Precision comparisons between theory and data in ttbar production at the LHC

Rene Poncelet

LEVERHULME TRUST

UNIVERSITY OF CAMBRIDGE

Isaac Newton Trust

erc
European Research Council
Established by the European Commission

Top-quark pairs at hadron colliders

Theory - Data comparisons in top-pair production have a long history

- Inclusive cross-sections
- Differential distributions
- Asymmetries
- Parameter extractions: PDF fits, top-quark mass measurements, alphaS,...
- ...

Most of these comparisons have been made for parton-level top-quarks:

✚ More “fundamental” properties
→ independent of acceptances and other experimental details

✚ Higher theory accuracy available

– Phase space extrapolation → MC model dependencies

But theory advances → better predictions for fiducial phase spaces

→ We can compare theory to data closer to what we measure

Theory advancements for di-lepton ttbar

NLO QCD/EW full off-shell:

NLO QCD corrections to WWbb production at hadron colliders
Denner, Dittmaier, Kallweit, Pozzorini, 1012.3975

Complete off-shell effects in top quark pair hadroproduction with leptonic decay at next-to-leading order
Bevilacqua, Czakon, van Hameren, Papadopoulos, Worek, 1012.4230

NLO electroweak corrections to off-shell top-antitop production with leptonic decays at the LHC
Denner, Pellen, 1607.05571

NWA @ NNLO:

Higher order corrections to spin correlations in top quark pair production at the LHC
Behring, Czakon, Mitov, Papanastasiou, Poncelet, 1901.05407

NNLO QCD corrections to leptonic observables in top-quark pair production and decay Czakon, Mitov, Poncelet, 2008.11133

b-quark fragmentation:

B-hadron production in NNLO QCD: application to LHC ttbar events with leptonic decays,
Czakon, Generet, Mitov and Poncelet, 2102.08267

NNLO + PS:

Next-to-Next-to-Leading Order Event Generation for Top-Quark Pair Production
Mazzitelli, Monni, Nason, Re, Wiesemann, Zanderighi, 2012.14267

Top-pair production at the LHC with MiNNLO_PS,
Mazzitelli, Monni, Nason, Re, Wiesemann and Zanderighi, 2112.12135

Technical advertisement slide

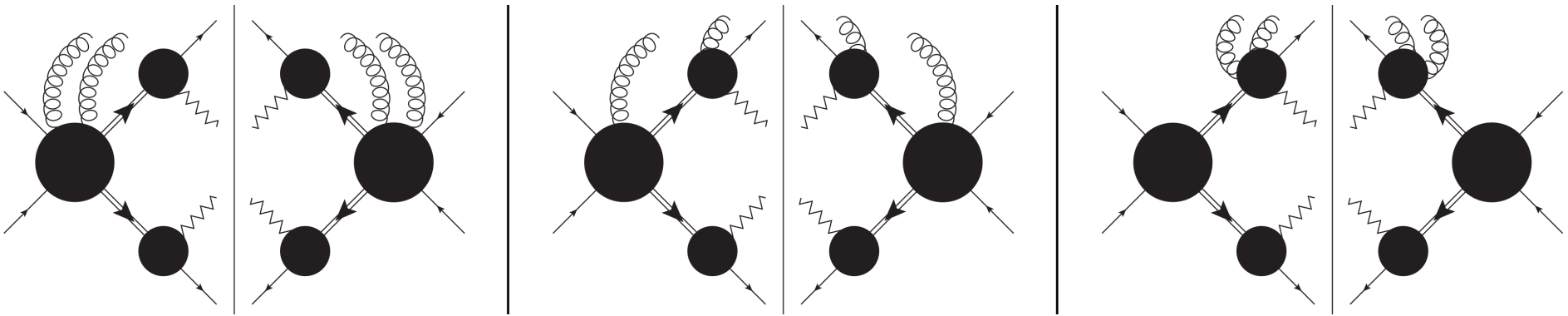
Calculations presented here have been performed with a in-house implementation of the sector-improved residue subtraction scheme.

A novel subtraction scheme for double-real radiation at NNLO Czakon, 1005.0274

Four-dimensional formulation of the sector-improved residue subtraction scheme Czakon, Heymes, 1408.2500

Single-jet inclusive rates with exact color at O(aS^4) Czakon, van Hameren, Mitov, Poncelet, 1907.12911

NNLO QCD Top-quark pair production in di-lepton channel with corrections to decays:



Details about Narrow-Width-Approximation & extensive study of experimental fiducial phase spaces and observables: **NNLO QCD corrections to leptonic observables in top-quark pair production and decay** Czakon, Mitov, Poncelet, 2008.11133

Theory-data comparison in fiducial phase spaces

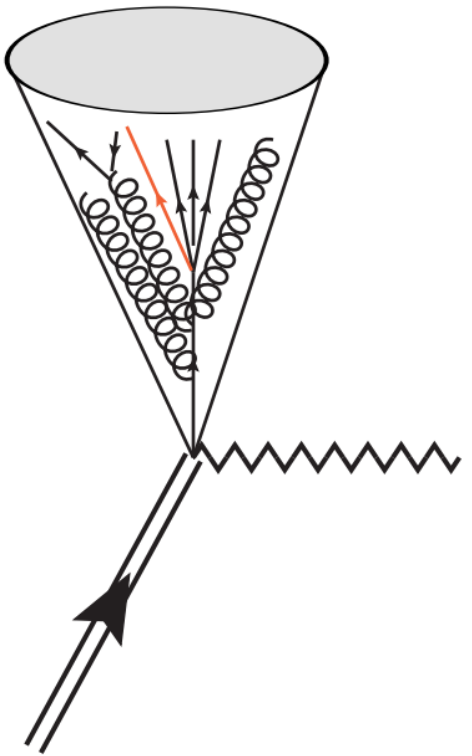
Top-quark pairs with fiducial cuts

A standard example for top-quark pair measurement:

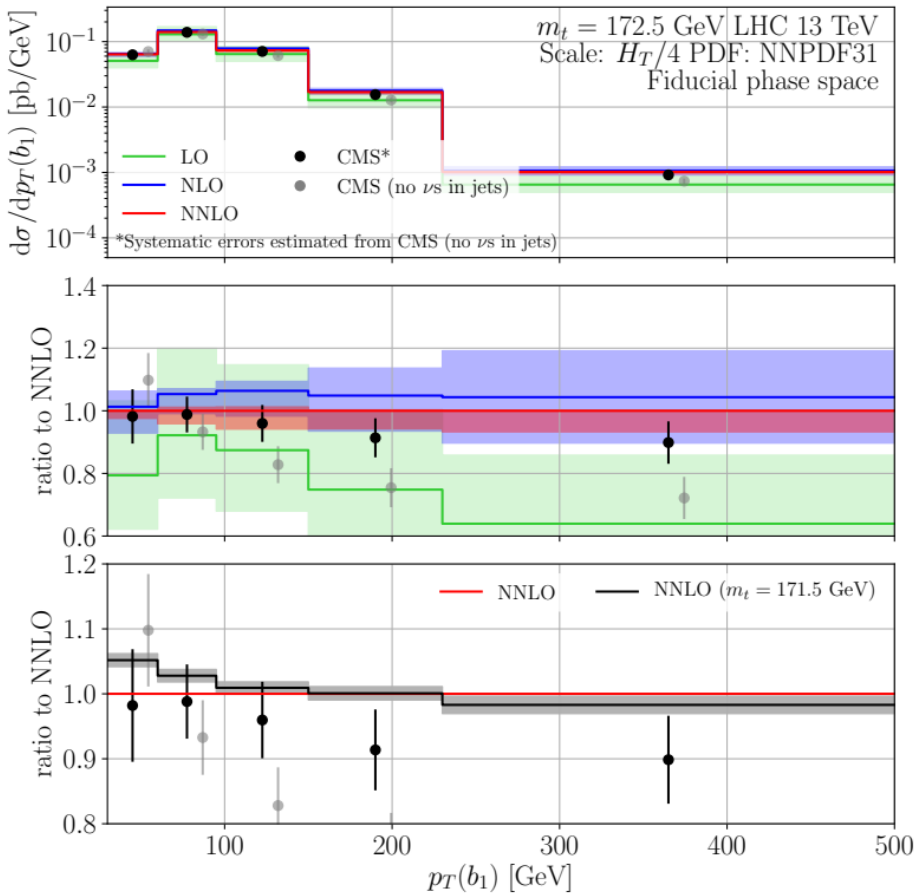
Measurements of ttbar differential cross sections in proton-proton collisions at \sqrt{s}= 13 TeV using events containing two leptons CMS, 1811.06625

- Fiducial cuts:
  - Leptons: pT(l) > 20 GeV & |y(l)| < 2.4 & m(ll) > 20 GeV
  - At least 2 jets: R = 0.4 anti-kT with pT > 30 GeV & |y| < 2.4
  - 2 b-tags
- Appealing: Possibility to reconstruct top-quarks without much extrapolation
- But sensitive to jet-modelling:
  - Full MC: parton-shower+hadronization+decays
  - Fixed-order prediction: inclusive QCD jets, no EW decays, only partons.

  ➔Requires corresponding corrections!
  Example: Decays into neutrinos → loss of jet momentum



NWA@NNLO vs. CMS [1811.06625]



- Significant differences in normalization and shape between two jet definitions
- Excellent description of corrected data (black) ← Thanks to CMS!
- NNLO QCD shows small scale dependence and PDF errors (black band in lower panel)
- Top-quark mass dependence (lower panel) might be used to extract m_t parameter
- Many more plots and observables in:

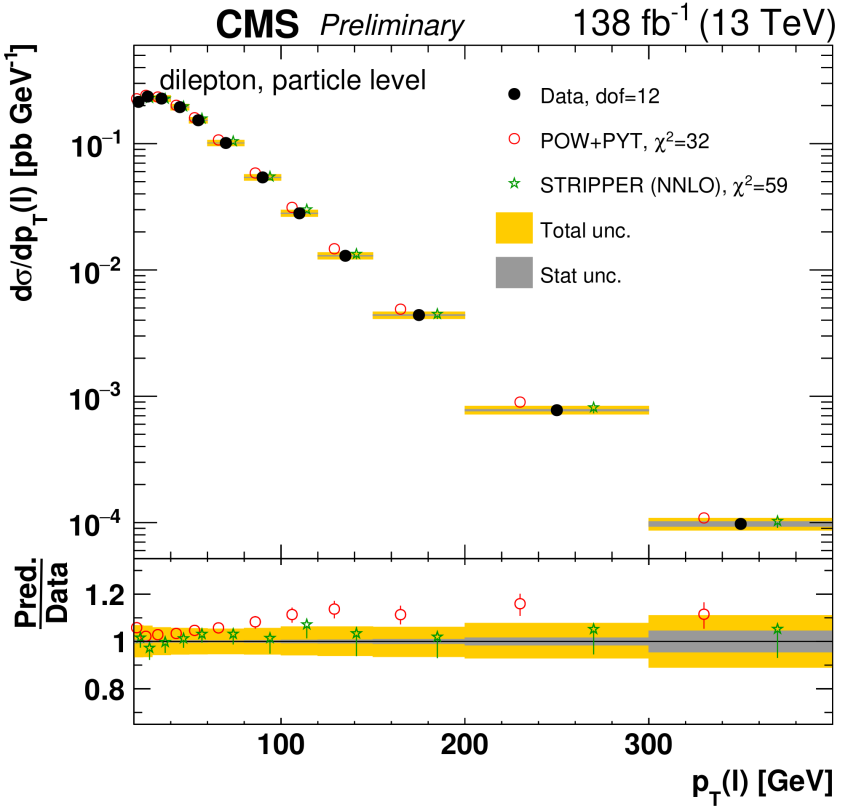
NNLO QCD corrections to leptonic observables in top-quark pair production and decay Czakon, Mitov, Poncelet, 2008.11133

Update:
NEW: CMS-PAS-TOP-20-006

CMS-PAS-TOP-20-006

- Same fiducial phase space as in 1811.06625
- Data compared to various predictions
  - Partonic top-quark observables: STRIPPER vs. MiNNLOPS vs. aN3LO
  - Leptonic and jet observables: Powheg+Pythia vs. STRIPPER(NNLO)
- In summary: very good description of data in fiducial volume.

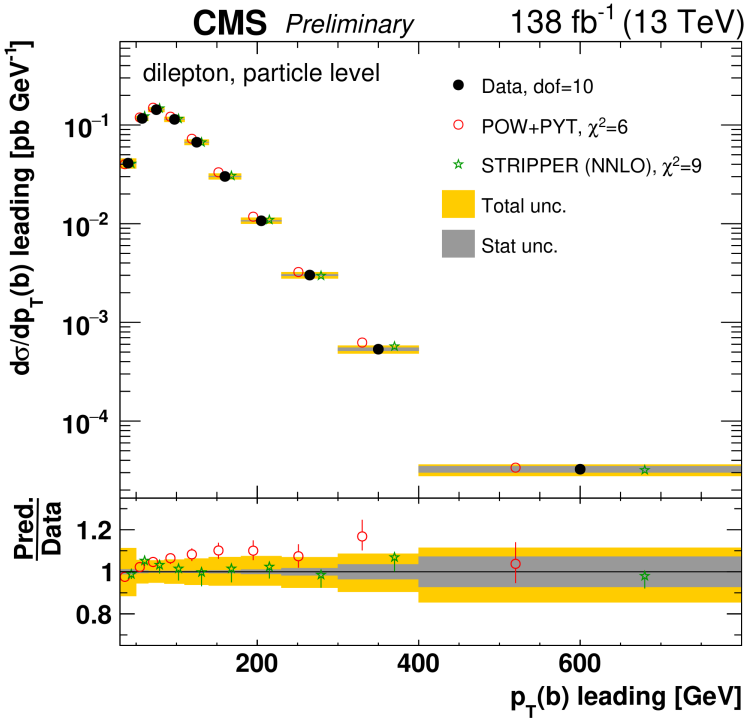
Lepton transverse momentum



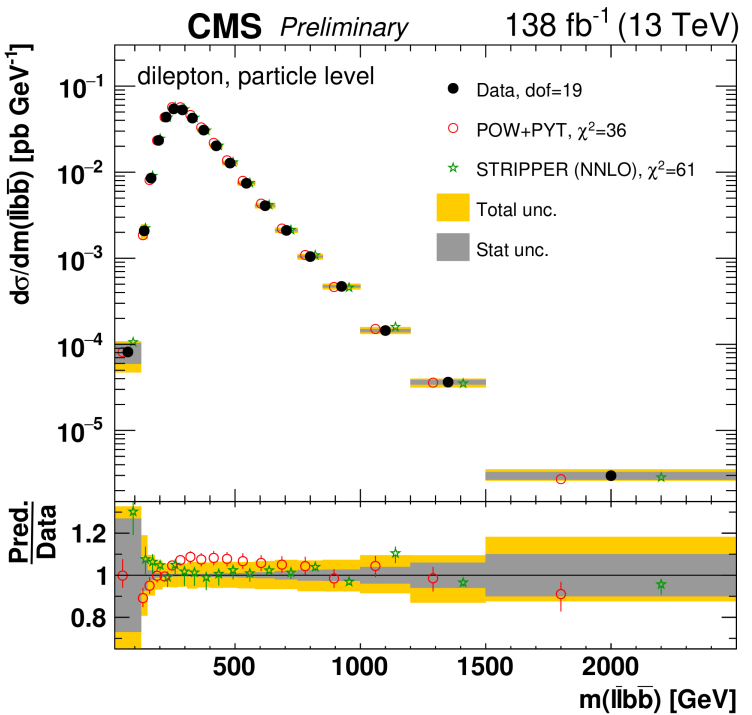
CMS-PAS-TOP-20-006: jet-observables

- Good normalization
- Good shape → looks sometimes even better then POW+PYT

Leading b-jet transverse momentum

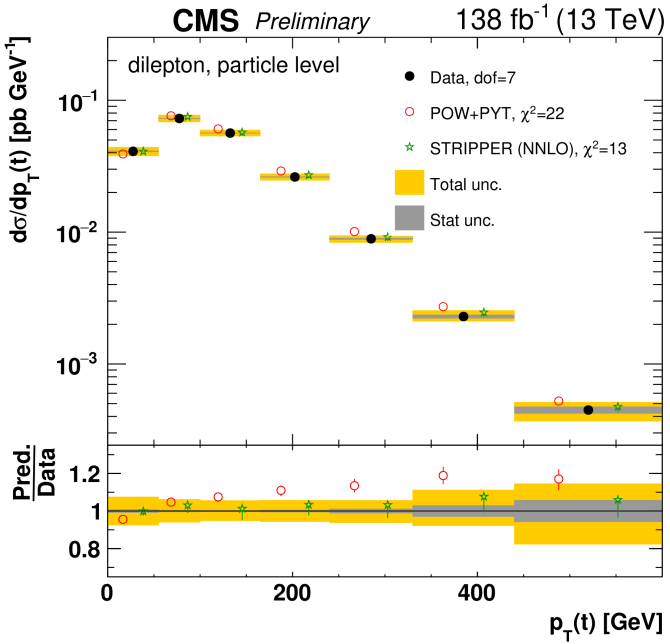


Invariant mass of lepton-pair + b-jet pair

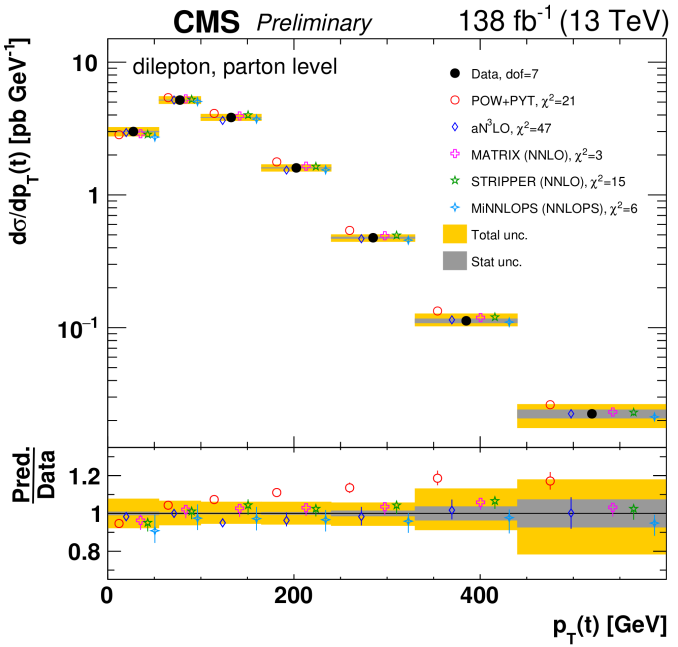


CMS-PAS-TOP-20-006: top-quarks

Reconstructed top-quark pT
with applied fiducial cuts



Extrapolated top-quark pT



Clearly improved description through NNLO QCD corrections → translates to the extrapolation

Reason: NNLO K-factors are similar for fiducial & inclusive spectrum in this case

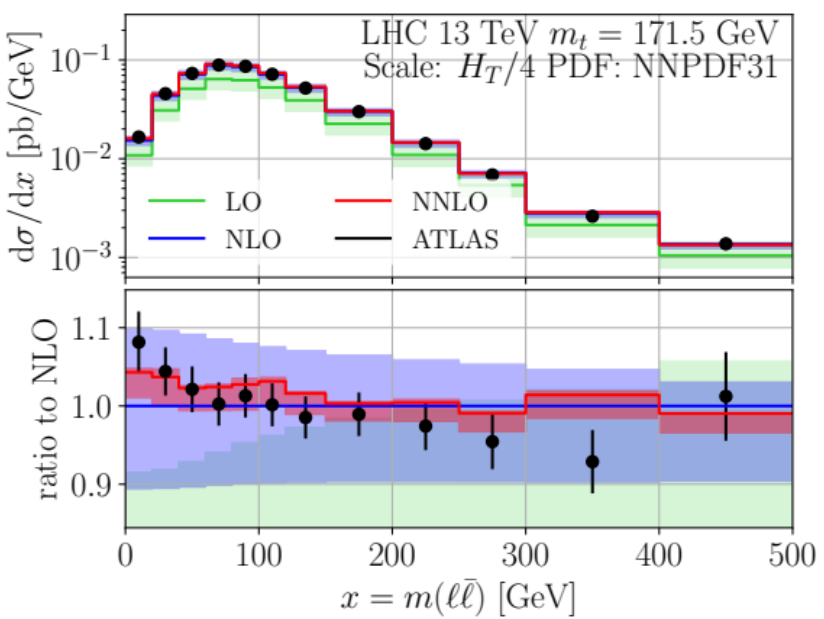
But what happens if not?

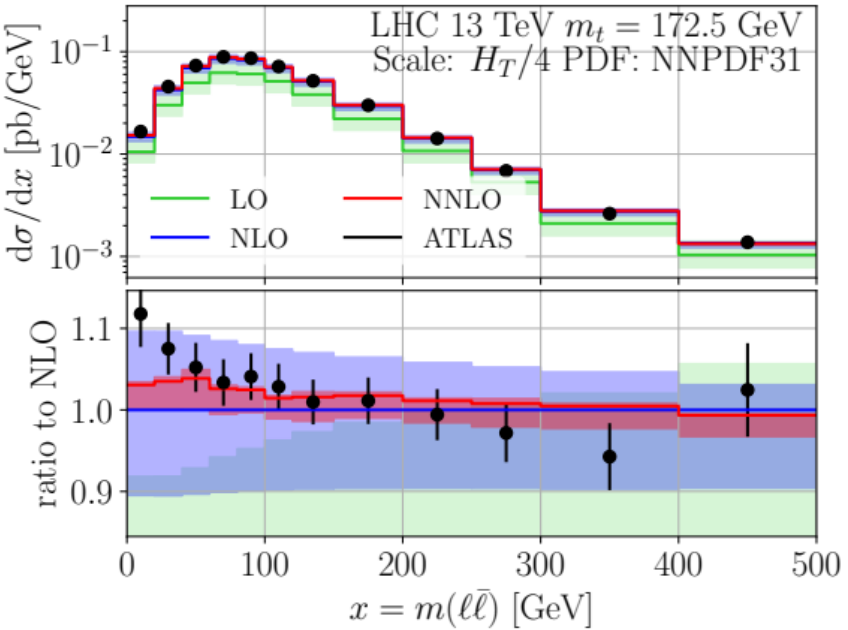
Top-quark mass from leptonic distributions

Mass sensitivity of leptonic observables I

Idea extract the top-quark mass parameter from differential distribution of decay products.
Theoretically "clean" measurement of the top-quark mass
→ requires higher order predictions to reduce overwhelming scale dependence.

Example: lepton-pair invariant mass compared to ATLAS data





Mass sensitivity of leptonic observables II

Fully fiducial phase space:

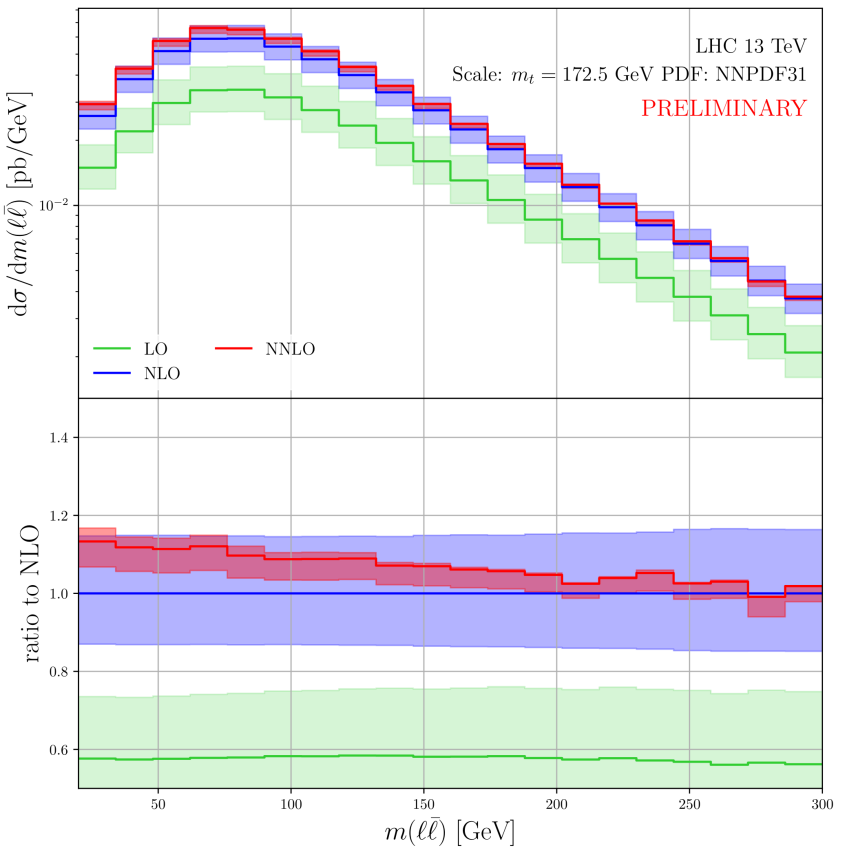
- pT(lep1) > 25, pT(lep2) > 20
- |y(lep)| < 2.4
- 2 R=0.4 anti-kT jets with pT(jet)> 30 and |y(jet)| < 2.4
- 1 b-tag jet

Various differential observables:

- m(ll), pT(ll)
- E(l), E(l)+E(lbar)
- pT(l), pT(l)+pT(lbar)

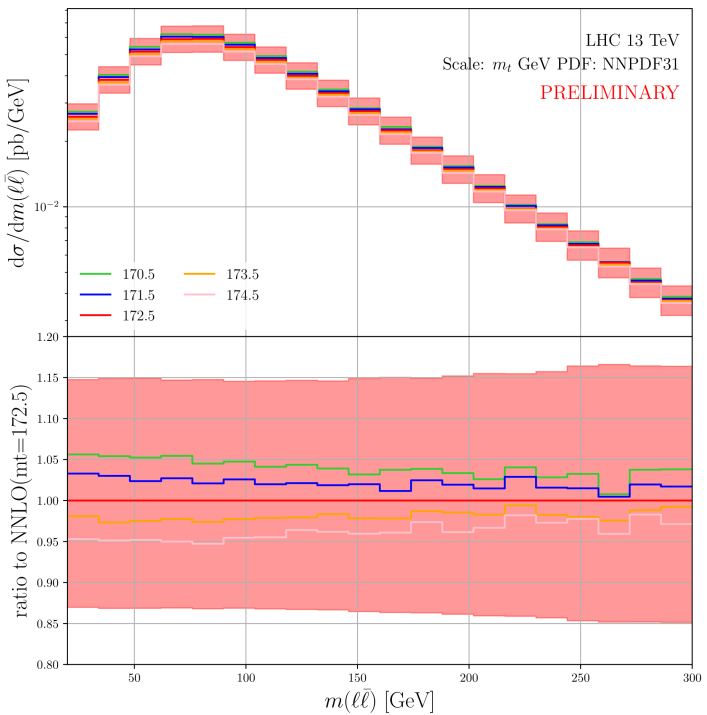
NNLO QCD corrections:

- Reduced scale uncertainty + shape differences

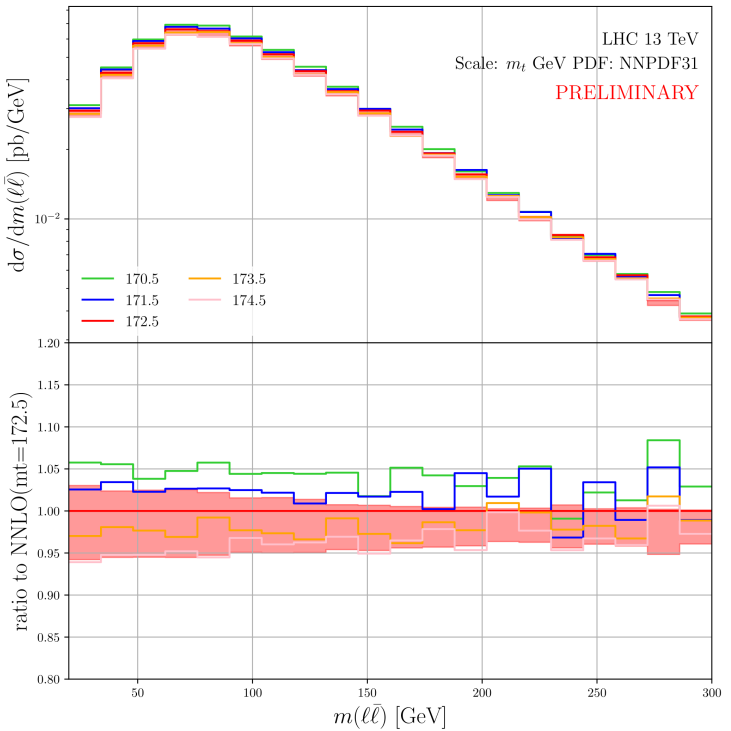


Mass sensitivity of leptonic observables III

NLO theory:
Scale uncertainty prohibitively large



NNLO theory:
Reduction of scale dependence by factor of 3-4
→ much better mass sensitivity

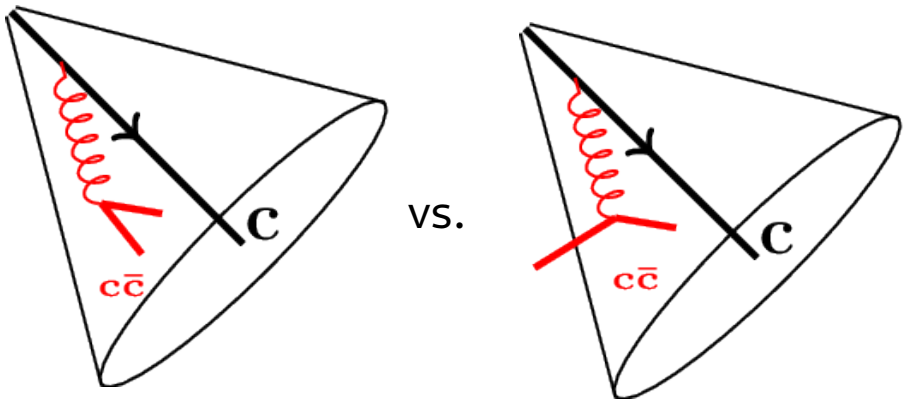


Flavour tagging

Flavour anti-kT

Well known problem in massless NNLO QCD:
A possible solution:
change the clustering
→ Flavour – KT algorithm

Infrared safe definition of jet flavor,
Banfi, Salam, Zanderighi, hep-ph/0601139



Anti-kT: $d_{ij} = \min(k_{T,i}^{-2}, k_{T,j}^{-2}) R_{ij}^2 \quad d_i = k_{T,i}^{-2}$

Proposed modification:

Infrared-safe flavoured anti-kT jets
Czakon, Mitov, Poncelet, 2205.11879

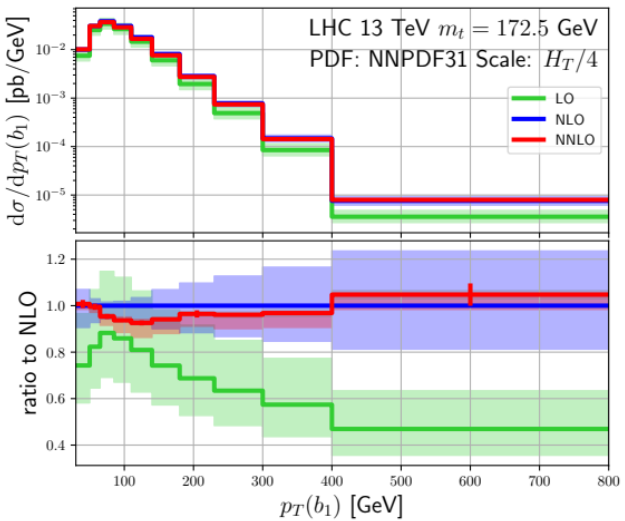
$$d_{i,j}^{(F)} = d_{i,j} \begin{cases} \mathcal{S}_{ij} & \text{i,j is flavoured pair} \\ 1 & \text{else} \end{cases}$$

$$\mathcal{S}_{ij} = 1 - \theta(1-x)\cos\left(\frac{\pi}{2}x\right) \quad \text{with} \quad x = \frac{k_{T,i}^2 + k_{T,j}^2}{2a k_{T,\max}^2}$$

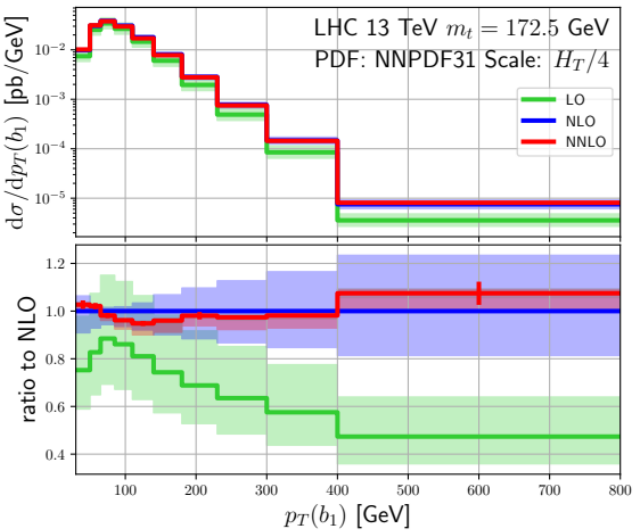
- Tests of IR safety
- Pheno @ NNLO:
  - Z+b-jet (including NLO+PS)
  - fiducial top-pairs

Flavour anti-kT for top-pairs: b-jets

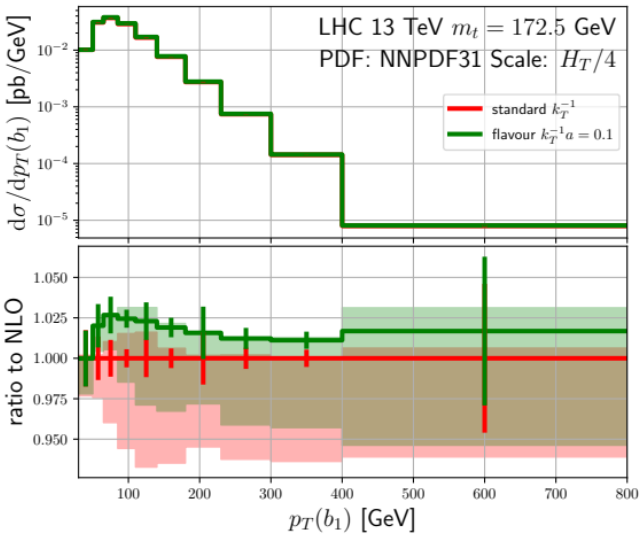
Anti-kT
(IR cutoff for $b\bar{b}b\bar{b}$ ch.)



Flavour Anti-kT



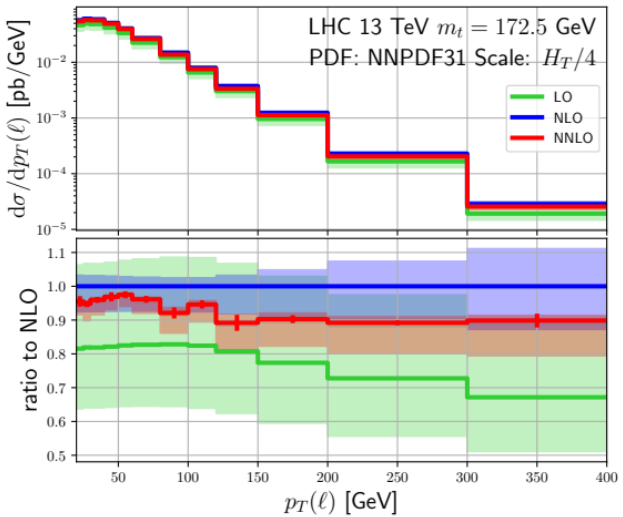
Ratio



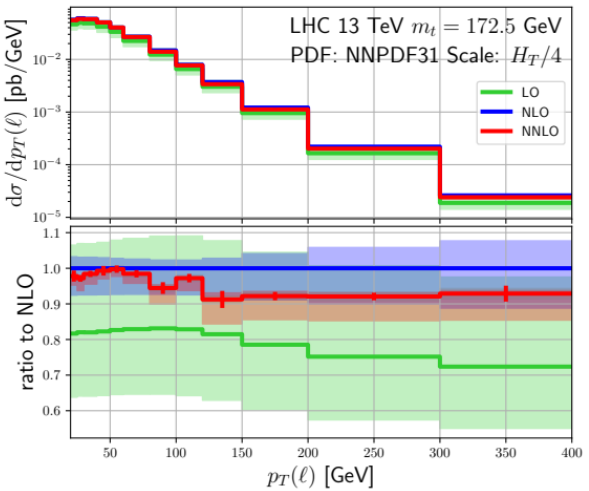
- Almost identical perturbative corrections for anti-kT and flavoured anti-kT
- Differences within NNLO scale dependence
  → small impact of IR problematic contributions in ttbar (NWA)

Flavour anti-kT for top-pairs: leptons

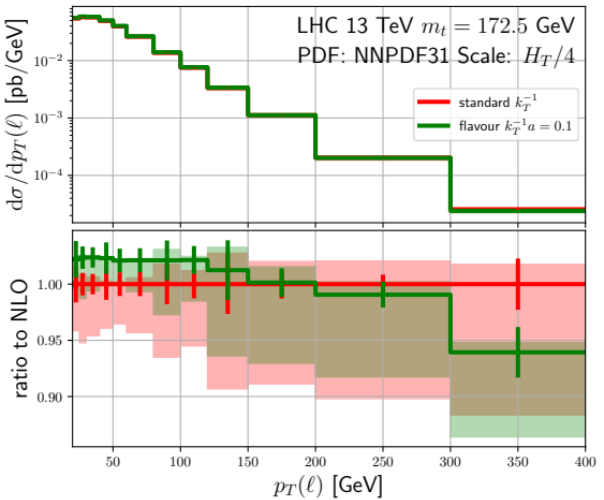
Anti-kT
(IR cutoff for $b\bar{b}b\bar{b}$ ch.)



Flavour Anti-kT



Ratio



- Almost identical perturbative corrections for anti-kT and flavoured anti-kT
- Differences within NNLO scale dependence
  → small impact of IR problematic contributions in ttbar (NWA)

Towards NWA@NNLO + NLO off-shell combinations

NWA + offshell combinations I

Message from NLO QCD/EW off-shell computations:

- Certain regions of phase space are sensitive to off-shell effects → NWA bad approximation
- A full NNLO QCD off-shell computation is not yet feasible

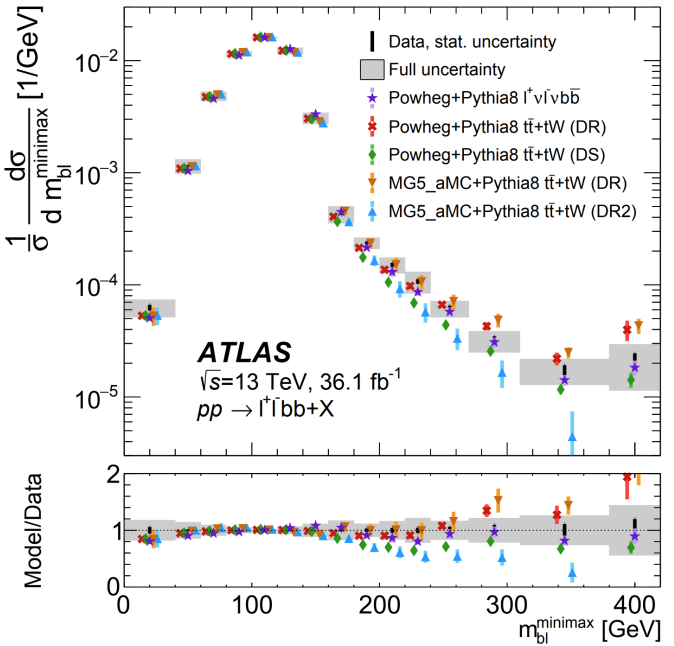
NWA @ NNLO QCD + NLO QCD/EW off-shell:

- A smooth transition between NLO off-shell and NNLO on-shell regions
- Goal: best prediction for a di-leptonic final states:

Can we compare this to data?

- Top-pair analyses subtract tW (single top) as background
- Non-resonant contribution typically small.

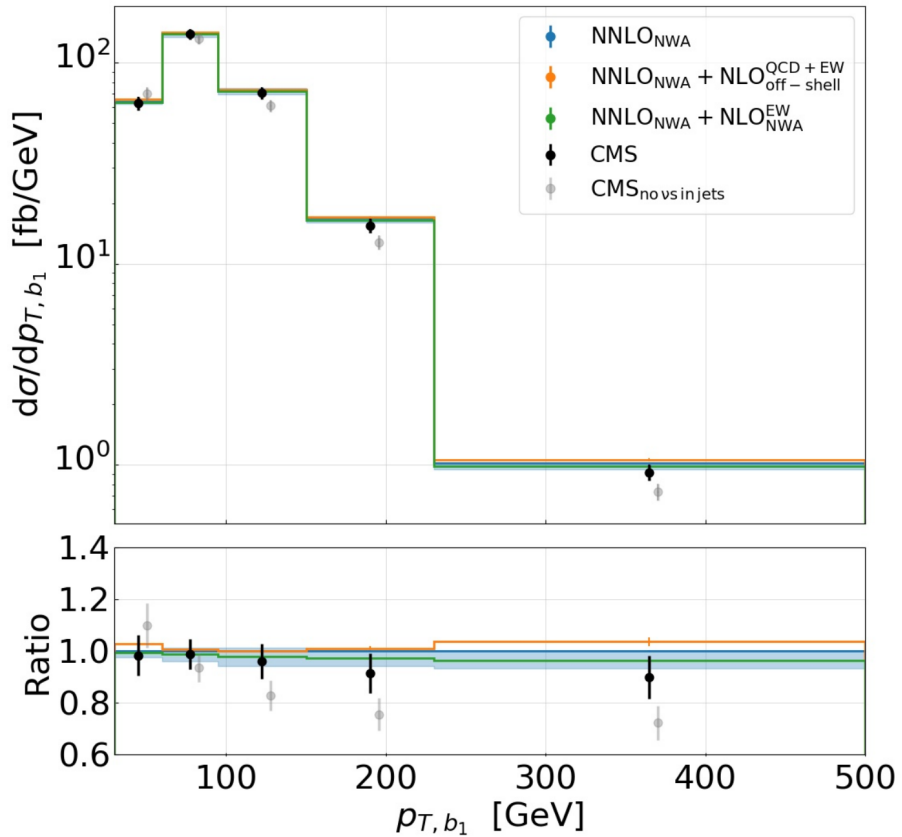
  → A combined tt + tW analysis would be required.

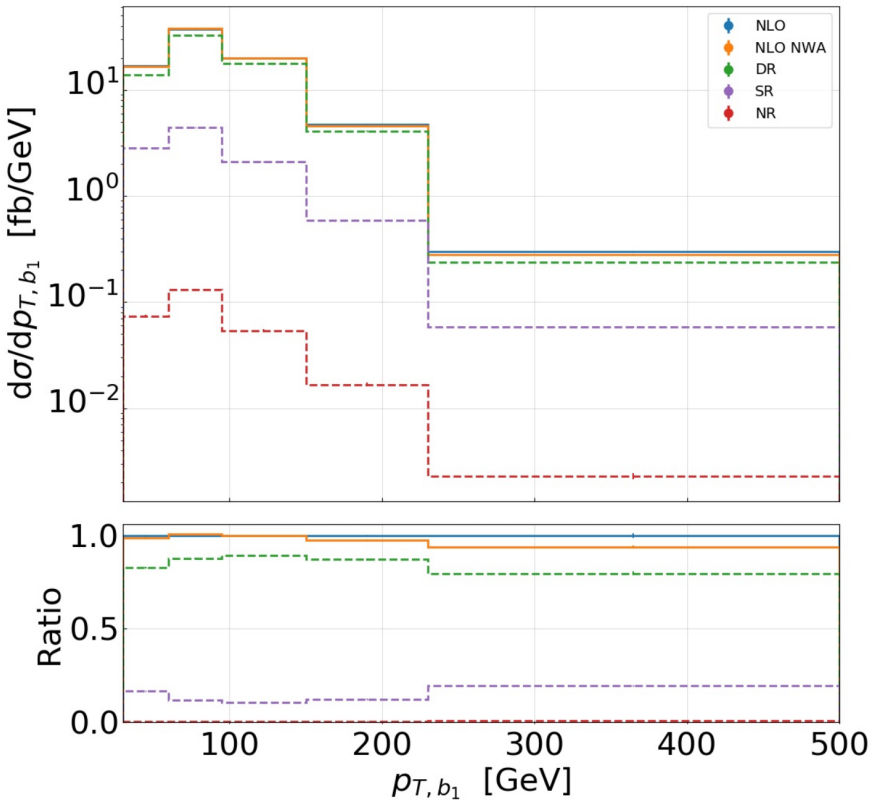


Probing the quantum interference between singly and doubly resonant top-quark production in pp collisions at \sqrt{s}=13 TeV with the ATLAS detector, ATLAS 1806.04667

NWA + offshell combinations II

Example: 1811.06625 (data with removed tW)





Summary and Outlook

- NNLO QCD predictions for fiducial phase spaces → New measurements
- Comparisons between fixed-order predictions and data require compatible object definition! → In particular jets
- Theory – data show very good agreement, including jet-observables
- Potential for top-quark mass measurements from lepton distributions
- Extrapolation?
  → Some shapes of fiducial cross sections are better described with NNLO QCD then with NLO+PS → What about NNLO + PS?

Outlook:

- Semi-leptonic/full-hadronic channels
- More studies about the interplay between fixed order and PS calculations
- Including b-fragmentation → Terry Generet's talk
- NNLO NWA + NLO off-shell combinations