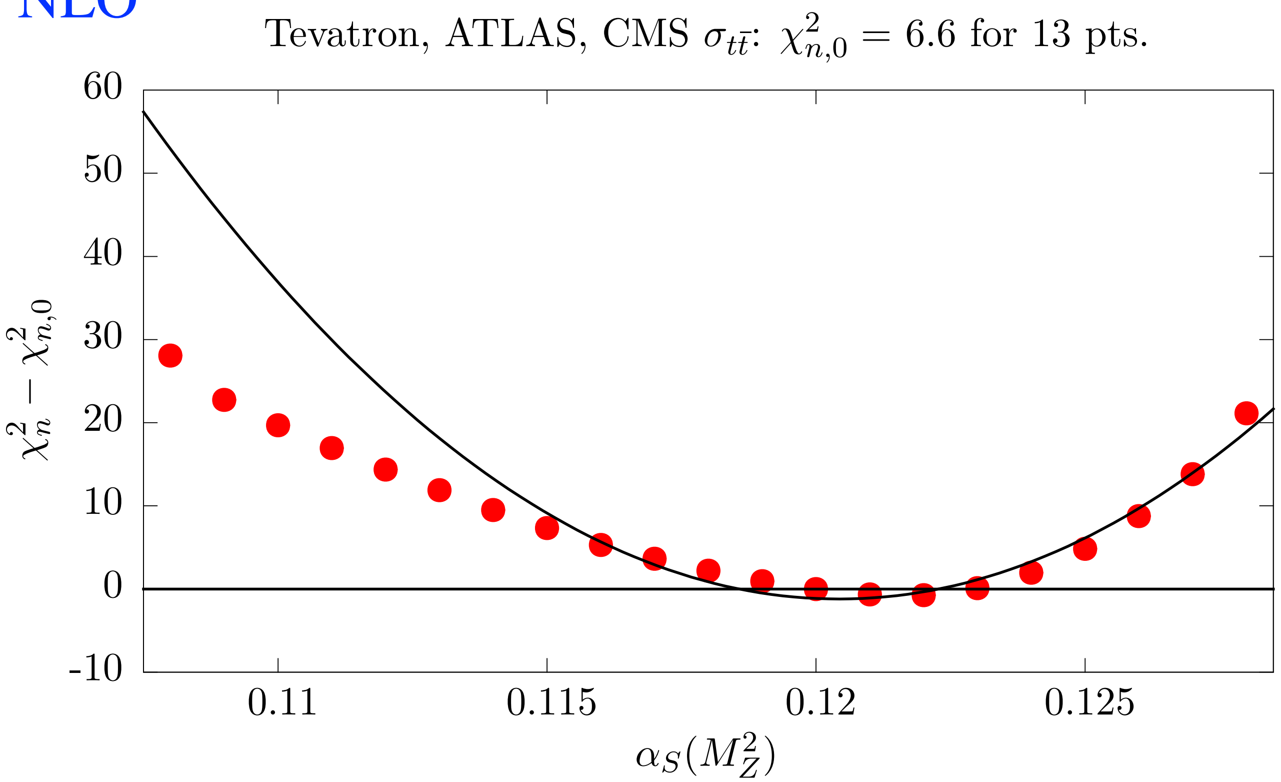


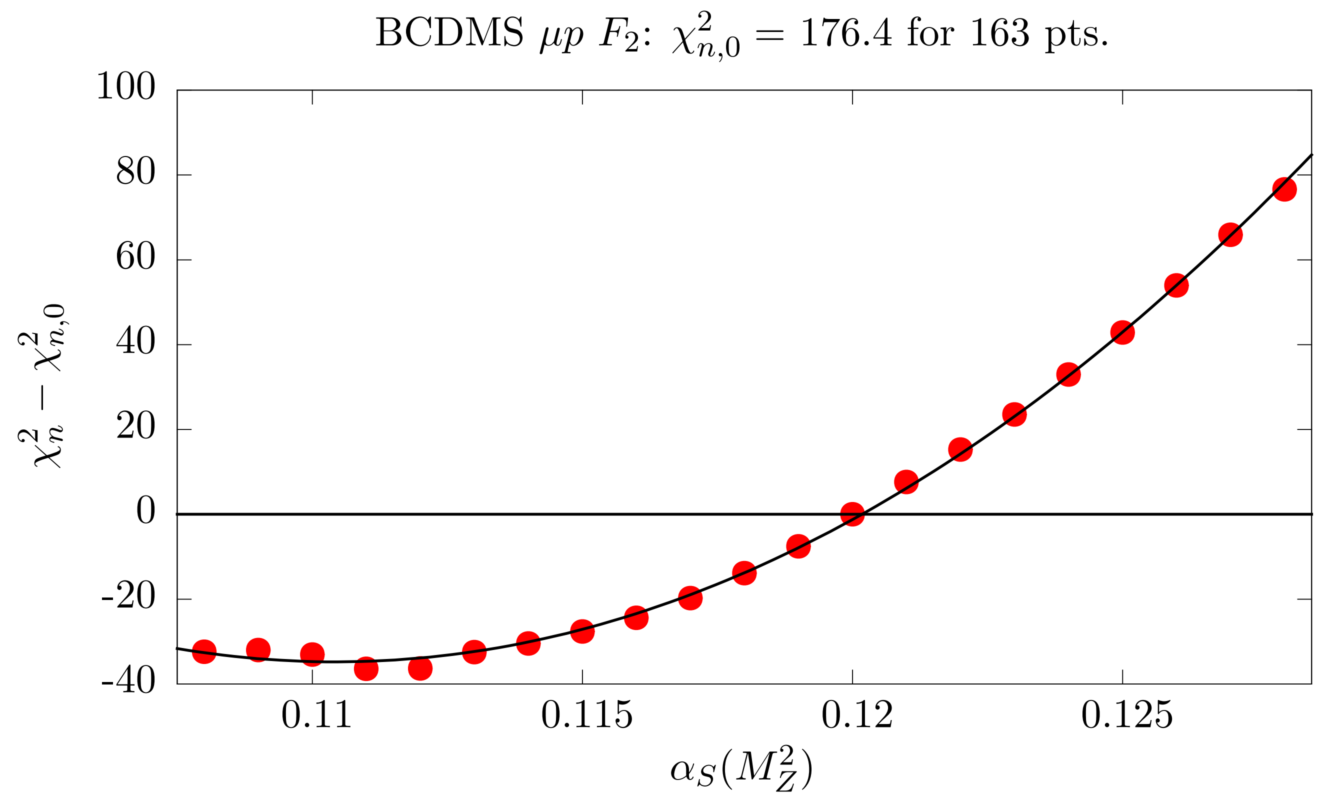
Uncertainty evaluation

- As in arXiv:0905.3531, use ‘dynamical tolerance’ to determine uncertainty on α_S .
- Upward/downwards variation determined such that all data sets are described within their 68% (90%) C.L.
- Implies that one data set will determine precise upper/lower limit, but generally next best limit will be close.

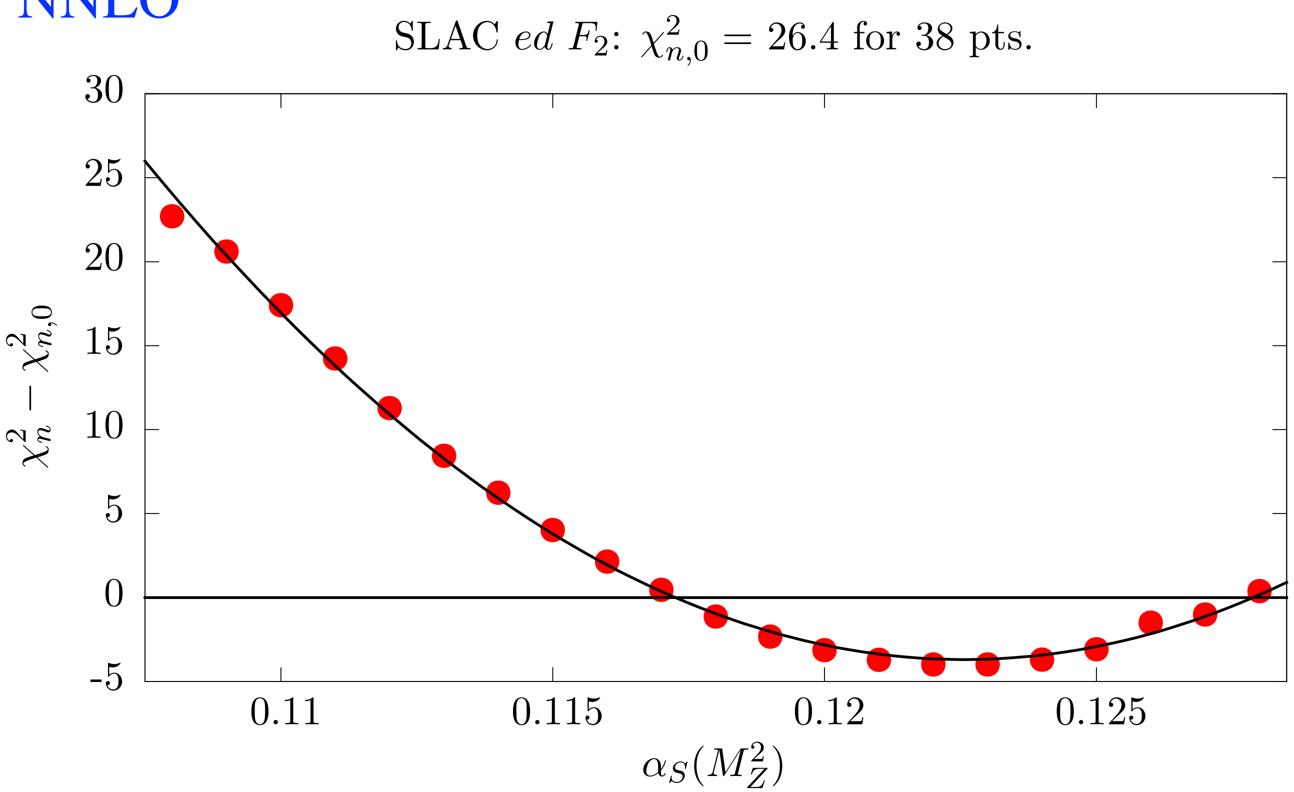


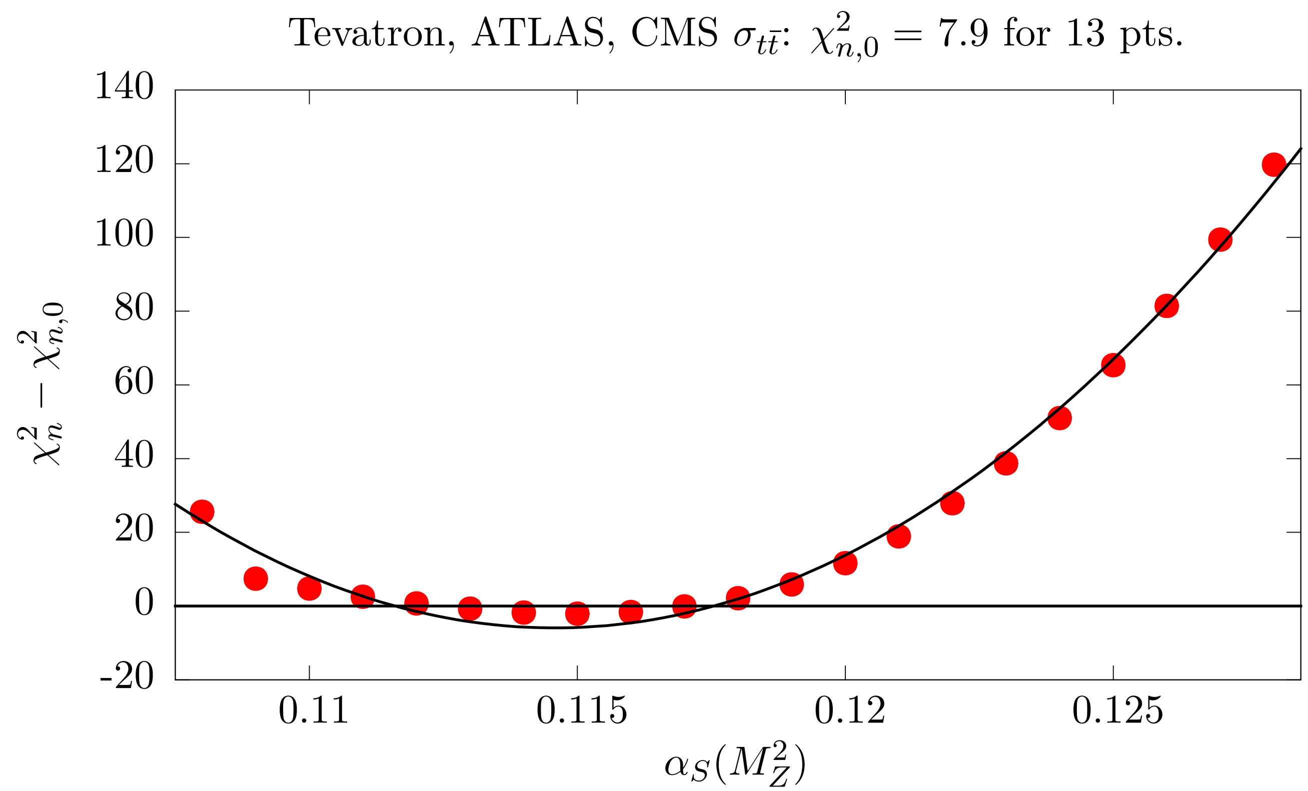
NLO





NNLO





More constraining data sets on α_S uncertainty.

- Initial estimate of error on α_S indicate that $t\bar{t}$ data constrains variation in one direction at both NLO and NNLO.

- However, effect of $t\bar{t}$ data on central α_S value is minimal.

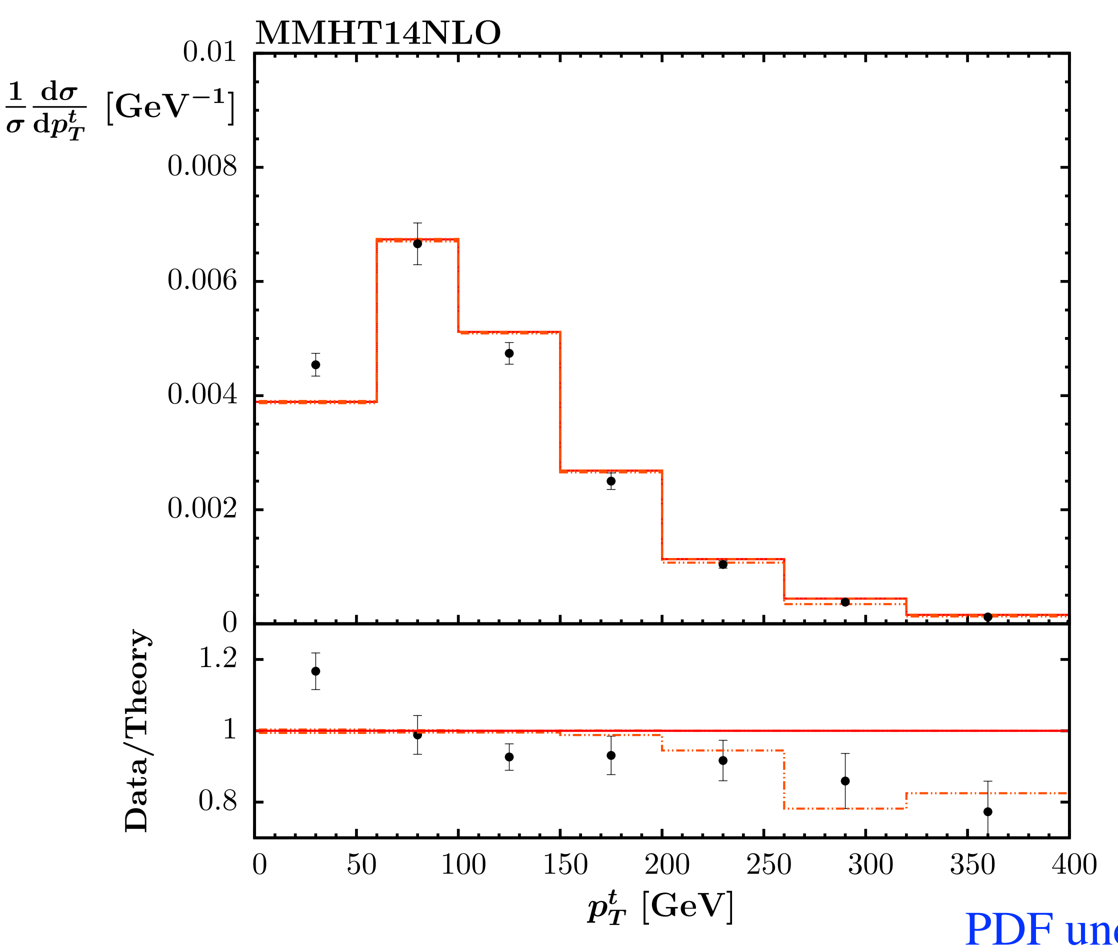
- In fit, $m_t = 172.5$ GeV is taken (as in data), but with error of 1 GeV. Final values determined from fit are $m_t(\mathrm{NLO}, \mathrm{NNLO}) = 171.7, 174.2$ GeV while world average is $m_t = (173.34 \pm 0.76)$ GeV. Taking this instead of $m_t = (172.5 \pm 1)$ GeV will effect α_S error determination.

- $\alpha_S - t\bar{t}$ correlation under study.

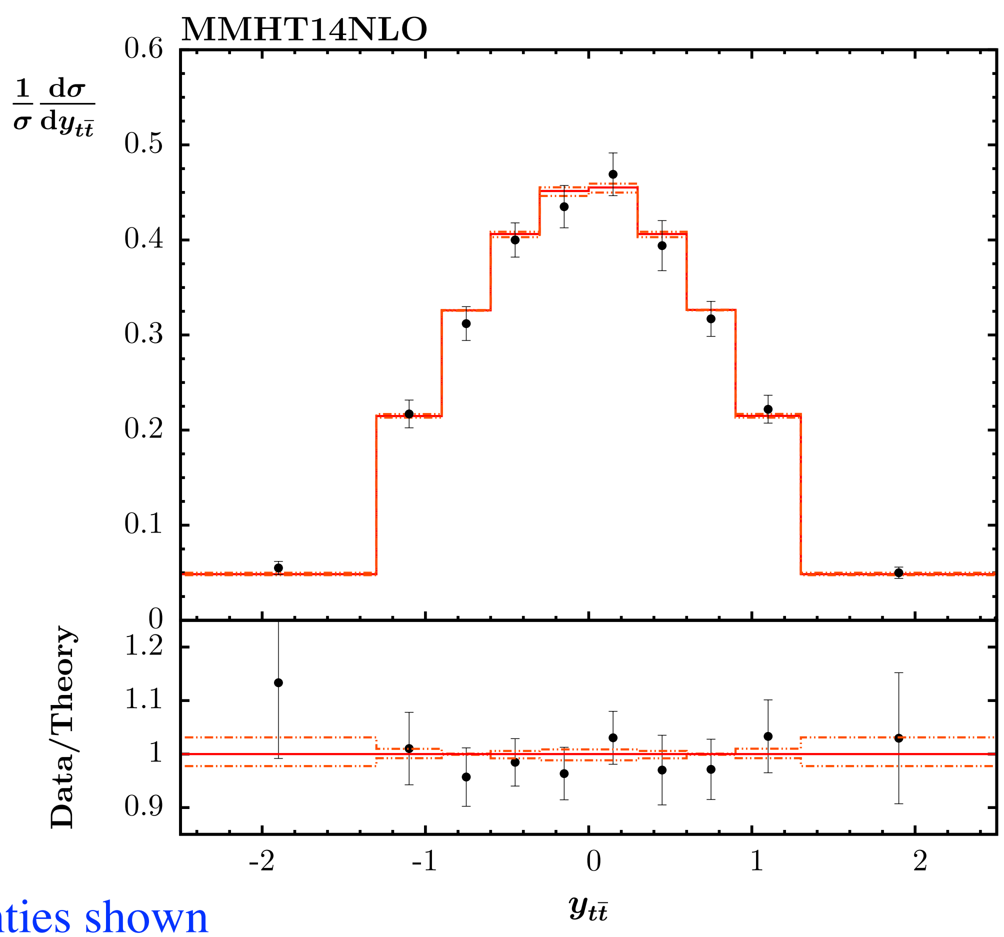
$t\bar{t}$ differential data comparison

- Variety of LHC data being released which are not included in the fit as they do not meet cutoff date, or due to theory limitations (or both).
- e.g. CMS (Eur.Phys.J. C73, 2339 (2013)) measurement of $t\bar{t}$ production.
- Currently NNLO theory only available for total cross section. Suggestions that NLO theory may be deficient for differential observables $\Rightarrow$ omit from fit at current time.

$p_\perp$ dist. - described quite poorly (missing higher orders?)



Rapidity dist. - described well



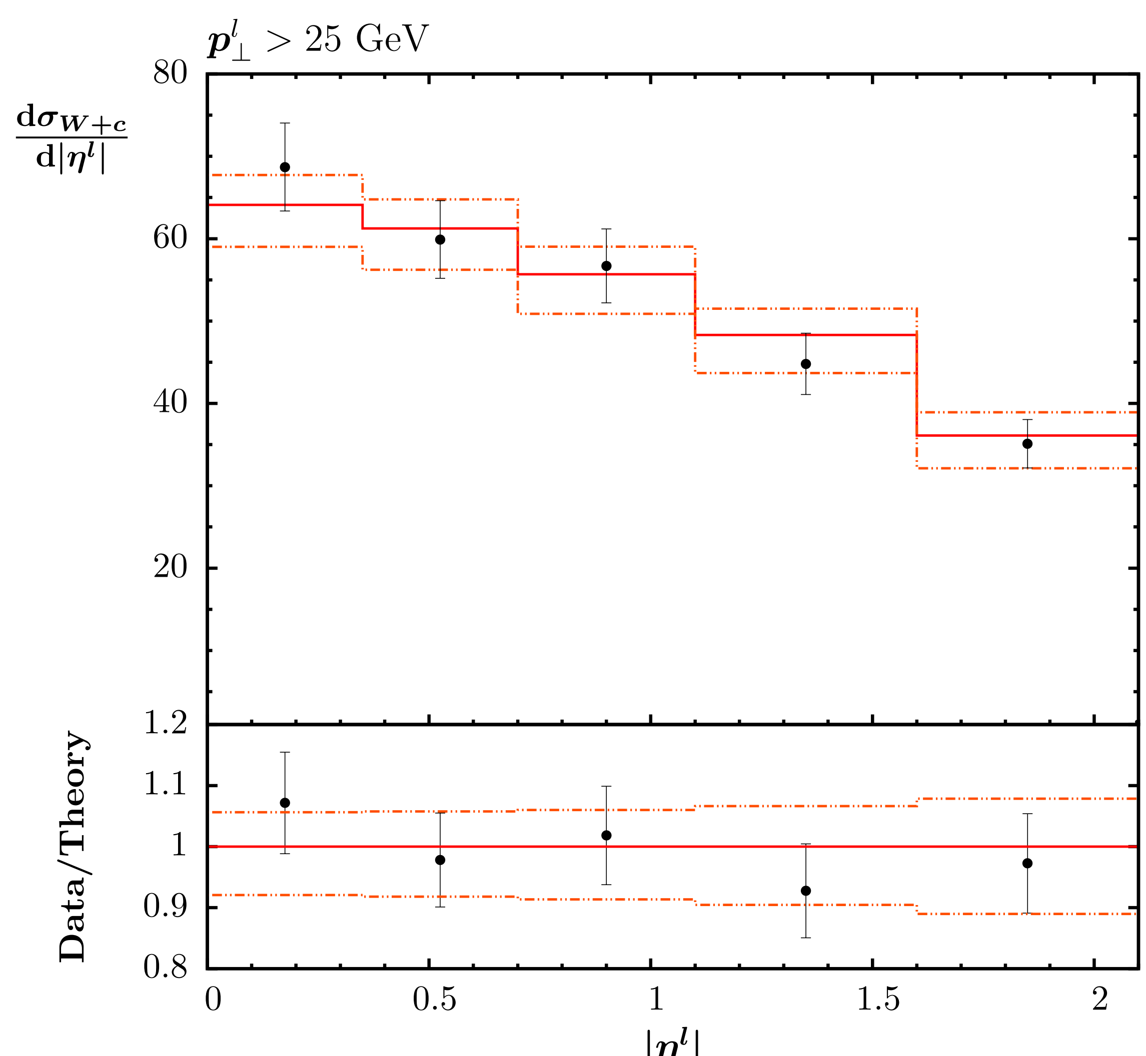
PDF uncertainties shown

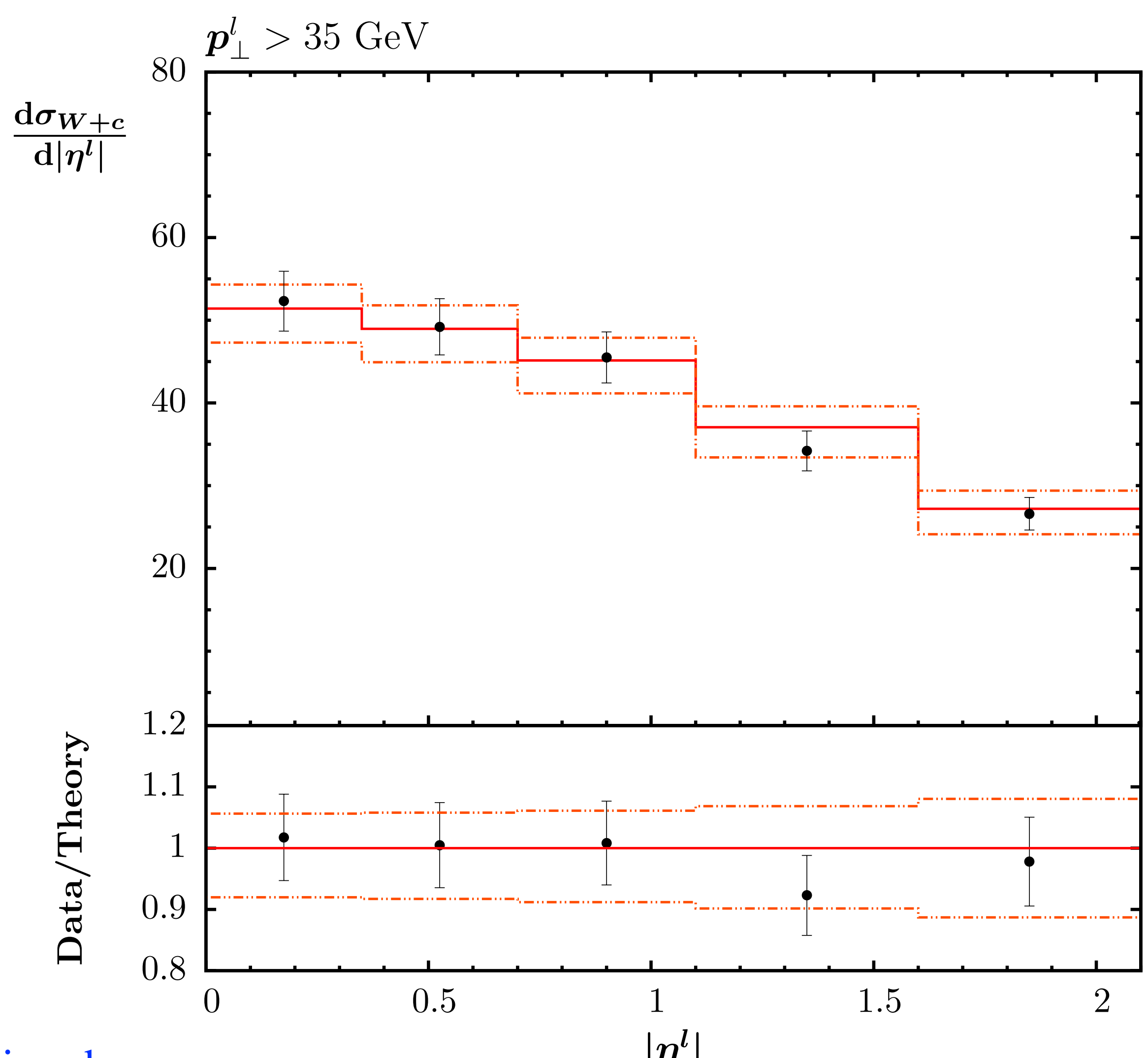
$W + c$ differential data comparison

- CMS W+c data (JHEP 02 (2014) 013) not included, as published in 2014.

	GeV	data	MSTW2008	MMHT2014
$\sigma(W+c)$	$p_T^{\rm lep} > 25$	$107.7 \pm 3.3(\text{stat.}) \pm 6.9(\text{sys.})$	102.8 ± 1.7	110.2 ± 8.1
$\sigma(W+c)$	$p_T^{\rm lep} > 35$	$84.1 \pm 2.0(\text{stat.}) \pm 4.9(\text{sys.})$	80.4 ± 1.4	86.5 ± 6.5

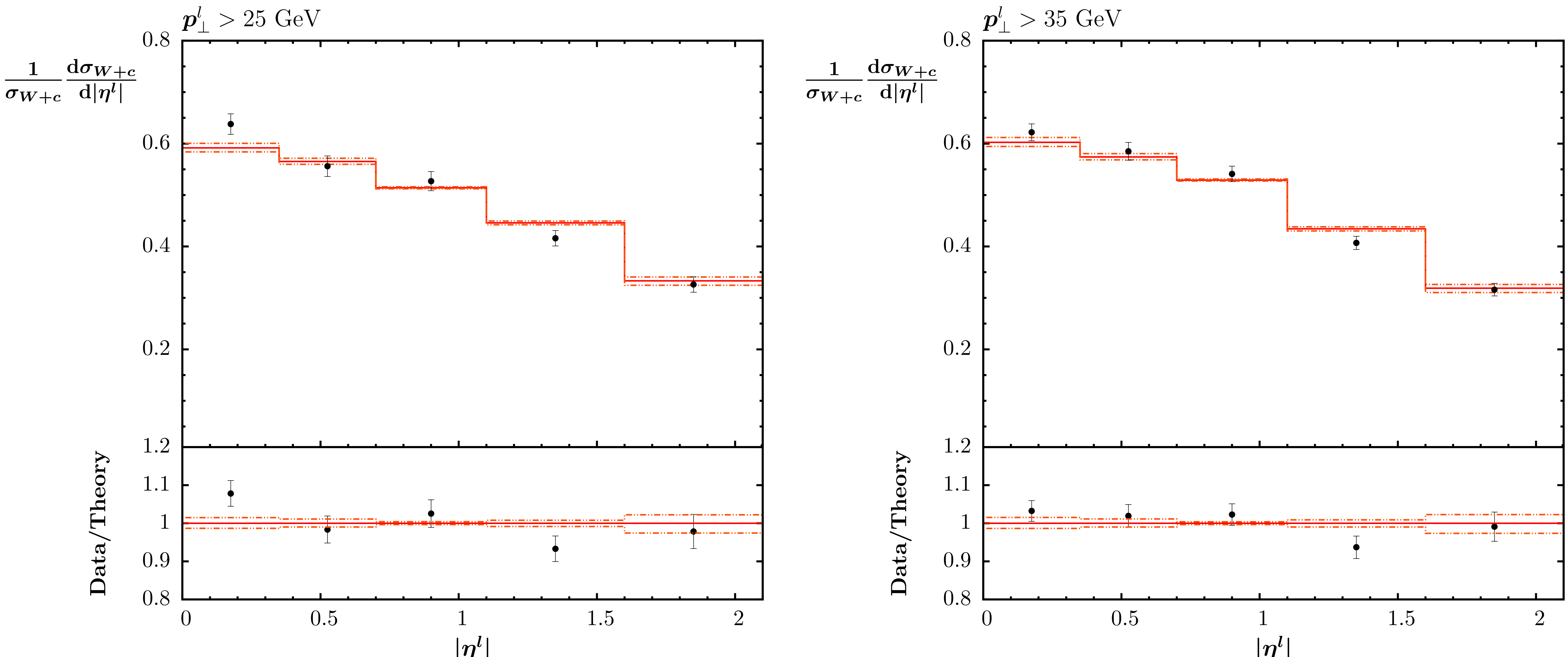
- MMHT14 gives good description of absolute cross section and η^l distribution but with large errors (due to $s + \bar{s}$ uncertainty).





PDF uncertainties shown

• PDF (and experimental) uncertainties smaller in normalized distributions. Description fairly good.



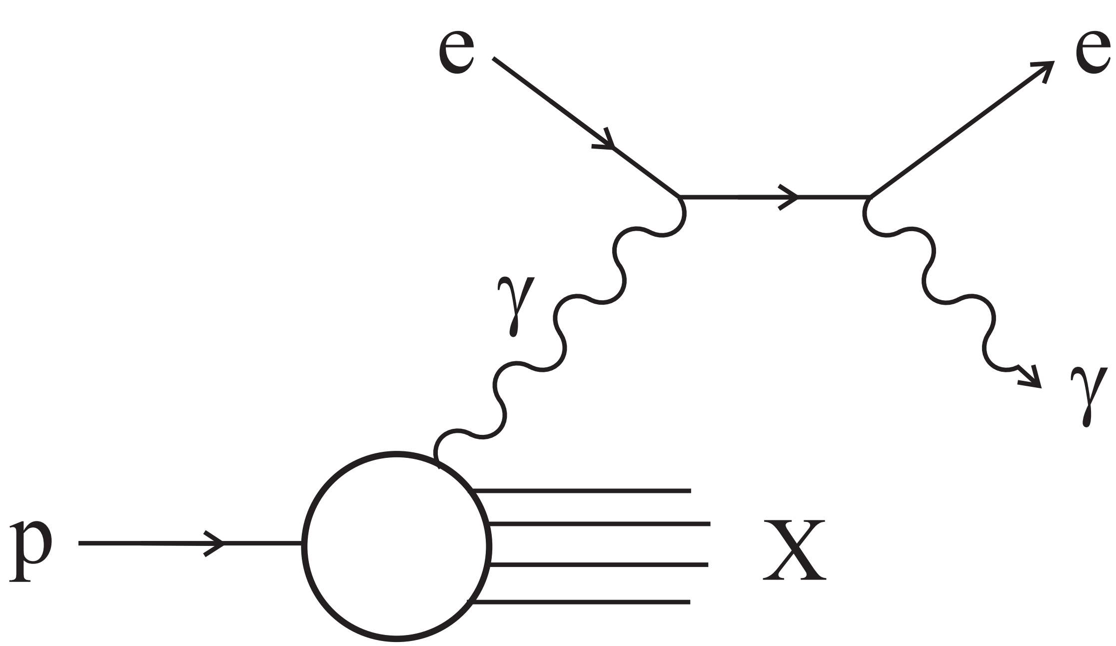
PDF uncertainties shown

PDFs with QED contributions

- In era of high precision phenomenology at the LHC: PDFs determined to NNLO in QCD an important part of this.
- However at this level of accuracy it is important to properly account for electroweak corrections. At LHC can be relevant for a range of processes (W, Z, WH, ZH, WW, $t\bar{t}$, jets...).

$\longrightarrow$ For consistent treatment need PDFs which incorporate QED:

- QED corrections to DGLAP evolution (isospin symmetry broken).
- Introduction of photon PDF, $\gamma(x, Q^2)$.



$$\frac{\partial\gamma(x,Q^2)}{\partial \log Q^2} = \frac{\alpha}{2\pi}\int_x^1 \frac{dy}{y}\left(P_{\gamma\gamma}\otimes\gamma + \sum_1 e_i^2 P_{\gamma q}\otimes q_i\right)$$

PDFs and QED: past work

- MRST2004QED: first set to include QED contributions. Model assumed, with $\gamma(x, Q^2)$ generated by one-photon emission off valence quarks at LL:

$$
\begin{aligned}
\gamma^p(x, Q_0^2) &= \frac{\alpha}{2\pi}\left[\frac{4}{9}\log\left(\frac{Q_0^2}{m_u^2}\right)u_0(x) + \frac{1}{9}\log\left(\frac{Q_0^2}{m_d^2}\right)d_0(x)\right] \otimes \frac{1+(1-x)^2}{x} \\
\gamma^n(x, Q_0^2) &= \frac{\alpha}{2\pi}\left[\frac{4}{9}\log\left(\frac{Q_0^2}{m_u^2}\right)d_0(x) + \frac{1}{9}\log\left(\frac{Q_0^2}{m_d^2}\right)u_0(x)\right] \otimes \frac{1+(1-x)^2}{x}
\end{aligned}
$$

additional freedom from:

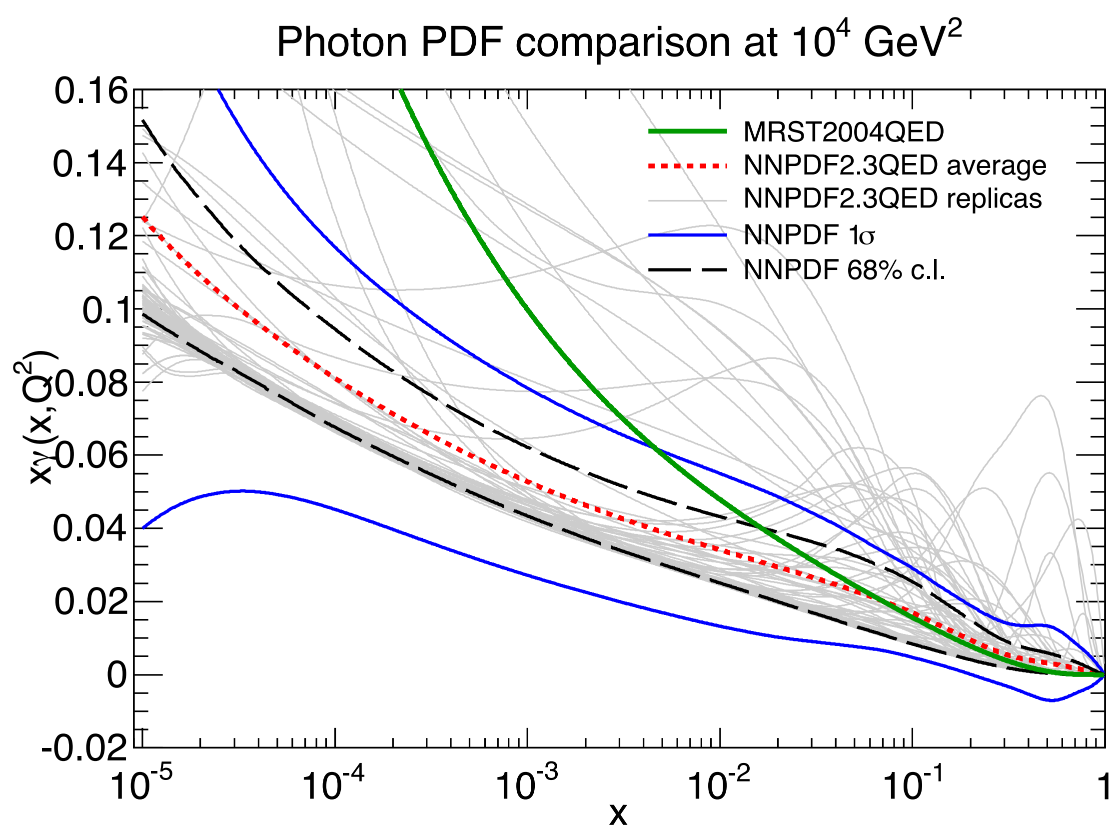
- Choice of quark mass (current/constituent?).
- Model of isospin violation. Naturally generated by evolution but can also include at starting scale, Q_0.

- Results compared to ZEUS measurement of isolated photon DIS (found to be consistent) but no fit performed.

PDFs and QED: other groups

- NNPDF2.3QED: first attempt at global fit to photon PDF:
  - No model assumption. General (positive definite) form.
  - $\gamma(x, Q^2)$ fitted to DIS only (weakly constrained), combined with NNPDF2.3 and then reweighted with LHC data (LHCb low mass DY, ATLAS W, Z and ATLAS high mass DY).
  - At lower x, disagreement with MRST2004QED develops as Q^2 increases above Q_0^2

- Preliminary CTEQ analysis:
  - 'Radiative ansatz', similar to MRST2004QED model, but with additional freedom.
  - Fit performed to ZEUS isolated photon DIS data.
  - Results consistent with NNPDF2.3QED, but lower than MRST2004QED.



PDFs and QED: MMHT plans

- Update of MRST2004QED set clearly due, and necessary.
- MMHT14: currently no EW corrections included in fit (e.g. in ATLAS high mass DY, LHCb DY...). Corrections not crucial with current experimental precision, but in future this will be less true.

$\longrightarrow$ Decision made to consistently include these in future work as part of 'MMHTQED' set.

PDFs and QED: MMHT plans

- Difference with NNPDF2.3QED at low x and CTEQ finding that 'current mass' ansatz fails to fit ZEUS data indicates MRST model may be too restrictive.
- However, important to use our understanding of (entirely perturbative) QED to guide choice, especially as limited constraints currently exist.

$\longrightarrow$ Consider MRST-based model, but with relaxed assumptions, i.e.

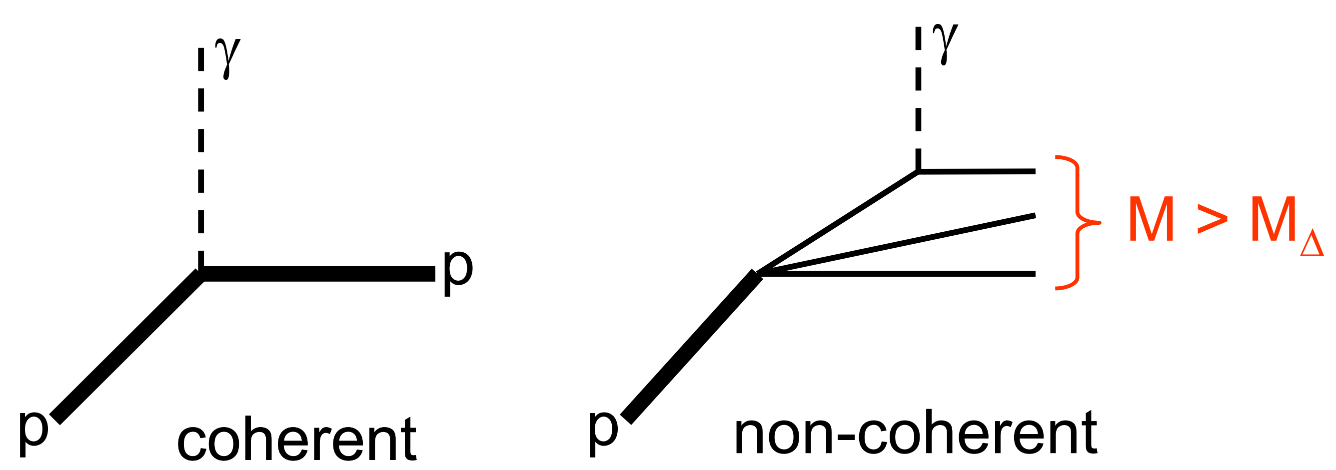
$$\begin{aligned}
\gamma^p(x,Q_0^2) &= \frac{\alpha}{2\pi}\left[\frac{4}{9}\log\left(\frac{Q_0^2}{m_u^2}\right)u_0(x)+\frac{1}{9}\log\left(\frac{Q_0^2}{m_d^2}\right)d_0(x)\right]\otimes\frac{1+(1-x)^2}{x}\\
\gamma^n(x,Q_0^2) &= \frac{\alpha}{2\pi}\left[\frac{4}{9}\log\left(\frac{Q_0^2}{m_u^2}\right)d_0(x)+\frac{1}{9}\log\left(\frac{Q_0^2}{m_d^2}\right)u_0(x)\right]\otimes\frac{1+(1-x)^2}{x}
\end{aligned}$$

With m_u, m_d as fit parameters (other freedom also to be explored).

- Same idea as prelim. CTEQ analysis.

PDFs and QED: other considerations

- Recent paper by Martin and Ryskin suggests other way in which theory input may need to be refined. arXiv:1406.2118
- Major part of $\gamma(x,Q^2)$ (in particular at low x) comes from 'coherent' emission, i.e. elastic process, due to EM charge of entire proton. Theoretically well understood process.

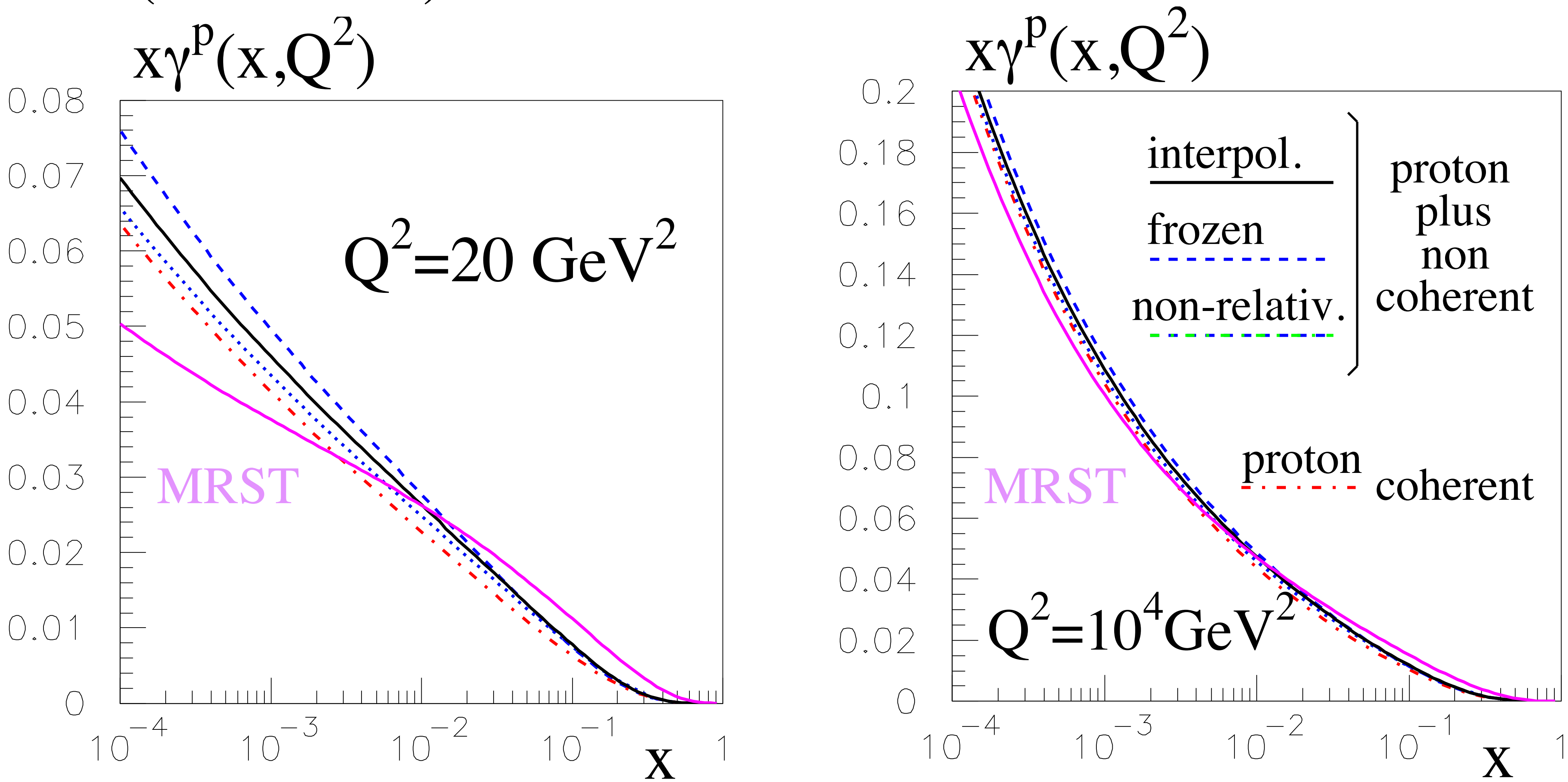


$$\gamma^N(x,Q_0^2) = \gamma^N_{\rm coh} + \gamma^N_{\rm incoh}$$

PDFs and QED: other considerations

- Coherent contribution about four times as large as incoherent at starting scale $\Rightarrow$ large effect.
- Tends to increase $\gamma(x, Q^2)$ at lower x (recall MRST2004QED already larger than NNPDF2.3QED at low x).

$\longrightarrow$ Will be very interesting to see goodness-of-fit when confronted with LHC (and HERA) data.

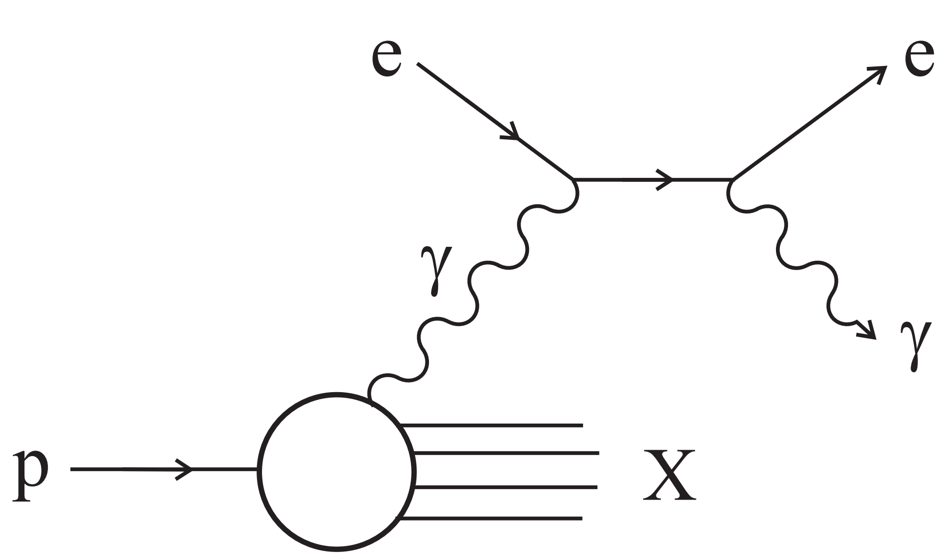


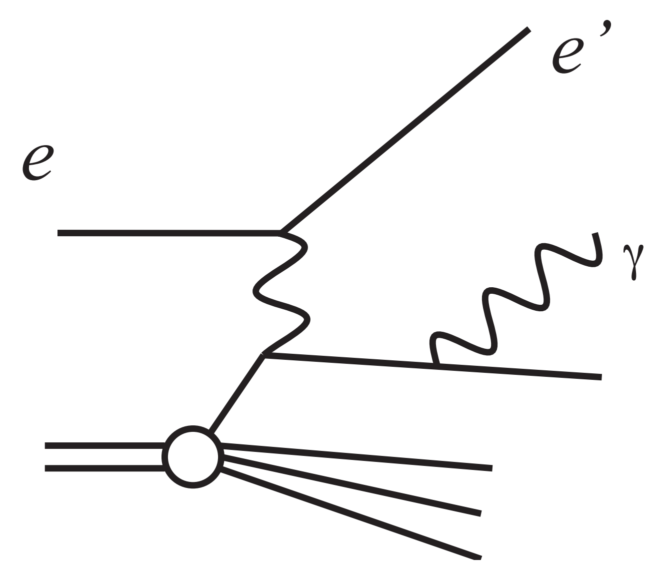
PDFs and QED: HERA

- H1 and ZEUS have measurements of isolated photon DIS

$$ep \to e\gamma + X$$

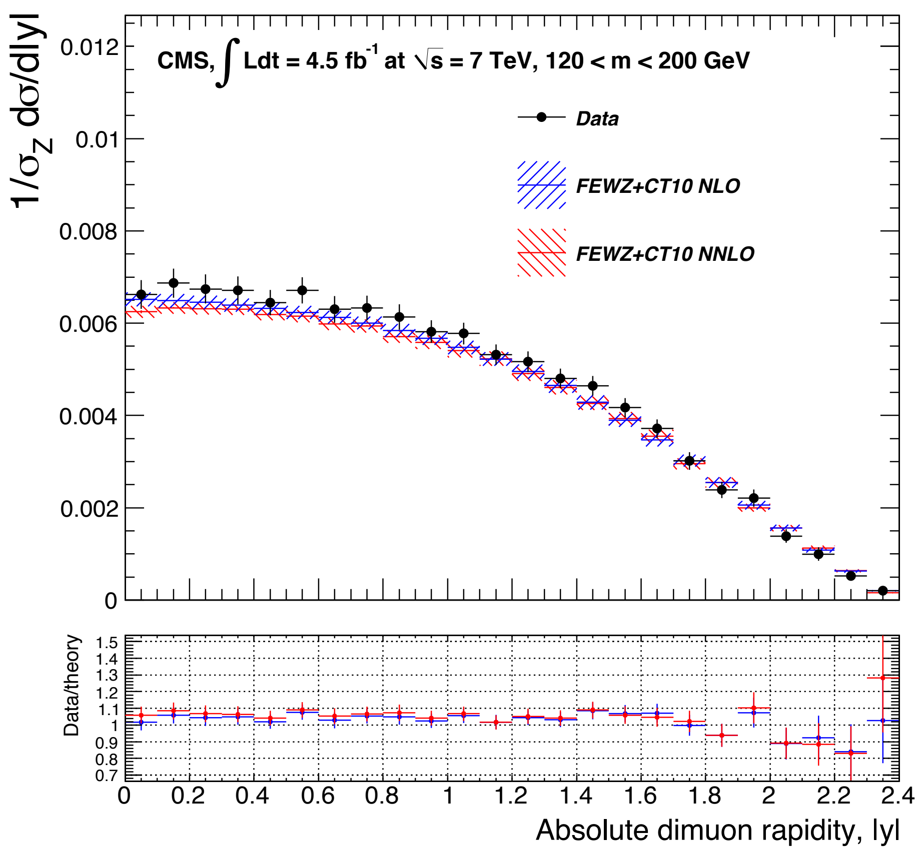
- $\gamma(x, Q^2)$ contribution enters at LO in α. Can give important constraint.
- Emission from quark line must also be included (large uncertainty - scale dep., quark fragmentation function), although at large negative η and high photon $E_\perp$ the photon-initiated dominates.



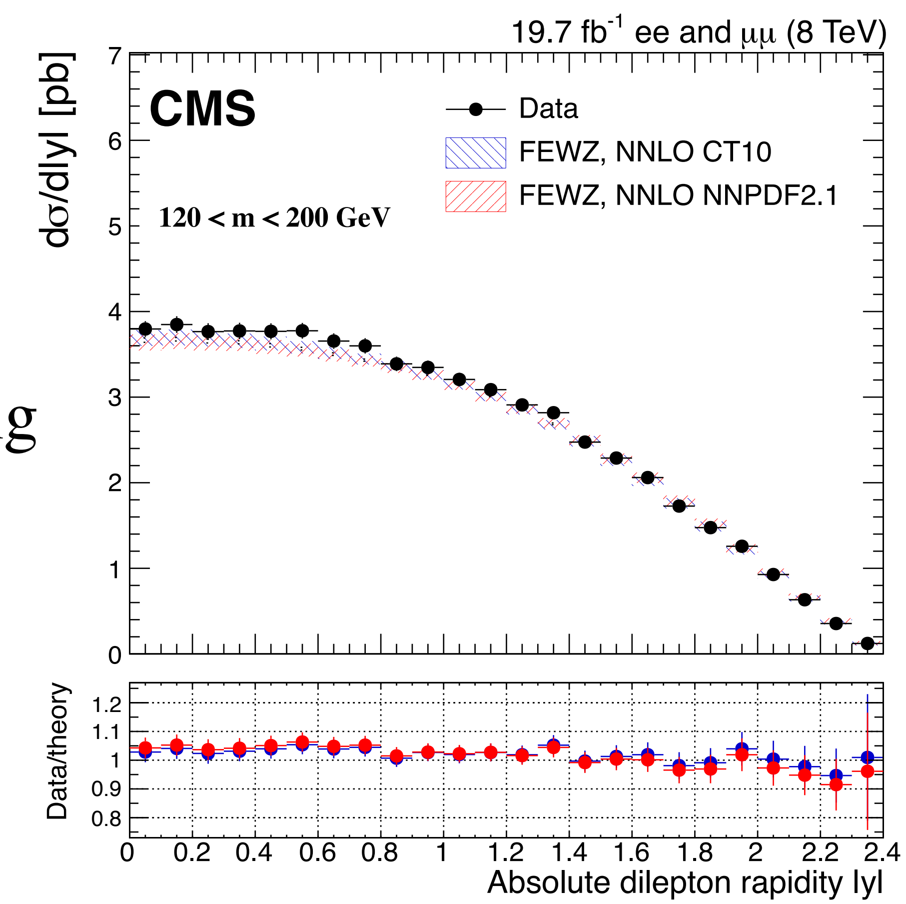


PDFs and QED: LHC

- Wide range of EW gauge boson production data at the LHC
  - ATLAS W, Z
  - ATLAS high mass DY
  - CMS double differential DY
  - LHCb forward DY
  - ...



Precision increasing →



- Constraints from other processes (e.g. WW) to be considered.

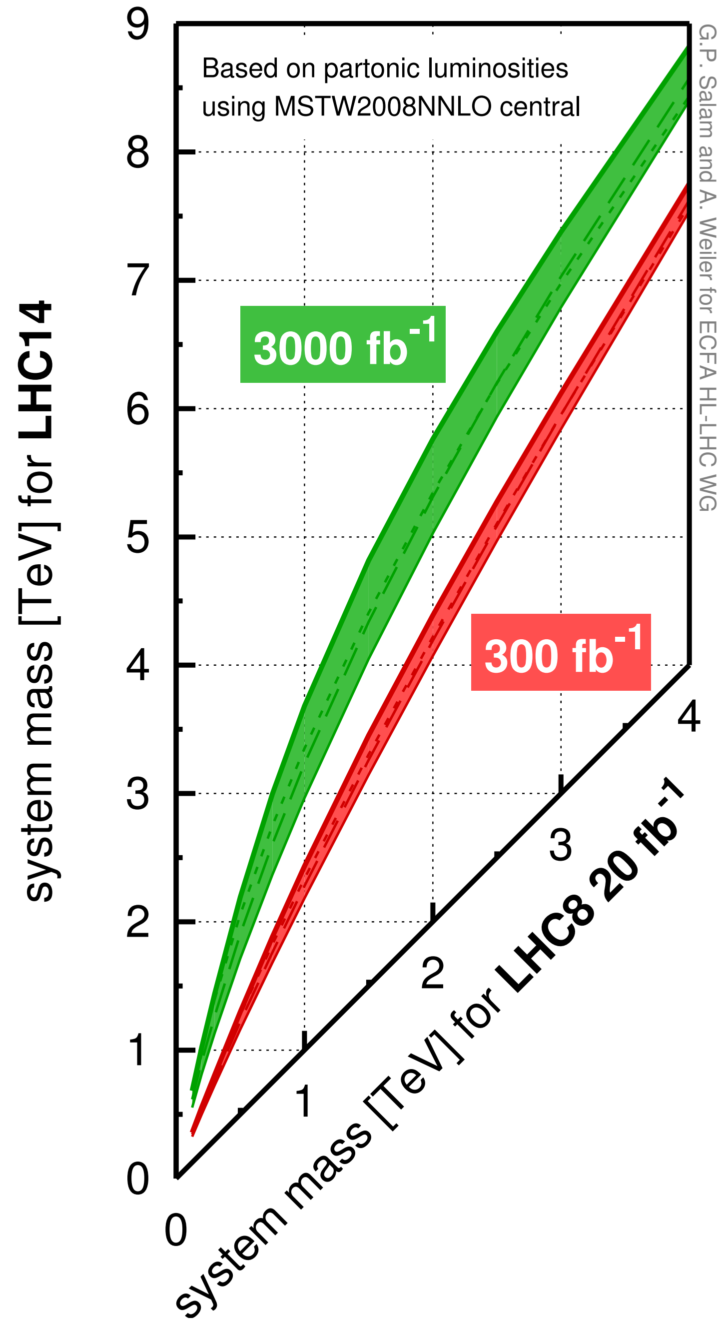
PDF uncertainties at high x

- By end of LS3 anticipate $\sim 300\,\text{fb}^{-1}$ of integrated lumi. collected.
- HL-LHC : a further $\sim 3000\,\text{fb}^{-1}$ projected.

$\longrightarrow$ Mass reach for heavy objects set to increase significantly.

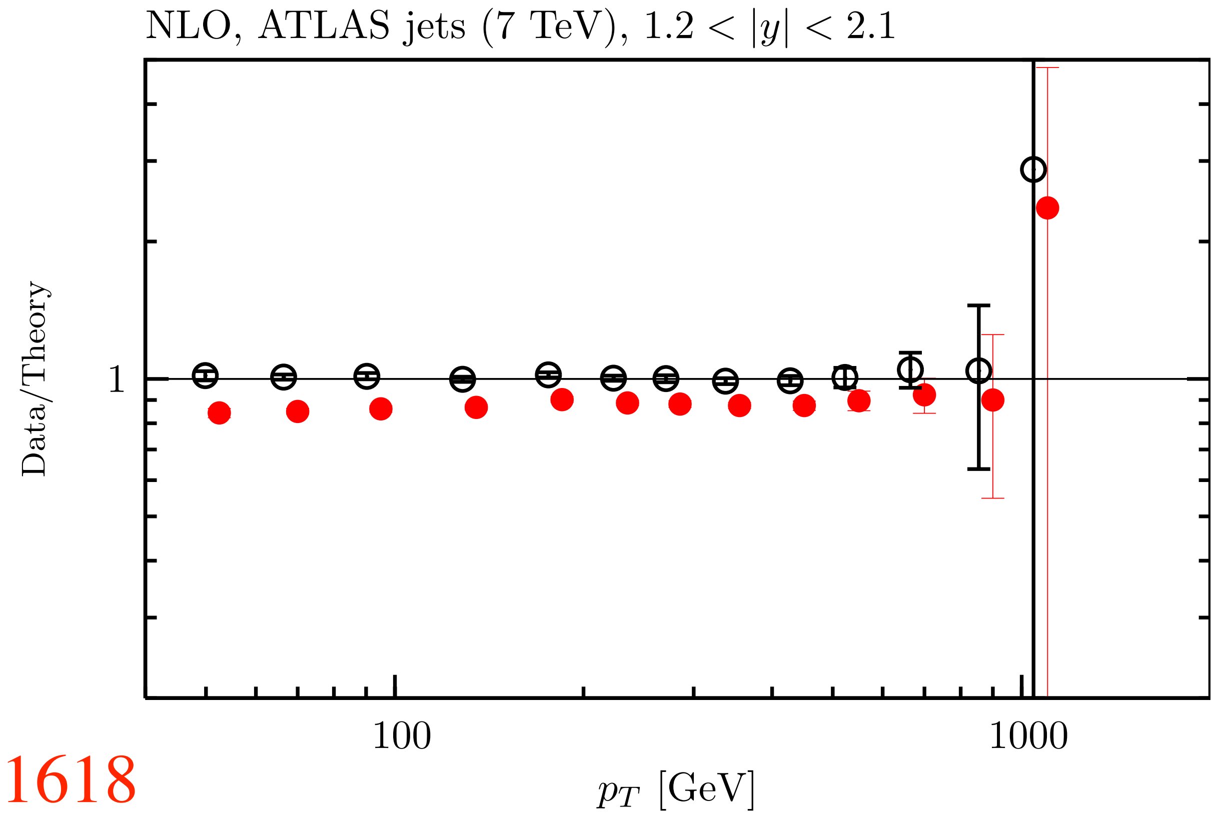
- In this case, a reliable determination of PDFs out to $x \sim 0.6,\ Q \sim 1\,\text{TeV}$ will be high priority.
- Currently far from being realized: little constraint in the higher x region.

$\longrightarrow$ Need to include as much high $p_\perp$ and/or forward y data as possible.



- ATLAS High $p_\perp$ jet data: samples out to $x \sim 0.6$ but uncertainties large.

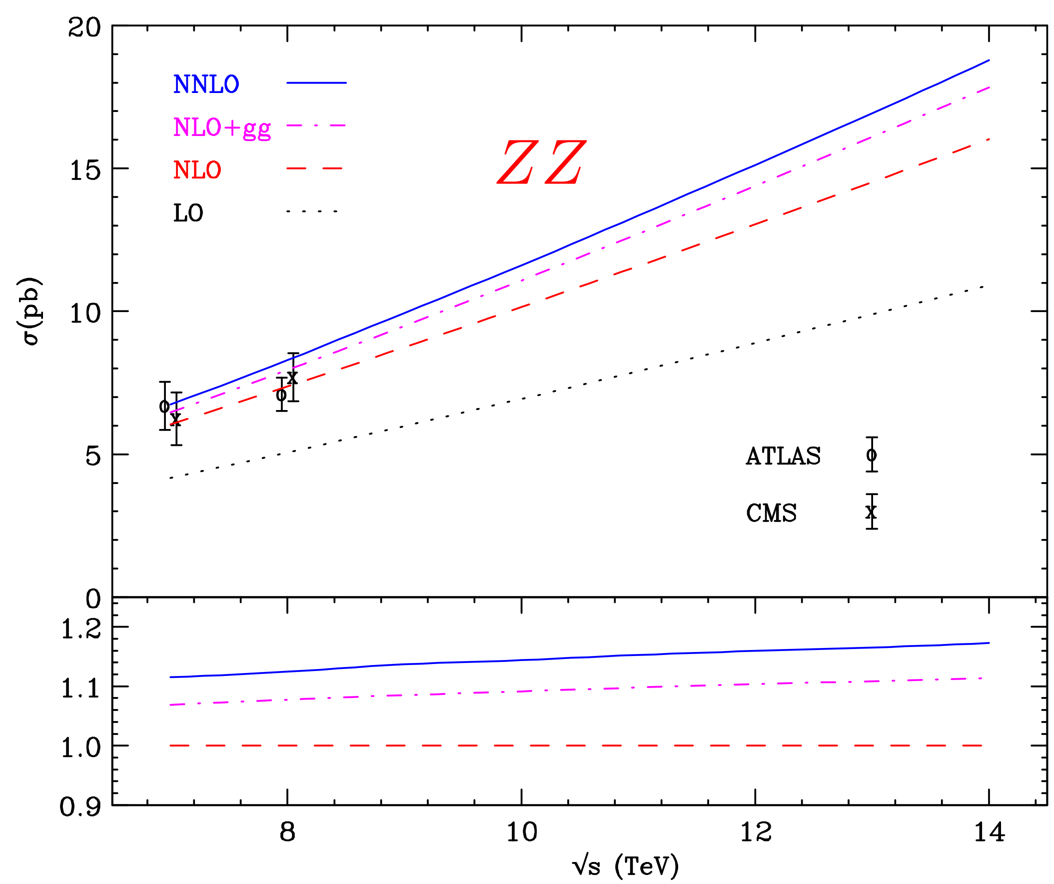
arXiv:1412.3989

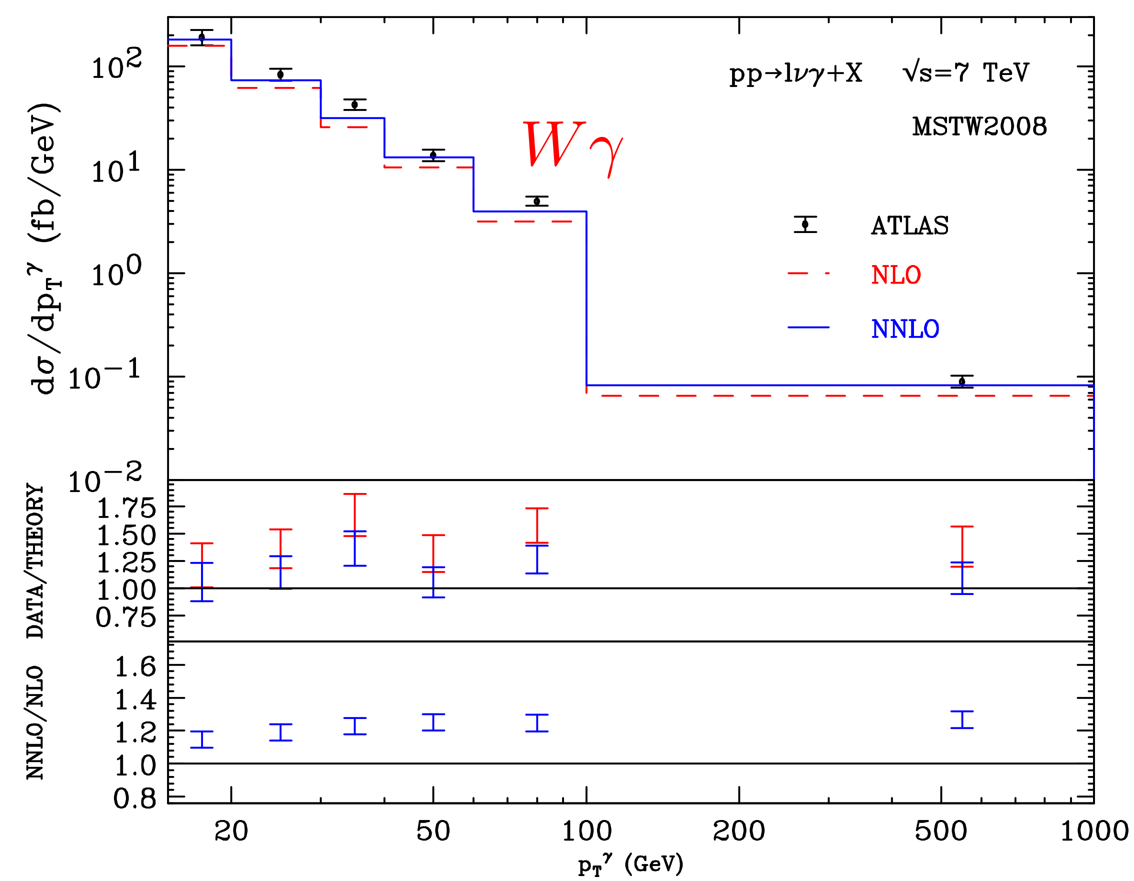


- Other processes:
$W\gamma$, ZZ, WW, forward $t\bar{t}$...
Rhorry's talk

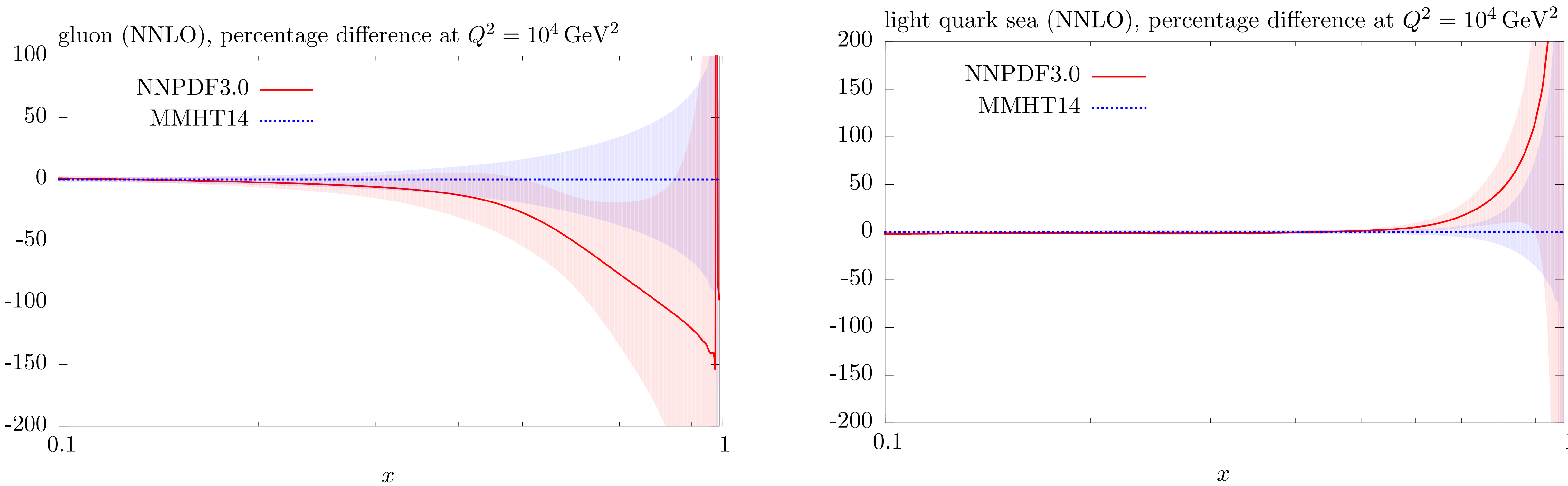
- Care needed not to hide new physics.

arXiv:1407.1618





• Compare MMHT14 and NNPDF3.0 for gluon and light quark sea:



- Gluon : sizable uncertainties enter above $x \sim 0.3$.
- Light quark sea : nowhere near as bad (already constrained by e.g. Z rapidity data).

• MMHT14 parameterise in terms of sea $S \equiv 2(\bar{u} + \bar{d}) + s + \bar{s}$., NNPDF in terms of valence quarks $V(x, Q_0^2) = (u - \bar{u} + d - \bar{d} + s - \bar{s})(x, Q_0^2)$ and other quark combinations.

• MMHT14 find $S \sim (1-x)^{12}$ while preprocessing factors for NNPDF have much smaller exponents $\Longrightarrow$ MMHT sea quark falls faster at high x. However everything well within (large) uncertainties.

Conclusions

- New MMHT14 PDFs publicly available. Include range of theoretical improvements and fit to further data (inc. LHC). Error sets released at LO, NLO and NNLO, and central sets for small range of α_S values.
- Immediate plans: detailed study of α_S variation, release of fixed flavour PDFs.
- Longer term: further release planned (already range of newer LHC data to include, HERA Run-II comb., and NNLO jets/$t\bar{t}$ differential anticipated).
- Other plans: PDF set including QED contributions, study of PDFs at high x, studies using aMCFAST interface (not discussed here).

arXiv:1412.3989