Implications of the NNLO top quark cross section and PDF analysis

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LHC Top Working Group
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Top quarks as gluon luminometers

- The knowledge of **the gluon PDF is essential for LHC phenomenology**, for **Higgs characterization**, and in **many BSM scenarios**

- Top quark pair production at the LHC is **directly sensitive to the gluon luminosity**, thus provides a potential new observable to constrain gluons in **global PDF analysis**

	TeVatron	LHC 7 TeV	LHC 8 TeV	LHC 14 TeV
gg	15.4%	84.8%	86.2%	90.2%
$qg + \bar{q}g$	-1.7%	-1.6%	-1.1%	0.5%
qq	86.3%	16.8%	14.9%	9.3%

Contribution to the NNLO+NNLL cross section from different subprocesses

In recent paper we explored the **phenomenology of the NNLO top cross-section**

In this talk we concentrate on

PDF, α_S and m_t sensitivity of the NNLO cross section

Impact of LHC data on the NNLO gluon PDF (and implications for New Physics searches)

Cross section ratios between 7, 8 and 14 TeV

PDF dependence of the top cross section

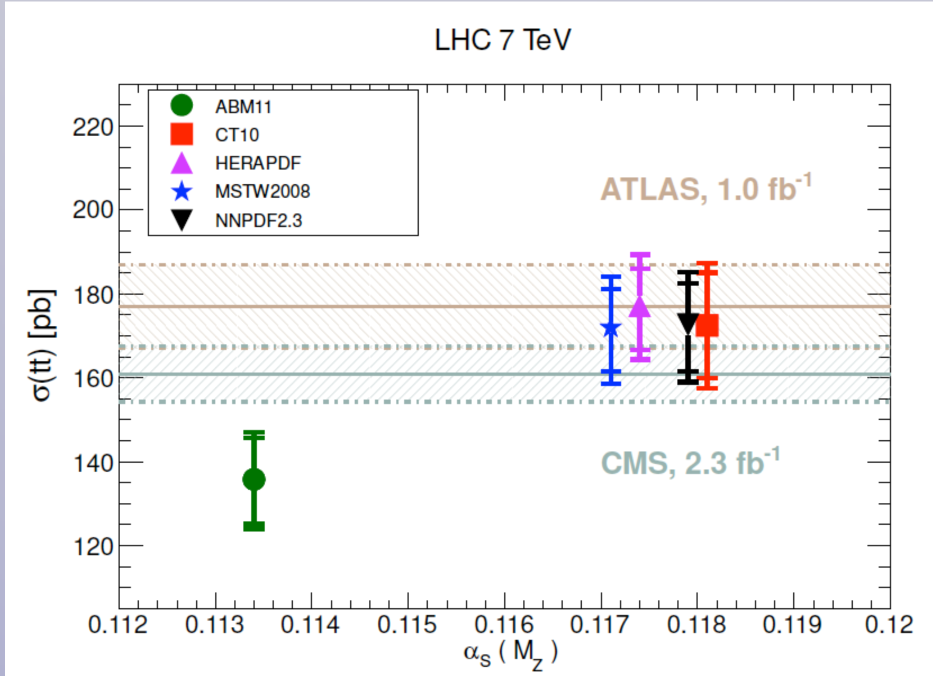
- Compute predictions at NNLO+NNLL (see Alex's talk) for different PDF sets with the associated theoretical uncertainties

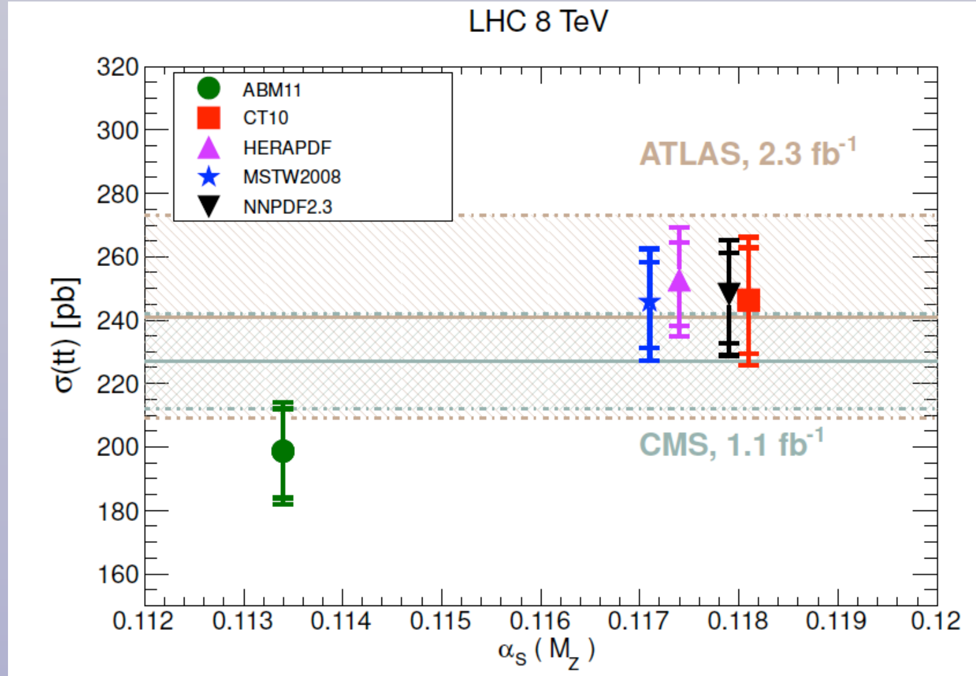
- Top mass fixed to $\mathbf{m_t = 173.3}$ **GeV**. Assume $\boldsymbol{\delta m_t = 1}$ **GeV**, and $\boldsymbol{\delta\alpha_S = 0.007}$

- Parametric uncertainties (PDFs, m_t, α_S) added in quadrature, then linearly to scale uncertainty

- Compare to the most precise **ATLAS** and **CMS** 7 and 8 TeV data

When available, experimental data is corrected to $m_t = 173.3$ GeV





PDF dependence of the top cross section

- Compute predictions at NNLO+NNLL (see Alex's talk) for different PDF sets with the associated theoretical uncertainties
- The contributions from the different sources of theory uncertainty are similar

$\delta_{\text{scale}} \approx 2.5 - 3.5\%$, $\delta_{\text{PDF}} \approx 3.0 - 4.5\%$, $\delta_{\alpha s} \approx 1.5 - 2.2\%$, $\delta_{\text{mt}} \approx 3.0\%$

$\delta_{\text{tot}} \approx 7.0 - 8.5\%$

LHC 7 TeV						
PDF set	σ_{tt} (pb)	δ_{scale} (pb)	δ_{PDF} (pb)	δ_{α_s} (pb)	δ_{m_t} (pb)	δ_{tot} (pb)
ABM11	135.8	$^{+3.5}_{-4.2}$ $(^{+2.6\%}_{-3.1\%})$	$^{+6.4}_{-6.4}$ $(^{+4.7\%}_{-4.7\%})$	$^{+0.0}_{-0.0}$ $(^{+0.0\%}_{-0.0\%})$	$^{+4.3}_{-4.2}$ $(^{+3.2\%}_{-3.1\%})$	$^{+11.2}_{-11.8}$ $(^{+8.2\%}_{-8.7\%})$
CT10	172.5	$^{+4.6}_{-6.0}$ $(^{+2.7\%}_{-3.5\%})$	$^{+8.0}_{-6.5}$ $(^{+4.6\%}_{-3.8\%})$	$^{+3.7}_{-3.7}$ $(^{+2.2\%}_{-2.2\%})$	$^{+5.3}_{-5.1}$ $(^{+3.1\%}_{-3.0\%})$	$^{+14.9}_{-15.0}$ $(^{+8.6\%}_{-8.7\%})$
HERA1.5	177.2	$^{+4.8}_{-4.2}$ $(^{+2.7\%}_{-2.3\%})$	$^{+4.0}_{-6.4}$ $(^{+2.3\%}_{-3.6\%})$	$^{+3.0}_{-3.0}$ $(^{+1.7\%}_{-1.7\%})$	$^{+5.4}_{-5.2}$ $(^{+3.1\%}_{-2.9\%})$	$^{+12.2}_{-12.9}$ $(^{+6.9\%}_{-7.3\%})$
MSTW08	172.0	$^{+4.4}_{-5.8}$ $(^{+2.6\%}_{-3.4\%})$	$^{+4.7}_{-4.7}$ $(^{+2.7\%}_{-2.7\%})$	$^{+2.9}_{-2.9}$ $(^{+1.7\%}_{-1.7\%})$	$^{+5.3}_{-5.1}$ $(^{+3.1\%}_{-3.0\%})$	$^{+12.1}_{-13.4}$ $(^{+7.0\%}_{-7.8\%})$
NNPDF2.3	172.7	$^{+4.6}_{-6.0}$ $(^{+2.7\%}_{-3.5\%})$	$^{+5.2}_{-5.2}$ $(^{+3.0\%}_{-3.0\%})$	$^{+2.7}_{-2.7}$ $(^{+1.6\%}_{-1.6\%})$	$^{+5.3}_{-5.2}$ $(^{+3.1\%}_{-3.0\%})$	$^{+12.5}_{-13.7}$ $(^{+7.2\%}_{-8.0\%})$

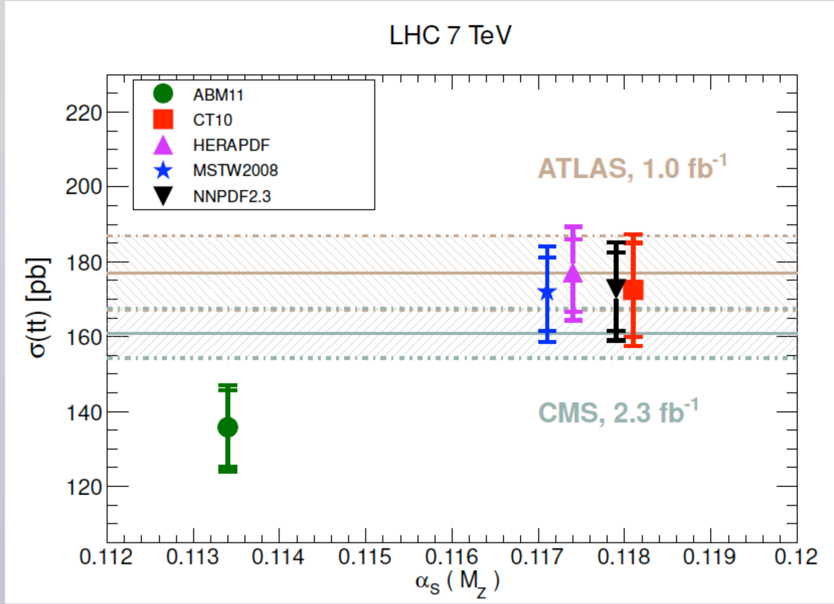
Not a single factor limits the accuracy of the theory prediction

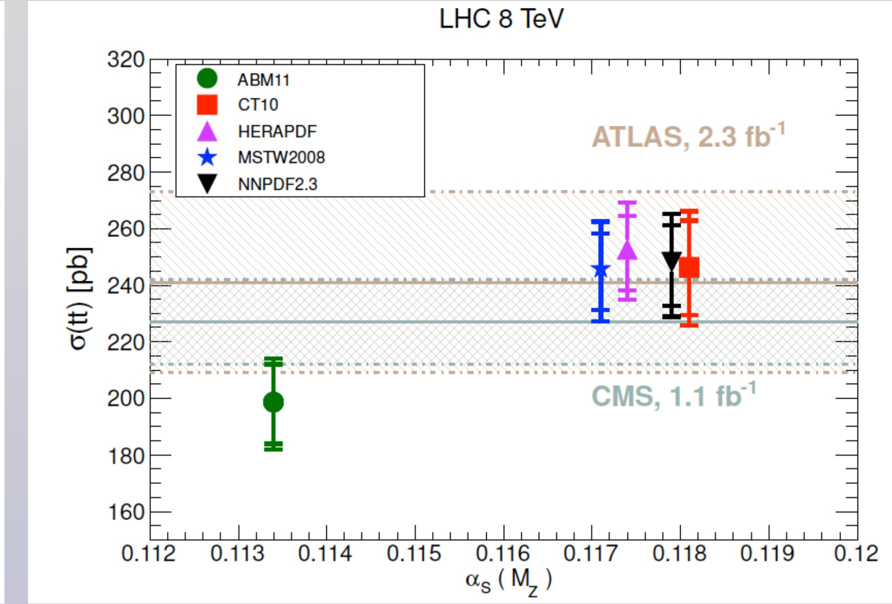
***Scale**, **PDF** and **top mass** uncertainties all of the similar order*

Similar conclusions for other LHC energies

(*) For ABM11, $\delta_{\alpha s}$ included in δ_{PDF}

PDF dependence of the top cross section





- Most PDF sets provide a **good quantitative description** of Tevatron and LHC top data
- **ABM11** is systematically lower than **other PDF sets** and than **experimental data**

$$\chi^2 = \sum_{i=1}^{N_{\rm dat}} \frac{\left(\sigma_{t\bar{t}}^{(\rm exp)} - \sigma_{t\bar{t}}^{(\rm th)}\right)^2}{\delta_{\rm tot}^{(\rm exp)2}}$$

$$P = \frac{1}{N_{\rm dat}} \sum_{i=1}^{N_{\rm dat}} \frac{\left(\sigma_{t\bar{t}}^{(\rm exp)} - \sigma_{t\bar{t}}^{(\rm th)}\right)^2}{\delta_{\rm tot}^{(\rm exp)2} + \delta_{\rm tot}^{(\rm th)2}}$$

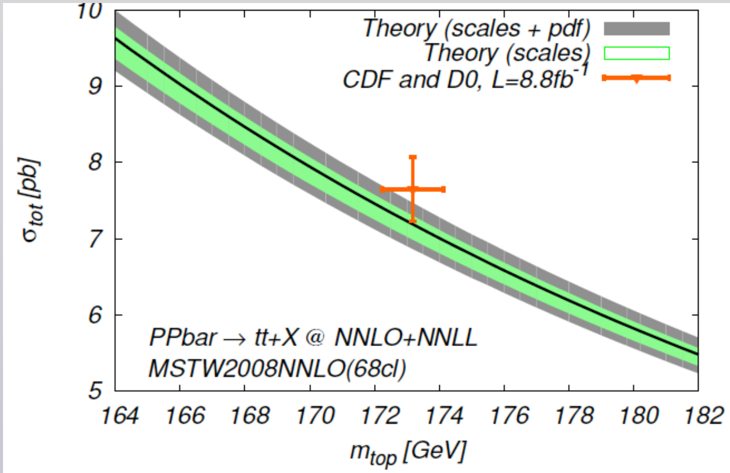
	$\chi^2_{\rm tev}$	$\chi^2_{\rm lhc7}$	$\chi^2_{\rm lhc8}$	$\chi^2_{\rm tot}$	$\chi^2_{\rm tot}/N_{\rm dat}$	P
AMB11	3.5	31.4	5.3	40.2	8.0	3.2
CT10	0.4	3.3	1.7	5.3	1.1	0.3
HERAPDF15	0.0	6.1	3.1	9.2	1.8	0.5
MSTW08	1.3	3.1	1.6	6.0	1.2	0.4
NNPDF2.3	0.9	3.4	2.0	6.3	1.3	0.4

LHC top data already discriminates between PDF sets

Dependence on the top quark mass

- Compare total theory uncertainty **with** and **without top quark mass uncertainty**

- Thanks to the improvement of the NNLO calculation, now all theory uncertainties of similar size, only **mild reduction (< 1.5%)** in the total theory errors if one assumes that $\delta_{mt} \approx 0$



Collider	σ_{tt} (pb)	$\delta_{\mathrm{PDF+scales}+\alpha_s}$ (pb)	δ_{tot} (pb)
Tevatron	7.258	+0.267 (+3.7%) −0.352 (−4.9%)	+0.390 (+5.4%) −0.469 (−6.5%)
LHC 7 TeV	172.7	+10.4 (+6.0%) −11.8 (−6.8%)	+12.5 (+7.2%) −13.7 (−8.0%)
LHC 8 TeV	248.1	+14.0 (+5.6%) −16.2 (−6.5%)	+17.1 (+6.9%) −19.1 (−7.7%)
LHC 14 TeV	977.5	+44.1 (+4.5%) −55.8 (−5.7%)	+57.4 (+5.9%) −68.5 (−7.0%)

Dependence on the strong coupling

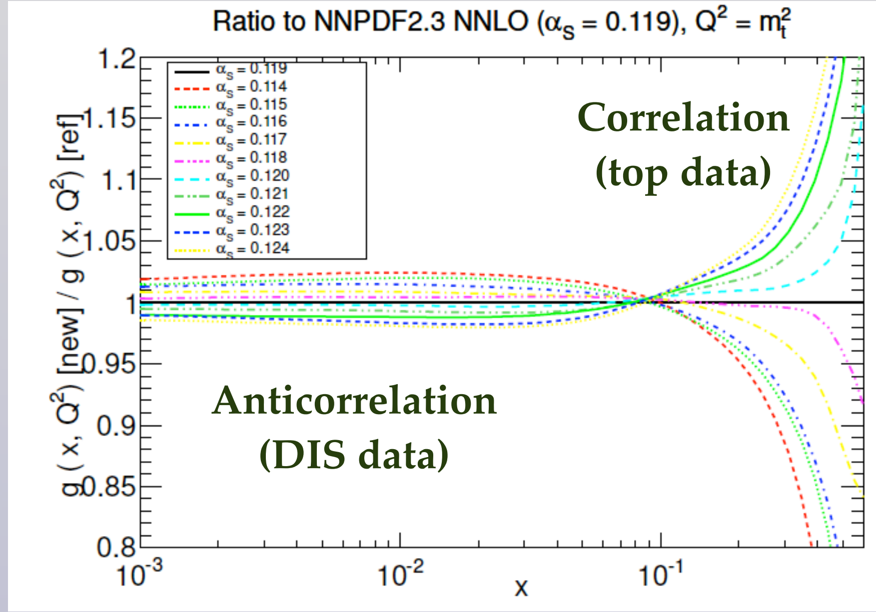
- The same reasons that suggest the use of top data for PDFs motivate the **extraction of the strong coupling $\alpha_S(M_Z)$** from the total cross-section

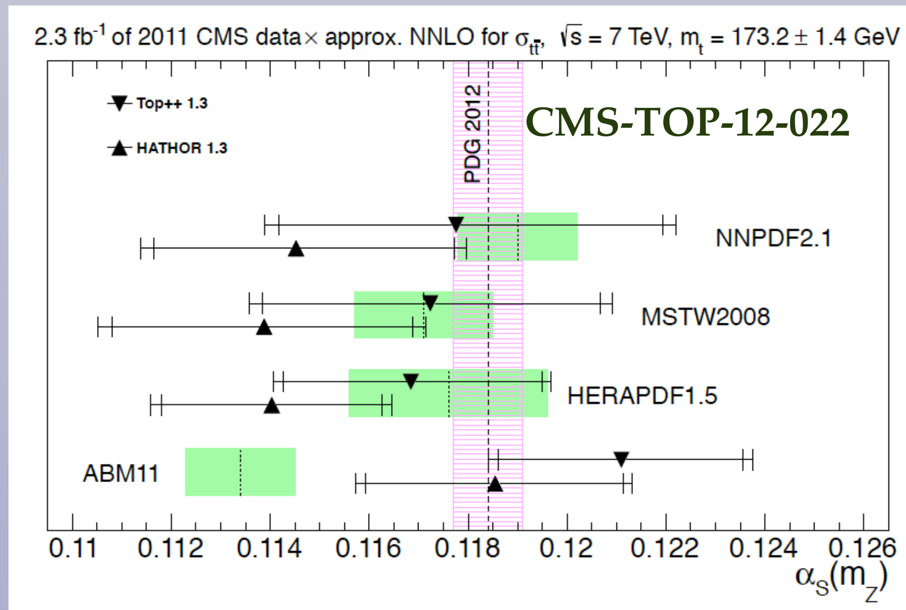
  Small scale uncertainties at NNLO

  Reduced non-perturbative corrections as compared to jets

- The dependence between σ(top) and $\alpha_S(M_Z)$ is enhanced as compared to the naive power counting because of **correlation between $\alpha_S(M_Z)$ and the gluon at large-x**

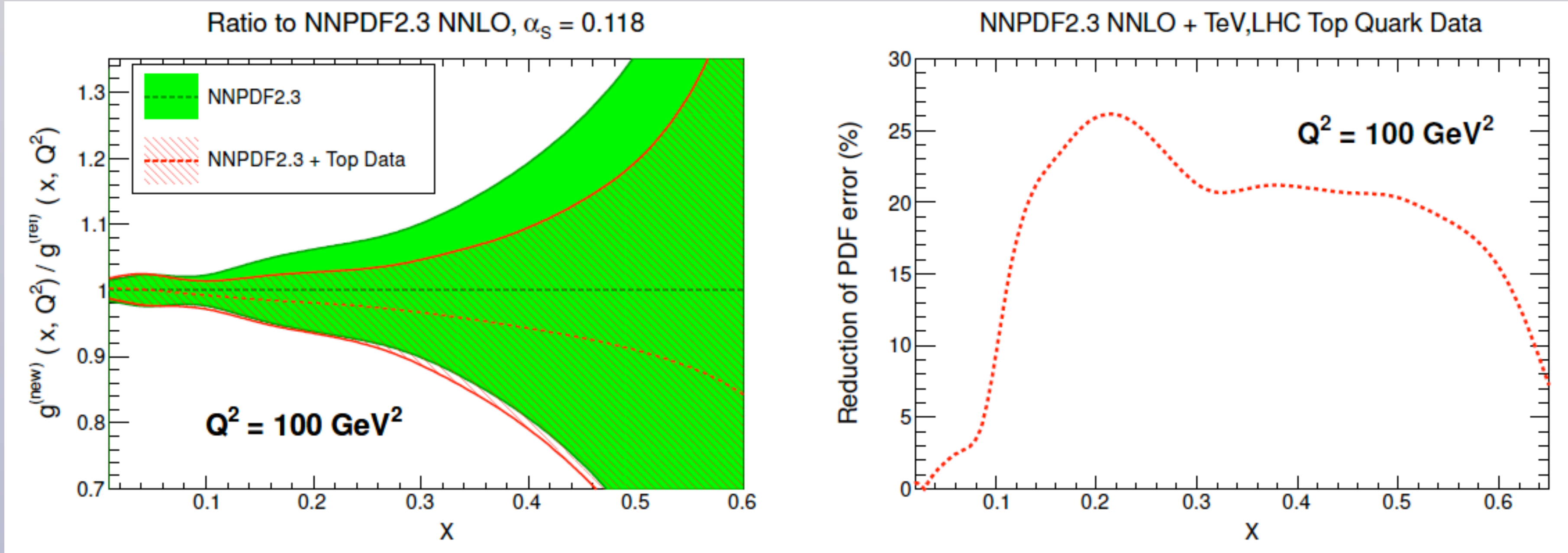
- First determination by **CMS** based on approximate NNLO, results based on full NNLO in preparation



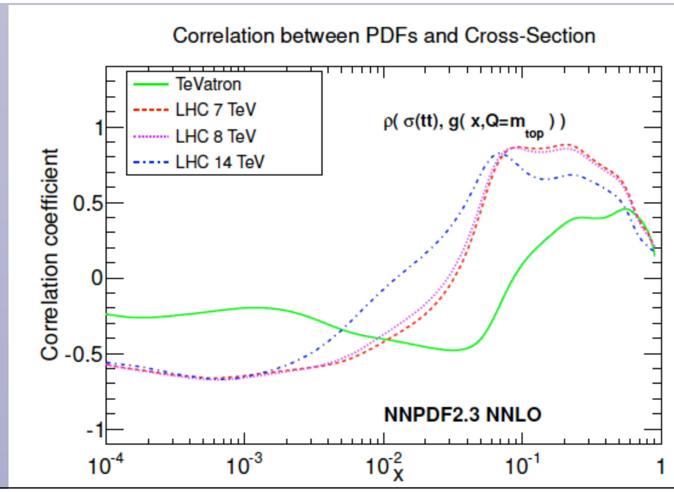


Pinning down the gluon with top data

- Top quark cross-section data **discriminates between PDF sets**
- In addition, it can also be used to **reduce the PDF uncertainties** within a single PDF set
- We included the most precise top quark data into the **NNPDF2.3** global PDF analysis



- Top quark cross-section data **reduces the PDF uncertainty** in the **large-x gluon** by up to **20%**
- The impact is restricted to the region between **0.1<x<0.5**, where the correlation between the gluon and the top cross section is most significant



Pinning down the gluon with top data

- Adding data from lower energy colliders: reduced theory uncertainties at higher energies
- Adding **TeV+LHC7** data to NNPDF2.3, we obtain the **best possible theory prediction for LHC8**
- Not only PDF uncertainty reduced, also central value **shifts** to increase agreement with data

Collider	Ref	Ref+TeV	Ref +TeV+LHC7	Ref+TeV+LHC7+8
Tevatron	7.26 ± 0.12	-	-	-
LHC 7 TeV	172.5 ± 5.2	172.7 ± 5.1	-	-
LHC 8 TeV	247.8 ± 6.6	248.0 ± 6.5	245.0 ± 4.6	-
LHC 14 TeV	976.5 ± 16.4	976.2 ± 16.3	969.8 ± 12.0	969.6 ± 11.6

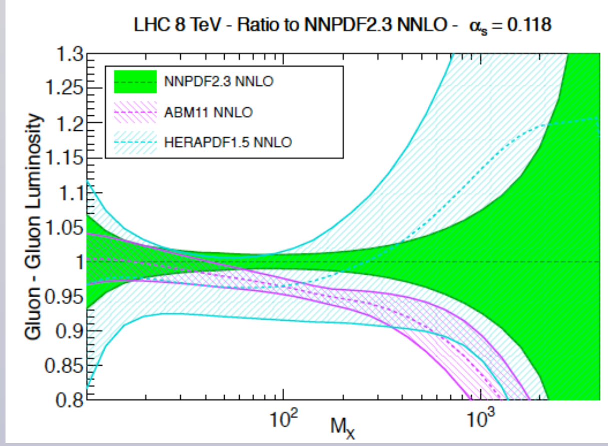
PDF uncertainty only

- Using TeV+LHC7 data, optimal fit description for LHC8
- The **precise LHC7** data carry most of the information, but full 8 TeV analysis still missing

Collider	χ^2 (Total, $N_{\rm dat} = 5$)	χ^2 (LHC 8 TeV, $N_{\rm dat} = 2$)
NNPDF2.3	6.28	1.64
NNPDF2.3 + TeV,LHC data	4.88	1.24
NNPDF2.3 + TeV,LHC7 data	4.87	1.24

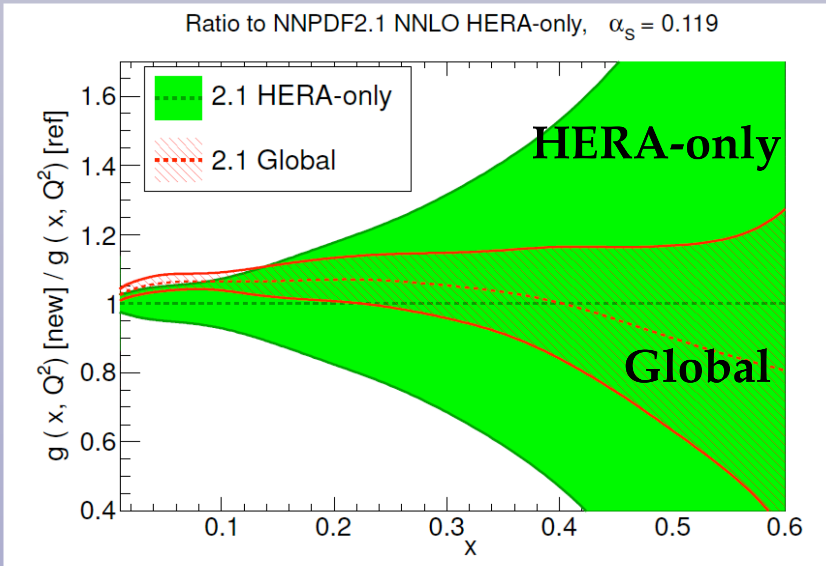
Impact in DIS-only fits

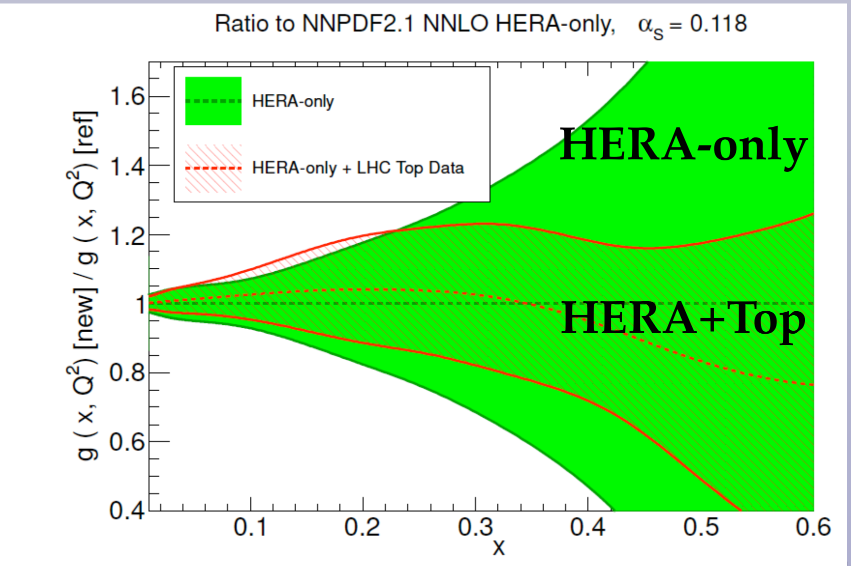
- PDF fits based on **reduced datasets**, such as HERAPDF, display large PDF uncertainties for the gluon due to the lack of direct constraints



gg luminosity

- Top quark data can be included in a **NNLO fit based on HERA data**
  - *Substantial reduction of PDF uncertainties*
  - *The HERA+Top gluon PDF is close to the gluon from the global PDF fit*

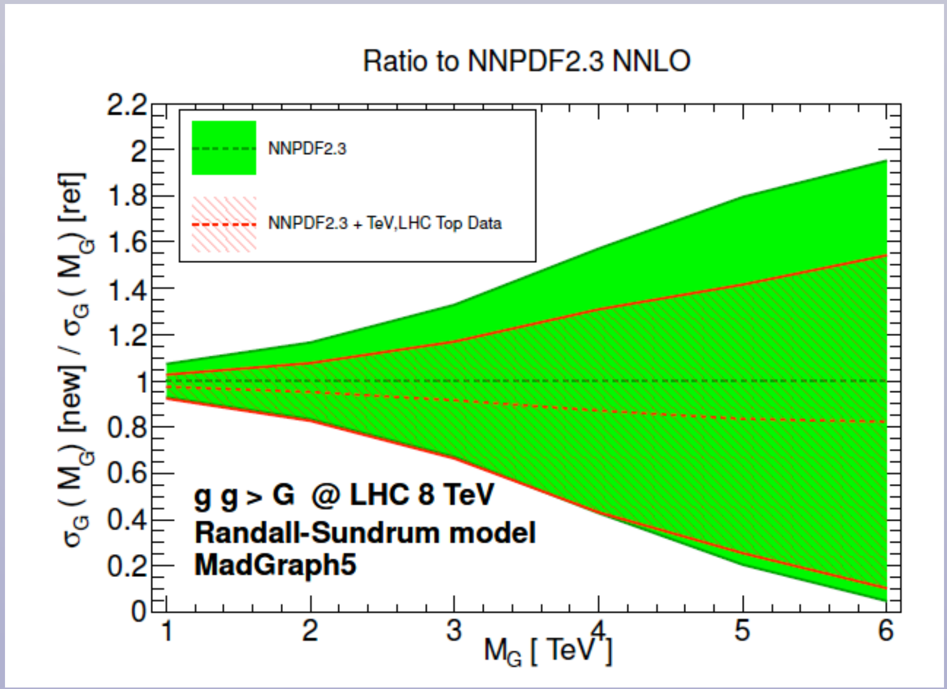




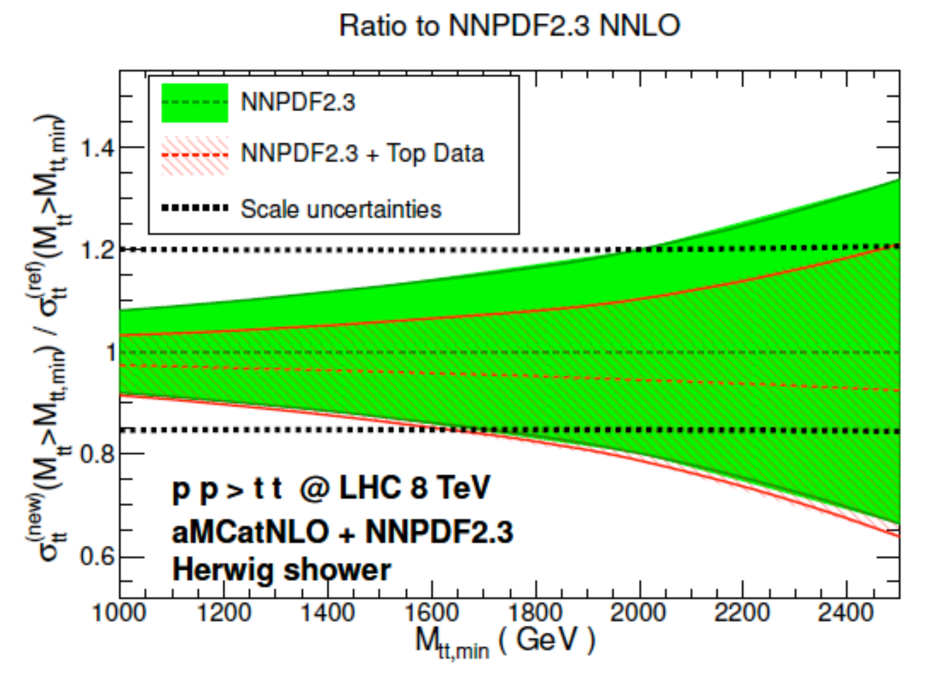
Impact in BSM searches

- Thanks to the top quark data, the **smaller large-x gluon PDF uncertainties** improve the theory predictions for gluon-initiated BSM processes
- *Example 1*: reduction of PDF errors for **high mass Graviton production** in warped extra dimensions scenarios
- *Example 2*: reduction of PDF errors in the **high mass tail of the M_{tt} distribution**, used for searches of **resonances decaying into top pairs**

High mass KK graviton production



High mass tail of the M_{tt} distribution

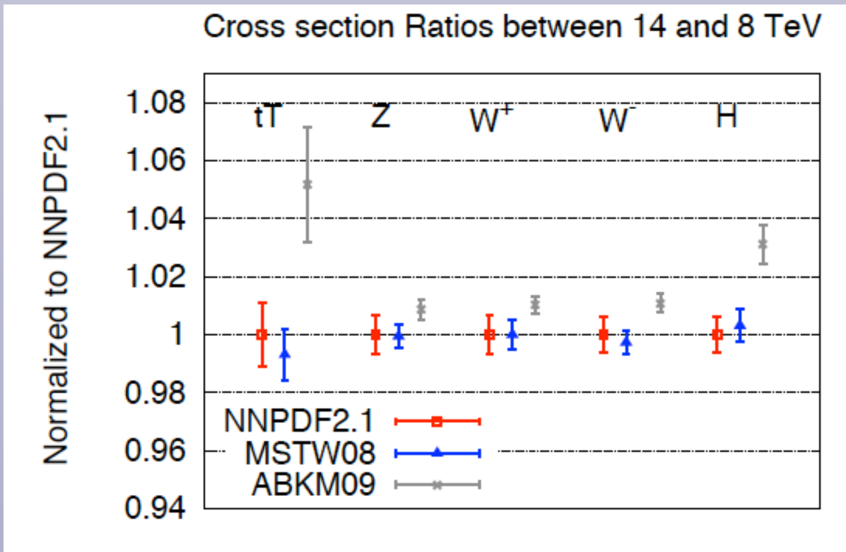


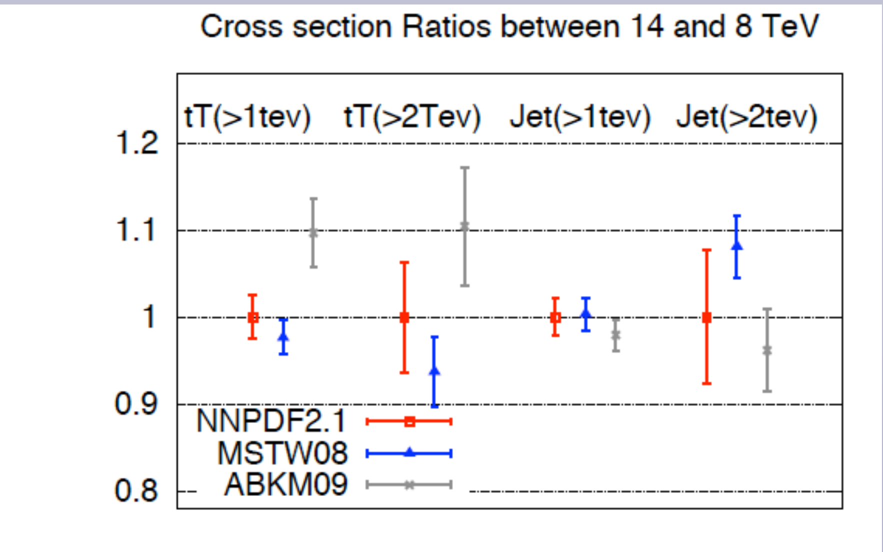
Cross section Ratios between 7, 8 and 14 TeV

- The **staged increase of the LHC beam energy** provides a new class of interesting observables: **cross section ratios** for different beam energies

$$R_{E_2/E_1}(X) \equiv \frac{\sigma(X,E_2)}{\sigma(X,E_1)} \qquad R_{E_2/E_1}(X,Y) \equiv \frac{\sigma(X,E_2)/\sigma(Y,E_2)}{\sigma(X,E_1)/\sigma(Y,E_1)}$$

- These ratios can be computed with **very high precision** due to the large degree of **correlation of theoretical uncertainties** at different energies
- **Experimentally** these ratios can also be measured accurately since many systematics, like luminosity or jet energy scale, **cancel partially in the ratios**
- These ratios allow **stringent precision tests of the SM**, like **PDF discrimination**





M. Mangano, J. Rojo, arXiv:1206.3557

Cross section Ratios of top cross sections

LHC 8 TeV / 7 TeV ratio

PDF set	σ_{tt}	$\delta_{\rm scale}$	$\delta_{\rm PDF}$	δ_{α_s} (pb)	δ_{m_t}	$\delta_{\rm tot}$
ABM11	1.463	$^{+0.001}_{-0.002}$ $(^{+0.1\%}_{-0.1\%})$	$^{+0.006}_{-0.006}$ $(^{+0.4\%}_{-0.4\%})$	$^{+0.000}_{-0.000}$ $(^{+0.0\%}_{-0.0\%})$	$^{+0.001}_{-0.001}$ $(^{+0.1\%}_{-0.1\%})$	$^{+0.007}_{-0.008}$ $(^{+0.5\%}_{-0.5\%})$
CT10	1.428	$^{+0.001}_{-0.001}$ $(^{+0.1\%}_{-0.1\%})$	$^{+0.008}_{-0.010}$ $(^{+0.5\%}_{-0.7\%})$	$^{+0.002}_{-0.002}$ $(^{+0.2\%}_{-0.2\%})$	$^{+0.001}_{-0.001}$ $(^{+0.1\%}_{-0.1\%})$	$^{+0.009}_{-0.011}$ $(^{+0.6\%}_{-0.8\%})$
HERA1.5	1.426	$^{+0.001}_{-0.002}$ $(^{+0.0\%}_{-0.1\%})$	$^{+0.003}_{-0.003}$ $(^{+0.2\%}_{-0.2\%})$	$^{+0.001}_{-0.001}$ $(^{+0.1\%}_{-0.1\%})$	$^{+0.001}_{-0.001}$ $(^{+0.1\%}_{-0.1\%})$	$^{+0.004}_{-0.005}$ $(^{+0.3\%}_{-0.4\%})$
MSTW08	1.429	$^{+0.001}_{-0.001}$ $(^{+0.1\%}_{-0.1\%})$	$^{+0.004}_{-0.004}$ $(^{+0.2\%}_{-0.2\%})$	$^{+0.001}_{-0.001}$ $(^{+0.1\%}_{-0.1\%})$	$^{+0.001}_{-0.001}$ $(^{+0.1\%}_{-0.1\%})$	$^{+0.005}_{-0.005}$ $(^{+0.3\%}_{-0.3\%})$
NNPDF2.3	1.437	$^{+0.001}_{-0.001}$ $(^{+0.1\%}_{-0.1\%})$	$^{+0.006}_{-0.006}$ $(^{+0.4\%}_{-0.4\%})$	$^{+0.001}_{-0.001}$ $(^{+0.1\%}_{-0.1\%})$	$^{+0.001}_{-0.001}$ $(^{+0.1\%}_{-0.1\%})$	$^{+0.007}_{-0.007}$ $(^{+0.5\%}_{-0.5\%})$
ATLAS	1.36					$\pm$ 0.11 (8%)
CMS	1.40					$\pm$ 0.08 (6%)

7 TeV: permille accuracy

14 TeV: **1-2% accuracy**

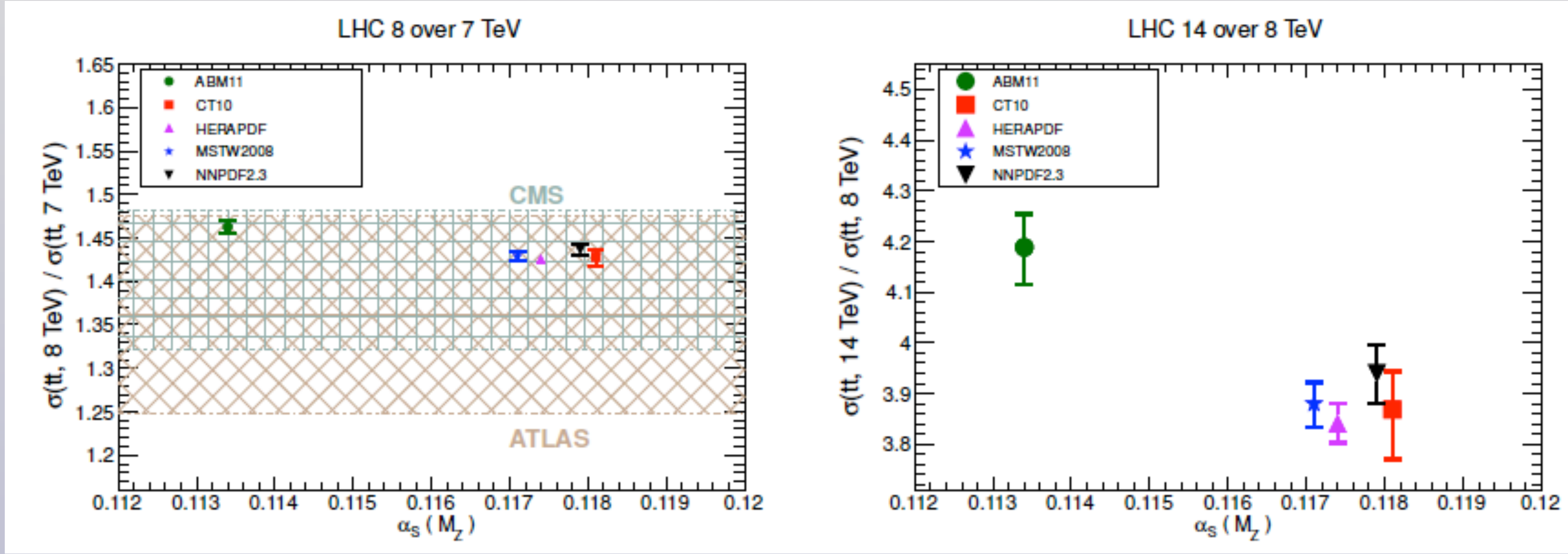
Compare to **7-8%** of absolute xsec

LHC 14 TeV / 8 TeV ratio

PDF set	σ_{tt}	$\delta_{\rm scale}$	$\delta_{\rm PDF}$	δ_{α_s} (pb)	δ_{m_t}	$\delta_{\rm tot}$
ABM11	4.189	$^{+0.008}_{-0.016}$ $(^{+0.2\%}_{-0.4\%})$	$^{+0.057}_{-0.057}$ $(^{+1.4\%}_{-1.4\%})$	$^{+0.000}_{-0.000}$ $(^{+0.0\%}_{-0.0\%})$	$^{+0.012}_{-0.012}$ $(^{+0.3\%}_{-0.3\%})$	$^{+0.067}_{-0.074}$ $(^{+1.6\%}_{-1.8\%})$
CT10	3.869	$^{+0.006}_{-0.009}$ $(^{+0.2\%}_{-0.2\%})$	$^{+0.068}_{-0.088}$ $(^{+1.8\%}_{-2.3\%})$	$^{+0.020}_{-0.020}$ $(^{+0.5\%}_{-0.5\%})$	$^{+0.010}_{-0.010}$ $(^{+0.2\%}_{-0.2\%})$	$^{+0.077}_{-0.100}$ $(^{+2.0\%}_{-2.6\%})$
HERA1.5	3.841	$^{+0.005}_{-0.012}$ $(^{+0.1\%}_{-0.3\%})$	$^{+0.033}_{-0.025}$ $(^{+0.9\%}_{-0.7\%})$	$^{+0.010}_{-0.010}$ $(^{+0.3\%}_{-0.3\%})$	$^{+0.009}_{-0.010}$ $(^{+0.2\%}_{-0.2\%})$	$^{+0.041}_{-0.041}$ $(^{+1.1\%}_{-1.1\%})$
MSTW08	3.880	$^{+0.006}_{-0.009}$ $(^{+0.2\%}_{-0.2\%})$	$^{+0.036}_{-0.036}$ $(^{+0.9\%}_{-0.9\%})$	$^{+0.011}_{-0.011}$ $(^{+0.3\%}_{-0.3\%})$	$^{+0.010}_{-0.010}$ $(^{+0.2\%}_{-0.2\%})$	$^{+0.045}_{-0.048}$ $(^{+1.2\%}_{-1.2\%})$
NNPDF2.3	3.940	$^{+0.006}_{-0.010}$ $(^{+0.2\%}_{-0.3\%})$	$^{+0.048}_{-0.048}$ $(^{+1.2\%}_{-1.2\%})$	$^{+0.009}_{-0.009}$ $(^{+0.2\%}_{-0.2\%})$	$^{+0.010}_{-0.010}$ $(^{+0.3\%}_{-0.3\%})$	$^{+0.056}_{-0.060}$ $(^{+1.4\%}_{-1.5\%})$

Ratios at NNLO+NNLL within uncertainty band of NLO+NNLL: validation of estimate of scale error in ratios

Cross section Ratios of top cross sections



- Available data for 8/7 not precise to discriminate between PDF sets

100% correlation of sys errors (but lumi)

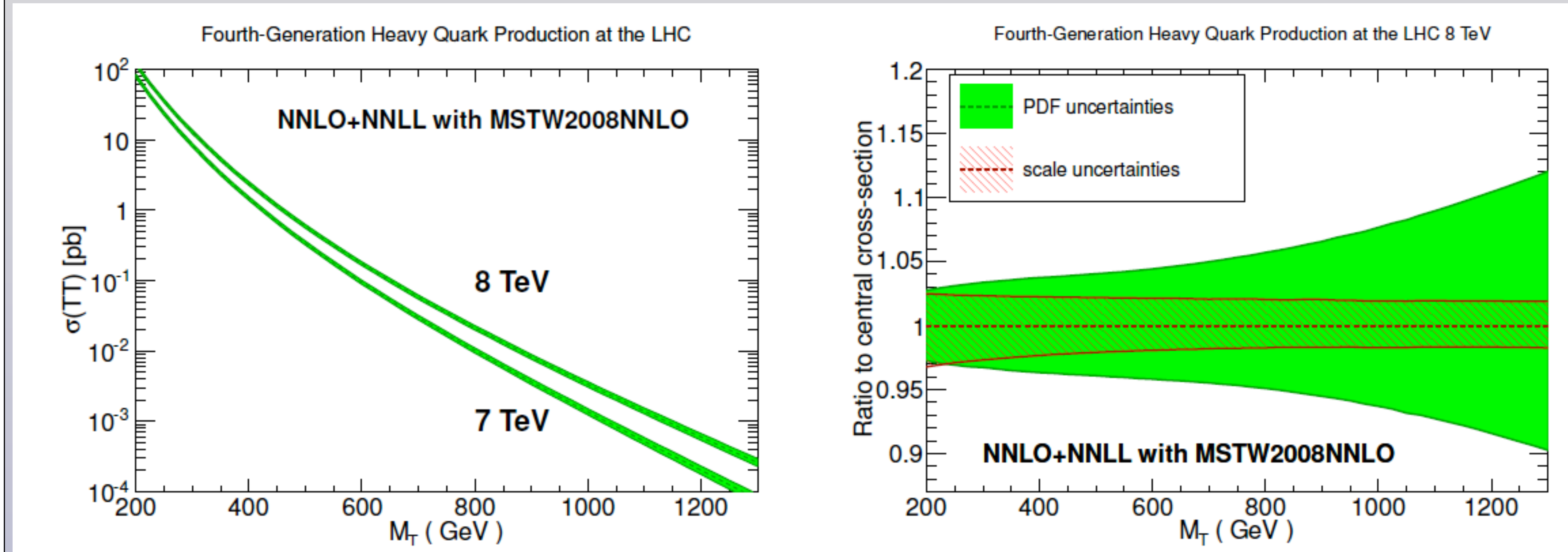
$$\sigma^{(\mathrm{Atlas})}_{\mathrm{LHC}8/7}(t\bar{t}) = 1.36 \pm 0.11 \text{ pb } (8\%)\,,$$
$$\sigma^{(\mathrm{CMS})}_{\mathrm{LHC}8/7}(t\bar{t}) = 1.40 \pm 0.08 \text{ pb } (6\%)\,.$$

No correlation of systematic errors

$$\sigma^{(\mathrm{Atlas})}_{\mathrm{LHC}8/7}(t\bar{t}) = 1.36 \pm 0.20 \text{ pb } (15\%)\,,$$
$$\sigma^{(\mathrm{CMS})}_{\mathrm{LHC}8/7}(t\bar{t}) = 1.40 \pm 0.11 \text{ pb } (8\%)\,,$$

- For the 14/8 TeV ratio, **spread of PDF sets** at the **10% level:** achievable with the expected precision, but needs a dedicated measurement

Fourth-generation heavy quark production

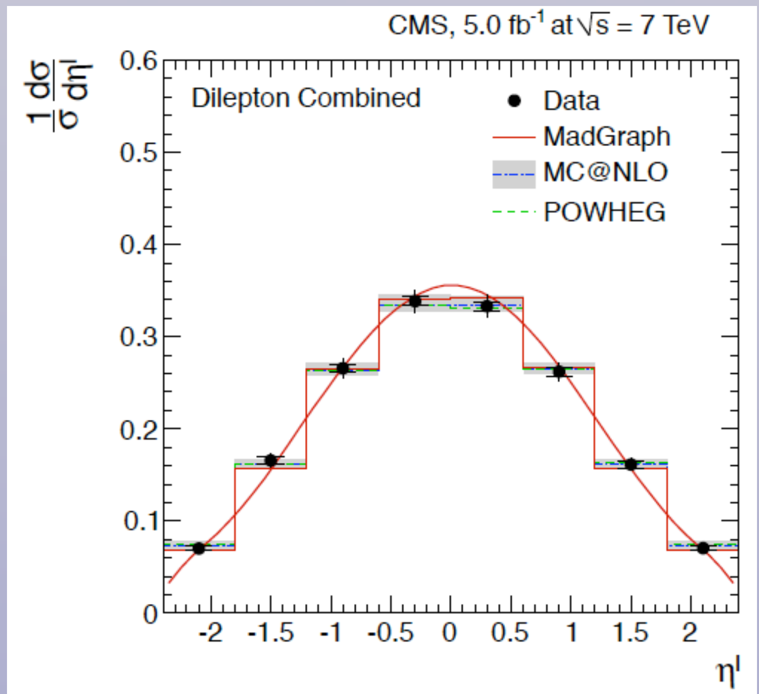


- Arise naturally in BSM scenarios with **strongly coupled dynamics**
- Computed **NNLO+NNLL** predictions as function of the T quark mass
- PDF uncertainties dominant for very heavy T quarks

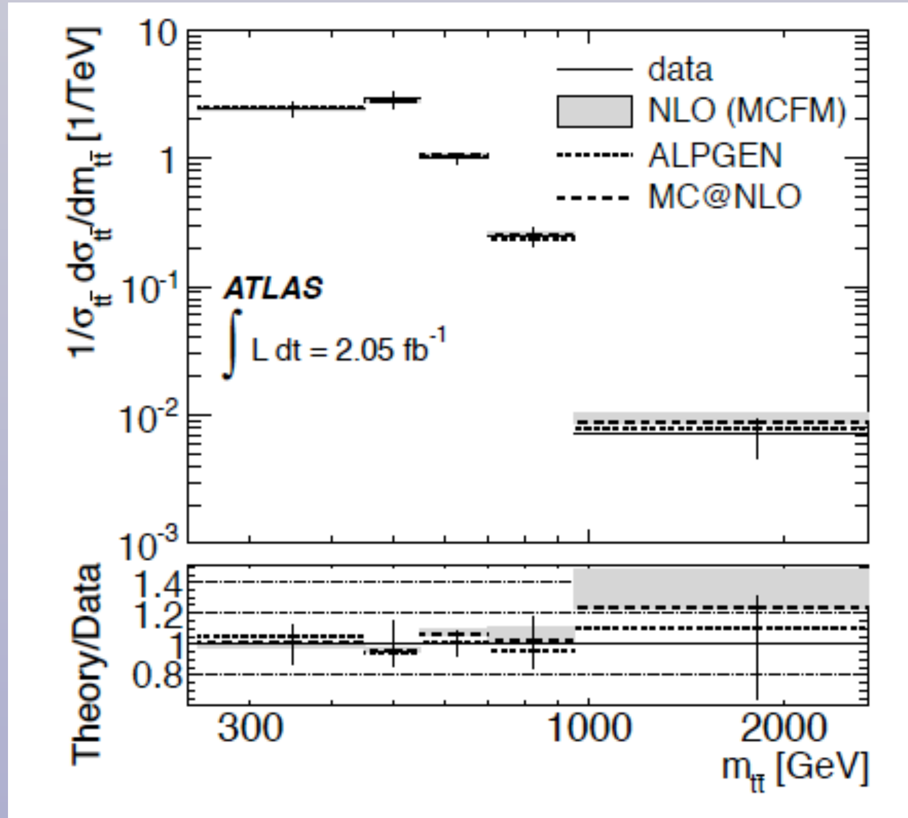
Top differential distributions

- On top of inclusive top cross sections, ATLAS and CMS have also measured **differential distributions** of top quarks and their decay products
- **Full experimental covariance matrix** available
- NNLO not available, only NLO + resummation for some distributions
- Update PDF studies on total cross sections to **differential distributions**

CMS, arxiv:1211.2220



ATLAS, arxiv:1207.5644



Summary

- **Top quark production** is a key process at the LHC
- Thanks for the NNLO calculation, various **phenomenological applications** of the total cross section become possible
- The **PDF, scale and top mass** uncertainties are now of the same order
- The cross-section data discriminate between PDF sets, is sensitive to the value of $\alpha_S(M_Z)$ and **reduces the large-x gluon PDF uncertainties**
- **The improved gluon PDF** leads to better predictions for various BSM-relevant processes
- The cross-section ratio between **14 and 8 TeV** has a strong physics motivation, but a dedicated measurement strategy is required