Highlights of ATLAS Top physics results

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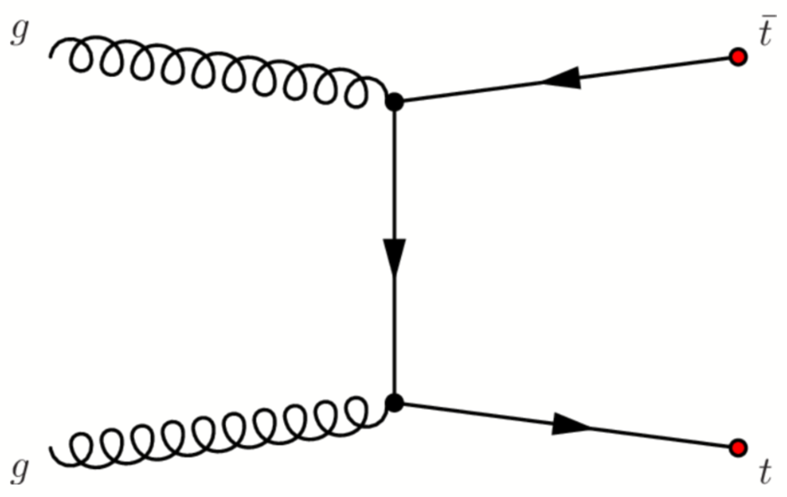
On behalf of the ATLAS collaboration

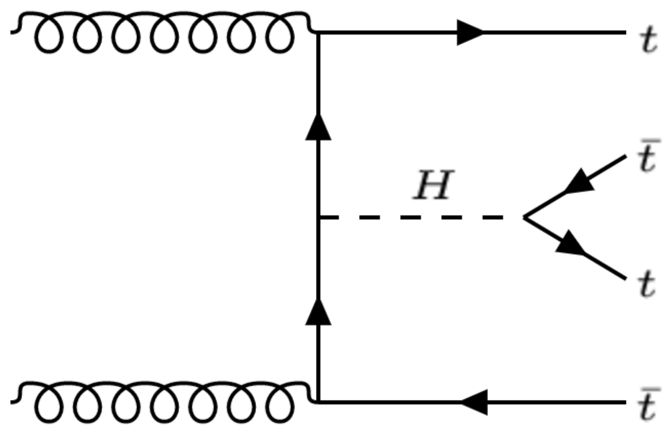
ATLAS EXPERIMENT

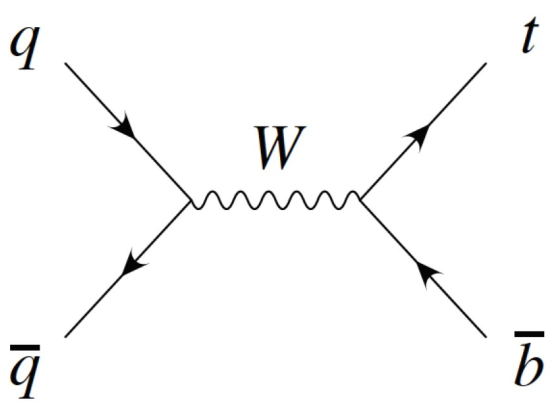
ROYAL HOLLOWAY UNIVERSITY OF LONDON

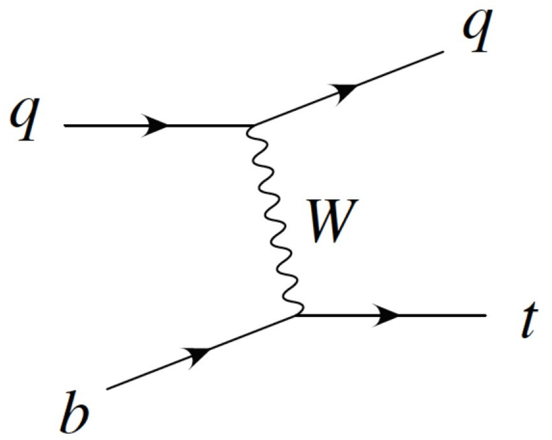
Introduction - the top quark

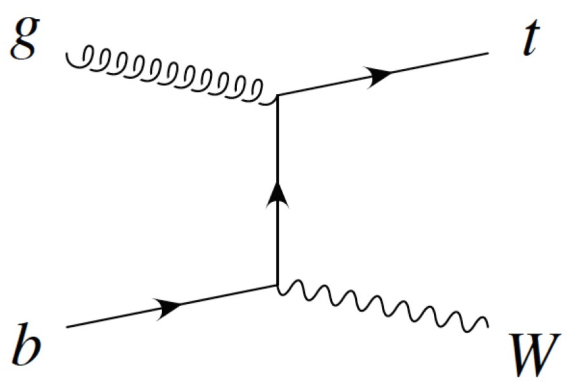
- Top quark
  - Heaviest fundamental particle $m_t \sim 172.5\ \mathrm{GeV}$
  - Produced as couple ($t\bar{t}$), singly or in association with other particles (W, H, γ, etc.)
  - Sensitive to BSM physics
    - Coupling to new particles
  - High production cross section at LHC: ~120M pairs in Run2 ($140\ \mathrm{fb}^{-1}$)
  - Decays ~100% of the times in bW
    - W can decay leptonically ($\ell\nu$) or hadronically ($qq' \to$ jets)

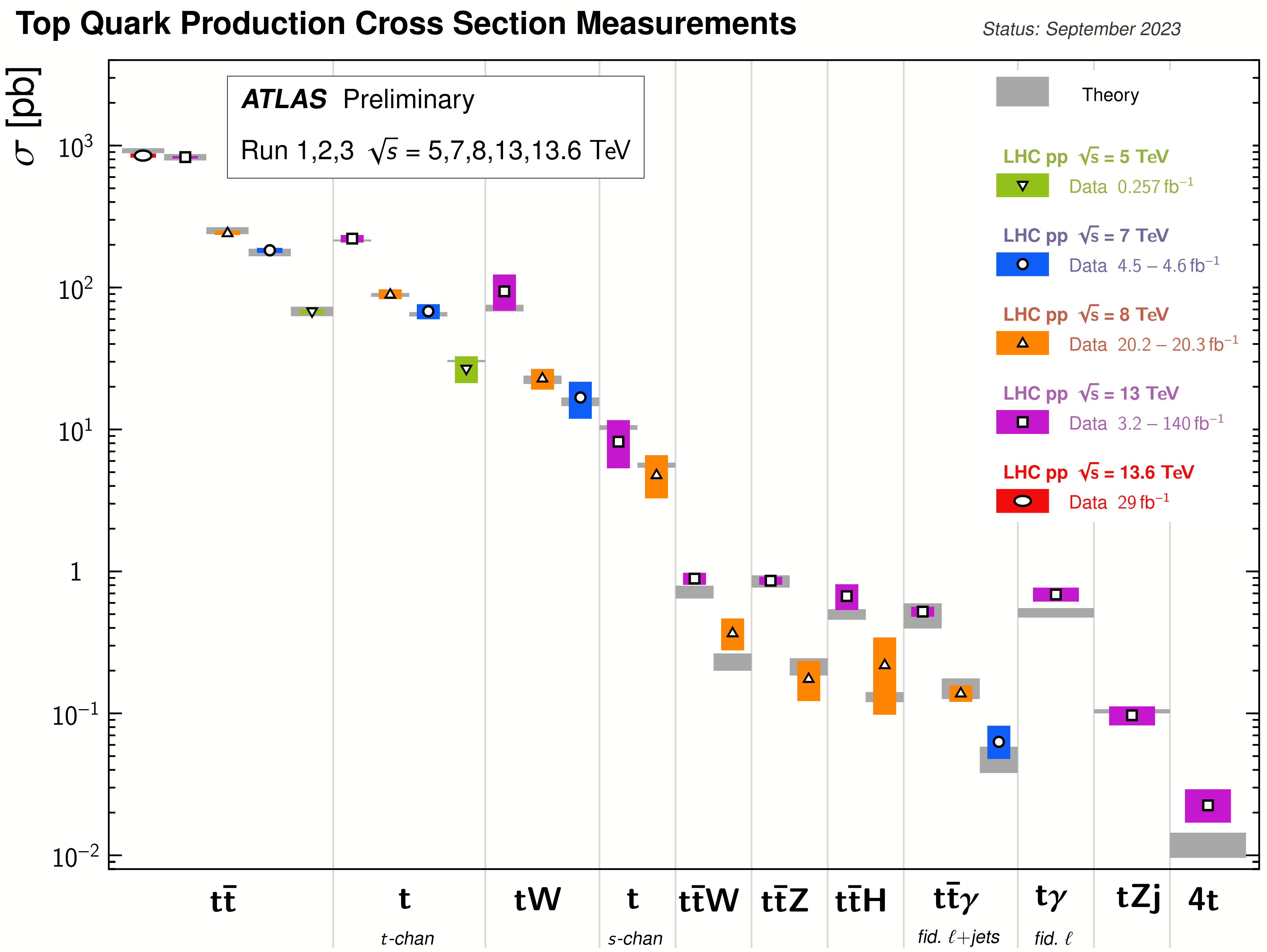








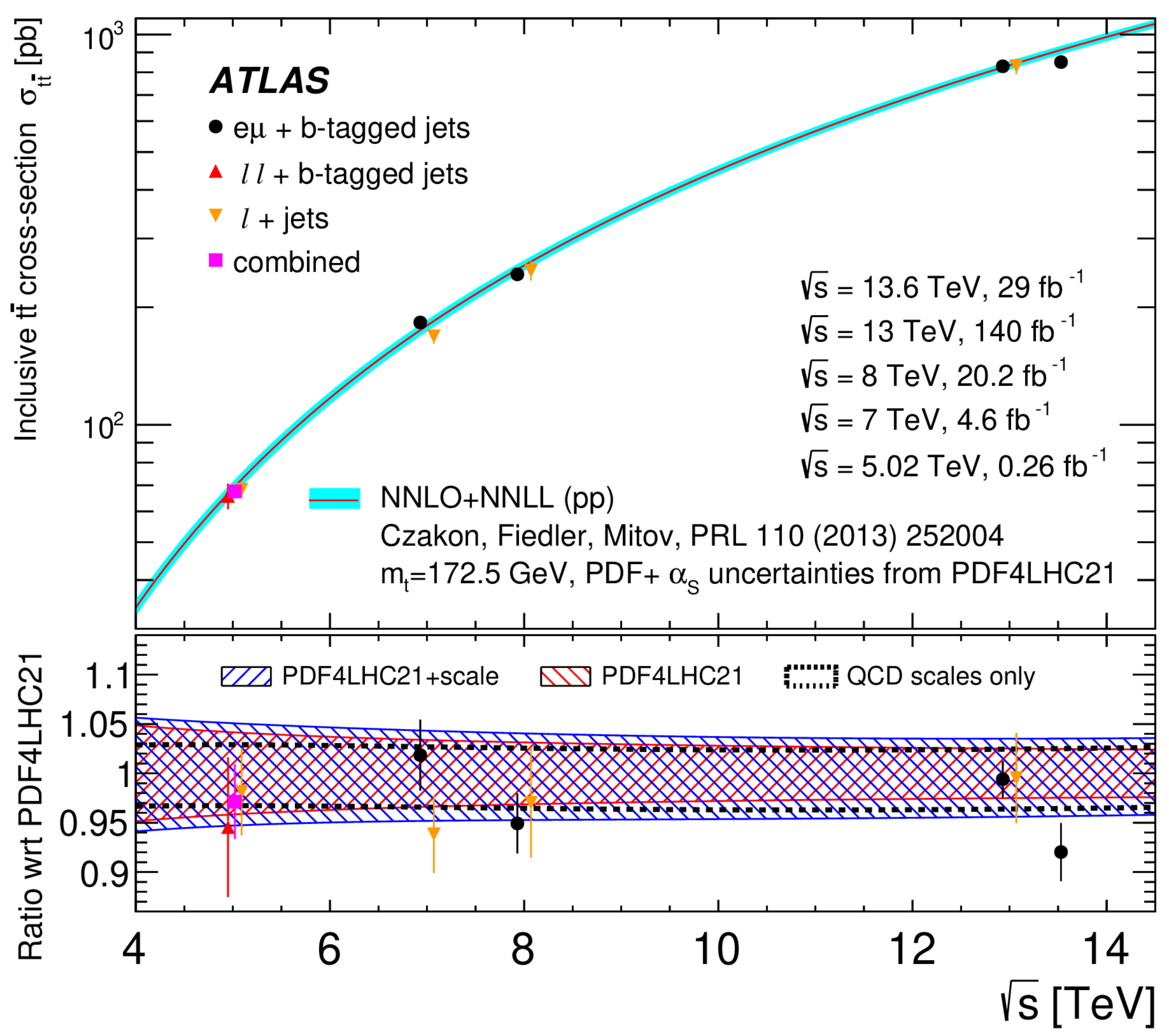




ATLAS Top Cross Section Public Results

Introduction - the top quark

Review of a selection of recent highlights from ATLAS Top Physics program



Taken From arXiv: 2308.09529

CROSS SECTION
- inclusive/differential
- t/tt/tttt
- SM/BSM test, EFT

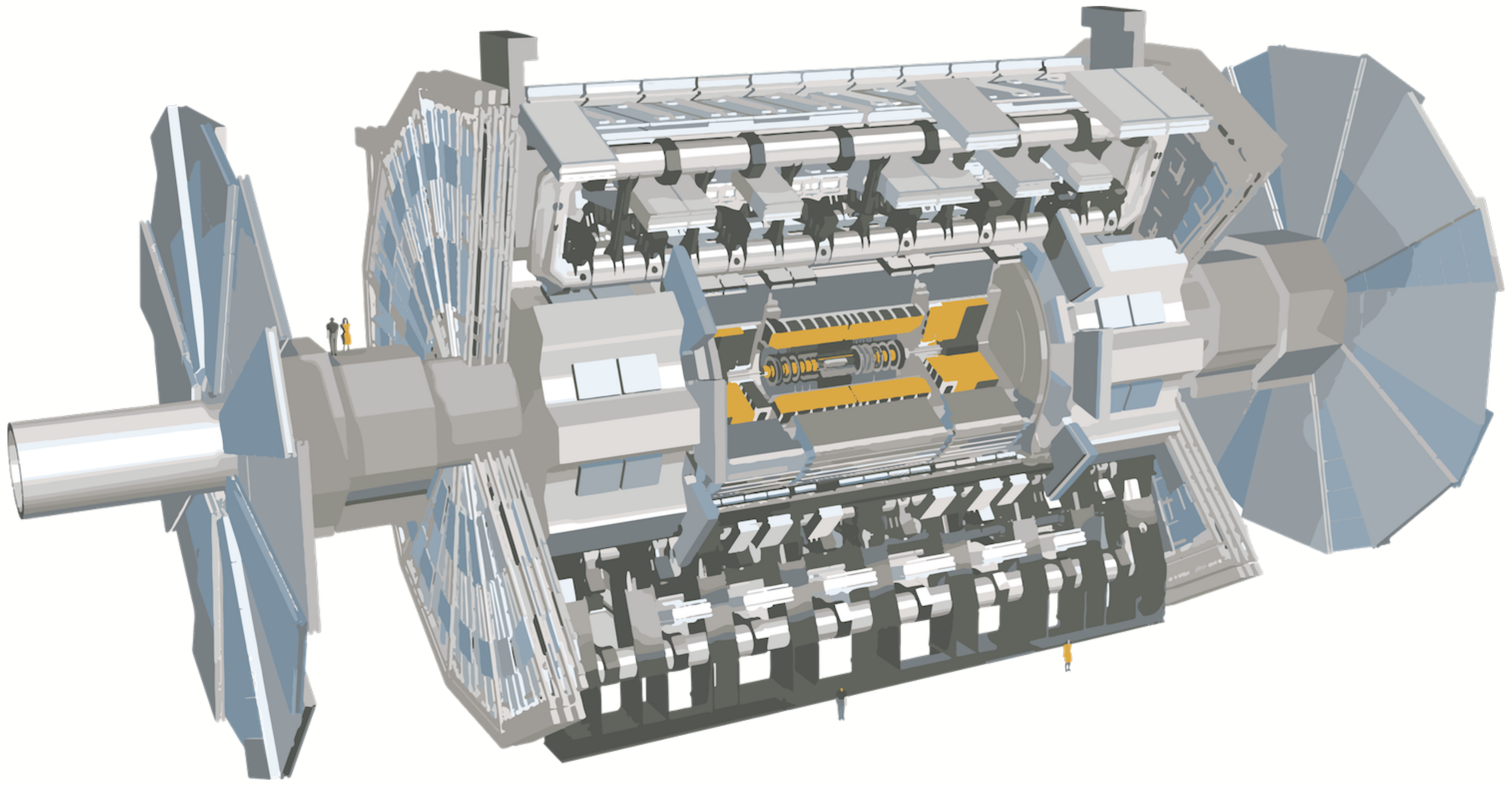
t+X
- ttV, ty, tty, tH
- background to BSM
- test SM/BSM theories

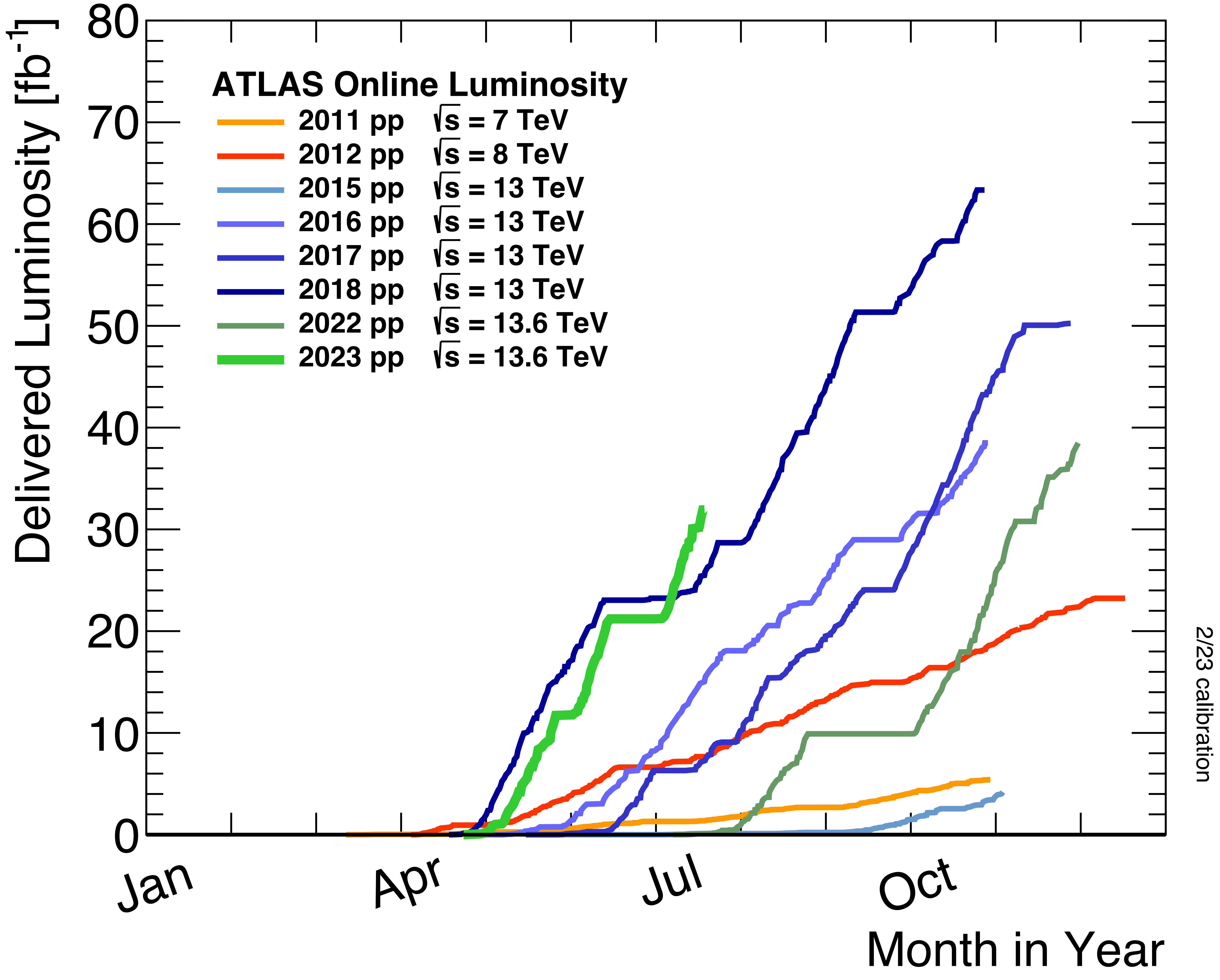
PROPERTIES
- mass
- entanglement
- charge asymmetry

The ATLAS experiment

ATLAS DETECTOR

- Inner Detector
- Calorimeters
- Muon Spectrometer
- 2T magnetic field
- 2 levels trigger system: hardware and software





LuminosityPublicResultsRun3

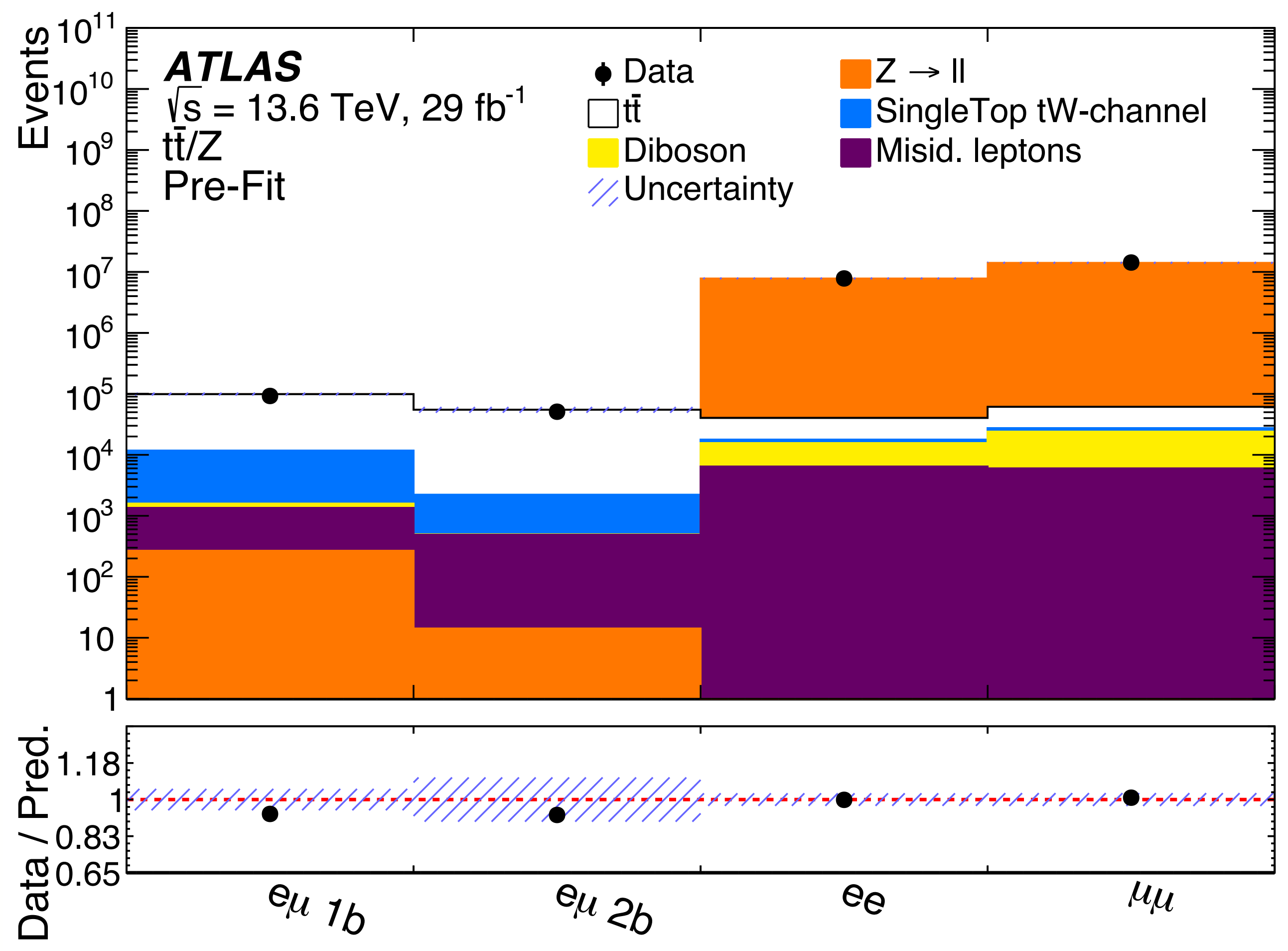
Run3 tt and Z cross section @ $\sqrt{s} = 13.6$ TeV

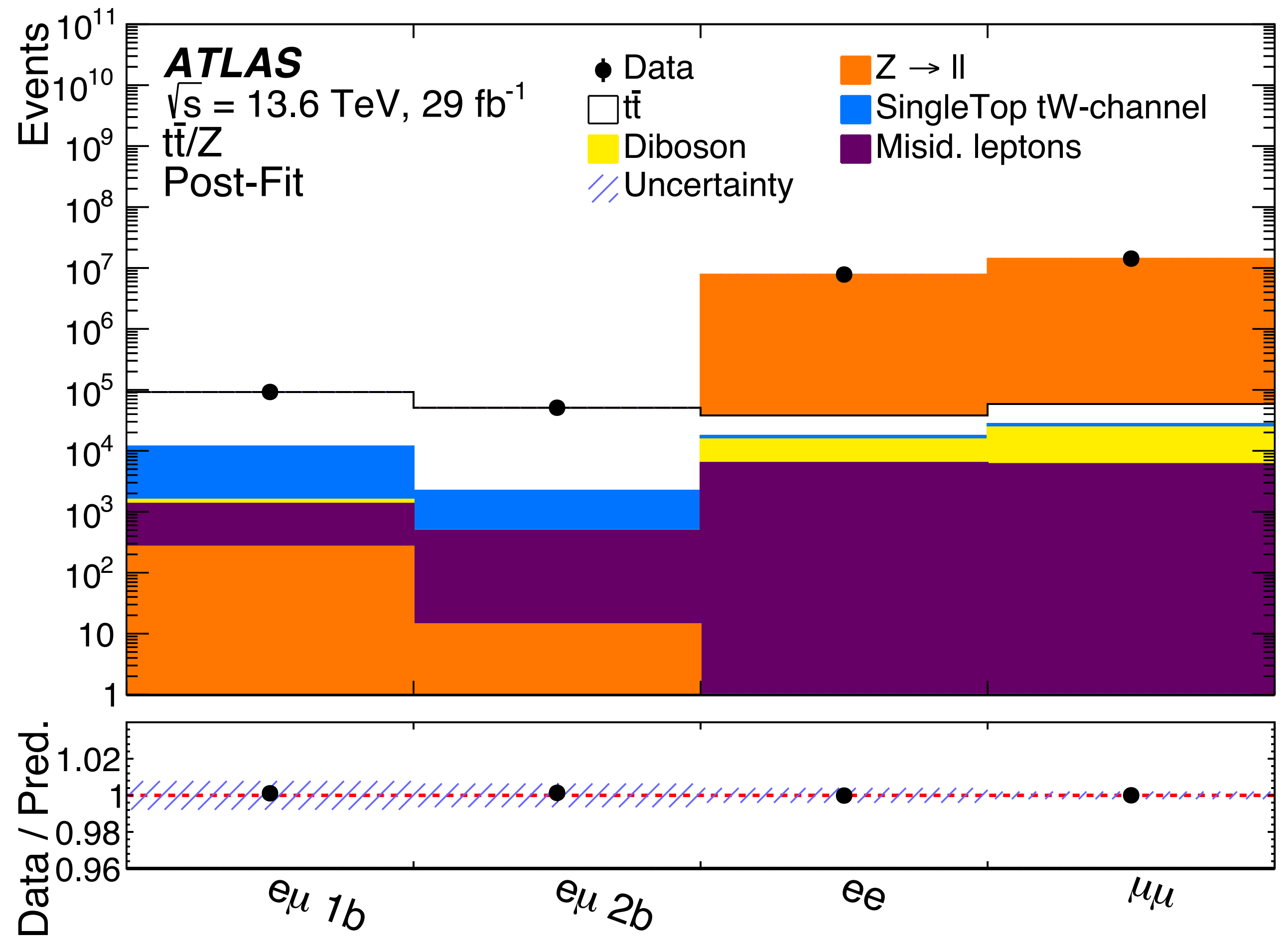
GOAL & MOTIVATION

- First $t\bar{t}$ cross-section measurement at $\sqrt{s} = 13.6$ TeV
  - 29fb^{-1}
  - Test upgraded detector and software
- Measuring the ratio of $t\bar{t}$ and Z cross-sections leads to cancellation of systematics
- SM/BSM tests

STRATEGY

- Use profile likelihood approach to extract $\sigma_{t\bar{t}}$, σ_Z, $R_{t\bar{t}/Z}$, ϵ_b
- Define 3 regions:
  - ee, $\mu\mu$
    - $66 \text{ GeV} < \text{m}_{\text{ll}} < 116 \text{ GeV}$, measure $R_{t\bar{t}/Z}$
  - $e\mu$
    - measure $R_{t\bar{t}/Z}$ and $\sigma_{t\bar{t}}$
- Use b-tag counting method to extract $\sigma_{t\bar{t}}$
  - $N_1 = L\sigma_{t\bar{t}}\epsilon_{e\mu}2\epsilon_b(1 - C_b\epsilon_b) + N_1^{\text{bkg}}$
  - $N_2 = L\sigma_{t\bar{t}}\epsilon_{e\mu}C_b\epsilon_b^2 + N_2^{\text{bkg}}$

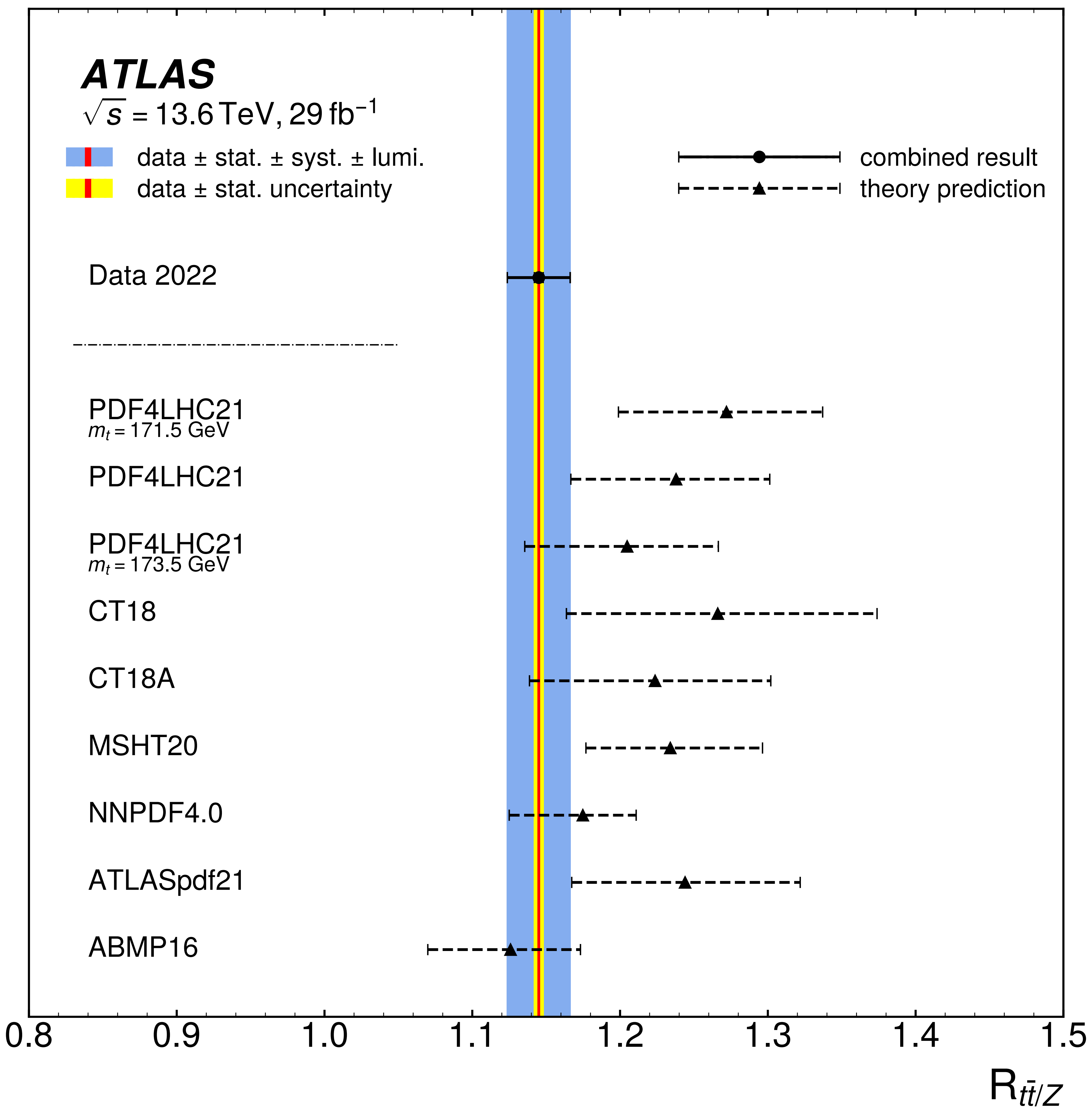




Run3 tt and Z cross section @ $\sqrt{s} = 13.6$ TeV

RESULTS

- Fitted values:
  - $\sigma_{t\bar{t}} = 850 \pm 3(\text{stat.}) \pm 18(\text{syst.}) \pm 20(\text{lumi.})$ pb
    - 3.2% relative uncertainty, limited by luminosity measurement and lepton uncertainty
  - $\sigma^{\text{fid.}}_{Z\to\ell\ell} = 744 \pm 11(\text{stat.} + \text{syst.}) \pm 16(\text{lumi.})$ pb
  - $R_{t\bar{t}/Z} = 1.145 \pm 0.003(\text{stat.}) \pm 0.021(\text{syst.}) \pm 0.002(\text{lumi.})$
    - 1.9% relative uncertainty
- Expected values:
  - $\sigma^{\text{theory}}_{t\bar{t}} = 924^{+32}_{-40}(\text{scale} + \text{PDF})$ pb
  - $\sigma^{\text{fid.,theory}}_{Z\to\ell\ell} = 746^{+21}_{-22}(\text{scale} + \text{PDF} + \alpha_s)$ pb
  - $R^{\text{theory}}_{t\bar{t}/Z} = 1.245 \pm 0.076(\text{scale} + \text{PDF})$



Dilepton and single-lepton $t\bar{t}$ production differential cross sections

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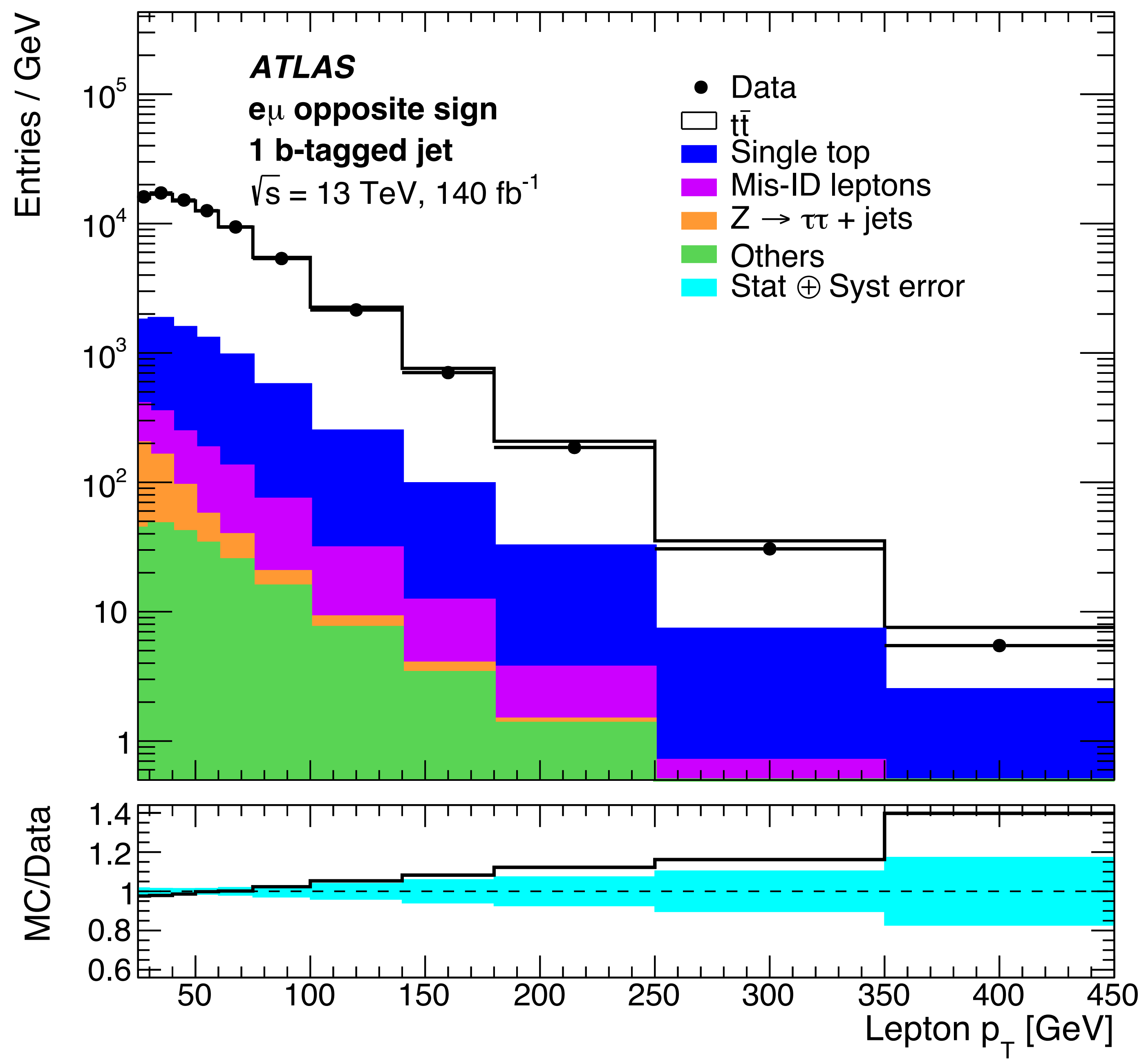
GOAL & MOTIVATION

- Measure the $t\bar{t}$ single and double differential cross-section
  - $\sqrt{s} = 13$ TeV
- Differential measurements can be used to
  - MC tuning and pQCD test
    - Especially double differential ones
  - Provide inputs for PDFs
  - Measure SM parameters such as α_s and m_t

STRATEGY

- Dilepton:
  - Select events with an $e\mu$ pair in the final state
  - Divide the events based on the b-tagged jets
  - Use b-tag counting method to extract $\sigma_{t\bar{t}}$
- Single-lepton:
  - Divide the events based on the number of jets
    - $t\bar{t}$, $t\bar{t}$+1 jet, $t\bar{t}$+2jets



Dilepton and single-lepton $t\bar{t}$ production differential cross sections

ATLAS EXPERIMENT

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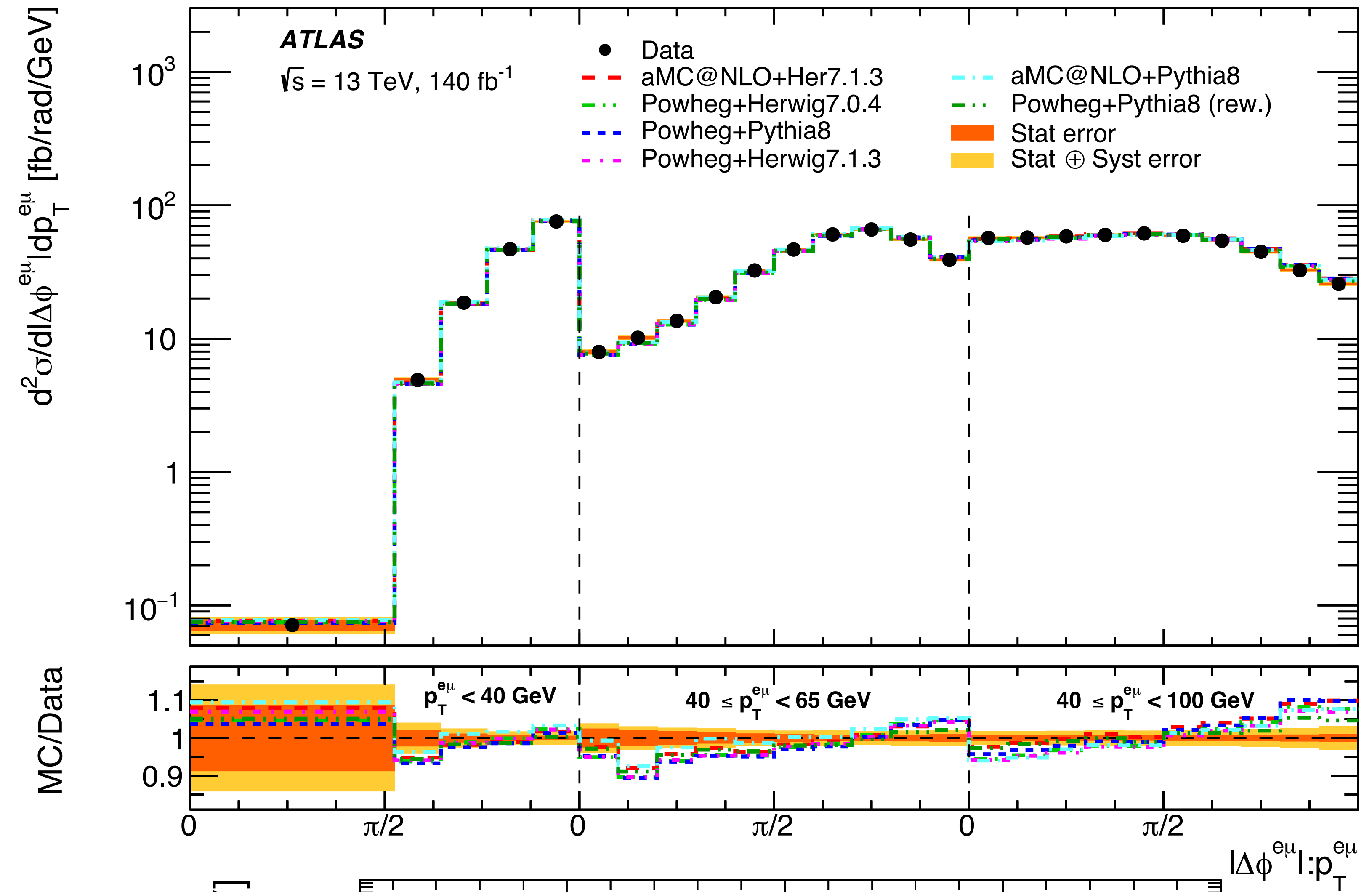
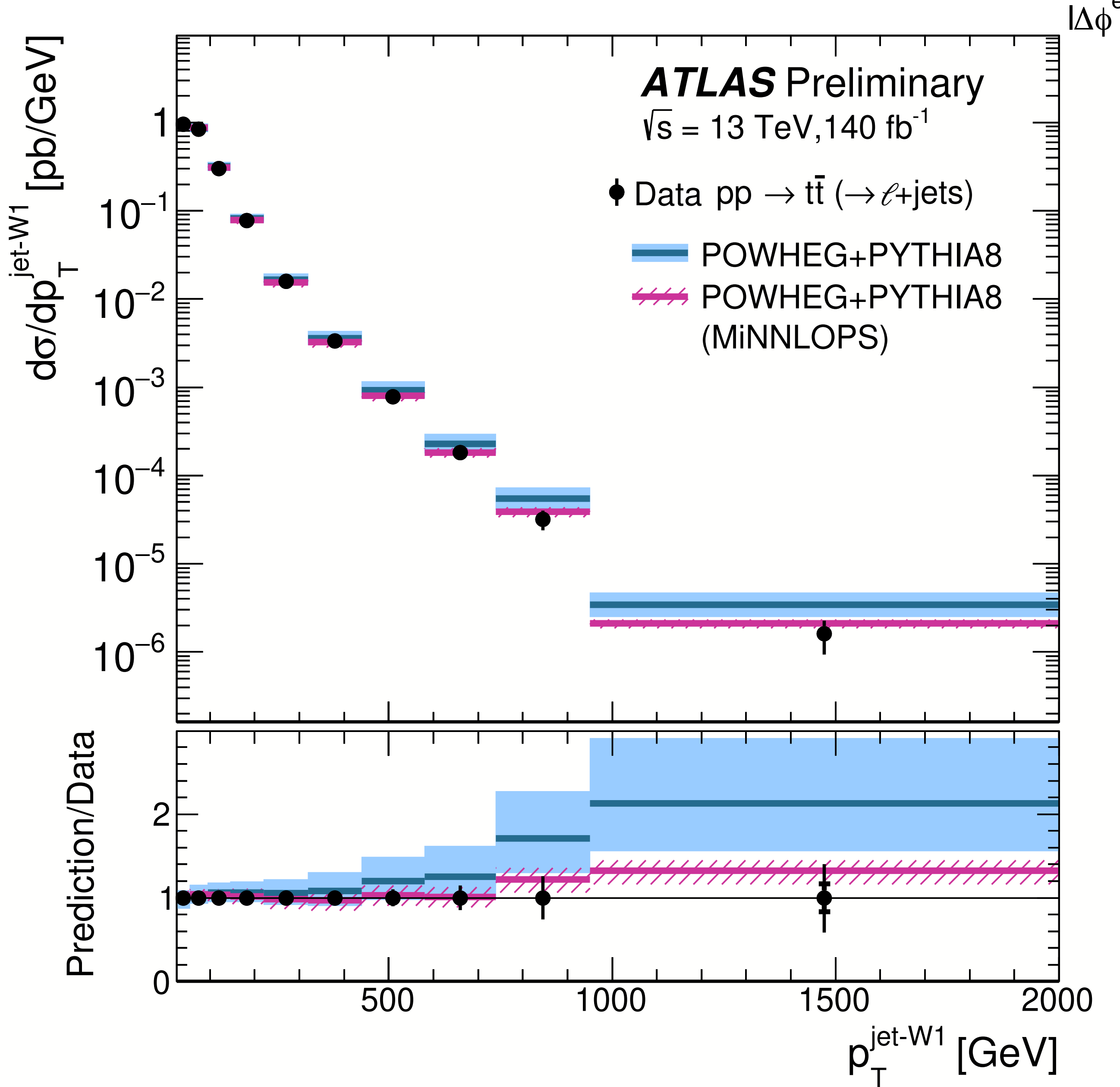
RESULTS

- Dilepton:
  - Total fiducial cross section:
    - $\sigma_{t\bar{t}}^{\text{fid}} = 10.53 \pm 0.02(\text{stat.}) \pm 0.13(\text{syst.}) \pm 0.10(\text{lumi.}) \pm 0.02(\text{beam})$ pb
  - Total inclusive cross section:
    - $\sigma_{t\bar{t}} = 829 \pm 1(\text{stat.}) \pm 13(\text{syst.}) \pm 8(\text{lumi.}) \pm 2(\text{beam})$ pb
      - Most precise $\sigma_{t\bar{t}}$ to date with 1.8% relative uncertainty
    - $\sigma_{t\bar{t}}^{pred} = 832^{+20}_{-29}\,(\text{scale}) \pm 23(\text{m}_t) \pm 35(\text{PDF} + \alpha_s)$ pb
  - Differential cross sections:
    - No generators matches with data within the uncertainty
- Single-lepton:
  - Results are compared with NLO and NNLO predictions
  - $t\bar{t}$, $t\bar{t}$+1jet, $t\bar{t}$+2jet:
    - NNLO better agreement with lower uncertainties for most observables





Eur. Phys. J. C 83 (2023) 496

Observation of four-top-quark production

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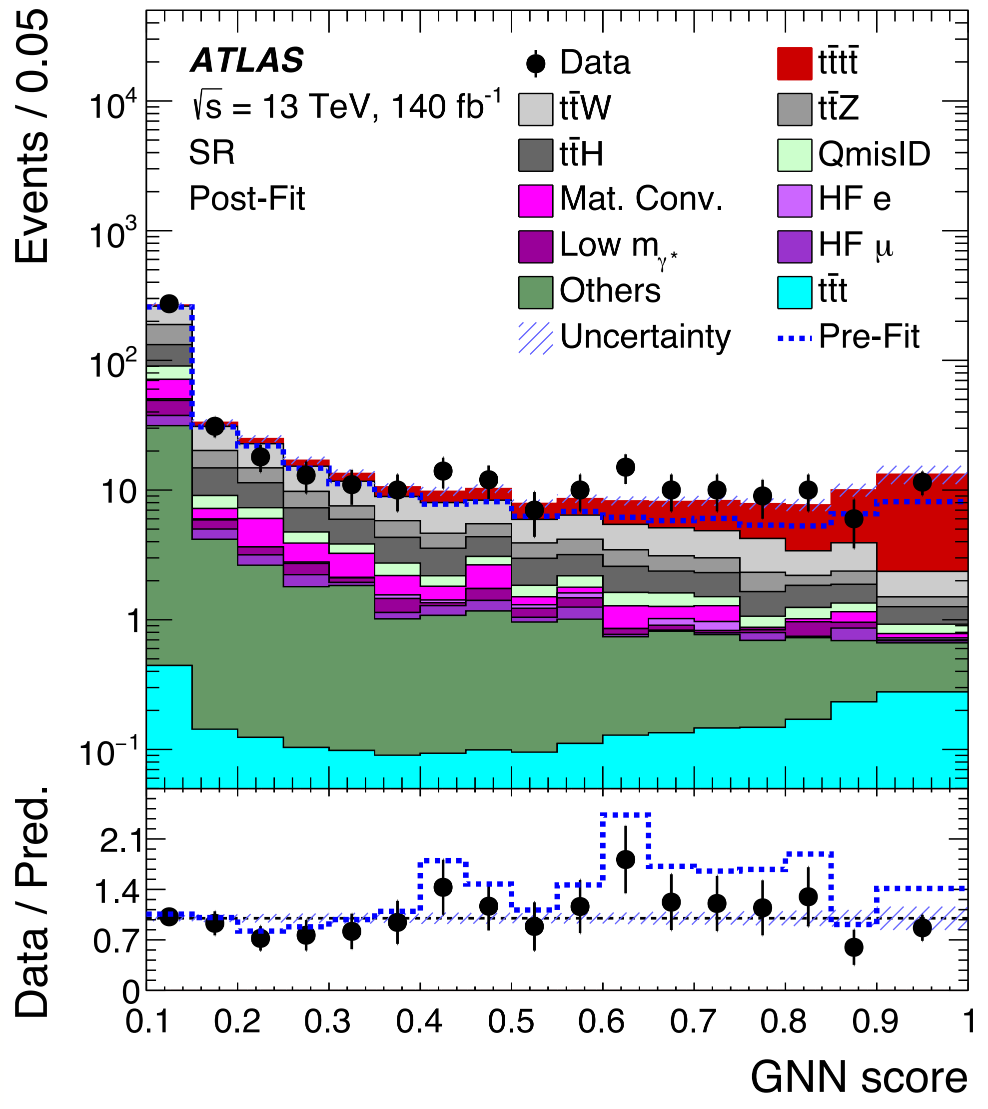
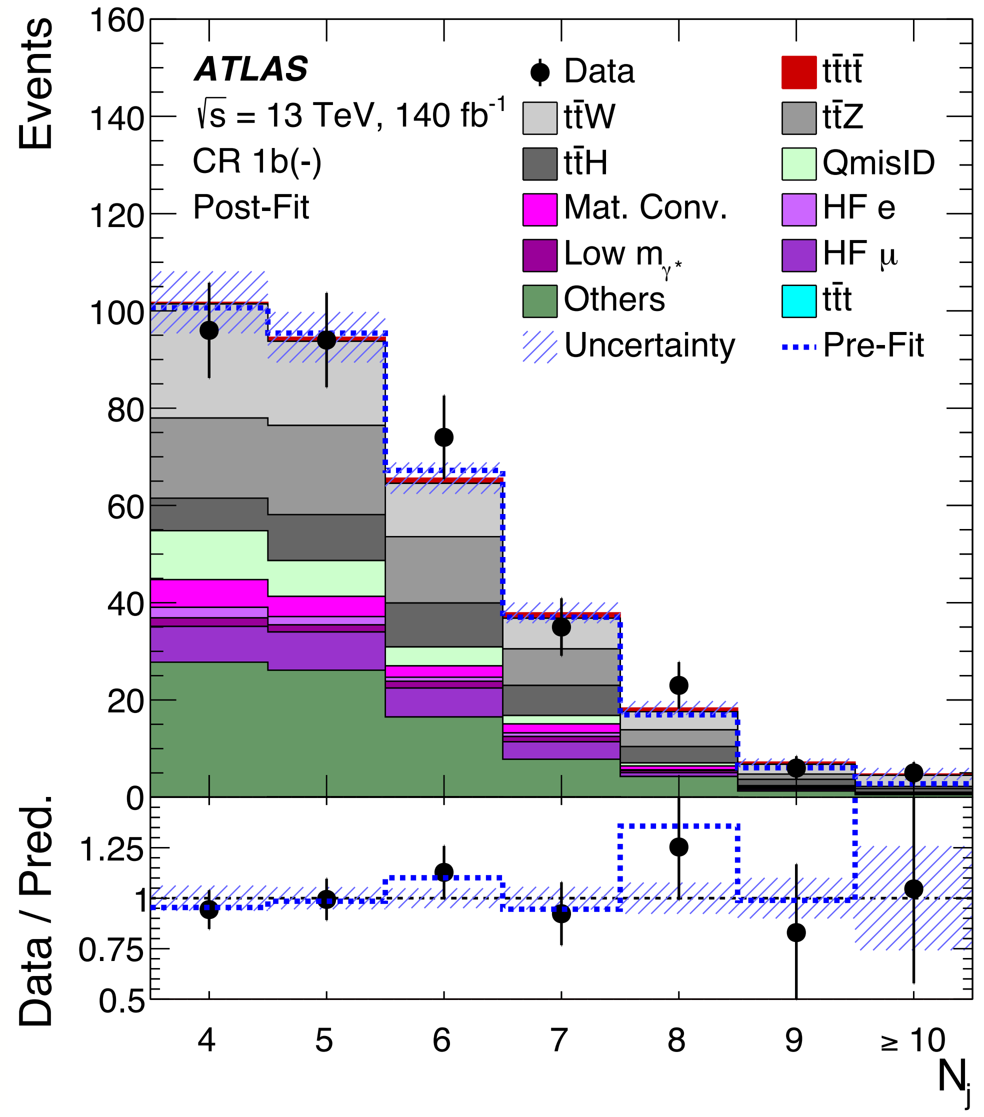
MOTIVATION

- Measure the $t\bar{t}t\bar{t}$ cross-section
  - rare SM process
    - Strict tests of SM
  - Production enhanced in BSM theories
    - Hint of new physics?

STRATEGY

- Use maximum likelihood fit to extract $\sigma_{t\bar{t}t\bar{t}}$
  - Split in Signal Region (SR) and Control Region (CR)
  - Use GNN to enhance the performance in SR
  - Fit GNN in SR and CR distributions
- Set limits on
  - ttt, EFT operators (BSM $t\bar{t}t\bar{t}$), top Yukawa and oblique Higgs



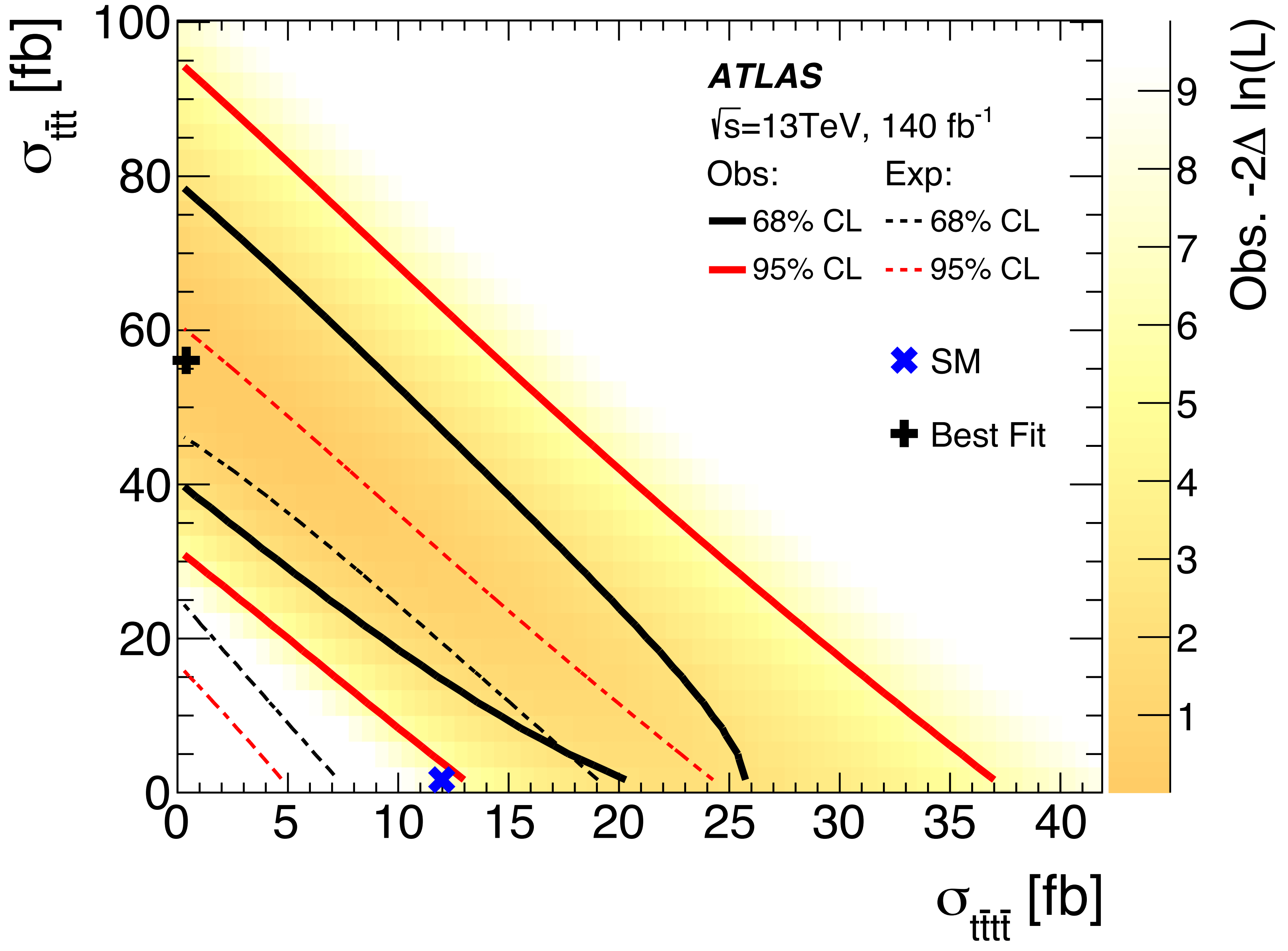


Eur. Phys. J. C 83 (2023) 496

Observation of four-top-quark production

RESULTS

- Signal Strength:
  - $\mu = \sigma^{data}_{t\bar{t}t\bar{t}} / \sigma^{SM}_{t\bar{t}t\bar{t}} = 1.9 \pm 0.4\,(\text{stat})^{+0.7}_{-0.4}\,(\text{syst}) = 1.9^{+0.8}_{-0.5}$
    - 6.1σ deviation from a background only hypothesis
- Cross Section
  - $\sigma_{t\bar{t}t\bar{t}} = 22.5^{+4.7}_{-4.3}(\text{stat})^{+4.6}_{-3.4}(\text{syst})\ \text{fb} = 22.5^{+6.6}_{-5.5}\ \text{fb}$
    - ~30% relative uncertainty
  - $\sigma^{SM,NLO}_{t\bar{t}t\bar{t}} = 12.0 \pm 2.4\ \text{fb}$ [ref]
- Limits on the top-quark Yukawa coupling strength modifier:
  - $\kappa_t < 1.8\ (1.6)$
- Limits on EFT operators
  - Sensitive to $O^1_{tt}, O^1_{QQ}, O^1_{Qt}, O^8_{Qt}$
- Limits on Higgs oblique parameter $\hat{H}$ (BSM self-energy correction term)
  - $\hat{H} < 0.20\ \ (0.12),\ \hat{H}^{SM} = 0$



Operators	Expected C_i/Λ^2 [TeV $^{-2}$]	Observed C_i/Λ^2 [TeV $^{-2}$]
O^1_{QQ}	[-2.4, 3.0]	[-3.5, 4.1]
O^1_{Qt}	[-2.5, 2.0]	[-3.5, 3.0]
O^1_{tt}	[-1.1, 1.3]	[-1.7, 1.9]
O^8_{Qt}	[-4.2, 4.8]	[-6.2, 6.9]

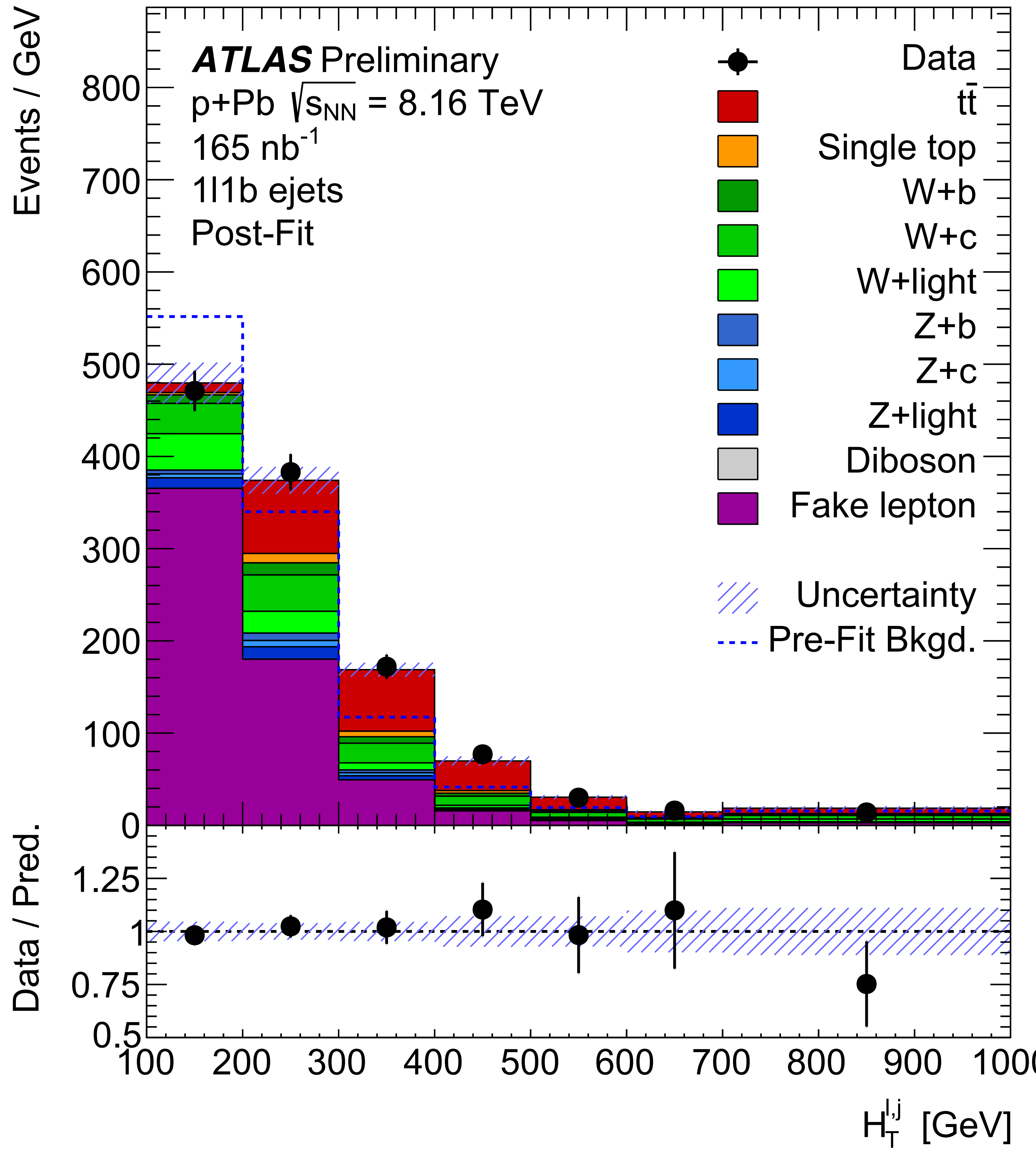
Observation of $t\bar{t}$ production in p+Pb collisions

GOAL & MOTIVATION

- Measure top quark production in p+Pb collisions
  - Never observed before by ATLAS
    - Test of SM
  - Probe nuclear modification to PDFs

STRATEGY

- Divide the data in SRs and CRs
- Extract the signal strength with profile likelihood approach
  - Fit H_T^{ljet} in all SRs



Observation of $t\bar{t}$ production in p+Pb collisions

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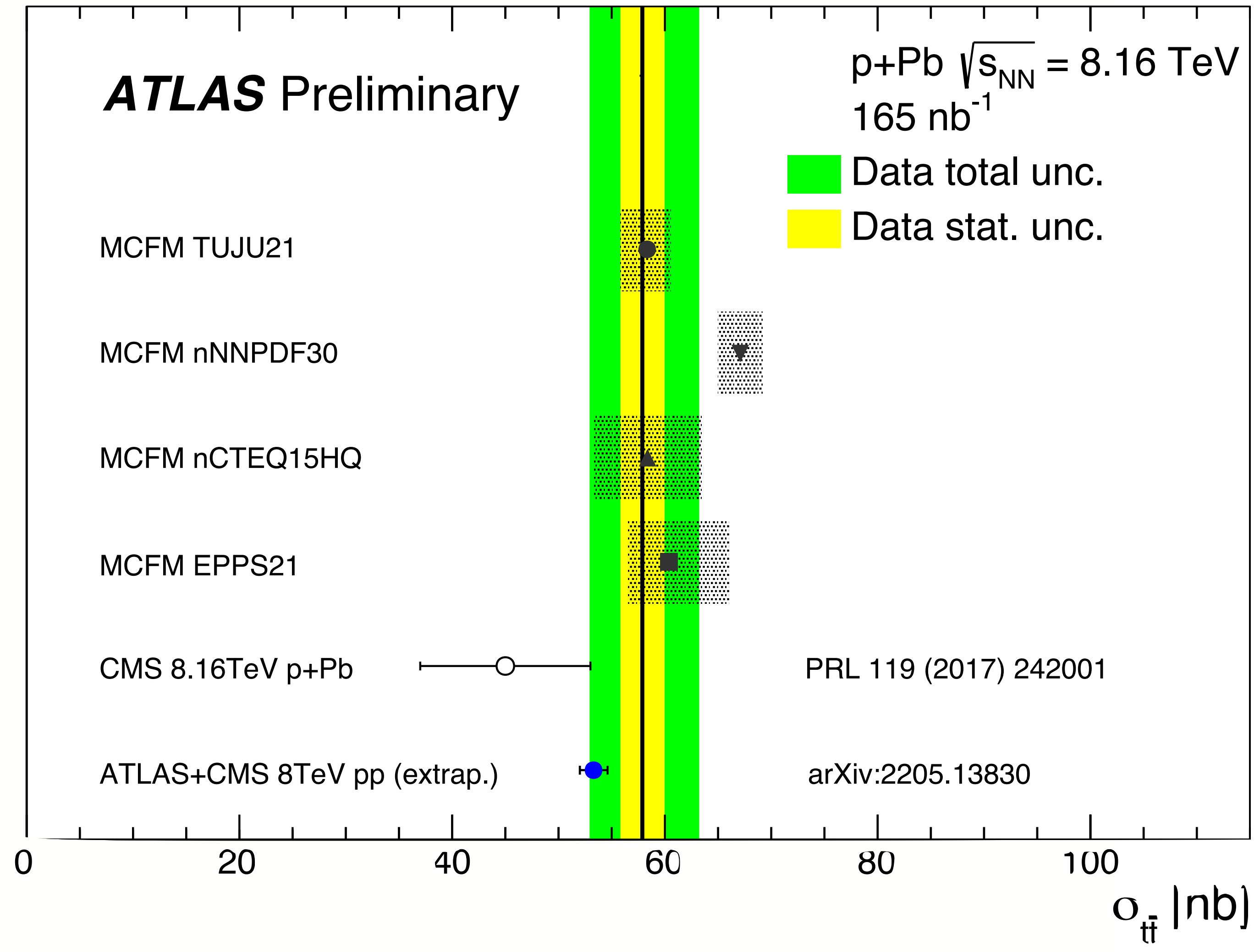
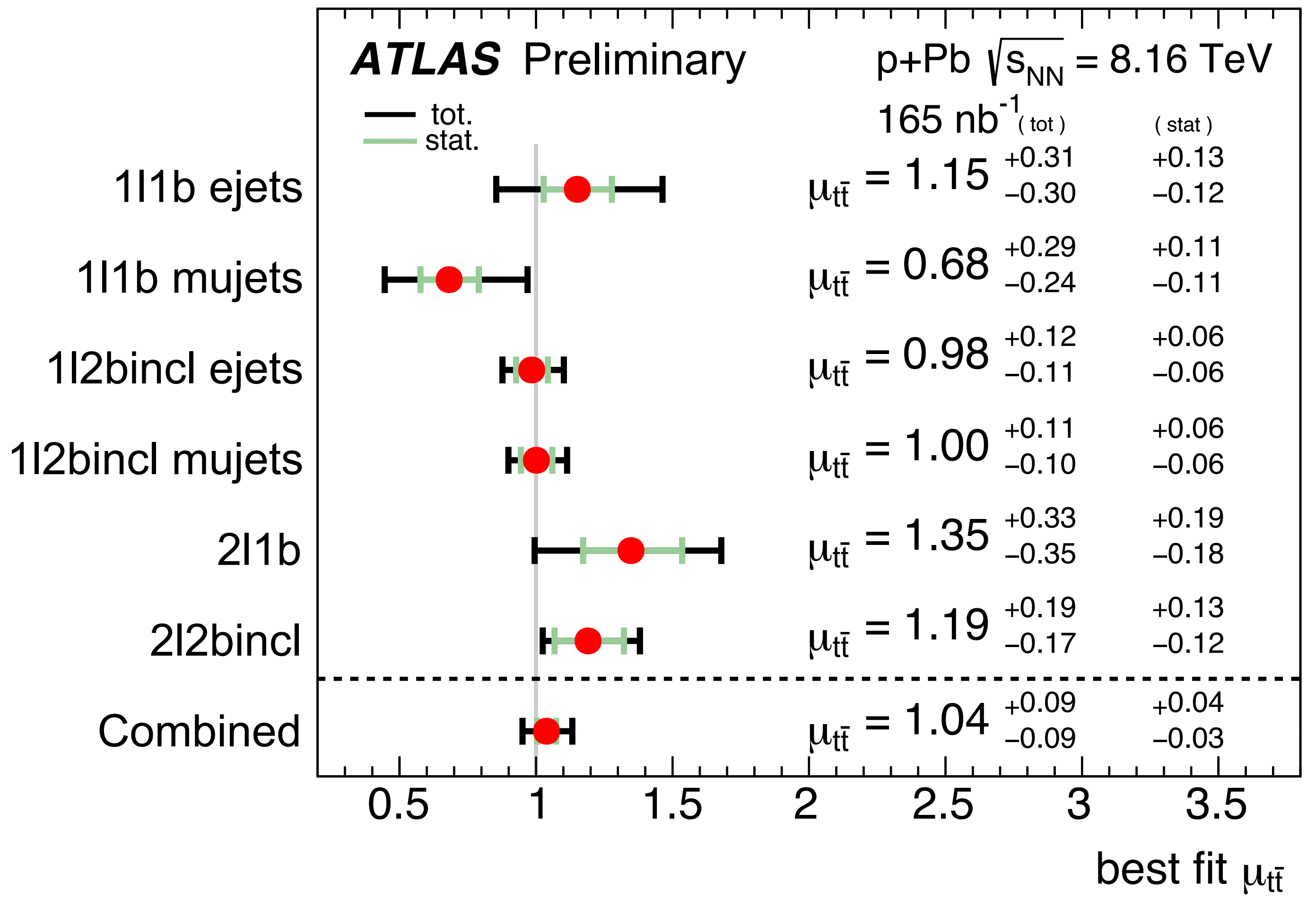
RESULTS

- Measure $\sigma_{t\bar{t}} = \mu_{t\bar{t}} \cdot A_{Pb} \cdot \sigma_{t\bar{t}}^{th}$
- $\sigma_{t\bar{t}} = 57.9 \pm 2.0\,(\text{stat})\,{}^{+4.9}_{-4.5}\,(\text{syst})\ \text{nb} = 57.9^{+5.3}_{-4.9}\ \text{nb}$
  - ~10% relative uncertainty
  - The background-only hypothesis is rejected with more than 5σ significance
- Measurement in agreement with theoretical SM predictions





arXiv:2310.01518 ATLAS-CONF-2023-026

Measurement of t-channel single-top production at $\sqrt{s} = 5.02$ TeV and $\sqrt{s} = 13$ TeV

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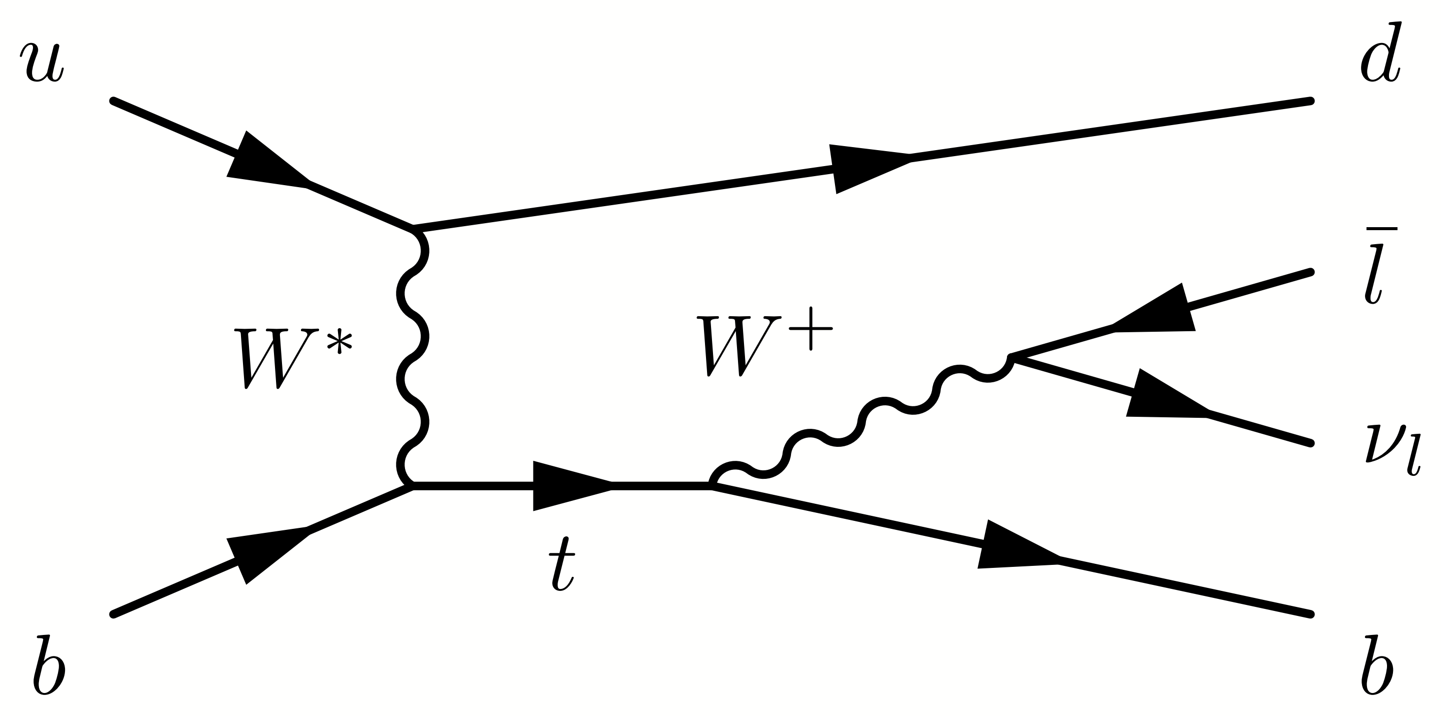
GOAL & MOTIVATION

- Measure top and anti-top production in the t-channel
  - Test SM theoretical predictions
    - Deviations can be due to BSM physics
  - Measure the ratio of top and anti-top production
  - Measure EFT coefficients (13TeV only)
  - Measure CKM elements

STRATEGY

- 5 TeV
  - Use BDT to discriminate signal and bkg
  - Divide events in t and $\bar{t}$ subsamples
  - Profile likelihood fit the BDT distributions
    - Extract σ and R_t
- 13 TeV
  - Divide in SRs and CRs
  - Use NN to discriminate signal and bkg
  - Profile likelihood fit
    - NN distribution in the SRs
    - $\Delta\phi\left(E_T^{miss}, \ell\right)$ and event yields in CRs



Measurement of t-channel single-top production at $\sqrt{s} = 5.02$ TeV and $\sqrt{s} = 13$ TeV

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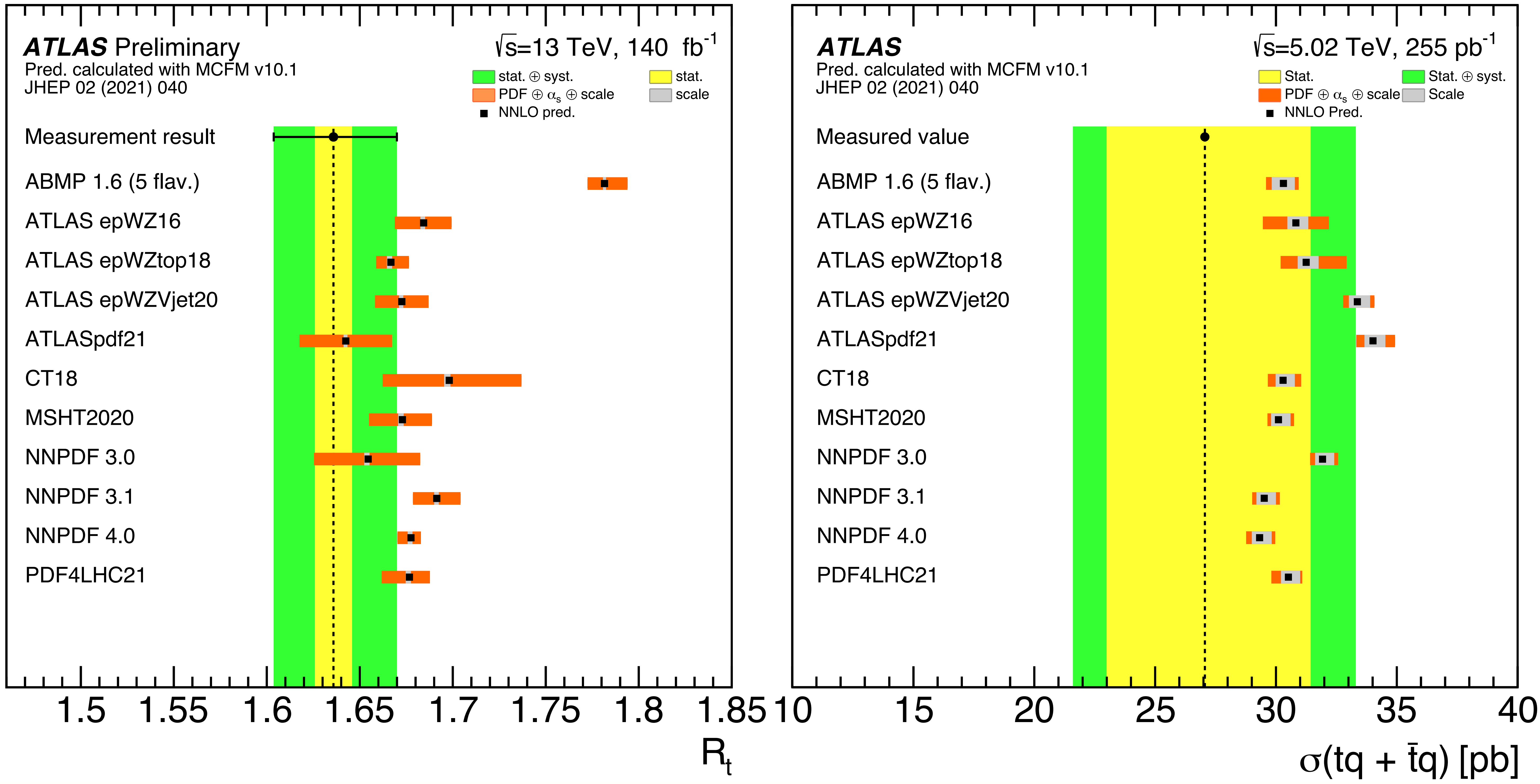
RESULTS

- $\sqrt{s} = 5.02$ TeV
  - $\sigma(tq + \bar{t}q) = 27.1^{+4.4}_{-4.1}\,(\text{stat})^{+4.4}_{-3.7}\,(\text{syst})$ pb
  - $R_t = 2.73^{+1.43}_{-0.82}\,(\text{stat})^{+1.01}_{-0.29}\,(\text{syst})$
  - $f_{LV} \cdot V_{tb} = 0.94^{+0.11}_{-0.10}$
- $\sqrt{s} = 13$ TeV
  - $\sigma(tq + \bar{t}q) = 221 \pm 13$ pb and $R_t = 1.636^{+0.036}_{-0.034}$
  - $-0.25 < C^{(1,3)}_{qQ} < 0.12$
  - $f_{LV} \cdot V_{tb} = 1.016 \pm 0.031$
- Most of the predictions overestimate the measured values while being compatibile
  - ABMP PDF prediction is incompatible by 3σ with the 13TeV R_t measurement



Jet substructure in boosted $t\bar{t}$ events

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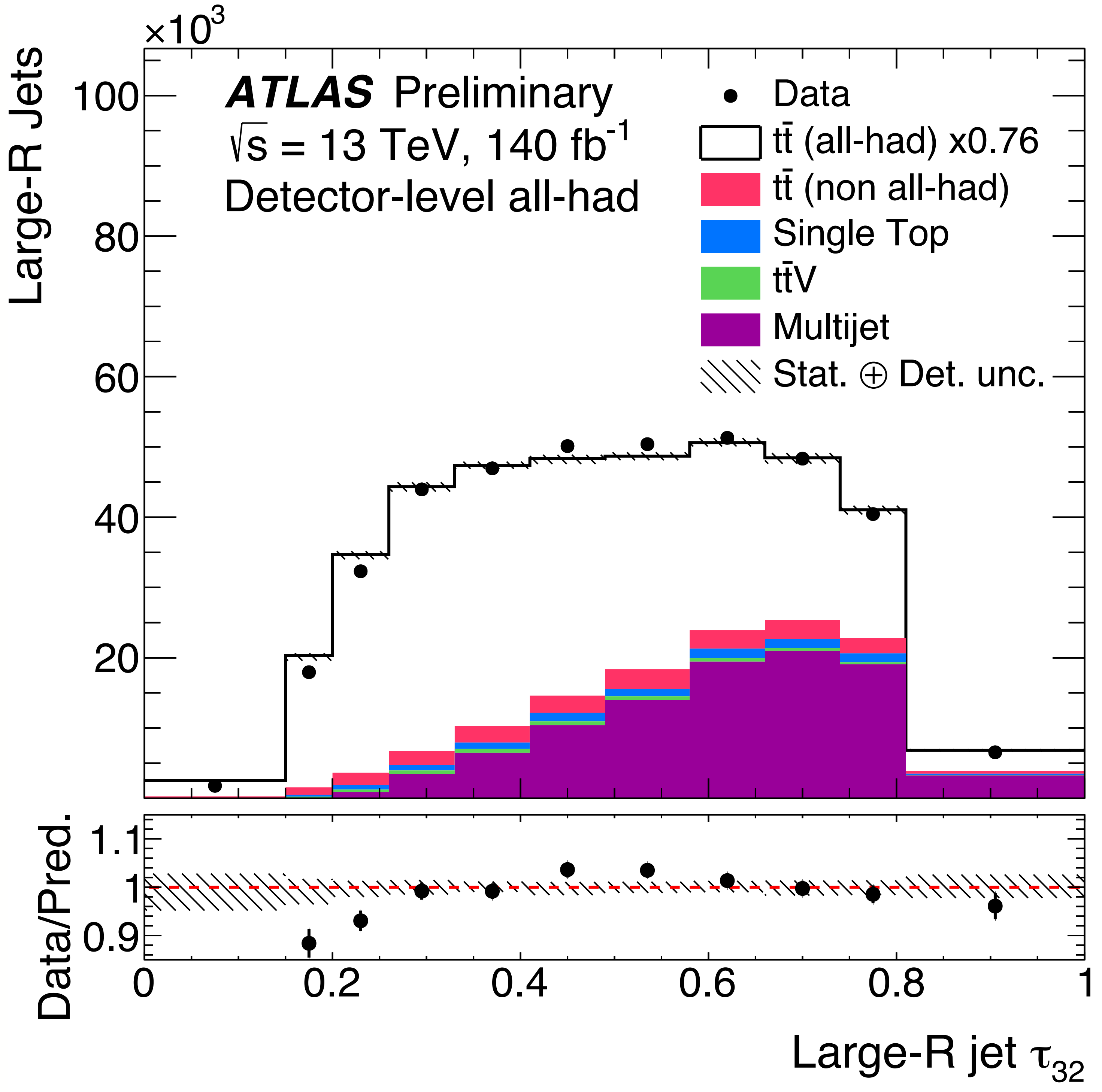
MOTIVATION

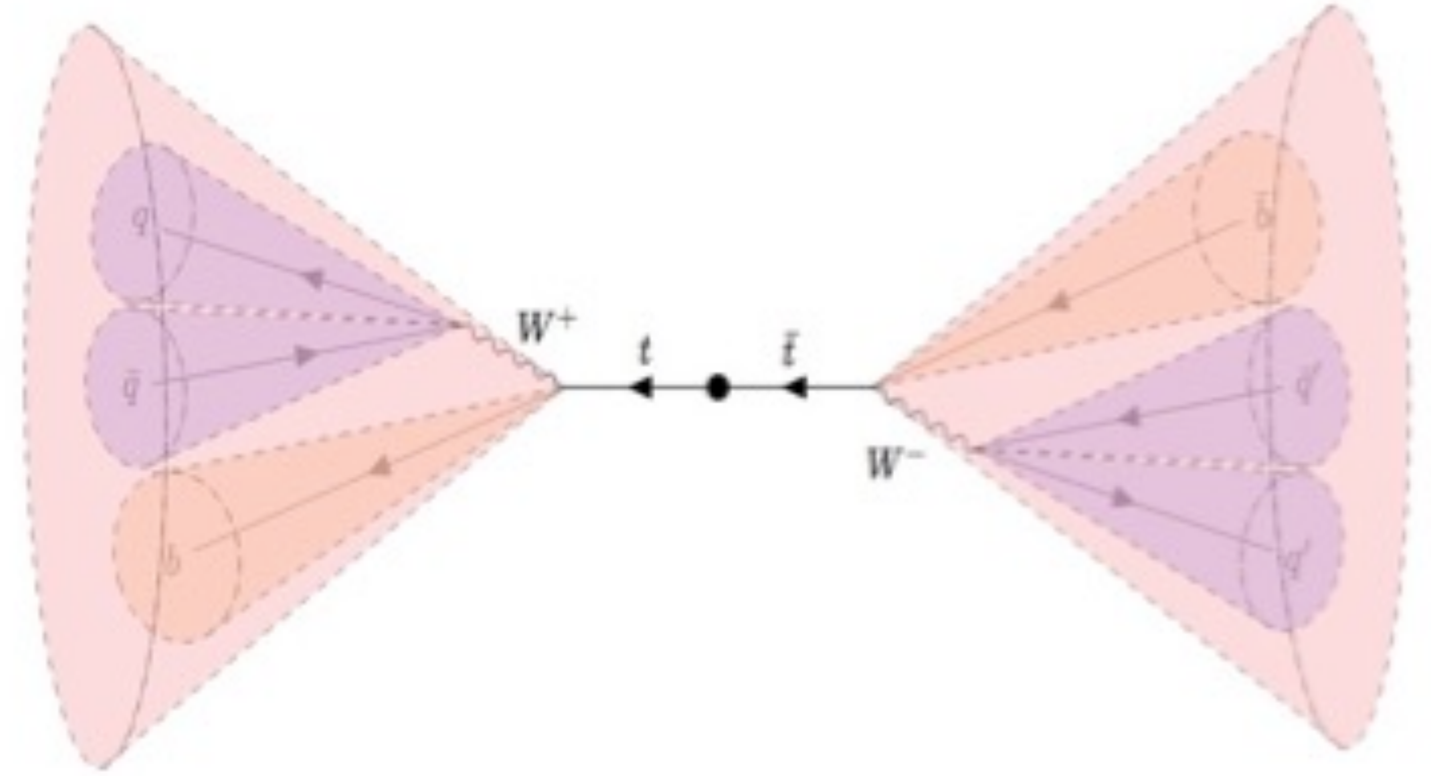
- Measure the substructure of large-R jets containing the decays of high-p_T top quarks
  - Sensitive to soft QCD $t\bar{t}$ production
  - Useful for MC tuning
  - Sensitive to new physics

STRATEGY

Reconstruct variables sensitive to FSR, 2/3 prong structure:

- Use only tracks at detector level and charged constituents at particle level
- Unfold to particle-level using IBU (6 iterations)
- Use both single lepton and all-hadronic events
  - 1 lep, m_{lb}<120GeV, ≥1b-tag(DL1r@77%), 1 reclustered largeR jet
  - 0 lep, ≥2 topo-clusters largeR jet, ≥1b-tag(DL1r@70%), ≥1top-tag(@80%)



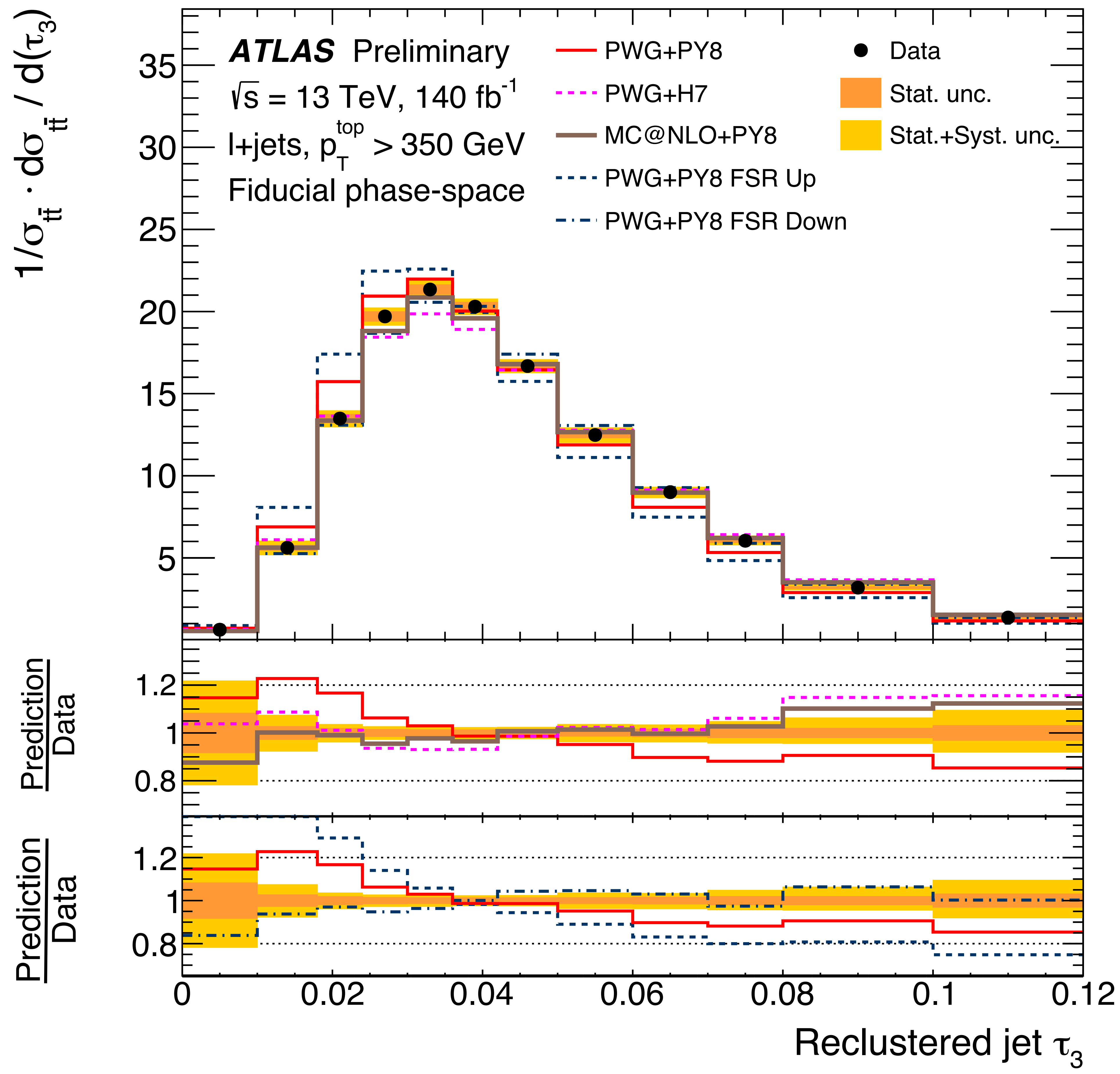


Jet substructure in boosted $t\bar{t}$ events

RESULTS

Single and Double differential results

- Good agreement in variables sensitive to 2-prong, poorer to 3-prong
  - MC estimates more 3-prong structures
  - FSR_d and PWGH7 better agreement
- FSR-sensitive
  - Compatible with MC, prefer higher α_S^{FSR}
- Some variables measured as a function of large-R jet mass and p_T



Search for FCNC in $tqH\left(\gamma\gamma\right)$

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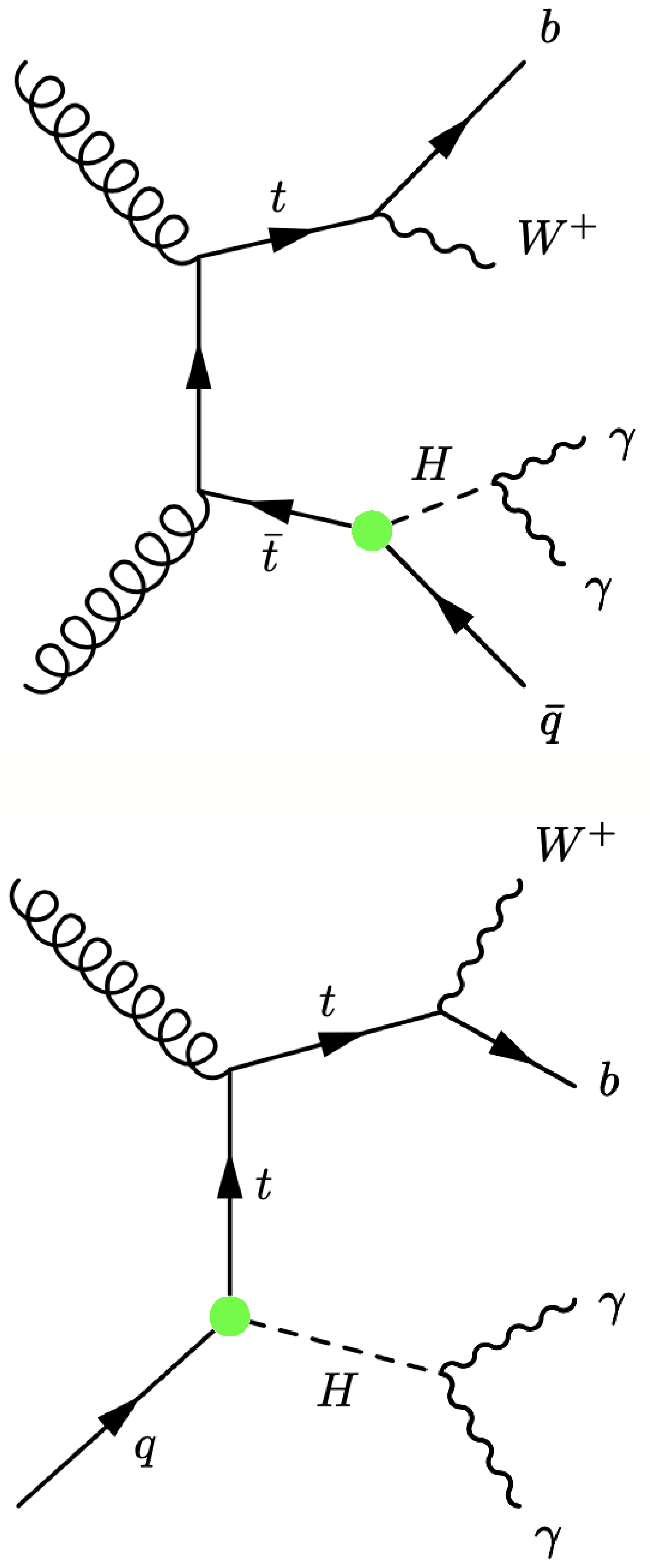
GOAL & MOTIVATION

- Measure $tqH\left(\gamma\gamma\right)$ vertex from top decay and top production
- FCNC in tqH might come from BSM
  - FCNC is forbidden at tree level in SM
  - Suppressed at higher orders
- Combine this search with the searches in $tqH\left(\tau\tau\right)$ and $tqH\left(b\bar{b}\right)$

STRATEGY

- Likelihood fit
  - Both leptonic and hadronic channels
  - Use BDT to discriminate signal and bkg
  - Divide events in 6 (hadronic) and 4 (leptonic) categories and fit them
- Hypothesis on BR are probed with a test statistic based on a profile likelihood ratio



Search for FCNC in $tqH\left(\gamma\gamma\right)$

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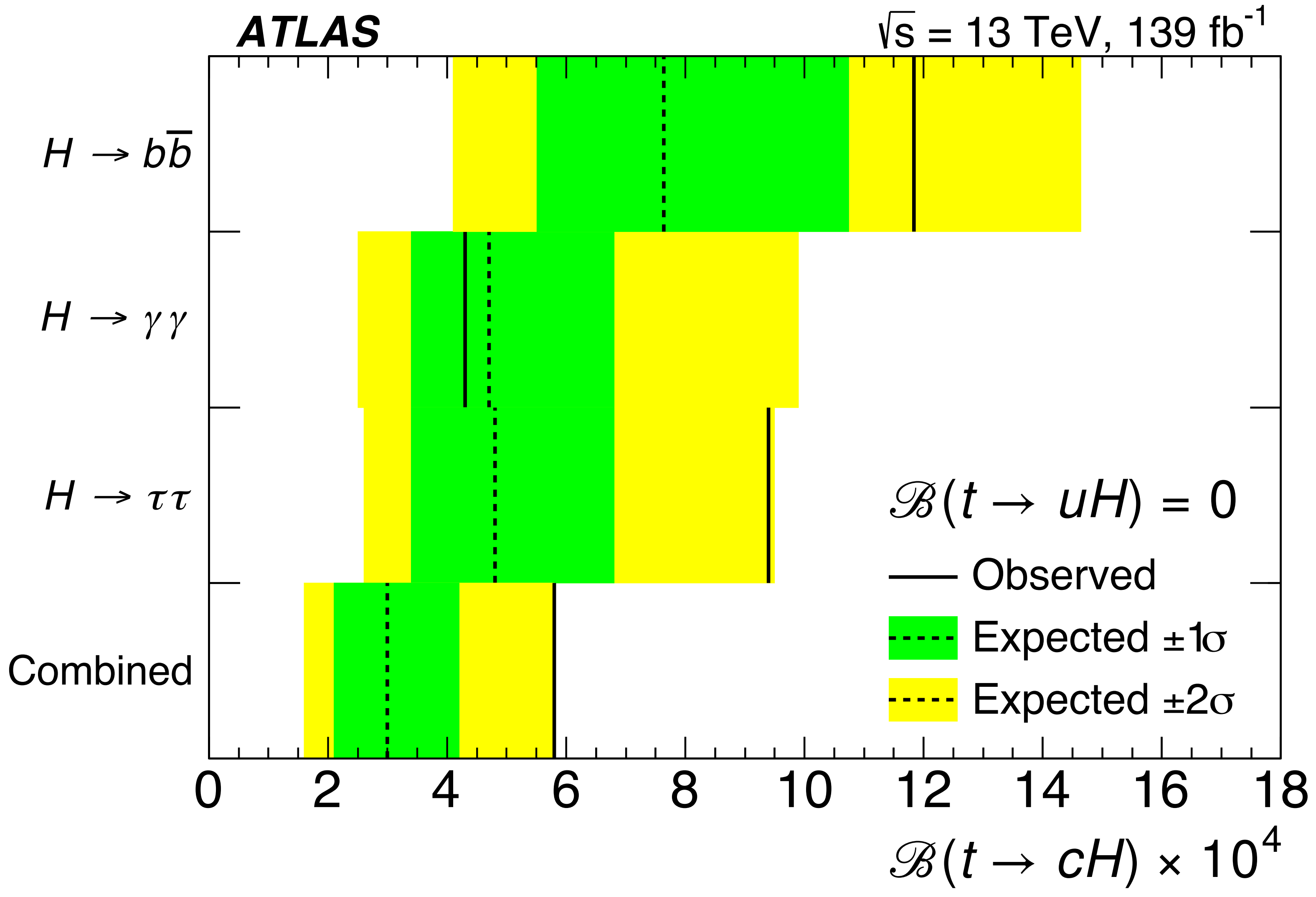
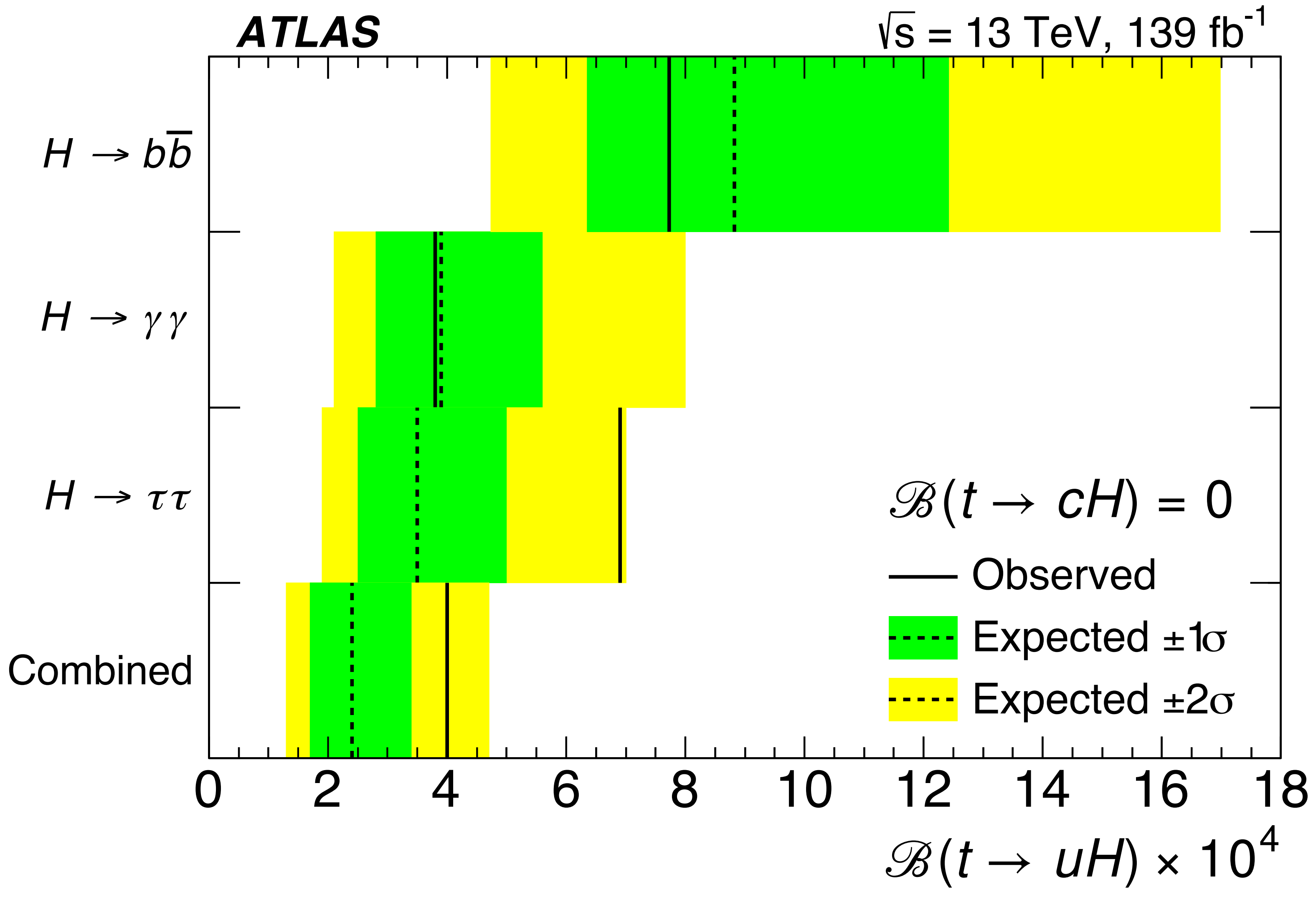
RESULTS

- $tqH(\gamma\gamma)$
  - $BR\left(t \to cH\right) < 4.3 \times 10^{-4}$ $\left(4.7 \times 10^{-4}\right)$
  - $BR\left(t \to uH\right) < 3.8 \times 10^{-4}$ $\left(3.9 \times 10^{-4}\right)$
- Combination
  - $BR\left(t \to cH\right) < 5.8 \times 10^{-4}$ $\left(3.0 \times 10^{-4}\right)$
  - $BR\left(t \to uH\right) < 4.0 \times 10^{-4}$ $\left(2.4 \times 10^{-4}\right)$





$t\bar{t}W$ and $t\bar{t}Z$ inclusive and differential

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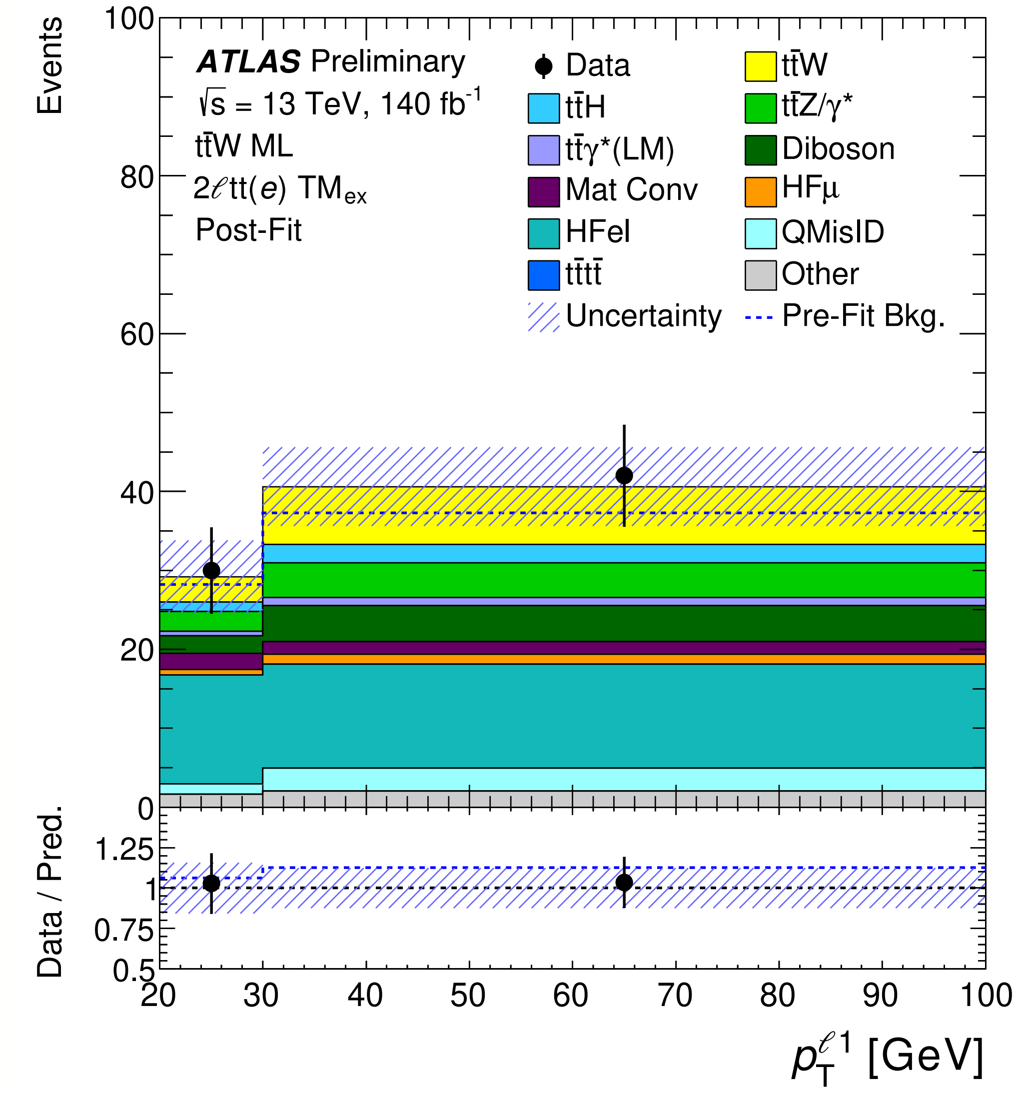
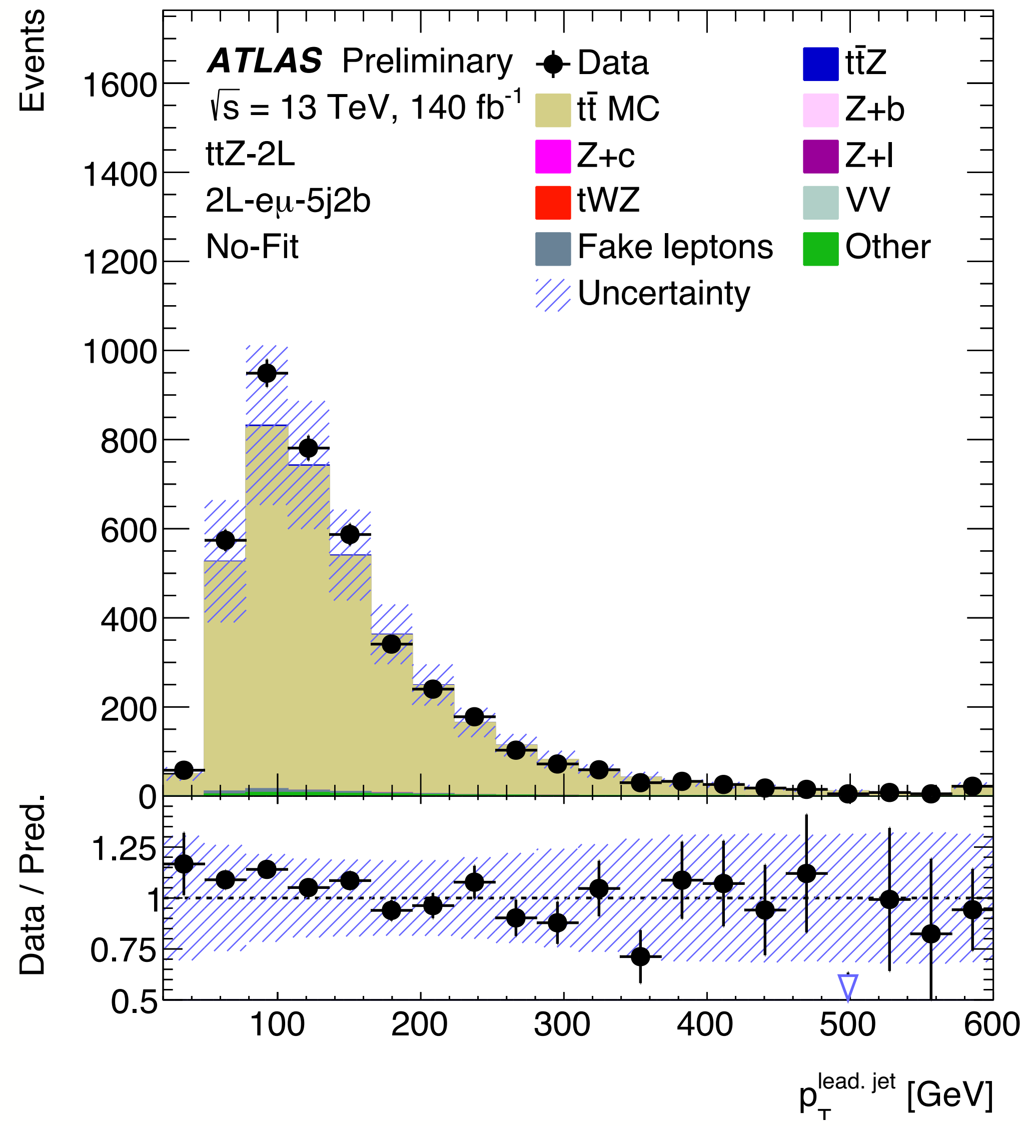
GOAL & MOTIVATION

- Measure $t\bar{t}W$ and $t\bar{t}Z$ production
  - Rare processes
    - Strict test of SM
  - Background to many other rare processes
- $t\bar{t}W$:
  - understand data/SM tensions from previous measurements (Eur. Phys. J. C 77, 40 (2017))
- $t\bar{t}Z$:
    - Provide EFT interpretation
    - Search for top-quark spin correlation

STRATEGY

- Categorise events in 2ℓSS and 3ℓ ($t\bar{t}W$)
- Categorise events in 2ℓ, 3ℓ and 4ℓ ($t\bar{t}Z$)
- Divide selected events in SRs and CRs
  - Further split if inclusive or differential ($t\bar{t}W$)
- Inclusive cross section
  - Profile Likelihood fit the yields in all SRs and CRs
- Differential cross sections
  - Profile Likelihood unfolding
    - Using the binned observable distribution in all the SRs and CRs ($t\bar{t}W$)
    - Using the binned observable distribution in 3ℓ and 4ℓ ($t\bar{t}Z$)

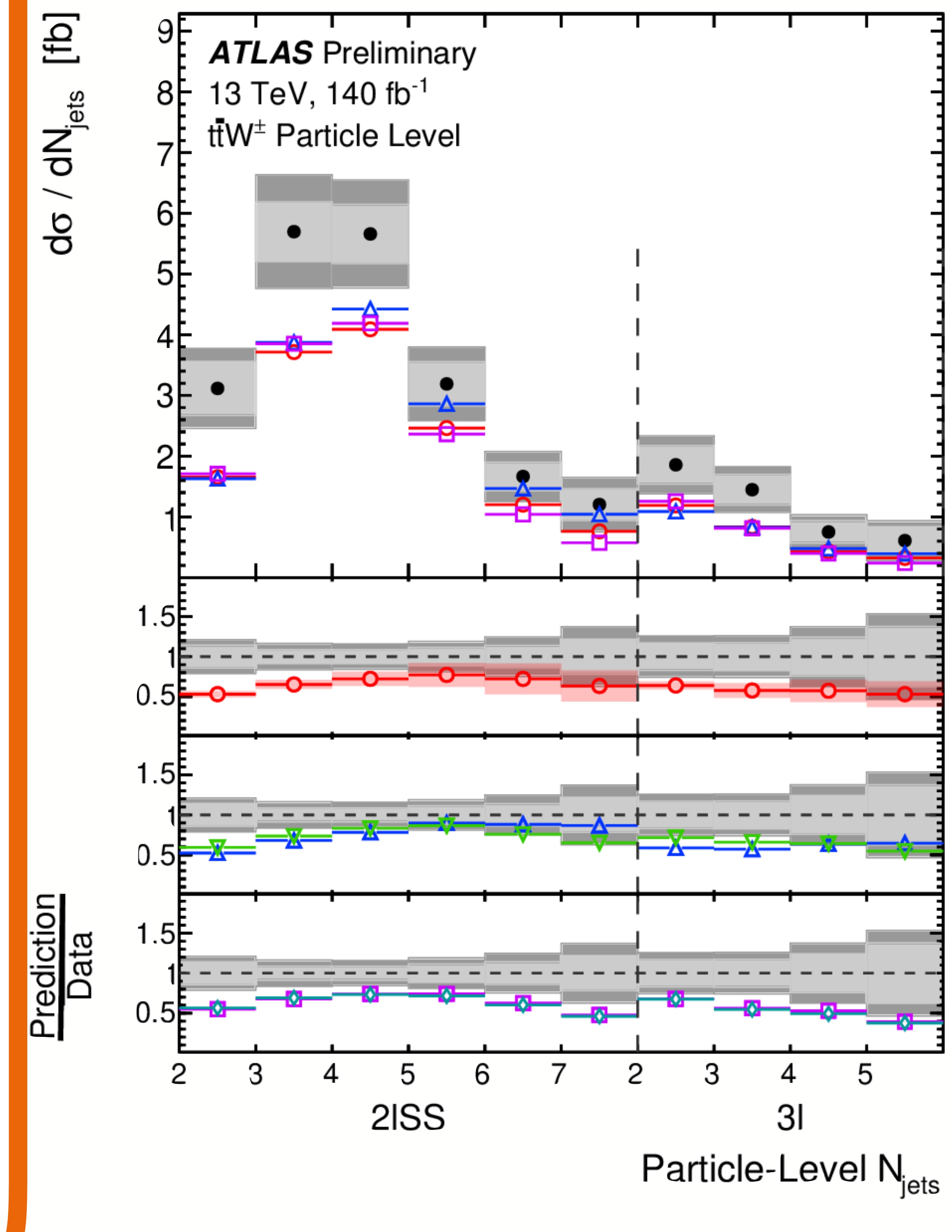


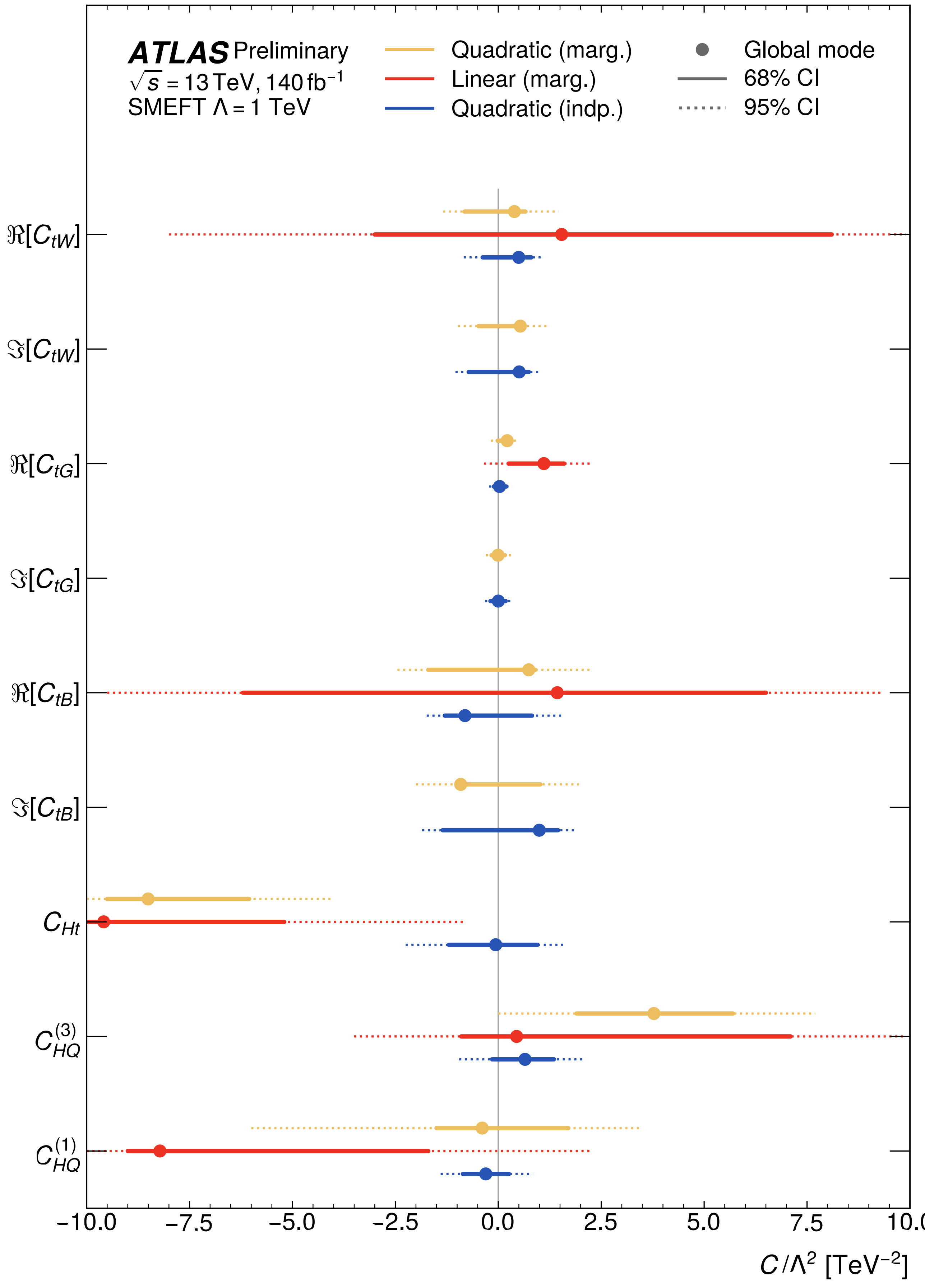


$t\bar{t}W$ and $t\bar{t}Z$ inclusive and differential

RESULTS

- *ttW*
  - Inclusive
    - $\sigma\left(t\bar{t}W\right) = 890 \pm 50\ (\text{stat.}) \pm 70\ (\text{syst.}) = 890 \pm 80\ \text{fb}$
      - 9% relative uncertainty. Limited by signal modelling
    - $\sigma\left(t\bar{t}W\right)^{NLO} = 722^{+70}_{-78}\ (\text{scale}) \pm 7\ (\text{PDF})\ \text{fb}$
      - Compatible at 1.5σ level
    - $R\left(t\bar{t}W\right) = 1.95^{+0.21}_{-0.18}\ (\text{stat.})^{+0.16}_{-0.13}\ (\text{syst.})$
    - $A_C^{\text{rel}} = \dfrac{\sigma(t\bar{t}W^+) - \sigma(t\bar{t}W^-)}{\sigma(t\bar{t}W^+) + \sigma(t\bar{t}W^-)} = 0.32 \pm 0.05\ (\text{stat.}) \pm 0.03\ (\text{syst.})$
  - Differential
    - Predictions disagree by a normalisation factor
- *ttZ*
  - Inclusive
    - $\sigma\left(t\bar{t}Z\right) = 0.86 \pm 0.04\ (\text{stat.}) \pm 0.04\ (\text{syst.})\ \text{pb}$
      - 6.5% relative uncertainty. Limited by background modelling
      - Reduced by 35% from previous measurement with same dataset! (ref)





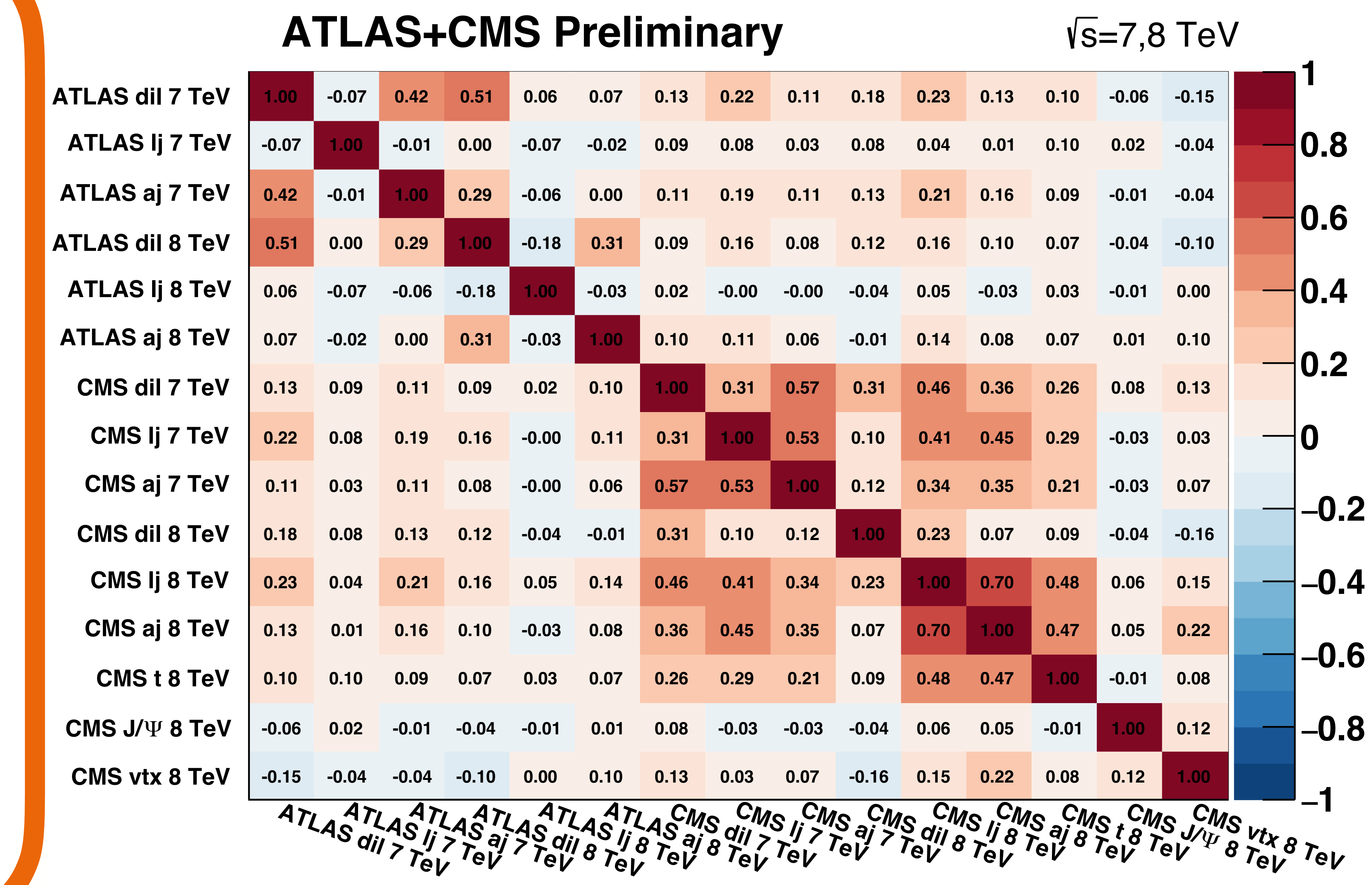
Combination of top mass measurement

GOAL & MOTIVATION

- Combine 15 top mass measurements
  - Both from ATLAS and CMS
  - $\sqrt{s} = 7$ and 8 TeV
  - Measured in both $t\bar{t}$ and t events

STRATEGY

- Combine using the best linear unbiased estimate (BLUE) method
  - Define an estimator $m_t = \Sigma_i w^i m_t^i$
  - w^i are defined by minimising the uncertainty in m_t
  - Consider all the measurements as statistically uncorrelated
  - Divide the systematics in 25 categories
    - Define a correlation strength ρ=0;0.5;0.85



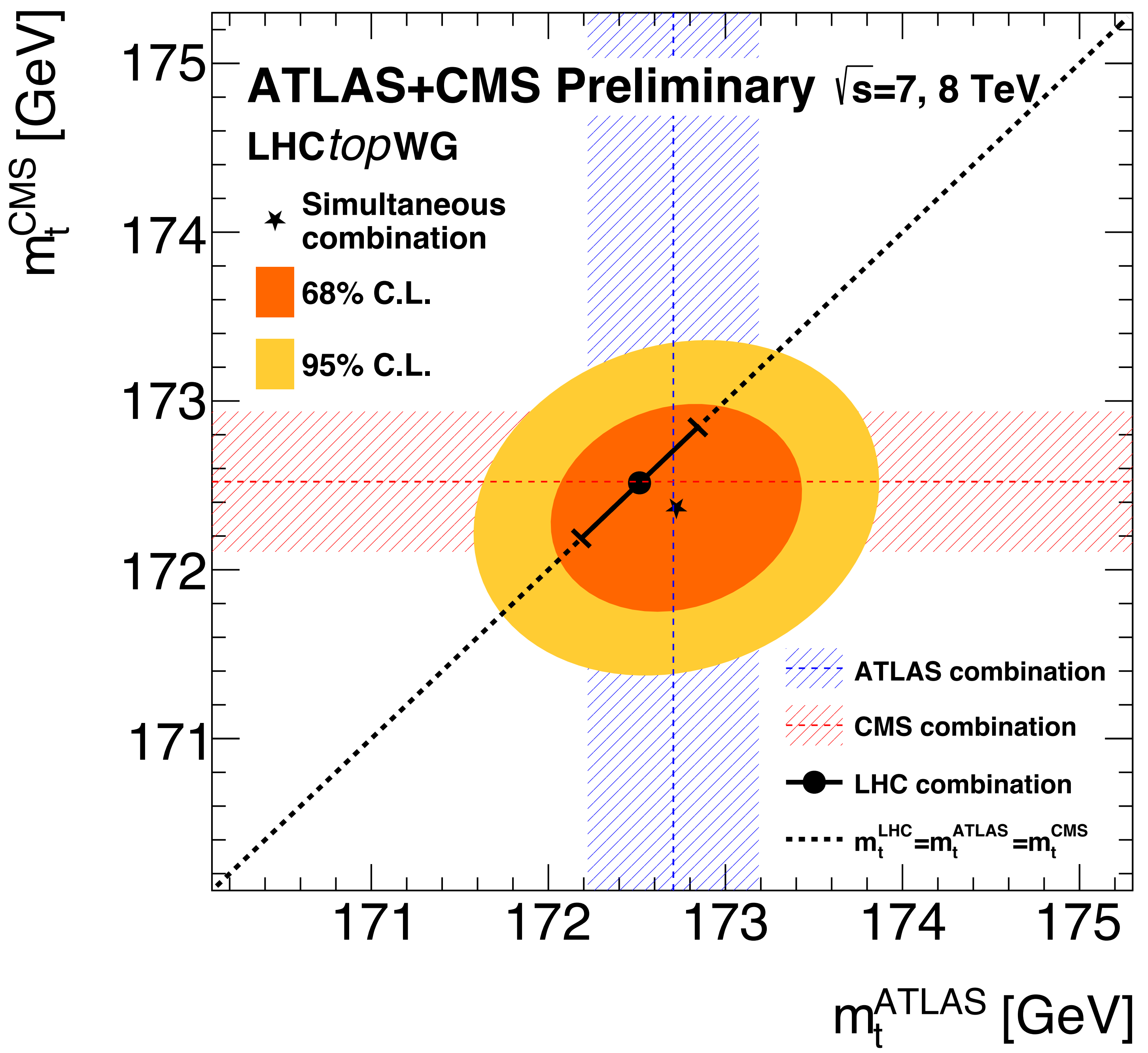
Combination of top mass measurement

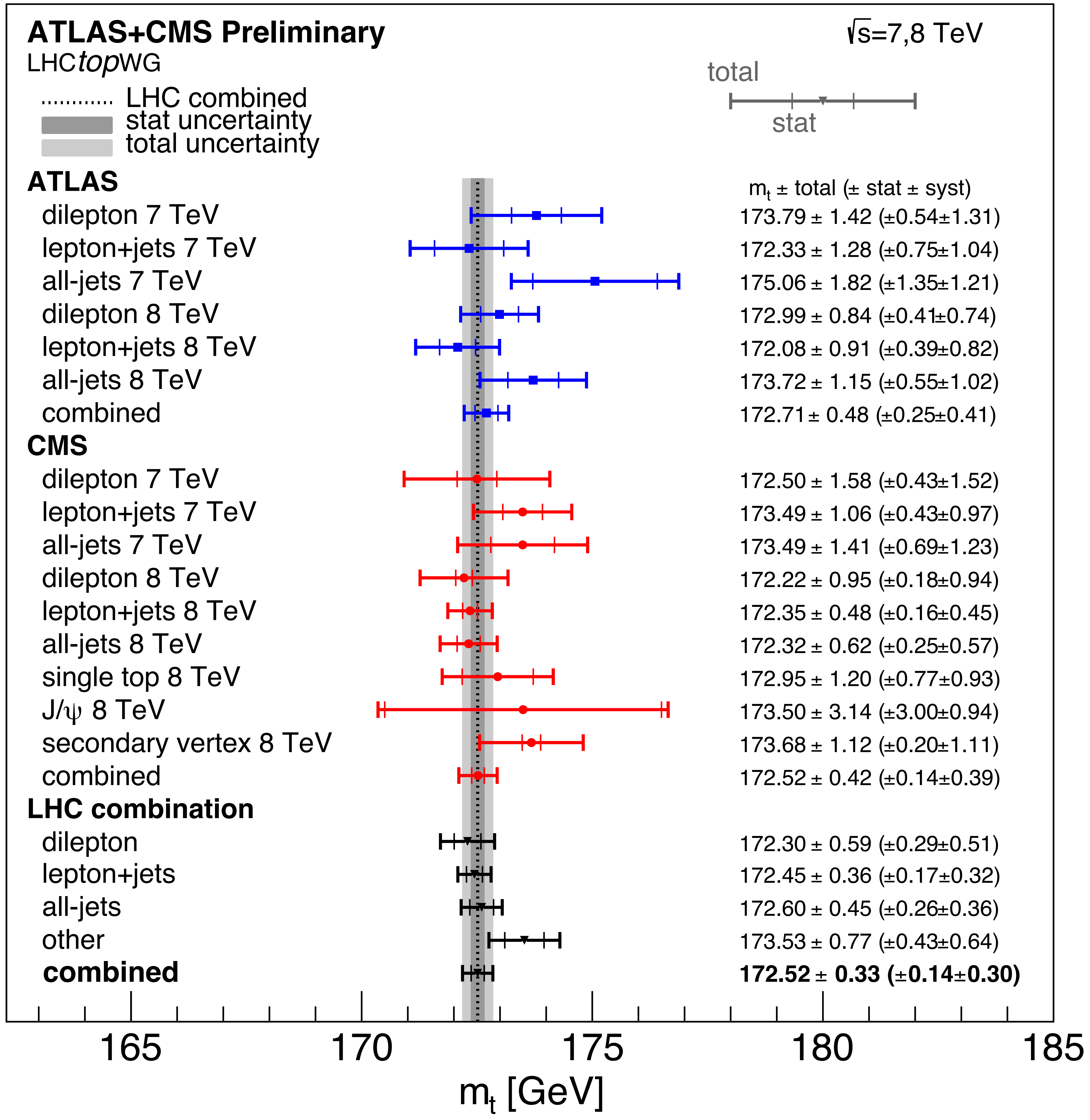
ATLAS EXPERIMENT

ROYAL HOLLOWAY UNIVERSITY OF LONDON

RESULTS

- ATLAS: $m_t = 172.71 \pm 0.25\ (\text{stat.}) \pm 0.41\ (\text{syst.})\ \text{GeV}$
- CMS: $m_t = 172.52 \pm 0.14\ (\text{stat.}) \pm 0.39\ (\text{syst.})\ \text{GeV}$
- LHC: $m_t = 172.52 \pm 0.14\ (\text{stat.}) \pm 0.30\ (\text{syst.})\ \text{GeV}$
  - 0.2% relative uncertainty!





Observation of quantum entanglement in top pairs

ATLAS EXPERIMENT

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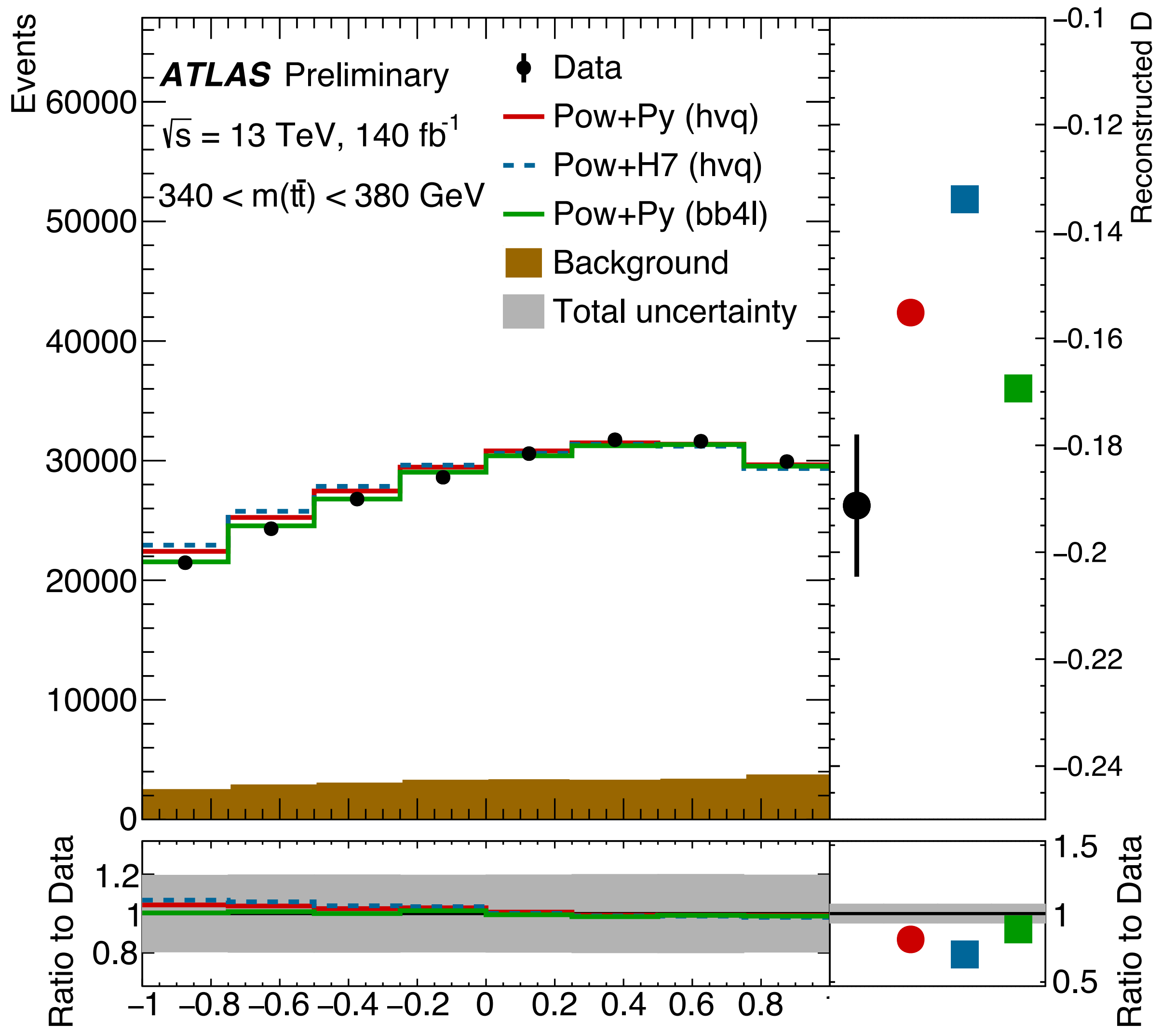
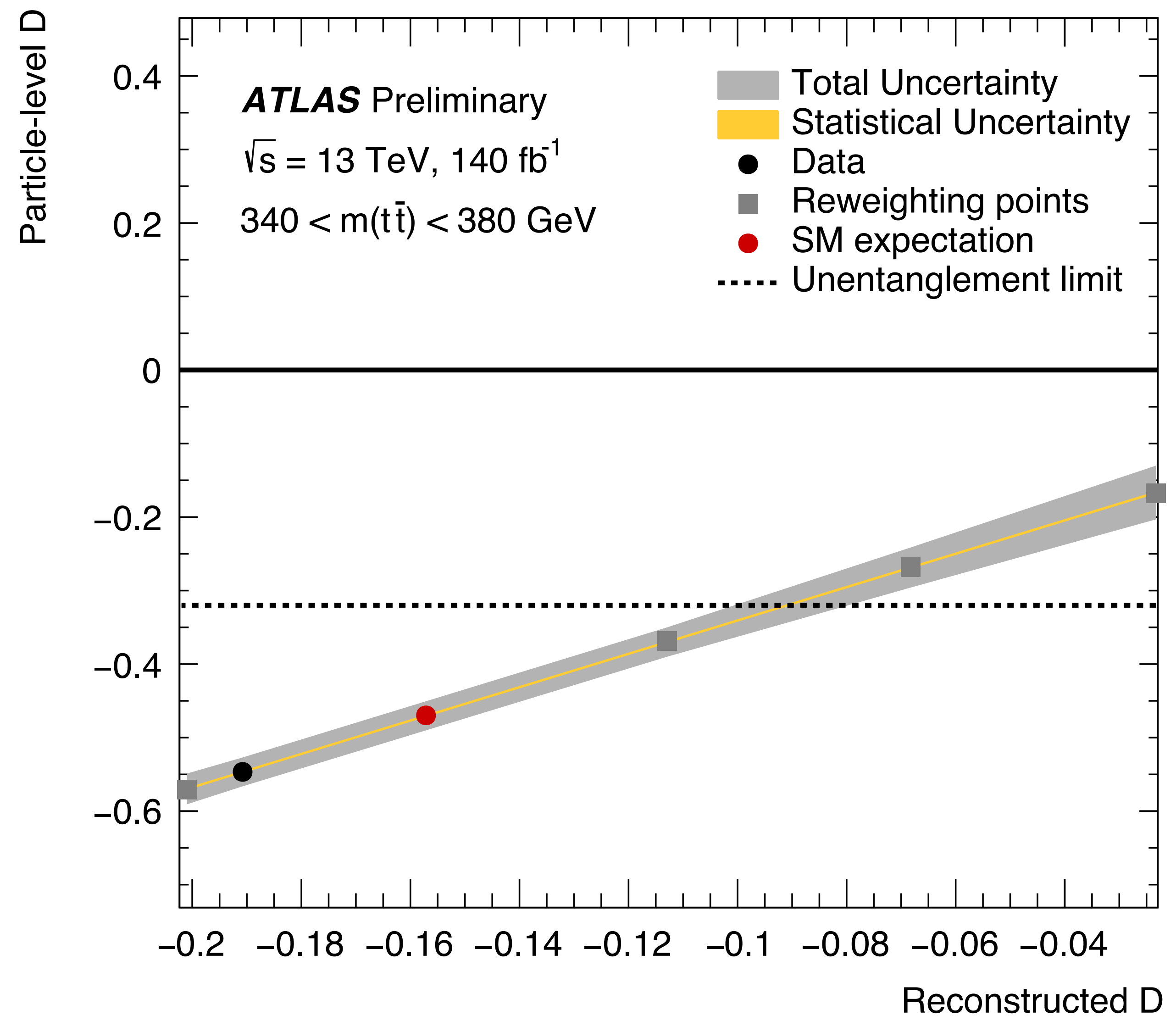
GOAL & MOTIVATION

- Measure the entanglement of a top-quark pair
  - Entangled particles $\rightarrow$ their quantum state cannot be described independently
  - The top quark decays before hadronising
    - Can measure its quantum state
  - Entanglement has never been measured at such high energies

STRATEGY

- Exploit the spin of the top as an entanglement marker using dilepton $t\bar{t}$ events
- Measure $D = tr\left[C\right]/3 = -3 \cdot < \cos\left(\phi\right) >$
  - C is the correlation matrix
  - $< \cos\left(\phi\right) >$ is the average of the cosine of angle between the charged lepton
- Define 3 regions
  - SR: $340 < m_{t\bar{t}} < 380$ GeV
  - VR1: $380 < m_{t\bar{t}} < 500$ GeV
  - VR2: $m_{t\bar{t}} > 500$ GeV
- Correct measured D to particle level with calibration curve
  - Maps detector level to particle level
- $D < -1/3 \rightarrow$ entanglement

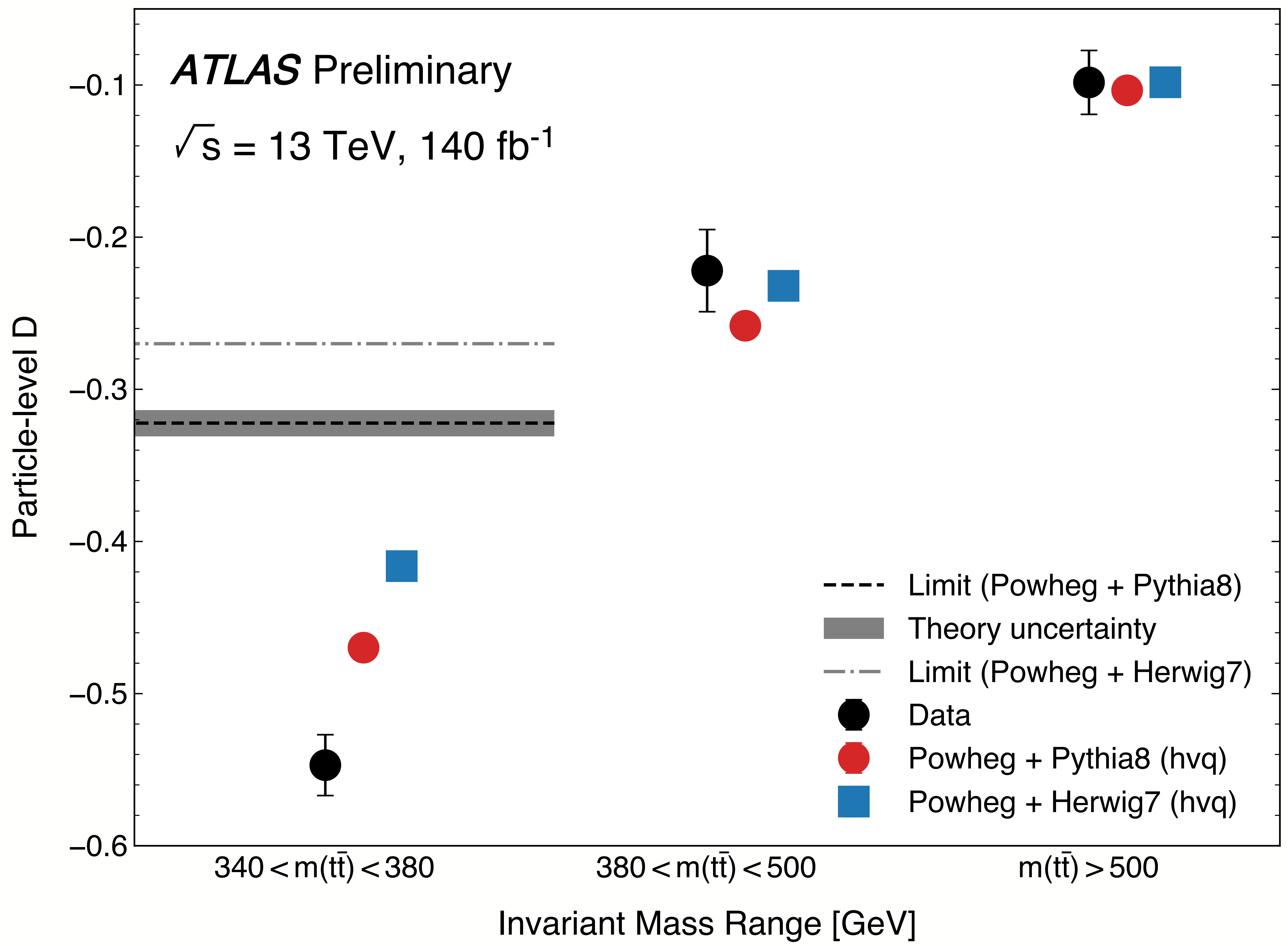




Observation of quantum entanglement in top pairs

RESULTS

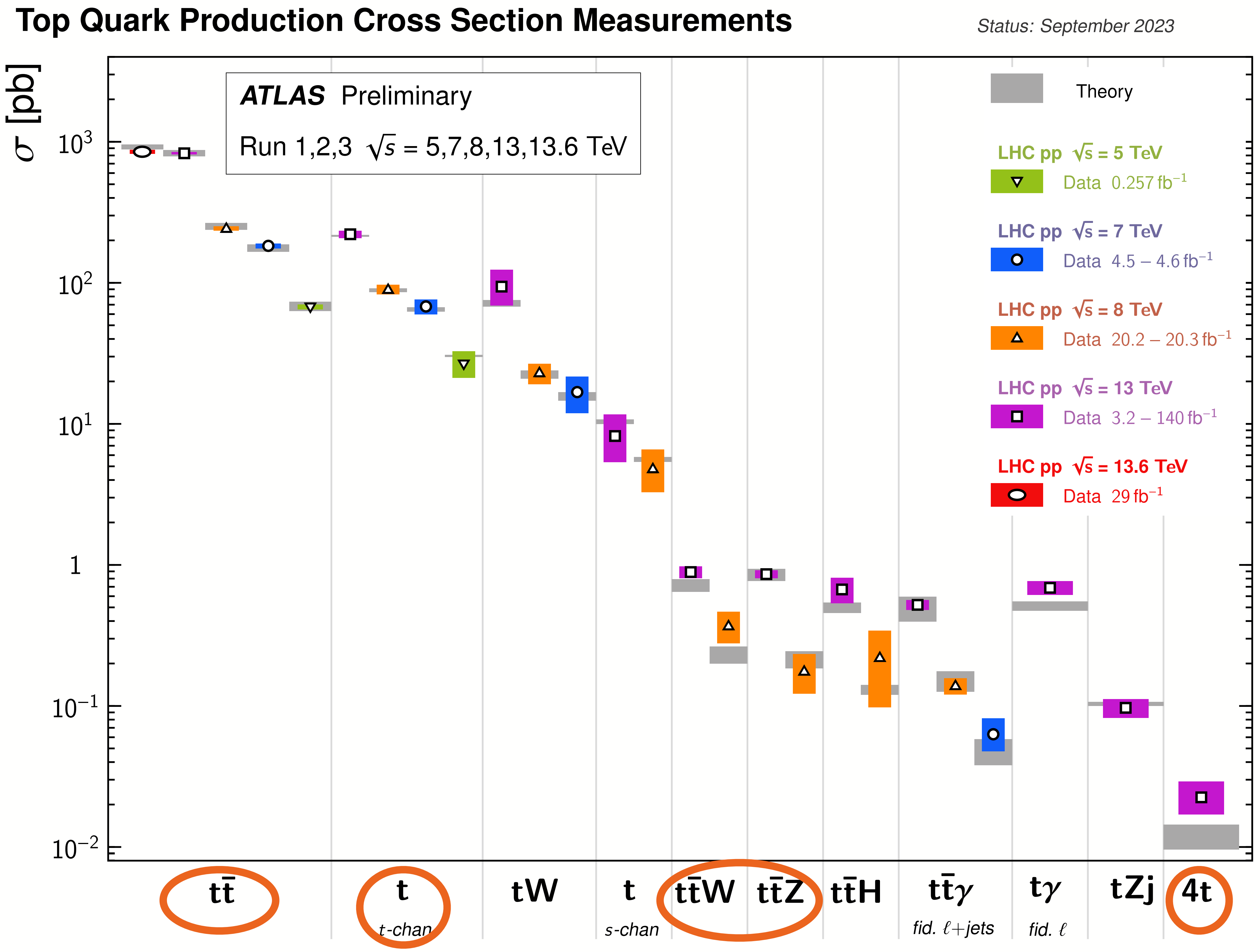
- SR:
  - $D = -0.547 \pm 0.002\,(\text{stat}) \pm 0.021\,(\text{syst})$
    - ~5% relative uncertainty, limited by signal modelling
    - 5σ away from a non entanglement scenario
  - $D^{\text{expected}} = -0.470 \pm 0.002\,(\text{stat}) \pm 0.018\,(\text{syst})$
- VR1:
  - $D = -0.222 \pm 0.001\,(\text{stat}) \pm 0.027\,(\text{syst})$
  - $D^{\text{expected}} = -0.258 \pm 0.001\,(\text{stat}) \pm 0.026\,(\text{syst})$
- VR2:
  - $D = -0.098 \pm 0.001\,(\text{stat}) \pm 0.021\,(\text{syst})$
  - $D^{\text{expected}} = -0.103 \pm 0.001\,(\text{stat}) \pm 0.021\,(\text{syst})$
- Discrepancy between data and MC in the SR
- Discrepancy between different MC predictions in the SR
- Agreement in the CRs



Summary

Several new results have been published within the ATLAS top-physics programme

- Cross-section
  - $t\bar{t}$ cross section measurement at 13.6 TeV
  - Observation of 4top
  - t-channel single-top cross section measurement at 5TeV and 13TeV
  - Differential dilepton and lepton+jets $t\bar{t}$ cross section measurement at 13TeV
  - Observation of $t\bar{t}$ in p-Pb collisions
  - Measurement of jet substructure in boosted $t\bar{t}$ events
- top+X
  - $t\bar{t}W$ and $t\bar{t}Z$ total and differential cross-section
  - FCNC searches in $tqH(\gamma\gamma)$ and combination
- Properties
  - Top-mass combination
  - Observation of quantum entanglement in top quark pair production



And much more!

BACKUP

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Run3 tt and Z cross section @ $\sqrt{s} = 13.6$ TeV

SELECTION

Preselection

- single-lepton triggers with logical OR applied
- 2 leptons with $p_T > 27$ GeV + trigger-matching

- **Selection**
  - =2 leptons with opposite charge ($p_T > 27$ GeV)
    - Electrons: TightLH ID, Tight_VarRad isolation
    - Muons: medium ID, Tight_VarRad isolation
  - emu channel: ≥ 1 jet, $p_T > 30$ GeV, b-tagged @77% efficiency, DL1dv01 tagger

UNCERTAINTIES

	Category	Uncert. [%]		
		$\sigma_{t\bar{t}}$	$\sigma^{\text{fid.}}_{Z\to\ell\ell}$	$R_{t\bar{t}/Z}$
$t\bar{t}$	$t\bar{t}$ parton shower/hadronisation	1.1	0.01	1.0
	$t\bar{t}$ scale variations	0.2	< 0.01	0.2
	Top quark p_T reweighting	0.6	0.02	0.5
Z	Z scale variations	0.2	0.5	0.3
Bkg.	Single top modelling	0.4	0.01	0.4
	Diboson modelling	0.1	0.06	< 0.01
	Mis-Id leptons	0.5	0.1	0.5
Lept.	Electron reconstruction	1.0	1.1	0.5
	Muon reconstruction	1.5	1.2	0.8
	Lepton trigger	0.4	0.7	0.8
Jets/tagging	Jet reconstruction	0.4	0.1	0.3
	Flavour tagging	0.2	0.01	0.2
	PDFs	0.4	0.2	0.4
	Pileup	1.1	1.1	< 0.01
	Luminosity	2.3	2.2	0.3
	Systematic Uncertainty	3.5	3.0	2.0
	Statistical Uncertainty	0.5	0.03	0.5
	Total Uncertainty	3.5	3.0	2.0

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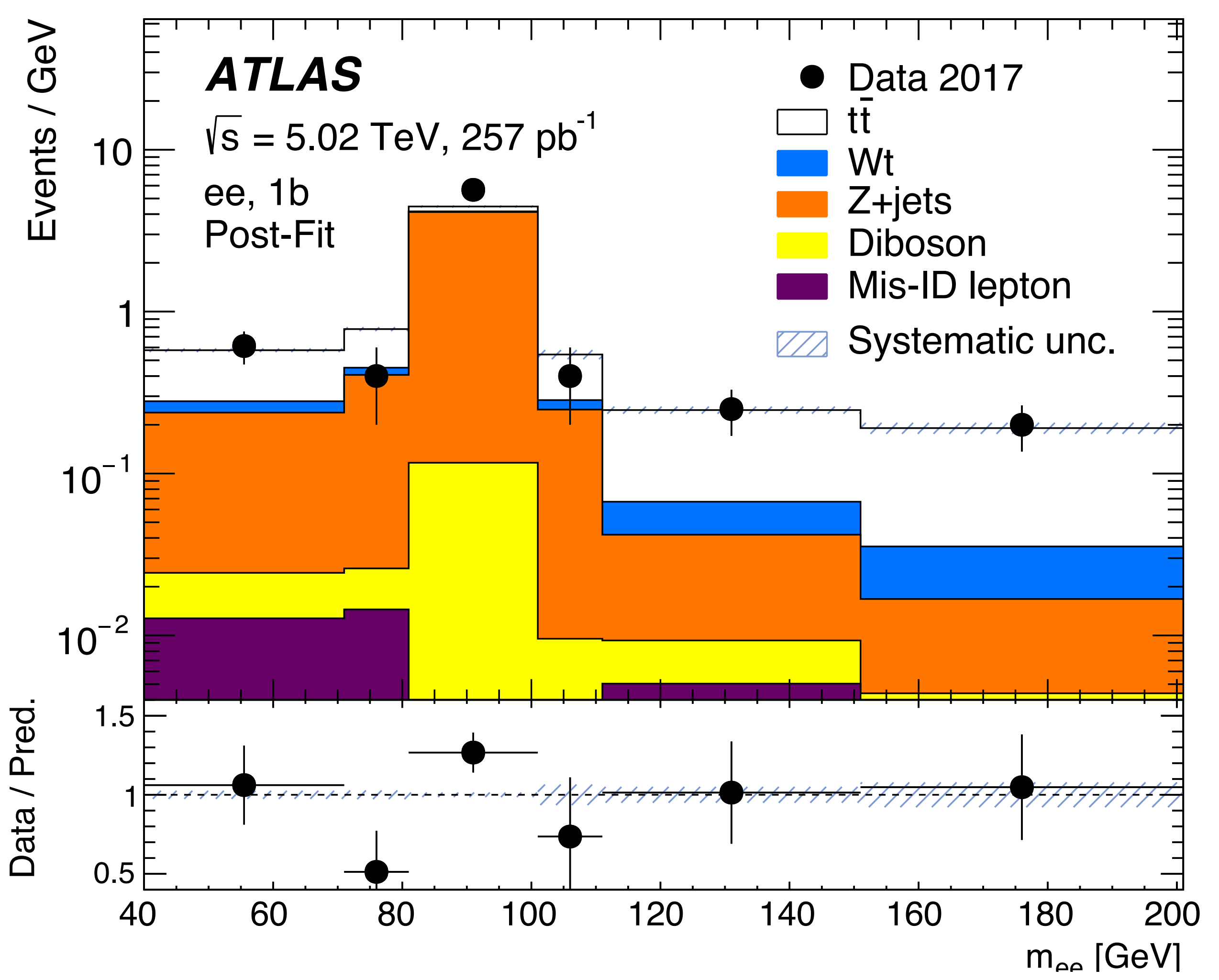
$t\bar{t}$ cross sections @ $\sqrt{s} = 5$ TeV

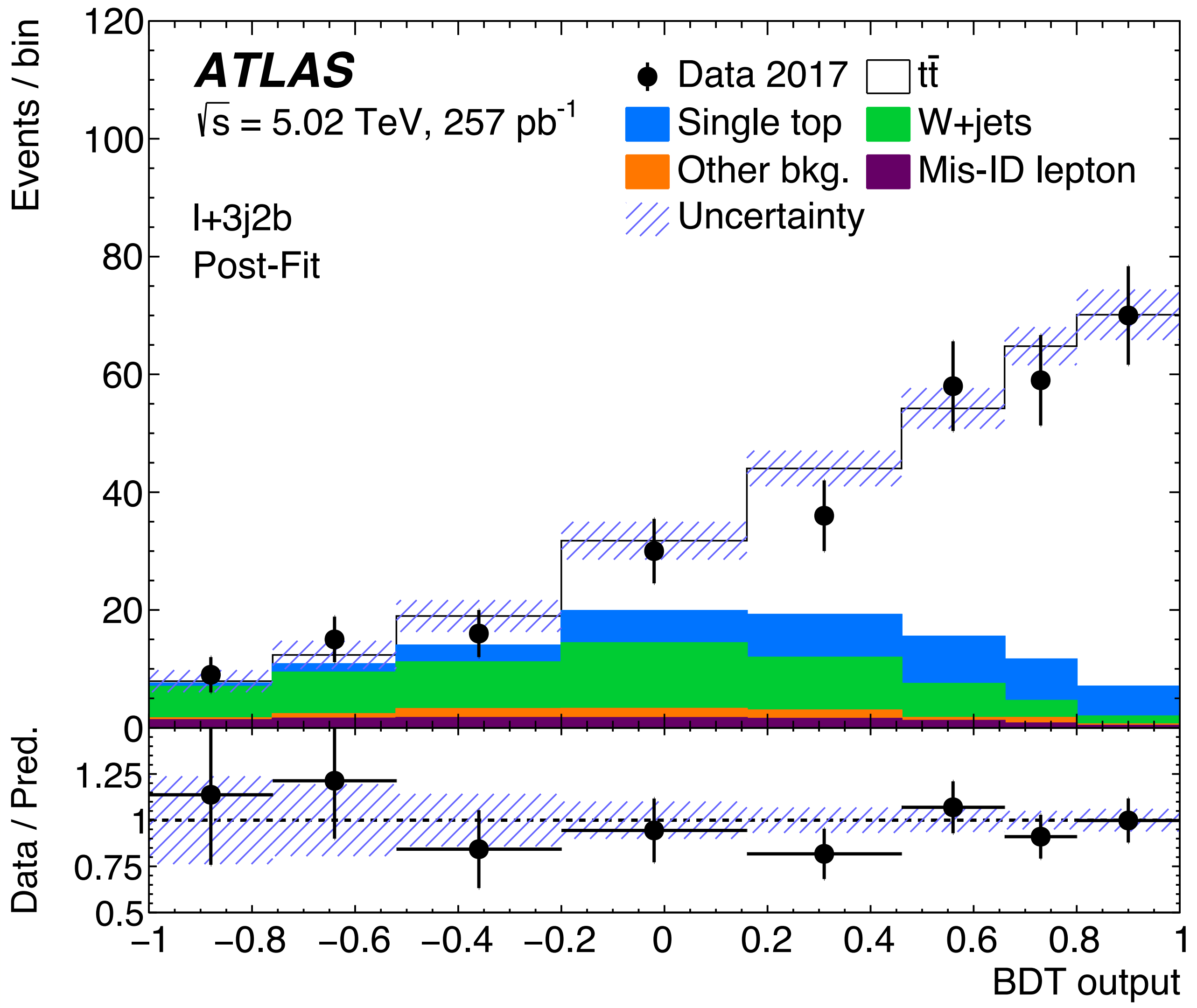
GOAL & MOTIVATION

- Measure the $t\bar{t}$ production cross-section @ $\sqrt{s} = 5.02$ TeV
  - 257pb^{-1}
- Test pQCD calculations
- Provide input for PDF

STRATEGY

- Dilepton channel
  - Maximum likelihood fit
  - Opposite flavour
    - b-tagging counting method
  - Same flavour
    - binned b-tagging counting method
- Single lepton channel
  - Maximum likelihood fit
  - Split by N-jets/N-bjets
    - data/MC fit BDT output
- Combine channels

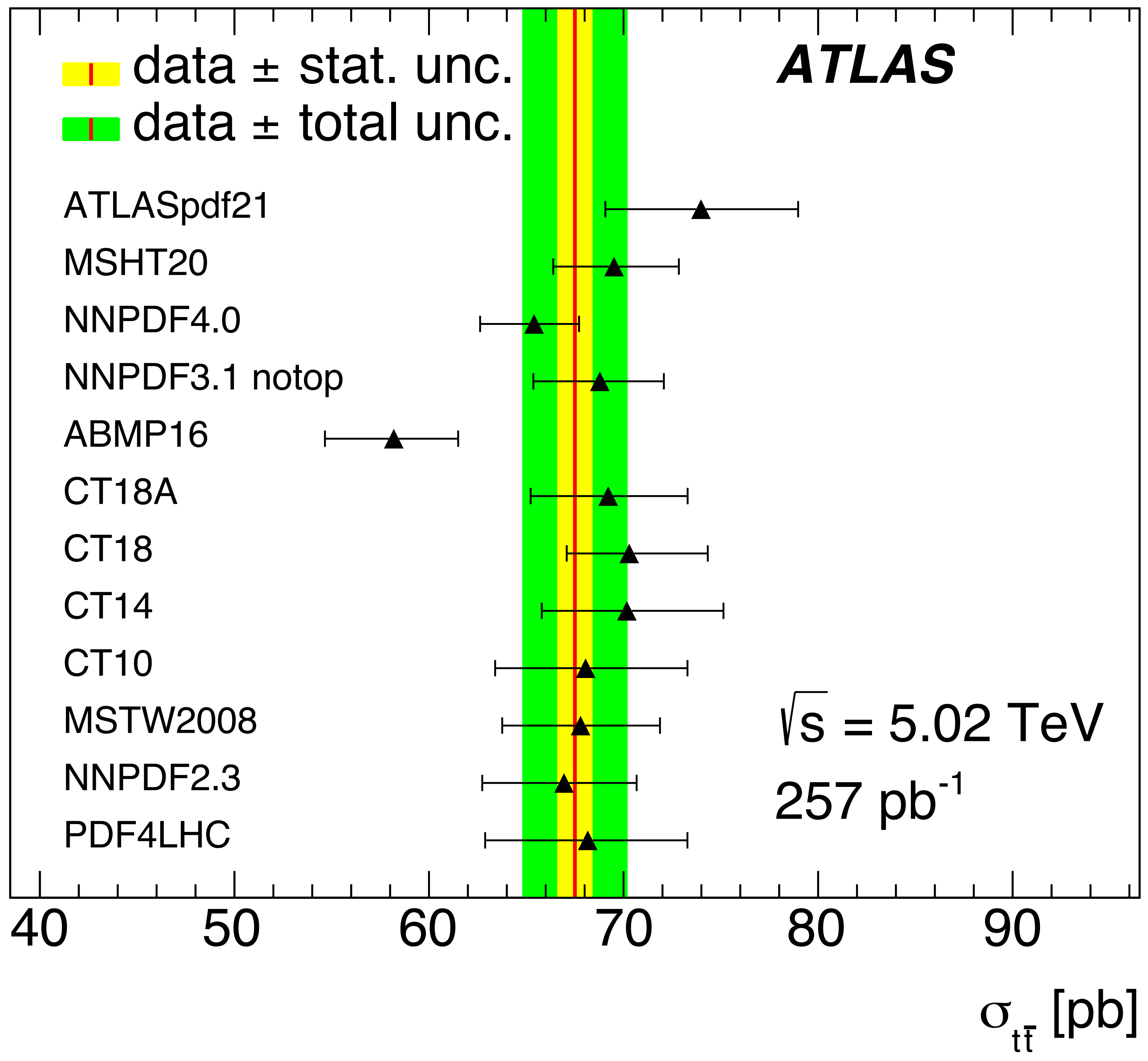




$t\bar{t}$ cross sections @ $\sqrt{s} = 5$ TeV

RESULTS

- Dilepton:
  - $\sigma_{t\bar{t}} = 65.7 \pm 4.5(\text{stat.}) \pm 1.6(\text{syst.}) \pm 1.2(\text{lumi.}) \pm 0.2(\text{beam})$ pb
- Single Lepton:
  - $\sigma_{t\bar{t}} = 68.2 \pm 0.9(\text{stat.}) \pm 2.9(\text{syst.}) \pm 1.1(\text{lumi.}) \pm 0.2(\text{beam})$ pb
- Combined:
  - $\sigma_{t\bar{t}} = 67.5 \pm 0.9(\text{stat.}) \pm 2.3(\text{syst.}) \pm 1.1(\text{lumi.}) \pm 0.2(\text{beam})$ pb



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$t\bar{t}$ cross sections @ $\sqrt{s} = 5$ TeV

ATLAS EXPERIMENT

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SELECTION

Both dilepton and single-lepton channels use the same objects:

- Single electron or single muon triggers, fully efficient for leptons with pT > 15 GeV
- Electrons: Medium LH, pT > 18 GeV (dilepton), 25 GeV (single-lepton), |eta| < 2.47

including transition region electrons in dilepton channel

- Muons: Medium, pT > 18 GeV (dilepton), 25 GeV (single-lepton), |eta| < 2.5
- FCTight isolation both for electrons and muons
- Jets: EMPflow jets, pT > 20 GeV (single-lepton), 25 GeV (dilepton), |eta| < 2.5, JVT cut
- b-tagging: DL1r at 85% efficiency (dilepton) and 70% (single-lepton)
- Lepton and jet pT cuts, as well as DL1r WPs optimised in both channels

- Event selections:
  - Dilepton:
    - exactly 2 opposite-sign leptons (eμ ee, μμ), exactly 1 or 2 b-tagged jets, m(ll) > 15 GeV in eμ, in same-flavour channels m(ll) > 40 GeV and MET > 30 GeV
  - Single-lepton:
    - exactly 1 electron or muon, ≥ 2 jets, of which at least 1 must be b-tagged, MET > 30 GeV and mTW > 30 GeV (a bit looser cut with ≥ 5 jets 2 b-jets selection)

REGIONS CRITERIA

Region	Jet multiplicity	b-jet multiplicity
$\ell + 2j \geq 1b$	2	≥ 1
$\ell + 3j\ 1b$	3	1
$\ell + 3j\ 2b$	3	2
$\ell + \geq 4j\ 1b$	≥ 4	1
$\ell + 4j\ 2b$	4	2
$\ell + \geq 5j\ 2b$	≥ 5	2

UNCERTAINTIES

Category	$\delta\sigma_{t\bar{t}}$ [%]		
	Dilepton	Single lepton	Combination
$t\bar{t}$ generator†	1.2	1.0	0.8
$t\bar{t}$ parton-shower/hadronisation*,†	0.3	0.9	0.7
$t\bar{t}$ h_{damp} and scale variations†	1.0	1.1	0.8
$t\bar{t}$ parton distribution functions†	0.2	0.2	0.2
Single-top background	1.1	0.8	0.6
W/Z + jets background*	0.8	2.4	1.8
Diboson background	0.3	0.1	< 0.1
Misidentified leptons*	0.7	0.3	0.3
Electron identification/isolation	0.8	1.2	0.8
Electron energy scale/resolution	0.1	0.1	< 0.1
Muon identification/isolation	0.6	0.2	0.3
Muon momentum scale/resolution	0.1	0.1	0.1
Lepton-trigger efficiency	0.2	0.9	0.7
Jet-energy scale/resolution	0.1	1.1	0.8
$\sqrt{s}$ = 5.02 TeV JES correction	0.1	0.6	0.5
Jet-vertex tagging	< 0.1	0.2	0.2
Flavour tagging	0.1	1.1	0.8
$E_{\text{T}}^{\text{miss}}$	0.1	0.4	0.3
Simulation statistical uncertainty*	0.2	0.6	0.5
Data statistical uncertainty*	6.8	1.3	1.3
Total systematic uncertainty	3.1	4.2	3.7
Integrated luminosity	1.8	1.6	1.6
Beam energy	0.3	0.3	0.3
Total uncertainty	7.5	4.5	3.9

dilepton $t\bar{t}$ production differential cross sections

ATLAS EXPERIMENT

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Selections:

- Single electron
- Single muon
- No requirements on jets
- No requirements on MET, HT, Mll
- Categorization in regions using the # of b-jets
- OS region -> Signal region

SELECTION

•**Electrons:**

- pW >25GeV&& η <1.37or1.52< η <2.47
- ID: Tight
- Efficiency Systematic Model: SIMPLIFIED
- Applied standard OR, TTVA and cut on d0-significance

• **Muons:**

- pW >25GeV&& η <2.5
- ID: Medium
- Applied standard OR, TTVA and cut on d0-significance

- **Jets**:
  - pW >25GeV&& η <2.5
  - JVT WP: Medium
  - Collection Name: AntiKt4EMTopoJets
- **b-tagging**:

• WP: 70% (mv2c10 > 0.83)

UNCERTAINTIES

Source of uncertainty	$\Delta\sigma^{\text{fid}}_{t\bar{t}}/\sigma^{\text{fid}}_{t\bar{t}}$ [%]	$\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ [%]
Data statistics	0.15	0.15
MC statistics	0.04	0.04
Matrix element	0.12	0.16
h_{damp} variation	0.01	0.01
Parton shower	0.08	0.22
$t\bar{t}$ + heavy flavour	0.34	0.34
Top p_{T} reweighting	0.19	0.58
Parton distribution functions	0.04	0.43
Initial-state radiation	0.11	0.37
Final-state radiation	0.29	0.35
Electron energy scale	0.10	0.10
Electron efficiency	0.37	0.37
Electron isolation (in situ)	0.51	0.51
Muon momentum scale	0.13	0.13
Muon reconstruction efficiency	0.35	0.35
Muon isolation (in situ)	0.33	0.33
Lepton trigger efficiency	0.05	0.05
Vertex association efficiency	0.03	0.03
Jet energy scale & resolution	0.10	0.10
b-tagging efficiency	0.07	0.07
$t\bar{t}/Wt$ interference	0.37	0.37
Wt cross-section	0.52	0.52
Diboson background	0.34	0.34
$t\bar{t}V$ and $t\bar{t}H$	0.03	0.03
Z + jets background	0.05	0.05
Misidentified leptons	0.32	0.32
Beam energy	0.23	0.23
Luminosity	0.93	0.93
Total uncertainty	1.6	1.8

dilepton $t\bar{t}$ production differential cross sections

SINGLE DIFFERENTIAL χ^2

Generator N_{dof}	p_{T}^{ℓ} 9	$\lvert\eta^{\ell}\rvert$ 23	$p_{\mathrm{T}}^{e\mu}$ 9	$p_{\mathrm{T}}^{e}+p_{\mathrm{T}}^{\mu}$ 10	$E^{e}+E^{\mu}$ 14	$m^{e\mu}$ 20	$\lvert\Delta\phi^{e\mu}\rvert$ 29	$\lvert y^{e\mu}\rvert$ 29
POWHEG+PYTHIA 8	196	132	12.0	130	33	102	193	47
POWHEG+PYTHIA 8 - top p_{T} rew.	51	114	7.8	42	20.4	53	65	45.2
POWHEG+PYTHIA 8 - $h_{\mathrm{damp}} \times 2$	228	139	26	167	38	97	121	45.3
POWHEG+PYTHIA 8 - PDF4LHC	186	100	11.5	125	32	93	185	33.6
POWHEG+PYTHIA 8 - ISR up	149	111	17.3	120	34	79	66	50
POWHEG+PYTHIA 8 - ISR down	216	159	10.6	131	30	113	311	44.5
POWHEG+PYTHIA 8 - Rad up	164	115	27	139	38	78	49	47.6
POWHEG+PYTHIA 8 - Rad down	216	159	10.6	131	30	113	311	44.5
POWHEG+PYTHIA 8 - FSR up	216	132	12.5	143	35	106	194	46.8
POWHEG+PYTHIA 8 - FSR down	171	139	9.5	118	30	98	185	49
POWHEG+PYTHIA 8 - MEC off	42	136	41	37	16.5	83	181	42.7
aMC@NLO+PYTHIA 8	16.5	126	48	14.4	14.3	89	300	50
aMC@NLO+HERWIG 7.0.4	98	137	24	74	24.1	29.1	110	54
Powheg+Herwig 7.0.4	113	104	28	82	28	135	271	45.8
Powheg+Herwig 7.1.3	101	107	31	75	25.5	138	259	45.5

DOUBLE DIFFERENTIAL χ^2

Generator N_{dof}	$\lvert y^{e\mu}\rvert : m^{e\mu}$ 39	$\lvert\Delta\phi^{e\mu}\rvert : m^{e\mu}$ 39	$\lvert\Delta\phi^{e\mu}\rvert : p_{\mathrm{T}}^{e\mu}$ 24	$\lvert\Delta\phi^{e\mu}\rvert : E^{e}+E^{\mu}$ 39
POWHEG+PYTHIA 8	131	364	264	263
POWHEG+PYTHIA 8 - top p_{T} rew.	82	140	81	96
POWHEG+PYTHIA 8 - $h_{\mathrm{damp}} \times 2$	129	250	182	183
POWHEG+PYTHIA 8 - PDF4LHC	114	351	252	253
POWHEG+PYTHIA 8 - ISR up	108	153	105	112
POWHEG+PYTHIA 8 - ISR down	143	562	413	409
POWHEG+PYTHIA 8 - Rad up	109	130	90	104
POWHEG+PYTHIA 8 - Rad down	143	562	413	409
POWHEG+PYTHIA 8 - FSR up	137	374	271	268
POWHEG+PYTHIA 8 - FSR down	122	349	247	255
POWHEG+PYTHIA 8 - MEC off	107	276	219	237
aMC@NLO+PYTHIA 8	108	436	363	386
aMC@NLO+HERWIG 7.0.4	95	270	154	162
Powheg+Herwig 7.0.4	151	400	334	345
Powheg+Herwig 7.1.3	147	392	318	336

Observation of four-top-quark production

ATLAS EXPERIMENT

ROYAL HOLLOWAY UNIVERSITY OF LONDON

SELECTION

	Electrons	Muons	Jets	b−jets
p_T [GeV]	$> 15(28)$	$> 15(28)$	> 20	> 20
η	< 1.37 or $1.52 - 2.47$	< 2.5	< 2.5	< 2.5
ID quality	Tight ECIDS ($ee, e\mu$)	Medium	cleaning + JVT	DL1r 77%
Isolation	PLImprovedTight	PLImprovedTight		
Track Vertex:				
- $\lvert d_0/\sigma_{d_0}\rvert$	< 5	< 3		
- $\lvert z_0 \sin\theta\rvert$ [mm]	< 0.5	< 0.5		

EFT AND μ INTERVALS

Processes	95% CL cross section interval [fb] $\mu_{t\bar{t}t\bar{t}} = 1$	95% CL cross section interval [fb] $\mu_{t\bar{t}t\bar{t}} = 1.9$
$t\bar{t}t$	[4.7, 60]	[0, 41]
$t\bar{t}tW$	[3.1, 43]	[0, 30]
$t\bar{t}tq$	[0, 144]	[0, 100]

Operators	Expected C_i/Λ^2 [TeV $^{-2}$]	Observed C_i/Λ^2 [TeV $^{-2}$]
O^1_{QQ}	[-2.4, 3.0]	[-3.5, 4.1]
O^1_{Qt}	[-2.5, 2.0]	[-3.5, 3.0]
O^1_{tt}	[-1.1, 1.3]	[-1.7, 1.9]
O^8_{Qt}	[-4.2, 4.8]	[-6.2, 6.9]

REGIONS DEFINITION

Region	Channel	N_j	N_b	Other selection	Fitted variable
CR Low m_{γ^*}	SS, ee or eμ	$4 \leq N_j < 6$	≥ 1	ℓ_1 or ℓ_2 is from virtual photon (γ^*) decay ℓ_1 and ℓ_2 are not from photon conversion	counting
CR Mat. Conv.	SS, ee or eμ	$4 \leq N_j < 6$	≥ 1	ℓ_1 or ℓ_2 is from photon conversion	counting
CR HF μ	e$\mu\mu$ or $\mu\mu\mu$	≥ 1	$= 1$	$100 < H_T < 300$ GeV $E_T^{miss} > 50$ GeV total charge = ±1	$p_T^{\ell_3}$
CR HF e	eee or eeμ	≥ 1	$= 1$	$100 < H_T < 275$ GeV $E_T^{miss} > 35$ GeV total charge = ±1	$p_T^{\ell_3}$
CR $t\bar{t}W^+$+jets	SS, eμ or $\mu\mu$	≥ 4	≥ 2	$\lvert\eta(e)\rvert < 1.5$ when $N_b = 2$: $H_T < 500$ GeV or $N_j < 6$ when $N_b \geq 3$: $H_T < 500$ GeV total charge > 0	N_j
CR $t\bar{t}W^-$+jets	SS, eμ or $\mu\mu$	≥ 4	≥ 2	$\lvert\eta(e)\rvert < 1.5$ when $N_b = 2$: $H_T < 500$ GeV or $N_j < 6$ when $N_b \geq 3$: $H_T < 500$ GeV total charge < 0	N_j
CR 1b(+)	2LSS+3L	≥ 4	$= 1$	ℓ_1 and ℓ_2 are not from photon conversion $H_T > 500$ GeV total charge > 0	N_j
CR 1b(-)	2LSS+3L	≥ 4	$= 1$	ℓ_1 and ℓ_2 are not from photon conversion $H_T > 500$ GeV total charge < 0	N_j
SR	2LSS+3L	≥ 6	≥ 2	$H_T > 500$ GeV	GNN score

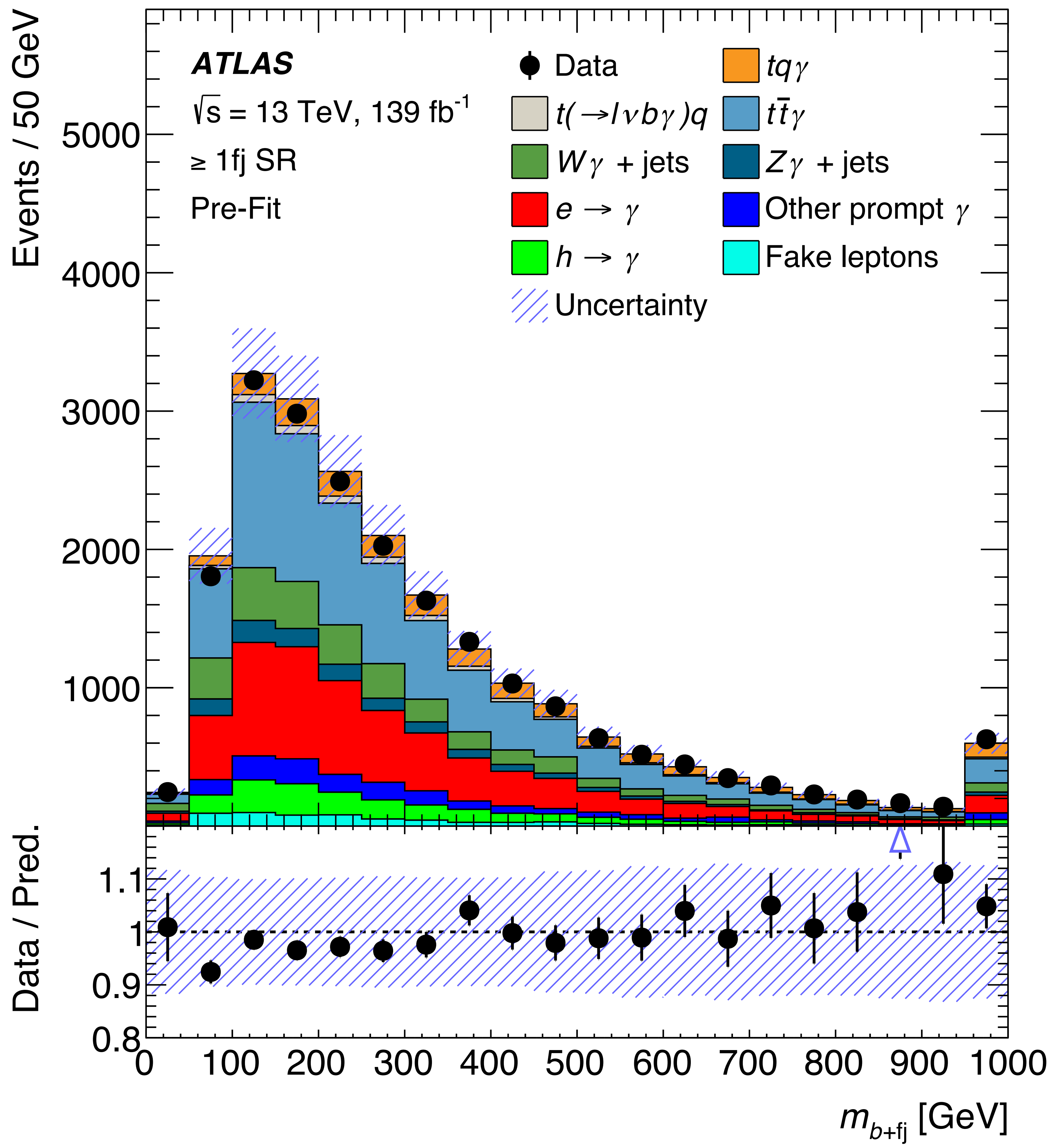
Observation of $t\gamma$

MOTIVATION

- Measure the rare production of a top quark in association with a photon
  - Probe top quark's EW couplings
  - Probe BSM theories

STRATEGY

- Measure fiducial parton- and particle-level cross-section
- Use NN to discriminate signal and bkg in SR
- Profile Likelihood fit in SRs and CRs
  - Fit NN outputs in SRs
  - Fit NN outputs and event yield in CRs

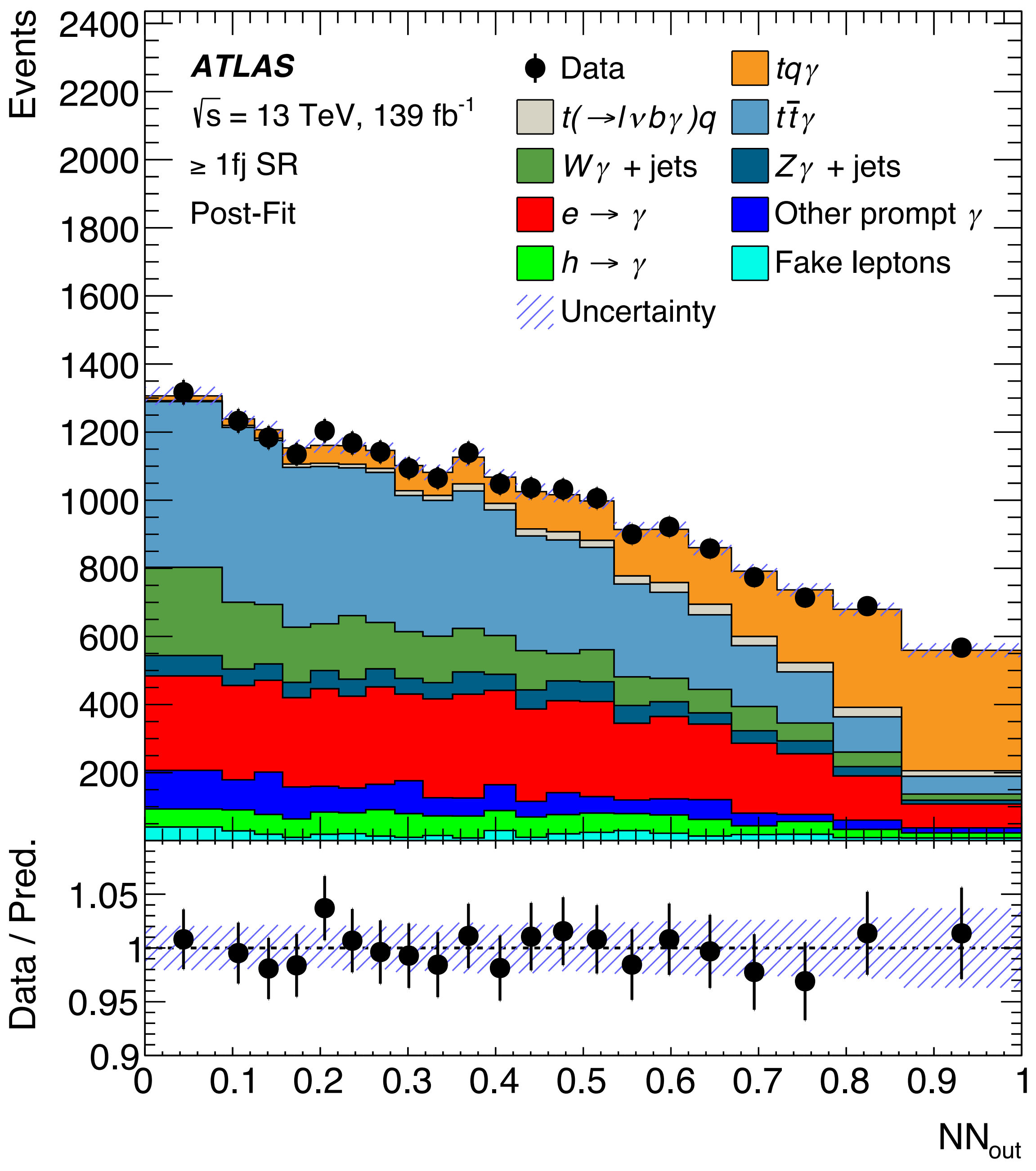


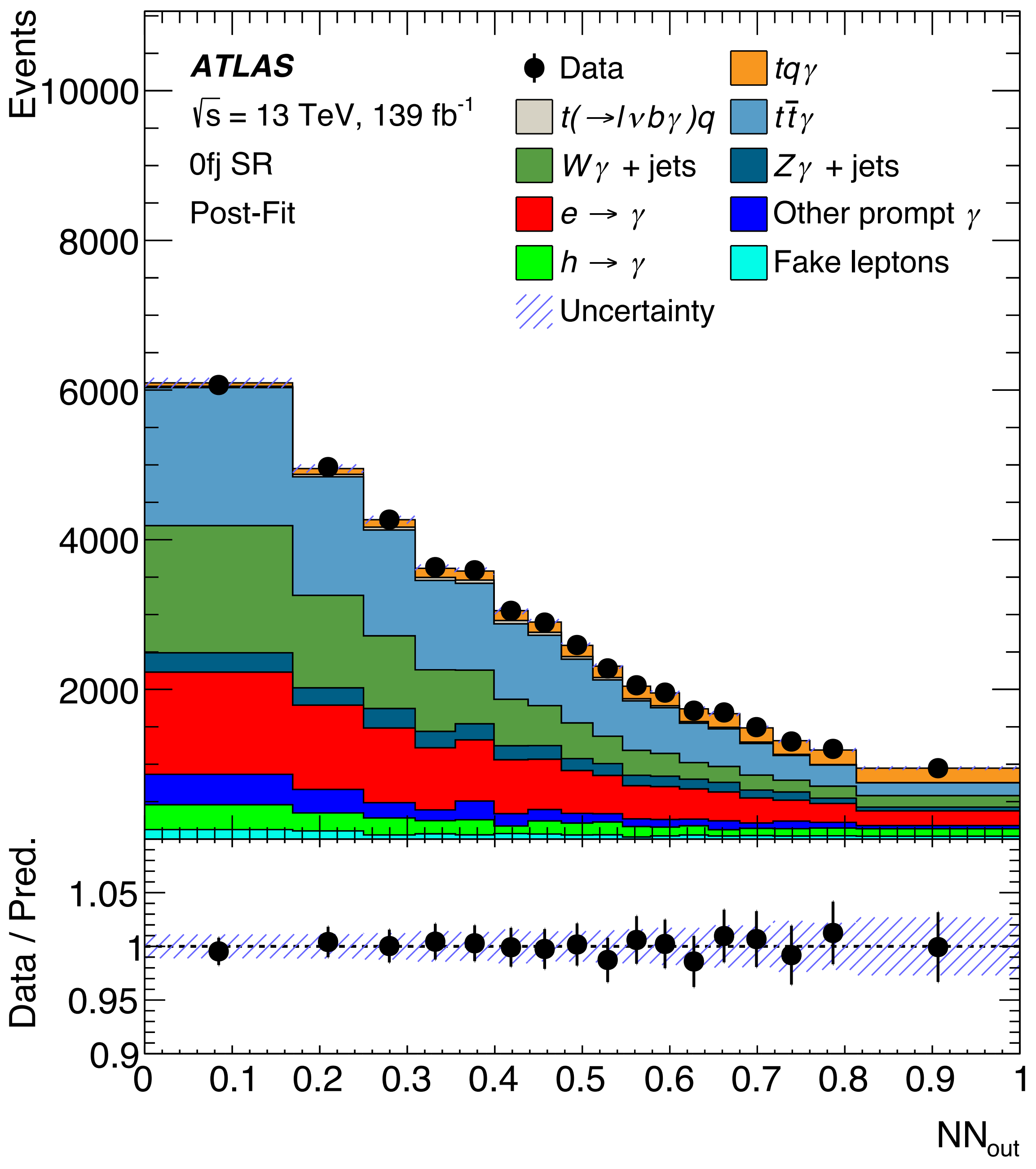
Phys. Rev. Lett. 131 (2023) 181901

Observation of $t\gamma$

RESULTS

- Fiducial parton-level cross-section:
  - $\sigma_{tq\gamma} \times \mathcal{B}\left(t \to \ell \nu b\right) = 688 \pm 23(\text{stat.})\ ^{+75}_{-71}(\text{syst.})\ \text{fb}$
- Fiducial particle-level cross-section:
  - $\sigma_{tq\gamma} \times \mathcal{B}\left(t \to \ell \nu b\right) + \sigma_{t(\to \ell \nu b \gamma)} = 303 \pm 9(\text{stat.})\ ^{+33}_{-32}(\text{syst.})\ \text{fb}$
- $tq\gamma$ signal strength
  - $9.3\sigma\ \ (\text{expected } 6.8\sigma)$





arXiv:2302.01283

Observation of $t\gamma$

SELECTION

- Signal modelling
- Definition of SRs and CRs for $t\bar{t}\gamma$ and $W\gamma$+jets
  - SRs for events with $\geq$ 1 and 0 forward jets
- Categorize events in MC into
  - prompt photons, $e \to \gamma$ fakes or $h \to \gamma$ fakes
- Estimate $e \to \gamma$
  - data-driven estimation with tag-and-probe method $\frac{N(Z\to e(e\to\gamma))}{N(Z\to ee)}$
- Estimate $h \to \gamma$
  - data-driven estimation with ABCD method
- Estimate non-prompt lepton contribution
  - data-driven estimation with matrix method
- Signal and background discrimination using neural networks
- Binned profile likelihood fit to SRs and CRs
  - **Observation!**
  - Fiducial cross section measurements

PRE-SELECTION REGION

Object/Variable	PSR
Photons	≥ 1 w/ $p_T > 20$ GeV
Leptons	$= 1$ w/ $p_T > 27$ GeV
Jets	≥ 1 w/ $p_T > 25$ GeV
being b-tagged	$= 1$ DL1r 70% WP
E_T^{miss}	> 30 GeV
$m_{e\gamma}$	not in $[80, 100]$ GeV

SIGNAL AND CONTROL REGIONS

Object/Variable	inc SR		$t\bar{t}\gamma$ CR	$W\gamma$ CR
Photons	≥ 1 w/ $p_T > 20$ GeV		≥ 1 w/ $p_T > 20$ GeV	≥ 1 w/ $p_T > 20$ GeV
Leptons	$= 1$ w/ $p_T > 27$ GeV		1 w/ $p_T > 27$ GeV	$= 1$ w/ $p_T > 27$ GeV
Jets	≥ 1 w/ $p_T > 25$ GeV		**≥ 2 w/ $p_T > 25$ GeV**	≥ 1 w/ $p_T > 25$ GeV
being b-tagged	$= 1$ DL1r 70%		$= 1$ DL1r 70%	**$= 0$ DL1r 70%**
	$= 1$ DL1r 85%		**>1 DL1r 85%**	**≥ 1 DL1r 85%**
E_T^{miss}	> 30 GeV		> 30 GeV	> 30 GeV
$m_{e\gamma}$	not in $[80, 100]$ GeV		not in $[80, 100]$ GeV	not in $[80, 100]$ GeV
	0fj SR	$\geq$ 1fj SR		
Jets with $\lvert\eta\rvert > 2.5$	$=0$	≥ 1		

Observation of $t\gamma$

PARTICLE LEVEL UNCERTAINTIES

Uncertainty	$\Delta\sigma/\sigma$
$t\bar{t}\gamma$ modeling	±5.5%
Background MC statistics	±3.5%
$tq\gamma$ MC statistics	±3.3%
$t\bar{t}$ modeling	±2.4%
$tq\gamma$ modeling	±2.0%
$t\,(\rightarrow \ell\nu b\gamma)\,q$ modeling	±1.9%
Additional background uncertainties	±1.9%
$t\,(\rightarrow \ell\nu b\gamma)\,q$ MC statistics	±0.3%
$h \rightarrow \gamma$ photon fakes	±2.0%
Lepton fakes	±1.9%
$e \rightarrow \gamma$ photon fakes	±0.6%
Luminosity	±2.2%
Pileup	±1.2%
Jets and $E_{\mathrm{T}}^{\mathrm{miss}}$	±3.6%
Photons	±2.5%
Leptons	±0.9%
b-tagging	±0.9%
Total systematic uncertainty	±10.6%

PARTON LEVEL UNCERTAINTIES

Uncertainty	$\Delta\sigma/\sigma$
$t\bar{t}\gamma$ modeling	±5.5%
Background MC statistics	±3.6%
$t\,(\rightarrow \ell\nu b\gamma)\,q$ modeling	±3.3%
$tq\gamma$ MC statistics	±3.0%
$t\bar{t}$ modeling	±2.3%
$tq\gamma$ modeling	±2.3%
Additional background uncertainties	±2.0%
$t\,(\rightarrow \ell\nu b\gamma)\,q$ MC statistics	±0.3%
Lepton fakes	±2.2%
$h \rightarrow \gamma$ photon fakes	±2.1%
$e \rightarrow \gamma$ photon fakes	±0.6%
Luminosity	±2.2%
Pileup	±1.3%
Jets and $E_{\mathrm{T}}^{\mathrm{miss}}$	±3.5%
Photons	±2.5%
Leptons	±0.9%
b-tagging	±0.7%
Total systematic uncertainty	±10.7%

NN INPUTS

Input feature	Used in 0fj SR NN	Used in ≥ 1fj SR NN
$\eta(\gamma)$	✓	
$p_{\mathrm{T}}(\ell)$	✓	
$\eta(\ell)$	✓	
Is ℓ an electron or muon?		✓
$p_{\mathrm{T}}(b)$	✓	✓
$\eta(b)$	✓	
b-tagging bin	✓	✓
$p_{\mathrm{T}}(\mathrm{fj})$		✓
m_t	✓	✓
H_{T}	✓	✓
$\Delta R(\gamma, \ell)$	✓	✓
$p_{\mathrm{T}}(t, \gamma)$	✓	
$m_{\mathrm{T}}(\ell, E_{\mathrm{T}}^{\mathrm{miss}})$		✓
$\Delta R(\ell, b)$	✓	✓
$m(\ell, b)$		✓
$m_{\mathrm{T}}(\gamma, \ell, E_{\mathrm{T}}^{\mathrm{miss}})$	✓	✓
$E(\gamma, \mathrm{fj})$		✓
$\Delta\eta(\gamma, \mathrm{fj})$		✓
$\Delta R(\ell, \mathrm{fj})$		✓
$m(b, \mathrm{fj})$		✓

Search for FCNC in $tqH\,(\tau\tau)$ and tqZ

ATLAS EXPERIMENT

ROYAL HOLLOWAY UNIVERSITY OF LONDON

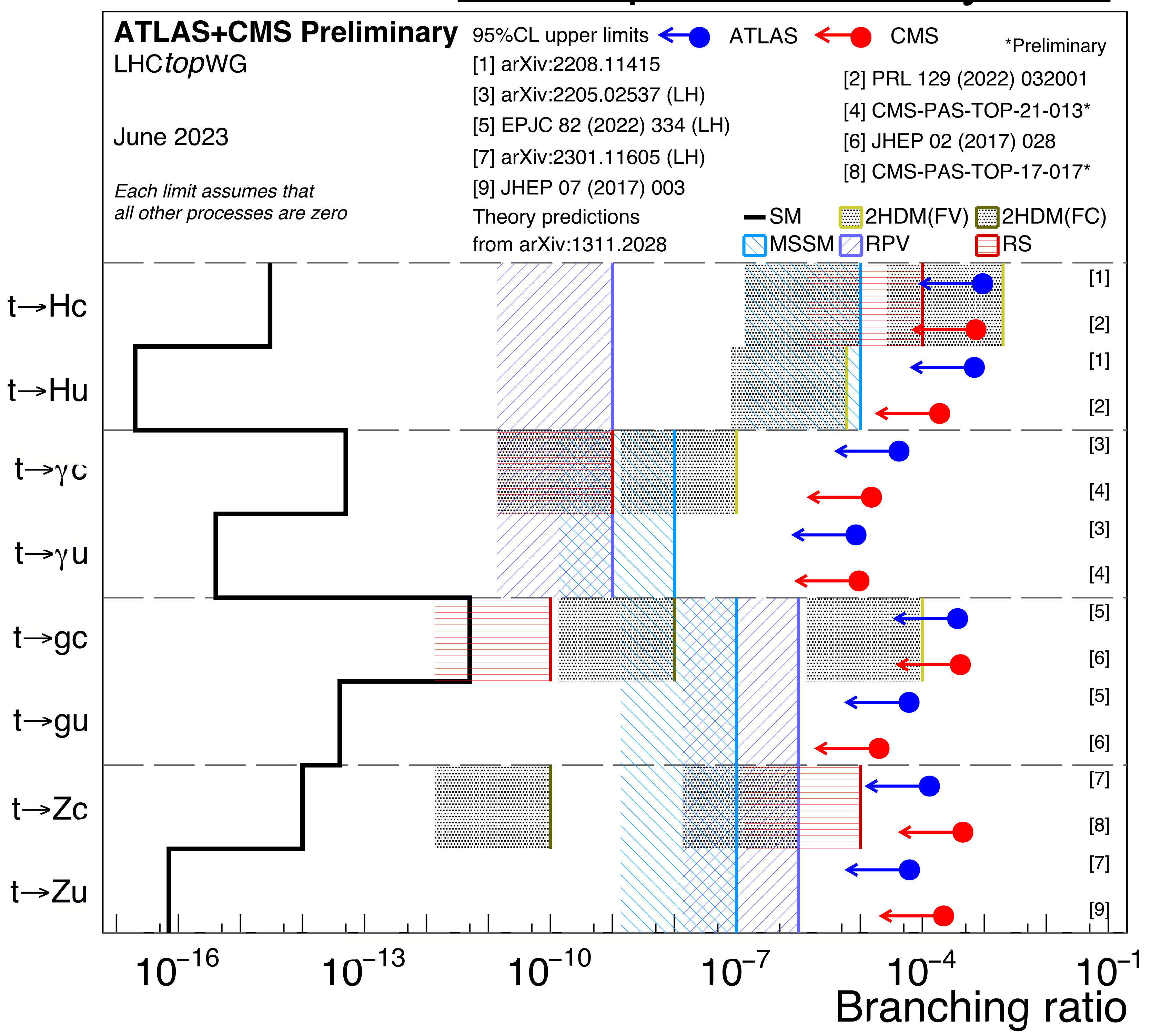
GOAL & MOTIVATION

- Measure tqH and tqZ production from $t\bar{t}$ events
- FCNC in tqH might come from BSM
  - FCNC is forbidden at tree level in SM
  - Suppressed at higher orders

STRATEGY

- tqH measurement
  - Divide selected events in SRs, VRs and CRs
  - Use BDT to discriminate signal and bkg
  - Profile Likelihood fit the BDT distributions
  - Upper limits on the BR -> limits one the EFT D6 Wilson coefficients $C_{u\phi}$, $C_{u\phi}$
- tqZ measurement
  - Divide selected events in SRs, VRs and CRs
  - Use GBDT to discriminate signal and bkg
  - Profile Likelihood fit the BDT distributions in SRs, kinematic distribution in CRs
  - Upper limits on the BR -> limits one the EFT D6 Wilson coefficients C_{uW}, C_{uB}

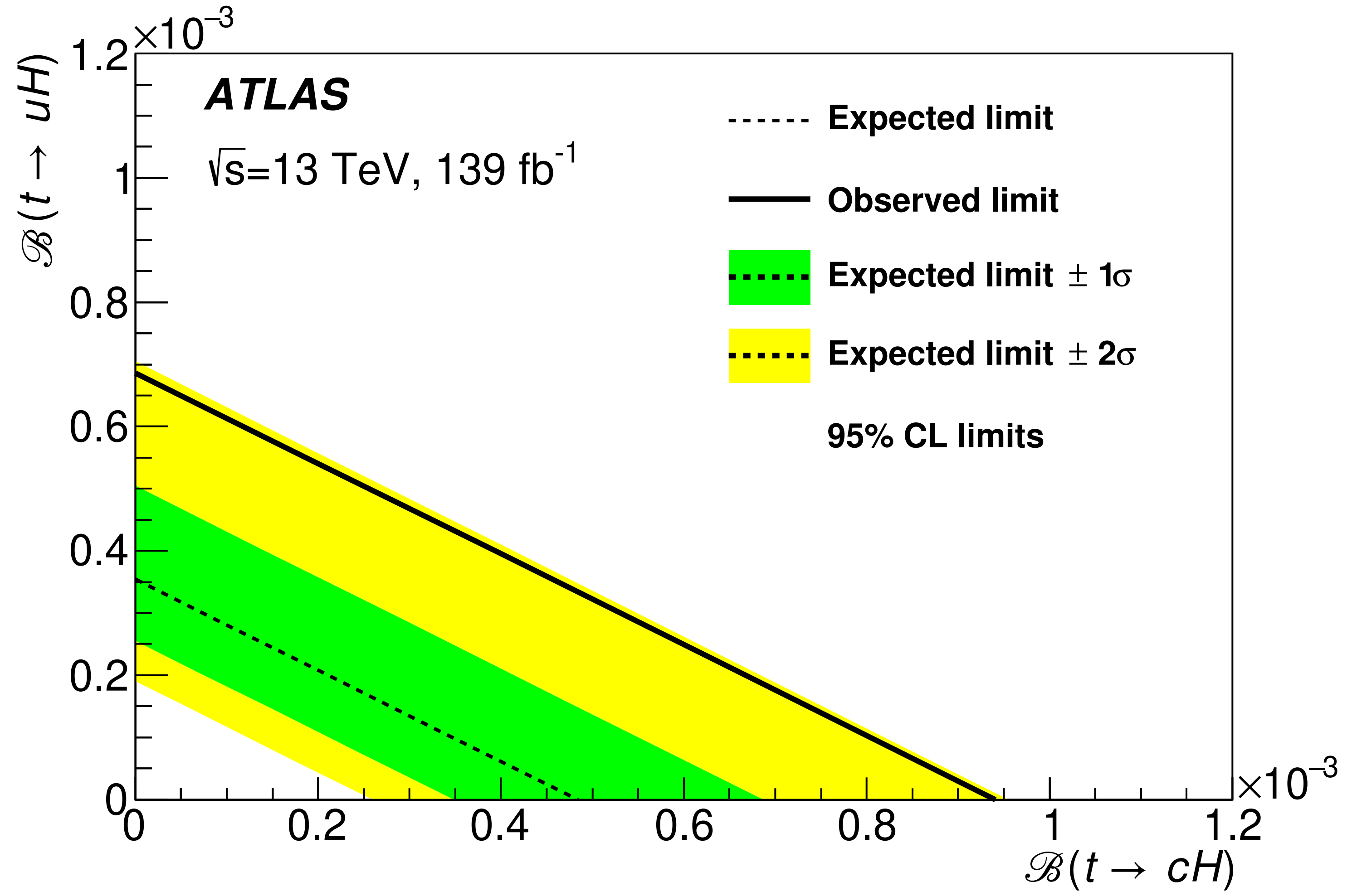
LHCTopWGSummaryPlots

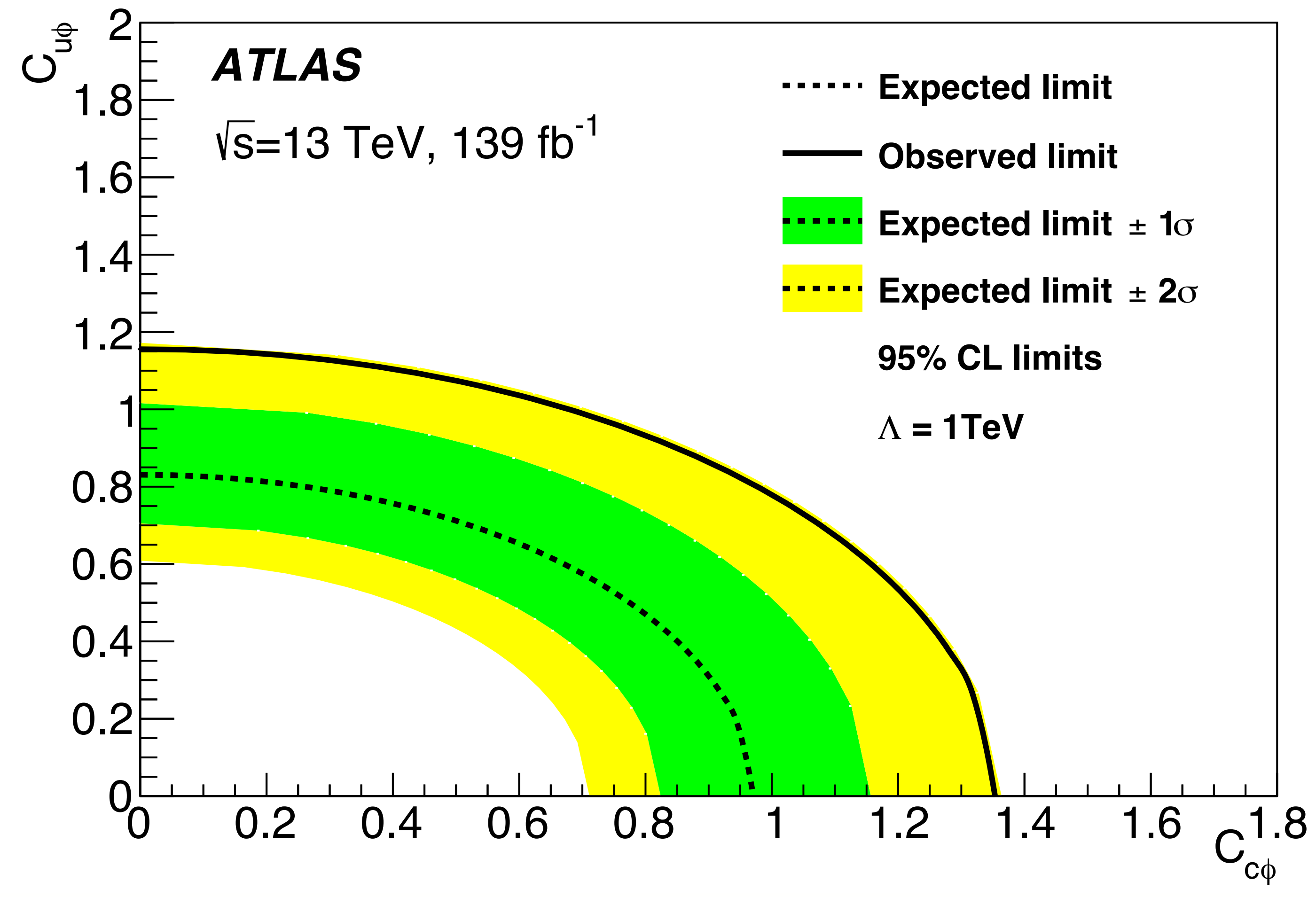


Search for FCNC in $tqH\,(\tau\tau)$ and tqZ

RESULTS

- tqH
  - Slight excess in data with 2.3σ significance
  - Observed (expected) 95% CL upper limit on $t \to cH$:
    - $9.4 \times 10^{-4}\ \left(4.8^{+2.2}_{-1.4} \times 10^{-4}\right)$
  - Observed (expected) 95% CL upper limit on $t \to uH$:
    - $6.9 \times 10^{-4}\ \left(3.5^{+1.5}_{-1.0} \times 10^{-4}\right)$
  - Limits on D& Wilson coefficient for new physics at a scale $\Lambda = 1$ TeV
    - $C_{c\phi} < 1.35\,(0.97)$
    - $C_{u\phi} < 1.16\,(0.82)$
- tqZ
  - Good agreement with SM
  - Observed (expected) 95% CL upper limit on $t \to Zu$:
    - left-handed: $6.2 \times 10^{-5}\ \left(4.9^{+2.2}_{-1.4} \times 10^{-5}\right)$
    - right-handed: $6.6 \times 10^{-5}\ \left(5.1^{+2.1}_{-1.4} \times 10^{-5}\right)$
  - Observed (expected) 95% CL upper limit on $t \to Zc$:
    - left-handed: $13 \times 10^{-5}\ \left(11^{+5}_{-3} \times 10^{-5}\right)$
    - right-handed: $12 \times 10^{-5}\ \left(10^{+4}_{-3} \times 10^{-5}\right)$
  - Limits on D& Wilson coefficient for new physics at a scale $\Lambda = 1$ TeV
    - $C_{uW}^{(13)*}$ and $C_{uB}^{(13)*}$ $< 0.15\ \left(0.13^{+0.03}_{-0.02}\right)$
    - $C_{uW}^{(31)}$ and $C_{uB}^{(31)}$ $< 0.16\ \left(0.14^{+0.03}_{-0.02}\right)$





Search for FCNC in $tqH\,(\tau\tau)$

Table 1: Summary of 95% CL upper limits on $\mathcal{B}(t \to cH)$ and $\mathcal{B}(t \to uH)$, significance and best-fit branching ratio in the signal regions with a benchmark branching ratio of $\mathcal{B}(t \to qH) = 0.1\%$. The expected significance is obtained from an Asimov fit with a signal injection corresponding to a branching ratio of 0.1%.

Signal Region	$t \to cH$ 95% CL upper limit [10^{-3}] Observed (Expected)	$t \to cH$ Significance	$t \to cH$ $\mathcal{B}$ [10^{-3}]	$t \to uH$ 95% CL upper limit [10^{-3}] Observed (Expected)	$t \to uH$ Significance	$t \to uH$ $\mathcal{B}$ [10^{-3}]
$t_h\tau_{\text{had}}\tau_{\text{had}}$-2j	$1.80\,(2.72^{+1.18}_{-0.76})$	−0.96 (0.78)	$-1.03^{+1.03}_{-1.03}$	$1.07\,(1.60^{+0.71}_{-0.45})$	−0.90 (1.31)	$-0.55^{+0.58}_{-0.58}$
$t_h\tau_{\text{had}}\tau_{\text{had}}$-3j	$1.14\,(1.02^{+0.45}_{-0.29})$	0.34 (1.87)	$0.16^{+0.47}_{-0.47}$	$0.97\,(0.86^{+0.38}_{-0.24})$	0.36 (2.25)	$0.14^{+0.40}_{-0.40}$
Hadronic combination	$1.00\,(0.95^{+0.42}_{-0.27})$	0.26 (1.99)	$0.11^{+0.43}_{-0.43}$	$0.76\,(0.76^{+0.33}_{-0.21})$	0.12 (2.52)	$0.04^{+0.34}_{-0.34}$
$t_\ell\tau_{\text{had}}$-2j	$4.77\,(4.23^{+1.72}_{-1.18})$	0.41 (0.47)	$0.85^{+2.06}_{-2.06}$	$3.84\,(3.48^{+1.42}_{-0.97})$	0.36 (0.58)	$0.61^{+1.68}_{-1.68}$
$t_\ell\tau_{\text{had}}$-1j	$3.80\,(3.56^{+1.51}_{-0.99})$	0.22 (0.58)	$0.36^{+1.70}_{-1.70}$	$2.98\,(2.78^{+1.17}_{-0.78})$	0.22 (0.73)	$0.29^{+1.33}_{-1.33}$
$t_h\tau_{\text{lep}}\tau_{\text{had}}$-2j	$4.71\,(5.71^{+2.68}_{-1.60})$	−0.52 (0.38)	$-1.36^{+2.56}_{-2.56}$	$2.50\,(2.97^{+1.25}_{-0.83})$	−0.47 (0.70)	$-0.66^{+1.38}_{-1.38}$
$t_h\tau_{\text{lep}}\tau_{\text{had}}$-3j	$2.71\,(2.71^{+1.25}_{-0.76})$	−0.03 (0.77)	$-0.03^{+1.26}_{-1.26}$	$2.02\,(2.03^{+0.86}_{-0.57})$	−0.05 (0.99)	$-0.03^{+0.98}_{-0.98}$
$t_\ell\tau_{\text{had}}\tau_{\text{had}}$	$1.35\,(0.61^{+0.27}_{-0.17})$	2.64 (3.31)	$0.74^{+0.33}_{-0.33}$	$0.97\,(0.44^{+0.19}_{-0.12})$	2.64 (4.38)	$0.53^{+0.24}_{-0.24}$
Leptonic combination	$1.25\,(0.58^{+0.25}_{-0.16})$	2.61 (3.46)	$0.69^{+0.31}_{-0.31}$	$0.88\,(0.41^{+0.18}_{-0.11})$	2.60 (4.62)	$0.49^{+0.22}_{-0.22}$
Combination	$0.94\,(0.48^{+0.20}_{-0.14})$	2.34 (4.02)	$0.51^{+0.24}_{-0.24}$	$0.69\,(0.35^{+0.15}_{-0.10})$	2.31 (5.18)	$0.37^{+0.18}_{-0.18}$

PRESELECTION

Requirement	Leptonic channels $t_h\tau_{\text{lep}}\tau_{\text{had}}$	Leptonic channels $t_\ell\tau_{\text{had}}\tau_{\text{had}}$	Leptonic channels $t_\ell\tau_{\text{had}}$	Hadronic channel $t_h\tau_{\text{had}}\tau_{\text{had}}$
Trigger	single-lepton trigger			di-τ trigger
Leptons	=1 isolated e or μ			=0 isolated e or μ
τ_{had}	=1 τ_{had}	=2 τ_{had}	=1 τ_{had}	=2 τ_{had}
Electric charge (Q)	$Q_\ell \times Q_{\tau_{\text{had1}}} = -1$	$Q_{\tau_{\text{had1}}} \times Q_{\tau_{\text{had2}}} = -1$	$Q_\ell \times Q_{\tau_{\text{had1}}} = 1$	$Q_{\tau_{\text{had1}}} \times Q_{\tau_{\text{had2}}} = -1$
Jets	≥3 jets	≥1 jets	≥2 jets	≥3 jets
b-tagging	=1 b-jets			=1 b-jets

REGIONS DEFINITIONS

	Regions	b-jets	Light-flavour jets	Leptons	Hadronic τ decays	Charge
SR	$t_\ell\tau_{\text{had}}\tau_{\text{had}}$	1	≥ 0	1	2	$\tau_{\text{had}}\tau_{\text{had}}$ OS
	$t_\ell\tau_{\text{had}}$-1j	1	1	1	1	$t_\ell\tau_{\text{had}}$ SS
	$t_\ell\tau_{\text{had}}$-2j	1	2	1	1	$t_\ell\tau_{\text{had}}$ SS
	$t_h\tau_{\text{lep}}\tau_{\text{had}}$-2j	1	2	1	1	$\tau_{\text{lep}}\tau_{\text{had}}$ OS
	$t_h\tau_{\text{lep}}\tau_{\text{had}}$-3j	1	≥ 3	1	1	$\tau_{\text{lep}}\tau_{\text{had}}$ OS
	$t_h\tau_{\text{had}}\tau_{\text{had}}$-2j	1	2	0	2	$\tau_{\text{had}}\tau_{\text{had}}$ OS
	$t_h\tau_{\text{had}}\tau_{\text{had}}$-3j	1	≥ 3	0	2	$\tau_{\text{had}}\tau_{\text{had}}$ OS
VR	$t_\ell\tau_{\text{had}}\tau_{\text{had}}$-SS	1	≥ 0	1	2	$\tau_{\text{had}}\tau_{\text{had}}$ SS
	$t_h\tau_{\text{had}}\tau_{\text{had}}$-3j SS	1	≥ 3	0	2	$\tau_{\text{had}}\tau_{\text{had}}$ SS
CRtt	$t_\ell t_\ell 1b\tau_{\text{had}}$	1	≥ 0	2	1	$t_\ell t_\ell$ OS
	$t_\ell t_\ell 2b\tau_{\text{had}}$	2	≥ 0	2	1	$t_\ell t_\ell$ OS
	$t_\ell t_h 2b\tau_{\text{had}}$-2jSS	2	2	1	1	$t_\ell\tau_{\text{had}}$ SS
	$t_\ell t_h 2b\tau_{\text{had}}$-2jOS	2	2	1	1	$t_\ell\tau_{\text{had}}$ OS
	$t_\ell t_h 2b\tau_{\text{had}}$-3jSS	2	≥ 3	1	1	$t_\ell\tau_{\text{had}}$ SS
	$t_\ell t_h 2b\tau_{\text{had}}$-3jOS	2	≥ 3	1	1	$t_\ell\tau_{\text{had}}$ OS

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Search for FCNC in tqZ

CRs SELECTIONS

Common selections			
Exactly 3 leptons with $p_T(\ell_1) > 27$ GeV			
$t\bar{t}$ CR	$t\bar{t}Z$ CR	Sideband CR1	Sideband CR2
≥ 1 OS pair, no OSSF	≥ 1 OSSF pair with $\lvert m_{\ell\ell} - m_Z\rvert < 15$ GeV	≥ 1 OSSF pair with $\lvert m_{\ell\ell} - m_Z\rvert < 15$ GeV	≥ 1 OSSF pair with $\lvert m_{\ell\ell} - m_Z\rvert < 15$ GeV
–	–	–	$m_T(\ell_W, \nu) > 40$ GeV
≥ 1 jet	≥ 4 jets	≥ 2 jets	1 jet
1 b-jet	2 b-jets	1 b-jet	1 b-jet
–	–	$\lvert m^{\text{reco}}_{j_a\ell\ell} - m_t\rvert > 2\sigma_{t_{\text{FCNC}}}$	–
–	–	$\lvert m^{\text{reco}}_{j_b\ell_W\nu} - m_t\rvert > 2\sigma_{t_{\text{SM}}}$	$\lvert m^{\text{reco}}_{j_b\ell_W\nu} - m_t\rvert > 2\sigma_{t_{\text{SM}}}$

SRs SELECTIONS

Common selections		
Exactly 3 leptons with $p_T(\ell_1) > 27$ GeV ≥ 1 OSSF pair, with $\lvert m_{\ell\ell} - m_Z\rvert < 15$ GeV		
SR1	SR2	
≥ 2 jets	1 jet	2 jets
1 b-jet	1 b-jet	1 b-jet
–	$m_T(\ell_W, \nu) > 40$ GeV	$m_T(\ell_W, \nu) > 40$ GeV
$\lvert m^{\text{reco}}_{j_a\ell\ell} - m_t\rvert < 2\sigma_{t_{\text{FCNC}}}$	–	$\lvert m^{\text{reco}}_{j_a\ell\ell} - m_t\rvert > 2\sigma_{t_{\text{FCNC}}}$
–	$\lvert m^{\text{reco}}_{j_b\ell_W\nu} - m_t\rvert < 2\sigma_{t_{\text{SM}}}$	$\lvert m^{\text{reco}}_{j_b\ell_W\nu} - m_t\rvert < 2\sigma_{t_{\text{SM}}}$

SIGNAL STRENGHT μ PARAMETERS

Vertex	Coupling	μ
tZu	LH	0.08 ± 0.12 (stat.) ± 0.08 (syst.)
tZu	RH	0.10 ± 0.12 (stat.) ± 0.08 (syst.)
tZc	LH	0.10 ± 0.17 (stat.) ± 0.14 (syst.)
tZc	RH	0.06 ± 0.16 (stat.) ± 0.13 (syst.)

95%CL ON BR AND COUPLING

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}	$10^{+4}_{-3} \times 10^{-5}$
$\lvert C^{(13)*}_{uW}\rvert$ and $\lvert C^{(13)*}_{uB}\rvert$	tZu	LH	0.15	$0.13^{+0.03}_{-0.02}$
$\lvert C^{(31)}_{uW}\rvert$ and $\lvert C^{(31)}_{uB}\rvert$	tZu	RH	0.16	$0.14^{+0.03}_{-0.02}$
$\lvert C^{(23)*}_{uW}\rvert$ and $\lvert C^{(23)*}_{uB}\rvert$	tZc	LH	0.22	$0.20^{+0.04}_{-0.03}$
$\lvert C^{(32)}_{uW}\rvert$ and $\lvert C^{(32)}_{uB}\rvert$	tZc	RH	0.21	$0.19^{+0.04}_{-0.03}$
	SR1+CRs			
$\mathcal{B}(t \to Zq)$	tZu	LH	9.7×10^{-5}	$8.6^{+3.6}_{-2.4} \times 10^{-5}$
$\mathcal{B}(t \to Zq)$	tZu	RH	9.5×10^{-5}	$8.2^{+3.4}_{-2.3} \times 10^{-5}$
	SR2+CRs			
$\mathcal{B}(t \to Zq)$	tZu	LH	7.8×10^{-5}	$6.1^{+2.7}_{-1.7} \times 10^{-5}$
$\mathcal{B}(t \to Zq)$	tZu	RH	9.0×10^{-5}	$6.6^{+2.9}_{-1.8} \times 10^{-5}$

$t\bar{t}W$ inclusive and differential

SRs SELECTION

Signal region preselection	$2\ell SS$	3ℓ
Lepton definition	TT	LTT
Lepton p_T [GeV]	(20, 20)	(10, 20, 20)
N_{jets}	≥ 2	
N_{b-jets}	$\geq 1\ b^{60\%}$ or $\geq 2\ b^{77\%}$	
$m^{SF}_{\ell^\pm\ell^\pm}$ or $m^{SF}_{\ell^+\ell^-}$ [GeV]	> 12	
$\lvert m^{SF}_{\ell^+\ell^-} - m_Z \rvert$ [GeV]	–	> 10
$\lvert m_{\ell\ell\ell} - m_Z \rvert$ [GeV]	–	> 10
	Inclusive cross section measurement	
Lepton charge split	$(\ell^+\ell^+, \ell^-\ell^-)$	$(\ell^+\ell^-\ell^-, \ell^-\ell^+\ell^+)$
Lepton flavour split	$(\mu\mu,\ e\mu,\ \mu e,\ ee)$	-
Jet multiplicity split	(3, 4, $\geq$5)	(2, $\geq$3)
b-jet multiplicity split	(1, $\geq$2)	
Total inclusive SRs	48	8
	Differential cross section measurement	
Lepton charge split	$(\ell^+\ell^+, \ell^-\ell^-)$	$(\ell^+\ell^-\ell^-, \ell^-\ell^+\ell^+)$
Number of OS-SF pairs split	–	(0, 1, 2)
Total differential SRs	2	6

CRs SELECTION

Control regions for:	Diboson	$t\bar{t}Z$	Conversions	HF non-prompt
N_{jets}	2 or 3	≥ 4	≥ 0	≥ 2
N_{b-jets}	$1\ b^{60\%}$	$\geq 1\ b^{60\%}$ or $\geq 2\ b^{77\%}$	$0\ b^{77\%}$	$1\ b^{77\%}$
Lepton requirement	3ℓ		$\mu\mu e^*$	2ℓSS
Lepton definition	(L, M, M)			(T, M_{ex}) —— (M_{ex}, T) —— (M_{ex}, M_{ex})
Lepton p_T [GeV]	(10, 20, 20)			(20, 20)
$m^{SF}_{\ell^+\ell^-}$ [GeV]	> 12		> 12	–
$\lvert m^{SF}_{\ell^+\ell^-} - m_Z \rvert$ [GeV]	< 10		> 10	–
$\lvert m_{\ell\ell\ell} - m_Z \rvert$ [GeV]	–		< 10	–
$m_T(\ell_0, E_T^{miss})$ [GeV]	–			< 250 for TM_{ex} and $M_{ex}T$ pairs
Region split	–	–	internal / material	subleading $e/\mu \times (TM_{ex}, M_{ex}T, M_{ex}M_{ex})$
Region naming	3ℓVV	3ℓttZ	3ℓIntC 3ℓMatC	$2\ell tt(e)_{TM_{ex}}$, $2\ell tt(e)_{M_{ex}T}$, $2\ell tt(e)_{M_{ex}M_{ex}}$ $2\ell tt(\mu)_{TM_{ex}}$, $2\ell tt(\mu)_{M_{ex}T}$, $2\ell tt(\mu)_{M_{ex}M_{ex}}$

FIDUCIAL SELECTION

	Objects
Electrons	$p_T \geq 10$ GeV and $\lvert\eta\rvert < 2.47$ (excluding the LAr crack region with $1.37 < \lvert\eta\rvert < 1.52$)
Muons	$p_T \geq 10$ GeV and $\lvert\eta\rvert < 2.5$
Jets	Anti-k_t $R = 0.4$ jets with $p_T \geq 25$ GeV and $\lvert\eta\rvert < 2.5$
b-jets	Tagged if jet contains a ghost-matched b-hadron with $p_T > 5$ GeV
E_T^{miss}	Vector sum of $p_T(\nu)$ for all neutrinos in the event not from hadron decays
	Overlap removal
Electron–jet	If $\Delta R(e, \text{jet}) < 0.2$ (excluding b-jets with $p_T < 200$ GeV) remove jet
Jet–lepton	If $\Delta R(\ell, \text{jet}) < \min(0.4, 0.04 + 10\,\text{GeV}/p_{T,\ell})$ remove lepton
	Selections
2ℓ	Exactly two leptons with the same charge Both leptons have $p_T \geq 20$ GeV $N_{jets} \geq 3$ ($N_{jets} \geq 2$) with at least one b-jet for inclusive (differential) fit $m_{\ell\ell} > 12$ GeV for same-flavour pairs
3ℓ	Exactly three leptons with a total charge of $\pm 1e$ Both leptons from the same-sign lepton pair are required to have $p_T \geq 20$ GeV $N_{jets} \geq 1$ with at least one b-jet $m_{\ell\ell} > 12$ GeV & $\lvert m_{\ell\ell} - m_Z \rvert > 10$ GeV (for OS-SF $\ell\ell$) $\lvert m_{\ell\ell\ell} - m_Z \rvert > 10$ GeV

$t\bar{t}W$ inclusive and differential

ATLAS EXPERIMENT

ROYAL HOLLOWAY UNIVERSITY OF LONDON

UNCERTAINTIES

	$\frac{\Delta\sigma(t\bar{t}W)}{\sigma(t\bar{t}W)}$ [%]	$\frac{\Delta\sigma_{\text{fid}}(t\bar{t}W)}{\sigma_{\text{fid}}}$ [%]	$\frac{\Delta R(t\bar{t}W)}{R(t\bar{t}W)}$ [%]	$\frac{\Delta A_C^{\text{rel}}}{A_C^{\text{rel}}}$ [%]
$t\bar{t}W$ ME and PS modelling	6.0	7.0	6.0	8.0
Prompt lepton bkg. norm.	2.6	2.5	1.6	2.2
Lepton isolation BDT	2.3	2.3	1.0	1.2
Fakes/VV/$t\bar{t}Z$ norm. (free-floated)	2.3	2.7	1.8	2.5
Non-prompt lepton bkg. modelling	1.9	1.7	2.3	3.1
Trigger	1.9	1.8	0.5	0.7
MC statistics	1.5	1.6	1.9	2.5
$t\bar{t}W$ PDF	1.5	1.4	2.1	2.8
Jet energy scale	1.4	1.9	0.8	1.1
Prompt lepton bkg. modelling	1.3	1.3	1.3	1.9
Luminosity	1.0	1.0	0.08	0.13
Charge Mis-ID	0.7	0.7	0.4	0.5
Jet energy resolution	0.5	0.6	0.7	0.31
Flavour tagging	0.28	0.33	0.5	1.0
$t\bar{t}W$ Scale	0.21	0.9	1.4	1.9
Electron/photon reco.	0.15	0.2	0.12	0.3
MET	<0.10	<0.10	0.17	0.4
Muon	<0.10	<0.10	<0.10	0.4
Pile-up	<0.10	0.25	<0.10	0.3
Total syst.	8	10	8	10
Data statistics	5	5	10	16
Total	9	11	13	19

χ^2

Observable	NDF	Sherpa 2.2.10		Off-Shell		MG5aMC+Py8 FxFx		MG5aMC+Py8 Incl.		Powheg+Py8		Powheg+H7	
		χ^2	p-value	χ^2	p-value	χ^2	p-value	χ^2	p-value	χ^2	p-value	χ^2	p-value
N_{jets}	3	0.2	0.98	-	-	0.2	0.98	0.3	0.97	1.0	0.80	1.1	0.79
$H_{\text{T,jets}}$	4	1.4	0.84	-	-	0.9	0.92	1.9	0.75	2.4	0.66	3.3	0.51
$H_{\text{T,lep}}$	5	1.0	0.96	3.4	0.64	1.3	0.94	1.7	0.88	1.5	0.91	1.4	0.93
$\Delta R_{\text{lb, lead}}$	5	4.0	0.55	3.5	0.63	5.0	0.42	3.7	0.59	3.7	0.60	3.8	0.58
$\lvert\Delta\phi_{\text{ll, SS}}\rvert$	5	2.7	0.75	2.2	0.81	2.6	0.76	2.2	0.82	2.4	0.79	2.3	0.80
$\lvert\Delta\eta_{\text{ll, SS}}\rvert$	5	2.6	0.77	5.6	0.35	2.9	0.72	2.3	0.80	2.0	0.84	2.1	0.83
$M_{\text{jj, lead}}$	5	0.1	1.00	-	-	0.2	1.00	0.4	0.99	0.7	0.98	1.0	0.96

$t\bar{t}Z$ inclusive and differential

2ℓ SR

Variable	Preselection		
N_ℓ $(\ell = e, \mu)$	$= 2$		
	$= 1$ OSSF lepton pair with $\lvert m_{\ell\ell} - m_Z\rvert < 10$ GeV		
$p_T\ (\ell_1, \ell_2)$	$> 30,\ 15$ GeV		
	SR-2ℓ-5j2b	**SR-2ℓ-6j1b**	**SR-2ℓ-6j2b**
$N_{jets}\ (p_T > 25$ GeV$)$	$= 5$	≥ 6	≥ 6
$N_{b-\text{tagged jets@77\%}}$	≥ 2	$= 1$	≥ 2

3ℓ SR

Variable	Preselection		
N_ℓ $(\ell = e, \mu)$	$= 3$		
	≥ 1 OSSF lepton pair with $\lvert m_{\ell\ell} - m_Z\rvert < 10$ GeV		
	for all OSSF combinations: $m_{OSSF} > 10$ GeV		
$p_T\ (\ell_1, \ell_2, \ell_3)$	$> 27,\ 20,\ 15$ GeV		
$N_{jets}\ (p_T > 25$ GeV$)$	≥ 3		
$N_{b-\text{tagged jets}}$	≥ 1@85%		
	SR-3ℓ-ttZ	**SR-3ℓ-tZq**	**SR-3ℓ-WZ**
DNN-tZq output	< 0.40	≥ 0.40	—
DNN-WZ output	< 0.22	< 0.22	≥ 0.22
$N_{b-\text{tagged jets}}$	—	—	≥ 1@60%

4ℓ SR

Variable	Preselection	
N_ℓ $(\ell = e, \mu)$	$= 4$	
	≥ 1 OSSF lepton pair with $\lvert m_{\ell\ell} - m_Z\rvert < 20$ GeV	
	for all OSSF combinations: $m_{OSSF} > 10$ GeV	
$p_T\ (\ell_1, \ell_2, \ell_3, \ell_4)$	$> 27,\ 7,\ 7,\ 7$ GeV	
The sum of lepton charges	$= 0$	
$N_{jets}\ (p_T > 25$ GeV$)$	≥ 2	
$N_{b-\text{tagged jets}}$	≥ 1@85%	
	SR-4ℓ-SF	**SR-4ℓ-DF**
$\ell\ell^{\text{non-}Z}$	e^+e^- or $\mu^+\mu^-$	$e^\pm\mu^\mp$
DNN output	≥ 0.4	—

PARTICLE AND PARTON SELECTIONS

Particle-level selection	
3ℓ channel	4ℓ channel
Exactly 3 leptons, with $p_T(\ell_1, \ell_2, \ell_3) > 27, 20, 15$ GeV	Exactly four leptons, with $p_T(\ell_1, \ell_2, \ell_3, \ell_4) > 27, 7, 7, 7$ GeV
The sum of charges is ± 1	The sum of charges is $= 0$
At least 3 jets, with $p_T > 25$ GeV	At least 2 jets, with $p_T > 25$ GeV
At least 1 b-jet (jet ghost-matched to a b-hadron)	
At least one OSSF lepton pair, with $\lvert m_{\ell\ell} - m_Z\rvert < 10$ GeV	
Parton-level selection	
3ℓ channel	4ℓ channel
$t\bar{t} \to e^\pm/\mu^\pm$ + jets	$t\bar{t} \to e^\pm\mu^\mp/e^\pm e^\mp/\mu^\pm\mu^\mp$
$Z \to e^\pm e^\mp/\mu^\pm\mu^\mp$	
$\lvert m_{\ell\ell} - m_Z\rvert < 15$ GeV	

$t\bar{t}Z$ inclusive and differential

ATLAS EXPERIMENT

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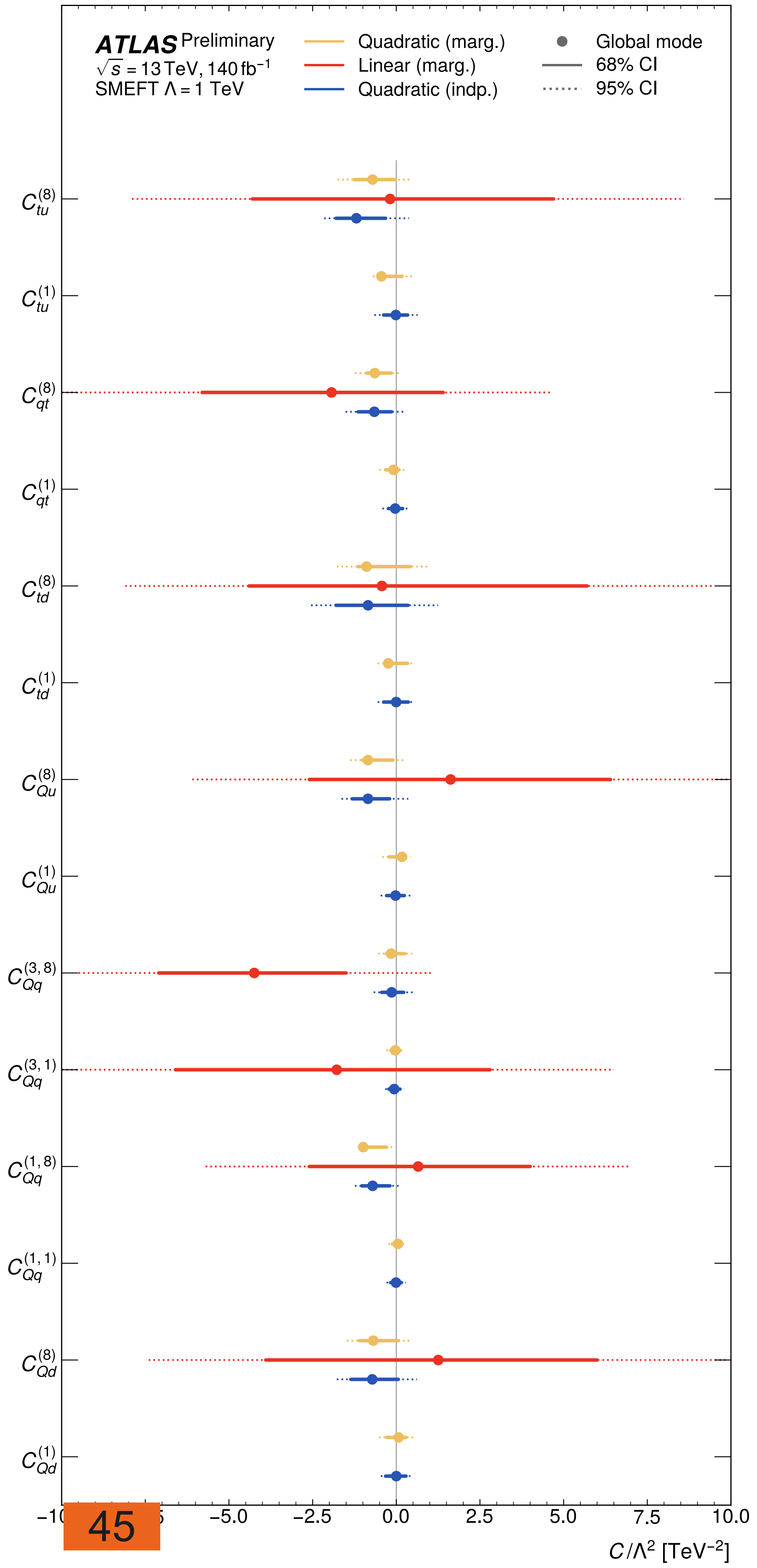
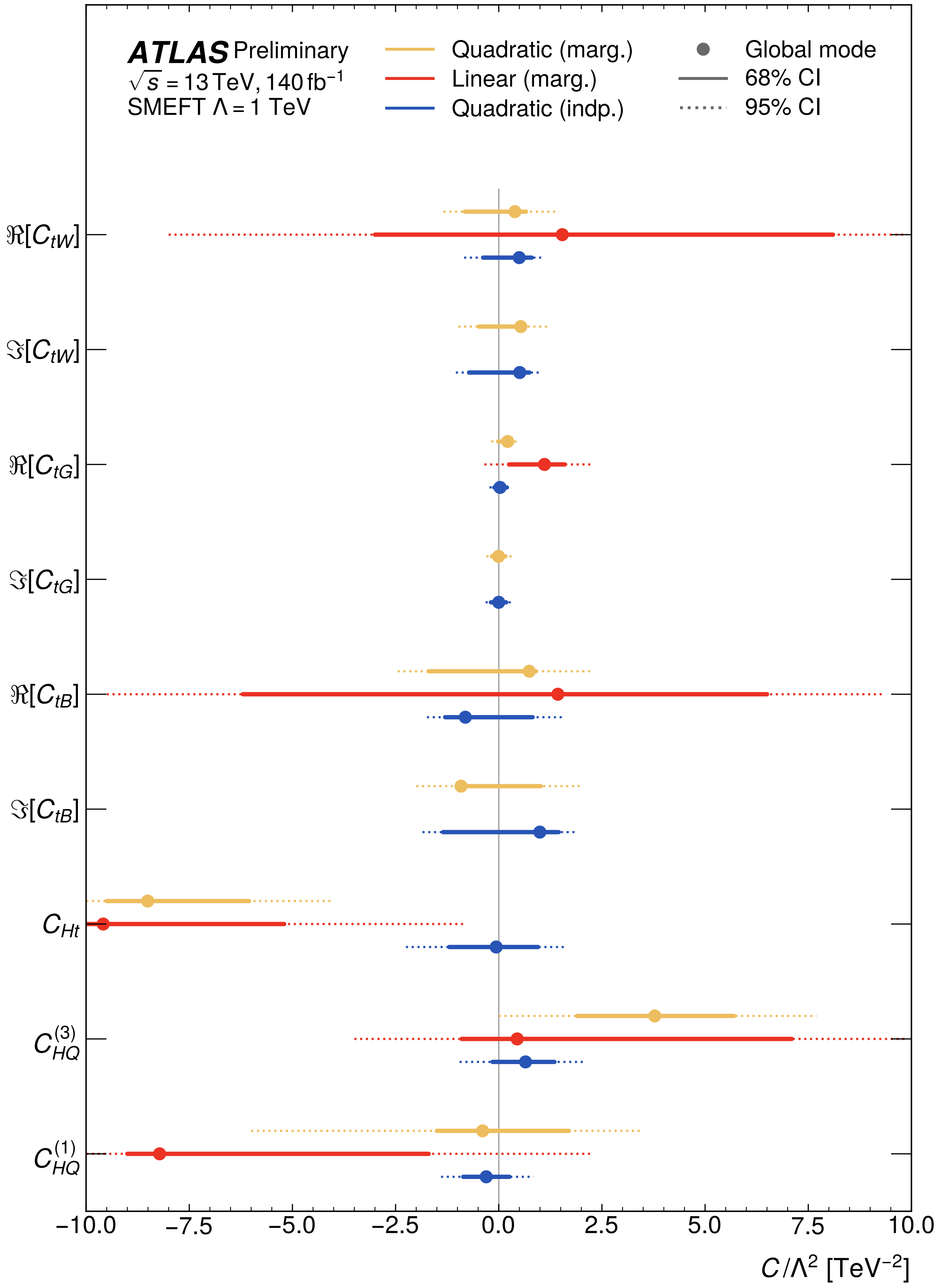
EFT COEFFICIENTS





INCLUSIVE CROSS SECTION

Channel	$\sigma_{t\bar{t}Z}$
Dilepton	0.84 ± 0.11 pb = 0.84 ± 0.06 (stat.) ± 0.09 (syst.) pb
Trilepton	0.84 ± 0.07 pb = 0.84 ± 0.05 (stat.) ± 0.05 (syst.) pb
Tetralepton	$0.97^{+0.13}_{-0.12}$ pb = 0.97 ± 0.11 (stat.) ± 0.05 (syst.) pb
Combination (2ℓ, 3ℓ & 4ℓ)	0.86 ± 0.06 pb = 0.86 ± 0.04 (stat.) ± 0.04 (syst.) pb

UNCERTAINTIES

Uncertainty Category	$\Delta\sigma_{t\bar{t}Z}/\sigma_{t\bar{t}Z}$ [%]
Background normalisations	2.0
Jets and $E_{\mathrm{T}}^{\mathrm{miss}}$	1.9
b-tagging	1.7
$t\bar{t}Z$ μ_F and μ_R scales	1.6
Leptons	1.6
Z +jets modelling	1.5
tWZ modelling	1.1
$t\bar{t}Z$ showering	1.0
$t\bar{t}Z$ A14	1.0
Luminosity	1.0
Diboson modelling	0.8
tZq modelling	0.7
PDF (signal & backgrounds)	0.6
MC statistical	0.5
Other backgrounds	0.5
Fake leptons	0.4
Pile-up	0.3
Data-driven $t\bar{t}$	0.1

$t\bar{t}Z$ inclusive and differential

p-values FOR DIFFERENTIAL MEASUREMENTS

		aMC@NLO +Pythia 8		Sherpa 2.2.1 (incl.)		Sherpa 2.2.11 (multi-leg)	
	Variable	parton	particle	parton	particle	parton	particle
3ℓ	$\lvert\Delta\phi(Z,t^{l})\rvert/\pi$	0.12	0.09	0.09	0.05	0.14	0.09
	$\lvert\Delta y(Z,t^{l})\rvert$	0.08	0.05	0.09	0.05	0.08	0.04
	H_T^{l}	0.04	0.04	0.06	0.07	0.11	0.1
	$p_T^{l,non-Z}$	0.75	0.75	0.44	0.63	0.44	0.51
	N_{jets}	-	0.55	-	0.9	-	0.82
4ℓ	N_{jets}	-	0.36	-	0.43	-	0.55
	$\lvert\Delta\phi l,l\rvert/\pi$	0.68	0.67	0.52	0.65	0.52	0.77
	H_T^{l}	0.04	0.04	0.02	0.04	0.03	0.04
$3\ell+4\ell$	$\lvert y^{Z}\rvert$	0.77	0.78	0.70	0.77	0.64	0.77
	p_T^{Z}	0.09	0.08	0.13	0.13	0.22	0.23
	$\cos\theta *^{Z}$	0.20	0.17	0.21	0.19	0.24	0.22
	$\lvert\Delta\phi(t\bar{t},Z)\rvert/\pi$	0.84	0.82	0.08	0.53	0.07	0.56
	$m^{t\bar{t}}$	0.89	0.97	0.8	0.92	0.49	0.83
	$m^{t\bar{t}Z}$	0.86	0.93	0.64	0.91	0.58	0.91
	p_T^{top}	0.45	0.56	0.2	0.59	0.22	0.39
	$p_T^{t\bar{t}}$	0.09	0.07	0.05	0.05	0.07	0.1
	$\lvert y^{t\bar{t}Z}\rvert$	0.95	0.8	0.86	0.85	0.66	0.65

f_{SM} PARAMETERS

Distribution	Channel	Expected values	Observed values
$\cos\varphi$	$3\ell+4\ell$	$1^{+1.39}_{-1.38}$	$-0.09^{+1.34}_{-1.28}$
$\cos\theta_r^{+}\cdot\cos\theta_r^{-}$	$3\ell+4\ell$	$1^{+1.83}_{-1.82}$	$1.17^{+1.80}_{-1.76}$
$\cos\theta_k^{+}\cdot\cos\theta_k^{-}$	$3\ell+4\ell$	$1^{+1.78}_{-1.78}$	$1.39^{+1.72}_{-1.73}$
$\cos\theta_n^{+}\cdot\cos\theta_n^{-}$	$3\ell+4\ell$	$1^{+1.87}_{-1.86}$	$-1.05^{+2.06}_{-1.96}$
$\cos\theta_r^{+}\cdot\cos\theta_k^{-}+\cos\theta_r^{-}\cdot\cos\theta_k^{+}$	$3\ell+4\ell$	$1^{+1.93}_{-1.93}$	$0.36^{+1.99}_{-1.93}$
$\cos\theta_r^{+}$	$3\ell+4\ell$	$1^{+1.81}_{-1.80}$	$1.56^{+1.86}_{-1.98}$
$\cos\theta_r^{-}$	$3\ell+4\ell$	$1^{+1.82}_{-1.78}$	$1.81^{+1.63}_{-1.68}$
$\cos\theta_k^{+}$	$3\ell+4\ell$	$1^{+1.69}_{-1.67}$	$2.00^{+1.65}_{-1.70}$
$\cos\theta_k^{-}$	$3\ell+4\ell$	$1^{+1.68}_{-1.68}$	$2.31^{+1.68}_{-1.68}$

ρ COEFFICIENTS

Coefficient	Expression
c_{rr}	$-9\langle\cos\theta_r^{+}\cdot\cos\theta_r^{-}\rangle$
c_{kk}	$-9\langle\cos\theta_k^{+}\cdot\cos\theta_k^{-}\rangle$
c_{nn}	$-9\langle\cos\theta_n^{+}\cdot\cos\theta_n^{-}\rangle$
c_{rk}	$-9\langle\cos\theta_r^{+}\cdot\cos\theta_k^{-}+\cos\theta_r^{-}\cdot\cos\theta_k^{+}\rangle$
c_{kn}	$-9\langle\cos\theta_k^{+}\cdot\cos\theta_n^{-}+\cos\theta_k^{-}\cdot\cos\theta_n^{+}\rangle$
c_{rn}	$-9\langle\cos\theta_r^{+}\cdot\cos\theta_n^{-}+\cos\theta_r^{-}\cdot\cos\theta_n^{+}\rangle$
c_{r}	$-9\langle\cos\theta_k^{+}\cdot\cos\theta_n^{-}-\cos\theta_k^{-}\cdot\cos\theta_n^{+}\rangle$
c_{k}	$-9\langle\cos\theta_n^{+}\cdot\cos\theta_r^{-}-\cos\theta_n^{-}\cdot\cos\theta_r^{+}\rangle$
c_{n}	$-9\langle\cos\theta_r^{+}\cdot\cos\theta_k^{-}-\cos\theta_r^{-}\cdot\cos\theta_k^{+}\rangle$
b_r^{+}	$3\langle\cos\theta_r^{+}\rangle$
b_r^{-}	$3\langle\cos\theta_r^{-}\rangle$
b_k^{+}	$3\langle\cos\theta_k^{+}\rangle$
b_k^{-}	$3\langle\cos\theta_k^{-}\rangle$
b_n^{+}	$3\langle\cos\theta_n^{+}\rangle$
b_n^{-}	$3\langle\cos\theta_n^{-}\rangle$

Measurements of the top-quark mass

ATLAS EXPERIMENT

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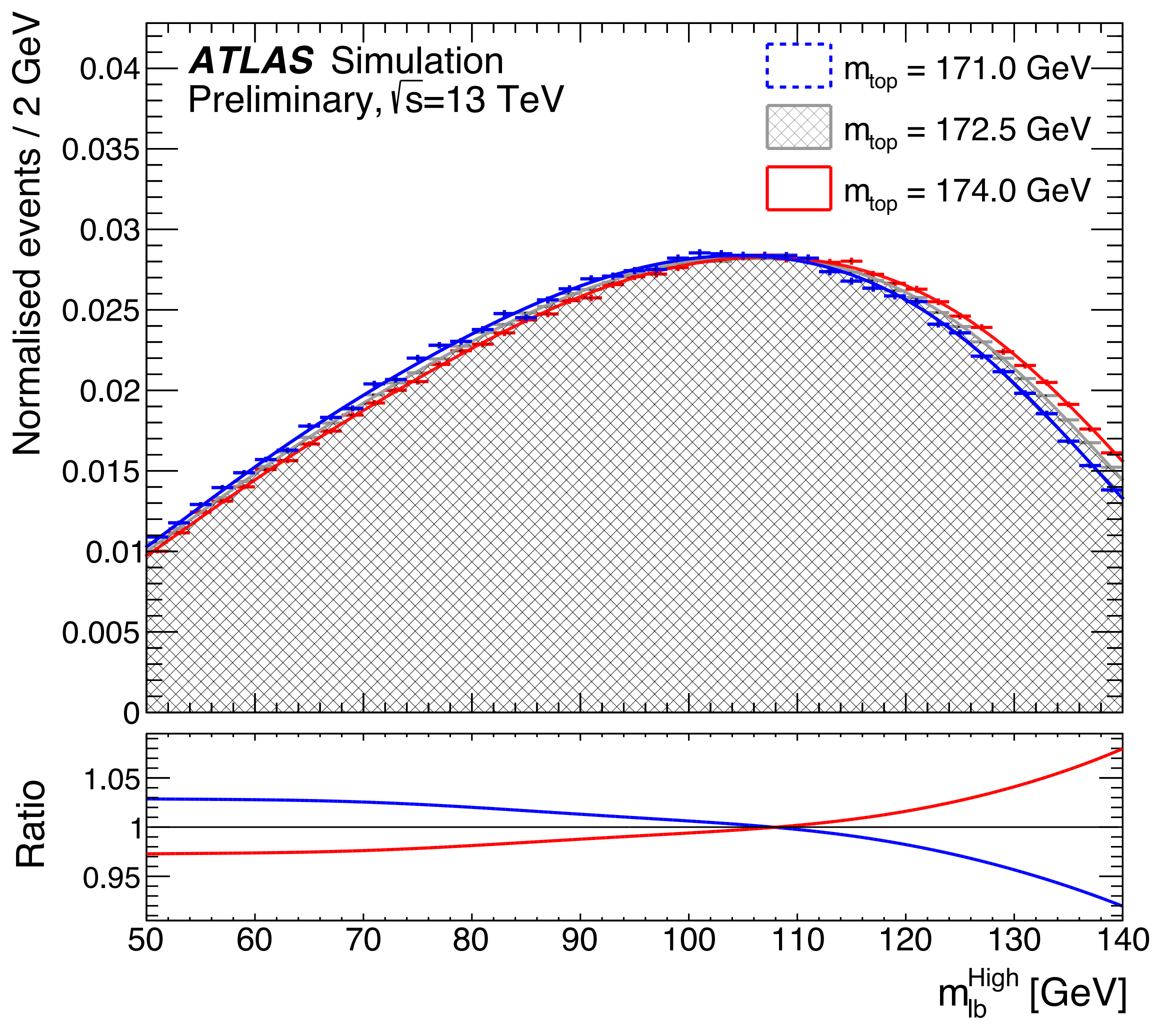
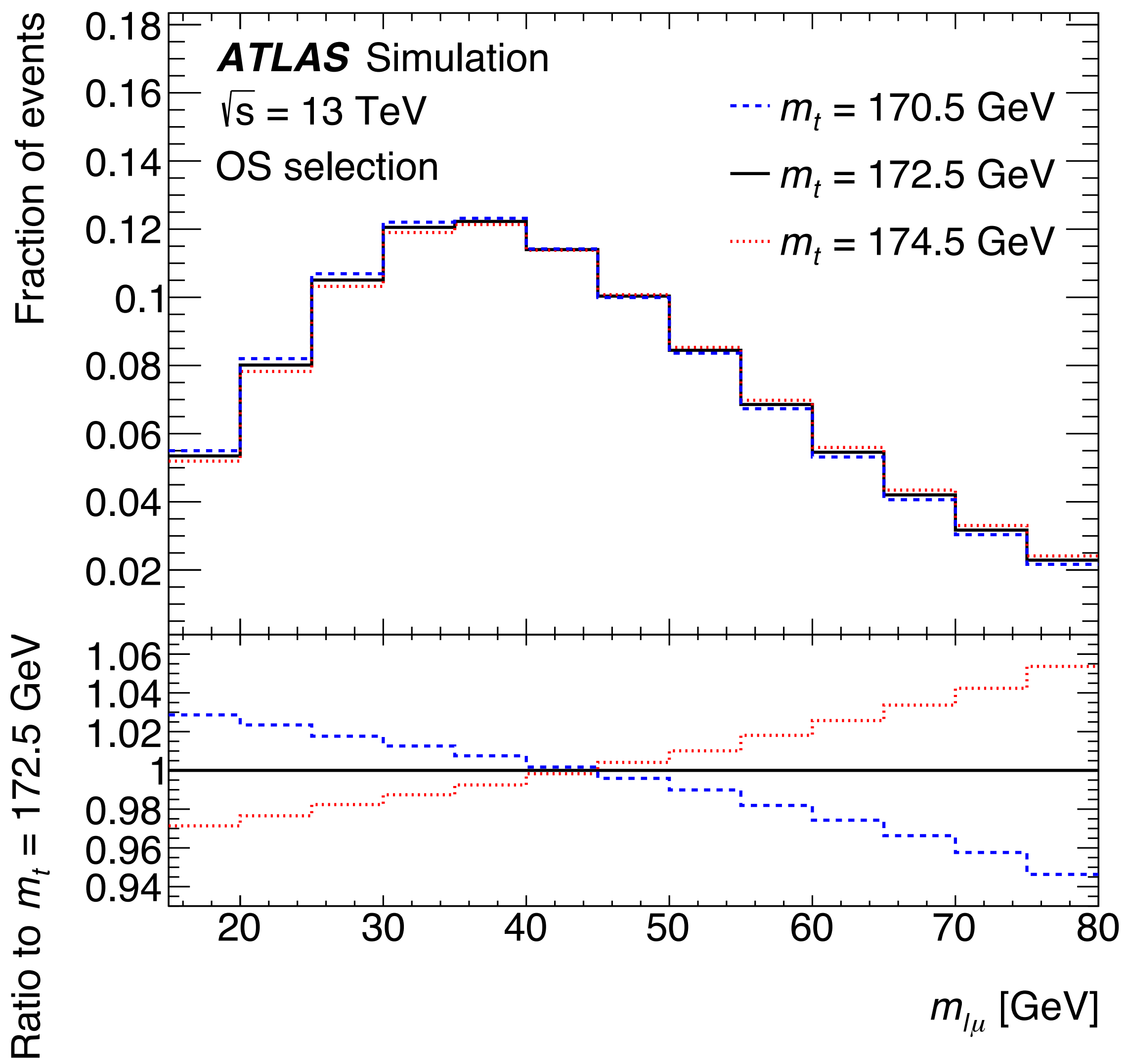
GOAL & MOTIVATION

- Measure mass of top quark
  - Crucial role in SM extensions
    - connected to the EW vacuum stability
  - Internal consistency of the SM

STRATEGY

- Template top mass measurement in dilepton $t\bar{t}$ events
  - Unbinned maximum likelihood fit to data of the $m^{\ell b}$ distribution
- top mass measurement in single lepton $t\bar{t}$ events using a leptonic invariant mass
  - Select events with a soft muon from the b-hadron
  - Binned-template profile likelihood fit to data of the $m^{\ell \mu}$ distribution

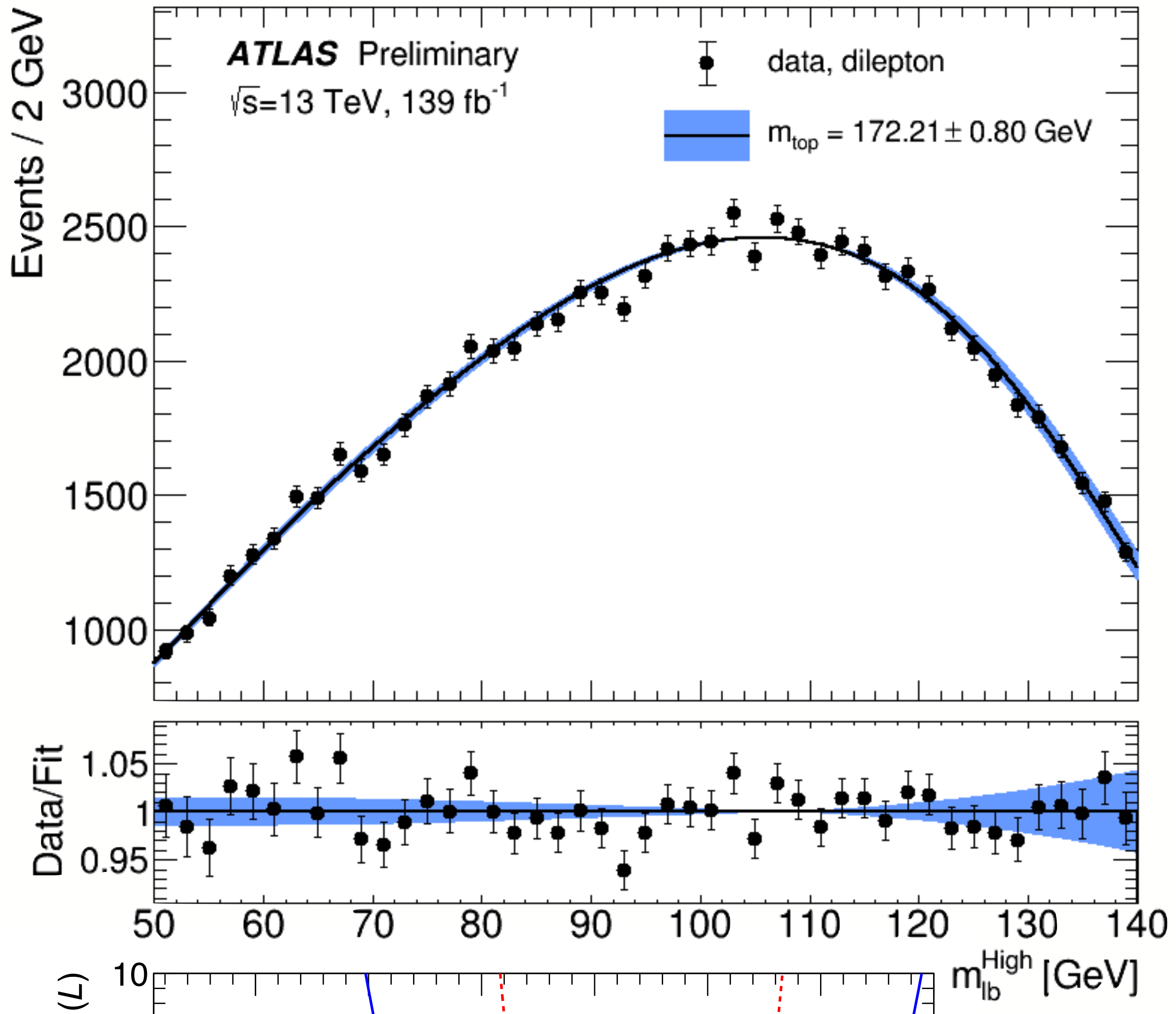


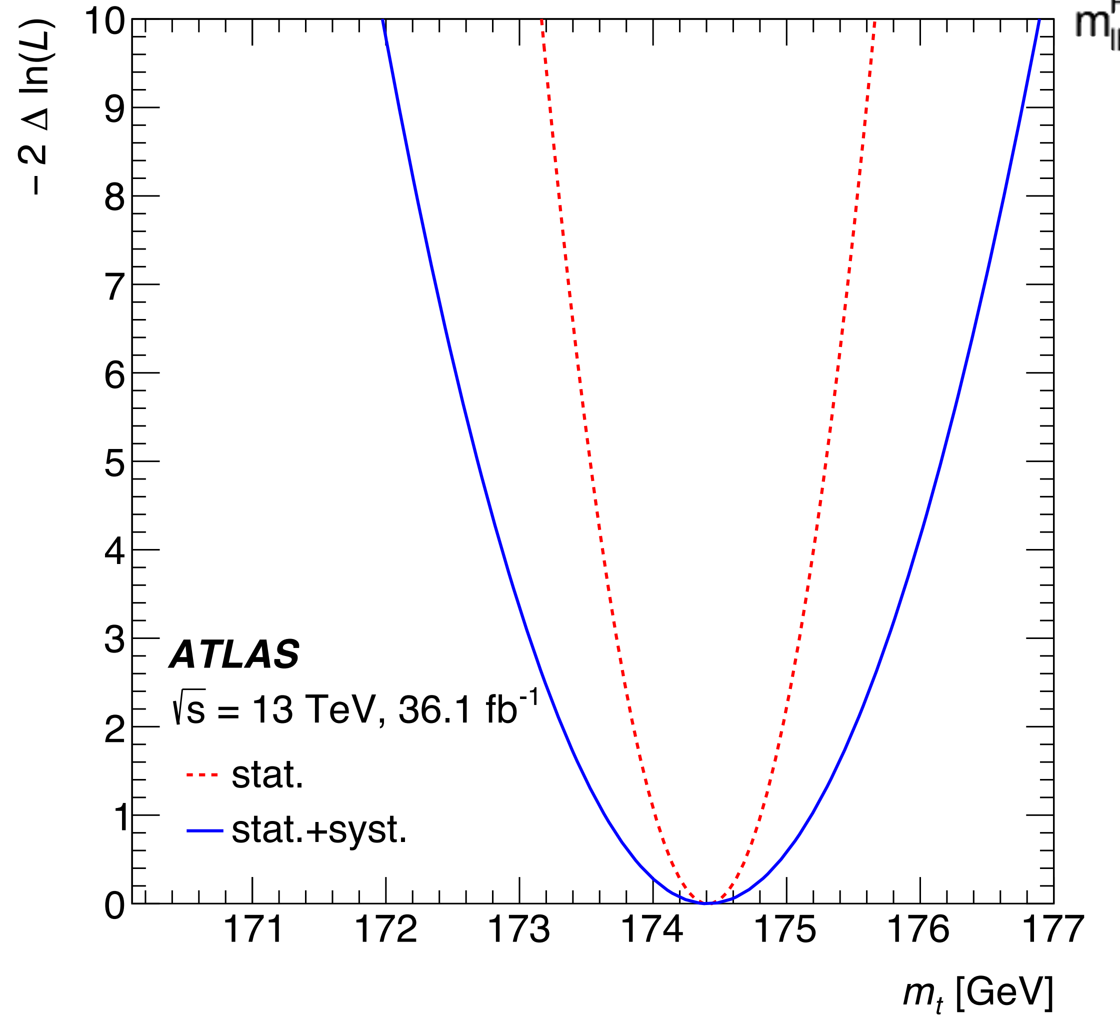


Measurements of the top-quark mass

RESULTS

- Template mass measurement
  - $m_t = 172.21 \pm 0.20\ (\text{stat.}) \pm 0.67\ (\text{syst.}) \pm 0.39\ (\text{recoil})\ \text{GeV}$
- Template mass measurement
  - $m_t = 174.41 \pm 0.39\ (\text{stat.}) \pm 0.66\ (\text{syst.}) \pm 0.25\ (\text{recoil})\ \text{GeV}$





JHEP06(2023)019

Measurements of the top-quark mass (SMT)

ATLAS EXPERIMENT

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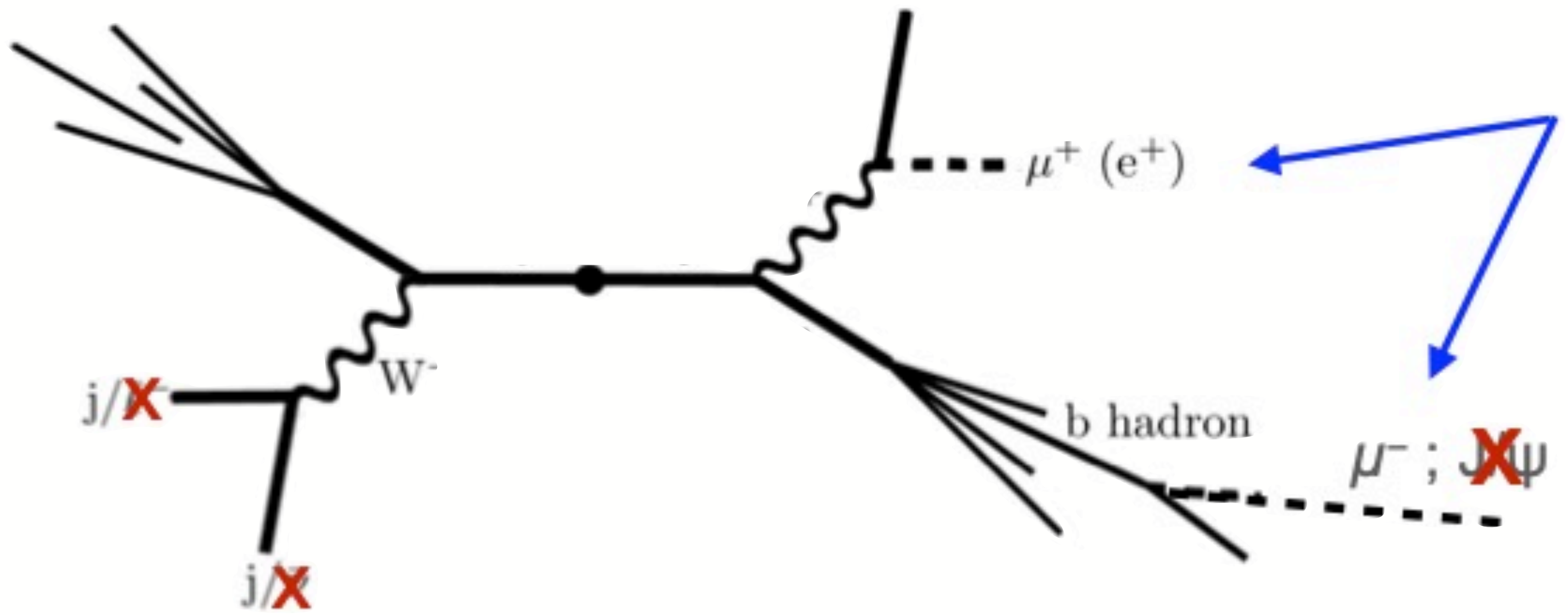
Event selection $t\bar{t}$ lepton $(e\mu)$+jets:

- $p_T^{e,\mu} > 27$ GeV
- $E_T^{miss} > 30\ \mathrm{GeV};\ \mathrm{E_T^{miss}} + \mathrm{m_T(W)} > 60\ \mathrm{GeV}$
- ≥ 4 jets with $p_T > 30$ GeV
- ≥ 1 Soft Muon Tagged jet
  - $p_T^{\mu} > 8\ \mathrm{GeV},\ \Delta\mathrm{R}^{\mu-\mathrm{jet\,axis}} < 0.4$
  - $p_T^{jet} > 25$ GeV, $\Delta R^{\mu-Wlep} < 2$
- ≥ 1 Displaced-vertex $\left(\epsilon = 77\ \%\right)$ tagged jet



UNCERTAINTIES

Source	Unc. on m_t [GeV]	Stat. precision [GeV]
Statistical and datasets		
Data statistics	0.39	
Signal and background model statistics	0.17	
Luminosity	< 0.01	±0.01
Pile-up	0.07	±0.03
Modelling of signal processes		
Monte Carlo event generator	0.04	±0.06
b, c-hadron production fractions	0.11	±0.01
b, c-hadron decay BRs	0.40	±0.01
b-quark fragmentation r_b	0.19	±0.06
Parton shower α_S^{FSR}	0.07	±0.04
Parton shower and hadronisation model	0.06	±0.07
Initial-state QCD radiation	0.23	±0.08
Colour reconnection	< 0.01	±0.02
Choice of PDFs	0.07	±0.01
Modelling of background processes		
Soft muon fake	0.16	±0.03
Multijet	0.07	±0.02
Single top	0.01	±0.01
W/Z+jets	0.17	±0.01
Detector response		
Leptons	0.12	±0.01
Jet energy scale	0.13	±0.02
Soft muon jet p_T calibration	< 0.01	±0.01
Jet energy resolution	0.08	±0.07
b-tagging	0.10	±0.01
Missing transverse momentum	0.15	±0.01
Total stat. and syst. uncertainties (excluding recoil)	0.77	±0.03
Recoil uncertainty	0.25	
Total uncertainty	0.81	

RECOIL UNCERTAINTY

In the modelling of the parton shower of the b-quark from $t \rightarrow W\,b$ with Pythia 8.2, there is the possibility to change the default gluon recoil scheme from **recoiling against the b-quark**, to **recoiling against the W-boson** or **with the top-quark itself serving as recoiler for second and subsequent gluon emission of the b-quark.**

The alternative schemes gives:

- wider angle gluon radiation
  - Energy deposit not reclustered in jets
- lower gluon-energy emission
  - Alters the modelling of the b-quark fragmentation and hardening the b-hadron momenta

Both the alternative recoil schemes give similar results

Measurements of the top-quark mass (template)

ATLAS EXPERIMENT

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SELECTION

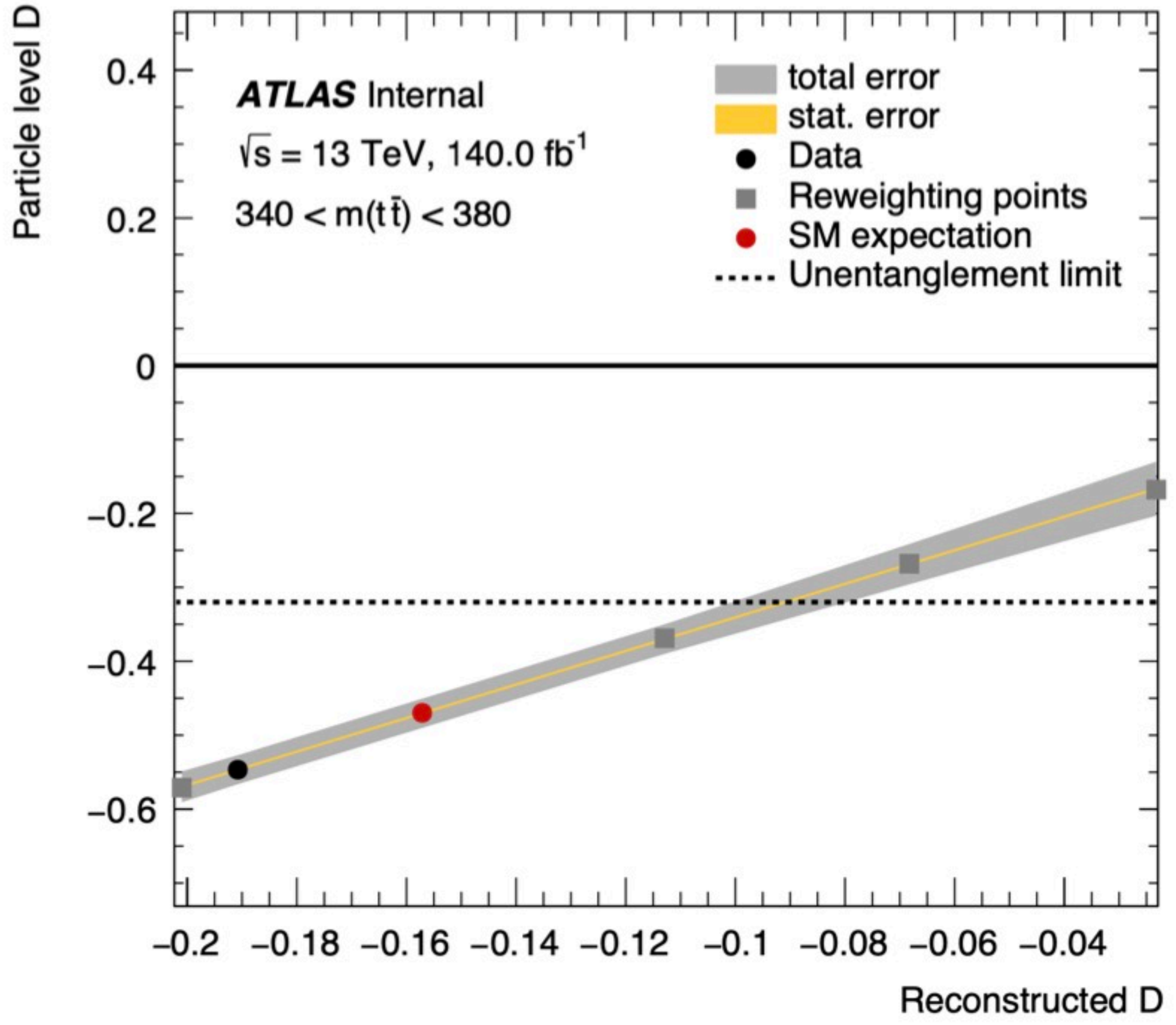
- good primary vertex, jet cleaning cuts, use EMPFlow jets
- single lepton trigger, exactly two isolated OS leptons with $p_{\mathrm{T}} > 28$ GeV
- ≥ 2 jets, exactly 2 b-tagged jets (70% WP, DL1r)
- $m_{\ell\ell} > 15$ GeV
- reject events with $80 \leq m_{\ell\ell} \leq 100$ GeV for ee and $\mu\mu$ channels
- requirement on the DNN value of this pair: $\mathrm{DNN}_{\mathrm{High}} > 0.65$
- requirement on $p_T^{\ell b}$ itself: $p_{T,lb}^{\mathrm{High}} > 160$ GeV
- require the chosen pair to contain the higher-p_T b-tagged jet
- Final selection: $50 \leq m_{\ell b}^{\mathrm{High}} \leq 140$ GeV

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

Observation of quantum entanglement in top pairs

- **The calibration curve is constructed by taking Reco-Truth pairs at 5 different hypothesis points and linearly interpolating between them.**

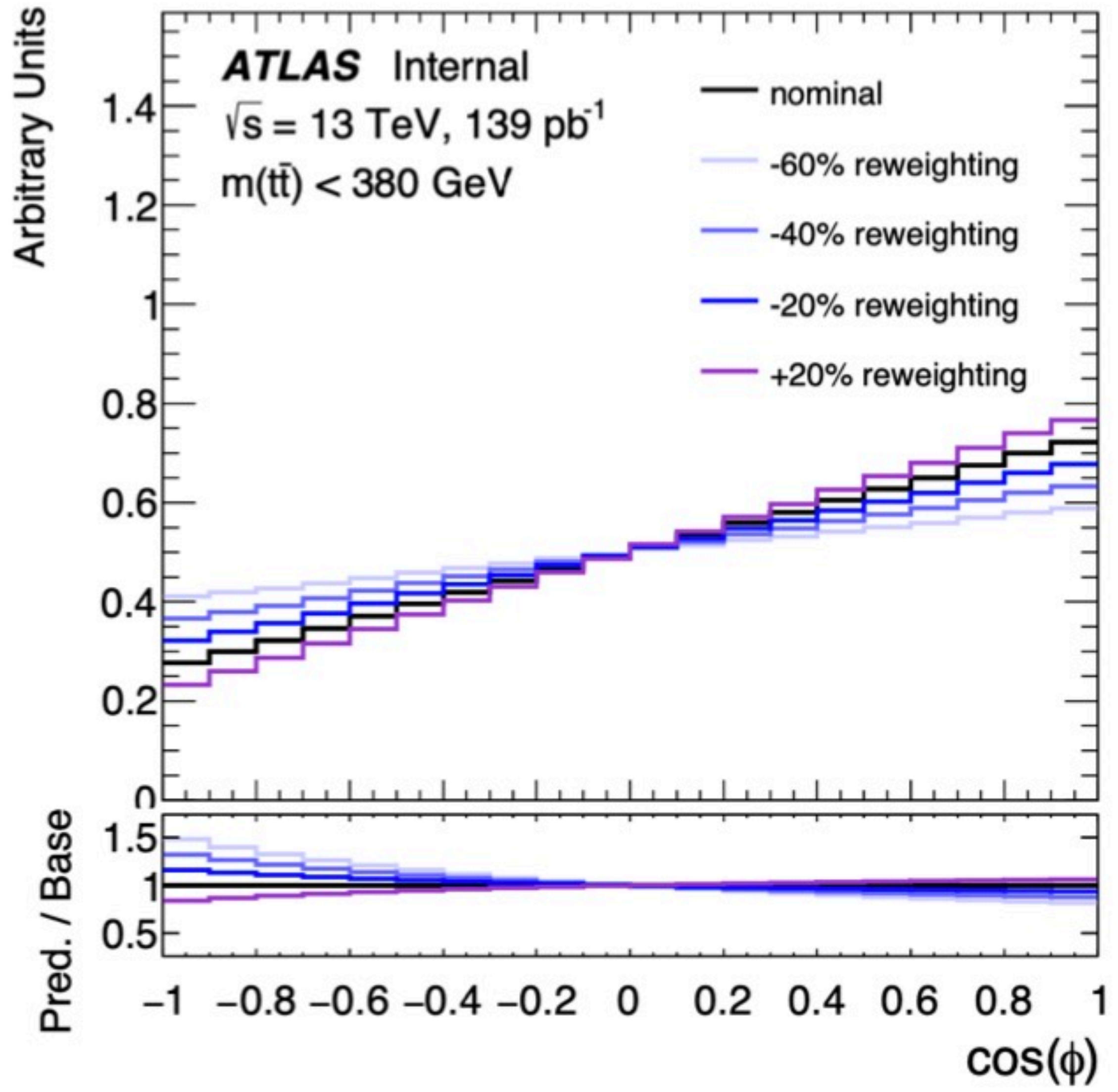


- **These hypothesis points correspond to the SM and 4 different reweighing points:**
  (+20%, -20%, -40%, -60%)

- **The observed data are corrected using this curve to move from the observed Reco to the corrected Truth value.**

Observation of quantum entanglement in top pairs

- **How these alternative hypothesis points are constructed is one of the key points of the measurement.**
- **We cannot dial entanglement up or down in the MC, so we reweight the cos(Φ) distribution as a function of m($t\bar{t}$).**



- **If this is not done correctly, the relation:**

$$D = \frac{tr[\rho]}{3} = -3 \cdot < \cos(\phi) >$$

does not hold.

- **The method we have used ensures that this relationship remains correct.**

Observation of quantum entanglement in top pairs

ATLAS EXPERIMENT

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UNCERTAINTIES

Systematic source	$\Delta D_{\text{observed}}(D = -0.547)$	ΔD (%)	$\Delta D_{\text{expected}}(D = -0.470)$	ΔD (%)
Signal Modelling	0.017	3.2	0.015	3.2
Electrons	0.002	0.4	0.002	0.4
Muons	0.001	0.1	0.001	0.1
Jets	0.004	0.7	0.004	0.8
b-tagging	0.002	0.4	0.002	0.4
Pile-up	< 0.001	< 0.1	< 0.001	< 0.1
$E_{\text{T}}^{\text{miss}}$	0.002	0.3	0.002	0.4
Backgrounds	0.010	1.8	0.009	1.8
Total Statistical Uncertainty	0.002	0.3	0.002	0.4
Total Systematic Uncertainty	0.021	3.8	0.018	3.9
Total Uncertainty	0.021	3.8	0.018	3.9

JHEP08(2023)077 JHEP07(2023)033 Phys. Lett. B 843 (2023) 137848

Charge asymmetry measurements

GOAL & MOTIVATION

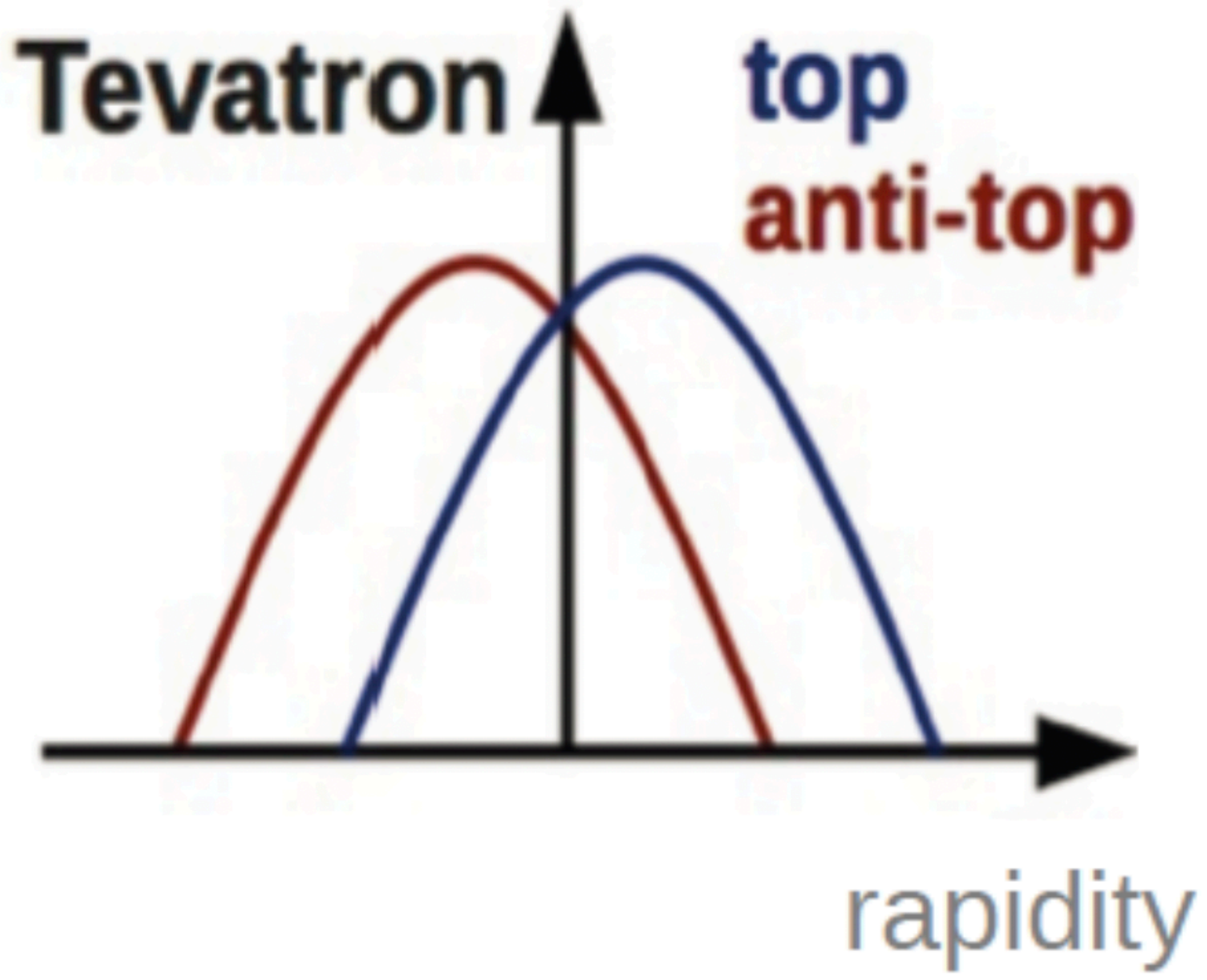
- Measure the top quark and leptonic charge asymmetry in tt(+X) events
  - Statistically limited in previous measurements
  - Altered by several BSM theories
    - Dependency on $m_{t\bar{t}}$

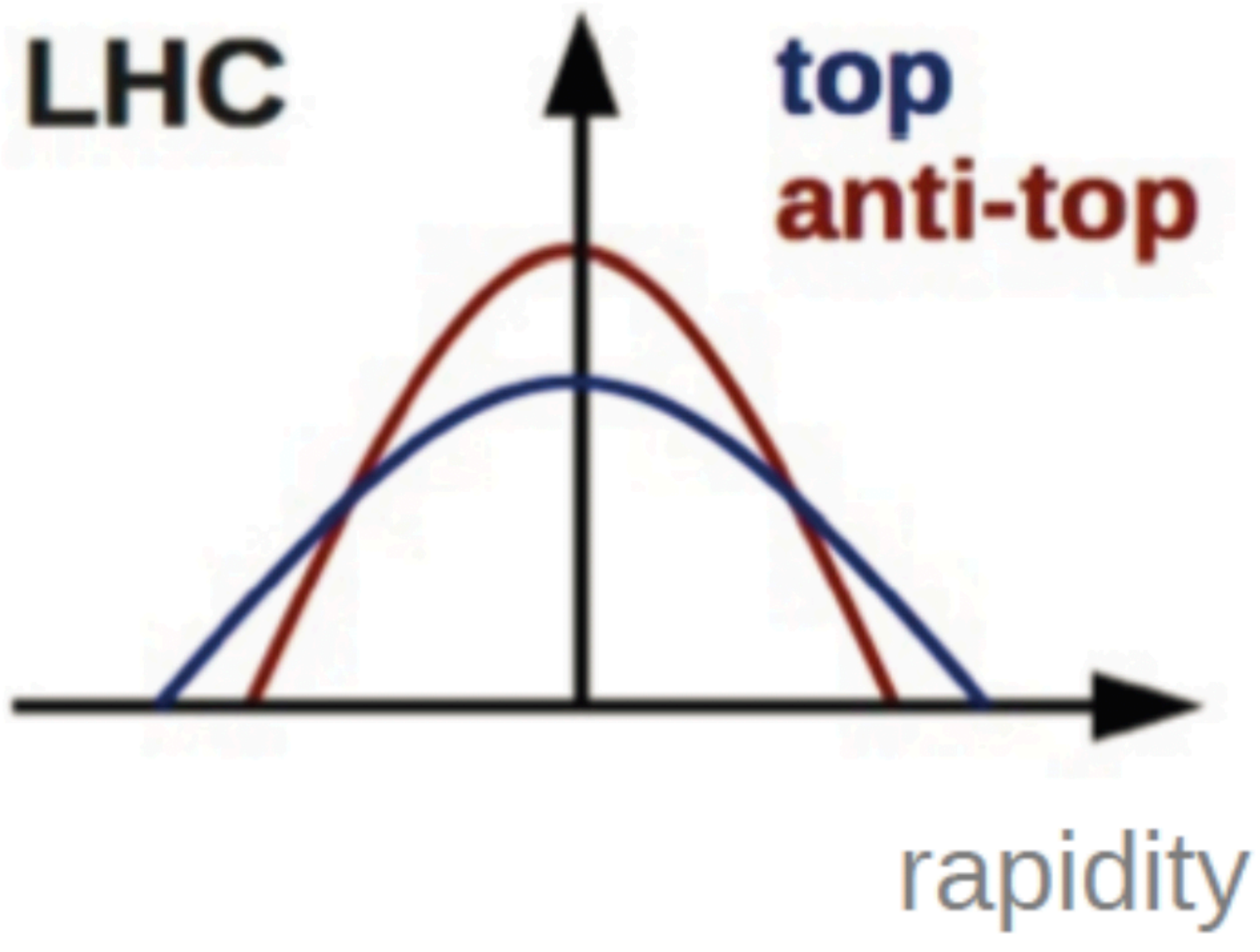
$$A_c^t = \frac{N(\Delta y^t > 0) - N(\Delta y^t < 0)}{N(\Delta y^t > 0) + N(\Delta y^t < 0)}$$

$$A_c^l = \frac{N(\Delta \eta^l > 0) - N(\Delta \eta^l < 0)}{N(\Delta \eta^l > 0) + N(\Delta \eta^l < 0)}$$

STRATEGY

- Charge asymmetry in $t\bar{t}$ events
  - Inclusive and differential
  - Single lepton and dilepton
  - Combine channels when unfolding with Fully Bayesian Unfolding approach
  - Effective Filed Theory interpretation
- Charge asymmetry in $t\bar{t}\gamma$
  - Unfold to particle-level with Profile Likelihood Unfolding approach
- Charge asymmetry in $t\bar{t}W$
  - Define 4 SRs and 4CRs
    - Fit all regions for detector-level measurement
    - PLU in SRs for particle-level

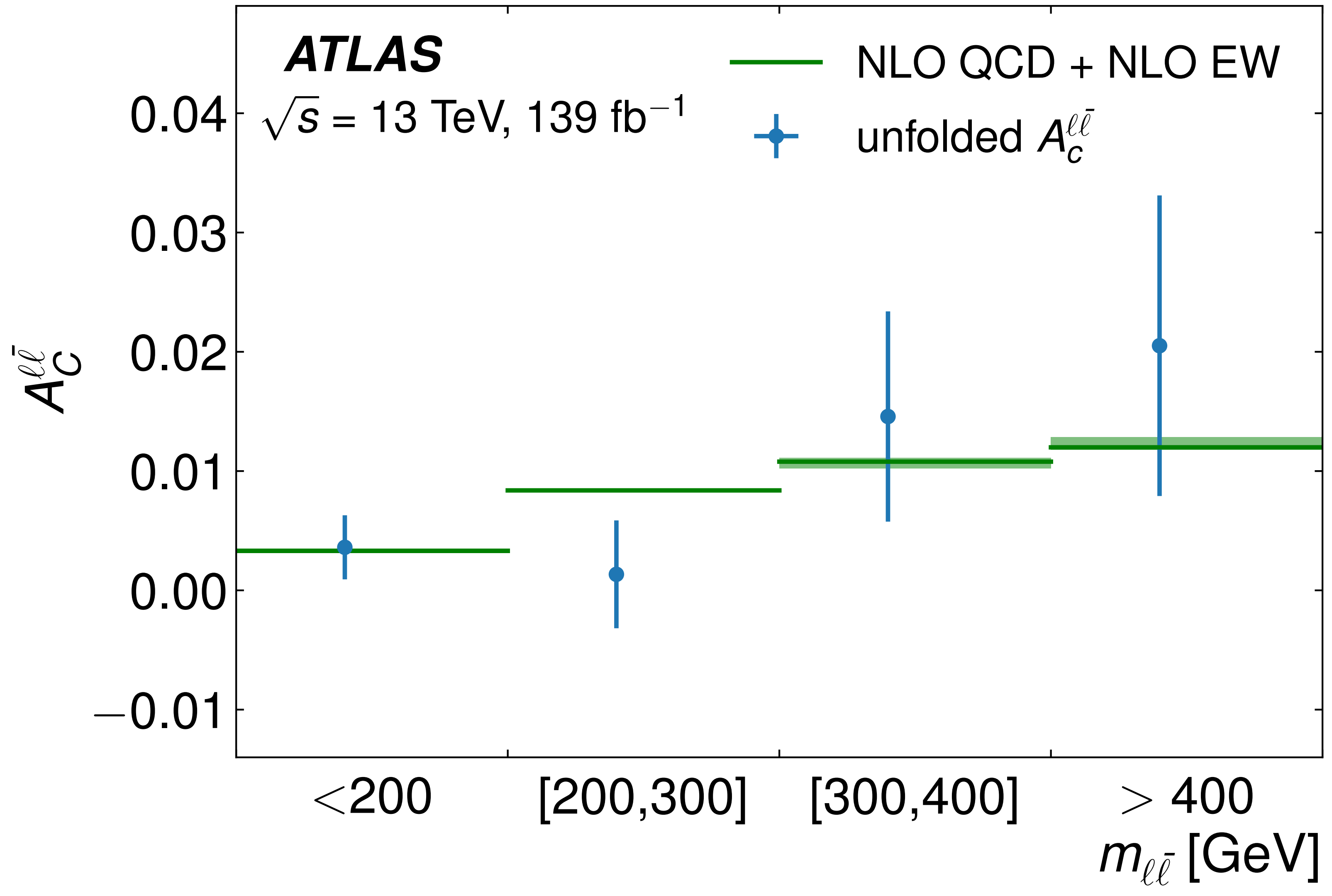


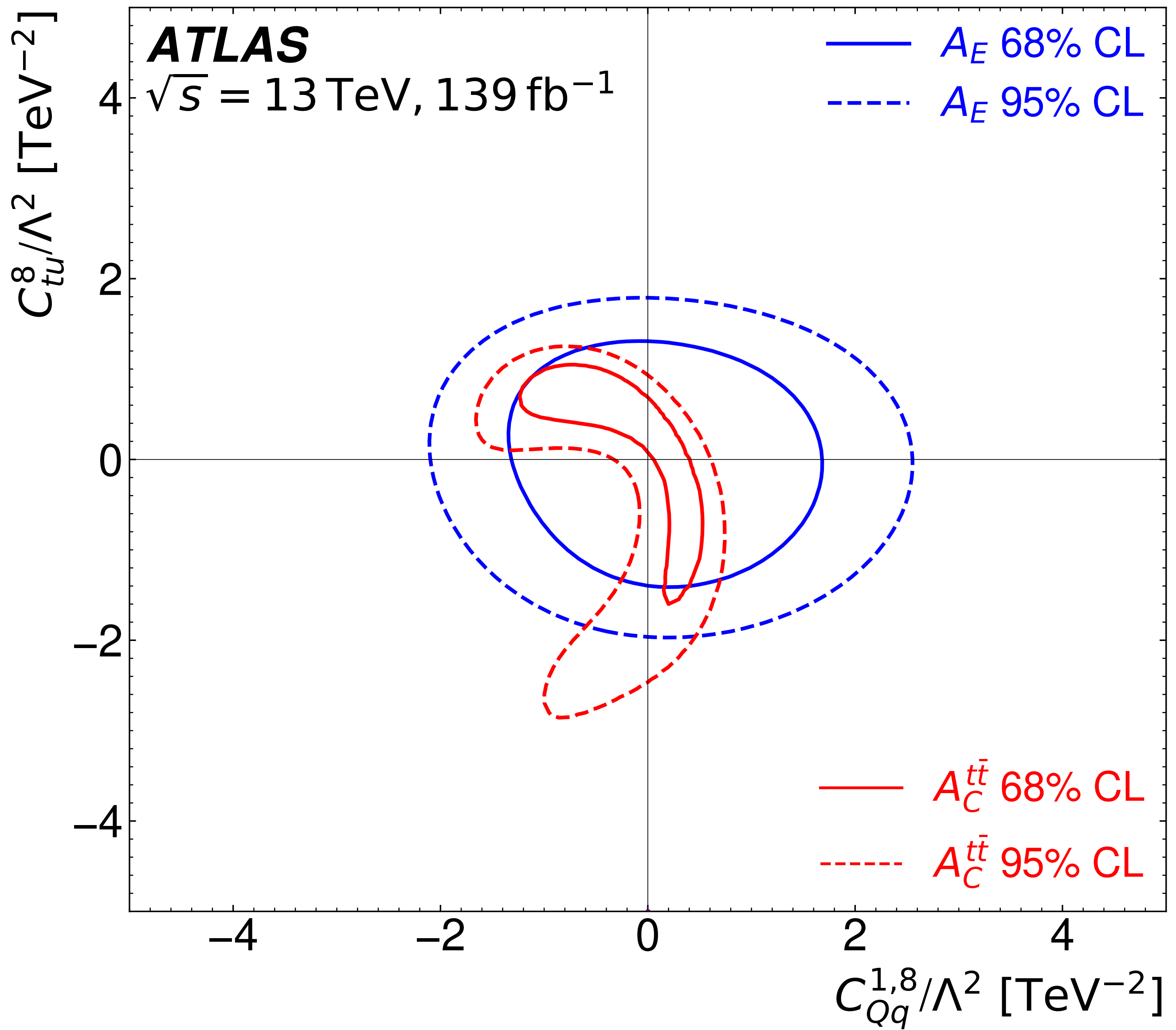


Charge asymmetry measurements

RESULTS

- Charge asymmetry in $t\bar{t}$ events
  - $A_C^{\ell} = -0.0068 \pm 0.0015\ (\text{stat} + \text{syst})$
    - Differs from 0 by 4.7σ $\rightarrow$ evidence of charge asymmetry
  - Inclusive and differential measurements improve the 95% CL limit on C_{tu}^{8}/Λ^2
- Charge asymmetry in $t\bar{t}\gamma$
  - $A_C = -0.003 \pm 0.024\,(\text{stat}) \pm 0.017\ (\text{syst})$
  - $A_C^{\text{SM}} = -0.014 \pm 0.001\ (\text{scale})$
- Charge asymmetry in $t\bar{t}W$
  - $A_C^{\ell}\left(t\bar{t}W\right) = -0.12 \pm 0.14\,(\text{stat}) \pm 0.05\ (\text{syst})$





Phys. Lett. B 843 (2023) 137848

Charge asymmetry measurements ($t\bar{t}\gamma$)

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- Selection (recommended objects)
  - 1 isolated photon with $p_T > 20$ GeV, $|\eta| < 2.37$, exclude crack region (also e)
  - 1 μ or e with $|\eta^{\mu}| < 2.5$, $|\eta^{e}| < 2.47$, $p_T > 25$ GeV, exclude $85 < m(e,\gamma) < 95$ GeV
  - $\geq$4 jets with $p_T > 25$ GeV
  - and $\geq$1 b-tagged jet passing the WP77% (DL1r)

UNCERTAINTIES

Total uncertainty	0.029
Statistical uncertainty	0.024
MC statistical uncertainties	
Background processes	0.008
$t\bar{t}\gamma$ production	0.004
Modelling uncertainties	
$t\bar{t}\gamma$ production modelling	0.003
Background modelling	0.002
Prompt background normalisation	0.002
Experimental uncertainties	
Jet	0.009
Fake-lepton background estimate	0.005
E_T^{miss}	0.005
Fake-photon background estimates	0.003
Photon	0.001
b-tagging	0.001
Other experimental	0.004

Charge asymmetry measurements ($t\bar{t}W$)

SELECTION AND REGION DEFINITIONS

	Preselection			
N_ℓ ($\ell = e/\mu$)	$= 3$			
p_T^ℓ ($1^{st}/2^{nd}/3^{rd}$)	≥ 30 GeV, ≥ 20 GeV, ≥ 15 GeV			
Sum of lepton charges	± 1			
$m_{\ell\ell}^{OSSF}$	≥ 30 GeV			
	Region-specific requirements			
	SR-1b-lowN_{jets}	**SR-1b-highN_{jets}**	**SR-2b-lowN_{jets}**	**SR-2b-highN_{jets}**
N_{jets}	[2, 3]	≥ 4	[2, 3]	≥ 4
$N_{b\text{-jets}}$	$= 1$	$= 1$	≥ 2	≥ 2
E_T^{miss}	≥ 50 GeV	≥ 50 GeV	–	–
$N_{Z\text{-cand.}}$	$= 0$			
Lepton criteria	TTT			
e/γ ambiguity-cuts	satisfy all			
	CR-$t\bar{t}Z$	**CR-HF$_e$**	**CR-HF$_\mu$**	**CR-γ-conv**
$\ell^{1st/2nd/3rd}$	$\ell\ell\ell$	$\ell\ell e$	$\ell\ell\mu$	$\ell\ell e$, $\ell e\ell$, $e\ell\ell$
N_{jets}	≥ 4	≥ 2	≥ 2	≥ 2
$N_{b\text{-jets}}$	≥ 2	$= 1$	$= 1$	≥ 1
E_T^{miss}	–	< 50 GeV	< 50 GeV	< 50 GeV
$N_{Z\text{-cand.}}$	$= 1$	$= 0$	$= 0$	$= 0$
Lepton criteria	TTT	$TT\overline{T}$	$TT\overline{T}$	TTT
e/γ ambiguity-cuts	satisfy all	satisfy all	satisfy all	≥ 1 fail

UNCERTAINTIES

	$\Delta A_c^\ell(t\bar{t}W)^{PL}$
Experimental uncertainties	
Leptons	0.014
Jet energy resolution	0.011
Pile-up	0.008
Jet energy scale	0.004
E_T^{miss}	0.002
Luminosity	0.001
Jet vertex tagger	0.001
MC modelling uncertainties	
$t\bar{t}W$ modelling	0.022
$t\bar{t}Z$ modelling	0.017
HF$_{e/\mu}$ modelling	0.015
Others modelling	0.015
WZ/ZZ + jets modelling	0.014
$t\bar{t}H$ modelling	0.006
Other uncertainties	
Unfolding bias	0.004
$\Delta\eta^\pm$ CR-dependency	0.039
MC statistical uncertainty	0.027
Response matrix	0.009
Data statistical uncertainty	0.170
Total uncertainty	0.179

Charge asymmetry measurements ($t\bar{t}$)

ATLAS EXPERIMENT

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RESULTS AND UNCERTAINTIES

$A_c^{t\bar{t}}$ vs $m_{t\bar{t}}$

		Channel	$A_C^{t\bar{t}}$ (Data 139 fb^{-1})	Stat.	Syst.	Total unc.	SM prediction
Inclusive		Single-lepton	0.0068	0.0011	0.0011	0.0015	
		Dilepton	0.0070	0.0034	0.0035	0.0049	$0.0064^{+0.0005}_{-0.0006}$
		Combination	0.0068	0.0010	0.0010	0.0015	
$m_{t\bar{t}}$	< 500 GeV	Single-lepton	0.0074	0.0028	0.0028	0.0039	
		Dilepton	−0.0030	0.0114	0.0084	0.0141	$0.0056^{+0.0006}_{-0.0006}$
		Combination	0.0059	0.0027	0.0024	0.0036	
	500–750 GeV	Single-lepton	0.0054	0.0020	0.0015	0.0025	
		Dilepton	0.0180	0.0061	0.0066	0.0089	$0.0072^{+0.0006}_{-0.0006}$
		Combination	0.0055	0.0019	0.0013	0.0023	
	750–1000 GeV	Single-lepton	0.0080	0.0048	0.0040	0.0062	
		Dilepton	−0.0147	0.0188	0.0120	0.0223	$0.0079^{+0.0004}_{-0.0006}$
		Combination	0.0102	0.0046	0.0030	0.0056	
	1000–1500 GeV	Single-lepton	0.0234	0.0075	0.0050	0.0090	
		Dilepton	0.0663	0.0371	0.0244	0.0444	$0.0096^{+0.0009}_{-0.0009}$
		Combination	0.0246	0.0074	0.0045	0.0087	
	> 1500 GeV	Single-lepton	0.0133	0.0288	0.0076	0.0298	
		Dilepton	−0.1313	0.1444	0.0590	0.1560	$0.0094^{+0.0015}_{-0.0011}$
		Combination	0.0014	0.0280	0.0068	0.0288	

$A_c^{t\bar{t}}$ vs $p_T^{t\bar{t}}$

		Channel	$A_C^{t\bar{t}}$ (Data 139 fb^{-1})	Stat.	Syst.	Total unc.	SM prediction
$p_{T,t\bar{t}}$	< 30 GeV	Single-lepton	0.0134	0.0034	0.0031	0.0046	
		Dilepton	0.0041	0.0105	0.0103	0.0147	$0.0150^{+0.0006}_{-0.0046}$
		Combination	0.0118	0.0032	0.0025	0.0041	
	30–120 GeV	Single-lepton	0.0044	0.0027	0.0027	0.0038	
		Dilepton	0.0179	0.0096	0.0103	0.0141	$0.0009^{+0.0028}_{-0.0012}$
		Combination	0.0058	0.0026	0.0026	0.0037	
	> 120 GeV	Single-lepton	−0.0015	0.0047	0.0064	0.0080	
		Dilepton	−0.0061	0.0122	0.0062	0.0137	$0.0044^{+0.0030}_{-0.0014}$
		Combination	−0.0019	0.0044	0.0048	0.0065	
$\beta_{z,t\bar{t}}$	0–0.3	Single-lepton	0.0022	0.0040	0.0039	0.0056	
		Dilepton	−0.0135	0.0179	0.0119	0.0215	$0.0011^{+0.0005}_{-0.0004}$
		Combination	<0.0001	0.0039	0.0035	0.0052	
	0.3–0.6	Single-lepton	0.0074	0.0031	0.0025	0.0040	
		Dilepton	−0.0010	0.0116	0.0076	0.0139	$0.0023^{+0.0006}_{-0.0004}$
		Combination	0.0065	0.0029	0.0023	0.0037	
	0.6–0.8	Single-lepton	0.0017	0.0028	0.0023	0.0037	
		Dilepton	0.0104	0.0090	0.0076	0.0118	$0.0042^{+0.0003}_{-0.0003}$
		Combination	0.0026	0.0027	0.0021	0.0034	
	0.8–1.0	Single-lepton	0.0130	0.0026	0.0038	0.0046	
		Dilepton	0.0208	0.0069	0.0050	0.0085	$0.0146^{+0.0012}_{-0.0014}$
		Combination	0.0163	0.0024	0.0030	0.0039	

Charge asymmetry measurements ($t\bar{t}$)

$A_c^{\ell\bar{\ell}}$ RESULTS AND UNCERTAINTIES

		Data 139 fb^{-1}				SM prediction
		$A_C^{\ell\bar{\ell}}$	Stat.	Syst.	Total unc.	
Inclusive		0.0054	0.0012	0.0023	0.0026	$0.0040^{+0.0002}_{-0.0001}$
$m_{\ell\bar{\ell}}$	< 200 GeV	0.0036	0.0014	0.0023	0.0027	$0.0033^{+0.0001}_{-0.0001}$
	200–300 GeV	0.0013	0.0041	0.0020	0.0046	$0.0084^{+0.0002}_{-0.0001}$
	300–400 GeV	0.0146	0.0085	0.0030	0.0090	$0.0108^{+0.0003}_{-0.0006}$
	> 400 GeV	0.0205	0.0123	0.0036	0.0128	$0.0120^{+0.0009}_{-0.0002}$
$p_{T,\ell\bar{\ell}}$	< 20 GeV	0.0176	0.0063	0.0031	0.0070	$0.0026^{+0.0002}_{-0.0002}$
	20–70 GeV	0.0055	0.0020	0.0028	0.0034	$0.0034^{+0.0001}_{<0.0001}$
	> 70 GeV	0.0041	0.0018	0.0020	0.0027	$0.0050^{+0.0002}_{-0.0003}$
$\beta_{z,\ell\bar{\ell}}$	0–0.3	−0.0020	0.0028	0.0008	0.0029	$0.0022^{+0.0001}_{-0.0001}$
	0.3–0.6	0.0050	0.0024	0.0043	0.0049	$0.0016^{+0.0001}_{-0.0001}$
	0.6–0.8	0.0068	0.0026	0.0037	0.0045	$0.0034^{<0.0001}_{-0.0001}$
	0.8–1.0	0.0096	0.0028	0.0014	0.0031	$0.0069^{+0.0003}_{-0.0003}$

Charge asymmetry measurements ($t\bar{t}$)

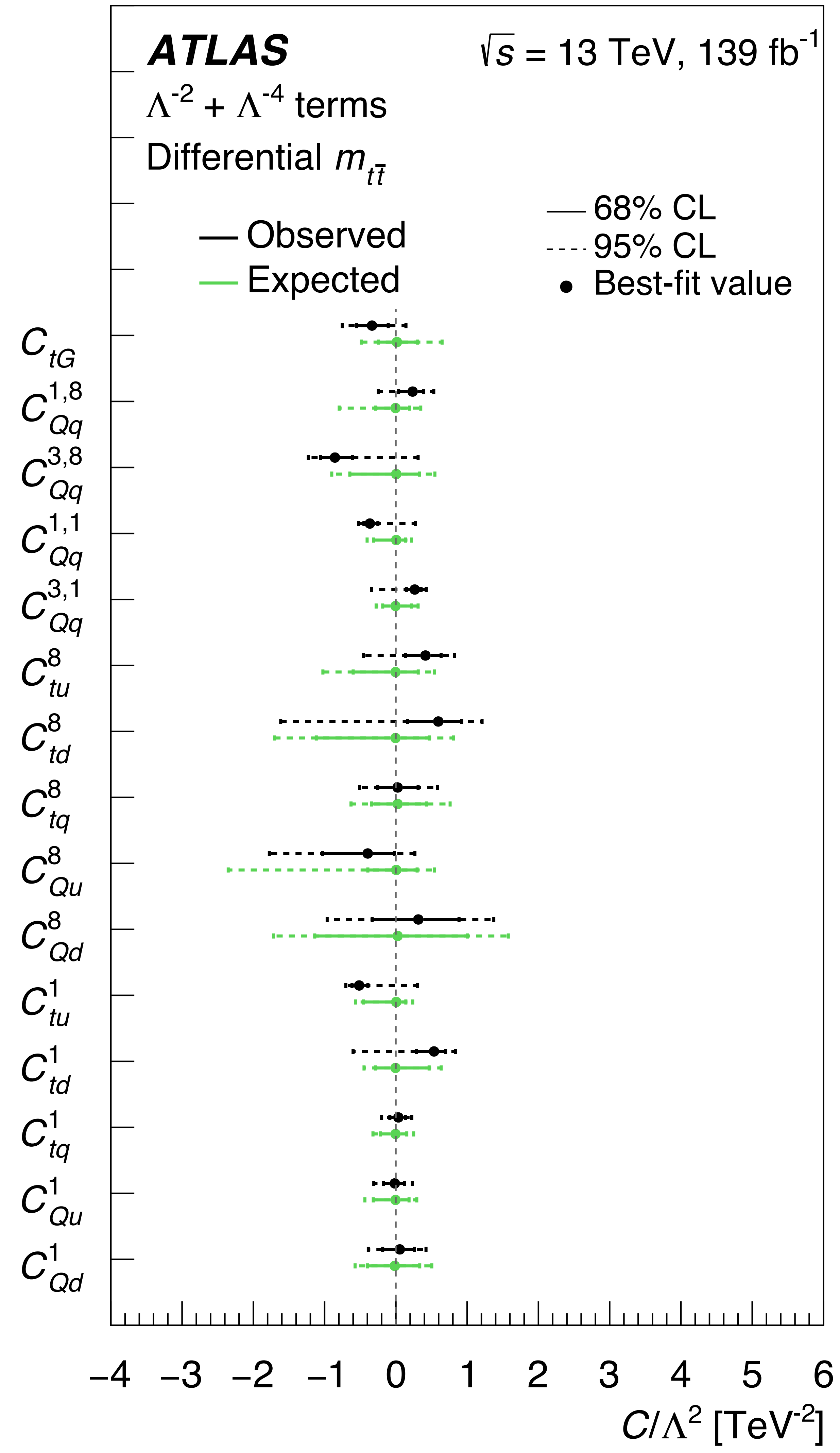
EFT COEFFICIENTS

Individual bounds (in units of TeV^{-2}) from the inclusive $A_C^{t\bar{t}}$ measurement.

	Linear fit including terms $\propto \Lambda^{-2}$		*Quadratic* fit adding $(D6)^2$ terms $\propto \Lambda^{-4}$	
Operator coefficient	68% CL	95% CL	68% CL	95% CL
C_{tG}/Λ^2	[−0.54, 0.37]	[−0.89, 1.03]	[−0.56, 0.37]	[−0.97, 0.99]
$C_{Qq}^{1,8}/\Lambda^2$	[−0.32, 0.61]	[−0.78, 1.10]	[−0.37, 0.51]	[−3.47, 0.84]
$C_{Qq}^{3,8}/\Lambda^2$	[−0.88, 1.63]	[−2.10, 2.94]	[−1.97, 0.90]	[−2.41, 1.33]
$C_{Qq}^{1,1}/\Lambda^2$	[−1.24, 2.29]	[−2.97, 4.13]	[−0.60, 0.48]	[−0.79, 0.67]
$C_{Qq}^{3,1}/\Lambda^2$	[−6.74, 3.73]	[−12.1, 8.99]	[−0.51, 0.57]	[−0.70, 0.75]
C_{tu}^{8}/Λ^2	[−0.60, 1.13]	[−1.44, 2.05]	[−2.93, 0.82]	[−3.38, 1.28]
C_{td}^{8}/Λ^2	[−0.97, 1.80]	[−2.30, 3.26]	[−4.34, 1.28]	[−5.05, 1.99]
C_{tq}^{8}/Λ^2	[−0.96, 0.54]	[−1.73, 1.29]	[−2.77, 0.45]	[−3.23, 0.93]
C_{Qu}^{8}/Λ^2	[−1.06, 0.59]	[−1.90, 1.41]	[−3.63, 0.51]	[−4.17, 1.06]
C_{Qd}^{8}/Λ^2	[−3.71, 2.08]	[−6.61, 5.02]	[−3.36, 1.29]	[−4.41, 2.35]
C_{tu}^{1}/Λ^2	[−0.81, 1.49]	[−1.93, 2.69]	[−0.80, 0.53]	[−1.02, 0.75]
C_{td}^{1}/Λ^2	[−17.6, 32.7]	[−41.8, 59.4]	[−0.98, 0.96]	[−1.32, 1.30]
C_{tq}^{1}/Λ^2	[−1.25, 2.31]	[−3.00, 4.16]	[−0.34, 0.47]	[−0.55, 0.68]
C_{Qu}^{1}/Λ^2	[−2.40, 4.40]	[−5.76, 7.92]	[−0.43, 0.53]	[−0.68, 0.78]
C_{Qd}^{1}/Λ^2	[−53.0, 88.0]	[−134, 152]	[−0.72, 0.74]	[−1.10, 1.12]

Individual bounds (in units of TeV^{-2}) from the differential $A_C^{t\bar{t}}$ measurement versus $m_{t\bar{t}}$.

	Linear fit including terms $\propto \Lambda^{-2}$		*Quadratic* fit adding $(D6)^2$ terms $\propto \Lambda^{-4}$	
Operator coefficient	68% CL	95% CL	68% CL	95% CL
C_{tG}/Λ^2	[−0.53, −0.11]	[−0.70, 0.14]	[−0.55, −0.11]	[−0.75, 0.14]
$C_{Qq}^{1,8}/\Lambda^2$	[0.03, 0.49]	[−0.20, 0.73]	[0.04, 0.39]	[−0.25, 0.53]
$C_{Qq}^{3,8}/\Lambda^2$	[−0.61, 0.45]	[−1.13, 1.00]	[−1.06, −0.61]	[−1.23, 0.31]
$C_{Qq}^{1,1}/\Lambda^2$	[−0.06, 0.39]	[−0.28, 0.62]	[−0.45, −0.25]	[−0.52, 0.28]
$C_{Qq}^{3,1}/\Lambda^2$	[−0.15, 0.98]	[−0.69, 1.56]	[0.15, 0.35]	[−0.34, 0.43]
C_{tu}^{8}/Λ^2	[0.12, 0.96]	[−0.28, 1.38]	[0.14, 0.63]	[−0.45, 0.82]
C_{td}^{8}/Λ^2	[0.18, 1.47]	[−0.45, 2.13]	[0.17, 0.92]	[−1.62, 1.21]
C_{tq}^{8}/Λ^2	[−0.36, 0.46]	[−0.76, 0.88]	[−0.25, 0.31]	[−0.51, 0.58]
C_{Qu}^{8}/Λ^2	[−0.71, −0.05]	[−1.03, 0.29]	[−1.03, −0.02]	[−1.78, 0.27]
C_{Qd}^{8}/Λ^2	[0.25, 3.46]	[−1.28, 5.14]	[−0.33, 0.89]	[−0.96, 1.37]
C_{tu}^{1}/Λ^2	[−0.02, 0.40]	[−0.21, 0.61]	[−0.62, −0.39]	[−0.70, 0.31]
C_{td}^{1}/Λ^2	[−1.24, 0.22]	[−1.94, 1.00]	[0.29, 0.70]	[−0.60, 0.84]
C_{tq}^{1}/Λ^2	[−0.10, 0.38]	[−0.35, 0.63]	[−0.08, 0.14]	[−0.20, 0.22]
C_{Qu}^{1}/Λ^2	[−0.47, 0.24]	[−0.85, 0.58]	[−0.18, 0.12]	[−0.31, 0.23]
C_{Qd}^{1}/Λ^2	[−0.27, 1.24]	[−1.13, 1.90]	[−0.19, 0.26]	[−0.39, 0.42]



Combination of top mass measurement

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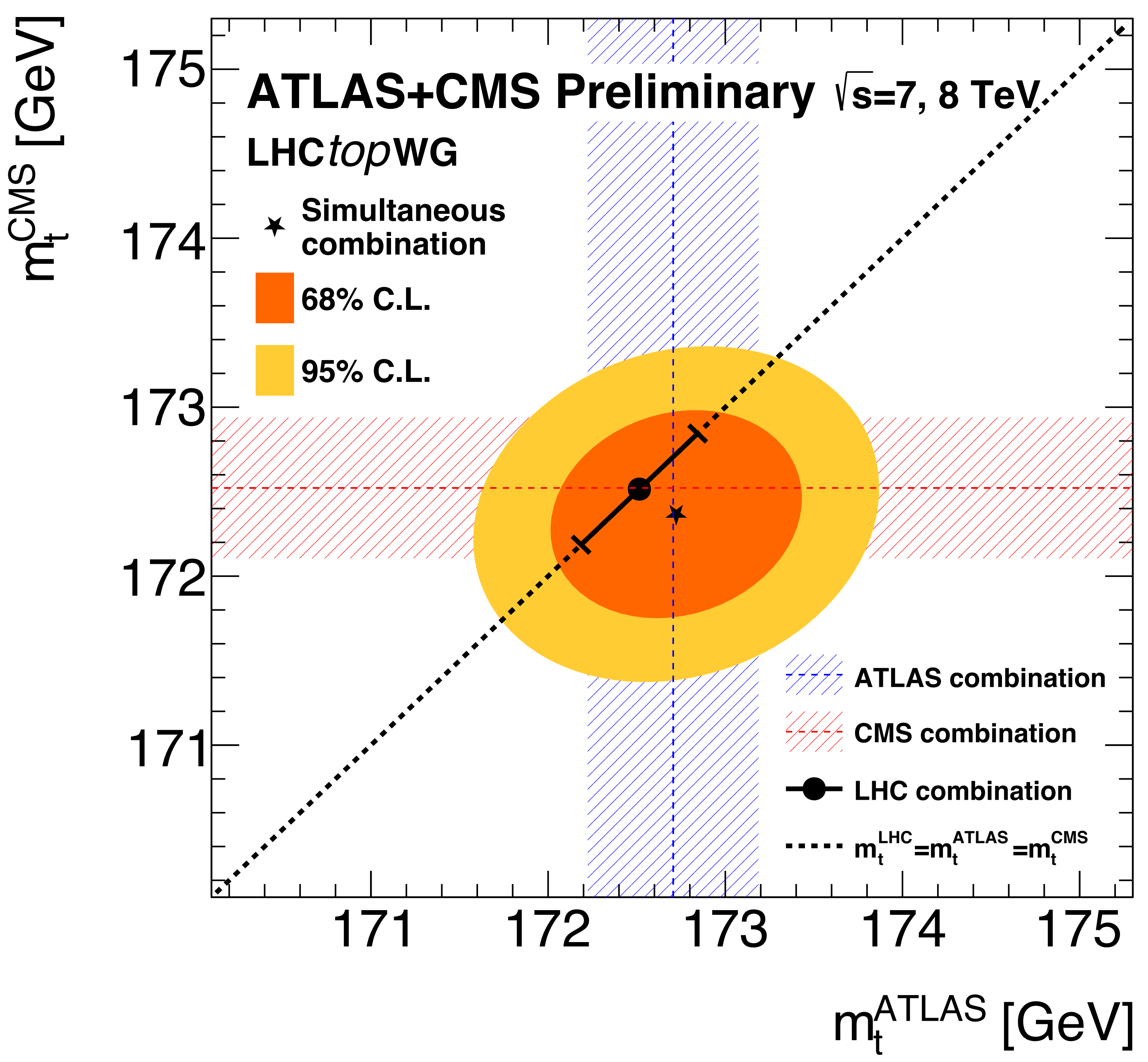
ATLAS vs CMS



UNCERTAINTIES

Uncertainty category	Uncertainty impact [GeV]		
	LHC	ATLAS	CMS
LHC b-JES	0.18	0.17	0.25
b tagging	0.09	0.16	0.03
ME generator	0.08	0.13	0.14
LHC JES 1	0.08	0.18	0.06
LHC JES 2	0.08	0.11	0.10
Method	0.07	0.06	0.09
CMS B hadron BR	0.07	—	0.12
LHC radiation	0.06	0.07	0.10
Leptons	0.05	0.08	0.07
JER	0.05	0.09	0.02
Top quark p_T	0.05	—	0.07
Background (data)	0.05	0.04	0.06
Color reconnection	0.04	0.08	0.03
Underlying event	0.04	0.03	0.05
LHC g-JES	0.03	0.02	0.04
Background (MC)	0.03	0.07	0.01
Other	0.03	0.06	0.01
LHC l-JES	0.03	0.01	0.05
CMS JES 1	0.03	—	0.04
Pileup	0.03	0.07	0.03
LHC JES 3	0.02	0.07	0.01
LHC hadronization	0.02	0.01	0.01
p_T^{miss}	0.02	0.04	0.01
PDF	0.02	0.06	<0.01
Trigger	0.01	0.01	0.01
Total systematics	0.30	0.41	0.39
Statistical	0.14	0.25	0.14
Total	0.33	0.48	0.42

UNCERTAINTIES CORRELATIONS

Uncertainty category	ρ	Scan range	$\Delta m_t/2$ [MeV]	$\Delta\sigma_{m_t}/2$ [MeV]
LHC JES 1	0	—	—	—
LHC JES 2	0	$[-0.25, +0.25]$	8	7
LHC JES 3	0.5	$[+0.25, +0.75]$	1	<1
LHC b-JES	0.85	$[+0.5, +1]$	26	5
LHC g-JES	0.85	$[+0.5, +1]$	2	<1
LHC l-JES	0	$[-0.25, +0.25]$	1	<1
CMS JES 1	—	—	—	—
JER	0	$[-0.25, +0.25]$	5	1
Leptons	0	$[-0.25, +0.25]$	2	2
b tagging	0.5	$[+0.25, +0.75]$	1	1
p_T^{miss}	0	$[-0.25, +0.25]$	<1	<1
Pileup	0.85	$[+0.5, +1]$	2	<1
Trigger	0	$[-0.25, +0.25]$	<1	<1
ME generator	0.5	$[+0.25, +0.75]$	<1	4
LHC radiation	0.5	$[+0.25, +0.75]$	7	1
LHC hadronization	0.5	$[+0.25, +0.75]$	1	<1
CMS B hadron BR	—	—	—	—
Color reconnection	0.5	$[+0.25, +0.75]$	3	1
Underlying event	0.5	$[+0.25, +0.75]$	1	<1
PDF	0.85	$[+0.5, +1]$	1	<1
Top quark p_T	—	—	—	—
Background (data)	0	$[-0.25, +0.25]$	8	2
Background (MC)	0.85	$[+0.5, +1]$	2	<1
Method	0	—	—	—
Other	0	—	—	—

Observation of $t\bar{t}$ production in p+Pb collisions

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UNCERTAINTIES

Source	unc. up	unc. down
Jet energy scale	+0.048	-0.044
$t\bar{t}$ generator	+0.048	-0.043
Fake-lepton background	+0.030	-0.027
Background	+0.030	-0.025
Luminosity	+0.029	-0.025
Muon systs.	+0.024	-0.021
W+jets	+0.023	-0.020
b-tagging	+0.022	-0.021
Electron systs.	+0.018	-0.017
MC statistical uncertainties	+0.011	-0.010
Jet energy resolution	+0.005	-0.004
$t\bar{t}$ PDF	+0.001	-0.001
Total syst.	+0.088	-0.081

SELECTION

ℓ+jets

e+jets

- 1 isolated electron with $p_T > 18$ GeV,
- 0 isolated muons with $p_T > 18$ GeV,
- at least 4 HI jets with $p_T > 20$ GeV.

μ+jets

- 1 isolated muon with $p_T > 18$ GeV,
- 0 isolated electrons with $p_T > 18$ GeV,
- at least 4 HI jets with $p_T > 20$ GeV.

Dilepton

ee

- 2 isolated electrons with $p_T > 18$ GeV,
- 0 isolated muons with $p_T > 18$ GeV,
- opposite sign leptons,
- $m_{\ell\ell} > 45$ GeV and $m_{\ell\ell} \notin (80-100)$ GeV,
- at least 2 HI jets with $p_T > 20$ GeV.

$\mu\mu$

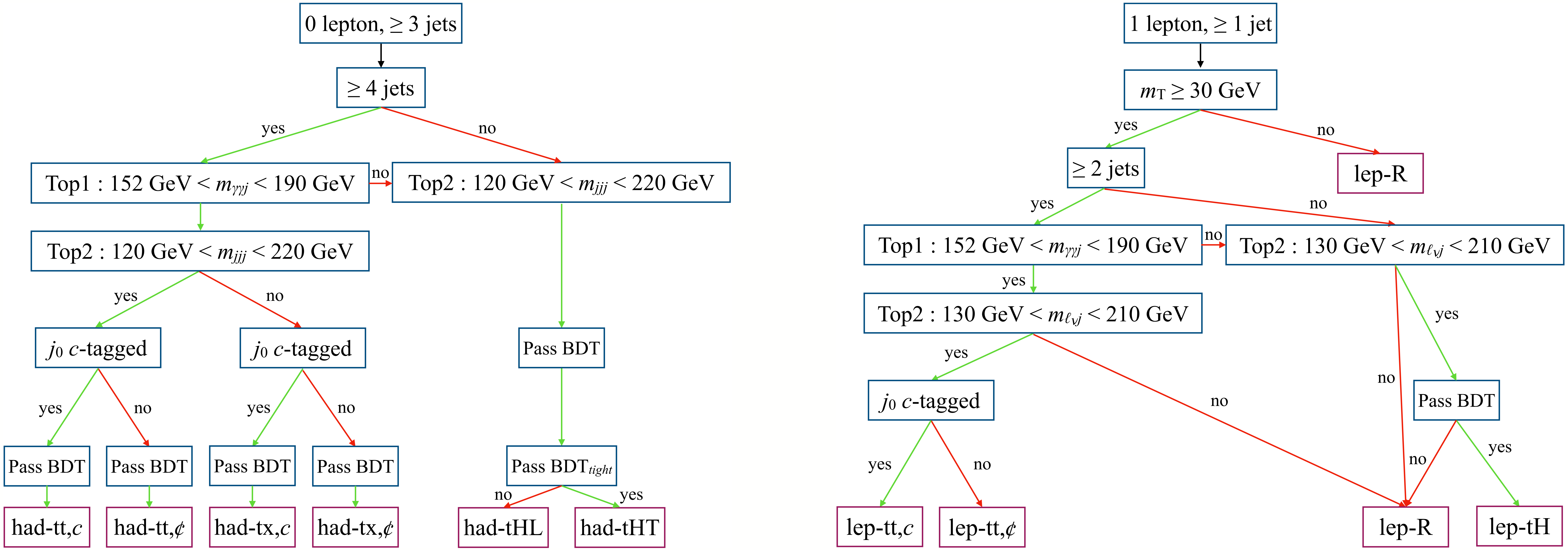
- 2 isolated muons with $p_T > 18$ GeV,
- 0 isolated electrons with $p_T > 18$ GeV,
- opposite sign leptons,
- $m_{\ell\ell} > 45$ GeV and $m_{\ell\ell} \notin (80-100)$ GeV,
- at least 2 HI jets with $p_T > 20$ GeV.

$e\mu$

- 1 isolated electron with $p_T > 18$ GeV,
- 1 isolated muon with $p_T > 18$ GeV,
- opposite sign leptons,
- $m_{\ell\ell} > 15$ GeV,
- at least 2 HI jets with $p_T > 20$ GeV.

Search for FCNC in $tqH\,(\gamma\gamma)$

SELECTIONS



Search for FCNC in $tqH\,(\gamma\gamma)$

ATLAS EXPERIMENT

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UNCERTAINTIES

Source	relative impact (%)
Experimental	
Photon energy resolution	1.5
Photon identification	0.4
Luminosity, pile-up modelling	0.3
Jet energy scale and resolution, flavour tagging	< 0.2
Theoretical	
Normalisation $(\sigma(pp \to t\bar{t}, tH), \mathcal{B}(H \to \gamma\gamma))$	1.1
Parton showering model	0.8
m_t value, NLO generator for $pp \to tH$	0.5
Resonant background	0.5
Non-resonant background	2.3

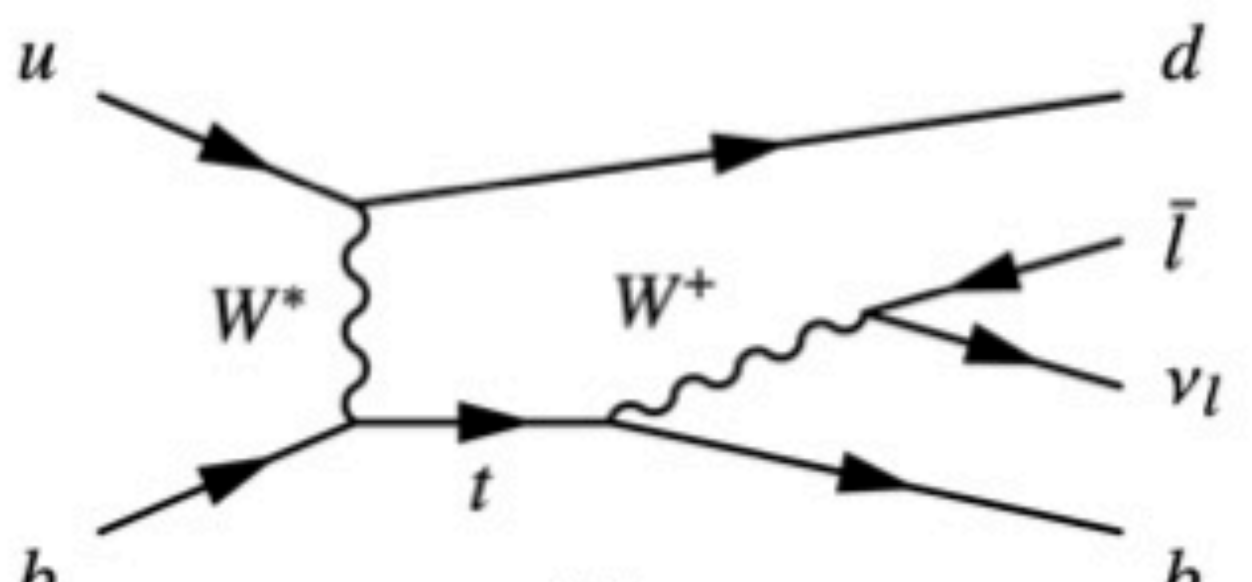
Measurement of t-channel single-top production at $\sqrt{s} = 13$ TeV

ATLAS EXPERIMENT

ROYAL HOLLOWAY UNIVERSITY OF LONDON

EVENT SELECTION

- exactly **one charged lepton** ℓ with $p_{\mathrm{T}} > 28$ GeV and $|\eta| < 2.5$
- veto events with additional loose leptons
- exactly **two jets** with $p_{\mathrm{T}} > 30$ GeV and $|\eta| < 4.5$
- exactly one jet with a ***b*-tag**
- $E_{\mathrm{T}}^{\mathrm{miss}} > 30$ GeV
- $m_{\mathrm{T}}(\ell E_{\mathrm{T}}^{\mathrm{miss}}) > 50$ GeV
- $m(\ell b) < 160$ GeV
- $p_{\mathrm{T}}(\ell) > 40 \cdot |\Delta\Phi(j_1, \ell)/\pi|$



(a)

- Orthogonal Regions for multijet normalization:
  - $E_{\mathrm{T}}^{\mathrm{miss}} < 30$ GeV for electron multijet
  - $p_{\mathrm{T}}(\ell) > 40 \cdot |\Delta\Phi(j_1, \ell)/\pi|$ for muon multijet

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UNCERTAINTIES

Uncertainty group	Relative on uncertainty on $\sigma(tq)$	$\sigma(\bar{t}q)$	$\sigma(tq+\bar{t}q)$	R_t
Data statistical	$+0.4$ / -0.4	$+0.5$ / -0.5	$+0.3$ / -0.3	$+0.6$ / -0.6
Signal modelling	$+4.9$ / -4.5	$+5.2$ / -4.7	$+5.0$ / -4.6	$+0.9$ / -0.9
Background modelling	$+1.8$ / -1.6	$+2.1$ / -1.9	$+1.8$ / -1.6	$+1.5$ / -1.4
MC statistical	$+1.1$ / -1.0	$+1.4$ / -1.3	$+1.2$ / -1.1	$+0.8$ / -0.8
PDFs	$+0.4$ / -0.4	$+1.2$ / -1.0	$+0.7$ / -0.6	$+0.9$ / -0.8
Jets	$+2.2$ / -2.0	$+3.0$ / -2.7	$+2.5$ / -2.3	$+1.0$ / -0.9
b-tagging	$+1.6$ / -1.5	$+1.7$ / -1.5	$+1.6$ / -1.5	$+0.2$ / -0.1
Leptons	$+1.1$ / -1.0	$+1.1$ / -1.0	$+1.1$ / -1.0	$+0.1$ / -0.1
Luminosity	$+0.9$ / -0.8	$+0.9$ / -0.9	$+0.9$ / -0.8	< 0.1
Total	$+5.9$ / -5.5	$+6.6$ / -6.2	$+5.9$ / -5.9	$+2.2$ / -2.1

CONTROL REGIONS

CR name	Defining requirement
`B-e-plus`	$q_e/e = +1,\ \|\eta(e)\| < 1.37,\ E_{\mathrm{T}}^{\mathrm{miss}} < 30\,GeV$
`B-e-minus`	$q_e/e = -1,\ \|\eta(e)\| < 1.37,\ E_{\mathrm{T}}^{\mathrm{miss}} < 30\,GeV$
`EC-e-plus`	$q_e/e = +1,\ \|\eta(e)\| > 1.52,\ E_{\mathrm{T}}^{\mathrm{miss}} < 30\,GeV$
`EC-e-minus`	$q_e/e = -1,\ \|\eta(e)\| > 1.52,\ E_{\mathrm{T}}^{\mathrm{miss}} < 30\,GeV$
CR μ-`plus`	$q_\mu/e = +1,\ 28\,GeV < p_{\mathrm{T}}(\mu) < 40\,\mathrm{GeV} \cdot \frac{\|\Delta\phi(j_1,\ell)\|}{\pi}$
CR μ-`minus`	$q_\mu/e = -1,\ 28\,GeV < p_{\mathrm{T}}(\mu) < 40\,\mathrm{GeV} \cdot \frac{\|\Delta\phi(j_1,\ell)\|}{\pi}$

arXiv:2310.01518

Measurement of t-channel single-top production at $\sqrt{s} = 5.02$ TeV

ATLAS EXPERIMENT

ROYAL HOLLOWAY UNIVERSITY OF LONDON

SELECTION

- **Topology requirements**
  - Exactly 1 lepton
    - Electron $|\eta_{cl}| \leq 2.47$ + exclude crack region
    - Muon $|\eta| \leq 2.5$
  - Exactly 2 jets
    - 1 untagged jet $1.5 \leq |\eta| \leq 4.0$
    - 1 b-tagged jet $|\eta| \leq 2.5$ and DL1R 60% WP
    - $\Delta\eta$ between jets ≥ 1.5
- **Kinematic requirements**
  - Lepton $p_T \geq 18$ GeV
  - Both jets $p_T \geq 23$ GeV
  - $E_T^{miss} \geq 15$ GeV
  - $m_T^W \geq 35$ GeV
  - Triangular $(m_T^W + E_T^{miss}) \geq 70$ GeV
  - $H_T \geq 185$ GeV
  - Mass of the lepton and b-tagged jet $m_{lb} \leq 165$ GeV
  - $m_W \leq 102$ GeV and 140 GeV $\leq m_{top} \leq 225$ GeV

arXiv:2310.01518

Measurement of t-channel single-top production at $\sqrt{s} = 5.02$ TeV

ATLAS EXPERIMENT

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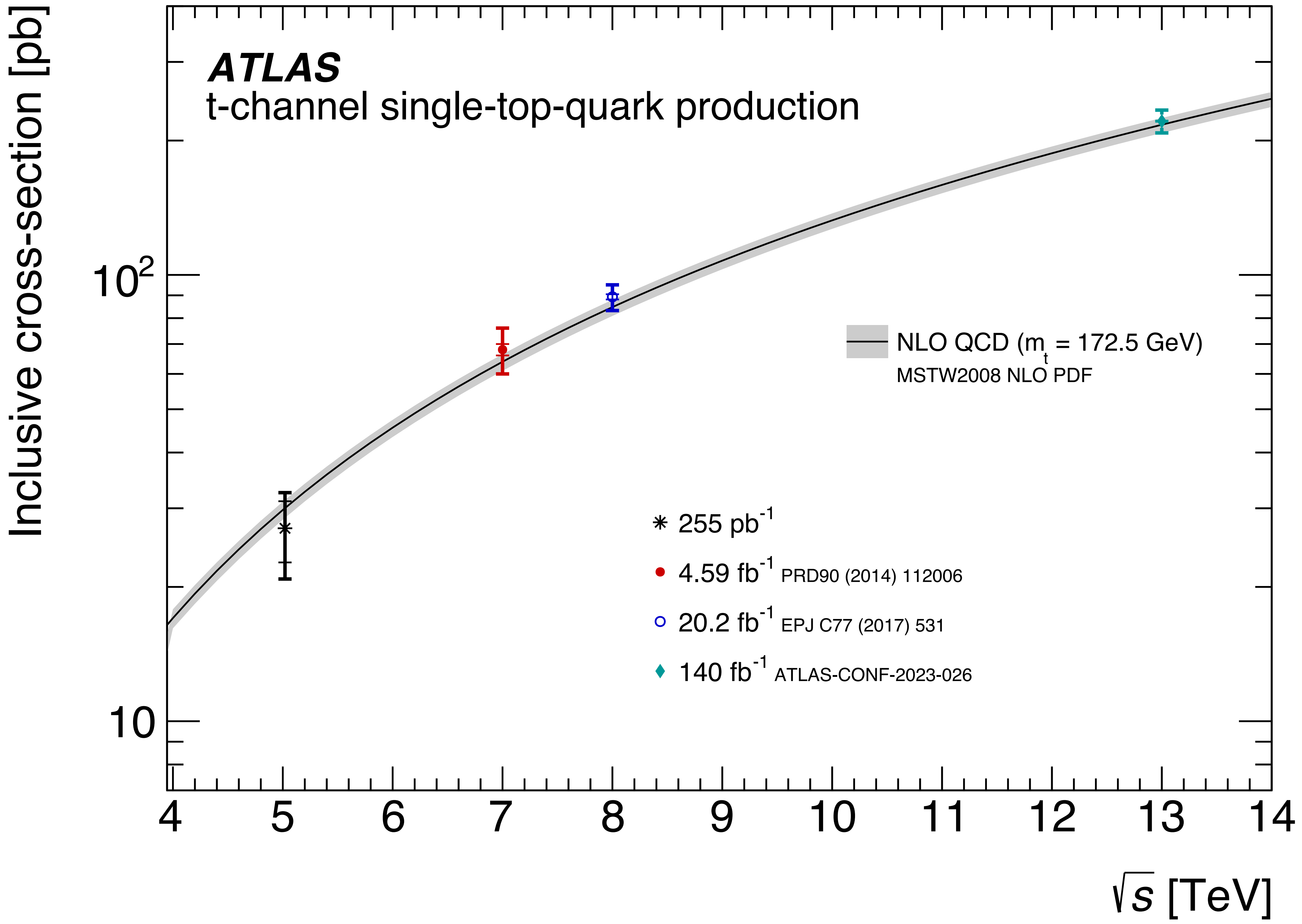
t-CHANNEL CROSS SECTIONS



UNCERTAINTIES

Category	$\delta\sigma(tq+\bar{t}q)/\sigma(tq+\bar{t}q)$ [%]	$\delta R_t/R_t$ [%]
Single-top quark signal modelling	8.6	4.1
Parton distribution functions	0.5	0.8
Misidentified leptons background	6.3	11.1
$W+\geq 1b$ jets modelling	3.9	4.4
$W+\geq 1c$ jets modelling	2.7	3.4
Z+jets normalisation	1.1	2.1
$t\bar{t}$ modelling	0.8	1.2
Single-top quark background modelling	0.6	2.1
$W+\geq 1$ light jets modelling	0.3	0.4
Diboson normalisation	0.1	0.3
Jet energy resolution	4.6	7.8
$\sqrt{s} = 5.02$ TeV JES correction	4.4	5.1
Jet energy scale	4.0	5.3
Flavour tagging	2.0	1.3
Electron reconstruction	1.4	0.5
Muon reconstruction	1.3	0.7
Integrated luminosity	1.3	0.4
$E_{\mathrm{T}}^{\mathrm{miss}}$	0.6	2.4
Jet-vertex tagging	0.07	0.05
Simulation's statistical uncertainty	2.3	6.5
Data's statistical uncertainty	16	38
Total systematic uncertainty	15	18
Total uncertainty	21	42

Jet substructure in boosted $t\bar{t}$ events

ATLAS EXPERIMENT

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ALL HADRONIC SELECTION

Objects	Detector-level Selection	
Leptons	**0 Electrons with** $E_T > 25$ GeV $\|\eta\| < 1.37$ $1.52 < \|\eta\| < 2.47$	**0 Muons with** $p_T > 25$ GeV $\|\eta\| < 2.5$
Large-R jets	≥ 2 with 122.5 GeV $< m_{jet} <$ 222.5 GeV **1** with $p_T > 500$ GeV **2** with $p_T > 350$ GeV $\|\eta\| < 2.0$	
b-tagging	DL1r at 70% WP $\geq$ **2** b-tagged VR track jets Ghost-Matching(b-jet, large-R jet) (for **2** highest-p_T large-R jets)	
Top-Tagging	DNN top-tag on non-probe large-R jet (JSSWTopTaggerDNN_Contained80)	

LEPTON+JETS SELECTION

Objects	Detector-level Selection	
Leptons (= **1** of either)	**Electrons** $p_T > 27$ GeV $\|\eta\| < 1.37$ $1.52 < \|\eta\| < 2.47$ $\|d_0/\sigma(d_0)\| < 5$ $\|\Delta z_0 sin(\theta)\| <$ 0.5 mm	**Muons** $p_T > 27$ GeV $\|\eta\| < 2.5$ $\|d_0/\sigma(d_0)\| < 3$ $\|\Delta z_0\| < 0.5$ mm
E_T^{miss}, m_T^W	$E_T^{miss} > 20$ GeV $E_T^{miss} + m_T^W > 60$ GeV	
EMPFlow small-R jets	$N_{jets} > 2$(implicitly) $p_T > 25$ GeV $\|\eta\| < 2.5$ JVT > 0.5 (if $p_T < 60$ GeV)	
Large-R reclustered (RC) jets	≥ 1 with 122.5 GeV $< m_{jet} <$ 222.5 GeV $p_T > 350$ GeV $\Delta R(\ell$, hadronic top$) \geq 1.0$ $N_{constituents} > 1$	
b-tagging	DL1r at 77% WP At least one b-tagged small-R jet At least one $\Delta R(b$-jet$, \ell) \leq 1.5$ leptonic-b-jet $\notin$ top-jet	
$m_{\ell b}$	$m_{\ell b} <$ 120GeV	

Jet substructure in boosted $t\bar{t}$ events

ATLAS EXPERIMENT

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OBSERVABLES DEFINITION

Variable name	Motivation
τ_{32}	Used in all top-taggers, sensitive to FSR and showering effects, not well described by the nominal prediction, not highly correlated with other variables.
τ_{21}	Used in several top-taggers, mildly correlated with the other measured variables
τ_3	Sensitive to FSR, not well described by the nominal prediction, better resolution than τ_4 to which it is highly correlated.
ECF2 ($\beta = 1$)	Not correlated to the other measured variables, not well described by the nominal predictions, very high resolution and low uncertainties.
D_2 ($\beta = 1$)	Used in all 2-prong jets taggers, sensitive to FSR and showering differences, not well described by the nominal prediction, better resolution than τ_4 to which it is highly correlated.
C_3 ($\beta = 1$)	Sensitive to FSR and showering differences, not correlated to the other measured variables, not well described by the nominal predictions.
p_T dispersion	Not well described by the nominal prediction and not correlated to other measured variables.
LHA	Sensitive to ISR differences, not correlated to the other measured variables, not well described by the nominal predictions.

Jet substructure in boosted $t\bar{t}$ events

ATLAS EXPERIMENT

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ALL HADRONIC χ^2

Observable	PWG+PY8		PWG+H7		MC@NLO+PY8		PWG+PY8(FSR Up)		PWG+PY8(FSR Down)	
	χ^2/NDF	p-value	χ^2/NDF	p-value	χ^2/NDF	p-value	χ^2/NDF	p-value	χ^2/NDF	p-value
τ_{32}	54/12	<0.01	19/12	0.09	15/12	0.24	165/12	<0.01	40/12	<0.01
τ_{21}	14/14	0.41	7/14	0.92	16/14	0.32	42/14	<0.01	8/14	0.91
τ_3	36/11	<0.01	42/11	<0.01	14/11	0.23	130/11	<0.01	23/11	0.02
$ECF2$	25/18	0.13	13/18	0.78	15/18	0.69	31/18	0.03	24/18	0.14
D_2	20/16	0.20	17/16	0.39	20/16	0.20	37/16	<0.01	15/16	0.49
C_3	11/14	0.65	6/14	0.97	3/14	1.00	35/14	<0.01	3/14	1.00
$p_{\mathrm{T}}^{\mathrm{d},*}$	27/12	<0.01	10/12	0.58	11/12	0.53	56/12	<0.01	24/12	0.02
LHA	14/17	0.65	9/17	0.92	20/17	0.29	14/17	0.69	19/17	0.32
D_2 vs m^{top}	61/42	0.03	62/42	0.02	59/42	0.05	118/42	<0.01	44/42	0.37
D_2 vs $p_{\mathrm{T}}^{\mathrm{top}}$	71/56	0.08	68/56	0.13	70/56	0.11	107/56	<0.01	93/56	<0.01
τ_{32} vs m^{top}	153/42	<0.01	72/42	<0.01	56/42	0.07	413/42	<0.01	77/42	<0.01
τ_{32} vs $p_{\mathrm{T}}^{\mathrm{top}}$	153/50	<0.01	103/50	<0.01	57/50	0.23	360/50	<0.01	114/50	<0.01

Jet substructure in boosted $t\bar{t}$ events

LEPTON+JETS χ^2

Observable	PWG+PY8		PWG+H7		MC@NLO+PY8		PWG+PY8(FSR Up)		PWG+PY8(FSR Down)	
	χ^2/NDF	p-value	χ^2/NDF	p-value	χ^2/NDF	p-value	χ^2/NDF	p-value	χ^2/NDF	p-value
τ_{32}	24/10	<0.01	14/10	0.20	9/10	0.52	61/10	<0.01	6/10	0.82
τ_{21}	7/10	0.75	6/10	0.80	6/10	0.80	11/10	0.36	6/10	0.84
τ_3	29/7	<0.01	17/7	0.02	10/7	0.17	58/7	<0.01	8/7	0.29
$ECF2$	17/11	0.10	12/11	0.39	14/11	0.26	20/11	0.05	15/11	0.19
D_2	11/12	0.55	8/12	0.82	8/12	0.76	14/12	0.27	7/12	0.88
C_3	29/8	<0.01	21/8	<0.01	13/8	0.13	57/8	<0.01	10/8	0.28
$p_{\mathrm{T}}^{\mathrm{d},*}$	21/9	0.01	6/9	0.78	10/9	0.35	35/9	<0.01	8/9	0.54
LHA	12/12	0.49	9/12	0.74	12/12	0.46	12/12	0.43	11/12	0.53
D_2 vs m^{top}	23/32	0.89	28/32	0.69	20/32	0.94	29/32	0.63	20/32	0.95
D_2 vs $p_{\mathrm{T}}^{\mathrm{top}}$	29/43	0.96	26/43	0.98	28/43	0.96	32/43	0.88	26/43	0.98
τ_{32} vs m^{top}	30/27	0.31	20/27	0.81	15/27	0.97	68/27	<0.01	11/27	1.00
τ_{32} vs $p_{\mathrm{T}}^{\mathrm{top}}$	50/37	0.08	36/37	0.53	34/37	0.62	94/37	<0.01	30/37	0.79

single-lepton $t\bar{t}$ production differential cross sections

ATLAS EXPERIMENT

ROYAL HOLLOWAY UNIVERSITY OF LONDON

Selection criteria

RECO LEVEL

- **Electrons:**
  - $p_T > 27$ GeV
  - $|\eta| < 1.37$ or $1.52 < |\eta| < 2.47$
  - FCTight isolation
- **Muons:**
  - $p_T > 27$ GeV
  - $|\eta| < 2.5$
  - FCTight isolation
- **Events with exactly one electron or one muon selected**
- **Jets:**
  - $p_T > 25$ GeV
  - $|y| < 2.5$
  - at least 4 AntiKtEMPFlowJets (2 of them b-tagged)
  - JVT medium rejection
- **b-tagging:**
  - two b-tagged jets (DL1r 70%)
- **Overlap removal:**
  - if e shares track with μ, e removed
  - jet removed if $\Delta R(e, jet) < 0.2$
  - ℓ removed if $\Delta R(\ell, jet) < 0.4$
- **PRW and SF (lepton ID, b-tag and JVT) applied to MC samples at reco level**

PARTICLE LEVEL (fiducial phase space)

→ one lepton (e or μ) with $p_T > 27$ GeV and $|\eta| < 2.5$

→ at least 4 AntiKt4TruthWZJets (2 ghost-matched with a B-hadron) with:

  → $p_T > 25$ GeV and $|y| < 2.5$

  → if $\Delta R(\ell, \mathrm{jet}) < 0.4$, ℓ is removed