Spin correlation in top-quark pair production in the 'precision'-era of the LHC

Dortmund

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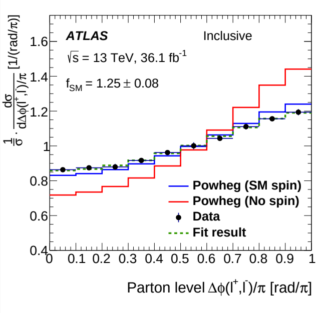
based on work with A. Behring, M. Czakon, A. Mitov and A. Papanastasiou.

1st July 2019

Cavendish Laboratory

Outline



[arXiv:1903.07570 ATLAS '19]

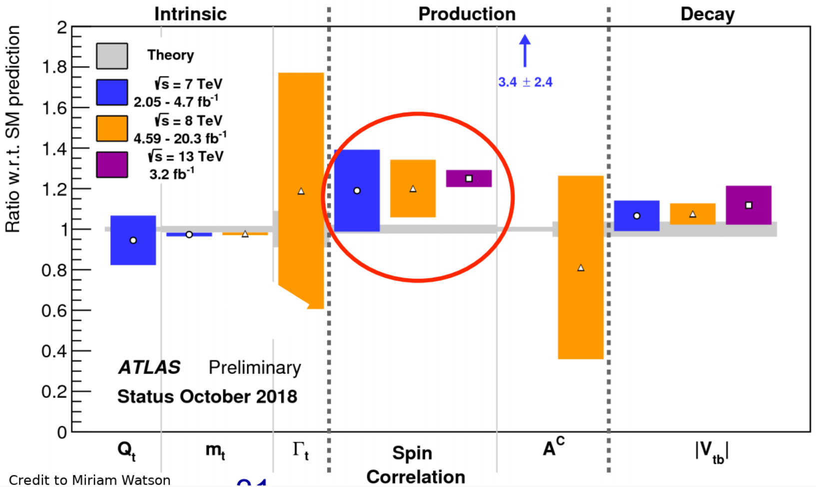
Content:

- Why is this observable interesting and
  what is the connection to spin-correlations in $t\bar{t}$?
- What has been measured? What has been observed?
- Theory point of view: fixed-order predictions and their phenomenology.

Introduction: Precision physics at the LHC

- So far no physics beyond the Standard Model
- NP might be out of reach of the LHCs energies $\rightarrow$ search for small deviations from SM predictions
- Top-quarks are an ideal probe:
  - Tightly connected to Higgs and EW physics (indirect constrains)
  - Important background or signature in many BSM scenarios
  - Rich phenomenology
  - Abundant and high quality data
- Many properties of the top-quark can predicted and tested: width, spin, charge, x-sections, . . .

Introduction: Precision top-quark physics at the LHC



Credit to Miriam Watson

Introduction: Spin-correlation

- Top-quark pair production is the main production mode at the LHC
- Tops are produced without polarization $\rightarrow$ spin-correlation between top and anti-top however sizable effect.
- The spin correlation can be represented through the spin density matrix:

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

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

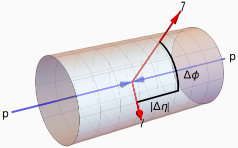
- Translates to similar defined coefficients for the decay-products:
  - Proportional to angular distribution with respect to top-quark directions
  - Spin-analysing power (charged leptons best choice)

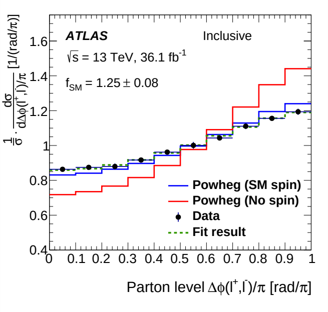
Introduction: Spin-correlation in leptonic observables

- Direct measurement of top-quark spin density matrix [CMS,PAS TOP-18-006]
  - full spin information
  - systematic difficulties (neutrinos $\rightarrow$ top-momenta)
- Leptonic observables are sensitive to $t\bar{t}$ spin-correlations: $\Delta\Phi_{\ell\ell}$ and $|\Delta\eta_{\ell\ell}|$
- Measurement of spin-correlation:

$$\mathrm{d}\sigma_i = f_{\mathrm{SM}}\,\mathrm{d}\sigma_i^{\mathrm{spin}} + (1 - f_{\mathrm{SM}})\,\mathrm{d}\sigma_i^{\mathrm{no\text{-}spin}}$$

- Azimuthal opening angle $\Delta\Phi_{\ell\ell}$:
  - Boosted top favor antiparallel leptons
  - Spin correlation counteracts
  - Effect of higher corrections? $\rightarrow t\bar{t}$ recoils against additional radiation



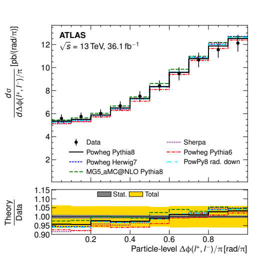


Introduction: Measurement of spin-correlation with $\Delta\Phi_{\ell\ell}$ by ATLAS

Measurement in arxiv:1903.07570

- Measurement in fiducial phase space defined by 'particle'-level cuts:
    - Different-flavor opposite-sign leptons with $p_T > 27(25)$ GeV and $|\eta| < 2.5$
    - ≥ 2 jets (≥ 1 b-jets) (anti-k_T, $R = 0.4$) with $p_T > 25$ GeV and $|\eta| < 2.5$
- Usage of MC (NLO QCD + Pythia) to extrapolate to full phase space
- In normalized distribution:
    - Most of the systematic errors cancel
    - Deviation from SM shows up: 3.2 σ

Fiducial:



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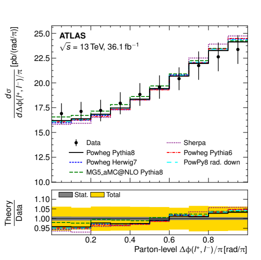

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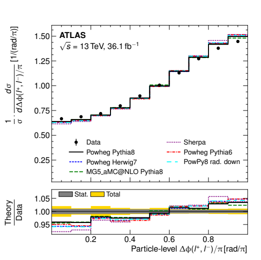
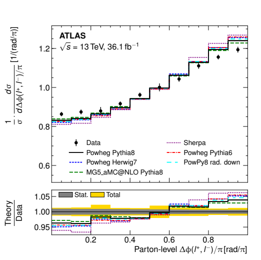


Inclusive - normalised:



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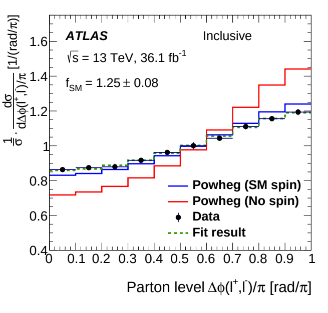
- Usage of MC (NLO QCD + Pythia) to extrapolate to full phase space
- In normalized distribution:
  - Most of the systematic errors cancel
  - Deviation from SM shows up: 3.2 σ
- The question: BSM or SM effect?
  $\rightarrow$ here the SM perspective



Fixed-order QCD predictions for top-quark pair production and decay

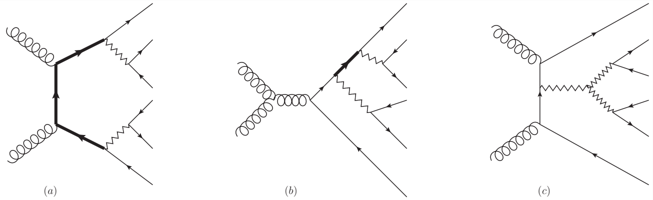
Fixed-order predictions: Production and decay

Narrow-Width-Approximation

- Considering limit $\Gamma_t/m_t \to 0$
- Factorization of production and decay
- Reduction of complexity by keeping crucial features of decay like spin-correlations
- Expected error of $\mathcal{O}(\Gamma_t/m_t)$

Off-shell calculations

- Considering the complete process: $pp \to \ell^+\ell^-\nu\bar{\nu}b\bar{b} + X$
- Technically challenging due to high multiplicity, difficult phase space
- Off-shell and non-resonant effects important in certain phase space regions



Fixed-order predictions: Narrow-Width-Approximation

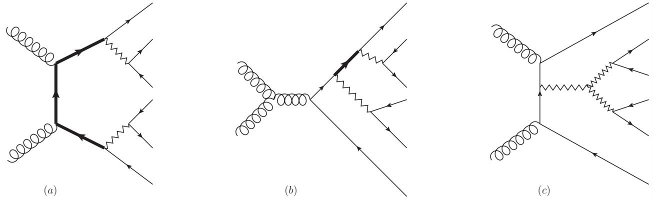
- top-quark have a short life time, decay before hadronization. $\Gamma_t \ll m_t$

$$\frac{1}{(p^2 - m_t^2)^2 + m_t^2\Gamma_t^2} \xrightarrow{\Gamma_t/m_t \to 0} \frac{\pi\delta(p^2 - m_t^2)}{m_t\Gamma_t}$$

- for on-shell top-quarks:

$$\not{p} + m_t = \sum_\lambda u_\lambda(p)\bar{u}_\lambda(p)$$

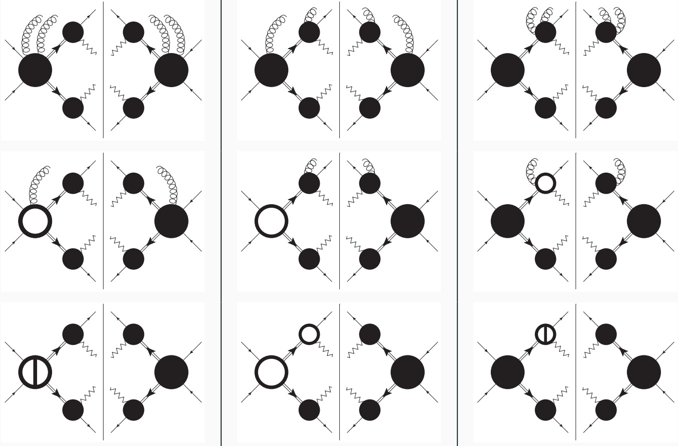
- factorization of production and decay, non/single-resonant diagrams are suppressed
- polarized matrix elements required



(a) (b) (c)

Fixed-order predictions: Production and decay in NWA @ NNLO QCD

NNLO x LO	NLO x NLO	LO x NNLO

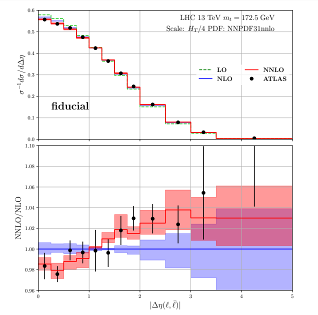


Fixed-order predictions: Production and decay in NWA @ NNLO QCD

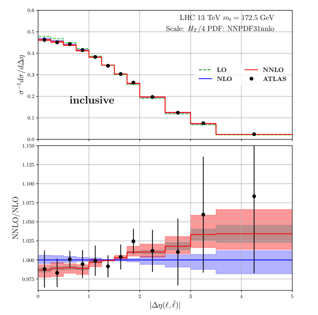
- Extension of the STRIPPER framework [Czakon et al 10'-19'] used for differential $t\bar{t}$
- Predictions for inclusive and fiducial phase spaces
- Many applications in work:
  - leptonic distributions
  - top-quark (differential) cross sections in fiducial phase space
  - top-quark mass extraction
  - ...
- Study of top-quark spin-correlation

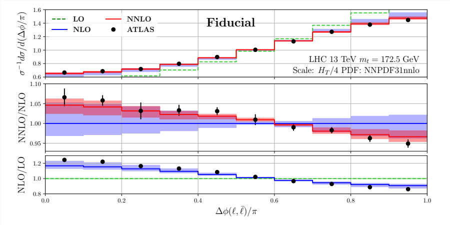
Fixed-order predictions: Spin-correlation @ NNLO QCD

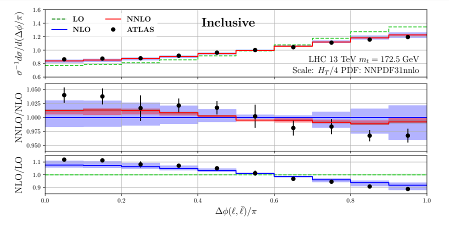
Fiducial phase space



Inclusive phase space



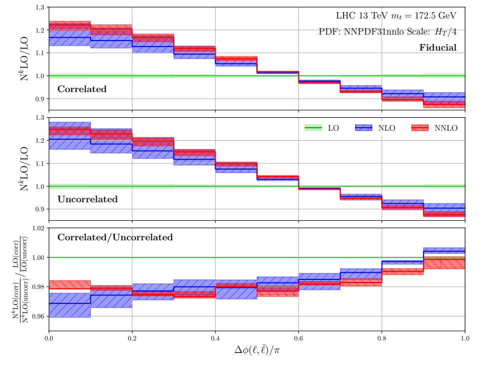


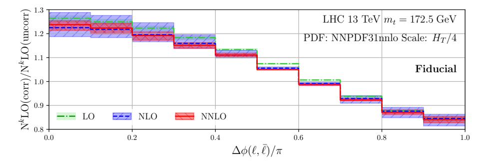


arxiv:1901.05407 [Behring,Czakon,Mitov,Papanastasiou,Poncelet '19]

Fixed-order predictions: Spin-correlation - checks and anatomy

- Radiation effects vs. spin correlation
- Scale dependence
- Parametric dependence/ fiducial phase space @ NLO
    - PDF (<1% in norm.)
    - m_t (small $<1\%$)
- Check of NLO EW and off-shell effects (small in fiducial region)





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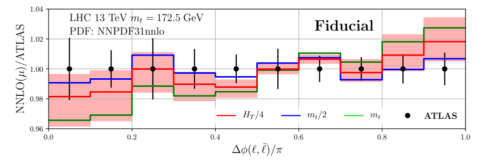

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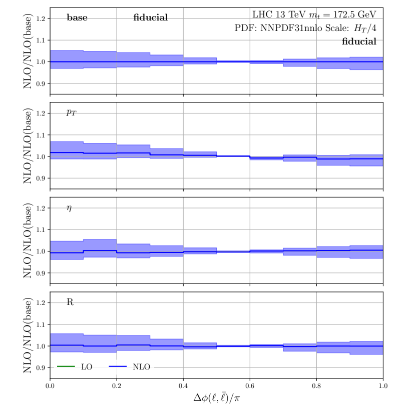

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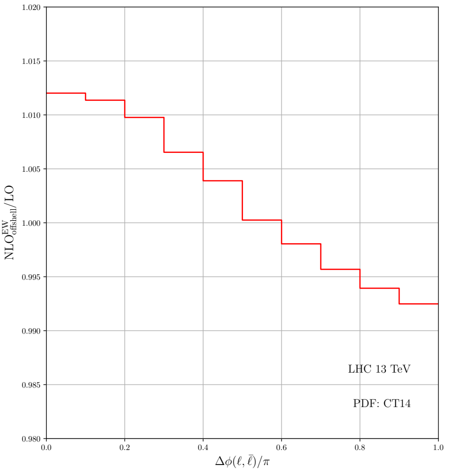
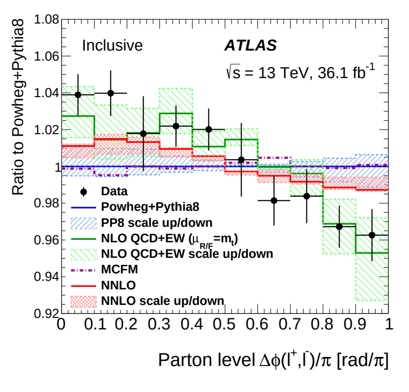


[arXiv:1903.07570 ATLAS '19]



Summary:

- NNLO QCD effect not sufficient to resolve tension for inclusive measurement
- Bernreuther et al prediction suggest large NLO EW effect, but expanded ratios have been used

Fixed-order predictions: Expanded ratios

Normalized distribution: $\frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}X}$

- Perturbative expansion:

$$\sigma = \sigma^0 + \alpha_S \sigma^1 + \alpha_S^2 \sigma^2 + \dots$$
$$\frac{\mathrm{d}\sigma}{\mathrm{d}X} = \frac{\mathrm{d}\sigma^0}{\mathrm{d}X} + \alpha_S \frac{\mathrm{d}\sigma^1}{\mathrm{d}X} + \alpha_S^2 \frac{\mathrm{d}\sigma^2}{\mathrm{d}X} + \dots$$

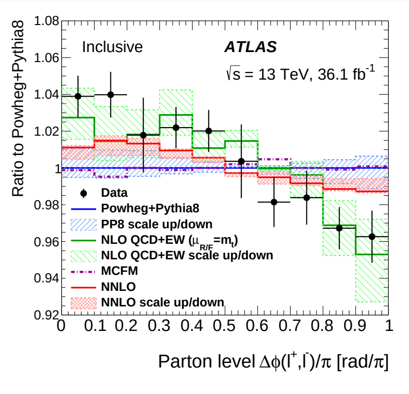
- Normalized distribution at NNLO:

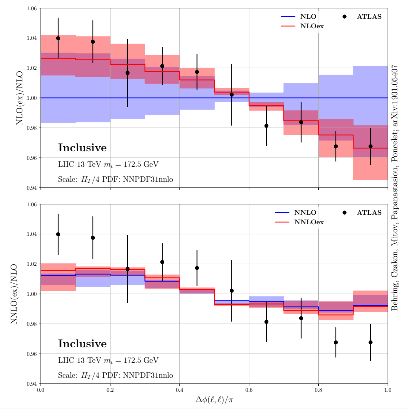
$$R = \frac{1}{\sigma^0 + \alpha_S \sigma^1 + \alpha_S^2 \sigma^2} \left(\frac{\mathrm{d}\sigma^0}{\mathrm{d}X} + \alpha_S \frac{\mathrm{d}\sigma^1}{\mathrm{d}X} + \alpha_S^2 \frac{\mathrm{d}\sigma^2}{\mathrm{d}X} \right) + \mathcal{O}\left(\alpha_S^3\right)$$

- Expanded ratio:

$$R^{\mathrm{NNLO,exp}} = R^0 + \alpha_S R^1 + \alpha_S^2 R^2 \ ,$$
$$R^0 = \frac{1}{\sigma^0} \frac{\mathrm{d}\sigma^0}{\mathrm{d}X} \ ,$$
$$R^1 = \frac{1}{\sigma^0} \frac{\mathrm{d}\sigma^1}{\mathrm{d}X} - \frac{\sigma^1}{\sigma^0} \frac{1}{\sigma^0} \frac{\mathrm{d}\sigma^0}{\mathrm{d}X} \ ,$$
$$R^2 = \frac{1}{\sigma^0} \frac{\mathrm{d}\sigma^2}{\mathrm{d}X} - \frac{\sigma^1}{\sigma^0} \frac{1}{\sigma^0} \frac{\mathrm{d}\sigma^1}{\mathrm{d}X} + \left(\left(\frac{\sigma^1}{\sigma^0} \right)^2 - \frac{\sigma^2}{\sigma^0} \right) \frac{1}{\sigma^0} \frac{\mathrm{d}\sigma^0}{\mathrm{d}X}$$

Fixed-order predictions: Expanded ratios

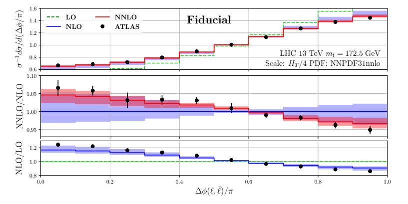




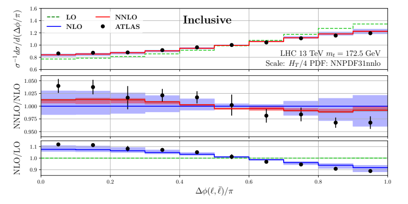
- Not an EW-effect (which is actually tiny)
- Everything consistent within scale dependence (7-point variation)
- NNLO QCD resolves this expansion 'ambiguity'

- The best available prediction lowers but does not resolve discrepancy between data and theory
- Predictions for the fiducial phase space are in much better agreement with data → extrapolation with NNLO prediction?

Fiducial phase space



Inclusive phase space



Summary & Outlook

Summary

- Measurement of spin-correlation through leptonic distribution shows so far largest deviation in top-sector
- Full NLO MC and fixed order NNLO QCD fail to describe extrapolated measurement:
  - small NNLO/NLO K-factor in inclusive phase space
  - much better description of data in fiducial phase space trough NNLO QCD (larger K-factor)
  - NLO-EW small effect in 'direction' of data but not sufficient
- Theorists remark: pQCD works! (lesson from expanded ratios)

Outlook

- Predictions for various leptonic distribution and application:
  - Top-quark differential distributions in fiducial phase space
  - Spin-density matrix
  - Top-quark mass measurement from leptonic distributions

Backup

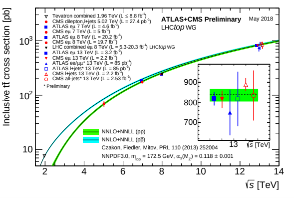
Total cross section

- NNLO QCD + NNLL soft gluon resummation
- Uncertainties of a few percent
- Remarkable agreement with measurements at 7, 8 and 13 TeV

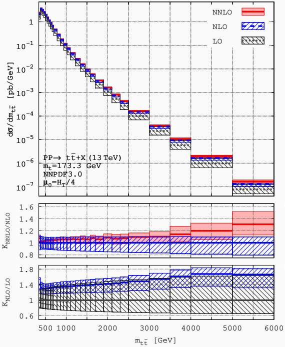
Differential

- Modification of shape for p_T and $m_{t\bar{t}}$
- Reduction of scale dependence
- Multi-dimensional distributions
- choice of dynamical scale is crucial $\rightarrow$ extensive study of perturbative convergence

arxiv:1303.6254 [Czakon,Fiedler,Mitov '13]

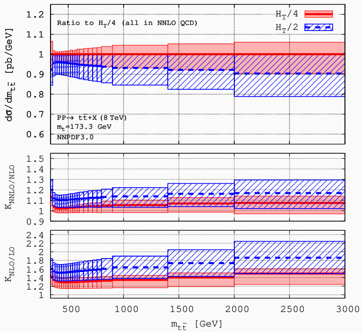


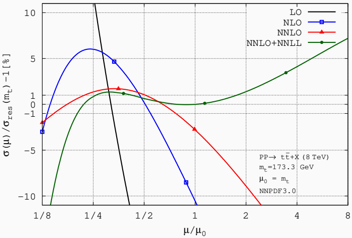
arxiv:1606.03350 [Czakon,Heymes,Mitov '16]



- Renormalization/Factorization scale dependence → major source of theory uncertainty
- What is a sensible scale choice? → possible metric: *principle of fasted convergence*
- Total cross section: $\mu = m_t/2$
- Differential cross sections? Probing a vast energy regime ⇒ dynamical scales
- $H_T/4$ established for most observables (except $m_T/2$ for $p_{T,t}$ distributions)

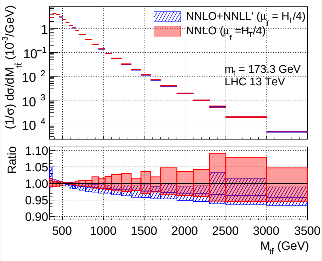
arxiv:1606.03350 [Czakon,Heymes,Mitov '16]

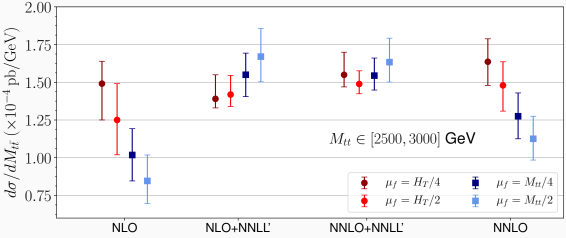




State-of-the-art: Resummation for differential observables

- Advances in resummation for differential observables
- Threshold (low p_T) and small-mass (high p_T - 'boosted tops') logarithms
- Stabilizes results w.r.t. scale choice form
- Results support $H_T/4$ as the 'best' scale since $H_T/4$ seems to capture most of of the resummation features





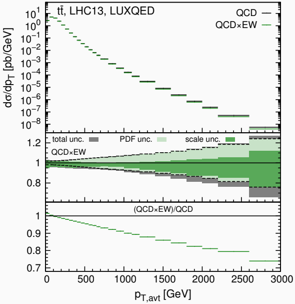
arxiv:1803.07623 [Czakon,Ferroglia,Heymes,Mitov,Pecjak,Scott,Wang,Yang '18]

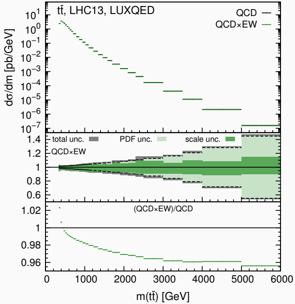
State-of-the-art: NLO-EW corrections

- Studied in additive and multiplicative approach
- Consistent treatment of Photon PDF → LUXqed sets
- Size of corrections are observable dependent:
  $p_{T,avt}$: up to -25% at high p_T (Sudakov logarithms),
  $>$ NNLO QCD scale dependence for $p_{T,avt} > 500$ GeV
  $y_t, y_{t\bar{t}}$: small effect ($<$ NNLO QCD scale dependence)
- multiplicative approach results in smaller scale dependence

Combination with NNLL' resummation → most complete SM description available

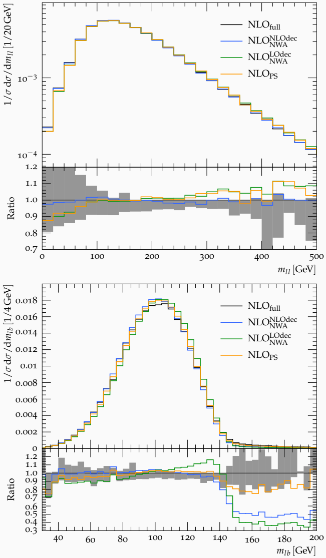
arxiv:1705.04105 [Czakon, Heymes, Mitov,Pagani,Tsinikos,Zaro '17]



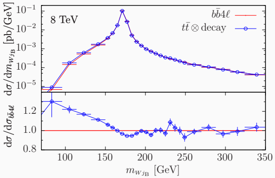


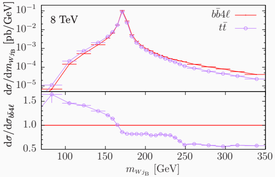
Production and decay: NLO for off-shell $t\bar{t}$

- NLO corrections to full $pp \to \ell^+\ell^-\nu\bar{\nu}b\bar{b} + X$
  [5FS: Bevilacqua et al, Denner et al, Heinrich et al,
  4FS: Frederix, Cascioli et al]
- Off-shell & non-resonant effects depend strongly on observable
- $\to$ NWA approximation valid for many observables
- Higher order corrections to decay are important!
- Kinematical thresholds and edges are sensitive to off-shell effects $\Rightarrow$ NWA does not give a valid description



Production and decay: NLO + PS for off-shell $t\bar{t}$





- Matching fixed order calculation to PS
- Technical subtlety: resonance-aware matching. Implementation in POWHEG framework
- Detailed comparison of:
  - "$t\bar{t}$": NWA, NLO production only (industry standard)
  - "$t\bar{t} \otimes$ decay": NWA, NLO production & decay , approximate LO finite width effects [Campbell,Ellis,Nason,Re '14]
  - "$b\bar{b}4\ell$": full off-shell [Jezo,Nason '15] [Jezo,Lindert,Nason,Oleari,Pozzorini '16]
- Upshot:
  - "$t\bar{t} \otimes$ decay" closer to "$b\bar{b}4\ell$" than "$t\bar{t}$" (in terms of shape and normalization)
  - NLO corrections to decay are crucial for NWA to be reliable to work