NNLO QCD corrections to top-quark production and decay

TOP workshop 2020

Rene Poncelet

in collaboration with M. Czakon and A. Mitov. Based on arXiv:2008.11133

14th September 2020

Cavendish Laboratory

Outline

Fixed-order NNLO QCD predictions for top-quark pair production
in the Narrow-Width-Approximation (NWA)
compared to LHC measurements

arXiv:1901.05407 and arXiv:2008.11133

Comprehensive analysis featuring fiducial/inclusive phase spaces:

- NEW: CMS, including cuts on b-jets
- ATLAS, inclusive in the hadronic radiation

$\rightarrow$ Implications for $\Delta\Phi(\ell\bar{\ell})$ in fiducial phase spaces

- NEW: Spin-Density-Matrix

Outline

All calculations presented here have been performed with a in-house implementation of the sector-improved residue subtraction scheme.

Czakon '10 Czakon Heymes '14 Czakon et. al. '14 - '20

$\rightarrow$ Details about the NWA implementation: arXiv:2008.11133, arXiv:1901.05407

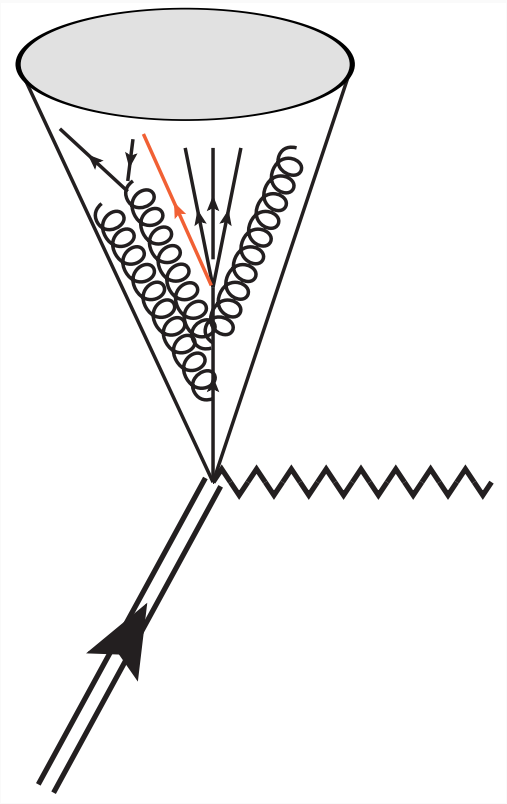
CMS fiducial analysis

arXiv:1811.06625

A classic $t\bar{t}$ analysis

- Truly fiducial analysis: Requirements on leptons and *b*-jets
- Appealing: Possibility to reconstruct top-quarks, little phase space extrapolation
- Sensitive to jet-modelling:
  - Full MC: parton-shower+hadronization+decays
    Decays into neutrinos $\rightarrow$ loss of jet momentum
  - Fixed-order prediction: inclusive QCD jets, no EW decays, only partons.

$\rightarrow$ not compatible!

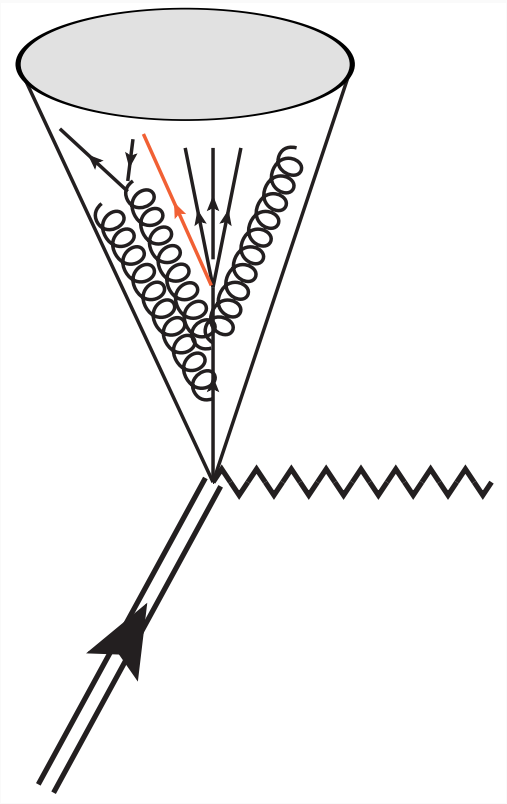


arXiv:1811.06625

A classic $t\bar{t}$ analysis

Fiducial phase space definition in our computation:

- $p_T(\ell) \geq 20$ GeV and $|\eta(\ell)| \leq 2.4$ for both charged leptons.
- $m(\ell\bar{\ell}) \geq 20$ GeV.
- 2 anti-k_T, $R = 0.4$ jets with $p_T \geq 30$ GeV, $|y| \leq 2.4$ and b-tag which are well separated from the leptons $\Delta R(j, \ell) \geq 0.4$. A b-tagged jet has non-vanishing bottomness.



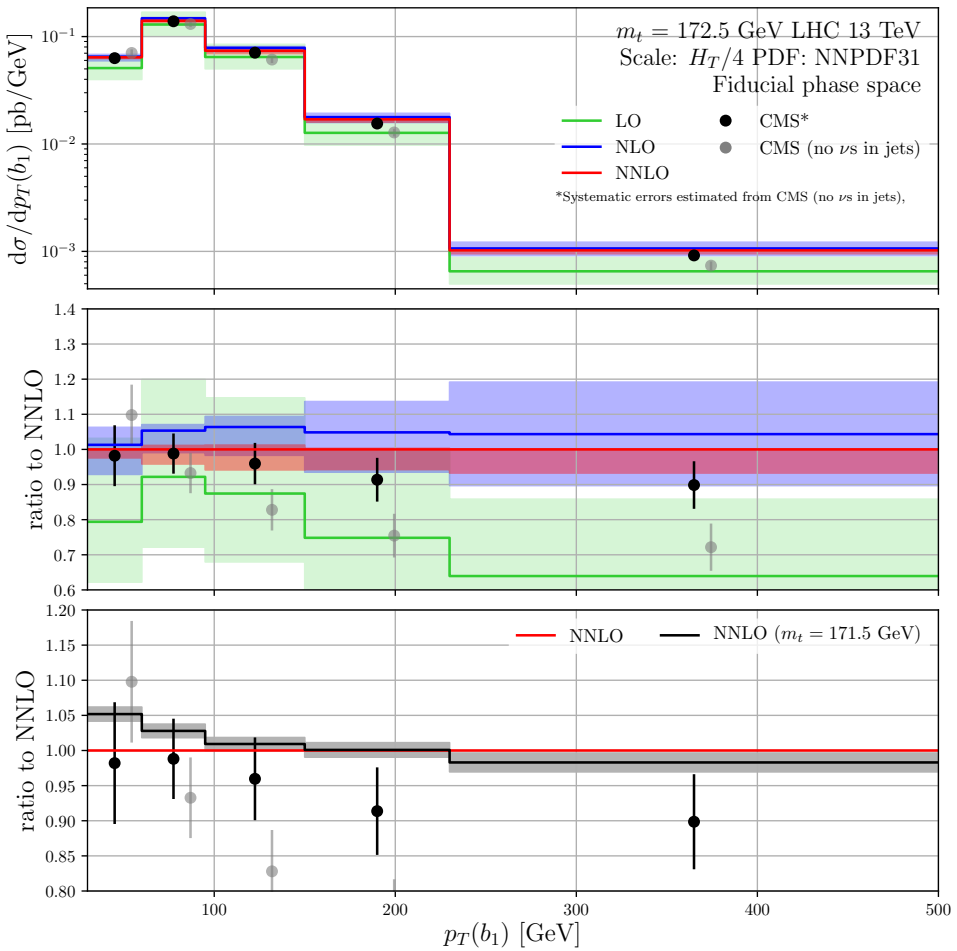
Jet modelling for comparison:

$\rightarrow$ CMS re-performed analysis with ν momenta included in jets

Thanks to CMS for this collaboration!

NEW: CMS fiducial analysis, b-jets

arXiv:2008.11133, data: arXiv:1811.06625



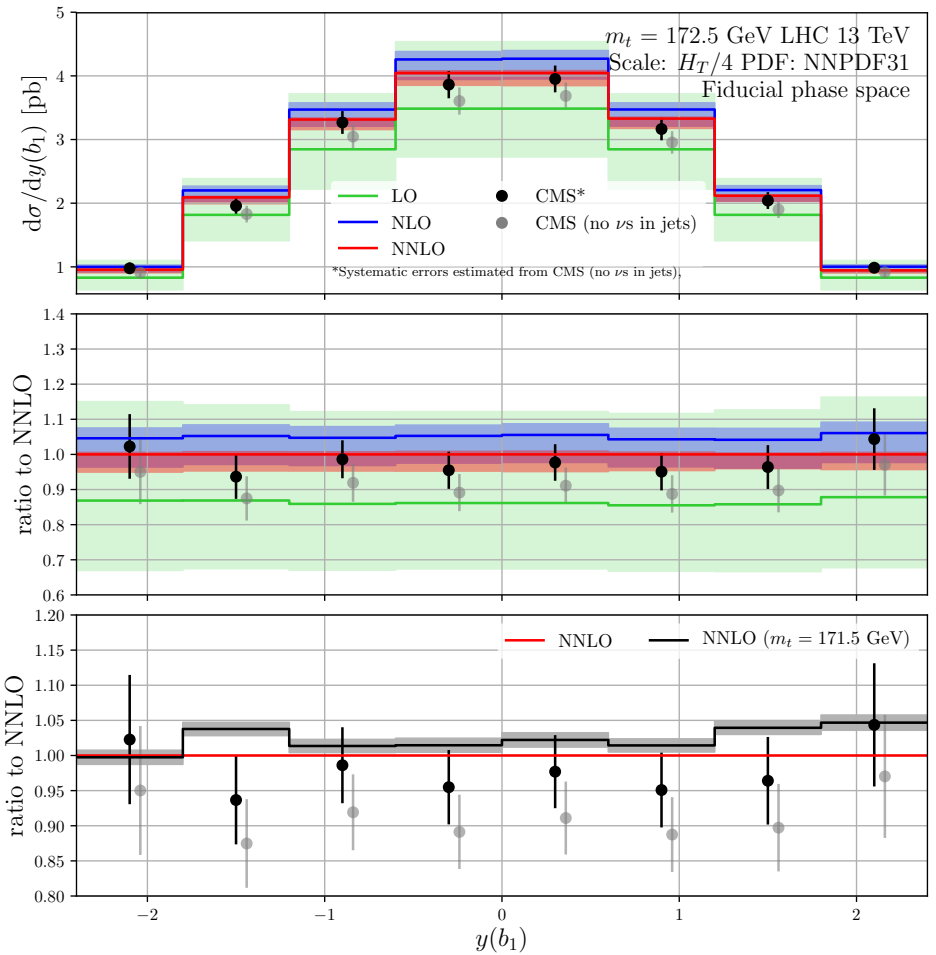
! Significant differences in normalization and shape between jet definitions

- Excellent description of reanalysed data (black)
- NNLO QCD shows small scale dependence and PDF errors (black band in lower panel)
- Top-quark mass dependence (lower panel) might be used to extract m_t parameter.

(black error bars: reanalysed data, grey error bars: original analysis)

NEW: CMS fiducial analysis, b-jets

arXiv:2008.11133, data: arXiv:1811.06625



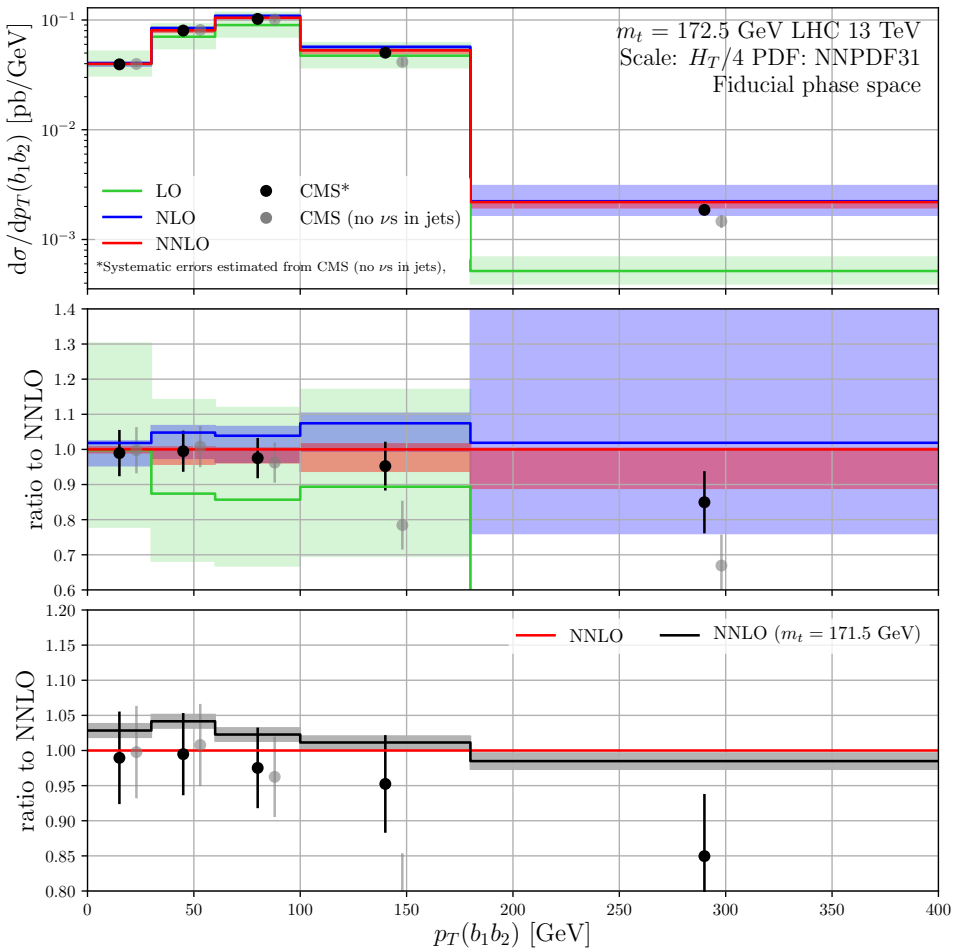
! Significant differences in normalization and shape between jet definitions

- Excellent description of reanalysed data (black)
- NNLO QCD shows small scale dependence and PDF errors (black band in lower panel)
- Top-quark mass dependence (lower panel) might be used to extract m_t parameter.

(black error bars: reanalysed data, grey error bars: original analysis)

NEW: CMS fiducial analysis, b-jets

arXiv:2008.11133, data: arXiv:1811.06625



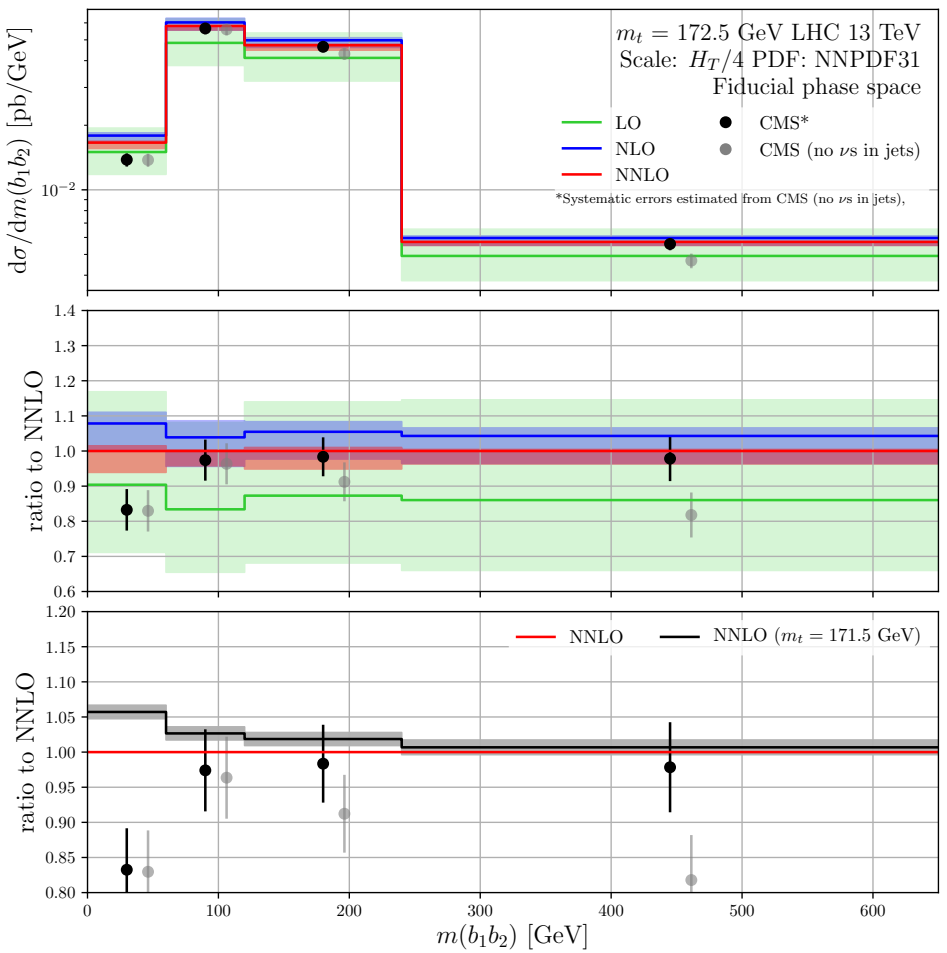
! Significant differences in normalization and shape between jet definitions

- Excellent description of reanalysed data (black)
- NNLO QCD shows small scale dependence and PDF errors (black band in lower panel)
- Top-quark mass dependence (lower panel) might be used to extract m_t parameter.

(black error bars: reanalysed data, grey error bars: original analysis)

NEW: CMS fiducial analysis, b-jets

arXiv:2008.11133, data: arXiv:1811.06625



- Low $m(b_1 b_2)$ spectrum not well described
- A variety of sources can be excluded: NWA, statistical uncertainty, m_t.

→ kinematic effect from b-jet mass, pronounced in fixed order theory with $m_b = 0$.

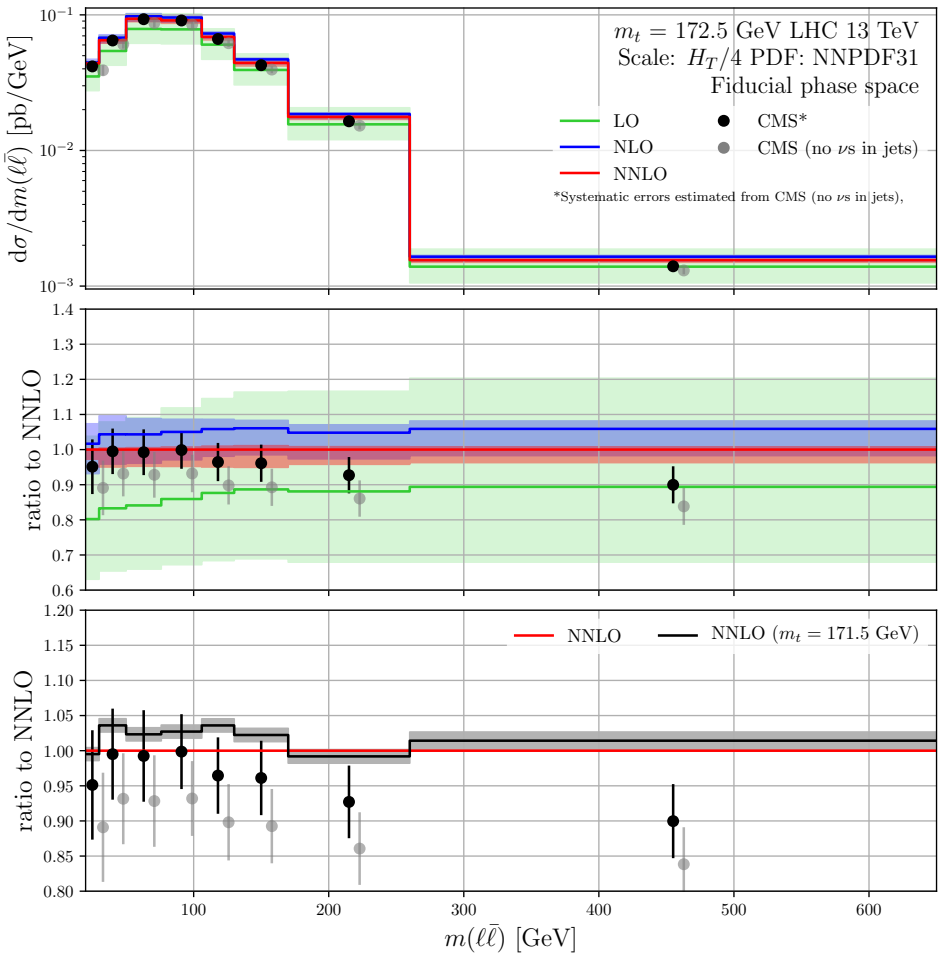
→ arXiv:1811.06625 : Better description in full fledged MC due to additional soft/collinear radiation in parton-showers → better jet-mass description.

(black error bars: reanalysed data, grey error bars: original analysis)

NEW: CMS fiducial analysis, leptons

- Normalization of lepton distributions affected by change in jet definition due to change in acceptance
- Typical pattern of NNLO corrections: smaller K-factor w.r.t. NLO. Strongly reduced scale dependence.
- Overall very good description of data.
- ! Shift $\Delta m_t = 1$ GeV comparable with theory uncertainty
- Many more plots in the paper!

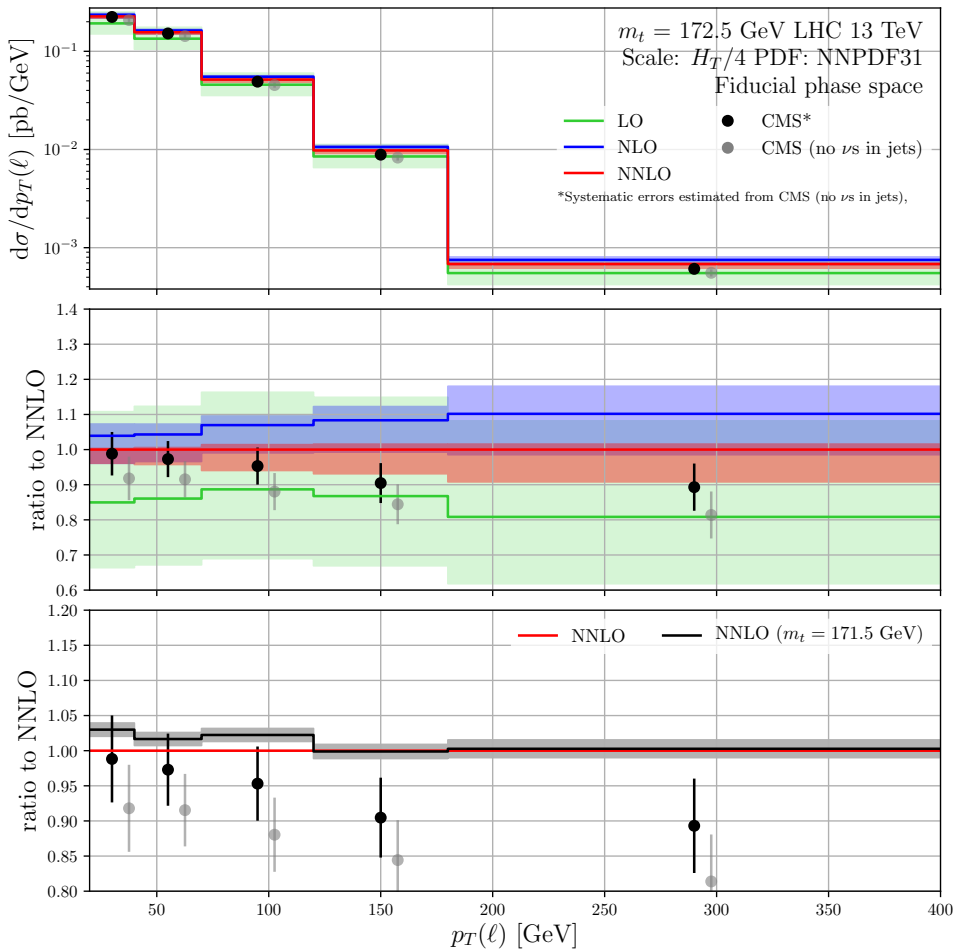
arXiv:2008.11133, data: arXiv:1811.06625



NEW: CMS fiducial analysis, leptons

- Normalization of lepton distributions affected by change in jet definition due to change in acceptance
- Typical pattern of NNLO corrections: smaller K-factor w.r.t. NLO. Strongly reduced scale dependence.
- Overall very good description of data.
- ! Shift $\Delta m_t = 1$ GeV comparable with theory uncertainty
- Many more plots in the paper!

arXiv:2008.11133, data: arXiv:1811.06625



ATLAS fiducial analysis

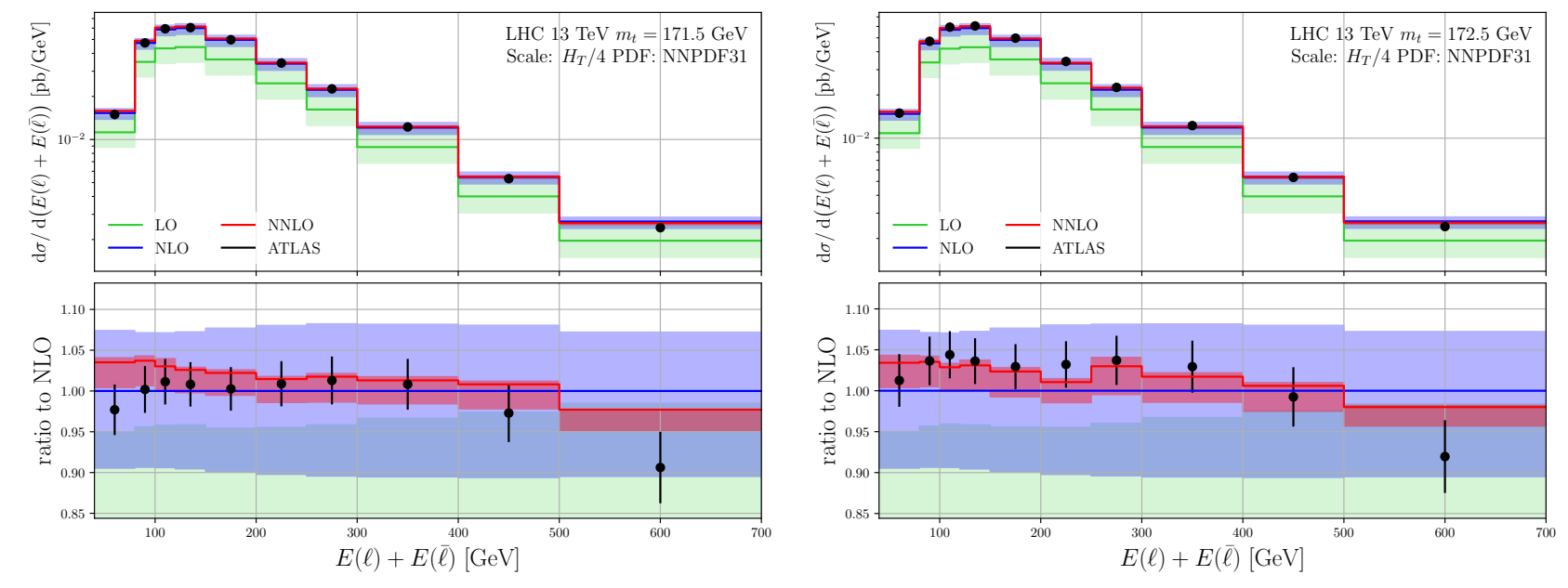
ATLAS analysis

- ATLAS arXiv:1910.08819: Multi-differential measurements
- Different approach: Extrapolation to hadronically inclusive phase space
  Fiducial phase space definition:
  - $p_T(\ell) \geq 20$ GeV
  - $|\eta(\ell)| \leq 2.5$
- Lepton observables only
- High experimental precision

$\rightarrow$ study of top-mass sensitivity @ NNLO QCD

ATLAS analysis

arXiv:2008.11133, data: arXiv:1910.08819

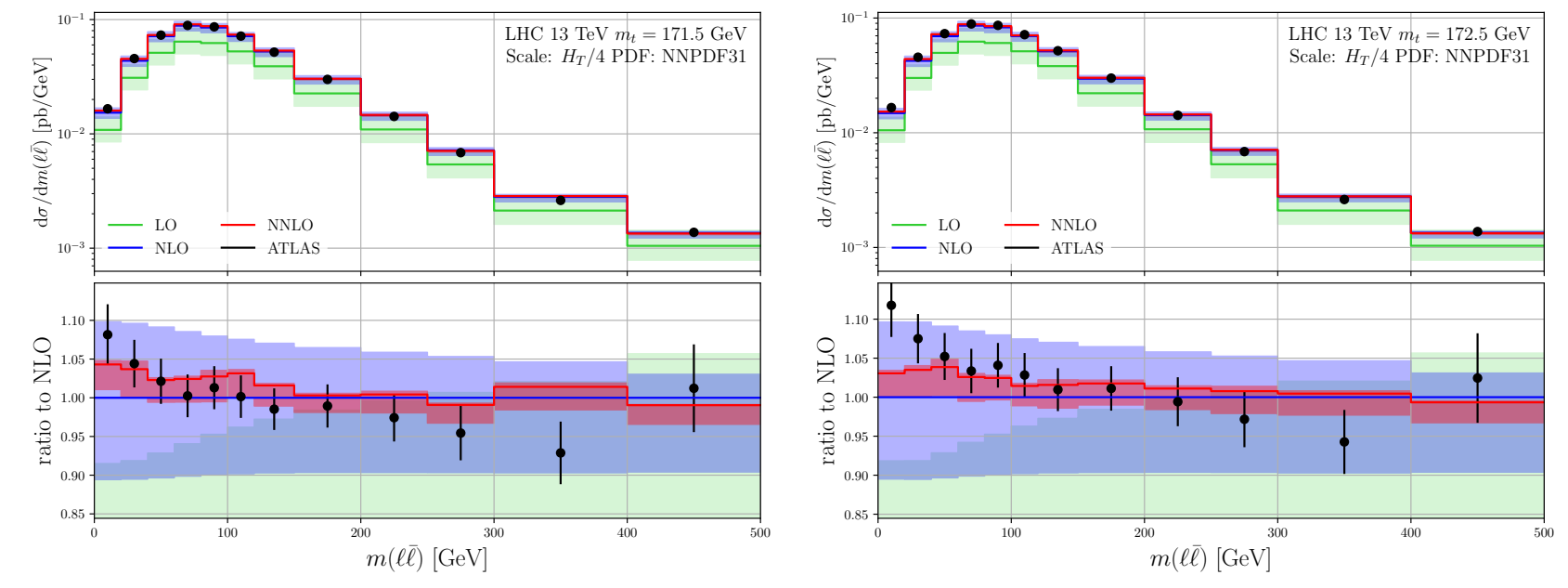


- Excellent description of data with NNLO. Significantly reduced scale dependence.
- $m(\ell\bar{\ell})$ as a proxy for $m(t\bar{t}) \rightarrow$ mass sensitive in lower range, $\Delta m_t = 1$ GeV $\Leftrightarrow$ scale dependence @ NNLO

(more observables in the paper!)

ATLAS analysis

arXiv:2008.11133, data: arXiv:1910.08819

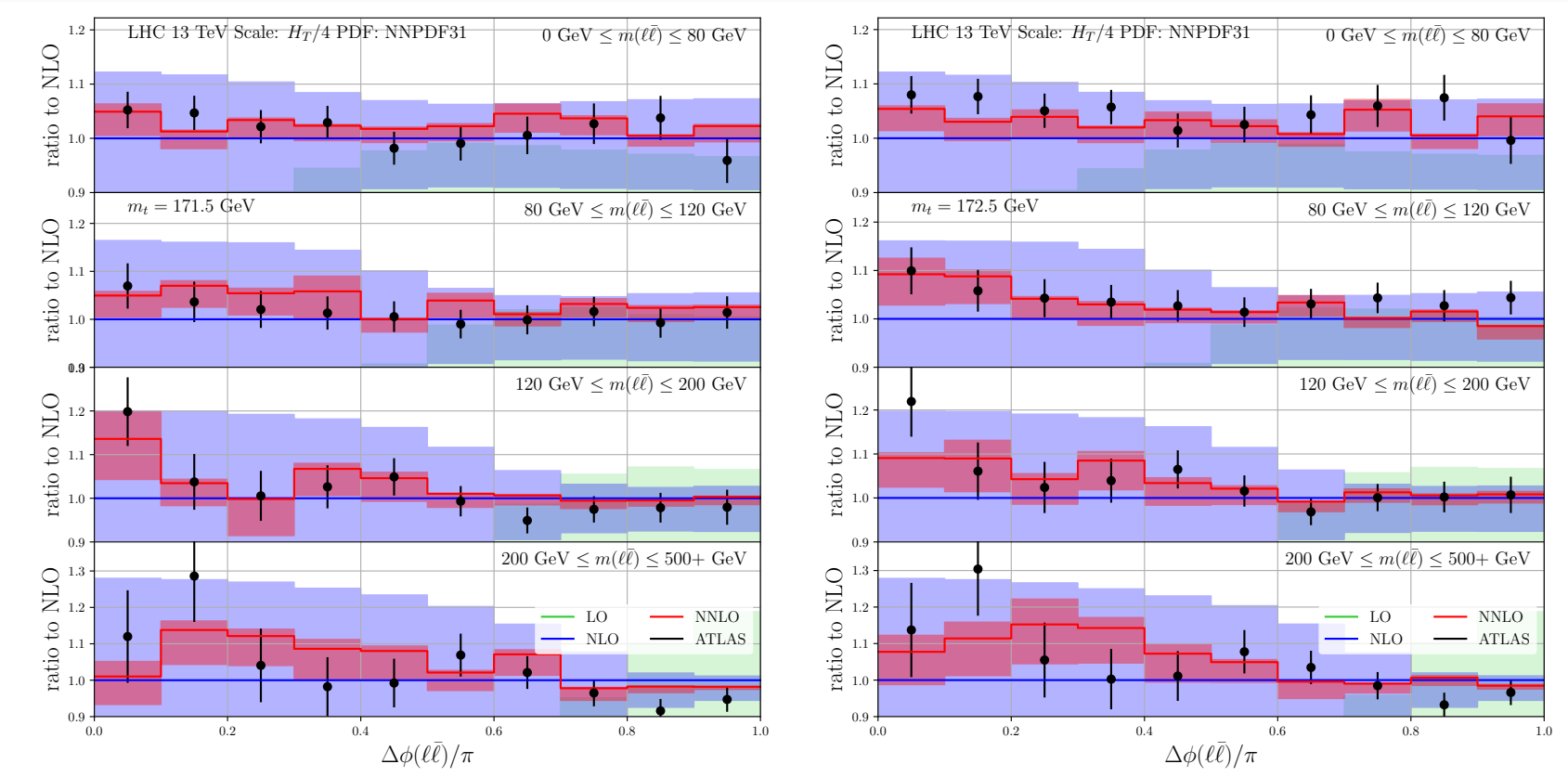


- Excellent description of data with NNLO. Significantly reduced scale dependence.
- $m(\ell\bar{\ell})$ as a proxy for $m(t\bar{t}) \rightarrow$ mass sensitive in lower range, $\Delta m_t = 1$ GeV $\Leftrightarrow$ scale dependence @ NNLO

(more observables in the paper!)

ATLAS analysis, double differential

arXiv:2008.11133, data: arXiv:1910.08819



- 2D-distributions are described accurately.
- $\Delta\Phi(\ell\bar{\ell})$ sensitive to top-quark spin correlations
- Similar to the study of spin-correlation as a function of $m(t\bar{t}) \rightarrow$ using $m(\ell\bar{\ell})$ as a proxy.

(more observables in the paper!)

Fiducial analysis summary

Fixed order predictions can very well describe differential distributions in fiducial phase spaces, including jets

$\Downarrow$

- Having a comparable jet definition is essential for these studies

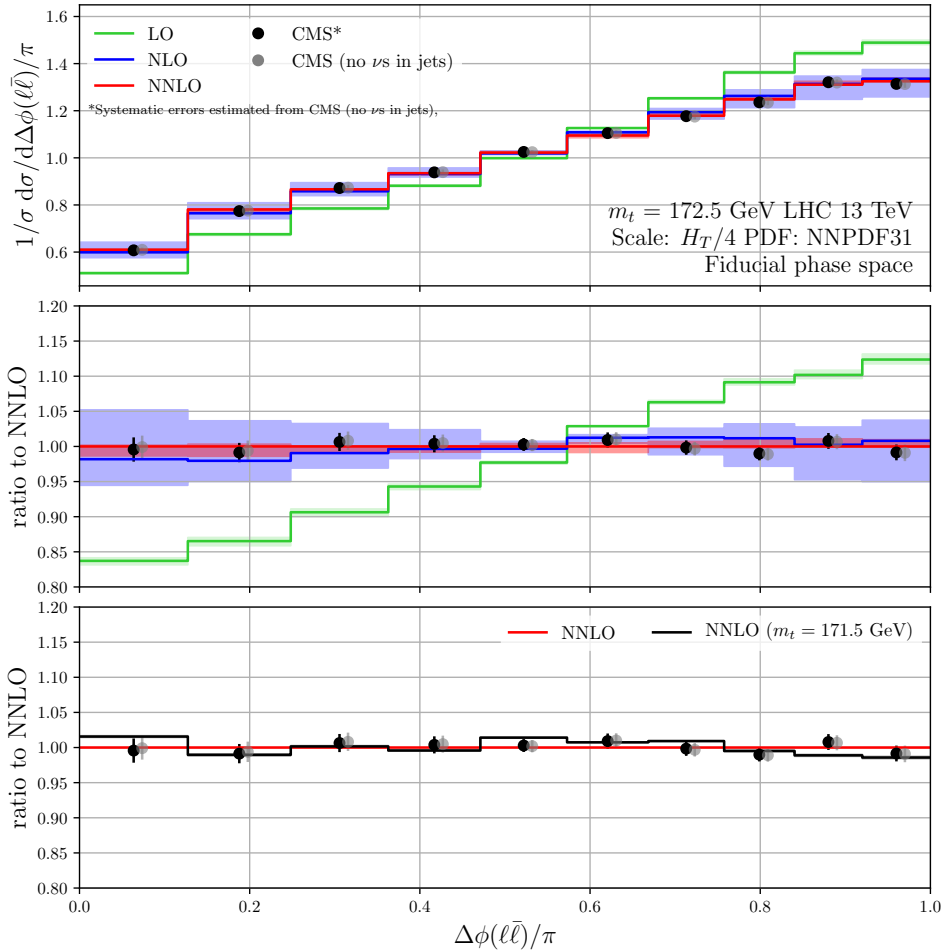
$\rightarrow$ Impact of undetected neutrino momenta

$\rightarrow$ Certainly more questions to investigate here

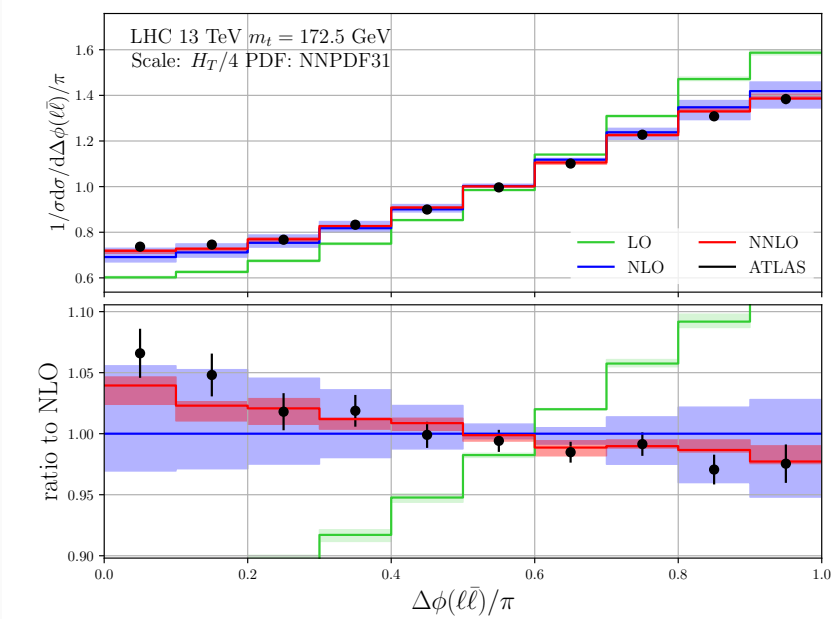
$\Delta\Phi(\ell\bar{\ell})$ in fiducial phase spaces

Fixed-order predictions can describe excellently $\Delta\Phi(\ell\bar{\ell})$ fiducial differential distributions with (and without) jet requirements

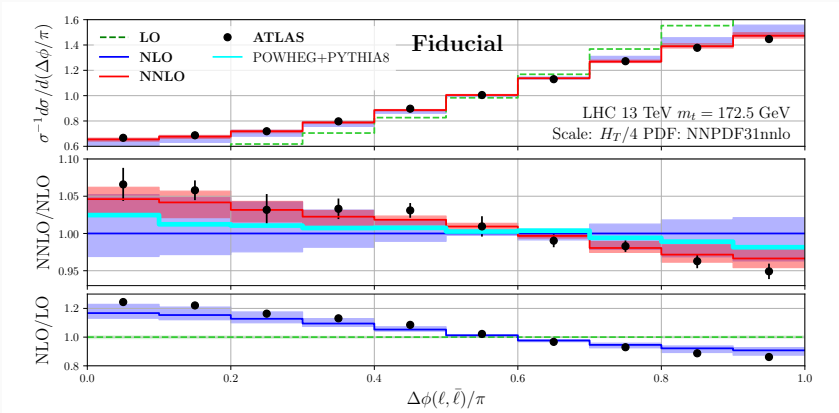
CMS arXiv:1811.06625



ATLAS arXiv:1910.08819



ATLAS arXiv:1903.07570



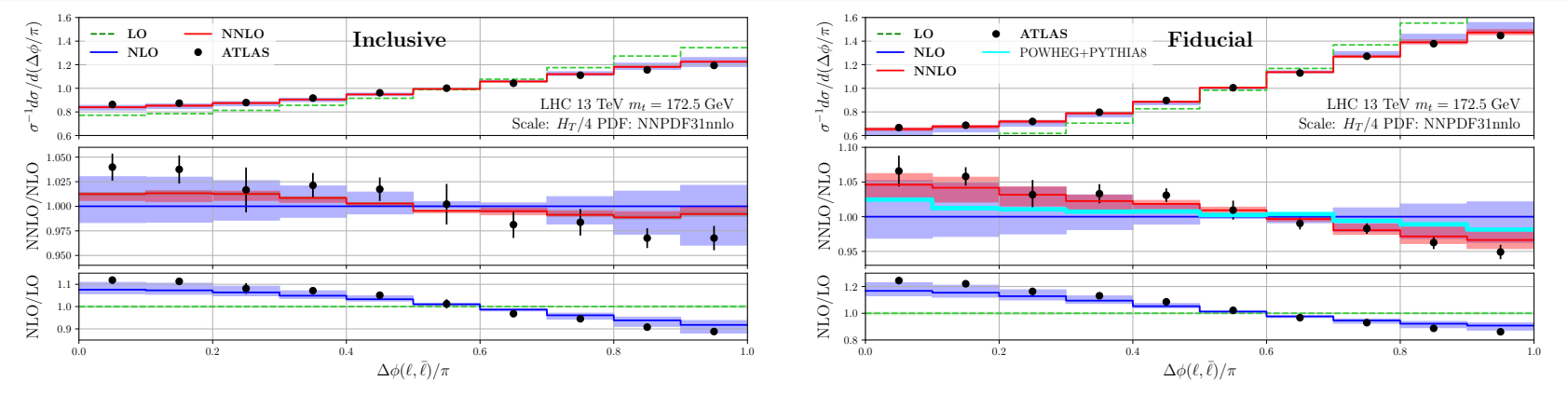
Plots: arXiv:2008.11133, arXiv:1901.05407

$\Delta\Phi(\ell\bar{\ell})$ in inclusive phase space

- Visible shape in data/NNLO in inclusive (extrapolated) phase space
- Flat data/NNLO in fiducial phase space

$\rightarrow$ Effect of Extrapolation? Should be investigated in more detail.

ATLAS arXiv:1903.07570



CMS fiducial analysis
top-quark reconstruction

CMS phase space

NWA: top-quark momenta are known in computation, in experiment not

Top-quark reconstruction

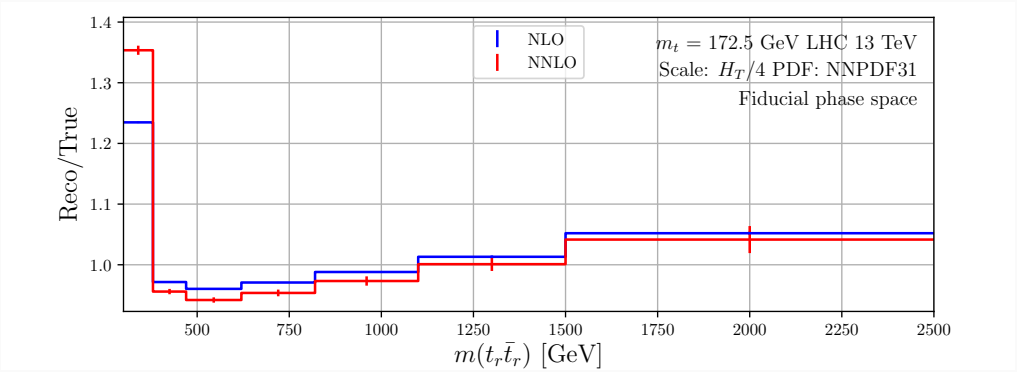
- Assuming W momenta known $\Rightarrow$ reconstruct top-quarks from b-jet momenta, $p_t = p_W + p_b$
- Assignment of b-jets based on the minimization of $|p_t^2 - m_t^2| + |p_{\bar{t}}^2 - m_t^2|$.

$\rightarrow$ top-quark momenta $p_{t_r}, p_{\bar{t}_r}$

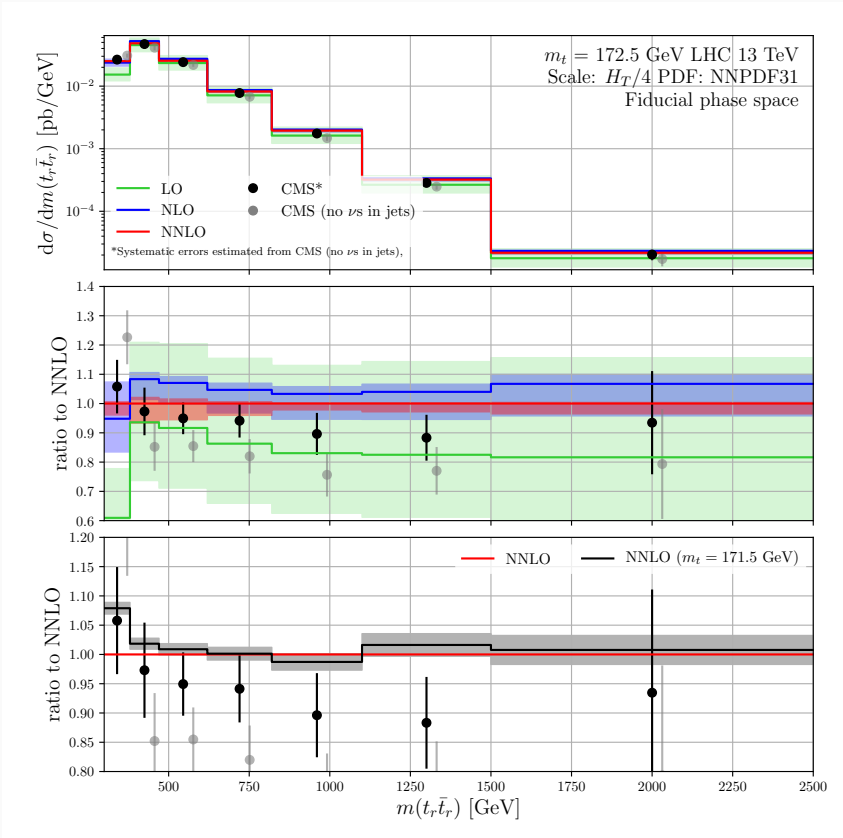
- Possibility to compare against 'true' (MC-truth) top-quarks

CMS analysis, invariant mass of top-quarks

- Threshold region sensitive to m_t
- Resummation and mass dependence for threshold region
  $\Rightarrow$ Yang's talk Wed
- ! Large sensitivity to jet-modelling (with (black) vs. without (grey) neutrinos)
- Comparison between MC-truth vs. reconstruction $\rightarrow$ threshold region is sensible to higher order corrections



arXiv:2008.11133, data: arXiv:1811.06625



CMS analysis, top-quarks

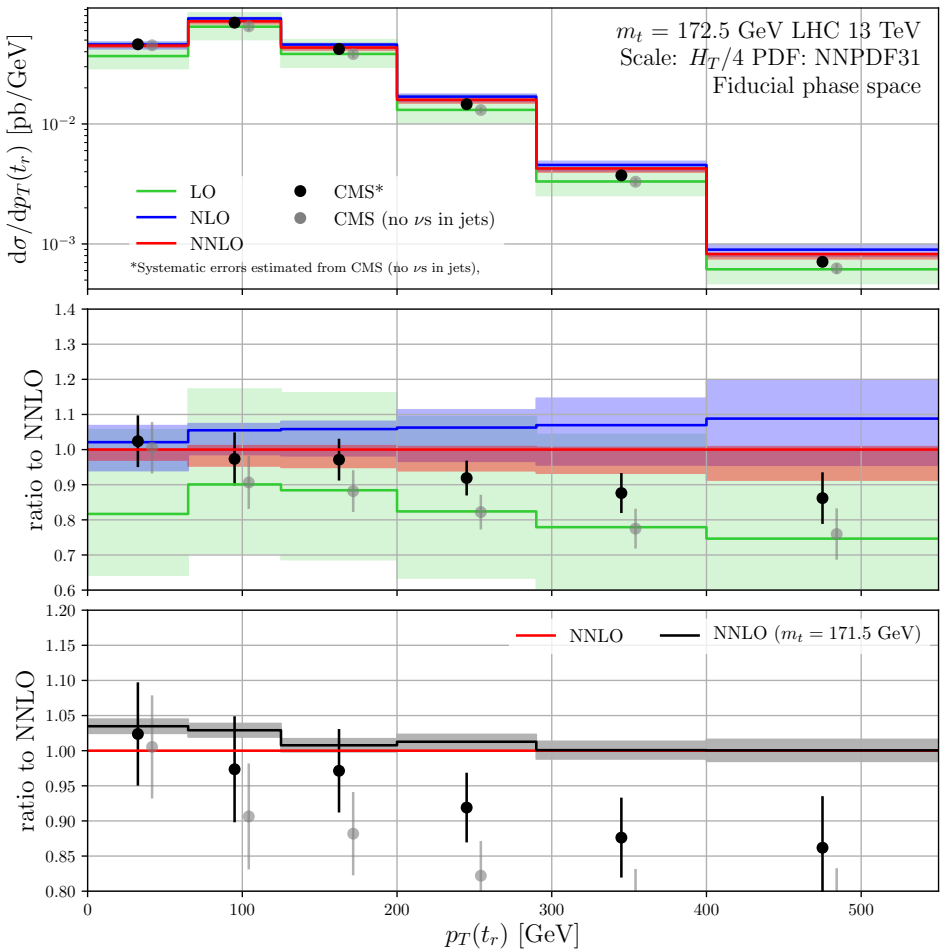
arXiv:2008.11133, data: arXiv:1811.06625

New aspects for p_T spectrum

- Good description in fiducial phase space in particular in high p_T tails. NNLO fixes the slope difference.

$\rightarrow$ Future study

- Inclusive phase space: Stronger slope between NNLO and data (extrapolation from arXiv:1811.06625) in p_T. Indicates that NNLO can improve fiducial analysis
  $\rightarrow$ improved extrapolation?



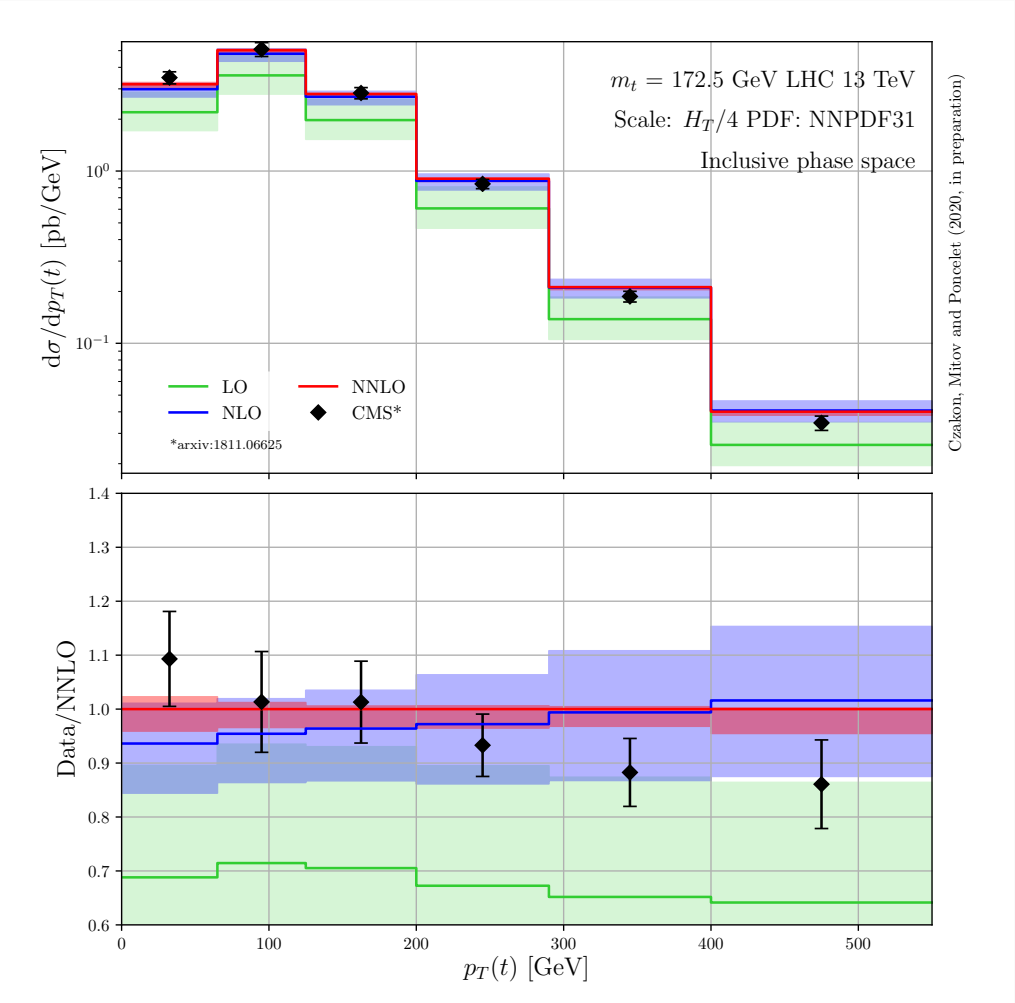
CMS analysis, top-quarks

New aspects for p_T spectrum

- Good description in fiducial phase space in particular in high p_T tails. NNLO fixes the slope difference.

$\rightarrow$ Future study

- Inclusive phase space: Stronger slope between NNLO and data (extrapolation from arXiv:1811.06625) in p_T. Indicates that NNLO can improve fiducial analysis
  $\rightarrow$ improved extrapolation?



NEW: Spin-density-matrix

Spin-density matrix

- The spin correlation can be represented through the spin density matrix:

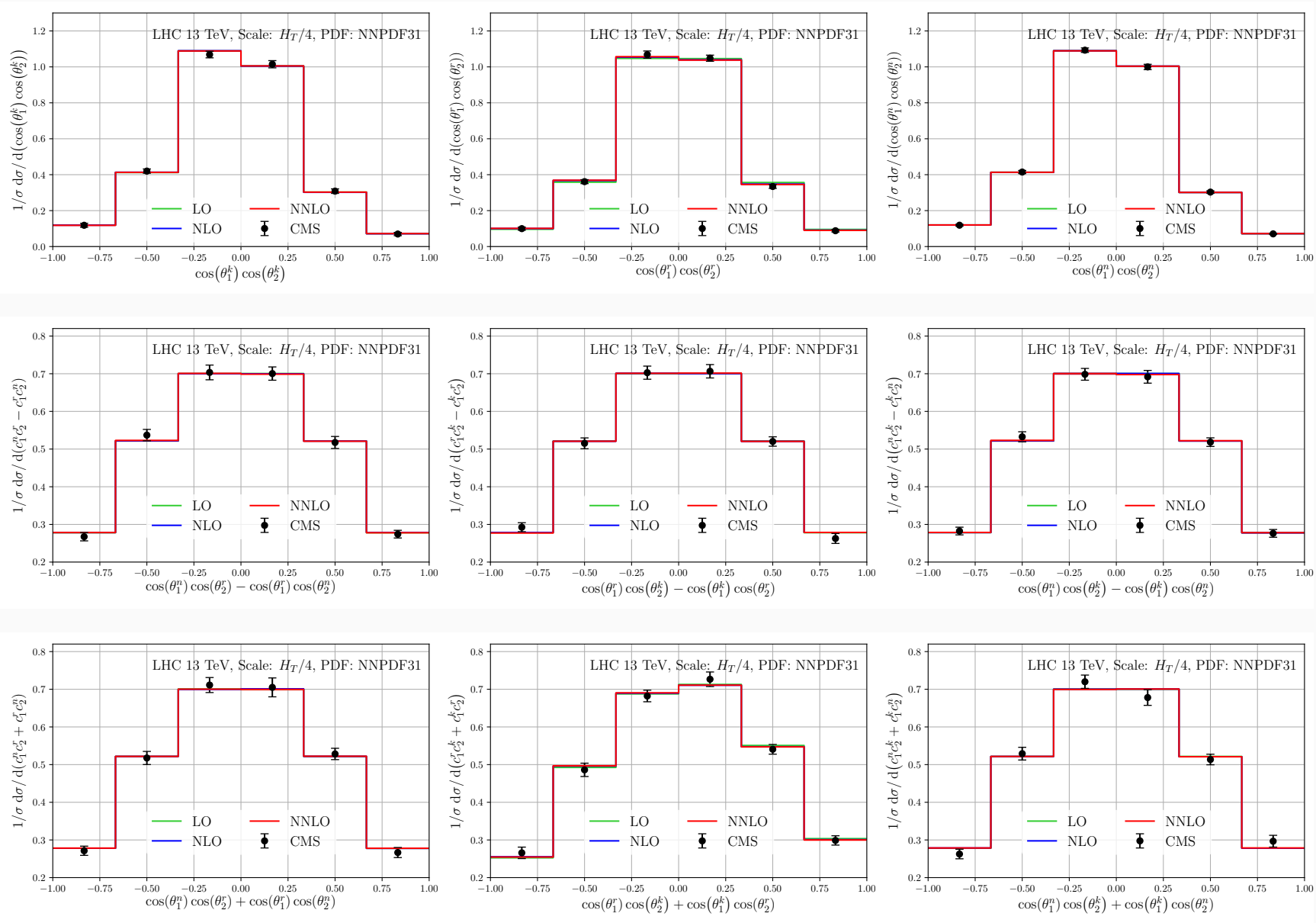
$$|\mathcal{M}(pp \to t\bar{t} \to (\ell^+\ell - \nu\bar{\nu}b\bar{b})|^2 \sim \mathrm{Tr}[\rho R \bar{\rho}]$$

$$R \sim \underbrace{\bar{A}\mathbb{1} \otimes \mathbb{1}}_{\text{spin-averaged}} + \underbrace{\bar{B}_i^+ \sigma^i \otimes \mathbb{1} + \bar{B}_i^- \mathbb{1} \otimes \sigma^i}_{\text{top-quark polarization}} + \underbrace{\bar{C}_{ij}\sigma^i \otimes \sigma^j}_{\text{spin-correlation}}$$

- Recent measurement: arXiv:1907.03729
- Translates to similar defined coefficients for the decay-products:
  - Proportional to angular distribution with respect to top-quark directions
  - Spin-analysing power (charged leptons best choice)
- Small to tiny corrections due to NNLO QCD $\rightarrow$ confirms previous findings

  arXiv:1901.05407
- Perfect agreement between measurements and theory predictions.
- However: studies dominated by systematic experimental uncertainties.

Spin-density matrix



Numbers for extracted coefficients in arXiv:2008.11133

Summary and Outlook

Summary and Outlook

- Precision top-quark physics in the fiducial phase space @ NNLO QCD.
- Suitable jet definition allows comparisons between fixed-order calculations and fiducial data.
- Improvements in terms of scale dependence through NNLO corrections push the precision of theory predictions.
  Theory uncertainties comparable to $\Delta m_t = 1$ GeV variation. Promising measurement approach!
- Implications for various observables: $\Delta\Phi$, $p_T(t)$, $m(t\bar{t})$ and extrapolation to inclusive top-quark pair phase spaces.
- Future:
  more studies of observables like $p_T(t_r)$ and extrapolation effects
  Extension of decay channels (jet+lepton)
  fragmentation of b-hadrons in top-quark decays $\rightarrow$ Alex' talk on Wed