Measurements of $t\bar{t}$ and single top quark with bosons with the ATLAS detector

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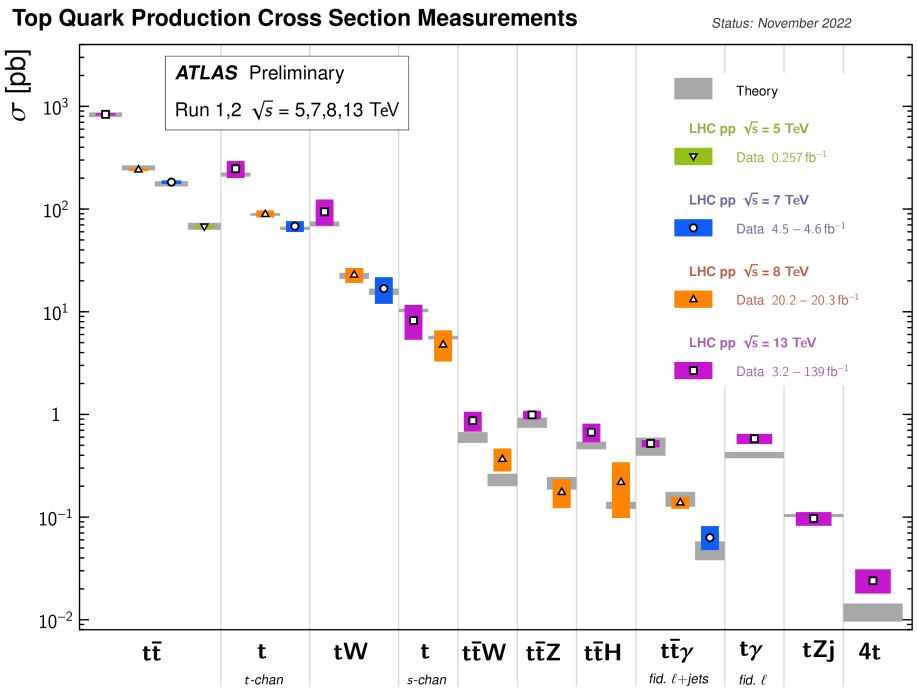
on behalf of the ATLAS Collaboration

Top quark production + bosons (Z, W, γ)

- 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. $t\bar{t}H$)
- Testing the SM: Enhanced $t\bar{t}$ charge asymmetry in $t\bar{t}\gamma$ and $t\bar{t}W$ processes
- Sensitive to new physics: e.g. Effective Field Theory interpretations

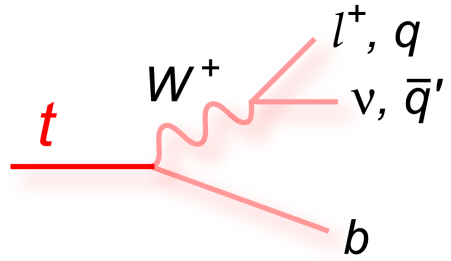


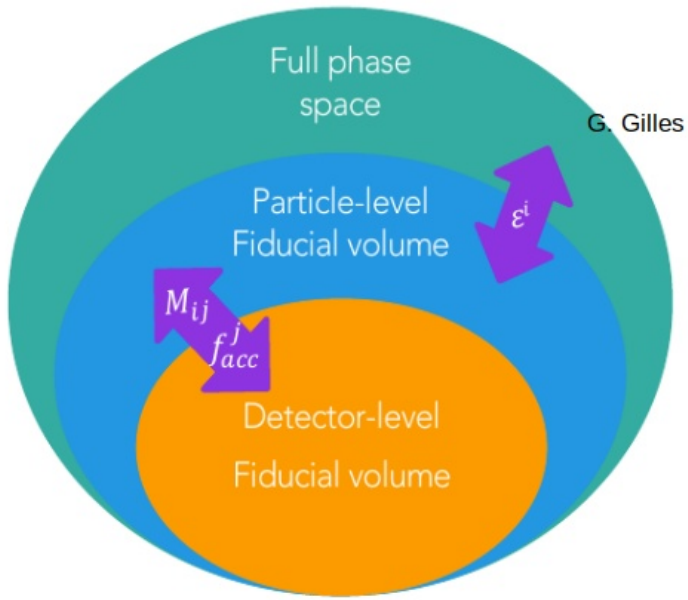
Run 2 large dataset allows measuring for the first time very rare processes, extending the scope of differential measurements and using top+X topologies to study top quark production properties!

This talk focuses on the most recent top quark + bosons results (cross sections and charge asymmetries!)

General strategy: inclusive and differential cross sections

- Strategy: focus on leptonic (e, μ) decays of top quarks (and W/Z boson)
  - Smaller BR than hadronic decays, smaller backgrounds
- Typically: multivariate analysis techniques to maximise sensitivity
- Inclusive cross section
  - Profile likelihood fit $\rightarrow$ Allows to constrain systematic uncertainties, improve precision
- 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

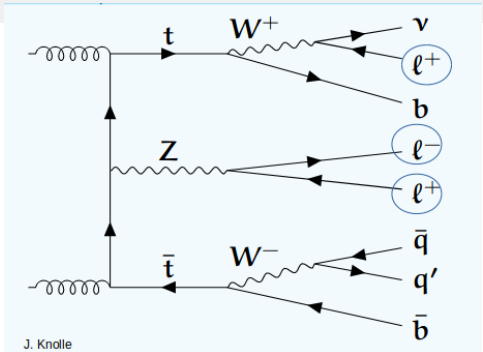




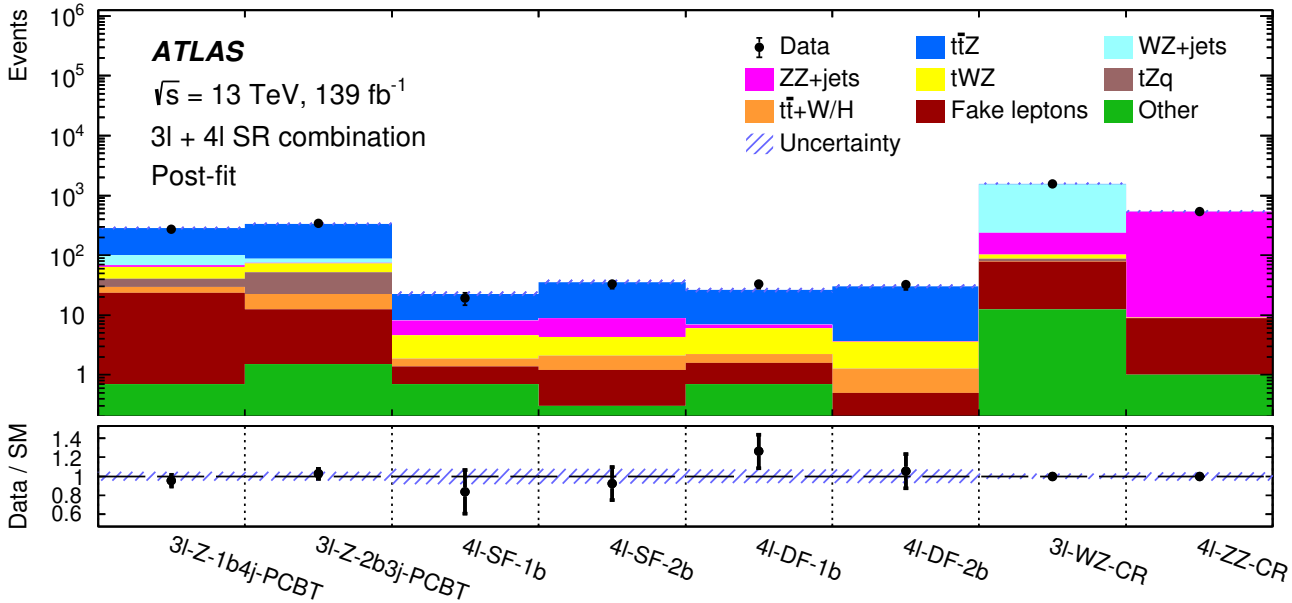
$$N_i^{unfolded} = \frac{1}{\varepsilon^i} \sum_i M_{ij}^{-1} \cdot f^j_{match} \cdot f^j_{acc} \cdot (N^j_{det} - N^j_{bkg})$$

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

$t\bar{t}Z$ cross-section measurements EPJC 81 (2021) 737



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



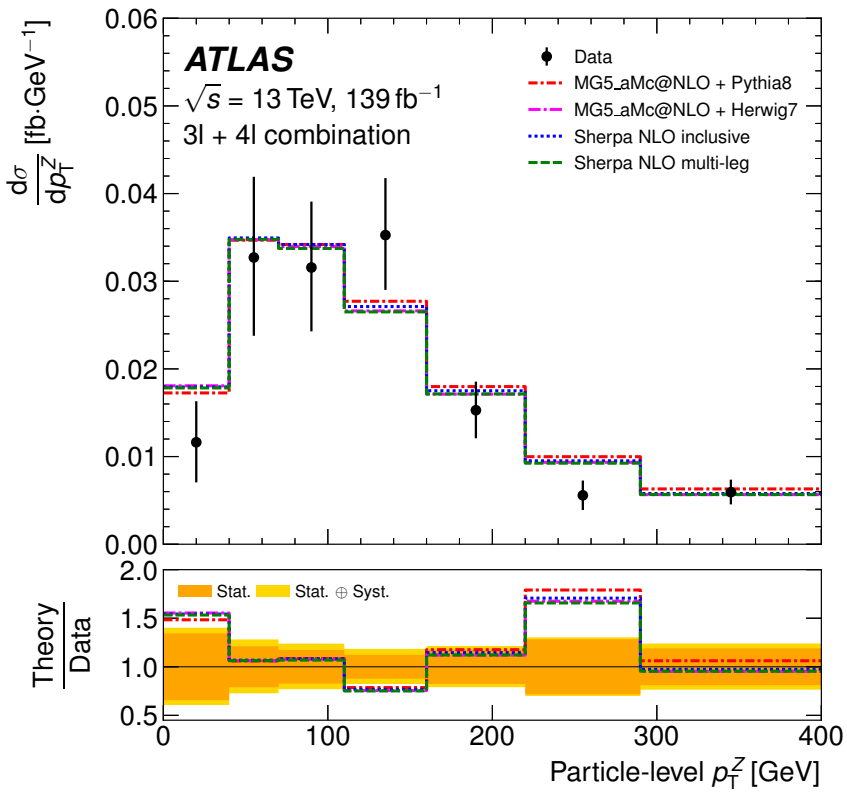
$$\sigma_{\text{fid}} = 0.99 \pm 0.05(\text{stat}) \pm 0.09(\text{syst})\,\text{pb}$$ ~10% precision

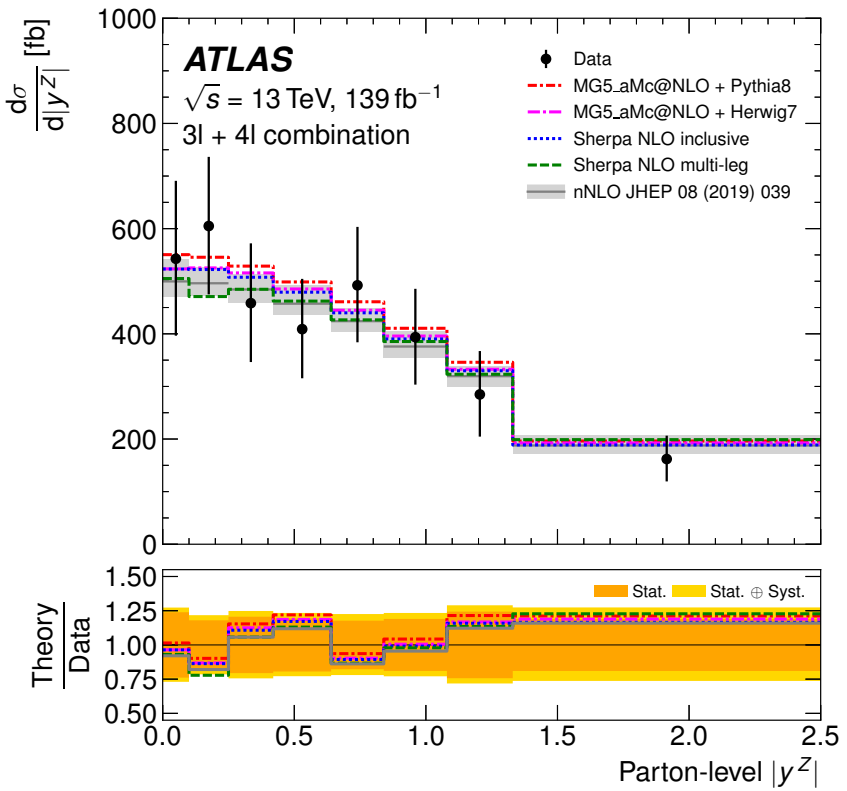
$\sigma_{NLO+NLL} = 0.86^{+0.07}_{-0.09}\,(\text{scale}) \pm 0.03\,(\text{PDF} + \alpha_S)$ pb [JHEP 08 (2019) 039]

Uncertainty dominated by signal/background modelling and b-tagging systematics

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

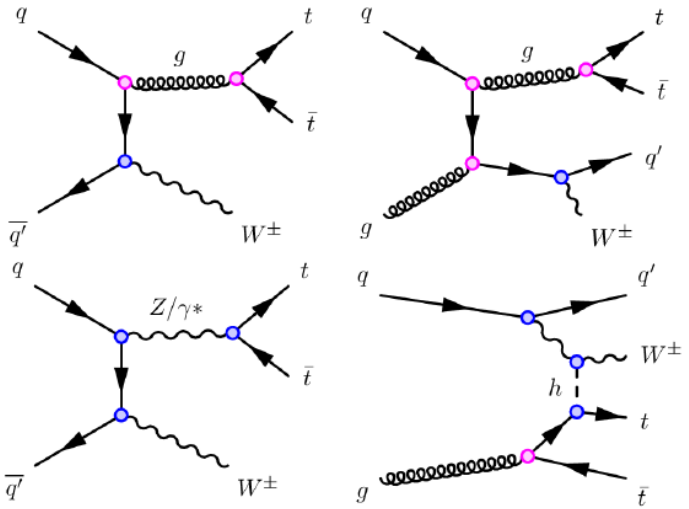
- Fiducial cross sections at particle and parton levels
- Performed in different channels: 3ℓ, 4ℓ or $3\ell + 4\ell$ combination
- Functions of kinematic variables of the Z boson, $t\bar{t}$ system, angular differences between objects, etc.
- NLO MC generators and calculations at NLO, NLO+NLL, nNLO describe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



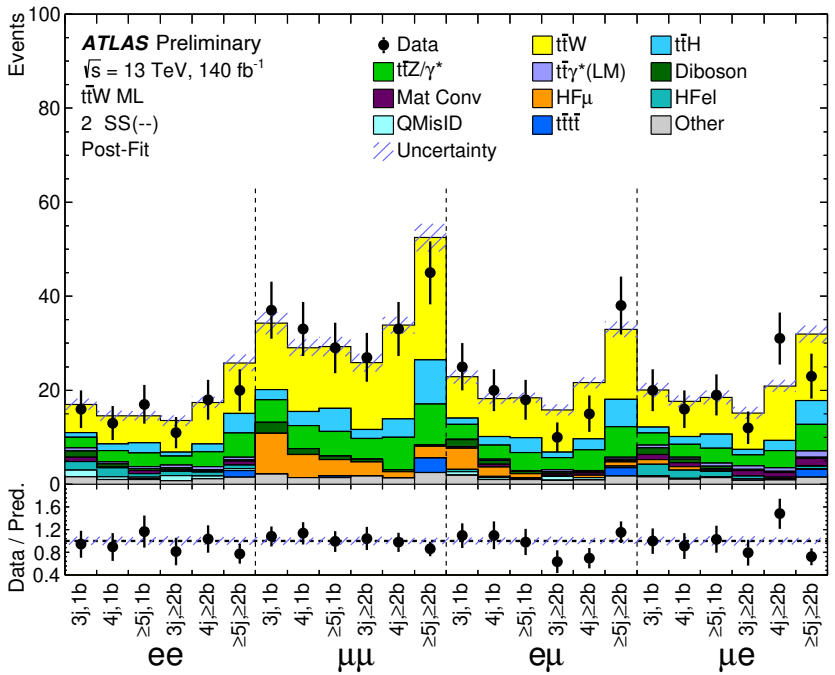


$t\bar{t}W$ inclusive and differential [ATLAS-CONF-2023-019]

- Previous measurements of $t\bar{t}W$ production yield slightly higher cross section than SM calculations
- Rich phenomenology from charge-asymmetric production and QCD and EWK corrections
- Dominant background for searches and other measurements (e.g. $t\bar{t}H$, $t\bar{t}t\bar{t}$): irreducible source of same-sign dilepton pairs



- Focus on events with 3ℓ or 2 same-sign ℓ
- Requirements on number of jets, b-tagged jets, lepton charge and flavour imposed to define signal/control regions
- Main backgrounds:
  - Irreducible: diboson, $t\bar{t}Z$
  - Reducible: fake/non-prompt leptons mainly from $t\bar{t}$ production, charge misID (electron)



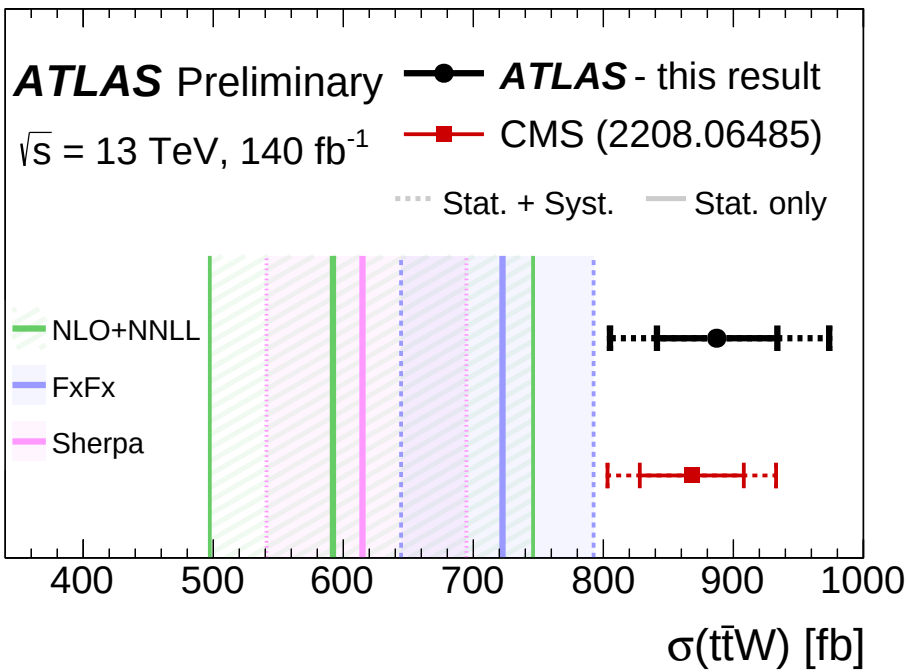
$t\bar{t}W$: inclusive cross section [ATLAS-CONF-2023-019]

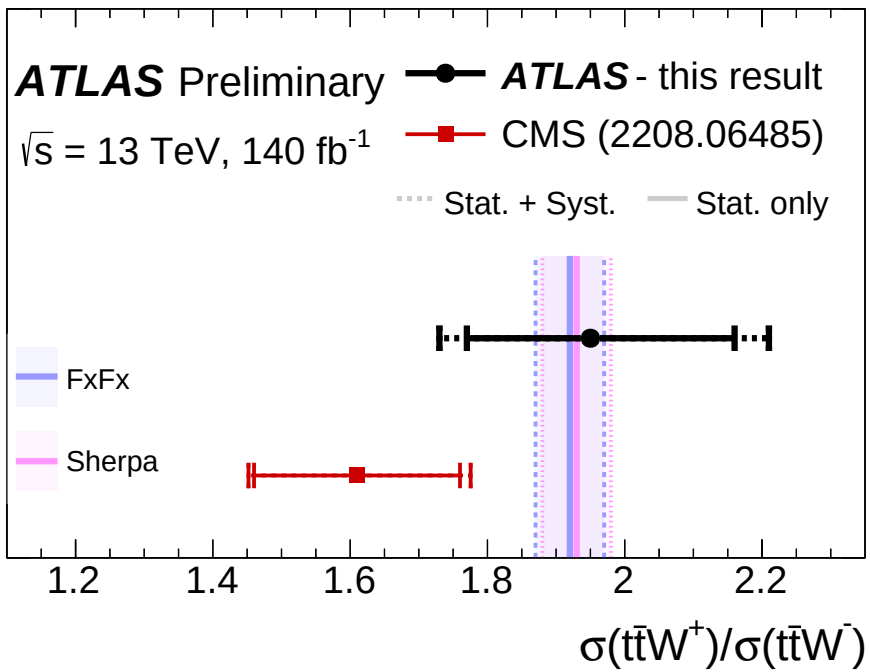
- Simultaneous profile likelihood fit to data using event yields in 56 signal and 10 control regions

$$\sigma_{\text{fid}} = 890 \pm 50(\text{stat}) \pm 70(\text{syst})\,\text{fb}$$ ~10% precision

$\sigma_{NLO+NLL} = 722^{+70}_{-78}\,(\text{scale}) \pm 7\,(\text{PDF})$ fb [JHEP 11 (2021) 29] - consistent at 1.5σ with theory calculation (FxFx)

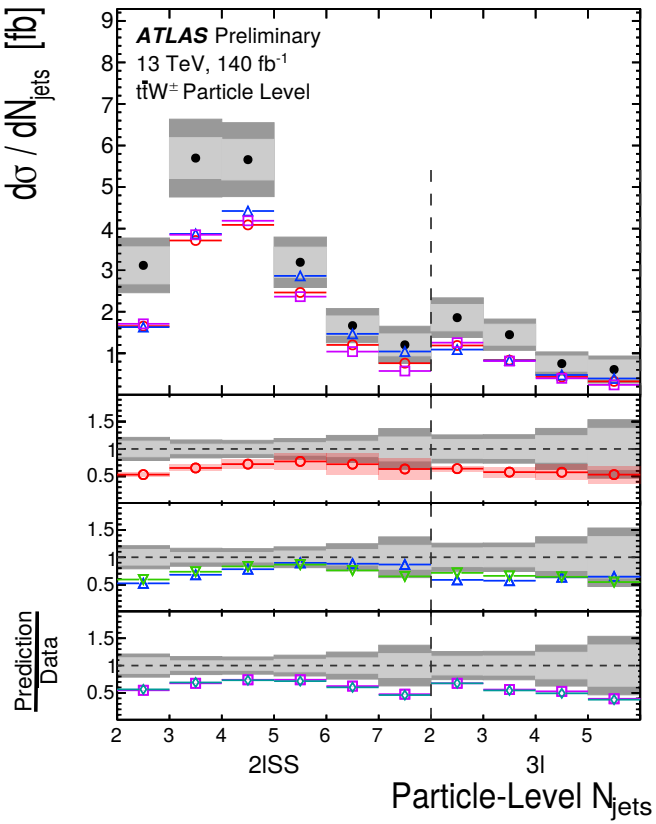
- Ratio $t\bar{t}W^+/t\bar{t}W^-$ and charge asymmetry in good agreement with prediction

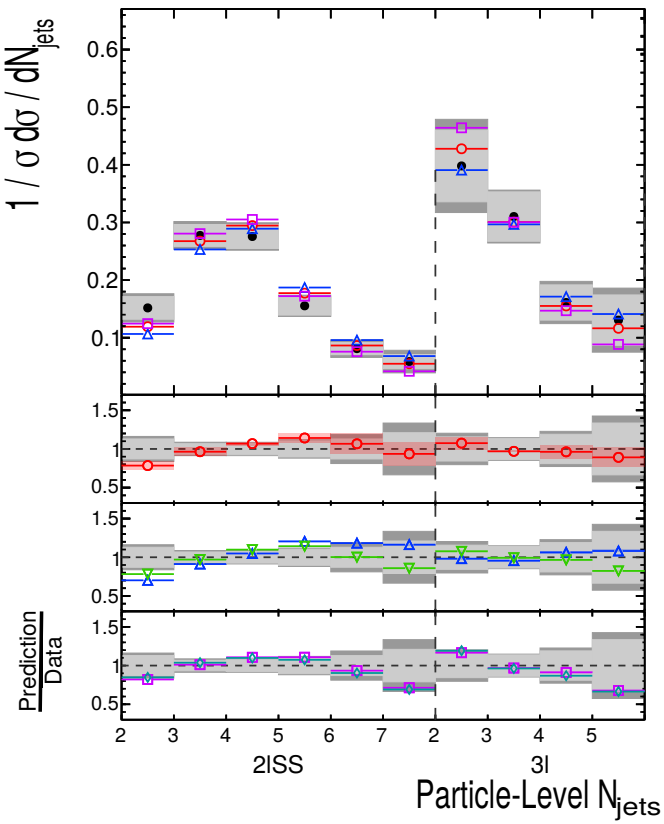


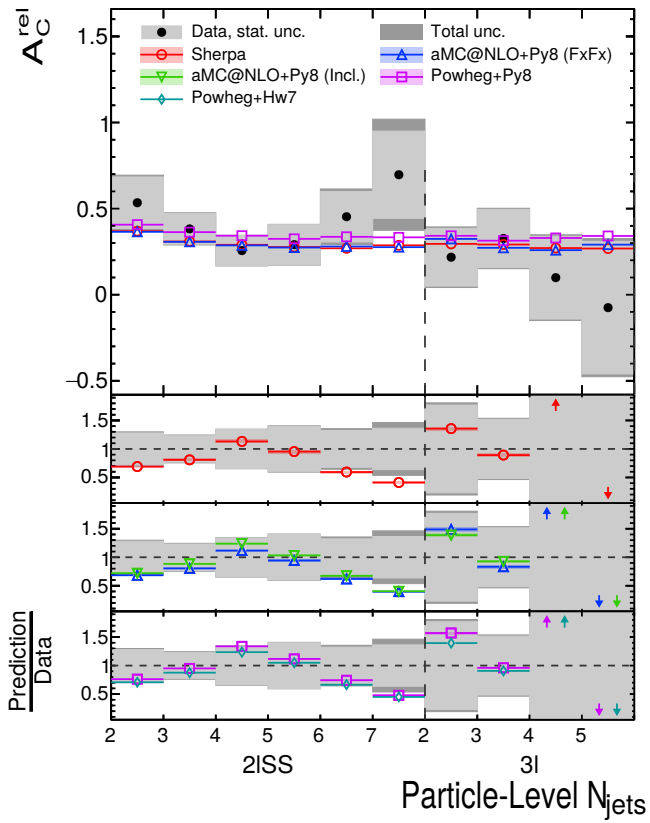


$t\bar{t}W$: differential cross section [ATLAS-CONF-2023-019]

- First absolute and normalised differential measurements for 7 observables using profile likelihood unfolding
  - Event properties (H_T, no. jets), angular distances between leptons and jets, etc
  - Shapes consistent between various MC and data

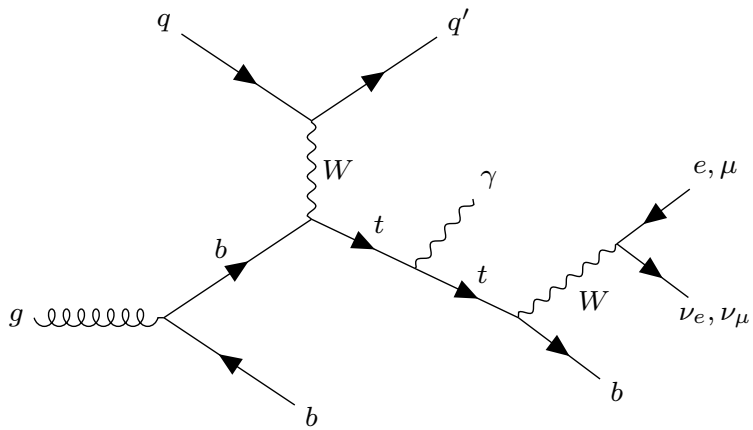






Observation of $tq\gamma$ [arXiv:2302.01283]

- Final state signature: one lepton, one photon, one b-tagged jet, one forward-jet and missing transverse energy
- Two signal regions are defined w/o and w/ forward jets
- Two control regions targeting prompt photon bkgs: $t\bar{t}\gamma$ CR and $W\gamma$
- Data-driven estimate of background processes with fake objects, e.g. e $\rightarrow \gamma$, jet $\rightarrow \gamma$
- Neural networks trained in each signal region to separate signal from the background



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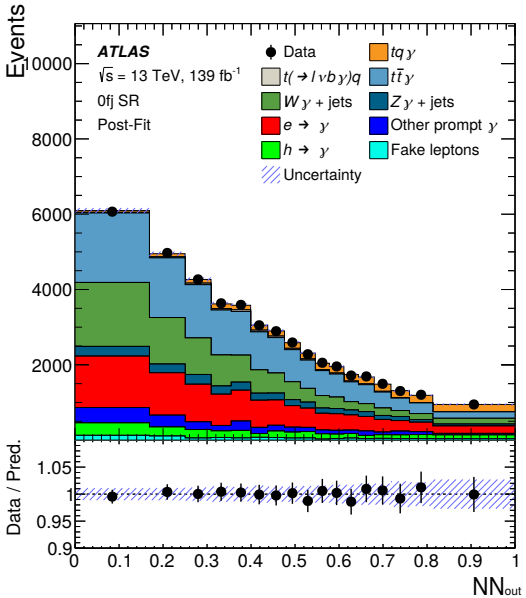
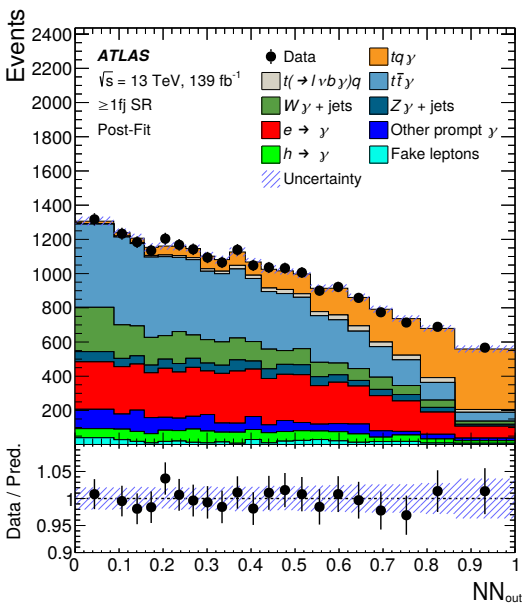




- Cross section measured with profile likelihood fit to SRs and CRs in fiducial phase space at parton level with γ radiated from the top quark, and a fiducial cross section at particle level
- Parton level:

$$\sigma_{tq\gamma} \times BR(t \to \ell\nu b) = 688 \pm 23(\text{stat})^{+75}_{-71}(\text{syst})\ \text{fb}$$

$(\sigma^{QCD+EW\ NLO}_{tq\gamma} = 515^{+36}_{-42}\ \text{fb})$

- Particle level:

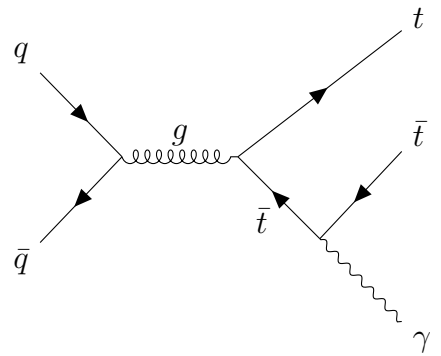
$$\sigma_{tq\gamma} \times BR(t \to \ell\nu b) + \sigma_{t\to\ell\nu b\gamma q} = 303 \pm 9(\text{stat})^{+33}_{-32}(\text{syst})\ \text{fb}$$

$(\sigma^{QCD+EW\ NLO}_{tq\gamma} = 217^{+27}_{-15}\ \text{fb})$

Compatible with SM within 2.1 (2.0) σ at parton (particle) level

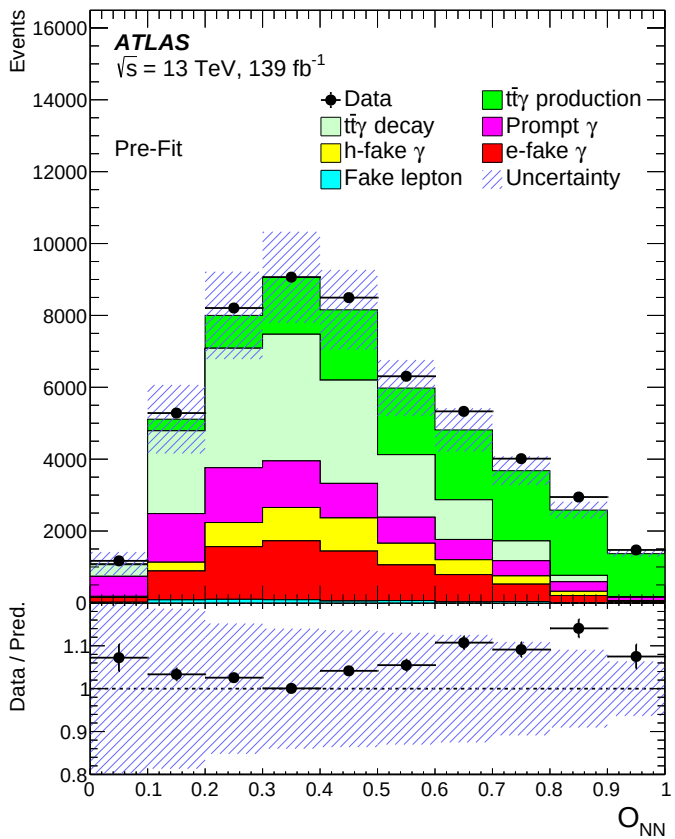
- Observed (expected) significance: 9.1 (6.7) σ: First observation of the process production
- Leading systematic uncertainty: $t\bar{t}\gamma$ and $t\bar{t}$ modelling, limited signal and background MC statistics

First measurement of A_C in $t\bar{t}\gamma$ [arXiv:2212.10552, accepted by PLB]



Enhanced asymmetry in $t\bar{t}\gamma$ production compared to $t\bar{t}$

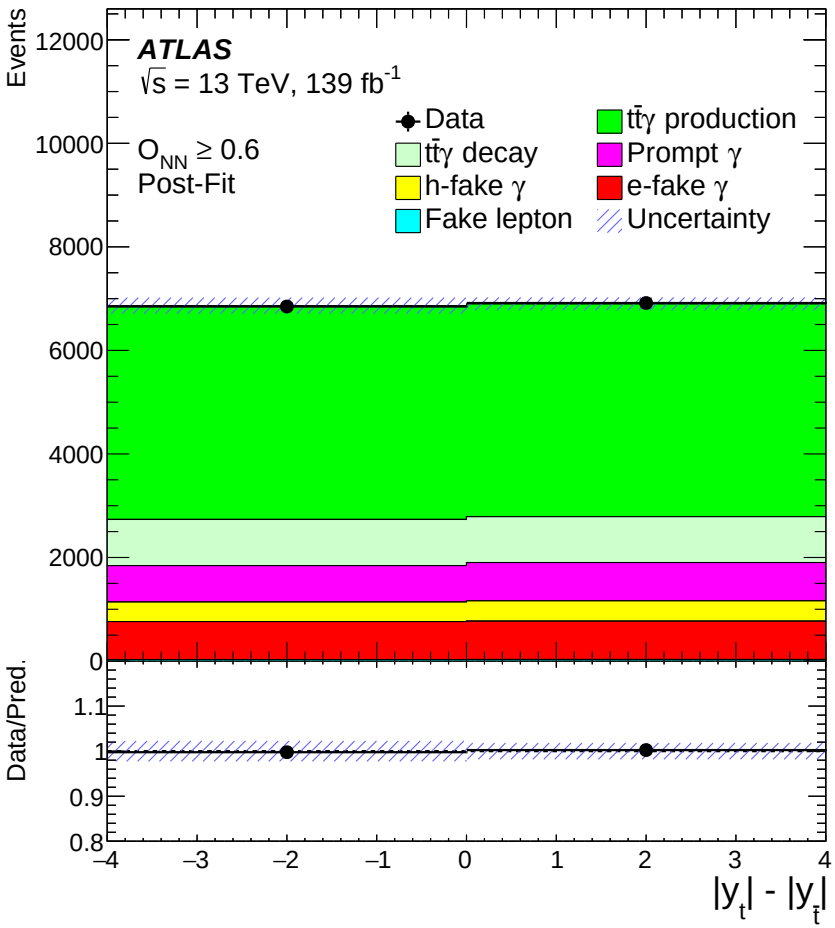
- Larger fraction of $q\bar{q}$ initiated processes
- Dominant LO EW contribution to A_C: interference between QED initial- and final-state radiation in $t\bar{t}\gamma$ *production* ($A_C < 0$, depends on phase space, -(1-2)%)



- Select events passing lepton+jets $t\bar{t}$ selection and exactly one high-p_T, isolated photon
- Same data-driven estimate of background processes with fake objects as $tq\gamma$ measurement
- Neural network to discriminate $t\bar{t}\gamma$ production from all types of backgrounds

First measurement of A_C in $t\bar{t}\gamma$ [arXiv:2212.10552, accepted by PLB]

- Reconstruct top quark pairs to define $y_t, y_{\bar{t}}$ (photon not part of the decay products)
- Maximum-likelihood unfolding of $|y_t| - |y_{\bar{t}}|$ performed simultaneously in two regions defined by the NN output discriminant ($O_{\mathrm{NN}} = 0.6$)



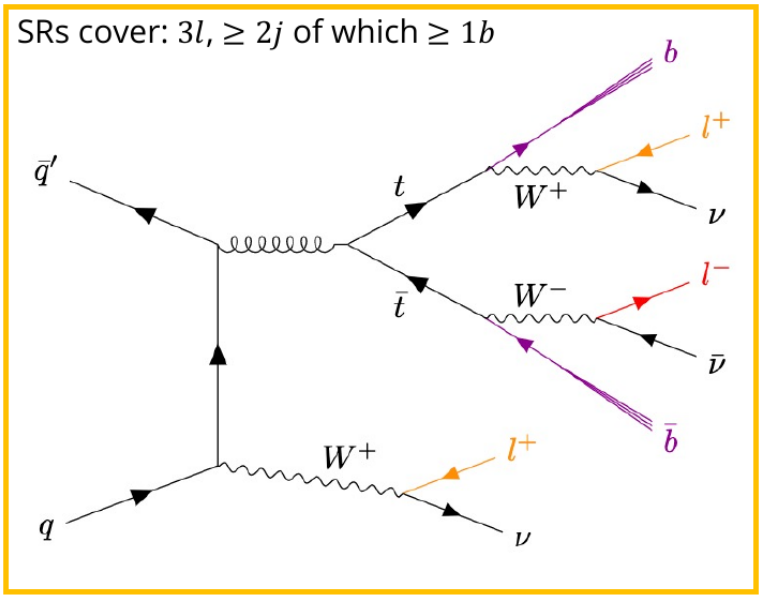
- $\boxed{A_C = -0.006 \pm 0.030}$
  $[\pm 0.024(\mathrm{stat}) \pm 0.018(\mathrm{syst})]$

  NLO SM $t\bar{t}\gamma$:
  $A_C = -0.014 \pm 0.001$ (scale)
- Dominated by stat. uncertainty in the data

First measurement of A_C in $t\bar{t}W$ [ATLAS-CONF-2022-062]

- Enhanced $t\bar{t}$ charge asymmetry: $t\bar{t}W$ dominated by $q\bar{q}$ initial state, W emission polarises top quarks: Large negative asymmetry in decay product

- First search for the leptonic charge asymmetry with $t\bar{t}W$, in the 3ℓ final state
- BDT to select correct even lepton (71% accuracy)
- Requirements on number of jets, b-tagged jets imposed to define signal regions



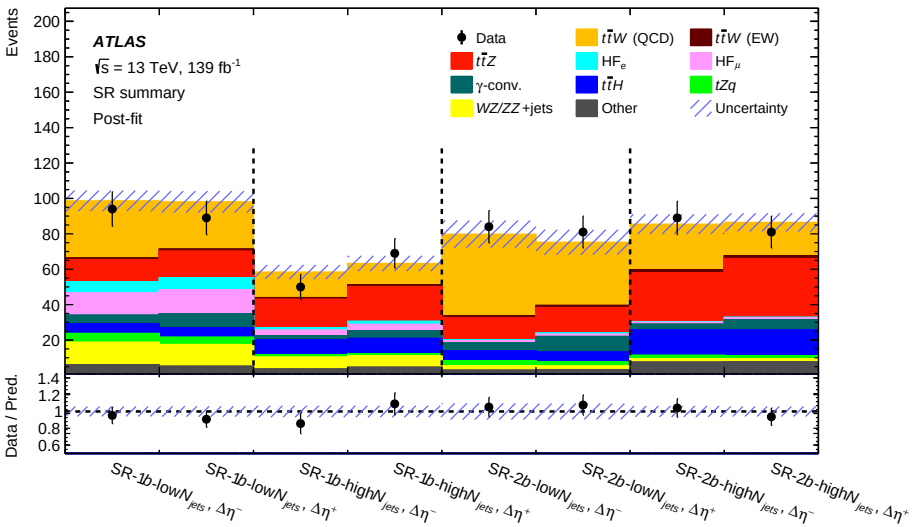
Odd lepton: always from (anti)top quark
Even leptons: need to select the correct one

[From M. Miralles]

- Main backgrounds ($t\bar{t}Z$, non-prompt leptons) are constrained in control regions

$t\bar{t}W$ $A_C^{\ell\ell}$: reconstruction and particle level [ATLAS-CONF-2022-062]

- Profile likelihood fit based on the event yields in each region to extract $A_C^{\ell\ell}$
  - 10 free-floating parameters extracted simultaneously



$$A_C^{\ell} = -0.123 \pm 0.136(\text{stat}) \pm 0.051(\text{syst})$$

$A_{C\,SM}^{\ell} = -0.084^{+0.005}_{-0.003}\ (\text{scale}) \pm 0.006\ (\text{MC stat})$
[Sherpa]

- Unfolding based on a profile-likelihood approach
- Measurement at particle level in a fiducial phase space close to the reco. level selection
- Lepton-top association is based on m_{lb} discriminant (instead of BDT)

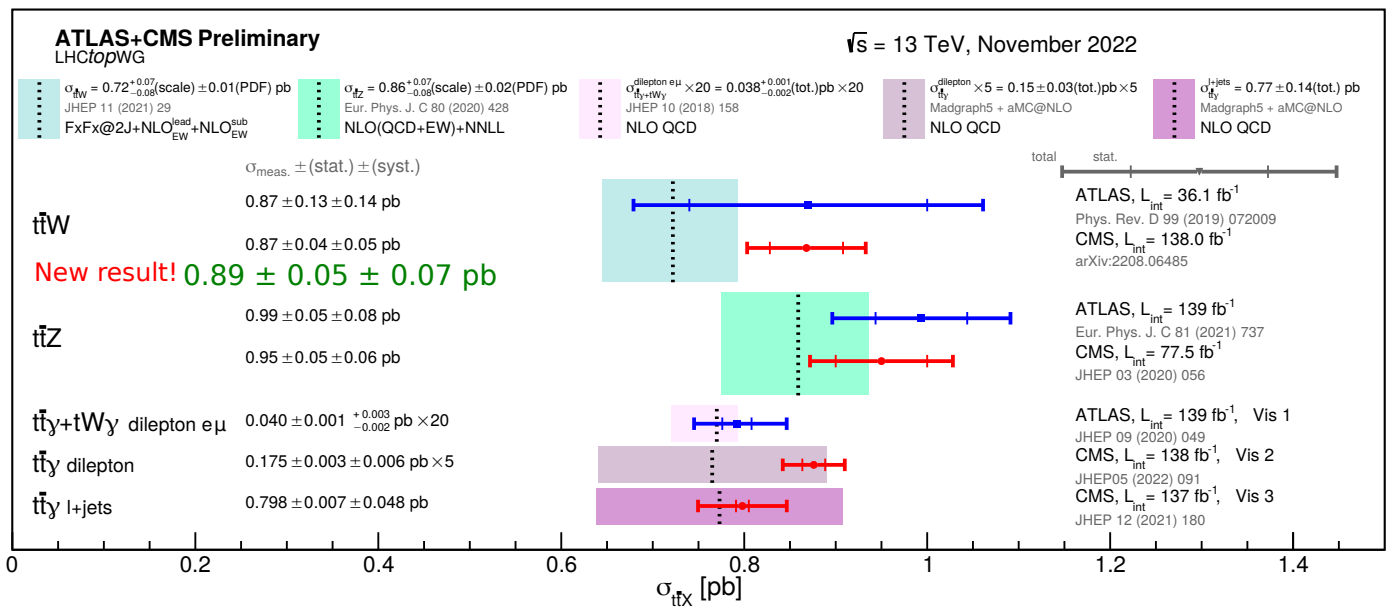
$$A_C^{\ell} = -0.112 \pm 0.170(\text{stat}) \pm 0.055(\text{syst})$$

$A_{C\,SM}^{\ell} = -0.063^{+0.007}_{-0.004}\ (\text{scale}) \pm 0.004\ (\text{MC stat})$
[Sherpa]

- Systematic uncertainty dominated by $t\bar{t}Z$ and $t\bar{t}W$ modelling

Summary

- Presented highlights of $t\bar{t}$ and single top quark production with associated bosons with the full Run 2 data
- $t\bar{t}W$ and $t\bar{t}Z$ inclusive and differential measurements (absolute and normalised)
  - Rare processes reaching precision regime!



- Observation for $tq\gamma$ has been achieved with 9σ significance
- Exploiting $t\bar{t}\gamma$, $t\bar{t}W$ topologies to measure properties of top quark production