Top production at the LHC

DIS 2019 - Turin

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Cavendish Laboratory

Outline

- Introduction
- Precision stable top-quark pair production
  - Recent theory developments:
    scale setting, resummation and EW corrections
  - Applications:
    PDFs and charge symmetry
- Production and decay
  - Towards realistic top-quark states
  - Off-shell $t\bar{t}$ @ NLO + PS
  - Production $\otimes$ Decay @ NNLO QCD

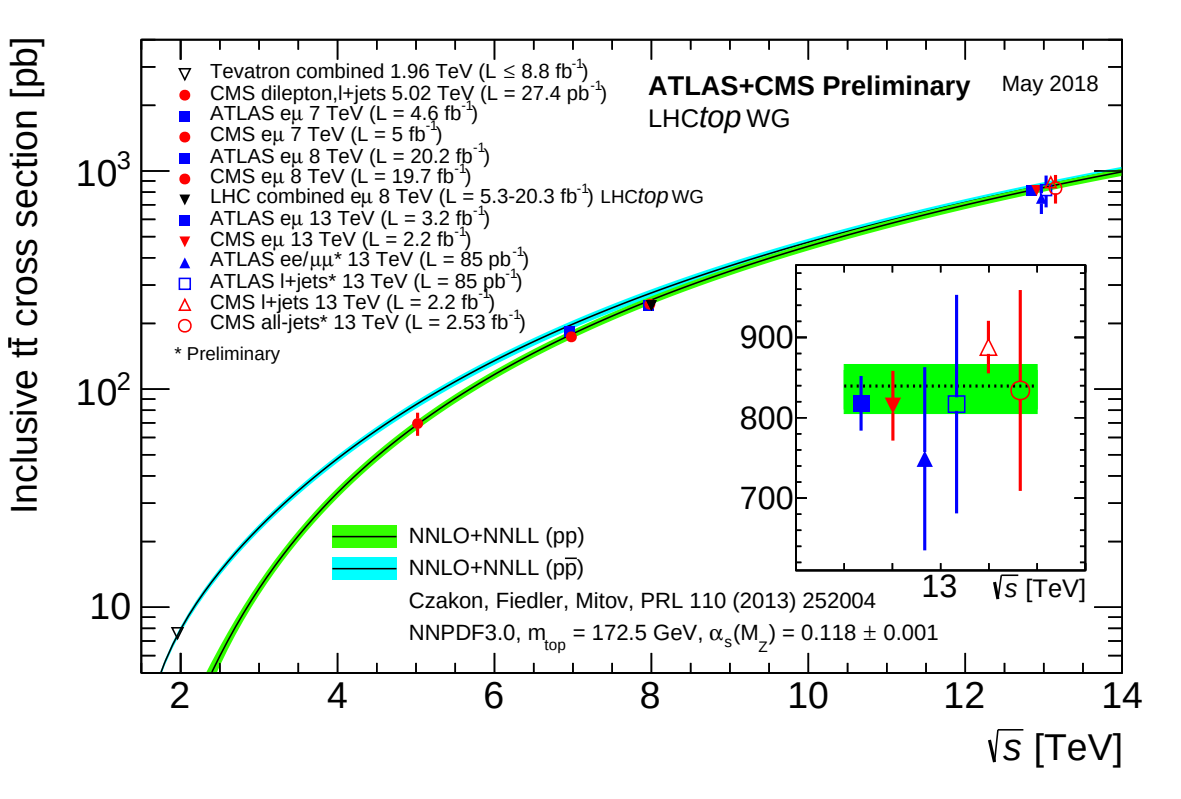
Top-quark production at the LHC

- Heaviest known particle $\rightarrow$ special place in the SM
- Abundantly produced at the LHC
  $\rightarrow$ top-quark factory
  $\rightarrow$ high quality and precision data
- Many opportunities to study QCD/SM in high precision
- Many connections to other fields: Higgs, BSM, EW precision
- High perturbative accuracy needed to describe and squeeze out most of the data available $\leftarrow$ this talk

State-of-the-art predictions for top quark pair production

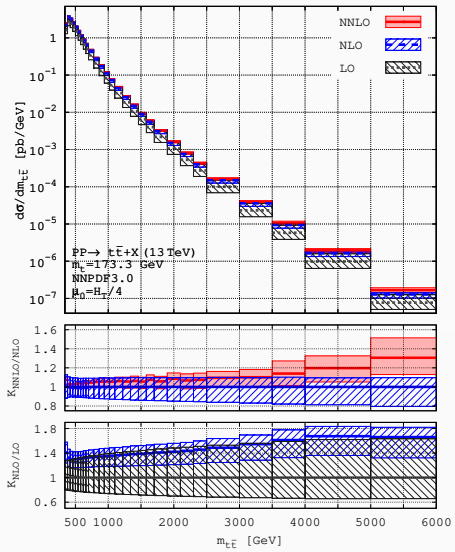
State-of-the-art: Total cross section for $t\bar{t}$ production

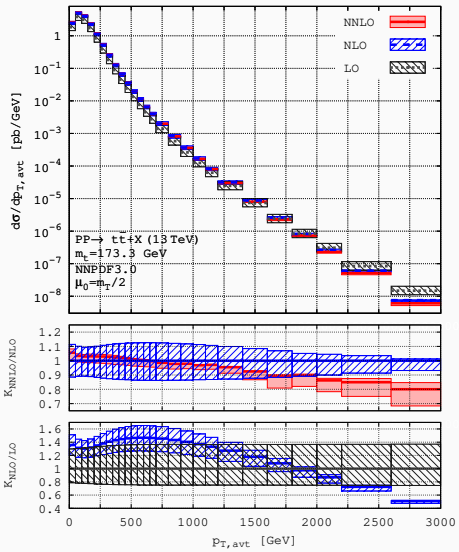
- NNLO QCD + NNLL soft gluon resummation
- Uncertainties of a few percent
- Remarkable agreement with measurements at 7, 8 and 13 TeV



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

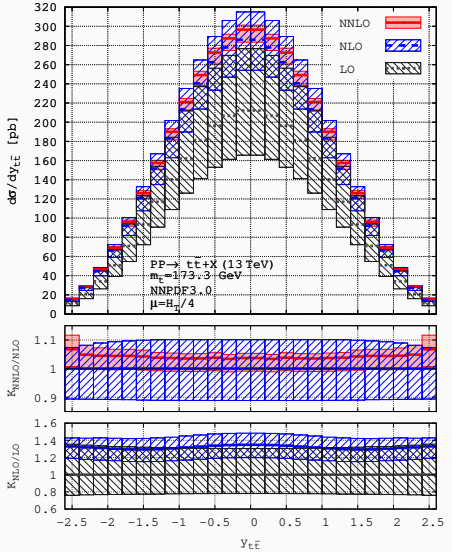
State-of-the-art: Differential $t\bar{t}$ cross sections @ NNLO QCD

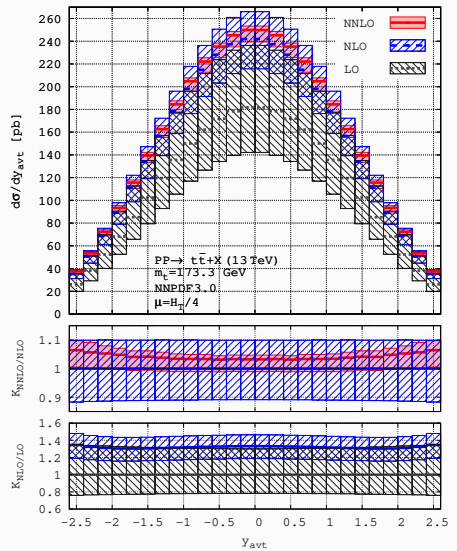




NNLO QCD

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



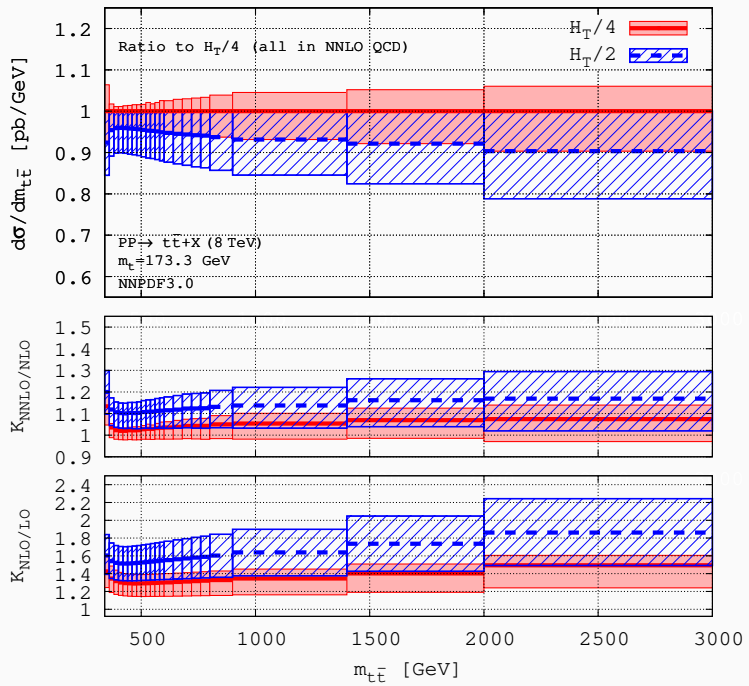


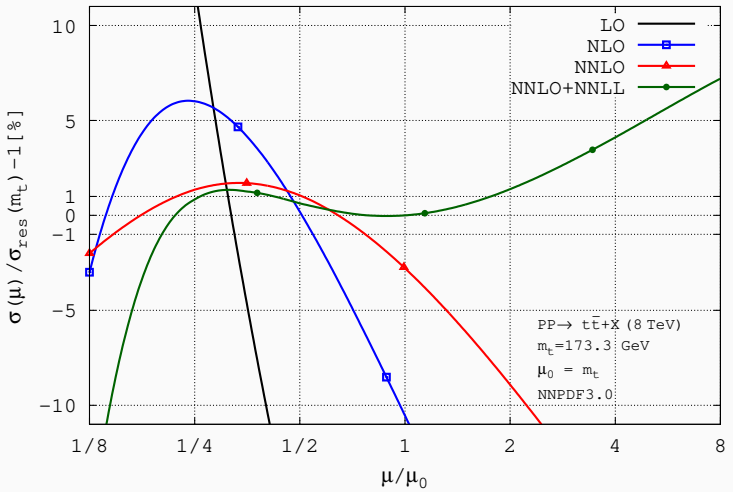
arxiv:1606.03350 [Czakon,Heymes,Mitov '16]

State-of-the-art: Renormalization and Factorization scale dependence

- 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)

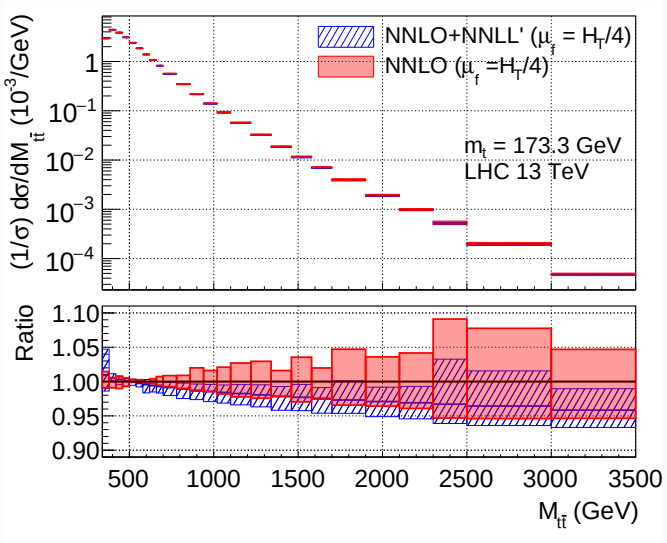
arxiv:1606.03350 [Czakon,Heymes,Mitov '16]

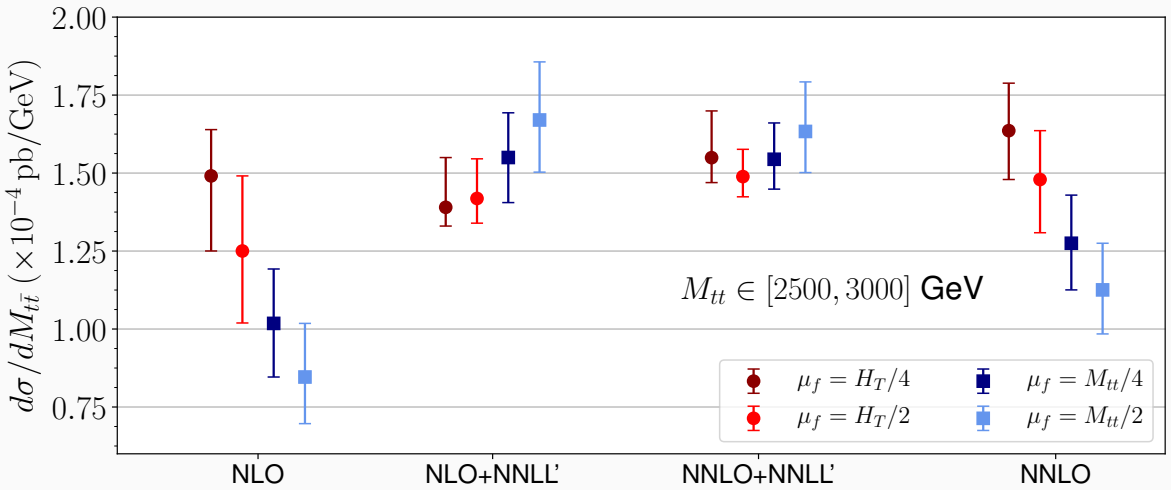




State-of-the-art: Resummation for differential observables

- 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



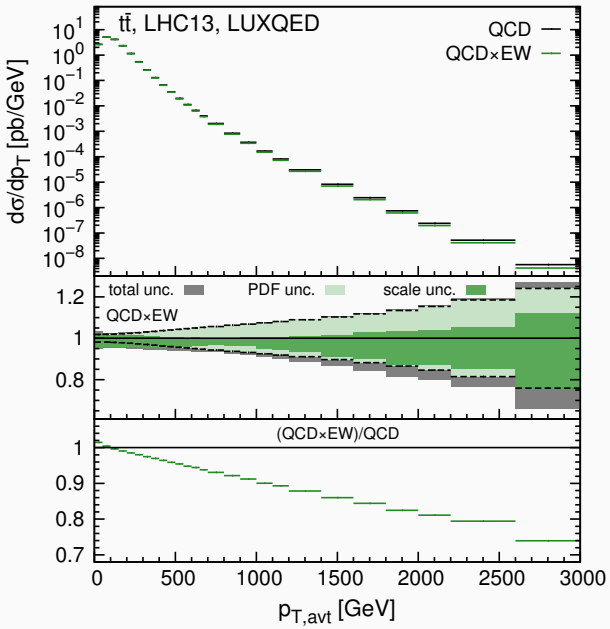


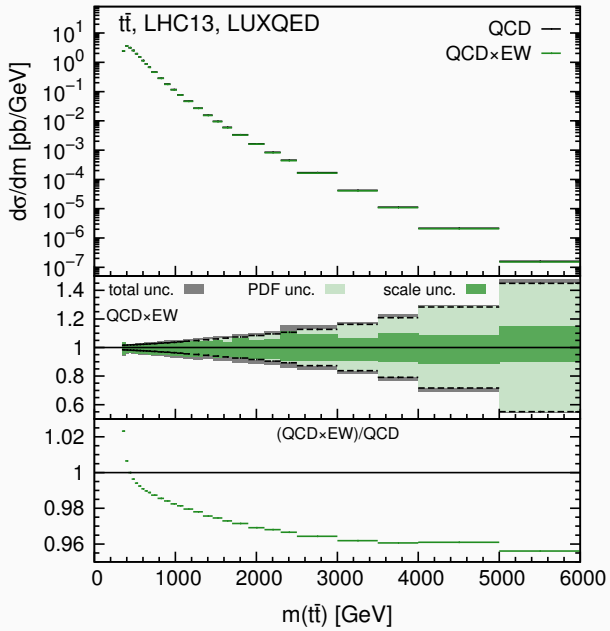
arxiv:1803.07623 [Czakon,Ferroglia,Heymes,Mitov,Pecjak,Scott,Wang,Yang '18]

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

- Studied in additive and multiplicative approach
- Observed strong PDF dependence
- 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 $\rightarrow$ most complete SM description available





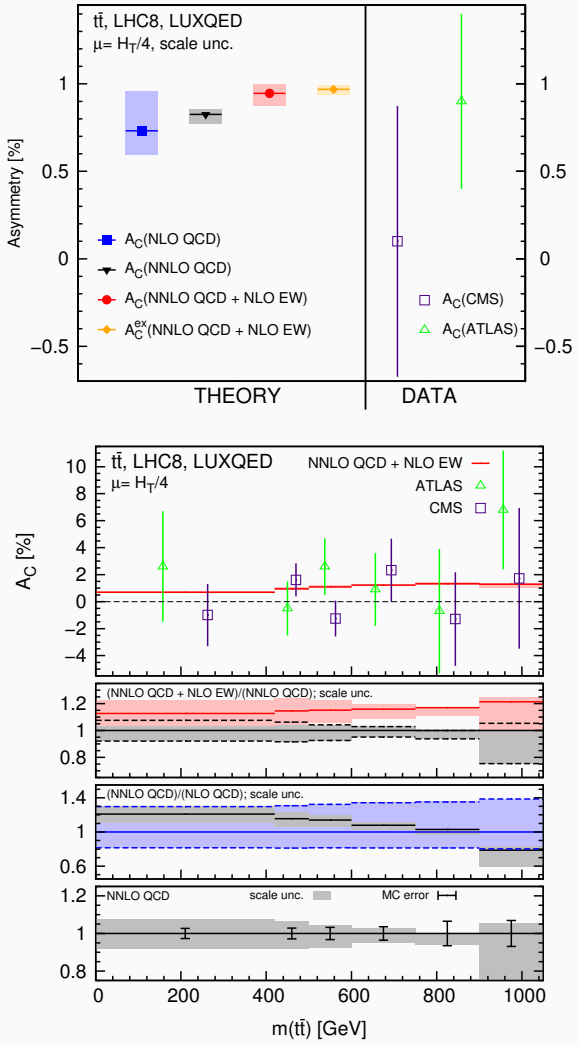
arxiv:1705.04105 [Czakon, Heymes, Mitov,Pagani,Tsinikos,Zaro '17]

Applications

Applications: LHC charge asymmetry

arxiv:1711.03945 [Czakon,Heymes,Mitov,Pagani,Tsinikos,Zaro '17]

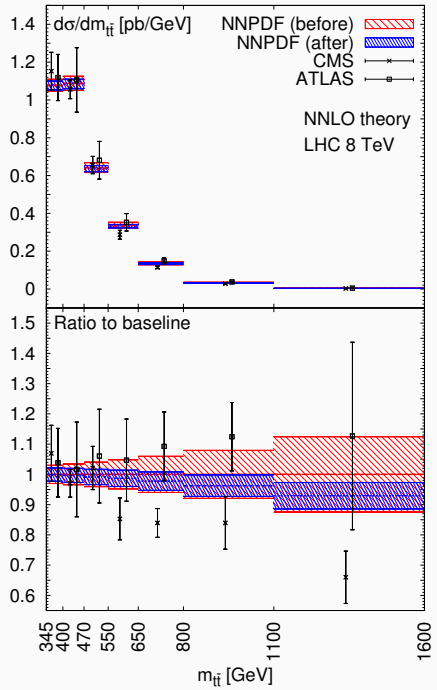
- Inclusive and differential charge asymmetry
- $A_c = \frac{\sigma^+_{\text{bin}} - \sigma^-_{\text{bin}}}{\sigma^+_{\text{bin}} + \sigma^-_{\text{bin}}}$ with $\sigma^{\pm}_{\text{bin}} = \int \theta(\pm\Delta|y|)\theta_{\text{bin}} \mathrm{d}\sigma$
- Small effect at the LHC ($\sim 1\%$)
- NNLO QCD + NLO EW accuracy (additive combination)
- Numerically challenging calculation
- Significant increasing effect of NNLO QCD and NLO EW
- Comparison to 8 TeV data in favour of SM
- Experimentally limited

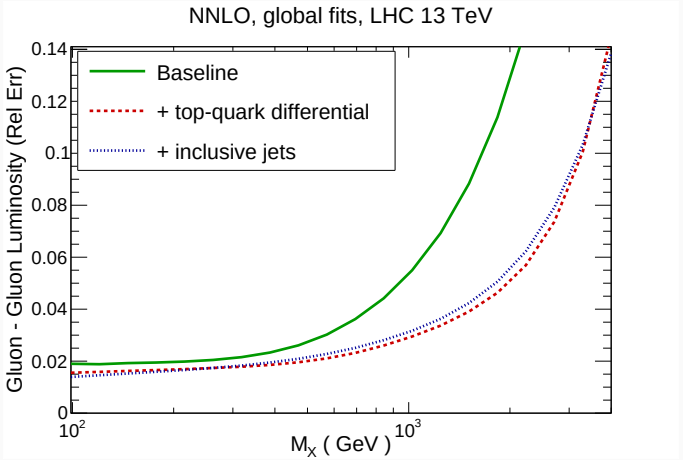


Applications: Top-quark meets PDF

- Excellent theoretical and experimental precision $\rightarrow$ PDF sensitivity
- $t\bar{t}$ data sensitive to large-x gluon PDF
- Differential top-quark data included in PDF fits
- Fit within NNPDF framework

  arxiv:1611.08609[Czakon,Hartland,Mitov,Nocera,Rojo '16]
  - Reduction of large-x gluon PDF uncertainties
  - Reduction of PDF uncertainties in fitted observables





Applications: Top-quark meets PDF $\rightarrow$ fastNLO

- NNLO QCD calculation are expensive $\mathcal{O}(10^5)$ CPU hours
- Changing setup (PDF, Scales, Histograms, Parameter) requires recalculation
- $\rightarrow$ fastNLO PDFs allow to separate the PDF integration.
- fastNLO tables for NNLO QCD available

  arxiv:1704.08551 [Czakon,Heymes,Mitov '17]
- New: double differential observables (CMS binning, 8 TeV)

  Czakon, Mitov, Papanastasiou (2018), to appear.

Production and decay

Production and decay: Towards realistic top-quark states

Elephant in the room:

Top-quarks are not stable and are measured utilising the decay products

- Decay products are measured in fiducial phase space $\rightarrow$ all previous results rely on the extrapolation of the phase space
- The phase space extrapolation relies heavily on MC modeling of the top-quark production and its decay
- The modeling might have more or less subtle impacts on results derived in the extrapolated phase space

Production and decay: Towards realistic top-quark states

Two main approaches to include the decay in prediction

Narrow-Width-Approximation

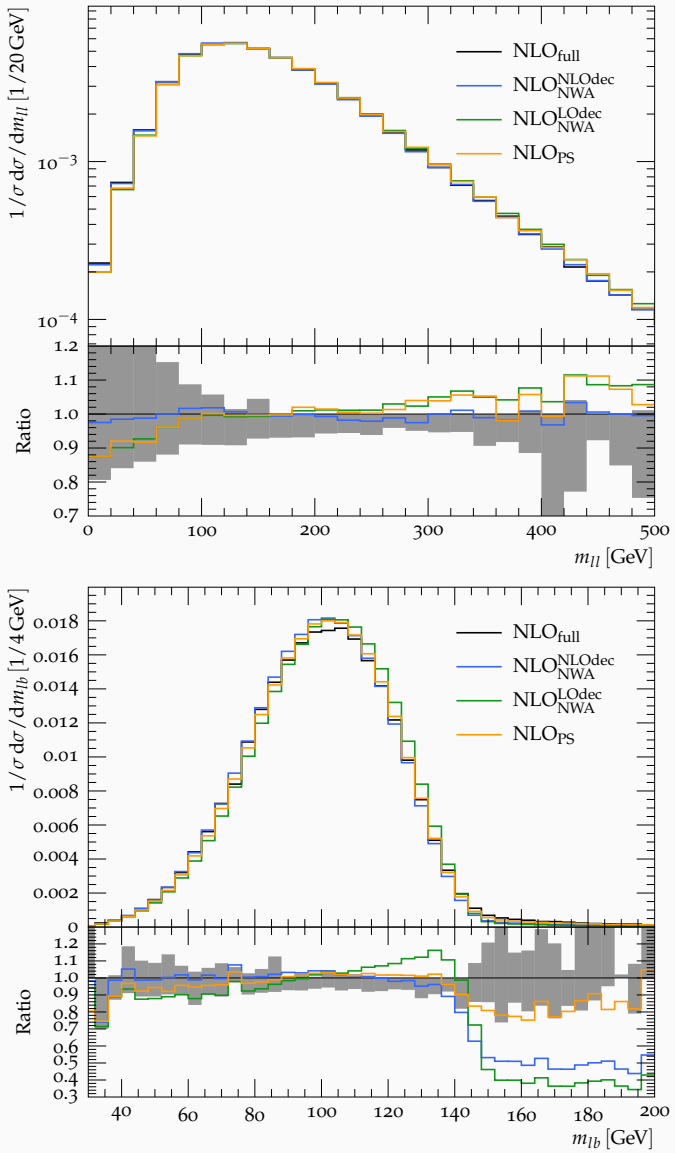
- Considering limit $\Gamma_t \to 0$
- Factorization of production and decay
- Reduction of complexity by keeping crucial features of decay like spin-correlations
- Expected error of $\mathcal{O}(\Gamma_t/m_t)$

Off-shell calculations

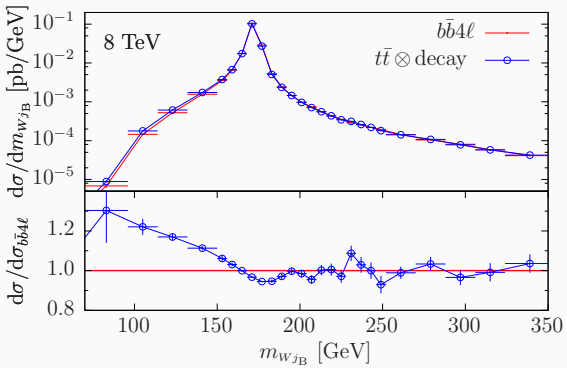
- Considering the complete process: $pp \to \ell^+\ell^-\nu\bar{\nu}b\bar{b} + X$
- Technically challenging due to high multiplicity, difficult phase space
- Off-shell and non-resonant effects important in certain phase space region

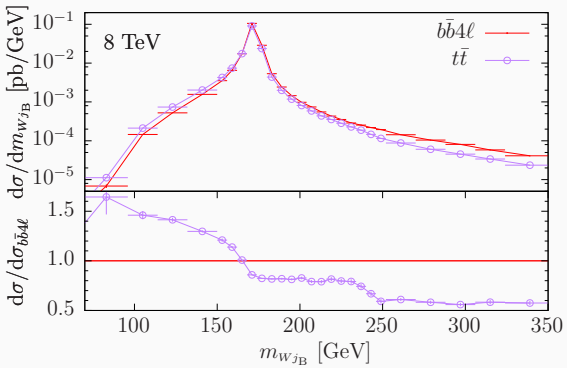
Production and decay: NLO for off-shell $t\bar{t}$

- 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 $t\bar{t}$

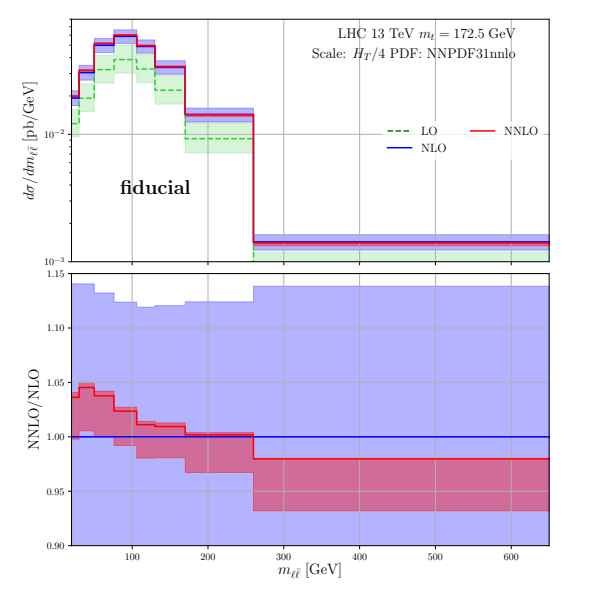


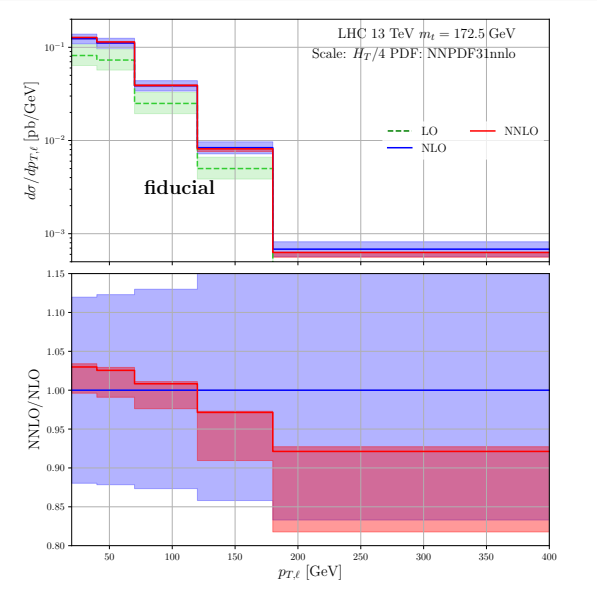


- Matching fixed order calculation to PS
- Technical subtlety: resonance-aware matching. Implementation in POWHEG framework
- Detailed comparison of:
  - "$t\bar{t}$": NWA, NLO production only (industry standard)
  - "$t\bar{t}\otimes$ decay": NWA, NLO production & decay , approximate LO finite width 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

- NNLO QCD correction to NWA with leptonic decays now available
- Extension of the STRIPPER framework 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

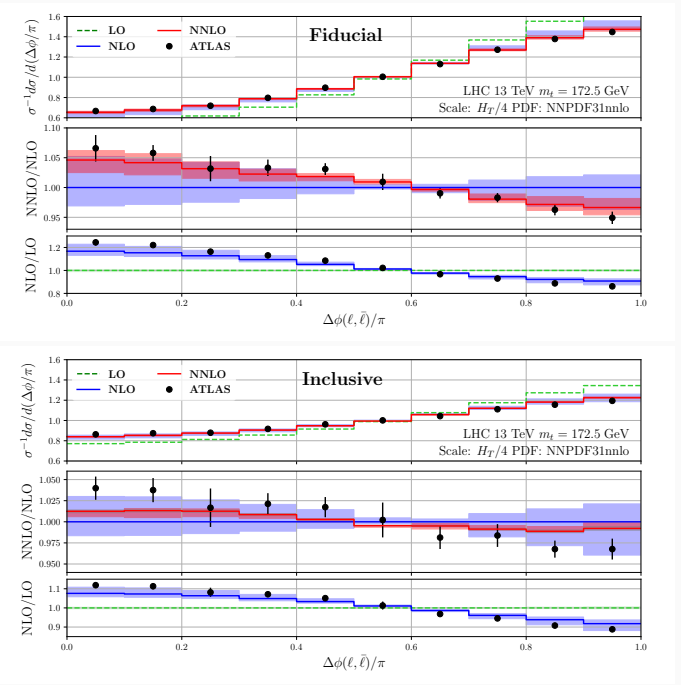
Preliminary





Production and decay: Spin-correlation @ NNLO QCD

- Leptonic observables are sensitive to $t\bar{t}$ spin-correlations.
  For example the azimuthal opening angle of the leptons: $\Delta\Phi_{\ell\ell}$
- Interesting due to observed tension between SM and LHC data in inclusive (extrapolated) phase space
- Comparison in fiducial phase space: NNLO QCD describes data well
- $\rightarrow$ extrapolation effect?



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

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- Interesting due to observed tension between SM and LHC data in inclusive (extrapolated) phase space
- Comparison in fiducial phase space: NNLO QCD describes data well
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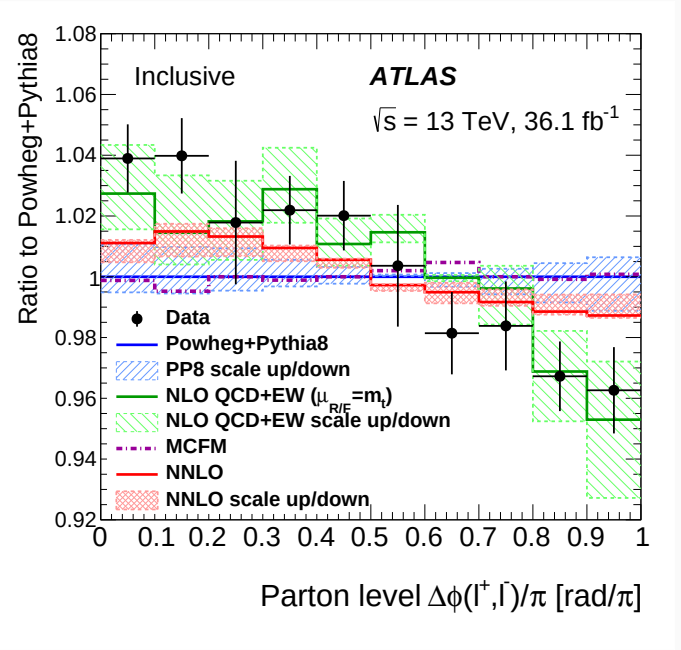
- Published results: [arXiv:1903.07570 ATLAS '19]
  (discrepancy resolved by EW effects?)

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



Summary & Outlook

Summary

- Top-quark production at the LHC is theoretically very well understood and under control and allows for precision test and parameter extraction of the SM
- Refined calculation (through resummation and/or NLO EW) allow to improve theoretical stability and understanding
- Precision calculations for more realistic final states including the top-quarks decay.
- NNLO QCD predictions including leptonic top-quark decays. Production cross sections and differential distributions in fiducial volumes.

Outlook

- Using precision predictions to get out as much as possible of LHC data
- SM model precision test and parameter estimations: m_t, α_S, PDFs,...
- Incoming NNLO QCD predictions including leptonic decays: differential distributions of decay products $\rightarrow$ overcome penalties of extrapolation