NNLO QCD top quark pair production and decay

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Top-quark pair production at the LHC

Experiment

- Outstanding performance of LHC
- CMS and ATLAS provide %-level measurements of differential observables for $t\bar{t}$-production
- potential for precise parameter extraction and Standard model consistency checks

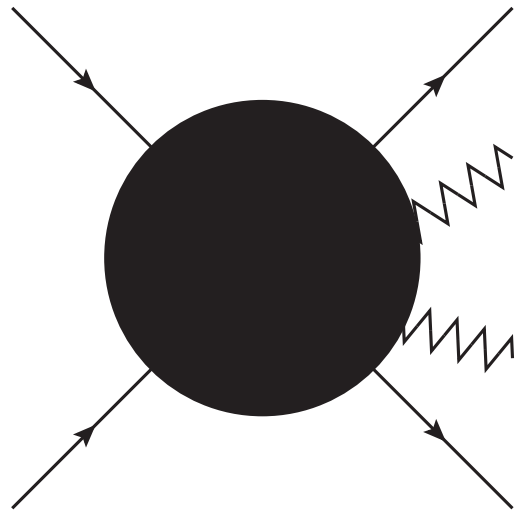
Theory of stable top-quarks

- fully differential NNLO QCD (+ NLO EW) for stable top-quarks [Czakon et at, 13-present]
- comparison with data lead to applications: m_t measurement, PDF fits,...
- extrapolation needed

Modelling realistic final states

Top quarks are not stable

- Short lifetime $\rightarrow$ decays before hadronization
- Weak decays sensitive to top-polarization
- measurable spin correlation effects in differential distributions of decay products and fiducial cross sections



Closer to measured objects: charged leptons, b-jets and missing energy

State of the art theory

Accurate modelling includes decays!

Next-to-leading order

- Narrow-Width-Approximation (NWA) [Berneuther et al; Melnikov, Schulze; Campbell,Ellis]
- Offshell [Bevilaqua et al; Denner et al; Falgari et al; Heinrich et al; Frederix et al]
- NWA + Parton Shower [Campbell,Ellis; Nason,Re]
- Offshell + PS [Jezo, Nason et al; Frederix et al]

Next-to-next-to-leading order

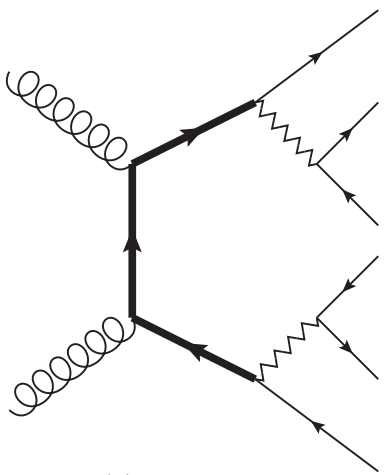
- NWA with approximate $\hat{\text{NNLO}}$ [Gao,Papanastasiou]

NEW:

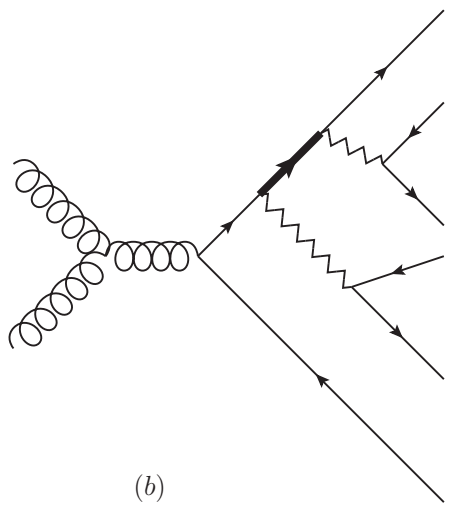
NWA with full NNLO corrections to production and decay!

Recap: Narrow-Width-Approximation

- Short life time $\Leftrightarrow$ small Γ_t
- Cross section factorizes in $\Gamma_t \to 0$ limit into production and decay
  $\Rightarrow$ separation of higher-order corrections
- To keep spin information: polarized amplitudes required!



(a)



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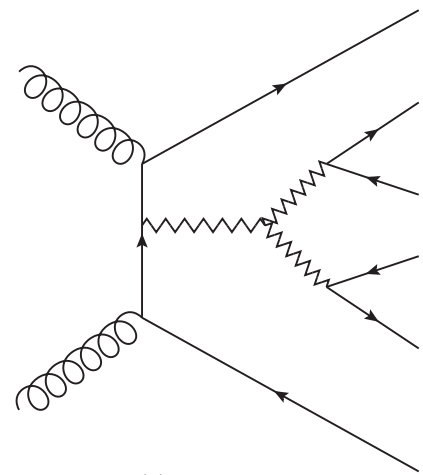
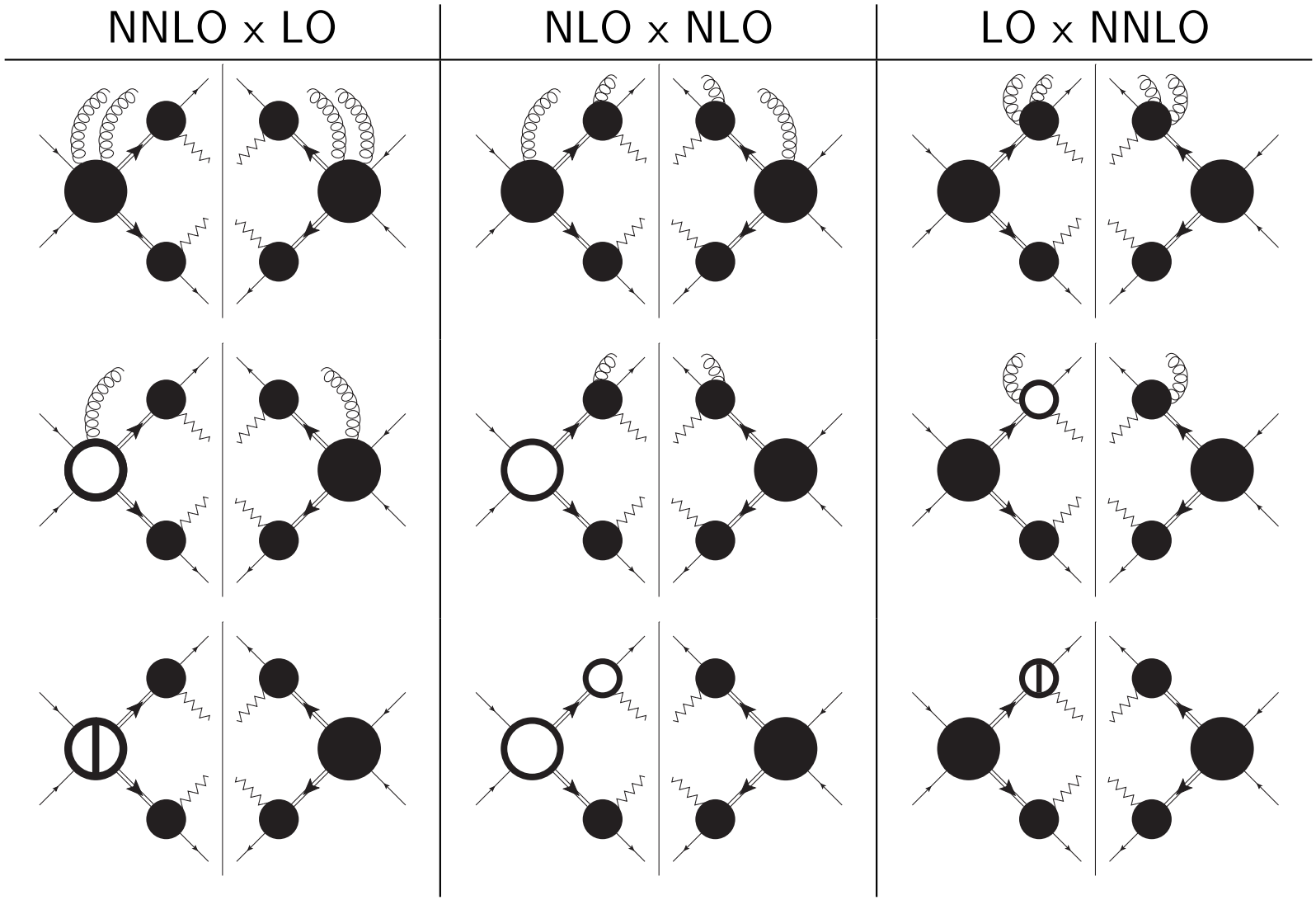


(c)

NWA @ NNLO - Ingredients I



NWA @ NNLO - Ingredients II

Framework

- Implementation of all required amplitudes in updated STRIPPER framework:
  - new phase space parameterization
  - implementation of NWA for selected processes
- Fully differential MC at NNLO
- Arbitrary IR-safe observables
- Efficient scale and PDF variation

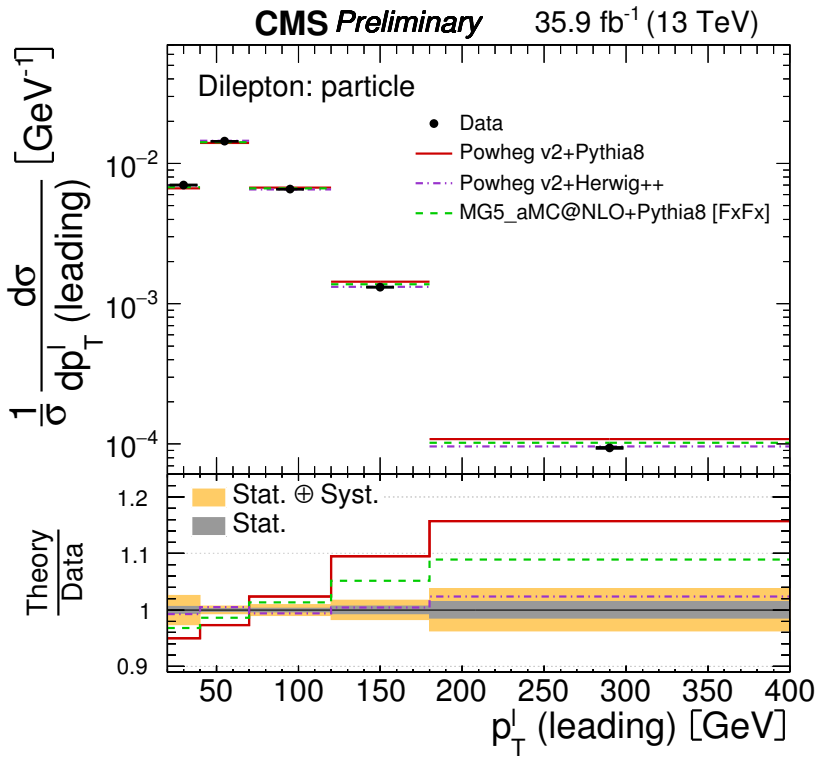
Γ_t treatment

- consistent expansion of $1/\Gamma_t$ factors in α_S
- Preservation of branching ratios in inclusive production $\sigma^{\text{NWA}}_{\text{NNLO}} = \sigma^{t\bar{t}}_{\text{NNLO}} \cdot \text{BR}(W \to \dots)$

Application: Differential measurements @LHC13

New differential top-quark measurements at 13 TeV

- %-level bin-wise uncertainties
- differential distributions:
  - decay products
  - reconstructed t-quarks
- Observables sensitive to spin-correlation



CMS: TOP-17-014

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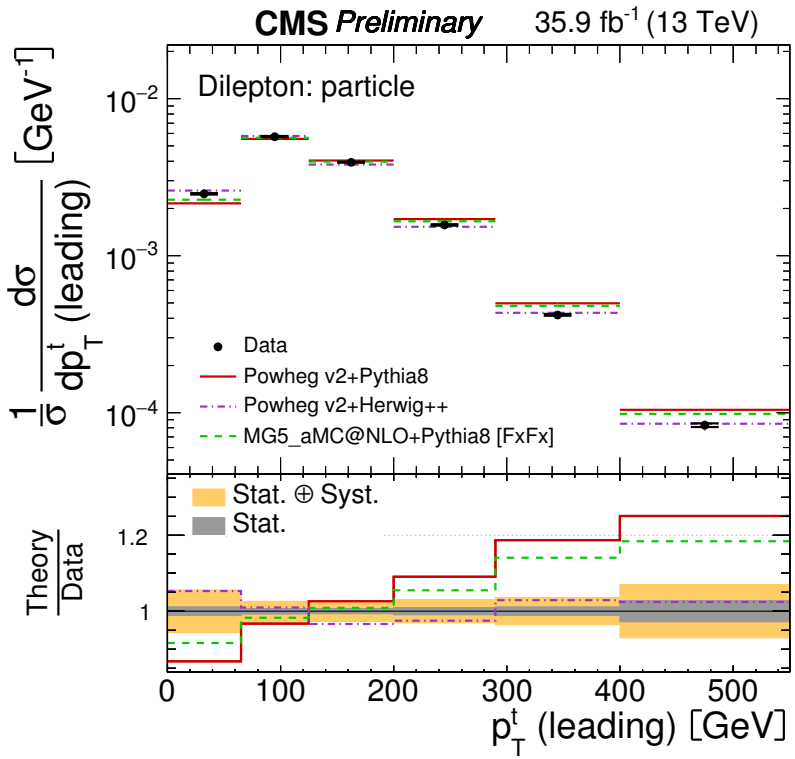


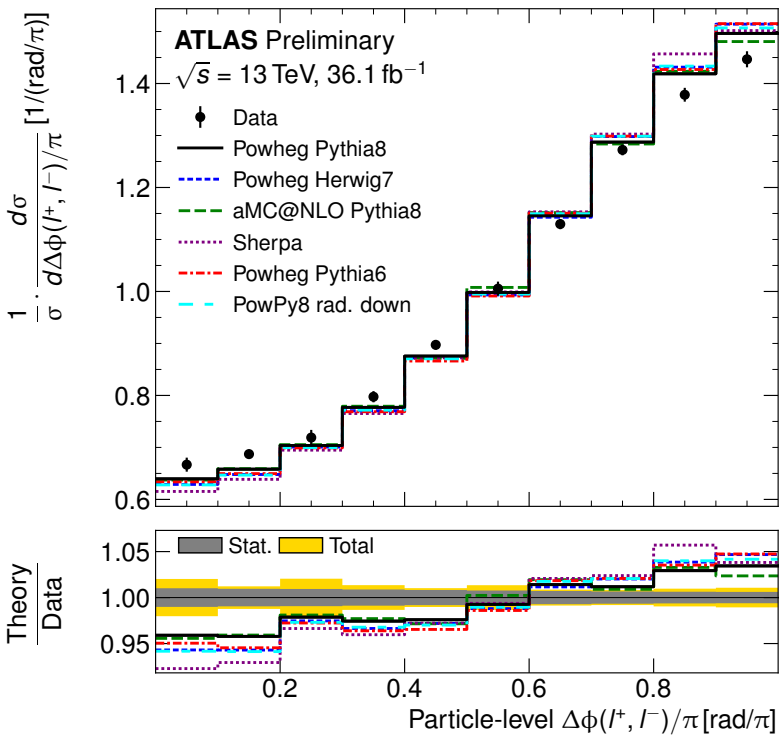
CMS: TOP-17-014

Example: Spin Correlation in $\Delta\phi(l, \bar{l})$

- Fiducial region ATLAS-CONF-2018-027:
  - 2 b-jets with $p_T > 30$ GeV, $|\eta| > 2.4$
  - 2 opposite sign leptons with 25 (20) GeV, $|\eta| > 2.4$
  - $m_{l\bar{l}} > 20$ GeV
- 'reconstructed' tops: currently truth MC information ($b/\bar{b}$-jets,charged lepton and neutrino momenta)
  $\rightarrow$ more realistic reconstruction planed
- dynamical scale settings. Here: $H_T/2$ with: $H_T = \sum_{i \in \{t,\bar{t}\}} \sqrt{m_t^2 + p_i^2}$

Example: Spin Correlation in $\Delta\phi(l, \bar{l})$ - inclusive

ATLAS-CONF-2018-027



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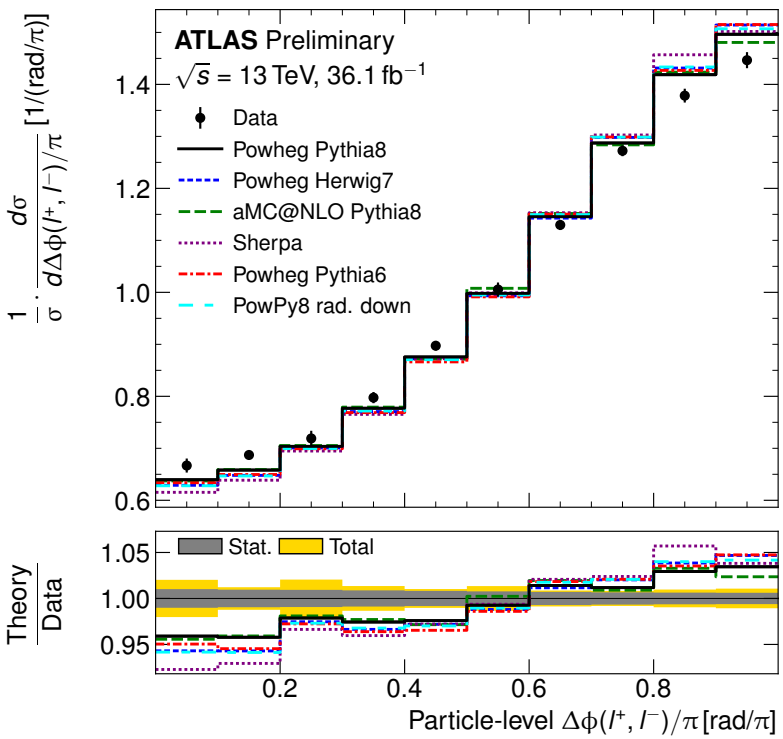
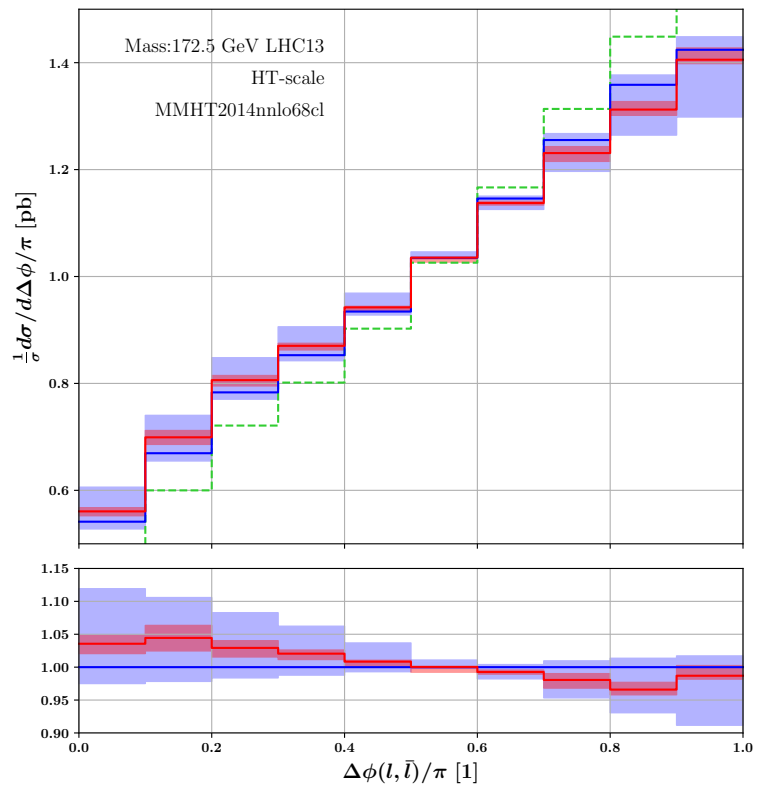


NWA @ NNLO predictions



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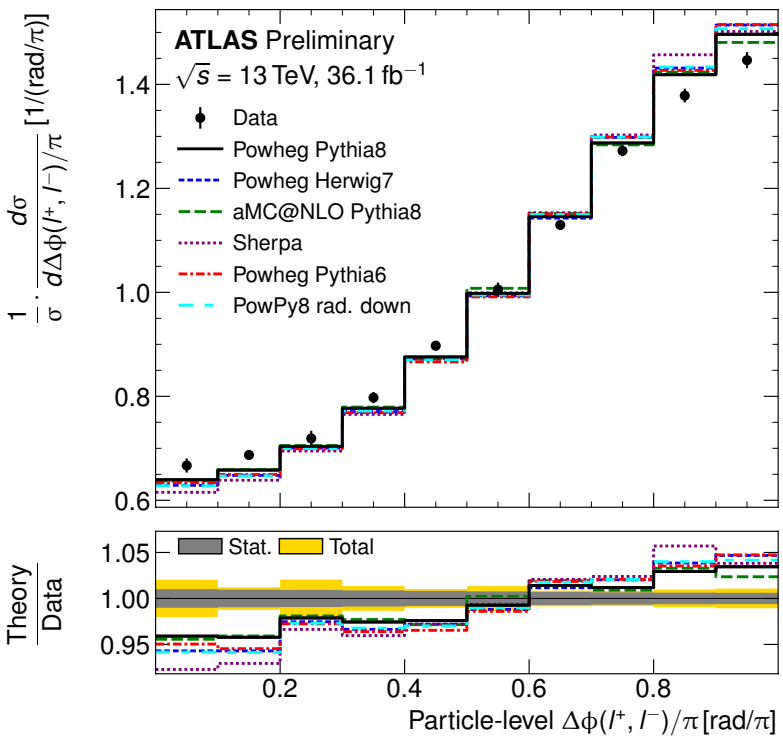

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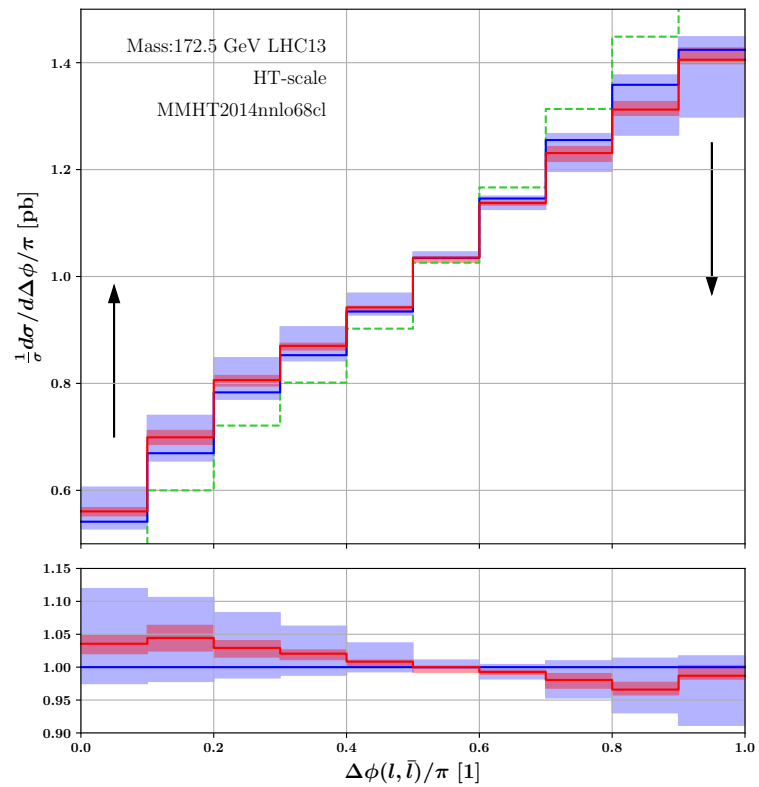
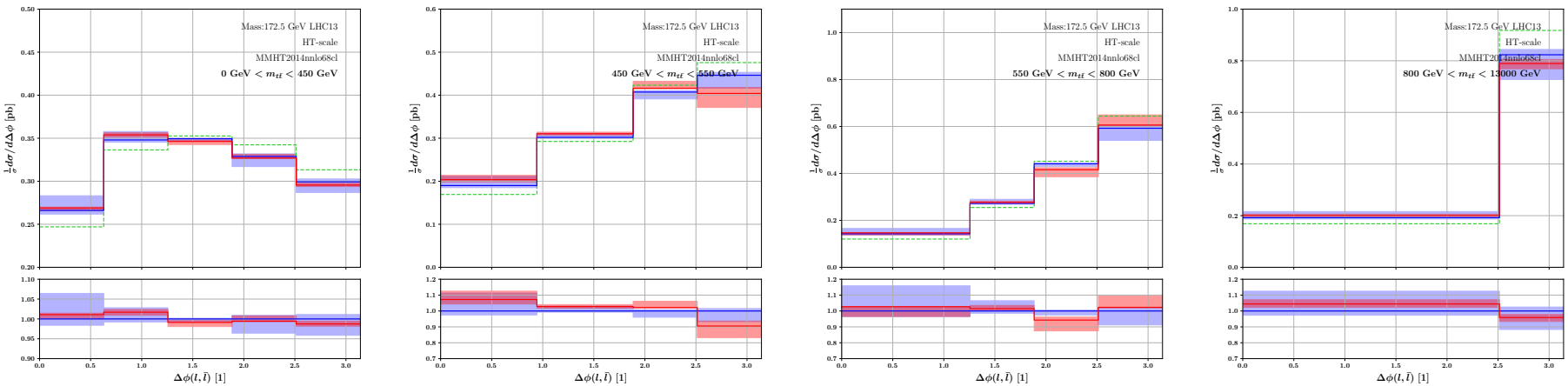


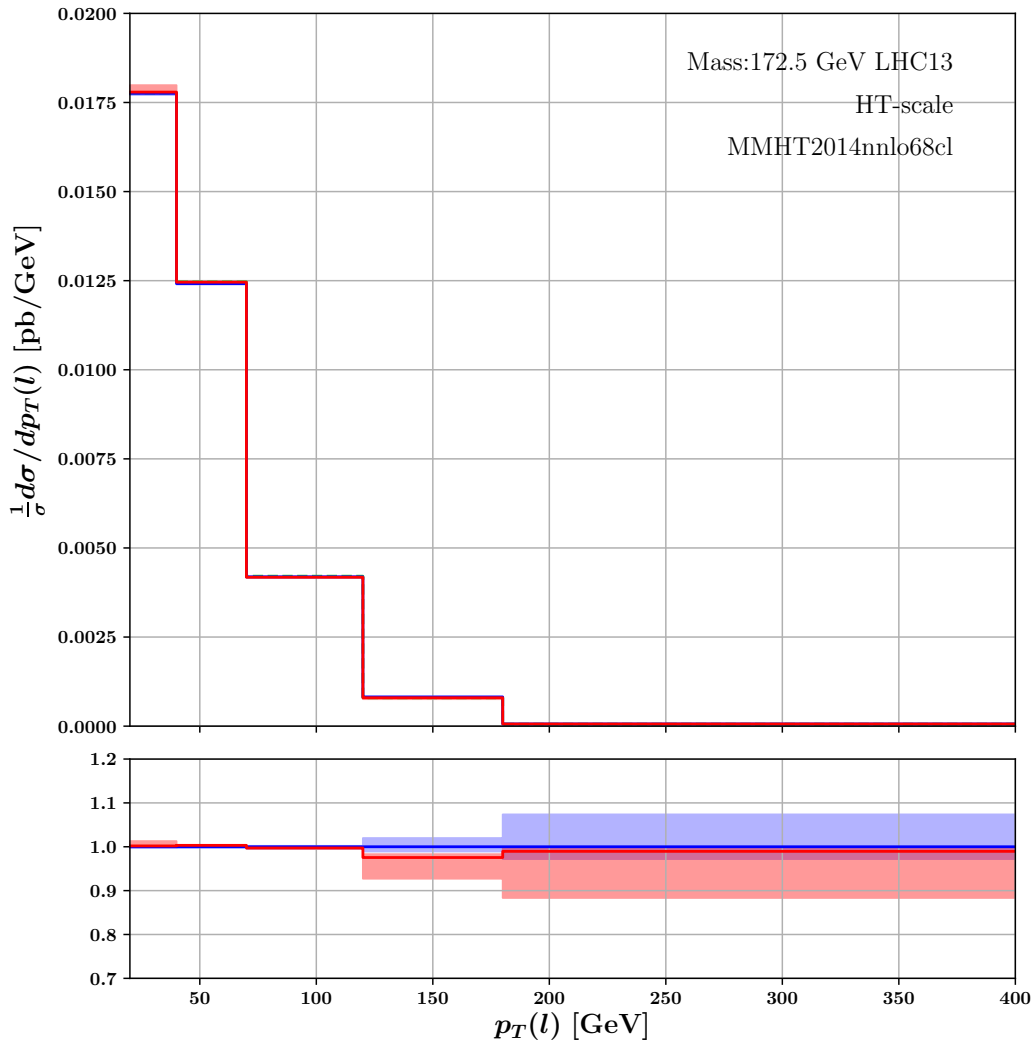
Predictions for differential distributions @ NNLO QCD

endless possibilities: double differential



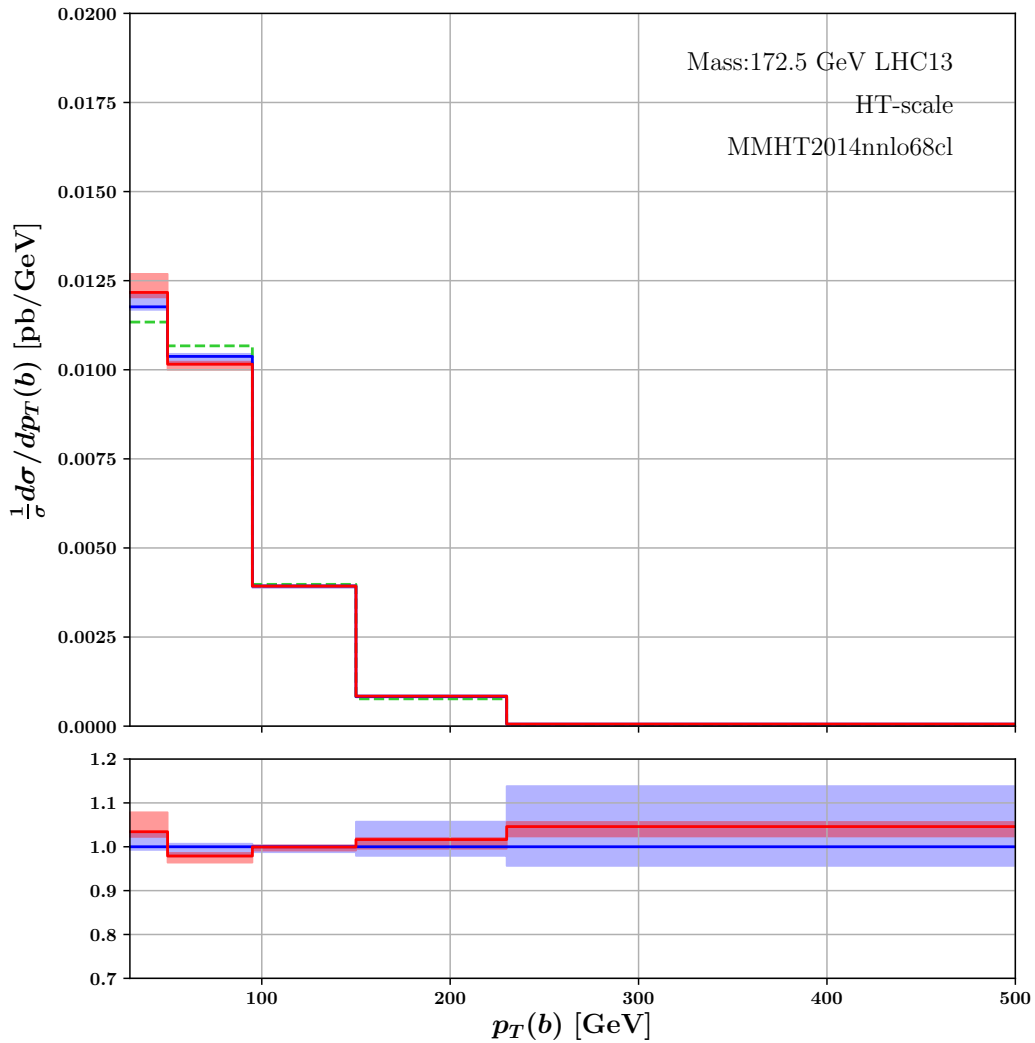
Predictions for differential distributions @ NNLO QCD

endless possibilities: p_T of lepton.



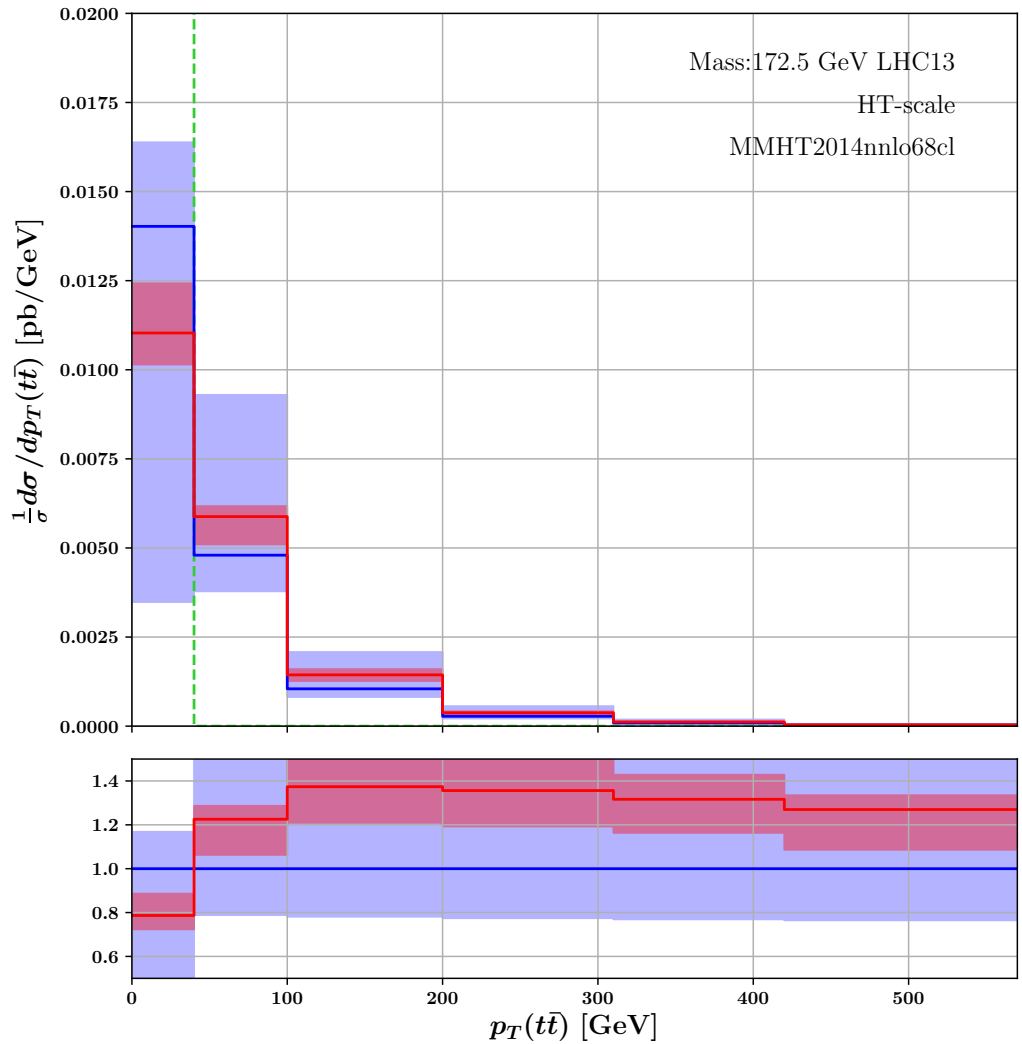
Predictions for differential distributions @ NNLO QCD

endless possibilities: p_T of leading b-jet.



Predictions for differential distributions @ NNLO QCD

endless possibilities: p_T of $t\bar{t}$ pair.



Conclusions and outlook

Summary

- fully differential $t\bar{t}$ production including decays @ NNLO within the NWA
- consistent treatment of corrections to production and decay
- NNLO corrections significantly modify shapes of differential distributions!
  $\rightarrow$ resolving $\Delta\Phi(l, \bar{l})$ discrepancy?!
- Improved scale dependence
- fiducial cross sections

Outlook

- m_t dependence of differential distributions
  $\rightarrow$ m_t extraction from σ_{fiducial}
- reconstruction effects?
- scale setting?