# Top properties (excluding mass) and ancillary measurements

The 16th international workshop on top quark physics TOP2023, September 24 to 29

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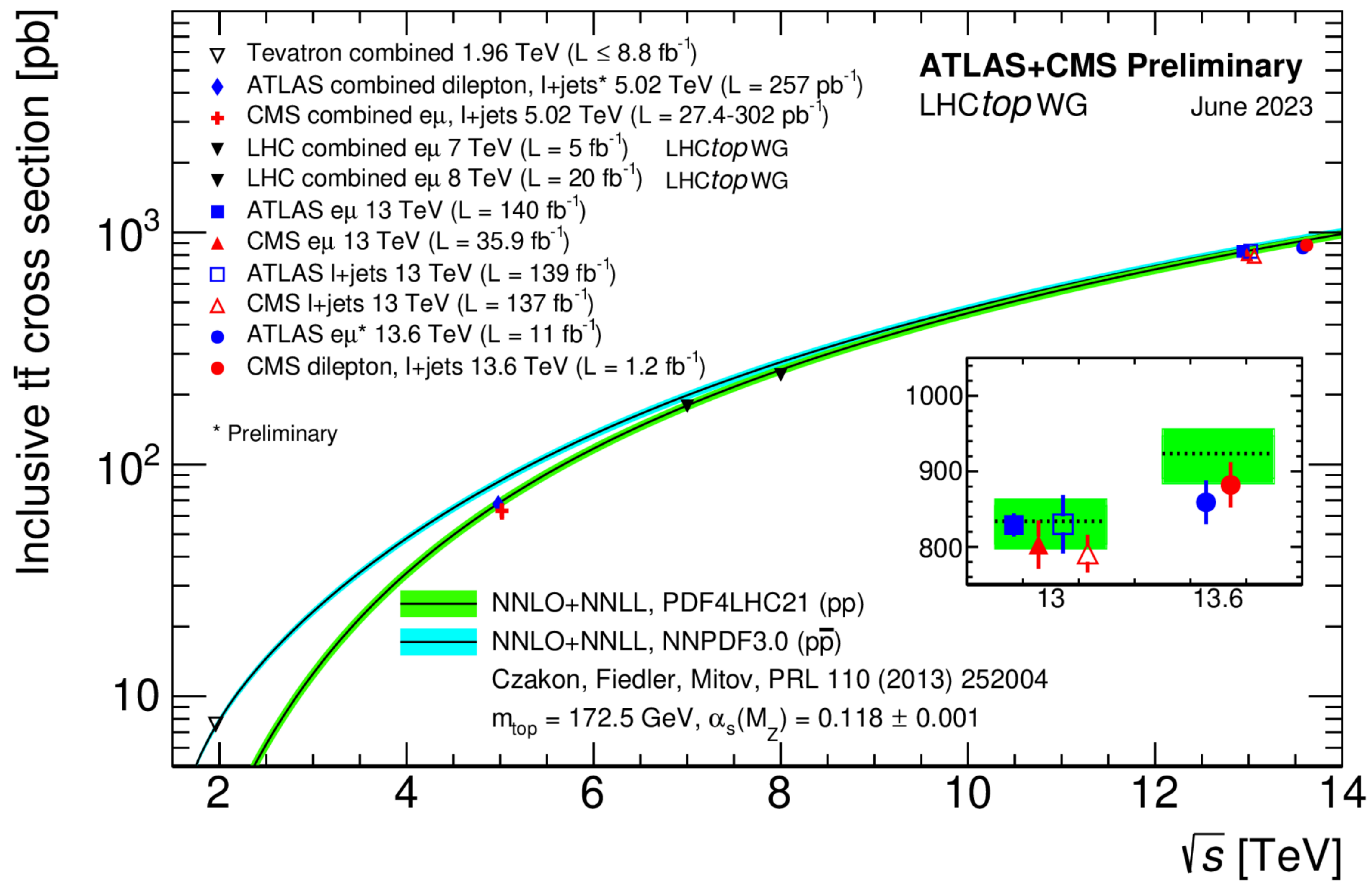
# The top quark, a very unique particle

- Top decays before hadronization
  - Lifetime of ~5 * $10^{-25}$ seconds. This allows the study of bare quark properties
- With the enormous amount of top quark pairs produced in the LHC (over 120 M!!), we are entering to the era of high precision measurements in the top quark sector

ATLAS+CMS




## This time:

- Charge asymmetry in inclusive $t\bar{t}$ production (CMS and ATLAS) an in association with a photon (ATLAS)
- W Boson Helicity fractions (ATLAS)
- Search for violation of Lorentz invariance in $t\bar{t}$ production (CMS)

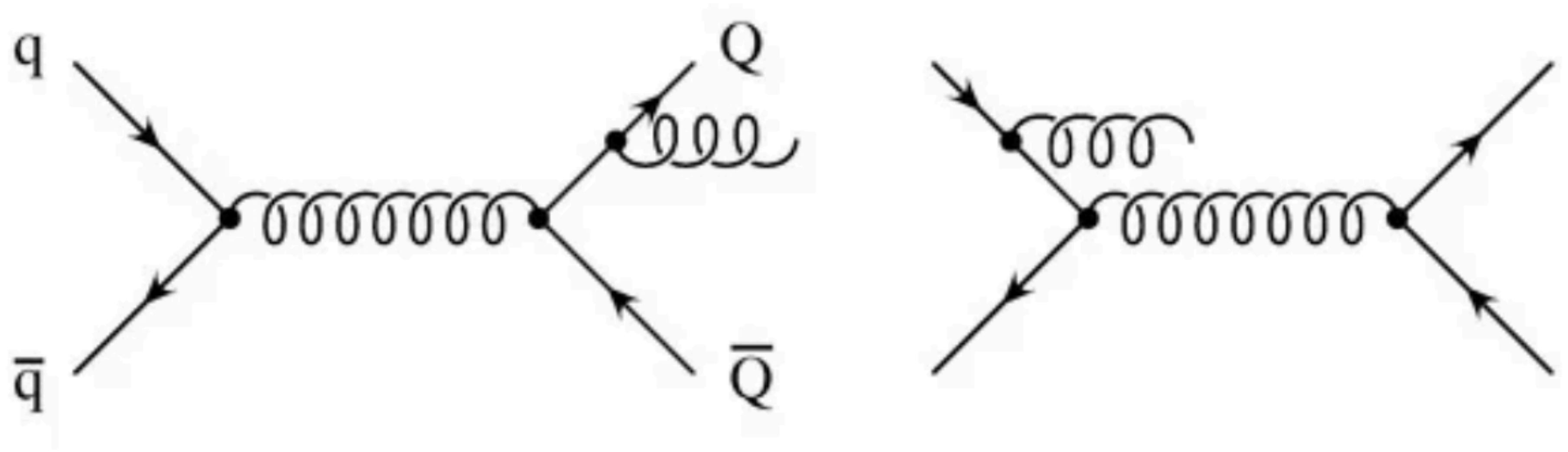


DESY. CMS ATLAS EXPERIMENT

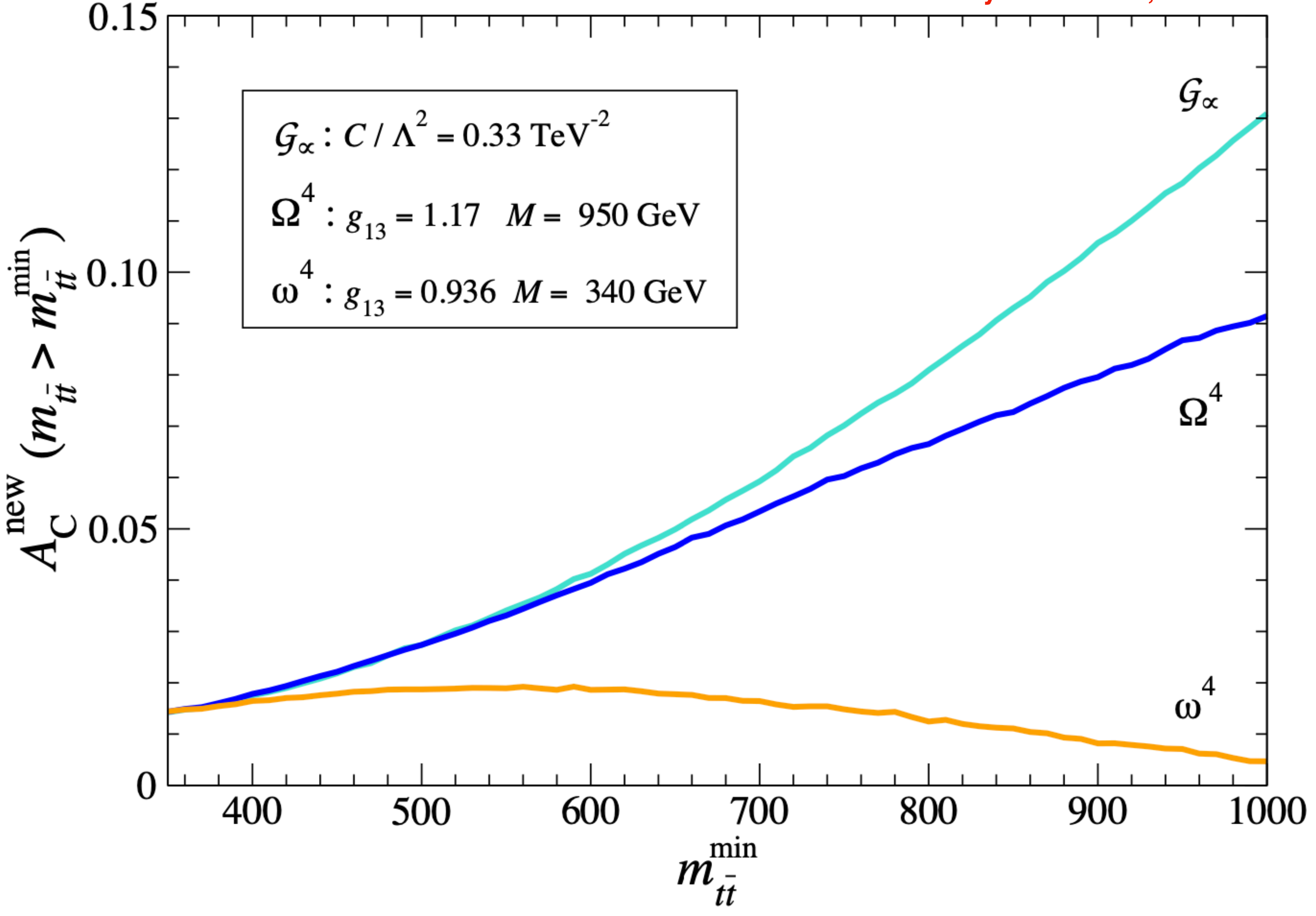
# Charge asymmetry

JHEP08(2023)077

- SM predicts a subtle difference in the angular distribution of top quarks and antiquarks, that could be enhanced by unknown physics.




Phys. Rev. D 84, 115013




- Combination of the **single-lepton** and **dilepton** channels
- For the single-lepton channel, aimed to reconstruct both the resolved (BDT) and boosted topologies (Top-tagging)
- Bayesian unfolding methods applied to correct for detector resolution and acceptance effect

Charge asymmetry

$$A_C^{t\bar{t}} = \frac{N(\Delta|y_{t\bar{t}}| > 0) - N(\Delta|y_{t\bar{t}}| < 0)}{N(\Delta|y_{t\bar{t}}| > 0) + N(\Delta|y_{t\bar{t}}| < 0)},$$

Leptonic asymmetry

$$A_C^{\ell\bar{\ell}} = \frac{N(\Delta|\eta_{\ell\bar{\ell}}| > 0) - N(\Delta|\eta_{\ell\bar{\ell}}| < 0)}{N(\Delta|\eta_{\ell\bar{\ell}}| > 0) + N(\Delta|\eta_{\ell\bar{\ell}}| < 0)},$$

DESY. ATLAS EXPERIMENT

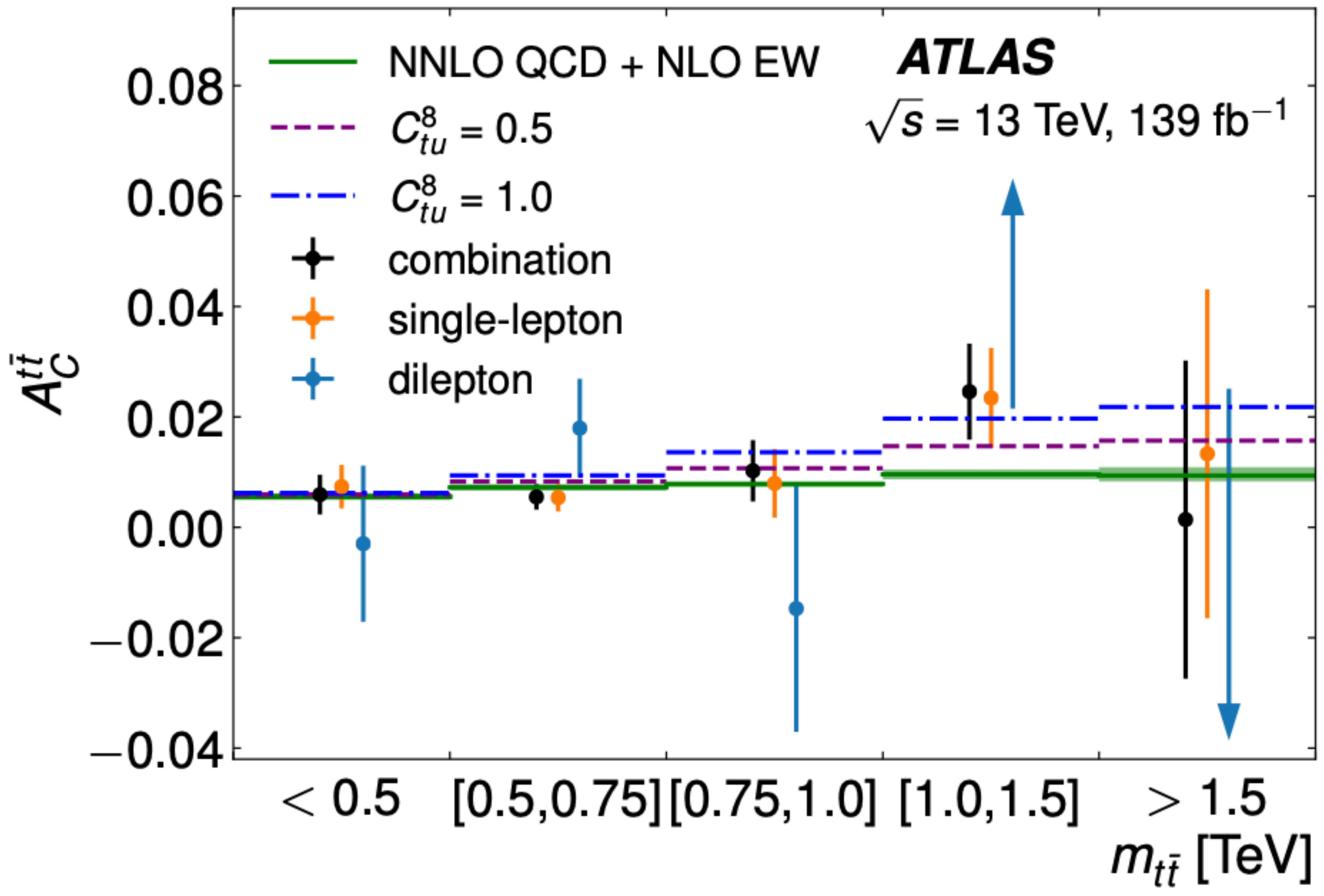
# Charge asymmetry

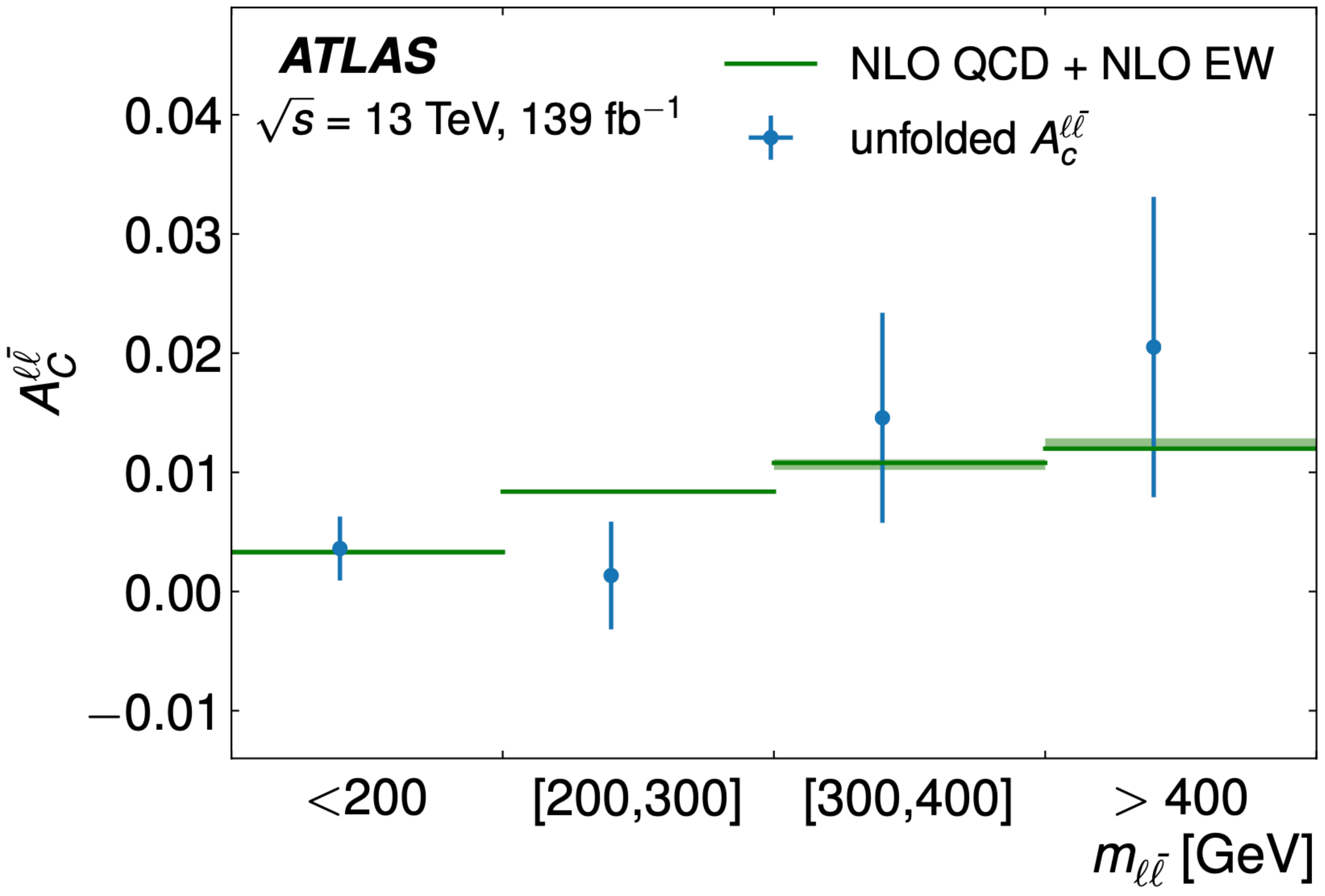
JHEP08(2023)077

- The combined inclusive $t\bar{t}$ charge asymmetry is measured to be

$A_C$ = 0.0068 ± 0.0015 (0.001 stat, 0.001 syst)

- Differs from zero asymmetry by 4.7 standard deviations
- Differential measurements done as function of the traverse momentum, invariant mass and longitudinal boost of the $t\bar{t}$ system
- Both inclusive and differential compatible with the SM predictions



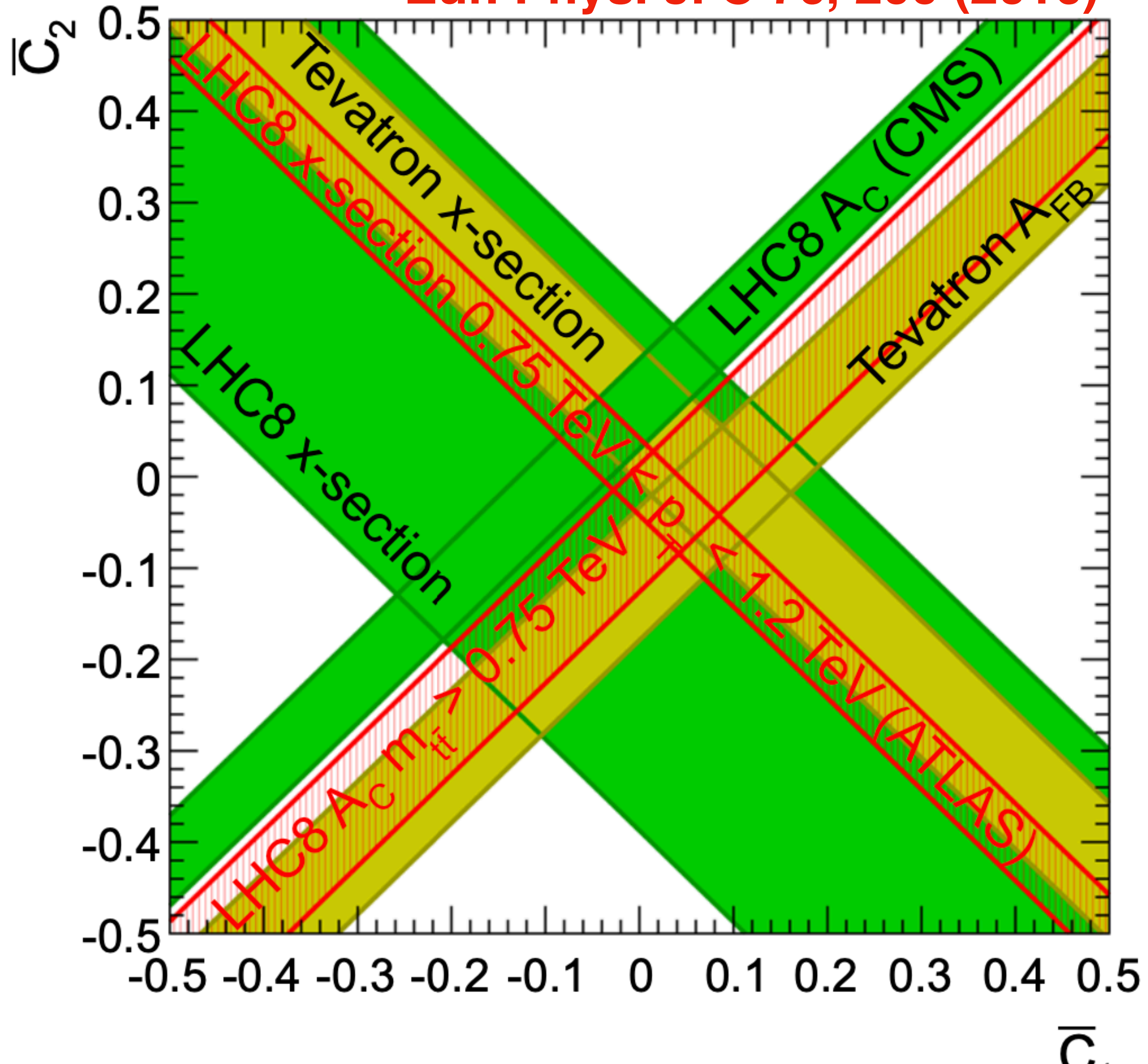



# Charge asymmetry

JHEP08(2023)077

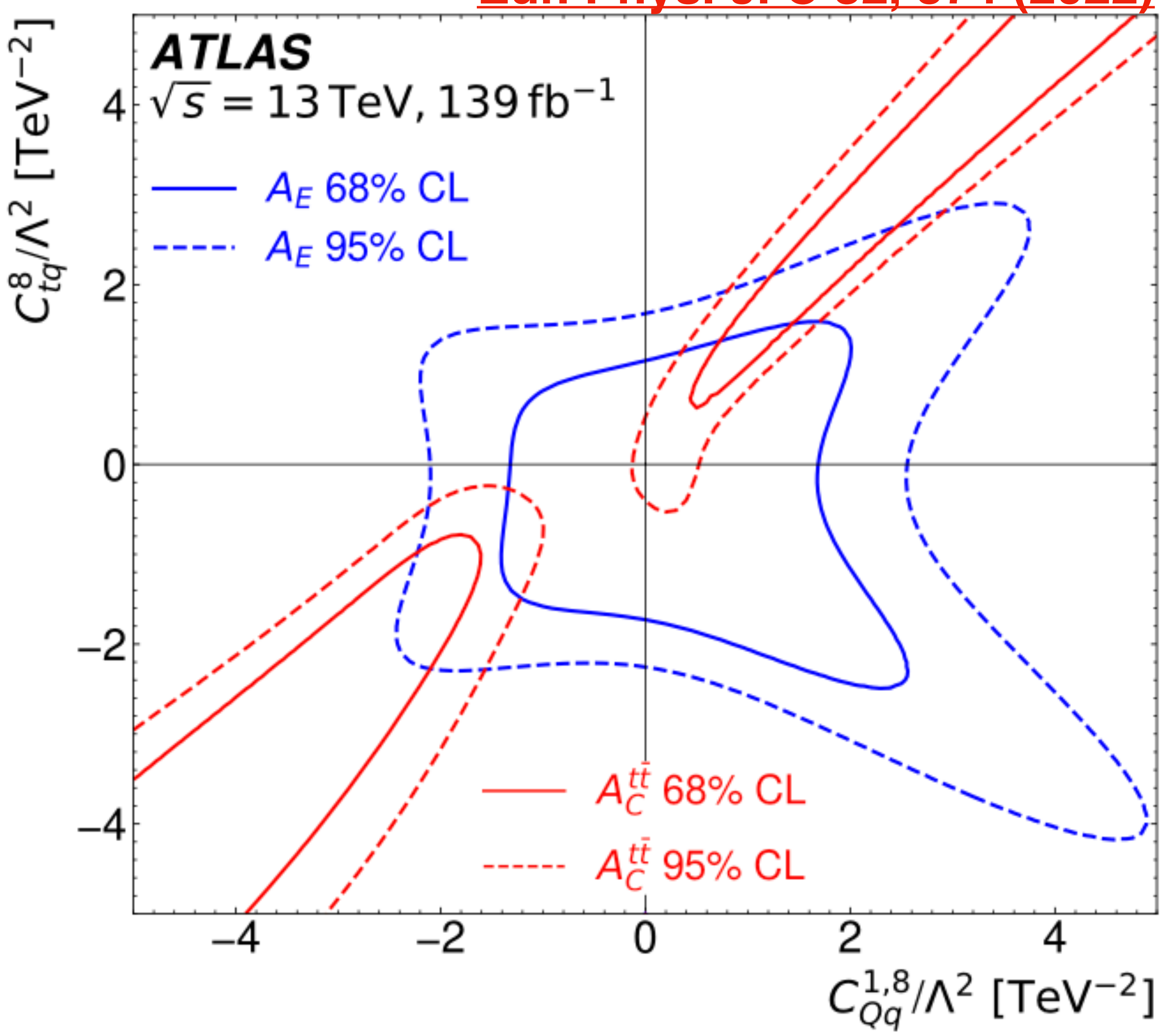
- Measurements interpreted in the framework of the SMEFT, very valuable in disentangling blind directions in global SMEFT fits

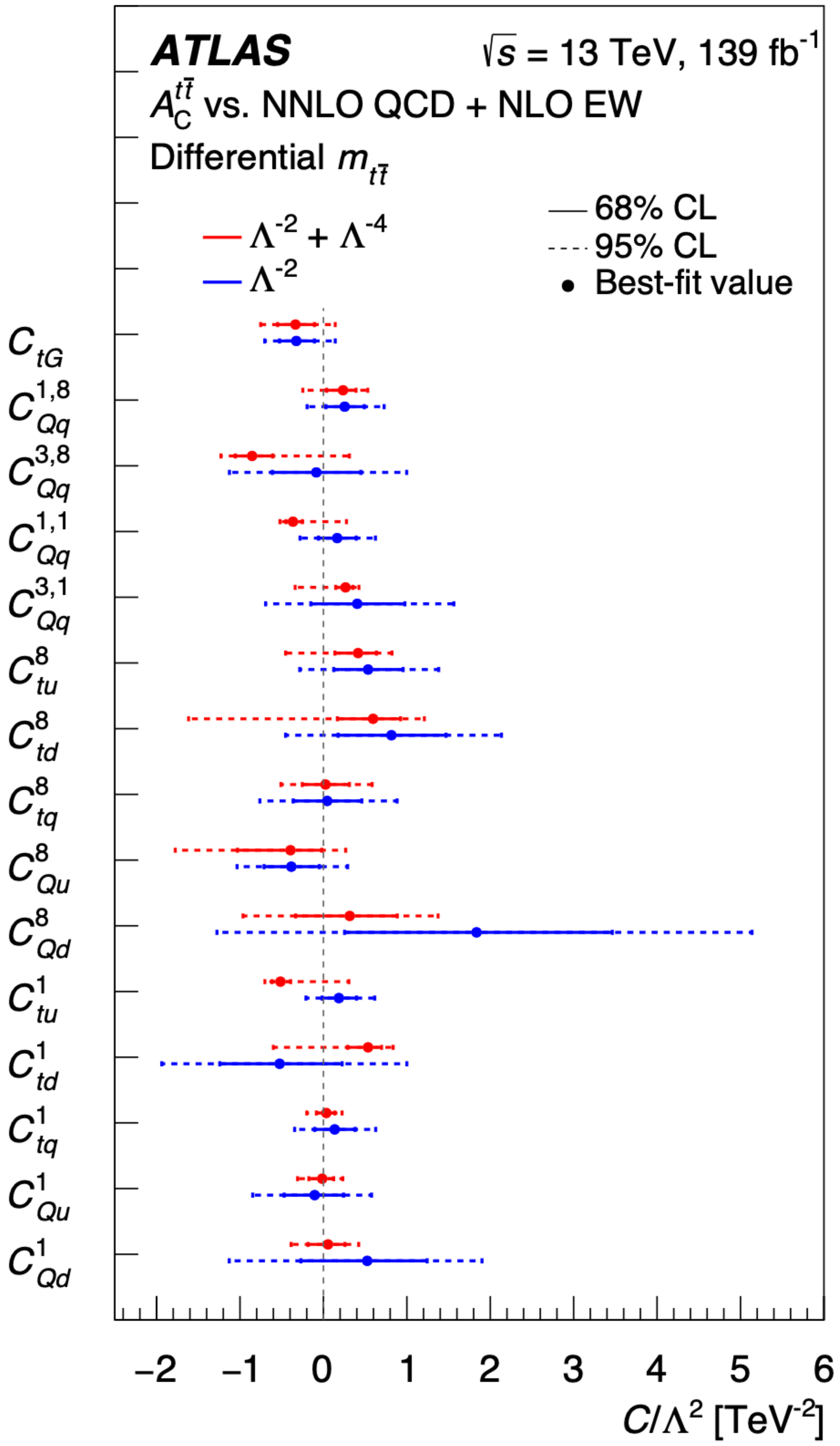
Eur. Phys. J. C 76, 200 (2016)



(a)

Eur. Phys. J. C 82, 374 (2022)



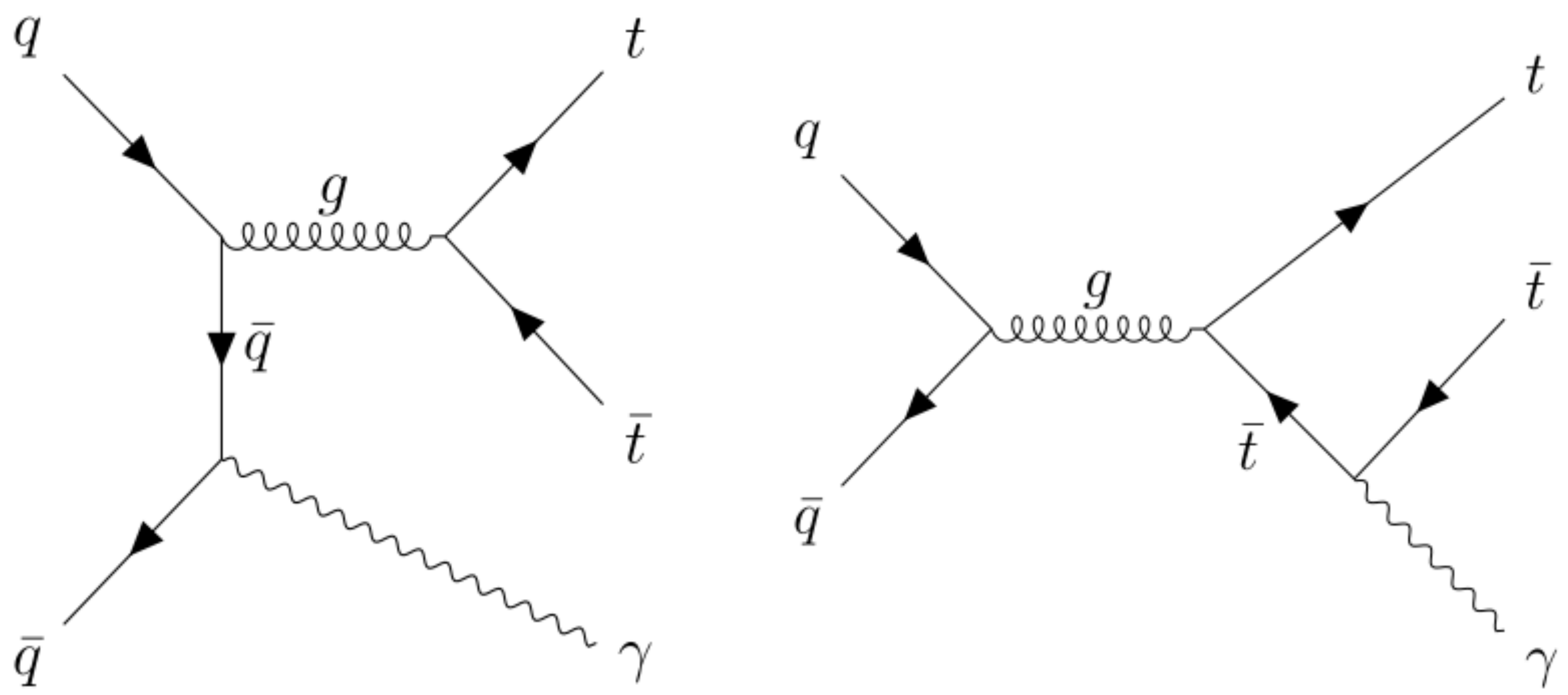

- Individual limits on the Wilson coefficients are derived from the inclusive charge asymmetry measurement and from the differential measurement versus $m_{t\bar{t}}$

- Considerably improvement on the limits derived from the LHC 8 TeV combination and from the Tevatron $A_{FB}$ combination

# Charge asymmetry ($t\bar{t} + \gamma$)

[Physics Letters B 843 (2023) 137848]

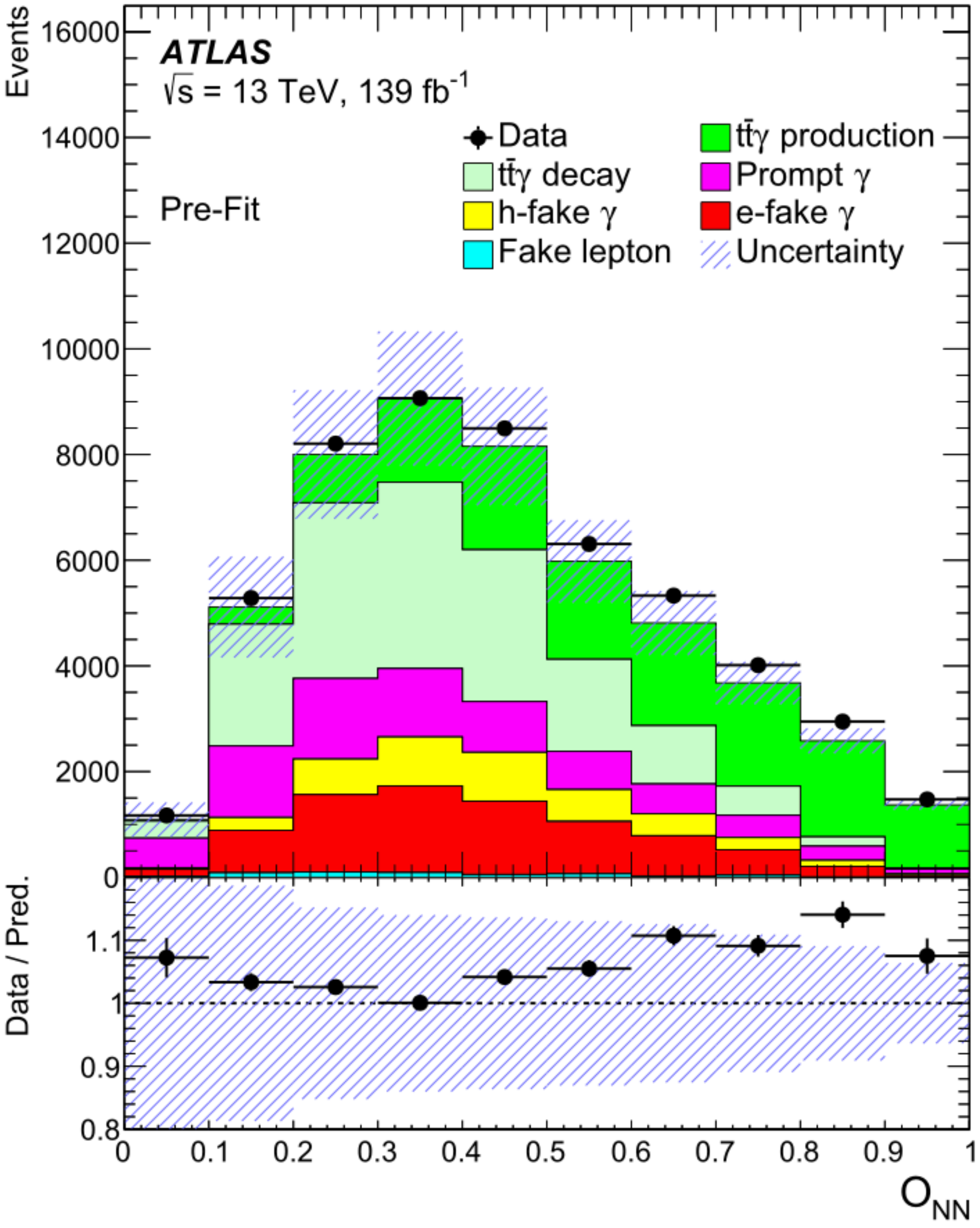
- The $t\bar{t}$ charge asymmetry is diluted at the LHC owing to the large fraction of gluon–gluon-initiated $t\bar{t}$ events, however, it is enhanced in other topologies like $t\bar{t} + \gamma$




- Asymmetry measured in the single lepton channel which have one high-$p$T lepton and at least four jets, two of which arise from $b$-quarks

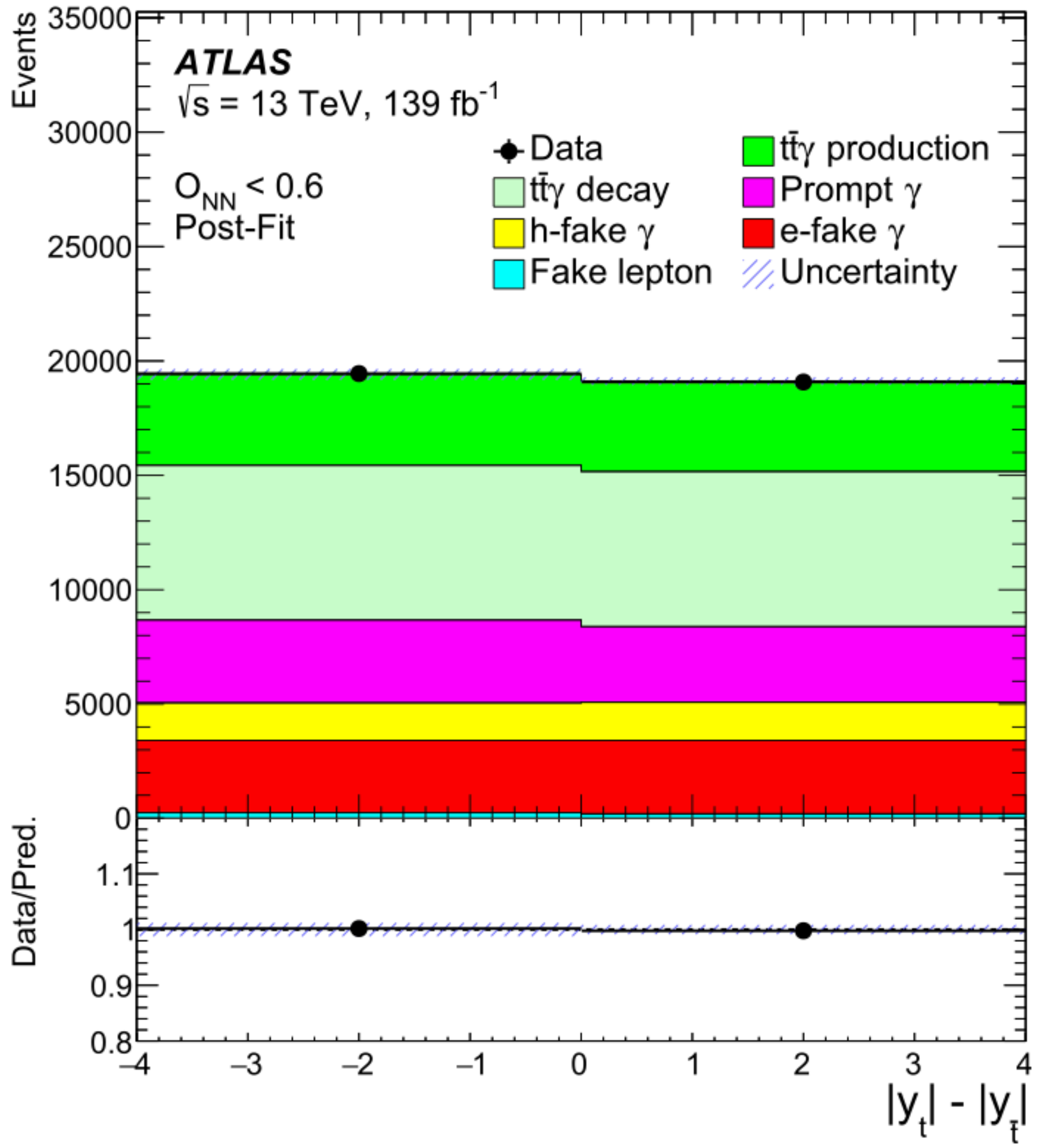
- The separation between signal and background processes is enhanced using a neural network (NN).

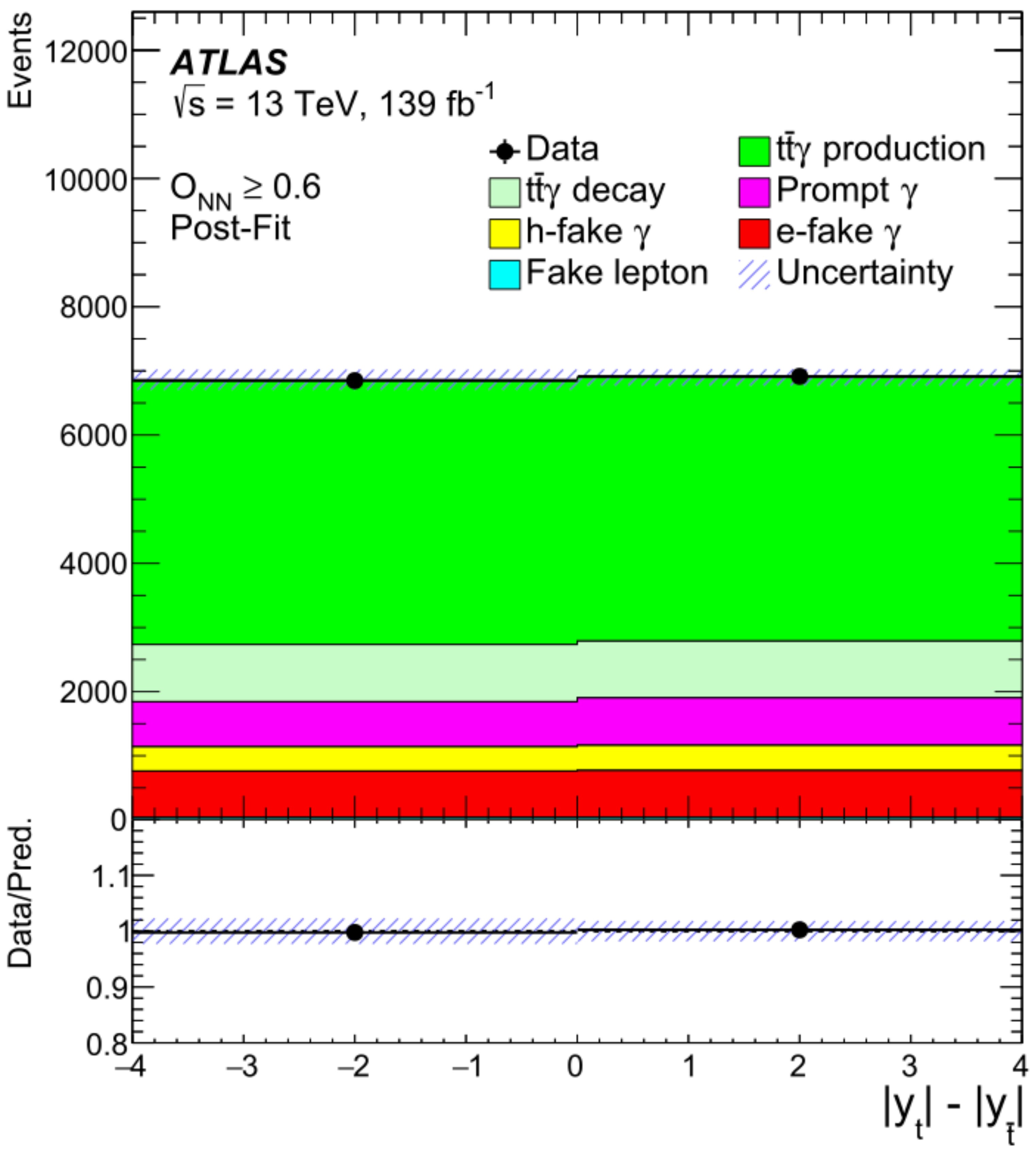
- Maximum-likelihood unfolding performed to correct for detector resolution and acceptance effect



# Charge asymmetry ($t\bar{t} + \gamma$)

Physics Letters B 843 (2023) 137848



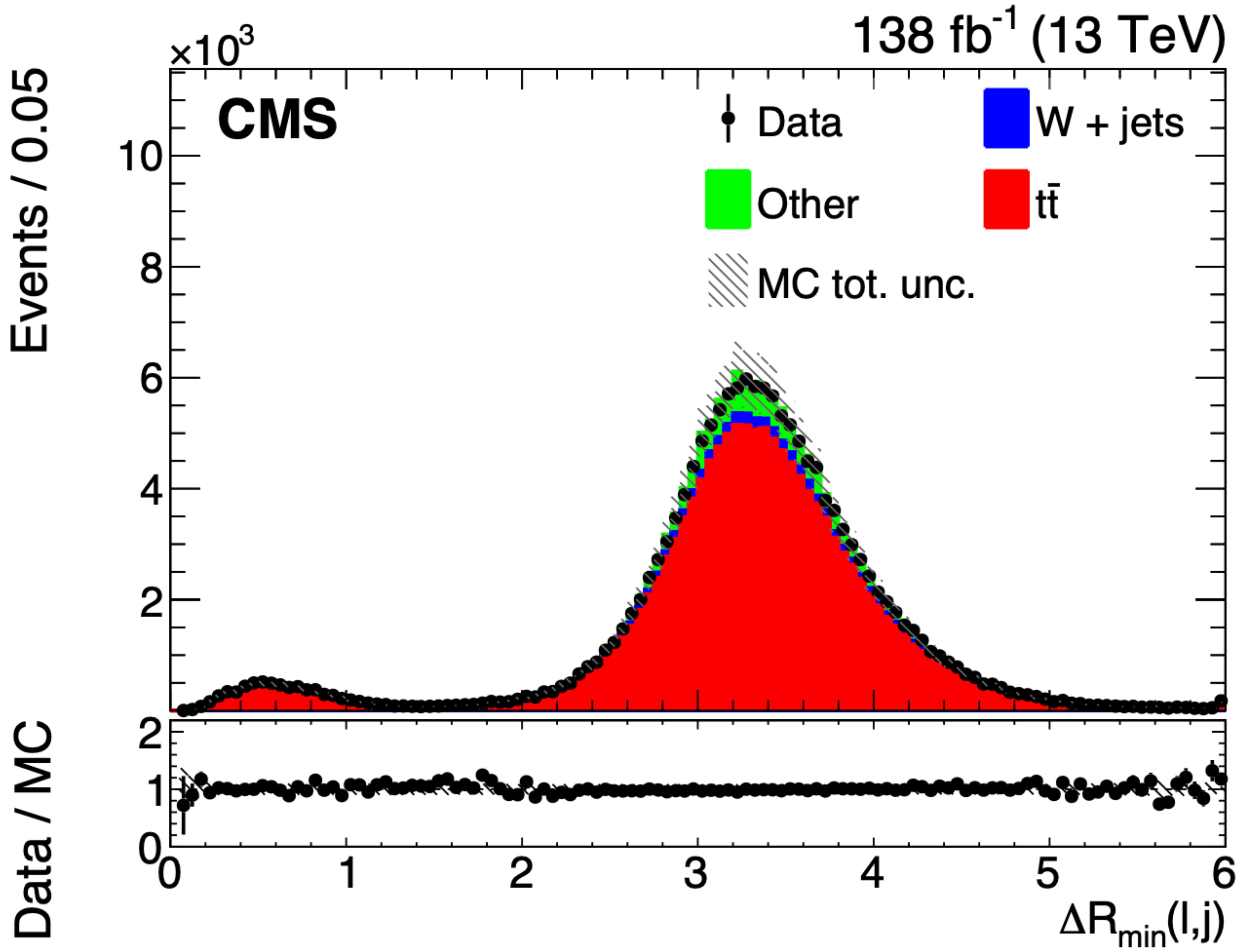

| | |
|---|---|
| **Total uncertainty** | 0.030 |
| **Statistical uncertainty** | 0.024 |
| **MC statistical uncertainties** | |
| $t\bar{t}\gamma$ production | 0.004 |
| Background processes | 0.008 |
| **Modelling uncertainties** | |
| $t\bar{t}\gamma$ production modelling | 0.003 |
| Background modelling | 0.002 |
| Prompt background normalisation | 0.003 |
| **Experimental uncertainties** | |
| Jet and $b$-tagging | 0.010 |
| Fake lepton background estimate | 0.005 |
| $E_{\mathrm{T}}^{\mathrm{miss}}$ | 0.009 |
| Fake photon background estimates | 0.004 |
| Photon | 0.003 |
| Other experimental | 0.004 |

- The inclusive charge asymmetry yields $A_C$ = **-0.003 ±0.029 = -0.003 ± 0.024(stat) ± 0.017(syst)**
- Found to be compatible with the SM prediction
- The precision is limited by the statistical uncertainty

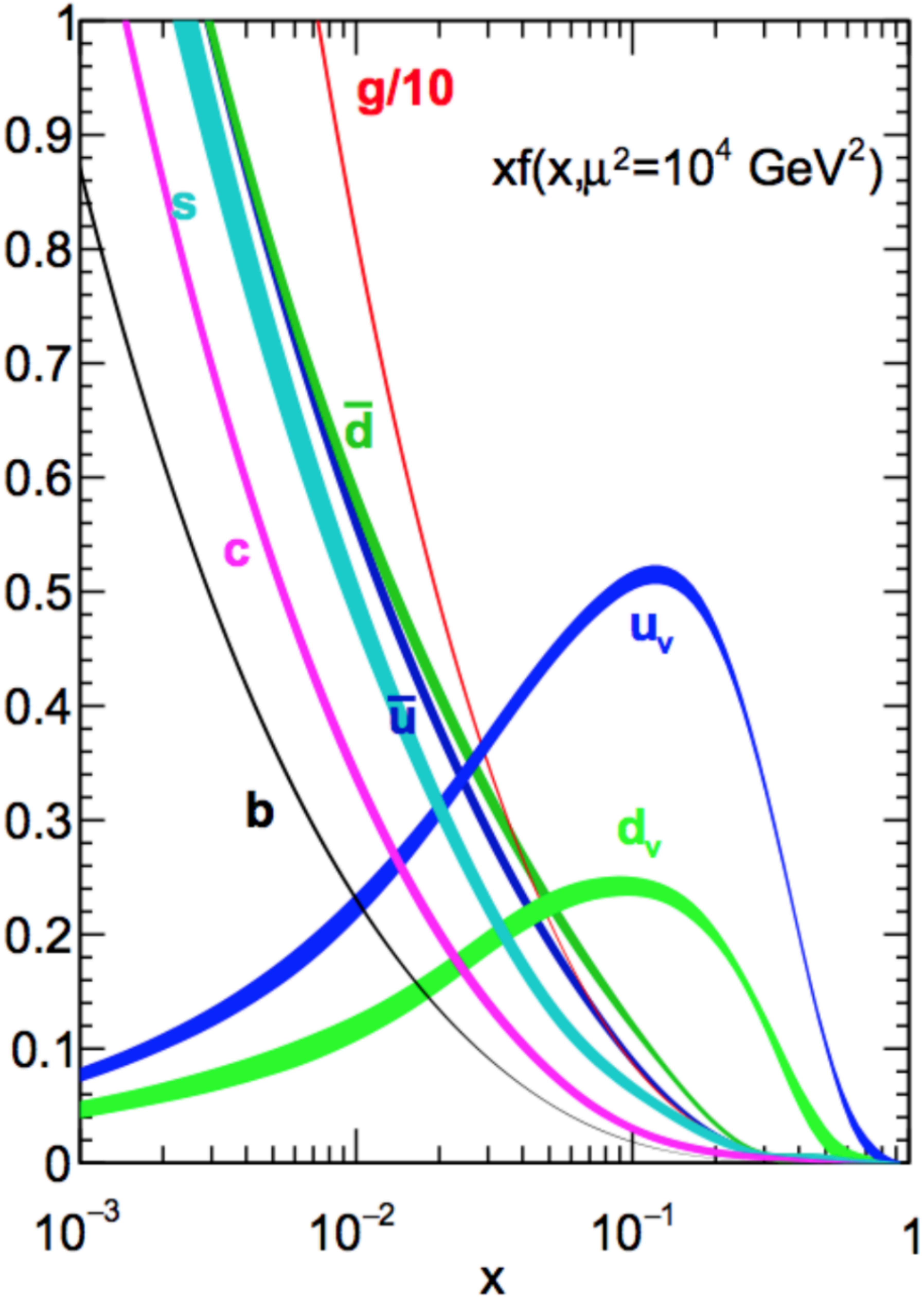
# Boosting charge asymmetry!

arXiv:2208.02751 (accepted by PLB)

- Selection is optimized for top quarks produced with large Lorentz boost, Looking for non-isolating leptons, unlike previous LHC results.




- Important for testing the standard model and searching for BSM physics
- Measured for events with a $t\bar{t}$ invariant mass larger than 750 GeV.



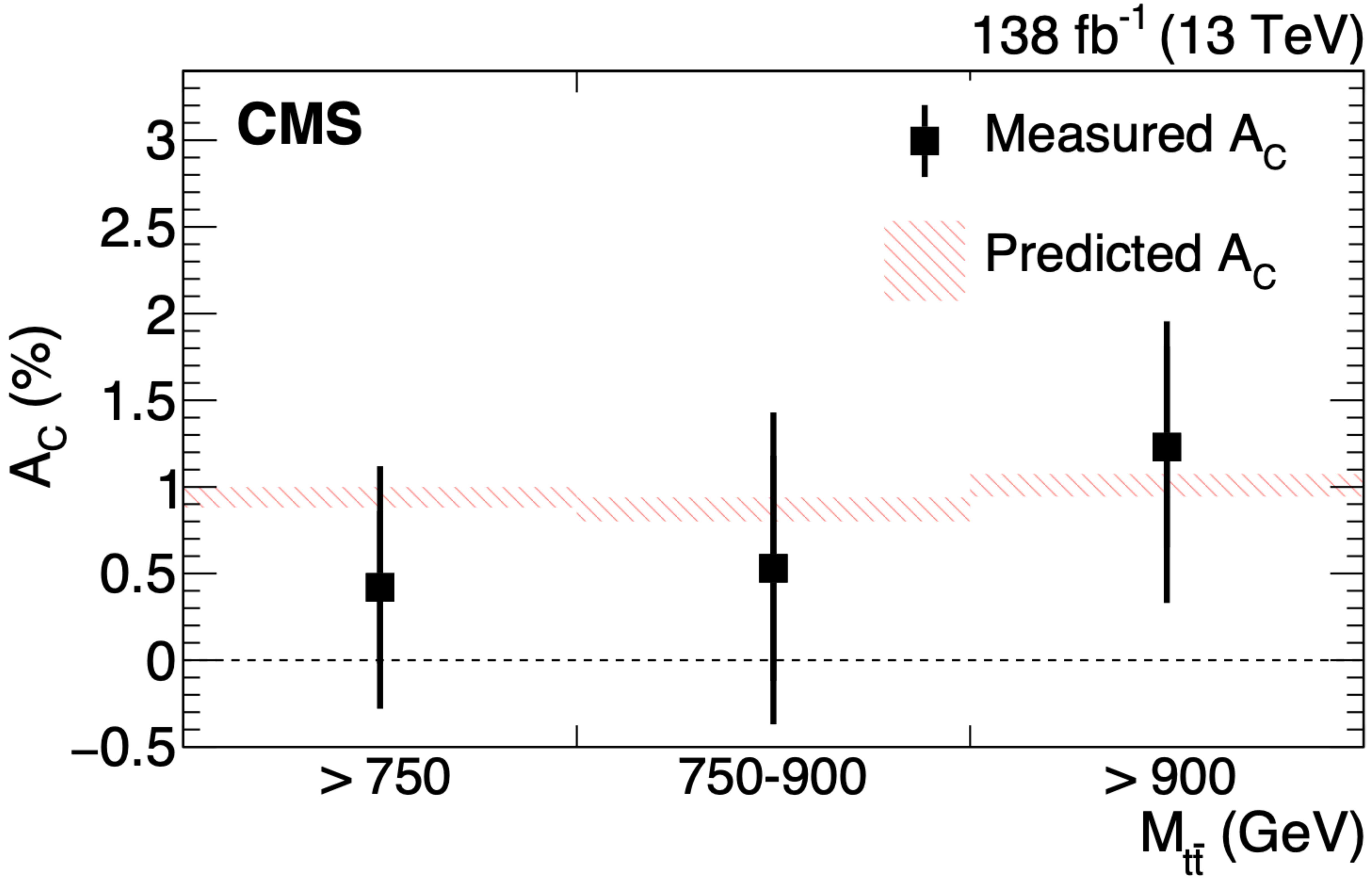
# Boosting charge asymmetry!

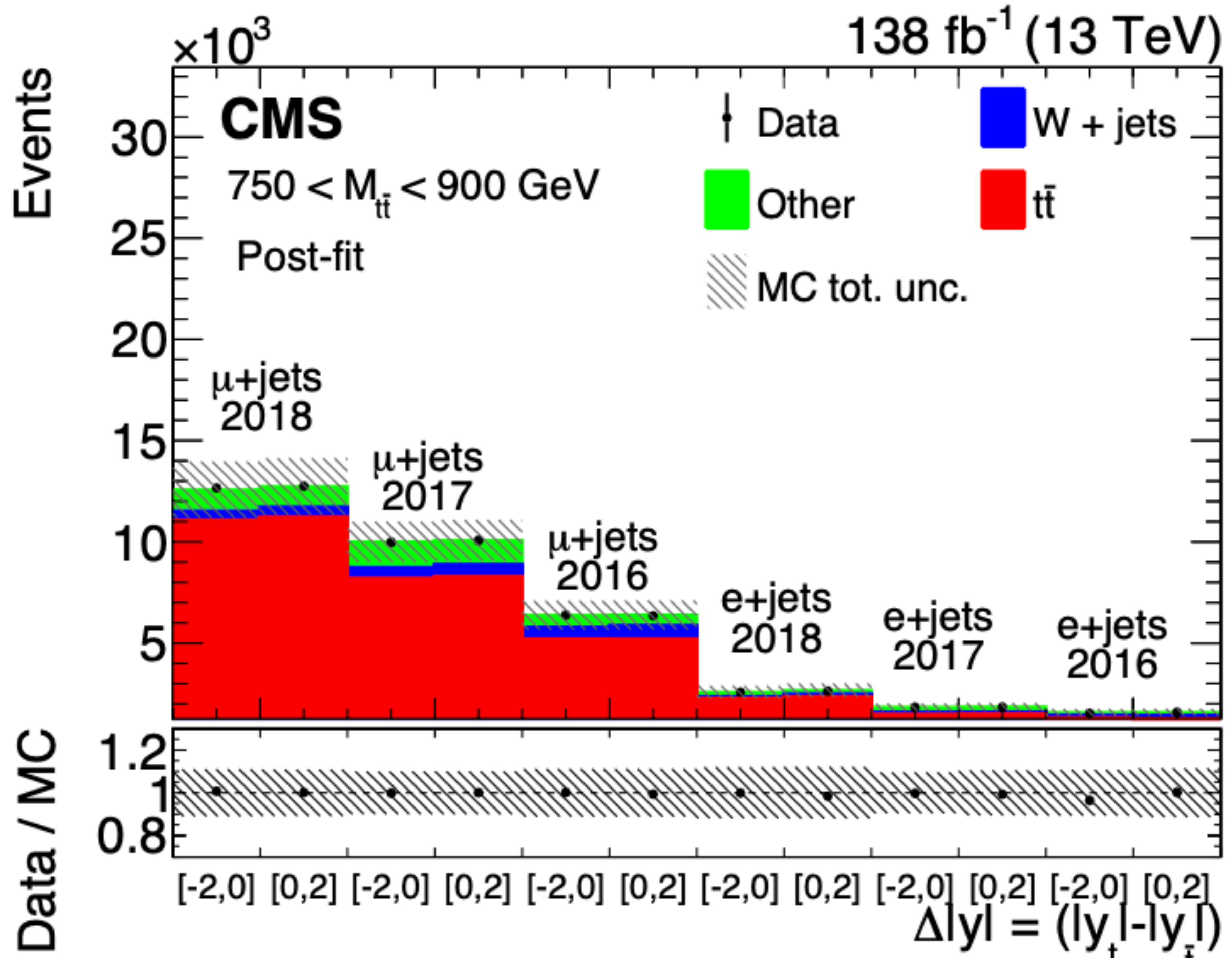
arXiv:2208.02751 (accepted by PLB)

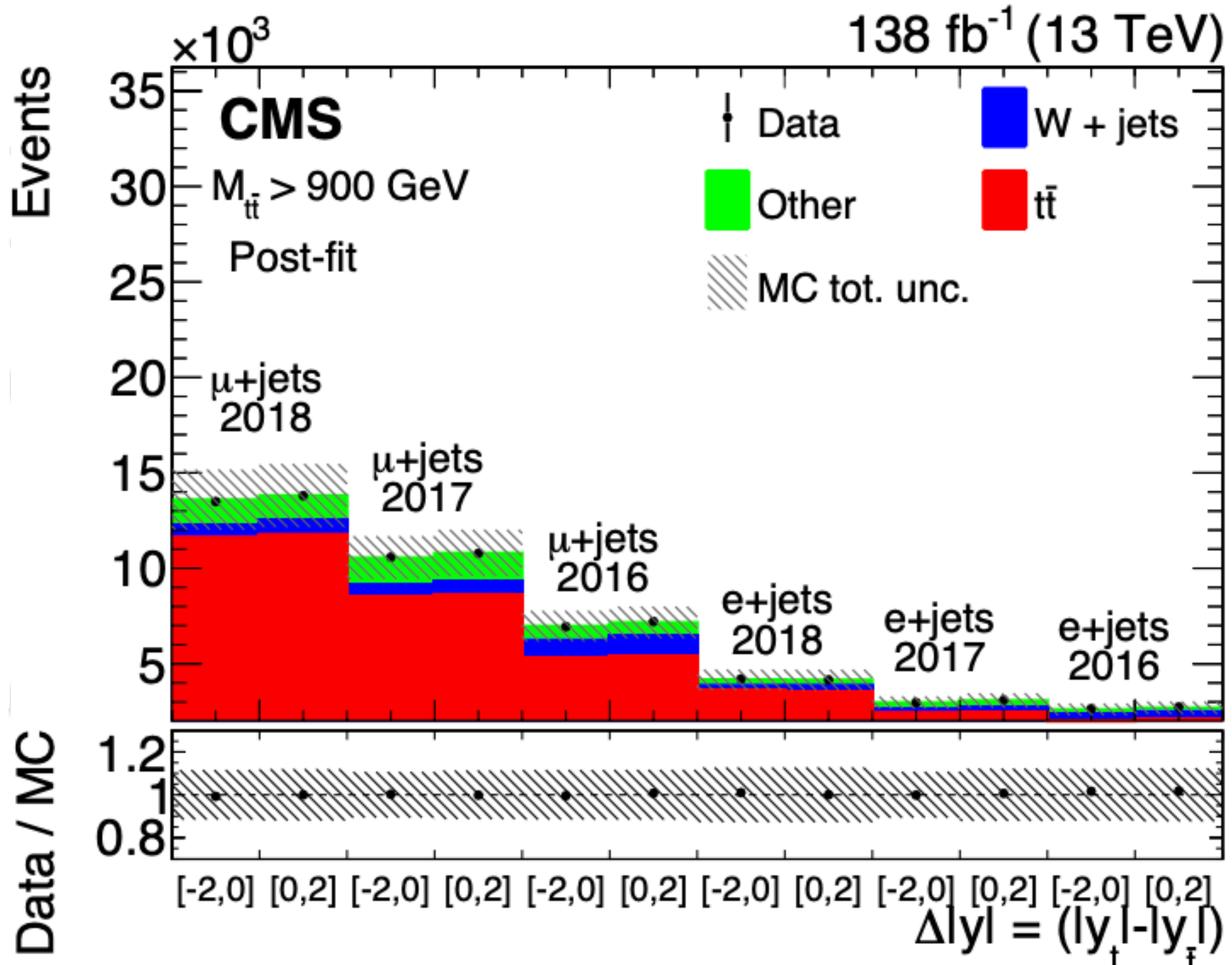
- Most precise charge asymmetry result from LHC ! (Error is dominated by the statistical component)

$$A_C = 0.0042^{+0.0064}_{-0.0069} \quad [\pm 0.0044(stat)]$$

- Compared to theoretical prediction with NNLO in QCD an NLO EW corrections
- Results are in very good agreement with the SM prediction



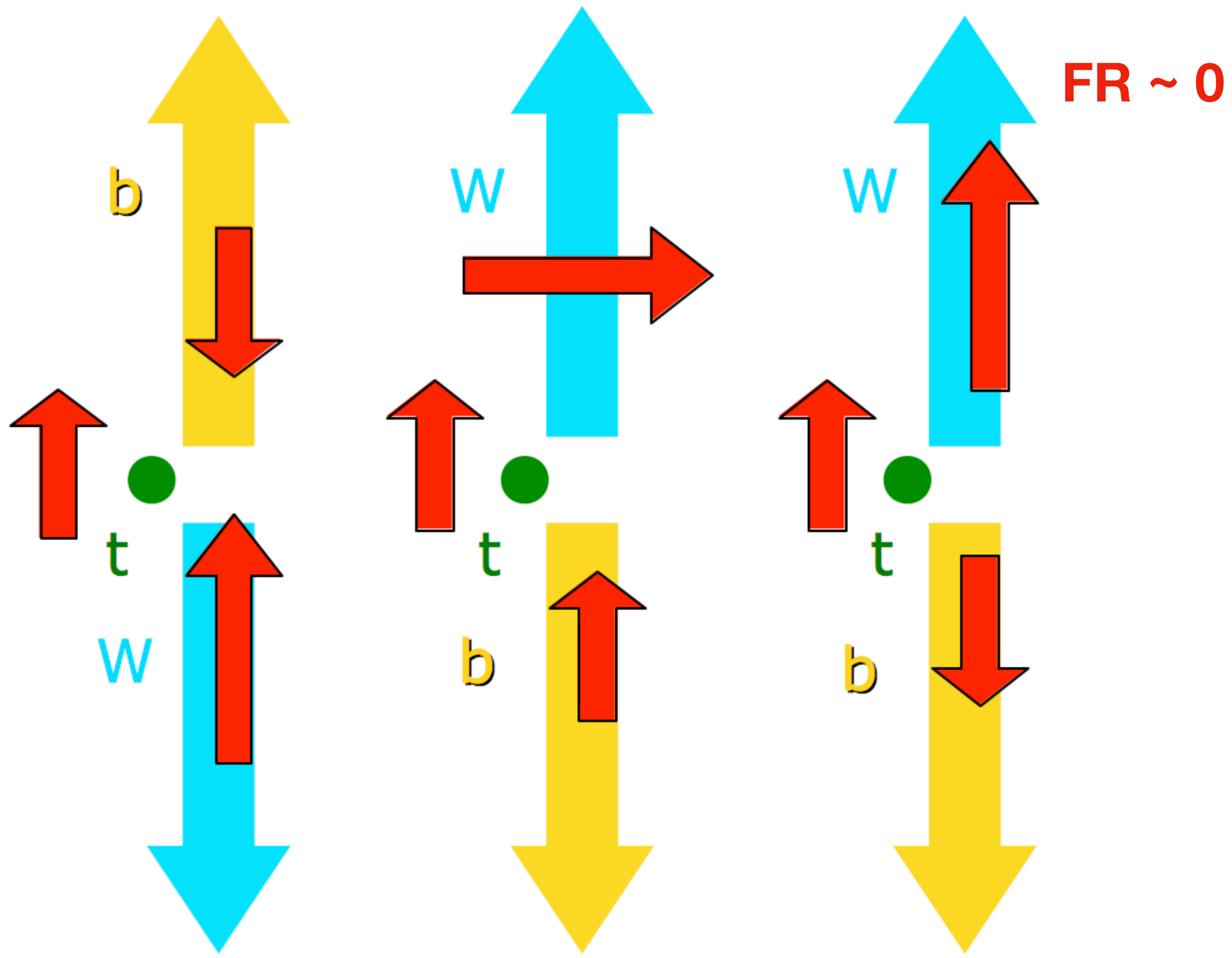



# W Boson Helicity

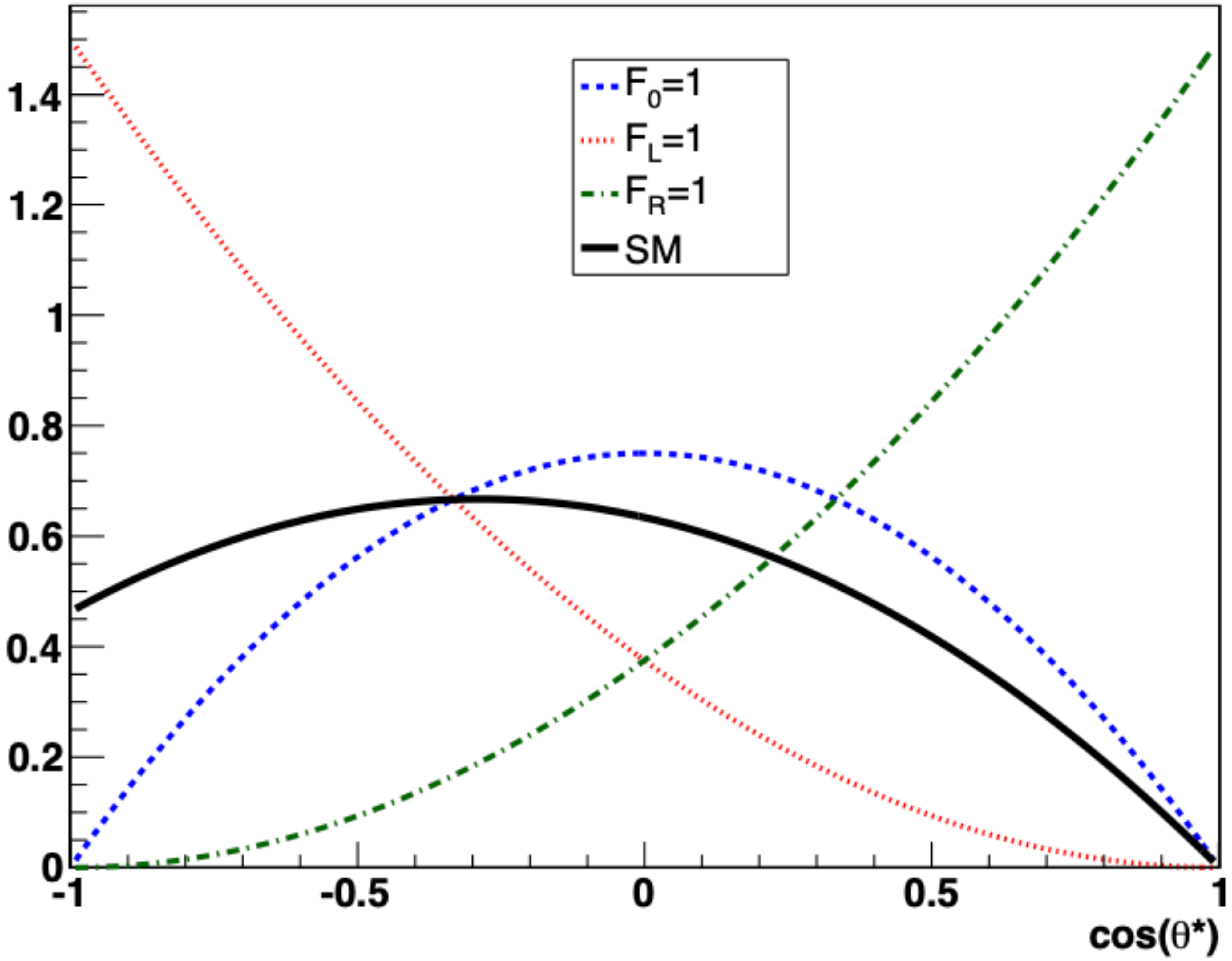
Phys. Lett. B 843 (2023) 137829

- Can be measured through the study of angular distributions of the top quark decay products. Important to understand the structure of be Wtb vertex
- The helicity angle $\theta^*$ is defined as the angle between the charged lepton and the reversed momentum direction of the b quark from the top decay
- W bosons can be polarized longitudinally ($F_0$) or left-handed ($F_L$), but not right-handed ($F_R$) which is strongly suppressed in the SM




Sensitive to anomalous Wtb couplings
(any significant $F_R$ = NP!)

Phys. Lett. B 762 (2016) 512



# W Boson Helicity

Phys. Lett. B 843 (2023) 137829

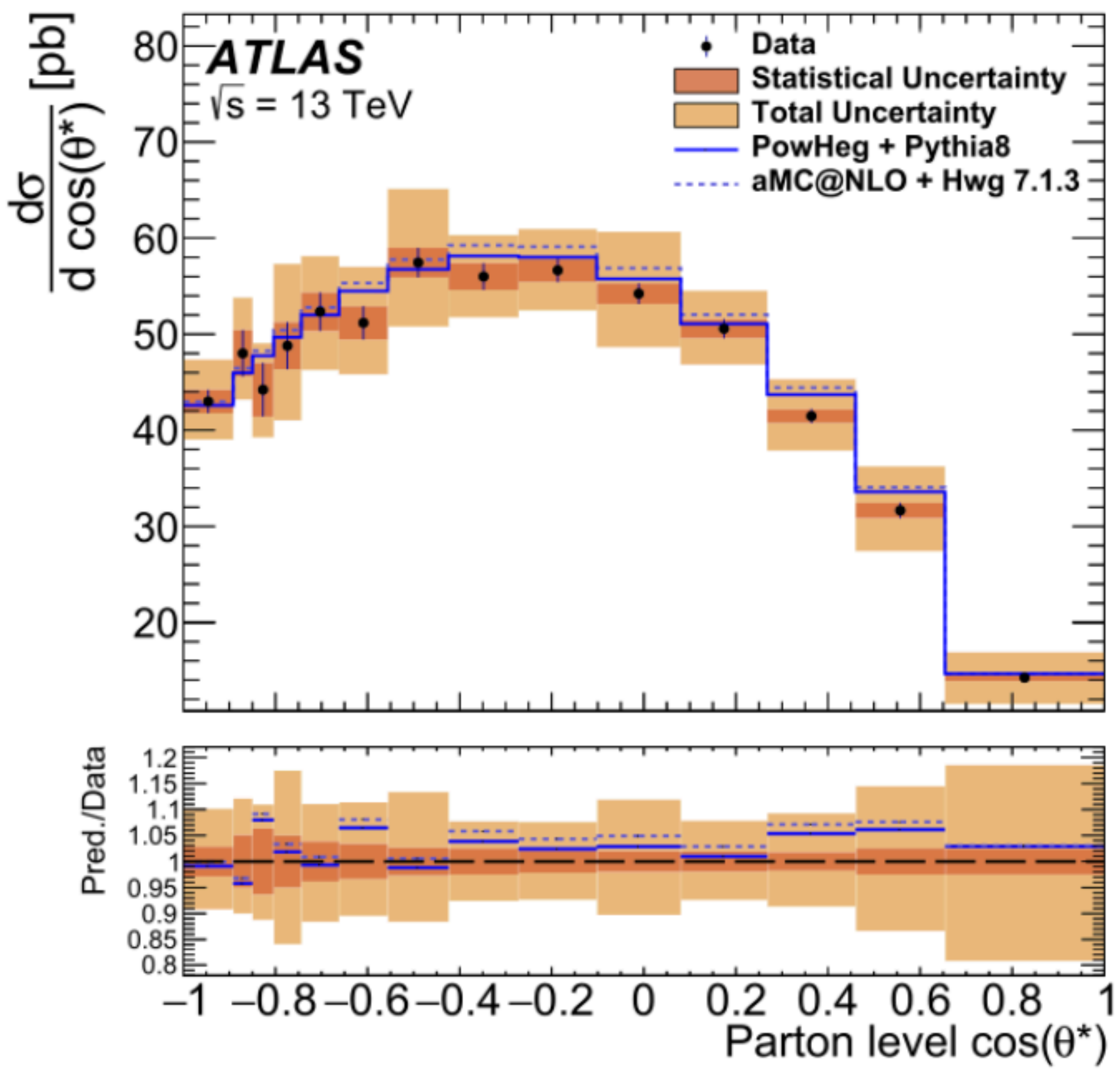
- The measurement is performed selecting $t\bar{t}$ events decaying into final states with two charged leptons (electrons or muons) and at least two b-tagged jets
- The polarization fractions are extracted from the differential cross-section distribution of the *cosθ**
- Parton-level results, corrected for the detector acceptance and resolution

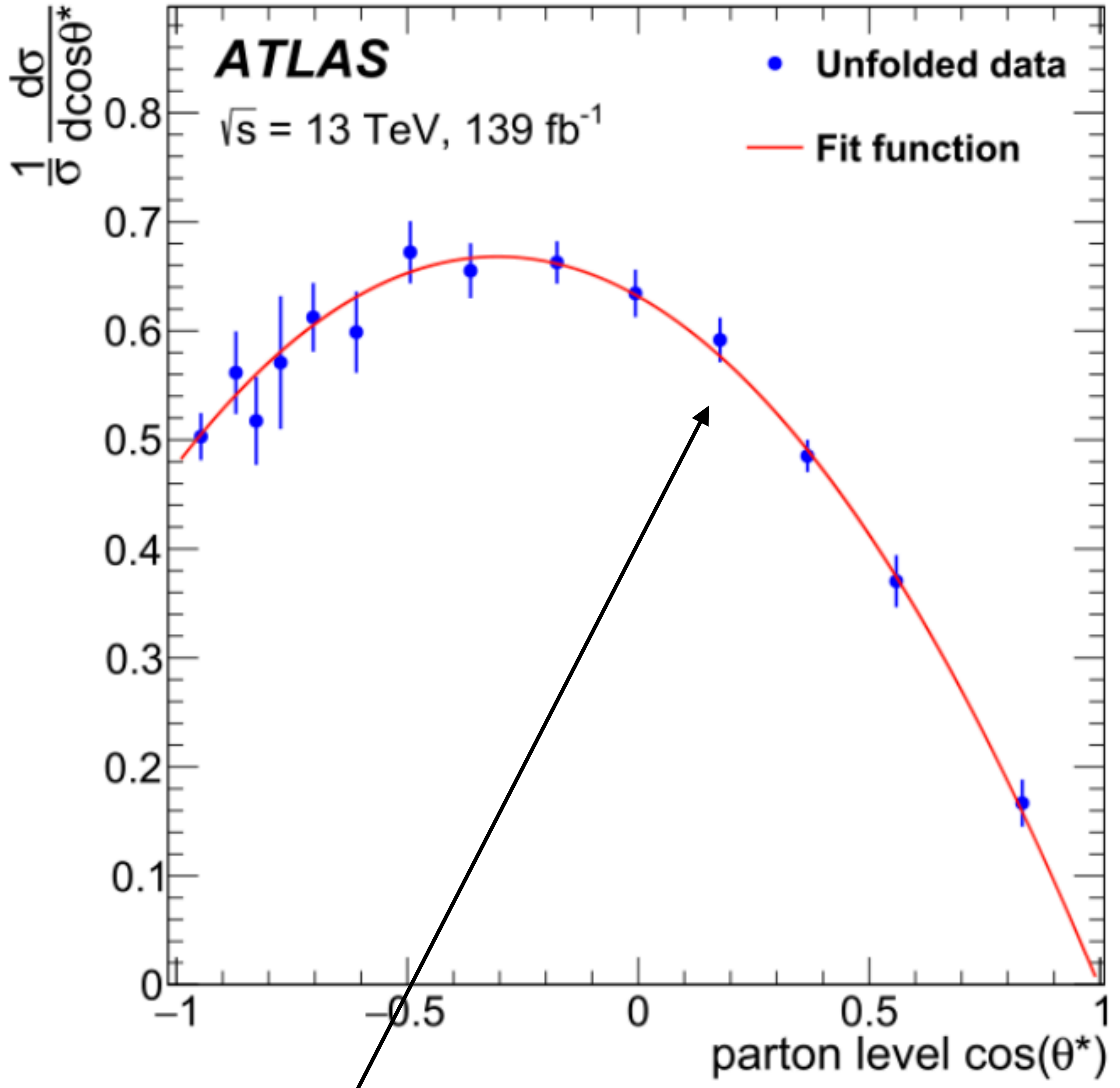
$f0 = 0.684 \pm 0.005\ (\text{stat.}) \pm 0.014\ (\text{syst.})$

$f\,L = 0.318 \pm 0.003\ (\text{stat.}) \pm 0.008\ (\text{syst.})$

$f\,R = -0.002 \pm 0.002\ (\text{stat.}) \pm 0.014\ (\text{syst.})$

In good agreement with the Standard Model prediction!!

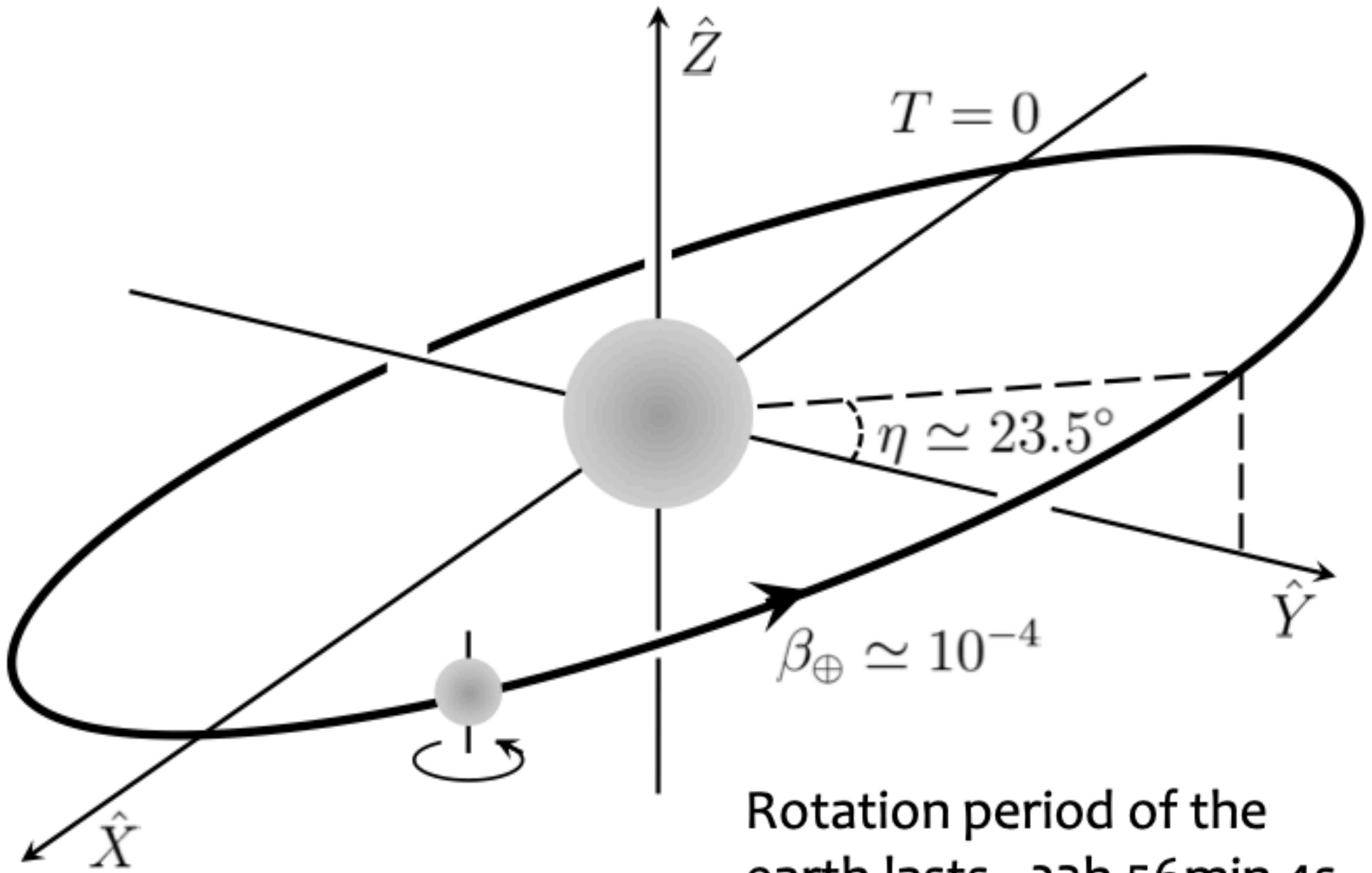



$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta^*} = \frac{3}{4}(1-\cos^2\theta^*)\,f_0 + \frac{3}{8}(1-\cos\theta^*)^2 f_L + \frac{3}{8}(1+\cos\theta^*)^2 f_R.$$

# Lorentz invariance violation

CMS-PAS-TOP-22-007




Rotation period of the earth lasts ~23h 56min 4s (UTC time ~UNIX time)

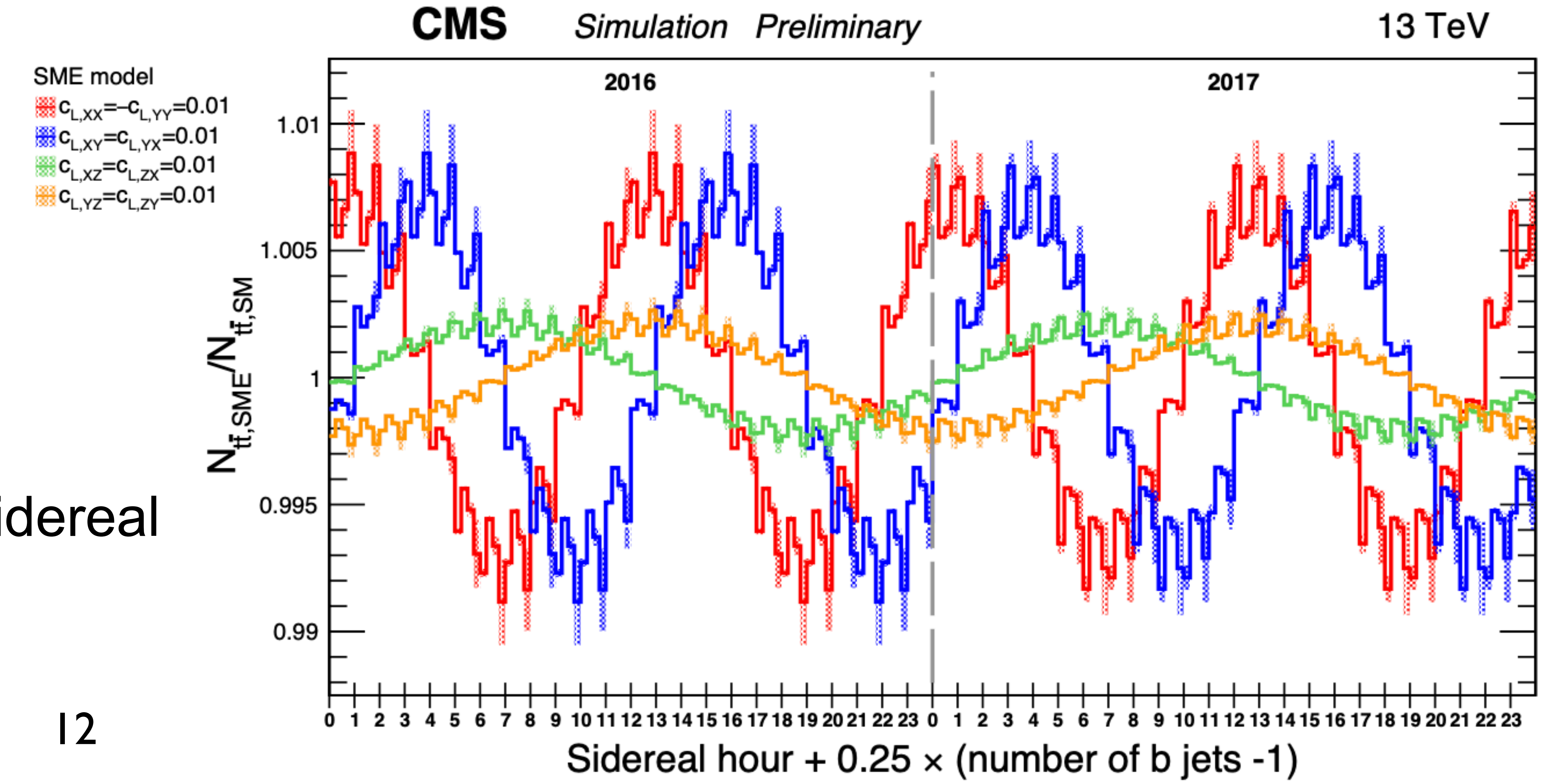
Lorentz-violating Standard Model Extension (SME)

- Motivated by String theory or quantum loop gravity
- Tested in many sectors, but only once with top quarks at D0 PRL 108 (2012) 261603

$$L_{\rm SME} = \frac{1}{2} i\bar{\psi}(\gamma^\nu + c^{\mu\nu}\gamma_\mu + d^{\mu\nu}\gamma_5\gamma_\mu)\overleftrightarrow{\partial_\nu}\psi - m_t\bar{\psi}\psi,$$

**SME coefficients: constant matrices (Lorentz violating)**
**Indicate preferential directions in spacetime**

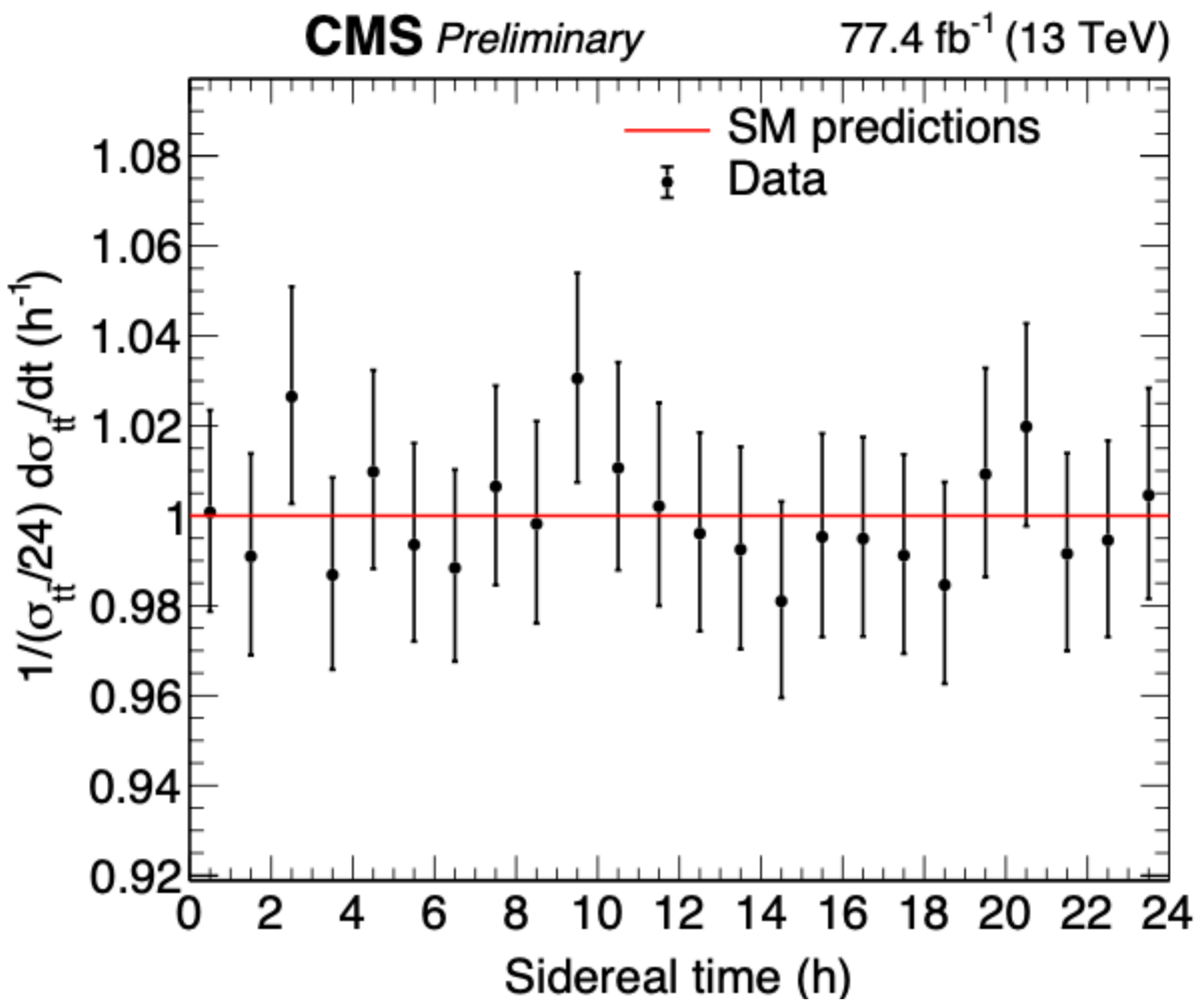
- CMS frame is rotating around the earth Z-axis → modulation of the top-anti top cross section with sidereal time

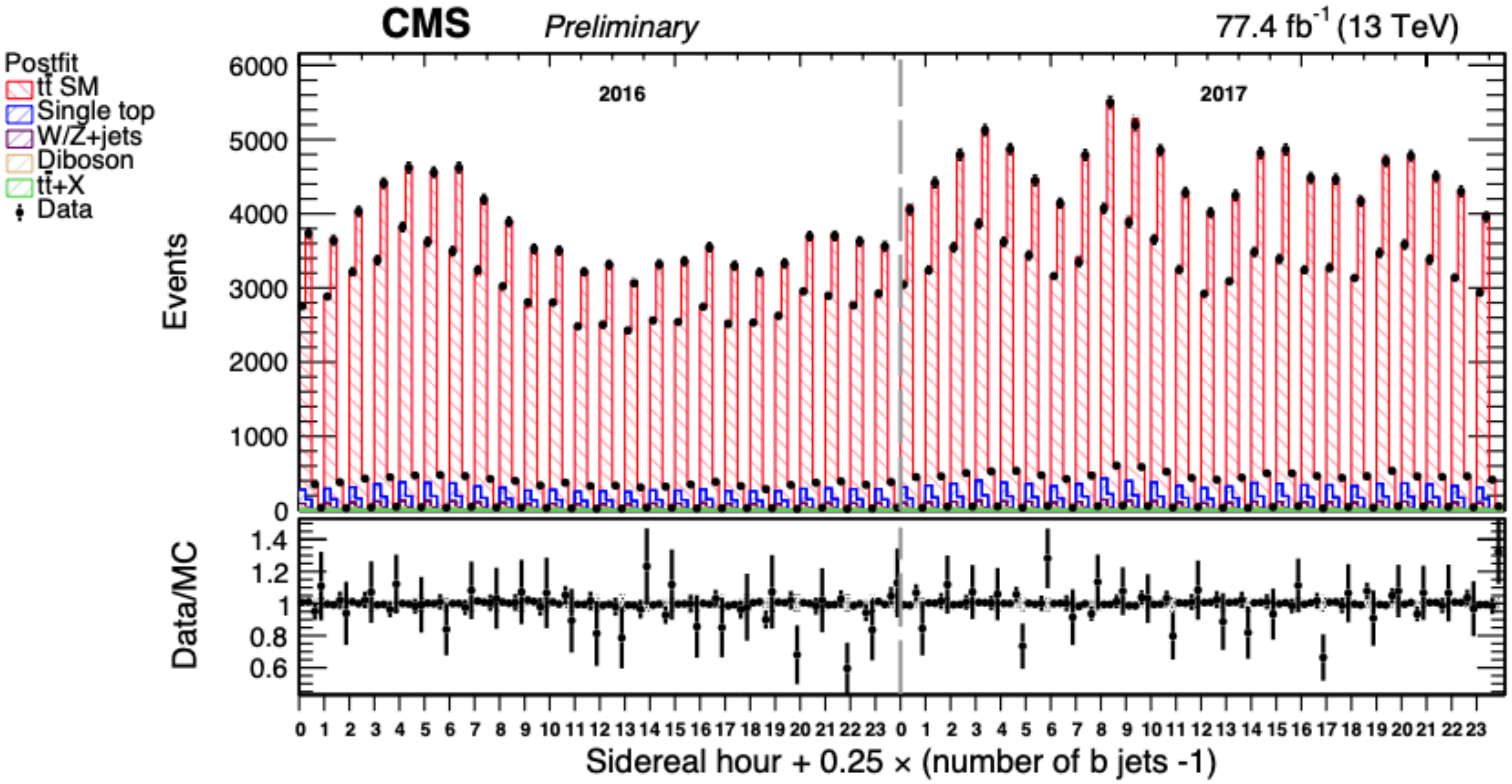


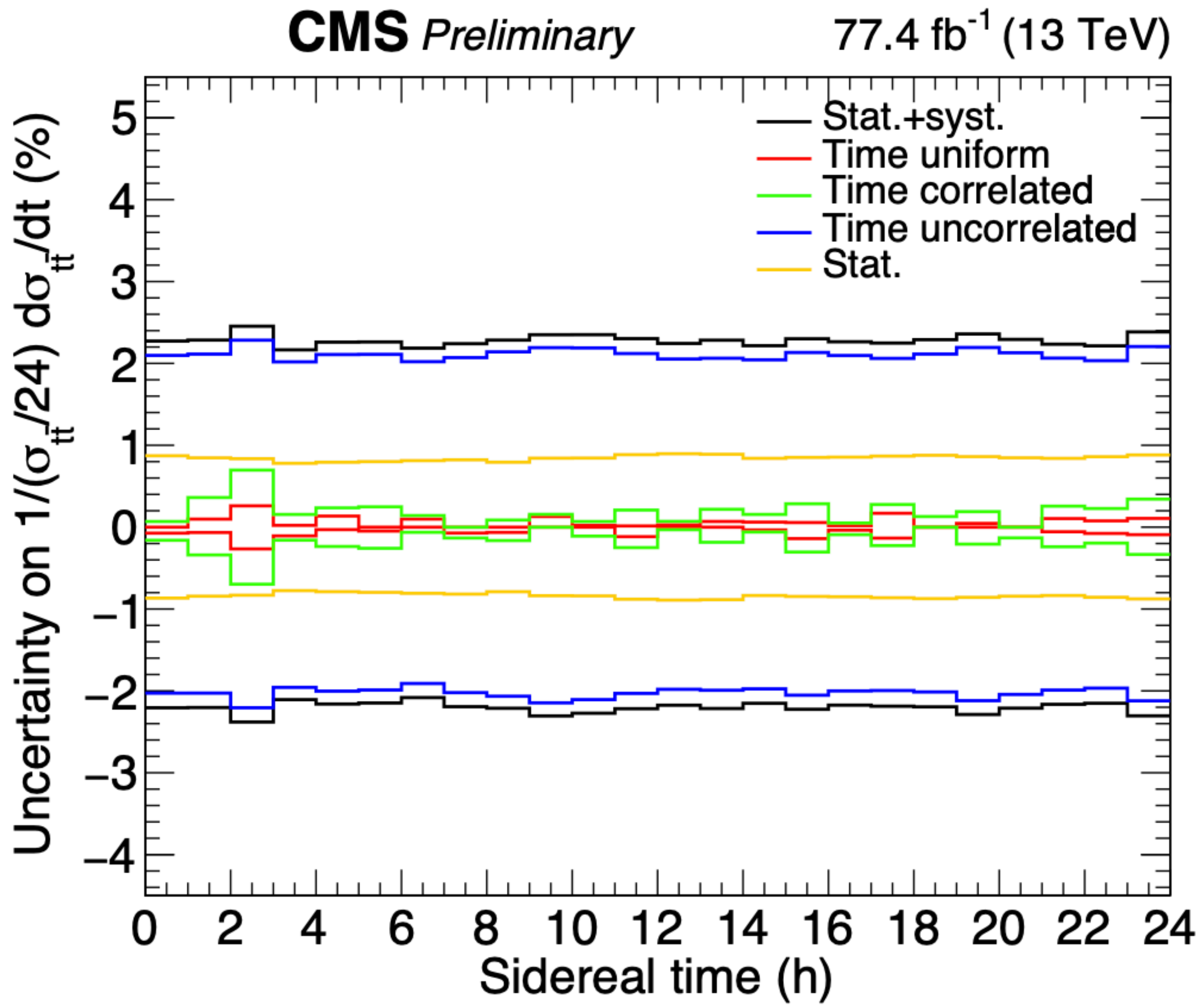
# Lorentz invariance violation

CMS-PAS-TOP-22-007

- First search for Lorentz invariance violation with top quark at the LHC in dileptonic $e\mu$ events from $t\bar{t}$ events in 77.4 fb$^{-1}$ (2016-2017 data).
- The normalized differential cross section for pp → $t\bar{t}$ production is measured as a function of sidereal time, in bins of hours within the sidereal day
- The discriminant observable between $t\bar{t}$ and background processes is built with the distribution in the number of b jets in each sidereal time bin



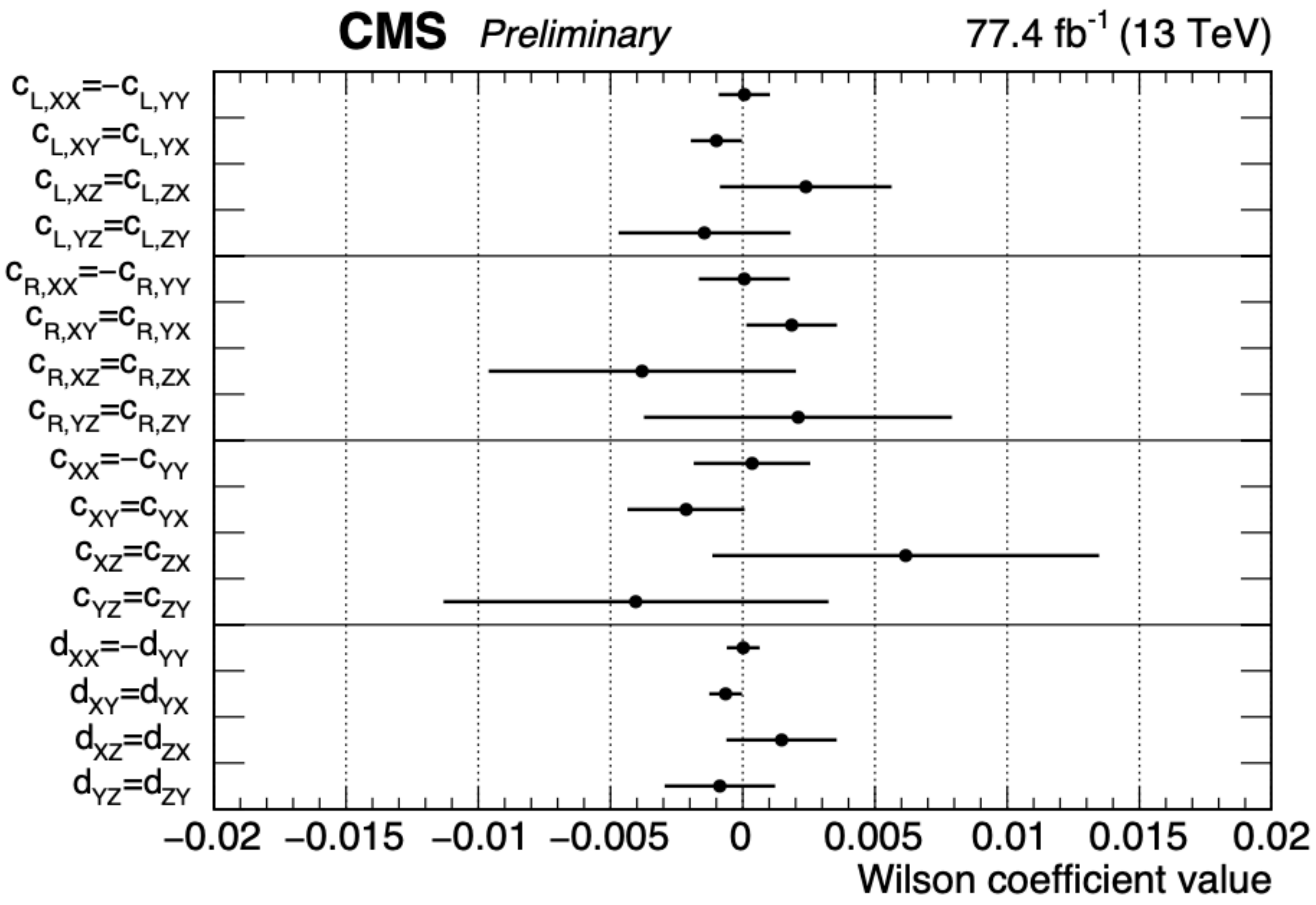
# Lorentz invariance violation

CMS-PAS-TOP-22-007

Likelihood fit is performed in two scenarios:

- Independently for each set of coefficient as single parameter of interest, all other parameters being set to zero
- Independently for each set of coefficient as single parameter of interest, with other parameters floating in the fit
- Measurements of the Lorentz-violating couplings are found to be compatible with the SM hypothesis

| Wilson coefficient | SM expected Others fixed to SM ($10^{-3}$ units) | Data Others fixed to SM ($10^{-3}$ units) | SM expected Others floating ($10^{-3}$ units) | Data Others floating ($10^{-3}$ units) |
|---|---|---|---|---|
| $c_{L,XX} = -c_{L,YY}$ | [−0.97; 0.97] | [−0.91; 1.03] | [−0.97; 0.97] | [−0.91; 1.03] |
| $c_{L,XY} = c_{L,YX}$ | [−0.97; 0.97] | [−1.94; −0.01] | [−0.97; 0.97] | [−1.96; −0.03] |
| $c_{L,XZ} = c_{L,ZX}$ | [−3.25; 3.25] | [−0.91; 5.58] | [−3.25; 3.25] | [−0.86; 5.63] |
| $c_{L,YZ} = c_{L,ZY}$ | [−3.26; 3.26] | [−4.66; 1.83] | [−3.27; 3.27] | [−4.7; 1.81] |
| $c_{R,XX} = -c_{R,YY}$ | [−1.71; 1.71] | [−1.65; 1.79] | [−1.71; 1.71] | [−1.66; 1.77] |
| $c_{R,XY} = c_{R,YX}$ | [−1.72; 1.72] | [0.11; 3.53] | [−1.72; 1.72] | [0.14; 3.56] |
| $c_{R,XZ} = c_{R,ZX}$ | [−5.81; 5.82] | [−9.52; 2.1] | [−5.82; 5.82] | [−9.61; 2.01] |
| $c_{R,YZ} = c_{R,ZY}$ | [−5.84; 5.84] | [−3.79; 7.86] | [−5.84; 5.84] | [−3.74; 7.91] |
| $c_{XX} = -c_{YY}$ | [−2.19; 2.19] | [−1.78; 2.62] | [−2.19; 2.19] | [−1.85; 2.55] |
| $c_{XY} = c_{YX}$ | [−2.19; 2.19] | [−4.27; 0.15] | [−2.19; 2.19] | [−4.36; 0.07] |
| $c_{XZ} = c_{ZX}$ | [−7.25; 7.25] | [−1.35; 13.27] | [−7.26; 7.25] | [−1.15; 13.48] |
| $c_{YZ} = c_{ZY}$ | [−7.29; 7.29] | [−11.16; 3.35] | [−7.29; 7.29] | [−11.31; 3.24] |
| $d_{XX} = -d_{YY}$ | [−0.62; 0.62] | [−0.6; 0.64] | [−0.62; 0.62] | [−0.6; 0.64] |
| $d_{XY} = d_{YX}$ | [−0.62; 0.62] | [−1.25; −0.02] | [−0.62; 0.62] | [−1.27; −0.03] |
| $d_{XZ} = d_{ZX}$ | [−2.09; 2.09] | [−0.65; 3.52] | [−2.09; 2.09] | [−0.62; 3.55] |
| $d_{YZ} = d_{ZY}$ | [−2.1; 2.1] | [−2.93; 1.24] | [−2.1; 2.1] | [−2.95; 1.23] |




**This constitutes the most precise test of Lorentz invariance using top quarks at a hadron collider!!!**

# Summary

- CMS and ATLAS have made a lot of progress in measuring the properties of the top quark at
- Run 2 have provided a set of data to start high precision measurements in the top quark sector:
    - **Charge asymmetry:** Improved results from CMS and ATLAS in different topologies
    - **W helicity**: new ATLAS result using the angle between the charged lepton from the W decay and the reversed momentum direction of the b quark from the top decay, limited by systematics
    - **Lorentz invariance:** Most precise result at a hadron collider in latest CMS result, absolute precision of 0.1-0.8% of Lorentz-violating couplings

Stay tuned, Run 3 already started with new $\sqrt{s} = 13.6$ TeV
Expected luminosity: 250 $fb^{-1}$

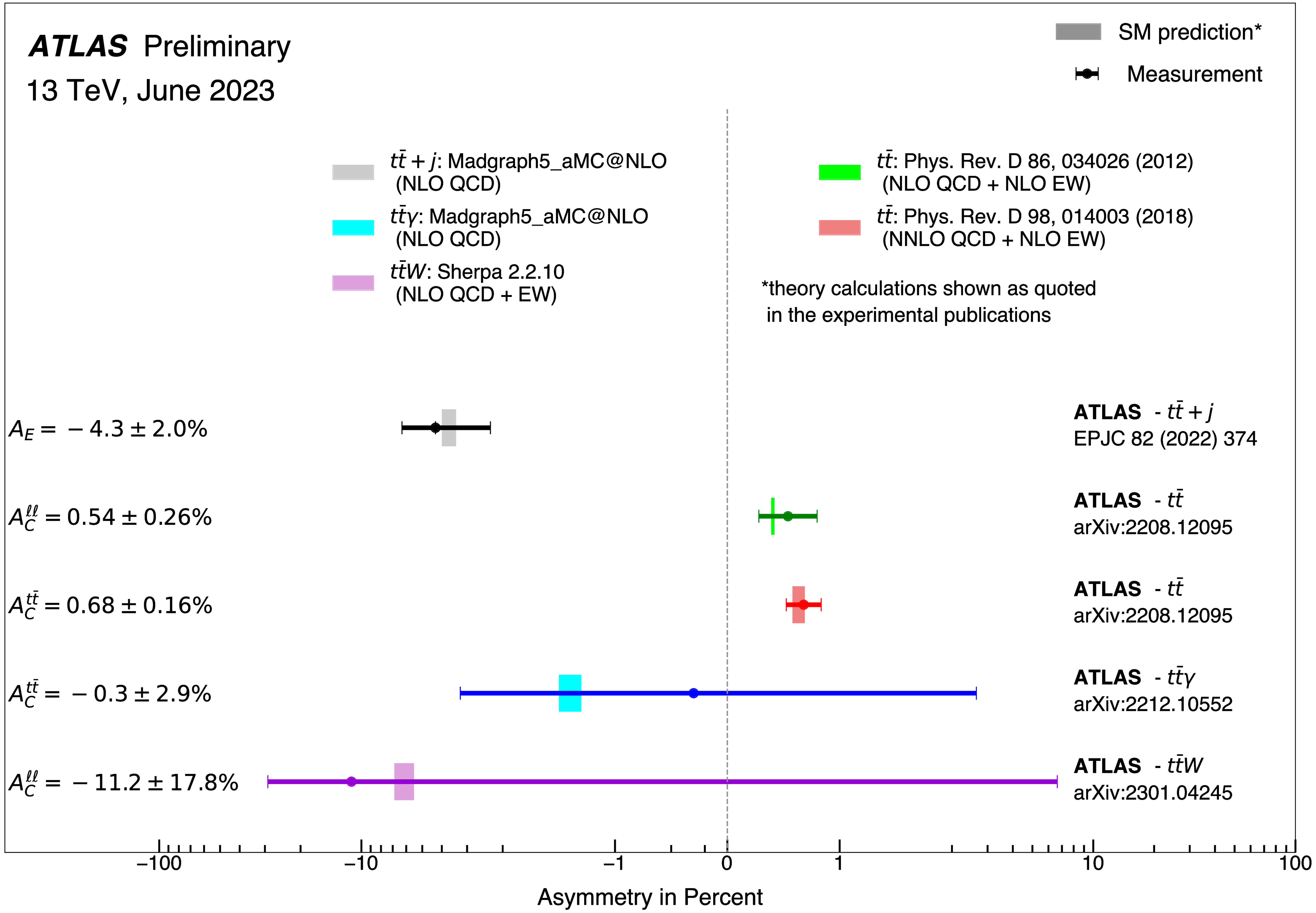
No evidence of NP

# Backup

# ATLAS charge asymmetry (summary)

ATLAS-PHYS-PUB-2023-013

- Summary of ATLAS measurements of the charge asymmetry in the top quark sector in inclusive tt̄ final states, in tt̄ production with extra jets, and in associated production of tt̄ with a photon and a W boson.
- The charge-asymmetry measurements in inclusive tt̄ final states are compared to NNLO QCD + NLO EWK (NLO QCD + NLO EW for the leptonic asymmetry)
- Theory bands represent uncertainties due to renormalization and factorization scales



# W Boson Helicity

Phys. Lett. B 843 (2023) 137829

- Summary of measured W helicity fractions by CMS and ATLAS at 7, 8 and 13 TeV, compared to theory predictions
- Analysis limited by the systematic uncertainties