Asymmetries in tt + X

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X

ATLAS
EXPERIMENT

UNIVERSITY OF CAPE TOWN
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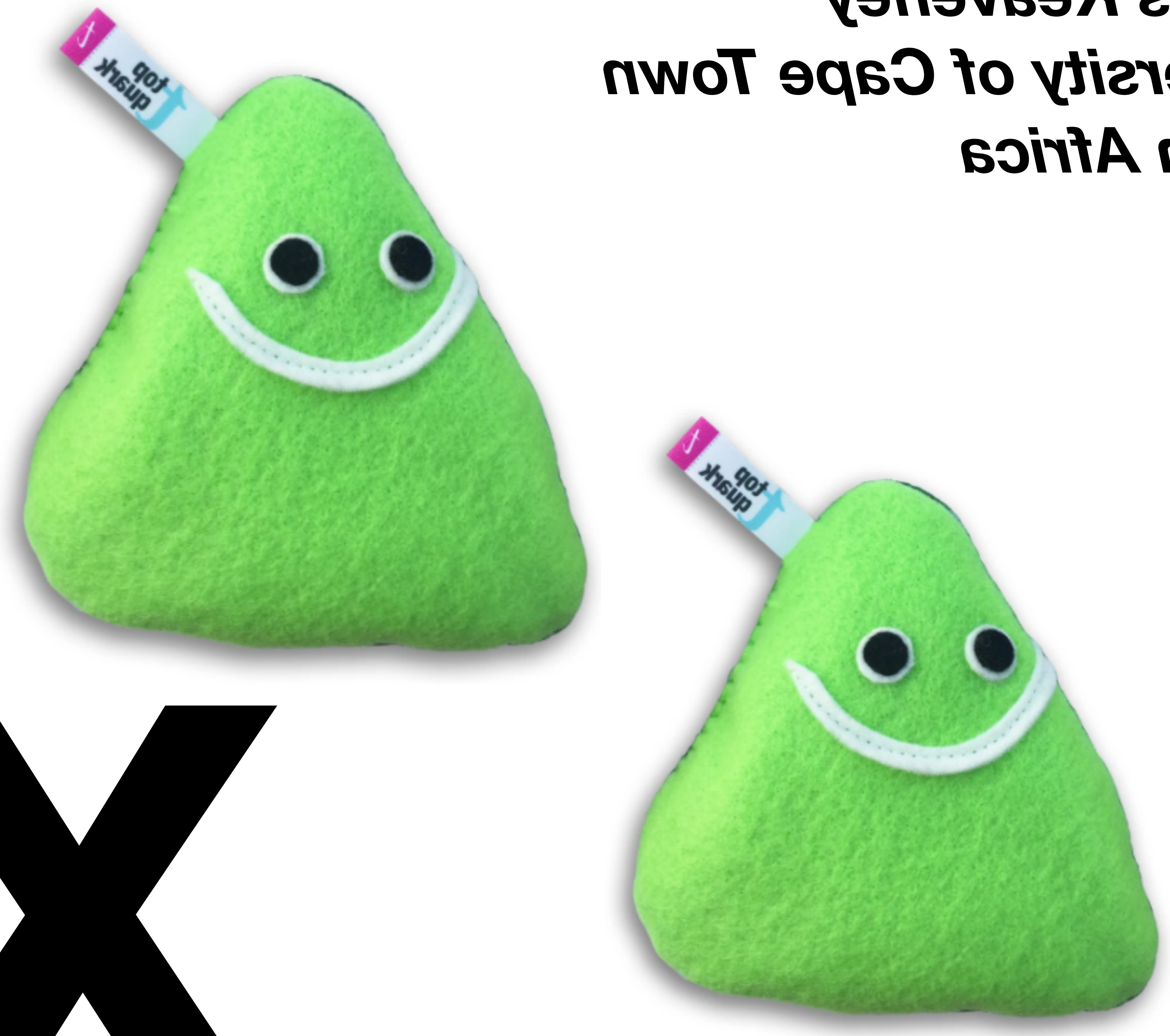

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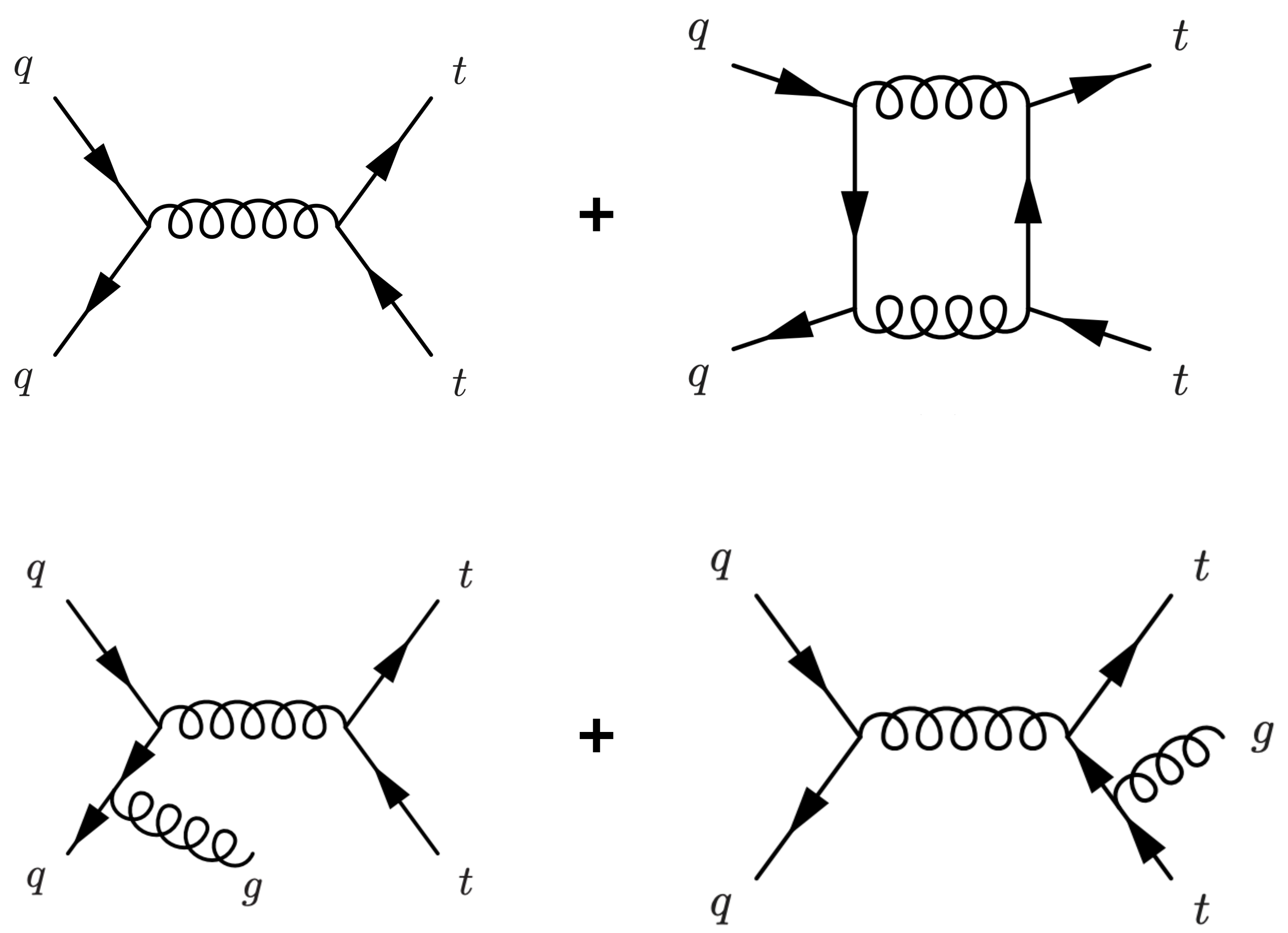
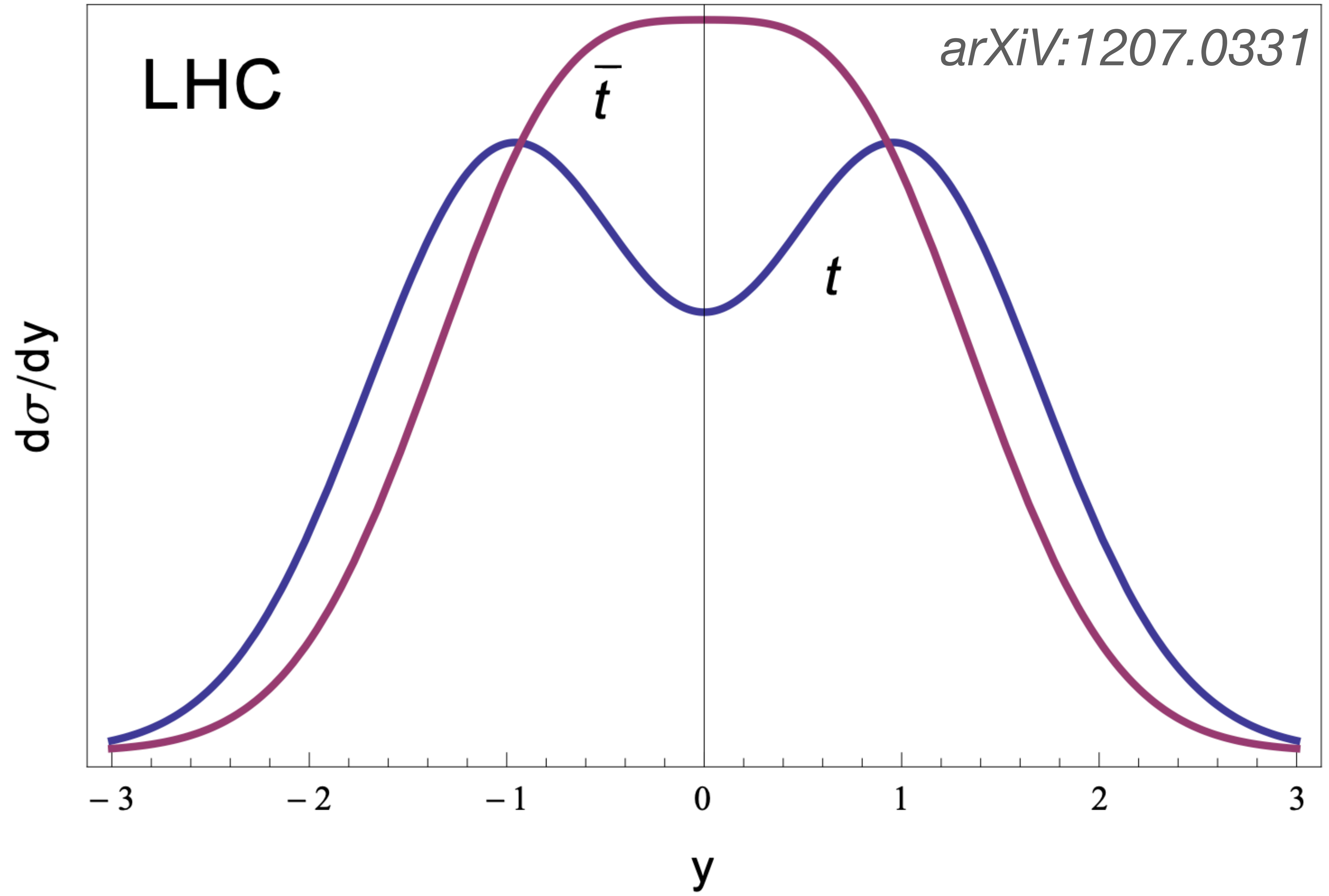
Asymmetries in tt + X - Standard Model

- ~ 15 % of $t\bar{t}$ rate at the 13 TeV LHC arises from the $q\bar{q}$ initial state
- $t\bar{t} + X$ *charge* asymmetry arises in $q\bar{q}$ initial state @ O(α_S^3) from interference between
  - Born & 1-loop
  - ISR & FSR in $t\bar{t}$ + 1 jet

arXiV:1406.1798





Asymmetries exhibit kinematic dependence

Asymmetries and kinematic dependence enhanced in BSM

Asymmetries in tt + X - Definitions

- *charge* asymmetry experimentally accessed via observables A_X
- variations of A_X exhibit various advantages/complementarities

top rapidity asymmetry

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

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

leptonic asymmetry

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

$$\Delta|\eta_{\ell\ell}| = |\eta_{\ell^-}| - |\eta_{\ell^+}|$$

energy asymmetry $t\bar{t} + j$ *arXiv: 1305.3272*

$$A_E(\theta_j) = \frac{\sigma^{opt}(\theta_j|\Delta E > 0) - \sigma^{opt}(\theta_j|\Delta E < 0))}{\sigma^{opt}(\theta_j|\Delta E > 0) + \sigma^{opt}(\theta_j|\Delta E < 0))}$$

$$\sigma^{opt}(\theta_j) = \sigma(\theta_j|y_{t\bar{t}j} > 0) + \sigma(\pi - \theta_j|y_{t\bar{t}j} < 0)$$

θ_j = jet scattering angle w.r.t. incoming parton

Measurement of the energy asymmetry in $t\bar{t}j$ production at 13 TeV with the ATLAS experiment and interpretation in the SMEFT framework

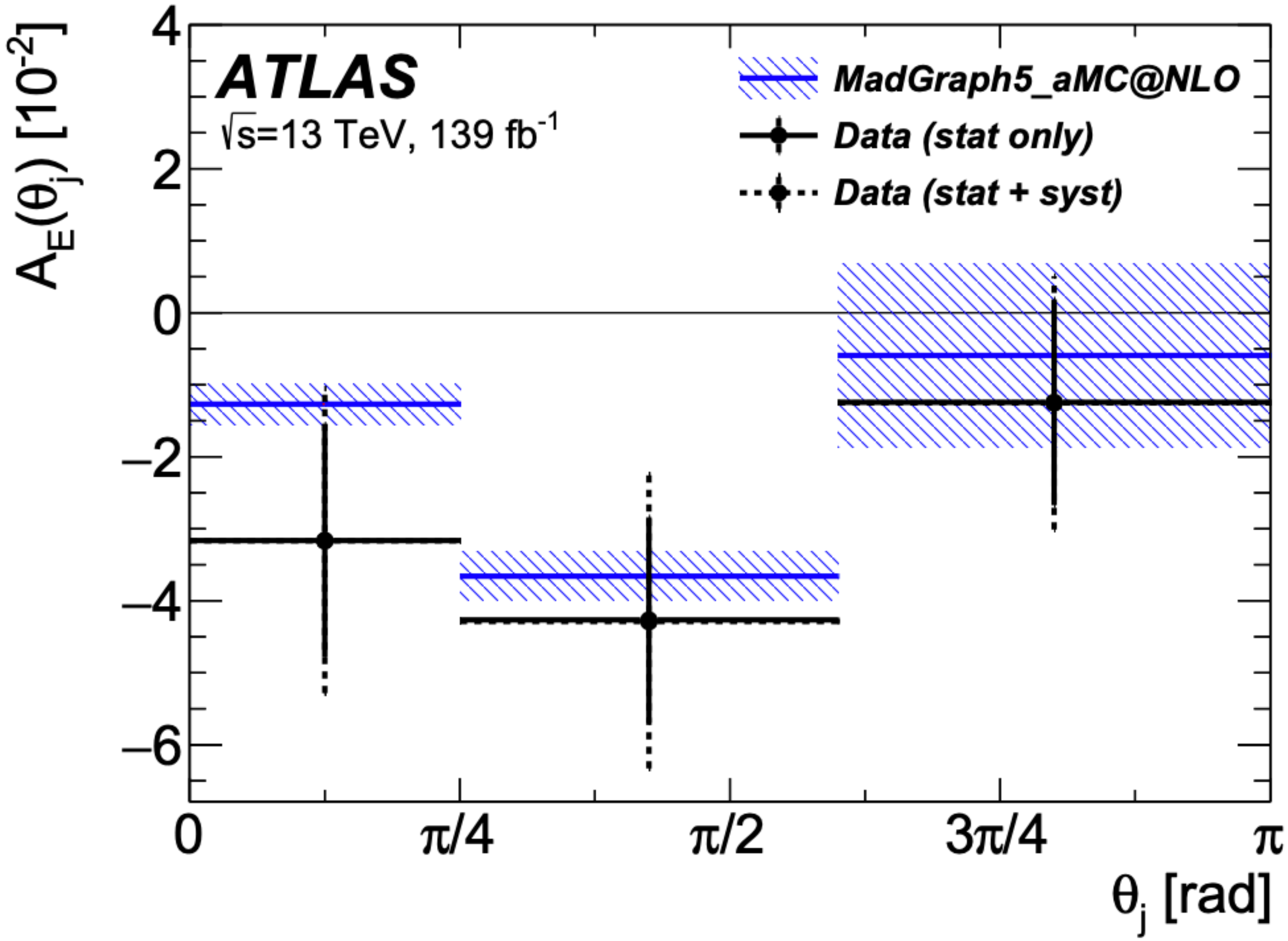
Eur. Phys. J. C 82 (2022) 374

$$A_E(\theta_j) \equiv \frac{\sigma^{\text{opt}}(\theta_j|\Delta E > 0) - \sigma^{\text{opt}}(\theta_j|\Delta E < 0)}{\sigma^{\text{opt}}(\theta_j|\Delta E > 0) + \sigma^{\text{opt}}(\theta_j|\Delta E < 0)}$$

$$\sigma^{\text{opt}}(\theta_j) = \sigma(\theta_j|y_{t\bar{t}j} > 0) + \sigma(\pi - \theta_j|y_{t\bar{t}j} < 0)$$

Motivation

- charge asymmetry can be measured as an **energy asymmetry** in $t\bar{t}j$ production, mainly generated in $gq \rightarrow t\bar{t}j$ arXiv: 1305.3272
- unique sensitivity to color/chiral structure in 4-fermion SMEFT operators
- ability to constrain new directions in SMEFT parameter space



Analysis strategy

- l+jets boosted regime + hard extra jet
- asymmetry extracted at particle level using max. likelihood unfolding

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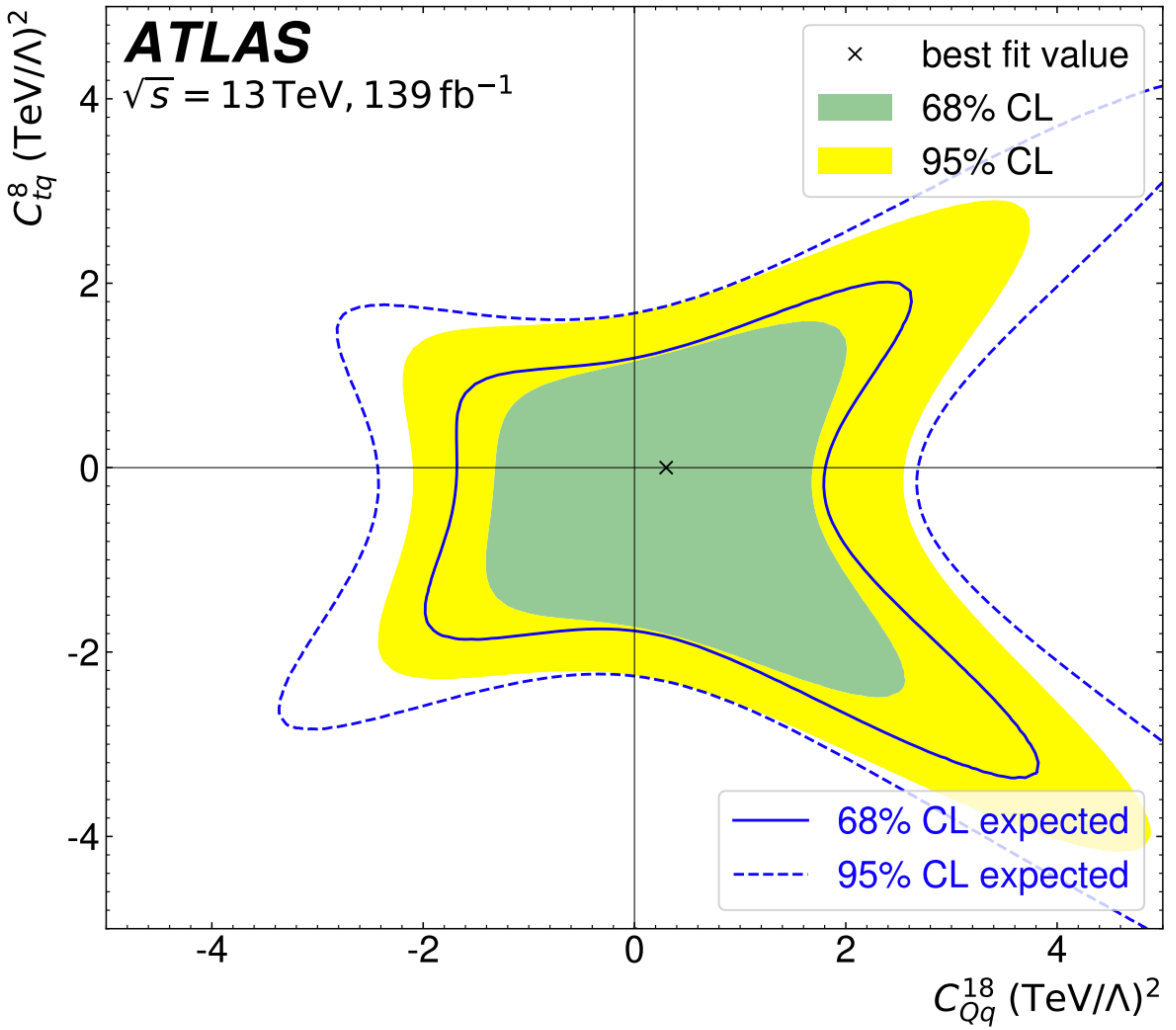

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Evidence for the charge asymmetry in $pp \to t\bar{t}$ production at $\sqrt{s}$ = 13 TeV with the ATLAS detector

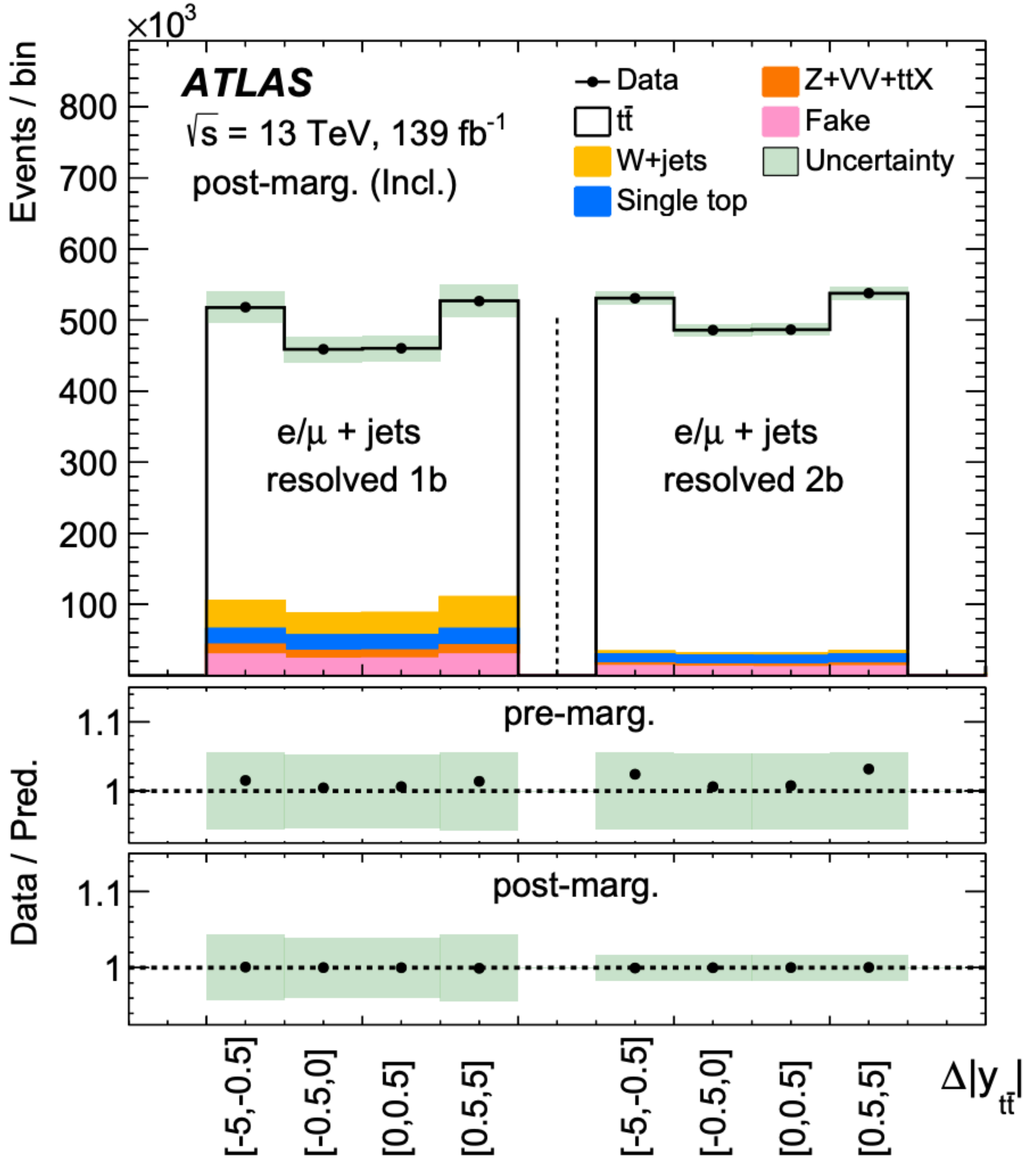
arXiv:2208.12095, submitted to JHEP

Motivation

- BSM scenarios predict $A_C^{t\bar{t}}$ dependence on $t\bar{t}$ kinematics, e.g. resonant axigluon
- $A_C^{t\bar{t}}$ sensitive to SMEFT operators encoding color/chirality structures, e.g, $O_{tu}^{8} = (\bar{t}\gamma_\mu T^A t)(\bar{u}_i \gamma^\mu T^A u_i)$
- SM $A_C^{t\bar{t}}$ expectation depends on kinematics, e.g, longitudinal boost ($\beta_{t\bar{t}}^{Z}$) of $t\bar{t}$ system

Strategy

- Inclusive & differential measurements of $A_C^{t\bar{t}}$ $A_C^{\ell\bar{\ell}}$
- l+jets & dilepton, resolved & boosted topologies
  - access to high p_T phase space
- Asymmetries extracted @ particle level vs. $p_{t\bar{t}}^{T}$, $\beta_{t\bar{t}}^{z}$ and $m_{t\bar{t}}$ after unfolding



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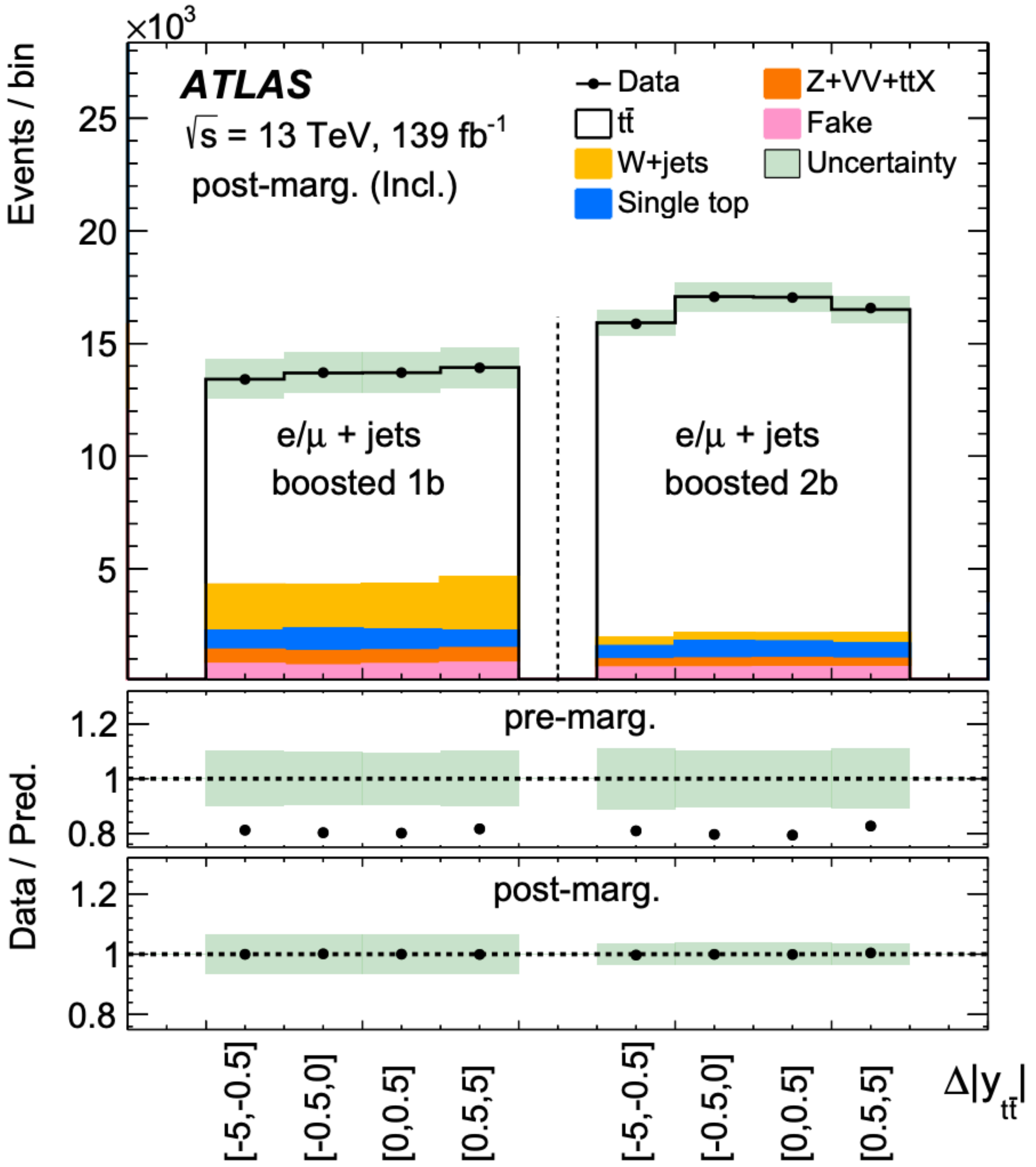

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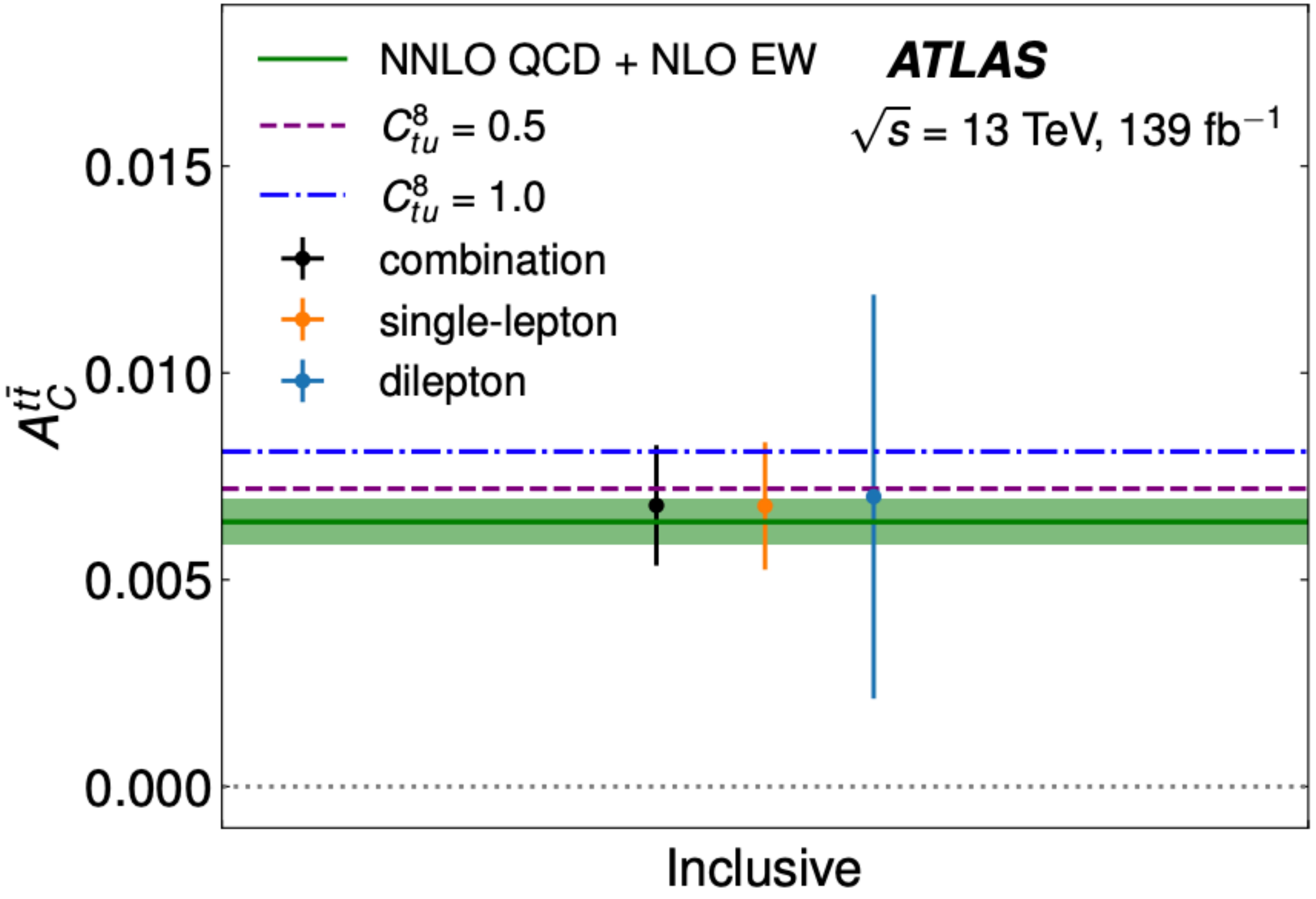
Results – Inclusive $A_C^{t\bar{t}}$

- Evidence for non-zero $A_C^{t\bar{t}}$ at **4.7σ**

- Statistically dominated precision but already probing state-of-the-art SM prediction

NEW! SMEFT Interpretation



	Post-marg. (pre-marg.) impact ×100
$t\bar{t}$ modelling	0.06 (0.08)
$t\bar{t}$ normalisation (flat prior)	0.02
Background modelling	0.04 (0.05)
Monte Carlo statistics	0.05
Small-R JES	0.03 (0.03)
Small-R JER	0.03 (0.03)
Large-R JES, JER	0.01 (0.01)
Leptons, E_T^{miss}	0.02 (0.03)
b-tagging eff.	0.01 (0.01)
Pile-up, JVT, luminosity	0.01 (0.01)
Statistical uncertainty	0.10
Total uncertainty	0.15

Evidence for the charge asymmetry in $pp \rightarrow t\bar{t}$ production at $\sqrt{s}$ = 13 TeV with the ATLAS detector

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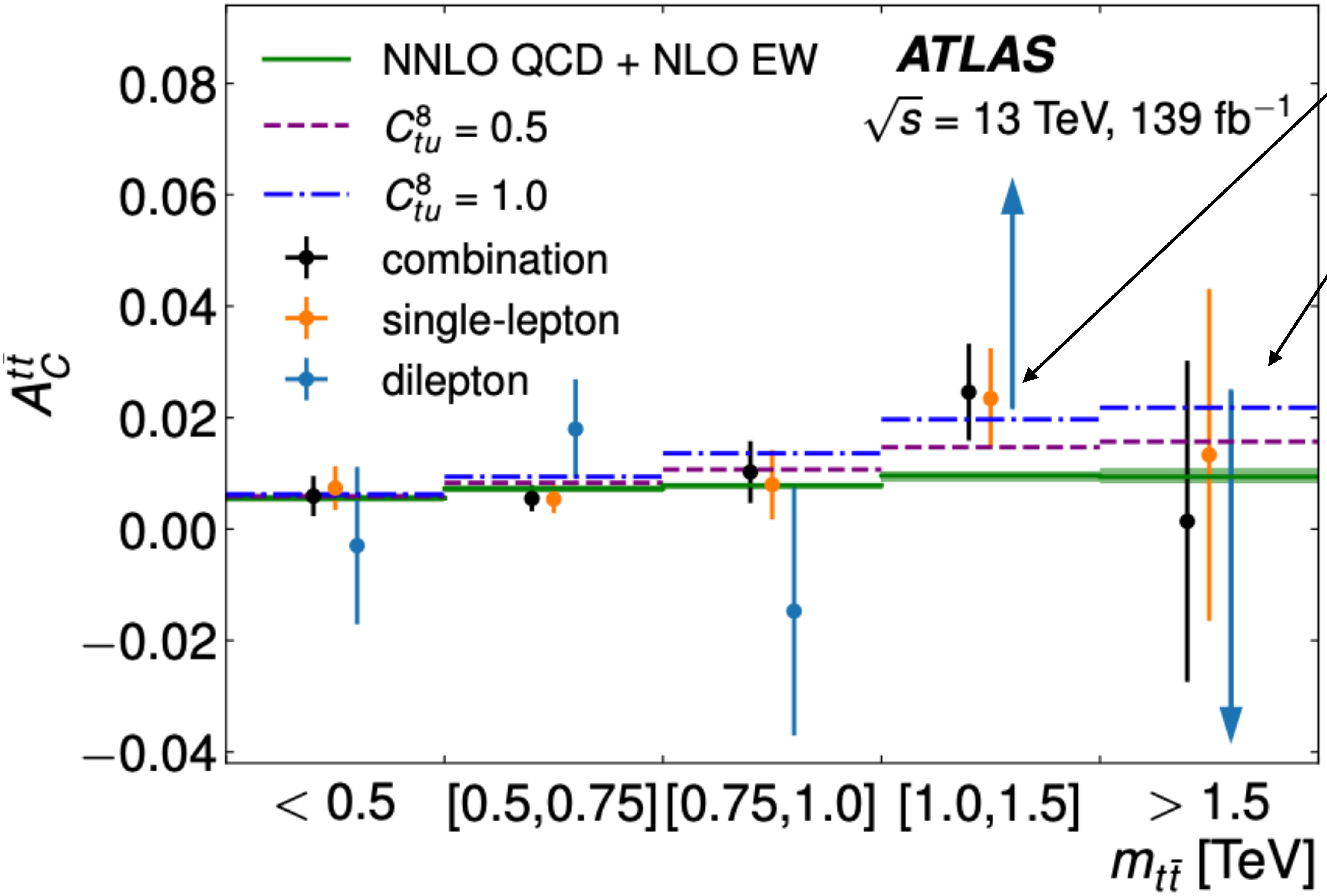
Results – Differential $A_C^{t\bar{t}}$ vs. $m_{t\bar{t}}$

- Close agreement with SM
- Even more statistically dominated
- Precision of most SMEFT-sensitive bins will rapidly improve with more data

NEW! SMEFT Interpretation



	Post-marg. (pre-marg.) impact ×100				
$m_{t\bar{t}}$ bin [GeV]	< 500	500–750	750–1000	1000–1500	> 1500
$t\bar{t}$ modelling	0.15 (0.22)	0.07 (0.10)	0.14 (0.27)	0.31 (0.45)	0.64 (0.80)
$t\bar{t}$ normalisation (flat prior)	0.06	0.02	0.08	0.06	0.18
Background modelling	0.09 (0.11)	0.06 (0.08)	0.13 (0.15)	0.22 (0.28)	0.84 (1.02)
Monte Carlo statistics	0.13	0.08	0.20	0.30	1.02
Small-R JES	0.09 (0.10)	0.05 (0.06)	0.13 (0.15)	0.15 (0.17)	0.43 (0.52)
Small-R JER	0.11 (0.16)	0.03 (0.05)	0.09 (0.15)	0.21 (0.29)	0.42 (0.65)
Large-R JES, JER	0.02 (0.02)	0.02 (0.02)	0.02 (0.03)	0.05 (0.05)	0.19 (0.28)
Leptons, E_T^{miss}	0.04 (0.06)	0.03 (0.04)	0.08 (0.10)	0.06 (0.08)	0.26 (0.39)
b-tagging eff.	0.02 (0.02)	0.01 (0.01)	0.03 (0.03)	0.03 (0.04)	0.27 (0.30)
Pile-up, JVT, luminosity	0.01 (0.01)	0.01 (0.01)	0.01 (0.01)	0.04 (0.04)	0.02 (0.02)
Statistical uncertainty	0.27	0.19	0.46	0.74	2.80
Total uncertainty	0.36	0.23	0.56	0.87	2.88

Evidence for the charge asymmetry in $pp \to t\bar{t}$ production at $\sqrt{s}$ = 13 TeV with the ATLAS detector

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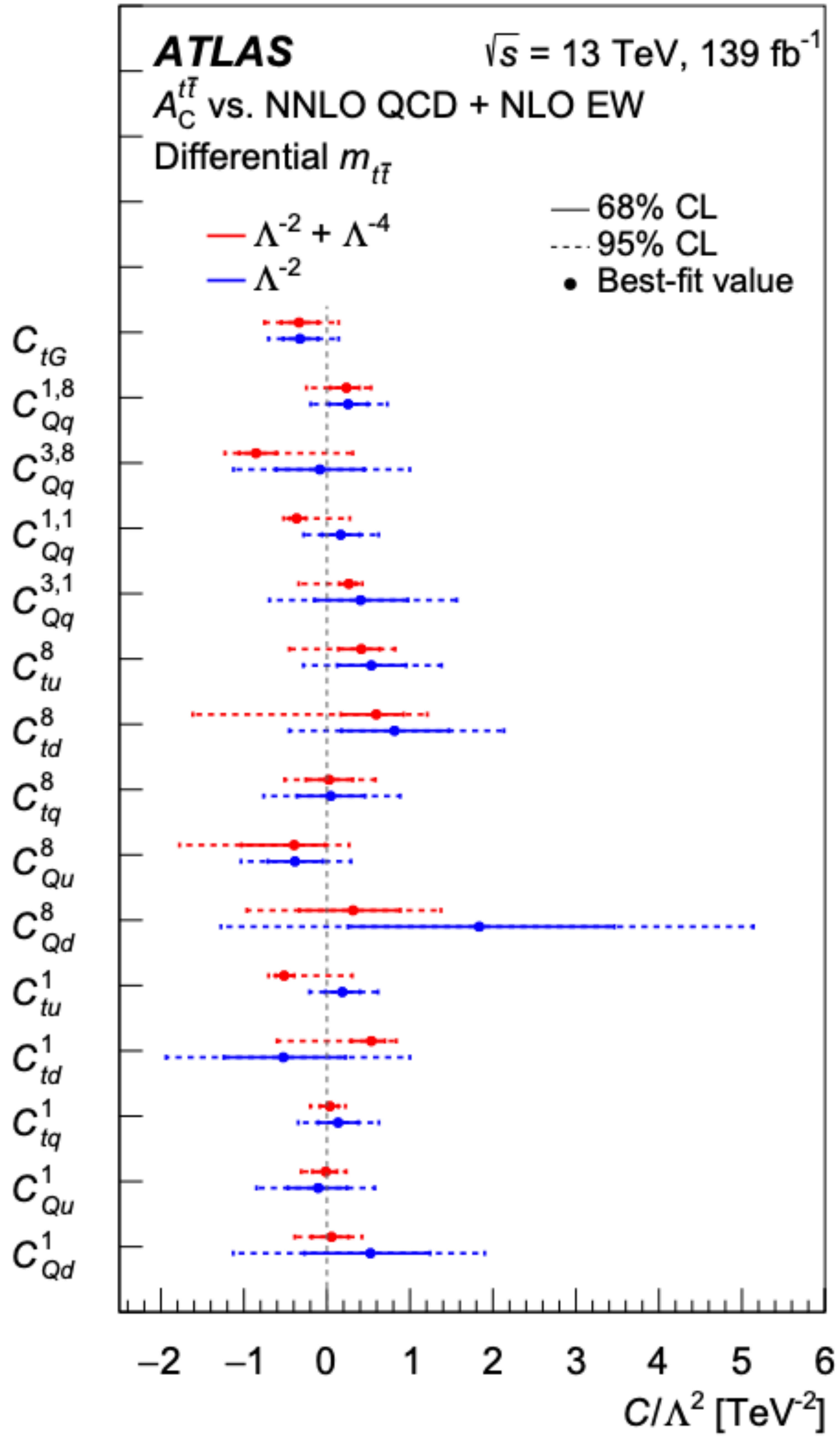
NEW! SMEFT Interpretation

- Inclusive and diff. (vs. $m_{t\bar{t}}$) $A_C^{t\bar{t}}$ results used to constrain SMEFT individually and in pairs
- Asymmetries parameterised as fcns of SMEFT parameters at **NLO (MG5_aMC@NLO + SMEFT @NLO)**
- **Results generally consistent with SM expectation**



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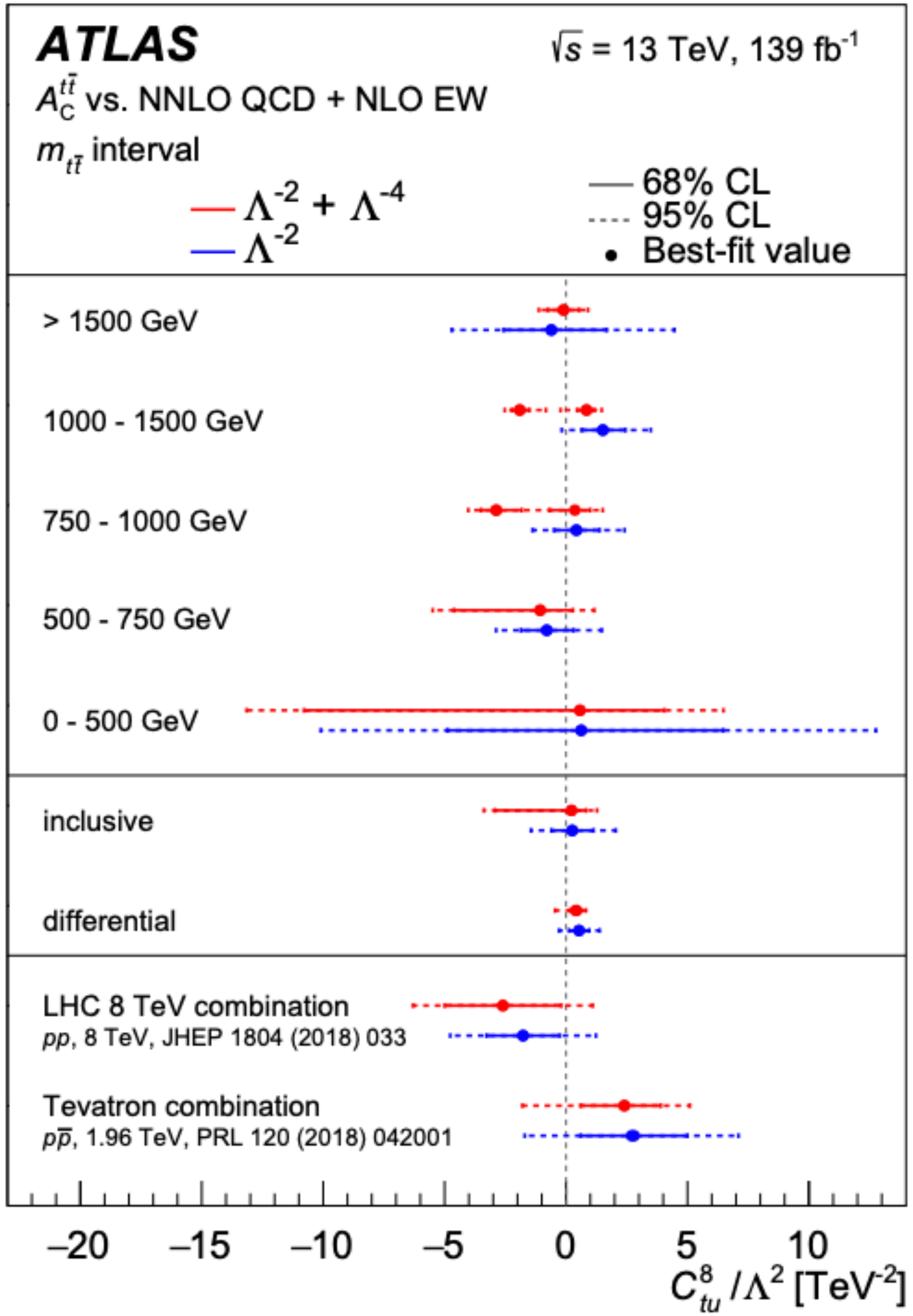

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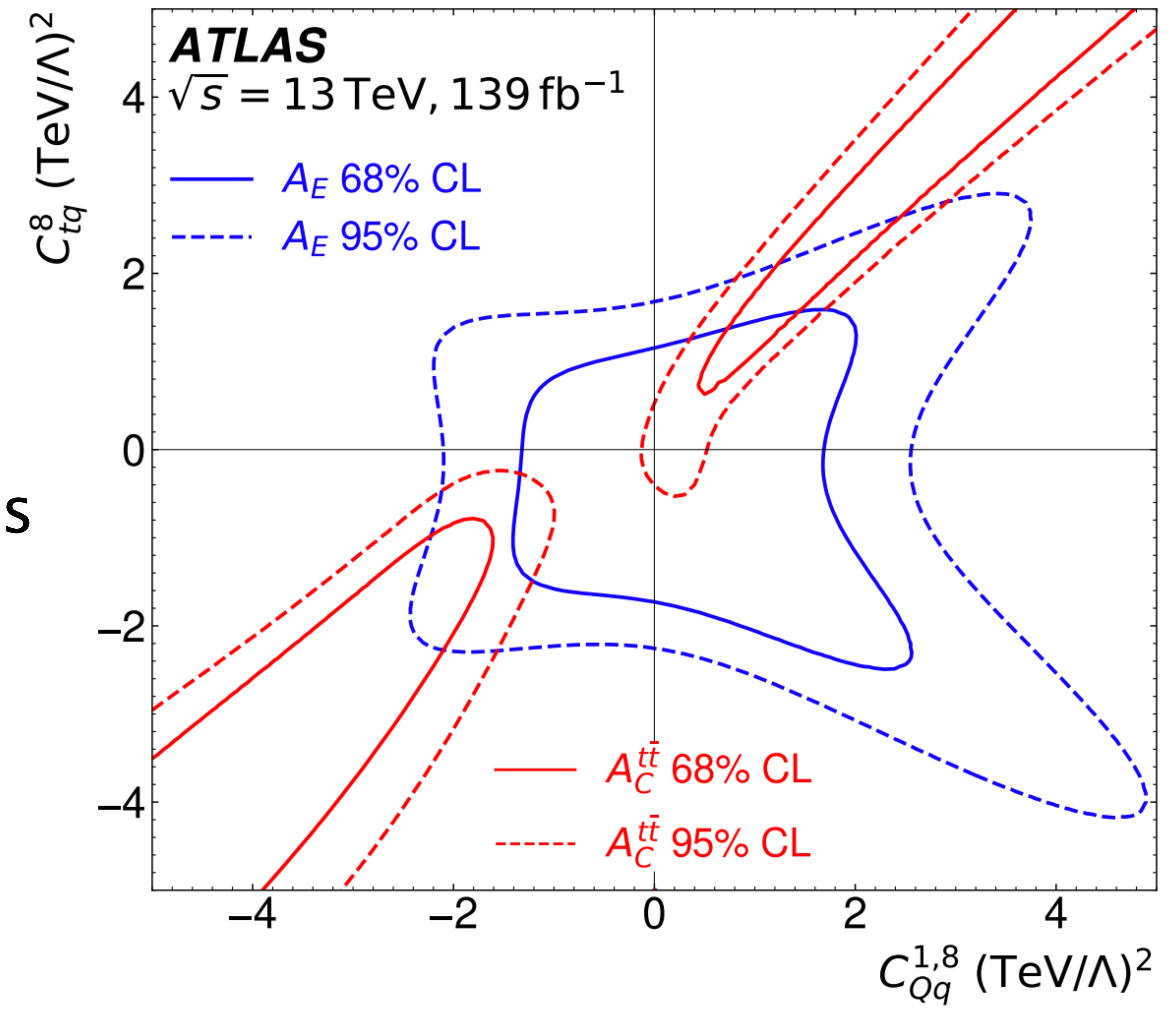


Complementarity of Energy and Rapidity asymmetries **made explicit in 2-D constraints**

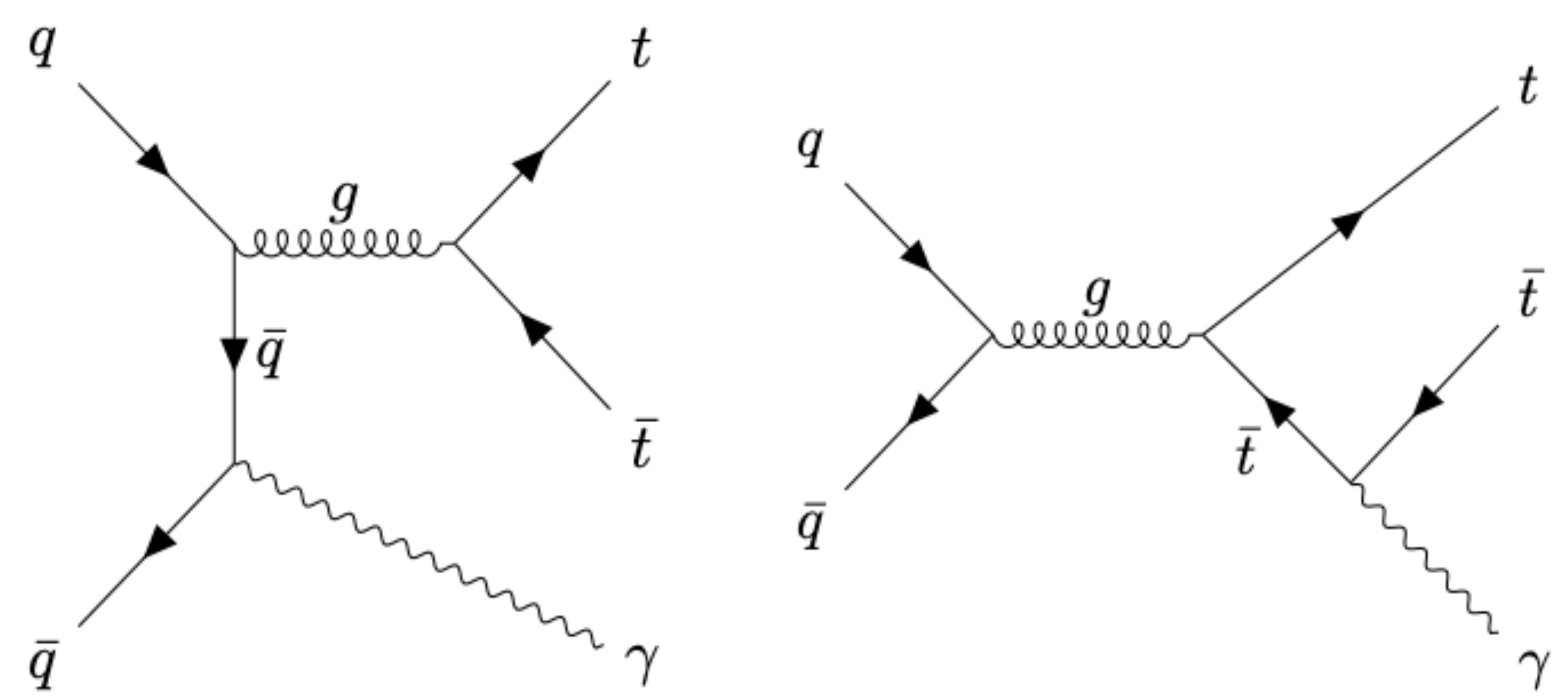
Measurement of the charge asymmetry in top quark pair production in association with a photon

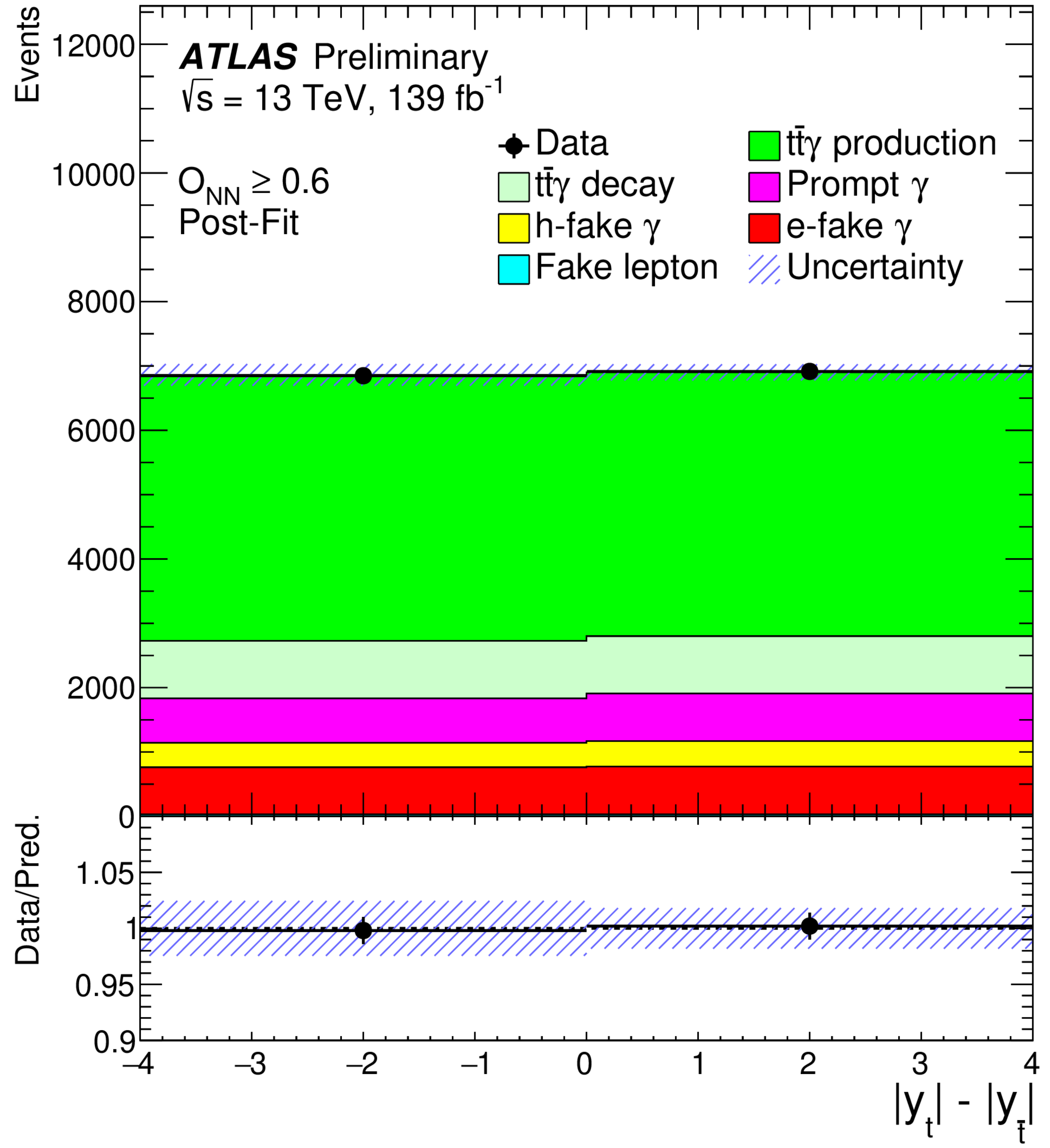
ATLAS-CONF-2022-049

NEW!

Motivation

- ttγ has enhanced contribution from $q\bar{q}$ initial state
  - **larger** asymmetry effects
  - dominant effect from ISR/FSR γ interference diagrams
    - -> **negative** asymmetry





Analysis strategy

- l+jets channel, neural net discriminator to maximise S/B
- Kinematic reconstruction to estimate $y_t, y_{\bar{t}}$
- $A_C^{t\bar{t}}$ extracted at particle level after unfolding procedure

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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

Result $A_C = -0.006 \pm 0.030 = -0.006 \pm 0.024(\mathrm{stat}) \pm 0.018(\mathrm{syst})$

SM prediction (MG5-AMC@NLO) $A_C = -0.014 \pm 0.001(\mathrm{scale})$

Search for leptonic charge asymmetry in $t\bar{t}W$ production in final states with three leptons at $\sqrt{s} = 13$ TeV
ATLAS-CONF-2022-062

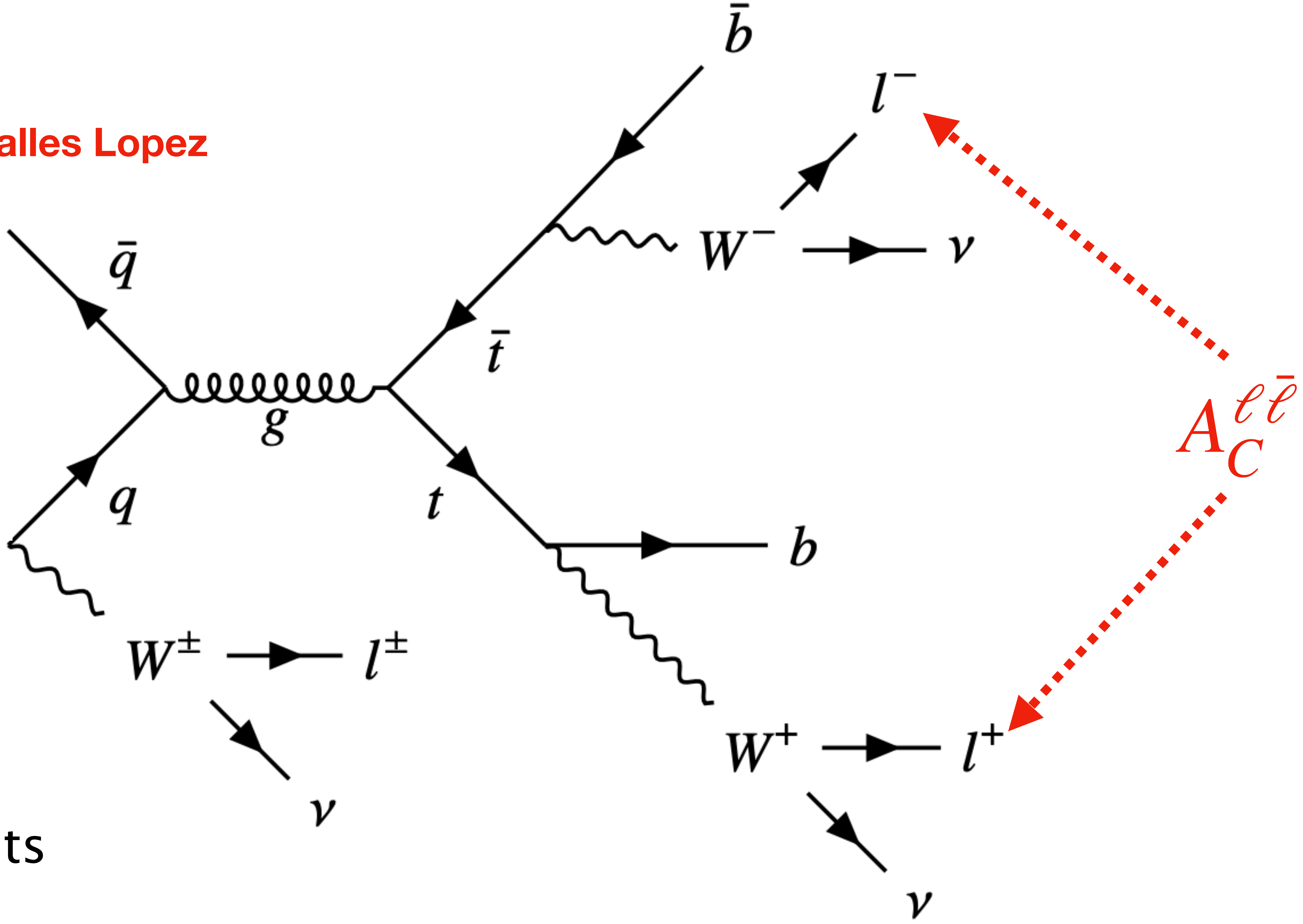
NEW! See slides in Tuesday's YSF from M.Miralles Lopez

Motivation

- $t\bar{t}W$ dominated by $q\bar{q}$ initial state
  - -> **large** $A_C^{t\bar{t}}$
- W emission polarises top quarks
  - Large **negative** asymmetry in decay product e.g. $A_C^{\ell\bar{\ell}}$

Analysis strategy

- Search for large $A_C^{\ell\bar{\ell}}$
- Trilepton channel, regions based on (b)jets
- BDT top select leptons from top decays
- $A_C^{\ell\bar{\ell}}$ extracted at reco and particle levels via max. likelihood fit and unfolding



Process	$t\bar{t}$	$t\bar{t}W$
A_c^t [%]	$0.45^{+0.09}_{-0.06}$	$2.24^{+0.43}_{-0.32}$
A_c^ℓ [%]	–	$-13.16^{-0.81}_{+1.12}$

Phys. Lett. B 736 (2014) 252 Eur. Phys. J. C. 81 (2021) 675

Search for leptonic charge asymmetry in $t\bar{t}W$ production in final states with three leptons at $\sqrt{s} = 13$ TeV ATLAS-CONF-2022-062

NEW! See slides in Tuesday's YSF from M.Miralles Lopez

Detector Level

Result

$$A_c^{\ell}(t\bar{t}W) = -0.123 \pm 0.136\,(\text{stat.}) \pm 0.051\,(\text{syst.})$$

SM prediction (Sherpa)

$$A_c^{\ell}(t\bar{t}W)_{\text{MC}} = -0.084\,^{+0.005}_{-0.003}\,(\text{scale}) \pm 0.006\,(\text{MC stat.})$$

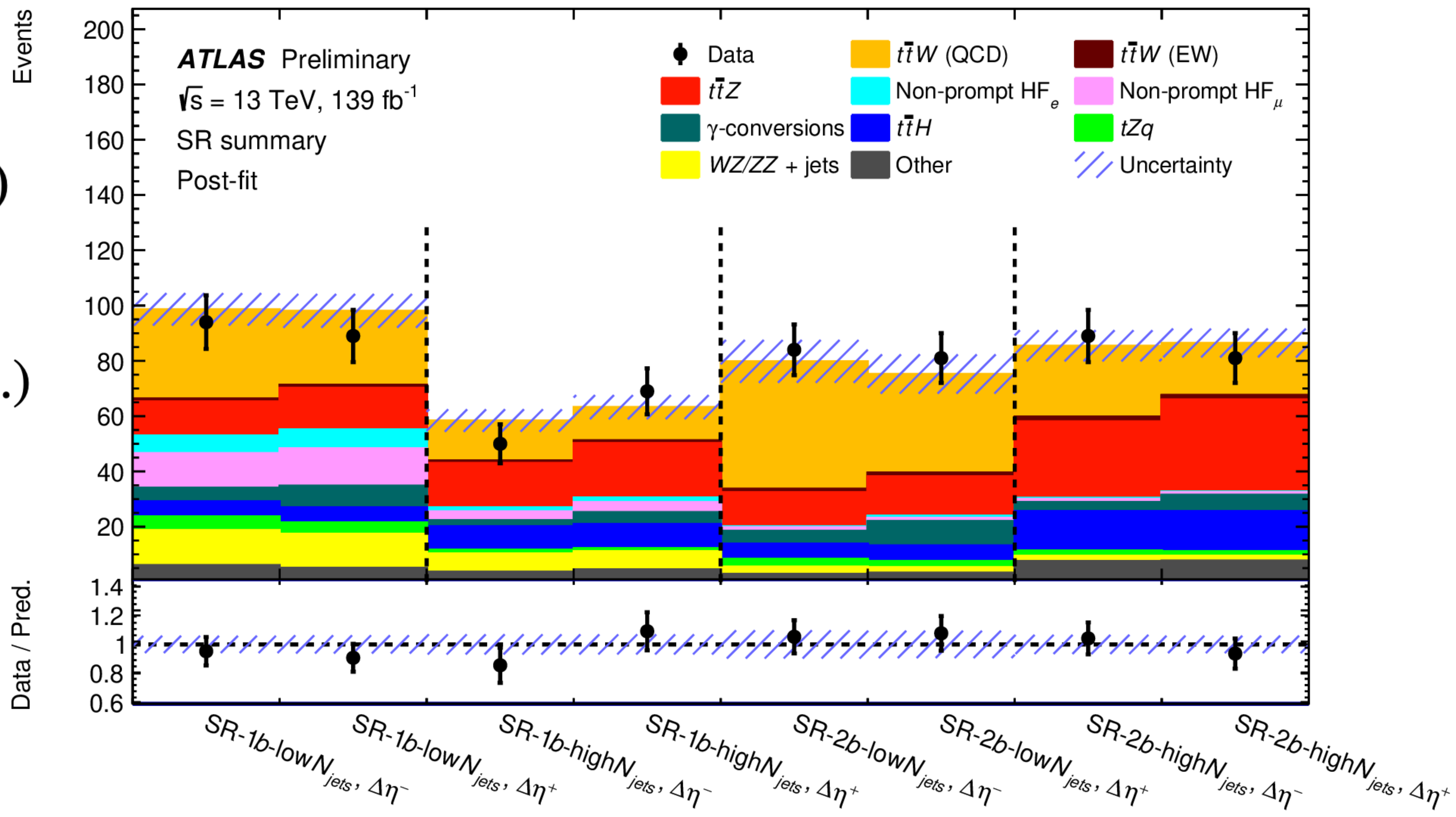
Particle Level

Result

$$A_c^{\ell}(t\bar{t}W)_{\text{PL}} = -0.112 \pm 0.170\,(\text{stat.}) \pm 0.055\,(\text{syst.})$$

SM prediction (Sherpa)

$$A_c^{\ell}(t\bar{t}W)_{\text{MC}} = -0.063\,^{+0.007}_{-0.004}\,(\text{scale}) \pm 0.004\,(\text{MC stat.})$$



Results consistent with SM but with large and dominant statistical uncertainties

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	$\Delta A_c^\ell(t\bar{t}W)$
Experimental uncertainties	
Jet energy resolution	0.013
Pile-up	0.007
b-tagging	0.005
Leptons	0.004
E_T^{miss}	0.004
Jet energy scale	0.003
Luminosity	0.001
MC modelling uncertainties	
$t\bar{t}W$ modelling	0.013
$t\bar{t}Z$ modelling	0.010
Non-prompt modelling	0.006
$t\bar{t}H$ modelling	0.005
Extra uncertainties	
$\Delta\eta^\pm$ dependency	0.046
MC statistical uncertainty	0.019
Data statistical uncertainty	0.136
Total uncertainty	0.145

Results consistent with SM but with large and dominant statistical uncertainties

Summary and conclusions

- $t\bar{t}+X$ *charge* asymmetries predicted to be non-zero in SM and grow with energy/angle
- asymmetries enhanced in BSM, e.g. SMEFT operators
- variations of top rapidity charge asymmetry have desirable properties
  - energy asymmetry - unique sensitivity to SMEFT
  - leptonic asymmetry - sensitive to top polarisation

- **ATLAS has measured top $t\bar{t}+X$ *charge* asymmetries in numerous regimes**
  - Top rapidity asymmetry in resolved and boosted $t\bar{t}$ topologies
  - leptonic asymmetry in resolved $t\bar{t}$ topologies
  - $t\bar{t}$ energy asymmetry
  - top rapidity asymmetry in $t\bar{t}+\gamma$ production
  - leptonic asymmetry in $t\bar{t}W$ topologies

- **Results broadly consistent with SM expectations and largely statistically dominated**
- **Novel SMEFT constraints derived**