Measurement of top-quark properties with the ATLAS detector at the LHC

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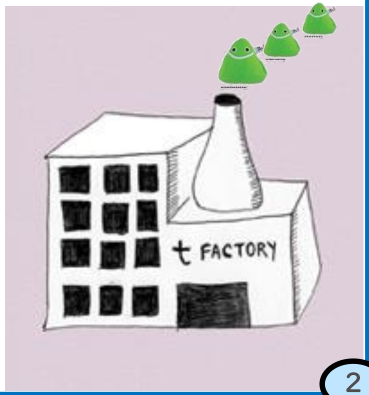
on behalf of the ATLAS collaboration

Interests in the Top quark physics

- Top quark?
  - Most massive known elementary particle so far discovered
    - With a mass ~173 GeV
    - Strong coupling to Higgs boson
    - Many BSM particles strongly couple with top quark
- Studying top quark
  - Precision test of pQCD, EWK
  - Many BSM searches from top production, **properties** and decay
  - Important background for a lot of LHC searches
- LHC is a Top-Factory
  - >100,000,000 $t\bar{t}$ pairs in LHC-Run2



Outline

- Focus on newer results
  - Spin correlations between t and $\bar{t}$ quarks
    - 1903.07570 Accepted by EPJC
  - Charge asymmetry
    - ATLAS-CONF-2019-026
  - Its decay width
    - ATLAS-CONF-2019-038
  - Lepton universality in leptonic W decay
    - ATLAS-CONF-2020-014

- All public results can be found [Link]

$t\bar{t}$ spin correlations in the $e\mu$ channel

- top-quark pairs should be produced without polarization
  → while spin of t and $\bar{t}$ are correlated
- The lifetime of the top quark
  - Shorter than the timescale for hadronization (10^{-23}s)
  - Shorter than the spin decorrelation time (10^{-21}s)

  ⇒ **the t and $\bar{t}$ quarks spin information is transferred directly to its decay products**

  → **Charged leptons carry full spin information** $(\boldsymbol{a_\ell \sim 1})$
- Simple $e\mu$ final state is used to this measurement
  - Angle between the leptons is sensitive to spin correlations
- Results are unfolded to both the parton-level and also the particle-level

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Analysis overview: $t\bar{t}$ spin correlations

- inclusive selection
  - exactly one electron and one muon of opposite charge
  - at least two jets and at least one of jets must be b-tagged
- reconstructed selections
  - at least two b-tagged jets with **tighter b-tag requirement**

To improve reconstruction (Neutrino Weighting)

Process	Inclusive selection ≥ 1 b-tag			Reconstructed selection ≥ 2 b-tags		
$t\bar{t}$	165 000	$\pm$	5000	75 000	$\pm$	4000
tW	8900	$\pm$	1400	1550	$\pm$	170
$t\bar{t}V$ and others	670	$\pm$	60	233	$\pm$	22
Diboson	580	$\pm$	60	15.1	$\pm$	2.8
$Z/\gamma^* \to \tau^+\tau^-$	420	$\pm$	70	26	$\pm$	17
Fake Lepton	1800	$\pm$	700	630	$\pm$	250
Expected	177 000	$\pm$	6000	78 000	$\pm$	4000
Observed	177 113			75 885		

purity 93%, 96%

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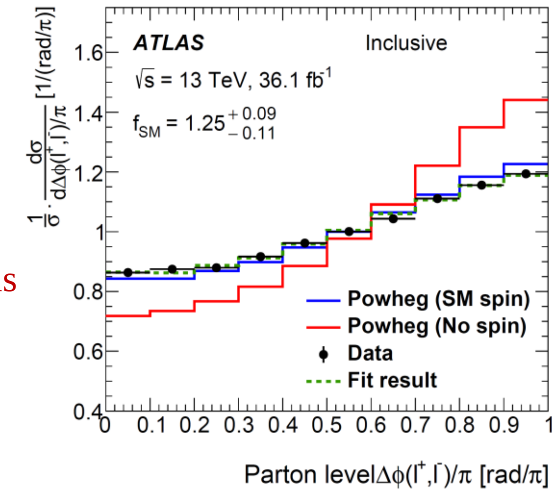
Results: $t\bar{t}$ spin correlations

- The observed spin correlation is slightly higher than the generator predictions

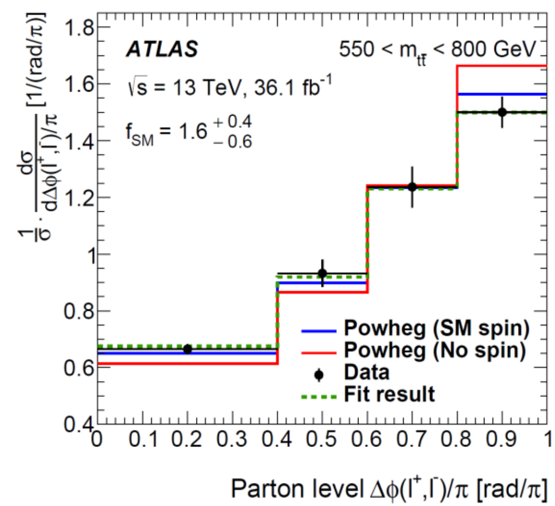
$$x_i = f_{\mathrm{SM}} \cdot x_{\mathrm{spin},\,i} + (1 - f_{\mathrm{SM}}) \cdot x_{\mathrm{nospin},\,i}$$

$x_{\mathrm{spin/nospin}}$; cross-sections under the SM spin/nospin hypothesis

- f_{SM} increases as a function of $m_{t\bar{t}}$
  - Due to larger uncertainties, none of the results deviate substantially from the SM expectation



Region	$f_{\mathrm{SM}} \pm$ (stat.,syst.,theory)	Significance (excl. theory)
Inclusive	$1.249 \pm 0.024 \pm 0.061 \,^{+0.067}_{-0.090}$	2.2 (3.8)
$m_{t\bar{t}} < 450$ GeV	$1.12 \pm 0.04 \,^{+0.12}_{-0.13} \,^{+0.06}_{-0.07}$	0.78 (0.87)
$450 \leq m_{t\bar{t}} < 550$ GeV	$1.18 \pm 0.08 \,^{+0.13}_{-0.14} \,^{+0.13}_{-0.15}$	0.84 (1.1)
$550 \leq m_{t\bar{t}} < 800$ GeV	$1.65 \pm 0.19 \,^{+0.31}_{-0.41} \,^{+0.26}_{-0.33}$	1.2 (1.4)
$m_{t\bar{t}} \geq 800$ GeV	$2.2 \pm 0.9 \,^{+2.5}_{-1.7} \,^{+1.2}_{-1.5}$	0.49 (0.61)



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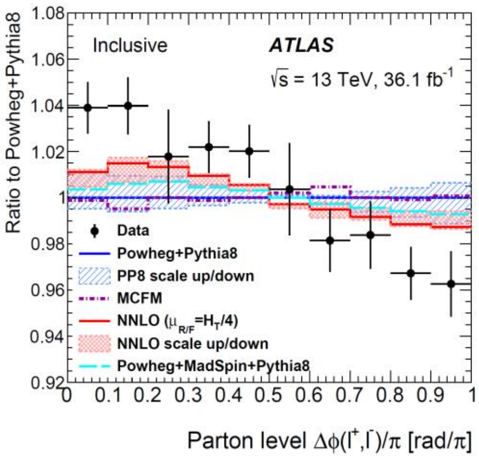
V.S. theories: $t\bar{t}$ spin correlations

Compare with various SM predictions

- Higher order calculations appear to reduce the tension
  - but still do not agree fully
- NLO in the strong and weak gauge couplings agrees better with the data
  - but large scale uncertainties
- NLO expansion with $\mu_R = \mu_F = m_t$ leads to comparable results
  - again with significant scale uncertainties
- NNLO prediction using the same expansion does not agree



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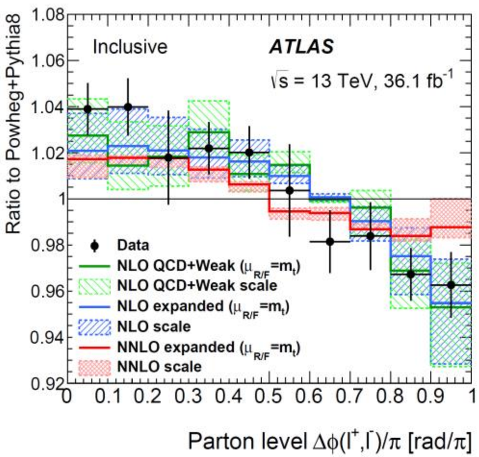
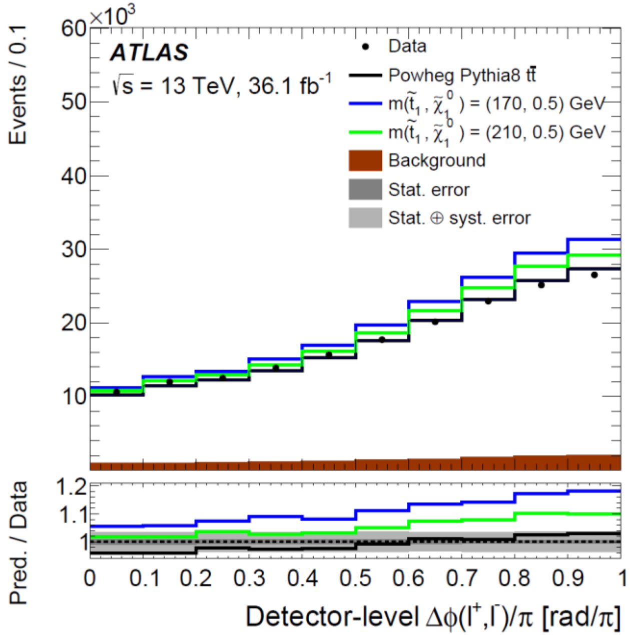
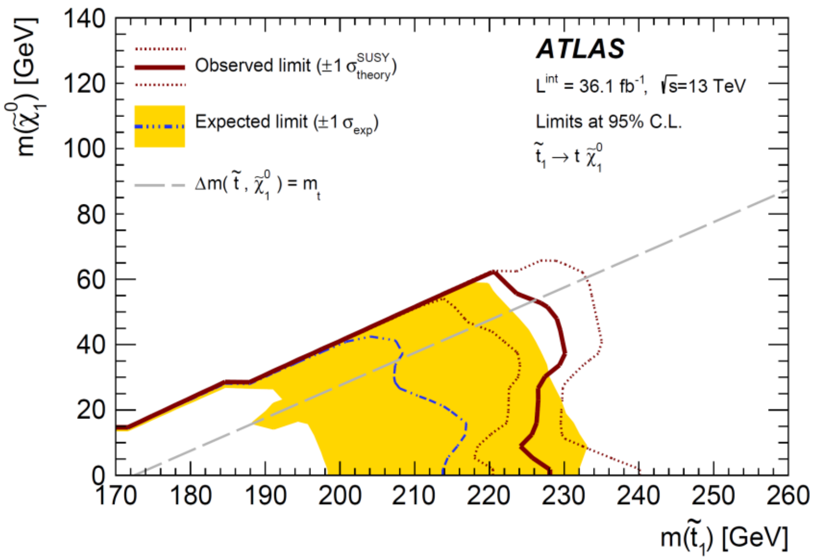


SUSY interpretation: $t\bar{t}$ spin correlations

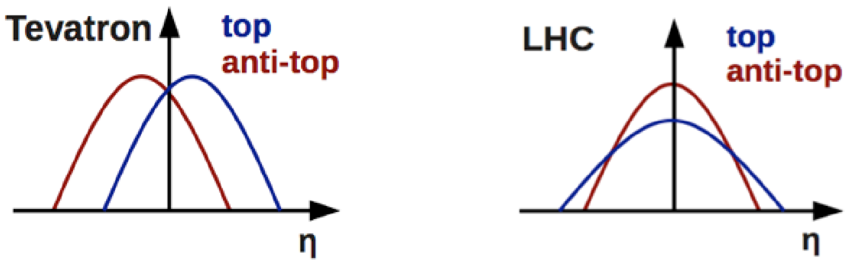
- A search is performed for stop pair decaying into SM top quarks and light neutralinos
- Top squarks with masses between 170 and 230 GeV are excluded for most kinematically allowed neutralino mass





$t\bar{t}$ charge asymmetry

- Interference between $t\bar{t}$ production processes causes asymmetry in t and $\bar{t}$ direction in the hadron colliders



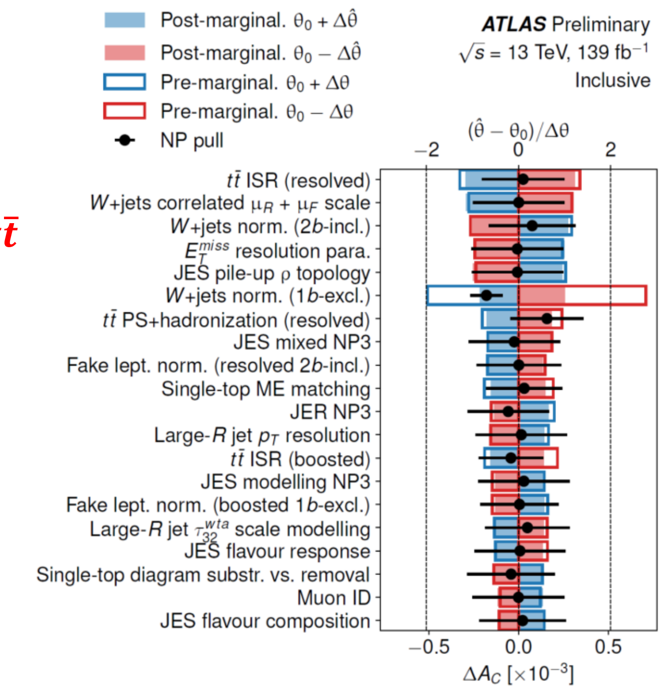
- This measurement is essential to test QCD higher order effect
- BSM physics can lead to enhancements in CA
- This asymmetry expected to be tiny in the LHC
  → this makes the measurement challenging

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

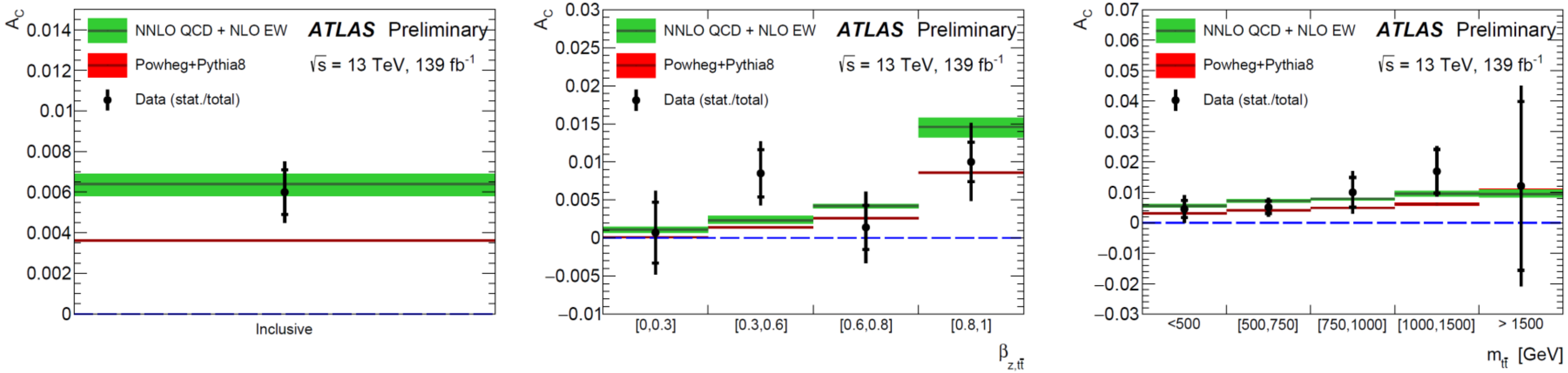
Analysis overview: $t\bar{t}$ charge asymmetry

- The measurement is made with a single lepton final state
  - both the resolved and boosted topologies
- Combined A_C are measured inclusively, and differentially as a function of the $m_{t\bar{t}}$ and $\beta_{Z,t\bar{t}}$
- A Bayesian unfolding procedure is applied
  - Systematic uncertainties are profiled as nuisance parameters

$$\mathcal{L}(\boldsymbol{D}|\boldsymbol{T}) = \int \mathcal{L}(\boldsymbol{D}|\boldsymbol{T},\boldsymbol{\theta}) \cdot \mathcal{N}(\boldsymbol{\theta})\, d\boldsymbol{\theta},$$



Results: $t\bar{t}$ charge asymmetry



- Measured inclusive A_C: 0.60% ± 0.15%
  - in agreement with the NNLO QCD + NLO EW predictions
  - 4 σ from zero

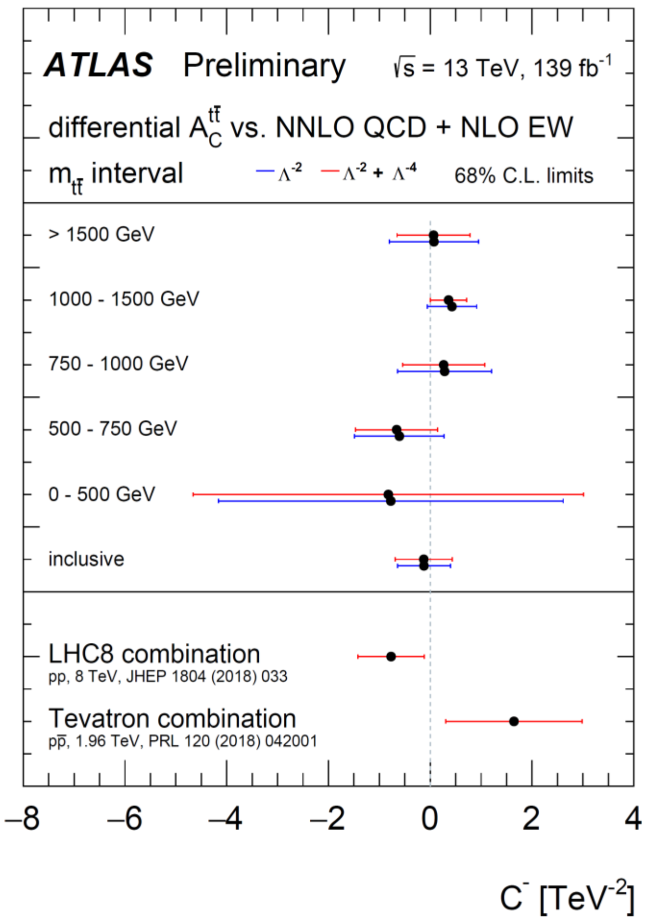
  ⇒ **First evidence for charge asymmetry in pp collisions**
- Also measured as a function of $m_{t\bar{t}}$ and $\beta_{Z,t\bar{t}}$
  - consistent with the Standard Model predictions

EFT interpretation: $t\bar{t}$ charge asymmetry

- The inclusive and $m_{t\bar{t}}$ measurements are interpreted in the EFT framework
- Derived limits on the linear combination of Wilson coefficients for dimension-six operators

$$C^{-}/\Lambda^2 = -4g_s^2/m_A^2.$$

- The measured data provide considerably tighter bounds than the combination of previous ATLAS and CMS measurements



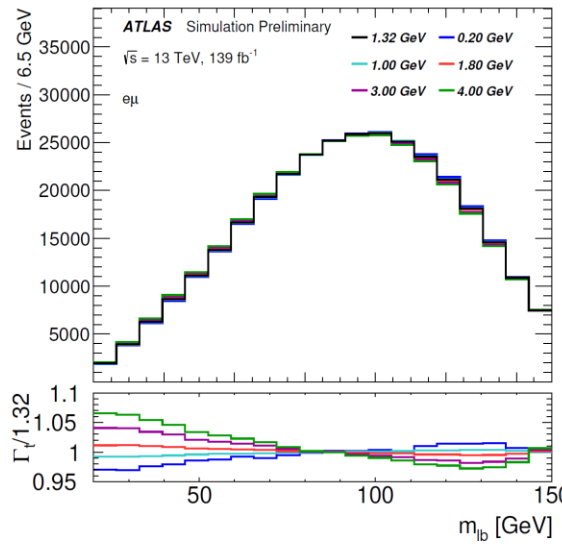
top-quark decay width

- Top quark decay width is one of the fundamental properties
- Due to its large mass the decay width is expected to be very large
  - most precise theoretical predictions NNLO $\Gamma_t = 1.322\ \text{GeV}$ @ $m_t = 172.5\ \text{GeV}$
- Possible deviations from SM due to
  - top quarks decaying into charged Higgs bosons
  - via Flavor Changing Neutral Current (FCNC) processes
  - models modifying CKM matrix elements like $|V_{tb}|$
- Direct approach to measure Γ_t
  - ☐ less precise than the indirect measurements
  - ✓ less model-dependent

Analysis overview: Decay width

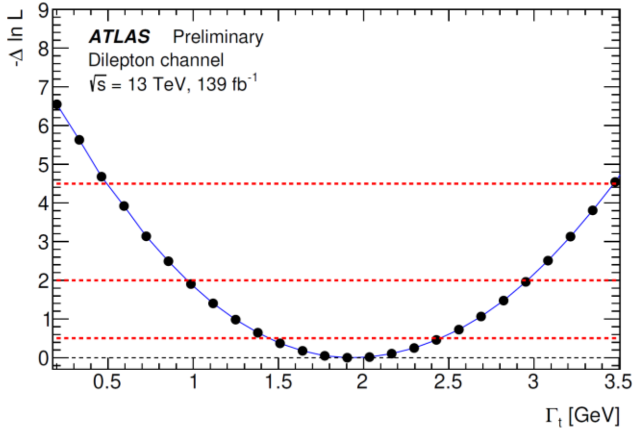
- The analysis focuses on $t\bar{t}$ events in the dilepton decay channel
  - 2 leptons + 2 jet
  - only for SF events Z and DY veto
  - $E_T^{miss} > 60$ GeV (to eliminate Z-jets)
- Reconstruct m_{lb} ← sensitive to Γ_t
- Profile-likelihood template fit technique
  - Templates with different underlying top-quark decay widths
  - Simultaneous fit in the three channels

	ee	$\mu\mu$	$e\mu$
$t\bar{t}$	34000±1700	49100±2500	176000±9000
Single top	1150± 60	1570± 80	5300± 260
Z+VV+$t\bar{t}X$	230± 120	390± 200	380± 190
Fake leptons	800± 400	41± 20	2100±1100
Total prediction	37000±1800	51100±2500	184000±9000
Data	37926	52166	186951

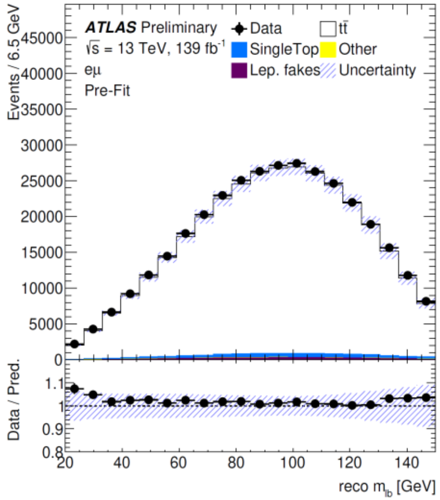


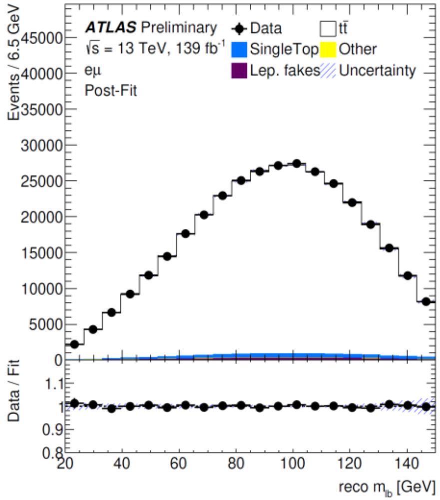
Result: Decay width

- $\Gamma_t = 1.9 \pm 0.5$ GeV for $m_t = 172.5$ GeV



Source	Impact on Γ_t [GeV]
Jet reconstruction	±0.24
Signal and bkg. modelling	±0.19
MC statistics	±0.14
Flavour tagging	±0.13
E_T^{miss} reconstruction	±0.09
Pile-up and luminosity	±0.09
Electron reconstruction	±0.07
PDF	±0.04
$t\bar{t}$ normalisation	±0.03
Muon reconstruction	±0.02
Fake-lepton modelling	±0.01





- in agreement with the Standard Model prediction

W→ τ / μ ratio from $t\bar{t}$ events

- The universality of the lepton couplings to the EW gauge boson $g_\ell(\ell = e, \mu, \tau)$ is a fundamental axiom of the SM
- Previously $R(\tau/\mu) = \mathrm{BR}(W \to \tau\nu_\tau)/\mathrm{BR}(W \to \mu\nu_\mu)$ has been measured at LEP
  - $R(\tau/\mu) = 1.070 \pm 0.026$
  - deviates from the SM by 2.7 σ

  → **motivating precise measurement at the LHC**

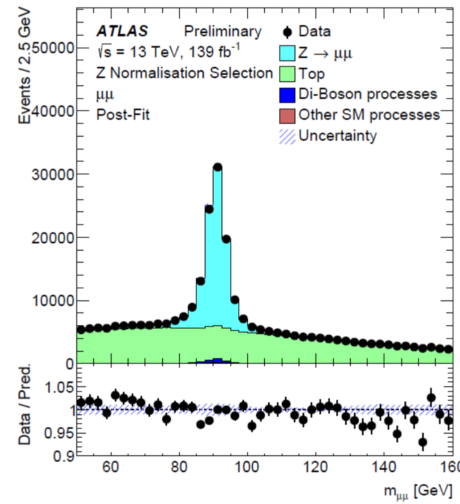
- This analysis measures the branching fraction ratio using dilepton $t\bar{t}$ events
  - gives an excellent sample of W boson
  - $W \to \tau\nu_\tau \to \mu\nu_\mu\nu_\tau\nu_\tau$ process is used to measure $\mathrm{BR}(W \to \tau\nu_\tau)$ ← use well know $\mathrm{BR}(\tau \to \mu\nu_\mu\nu_\tau) = 17.39 \pm 0.04\%$

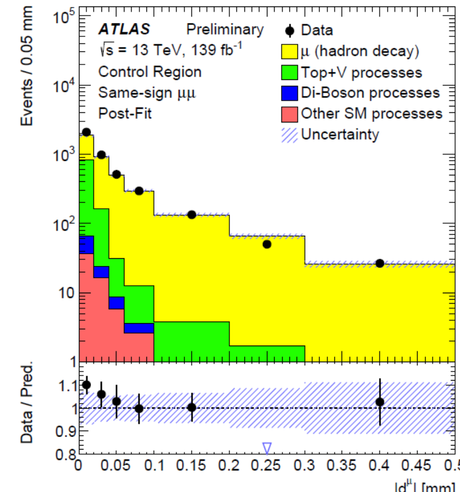
Analysis detail: W→ τ / μ ratio

- A tag and probe analysis is performed probing whether a muon comes from a prompt decay or via an intermediate tau
  - softer p_T spectrum
  - displacement of the decay vertex → |d0|

Backgrounds

- Z → $\mu\mu$+jets
  - a fit of di-muon invariant mass distributions is used to normalize this background
- Hadron decay fake muon
  - A same-sign charge selection is used to normalize this background



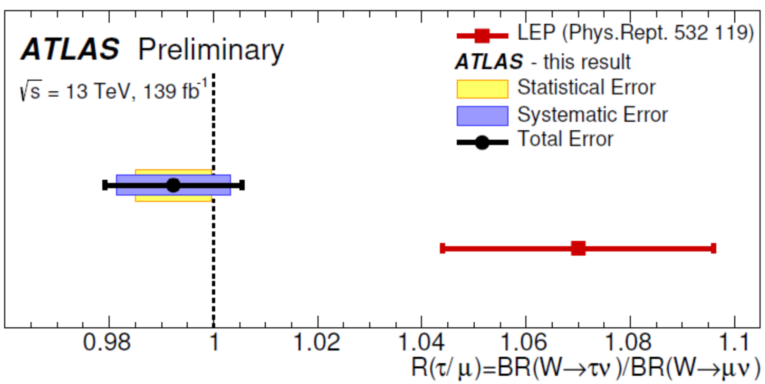


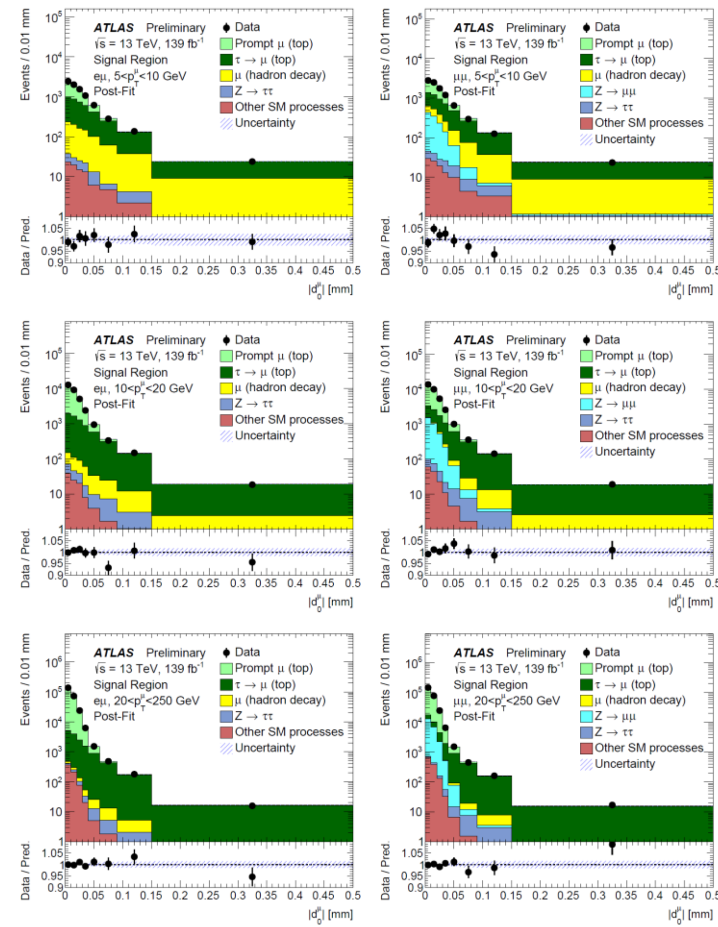
Results: W→ τ / μ ratio

- A profile likelihood fit is performed to extract $R(\tau/\mu)$ in "3×8 p_T and d_0 bins" for each $e\mu$ and $\mu\mu$ channels

$$R(\tau/\mu) = 0.992 \pm 0.013\ [\pm 0.007\ (\text{stat}) \ \pm\ 0.011\ (\text{syst})].$$

- The measurement is in good agreement with the SM and more precise than the LEP measurement





Summary

- ATLAS performed various top properties measurements
- **Spin Correlations**;
  - We are observing some significant tensions between data and theoretical predictions
  - this suggests our limited understanding of top quark production and decay
- **TCA**;
  - We are now also able to see subtle higher-order effects in top properties
- **Top decay width & W-> τ / μ ratio**;
  - SM still describe the data very well

- More results are in the pipeline
  → **Stay tuned !!**