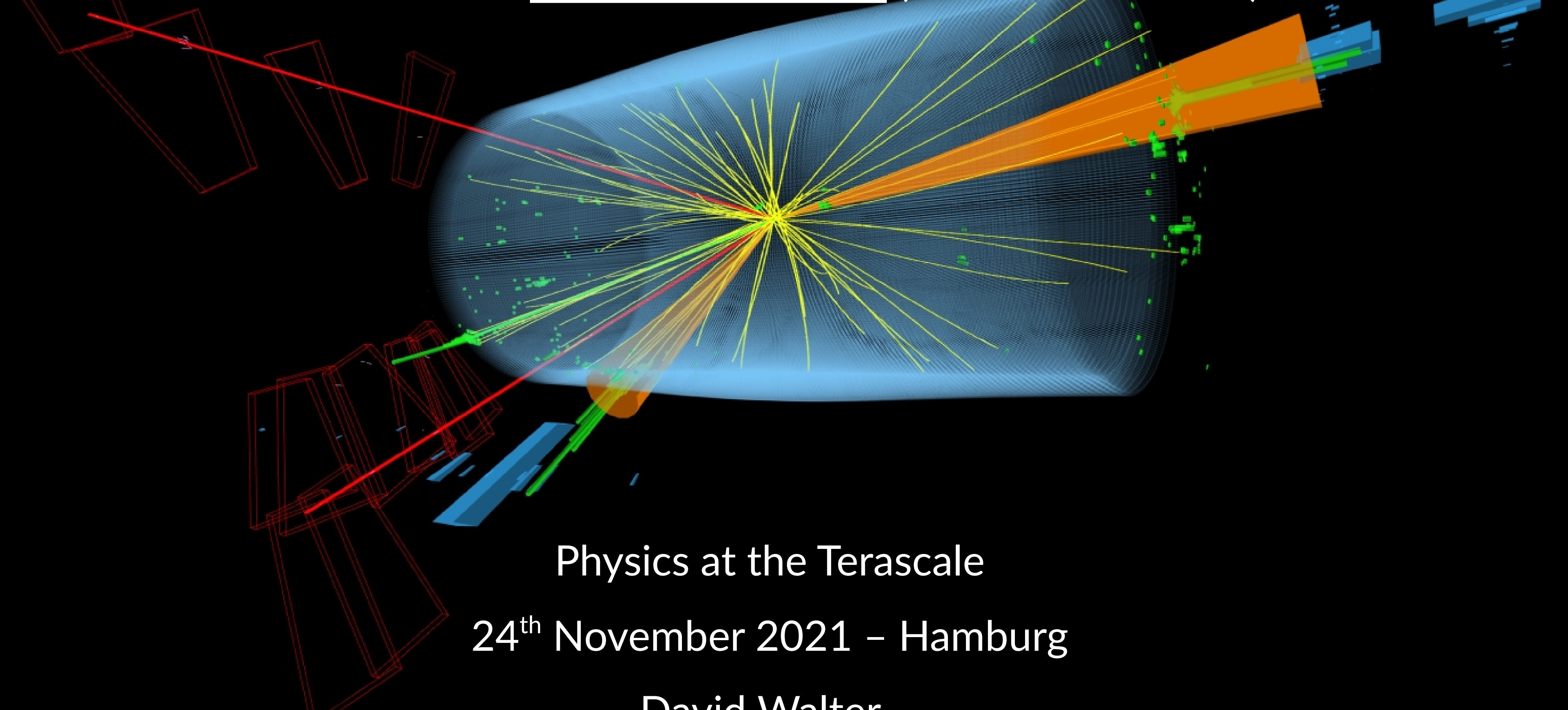
Inclusive & differential tZq measurements at √s = 13 TeV

Results from arXiv:2111.02860 (submitted to JHEP)



Physics at the Terascale

24th November 2021 – Hamburg

David Walter,
on behalf of the CMS collaboration

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

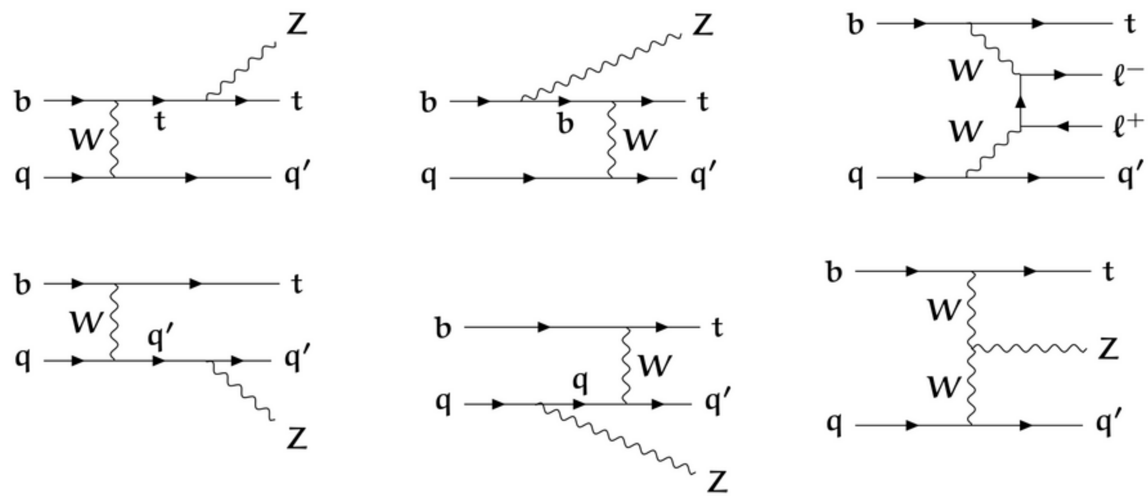
CMS

DESY.

Introduction

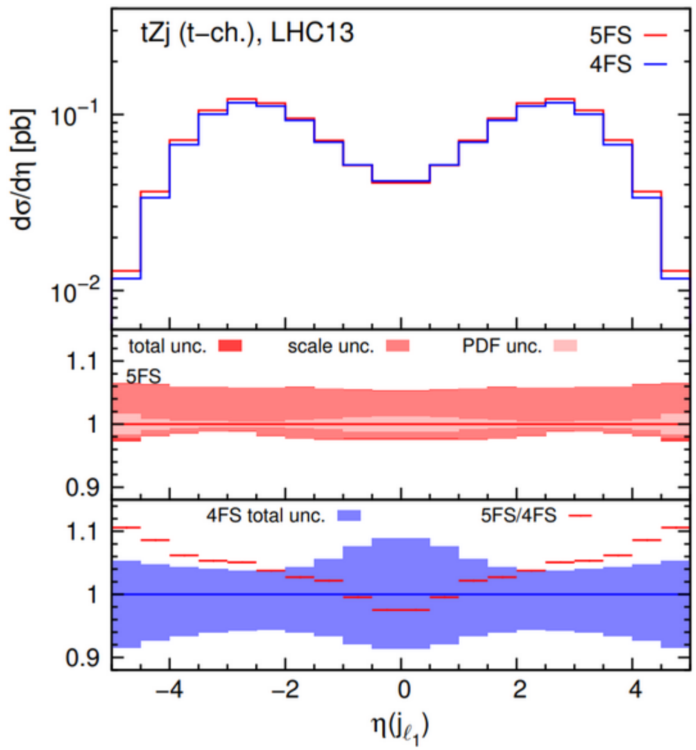
tZq process highly relevant

- Complementary to ttZ
- Rare couplings
- Electroweak produced
  - Polarized top quark



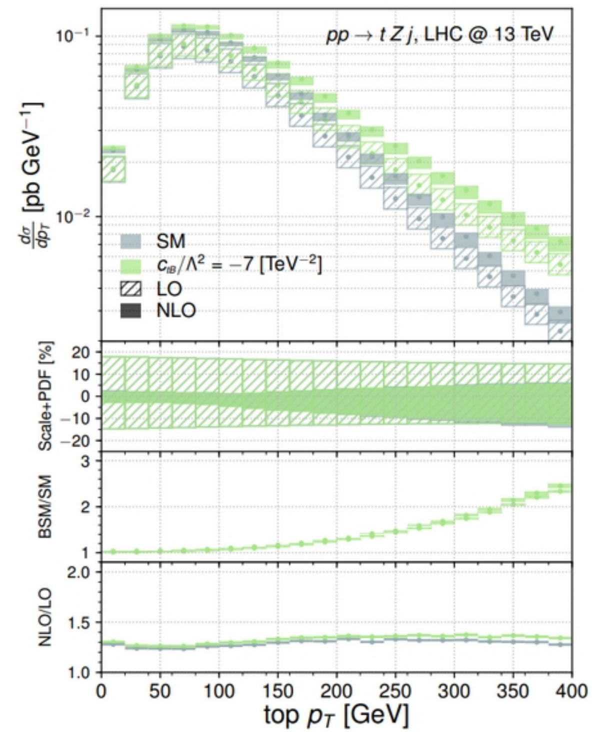
Different modeling aspects

(JHEP 08 (2020) 082)



Sensitive to EFT operators

(JHEP 10 (2018) 005)

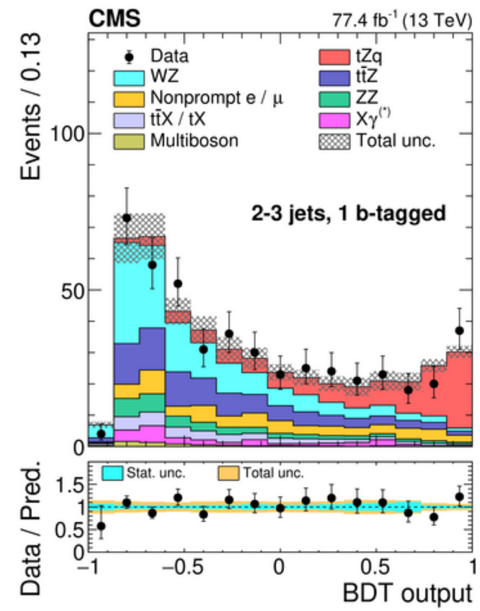


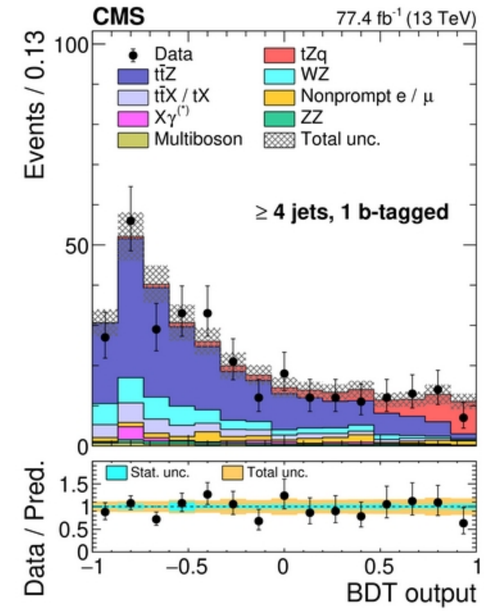
Introduction

Previous CMS measurement
(Phys. Rev. Lett. 122 (2019) 132003)

- Observation using partial Run-II data
- Inclusive cross section with ~15% precision

$$\sigma_{\mathrm{tZq}} = 111 \pm 13(\mathrm{stat.})^{+11}_{-9}(\mathrm{syst.})\mathrm{fb}$$



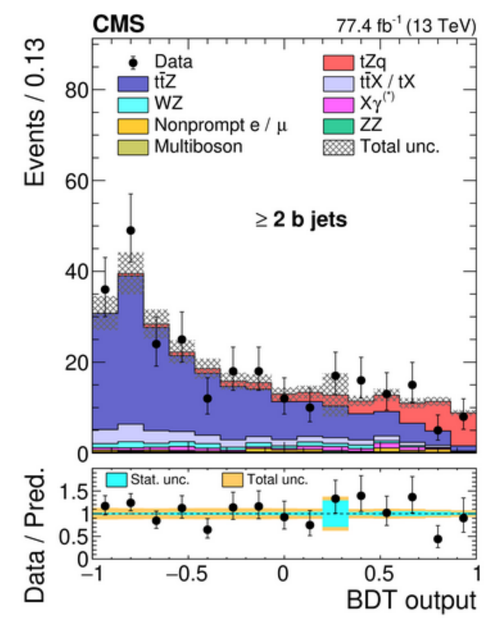


Theory (5FS) (Phys. Lett. B 779 (2018) 358)

$$\sigma_{\mathrm{tZq}} = 94.2 \pm 3.1(\mathrm{scale} + \mathrm{PDF})\mathrm{fb}$$

Today

- New result using full Run-II data
- Improved inclusive cross section
- First differential cross sections
- First measurement of the top quark spin asymmetry
  - Proportional to polarization

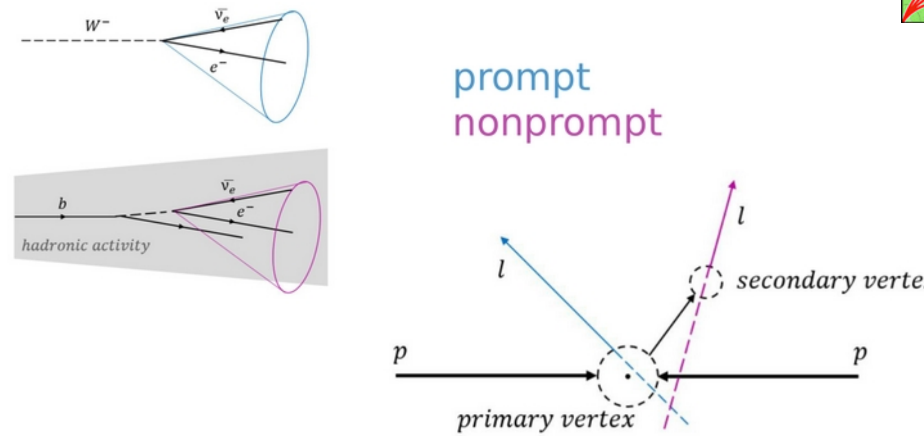


Event selection & reconstruction

Full Run-II data: 138 fb^{-1}

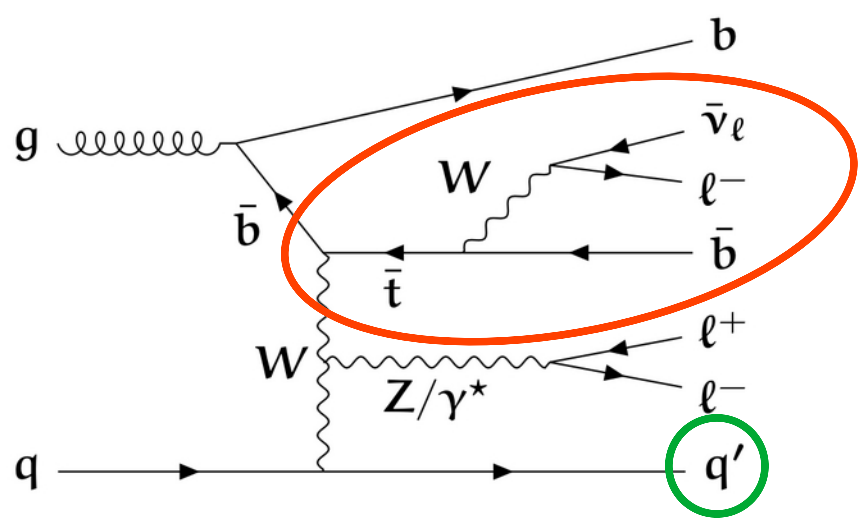
Three lepton final state (e/μ)

- Single/double/triple lepton triggers
- 3 Leptons $p_T > 25/15/10$ GeV
  - Improved prompt lepton MVA BDT
- OSSF lepton pair $|m_{ll} - m_Z| < 15$ GeV
- ≥ 2 Jets $p_T > 25$GeV $|\eta| < 5$
- ≥ 1 b-jet DeepJet: ε ≈ 85% MT ≈ 1% [gluon or u,d,s quark] 15% [c quark]

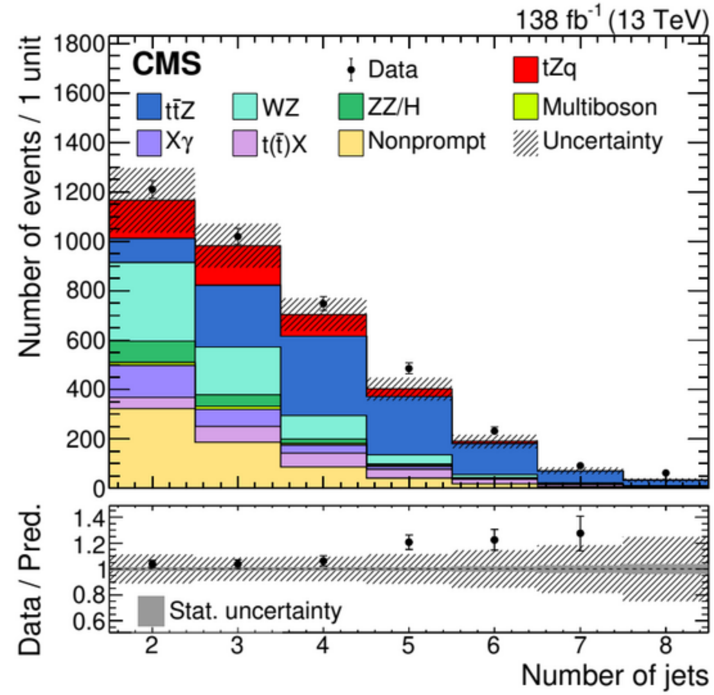


Analytic event reconstruction

- **Top quark**
  - E_T^{miss} from neutrino
  - W mass constraint → neutrino p_z
  - Choose b jet for best top mass
- **Recoiling jet**
  - Non b tagged jet with max p_T



Backgrounds



Different backgrounds in the signal region

Defined four control regions to:

- Verify modeling
- Constrain related uncertainties in fit

WZ:

- 0 b-jets

ttZ:

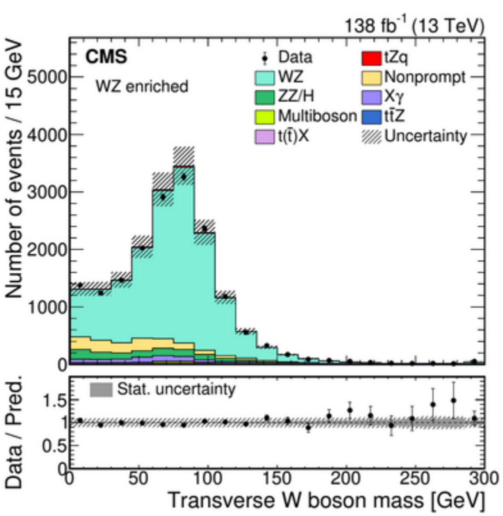
- 4 leptons
- ≥ 2 jets
- 1 Z candidate

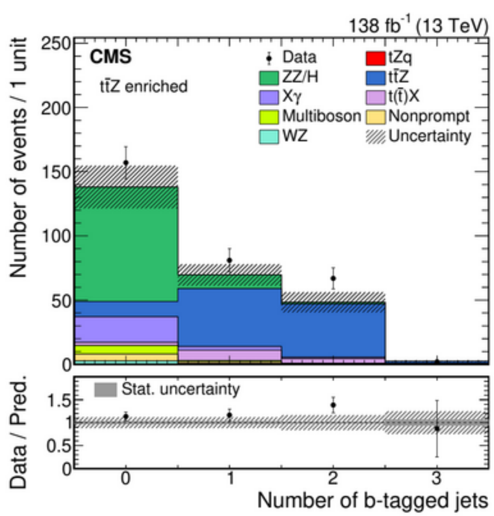
ZZ:

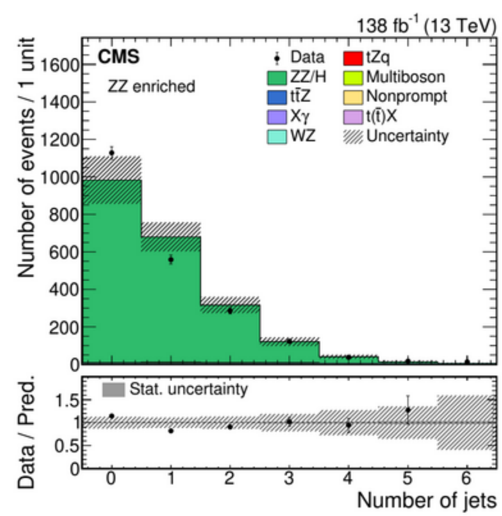
- 4 leptons
- 2 Z candidate

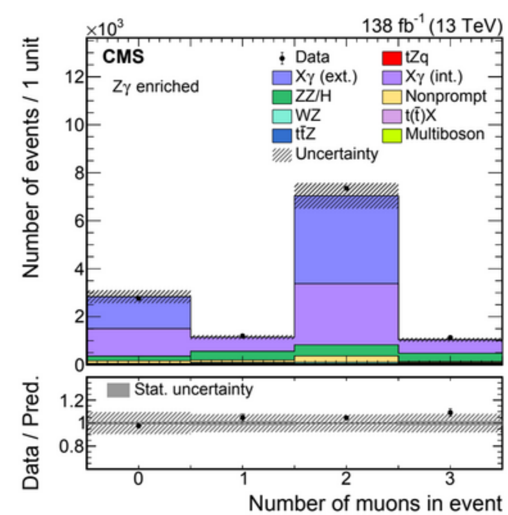
Zɣ:

- No Z candidate
- 3l Z candidate





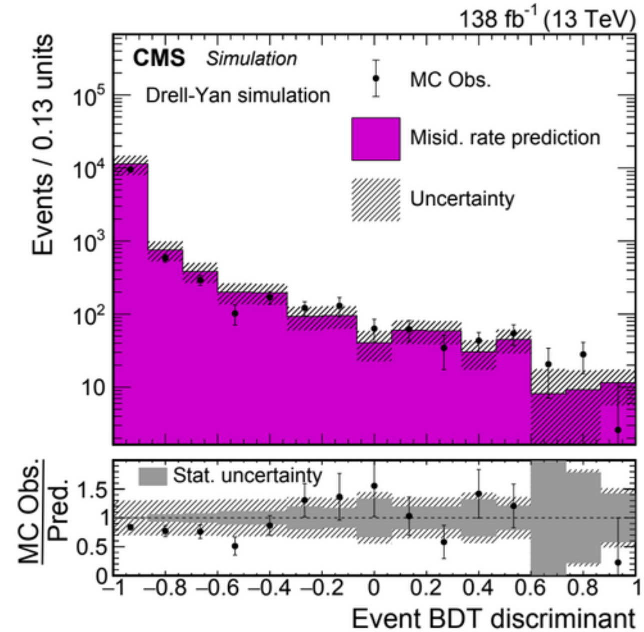


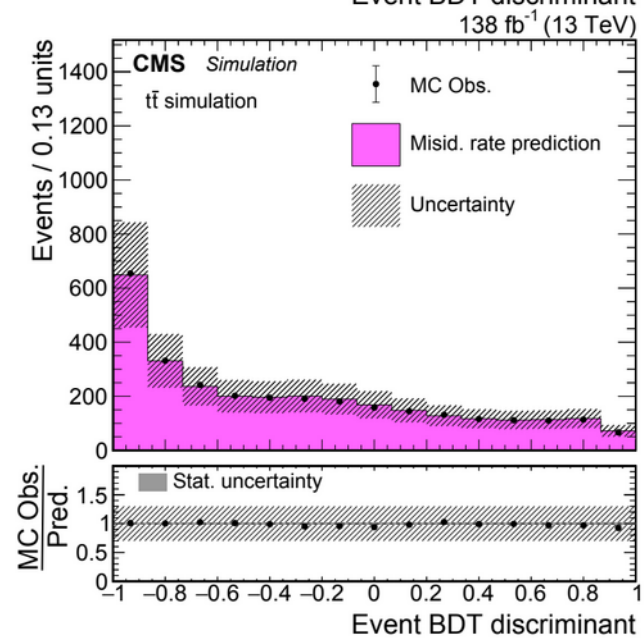


Backgrounds with nonprompt leptons

Data driven estimation using fake factors

- Probability for nonprompt lepton to pass ID
  - Measured in multijet enriched region
- Fake factors applied on data in sideband region
- Closure test in MC
  - Ensure measured fake factor can be applied to sideband region

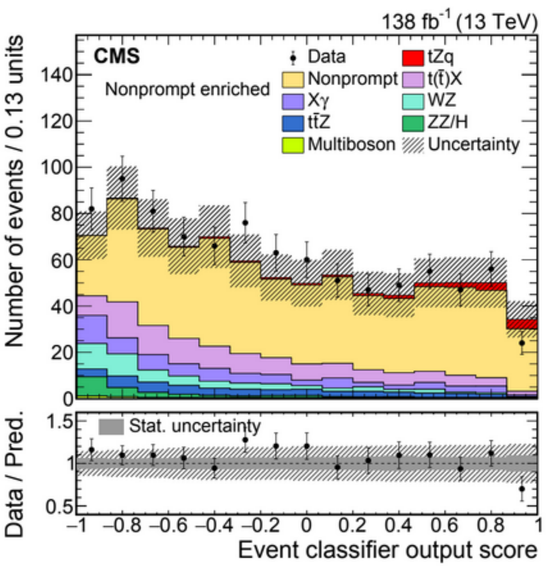


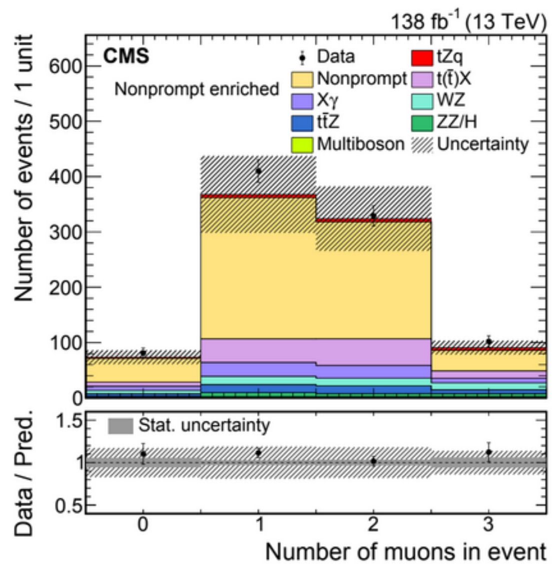


Validated in control region

Nonprompt:

- 1 b-jets, 2/3 jets, no Z candidate





→ Control region used in signal extraction

Signal extraction

MVA to isolate tZq

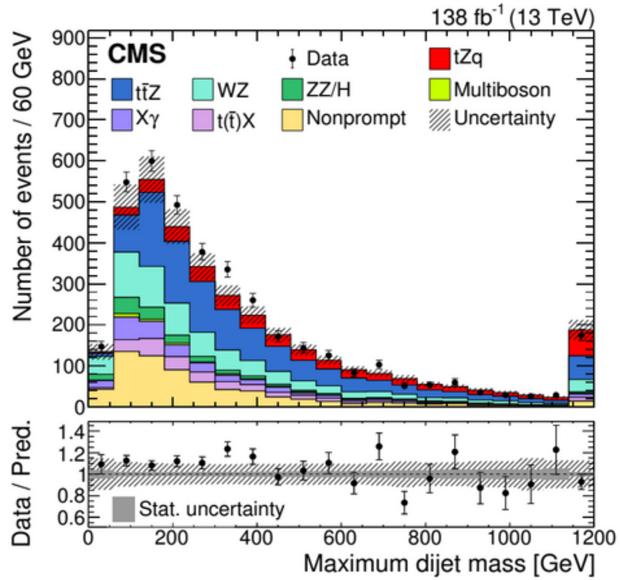
- Discriminating features related to
  - Recoiling jet
  - N_{jets} & $N_{b\text{-}jets}$
  - Z & top candidate
  - …

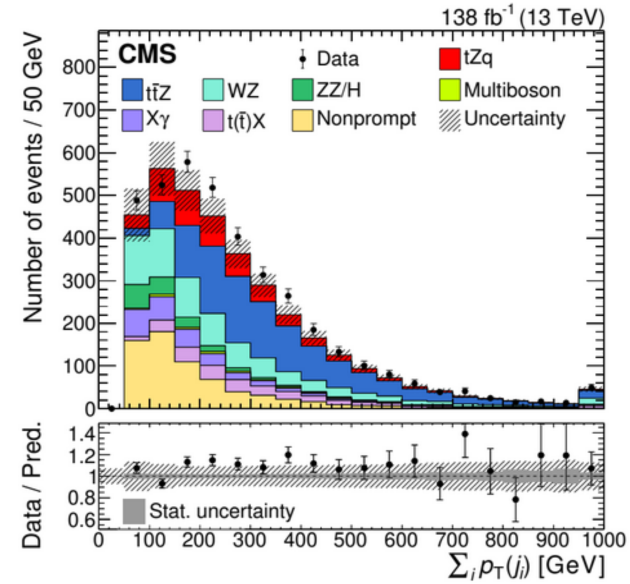
Inclusive:

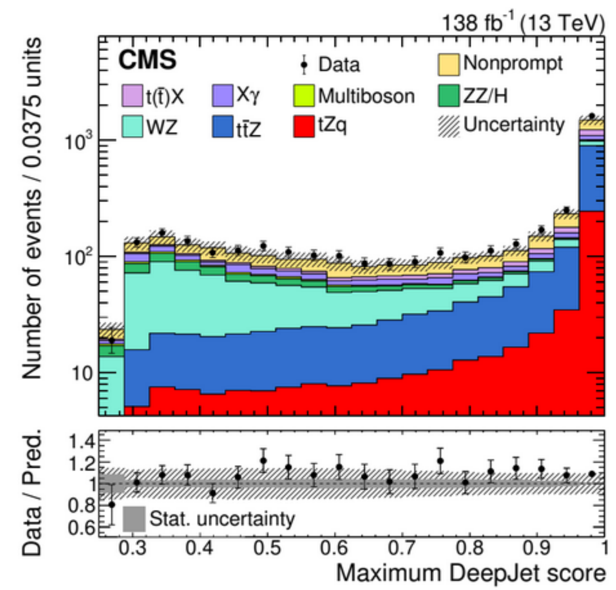
- BDT with 16 input variables

Differential:

- Multiclass NN with 22 input variables
- 5 classes for different backgrounds



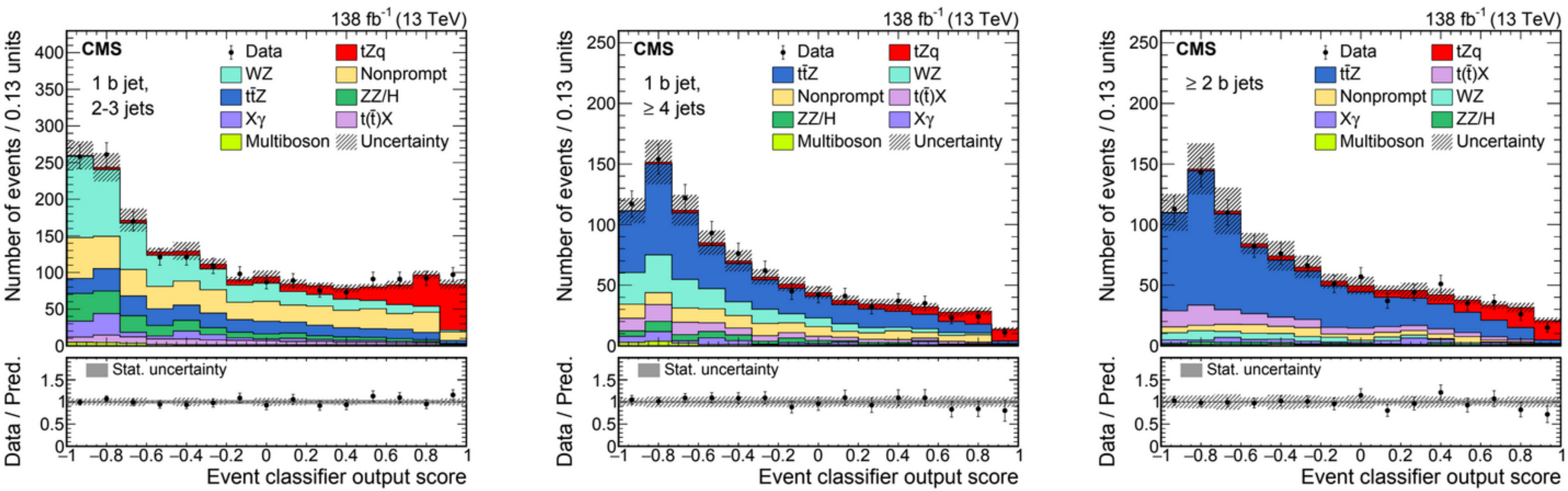




Inclusive cross section

Inclusive cross section measured with maximum likelihood fit

- BDT output in N_{jets} & $N_{b\text{-}jets}$ categories



Results:

$$\sigma_{\mathrm{tZq}} = 87.9^{+7.5}_{-7.3}(\mathrm{stat})^{+7.3}_{-6.0}(\mathrm{syst})\mathrm{fb}$$

~11% uncertainty

Also measured: Charge ratio

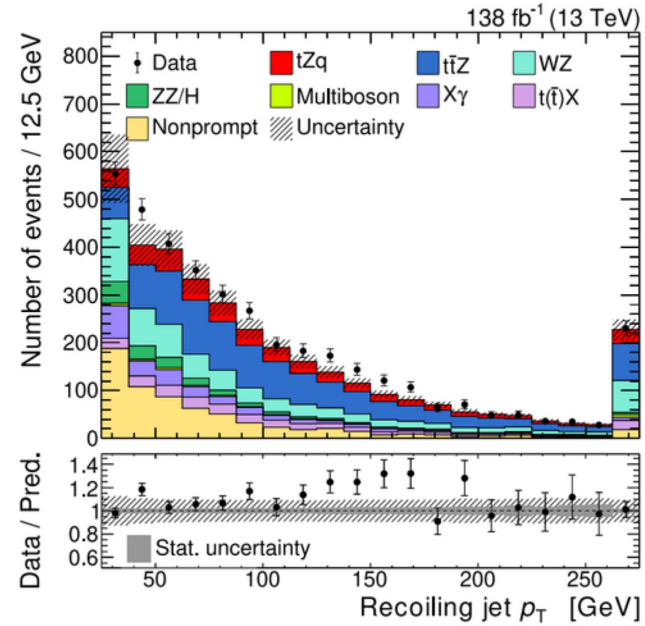
$$R = \frac{\sigma_{\mathrm{tZq}(\ell_t^+)}}{\sigma_{\bar{\mathrm{t}}\mathrm{Zq}(\ell_t^-)}} = 2.37^{+0.56}_{-0.42}(\mathrm{stat})^{+0.27}_{-0.13}(\mathrm{syst})$$

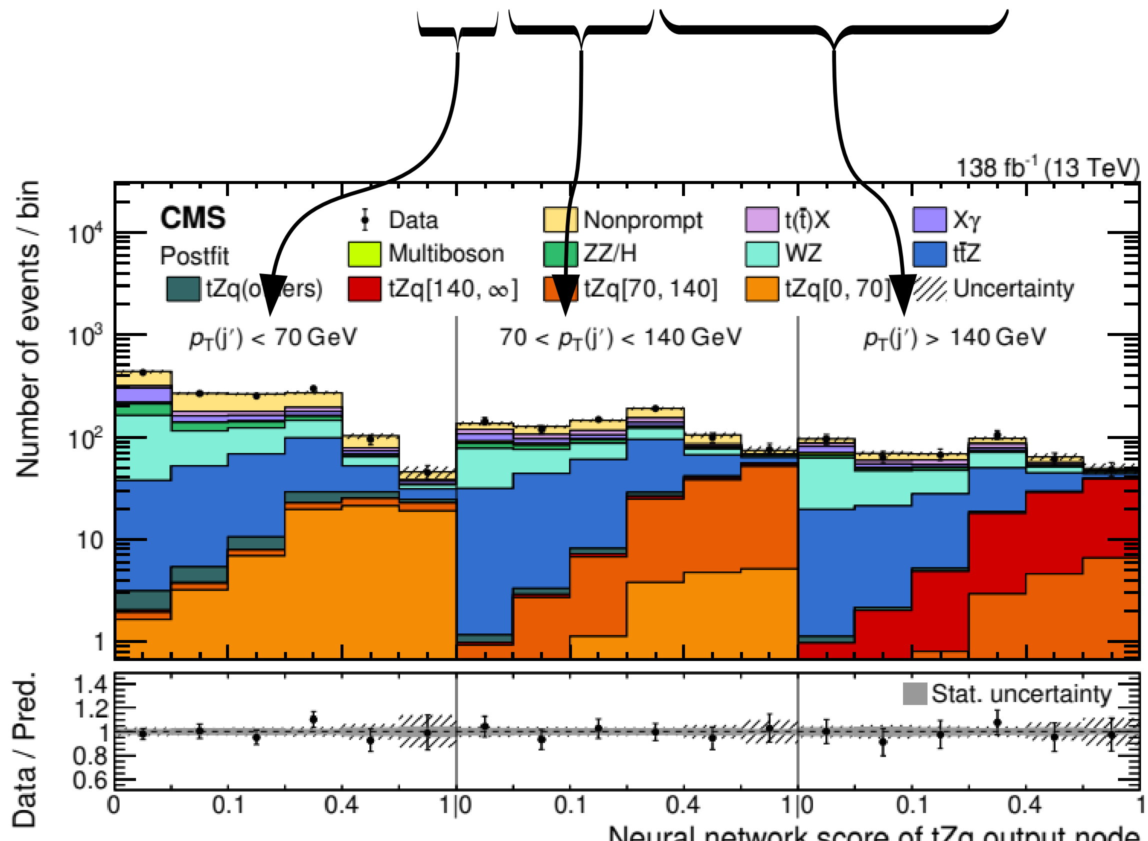
Likelihood based unfolding

Multidimensional likelihood

- Separate signal template for each generator level bin
- Fit histogram binned in observable x NN tZq score
- Including control regions

Unregularized profile likelihood fit





Directly accounted for

- Bin to bin migrations
- Background subtraction
- Systematic and statistic uncertainties

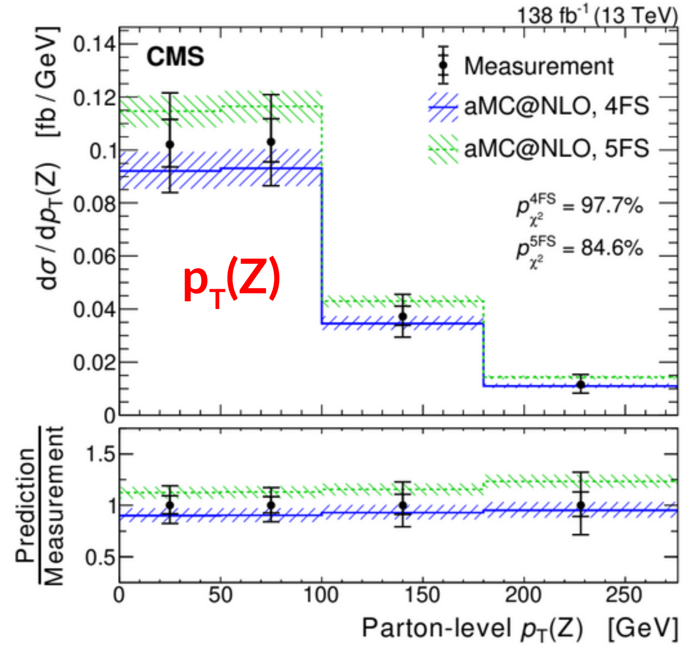
Differential cross sections

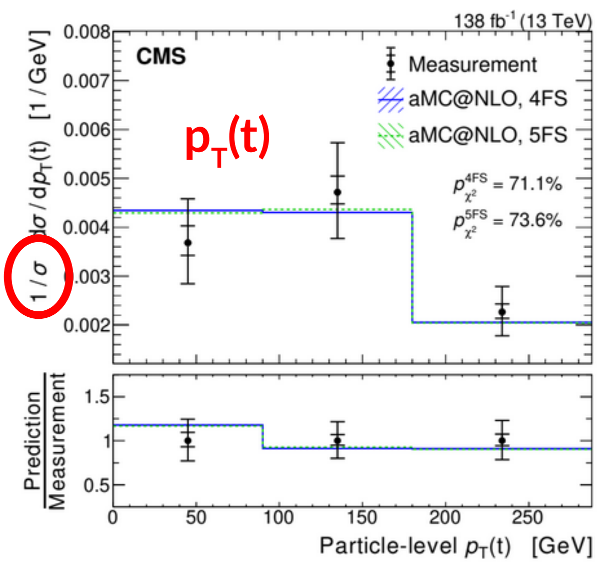
9 Observables chosen for
- Sensitivity to BSM physics
- Modeling aspects
- Measuring properties

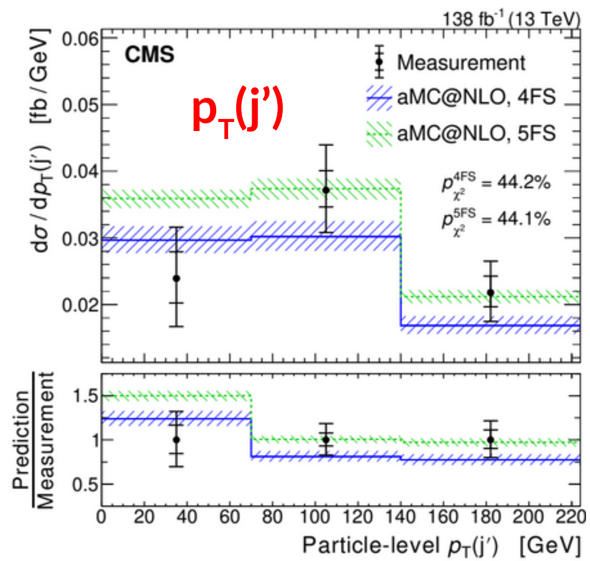
Parton & particle level, absolute & normalized

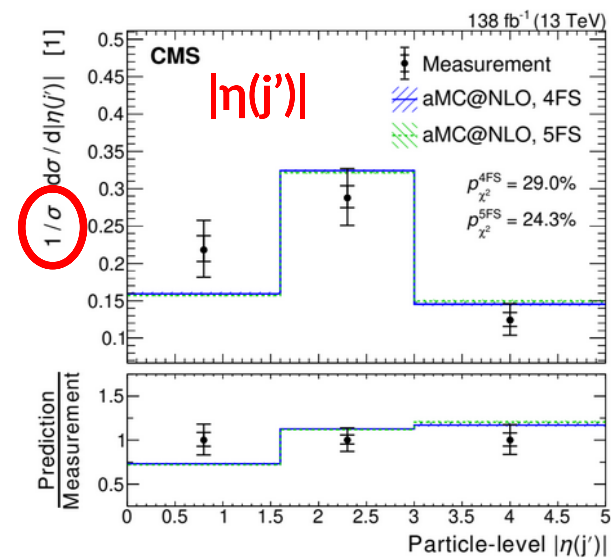
Precision in each bin
- Down to 15% for leptonic observabels
- Down to 20% for observables including jets

Compared to **4FS** & **5FS** simulation
- Yet not sensitive to differences





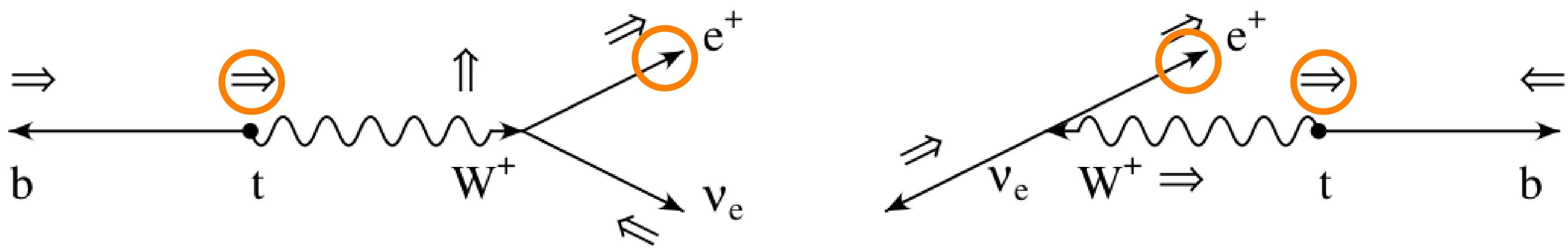




Top quark spin asymmetry

Electroweak produced top quarks

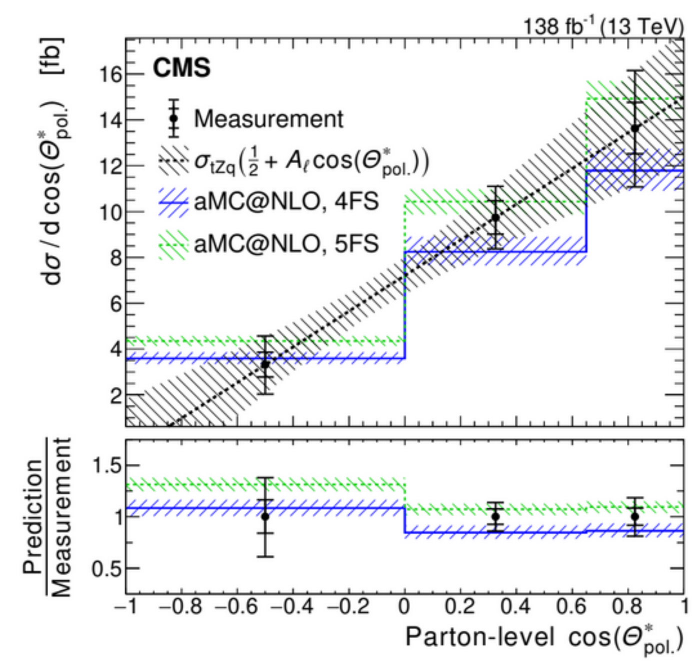
- Polarized
- Sensitive to anomalous couplings



- Lepton from top quark prefers to travel along direction of top quark spin
- Top quark travels in opposite direction of light flavored quark / recoiled jet
- Spin asymmetry measured in "optimized basis"

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\cos(\theta^\star_{\mathrm{pol}})} = \sigma_{\mathrm{tZq}}\left(\frac{1}{2} + A_\ell \cos(\theta^\star_{\mathrm{pol}})\right)$$

$$\cos(\theta^\star_{\mathrm{pol}}) = \frac{\vec{p}(\mathrm{q}'^\star)\cdot\vec{p}(\ell^\star_{\mathrm{t}})}{|\vec{p}(\mathrm{q}'^\star)|\,|\vec{p}(\ell^\star_{\mathrm{t}})|}$$



Reparameterized likelihood function

- Extracted directly in fit

$$A_\ell = 0.54 \pm 0.16(\mathrm{stat}) \pm 0.06(\mathrm{syst})$$

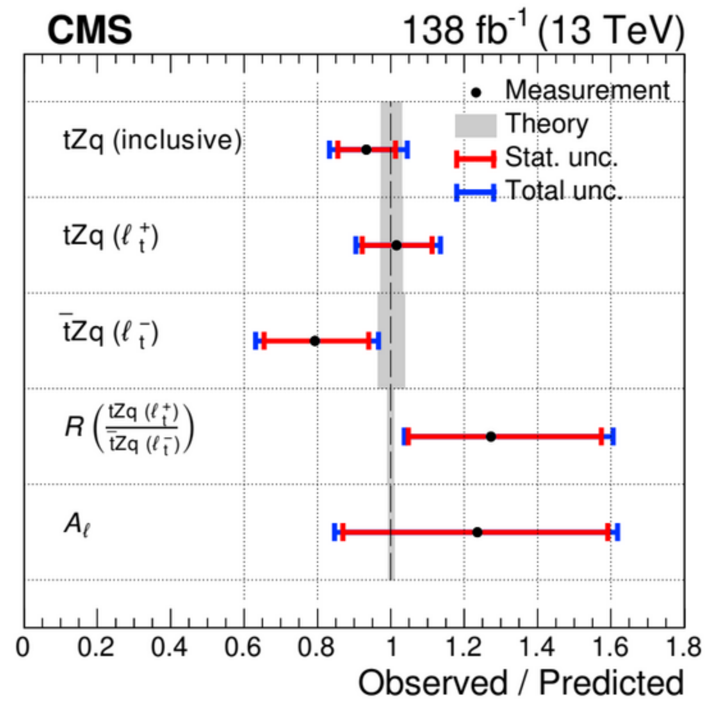
Summary & conclusion

Most precise inclusive cross section measurement
- Including charge ratios

First differential cross section measurement
First measurement of the top quark spin asymmetry

Still statistically dominated
- Significant systematic contribution

Overall good agreement with SM predictions



Higher statistics from Run 3 highly beneficial for this analysis: stay tuned!

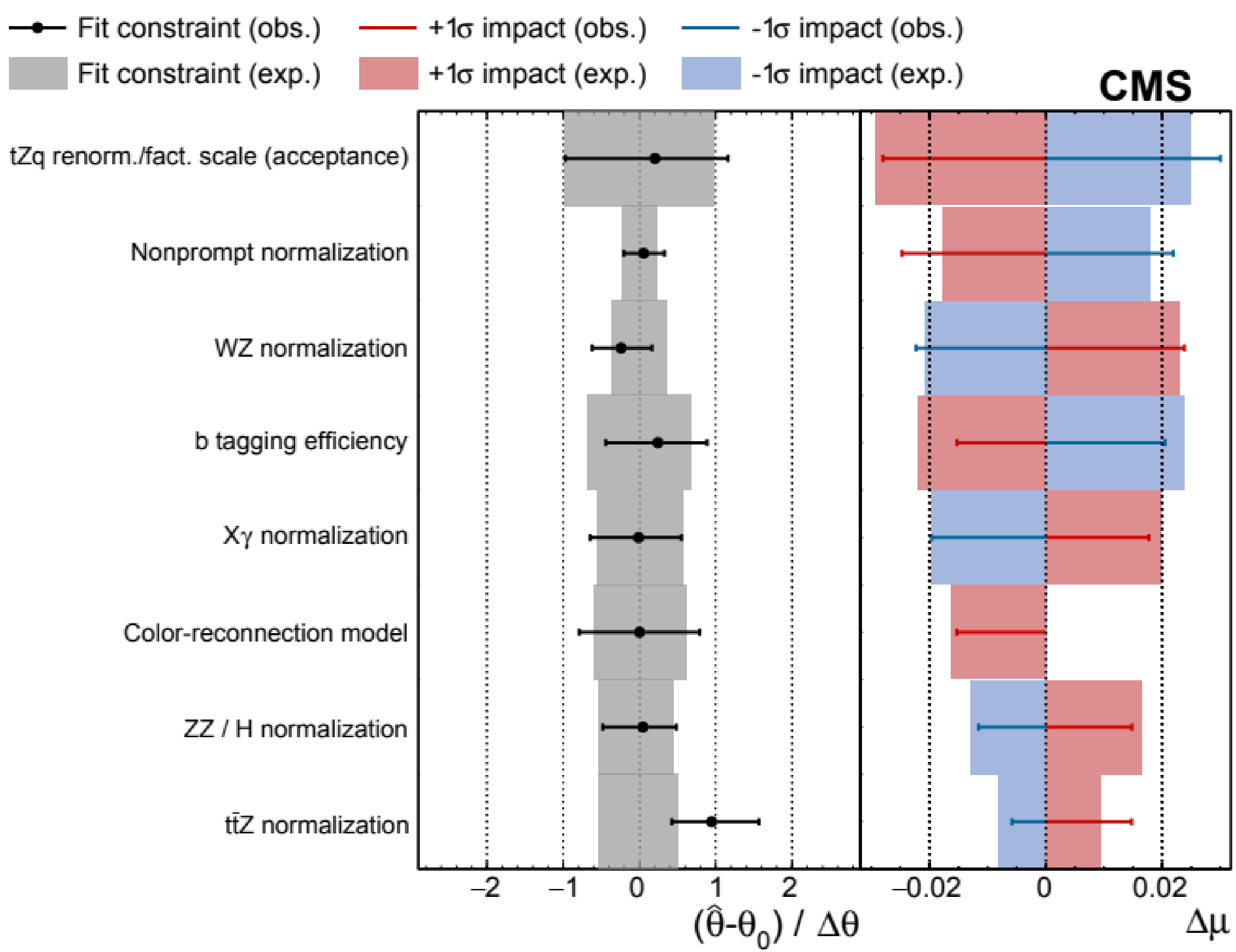
Thanks!

BACKUP

Inclusive cross section

Leading systematic uncertainties

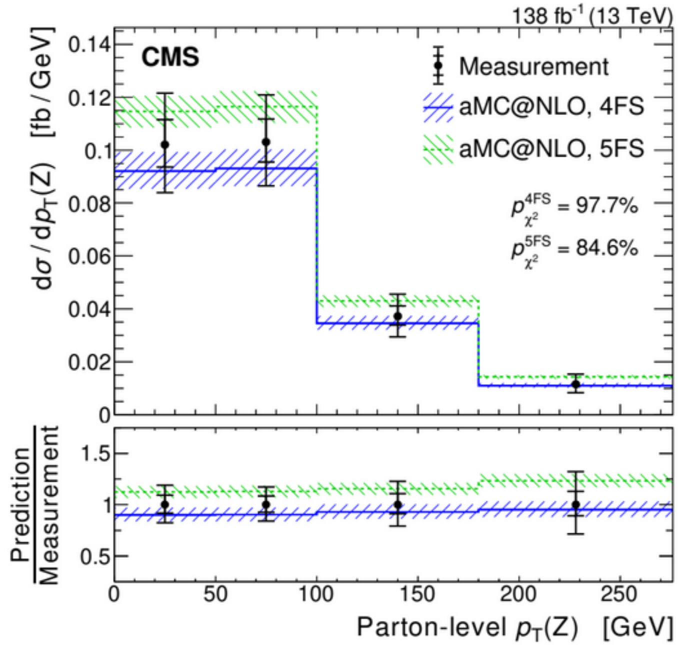
- Matrix element μ_R & μ_F
- Nonprompt background normalization constrained by control region

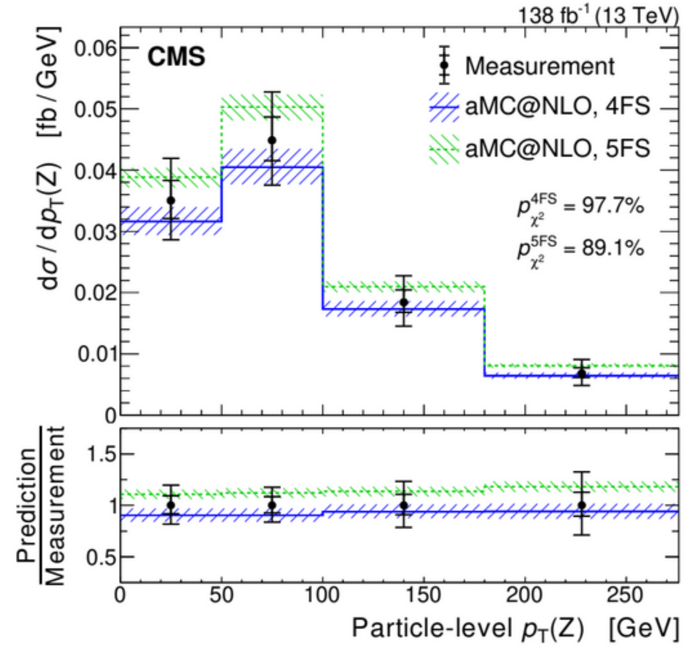


$p_T(Z)$

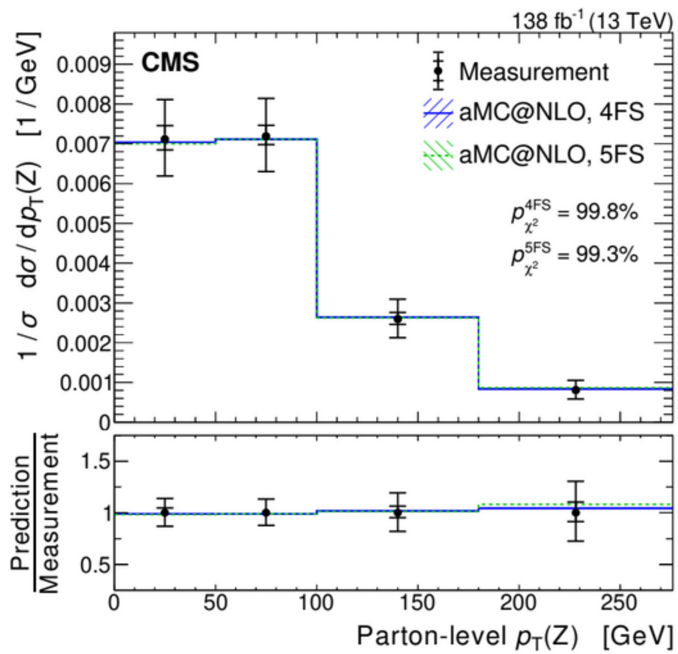
parton level | particle level

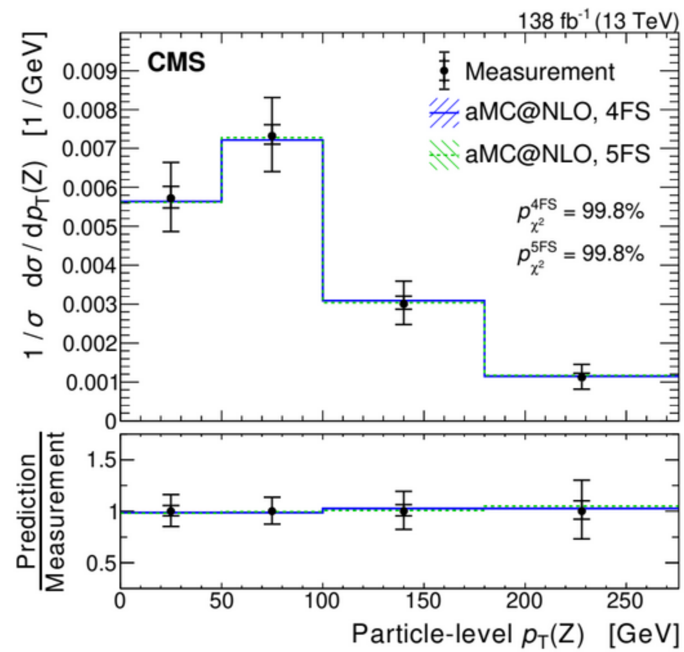
absolute





normalized

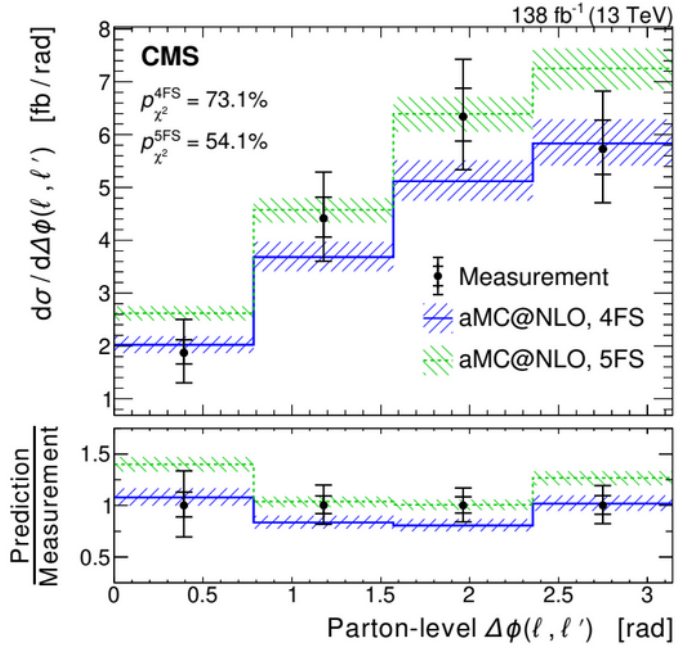


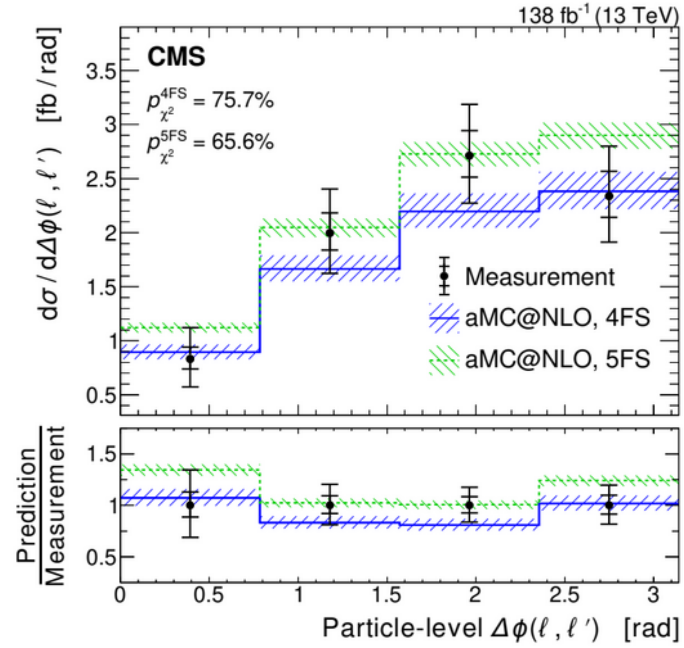


Δϕ(l,l)

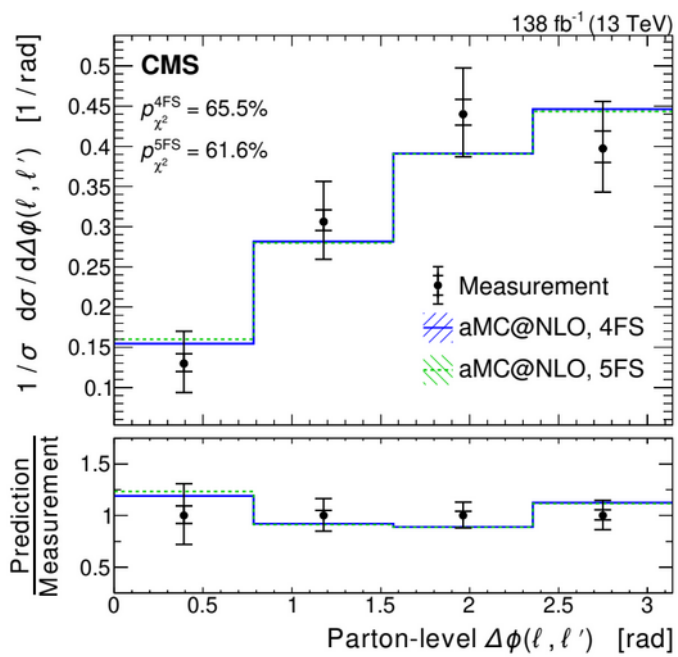
parton level | particle level

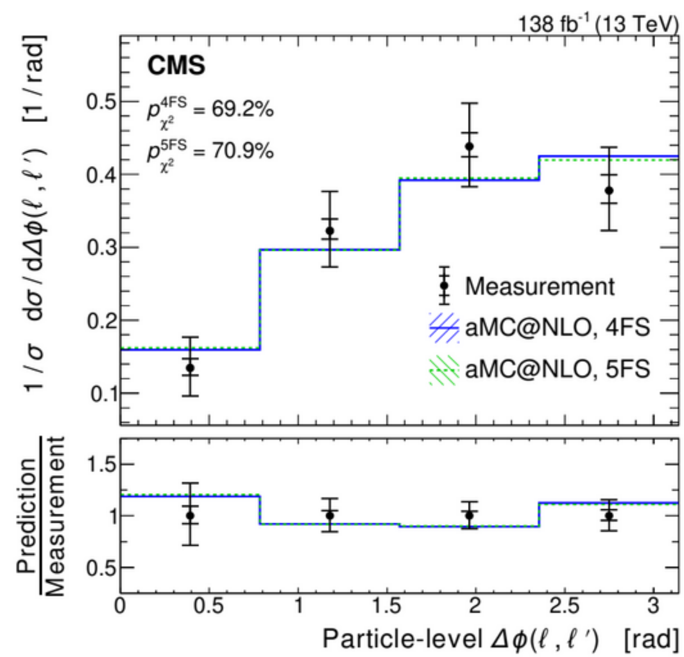
absolute





normalized



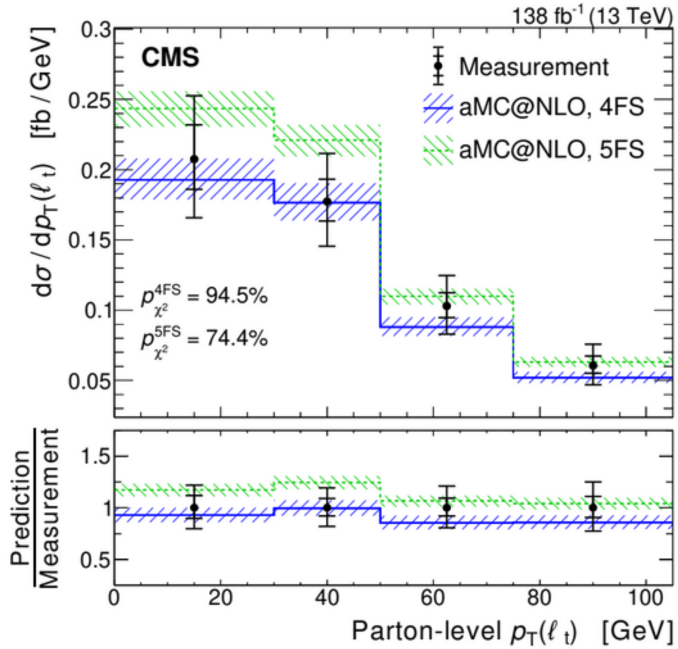


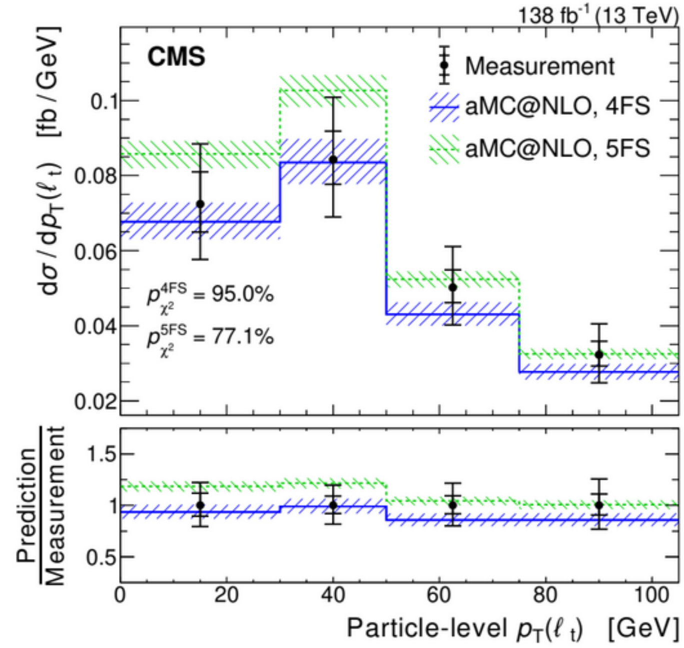
$p_T(l_t)$

parton level

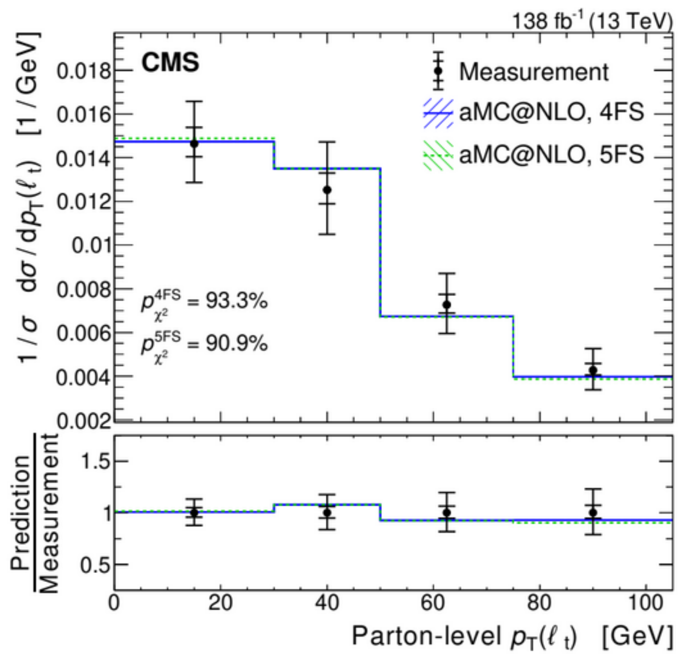
particle level

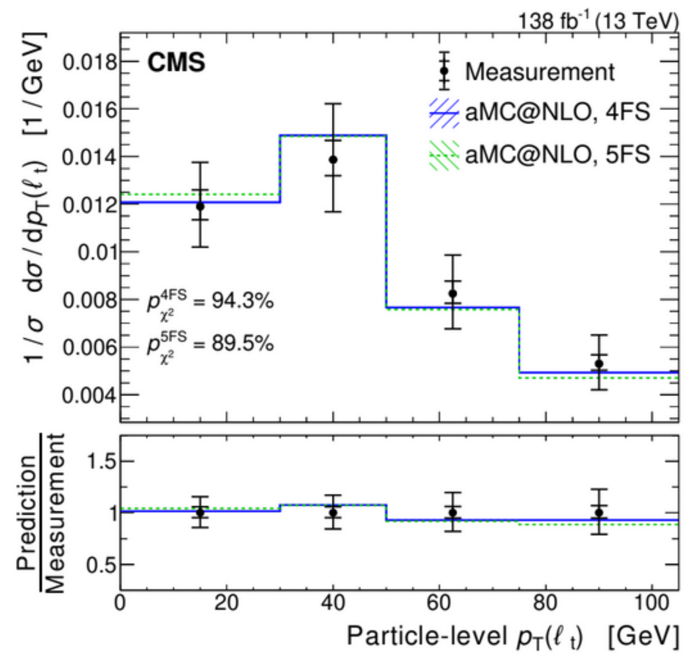
absolute





normalized



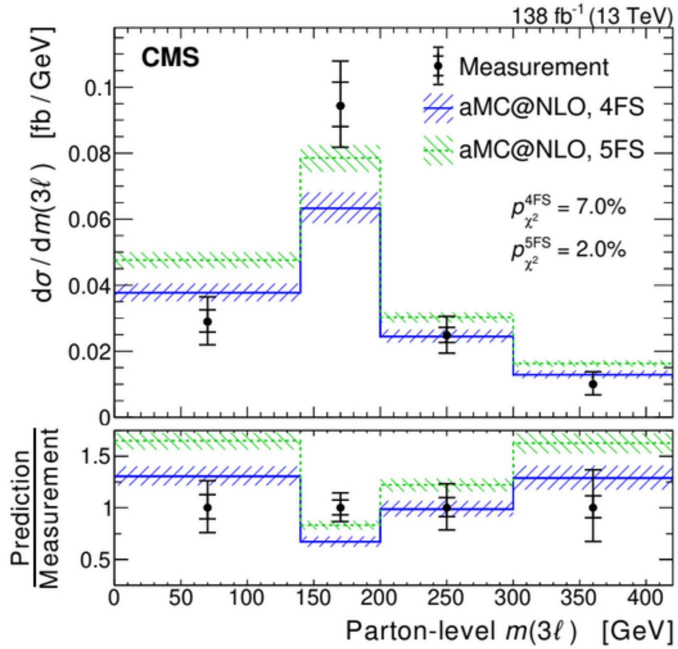


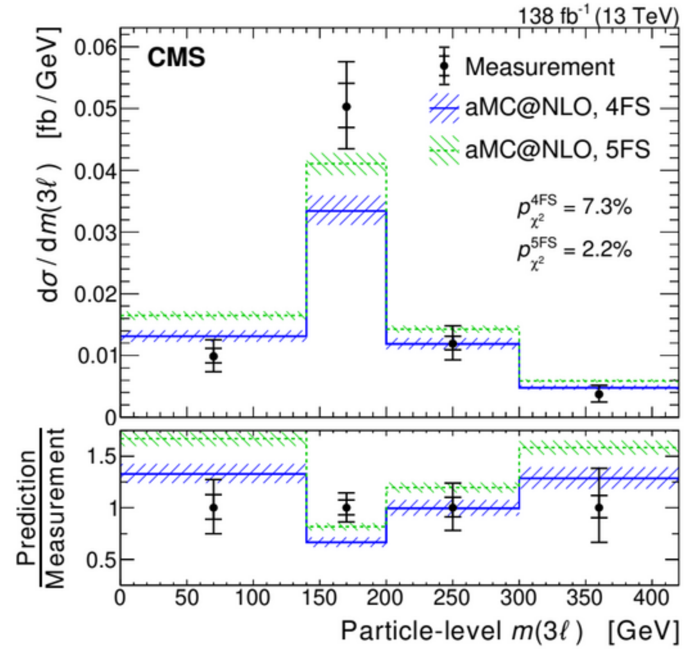
m(3l)

parton level

particle level

absolute





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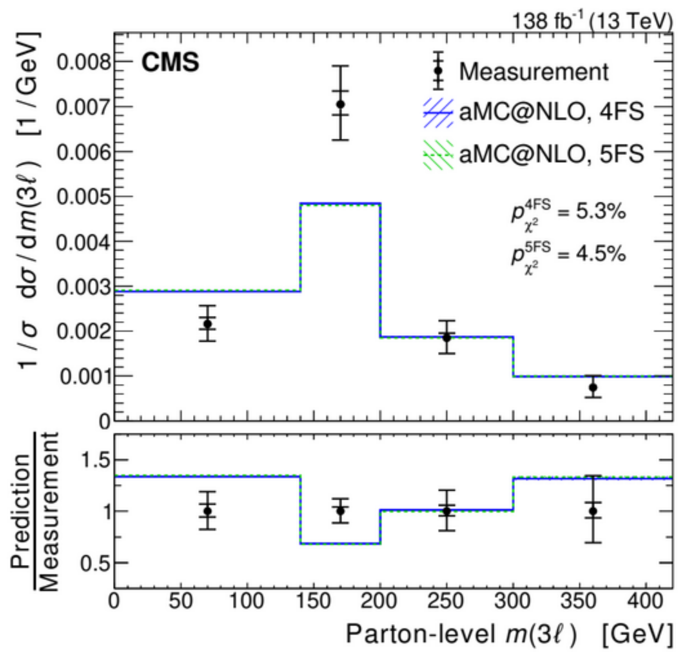
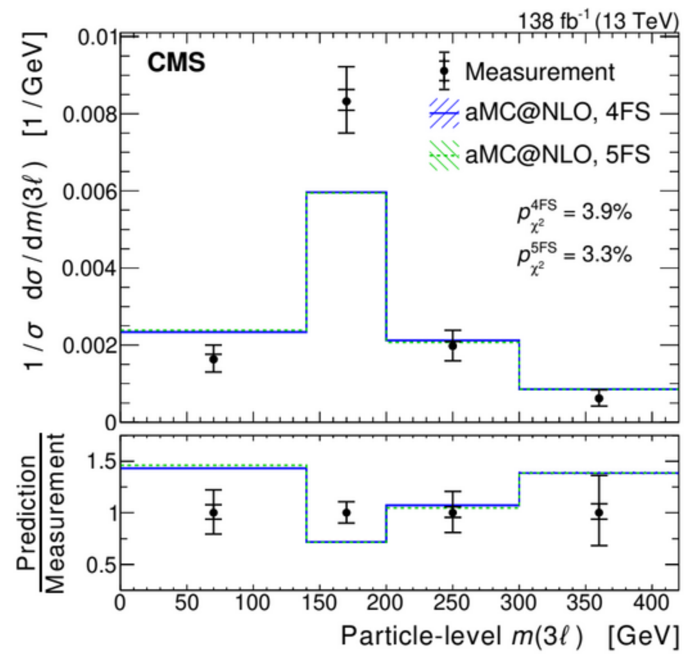
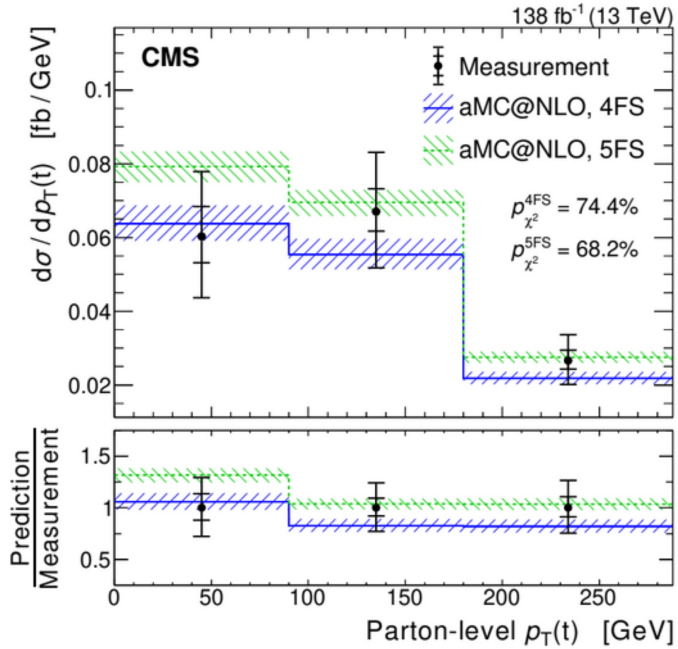


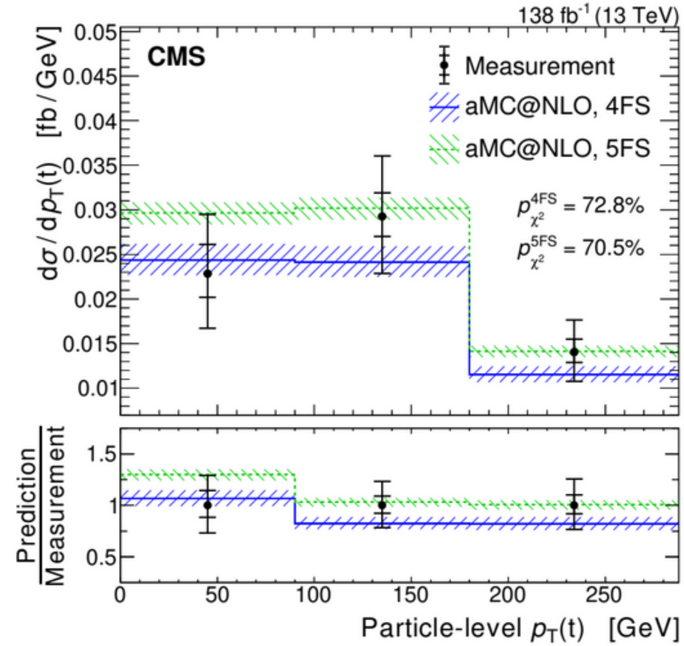


$p_T(t)$

parton level | particle level

absolute





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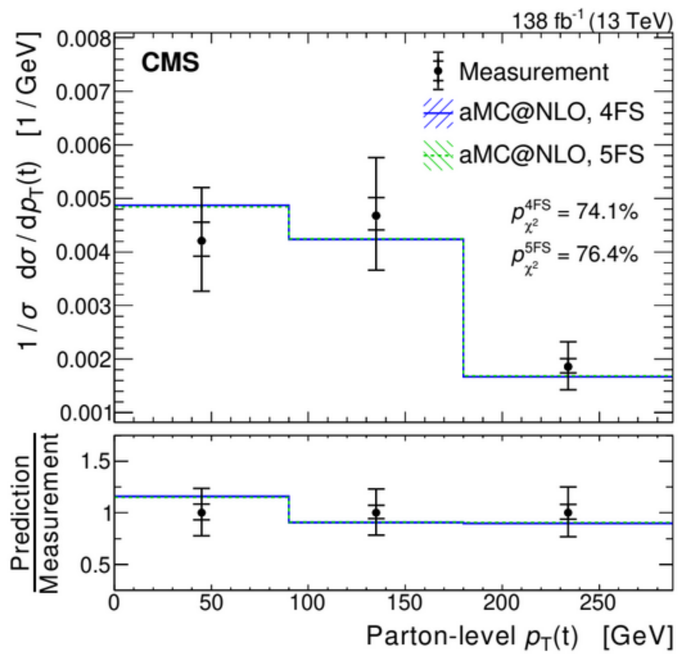
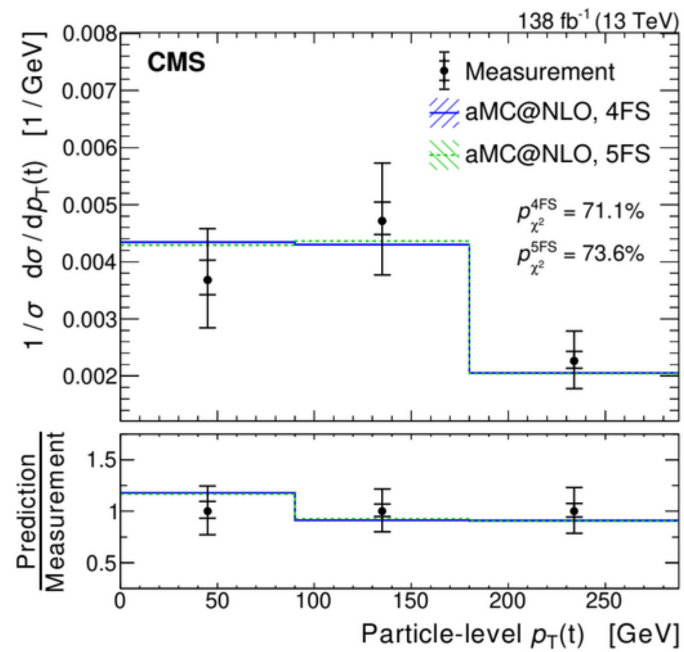


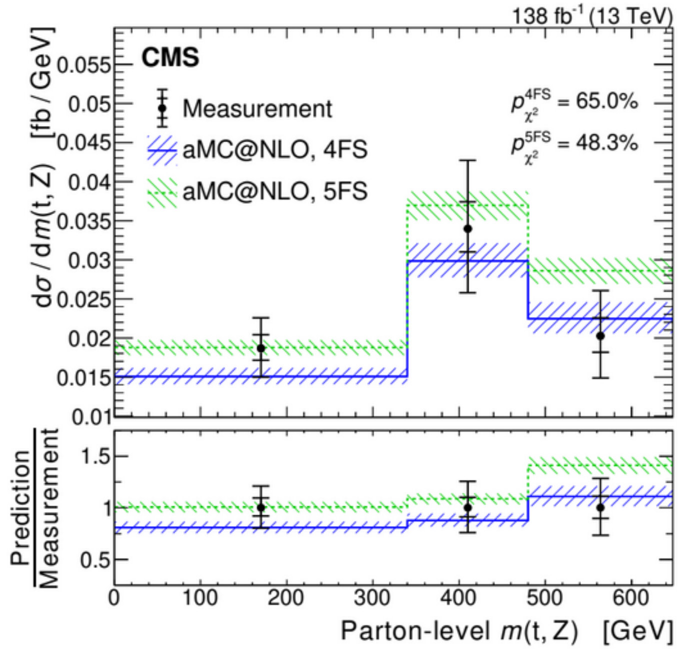


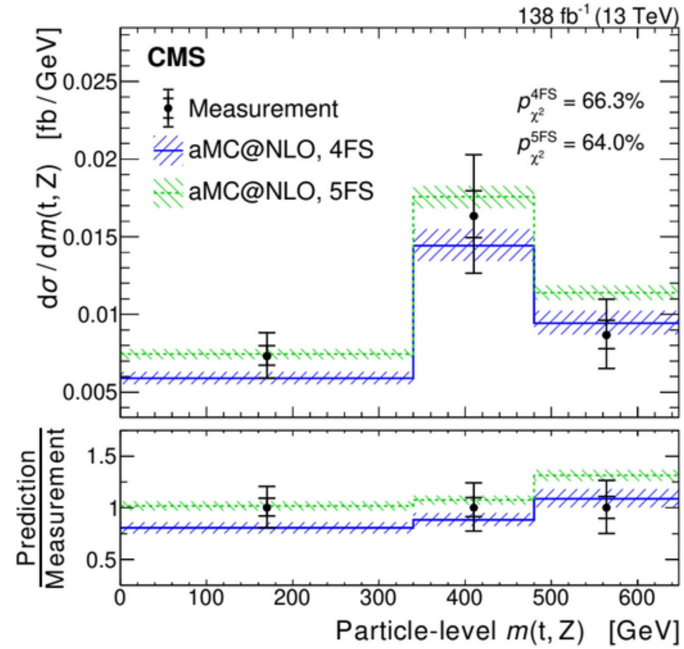
m(t,Z)

parton level

particle level

absolute





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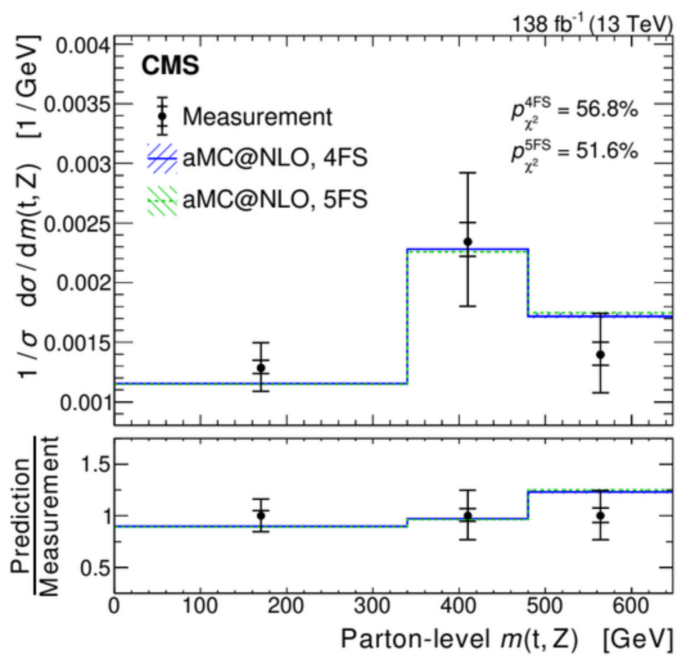
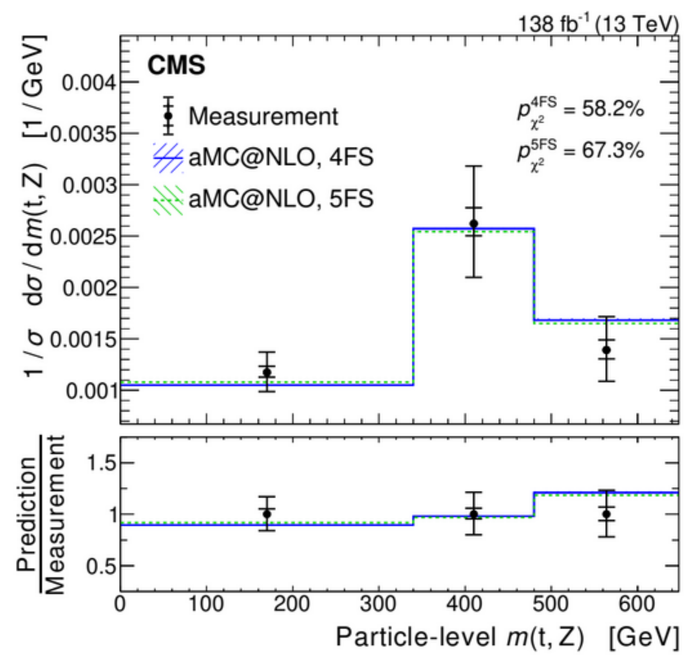




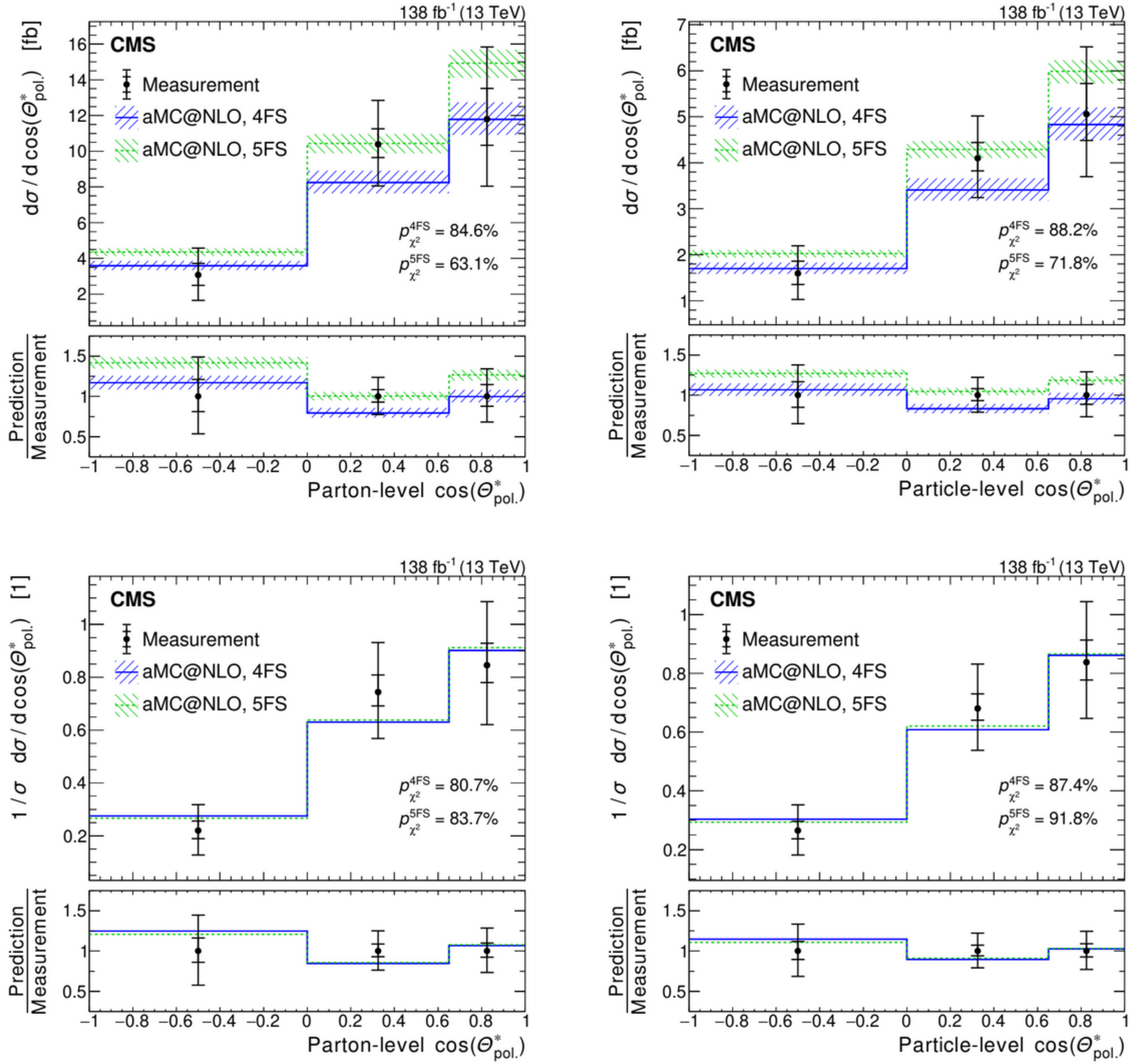
$\cos(\theta^{*}_{pol.})$

parton level

particle level

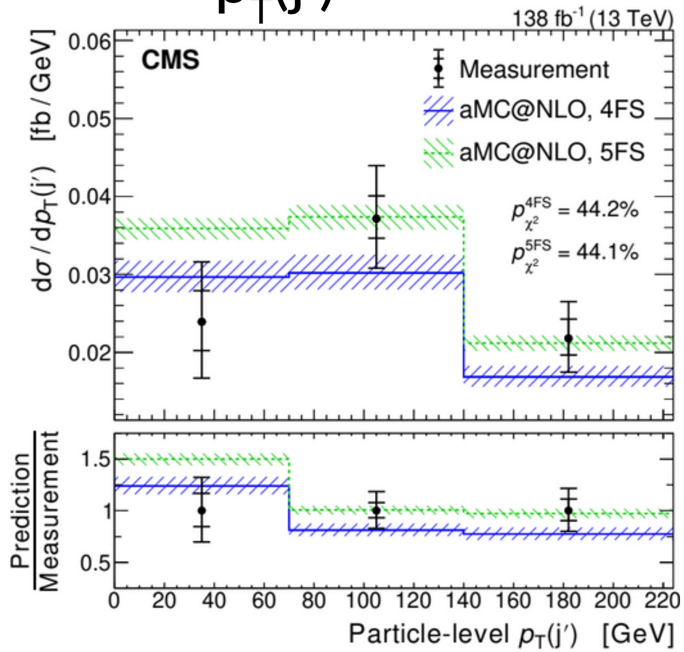
absolute

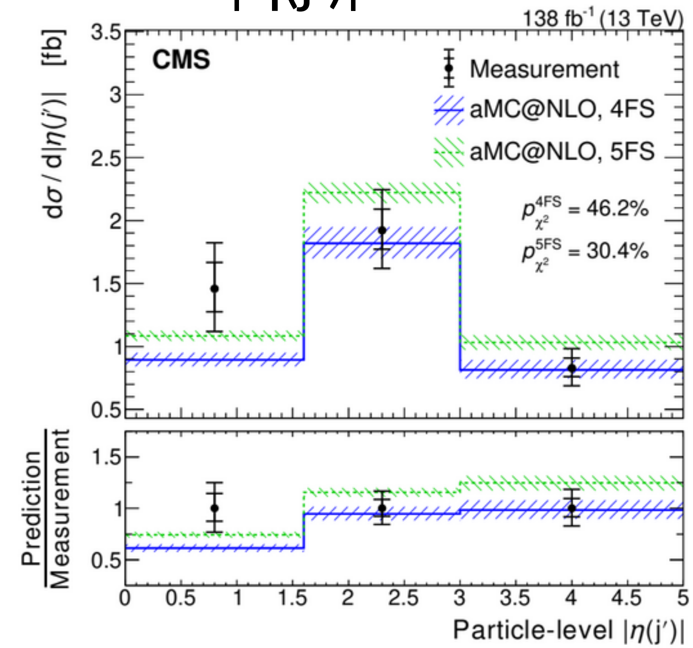
normalized



$p_T(j')$ | $|\eta(j')|$

absolute





normalized