Theory status of top quark properties

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Contents

- ✓ Top quark mass
- ✓ Top quark width
- ✓ Top Yukawa coupling
- ✓ Spin correlations in top quark pair production and decay
- ✓ Top quark pair charge asymmetry at LHC

Many new measurements are results not covered in this talk can be found in the talks by
- Malgorzata Worek
- Anna Kulesza
- Nils Faltermann

Top quark mass

Top quark mass

✓ The precise determination of the top quark mass is a major goal for the LHC

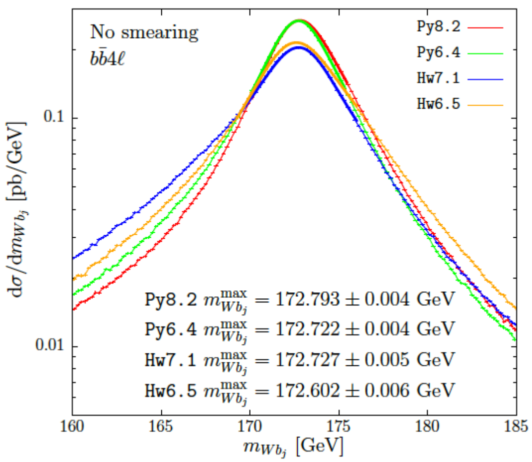
✓ This requires both precise measurements and high-quality theory predictions

✓ Typically, the top quark pole mass is being extracted. Two broad approaches:

- ✓ (1 of 2) Direct: reconstruct the top quark and then get the mass off of the Breit–Wigner.
- ✓ This task requires sophisticated Monte Carlos with full off-shell effects. This has been developed within POWHEG in the course of several years

Ferrario Ravasio, Ježo, Nason, Oleari 2018-2019

- ✓ Full top reconstruction is hard to do at higher orders so one needs a well defined proxy.
- ✓ Best known choice: maximum of the M_{Wbj} distribution



From arXiv:1906.09166

	$b\bar{b}4\ell - hvq$, $R = 0.5$ [MeV]		
	$m_{Wb_j}^{max}$	$m_{Wb_j}^{max}$ (smear)	$E_{b_j}^{max}$
Py8.2 (FSR)	24 ± 2	89 ± 2	257 ± 53
Py6.4 (FSR)	12 ± 2	-265 ± 2	-147 ± 106

Table 3: Differences between the $b\bar{b}4\ell$ and *hvq* predictions for $m_{Wb_j}^{max}$ (with and without smearing) and $E_{b_j}^{max}$, showered by Py8.2 and Py6.4.

- ✓ Can this be further improved on the theory side? Would be very hard!
  - ➢ All existing NNLO calculations are in the narrow-width approximation.
  - ➢ First calculations with NNLO precision + parton shower for stable tops

Mazzitelli, Monni, Nason, Re, Wiesemann, Zanderighi 2020

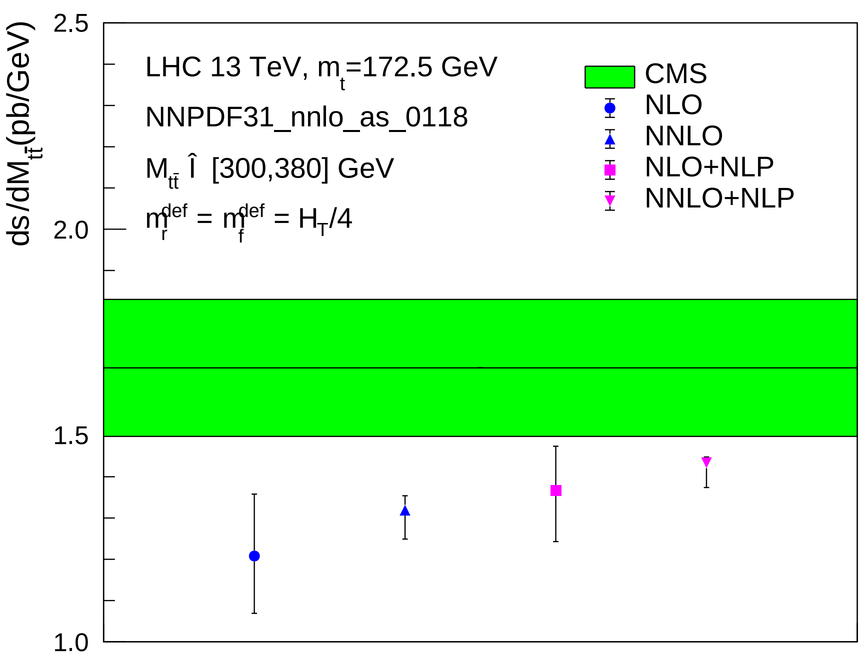
Top quark mass

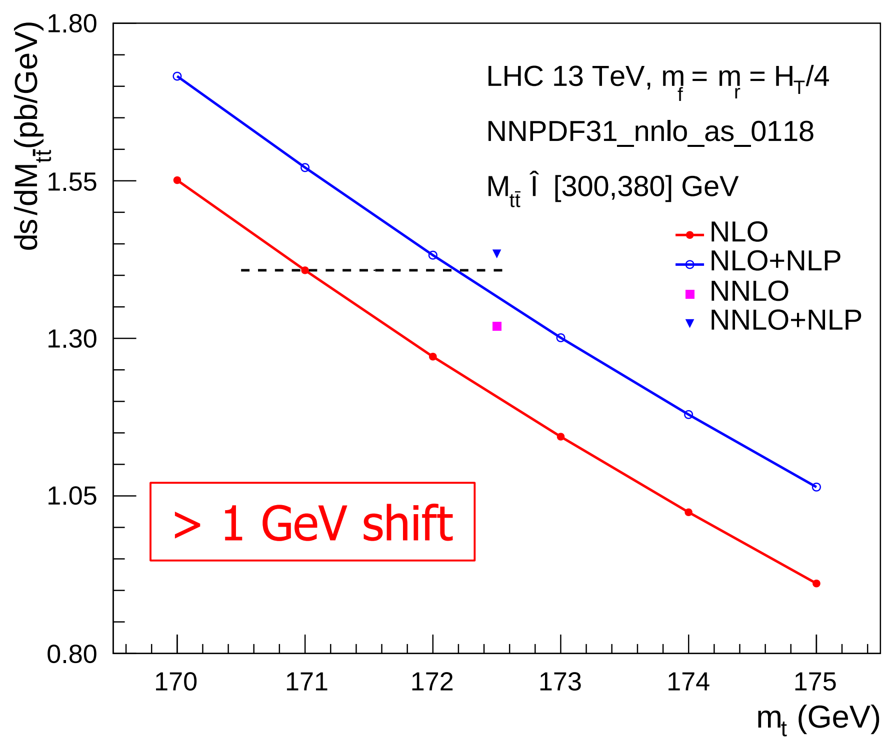
- ✓ Two broad approaches:
  - ✓ (2 of 2) Indirect: extract the pole mass (or any other mass definition that may be available) from calculations of kinematic distributions or cross sections
  - ✓ Many measurements; I'll mention two newer calculations relevant for the threshold behavior of the tt x-section (where most of the mass sensitivity is)

    1. Non-relativistic Coulomb corrections very close to threshold

    Ju, Wang, Wang, Xu, Xu, Li Lin Yang: 1908.02179, 2004.03088

    - ✓ Tiny effect on the cross-section but important for the first M_{tt} bin.





Top quark mass

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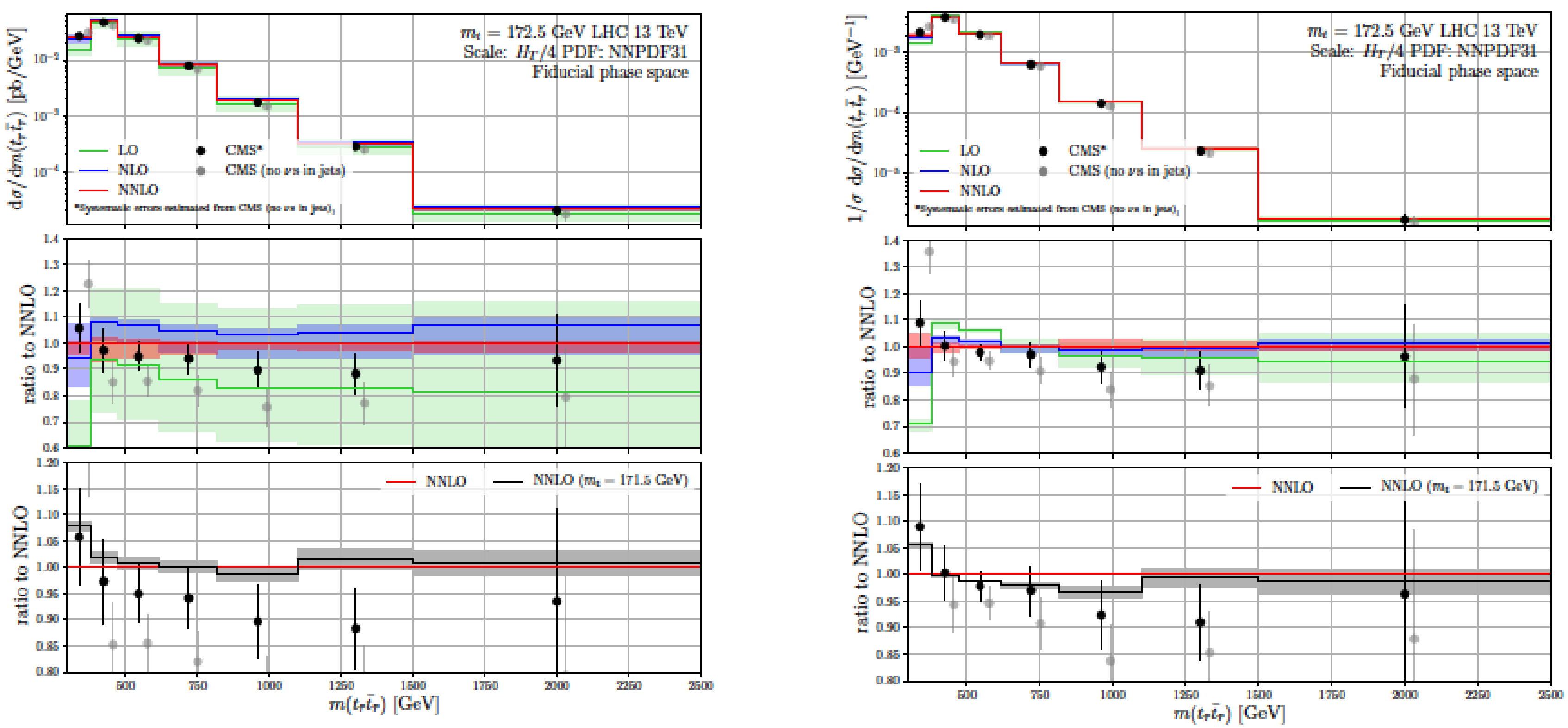
2. B-jet related subtleties and top definition have major impact on m_{top} in the threshold region

Czakon, Mitov, Poncelet arXiv:2008.11133



Top quark mass

- ✓ The extraction of the MSbar mass has attracted a lot of attention.
- ✓ Formally equivalent to the pole one at a given order, however, large numeric differences are present.
- ✓ Results between the two schemes have different convergence properties but this can be removed by a (good) scale choice.
- ✓ Recent NNLO calculation of differential (stable) tt production in the MSbar mass scheme

Catani, Devoto, Grazzini, Kallweit, Mazzitelli arXiv:2005.00557

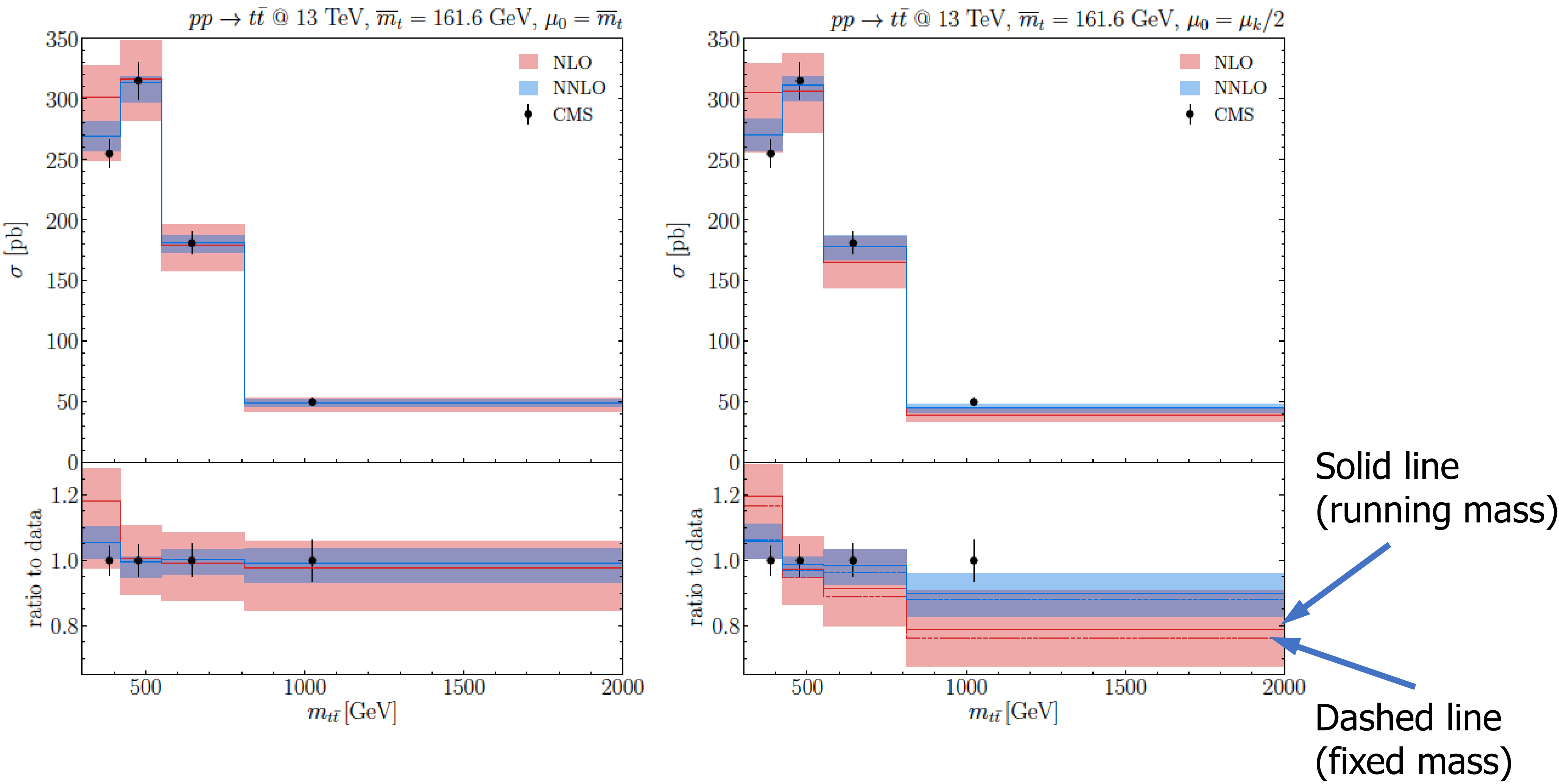
Differential distributions computed with pole or MSbar top mass are indeed found equivalent at NNLO:

> In Fig. 5 we also observe that the shape differences between the $\overline{\mathrm{MS}}$ and pole schemes are significantly reduced by the inclusion of high-order corrections, and they are already quite small at NNLO. Moreover, and importantly, in all the kinematical regions of Fig. 5 we note a sizeable overlap between the $\overline{\mathrm{MS}}$ and pole scheme uncertainty bands at NNLO: this fact shows the expected similarity between the two schemes once enough perturbative orders are included in the calculation.

- ✓ An interesting question: is the extraction of the Msbar mass somehow different (better, worse?) than in the pole scheme?

Top quark mass

Catani, Devoto, Grazzini, Kallweit, Mazzitelli arXiv:2005.00557



- ✓ Effects of running mass are very small:
  - ➢ Smaller than data uncertainty
  - ➢ Much smaller than the overall theory uncertainty

- ✓ It will be hard to extract …

Top quark width, Yukawa, helicity fractions, etc.

Top quark Width

- ✓ The top quark width is known at NNLO
  - ✓ Computed by many groups in the last 20 years. The most complete calculation involves NNLO QCD, NLO EW and off-shell effects

Jun Gao, Chong Sheng Li, Hua Xing Zhu 2012

- ✓ An interesting question is if this can be extended beyond NNLO in QCD (may be of interest for HL-LHC)
  - ➢ Recently, 3-loop corrections computed for muon decay and B-decays

Fael, Schönwald, Steinhauser 2020
Czakon, Czarnecki, Dowling 2021

  - ➢ A universal 3-loop contributions (the three-loop soft function for heavy-to-light quark decay) have also recently been computed

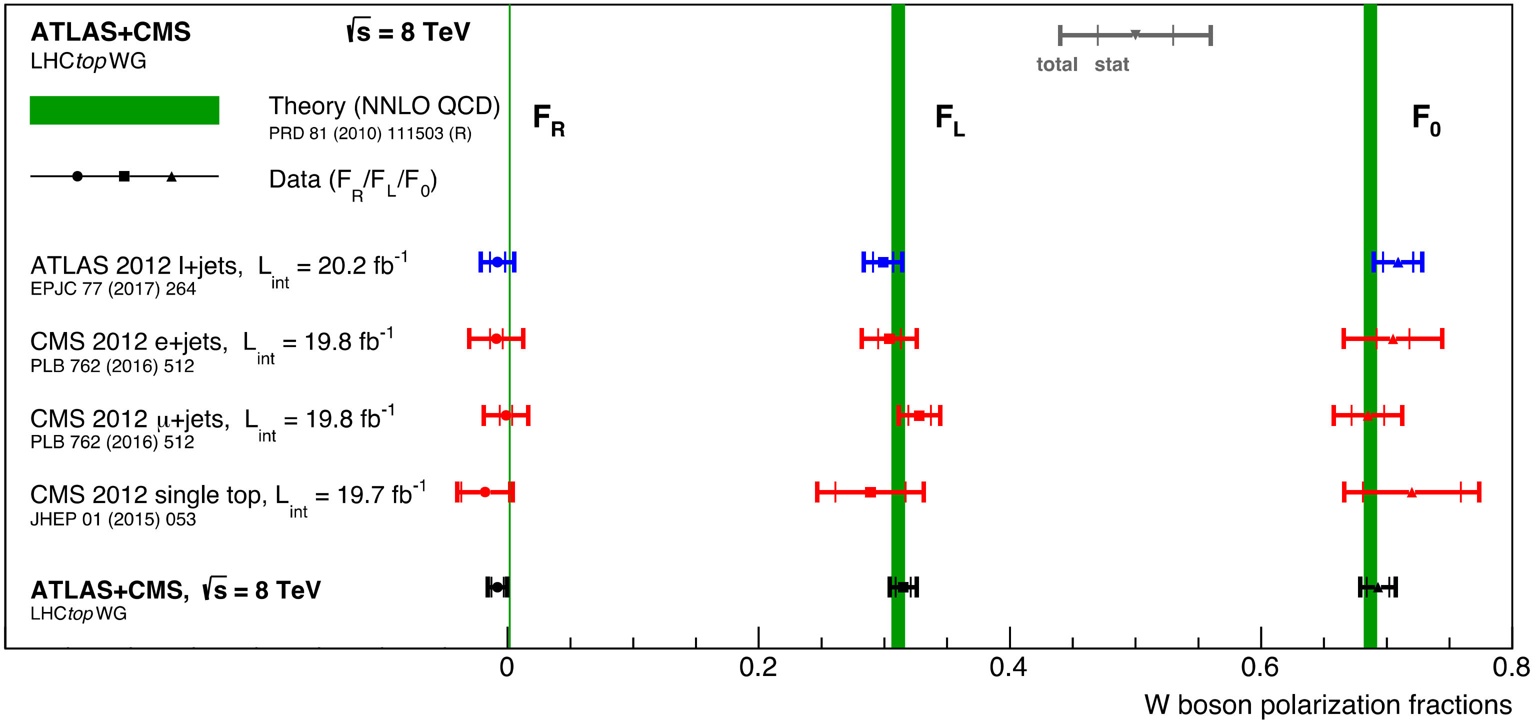
Brüser, Ze Long Liu, Stahlhofen 2019

  - ➢ Something to look forward to in the future?

W helicity fractions in top decay

✓ W-helicity fractions know at NNLO

Czarnecki, Korner, Piclum 2010



From arXiv:2106.03478

✓ The current precision of theory is higher than exp

Top Yukawa

✓ The determination of the top-Yukawa coupling is a major goal for the LHC

✓ Various processes can be utilized:

See also talks by
- Malgorzata Worek
- Anna Kulesza

✓ "Direct" measurement: ttH with H→bb

- ✓ The SM predictions for signals and backgrounds are at NLO and are very sophisticated
- ✓ Can further theory refinement be expected? And are they needed?
  - ✓ For backgrounds like ttbb this is extremely hard.
  - ✓ For ttH this may not be out of the question. A number of 2 → 3 processes are already known at NNLO (3γ,2γ+j, 3jet) so this process is not unfeasible anymore. The main obstacle is the availability of two-loop amplitudes.

Chawdhry, Czakon, Mitov, Poncelet 2019, 2020
Czakon, Mitov, Poncelet 2019, 2021

✓ Indirect: constrain Y_t from virtual contributions in processes like tttt and tt

Cao, Chen, Liu arXiv:1602.01934

- ✓ Further improvements to tttt production is unlikely, soon

See also talk by Stefan Richter

- ✓ The CMS study [arXiv:2009.07123] relies on NLO QCD+EW predictions for ttbar. This can already be computed at NNLO in QCD and NLO EW with leptonic decays

Czakon, Mitov, Poncelet '2020
Frederix, Tsinikos, Vitos '2021

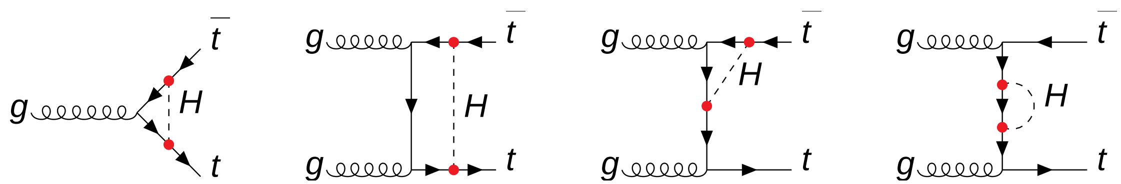
Top Yukawa

- ✓ Recent investigation of the CP properties of the top Yukawa coupling

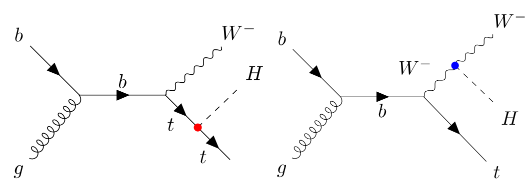
Martini, Pan, Schulze, Xiao 2021

$$\mathcal{L}(Htt) = -\frac{m_t}{v}\bar{\psi}_t\,(\kappa + \mathrm{i}\,\tilde{\kappa}\gamma_5)\,\psi_t\,H$$

- ✓ Comprehensive analysis in NLO SM kappa framework
- ✓ Considered are final states
  - ✓ without Higgs:



  - ✓ with Higgs (ttH and tH)



- ✓ Defining $f_{\rm CP} = \frac{|\tilde{\kappa}|^2}{|\kappa|^2 + |\tilde{\kappa}|^2}\,\mathrm{sign}\left(\frac{\tilde{\kappa}}{\kappa}\right)$ exclusion limits on f_{CP} are placed for 300fb^{-1} and 3000fb^{-1}
  - ➢ Limits depend on the final state

Spin-correlations in top-pair production and decay

&

Top-pair Asymmetry

The spin-density matrix formalism

Discussion based on: Czakon, Mitov, Poncelet arXiv:2008.11133
Formalism developed by: Bernreuther, Brandenburg hep-ph/9312210

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

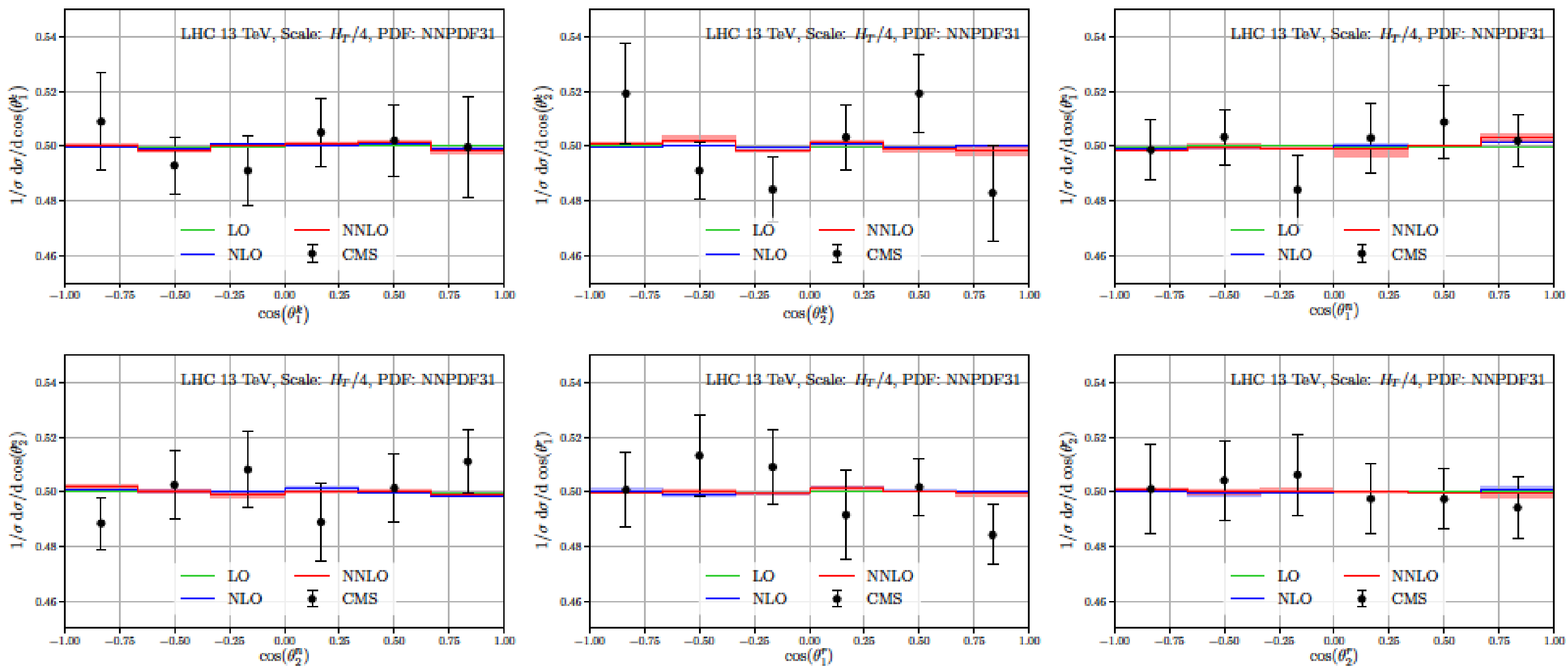
$$\mathrm{R} = \tilde{A}\,\mathbb{1}\otimes\mathbb{1} + \tilde{B}_i^+\sigma^i\otimes\mathbb{1} + \tilde{B}_i^-\mathbb{1}\otimes\sigma^i + \tilde{C}_{ij}\sigma^i\otimes\sigma^j$$

✓ In practice, one works with a proxy for the spin-density matrix R

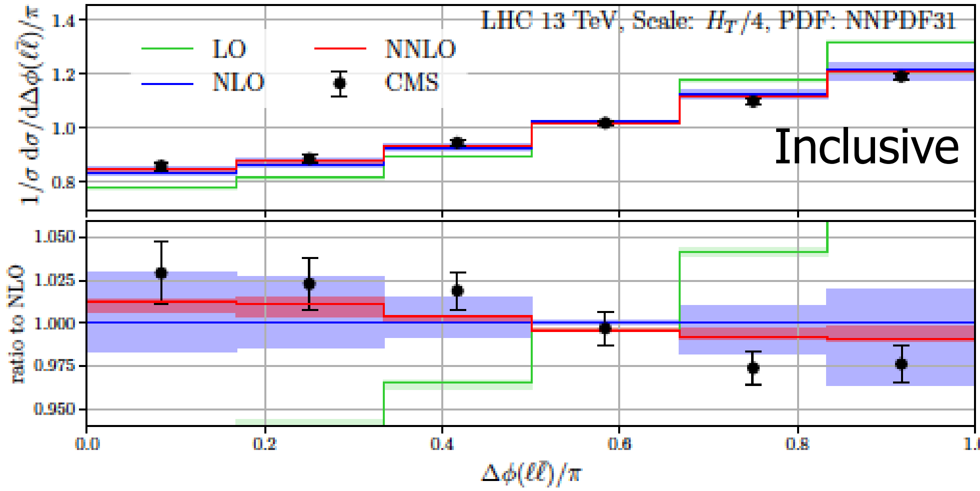
$$\frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta_1^i\,\mathrm{d}\cos\theta_2^j} = \frac{1}{4}\left(1 + B_1^i\cos\theta_1^i + B_2^j\cos\theta_2^j - C_{ij}\cos\theta_1^i\cos\theta_2^j\right)$$

✓ With all angles defined in a specially designed frame

✓ NNLO vs data for selected distributions (all have been computed):

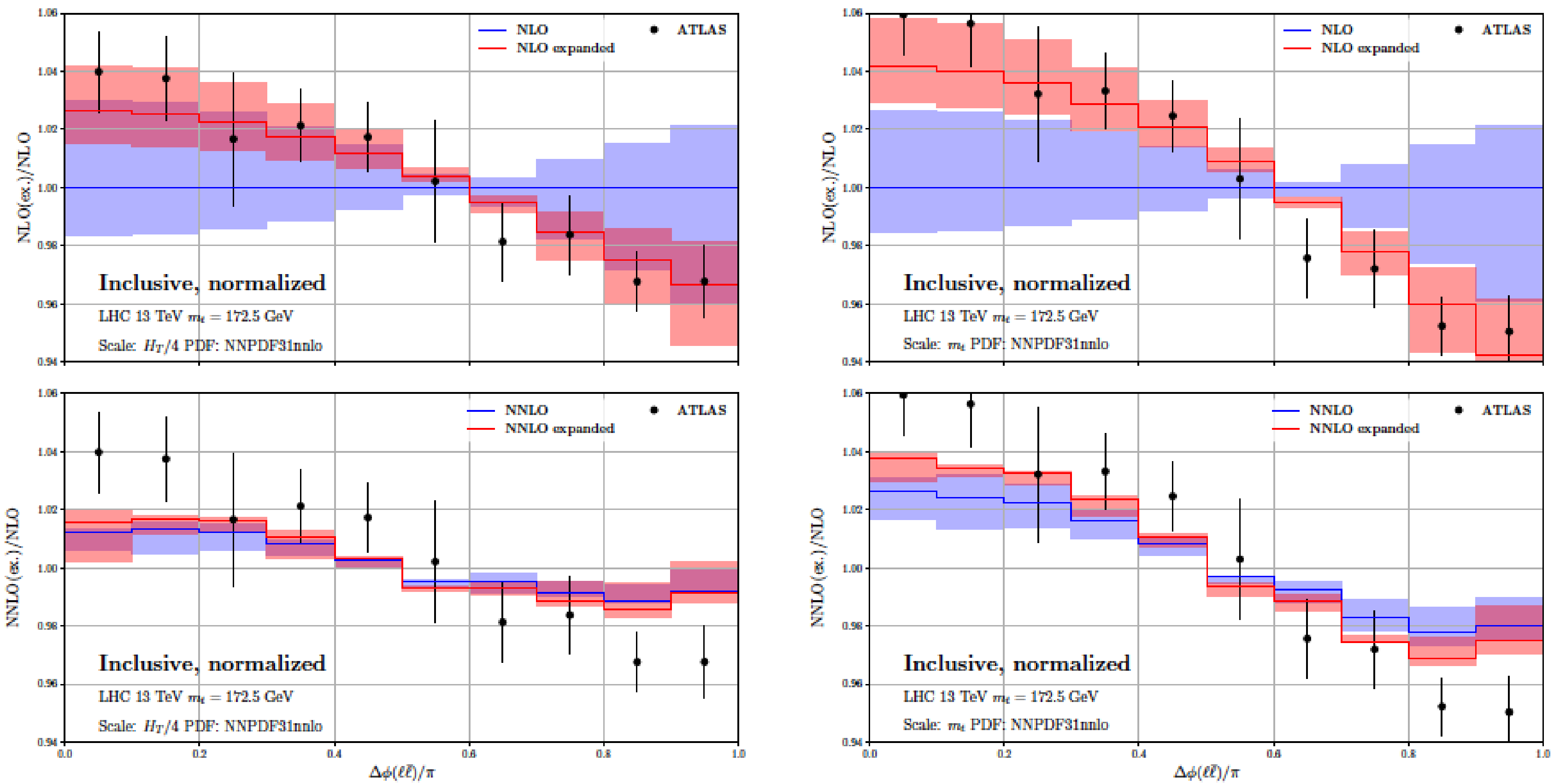


Spin correlations in angular distributions



Inclusive

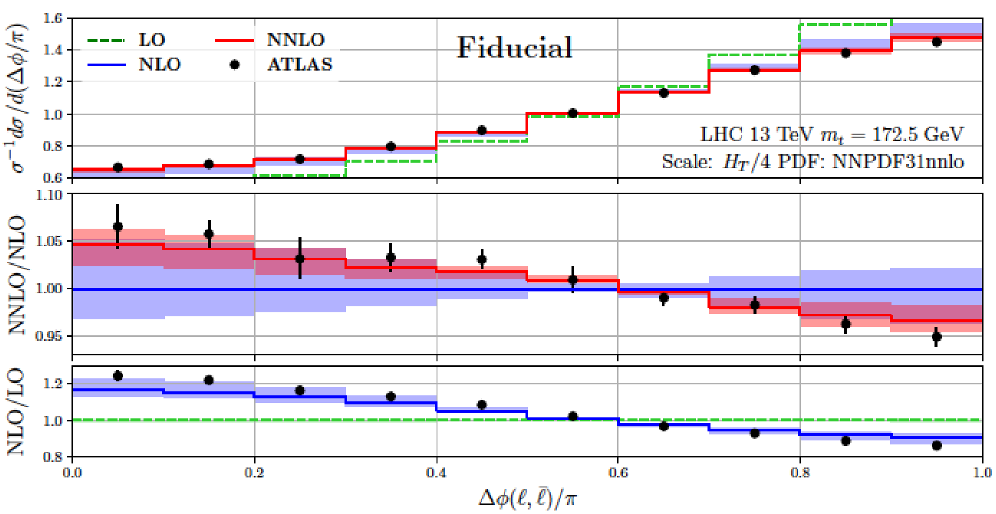
Czakon, Mitov, Poncelet
arXiv:2008.11133

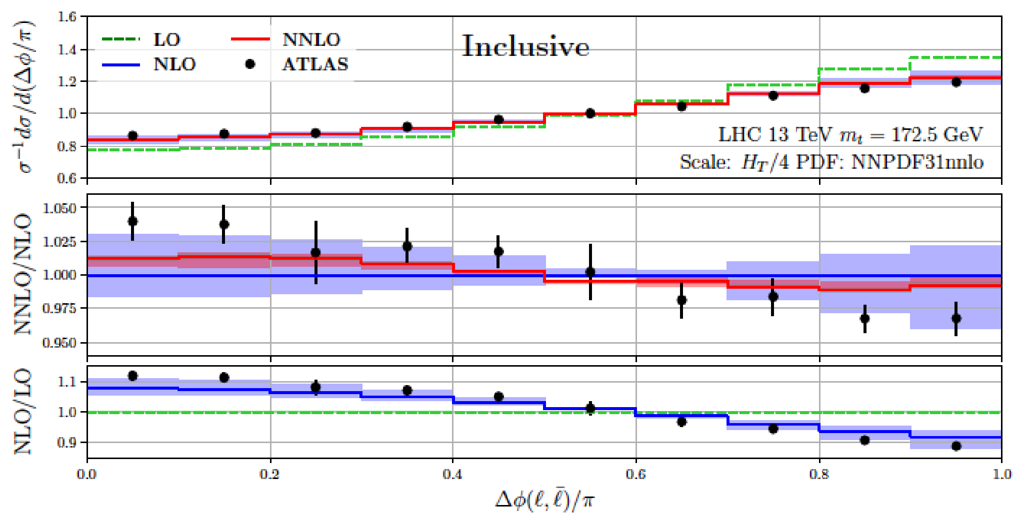


Spin correlations in angular distributions

Behring, Czakon, Mitov, Papanastasiou, Poncelet arXiv:1901.05407

- ✓ Main finding (compare to previous slide):
  - ✓ NNLO QCD describes data in the fiducial region
  - ✓ Does not describe it in the extrapolated (“Inclusive”) phase space (see previous slide)
  - ✓ Expanded definition does make a big difference at NLO but no difference a NNLO
- ✓ Results point towards the need for improved understanding of modeling of final states





Spin correlations in angular distributions

✓ New calculation of complete-NLO+LO decay (in NWA)

Frederix, Tsinikos, Vitos arXiv:2105.11478

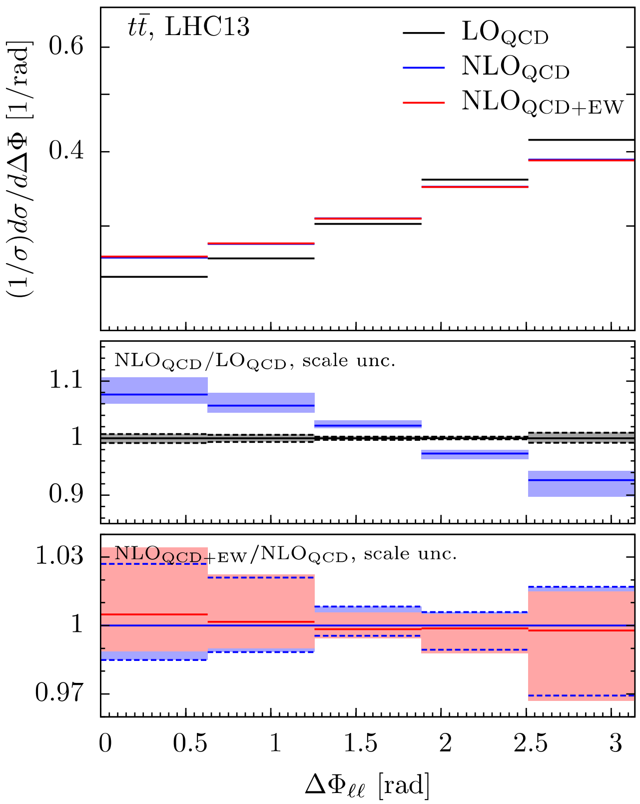
✓ Shown are corrections to tt spin correlations and asymmetries (at decay level)

See also talk by Nils Faltermann

➢ Note the existing NNLO QCD + NLO EW calculation is at top-quark-level

Czakon, Heymes, Mitov, Pagani, Tsinikos, Zaro 1711.03945

✓ It uses parameters that are compatible with the QCD calculations shown above



$$A_C^{\ell\ell} = \frac{\sigma(\Delta\eta_{\ell\ell} > 0) - \sigma(\Delta\eta_{\ell\ell} < 0)}{\sigma(\Delta\eta_{\ell\ell} > 0) + \sigma(\Delta\eta_{\ell\ell} < 0)} \qquad A_{\Delta\Phi} = \frac{\sigma(|\Delta\Phi_{\ell\ell}| > \frac{\pi}{2}) - \sigma(|\Delta\Phi_{\ell\ell}| < \frac{\pi}{2})}{\sigma(|\Delta\Phi_{\ell\ell}| > \frac{\pi}{2}) + \sigma(|\Delta\Phi_{\ell\ell}| < \frac{\pi}{2})},$$

		Unexpanded		Expanded	
Asymmetry	LO QCD [%]	NLO QCD [%]	NLO QCD+EW [%]	NLO QCD [%]	NLO QCD+EW [%]
A_C^{tt}	0	$0.453(5)^{+28.2\%}_{-20.5\%}$	$0.546(6)^{+25.1\%}_{-18.0\%}$	$0.62(2)^{+18.1\%}_{-14.8\%}$	$0.73(3)^{+13.8\%}_{-11.5\%}$
$A_C^{\ell\ell}$	0	$0.27(2)^{+29.3\%}_{-21.4\%}$	$0.33(3)^{+25.0\%}_{-17.8\%}$	$0.36(3)^{+19.3\%}_{-15.9\%}$	$0.45(4)^{+14.6\%}_{-12.0\%}$
$A_{\Delta\Phi}$	$17.51(1)^{+3.2\%}_{-2.8\%}$	$12.65(2)^{+8.3\%}_{-14.8\%}$	$12.42(3)^{+8.7\%}_{-15.5\%}$	$10.88(3)^{+7.2\%}_{-10.1\%}$	$10.58(4)^{+7.4\%}_{-10.5\%}$
$A_{\Delta\theta}$	$14.63(1)^{+4.0\%}_{-4.6\%}$	$16.03(2)^{+4.0\%}_{-2.2\%}$	$16.24(2)^{+4.1\%}_{-2.2\%}$	$16.54(3)^{+2.9\%}_{-1.7\%}$	$16.83(4)^{+2.8\%}_{-1.5\%}$

Thank you!