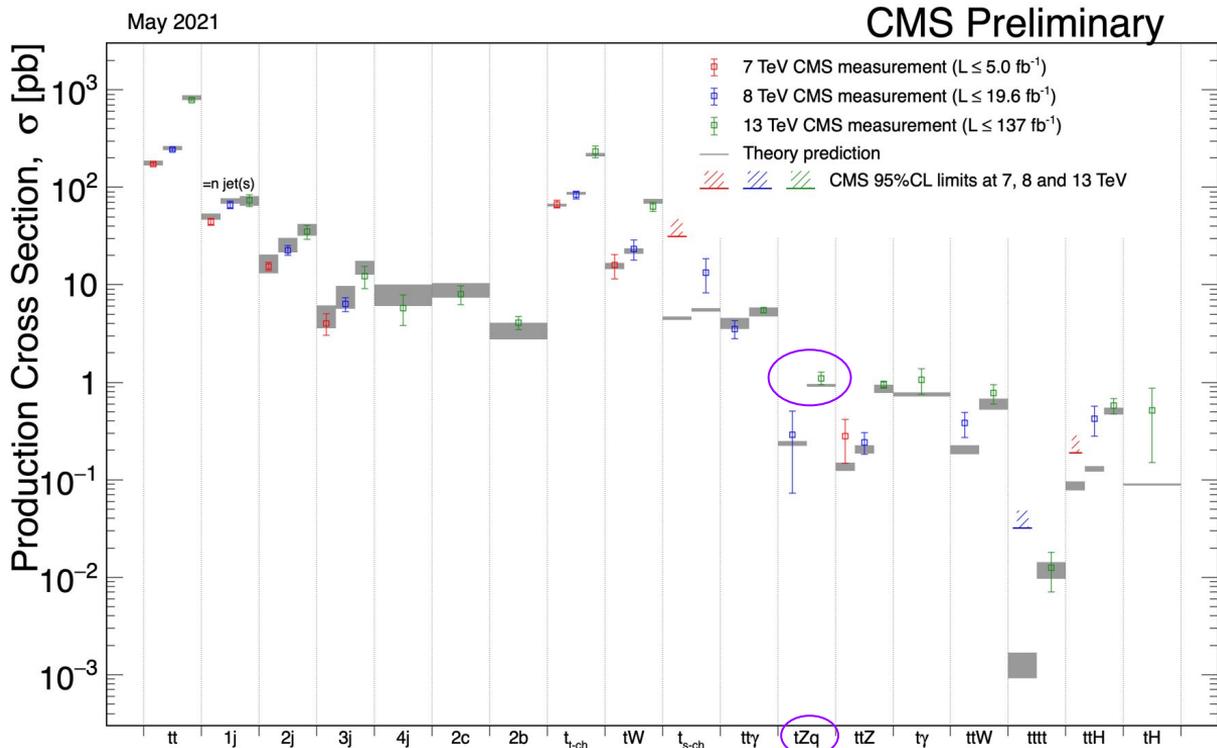




Inclusive and differential cross-section measurements of tZq at CMS

Luka Lambrecht,
on behalf of the CMS Collaboration

LHC Top Working Group meeting,
01 - 03 December 2021



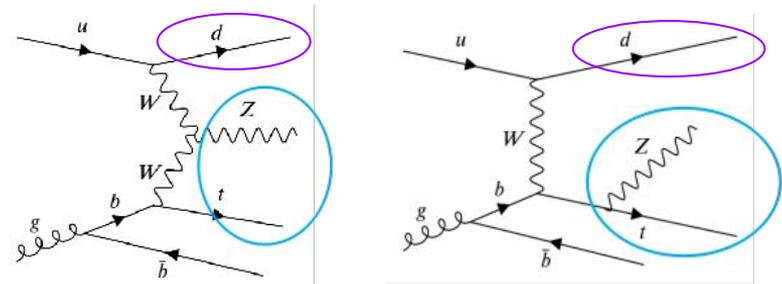
- Many interesting recent results in top quark physics at CMS.
- This talk: tZq : single top quark + Z boson
- Improved inclusive cross-section measurement.
- First differential cross-section measurements.

All results at: <http://cern.ch/go/pNj7>

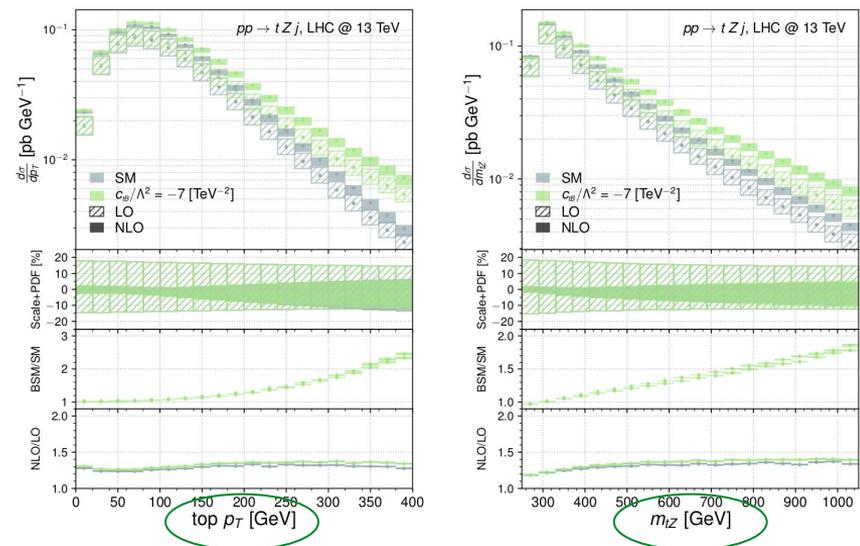
- tZq is a probe for new physics:
- Sensitive to: **ttZ- and WWZ couplings**, top quark **polarization**, **proton PDFs** via top quark-antiquark ratio.
 - Impacted by **FCNC** or more generally in the **SMEFT phenomenology** [1].
 - Especially in **differential measurements**, these effects become visible.

variables sensitive to new physics (e.g. **top pT**, **m(tZ)**)

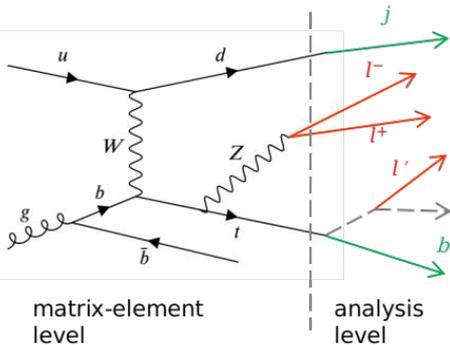
variables to study modelling (e.g. **forward jet pT** and **|η|**)



Earlier tZq measurements by CMS and ATLAS [2-4]
 → **precision: ±15%**



Example tZq event in tripleton channel:



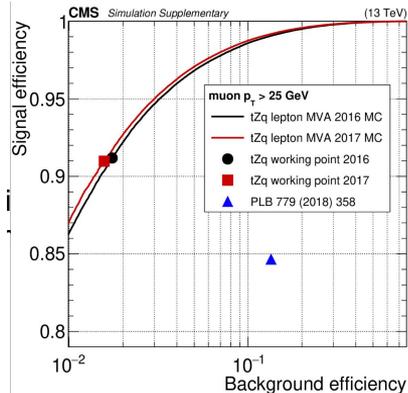
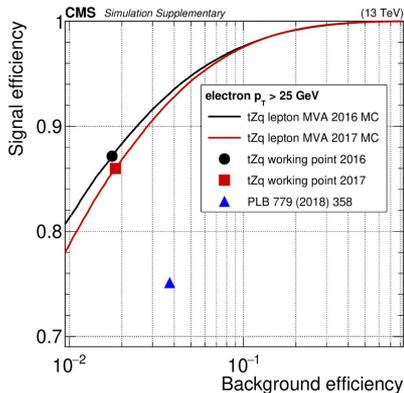
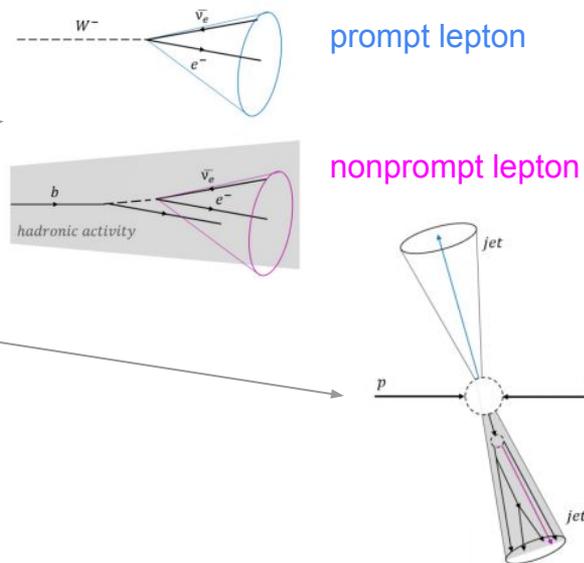
Event selection:

- 3 leptons (electrons or muons)
 - $p_T > 25 / 15 / 10$ GeV.
 - selection based on [new lepton MVA](#).
- ≥ 2 jets
 - $p_T > 25$ GeV
 - $|\eta| < 5$
- ≥ 1 b-jet
 - $|\eta| < 2.4$ (2016) / 2.5 (2017 / 2018)
 - medium deepFlavour / deepJet working point

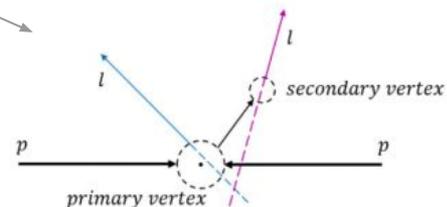
Event reconstruction:

- Z boson candidate: OSSF lepton pair with $|m(\text{ll}) - m(\text{Z})| < 15$ GeV.
- top quark candidate and accompanying b jet: reconstructed analytically.
- recoiling jet: leading non-b-tagged jet, tends to be forward.

- Crucial element: distinguish **prompt** from **nonprompt** leptons.
- Trained custom dedicated BDT to accomplish this.
- Major Input variable categories:
 - Isolation
 - Properties of closest jet
 - Impact parameter
- Based on earlier version for 2016+2017 tZq analysis, but updated, re-trained an optimized for full Run-II.

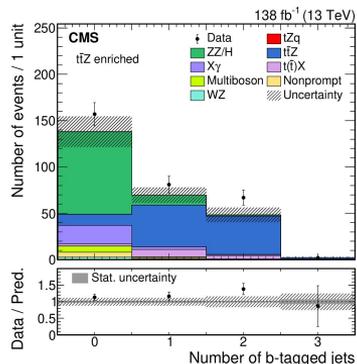
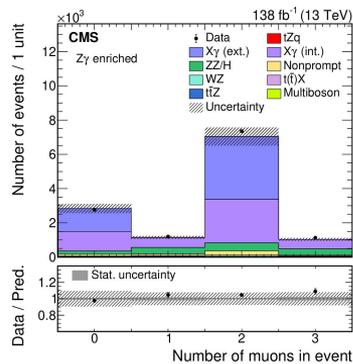
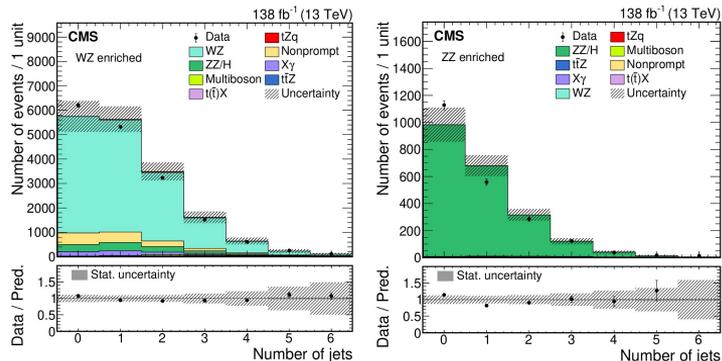


(older version, public results for newer version in the planning)



Backgrounds with prompt leptons

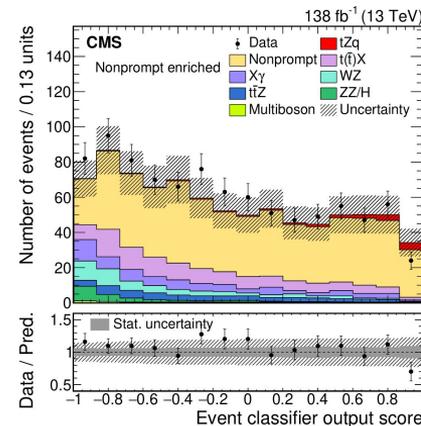
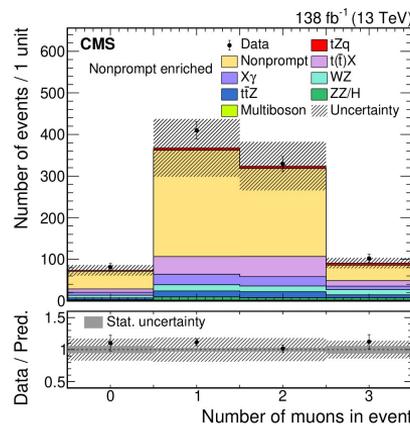
→ estimated from simulation.



Backgrounds with nonprompt leptons

→ estimated from data.

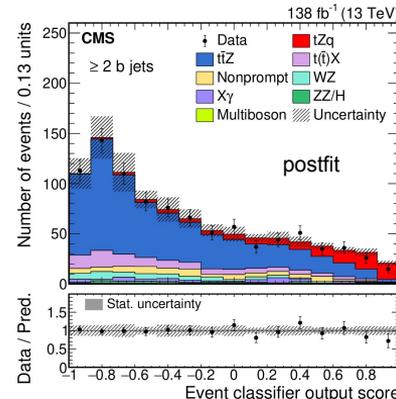
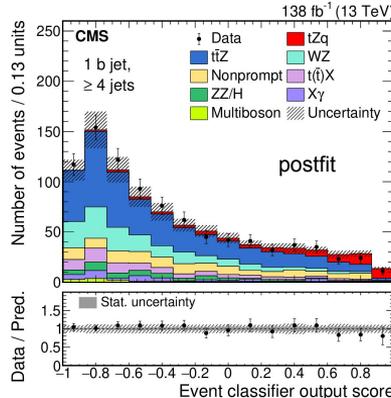
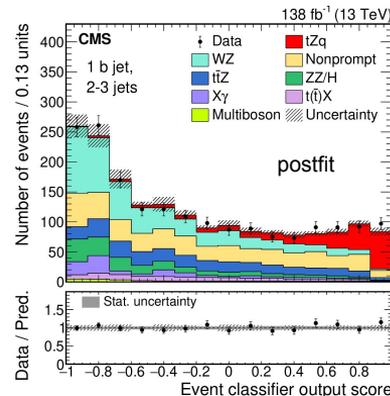
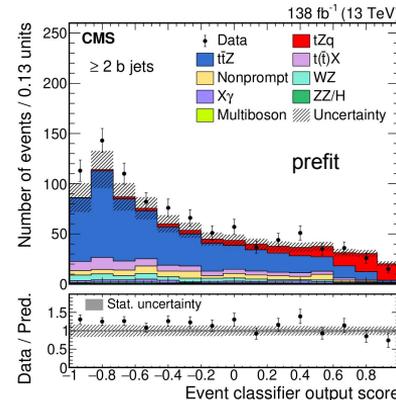
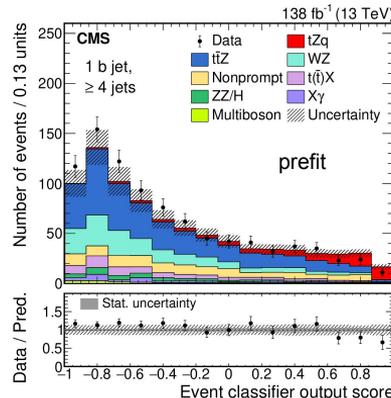
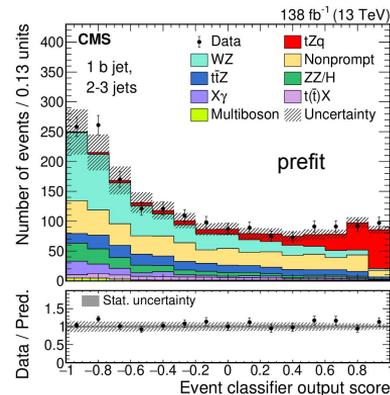
- Define 'fake rate' = P(lepton passes tight selection | lepton passes looser selection and lepton is nonprompt)
- Measure in QCD-enriched region.
- Apply in sideband to signal region.
- Verified in nonprompt-enriched region.



Inclusive measurement: method



- Train a **BDT** to distinguish tZq from backgrounds.
- Input variables based on:
 - presence of a **hard forward jet**.
 - presence of at least one **b-jet**.
 - **charge asymmetry** of the top quark.
 - **angular separation** between tagged objects.
 - number of **jets and b jets**.
- **Maximum likelihood fit** on BDT output distributions in signal region.
- **Simultaneous** for all years and categories.
- Also **including control regions** to constrain nuisance parameters.



Measured inclusive tZq cross-section:

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

→ total uncertainty of $\pm 11\%$

Improvement of about 25%

w.r.t. earlier measurements, due to

- larger data set.
- larger measurement region.
- improved lepton MVA.
- constraining nonprompt background (dominant in earlier measurements).

Standard model prediction:

$$\sigma_{tZq}^{\text{pred}} = 94.2^{+1.9}_{-1.8} (\text{scale})^{+2.5}_{-2.5} (\text{PDF}) \text{ fb}$$

As calculated with
Madgraph5_aMC@NLO

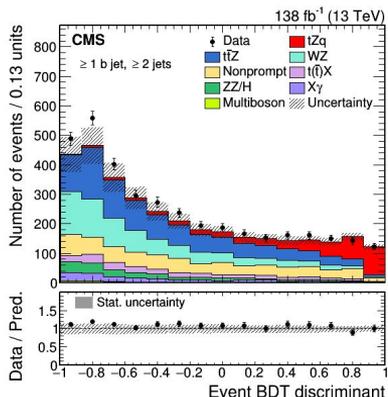
- in 5FS
- with dilepton masses $> 30 \text{ GeV}$.
- More details in [2]

Partial tZq cross-sections:

$$\sigma_{tZq}(l_t^+) = 62.2^{+5.9}_{-5.7} (\text{stat.})^{+4.4}_{-3.7} (\text{syst.}) \text{ fb}$$

$$\sigma_{tZq}(l_t^-) = 26.1^{+4.8}_{-4.6} (\text{stat.})^{+3.0}_{-2.8} (\text{syst.}) \text{ fb}$$

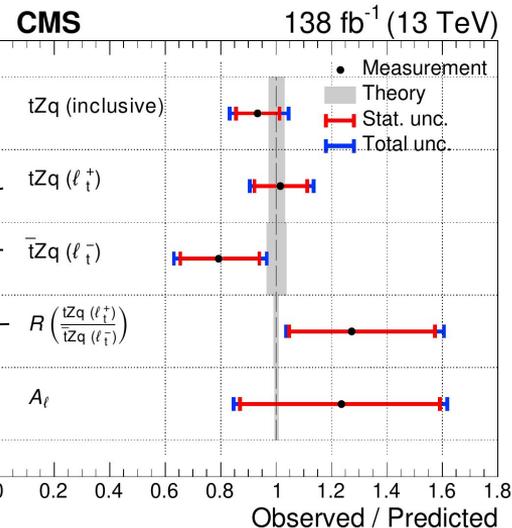
$$R = 2.37^{+0.56}_{-0.42} (\text{stat.})^{+0.27}_{-0.13} (\text{syst.}) \text{ fb}$$

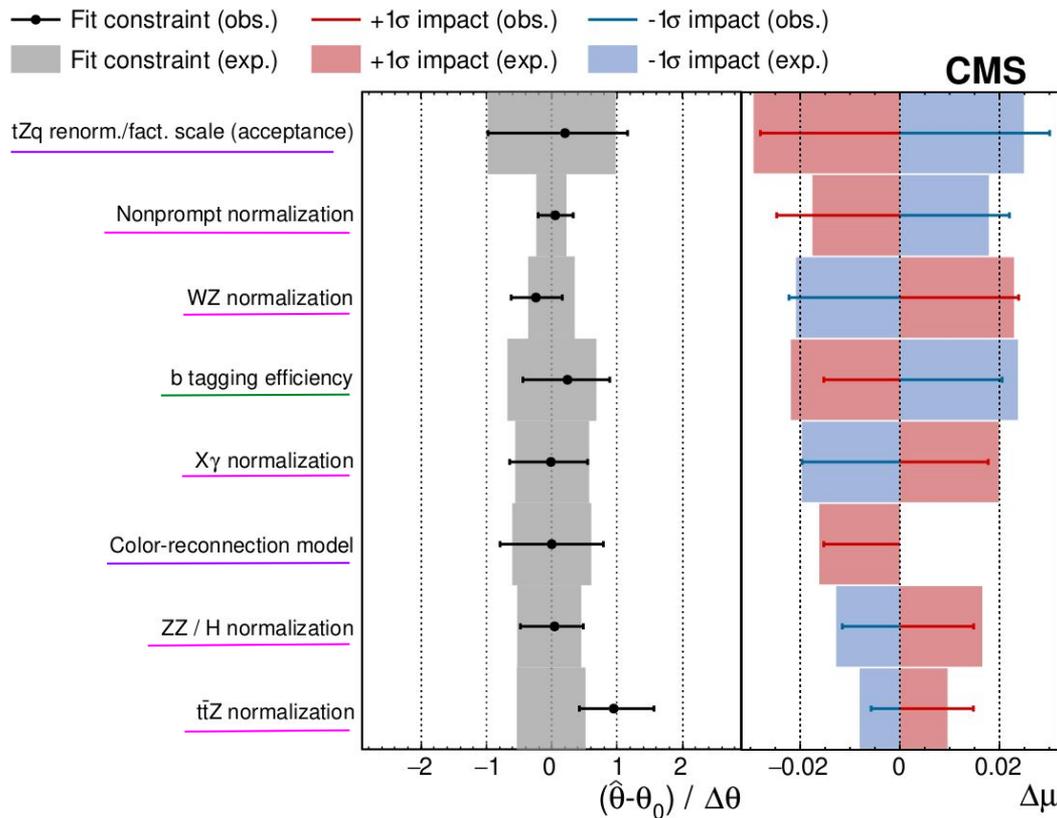


Splitting the signal region based on the charge of the lepton.

Directly extracting the ratio in a (modified) fit.

See later on!





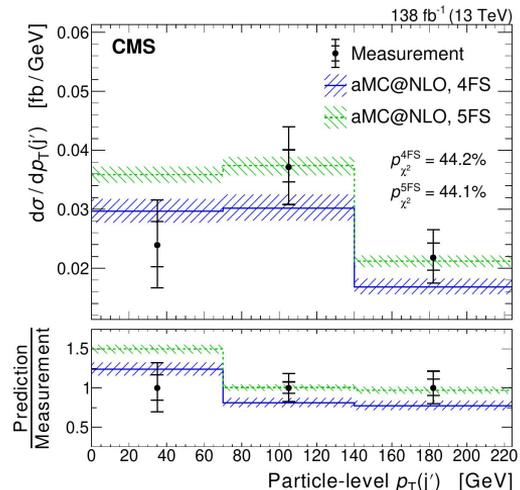
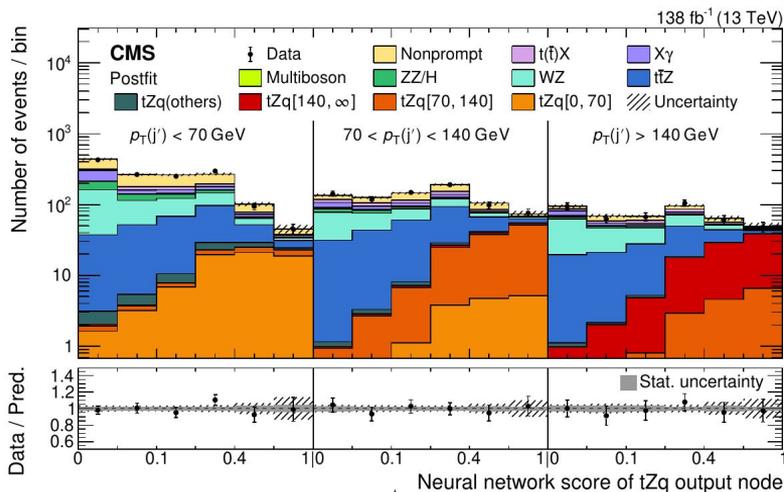
$$\sigma_{tZq} = 87.9^{+7.5}_{-7.3}(\text{stat.})^{+7.3}_{-6.0}(\text{syst.}) \text{ fb}$$

- Measurement is (still) **statistically limited**.
- Dominating systematic uncertainties:
 - **signal modeling**
 - **background normalizations**
 - **b-tagging efficiency**
- Some **correlations** observed, e.g. WZ normalization and lepton scale factor uncertainties.
- **No large pulls** observed, except for tZ normalization (consistent with [5]).

Differential measurement: method



$$\sigma_{tZq}^k = \int_{x_{tZq}^{\text{low}}(k)}^{x_{tZq}^{\text{high}}(k)} \frac{d\sigma_{tZq}}{dx_{tZq}} dx_{tZq}$$



Goal: obtain distributions of jet, lepton, Z boson and top quark kinematics **without detector distortions**.

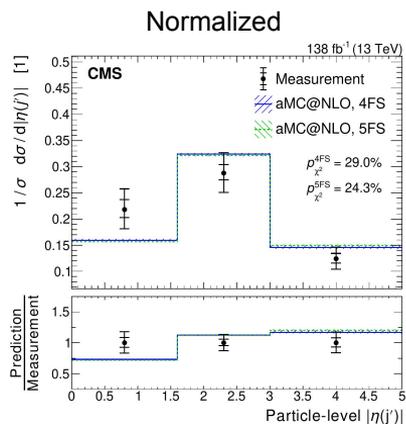
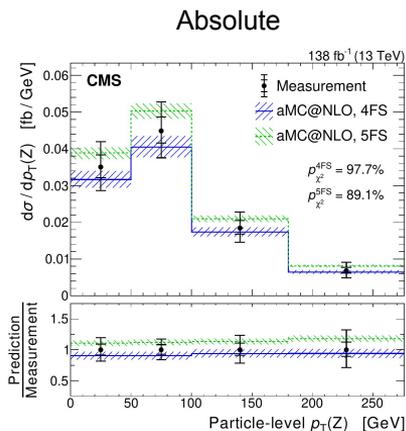
Method: **maximum likelihood based unfolding**.

- Split signal sample into generator bins (colours),
- Split signal region in corresponding detector bins.
- Perform simultaneous fit on MVA output for all signals / signal regions.

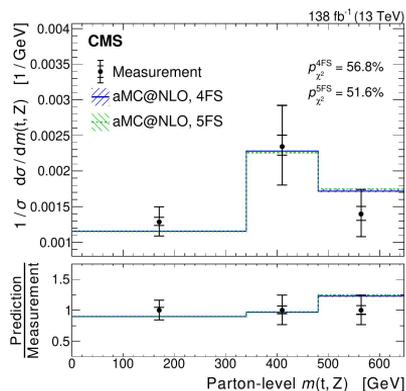
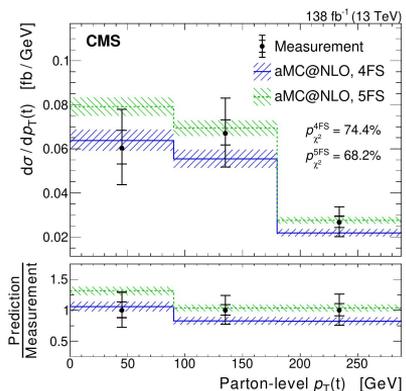
Differential measurement: results



Particle level



Parton level



Results:

- Differential results
 - absolute and normalized,
 - at particle and parton level.
- Observe **good agreement** between measurement and prediction.
- Uncertainties down to 15% for purely leptonic variables, down to 25% for hadronic variables.
- Compared to **both 4FS and 5FS prediction**.
→ no clear preference with current amount of data.
- Other variables: see published results or backup!

Differential measurement: spin asymmetry



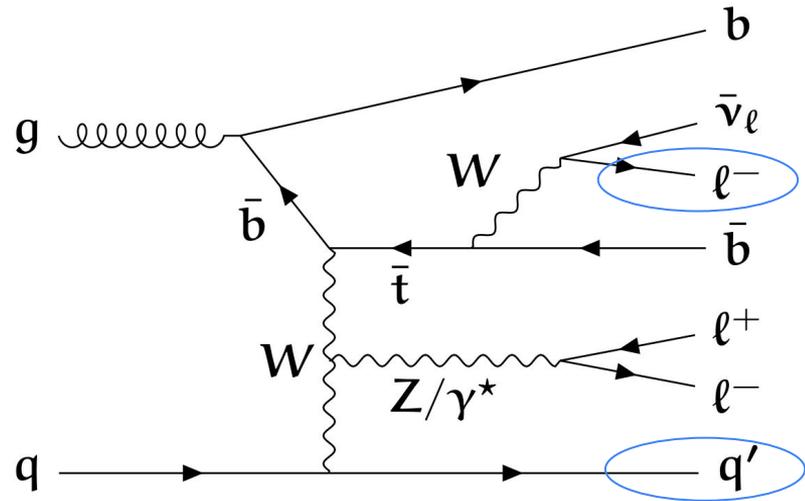
- In tZq, top quark is **highly polarized**.
- Consequence of **V-A nature of electroweak coupling**.
→ deviation could point to anomalous coupling structure.
- Measure polarization using related variable '**spin asymmetry**'.
- Spin asymmetry is related to the differential cross-section as function of polarization angle (at parton level):

$$\frac{d\sigma}{d\cos(\theta_{\text{pol}}^*)} = \sigma_{tZq} \cdot \left(\frac{1}{2} + A_\ell \cos(\theta_{\text{pol}}^*) \right)$$

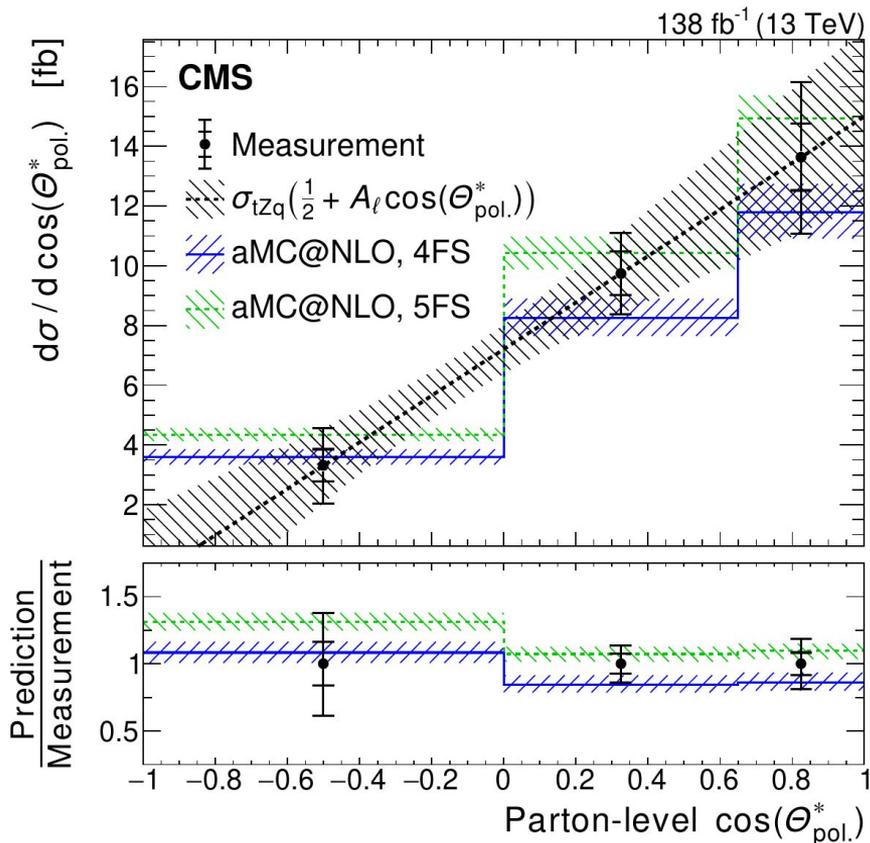
where the **polarization angle** is defined as

$$\cos(\theta_{\text{pol}}^*) = \frac{\vec{p}(q'^*) \cdot \vec{p}(\ell_t^*)}{|\vec{p}(q'^*)| |\vec{p}(\ell_t^*)|}$$

(all vectors evaluated in the rest frame of the top quark)



More details and recent results on top polarization [here](#)



- Spin asymmetry and polarization angle:

$$\frac{d\sigma}{d \cos(\theta_{\text{pol}}^*)} = \sigma_{tZq} \cdot \left(\frac{1}{2} + A_\ell \cos(\theta_{\text{pol}}^*) \right)$$

- Unfolded distribution of $\frac{d\sigma}{d \cos(\theta_{\text{pol}}^*)}$: see left
- Measurement: fit is reparametrized to extract spin asymmetry directly, with full likelihood and uncertainties.

- Prediction (for 4FS and 5FS):

$$A_\ell^{4\text{FS}} = 0.44 \quad A_\ell^{5\text{FS}} = 0.45$$

(with negligible uncertainties)

- Measurement result:

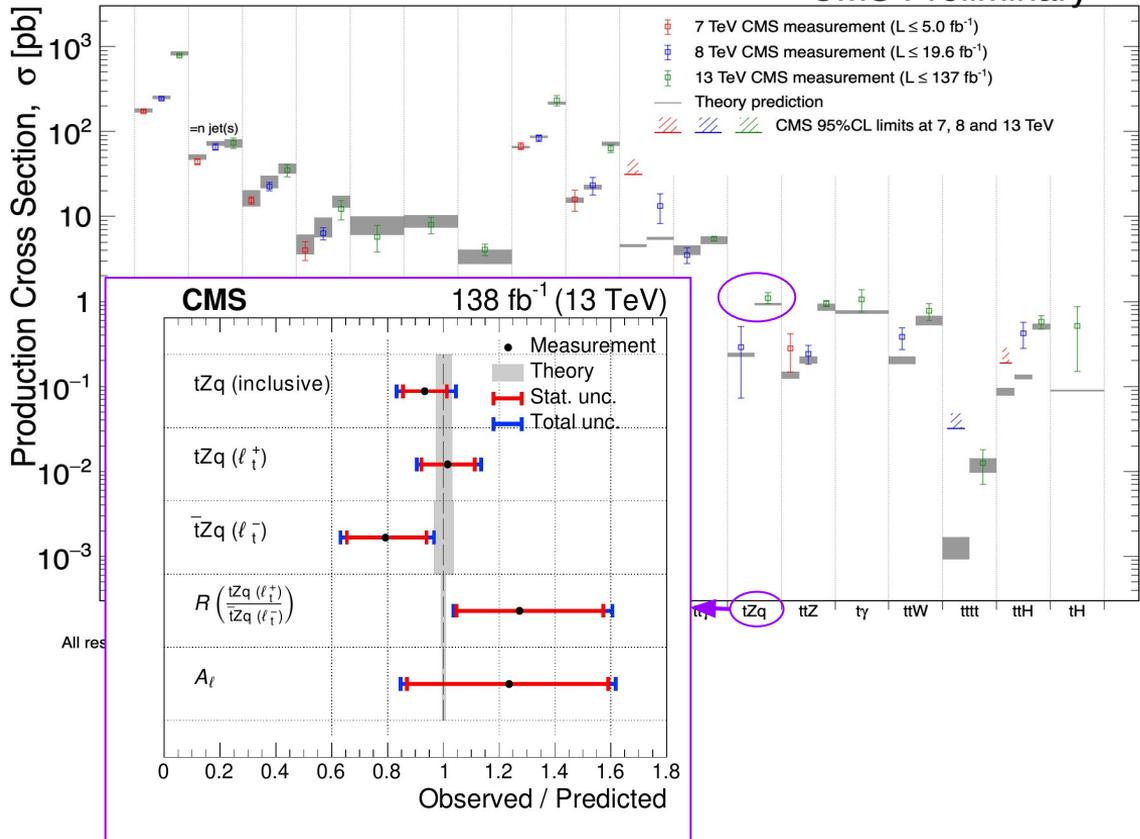
$$A_\ell = 0.54 \pm 0.16 (\text{stat}) \pm 0.06 (\text{syst})$$

Conclusion



CMS Preliminary

May 2021



Most precise measurements of tZq up to now.

Both inclusive and differential.

Important piece in testing the full experimentally accessible range of SM predictions.

All results consistent with SM expectations.

More information:
 CMS-TOP-20-010: [arXiv:2111.02860](https://arxiv.org/abs/2111.02860) [hep-ex],
 (submitted. to JHEP, in review)

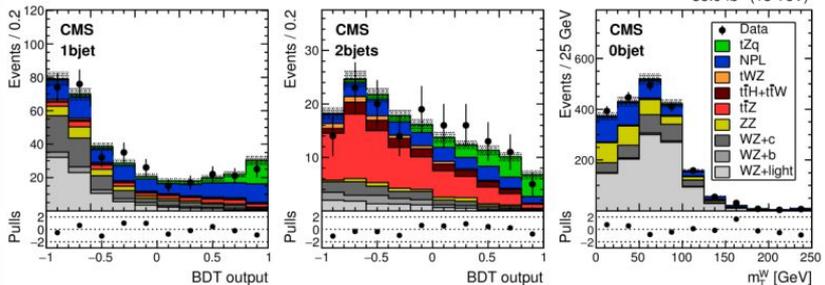


Backup

Earlier tZq analyses



First evidence with 2016 data [1]:



Standard model prediction:

$$\sigma_{tZq}^{\text{SM}} = 94.2_{-1.8}^{+1.9} \text{ (scale)} \pm 2.5 \text{ (PDF)} \text{ fb [1]}$$

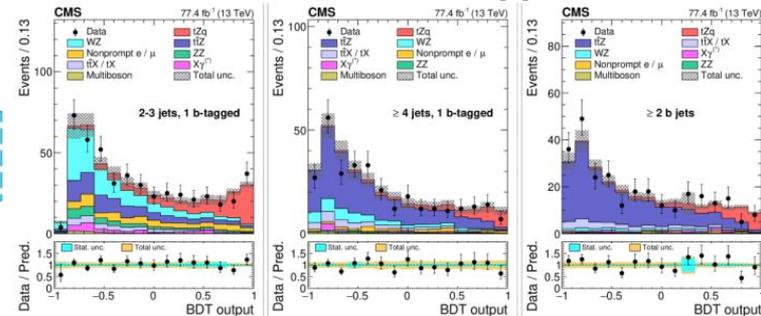
$$\sigma_{tZq} = 123_{-31}^{+33} \text{ (stat.) } \pm_{23}^{+29} \text{ (syst.) fb}$$

significance = 3.7 (obs.) / 3.1 (exp.)

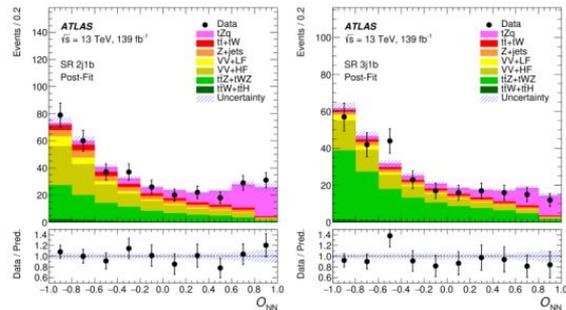
$$\sigma_{tZq} = 111 \pm 13 \text{ (stat.) } \pm_{9}^{+11} \text{ (syst.) fb } (\rightarrow \text{precision: } \pm 14\text{-}15\%)$$

significance = 8.2 (obs.) / 7.7 (exp.)

First observation with 2016+2017 data [2]:



Observation at ATLAS with full Run II dataset [3]:

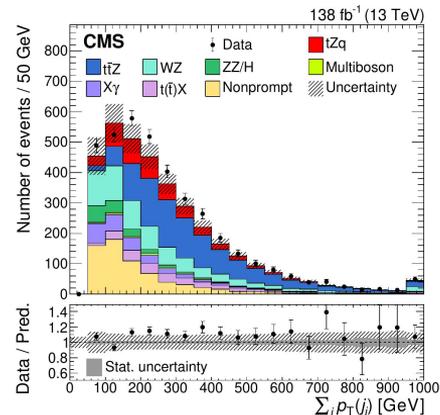
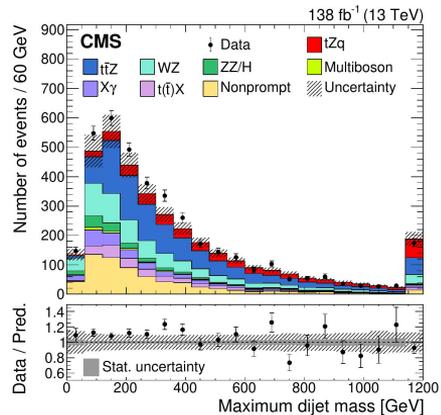
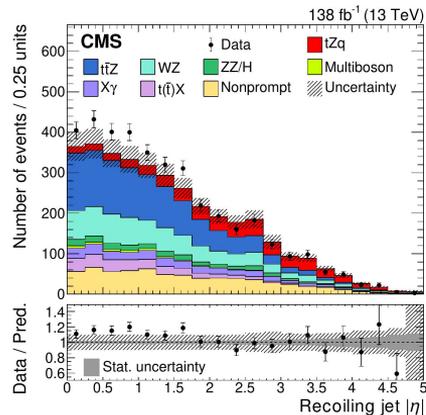
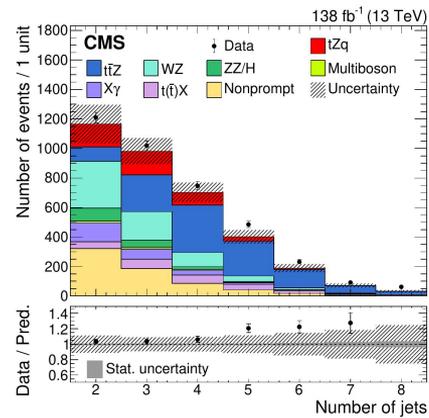
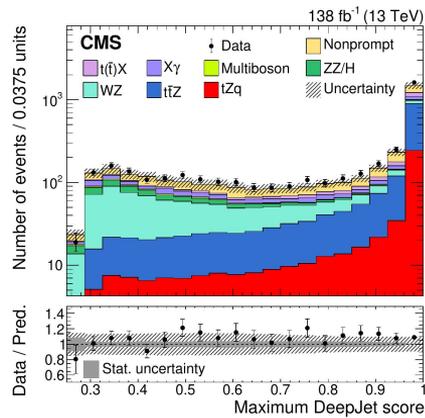
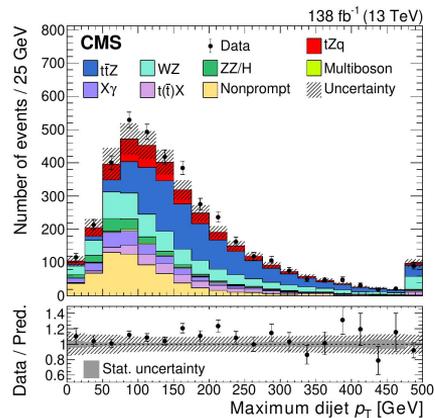


$$\sigma_{tZq} = 97 \pm 13 \text{ (stat.) } \pm 7 \text{ (syst.) fb } (\rightarrow \text{precision: } \pm 15\%)$$

Significance $\gg 5\sigma$ \rightarrow observation has been established.

Next challenges: improve precision on σ_{tZq} .
perform first differential measurement.

Discriminating variables



Inputs:

- Lepton
- Missing transverse energy (MET), assumed to come from a single neutrino.
- b-tagged jet(s)

Step 1:

Impose W-boson mass constraint on lepton + MET.

Gives a quadratic equation, to be solved for neutrino z-momentum:

Usually 2 solutions ($A > 0$).

In case $A < 0$, modify MET until $A = 0$.

$$p_{z,\nu}^{\pm} = \frac{\mu p_{z,\ell}}{p_{T,\ell}^2} \pm \sqrt{\frac{\mu^2 p_{z,\ell}^2}{p_{T,\ell}^4} - \frac{E_{\ell}^2 p_{T,\nu}^2 - \mu^2}{p_{T,\ell}^2}},$$

$$\text{with } \mu = \frac{m_W^2}{2} + p_{T,\ell} p_{T,\nu} \cos(\Delta\phi_{\ell,\nu}).$$

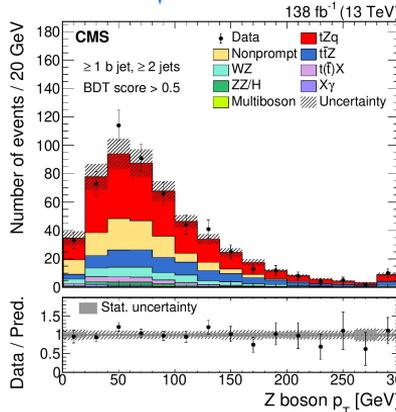
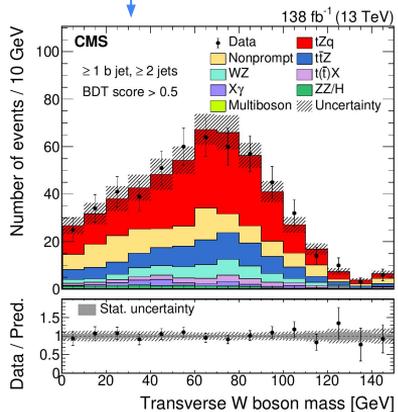
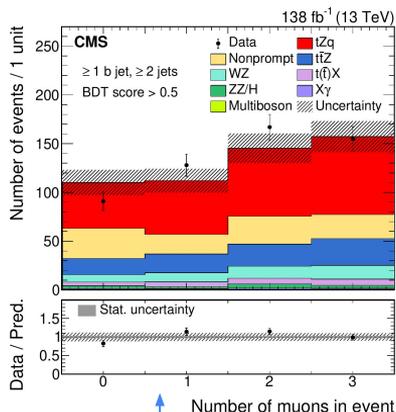
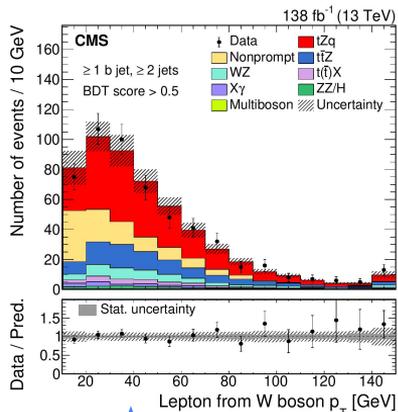
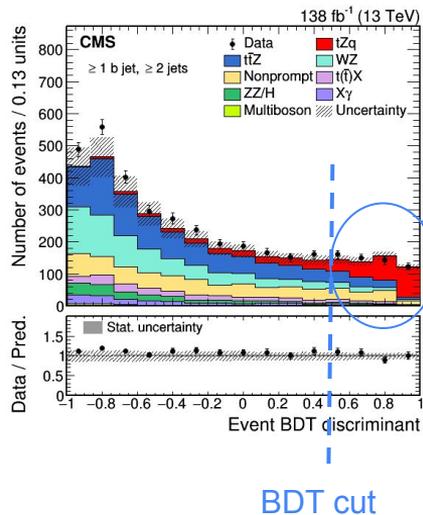
Step 2:

Combine lepton, neutrino and b-tagged jet and calculate invariant mass.

Repeat for every neutrino solution and b-tagged jet.

Choose combination with mass closest to nominal top mass.

Pure signal region

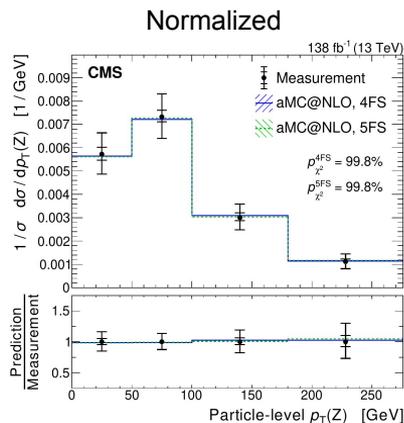
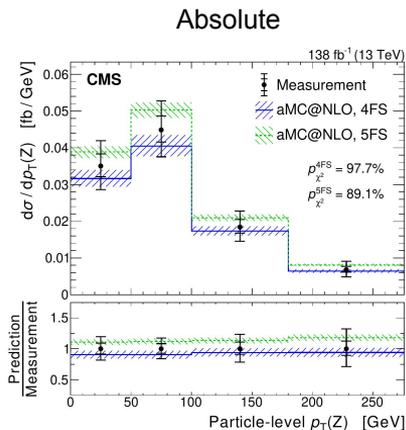


- Can introduce a relatively **pure tZq** signal region by cutting on BDT output.
- Gives first idea of **signal modeling and feasibility for unfolding**.
- Observe **good agreement and sufficient statistics for unfolding**.

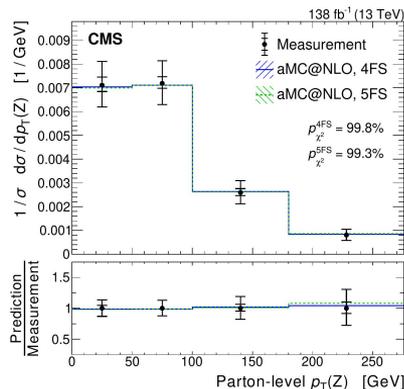
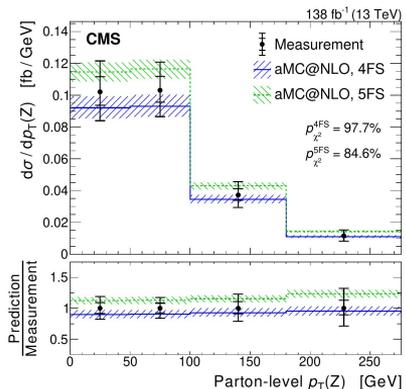
Differential measurement: results



Particle level



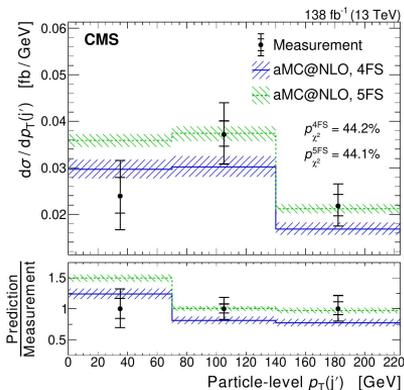
Parton level



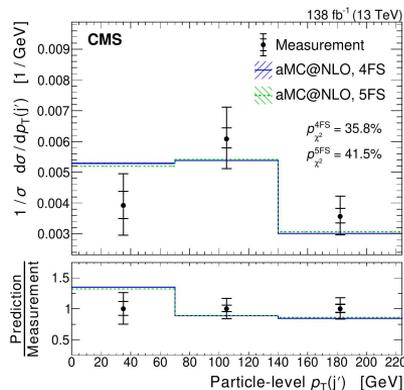
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- Uncertainties down to 15% for purely leptonic variables, down to 25% for hadronic variables.
- Compared to **both 4FS and 5FS prediction**.
→no clear preference with current amount of data.
- Other variables: see published results or backup!

Absolute



Normalized

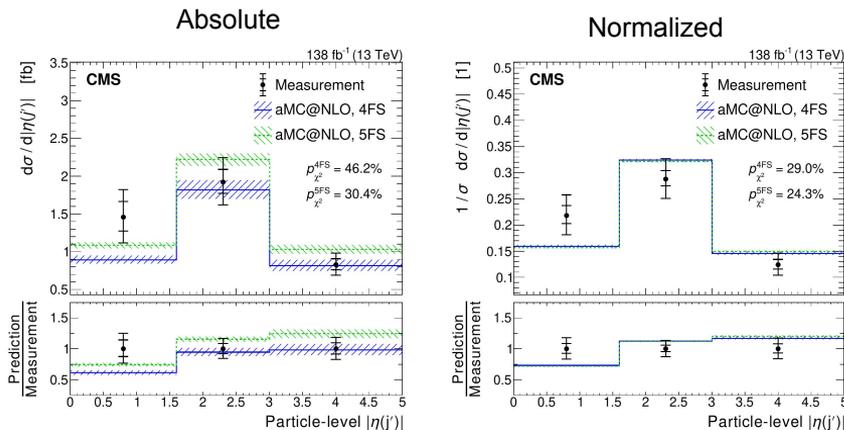


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Parton level

Particle level



Parton level

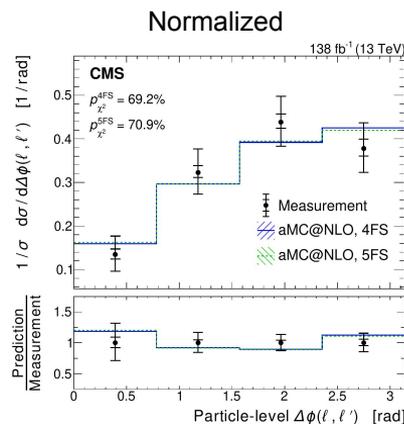
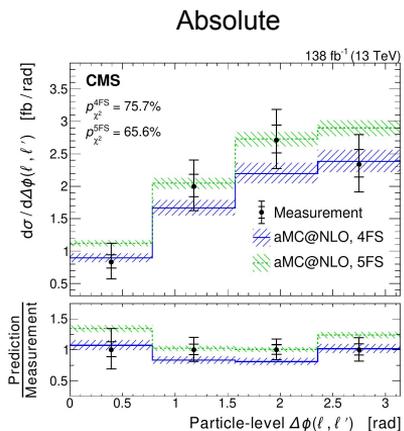
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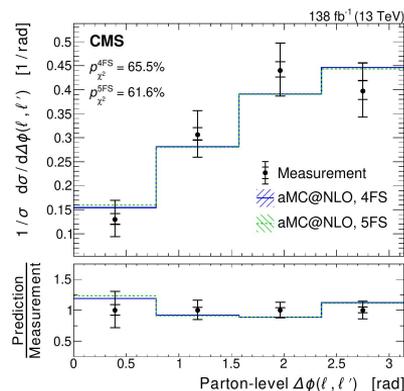
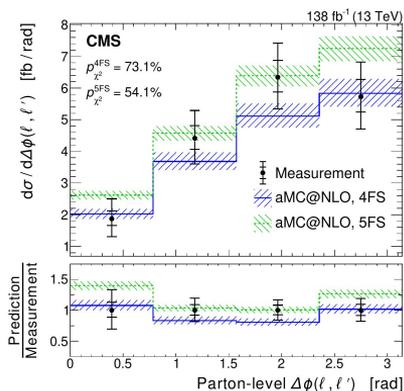
Differential measurement: results



Particle level



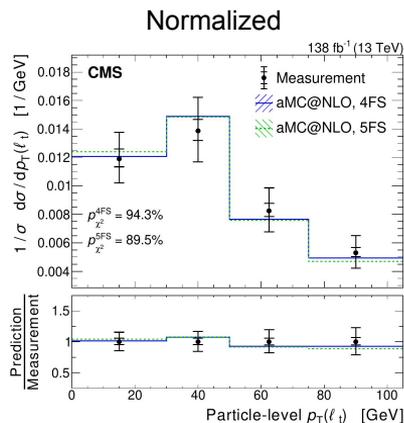
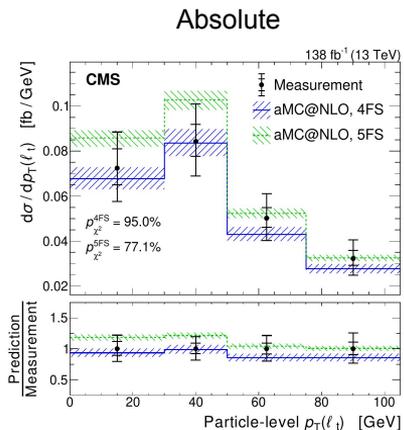
Parton level



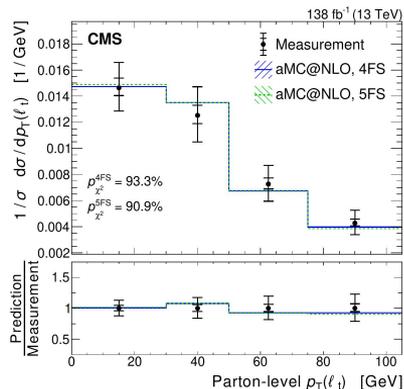
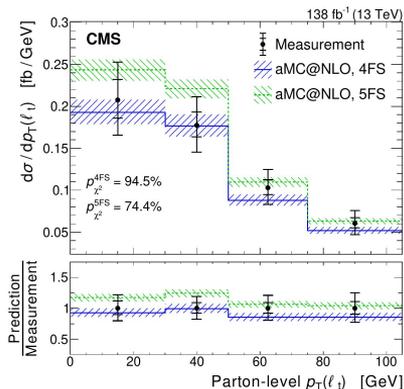
Results:

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- Compared to both 4FS and 5FS prediction.
 - no clear preference with current amount of data.
- Other variables: see published results or backup!

Particle level



Parton level



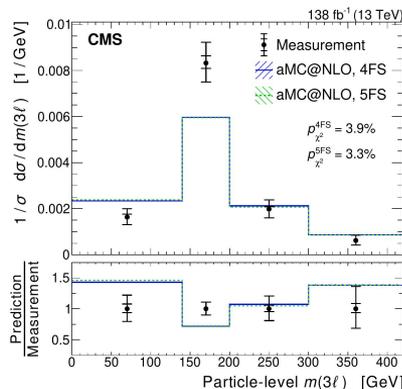
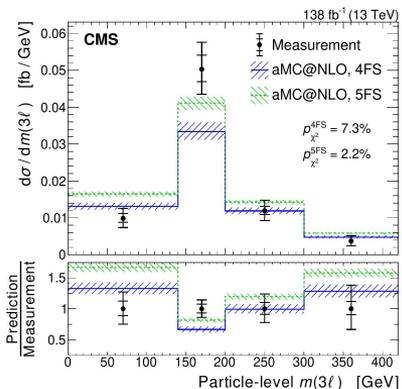
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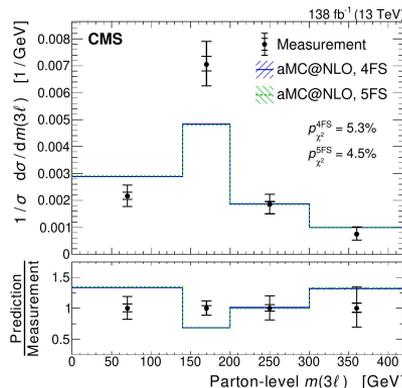
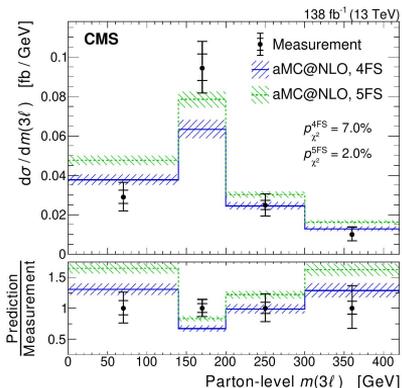
Absolute

Normalized

Particle level

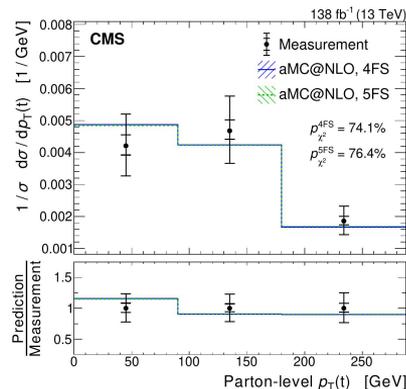
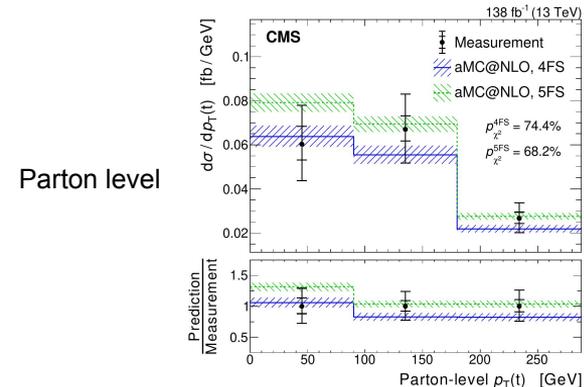
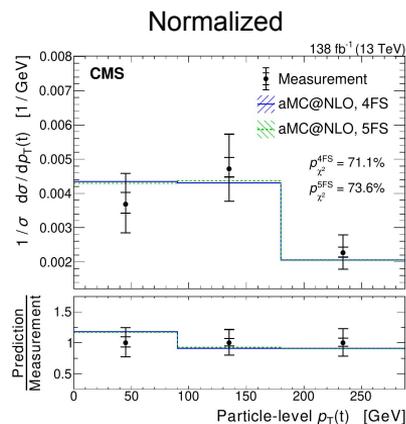
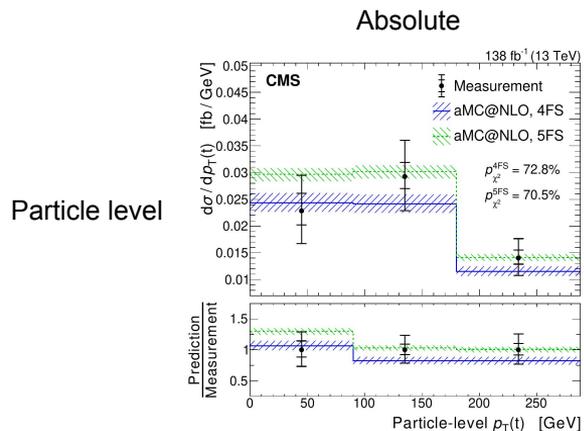


Parton level



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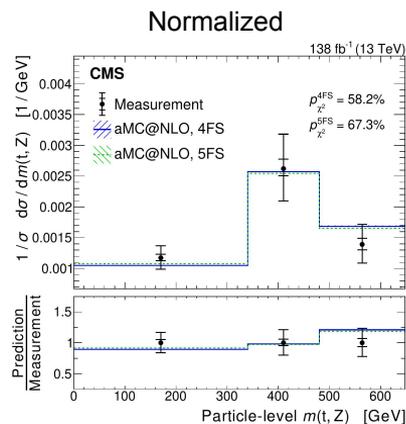
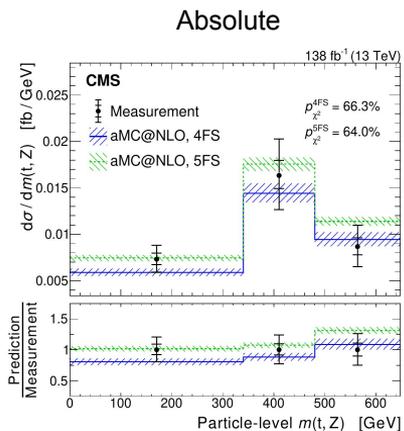
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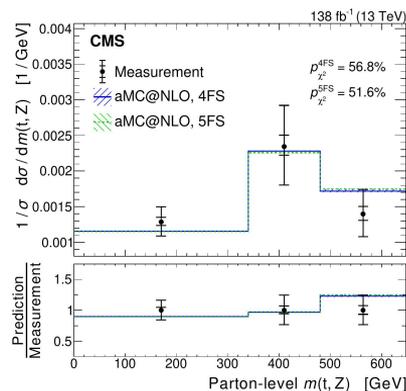
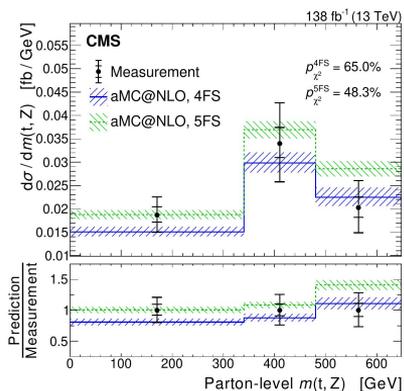
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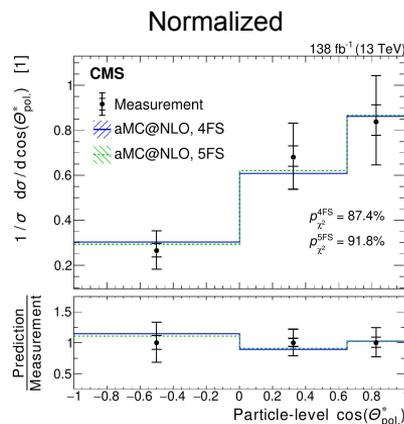
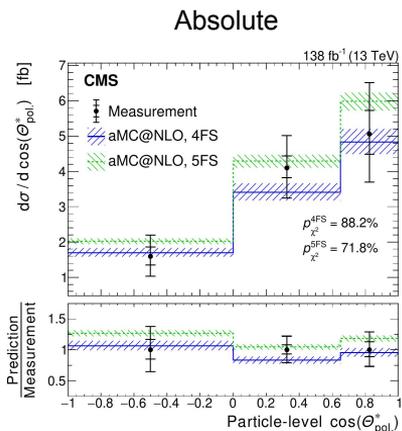
Parton level



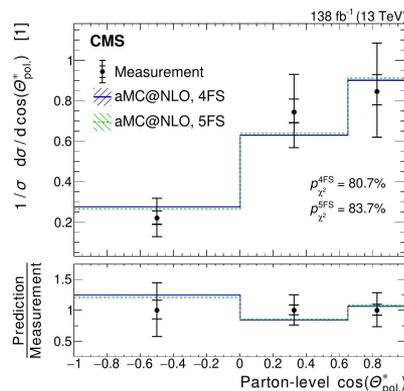
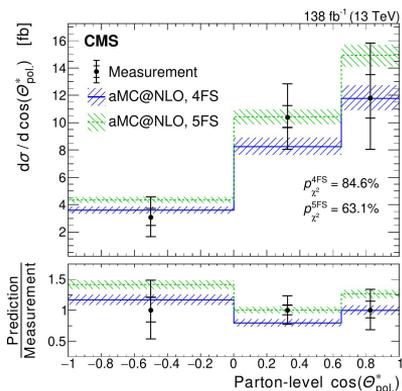
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