Top-quark (pole) mass extraction at NNLO accuracy

S. Alekhin\textsuperscript{1}, Maria Vittoria Garzelli\textsuperscript{1}, J. Mazzitelli\textsuperscript{2}, S.-O. Moch\textsuperscript{1}, O. Zenaiev\textsuperscript{1}

\textsuperscript{1} II Institut für Theoretische Physik, Universität Hamburg
\textsuperscript{2} PSI, Villigen

On the basis of
\texttt{arXiv:2311.05509}
published in JHEP
+ work in progress

LHCP Conference, Boston, MA
June 3-8, 2024
Why studying $t\bar{t}$ production?

- $m_t$ provides a hard scale
  $\Rightarrow$ ultimate probe of pQCD
  (NLO, aNNLO, NNLO, ...)

- Produced mainly via $gg$
  $\Rightarrow$ constrain gluon PDF at high $x$

- Production sensitive to $\alpha_S$ and $m_t$

- May provide insight into possible new physics

Example:

Simultaneous extraction of PDFs, $\alpha_S$, $m_t^{\text{pole}}$ using normalised triple-differential cross sections at NLO

Extended to $\overline{\text{MS}}$, MSR schemes in JHEP 04 (2021) 043 [Garzelli, Kemmler, Moch, Zenaiev]
Scope of our work

- Extraction of $m_t$ (+ proton PDFs, $\alpha_s$), by comparing double-(triple-)differential $pp \to t\bar{t} + X$ cross sections with NNLO calculations
  - however, for 3D cross sections in $M(t\bar{t})$, $y(t\bar{t})$, $N_{\text{jet}}$ [CMS arXiv:1904.05237], NNLO calculations are not yet available for $t\bar{t} + \text{jets} + X$

- For the time being we focus especially on PDF and $m_t^{\text{pole}}$ sensitivity and look at single-differential $M(t\bar{t})$ and double-differential $M(t\bar{t}), y(t\bar{t})$ cross sections
  - $M(t\bar{t})$ provides sensitivity to $m_t$
  - when combined with $y(t\bar{t})$, this provides sensitivity to PDFs via relation to partonic momentum fraction $x$:
    at LO $x_{1,2} = (M(t\bar{t})/\sqrt{s}) \exp[\pm y(t\bar{t})]$

- We also consider the most recent results for total cross sections.

- NNLO computations for total inclusive $pp \to t\bar{t} + X$ cross sections can be obtained with theory tools already publicly available since long.

- NNLO computations for total and multi-differential $pp \to t\bar{t} + X$ cross sections can now be performed thanks to the publicly available \textsc{matrix} framework [Catani, Devoto, Grazzini, Kallweit, Mazzitelli Phys.Rev.D 99 (2019) 5, 051501; JHEP 07 (2019) 100]
  - fully differential NNLO calculations were also published in JHEP 04 (2017) 071 [Czakon, Heymes, Mitov], but no public code available. Part of their predictions can however now be accessed through the \textsc{hightea} (database) platform.
Theoretical calculations with \texttt{MATRIX} + \texttt{PineAPPL} framework

- Using private version of \texttt{MATRIX} [Grazzini, Kallweit, Wiesemann, EPJC 78 (2018) 537]
- Interfaced to \texttt{PineAPPL} [Carrazza et al., JHEP 12 (2020) 108] to produce interpolation grids which are further used in \texttt{xFitter} https://gitlab.com/fitters/xfitter
  - reproduce NNLO calculations using any PDF + \(\alpha_s (M_Z)\) set and/or varied \(\mu_r, \mu_f\) in \(\sim \) seconds (with accuracy well below 1% in all bins)
  - interface implemented privately and only for the \(pp \to \bar{t}t + X\) process

- Further modifications to \texttt{MATRIX} to make possible runs with \(\Delta \sigma_{\bar{t}t} < 0.1\%\)
  - adapted to DESY Bird Condor cluster and local multicore machines
  - technical fixes related to memory and disk space usage, etc.

- We did runs with different \(m_t^{\text{pole}}\) values 165–177.5 GeV with step of 2.5 GeV and \(\Delta \sigma_{\bar{t}t} = 0.02\%\)
  - \(\approx 60000\) CPU hours/run (\(\sim 5\) years/run on a single CPU)
  - for differential distributions, statistical uncertainties in bins are \(\lesssim 0.5\%\)
    \(\rightarrow\) not negligible compared to data precision and included in \(\chi^2\) calculation

- Differential distributions obtained with fixed \(r_{cut} = 0.0015\) (\(q_T\) subtraction: see talks by S. Kallweit and S. Devoto)
  - checked that extrapolation to \(r_{cut} = 0\) for total \(\sigma(\bar{t}t + X)\) produces differences < 1%, see also S. Catani et al., JHEP 07 (2019) 100

- \(\mu_r = \mu_f = H_T/4, H_T = \sqrt{m_t^2 + p_T^2(t)} + \sqrt{m_{\bar{t}}^2 + p_T^2(\bar{t})},\) varied up and down by factor 2 with \(0.5 \leq \mu_r/\mu_f \leq 2\) (7-point variation)
Good agreement (assuming that CHM also have uncertainty $\sim 1\%$)
## ATLAS and CMS datasets used in this work: total cross sections

<table>
<thead>
<tr>
<th>experiment</th>
<th>decay channel</th>
<th>dataset</th>
<th>luminosity</th>
<th>√s</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS &amp; CMS</td>
<td>combined</td>
<td>2011</td>
<td>5 fb⁻¹</td>
<td>7 TeV</td>
</tr>
<tr>
<td>ATLAS &amp; CMS</td>
<td>combined</td>
<td>2012</td>
<td>20 fb⁻¹</td>
<td>8 TeV</td>
</tr>
<tr>
<td>ATLAS</td>
<td>dileptonic, semileptonic</td>
<td>2011</td>
<td>257 pb⁻¹</td>
<td>5.02 TeV</td>
</tr>
<tr>
<td>CMS</td>
<td>dileptonic</td>
<td>2011</td>
<td>302 pb⁻¹</td>
<td>5.02 TeV</td>
</tr>
<tr>
<td>ATLAS</td>
<td>dileptonic</td>
<td>2015-2018</td>
<td>140 fb⁻¹</td>
<td>13 TeV</td>
</tr>
<tr>
<td>ATLAS</td>
<td>semileptonic</td>
<td>2015-2018</td>
<td>139 fb⁻¹</td>
<td>13 TeV</td>
</tr>
<tr>
<td>CMS</td>
<td>dileptonic</td>
<td>2016</td>
<td>35.9 fb⁻¹</td>
<td>13 TeV</td>
</tr>
<tr>
<td>CMS</td>
<td>semileptonic</td>
<td>2016-2018</td>
<td>137 fb⁻¹</td>
<td>13 TeV</td>
</tr>
<tr>
<td>ATLAS</td>
<td>dileptonic</td>
<td>2022</td>
<td>11.3 fb⁻¹</td>
<td>13.6 TeV</td>
</tr>
<tr>
<td>CMS</td>
<td>dileptonic, semileptonic</td>
<td>2022</td>
<td>1.21 fb⁻¹</td>
<td>13.6 TeV</td>
</tr>
</tbody>
</table>

### Selection criteria:
- Data considered in the LHC Top Working Group (June 2023, there is a 2024 update that however we expect to play only a minor role on our results).
ATLAS and CMS datasets used in this work: single- and double-differential distributions

<table>
<thead>
<tr>
<th>Experiment</th>
<th>decay channel</th>
<th>dataset</th>
<th>luminosity</th>
<th>$\sqrt{s}$</th>
<th>observable(s)</th>
<th>$n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMS</td>
<td>semileptonic</td>
<td>2016–2018</td>
<td>137 fb$^{-1}$</td>
<td>13 TeV</td>
<td>$M(t\bar{t})$, $</td>
<td>y(t\bar{t})</td>
</tr>
<tr>
<td>CMS</td>
<td>dileptonic</td>
<td>2016</td>
<td>35.9 fb$^{-1}$</td>
<td>13 TeV</td>
<td>$M(t\bar{t})$, $</td>
<td>y(t\bar{t})</td>
</tr>
<tr>
<td>ATLAS</td>
<td>semileptonic</td>
<td>2015–2016</td>
<td>36 fb$^{-1}$</td>
<td>13 TeV</td>
<td>$M(t\bar{t})$, $</td>
<td>y(t\bar{t})</td>
</tr>
<tr>
<td>ATLAS</td>
<td>all-hadronic</td>
<td>2015–2016</td>
<td>36.1 fb$^{-1}$</td>
<td>13 TeV</td>
<td>$M(t\bar{t})$, $</td>
<td>y(t\bar{t})</td>
</tr>
<tr>
<td>CMS</td>
<td>dileptonic</td>
<td>2012</td>
<td>19.7 fb$^{-1}$</td>
<td>8 TeV</td>
<td>$M(t\bar{t})$, $</td>
<td>y(t\bar{t})</td>
</tr>
<tr>
<td>ATLAS</td>
<td>semileptonic</td>
<td>2012</td>
<td>20.3 fb$^{-1}$</td>
<td>8 TeV</td>
<td>$M(t\bar{t})$</td>
<td>6</td>
</tr>
<tr>
<td>ATLAS</td>
<td>dileptonic</td>
<td>2012</td>
<td>20.2 fb$^{-1}$</td>
<td>8 TeV</td>
<td>$M(t\bar{t})$</td>
<td>5</td>
</tr>
<tr>
<td>ATLAS</td>
<td>dileptonic</td>
<td>2011</td>
<td>4.6 fb$^{-1}$</td>
<td>7 TeV</td>
<td>$M(t\bar{t})$</td>
<td>4</td>
</tr>
<tr>
<td>ATLAS</td>
<td>semileptonic</td>
<td>2011</td>
<td>4.6 fb$^{-1}$</td>
<td>7 TeV</td>
<td>$M(t\bar{t})$</td>
<td>4</td>
</tr>
</tbody>
</table>

**Selection criteria:**

- we focus on $d\sigma/dM(t\bar{t})$ and $d^2\sigma/dM(t\bar{t})dy(t\bar{t})$ distributions.

- We use measurements where the experimental collaborations provide unfolding to the inclusive parton level ($t\bar{t}$) (MATTRIX is being extended at decayed-top level only now (see talk by S. Kallweit), LHCb data so far only available at the particle level).

- We used measurements normalized, to reduce the effect of lack of information concerning correlations of uncertainties between different experimental analyses (source by source available only in CMS dilepton analyses!).

- we used measurements for which info on bin-by-bin correlated uncertainties are available.
We focus especially on measurements at 13 TeV where double-differential $M(t\bar{t})$, $y(t\bar{t})$ cross sections at parton level are available not considered so far in any top-quark pole-mass extraction at NNLO.

1. CMS EPJ C80 (2020) 658 [1904.05237, TOP-18-004]:
   - 2D cross sections in dileptonic channel, $L = 35.9 \text{ pb}^{-1}$
   - for 3D $M(t\bar{t})$, $y(t\bar{t})$, $N_{\text{jet}}$ cross sections, NNLO is not available for $t\bar{t} + \text{jets} + X$

2. CMS Phys.Rev.D104 (2021) 9, 092013 [2108.02803, TOP-20-001]:
   - 2D cross sections in l+jets channel, $L = 137 \text{ pb}^{-1}$

3. ATLAS EPJ C79 (2019) 1028 [1908.07305]:
   - 2D cross sections in l+jets channel, $L = 36 \text{ pb}^{-1}$

4. ATLAS JHEP 01 (2021) 033 [2006.09274]:
   - 2D cross sections in all-hadronic channel, $L = 36.1 \text{ pb}^{-1}$
CMS [arXiv:1904.05237] vs NNLO predictions using different PDFs

- **Fixed** $m_t^{\text{pole}} = 172.5$ GeV, $\mu_r = \mu_f = H_T/4$
- **Reported** $\chi^2$ values with (and without) PDF uncertainties
- **All PDF sets** describe data reasonably well, with best description by ABMP16

S. Alekhin, M.V.G., J. Mazzitelli, S. Moch, O. Zenaiev Top-quark pole mass extraction at NNLO accuracy
Fixed $m_{t}^{\text{pole}} = 172.5$ GeV, $\mu_r = \mu_f = H_T/4$

Reported $\chi^2$ values with (and without) PDF uncertainties

All PDF sets describe data reasonably well

- But CT18, MSHT20 and NNPDF40 show clear trend w.r.t data at high $y(t\bar{t})$ (large $x$)

This is the most precise currently available dataset with finest bins
Fixed $m_{t}^\text{pole} = 172.5$ GeV, $\mu_r = \mu_f = H_T/4$

Reported $\chi^2$ values with (and without) PDF uncertainties

All PDF sets describe data reasonably well.

$\chi^2$/dof < 1 indicating possible overestimation of experimental uncertainties (additionally, the data covariance matrix is not singular, i.e. $\det(\text{cov}) \neq 0$: to be checked if this is related to some numerical inaccuracy or other reasons. This affects estimates of correlated uncertainties. Same issue in the $\sqrt{s} = 8$TeV ATLAS analysis [arXiv:1607.07281].

S. Alekhin, M.V.G., J. Mazzitelli, S. Moch, O. Zenaiev Top-quark pole mass extraction at NNLO accuracy

11/26
ATLAS [arXiv:2006.09274] vs NNLO predictions using different PDFs

Fixed $m^\text{pole}_t = 172.5$ GeV, $\mu_r = \mu_f = H_T/4$

Reported $\chi^2$ values with (and without) PDF uncertainties

All PDF sets describe data reasonably well

$\chi^2$/dof < 1 indicating possible overestimation of experimental uncertainties

S. Alekhin, M.V.G., J. Mazzitelli, S. Moch, O. Zenaiev Top-quark pole mass extraction at NNLO accuracy
Data vs double-diff NNLO predictions at $\sqrt{s} = 13$ TeV using different PDFs: summary

<table>
<thead>
<tr>
<th>PDF</th>
<th>$t\bar{t}$ data in PDF fit</th>
<th>$\chi^2$/NDP (all data)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>w/ PDF unc.</td>
</tr>
<tr>
<td>ABMP16</td>
<td>only total $\sigma(t\bar{t} + X)$</td>
<td>56/78</td>
</tr>
<tr>
<td>CT18</td>
<td>total and diff. $\sigma(t\bar{t} + X)$</td>
<td>80/78</td>
</tr>
<tr>
<td>MSHT20</td>
<td>total and diff. $\sigma(t\bar{t} + X)$</td>
<td>92/78</td>
</tr>
<tr>
<td>NNPDF4.0</td>
<td>total and diff. $\sigma(t\bar{t} + X)$</td>
<td>104/78</td>
</tr>
</tbody>
</table>

- No PDF fit include the datasets (1)-(4) that we considered
  - NNPDF4.0 include single-differential data from CMS studies [1803.08856, 1811.06625], using 2016 events, with partial overlap with the events used in the independent CMS Run 2 analyses that we considered. Additionally they include the double-differential Run 1 CMS dataset [arXiv:1703.01630], that we also include in our fits.
Using ABMP16, $\mu_r = \mu_f = H_T/4$

- Reported $\chi^2$ values with PDF uncertainties
- Large sensitivity to $m_t^{pole}$ in the first $M(t\bar{t})$ bin (and due to cross-section normalisation, also in other $M(t\bar{t})$ bins)
CMS [arXiv:2108.02803] vs NNLO predictions using different $m^\text{pole}_t$

- Using ABMP16, $\mu_r = \mu_f = H_T/4$
- Reported $\chi^2$ values with PDF uncertainties
- Large sensitivity to $m^\text{pole}_t$ in the first $M(t\bar{t})$ bin (and due to x-section normalisation, also in other $M(t\bar{t})$ bins)
- Fluctuations of theory predictions are $\lesssim 1\%$ and covered by the assigned uncertainty of 1\%
Using ABMP16, $\mu_r = \mu_f = H_T/4$

Reported $\chi^2$ values with PDF uncertainties

Large sensitivity to $m_t^{\text{pole}}$ in the first $M(t\bar{t})$ bin (and due to x-section normalisation, also in other $M(t\bar{t})$ bins)
Using ABMP16, $\mu_r = \mu_f = H_T/4$

Reported $\chi^2$ values with PDF uncertainties

Limited sensitivity to $m_t^{\text{pole}}$ in the $0 < M(t\bar{t}) < 700$ GeV bin, due to its wideness: this dataset is not used as standalone, but is still used in our global fits for $m_t^{\text{pole}}$ extraction.
Using ABMP16, $m_t^{\text{pole}} = 172.5$ GeV, $\mu = H_T/4$

Reported $\chi^2$ values with PDF uncertainties

Effect of scale variations at NNLO < 4% (at low $M(t\bar{t}) < 1\%$), due to strong cancellations in the normalization) (analogous size of scale uncertainties are obtained for theory predictions compared to the ATLAS double-differential datasets).
Using ABMP16, \( m_t^{\text{pole}} = 172.5 \text{ GeV}, \mu = H_T/4 \)

Reported \( \chi^2 \) values with PDF uncertainties

Effect of scale variations at NNLO \(+3\% \ -5\%\) comparable or even larger than experimental uncertainty: \( \Rightarrow \) this limits precision of \( m_t^{\text{pole}} \) extraction to \( \gtrsim 1 \text{ GeV} \)

Shall we go to aNNLO? See talk by M. Guzzi
Extraction of $m_t^{\text{pole}}$: global analysis

- $\chi^2$ minimum is determined using parabolic interpolation of 3 points with lowest $\chi^2$ values.
- Both experimental, theory numerical, and PDF uncertainties included in $\chi^2$.
- $\Delta m_t^{\text{pole}}$ uncertainty $\sim \pm 0.3 \text{ GeV}$ quoted in the plots takes into account all uncertainties included in the covariance matrix ($\Delta \chi^2 = 1$).
- Scale variations are not included in $\chi^2$ (the uncertainties do not follow a gaussian distribution) but they are done explicitly (offset method) (span an interval of $\sim 0.2 \text{ GeV}$).

S. Alekhin, M.V.G., J. Mazzitelli, S. Moch, O. Zenaiev Top-quark pole mass extraction at NNLO accuracy
Extraction of $m_t^{\text{pole}}$: slight tension ATLAS/CMS datasets

- Compatibility between $m_t^{\text{pole}}$ from the analysis of semileptonic and dileptonic data only within $2.5\sigma$, driven by the fact that CMS dileptonic analyses seem to prefer smaller $m_t^{\text{pole}}$ values than all others.

- It becomes fundamental to consider new analyses with full Run-2 statistics (ATLAS and CMS, dileptonic channel, full Run-2 integrated luminosity).

\[ m_t^{\text{pole}} = 172.5 \pm 0.7 \text{ GeV} \]

\[ \text{CMS 2011.04716} \]

\[ \text{CMS 1607.07281} \]

\[ \text{CMS 1808.02803} \]

\[ \text{CMS 1511.04716} \]

\[ \text{CMS 1703.01630} \]

\[ \text{CMS 1904.05237} \]
Extraction of $m_t^{\text{pole}}$: summary from Run-2

- Global Run-2 fit
  - For the fit to the CMS [arXiv:1904.05237] dataset, our NNLO results are consistent with the NLO ones published in the experimental paper itself.
    - $\sim 2\sigma$ difference w.r.t other LHC data (unfolding effect ?)
  - Coulomb and soft-gluon resummation effects near the $t\bar{t}$ production threshold are neglected: expected correction $\sim O(1 \text{ GeV})$ can be regarded as additional theoretical uncertainty
    - CMS Coll. EPJ C80 (2020) 658; Kiyo, Kuhn, Moch, Steinhauser, Uwer EPJ C60 (2009) 375; Mäkelä, Hoang, Lipka, Moch 2301.03546
    - these corrections will make possible $m_t^{\text{pole}}$ extraction with reduced uncertainty.

S. Alekhin, M.V.G., J. Mazzitelli, S. Moch, O. Zenaiev Top-quark pole mass extraction at NNLO accuracy
Extraction of $m_{t}^{\text{pole}}$: summary from Run-1+Run-2

<table>
<thead>
<tr>
<th></th>
<th>ATLAS+CMS Run1 differential</th>
<th>ATLAS+CMS Run2 differential</th>
<th>ATLAS+CMS Run1,2 total</th>
<th>ATLAS+CMS all</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABMP16</td>
<td></td>
<td></td>
<td></td>
<td>171.54 ± 0.24 ± 0.15 ±0.03 ±0.13</td>
</tr>
<tr>
<td>CT18</td>
<td></td>
<td></td>
<td></td>
<td>171.59 ± 0.22 ± 0.18 ±0.02 ±0.18</td>
</tr>
<tr>
<td>MSHT20</td>
<td></td>
<td></td>
<td></td>
<td>171.79 ± 0.22 ± 0.16 ±0.04 ±0.22</td>
</tr>
<tr>
<td>NNPDF40</td>
<td></td>
<td></td>
<td></td>
<td>172.15 ± 0.23 ± 0.08 ±0.19 ±0.49</td>
</tr>
</tbody>
</table>

**Global Run-1 + Run-2 fit:**
- extracted $m_{t}^{\text{pole}}$ values with precision $±0.3$ GeV are consistent with PDG value $172.5 ± 0.3$ GeV
  - data uncertainty $≈ 0.2 − 0.3$ GeV
  - PDF uncertainty $≈ 0.1 − 0.2$ GeV
  - NNLO scale uncertainty $≈ 0.1 − 0.2$ GeV

- in case of total cross-sections only, $m_{t}^{\text{pole}}$ uncertainties dominated by scale variation effects

- for each PDF set, compatibility within uncertainties between $m_{t}^{\text{pole}}$ extracted using Run-1 or Run-2 differential data

- compatibility within uncertainties among $m_{t}^{\text{pole}}$ extracted using as input different (PDF+$\alpha_s(M_Z)$) sets

- Significant dependence of the central $m_{t}^{\text{pole}}$ value on PDFs ($≈ 0.6$ GeV):
  - different $m_{t}^{\text{pole}}$ used in different PDFs
  - PDFs, $m_{t}^{\text{pole}}$ (and $\alpha_s(M_Z)$) should be determined simultaneously
Simultaneous fit of top-quark mass, PDFs, $\alpha_s(M_Z)$ in the ABMP framework, using most of the data listed before + single-top, is in progress: FIRST PRELIMINARY RESULTS

<table>
<thead>
<tr>
<th>$\alpha_s(M_Z, N_f = 5)$</th>
<th>$m_t(m_t)$ (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fitted</td>
<td>0.1150(9)</td>
</tr>
<tr>
<td></td>
<td>160.6(6)</td>
</tr>
<tr>
<td>0.114</td>
<td>160.2(4)</td>
</tr>
<tr>
<td>0.116</td>
<td>161.0(4)</td>
</tr>
<tr>
<td>0.118</td>
<td>161.9(4)</td>
</tr>
<tr>
<td>0.120</td>
<td>162.8(4)</td>
</tr>
<tr>
<td>0.122</td>
<td>163.5(4)</td>
</tr>
</tbody>
</table>

**Table:** The values of $m_t(m_t)$ obtained with different values of $\alpha_s$ in the ABMPtt fit.

- Correlations between PDF $g(x)$, $\alpha_s(M_Z)$ and $m_t(m_t)$ follows from the factorization theorem.
- Fit of $m_t(m_t)$ at fixed $\alpha_s(M_Z)$ shows positive correlation between $\alpha_s(M_Z)$ value and $m_t(m_t)$.
- When including the $\bar{t}t + X$ differential data, the correlation coefficient decreases w.r.t. to the ABMP16 analysis, whereas the best-fit $\alpha_s(M_Z)$ value remains approximately the same.
- Open question: compatibility with $\alpha_s(M_Z)$ from lattice QCD (see talk by L. Del Debbio)
Simultaneous fit of top-quark mass, PDFs, $\alpha_s(M_Z)$: agreement with total cross-section data

FIRST PRELIMINARY RESULTS

---

S. Alekhin, M.V.G., J. Mazzitelli, S. Moch, O. Zenaiev Top-quark pole mass extraction at NNLO accuracy
Summary and outlook

- Compared very recent LHC $t\bar{t} + X$ differential measurements with NNLO QCD predictions using the modified MATRIX framework
  - interfaced with PineAPPL to produce interpolation tables for convolution with different PDFs + $\alpha_s(M_Z)$
  - used further in xFitter to benchmark vs experimental data
- Double-differential $M(t\bar{t})$, $y(t\bar{t})$ x-sections are able to distinguish between modern PDF sets by ABMP, CT, MSHT, NNPDF
  - reasonable description by all PDF sets, with best description by ABMP16 when considering only the central set neglecting PDF uncertainties
  - including these data in PDF fits make it possible to further reduce gluon PDF uncertainties at large $x$
- $(1/\sigma)d\sigma/dM(t\bar{t})$ and $(1/\sigma)d^2\sigma/(dM(t\bar{t})dy(t\bar{t}))$ provide great sensitivity to $m_t^{\text{pole}}$
  - extracted $m_t^{\text{pole}}$ values with precision $\pm 0.3$ GeV and consistent with PDG value:
    e.g. using ABMP16 $m_t^{\text{pole}} = 171.54 \pm 0.24(\text{exp}) \pm 0.15(\text{PDF})^{+0.03}_{-0.13}(\mu)$ GeV
  - missing Coulomb and soft-gluon resummation effects: additional $\sim 1$ GeV uncertainty
  - additional dependence on PDFs $\sim 0.5$ GeV should be resolved in a simultaneous PDF + $m_t^{\text{pole}} + \alpha_s(M_Z)$ fit (in progress)
  - residual dependence on $m_t^{\text{MC}}$ (related to the unfolding) still needs to be estimated (important when $m_t^{\text{pole}}$ uncertainties become small).
- the considered distributions, especially those of Run 2, have much larger constraining power on $m_t$ than the total cross-sections, where the effects of correlations between $\alpha_s(M_Z)$ and $m_t$ are much larger.