State-of-the-art precision calculations for top quark production and decay

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in collaboration with
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based on arxiv:1901.05407 [Behring,Czakon,Mitov,Papanastasiou,RP '19]

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Introduction: Top-quark production at the LHC

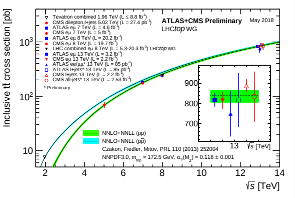
- Heaviest known particle $\rightarrow$ special place in the SM
- Many connections to other fields: Higgs, BSM, EW precision
- Many opportunities to study QCD/SM in high precision
- Abundantly produced at the LHC
  $\rightarrow$ top-quark factory
  $\rightarrow$ high quality and precision data
- High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

State-of-the-art: Total and differential $t\bar{t}$ cross sections

Total cross section

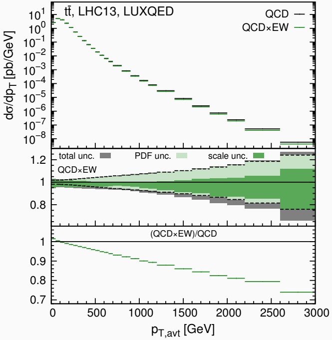
- NNLO QCD + NNLL soft gluon resummation
- Uncertainties of a few percent
- Remarkable agreement with measurements at 7, 8 and 13 TeV

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



Differential

- Reduction of scale dependence → dynamical scales
- NLO EW corrections
- NNLL' resummation for differential observables (threshold-, small-mass-logs)



Combination with NNLL' resummation → most complete SM description available

Elephant in the room:

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

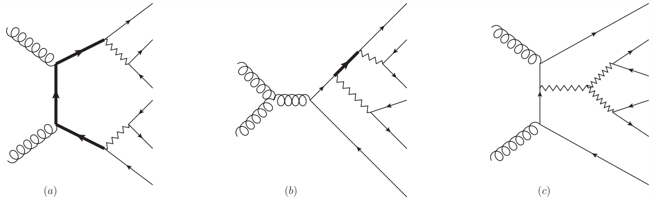
- Decay products are measured in fiducial phase space $\rightarrow$ all previous results rely on the extrapolation of the phase space
- The phase space extrapolation relies heavily on MC modeling of the top-quark production and its decay
- The modeling might have more or less subtle impacts on results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

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

Narrow-Width-Approximation

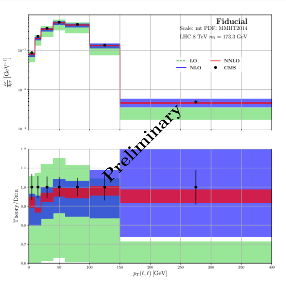
- Considering limit $\Gamma_t/m_t \to 0$
- Factorization of production and decay
- Reduction of complexity by keeping crucial features of decay like spin-correlations
- Expected error of $\mathcal{O}(\Gamma_t/m_t)$

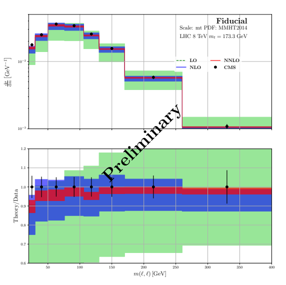


Production and decay: Production and decay in NWA @ NNLO QCD

- 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
- Study of top-quark spin-correlation

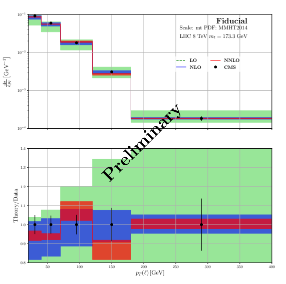
- comparison between CMS data [CMS,1505.04480] and NWA @ NNLO QCD
- good description of many distributions:
    - transverse momentum of ℓ and b-jets
    - rapidities of ℓ and b-jets
    - transverse momentum of lepton and b-jet pairs
    - invariant masses of lepton and b-jet pairs
- Work on 13 TeV update in progress

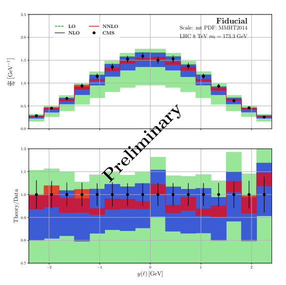




Production and decay: fiducial cross sections at 8 TeV

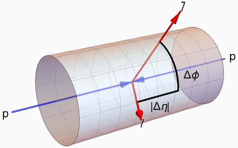
- comparison between CMS data [CMS,1505.04480] and NWA @ NNLO QCD
- good description of many distributions:
    - transverse momentum of ℓ and b-jets
    - rapidities of ℓ and b-jets
    - transverse momentum of lepton and b-jet pairs
    - invariant masses of lepton and b-jet pairs
- Work on 13 TeV update in progress

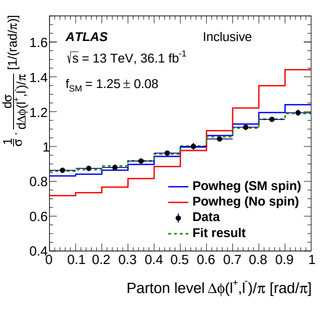




Production and decay: Spin-correlation @ NNLO QCD

- 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. For example the opening angles of the leptons: $\Delta\Phi_{\ell\ell}$ and $|\Delta\eta_{\ell\ell}|$
- Boosted top favor antiparallel leptons
- Spin correlation counter acts
- Effect of higher corrections?

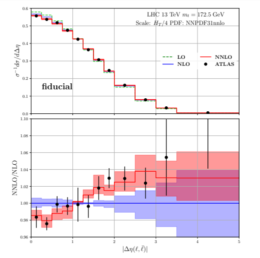


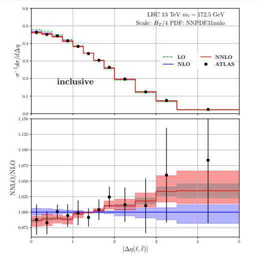


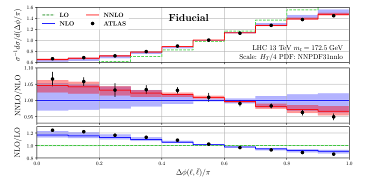
Production and decay: Spin-correlation @ NNLO QCD

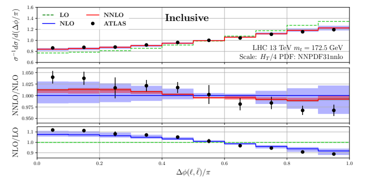
Fiducial phase space

Inclusive phase space







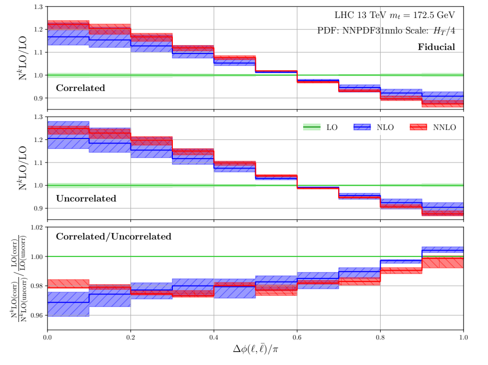


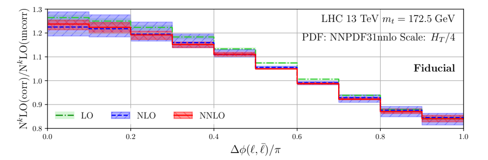
arxiv:1901.05407 [Behring,Czakon,Mitov,Papanastasiou,RP '19]

Extrapolation effects?

Production and decay: Spin-correlation - checks and anatomy

- Radiation effects vs. spin correlation
- Scale dependence
- Parameteric 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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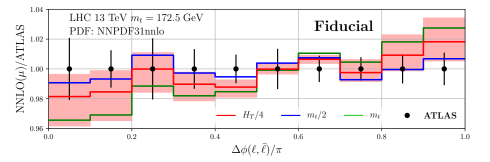
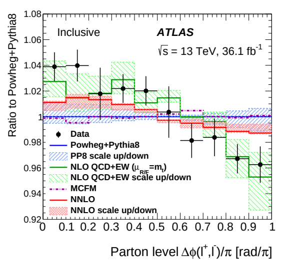


Production and decay: Spin-correlation @ NNLO QCD

- → extrapolation effect?
- [arXiv:1903.07570 ATLAS '19]
  Published results:



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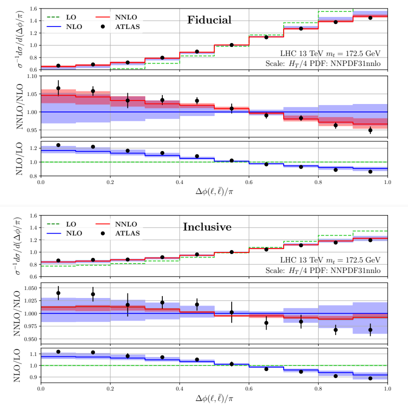


Summary & Outlook

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

Backup

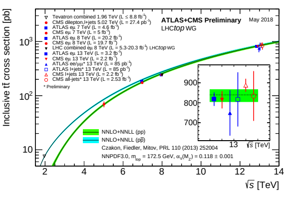
Total cross section

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

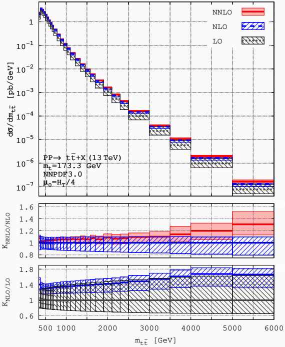
Differential

- 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]



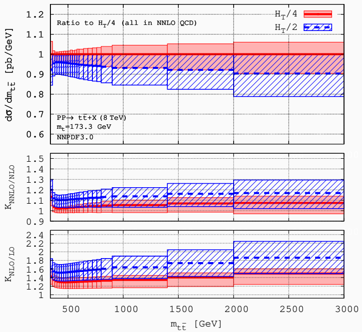
arxiv:1606.03350 [Czakon,Heymes,Mitov '16]

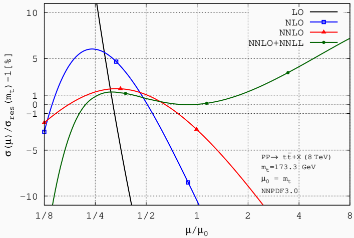


State-of-the-art: Renormalization and Factorization scale dependence

- 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)

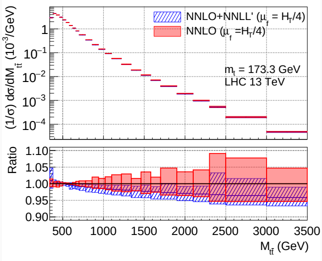
arxiv:1606.03350 [Czakon,Heymes,Mitov '16]

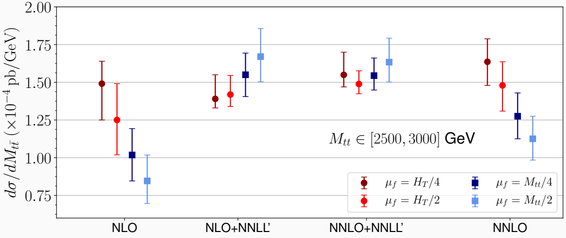




State-of-the-art: Resummation for differential observables

- 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





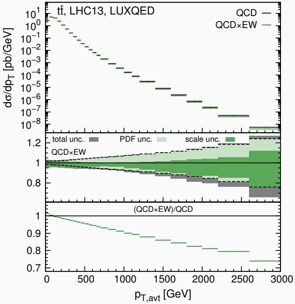
arxiv:1803.07623 [Czakon,Ferroglia,Heymes,Mitov,Pecjak,Scott,Wang,Yang '18]

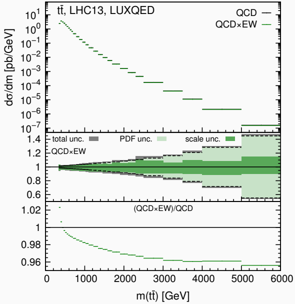
State-of-the-art: NLO-EW corrections

- Studied in additive and multiplicative approach
- 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

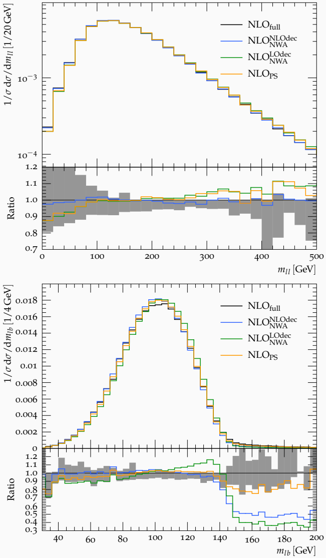
Combination with NNLL' resummation → most complete SM description available

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

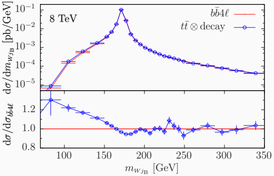


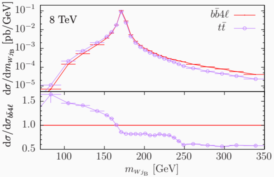


- NLO corrections to full $pp \to \ell^+\ell^-\nu\bar{\nu}b\bar{b} + X$
  [5FS: Bevilacqua et al, Denner et al, Heinrich et al, 4FS: Frederix, Cascioli et al]
- Off-shell & non-resonant effects depend strongly on observable
- $\to$ NWA approximation valid for many observables
- Higher order corrections 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