Recent highlights of top-quark physics with the ATLAS detector

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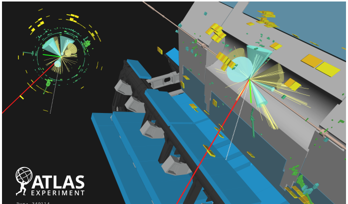
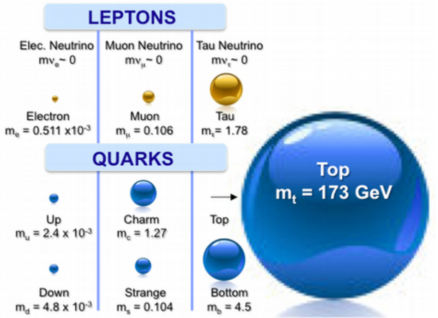
on behalf of the ATLAS Collaboration

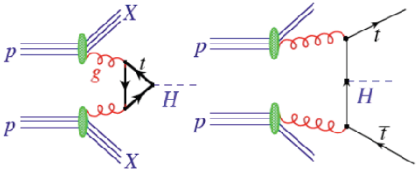
ICPPA-2020
5-9 October



The top quark: a unique particle

- Most massive elementary particle known to date. Special role in many theories beyond the Standard Model
- Short-lived, decays before hadronising. Possible to study the properties of a bare quark
- Precision tests of perturbative QCD
- Main background in many BSM searches
- Essential to study Higgs properties, measure top Yukawa coupling

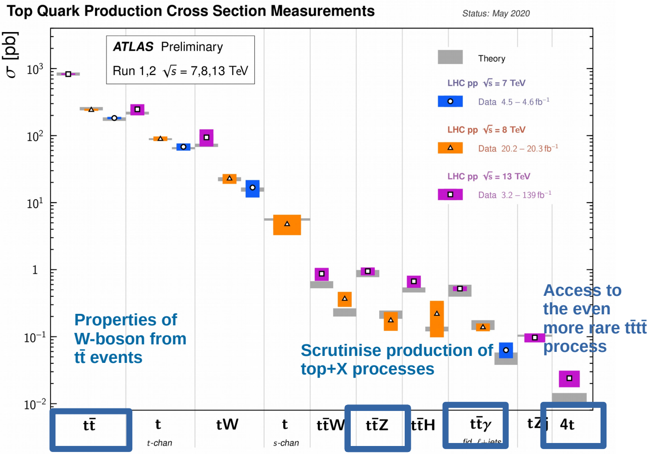




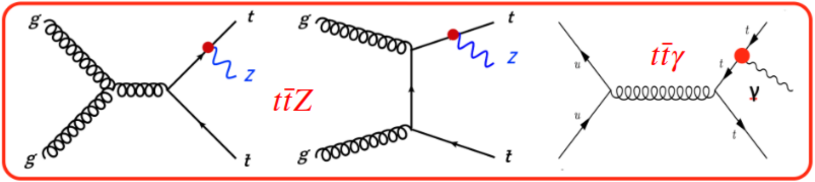
This talk focuses on some of the most recent top quark (+ friends) results by ATLAS with the full Run-2 13 TeV data

Top quark pairs + friends

- Studying processes with 0(5) of magnitude difference in production rate
- Plethora of measurements available: top-quark properties production/decays, associated production, couplings, ...



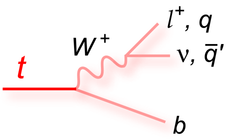
Studying $t\bar{t} + Z/\gamma$ process: what and why?

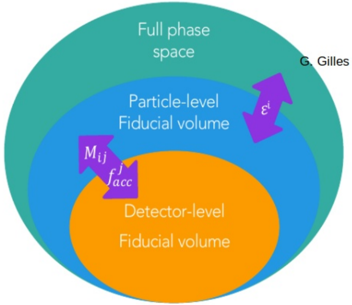


- Rare processes that test the electroweak couplings of the top quark to bosons
- Test higher order theoretical calculations and Monte Carlo simulations to improve the understanding of the modelling
- Irreducible background to several searches for BSM phenomena as well as to measurements of important SM processes (e.g. $t\bar{t}H$)
- Sensitive to new physics: eg. Effective Field Theory interpretations

General strategy: inclusive and differential cross sections

- Strategy: focus on leptonic (e, μ) decays of top quarks (and Z boson)
  - Smaller BR than hadronic decays, smaller backgrounds
- Inclusive cross section
  - Profile likelihood fit $\rightarrow$ Allows to constrain systematic uncertainties, improve precision
  - Include signal and control regions to reduce dependency on the backgrounds
- Differential cross section measurements
  - Unfolding: correct for detector efficiencies (ϵ^i), acceptances (f^j_{acc}, f^j_{match}) and migration (M_{ij}) to particle or parton level in full or fiducial phase space (requirements similar to those at detector level)

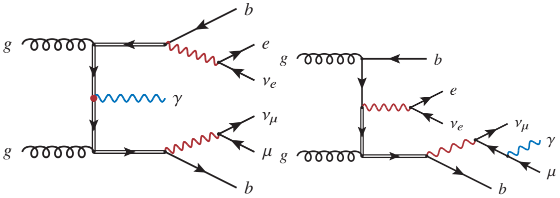




$$N_i^{unfolded} = \frac{1}{\varepsilon^i} \sum_j M_{ij}^{-1} \cdot f^j_{match} \cdot f^j_{acc} \cdot (N^j_{det} - N^j_{bkg})$$

$$\frac{d\sigma}{dX_i} = \frac{1}{\mathcal{L} \cdot \Delta X_i} \cdot N_i^{unfolded}$$

$t\bar{t}\gamma + tW\gamma$ cross section measurements, JHEP 09 (2020) 049

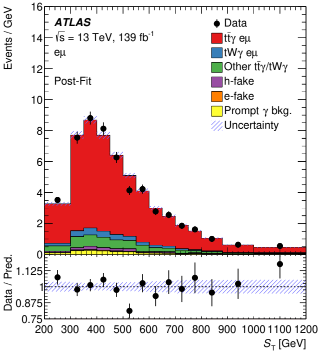


- Fiducial parton-level cross-section measurements on the $e\mu$ channel
  - Small BR but cleanest $t\bar{t}$ decay channel
- Profile likelihood fit to S_{T}

  $\boxed{\sigma_{\text{fid}} = 39.6 \pm 0.8(\text{stat})^{+2.5}_{-2.1}(\text{syst})\ \text{fb}}$

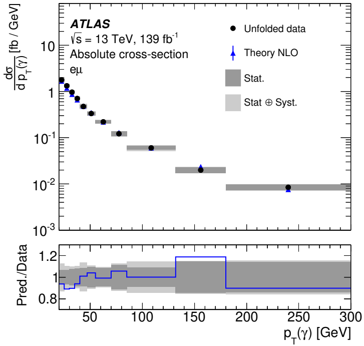
  ($\sim$6% precision)
- Compare to full NLO calculation for $pp \to e\mu\nu\nu bb\gamma$ (JHEP 1810 (2018) 158)

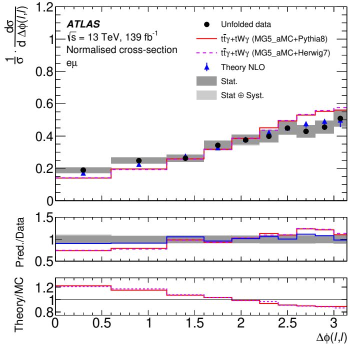
  $\sigma_{NLO} = 38.50^{+0.56}_{-2.18}(\text{scale})^{+1.04}_{-1.18}(\text{PDF})$ fb
- Dominant uncertainties: signal and background modelling



$t\bar{t}\gamma + tW\gamma$: absolute and norm. differential cross sections

- Variables: photon p_T and $|\eta|$, $\Delta R(\gamma,\ell)_{\min}$, $\Delta\phi(\ell,\ell)$ and $|\Delta\eta(\ell,\ell)|$

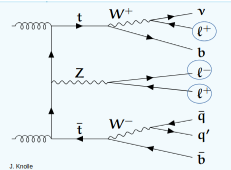


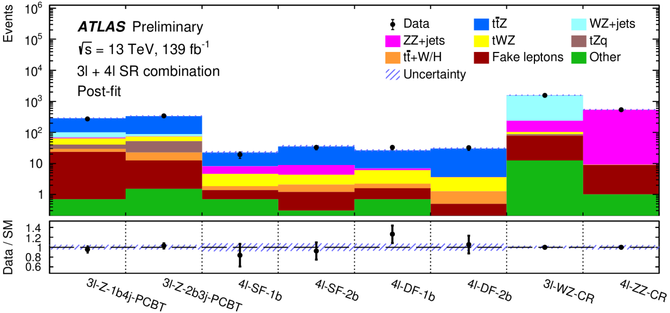


Predictions	$p_T(\gamma)$ (abs.) χ^2/ndf	p-value	$\Delta\phi(\ell,\ell)$ (norm.) χ^2/ndf	p-value
Theory NLO	16.0/16	0.45	5.8/9	0.76
MG5+PYTHIA8			30.8/9	<0.01
MG5+HERWIG7			31.6/9	<0.01

$t\bar{t}Z$ cross-section measurements, ATLAS-CONF-2020-028

- Most sensitive 3 and 4 lepton (e, μ) channels
- Requirements on number of jets, b-tagged jets, leptons imposed to define signal/control regions
  - Dominant backgrounds: WZ/ZZ+light jets
- Profile likelihood fit based on the event yields in each region



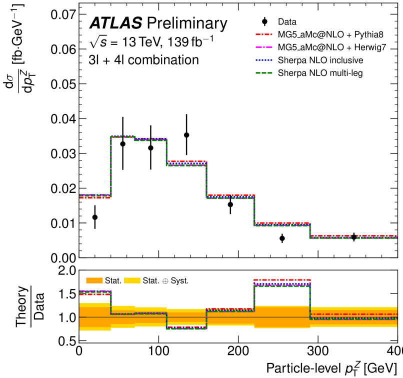


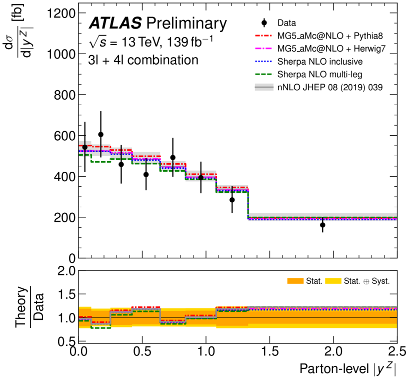
$\boxed{\sigma_{\text{fid}} = 1.05 \pm 0.05(\text{stat}) \pm 0.09(\text{syst})\,\text{pb}}$ ~10% precision

$\sigma_{NLO+NLL} = 0.86^{+0.07}_{-0.09}\,(\text{scale}) \pm 0.03\,(\text{PDF} + \alpha_S)$ pb [JHEP 08 (2019) 039]

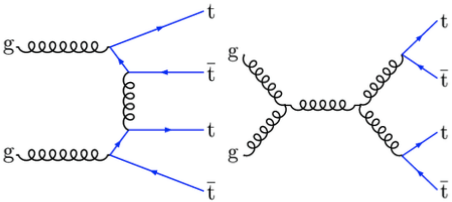
$t\bar{t}Z$: absolute and norm. differential cross sections

- Fiducial region unfolded at particle and parton levels
- Performed in different channels: 3ℓ, 4ℓ or $3\ell + 4\ell$ combination
- Functions of kinematic variables of the Z boson, $t\bar{t}$ system, angular differences between objects, etc.
- Compared to NLO MC generators and calculations at NLO, NLO+NLL, nNLO

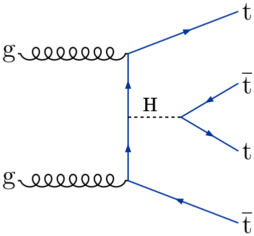




Search for SM $t\bar{t}t\bar{t}$ production, arXiv:2007.14858, accepted by EPJC

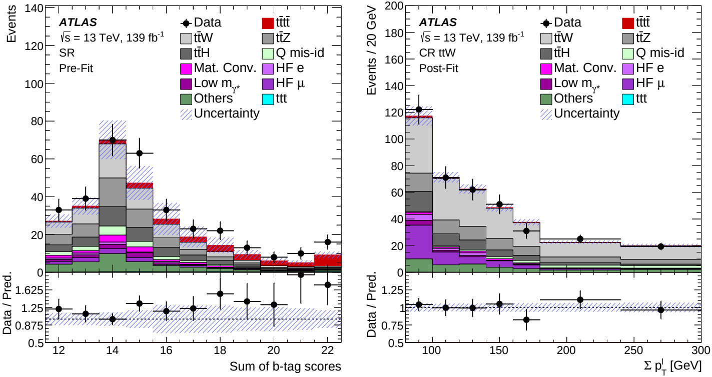


- Tiny cross section in SM: $\sigma^{SM}_{t\bar{t}t\bar{t}} \sim 12$ fb@13 TeV
  ... and very complex final state
- Many BSM models predict an increase:
  Particles decaying to top quarks or modified couplings, massive coloured bosons, composite Higgs/top, extra dimensions, SUSY...
- Measurements can be used to constrain y_t



Search for SM $t\bar{t}t\bar{t}$ production: strategy

- $\ell^{\pm}\ell^{\pm}$ or $\geq 3\ell$: 12% of total BR, but low background contamination
- Exploit jet multiplicity, jet flavour and event kinematics to separate signal/background events
  - Signal region: at least 6 jets and at least 2-bjets, H_{T} >500 GeV
- Main backgrounds:
  - $t\bar{t} + Z/H$+jets: MC estimate
  - $t\bar{t}W$ and non-prompt backgrounds: normalisations determined in CRs



Search for SM $t\bar{t}t\bar{t}$ production: results

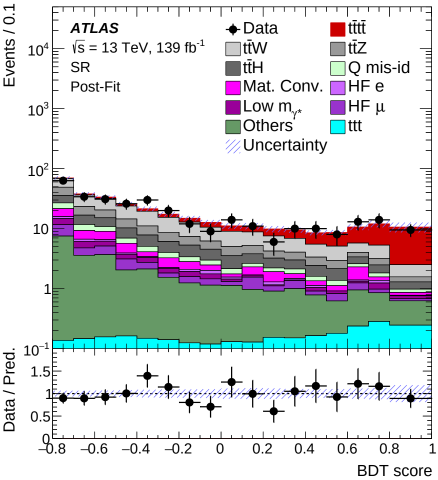
Signal extraction

- BDT used in signal region to separate $t\bar{t}t\bar{t}$ and background
- Simultaneous fit of signal region and 4 control regions

$$\boxed{\sigma_{t\bar{t}t\bar{t}} = 24^{+7}_{-6}\ \text{fb}}$$

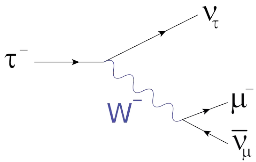
First evidence of $t\bar{t}t\bar{t}$ production with a significance of 4.4 σ compared to 2.4 σ expected

- Dominated by statistical uncertainties
- Main systematic uncertainties: $t\bar{t}W$ background

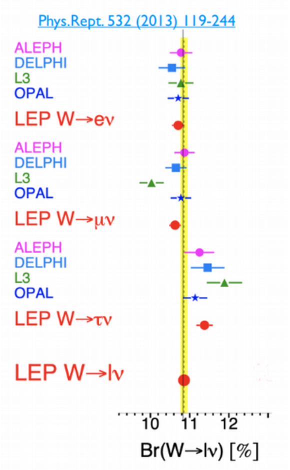


Lepton flavour universality, arXiv:2007.14040, sub. to Nature Physics

- Universality of the coupling of $\ell^{\pm}$ to W boson is a fundamental property of the SM
- Some disagreement (2.7σ) of the on-shell $W \to \tau\nu$ results seen at LEP
- Tested via $R(\tau/\mu) = B(W \to \tau\nu)/B(W \to \mu\nu)$
- Main challenge: differentiate between $W \to \tau\nu \to \mu\nu\nu\nu$ and $W \to \mu\nu$

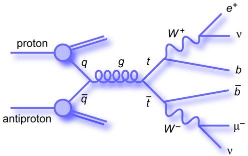


→ Use p_{T} and transverse impact parameter of the muons $|d_0^{\mu}|$

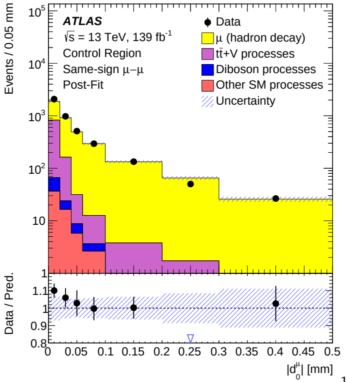


Measurement of lepton flavour universality: strategy

- Event selection: dileptonic $t\bar{t}$ events



- $|d_0^\mu|$ is the key variable: distance of closest approach of muon tracks in transverse plane wrt beamline
  - Shape of the distribution from $Z \to \mu\mu$ data events for prompt muons
- Major backgrounds estimated using control regions in data
  - $Z + 2b$-tagged jets in the $\mu\mu$ channel, muons from hadron decays

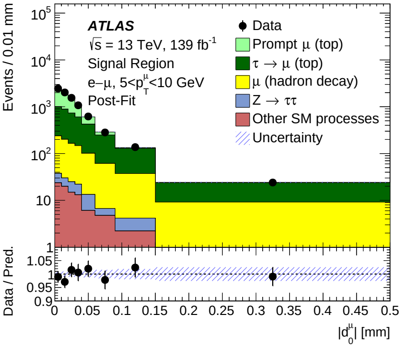


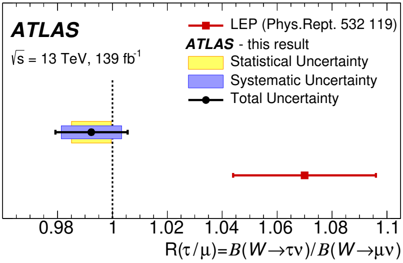
Measurement of lepton flavour universality: results

- Profile likelihood fit to $|d_0^\mu|$ distribution in regions of muon p_T and decay channel ($e\mu$, $\mu\mu$)

  $\boxed{R(\tau/\mu) = 0.992 \pm 0.007\,(\mathrm{stat}) \pm 0.011(\mathrm{syst})}$ (precision of 1.3%)

  - Leading systematic uncertainties: description of $|d_0^\mu|$ tail, parton shower uncertainties and muon identification/isolation
- Most precise result up to date and in agreement with the SM hypothesis





Summary

- Presented highlights of top-quark results with the full Run 2 data
- $t\bar{t}\gamma$ and $t\bar{t}Z$ inclusive and differential measurements in fiducial phase space (absolute and normalised)
  - Results compared with latest MC and higher order theory prediction: results compatible within uncertainties

  $\rightarrow$ Important to improve their modelling, explore parameters of EFT and other BSM models
- Evidence for the 4-top quark production has been achieved with 4.3σ significance!
- Most precise measurement of $R(\tau/\mu)$: Lepton flavour universality in agreement with the SM