# Top-quark differential distributions and the gluon PDF in the proton

QCD@LHC 2016

Emanuele R. Nocera
in collaboration with M. Czakon, N.P. Hartland, A. Mitov and J. Rojo

Rudolf Peierls Centre for Theoretical Physics - University of Oxford

University of Zurich - August 25, 2016

# Foreword

The gluon PDF at mid- large-$x$ values plays a leading role in many BSM scenarios
(gluino pair production, Kaluza-Klein graviton production, resonances in the $m_{t\bar{t}}$ spectrum, ...)
Usual constraints come from jets and inclusive top cross sections (Tevatron and LHC)
(though full NNLO QCD corrections to jet are not available)
Additional constraints from top differential distributions

Two new ingredients allow for the inclusion of top differential distributions in a PDF fit:
1) NNLO QCD corrections [PRL 116 082003,arXiv:1606.03350]
2) new measurements from ATLAS [arXiv:1511.04716] and CMS [EPJ C75 542] at $\sqrt{s} = 8$ TeV

Top inclusive cross sections/differential distributions are the only hadron processes
sensitive to the gluon at mid- large-$x$ values
which can be included in a PDF fit at NNLO without approximations

---

1) How ATLAS and CMS data compare with NNLO theoretical predictions?
2) What is the impact of top differential distributions on the gluon PDF of the proton?
3) Which (combination of) distributions is the most constraining?

# 1. Data and theory

# Experimental data

Differential cross sections for top-quark pair production in $pp$ collisions at $\sqrt{S} = 8$ TeV

ATLAS [arXiv:1511.04716] ($\mathcal{L} = 20.3$ fb$^{-1}$) CMS [EPJ C75 542] ($\mathcal{L} = 19.7$ fb$^{-1}$)

---

**1.** full phase-space measurements, in terms of $t$ and $t\bar{t}$ kinematic variables
   fiducial phase-space measurements, in terms of leptonic and jet variables, also available
   NNLO QCD corrections computed only at parton level so far

**2.** distributions with known NNLO QCD corrections: $p_T^t$, $y_t$, ($|y_t|$), $y_{t\bar{t}}$ ($|y_{t\bar{t}}|$), $m_{t\bar{t}}$

**3.** lepton + jets final state, $t\bar{t}$ pair reconstructed from its decays into $W^+bW^-\bar{b}$
   differential distributions for dilepton final state also available [arXiv:1607.07281; EPJ C75 542]

**4.** measurements at $\sqrt{s} = 7$ TeV (earlier) and at $\sqrt{s} = 13$ TeV (preliminary)
   larger uncertainties and/or lack of information on correlated systematics

---

**OPT 1** Normalized (to the total cross section) distributions

☑ some systematics cancel in the ratio (*e.g.* luminosity uncertainty)

☒ some PDF-sensitive information is lost (*e.g.* overall normalization of the gluon PDF)

need to include also corresponding total cross section data [EPJC 74 3109 ;JHEP 1608 029]

**OPT 2** Absolute distributions

☒ experimental uncertainties might be larger

☑ handle on the overall normalization of the gluon PDF

# Theoretical predictions

1. Complete NNLO QCD corrections for differential distributions [PRL 116 082003]
   derived from a fully differential partonic Monte Carlo calculation with stable top quarks
2. NNLO QCD corrections not (yet) in a format suitable for fast computations
   (but work in progress [M. Sutton])
   generate NLO theoretical predictions with `SHERPA` and produce corresponding `APPLgrids`
   benchmark the result with the complete NLO corrections (high-stat runs required)
   include NNLO corrections by multiplying NLO results by local $\mathcal{C}$-factors

$$\mathcal{C} = \frac{\hat{\sigma}^{\rm NNLO} \otimes \mathcal{L}^{\rm NNLO}}{\hat{\sigma}^{\rm NLO} \otimes \mathcal{L}^{\rm NNLO}}$$

3. Top quark (pole) mass $m_t = 173.3$ GeV
   ($m_t$ dependence not considered here [arXiv:1608.00765])
4. Dynamic scale selected based on the principle of fastest perturbative convergence
   applied to both differential and inclusive cross sections [arXiv:1606.03350]

$$y_t,\, y_{t\bar{t}},\, m_{t\bar{t}}: \quad \mu_R = \mu_F = \frac{1}{4}\left(\sqrt{m_t^2 + {p_T^t}^2} + \sqrt{m_t^2 + {p_T^{\bar{t}}}^2}\right)$$

$$p_T^t: \quad \mu_R = \mu_F = \frac{1}{2}\sqrt{m_t^2 + {p_T^t}^2}$$

5. Same settings used in the computation of the inclusive cross sections
   via `top++` [CPC 185 2930]

# Data/Theory comparison

1. PDF sets: NNPDF3.0 [JHEP 04 040], MMHT14 [EPJ C75 204], CT14 [PRD 93 033006], $N_f^{\max} = 5$
2. Initial scale for theoretical predictions above the $b$-quark threshold: $Q_0 = 5$ GeV
3. Strong running coupling consistent with each PDF set: $\alpha_s(M_Z) = 0.118$
4. Take into account all provided (bin-by-bin) correlations
   (including the statistical covariance matrix)
5. Define a figure of merit to quantify data/theory agreement

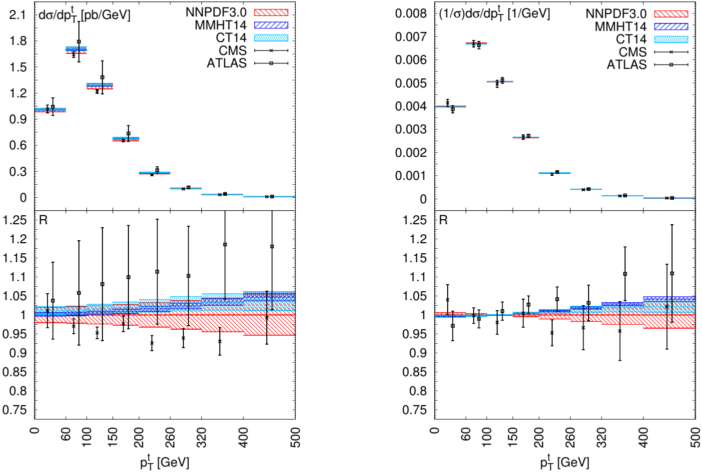
$$\chi^2 \{\mathcal{T}[D], \mathcal{E}\} = \sum_{i,j}^{N_{\rm dat}} (T_i[D] - E_i)\, c_{ij}^{-1}\, (T_j[D] - E_j)$$

$$c_{ij} = \delta_{ij} s_{ij}^2 + \left( \sum_{\alpha=1}^{N_c} \sigma_{i,\alpha}^{(c)} \sigma_{j,\alpha}^{(c)} + \sum_{\alpha=1}^{N_{\mathcal{L}}} \sigma_{i,\alpha}^{(\mathcal{L})} \sigma_{j,\alpha}^{(\mathcal{L})} \right) D_i D_j$$

$s_i$: uncorrelated unc.; $\sigma_{i,\alpha}^{(\mathcal{L})}$: $N_{\mathcal{L}}$ multiplicative norm. unc.; $\sigma_{i,\alpha}^{(c)}$ all other $N_c$ correlated unc.

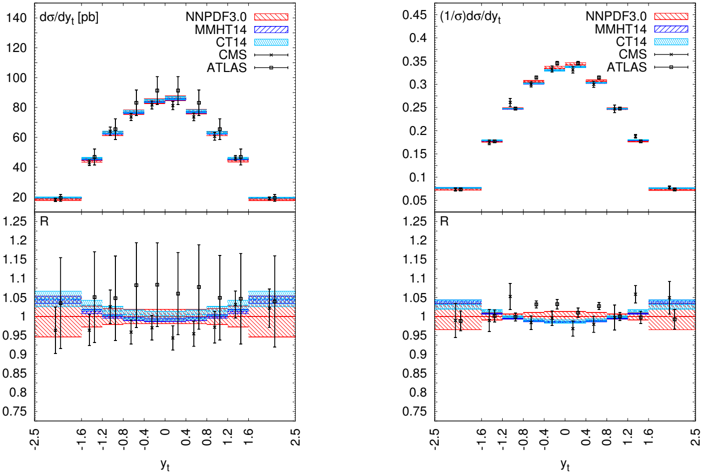
6. A few additional manipulations on experimental data
   - $\longrightarrow$ ATLAS $|y_t|$ and $|y_{t\bar{t}}|$ distributions are symmetrized into $y_t$ and $y_{t\bar{t}}$ distributions
   - $\longrightarrow$ reconstruct CMS absolute distributions by multiplying normalized distribution by $\sigma^{t\bar{t}}$ (retain the total systematic and luminosity uncertainties on $\sigma^{t\bar{t}}$)
   - $\longrightarrow$ symmetrize asymmetric uncertainties

# Data/Theory comparison: $p_T^t$



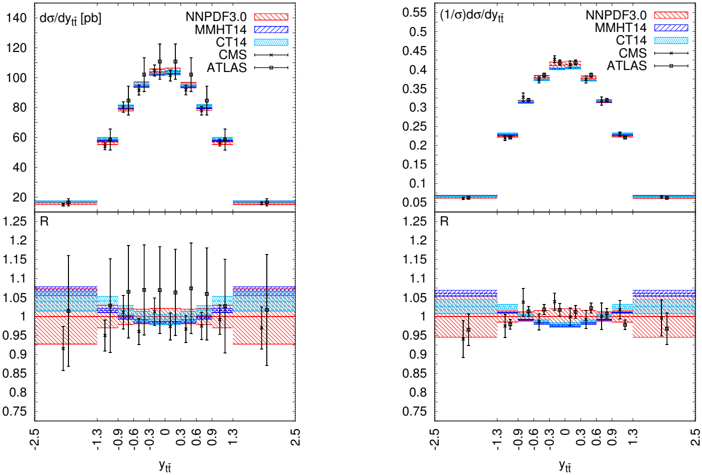

| PDF set | ATLAS $d\sigma/dp_T^t$ | CMS $d\sigma/dp_T^t$ | ATLAS $(1/\sigma)d\sigma/dp_T^t$ | CMS $(1/\sigma)d\sigma/dp_T^t$ |
|---|---|---|---|---|
| NNPDF3.0 | 0.84 (0.66) | 5.30 (4.57) | 3.13 (0.94) | 2.02 (0.50) |
| MMHT14 | 0.63 (0.45) | 6.93 (7.19) | 2.31 (0.54) | 3.14 (0.77) |
| CT14 | 0.75 (0.41) | 8.80 (8.95) | 2.30 (0.60) | 2.92 (0.61) |

# Data/Theory comparison: $y_t$



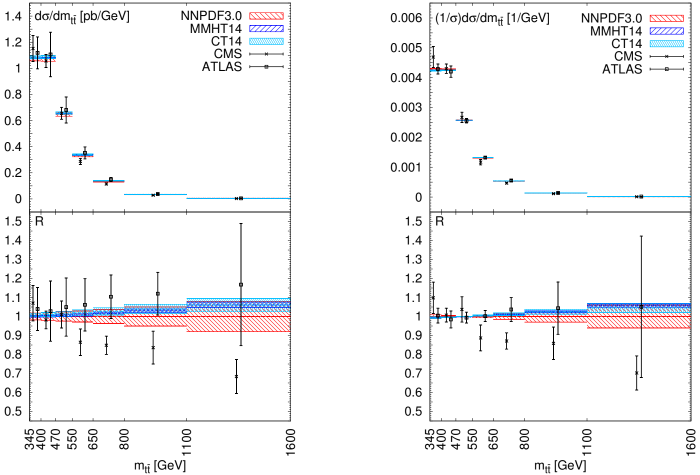

| PDF set | ATLAS $d\sigma/dy_t$ | CMS $d\sigma/dy_t$ | ATLAS $(1/\sigma)d\sigma/dy_t$ | CMS $(1/\sigma)d\sigma/dy_t$ |
|---|---|---|---|---|
| NNPDF3.0 | 0.73 (0.28) | 3.04 (1.05) | 4.06 (2.85) | 3.29 (1.49) |
| MMHT14 | 1.35 (0.29) | 2.12 (0.97) | 12.0 (6.79) | 2.41 (1.09) |
| CT14 | 1.32 (0.20) | 2.20 (1.46) | 10.7 (5.94) | 2.31 (0.95) |

# Data/Theory comparison: $y_{t\bar{t}}$




| PDF set | ATLAS $d\sigma/dy_{t\bar{t}}$ | CMS $d\sigma/dy_{t\bar{t}}$ | ATLAS $(1/\sigma)d\sigma/dy_{t\bar{t}}$ | CMS $(1/\sigma)d\sigma/dy_{t\bar{t}}$ |
|---|---|---|---|---|
| NNPDF3.0 | 0.84 (0.21) | 0.98 (0.74) | 3.99 (1.48) | 1.33 (0.74) |
| MMHT14 | 2.35 (0.29) | 2.26 (1.50) | 15.5 (5.47) | 3.26 (2.01) |
| CT14 | 2.85 (0.19) | 1.98 (1.70) | 13.5 (5.57) | 3.04 (1.57) |

# Data/Theory comparison: $m_{t\bar{t}}$




| PDF set | ATLAS $d\sigma/dm_{t\bar{t}}$ | CMS $d\sigma/dm_{t\bar{t}}$ | ATLAS $(1/\sigma)d\sigma/dm_{t\bar{t}}$ | CMS $(1/\sigma)d\sigma/dm_{t\bar{t}}$ |
|---|---|---|---|---|
| NNPDF3.0 | 0.77 (0.38) | 5.73 (4.36) | 1.57 (0.10) | 10.5 (3.87) |
| MMHT14 | 0.58 (0.25) | 7.30 (5.70) | 1.01 (0.05) | 13.5 (4.92) |
| CT14 | 0.60 (0.19) | 7.36 (6.11) | 1.08 (0.05) | 13.5 (4.86) |

# 2. Fits with top differential distributions

# Fit settings: a variant of the NNPDF3.0 analysis

1. Fixed order: NNLO QCD (no resummation, no EW corrections)
2. FONLL GM-VFNS, with $N_f^{\max} = 5$ active flavors
3. Pole mass scheme, $m_c = 1.275$ GeV and $m_b = 4.18$ GeV
4. Strong running coupling: $\alpha_s(M_Z) = 0.118$
5. Charm PDF generated perturbatively
6. Initial parametrization scale $Q_0 = 1$ GeV
7. Fit à la NNPDF (Monte Carlo sampling + Neural Network parametrization)
8. Take into account all provided (bin-by-bin) correlations
   (including the statistical covariance matrix)
9. Define a figure of merit to determine the best-fit parameters

$$\chi^2 \{\mathcal{T}[D], \mathcal{E}\} = \sum_{i,j}^{N_{\rm dat}} (T_i[D] - E_i)\, c_{ij}^{-1}\, (T_j[D] - E_j)$$

$$c_{ij}^{t_0} = \delta_{ij} s_i^2 + \sum_{\alpha=1}^{N_c} \sigma_{i,\alpha}^{(c)} \sigma_{j,\alpha}^{(c)} D_i D_j + \sum_{\alpha=1}^{N_{\mathcal{L}}} \sigma_{i,\alpha}^{(\mathcal{L})} \sigma_{j,\alpha}^{(\mathcal{L})} T_i^{(0)} T_j^{(0)}$$

$s_i$: uncorrelated unc.; $\sigma_{i,\alpha}^{(\mathcal{L})}$: $N_{\mathcal{L}}$ multiplicative norm. unc.; $\sigma_{i,\alpha}^{(c)}$ all other $N_c$ correlated unc.

# Taxonomy of the fits

| Data set | Fit ID 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| Baseline + | ☑ | ☑ | ☑ | ☑ | ☑ | ☑ | ☑ | ☑ | ☑ | ☑ |
| ATLAS $d\sigma/dp_T^t$ | | | ☑ | | | | | | | |
| ATLAS $d\sigma/dy_t$ | | | | ☑ | | | | | | |
| ATLAS $d\sigma/dy_{t\bar{t}}$ | | | | | ☑ | | | | | |
| ATLAS $d\sigma/dm_{t\bar{t}}$ | | | | | | ☑ | | | | |
| ATLAS $(1/\sigma)d\sigma/dp_T^t$ | | | | | | | ☑ | | | |
| ATLAS $(1/\sigma)d\sigma/dy_t$ | | | | | | | | ☑ | | |
| ATLAS $(1/\sigma)d\sigma/dy_{t\bar{t}}$ | | | | | | | | | ☑ | |
| ATLAS $(1/\sigma)d\sigma/dm_{t\bar{t}}$ | | | | | | | | | | ☑ |
| ATLAS $\sigma_{\mathrm{t\bar{t}}}$ | | ☑ | | | | | ☑ | ☑ | ☑ | ☑ |
| CMS $d\sigma/dp_T^t$ | | | ☑ | | | | | | | |
| CMS $d\sigma/dy_t$ | | | | ☑ | | | | | | |
| CMS $d\sigma/dy_{t\bar{t}}$ | | | | | ☑ | | | | | |
| CMS $d\sigma/dm_{t\bar{t}}$ | | | | | | ☑ | | | | |
| CMS $(1/\sigma)d\sigma/dp_T^t$ | | | | | | | ☑ | | | |
| CMS $(1/\sigma)d\sigma/dy_t$ | | | | | | | | ☑ | | |
| CMS $(1/\sigma)d\sigma/dy_{t\bar{t}}$ | | | | | | | | | ☑ | |
| CMS $(1/\sigma)d\sigma/dm_{t\bar{t}}$ | | | | | | | | | | ☑ |
| CMS $\sigma_{\mathrm{t\bar{t}}}$ | | ☑ | | | | | ☑ | ☑ | ☑ | ☑ |

Include only one distribution per experiment (avoid double counting)

Supplement normalized differential distributions with total inclusive cross section data

**Baseline 1:** HERA data only (legacy combinations of inclusive and charm measurements)

**Baseline 2:** `NNPDF3.0` no jets (top data are then the sole to constrain the gluon PDF)

# HERA-only fit: $\chi^2/N_{\rm dat}$

| Data set HERA only + | Fit ID 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| ATLAS $d\sigma/dp_T^t$ | 1.88 | 1.75 | **1.00** | 1.73 | 1.60 | 1.72 | 1.98 | 1.55 | 1.66 | 1.70 |
| ATLAS $d\sigma/dy_t$ | 0.78 | 0.55 | 0.50 | **0.84** | 0.61 | 0.73 | 0.74 | 0.68 | 0.67 | 0.73 |
| ATLAS $d\sigma/dy_{t\bar{t}}$ | 1.28 | 0.51 | 0.52 | 1.05 | **0.26** | 0.43 | 1.01 | 0.49 | 0.46 | 0.85 |
| ATLAS $d\sigma/dm_{t\bar{t}}$ | 2.04 | 1.46 | 1.49 | 1.52 | 1.58 | **1.78** | 0.89 | 1.90 | 1.92 | 1.28 |
| ATLAS $(1/\sigma)d\sigma/dp_T^t$ | 7.34 | 3.72 | 3.65 | 3.19 | 4.14 | 5.35 | **4.10** | 4.41 | 4.73 | 2.98 |
| ATLAS $(1/\sigma)d\sigma/dy_t$ | 8.78 | 1.74 | 1.27 | 3.81 | 1.25 | 3.65 | 3.19 | **1.40** | 1.29 | 3.98 |
| ATLAS $(1/\sigma)d\sigma/dy_{t\bar{t}}$ | 20.2 | 1.34 | 2.45 | 4.31 | 0.64 | 5.72 | 3.85 | 1.58 | **0.33** | 7.08 |
| ATLAS $(1/\sigma)d\sigma/dm_{t\bar{t}}$ | 8.85 | 3.55 | 4.16 | 3.87 | 4.61 | 7.17 | 2.49 | 6.48 | 6.86 | **1.34** |
| ATLAS $\sigma_{t\bar{t}}$ | 2.70 | **0.82** | 1.04 | 1.65 | 1.58 | 2.74 | **1.70** | **1.38** | **1.11** | **1.42** |
| CMS $d\sigma/dp_T^t$ | 9.05 | 3.15 | **2.64** | 4.85 | 4.39 | 5.51 | 5.53 | 9.13 | 8.44 | 4.41 |
| CMS $d\sigma/dy_t$ | 6.88 | 3.83 | 4.39 | **2.55** | 4.04 | 6.61 | 3.24 | 3.66 | 4.05 | 3.01 |
| CMS $d\sigma/dy_{t\bar{t}}$ | 3.74 | 1.28 | 1.58 | 1.44 | **1.31** | 2.27 | 0.90 | 1.80 | 1.53 | 1.99 |
| CMS $d\sigma/dm_{t\bar{t}}$ | 3.36 | 4.01 | 3.70 | 4.07 | 3.94 | **2.42** | 4.67 | 3.66 | 3.44 | 5.44 |
| CMS $(1/\sigma)d\sigma/dp_T^t$ | 2.43 | 3.09 | 2.45 | 3.28 | 2.65 | 2.48 | **2.94** | 2.34 | 2.39 | 3.70 |
| CMS $(1/\sigma)d\sigma/dy_t$ | 13.7 | 5.22 | 6.18 | 3.27 | 6.09 | 9.74 | 3.53 | **4.91** | 5.85 | 3.71 |
| CMS $(1/\sigma)d\sigma/dy_{t\bar{t}}$ | 8.37 | 1.46 | 1.68 | 1.52 | 1.70 | 2.49 | 1.54 | 1.34 | **1.24** | 2.03 |
| CMS $(1/\sigma)d\sigma/dm_{t\bar{t}}$ | 3.26 | 6.91 | 6.17 | 6.60 | 5.82 | 3.80 | 8.43 | 4.54 | 4.36 | **4.84** |
| CMS $\sigma_{t\bar{t}}$ | 2.79 | **0.59** | 0.89 | 1.17 | 1.29 | 0.94 | **1.39** | **1.27** | **1.93** | **1.38** |

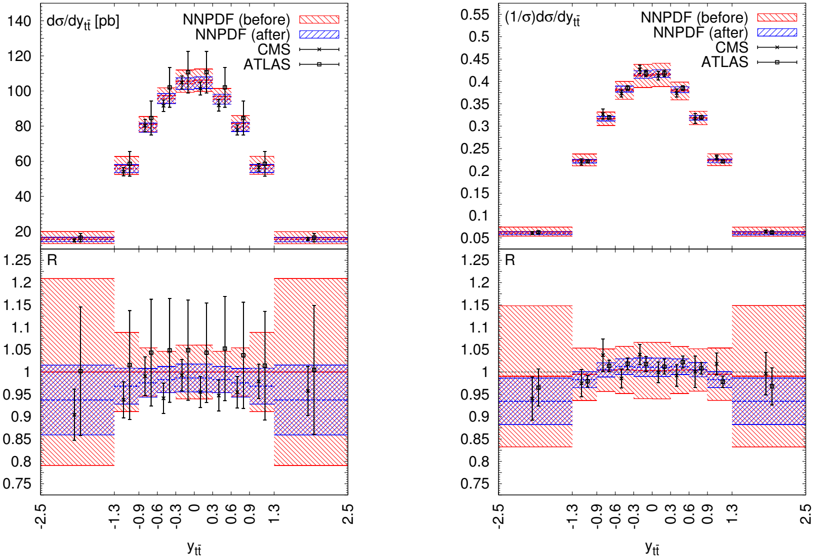
The values of the $\chi^2/N_{\rm dat}$ for the baseline data set are stable in all the fits
(and no significant deterioration of the global $\chi^2/N_{\rm dat}$ is observed)
Difficulty in the simultaneous description of both ATLAS and CMS data, except for $y_{t\bar{t}}$
(discrepancy in the reconstruction of parton-level observables? ATLAS/CMS correlations? . . . ?)
The $y_{t\bar{t}}$ distributions show the best $\chi^2/N_{\rm dat}$ irrespective of the fitted distribution
Preference for ATLAS distributions (lower $\chi^2/N_{\rm dat}$ values)

# Global fit (no jets): $\chi^2/N_{\rm dat}$

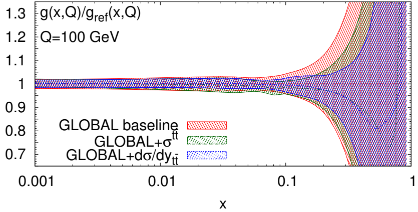
| Data set<br>NNPDF3.0 (no jets) + | Fit ID<br>1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| ATLAS $d\sigma/dp_T^t$ | 2.12 | 2.13 | **1.97** | 2.08 | 2.07 | 2.20 | 1.98 | 2.15 | 2.17 | 2.11 |
| ATLAS $d\sigma/dy_t$ | 0.68 | 0.64 | 0.61 | **0.72** | 0.55 | 0.63 | 0.74 | 0.60 | 0.62 | 0.69 |
| ATLAS $d\sigma/dy_{t\bar{t}}$ | 0.56 | 0.55 | 0.52 | 0.90 | **0.31** | 0.47 | 1.01 | 0.36 | 0.25 | 0.44 |
| ATLAS $d\sigma/dm_{t\bar{t}}$ | 0.71 | 1.08 | 0.95 | 0.91 | 0.97 | **1.03** | 0.89 | 1.11 | 1.22 | 1.15 |
| ATLAS $(1/\sigma)d\sigma/dp_T^t$ | 4.06 | 7.38 | 4.28 | 6.06 | 5.22 | 6.37 | **4.10** | 6.97 | 6.52 | 7.38 |
| ATLAS $(1/\sigma)d\sigma/dy_t$ | 3.09 | 1.89 | 1.79 | 3.25 | 1.54 | 1.82 | 3.19 | **1.71** | 1.49 | 1.74 |
| ATLAS $(1/\sigma)d\sigma/dy_{t\bar{t}}$ | 2.04 | 1.34 | 1.27 | 3.15 | 0.66 | 1.53 | 3.85 | 1.01 | **0.37** | 1.71 |
| ATLAS $(1/\sigma)d\sigma/dm_{t\bar{t}}$ | 1.80 | 3.16 | 2.83 | 2.38 | 2.79 | 3.30 | 2.49 | 3.35 | 4.20 | **3.57** |
| ATLAS $\sigma_{\rm t\bar{t}}$ | 3.29 | **1.46** | 1.93 | 2.74 | 2.84 | 2.82 | **1.70** | **1.64** | **1.57** | **1.58** |
| CMS $d\sigma/dp_T^t$ | 12.0 | 7.85 | **2.98** | 9.51 | 8.32 | 9.84 | 5.53 | 7.35 | 5.51 | 6.73 |
| CMS $d\sigma/dy_t$ | 3.59 | 3.65 | 3.97 | **3.07** | 4.48 | 4.16 | 3.24 | 3.90 | 4.93 | 4.12 |
| CMS $d\sigma/dy_{t\bar{t}}$ | 1.10 | 0.88 | 0.88 | 0.98 | **1.03** | 1.06 | 0.90 | 0.99 | 1.16 | 1.09 |
| CMS $d\sigma/dm_{t\bar{t}}$ | 5.91 | 4.02 | 4.42 | 4.73 | 4.42 | **4.07** | 4.67 | 3.93 | 3.44 | 3.72 |
| CMS $(1/\sigma)d\sigma/dp_T^t$ | 3.30 | 3.94 | 2.84 | 3.67 | 3.08 | 3.44 | **2.94** | 3.60 | 2.98 | 3.67 |
| CMS $(1/\sigma)d\sigma/dy_t$ | 3.65 | 4.47 | 4.53 | 3.52 | 5.02 | 4.68 | 3.53 | **4.67** | 5.98 | 5.05 |
| CMS $(1/\sigma)d\sigma/dy_{t\bar{t}}$ | 1.18 | 1.23 | 1.20 | 1.37 | 1.20 | 1.29 | 1.54 | 1.32 | **1.40** | 1.46 |
| CMS $(1/\sigma)d\sigma/dm_{t\bar{t}}$ | 9.94 | 7.31 | 7.86 | 8.60 | 7.89 | 7.23 | 8.47 | 7.12 | 6.16 | **6.82** |
| CMS $\sigma_{\rm t\bar{t}}$ | 4.15 | **0.50** | 1.38 | 1.49 | 1.60 | 1.99 | **1.39** | **0.77** | **0.56** | **0.60** |

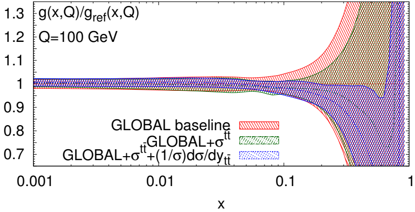
The values of the $\chi^2/N_{\rm dat}$ for the baseline data set are stable in all the fits
(and no significant deterioration of the global $\chi^2/N_{\rm dat}$) is observed
Difficulty in the simultaneous description of both ATLAS and CMS data, except for $y_{t\bar{t}}$
(discrepancy in the reconstruction of parton-level observables? ATLAS/CMS correlations? ...?)
The $y_{t\bar{t}}$ distributions show the best $\chi^2/N_{\rm dat}$ irrespective of the fitted distribution
Preference for ATLAS distributions (lower $\chi^2/N_{\rm dat}$ values)

# Global fit (no jets): impact on predictions



# Global fit (no jets): impact on the gluon PDF

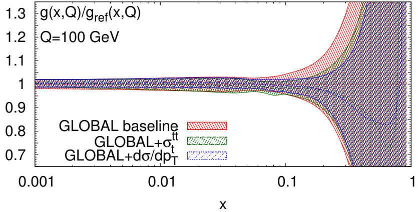


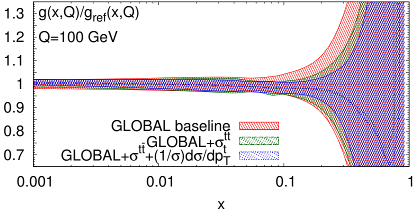




Normalized differential distributions supplemented with total cross sections turn out to be more constraining than absolute distributions

Significant reduction of the gluon uncertainty at mid- to large-$x$ values

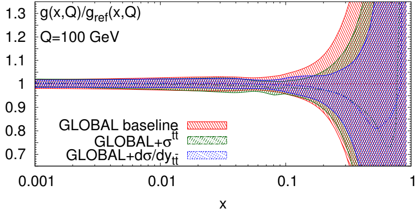
---

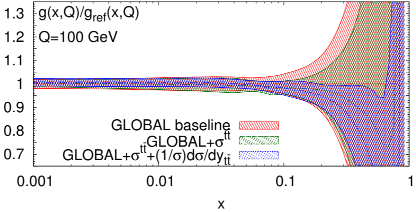



Similar trend from other distributions (with worse $\chi^2/N_{\rm dat}$ $\iff$ different constraining power)

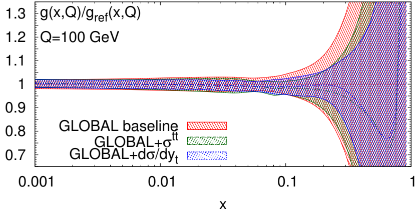
# Global fit (no jets): impact on the gluon PDF

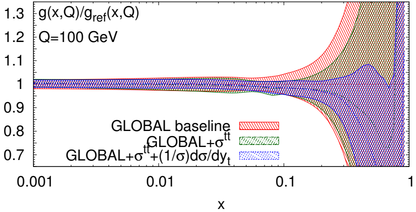



Normalized differential distributions supplemented with total cross sections turn out to be more constraining than absolute distributions

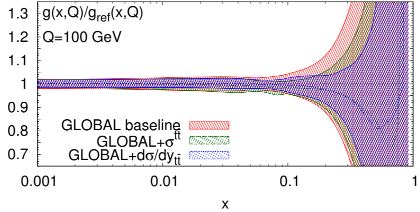
Significant reduction of the gluon uncertainty at mid- to large-$x$ values

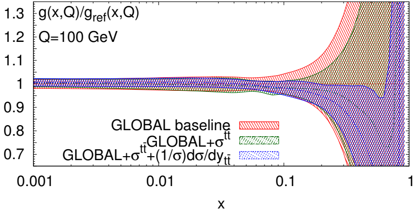



Similar trend from other distributions (with worse $\chi^2/N_{\mathrm{dat}} \Longleftrightarrow$ different constraining power)

# Global fit (no jets): impact on the gluon PDF

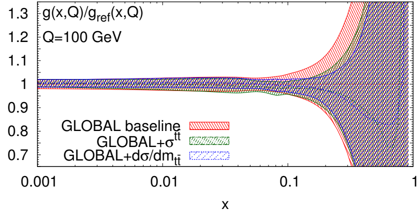


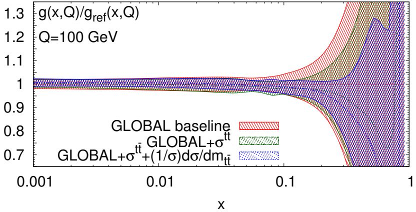




Normalized differential distributions supplemented with total cross sections turn out to be more constraining than absolute distributions

Significant reduction of the gluon uncertainty at mid- to large-$x$ values

---




Similar trend from other distributions (with worse $\chi^2/N_{\rm dat}$ $\Longleftrightarrow$ different constraining power)

# 3. Conclusions

# Summary and final remarks

**1.** I have presented a systematic data/theory comparison of $t\bar{t}$ differential distributions
certain amount of tension between ATLAS and CMS measurements, to be investigated
(different unfolding of parton-level quantities from measured quantities?)
(large correlations between ATLAS and CMS measurements?)
theoretical limiting factor: NNLO only available for top-level observables

**2.** I have presented a study of the impact of $t\bar{t}$ distributions on the gluon PDF
best constraining power: normalied distributions + total cross section
significant impact on the uncertainty of the gluon PDF
overall consistency of distributions limited to $y_{t\bar{t}}$ (CMS) and $y_t$ (ATLAS) distributions
these distributions will be included in the upcoming `NNPDF3.1` release

**3.** Useful future experimental/theoretical input:
estimate of the correlations among different distributions and between ATLAS and CMS
availability of measurements at 13 TeV (increased statistics and kinematic range)
computation of NNLO corrections for top quark differential distributions with top decays
evaluation of the impact of boosted top quark production

# Summary and final remarks

**1.** I have presented a systematic data/theory comparison of $t\bar{t}$ differential distributions
certain amount of tension between ATLAS and CMS measurements, to be investigated
(different unfolding of parton-level quantities from measured quantities?)
(large correlations between ATLAS and CMS measurements?)
theoretical limiting factor: NNLO only available for top-level observables

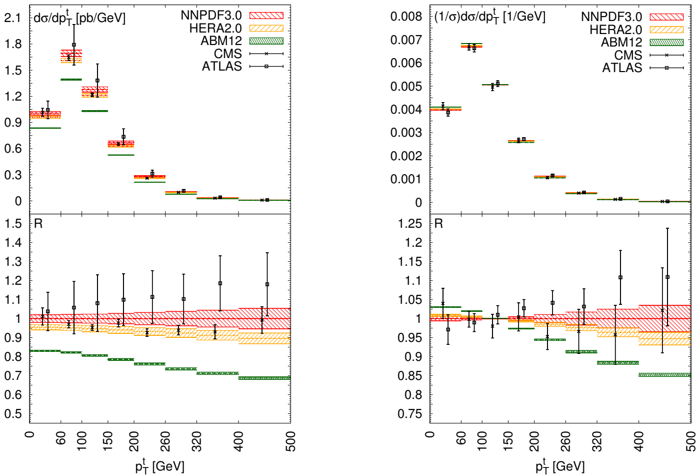
**2.** I have presented a study of the impact of $t\bar{t}$ distributions on the gluon PDF
best constraining power: normalied distributions + total cross section
significant impact on the uncertainty of the gluon PDF
overall consistency of distributions limited to $y_{t\bar{t}}$ (CMS) and $y_t$ (ATLAS) distributions
these distributions will be included in the upcoming `NNPDF3.1` release

**3.** Useful future experimental/theoretical input:
estimate of the correlations among different distributions and between ATLAS and CMS
availability of measurements at 13 TeV (increased statistics and kinematic range)
computation of NNLO corrections for top quark differential distributions with top decays
evaluation of the impact of boosted top quark production

**Thank you**

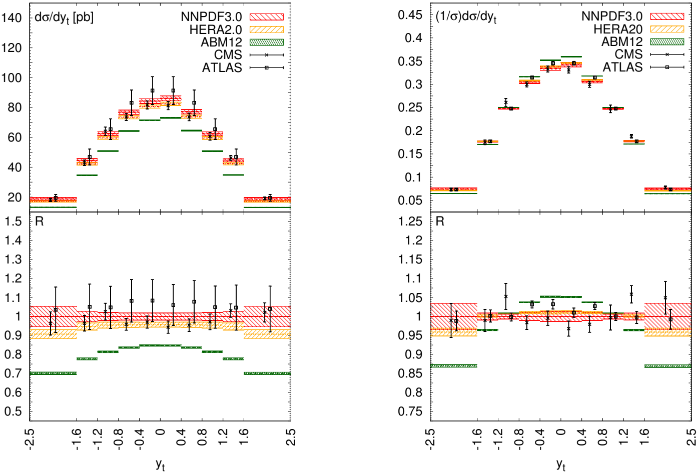
# 5. Extra material

# Data/Theory comparison: $p_T^t$



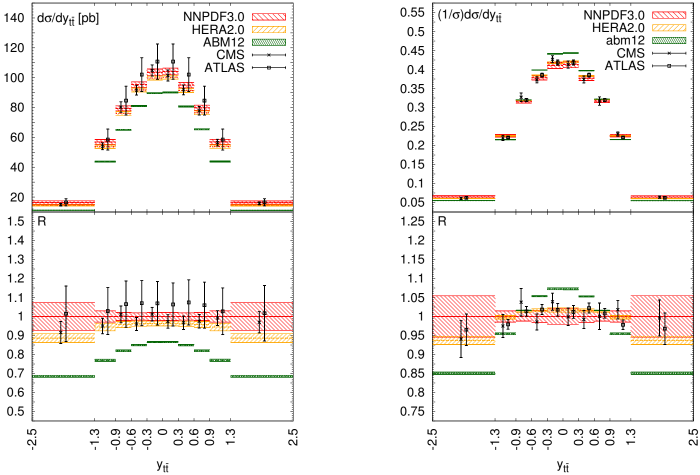

| PDF set | ATLAS $d\sigma/dp_T^t$ | CMS $d\sigma/dp_T^t$ | ATLAS $(1/\sigma)d\sigma/dp_T^t$ | CMS $(1/\sigma)d\sigma/dp_T^t$ |
|---|---|---|---|---|
| NNPDF3.0 | 0.84 (0.66) | 5.30 (4.57) | 3.13 (0.94) | 2.02 (0.50) |
| HERA2.0 | 1.13 (1.69) | 0.82 (1.05) | 5.19 (1.73) | 1.12 (0.33) |
| ABM12 | 1.94 (6.22) | 35.8 (55.2) | 13.9 (4.88) | 2.78 (0.80) |

# Data/Theory comparison: $y_t$



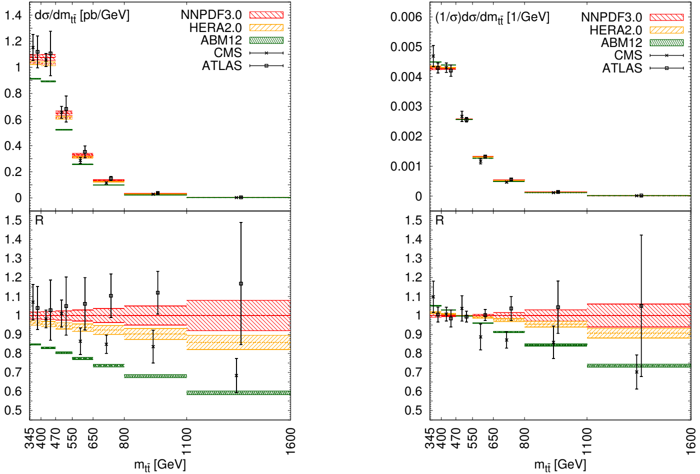

| PDF set | ATLAS $d\sigma/dy_t$ | CMS $d\sigma/dy_t$ | ATLAS $(1/\sigma)d\sigma/dy_t$ | CMS $(1/\sigma)d\sigma/dy_t$ |
|---|---|---|---|---|
| NNPDF3.0 | 0.73 (0.28) | 3.04 (1.05) | 4.06 (1.85) | 3.29 (1.49) |
| HERA2.0 | 0.72 (0.99) | 3.64 (1.49) | 1.75 (1.62) | 4.98 (2.28) |
| ABM12 | 1.44 (5.31) | 9.74 (22.1) | 15.4 (7.02) | 17.6 (8.67) |

# Data/Theory comparison: $y_{t\bar{t}}$



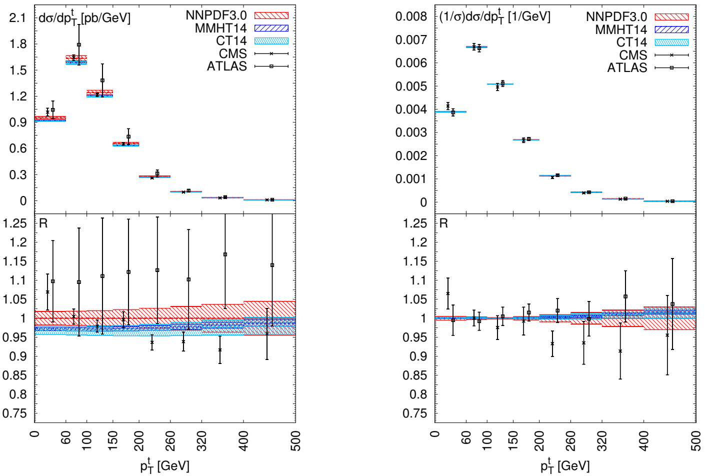

| PDF set | ATLAS $d\sigma/dy_{t\bar{t}}$ | CMS $d\sigma/dy_{t\bar{t}}$ | ATLAS $(1/\sigma)d\sigma/dy_{t\bar{t}}$ | CMS $(1/\sigma)d\sigma/dy_{t\bar{t}}$ |
|---|---|---|---|---|
| NNPDF3.0 | 0.84 (0.21) | 0.98 (0.74) | 3.99 (1.48) | 1.33 (0.74) |
| HERA2.0 | 0.53 (0.73) | 1.01 (0.78) | 1.19 (0.60) | 1.46 (0.81) |
| ABM12 | 1.04 (4.04) | 5.45 (18.0) | 20.0 (5.98) | 7.77 (4.99) |

# Data/Theory comparison: $m_{t\bar{t}}$



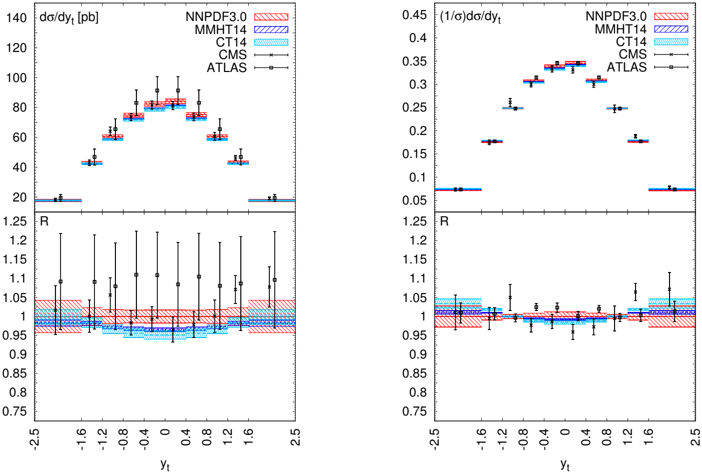

| PDF set | ATLAS $d\sigma/dm_{t\bar{t}}$ | CMS $d\sigma/dm_{t\bar{t}}$ | ATLAS $(1/\sigma)d\sigma/dm_{t\bar{t}}$ | CMS $(1/\sigma)d\sigma/dm_{t\bar{t}}$ |
|---|---|---|---|---|
| NNPDF3.0 | 0.77 (0.38) | 5.73 (4.36) | 1.57 (0.10) | 10.5 (3.87) |
| HERA2.0 | 1.40 (1.30) | 3.32 (1.49) | 4.35 (0.30) | 5.96 (2.29) |
| ABM12 | 3.81 (5.72) | 3.21 (5.22) | 21.0 (1.60) | 1.24 (0.48) |

# Data/Theory comparison: $p_T^t$ (NLO)



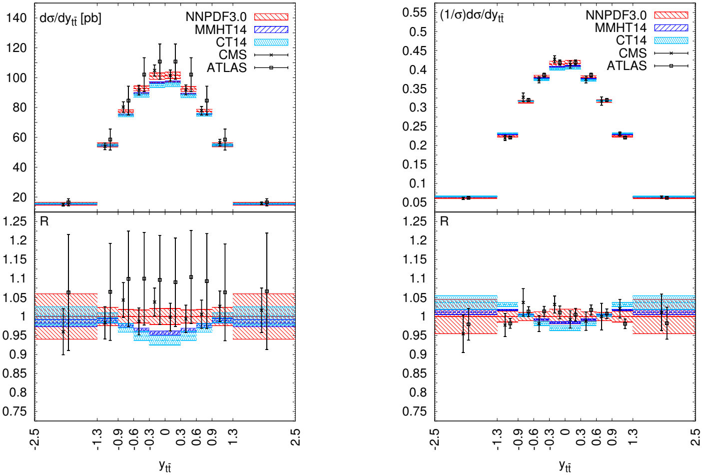

| PDF set | ATLAS $d\sigma/dp_T^t$ | CMS $d\sigma/dp_T^t$ | ATLAS $(1/\sigma)d\sigma/dp_T^t$ | CMS $(1/\sigma)d\sigma/dp_T^t$ |
|---|---|---|---|---|
| NNPDF3.0 | 0.58 (0.76) | 3.79 (3.21) | 1.55 (0.23) | 5.37 (1.26) |
| MMHT14 | 0.60 (1.10) | 2.75 (2.22) | 1.39 (0.18) | 5.80 (1.40) |
| CT14 | 0.62 (1.19) | 2.71 (2.21) | 1.45 (0.18) | 5.65 (1.37) |

# Data/Theory comparison: $y_t$ (NLO)



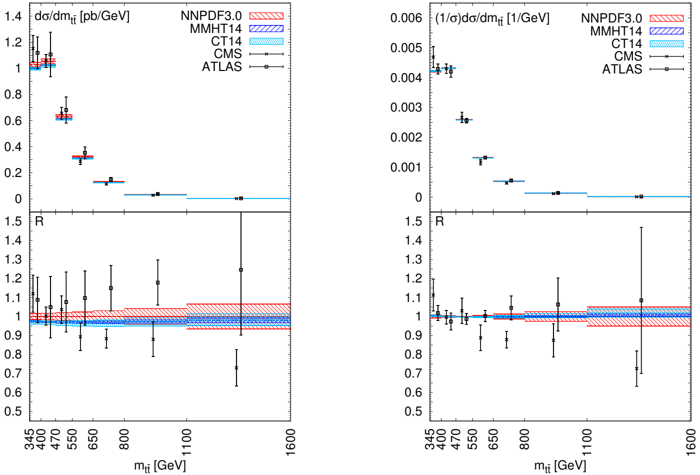

| PDF set | ATLAS $d\sigma/dy_t$ | CMS $d\sigma/dy_t$ | ATLAS $(1/\sigma)d\sigma/dy_t$ | CMS $(1/\sigma)d\sigma/dy_t$ |
|---|---|---|---|---|
| NNPDF3.0 | 0.59 (0.77) | 3.60 (0.93) | 1.83 (1.66) | 4.50 (2.09) |
| MMHT14 | 0.80 (1.06) | 2.61 (1.45) | 3.45 (2.53) | 3.41 (1.50) |
| CT14 | 1.13 (1.15) | 2.01 (1.55) | 7.11 (4.24) | 2.54 (1.04) |

# Data/Theory comparison: $y_{t\bar{t}}$ (NLO)



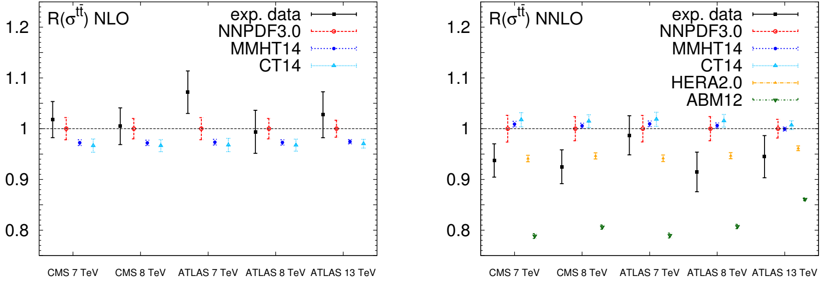

| PDF set | ATLAS $d\sigma/dy_{t\bar{t}}$ | CMS $d\sigma/dy_{t\bar{t}}$ | ATLAS $(1/\sigma)d\sigma/dy_{t\bar{t}}$ | CMS $(1/\sigma)d\sigma/dy_{t\bar{t}}$ |
|---|---|---|---|---|
| NNPDF3.0 | 0.68 (0.64) | 0.83 (0.33) | 2.09 (0.94) | 1.19 (0.64) |
| MMHT14 | 1.74 (0.83) | 1.22 (1.15) | 6.28 (2.81) | 1.81 (0.89) |
| CT14 | 3.20 (0.96) | 2.14 (1.78) | 4.05 (5.91) | 3.18 (1.61) |

# Data/Theory comparison: $m_{t\bar{t}}$ (NLO)




| PDF set | ATLAS $d\sigma/dm_{t\bar{t}}$ | CMS $d\sigma/dm_{t\bar{t}}$ | ATLAS $(1/\sigma)d\sigma/dm_{t\bar{t}}$ | CMS $(1/\sigma)d\sigma/dm_{t\bar{t}}$ |
|---|---|---|---|---|
| NNPDF3.0 | 1.06 (0.47) | 4.70 (2.73) | 3.91 (0.22) | 8.78 (3.38) |
| MMHT14 | 1.13 (1.17) | 4.69 (2.22) | 3.71 (1.59) | 8.80 (3.37) |
| CT14 | 1.10 (1.24) | 4.85 (2.23) | 3.51 (1.59) | 9.05 (3.48) |

# Data/Theory comparison: $\sigma^{t\bar{t}}$ (NLO and NNLO)




| PDF set | ATLAS $\sigma^{t\bar{t}}$ (NLO) | CMS $\sigma^{t\bar{t}}$ (NLO) | ATLAS $\sigma^{t\bar{t}}$ (NNLO) | CMS $\sigma^{t\bar{t}}$ (NNLO) |
|---|---|---|---|---|
| NNPDF3.0 | 1.11 | 1.14 | 2.21 | 1.36 |
| MMHT14 | 2.38 | 1.22 | 2.51 | 1.32 |
| CT14 | 2.71 | 1.59 | 2.19 | 1.72 |
| HERA2.0 | – | – | 0.74 | 0.21 |
| ABM12 | – | – | 12.6 | 16.7 |