Particle level top quark definition in dilepton channel

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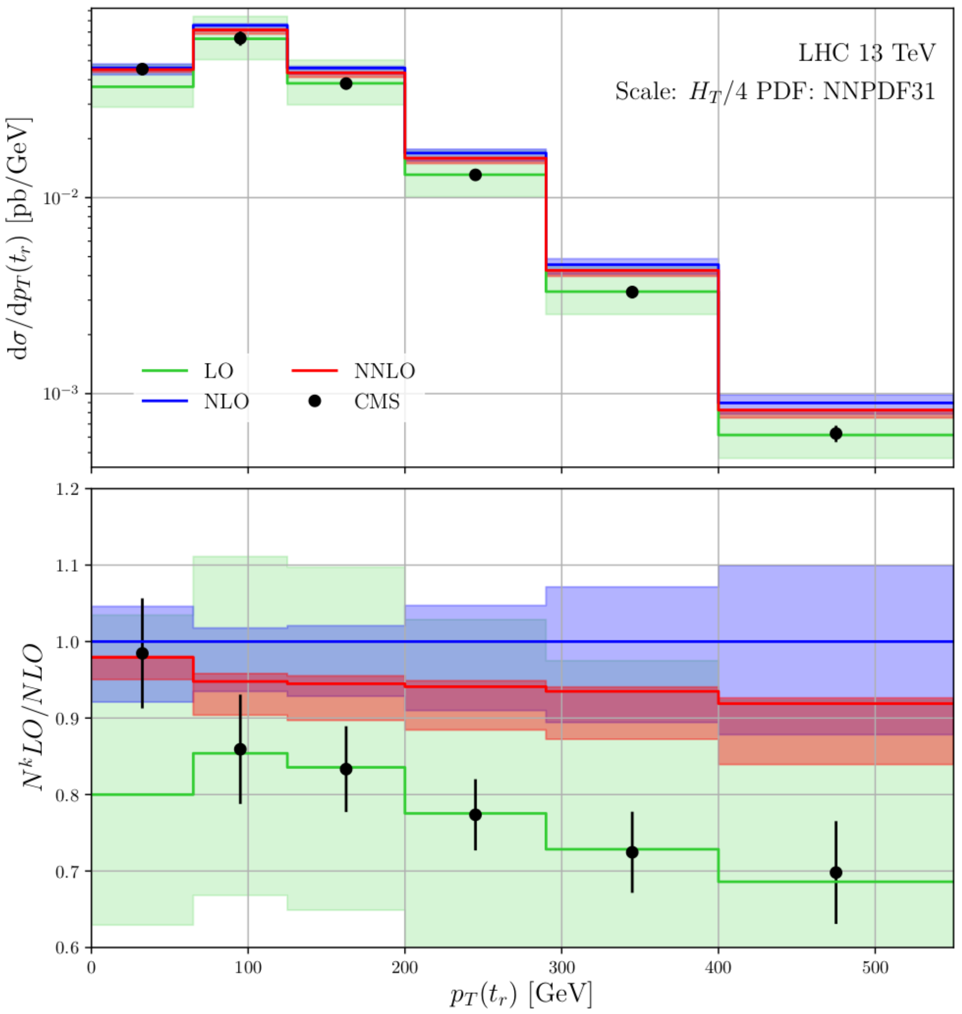
(DESY)

LHCtopWG open meeting, 14 May 2020

"Disagreement" between CMS data and NNLO predictions

Czakon, Mitov, Poncelet (in preparation)
PRL 123, 082001 (2019)



- **M. Czakon, A. Mitov, R. Poncelet reported disagreement between QCD NNLO predictions and particle-level data in dilepton channel from CMS paper [JHEP 02 (2019) 149]**

  → comparisons privately shared with CMS

  → at first look, data seem to be better described by LO predictions

  → these results motivated an effort to understand potential reasons and differences in definitions

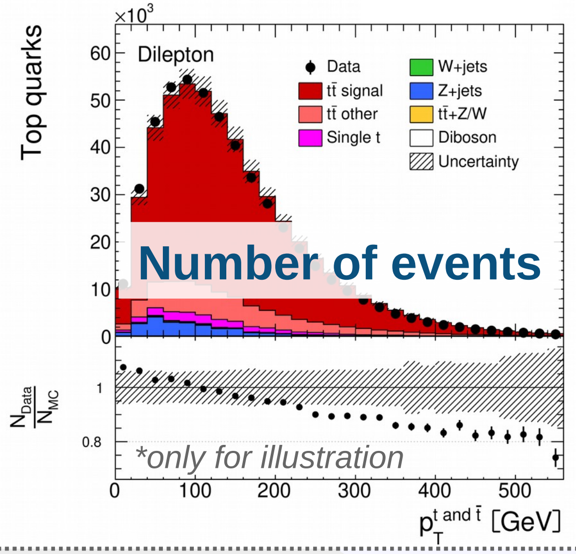
  → [JHEP 02 (2019) 149]: comparisons at parton level demonstrated good agreement between data and predictions

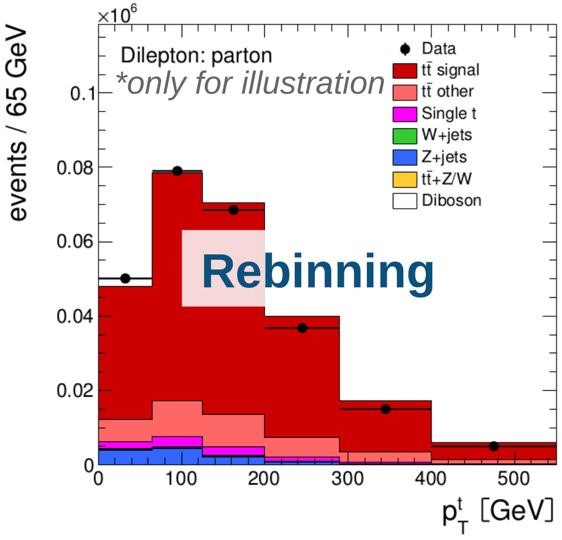
- **Presenting today first studies towards understanding this disagreement**

  → in contact with theoreticians

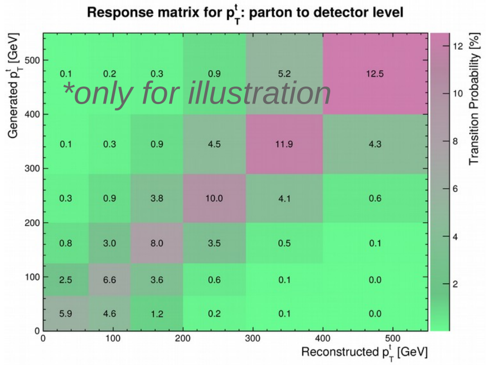
  → spoiler: disagreement partially driven by different jet definitions

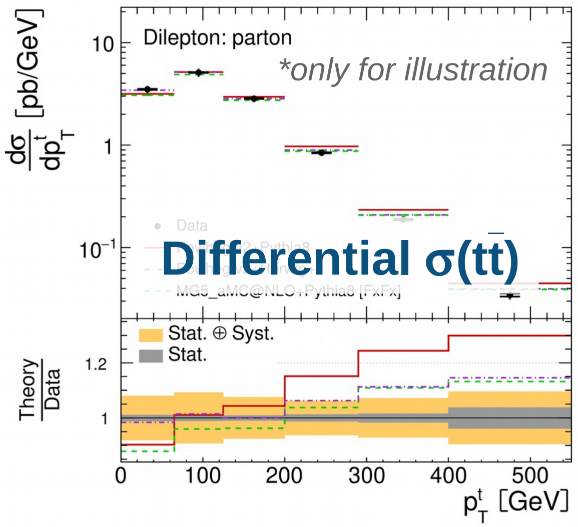
Differential cross section





Response matrix





normalized

$$\frac{1}{\sigma}\frac{d\sigma}{dX_i} = \frac{1}{\sigma}\frac{unfold\left(N^X_{data,i} - N^X_{BG,i}\right)}{\Delta^i_X \cdot \int \mathscr{L}\, dt}$$

absolute

Binning

Chosen to limit migration effects in and out of bins

Regularized unfolding (TUnfold)

- used to correct observed spectrum for detector effects
- regularization to remove unphysical components in solution

Phase space

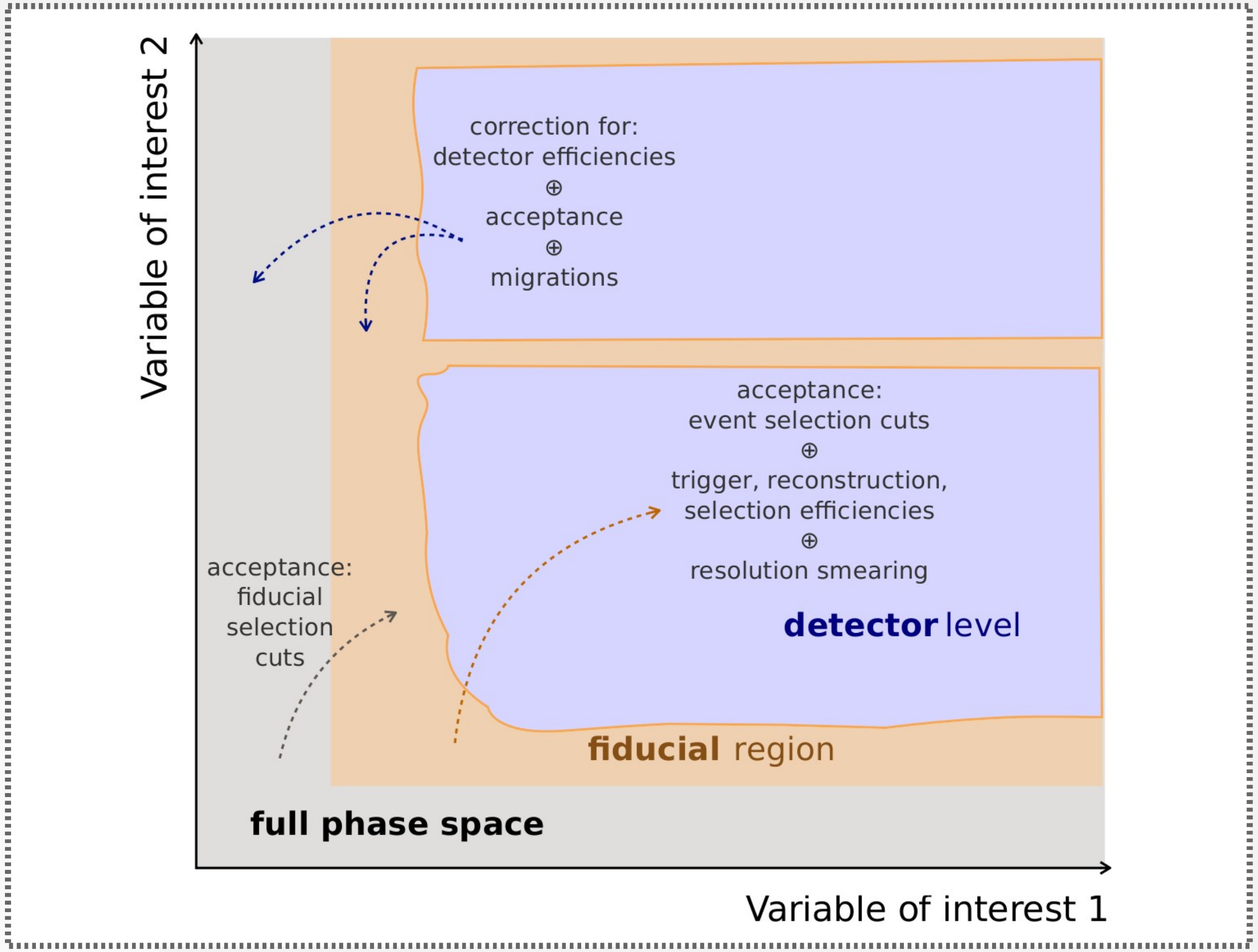
Correct to parton (particle) level in full (fiducial) phase space

Phase space definition

- Differential results extrapolated from **detector** level to **full** or **fiducial** phase space

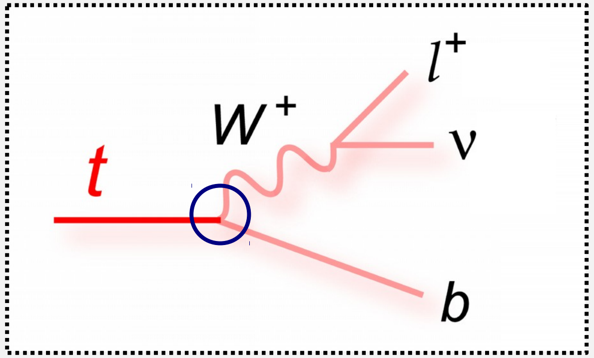
- **Full phase space**
  → not limited by any kinematic requirements
  → probe experimentally inaccessible regions
  → perturbative calculations usually defined in full phase space
  → *usually used to obtain parton level results*

- **Fiducial phase space**
  → in general, portion of full phase space constrained by specific criterion
  → defined closer to detector level to minimize extrapolation
  → smaller theoretical uncertainties expected
  → *usually used to obtain particle level results*

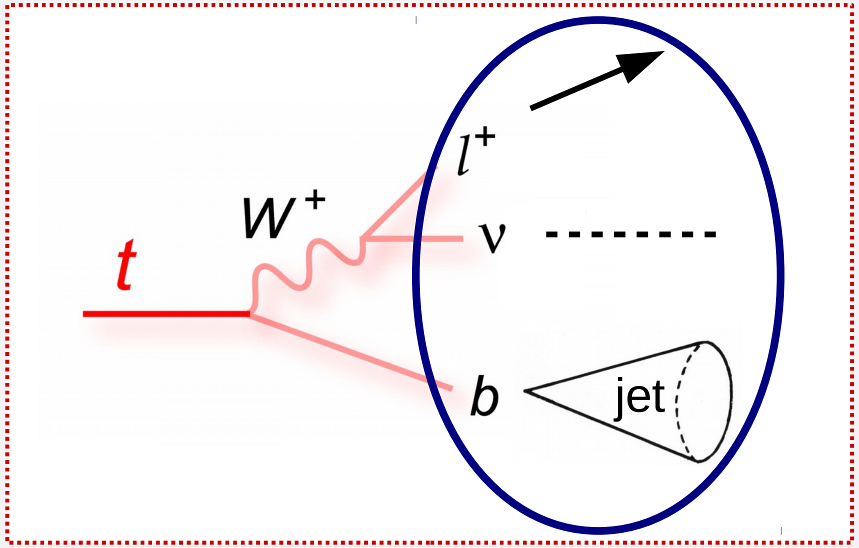


Top quark and phase space definition in [JHEP 02 (2019) 149]

- **Parton level** top quark in full phase space
  → after QCD radiation and before decay
  → results can be compared to predictions from perturbative calculations
  → extraction *of various parameters, e.g.:* α_S, m_t, PDFs



- **Particle level** top quark in fiducial phase space
  → based on stable particles after hadronization
  → reduced dependence on MC generator choice and tuning
  → fiducial phase space and objects defined closely to detector level
  → *useful for MC validation and tuning, and testing of new physics models*



… followed LHCtopWG recommendations for both definitions
(also described in CMS-NOTE-2017-004)

Particle level top quarks in [JHEP 02 (2019) 149]

- **Signal:** only prompt decays to ee, emu, mumu (i.e., no decays via tau)

- **Objects**

  → 2 oppositely-charged leptons, dressed: prompt leptons (not from hadrons) clustered with anti-kt jet algorithm (R = 0.1)

  → at least 2 neutrinos: prompt (not from hadrons)

  → at least 2 jets: clustered with anti-kt jet algorithm (FastJet, R = 0.4), clustered from all particle candidates except those associated with neutrinos and dressed leptons

  → at least 2 b-jets: identified using ghost B-hadron technique

- **Selection**

  → dressed leptons: p_T(lepton) > 20 GeV, $|\eta$(lepton)$|$ < 2.4, invariant mass of dilepton system > 20 GeV

  → (b)jets: p_T(jet) > 30 GeV, $|\eta$(jet)$|$ < 2.4, ΔR(jet,lepton) > 0.4

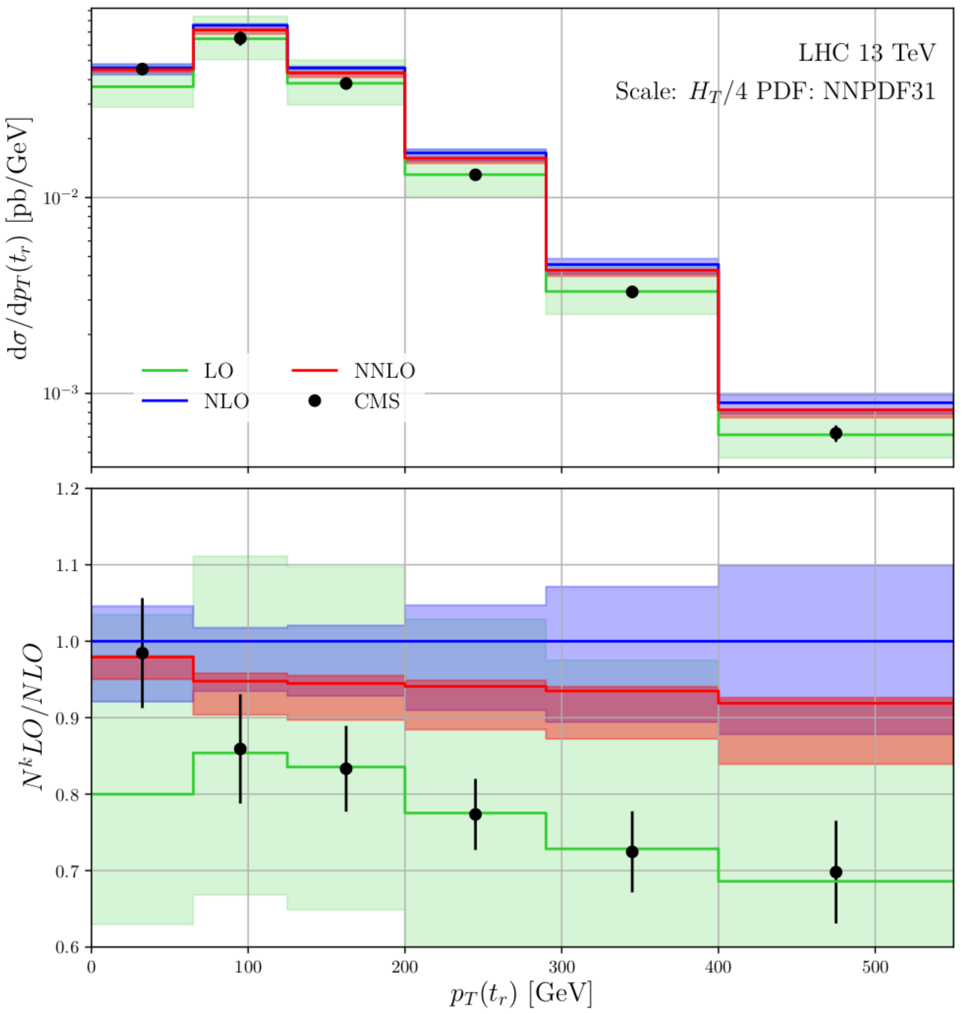
  → neutrinos: no further criterion

- **Top quarks and W bosons**

  → defined from decay products: sum of 4-momenta, permutations that minimize corresponding mass criteria, particle charges decided upon lepton charges entering the permutation

Particle level top quarks in NNLO predictions

Czakon, Mitov, Poncelet (in preparation)
PRL 123, 082001 (2019)



- **Comparison of NNLO predictions (Czakon, Mitov, Poncelet) with particle-level data from [JHEP 02 (2019) 149]**
- **Definitions on theoretical side** (major points relevant for experiment)

→ jet clustering based on partons, i.e., gluons and massless quark flavors

→ b-tags assigned via bottomness, 100% efficient

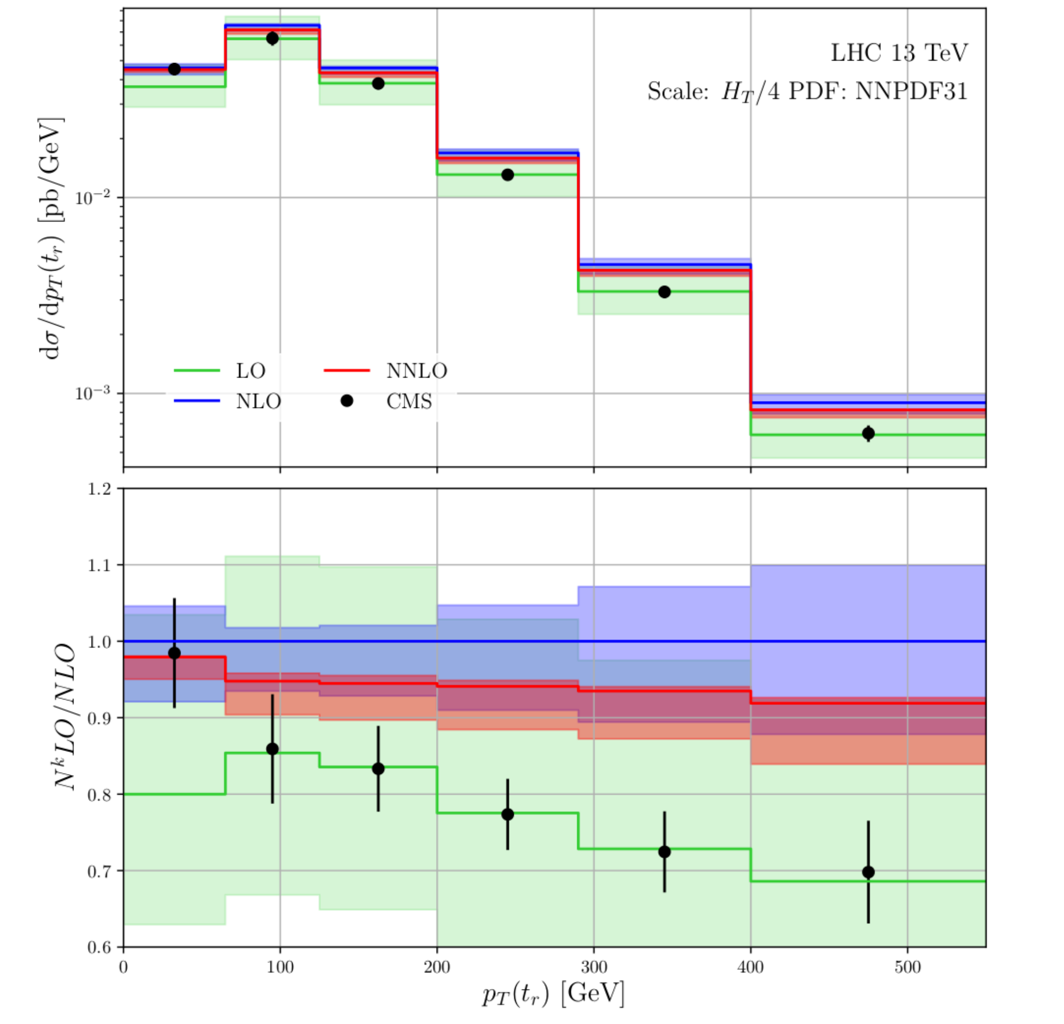
→ at NNLO in QCD, up to three partons form a jet

→ clustering via anti-kt algorithm as implemented in FastJet (R=0.4)

→ originally, data compared to <u>true</u> top quarks from predictions; later, predictions switched to reconstruction out of decay objects at particle level as used by CMS (described in previous slide)

Main differences between theoretical and experimental definitions

Czakon, Mitov, Poncelet (in preparation)
PRL 123, 082001 (2019)



- **From discussion between theoretical and experimental sides**

  → direct comparison not possible as both sides use different definitions

  → in the experiment, neutrinos from hadronic decays excluded in jet clustering

  → in the experiment, an NLO ME generator (Powheg v2) used to define fiducial phase space

  → in the experiment, jets include PS + hadronization corrections as implemented in Pythia8

  → any remaining disagreement in top-p_T spectrum between data and NNLO predictions at parton level propagates to particle level

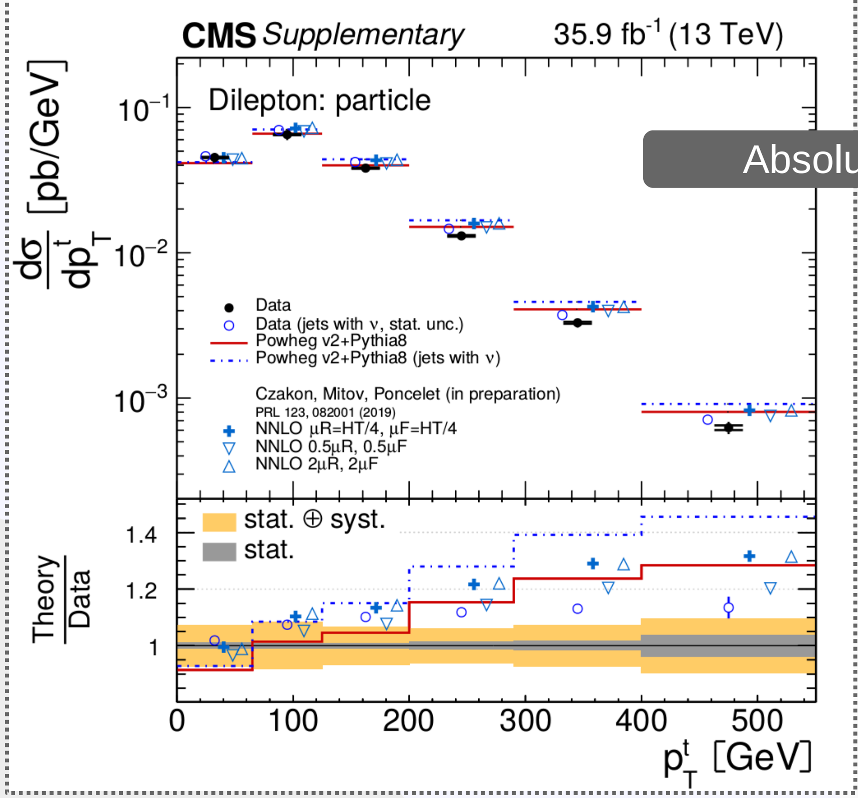
  → in the experiment: out-of-cone effects in jet clustering, ghost matching not 100% efficient, leptons are dressed

- **Started from checking jet clustering with neutrinos at particle level**

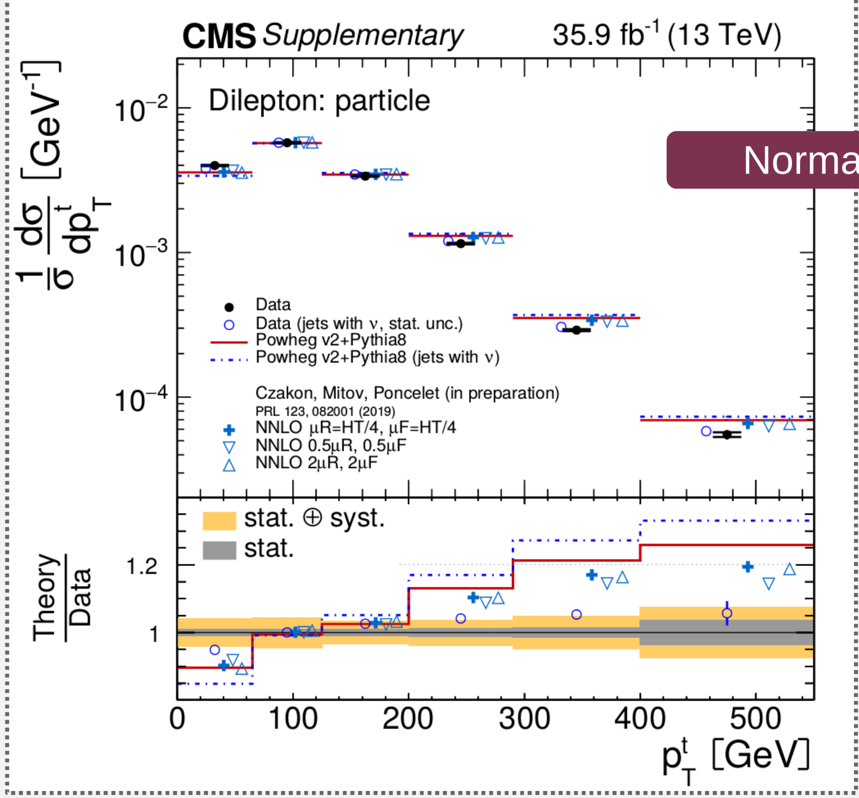
  → [JHEP 02 (2019) 149] nominal measurement was **rerun** with corresponding modifications propagated through whole analysis

  → results for few observables shown today, comparing with NNLO predictions side-by-side

Particle-level comparisons shown today



Absolute



Normalized

New comparisons are public in JHEP 02 (2019) 149 TWiki [↗]:

→ **black dots**: [JHEP 02 (2019) 149] data (total unc.)

→ **blue dots**: modified [JHEP 02 (2019) 149] data (<u>only</u> stat. unc.)

→ **red curve**: standard Powheg v2 + Pythia8

→ **blue curve**: modified Powheg v2 + Pythia8

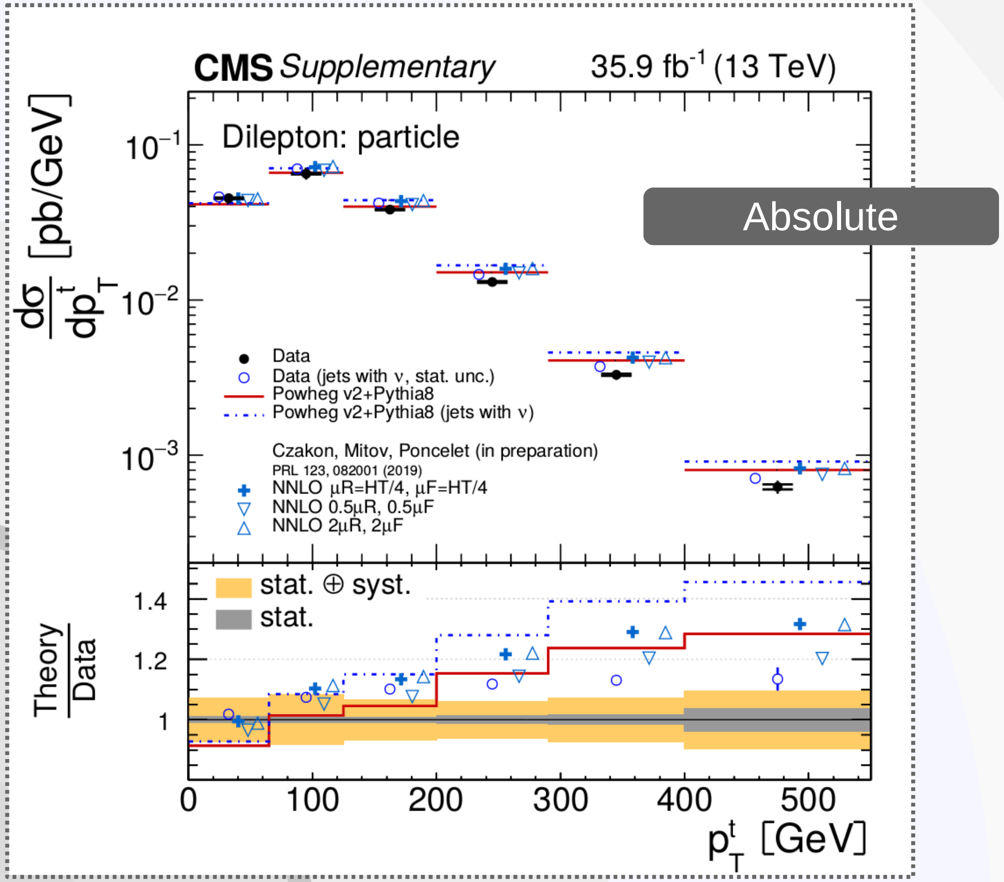
→ **teal crosses:** nominal QCD NNLO (Czakon, Mitov, Poncelet) and **teal triangles:** alternative scale choices

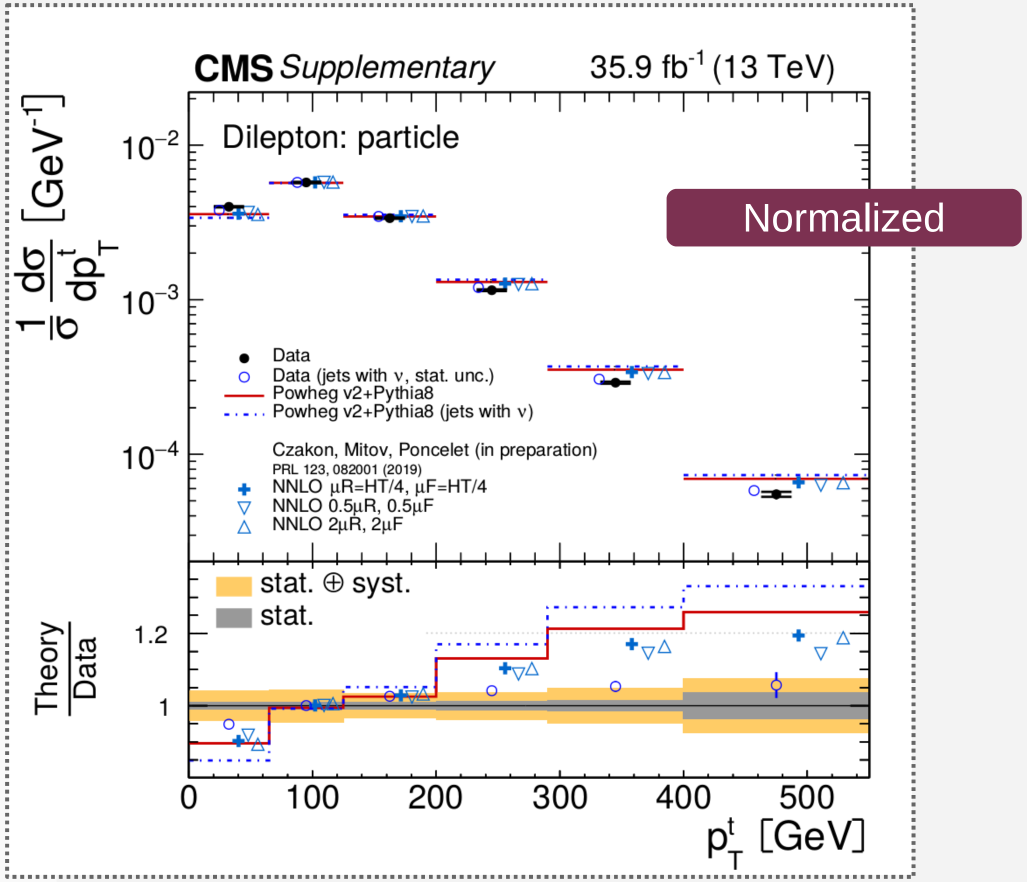
→ all ratios to standard data (**black dots**)

- To assess agreement, confront **QCD NNLO (teal crosses)** with **modified data (blue dots)**

Top quark p_T

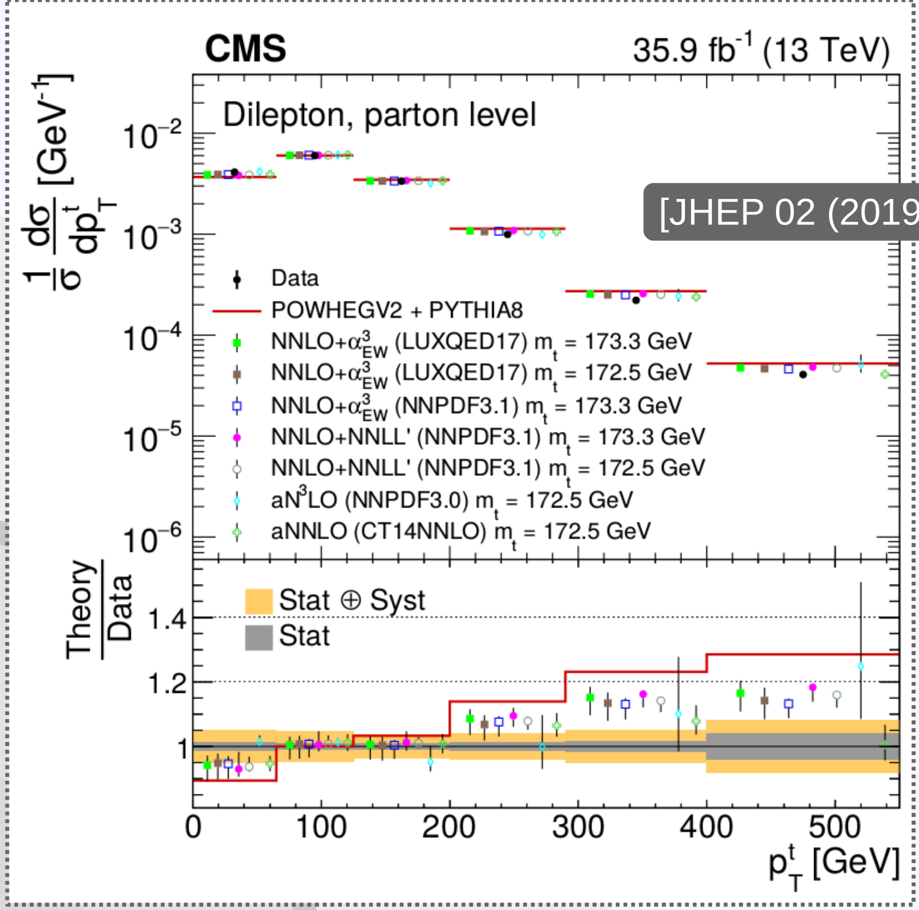
- **Data-to-theory agreement goes in correct direction:** modification of MC prediction at particle level modifies data up to same amount in % bin-by-bin
  - → about 15% difference in the tail between **modified data** and **NNLO**, but might agree within total uncertainties (if available)
  - → other sub-dominant effects might compensate for remaining differences (see slide 8)



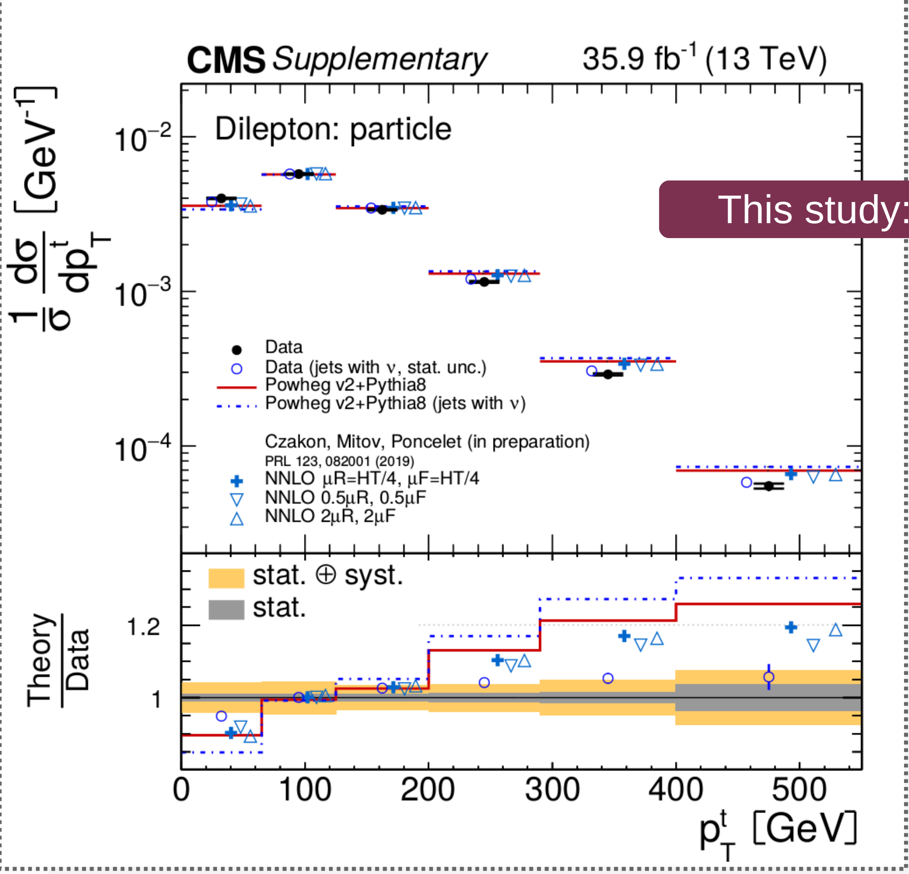


Top quark p_T: parton vs particle

- **[JHEP 02 (2019) 149]:** up to 15% difference at parton level between **data** and **NNLO** predictions in the tail
  → predictions in [JHEP 02 (2019) 149] include EWK, NNLL' corrections and different choices for PDF, m(top)
  → observe consistent slopes in top quark p_T (data vs theory) at parton and particle levels
  → missing corrections for predictions used in new study might provide potential for further improvement at particle level



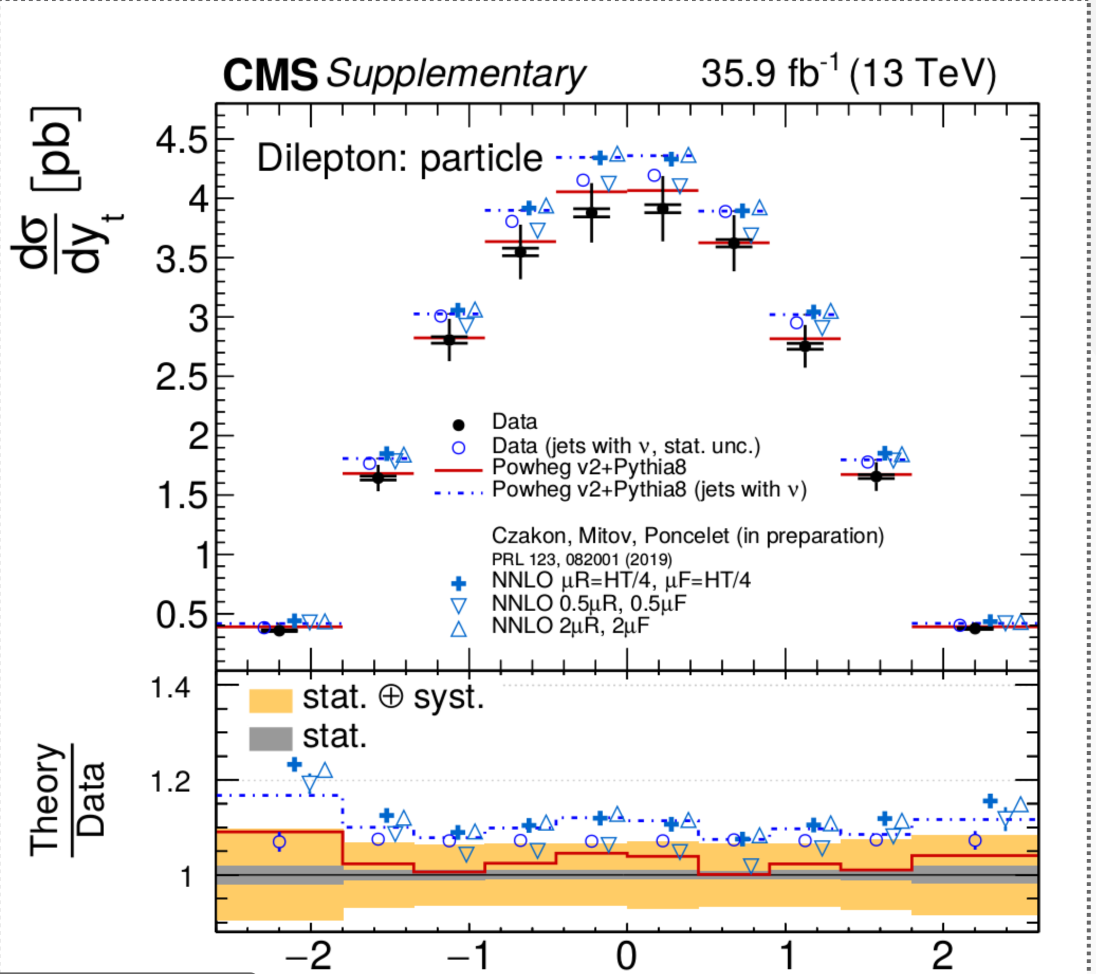
[JHEP 02 (2019) 149]: parton



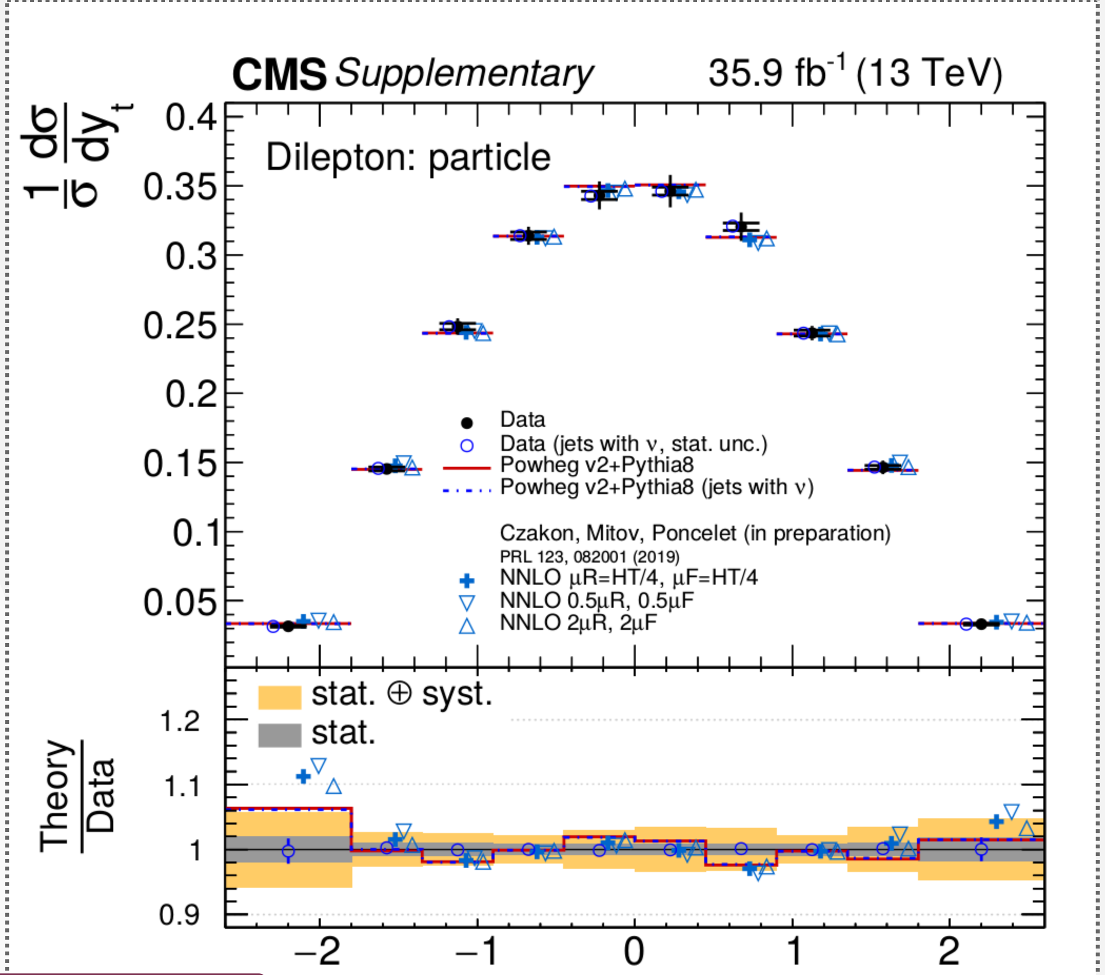
This study: particle

Top quark rapidity

- In this study, top rapidity sensitive mostly to modifications in acceptance
  → in absolute measurements, modified data about 7% higher than standard data



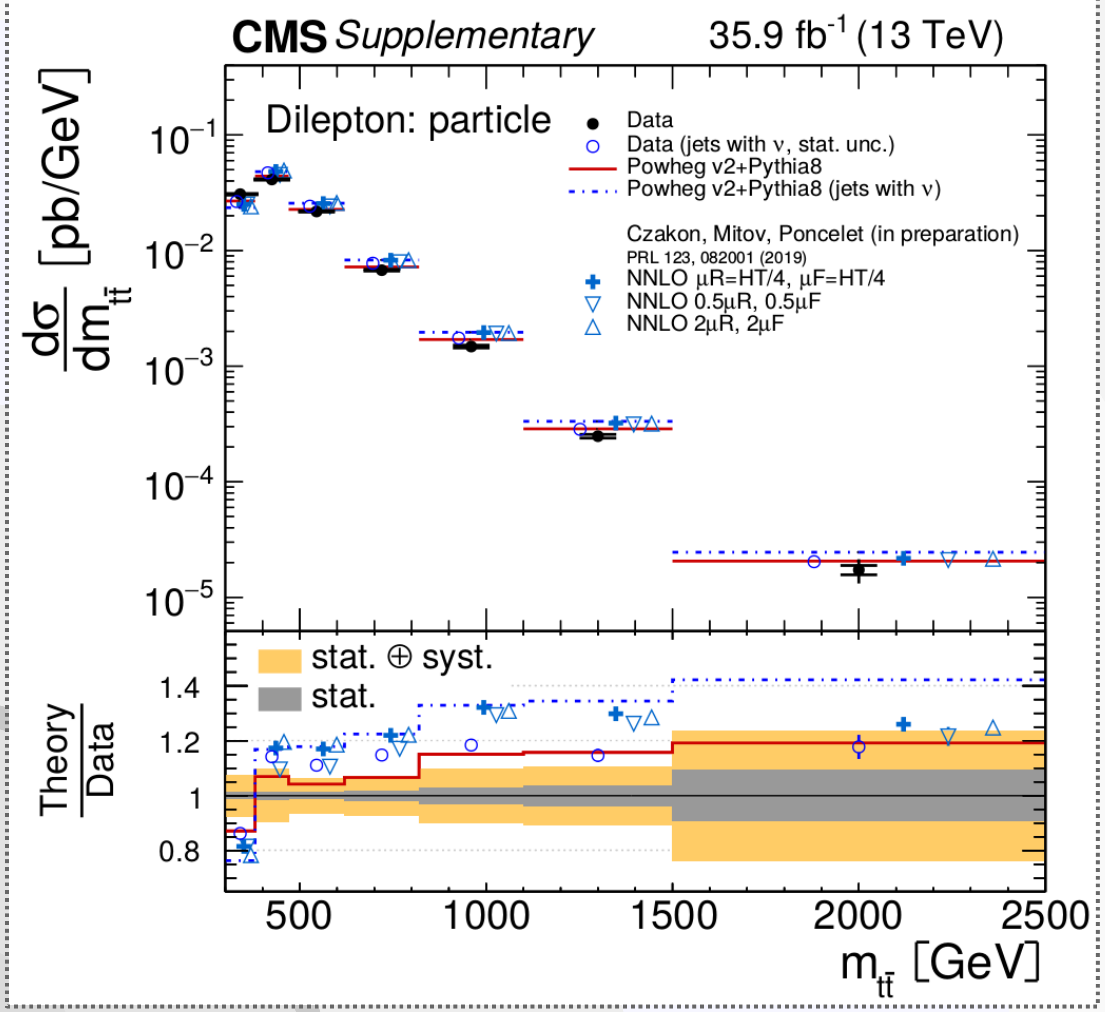
Absolute



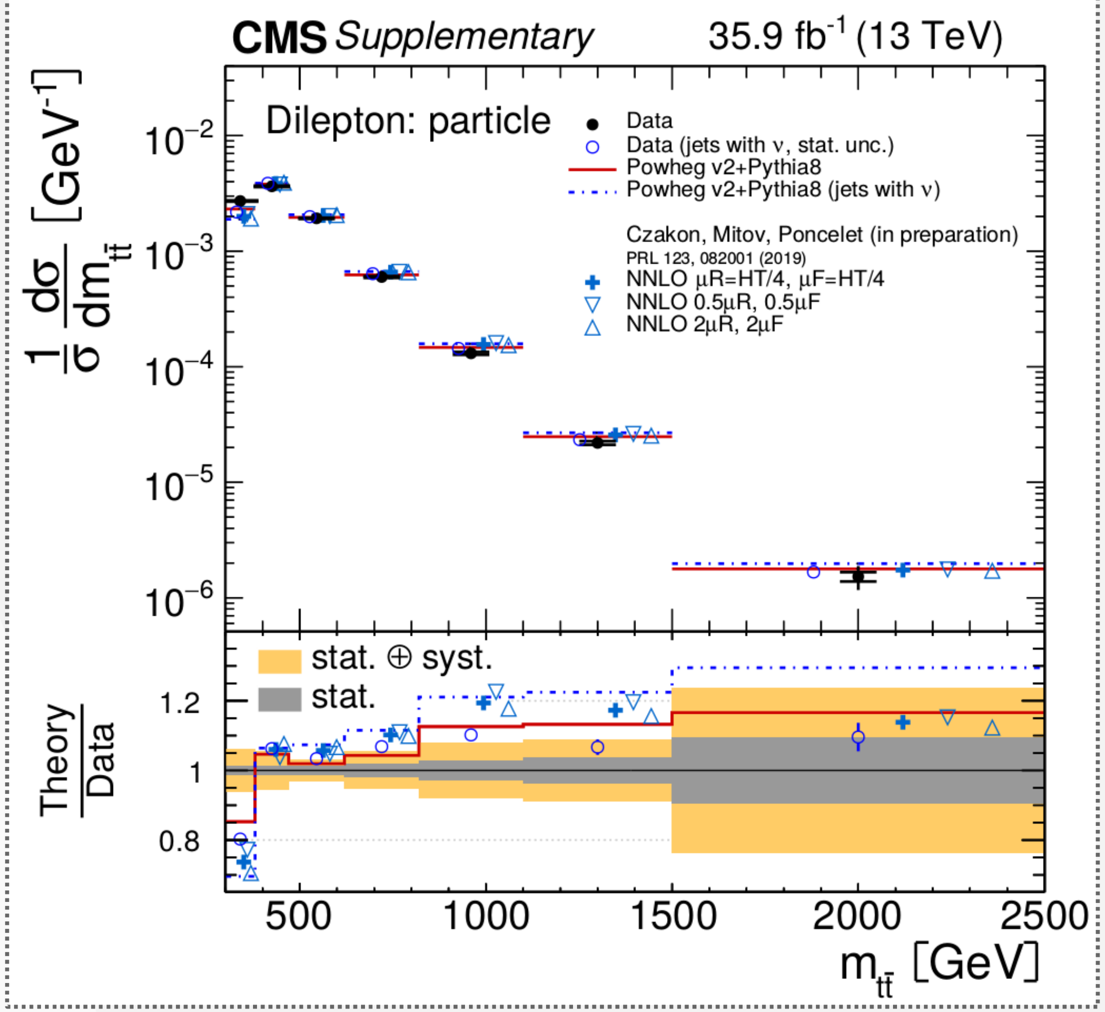
Normalized

Invariant mass of top quark pair

Absolute

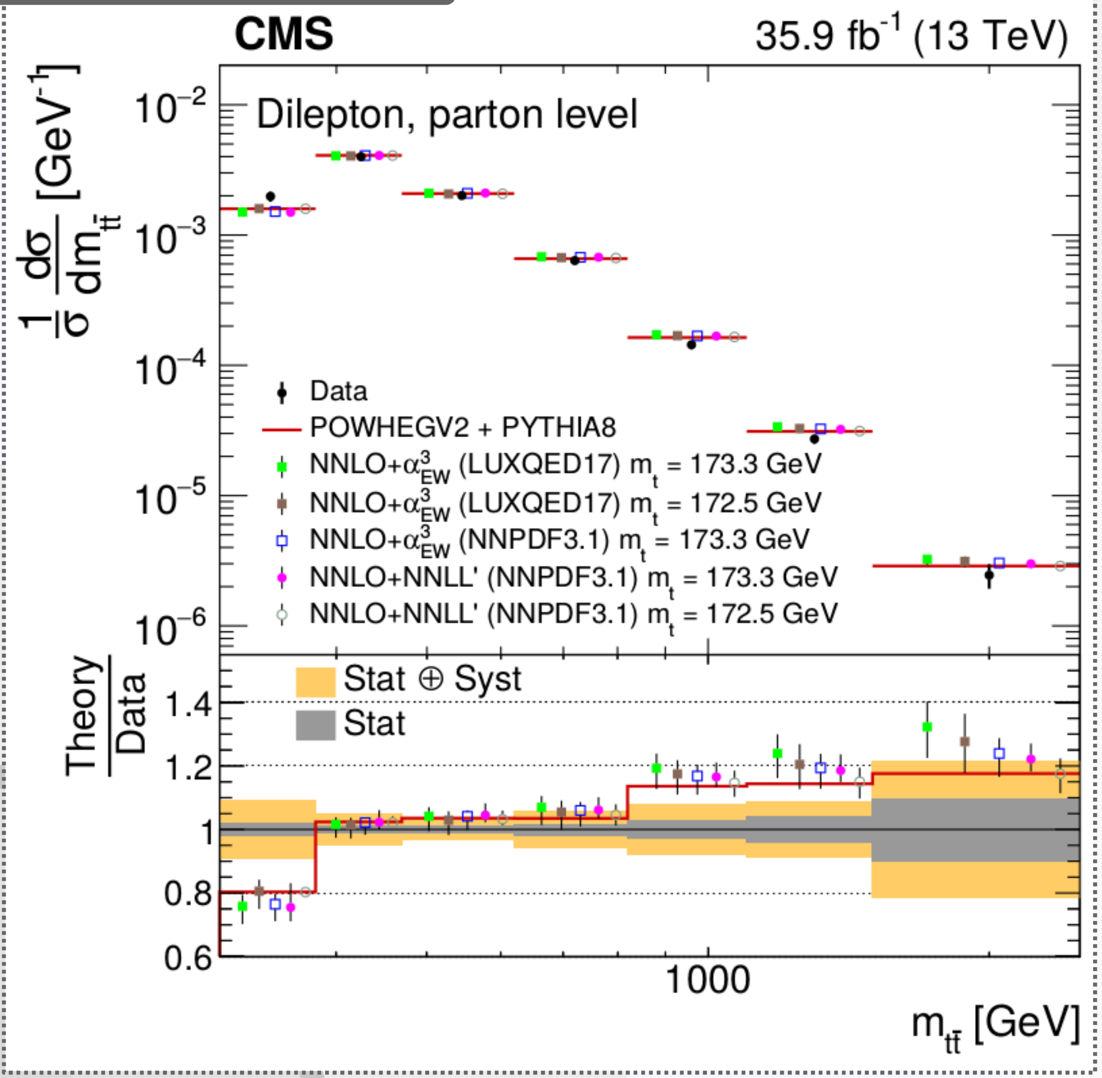


Normalized

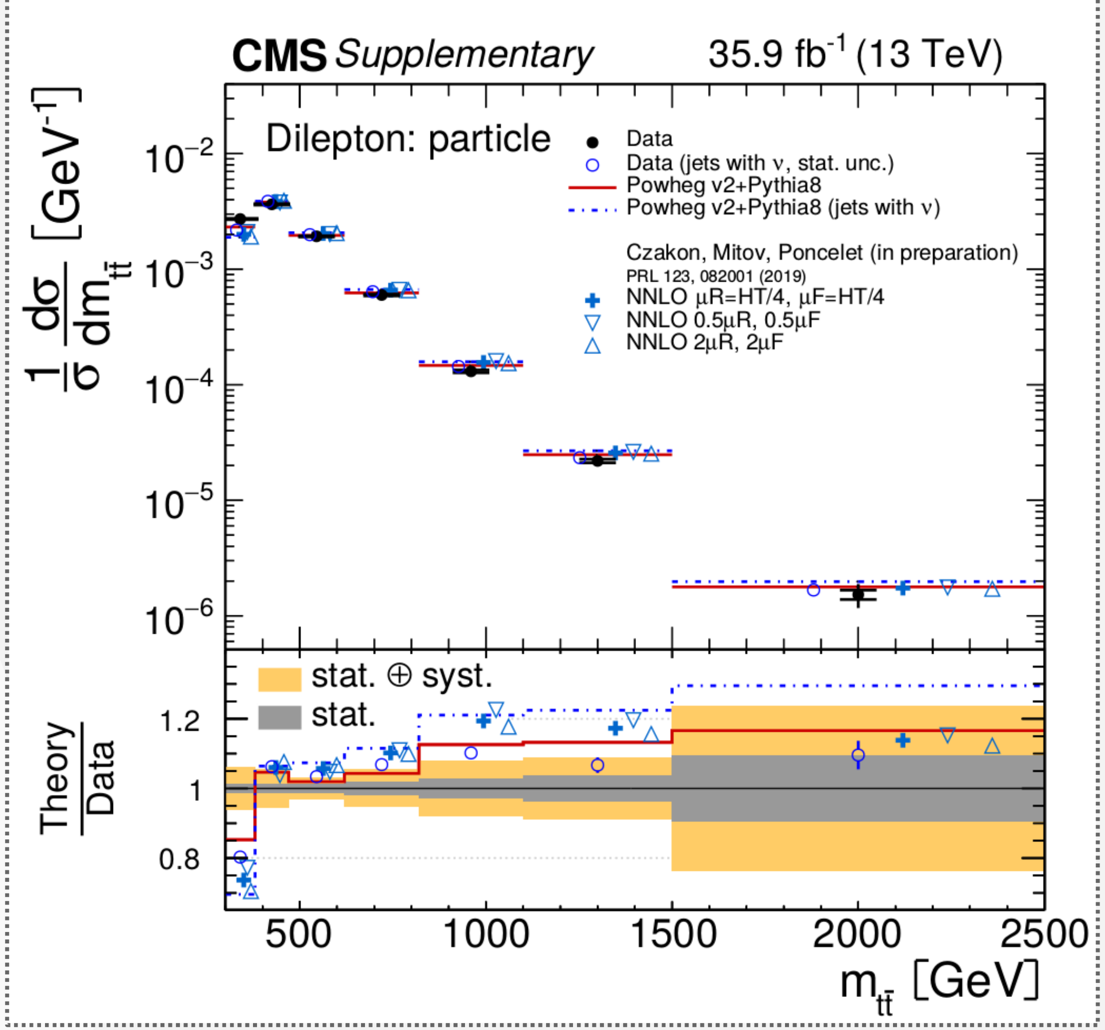


Invariant mass of top quark pair: parton vs particle

[JHEP 02 (2019) 149]: parton



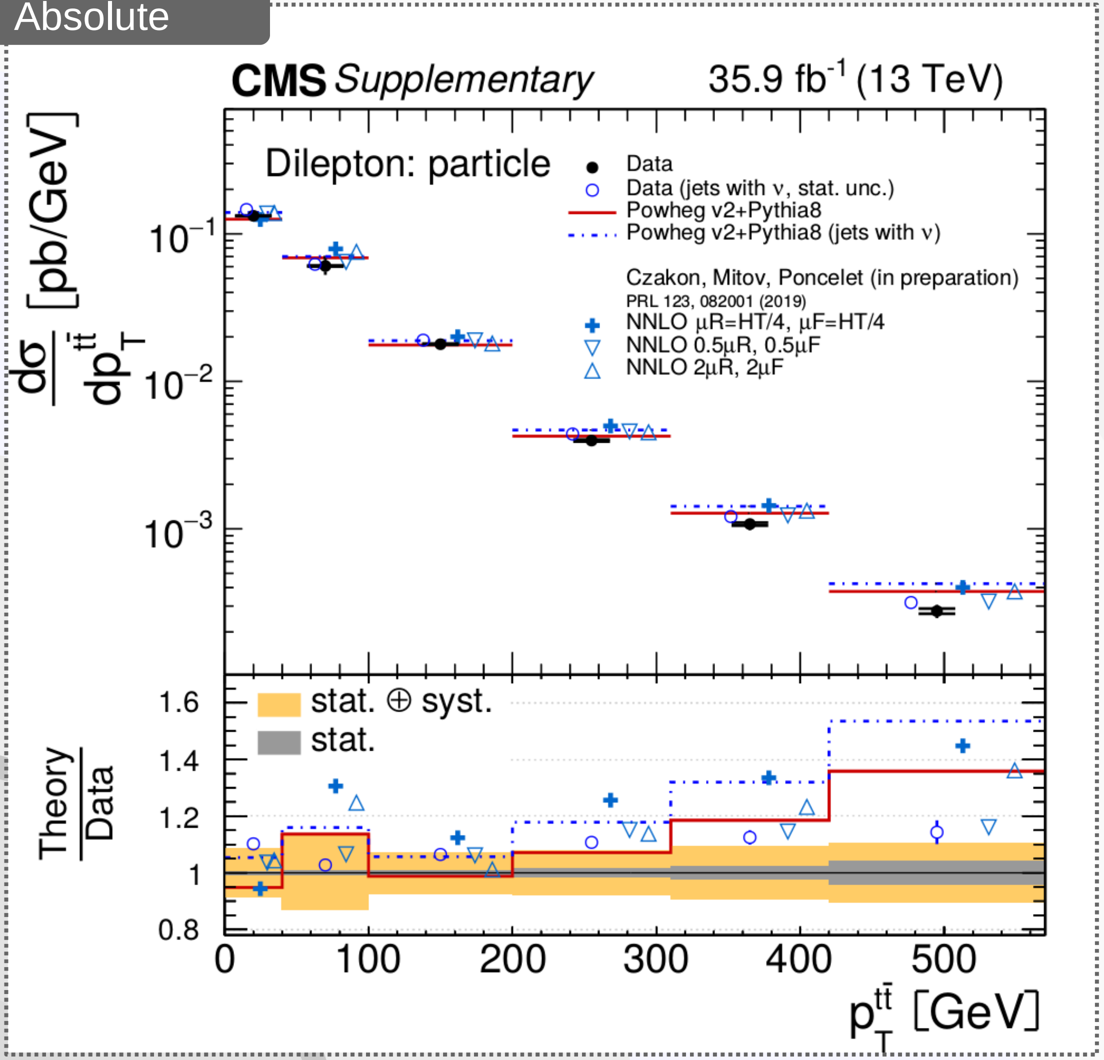
This study: particle



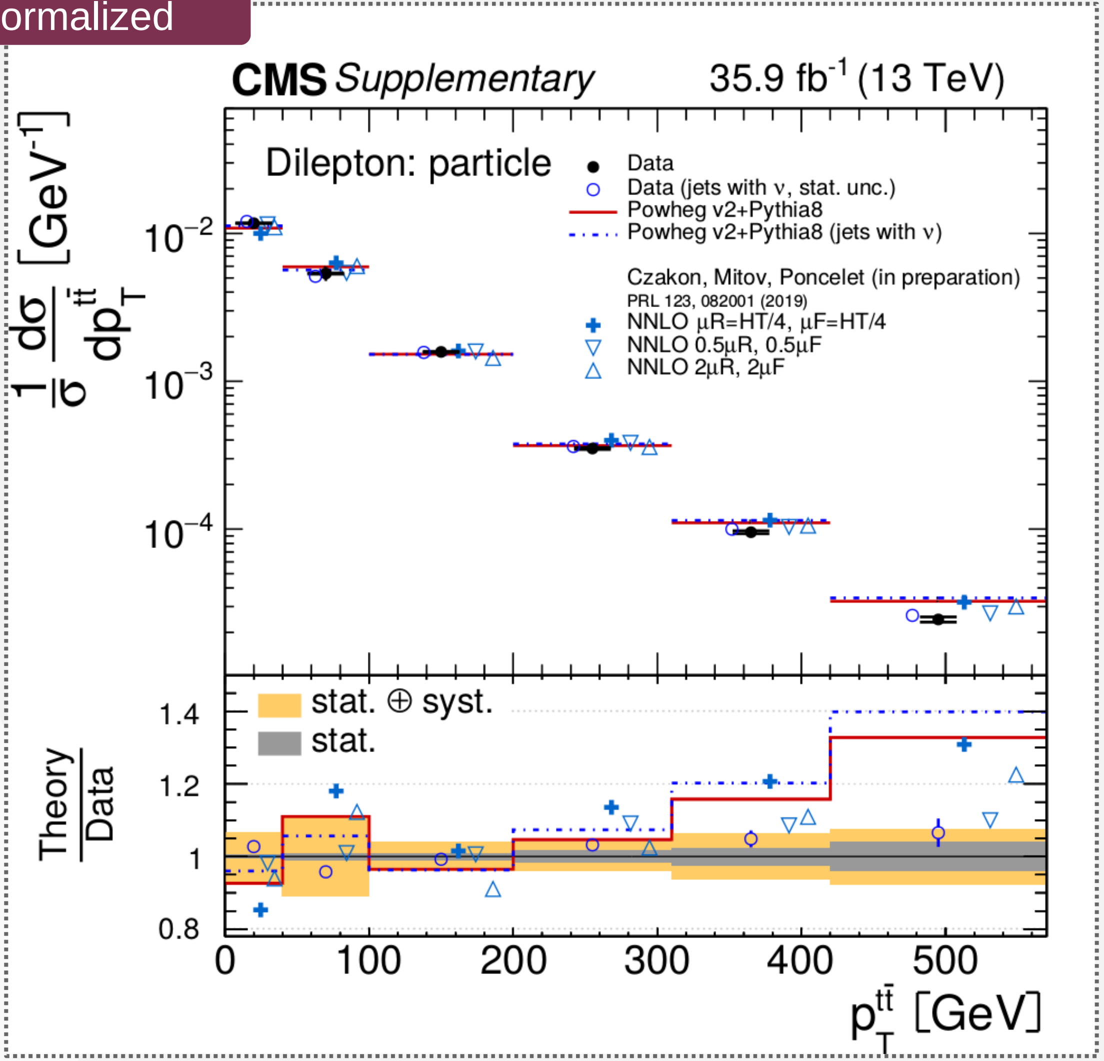
→ new study at particle level might improve upon observed trends at parton level

Top quark pair p_T

Absolute



Normalized

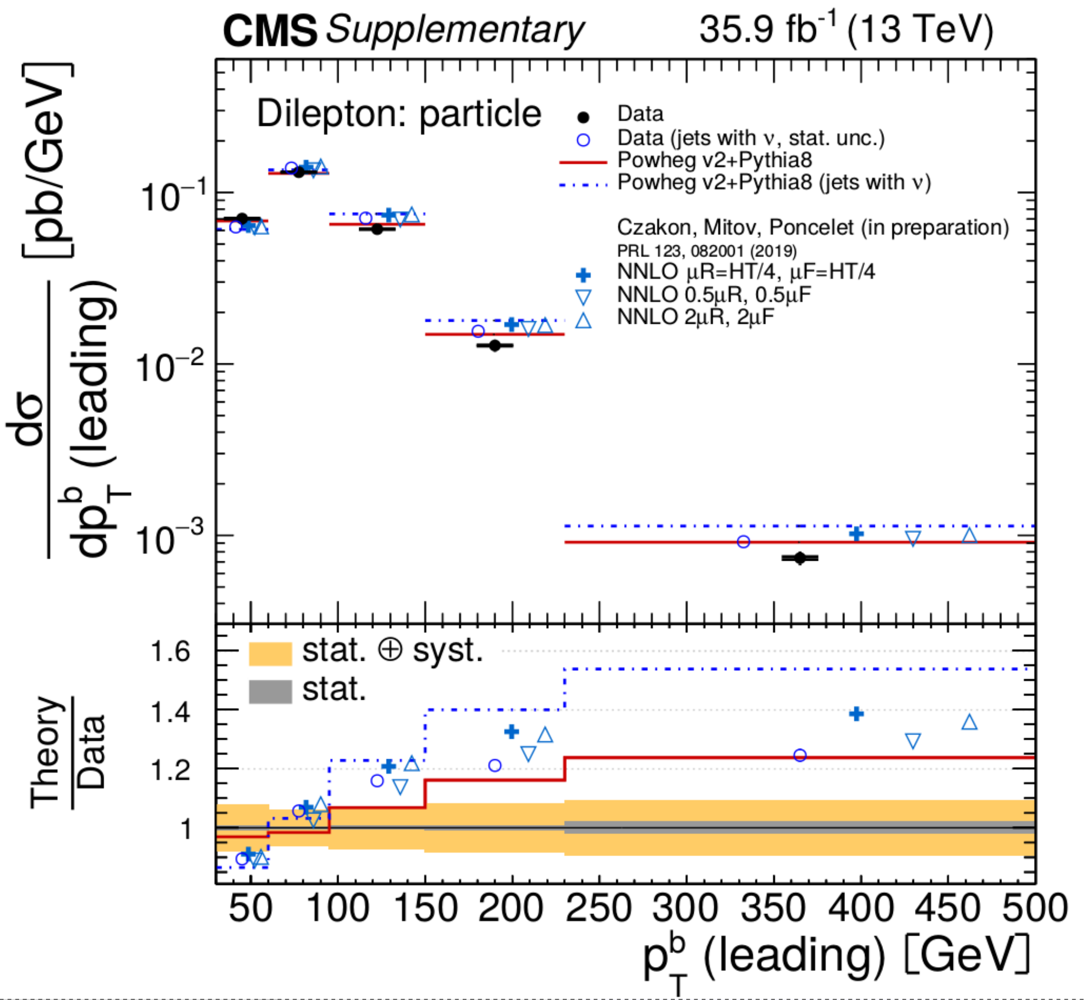


→ leading term of the top quark pair p_T appears at NLO; also impacts MC model used for data extrapolation

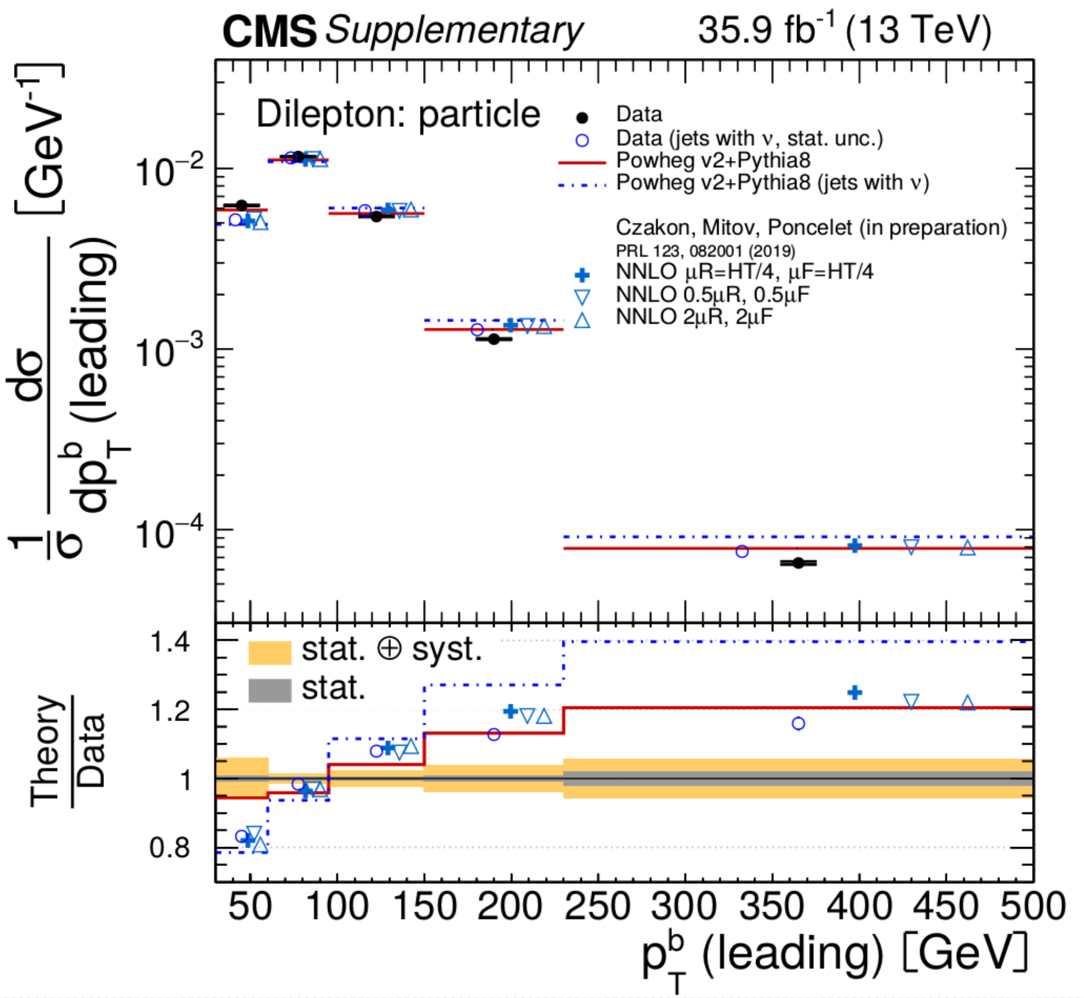
p_T of leading b jet

- Largest impact from new particle-level definition expected on b-jet observables related to momentum (see more in backup)

Absolute



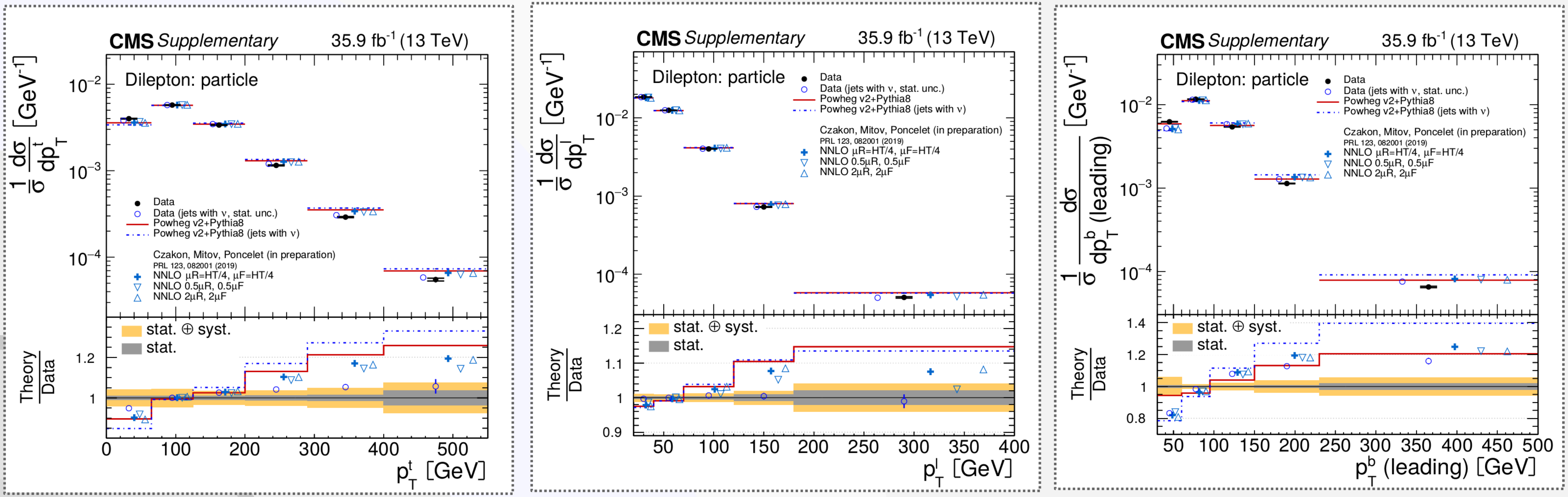
Normalized



p_T of top quarks, leptons and b jets (normalized)

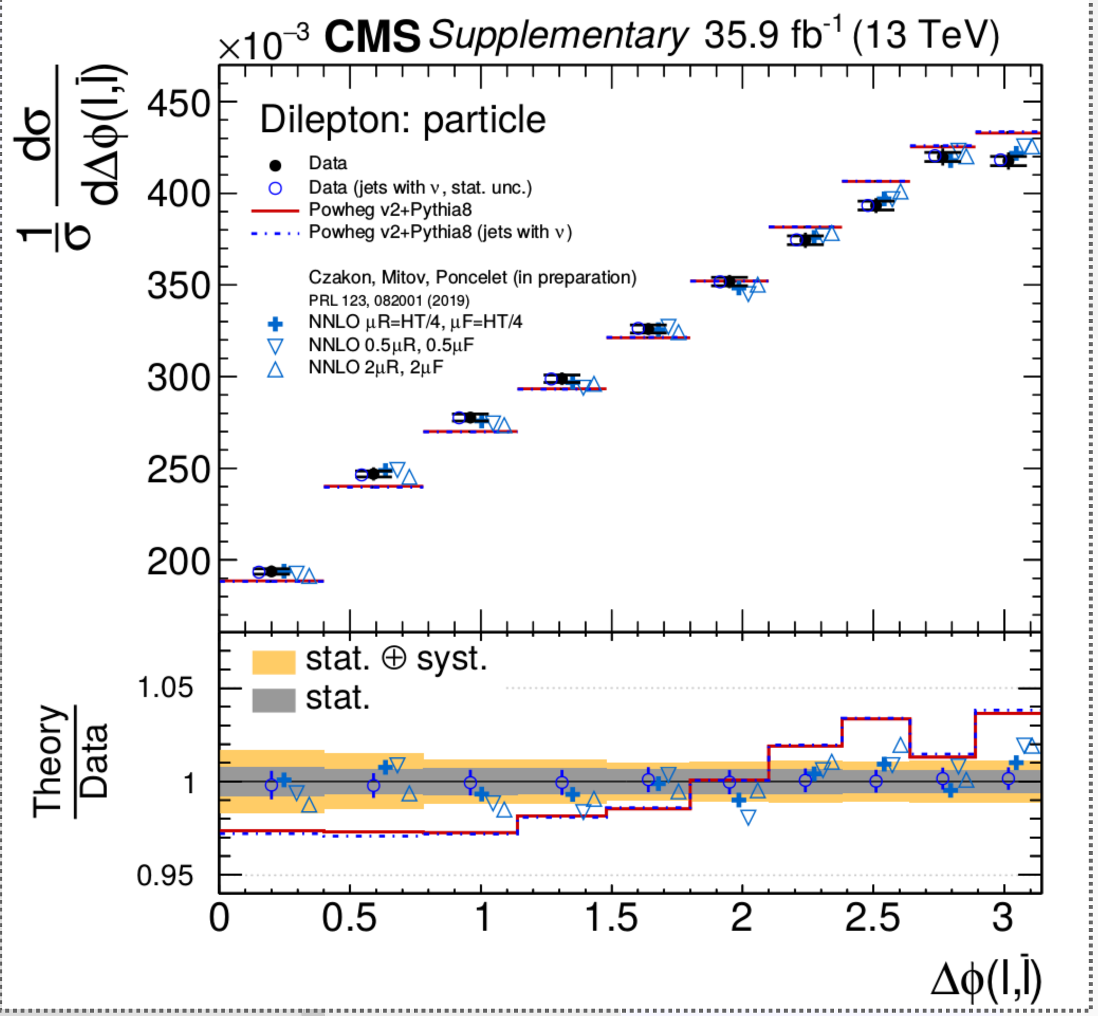
- Slope in top quark p_T consistently transferred to leptons and b-jets

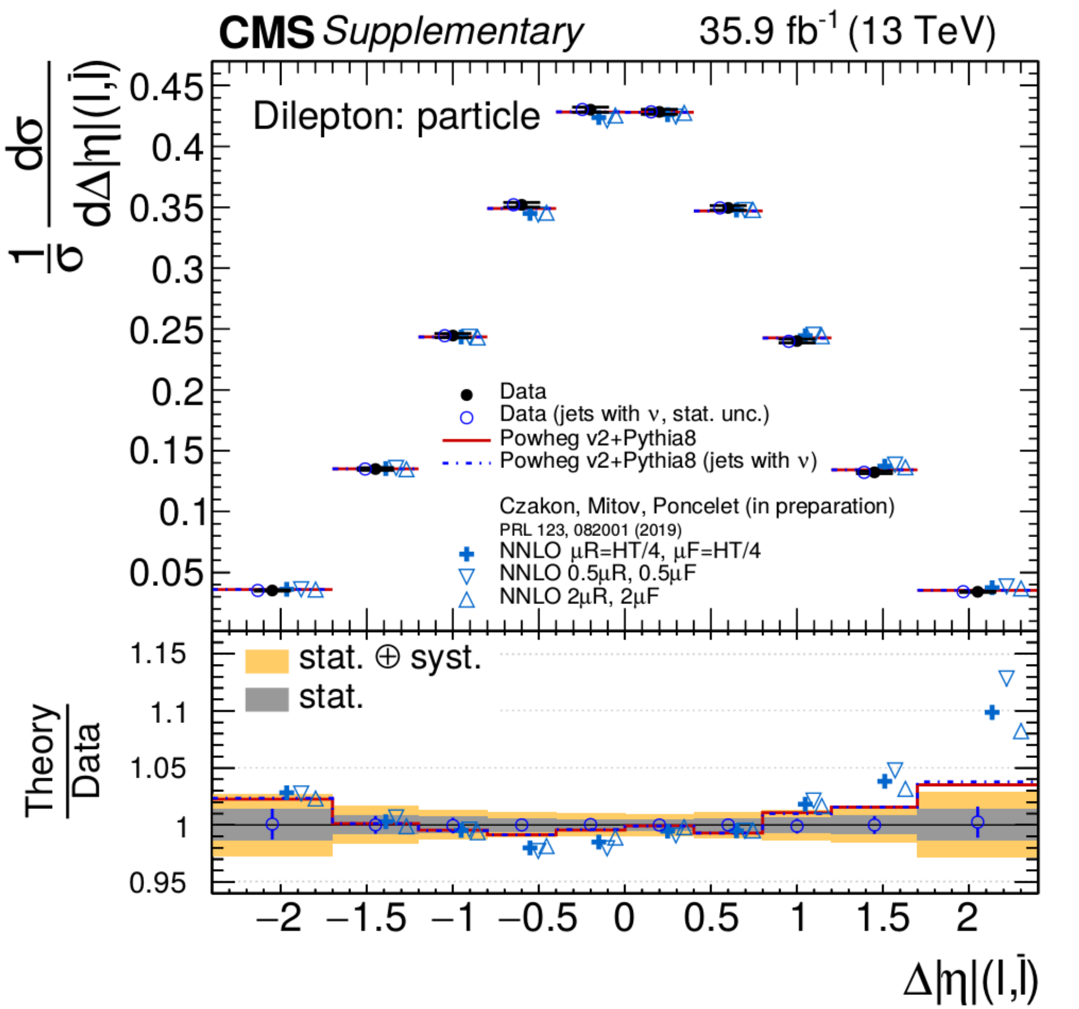
→ at first look, b-jets seem to be better described than leptons, but scales of ratios are different and up to 10% effects visible for both



Δϕ and Δ|η| between leptons (normalized)

- Leptons impacted mostly due to modification in acceptance
  → different centrality in Δ|η| between data and NNLO predictions





Summary

- “Disagreement” between CMS data [JHEP 02 (2019) 149] and NNLO predictions (by M. Czakon, A. Mitov, R. Poncelet) at particle level mostly due to different jet definitions
- Agreement improves after inclusion of neutrinos from hadronic decays to jet clustering in particle level data
- New comparisons available in JHEP 02 (2019) 149 TWiki [↗] (absolute and normalized cases for 17 observables)
- Possible next steps: → in theory, compare jet multiplicities at NLO vs NNLO to estimate impact on acceptance
  → in experiment, estimate scale factors from MC with PS+hadronization to correct jets in predictions

For discussion

- Unfolding of data for particle observables to different levels:
  → pseudo-top-like definition of particle level, i.e., reconstructed top quarks out of decay objects, use stable particles
  → hybrid definition: true top quarks (not reconstructed) and leptons at parton level, jets at particle level
  → parton level top quarks, leptons and jets
  → *… caveats and use cases for each definition?*
- Correction of parton level jets in predictions to particle level, e.g., using scale factors from MC with PS+hadronization

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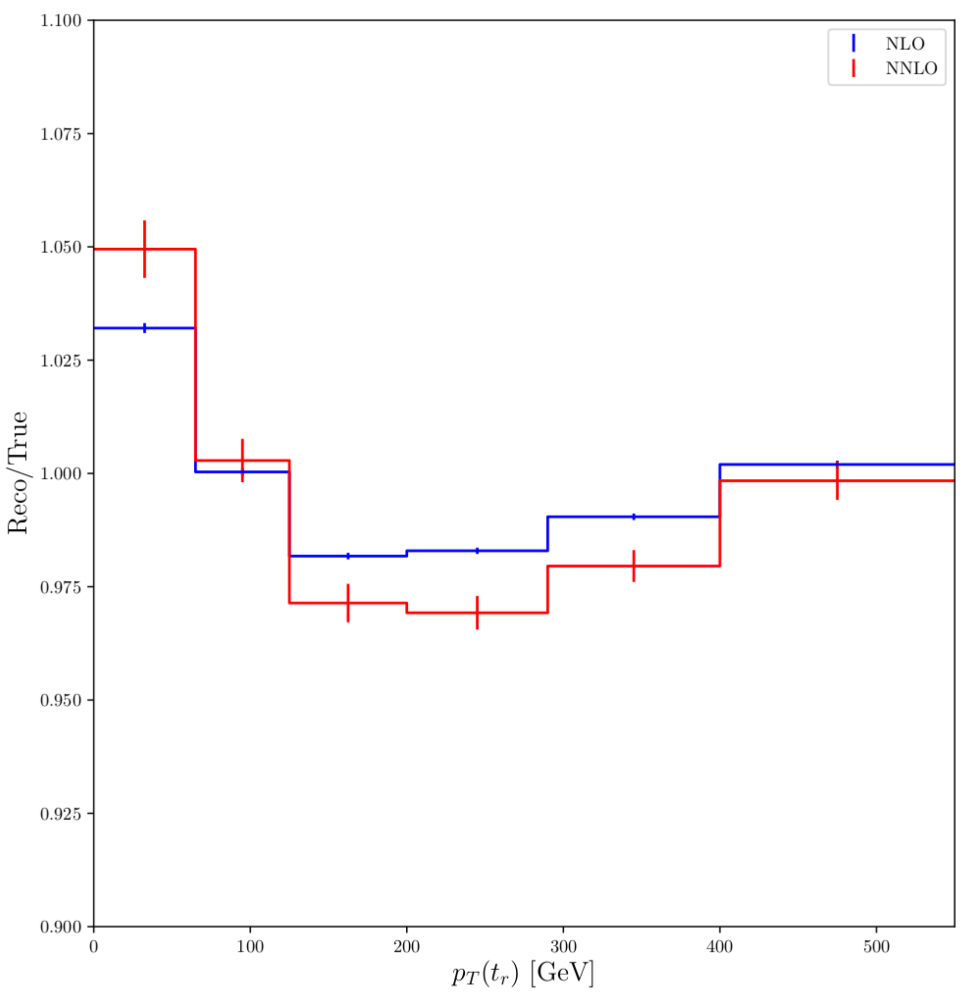
Thank you for your attention!

BACKUP

Top quarks in NNLO predictions

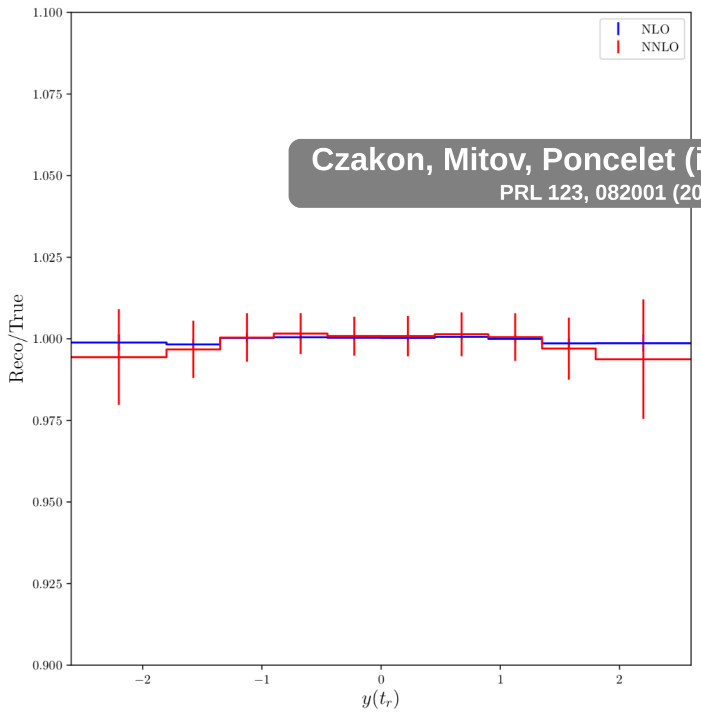
Czakon, Mitov, Poncelet (in preparation)
PRL 123, 082001 (2019)



- Originally, data compared to <u>true</u> top quarks from predictions; later, predictions switched to reconstruction out of decay objects at particle level as used by CMS

  → non-significant impact, though not negligible

  → larger effect on momentum-related observables



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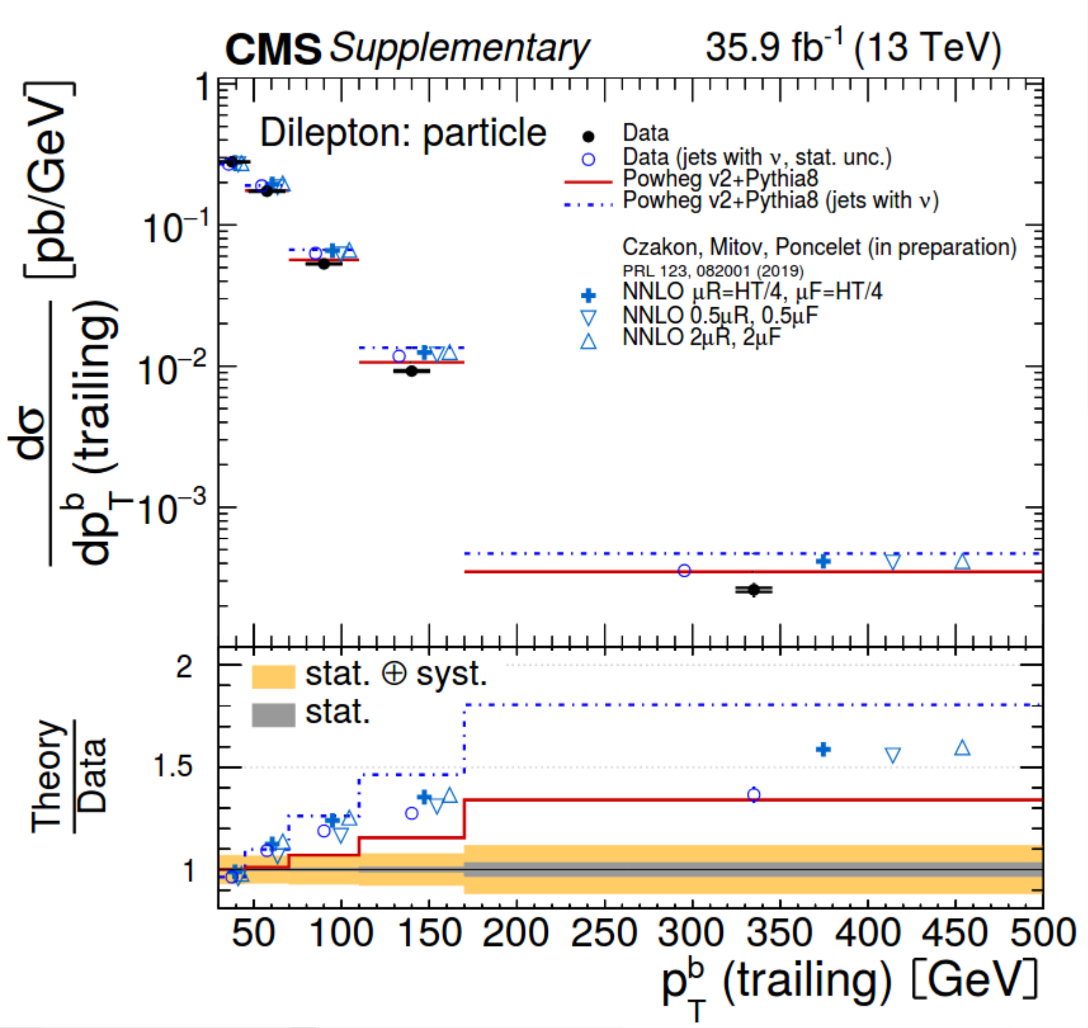
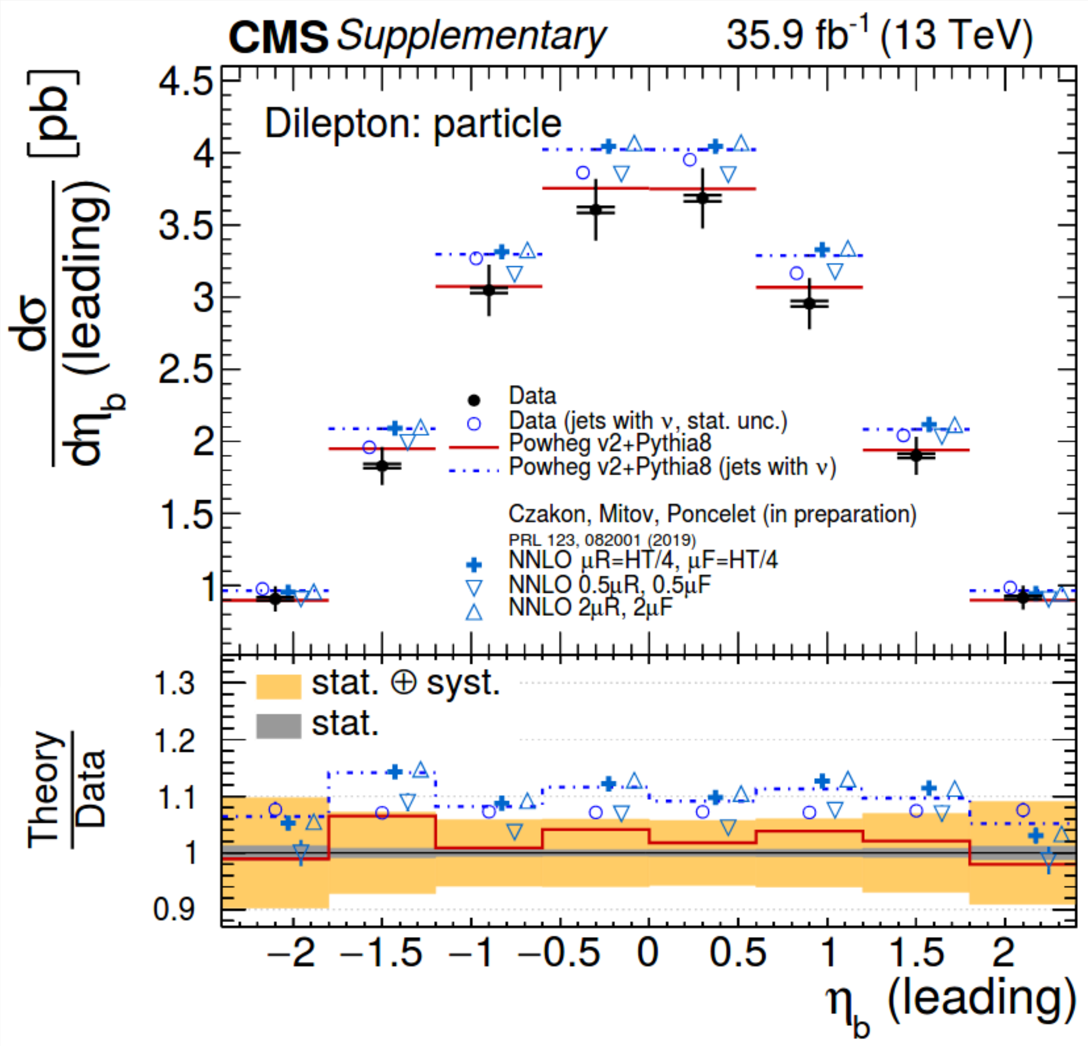
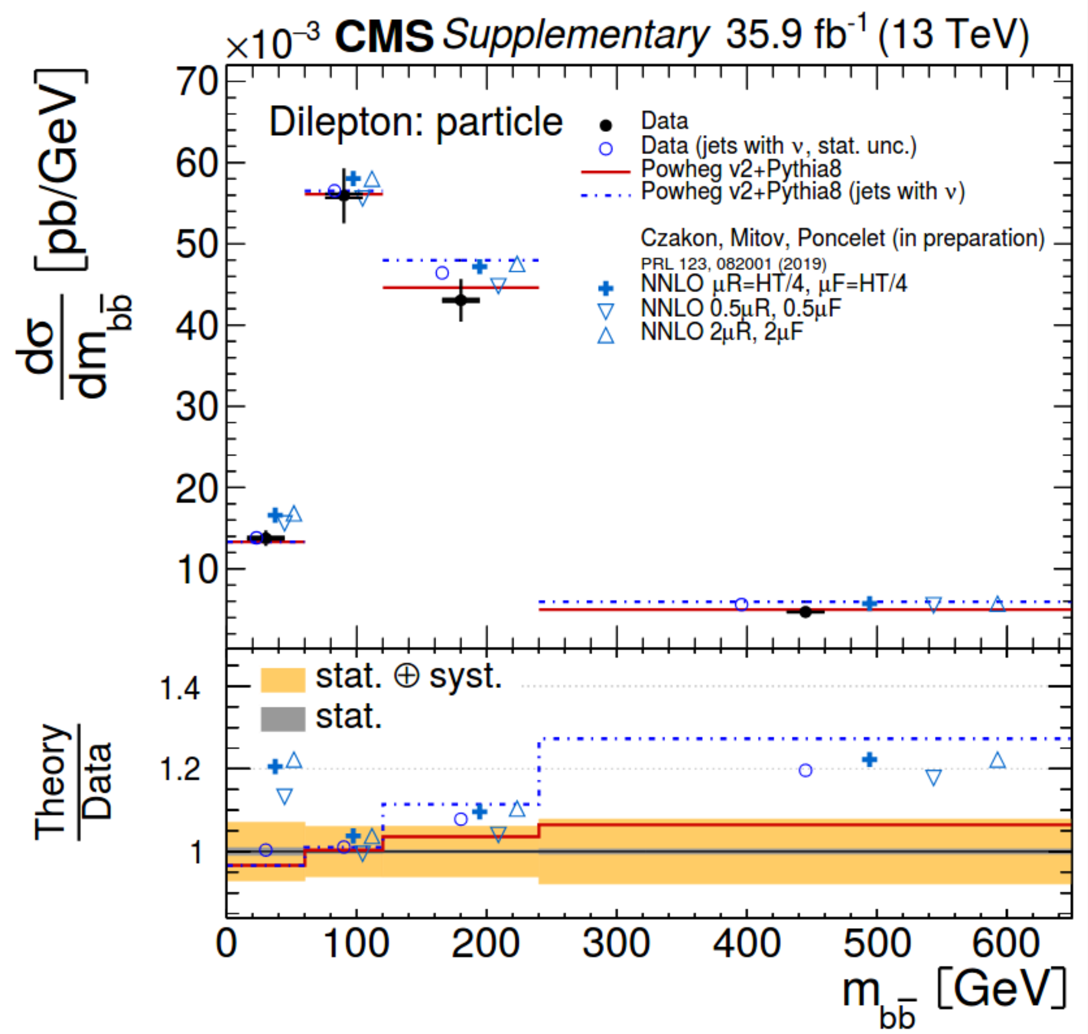
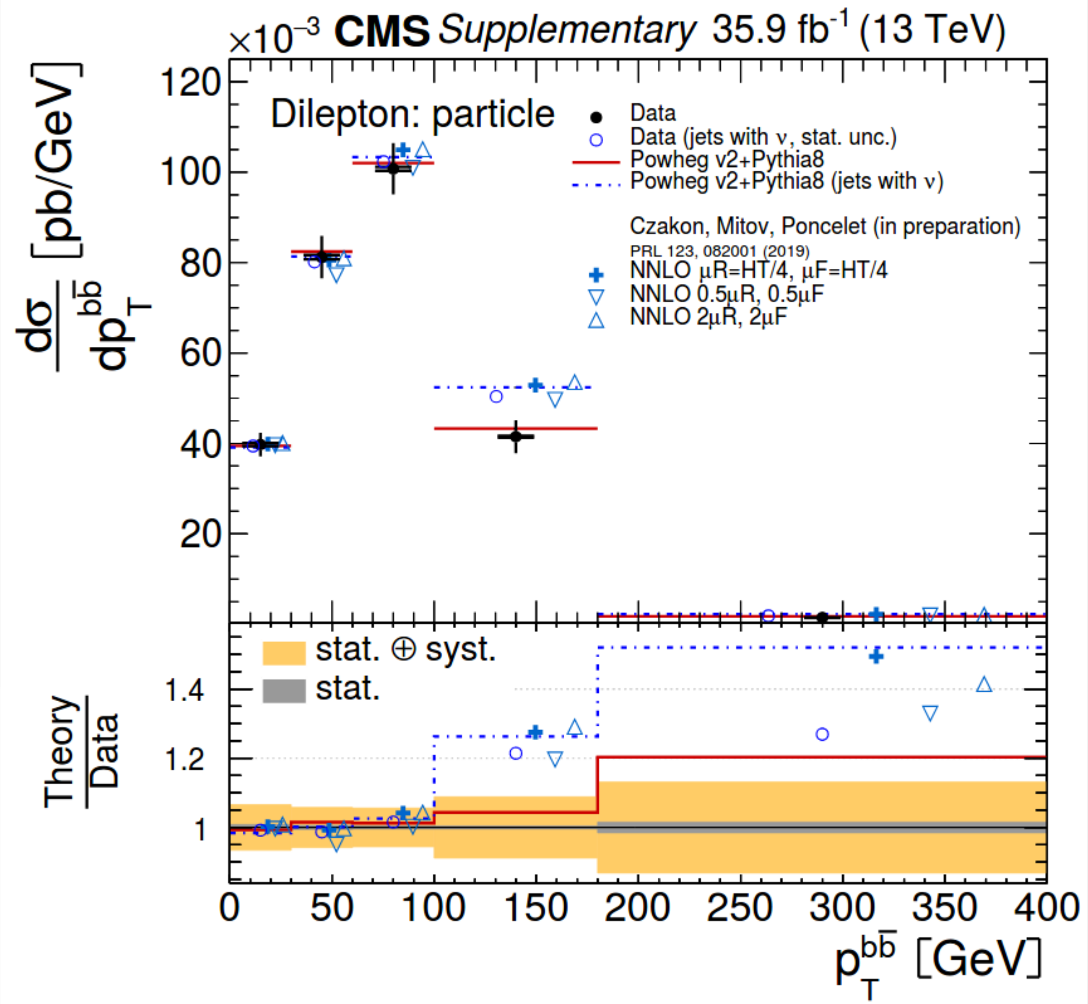
b-jet observables (absolute)



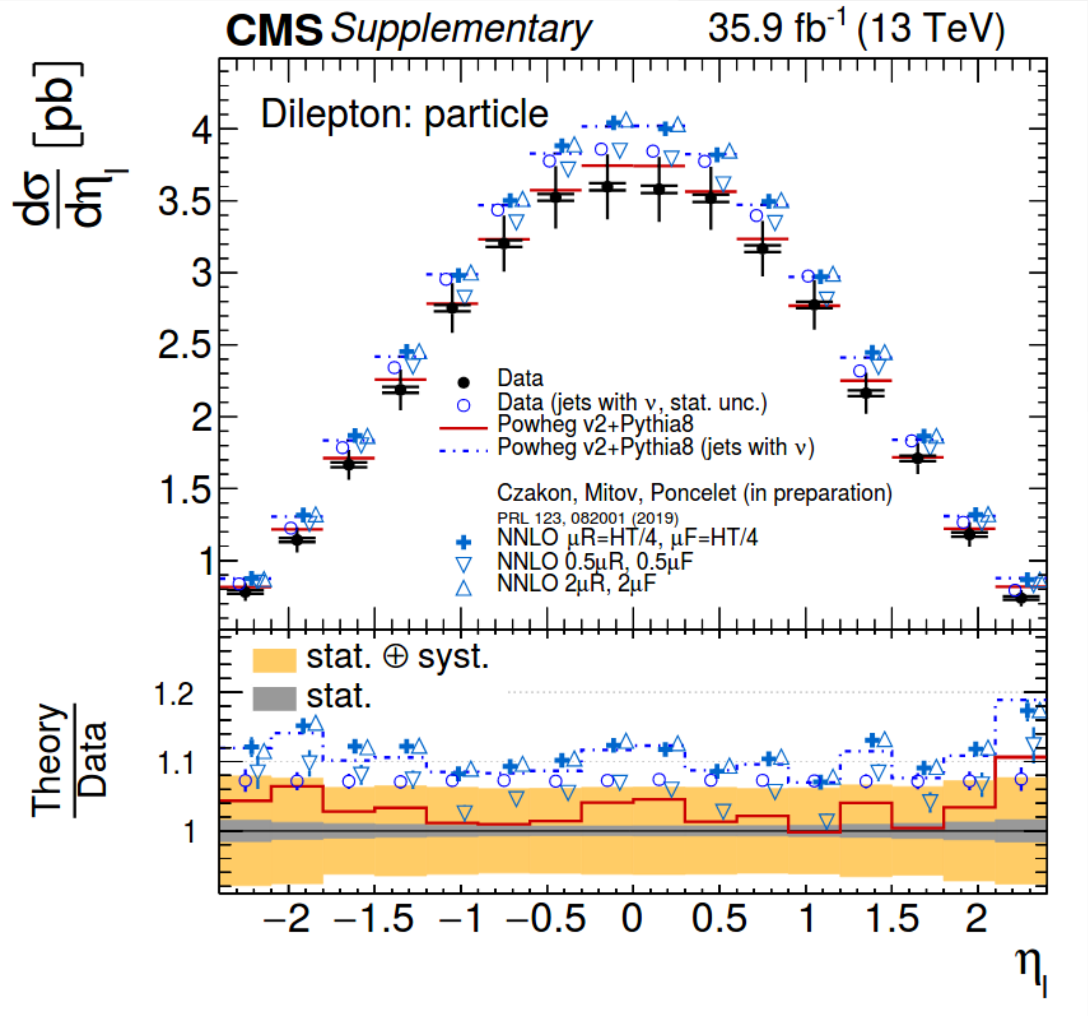


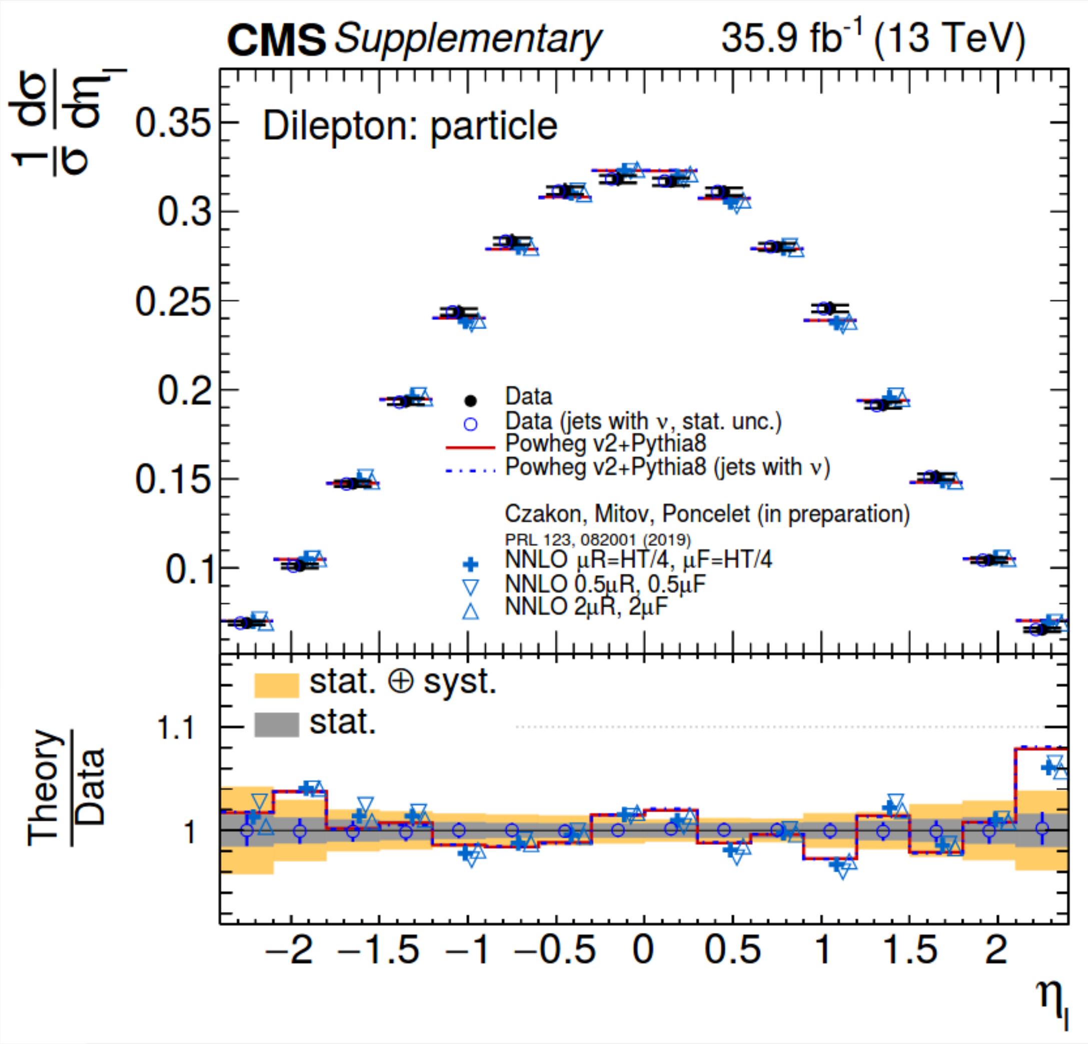
bbbar observables (absolute)





Lepton observables (absolute and normalized)





llbar observables (absolute)