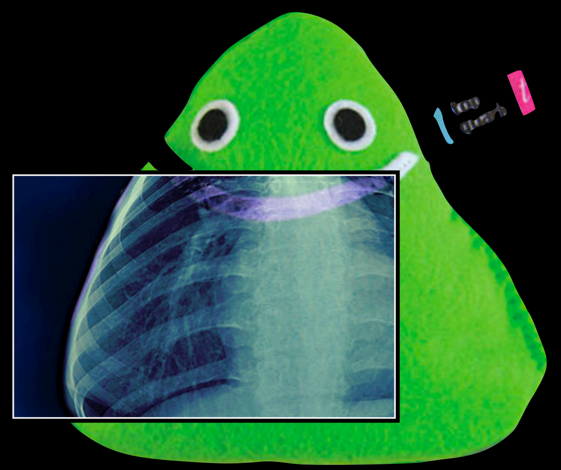
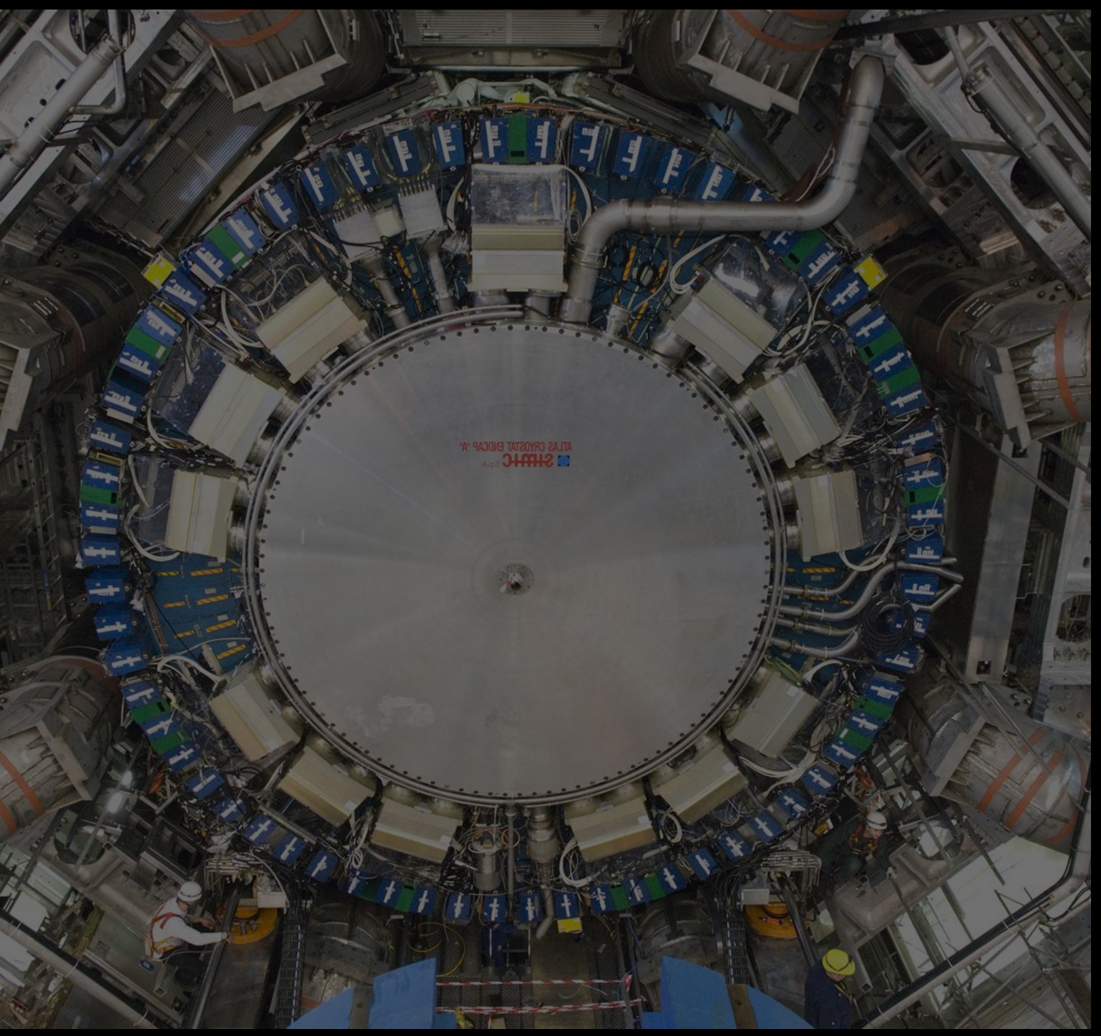
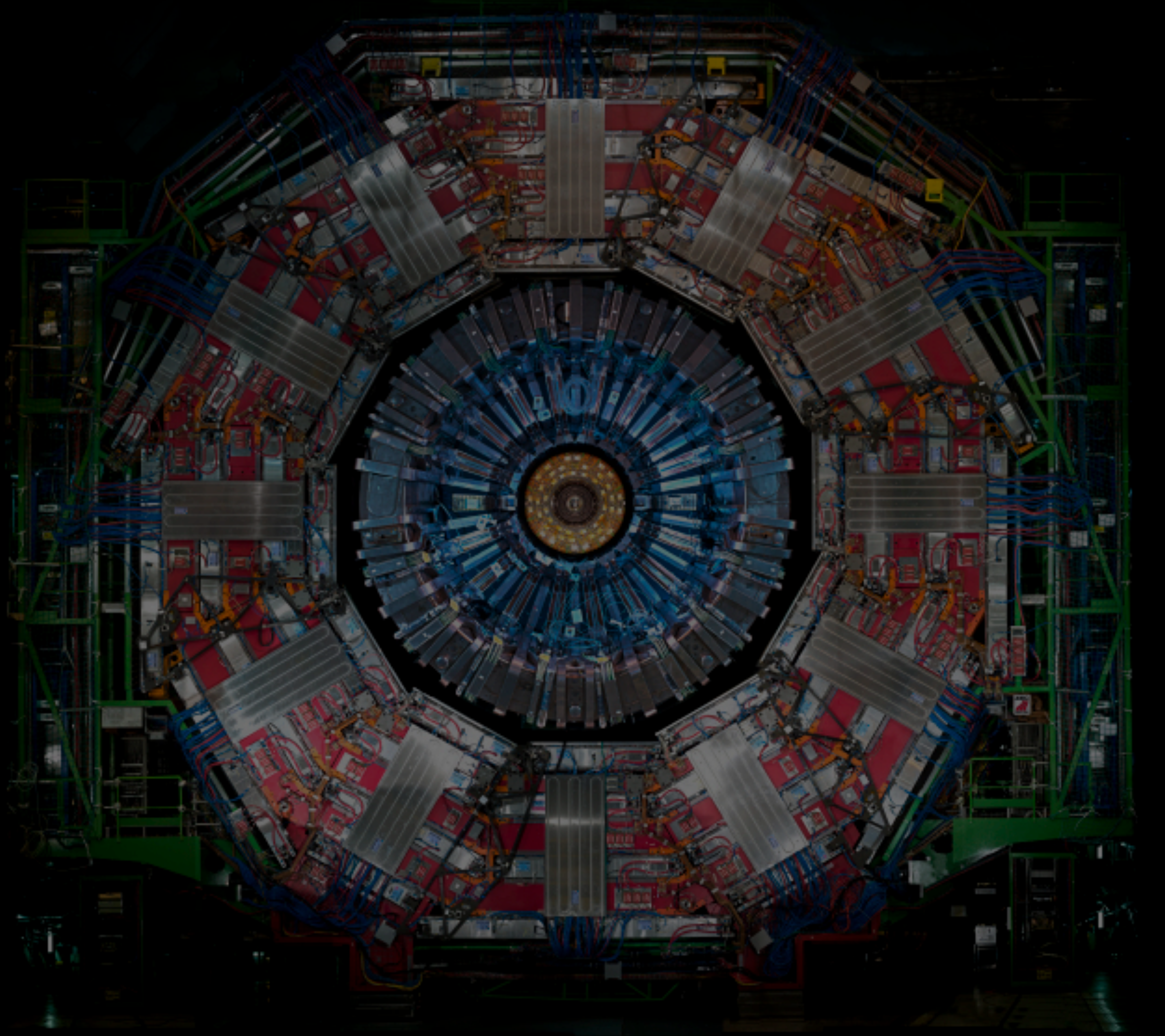
Top properties, including top mass



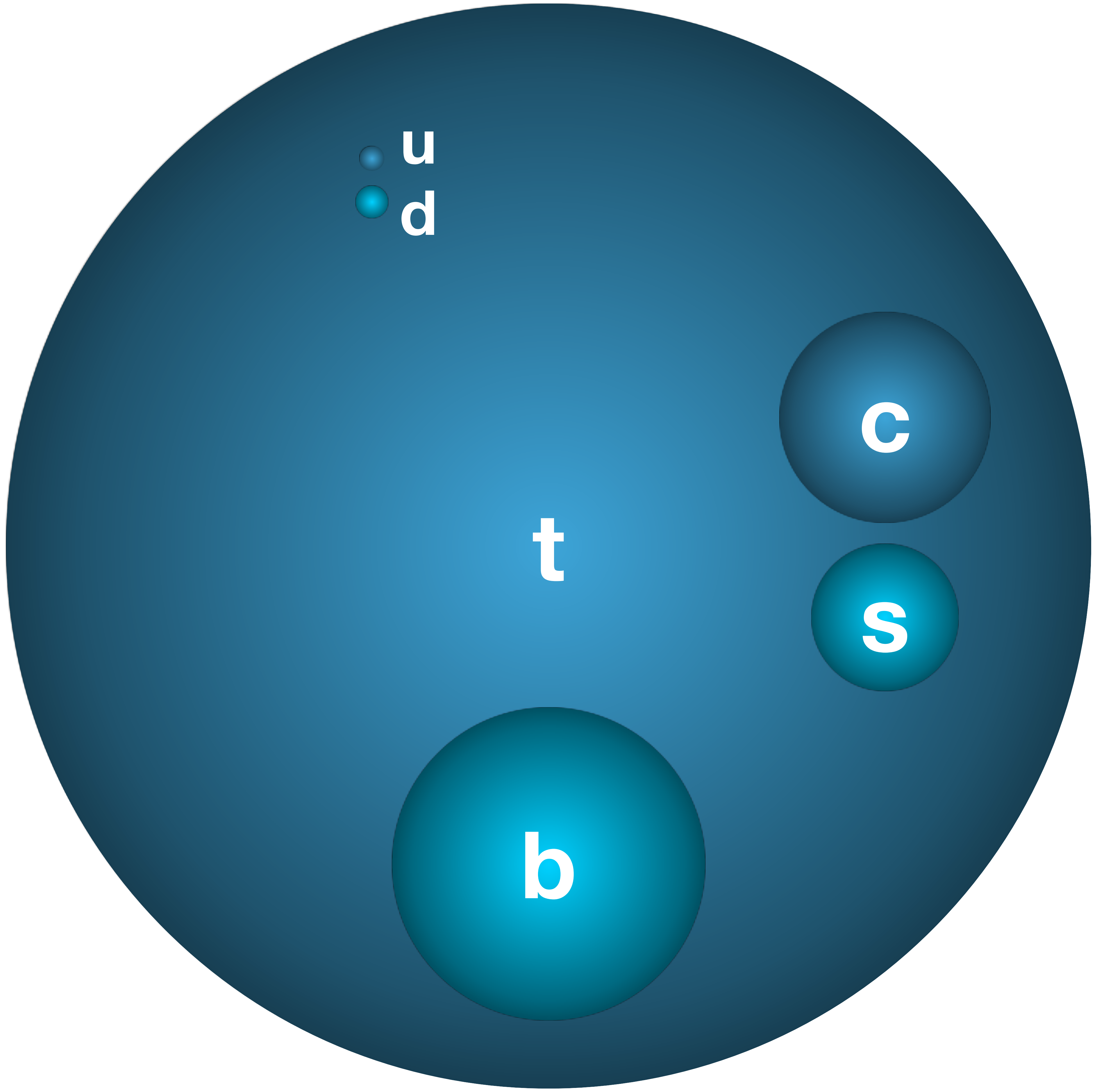
Tom Stevenson (University of Sussex)
on behalf of the ATLAS and CMS collaborations

11th Large Hadron Collider Physics Conference (LHCP2023)
26 May 2023

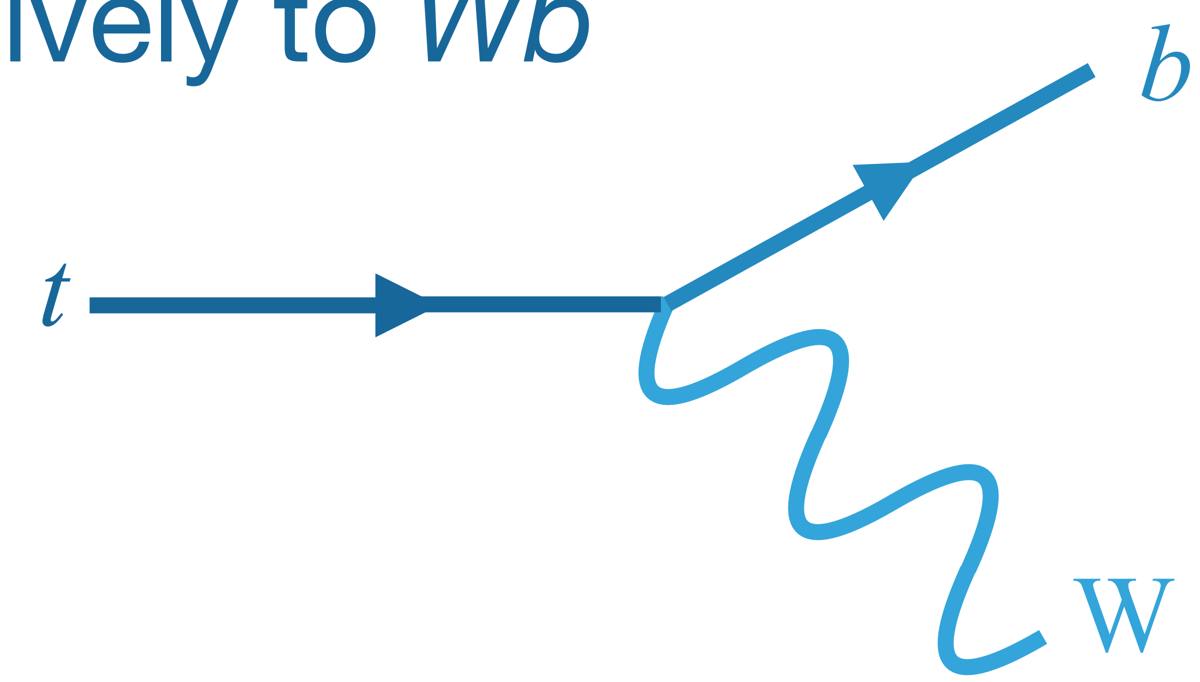




The Top Quark

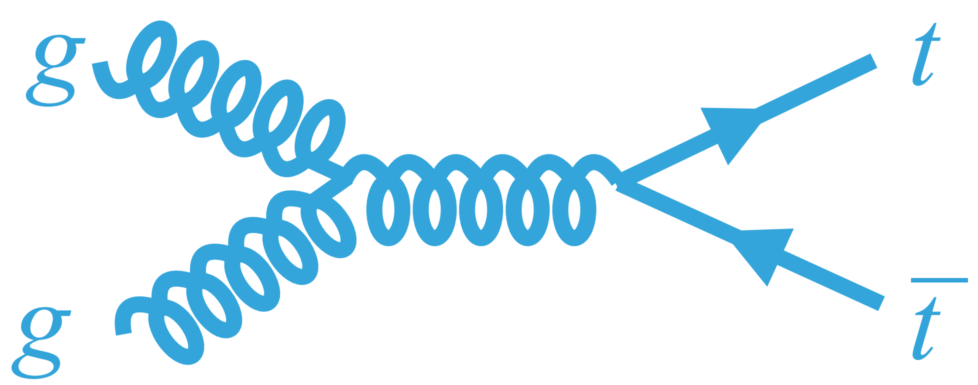


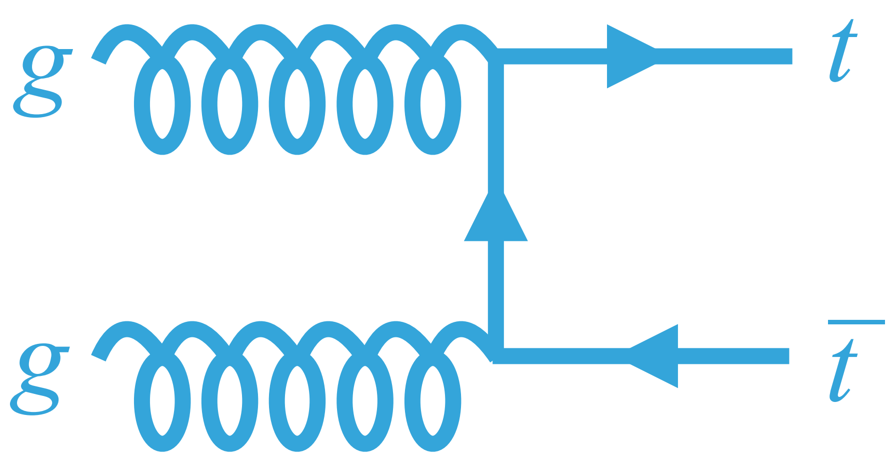
- Has special place in the Standard Model:
  - **Heaviest** elementary particle
  - Same mass scale scale as W, Z and Higgs bosons
  - Connection to **EW Symmetry Breaking** with large Yukawa coupling → **$\lambda \sim 1$**
- Unique quark:
  - Extremely short lifetime, **$\tau \sim 10^{-25}$ s**
  - Decays before hadronisation
    - Allows to probe properties of bare quark
    - Almost exclusively to *Wb*

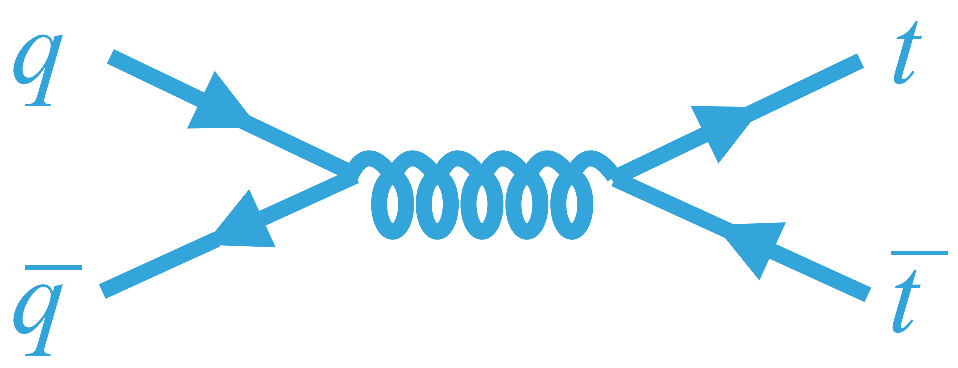


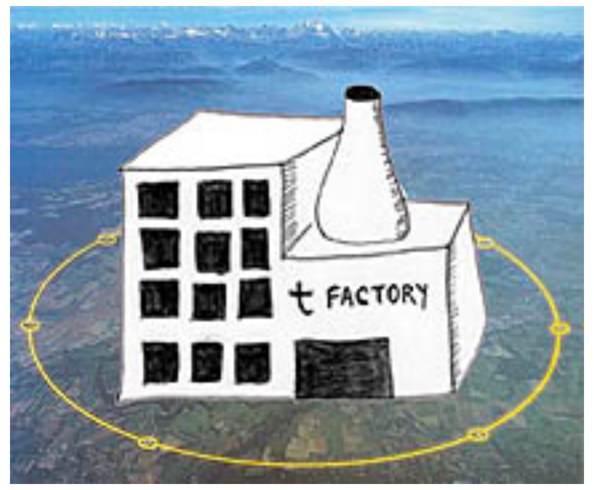
Top precision physics at the LHC

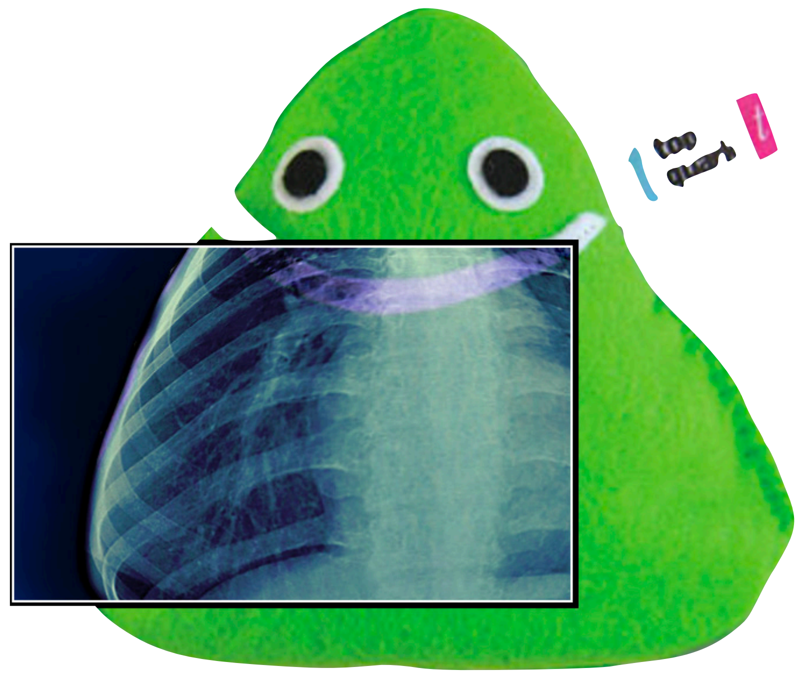
- LHC is a top quark factory
- Large production cross sections from high center-of-mass energy:
  - ~120M of top quark pairs produced during Run 2 in each experiment
  - More to come in Run 3!
- Allows for precision studies
  - Probe top quark properties:
    mass, width, charge asymmetry, …
  - Improve modelling → essential to understand and control better uncertainties
- Also can search for BSM effects!







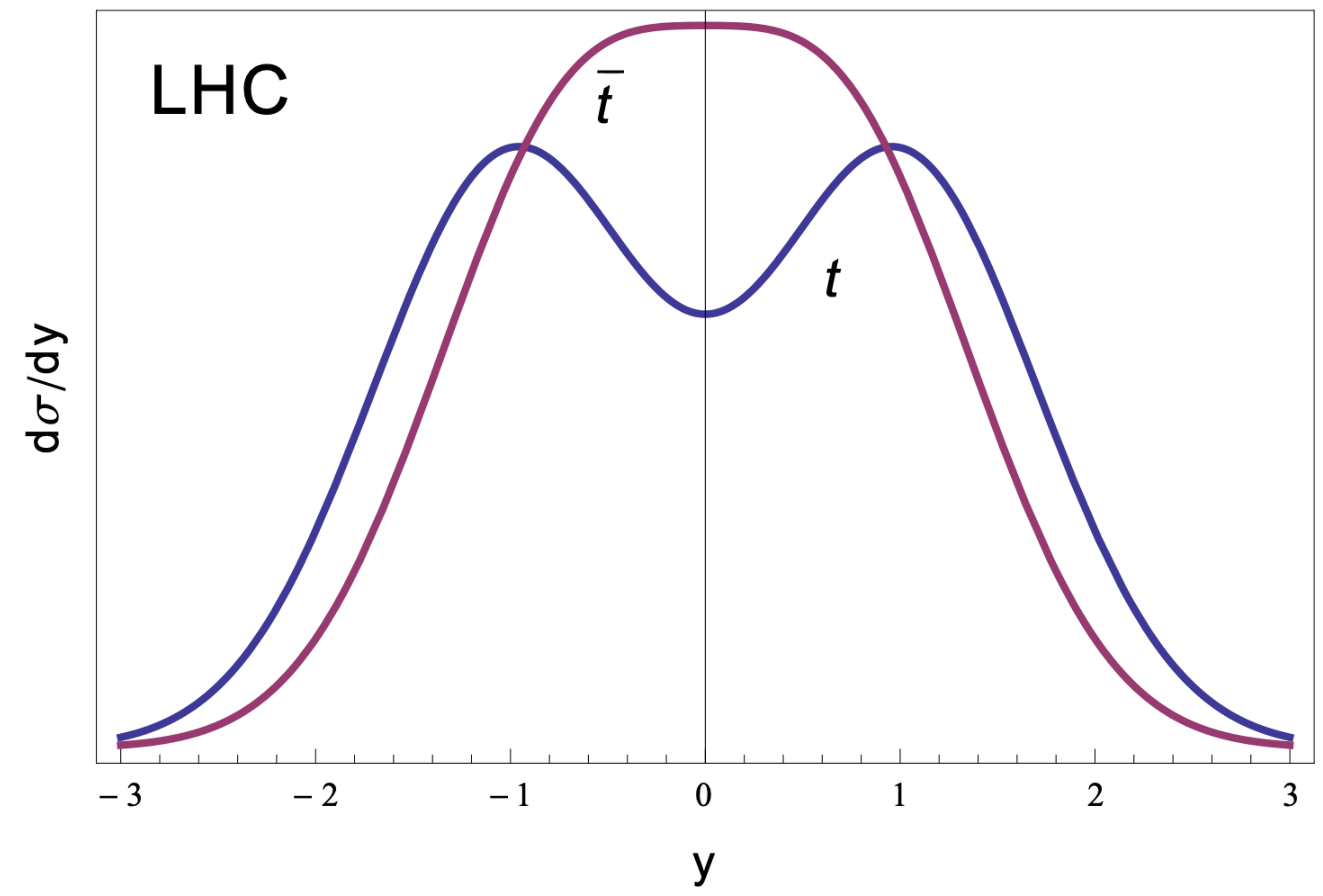




Many new top quark physics results obtained in the last year.
The complete list is available at these links: ATLAS CMS

Charge asymmetry in tt̄ production

- Asymmetry between t and $\bar{t}$ originates from higher order contributions to $q\bar{q} \rightarrow t\bar{t}$:
  - top (anti-)quark preferentially produced in direction of incoming (anti-)quark
- At the LHC:
  - Main production is $gg \rightarrow t\bar{t}$: symmetric
  - Valence quark momentum is on average larger than sea antiquark momentum
    → **more forward rapidity t and more central rapidity t̄**
  - Leptonic asymmetry can be defined in dileptonic channel
    - Doesn't require top reconstruction but asymmetry diluted
- BSM processes can interfere with SM processes and alter A_C



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

$$\Delta|y_{t\bar{t}}| = |y_t| - |y_{\bar{t}}|$$

Charge asymmetry in $t\bar{t}$ production

13 TeV – 139fb^{-1}
arXiv:2208.12095

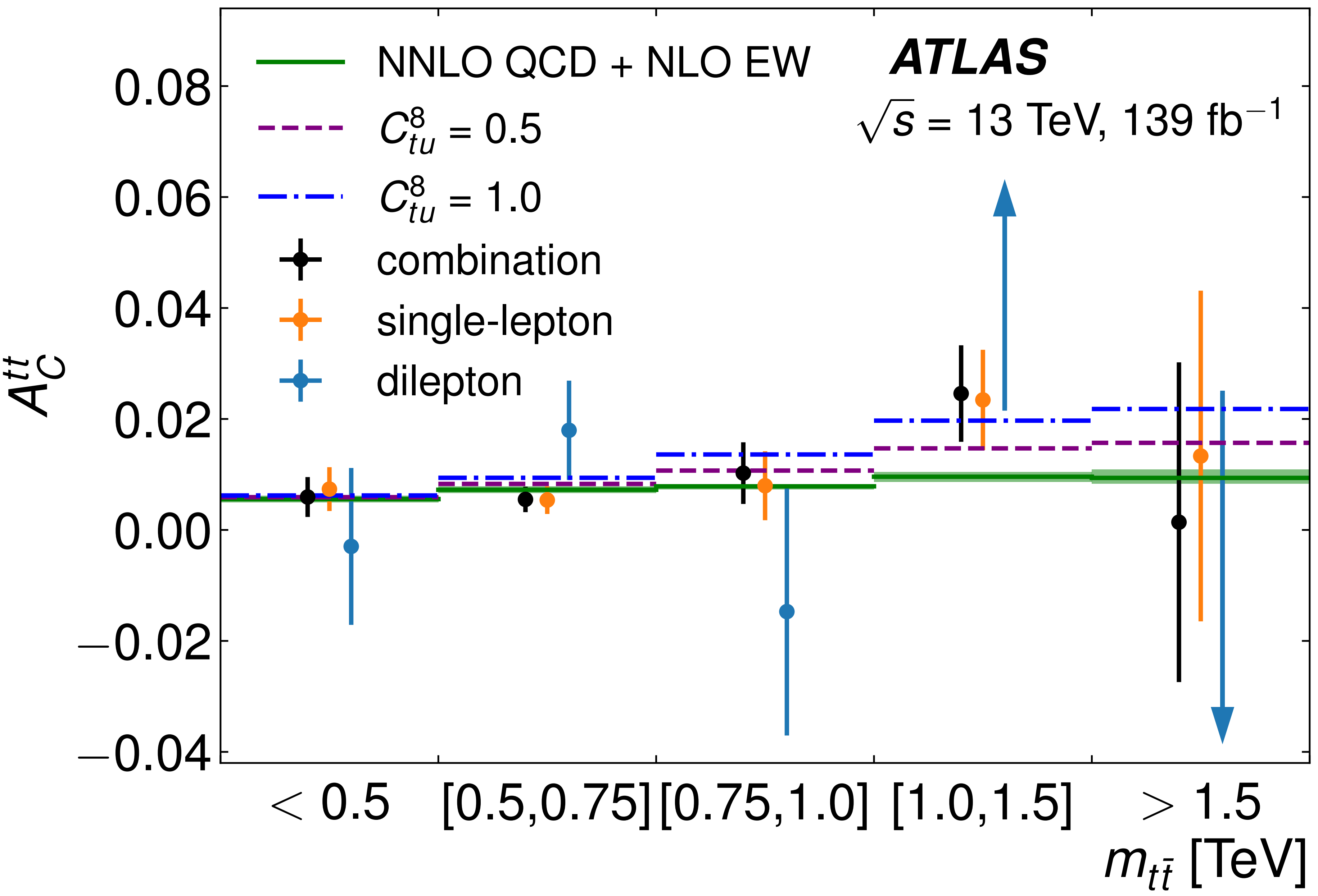
ATLAS EXPERIMENT

- Analysis uses both ℓ+jets and dilepton channels, considering resolved and boosted topologies
- A_C measured inclusively and as function of $\boldsymbol{m_{t\bar{t}}}$, $\boldsymbol{p_{T,t\bar{t}}}$, $\boldsymbol{\beta_{z,t\bar{t}}}$

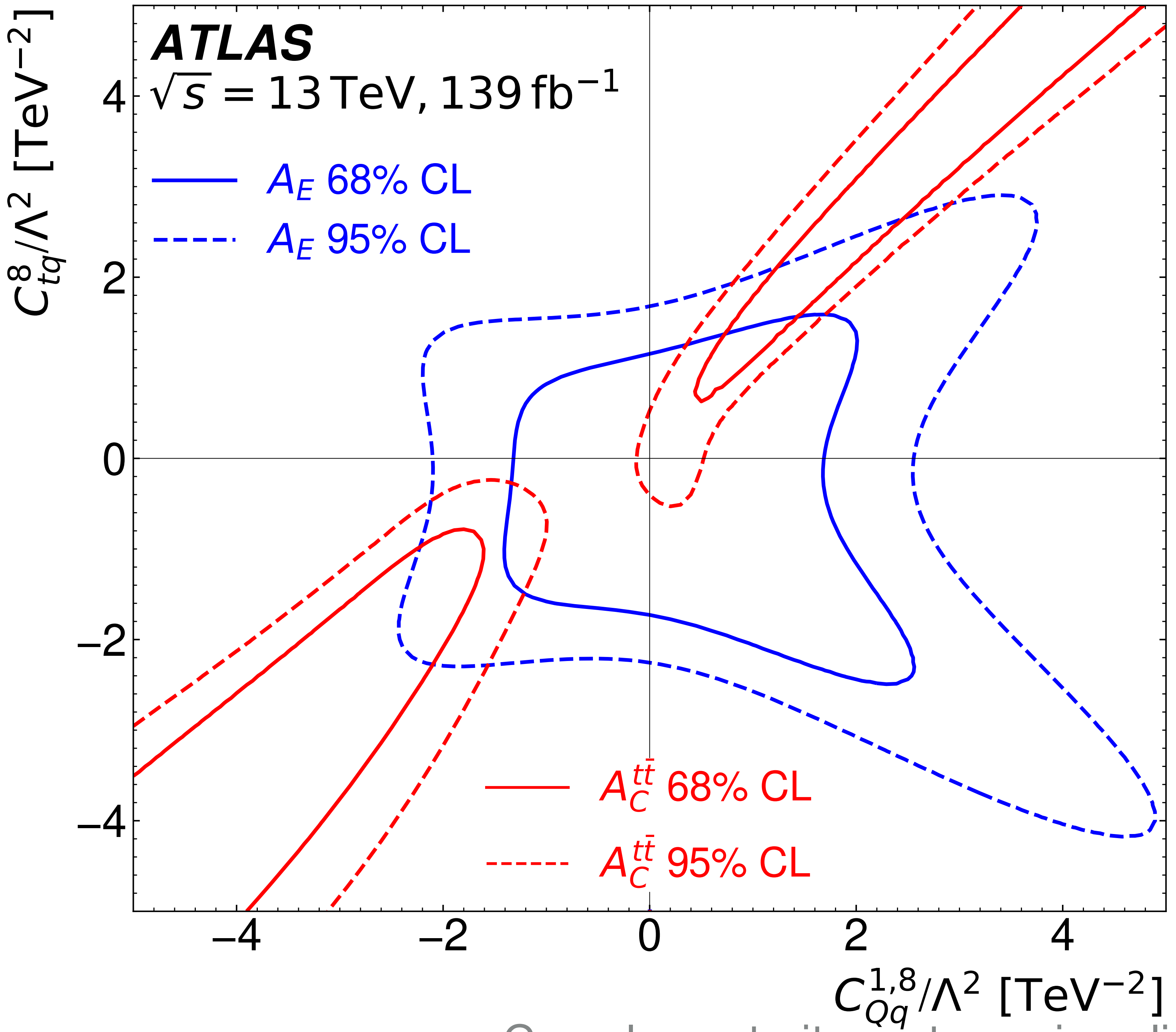
$$A_C^{t\bar{t}} = 0.0068 \pm 0.0015\,(\text{stat.} + \text{syst.})$$

Evidence! 4.7σ from no asymmetry

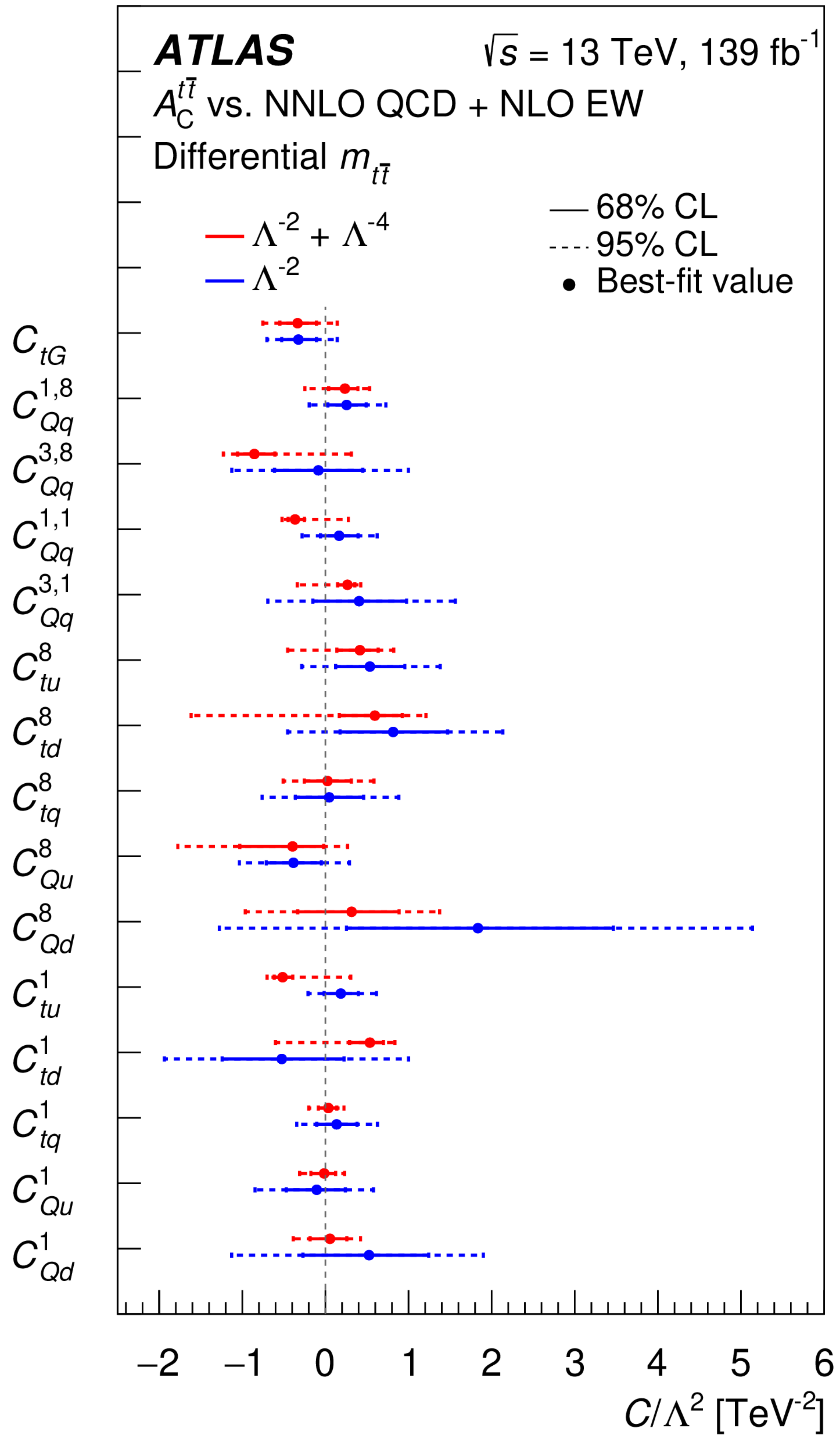
- Main uncertainties: statistical (0.0010), $t\bar{t}$ modeling syst. (0.0006)



NNLO QCD + NLO EW Prediction
Phys. Rev. D 98 (2018) 014003



Complementarity w.r.t. previous limits obtained from energy asymmetry A_E (Eur. Phys. J. C 82 (2022) 374)

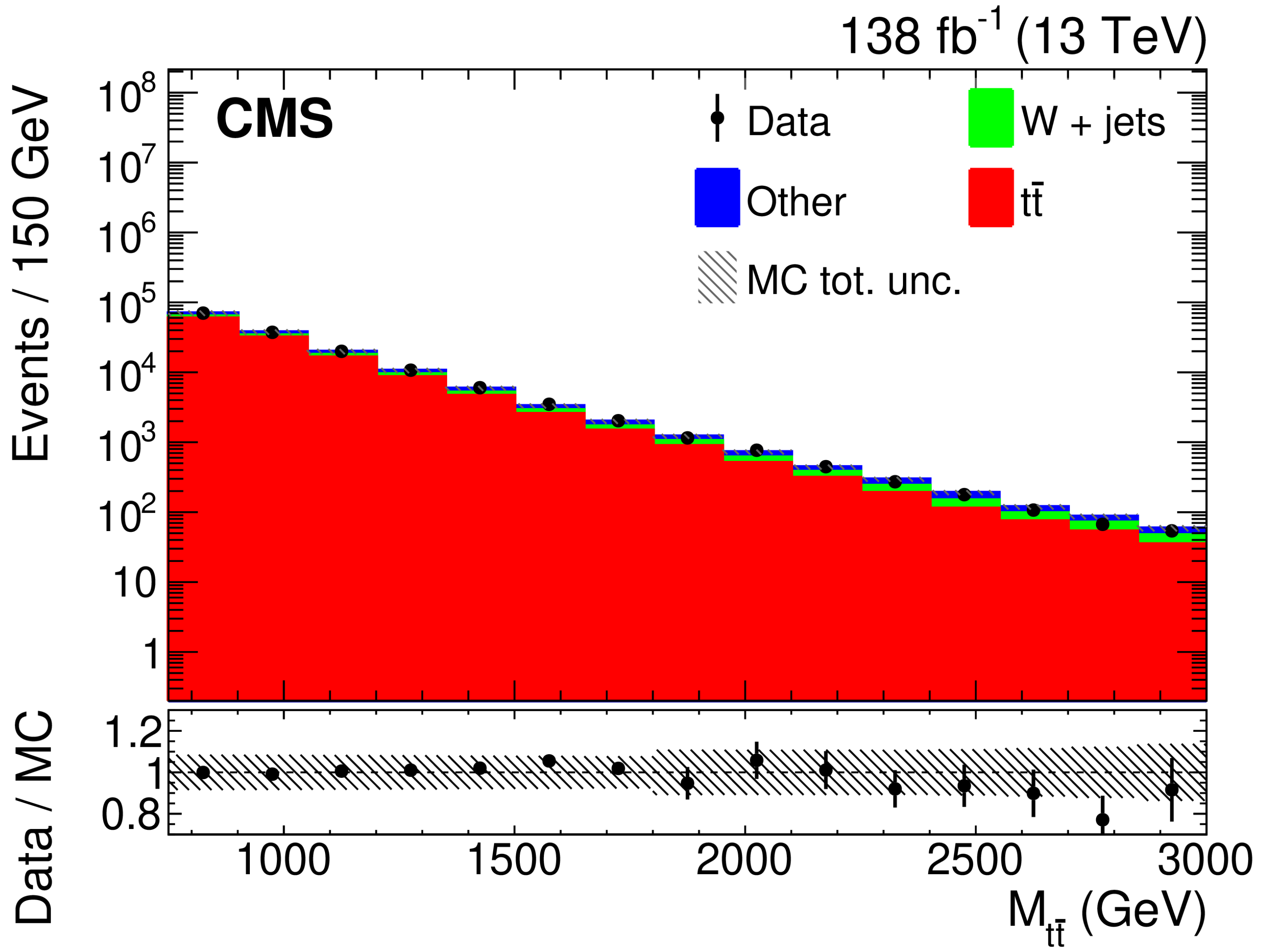


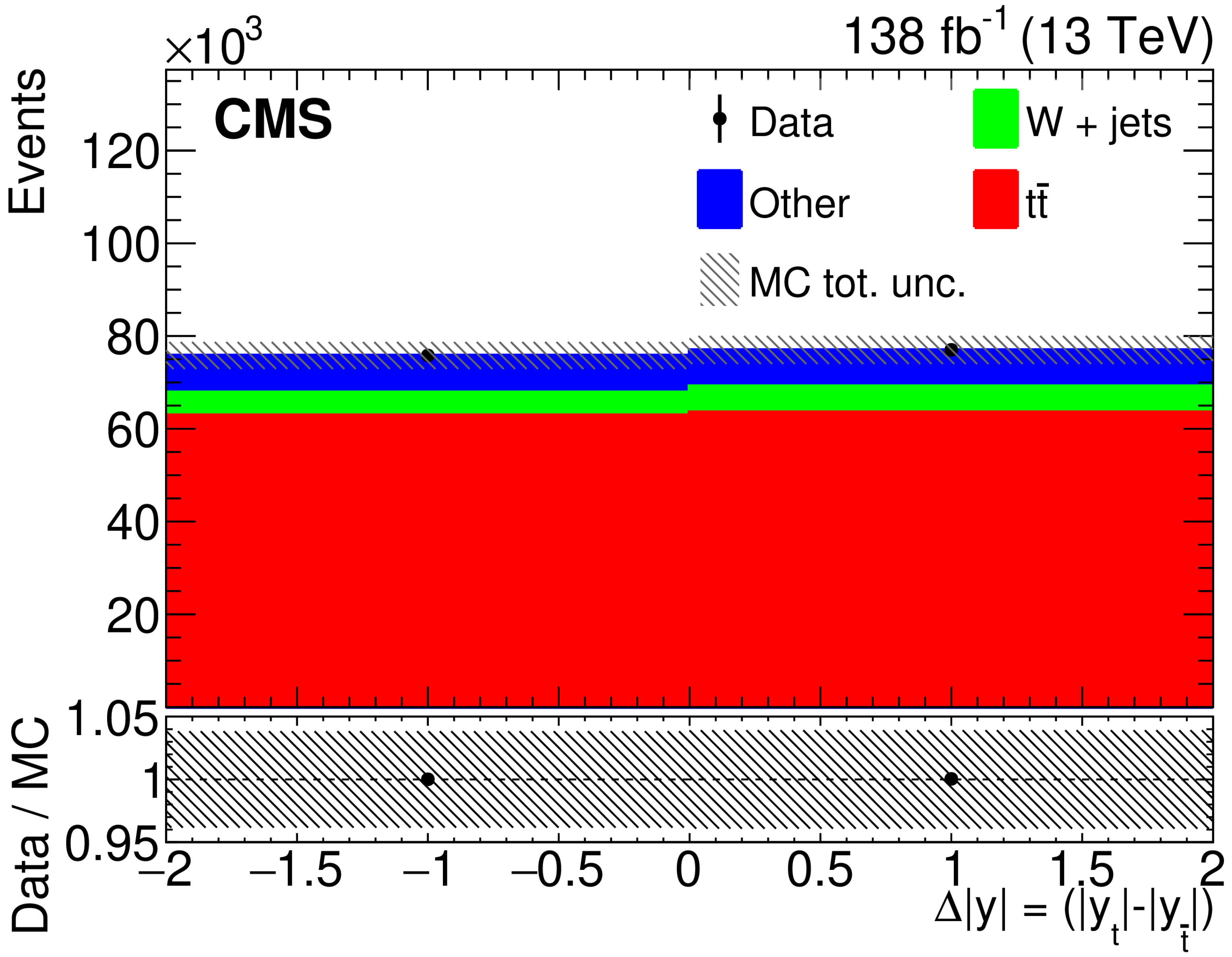
Interpretation in SMEFT fits

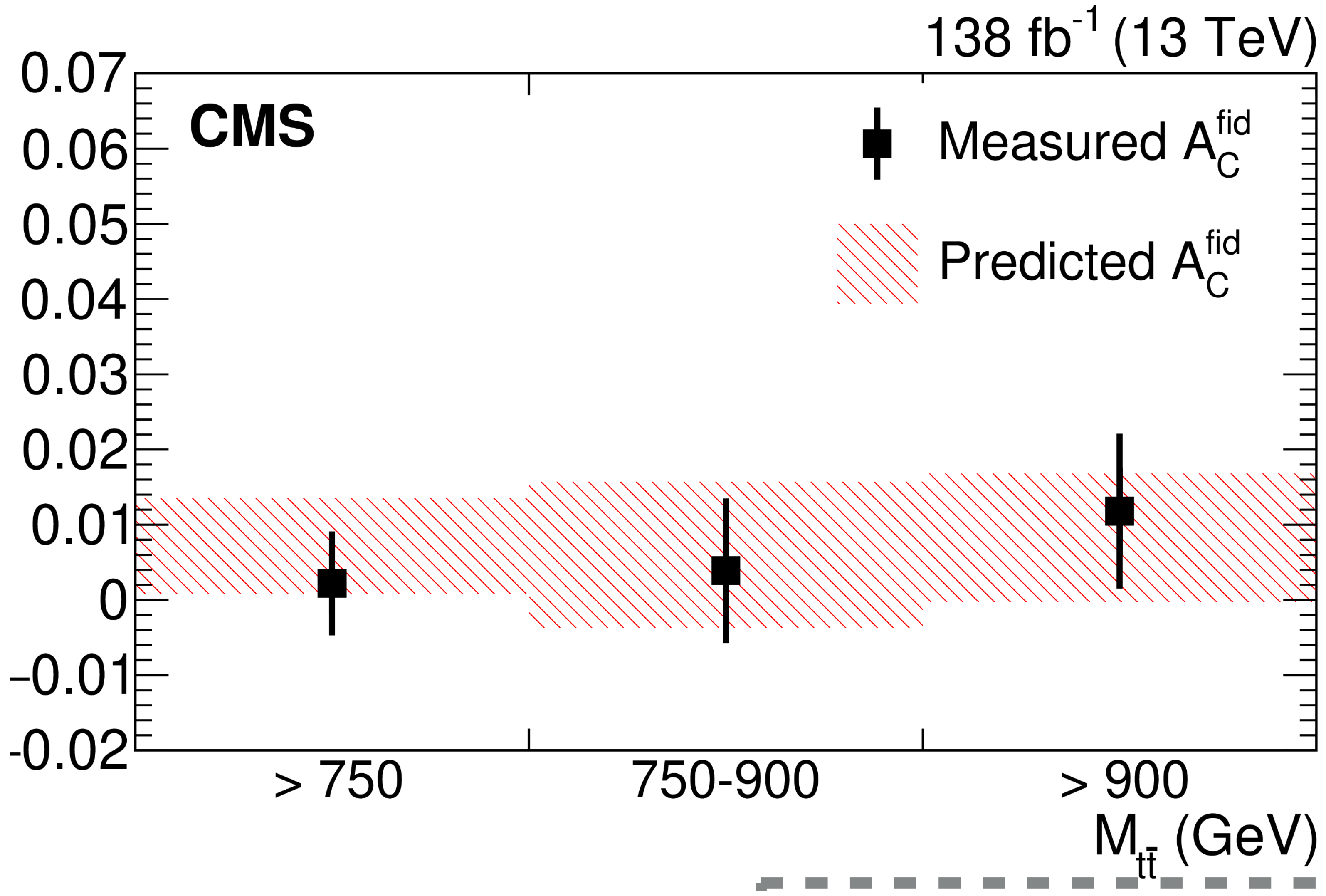
Charge asymmetry in boosted $t\bar{t}$

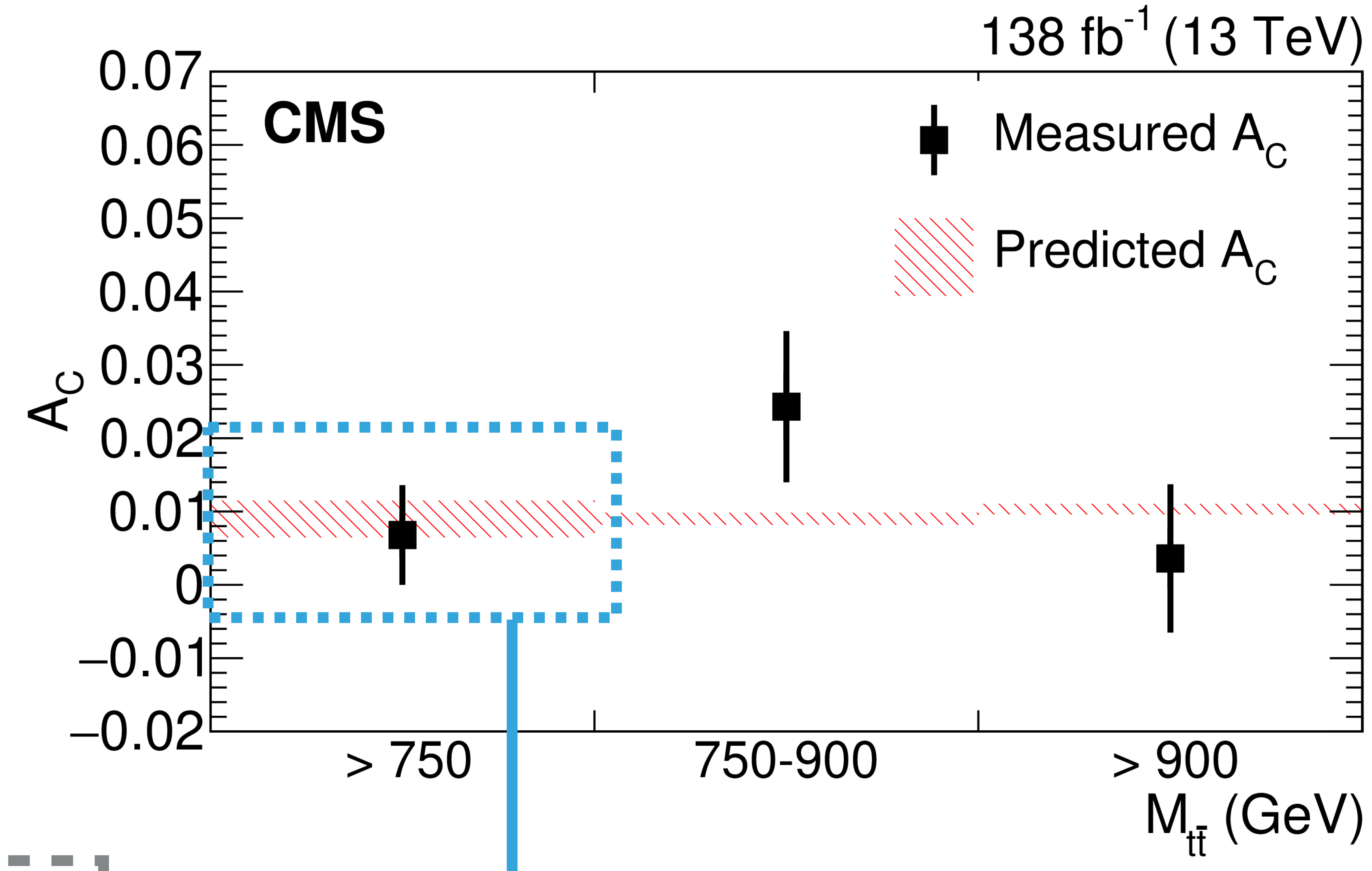
13 TeV – 138fb^{-1}
arXiv:2208.02751

- Analysis in ℓ+jets channel with boosted topologies
- Selection optimised for top quarks produced with **high Lorentz boost**
  - A_C measured in events with $\boldsymbol{m_{t\bar{t}} > 750}$ **GeV**
- Asymmetry unfolded to the **fiducial & full phase-space** with likelihood unfolding
  - In good agreement with the SM
- Measurement still **limited by statistical uncertainty**
  - Largest systematics: QCD scales, FSR, top p_T modelling, JEC







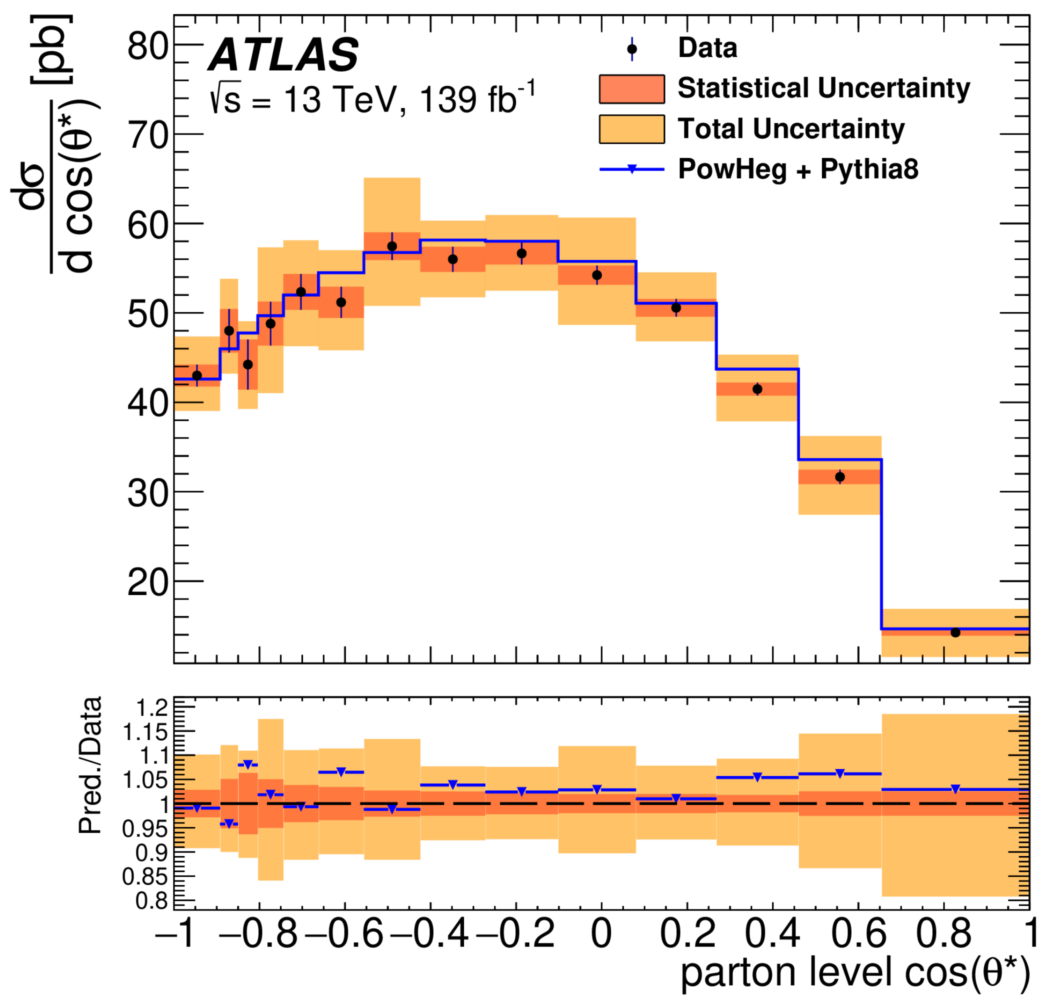


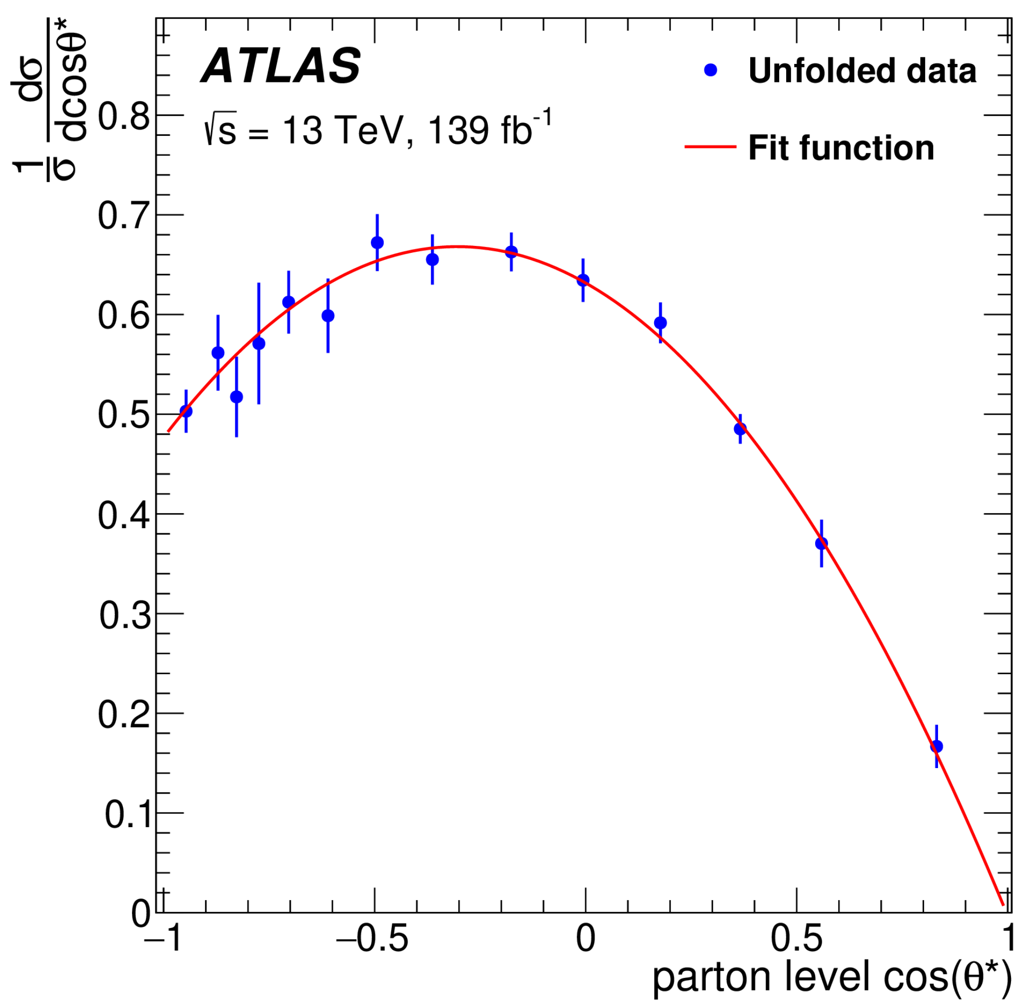
NNLO(QCD)+NLO(EW)
$A_C = 0.0094^{+0.0005}_{-0.0007}$
PRD 98 (2018) 014003

$$A_C = 0.0069^{+0.0065}_{-0.0069}$$

W polarisation

13 TeV – 139fb^{-1}
arXiv:2209.14903

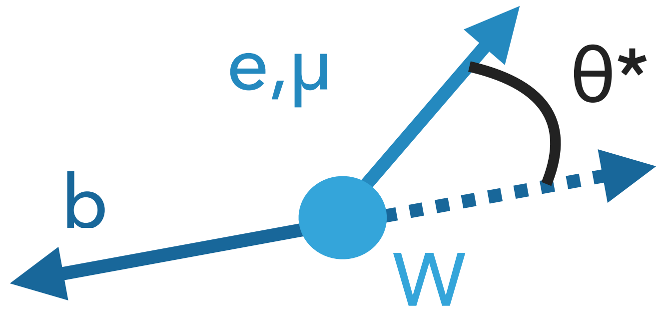


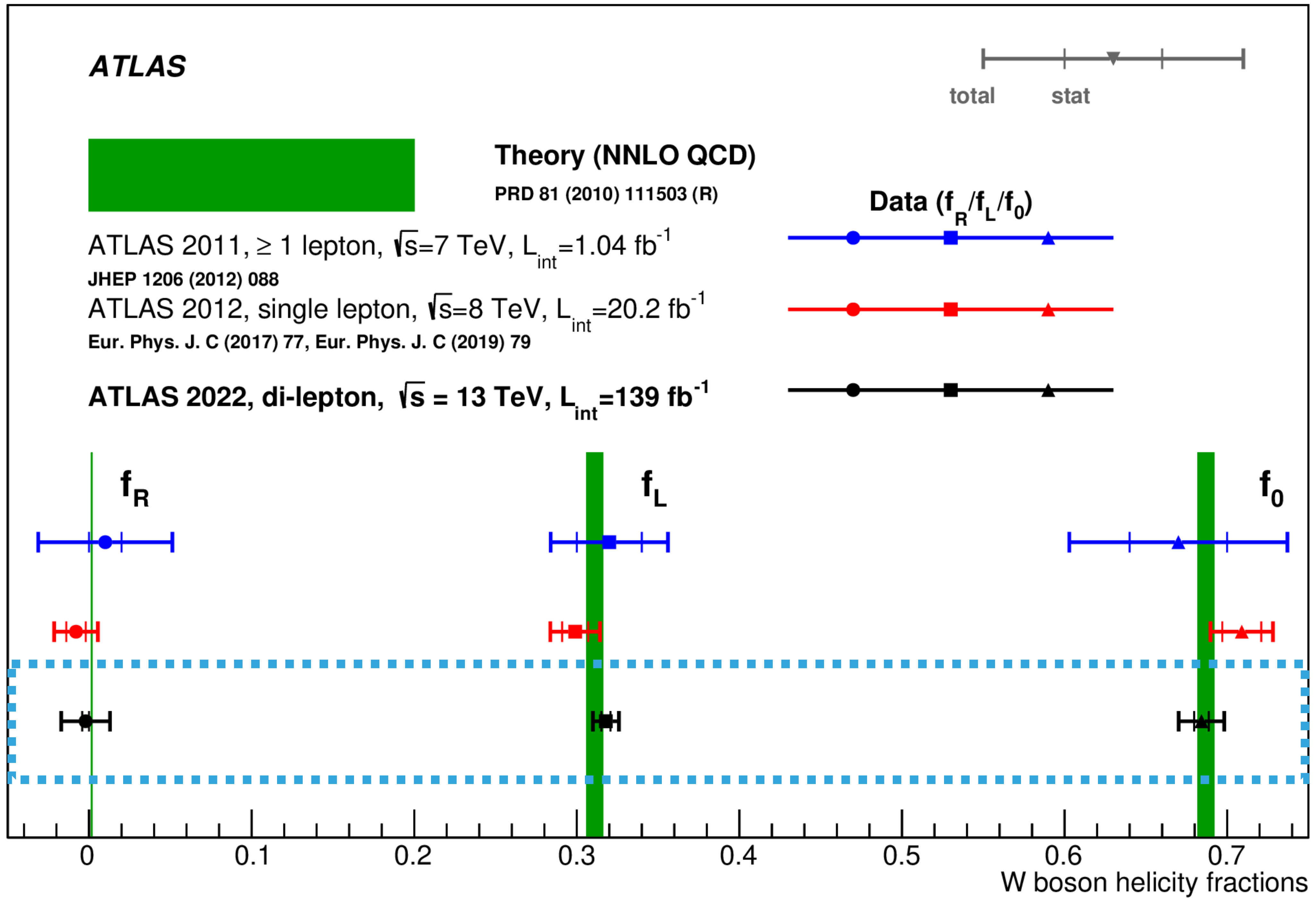


- Properties of top-quark decay vertex Wtb are determined by V-A structure of weak interaction in the SM
- Test compatibility with SM of fractions of longitudinal (***f_0***), left-handed (***f_L***) and right-handed (***f_R***) polarised W bosons (helicity fractions)

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

- Extracted in dileptonic ttbar events measuring ***cos(θ*)*** at **parton level**
  - *θ**: angle between momentum direction of charged lepton from W decay and reversed momentum direction of b-quark from top decay, computed in the W rest frame





NNLO calculation

$f_0 = 0.687 \pm 0.005$

$f_L = 0.311 \pm 0.005$

$f_R = 0.0017 \pm 0.0001$

PRD 81 (2010) 111503

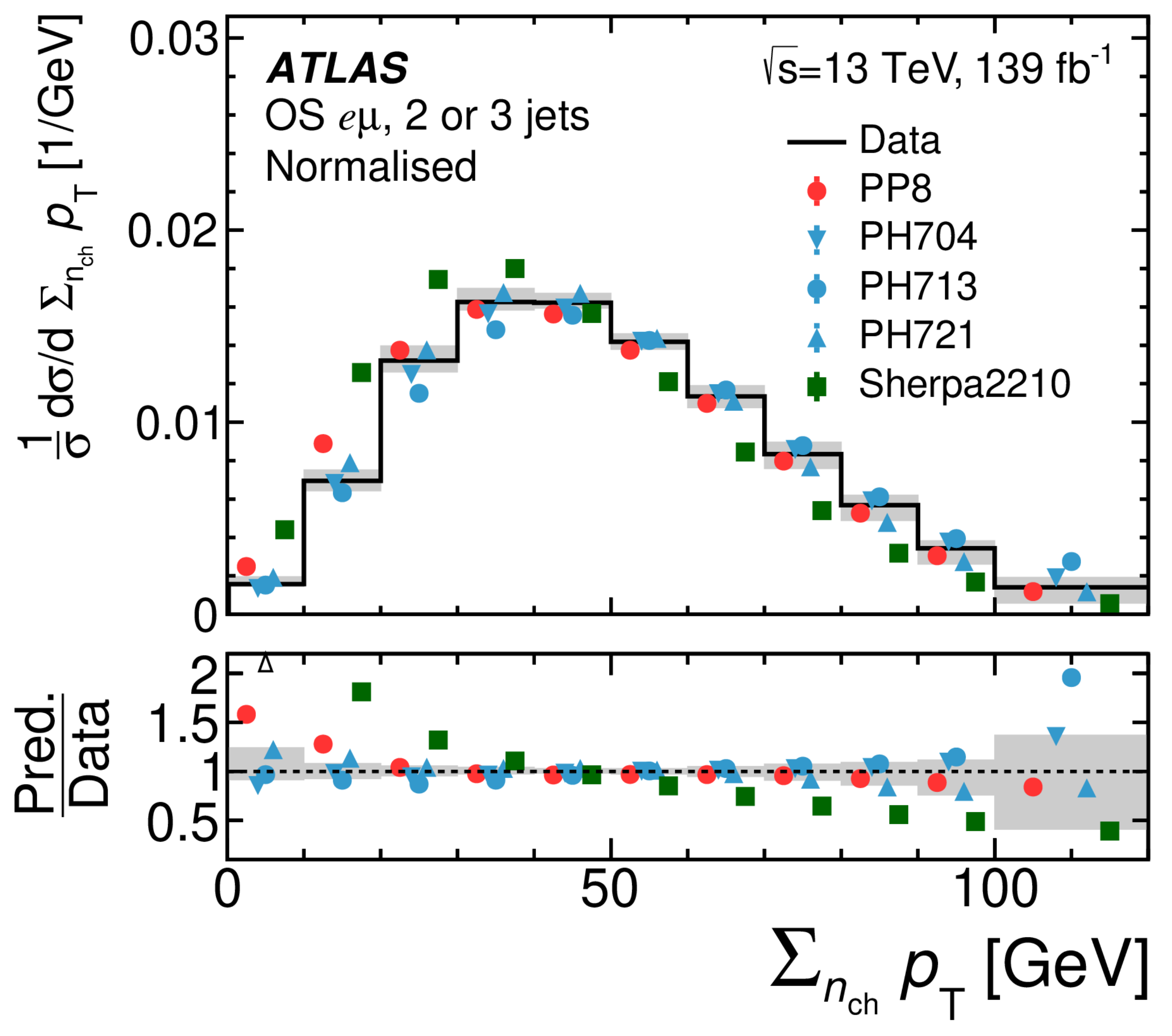
$$f_0 = 0.684 \pm 0.005\,(\text{stat.}) \pm 0.014\,(\text{syst.})$$
$$f_L = 0.318 \pm 0.003\,(\text{stat.}) \pm 0.008\,(\text{syst.})$$
$$f_R = -0.002 \pm 0.002\,(\text{stat.}) \pm 0.014\,(\text{syst.})$$

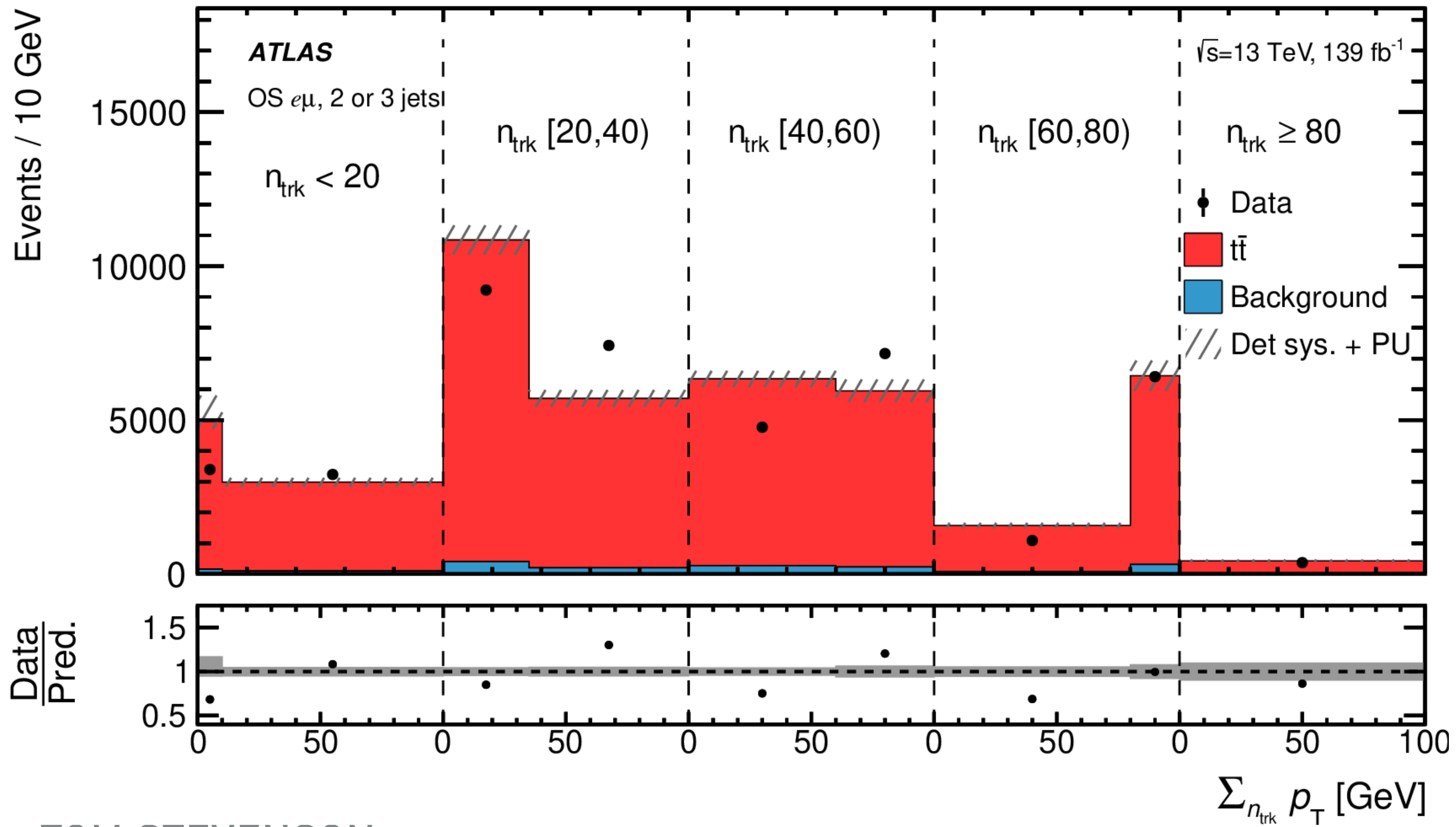
Systematic uncertainty dominated by $t\bar{t}$ production modelling (choice of matrix-element generator)

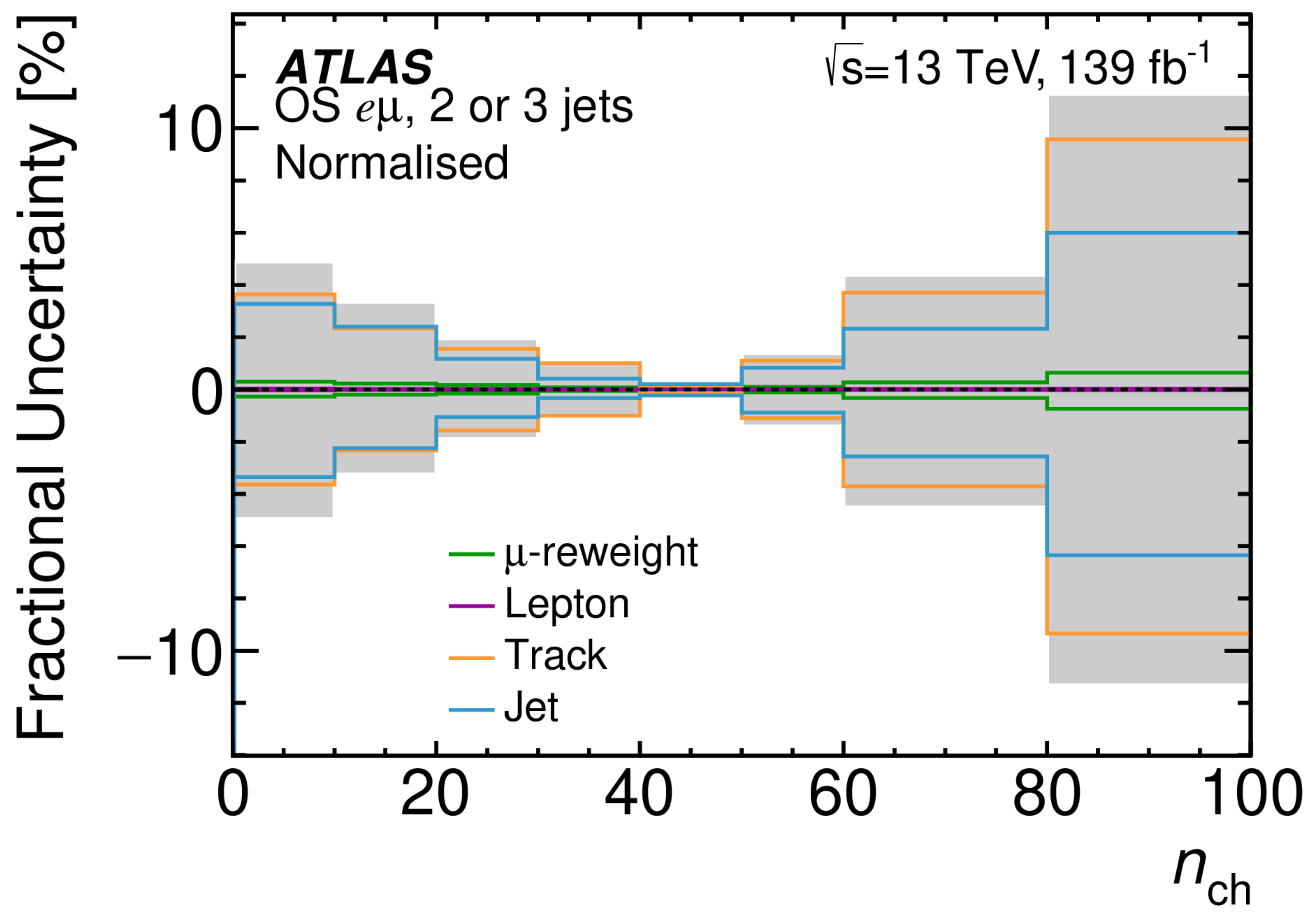
Colour reconnection

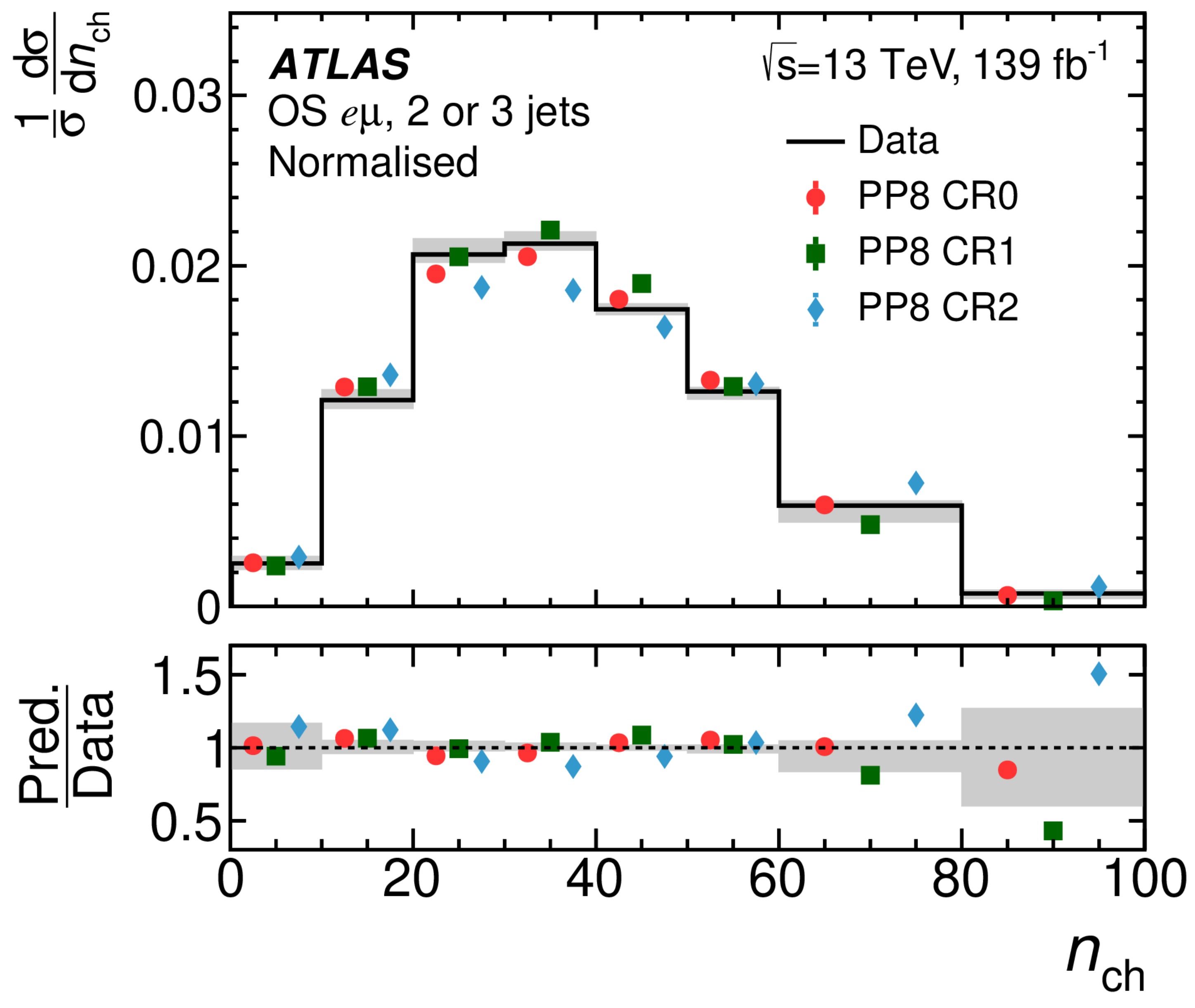
13 TeV – 139fb^{-1}
arXiv:2209.07874

- **Important phenomenon for MC generators**
  - Not simulated from first principles
  - Various **different** colour reconnection models used by **different** generators → need to be **constrained from data**
- Analysis using ***eμ*** $t\bar{t}$ events with 2 b-tagged jets
- **Unfolding** of sensitive distributions to **particle level** (IBU)
  - Charged-particle multiplicity - $\boldsymbol{n_{ch}}$
  - Scalar sum of charged particle p_T
  - Scalar sum of charged particle p_T in n_{ch} bins





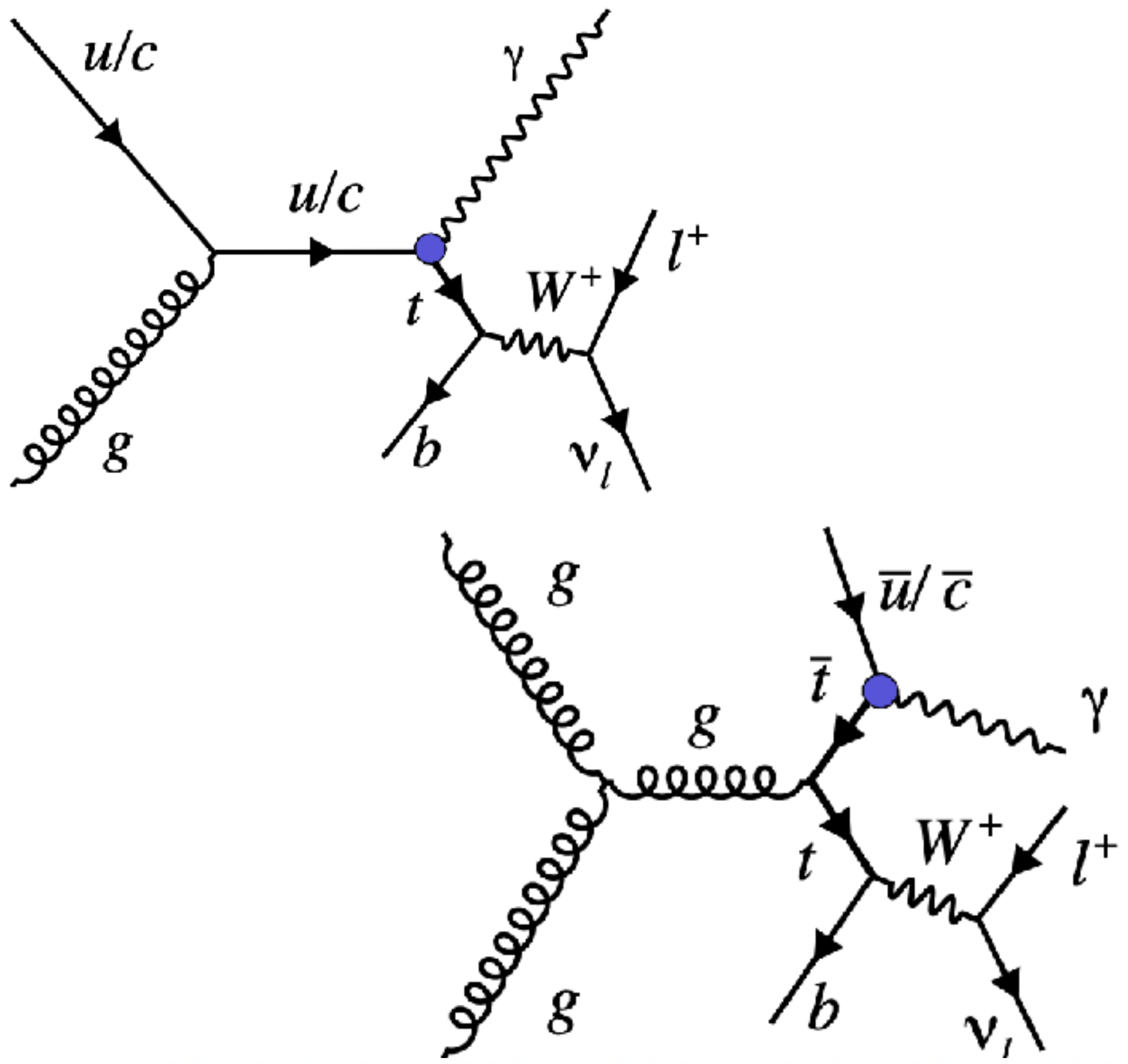




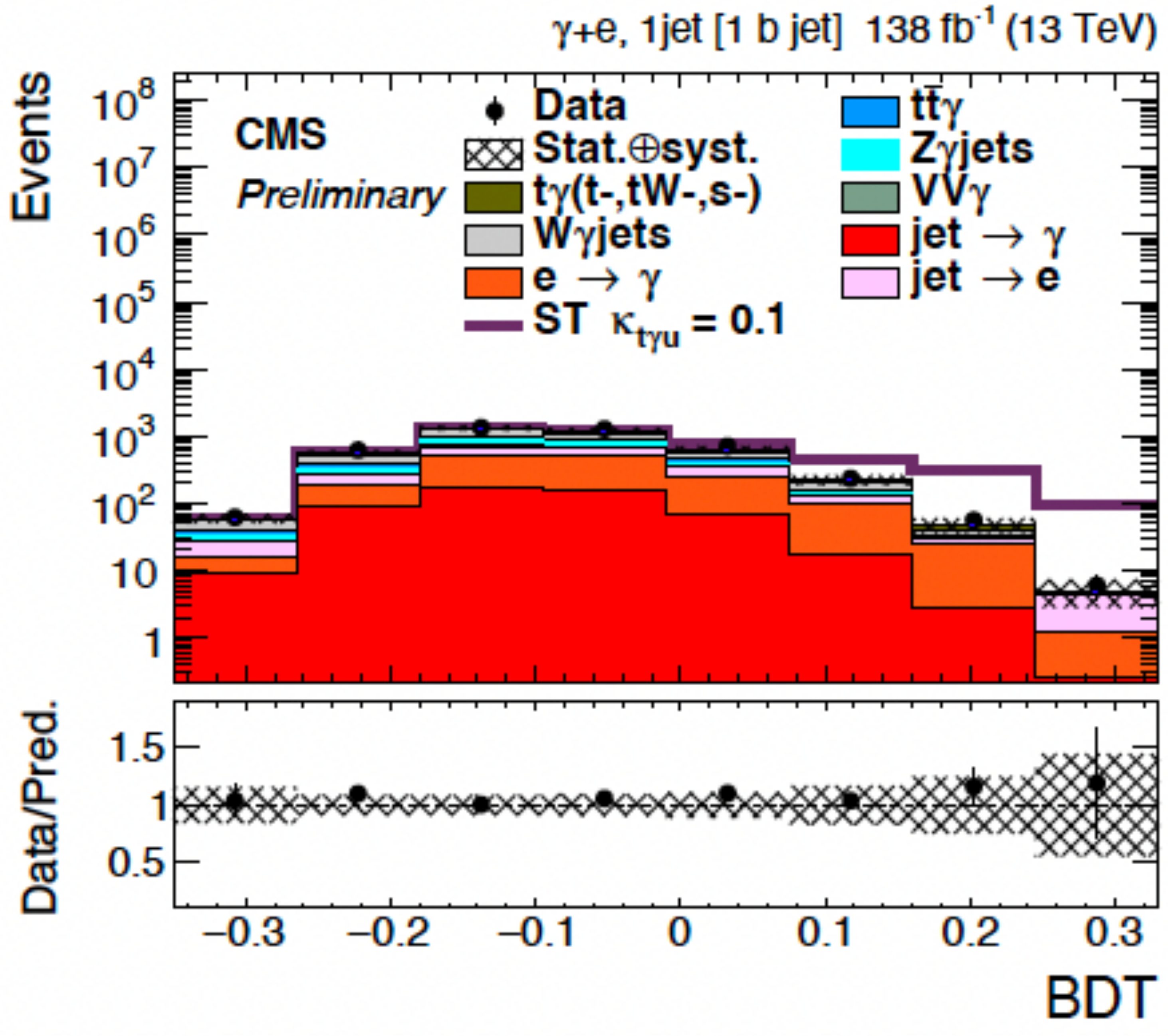
FCNC in tγ

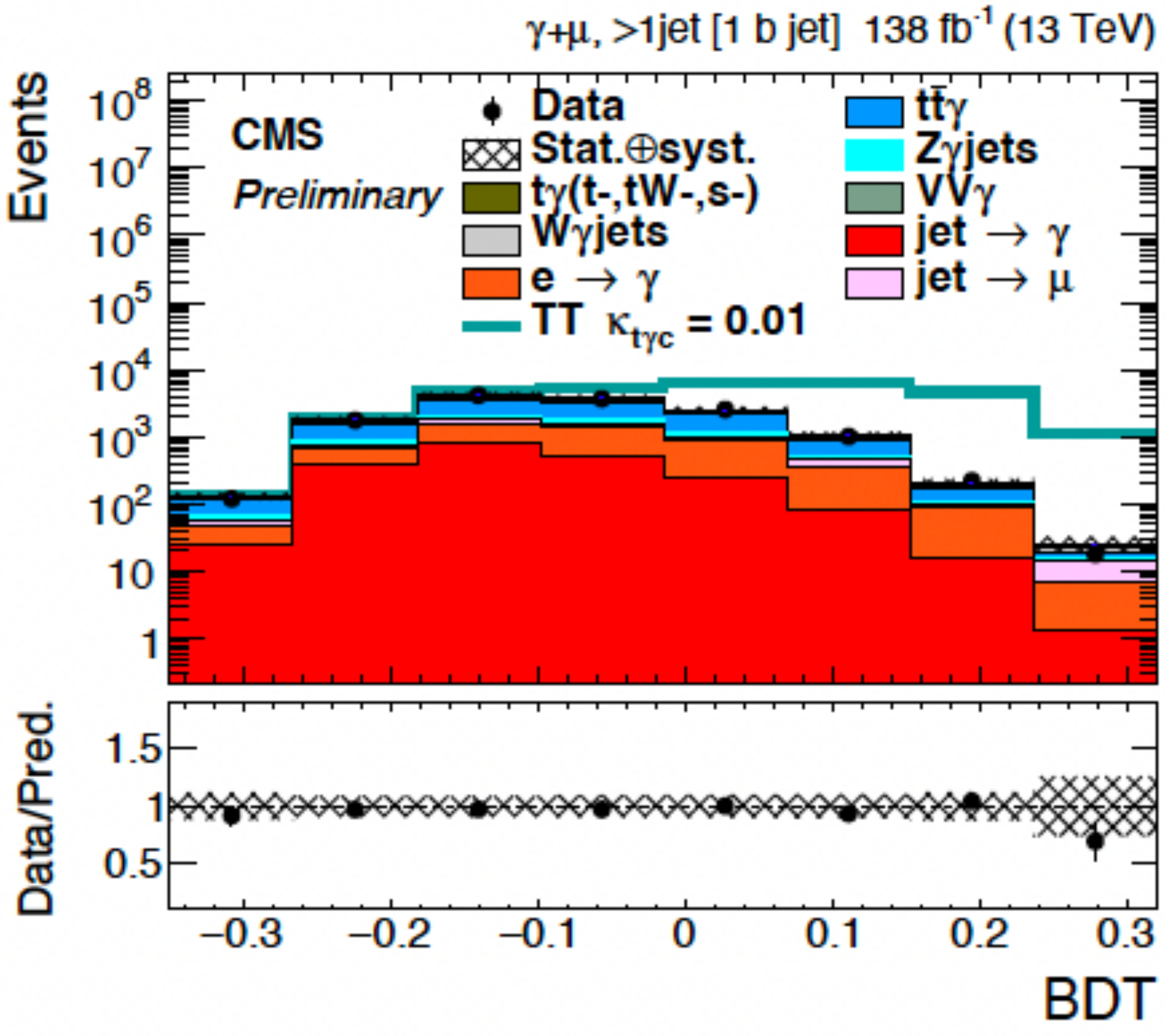
13 TeV – 138fb^{-1}
CMS-PAS-TOP-21-013

- Search for FCNC **top interactions in association with γ + jets**
- Final states with **1 lepton, 1γ** & jets
- **BDTs** to separate sig vs. bkg
- Obs (exp) **upper limits set on** FCNC **coupling strengths** ($\kappa_{tq\gamma}$) & **branching fractions** of top quark decays



Combined	Obs. limit	Exp. limit
$\kappa_{tu\gamma}$	6.2×10^{-3}	6.9×10^{-3}
$\kappa_{tc\gamma}$	7.7×10^{-3}	7.8×10^{-3}
$\mathcal{B}(t \to u + \gamma)$	0.95×10^{-5}	1.20×10^{-5}
$\mathcal{B}(t \to c + \gamma)$	1.51×10^{-5}	1.54×10^{-5}

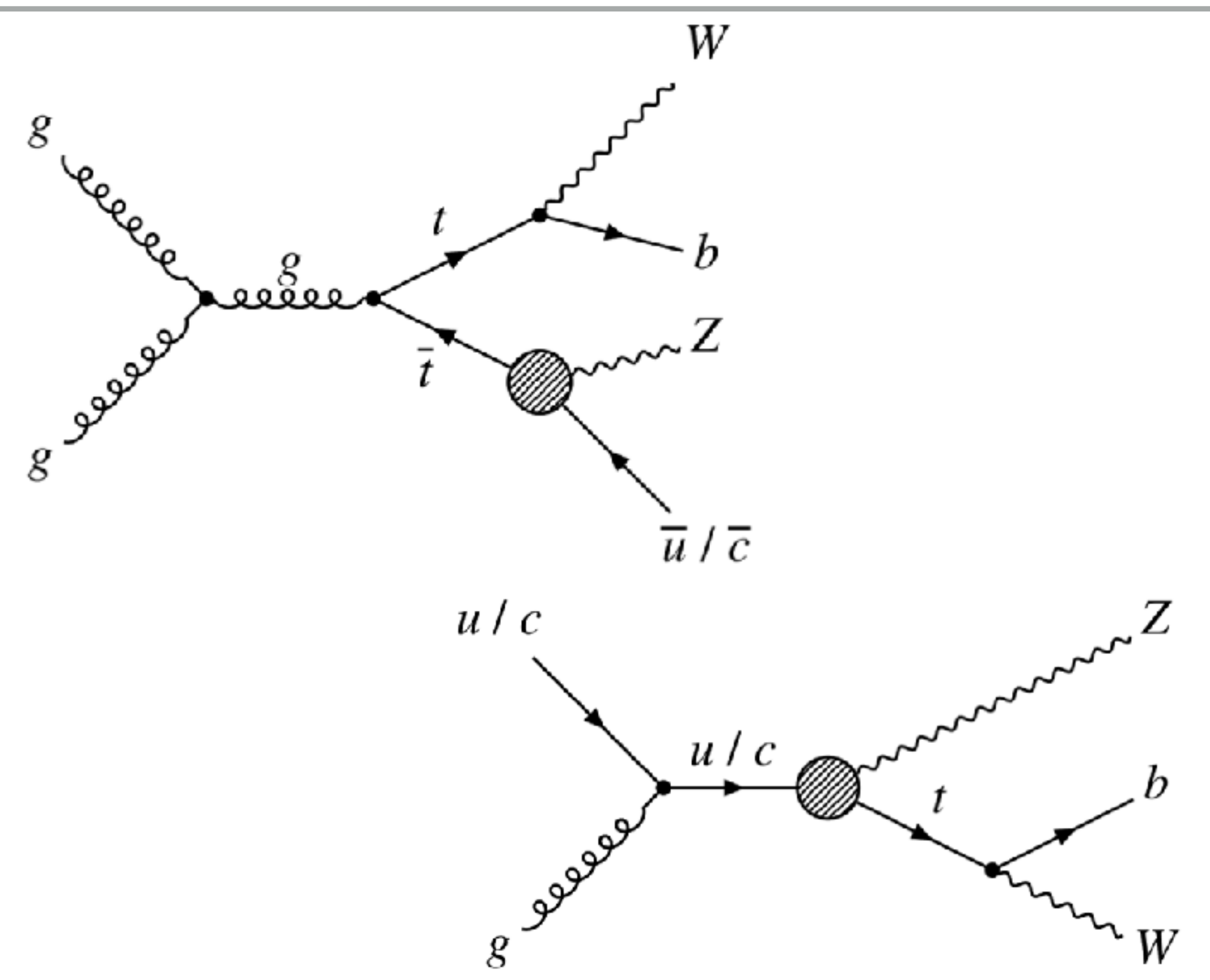




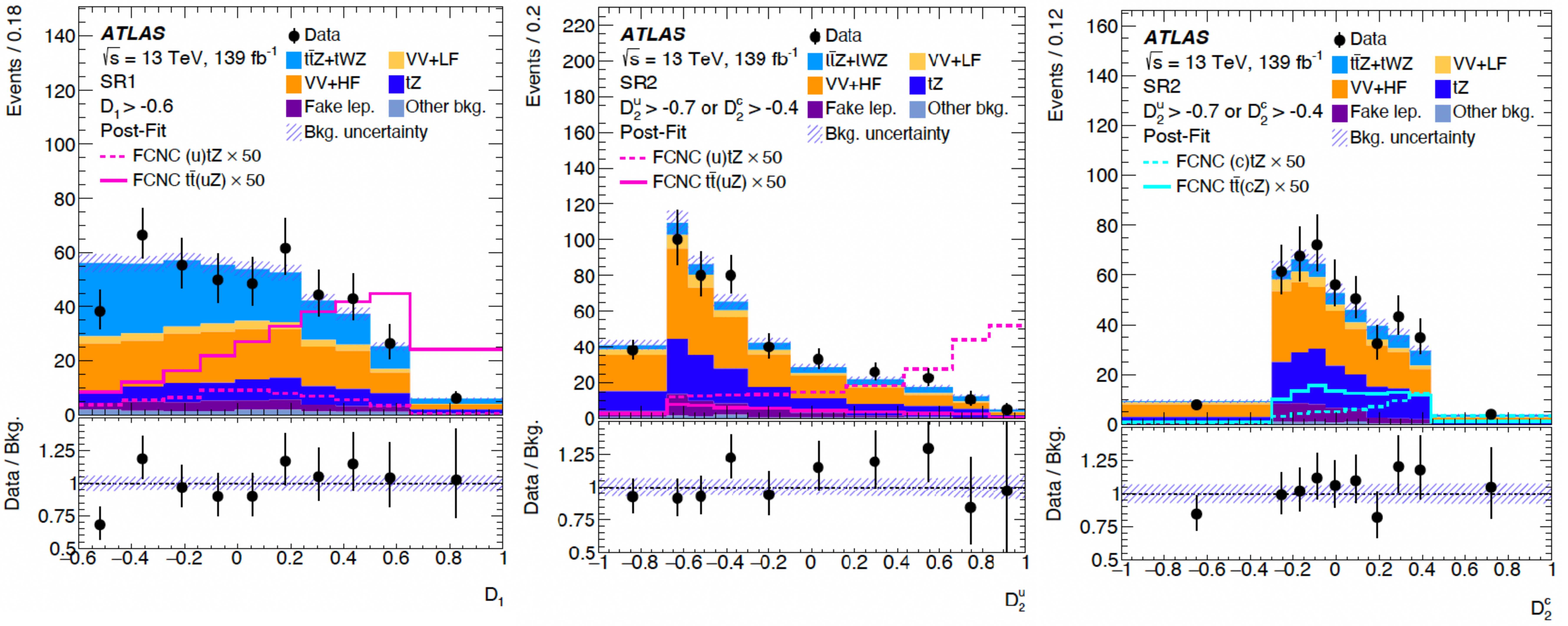
FCNC in tZ

13 TeV – 139fb^{-1}
TOPQ-2019-22

- Search for FCNC **top interactions in association with a *Z***
- Final states with **1 or 2 tops, 3 leptons,** 1 b-jet, MET
- **BDTs** to separate sig from bkg
- Obs (exp) **upper limits set** on FCNC coupling strengths & **branching fractions** of top quark decays



Observable	Vertex	Coupling	Observed	Expected
SRs+CRs				
$\mathcal{B}(t \to Zq)$	tZu	LH	6.2×10^{-5}	$4.9\,^{+2.1}_{-1.4} \times 10^{-5}$
$\mathcal{B}(t \to Zq)$	tZu	RH	6.6×10^{-5}	$5.1\,^{+2.1}_{-1.4} \times 10^{-5}$
$\mathcal{B}(t \to Zq)$	tZc	LH	13×10^{-5}	$11\,^{+5}_{-3} \times 10^{-5}$
$\mathcal{B}(t \to Zq)$	tZc	RH	12×10^{-5}	$10\,^{+4}_{-3} \times 10^{-5}$

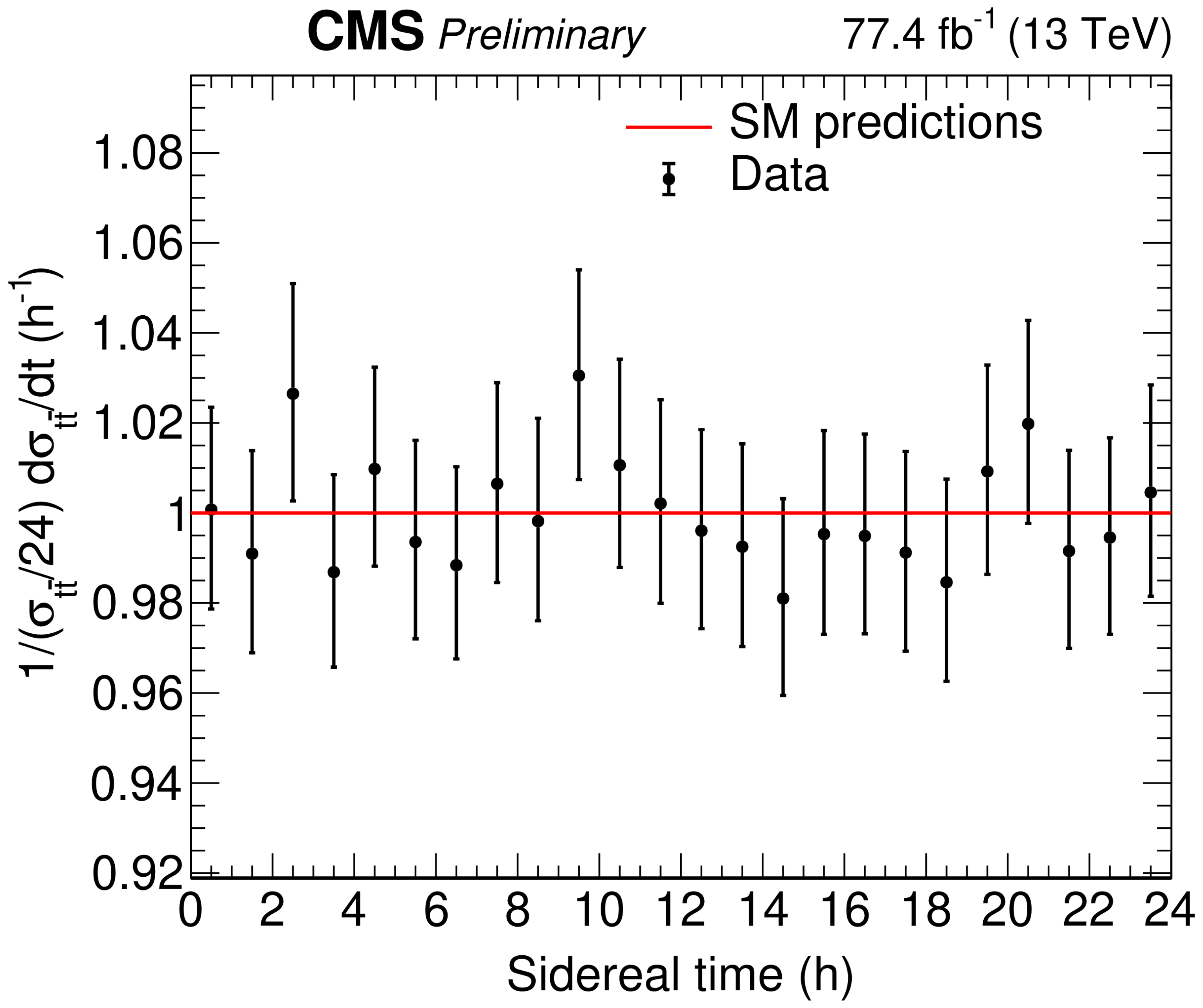


Search for Lorentz violation in $t\bar{t}$

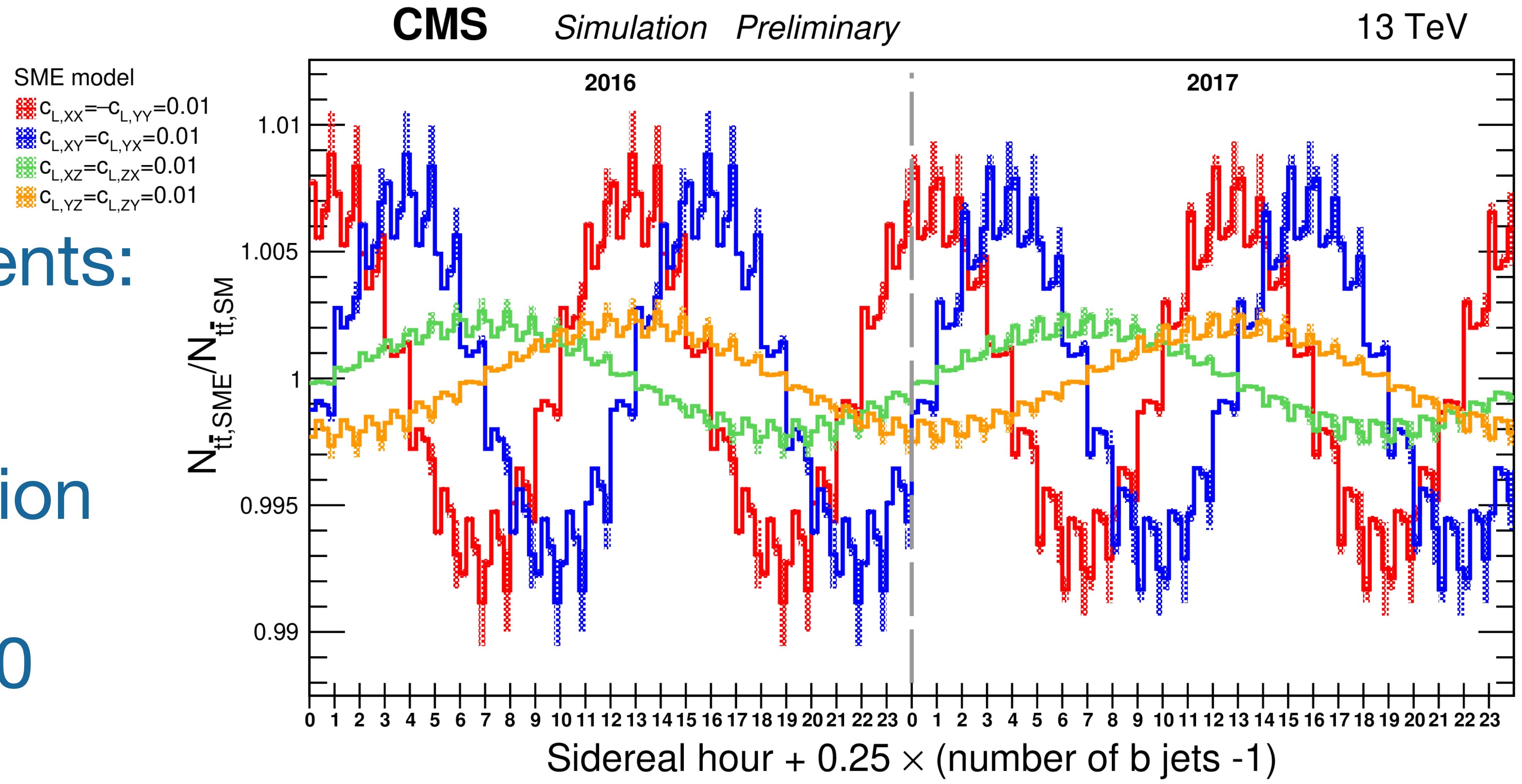
New for LHCP!

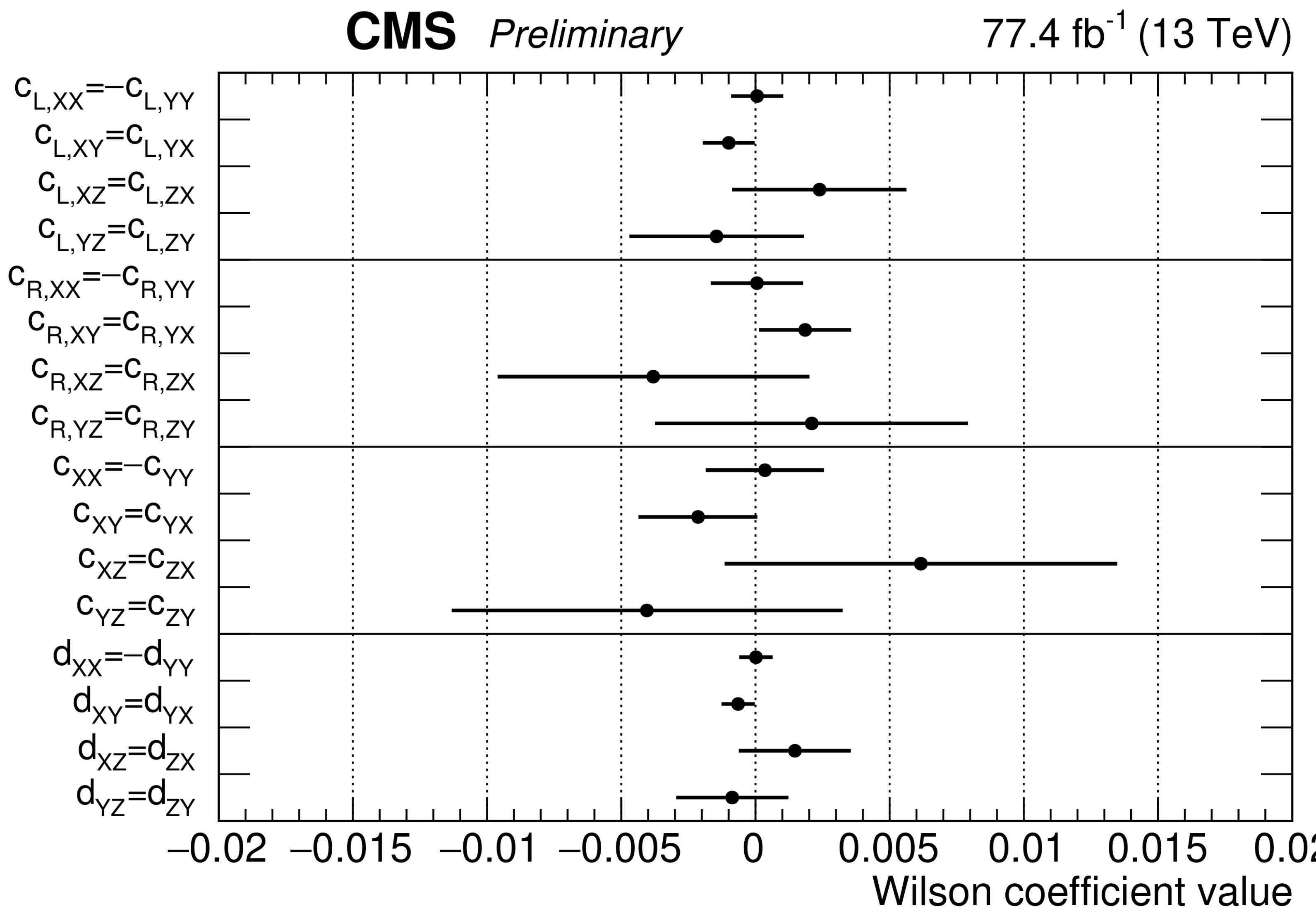
13 TeV – 77.4fb^{-1}
CMS-PAS-TOP-22-007

- Dilepton **eμ** final state with 2016 & 2017 Run 2 dataset
- Observable is **number of *b*-jets** in bins of **sidereal time**
  - Separate between $t\bar{t}$ and tW background
- Fit of normalised differential $\sigma_{t\bar{t}}$ as function of sidereal time
- Standard Model Extension (SME) model fit



- 4 directions:
  - XX, XY, XZ, YZ
- 4 families of coefficients:
  - c, d, cL, cR
- No significant deviation and significant improvement over D0



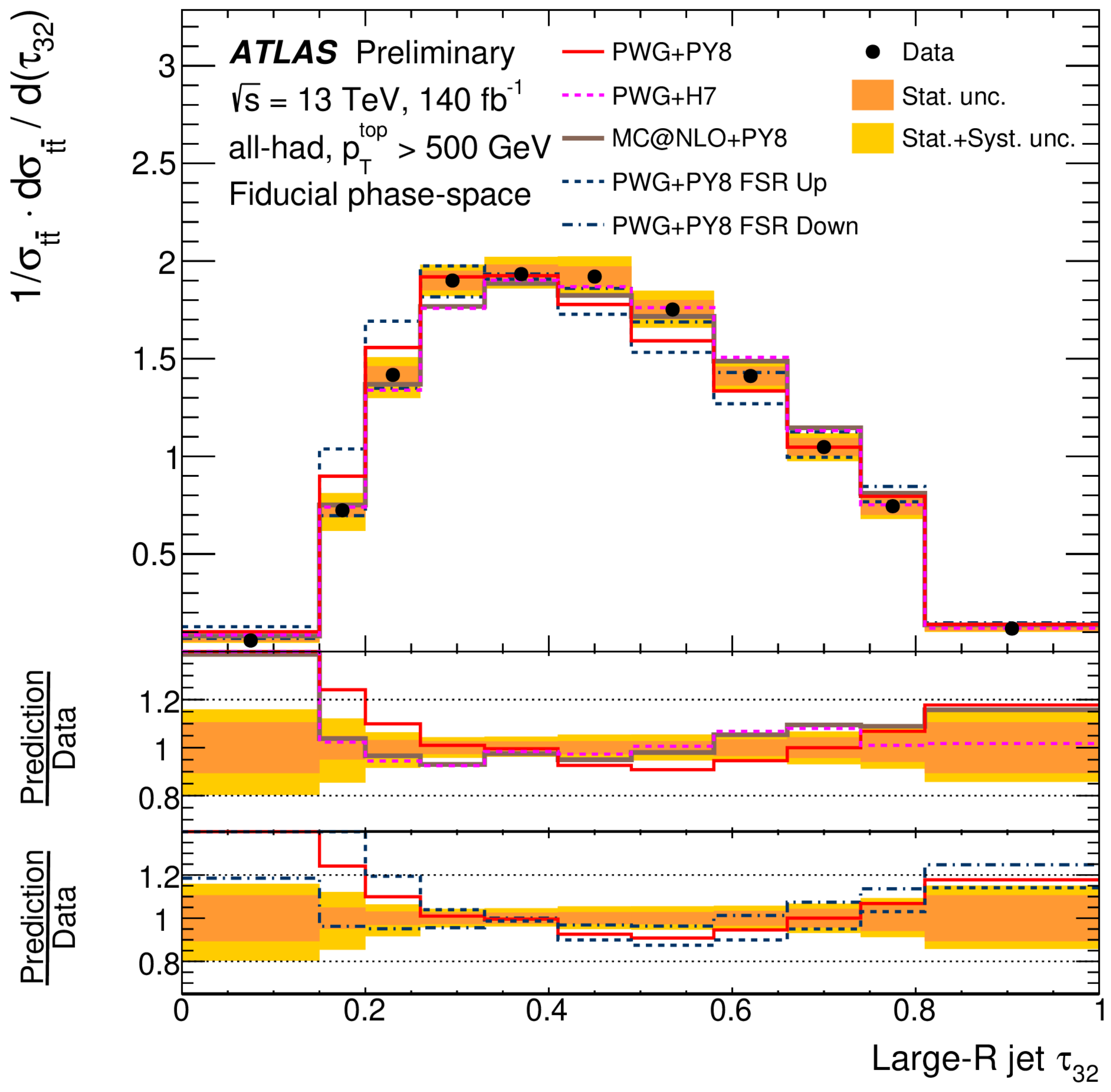


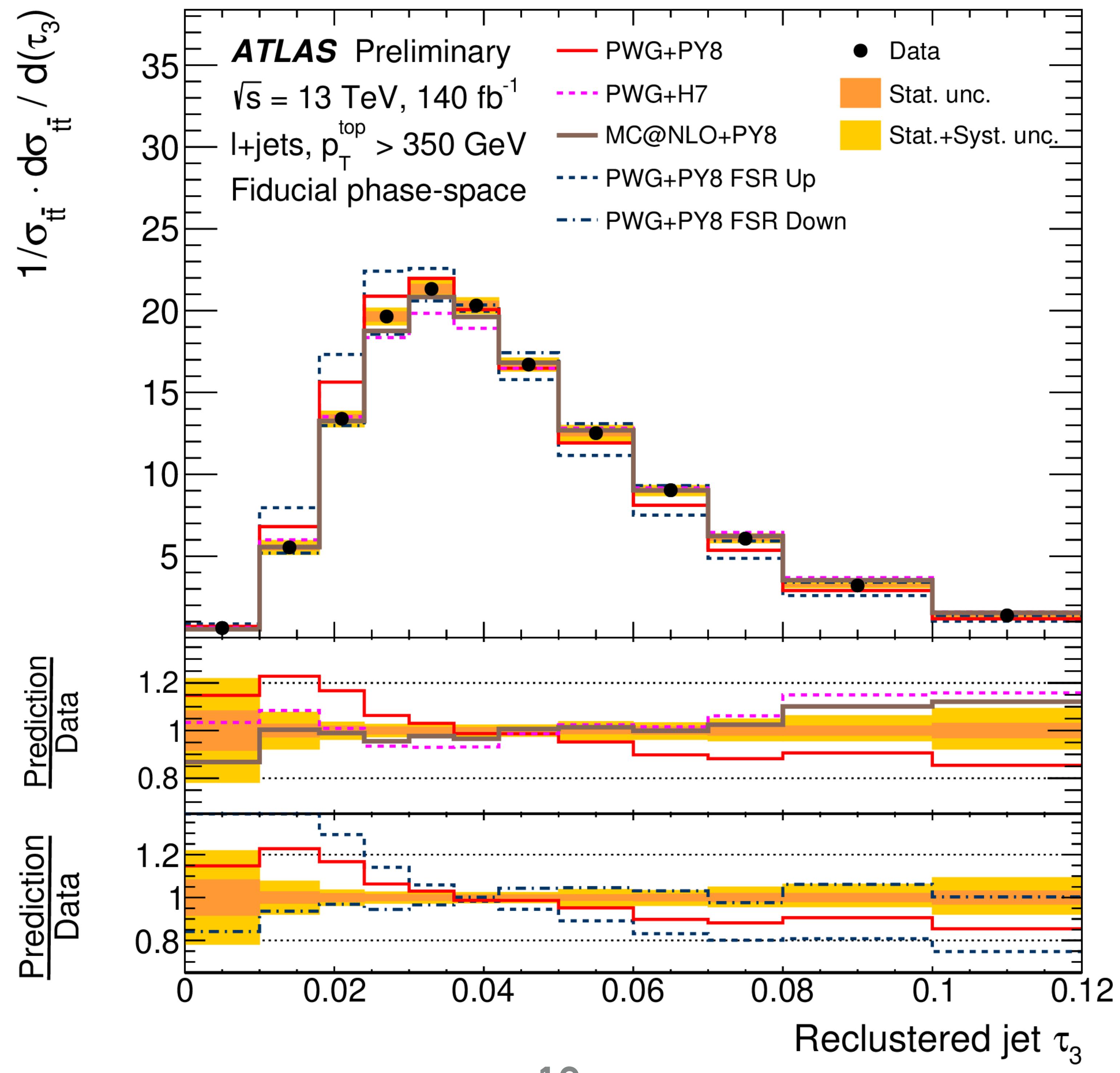
Jet Substructure in boosted $t\bar{t}$

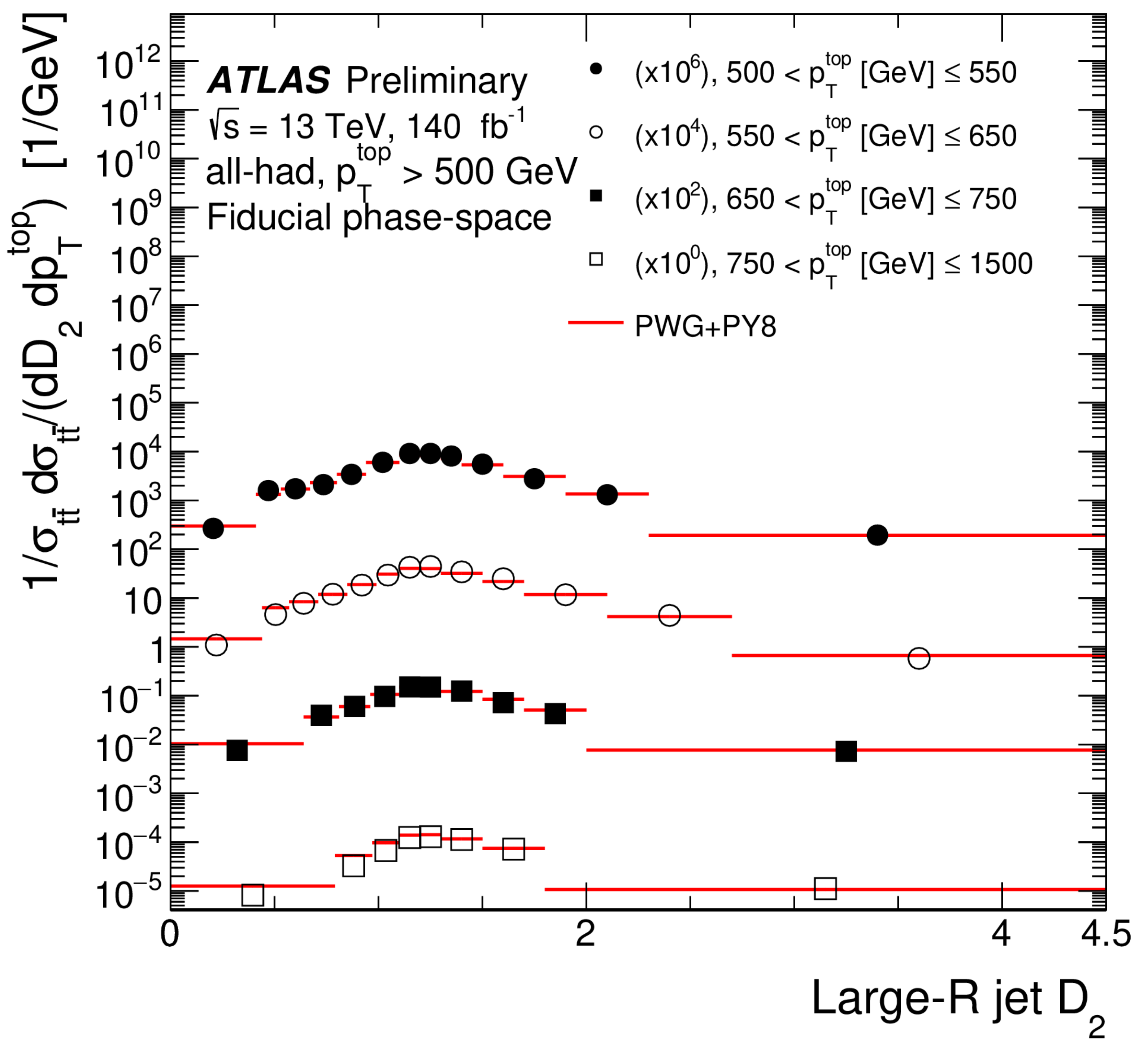
New for LHCP!

13 TeV – 140fb^{-1}
ATLAS-CONF-2023-027

- ℓ+jets and all hadronic channels to study **substructure** of jets from light-, b-quarks, gluons, and jets from the top-quark decay
- Boosted events
  - top-quark jets with $\boldsymbol{p_T > 350}$ **GeV**
- **One-** and **two-dimensional differential $\boldsymbol{\sigma_{t\bar{t}}}$** for eight substructure variables
  - Related to charged jet components

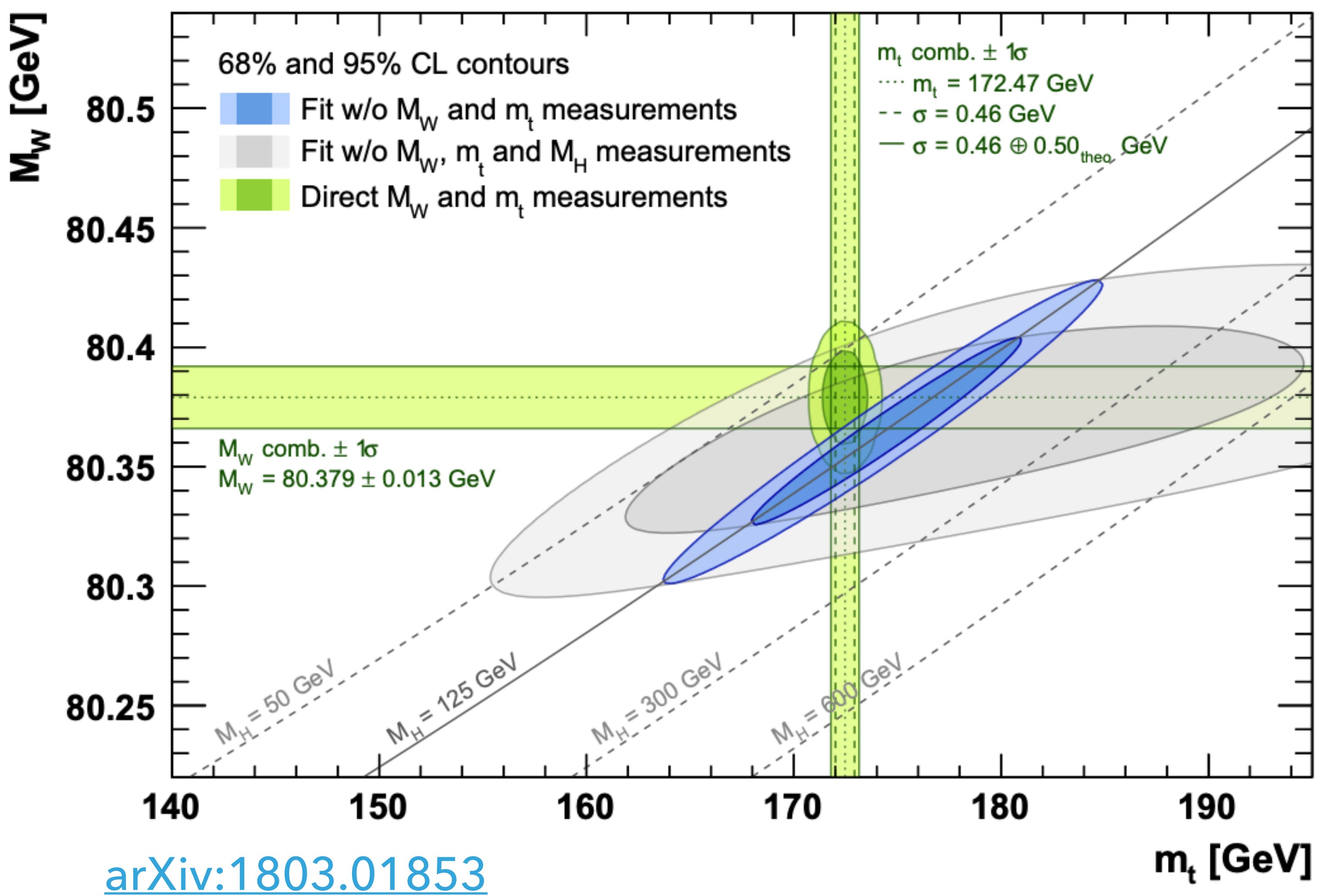




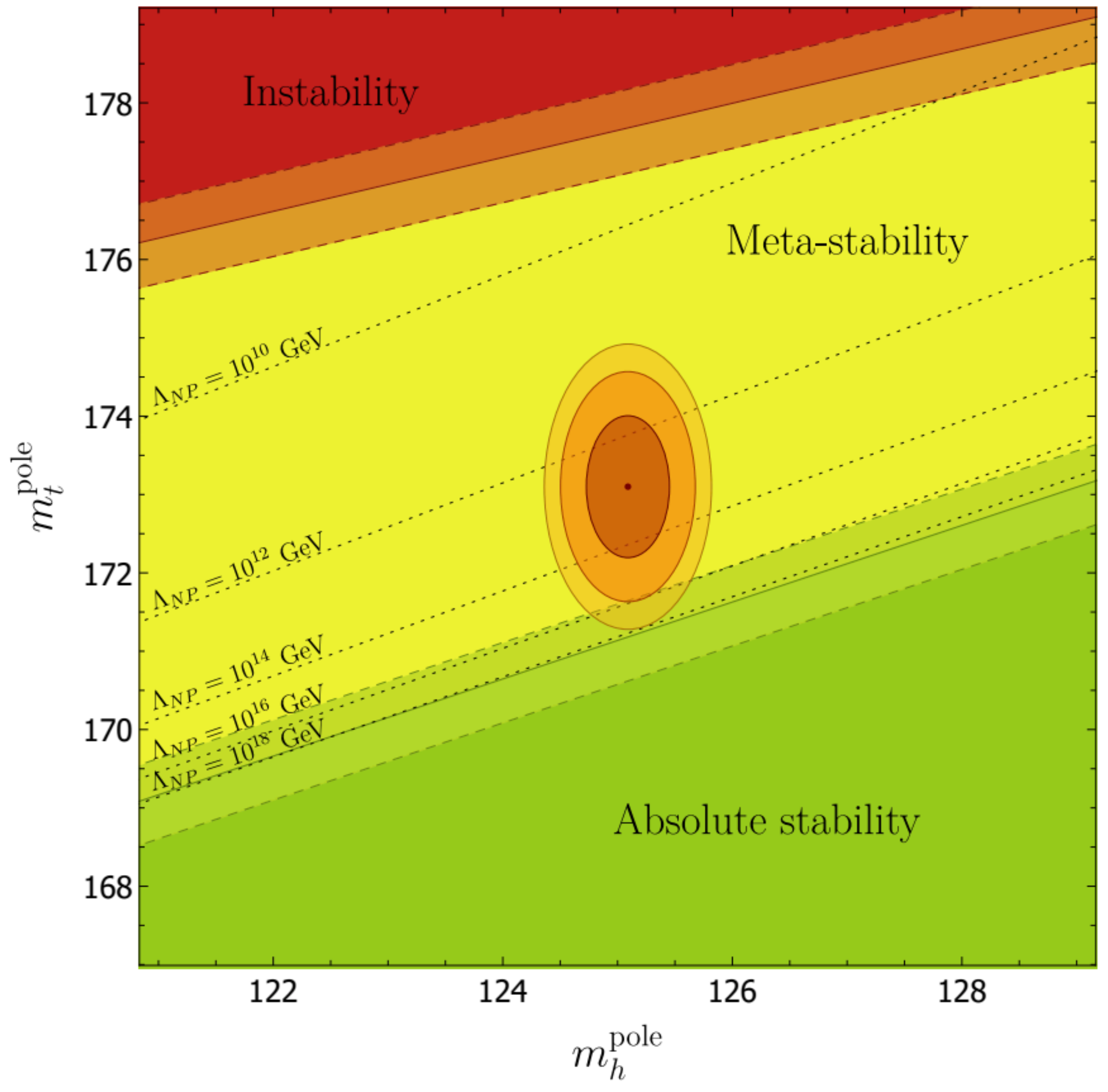


Top-quark mass

- m_t is fundamental parameter of the SM
- m_t, m_W & m_H measurements can be compared to EW fit predictions to check validity of SM
- EW vacuum is meta-stable in SM(?)
  - Implications on the fate of the universe
  - If no new physics up to the plank scale stability is dependent on m_H and m_t



arXiv:1803.01853



PRD 97 (2018) 056006

Direct m_t measurements

- Extraction from total or partial kinematic reconstruction of invariant mass of top decay products
- Comparison with MC calculations

$$m_t^{\mathrm{MC}}$$

Indirect measurements

- From cross-sections (inclusive or differential)
- Measure observable(s) with a strong dependence on m_t with data unfolding

$$m_t^{\mathrm{pole}}$$

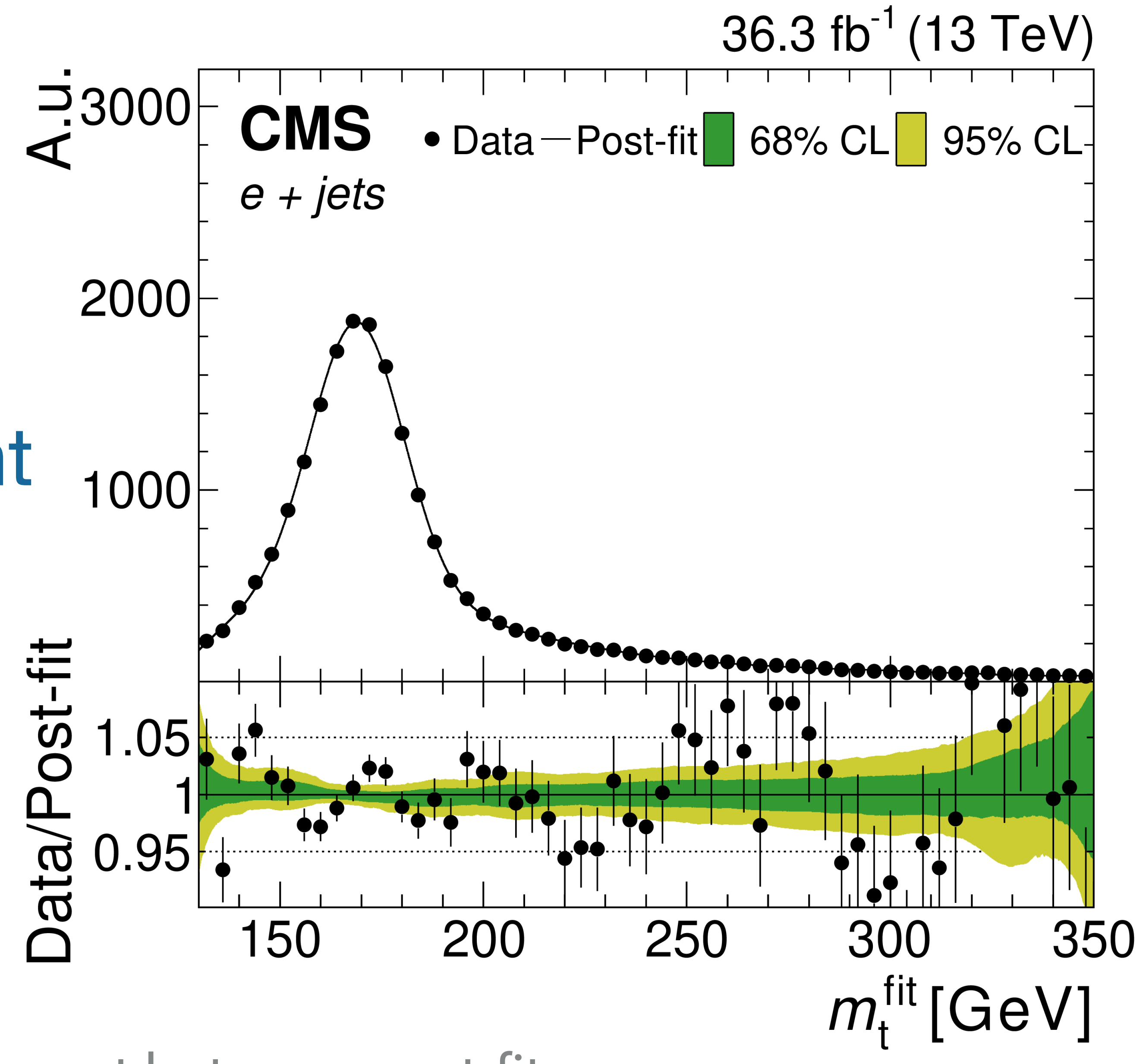
m_t in ℓ+jets channel with profile likelihood

13 TeV – 36fb^{-1}
arXiv:2302.01967

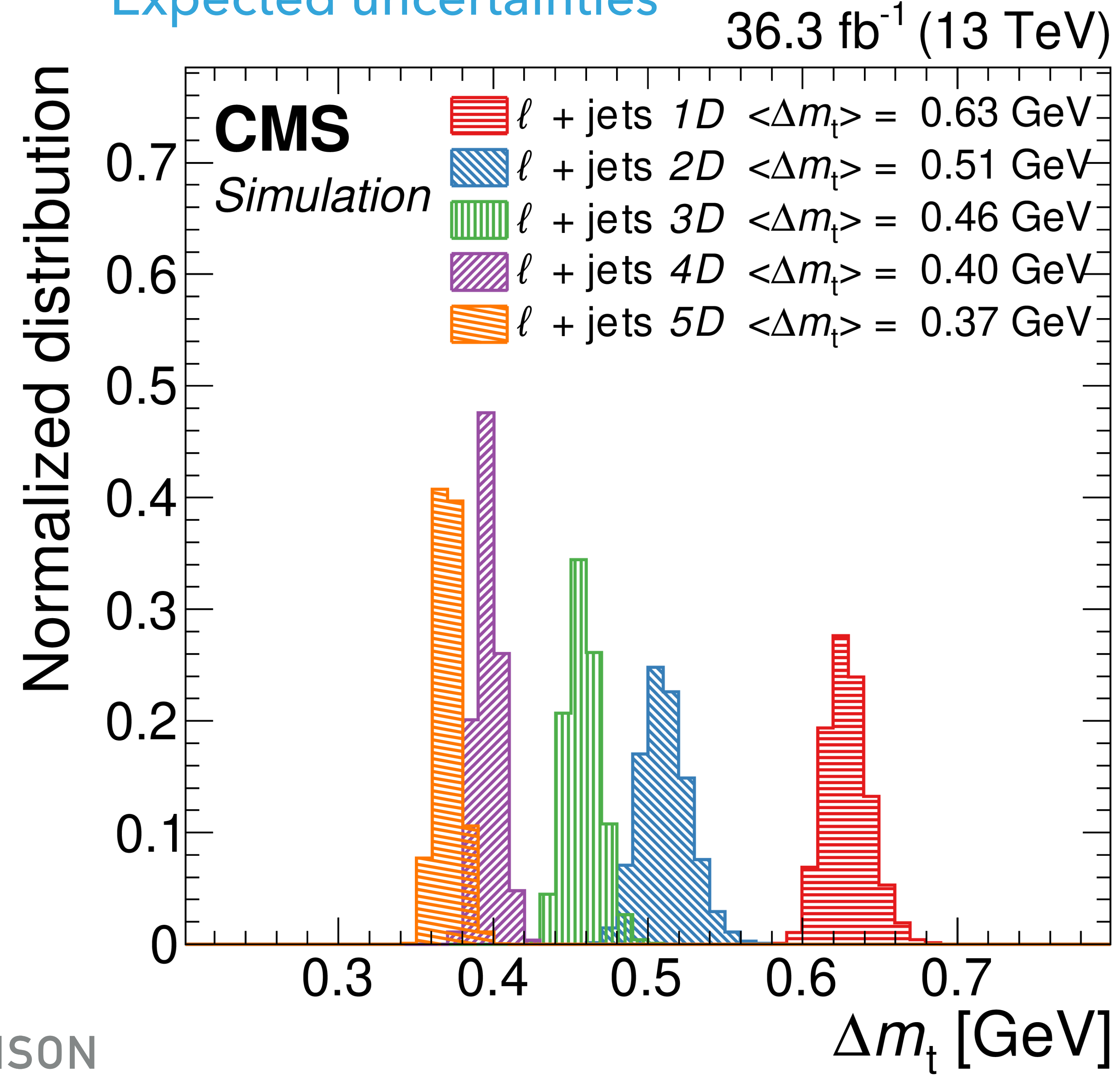
- Simultaneous fit of 5 observables with profile likelihood allows in-situ constraint of systematics
  - m_t^{fit}, $m_{\ell b}^{reco}$: sensitive to m_t
  - m_W^{reco}, $m_{\ell b}^{reco}/m_t^{fit}$, R_{bq}^{reco}: additional constraint on $t\bar{t}$ modelling

$$R_{bq}^{reco} = \frac{p_T^{b1} + p_T^{b2}}{p_T^{q1} + p_T^{q2}}$$

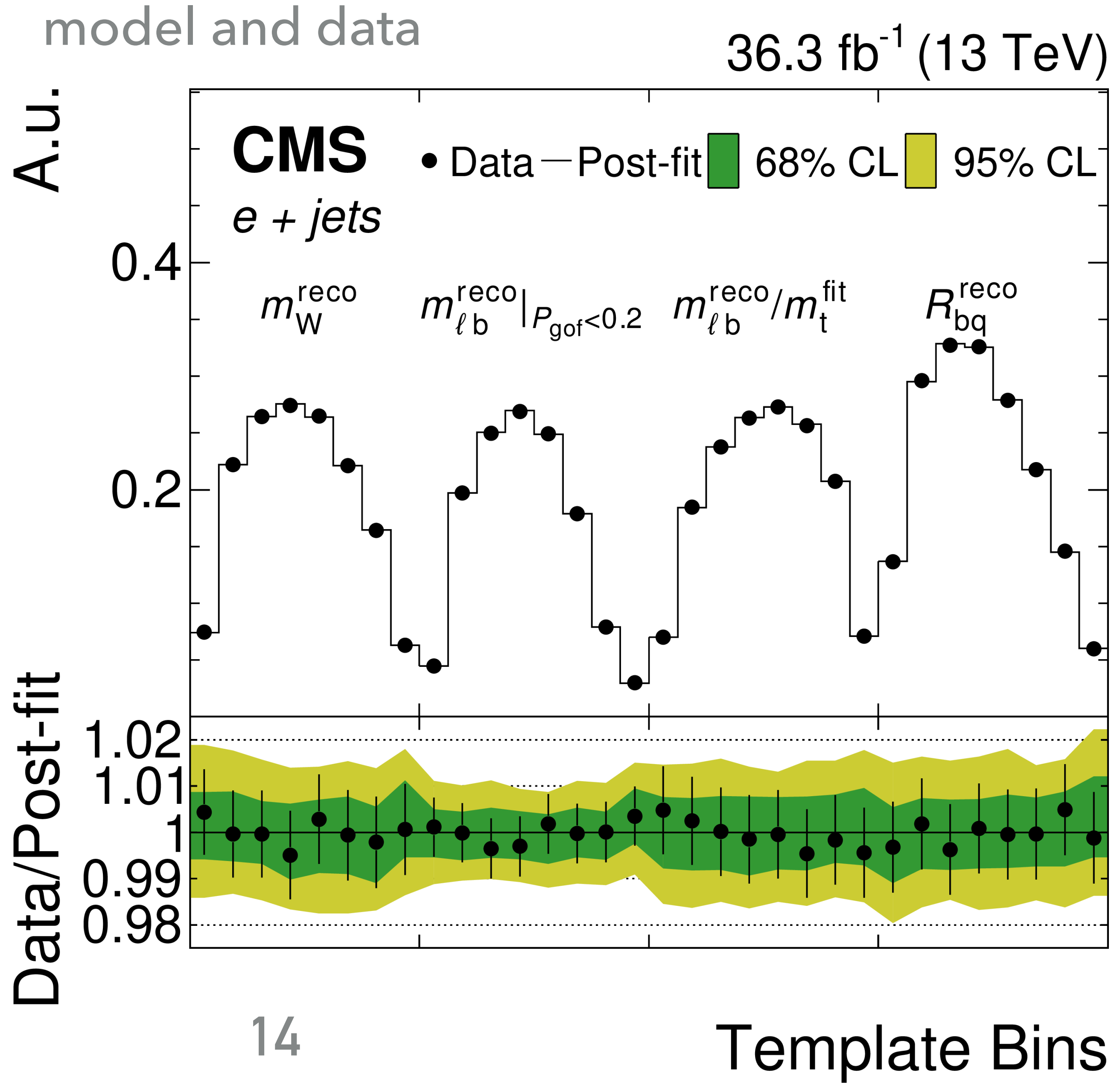
- Unprecedented precision result:
  - m_t^{5D} **= 171.77 ± 0.37 GeV**

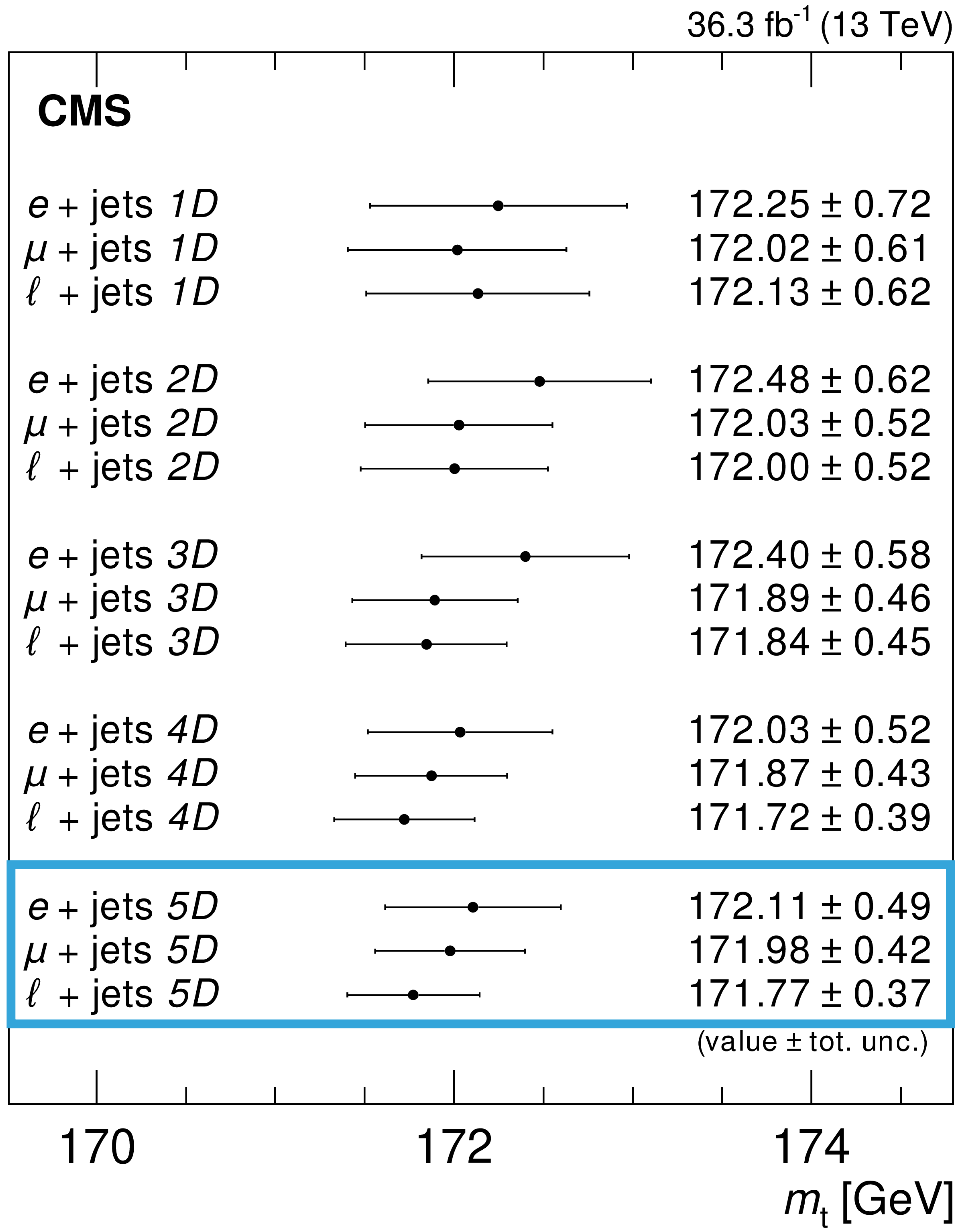


Expected uncertainties



Agreement between post-fit model and data



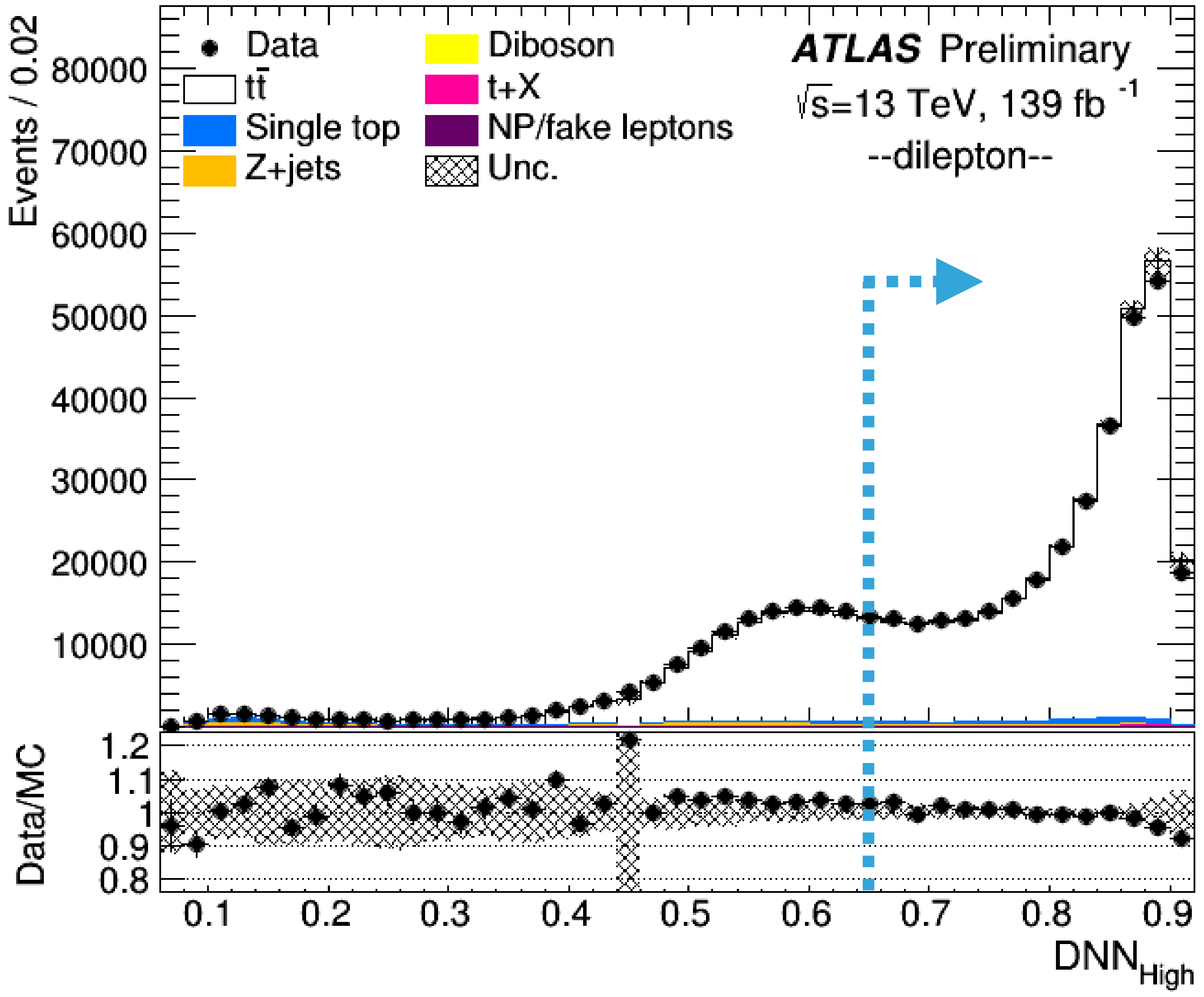


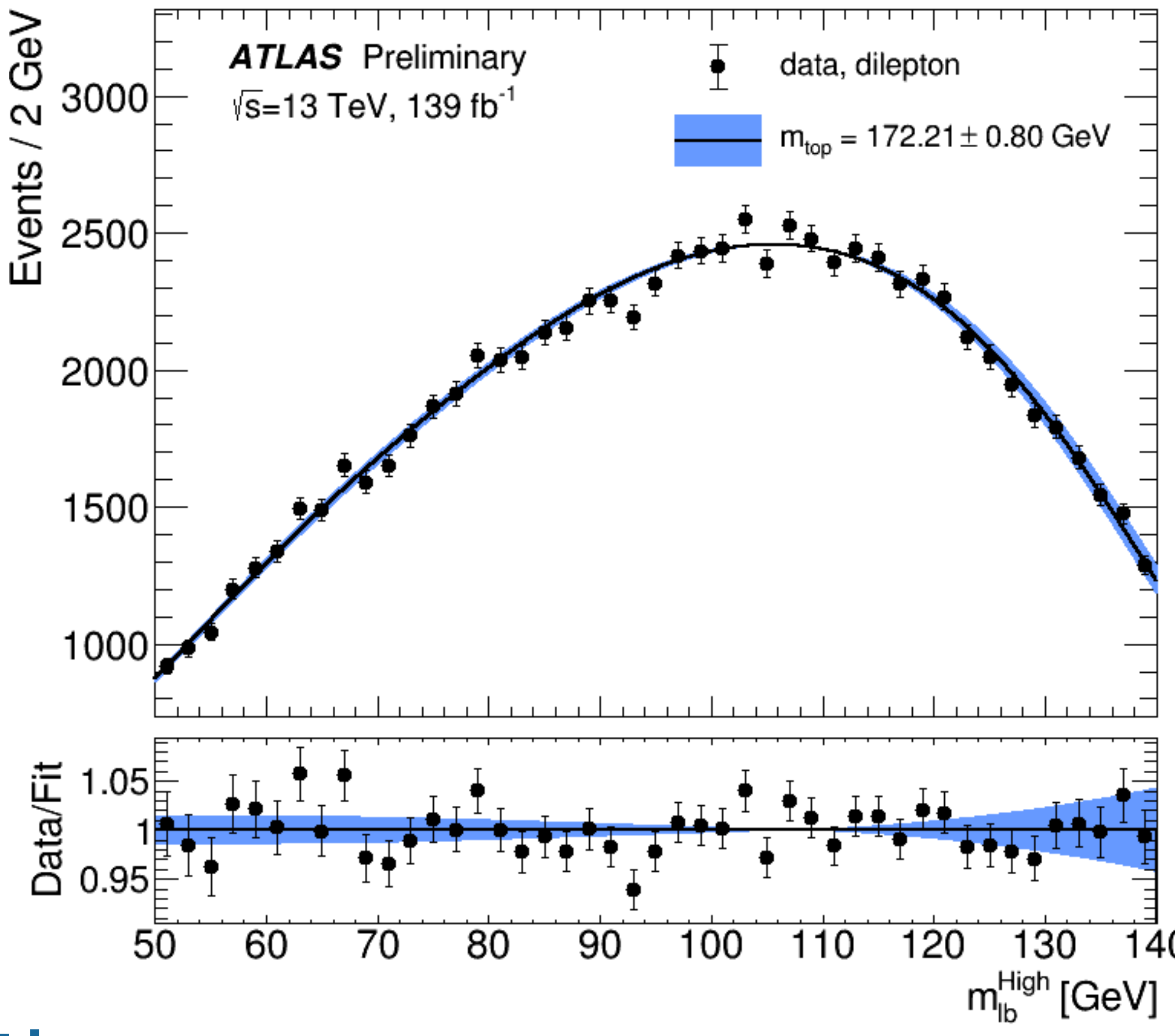
Dominant uncertainties from MC modelling: **parton shower**, **colour reconnection**

m_t in dilepton channel with template fit

13 TeV – 139fb[-1]
ATLAS-CONF-2022-058

- Partial m_t reconstruction:
  - Use DNN to match lepton and b-jet
- Selection optimised to improve precision:
  - **DNN > 0.65**
  - $p_T^{\ell b}$ > 160 GeV
  - ℓ-b with **highest $p_T^{\ell b}$ selected** → helps reduce signal modelling and jet-related uncertainties





	m_{top} [GeV]
Result	172.21
Statistics	0.20
Method	0.05 ± 0.04
Matrix-element matching	0.40 ± 0.06
Parton shower and hadronisation	0.05 ± 0.05
Initial- and final-state QCD radiation	0.17 ± 0.02
Underlying event	0.02 ± 0.10
Colour reconnection	0.27 ± 0.07
Parton distribution function	0.03 ± 0.00
Single top modelling	0.01 ± 0.01
Background normalisation	0.03 ± 0.02
Jet energy scale	0.37 ± 0.02
b-jet energy scale	0.12 ± 0.02
Jet energy resolution	0.13 ± 0.02
Jet vertex tagging	0.01 ± 0.01
b-tagging	0.04 ± 0.01
Leptons	0.11 ± 0.02
Pile-up	0.06 ± 0.01
Recoil effect	0.39 ± 0.09
Total systematic uncertainty (without recoil)	0.67 ± 0.05
Total systematic uncertainty (with recoil)	0.77 ± 0.06
Total uncertainty (without recoil)	0.70 ± 0.05
Total uncertainty (with recoil)	0.80 ± 0.06

new (and significant) uncertainty source

- Template fit to $m_{\ell b}$ distribution:

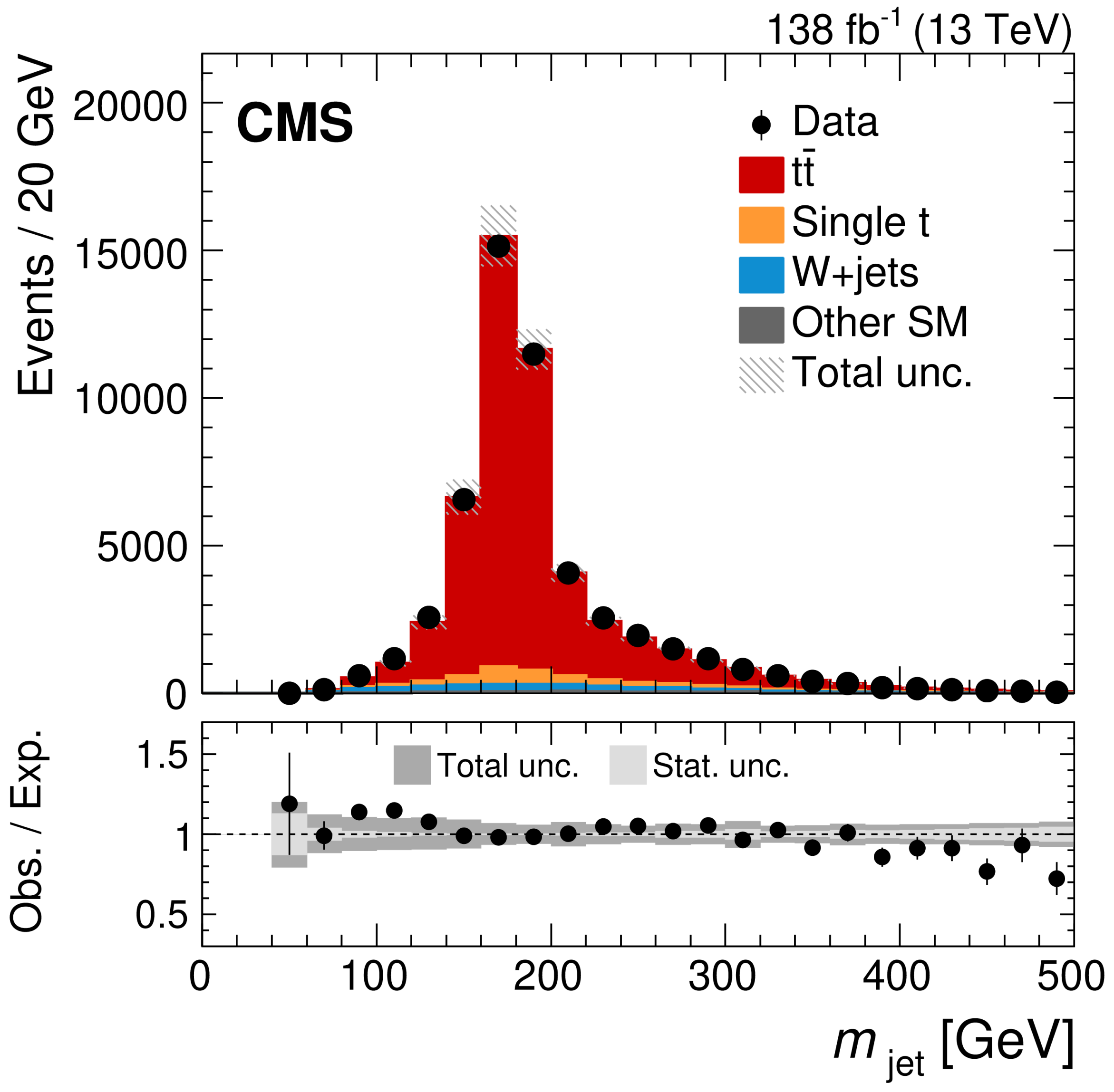
$$m_t = 172.21 \pm 0.20\,(\text{stat.}) \pm 0.67\,(\text{syst.}) \pm 0.39\,(\text{recoil})\,\text{GeV} = 172.21 \pm 0.80\,\text{GeV}$$

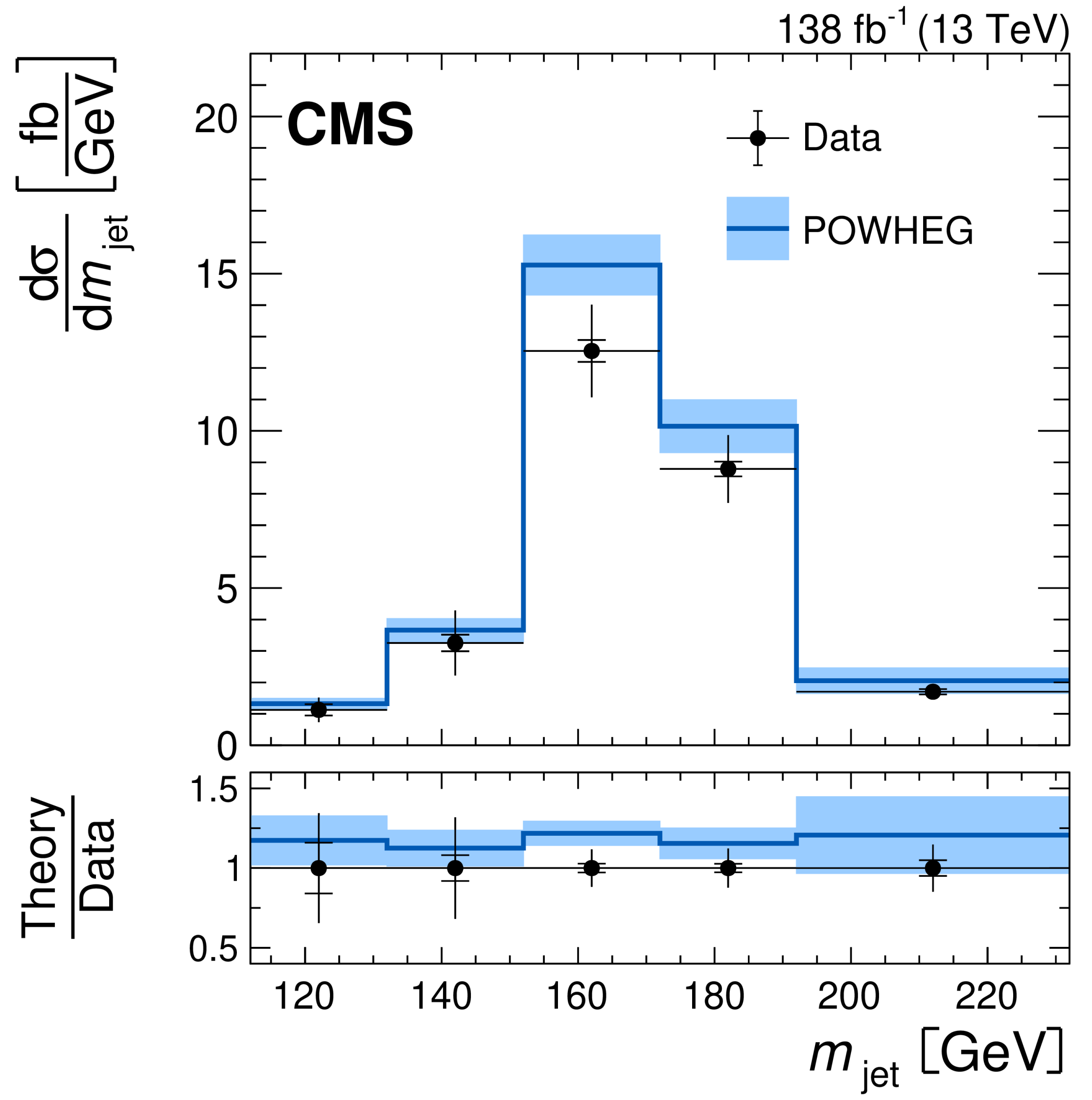
Improvement w.r.t. Run 1

m_t from boosted $t\bar{t}$

13 TeV – 138fb-1
arXiv:2211.01456

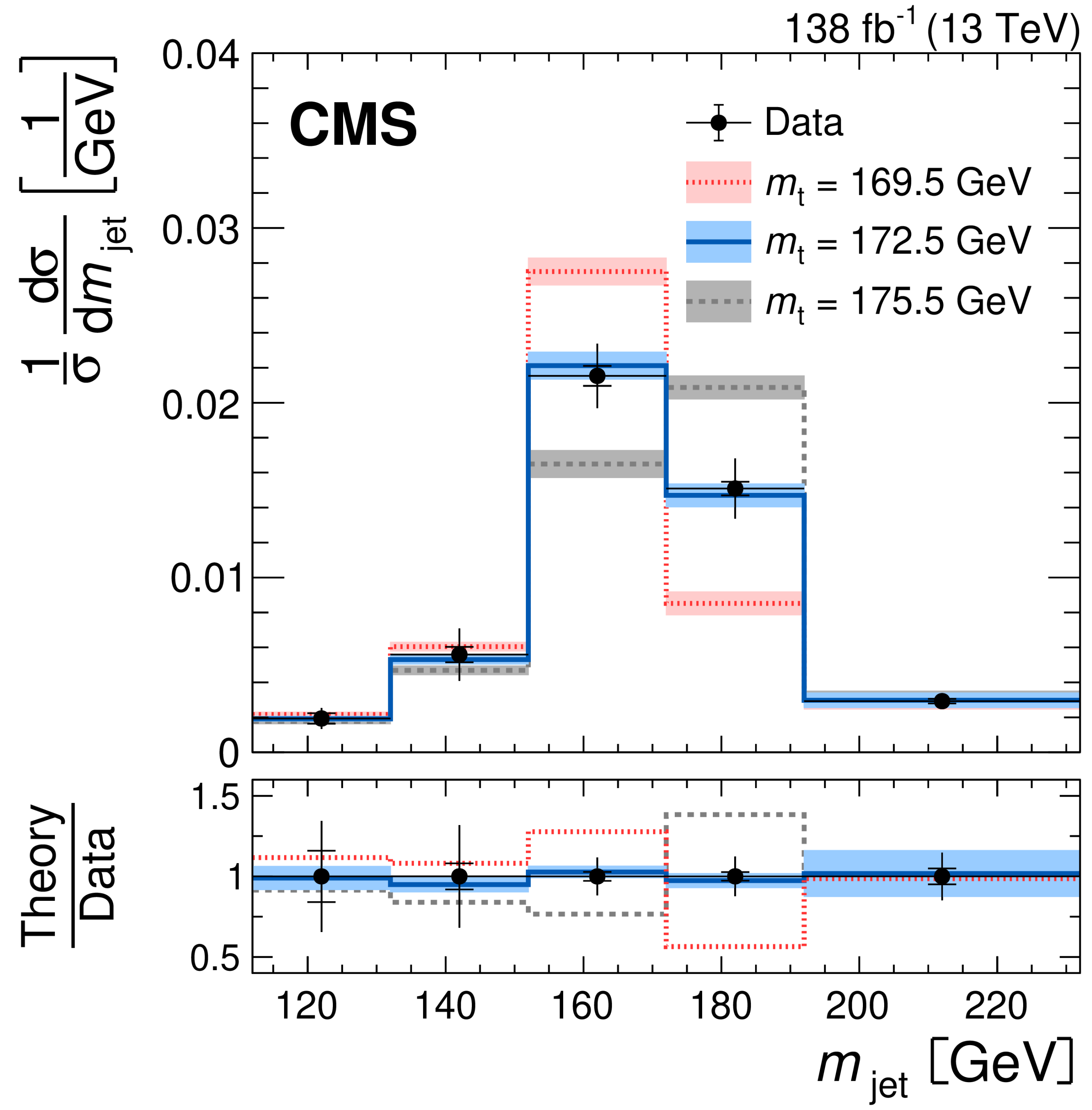
- Boosted top production in ℓ+jets channel
  - Decay products tend to collimate in large-R jet
  - **XCone R=1.2, p_T > 400 GeV**
  - large-R jet mass peak sensitive to m_t
- Unfolded to particle-level to then extract m_t
- Dedicated JMS calibration using substructure variables and jet mass → reduce uncertainties

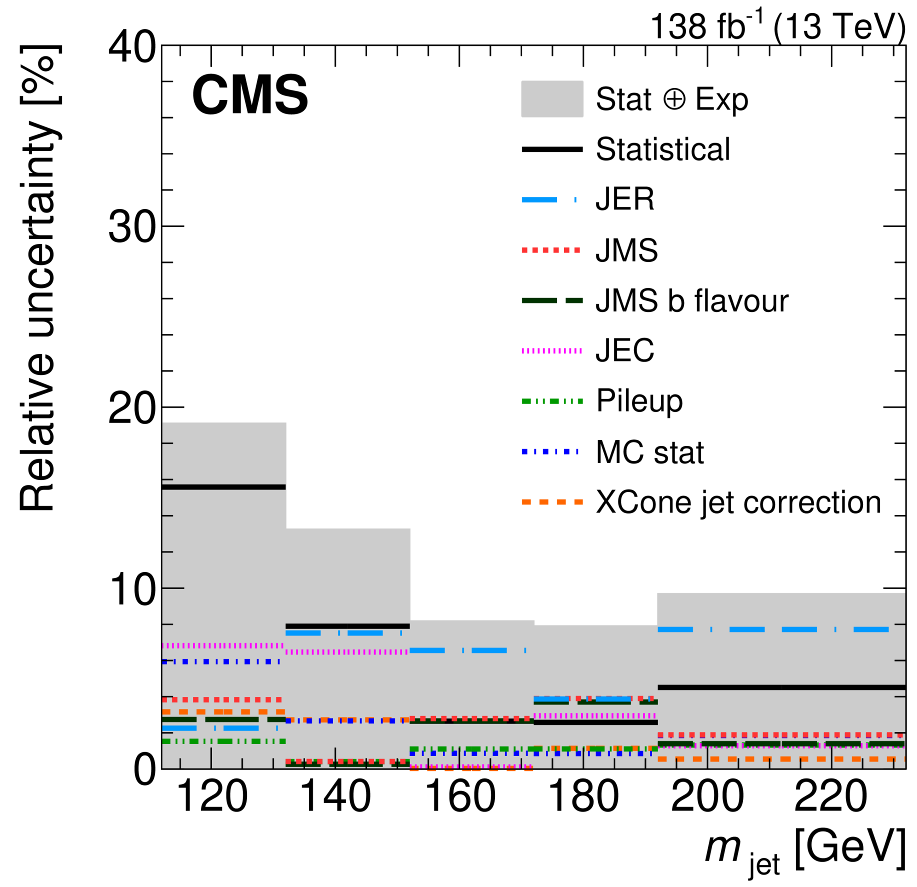


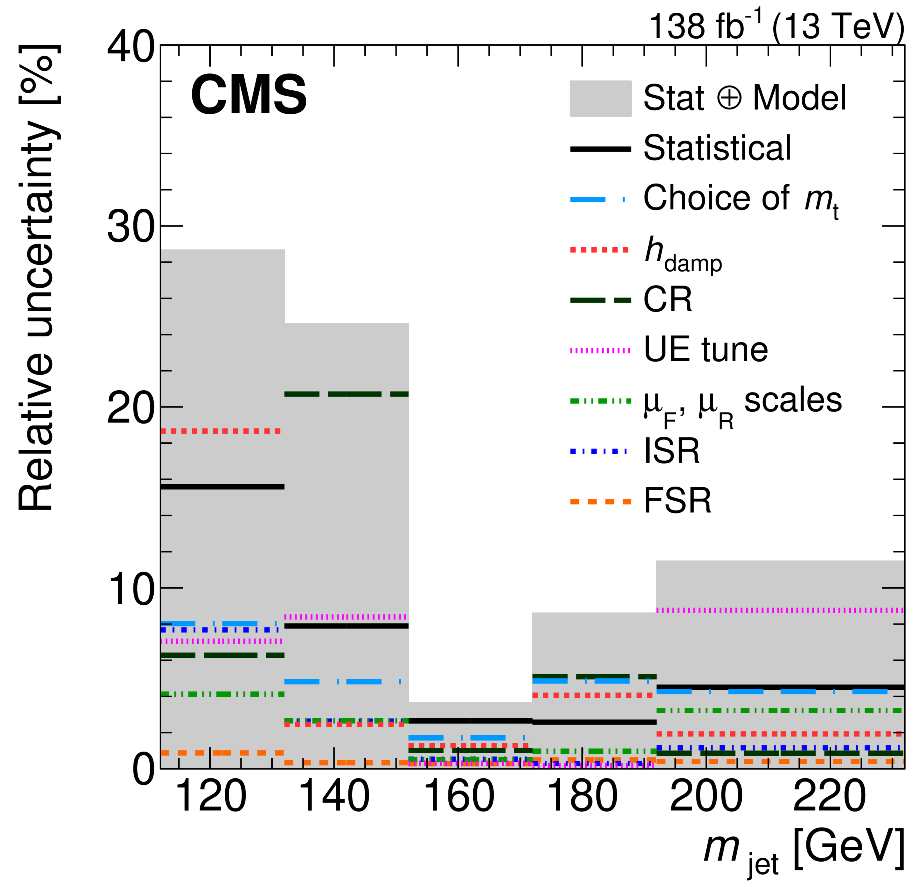


$$m_t = 172.76 \pm 0.22\,(\text{stat.}) \pm 0.57\,(\text{exp.}) \pm 0.48\,(\text{model}) \pm 0.24\,(\text{theo.})\,\text{GeV}$$
$$= 172.76 \pm 0.81\,\text{GeV}$$

Comparable precision to direct measurements, with very different uncertainties

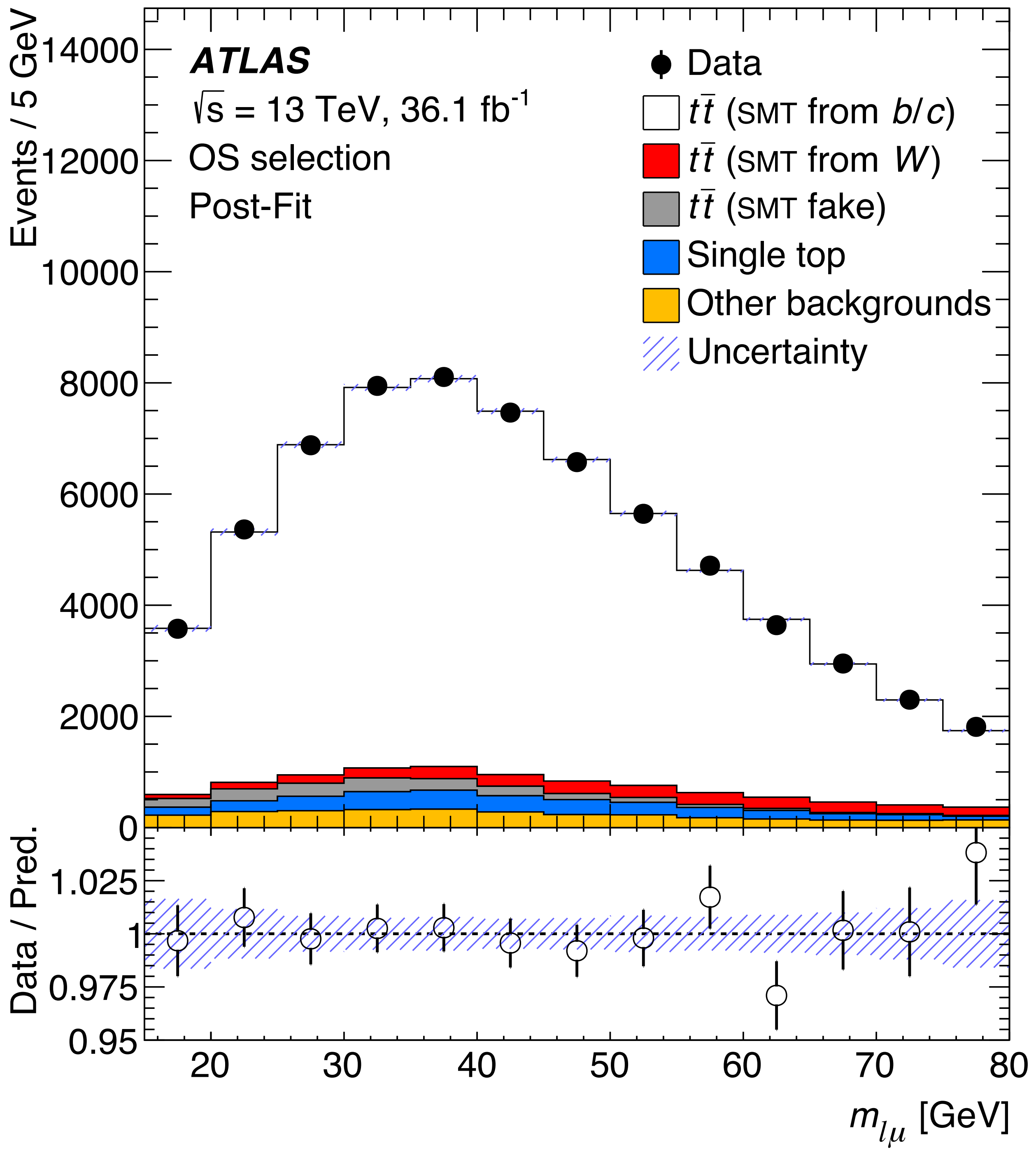


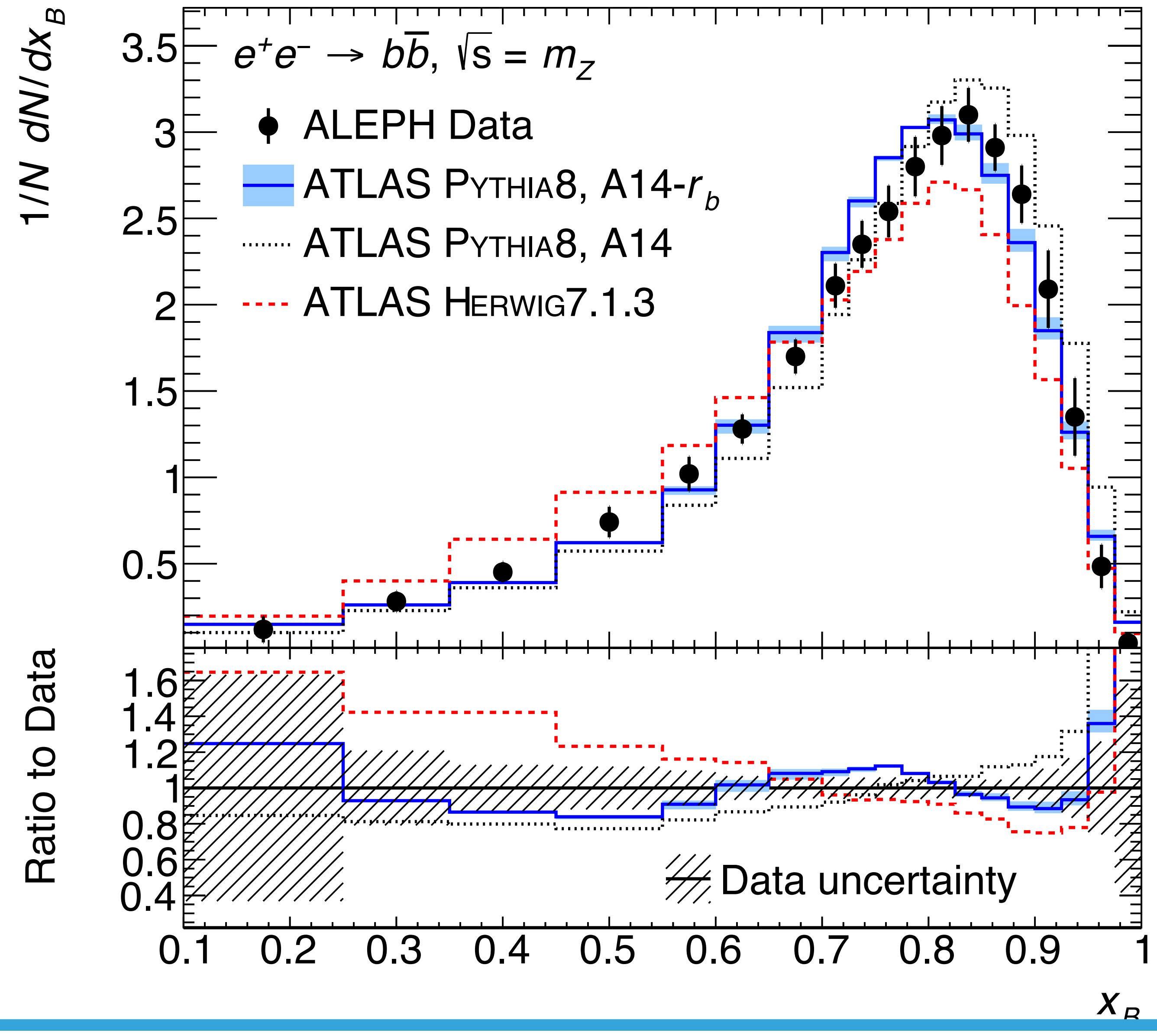


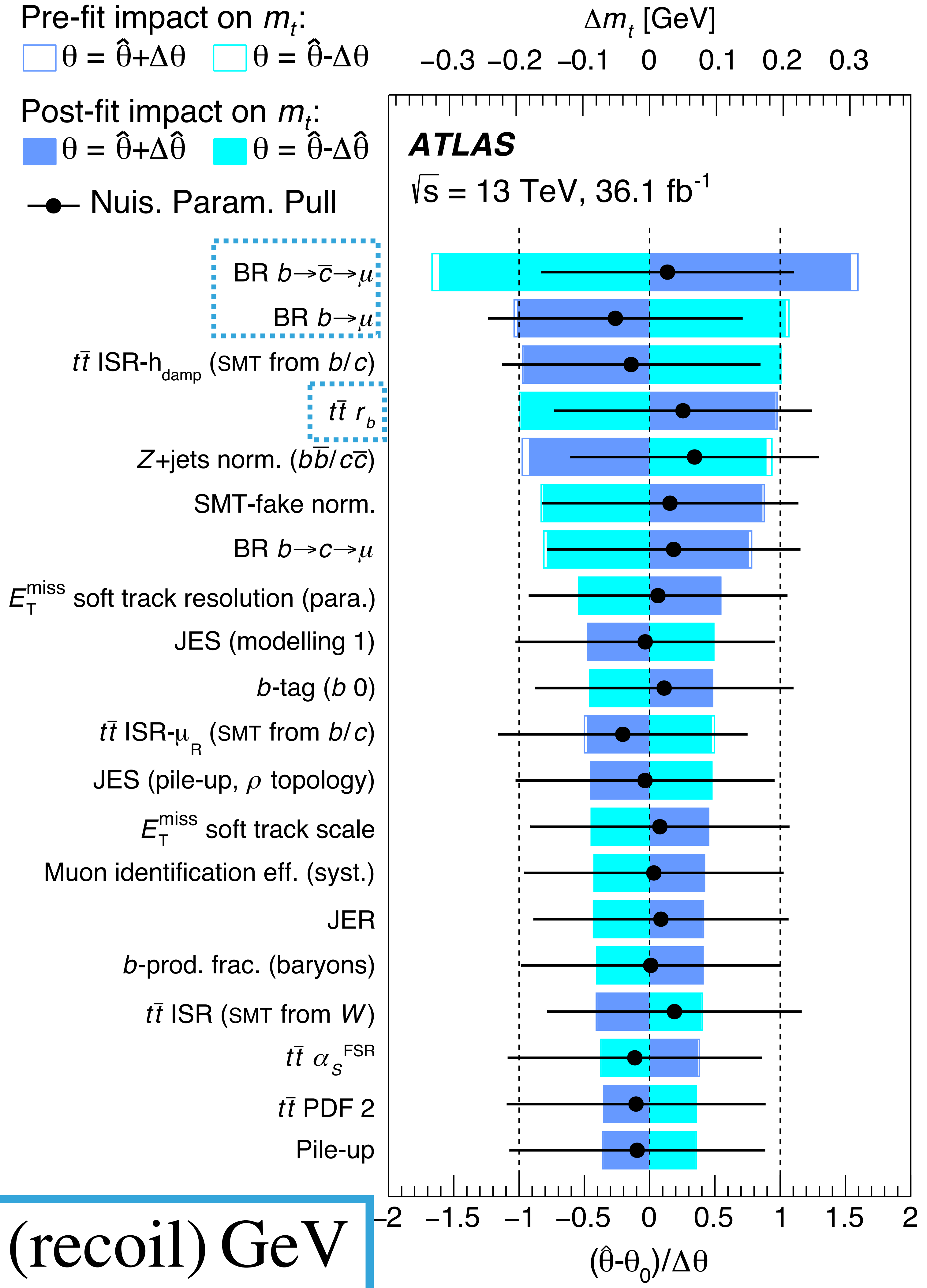


m_t with soft muon tagging

- Non-standard technique exploiting **soft-muon from b-hadron decays**
- Measure Invariant mass of prompt-lepton and soft-muon $m_{\ell\mu}$
  - **Purely leptonic observable** → reduced impact from jet related uncertainties
- Modelling of b-hadron production and decay very important
  - b-frag. retuned to LEP data







$$m_t = 174.41 \pm 0.39\,(\text{stat.}) \pm 0.66\,(\text{syst.}) \pm 0.25\,(\text{recoil})\,\text{GeV}$$
$$= 174.41 \pm 0.81\,\text{GeV}$$

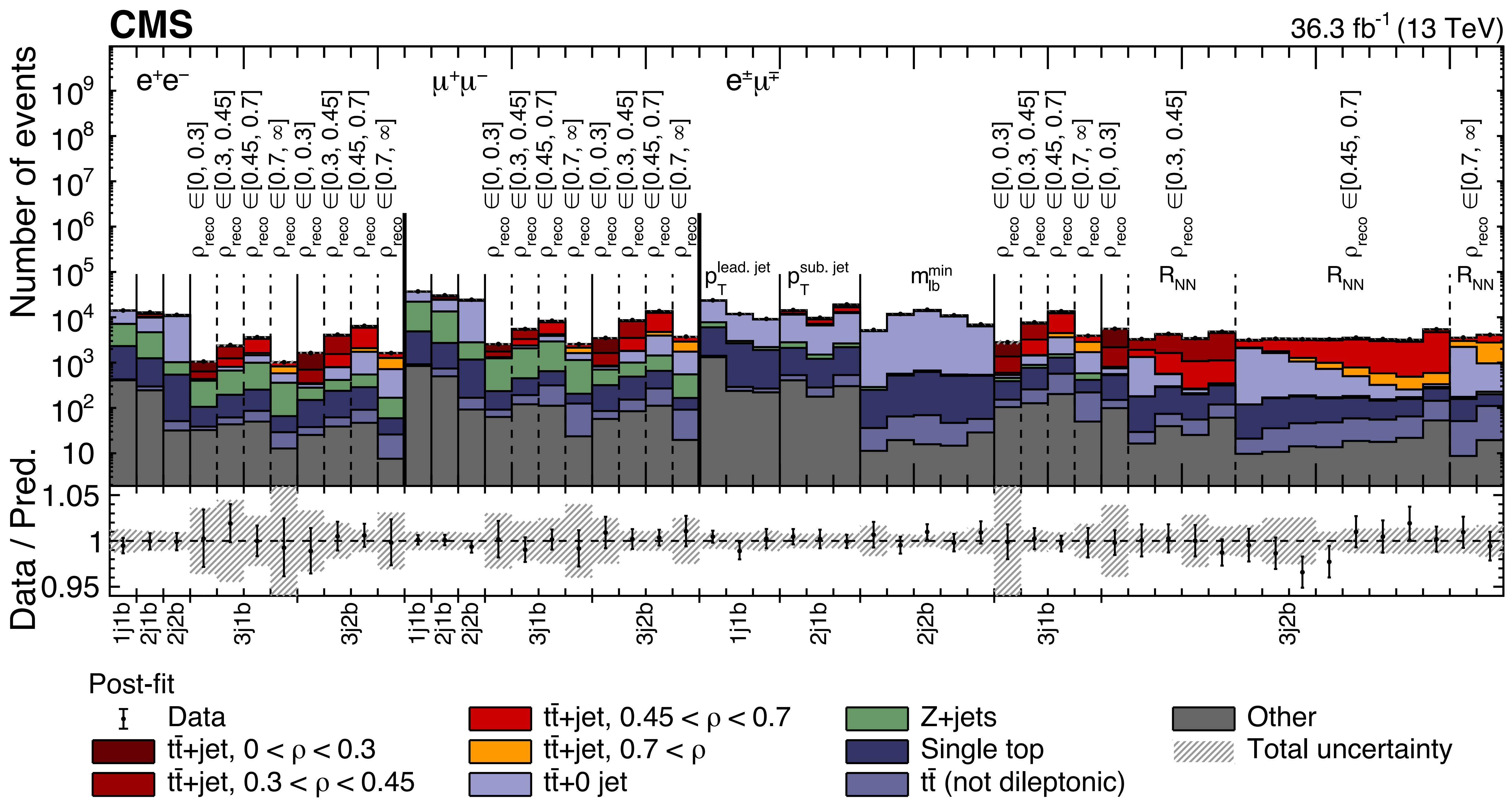
Indirect m_t from $t\bar{t}$+1j

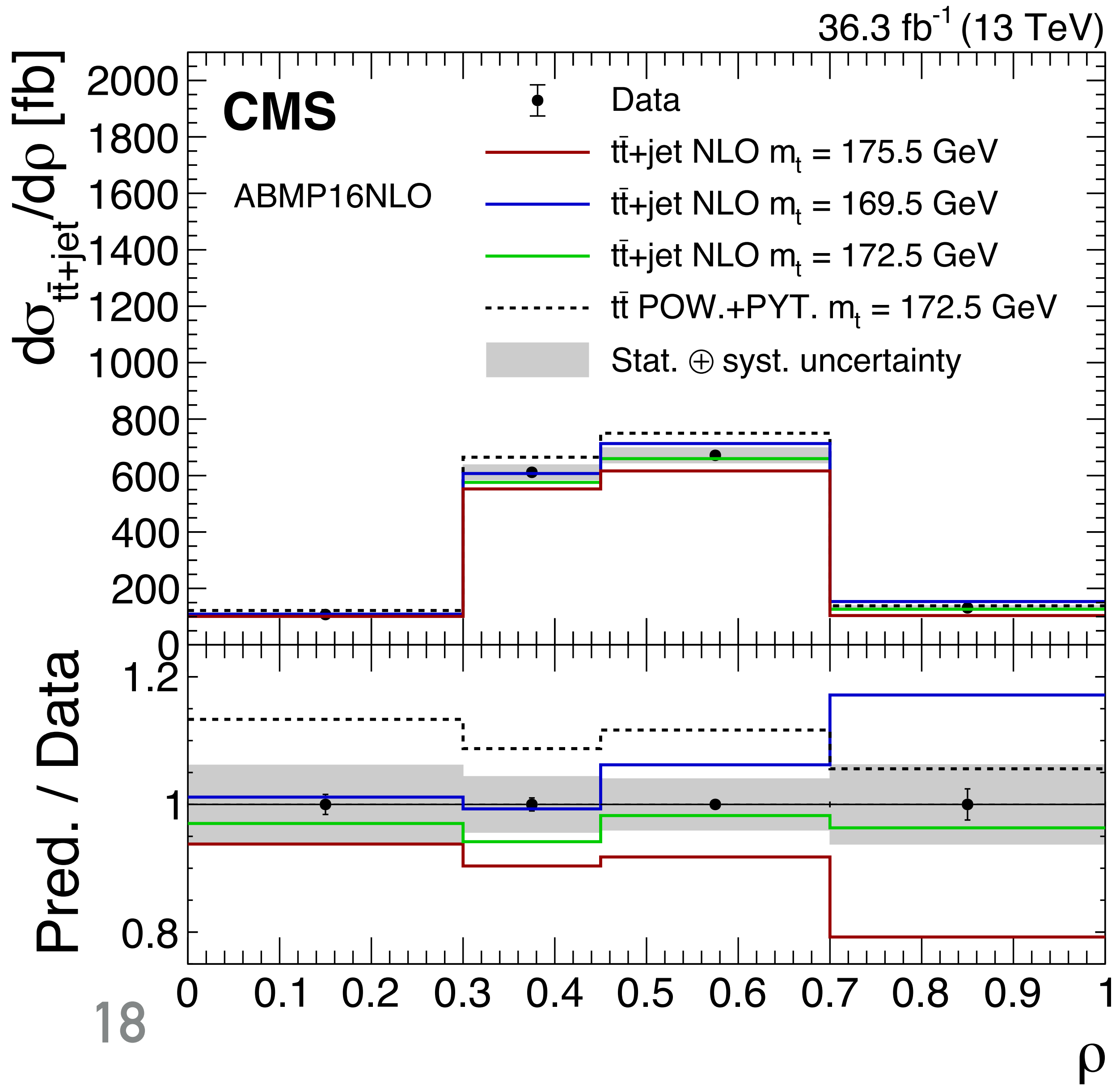
13 TeV – 36.3 fb^{-1}
arXiv:2207.02270

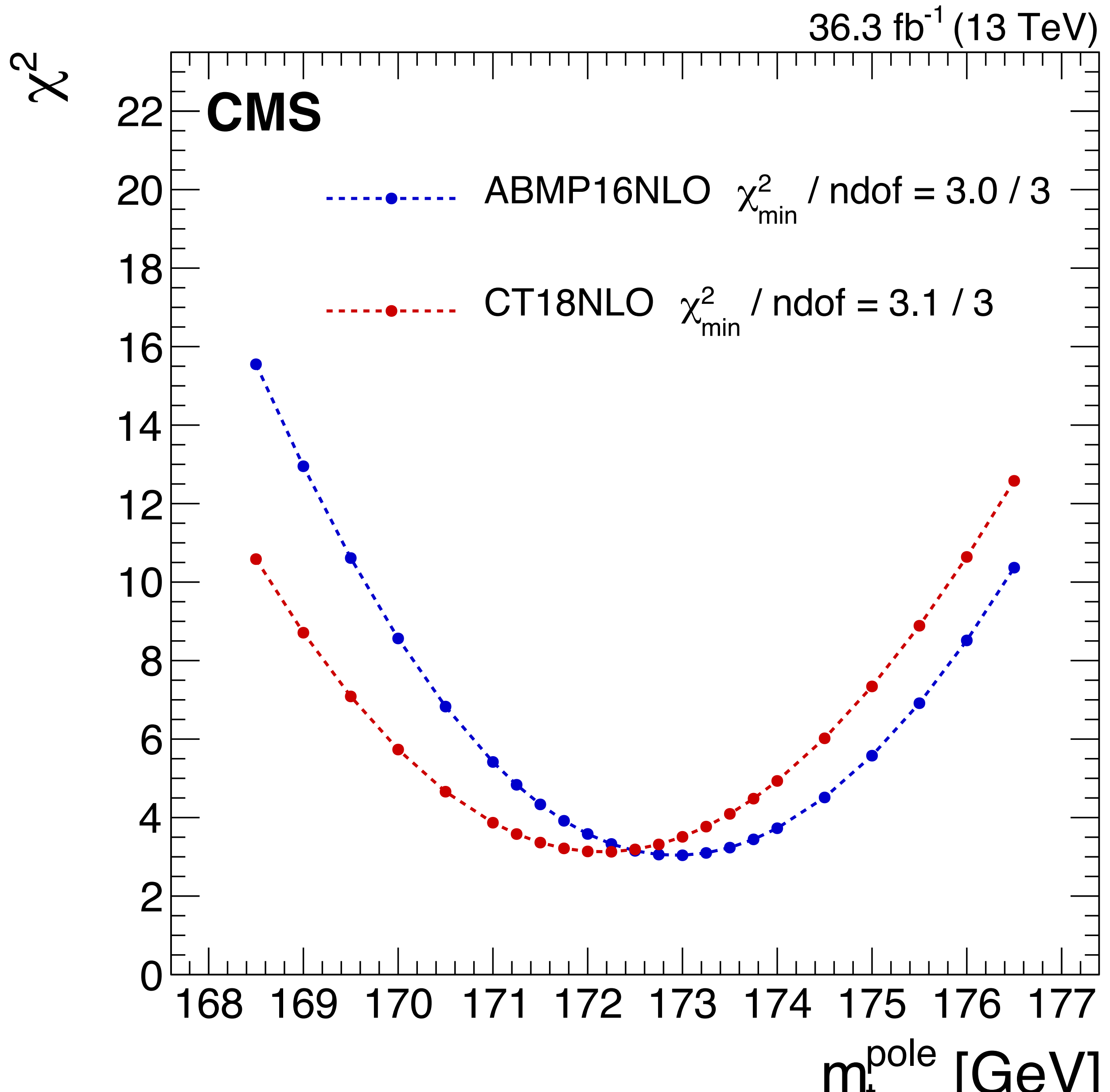
- Invariant mass of $t\bar{t}$+jet can be computed analytically
  - Sensitive to m_t^{pole} in threshold region
  - Use ρ variable

$$\rho = \frac{2m_0}{m_{t\bar{t}+jet}}$$

- Dileptonic $t\bar{t}$+1jet selection
  - NN for event classification
  - NN regression for reconstruction of ρ
- **Profile-likelihood unfolding** allows combination of several categories
  - Multiple regions also helps constrain uncertainties
- χ2 fit to NLO calculations to extract m_t^{pole}:
  - m_t^{pole} **= 172.94 ± 1.37 GeV** for AMBP16NLO
  - m_t^{pole} **= 172.16 ± 1.44 GeV** for CT18NLO

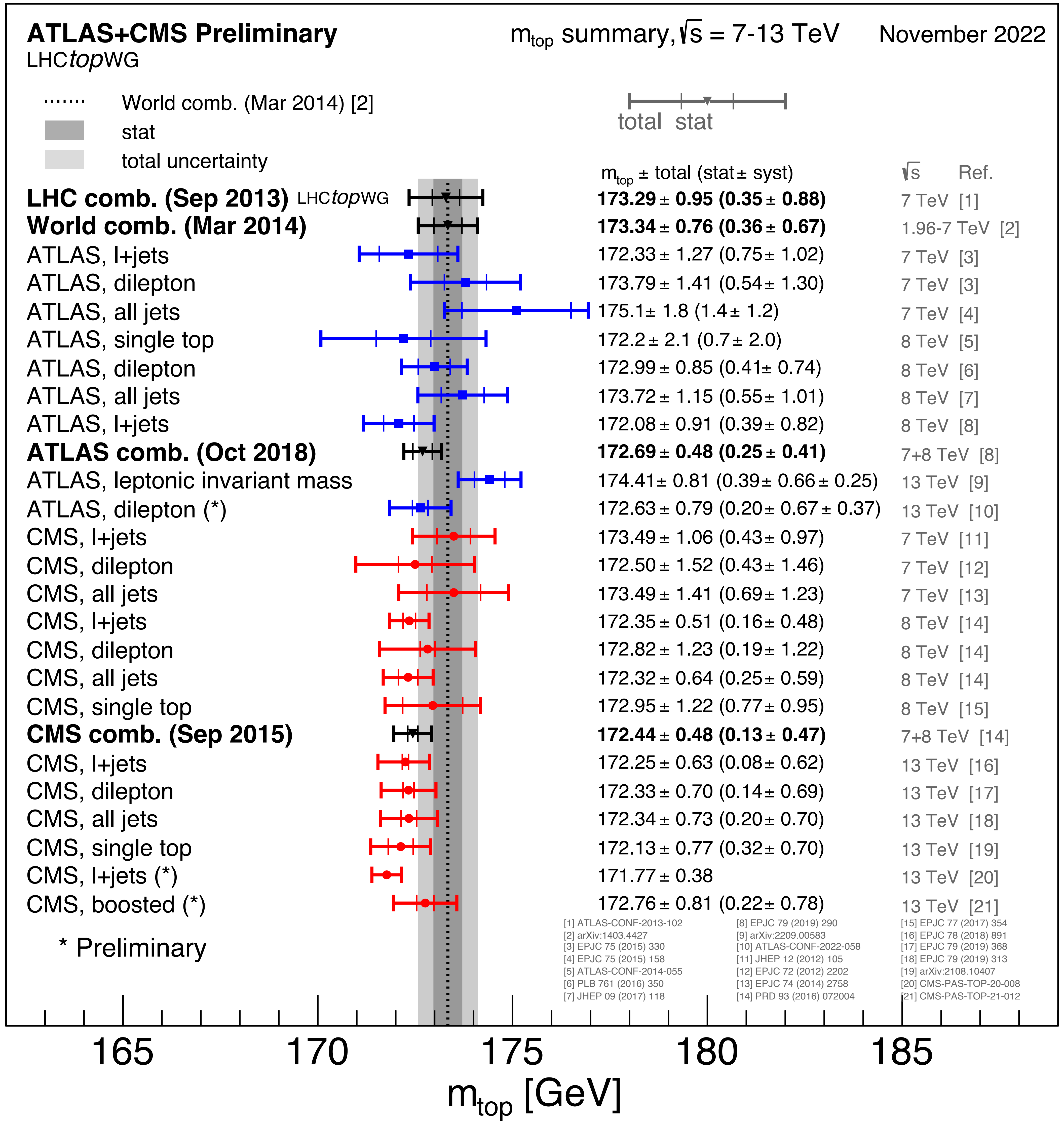




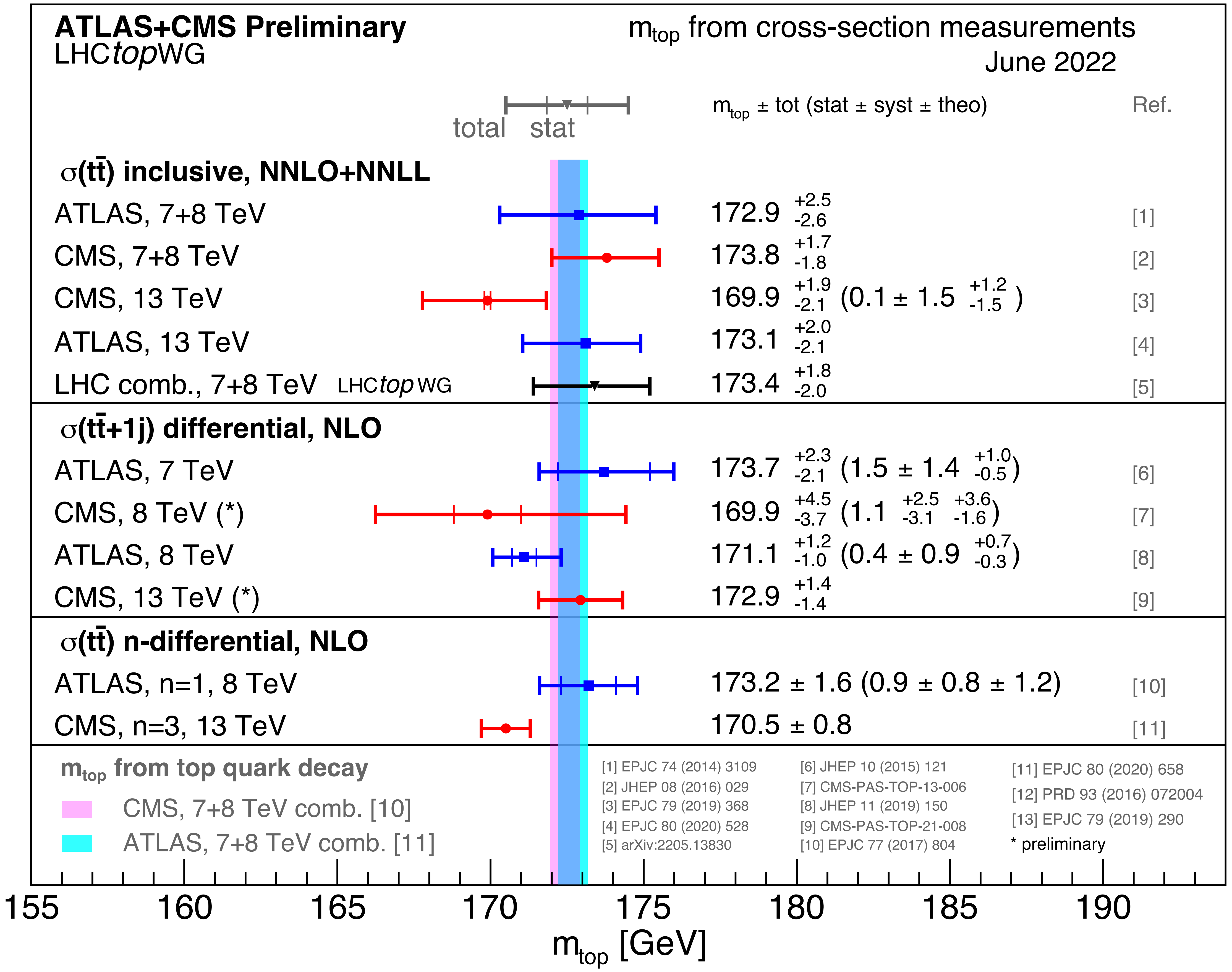


Top mass summary plots

ATL-PHYS-PUB-2022-050



Summary of the ATLAS and CMS measurements from top quark decay ("direct")



Summary of the ATLAS and CMS measurements of the top quark mass from $t\bar{t}$ production observables

Summary

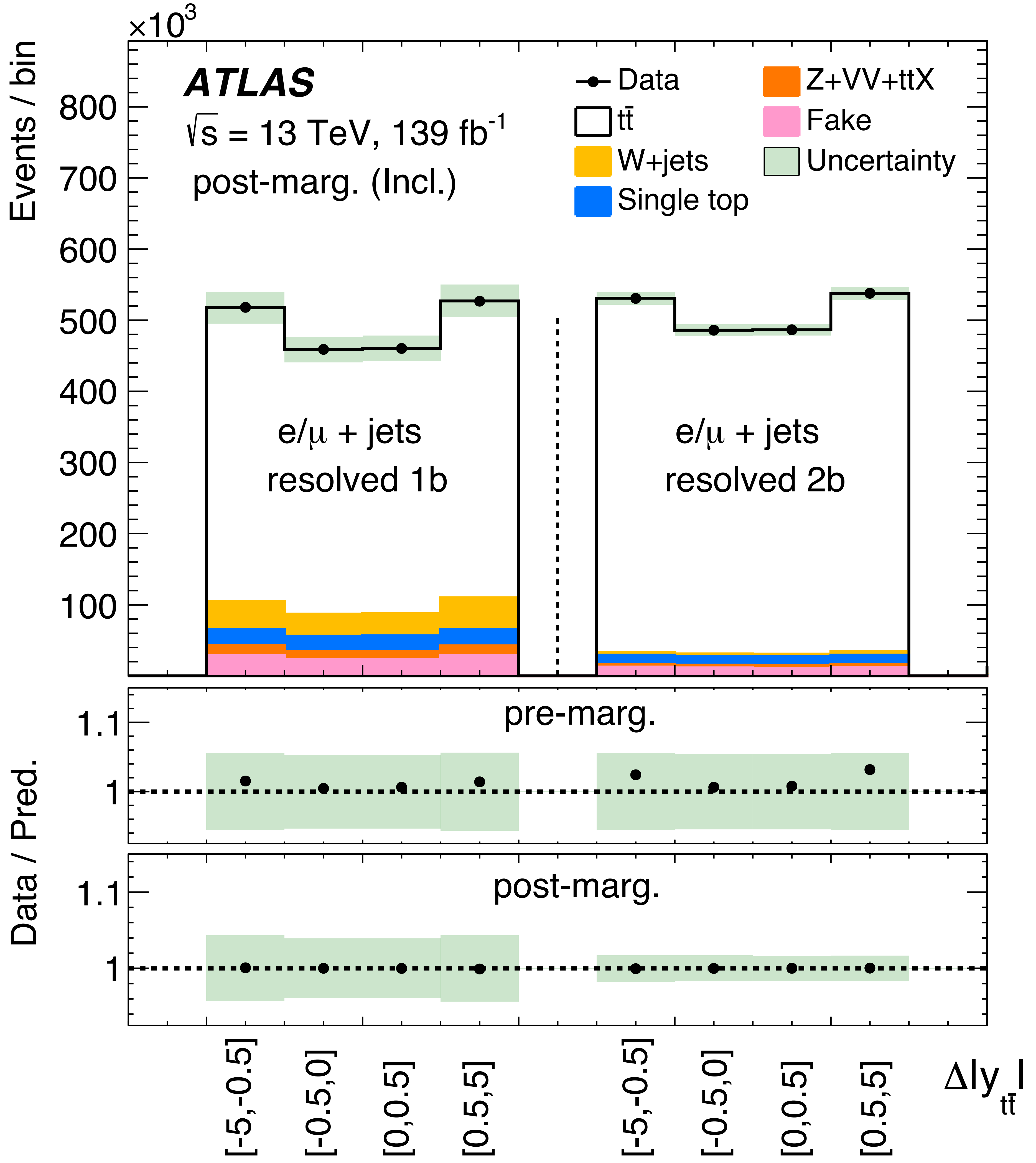
- LHC is providing largest top quark dataset
  - 100's millions in Run 2 & many more in Run 3!
- Measurement of top quark properties is extremely active area of study
  - Precision measurements test SM and search for new physics effects → so far good agreement with SM
  - Increasingly precise measurements using advanced analysis and statistical methods
- Many new results in pipeline!

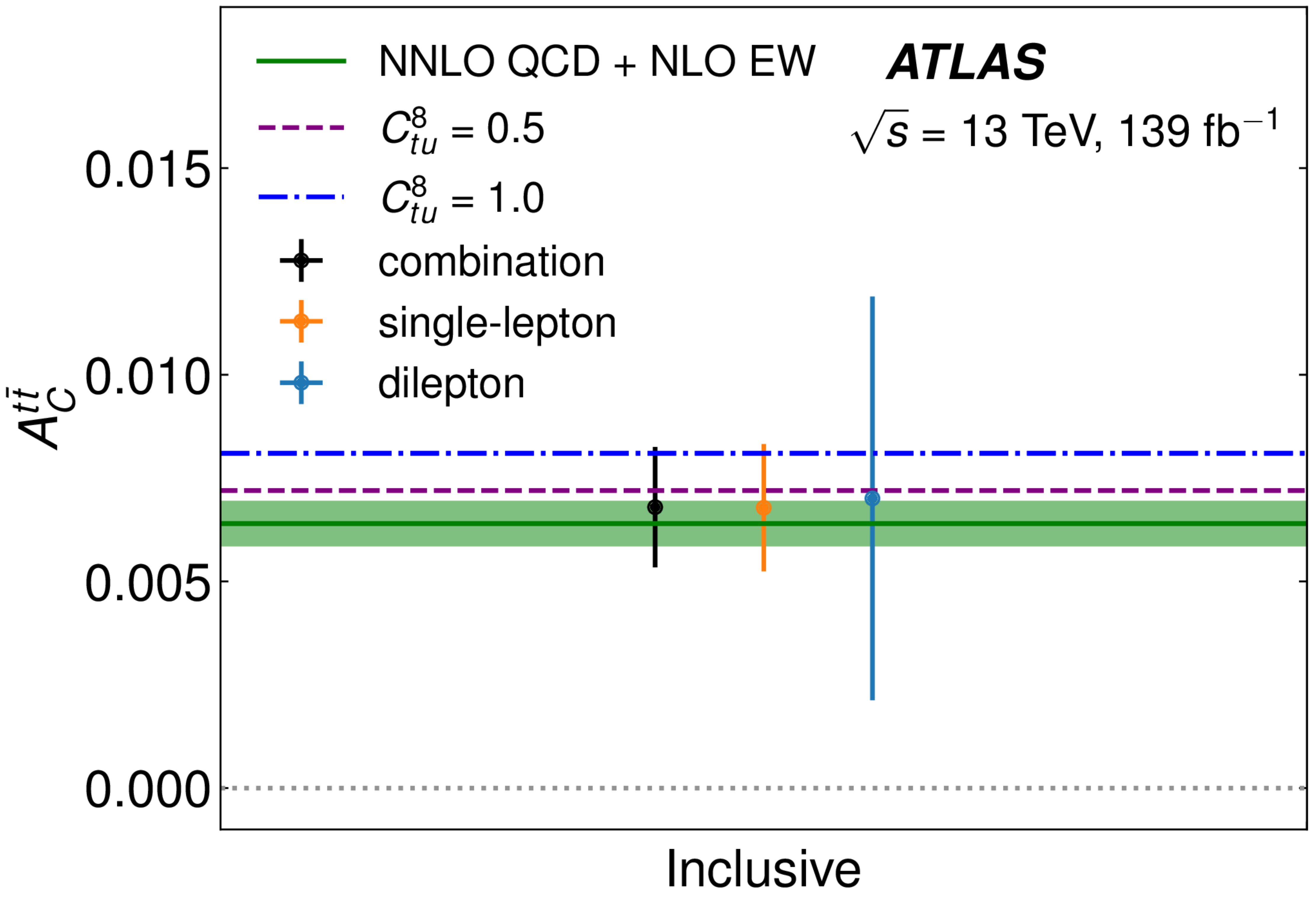
For more see talks by Mohammed Faraj, James Howarth, Ashley Parker, Adrian Salas, Nicolas Chanon & Melissa Quinnan

Additional Material

Charge asymmetry in $t\bar{t}$ production

13 TeV – 139fb^{-1}
arXiv:2208.12095





m_t in ℓ+jets channel with profile likelihood

13 TeV – 36fb-1
arXiv:2302.01967