

Recent highlights of top-quark cross section and properties measurements with the ATLAS detector at the LHC

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on behalf of ATLAS Collaboration

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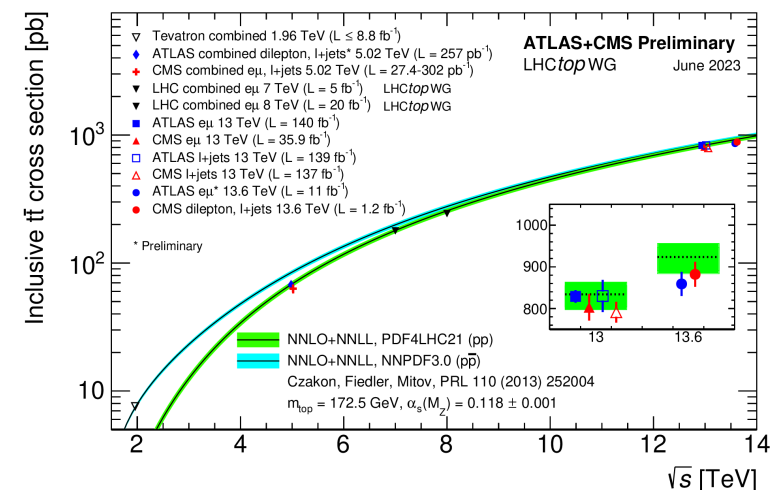
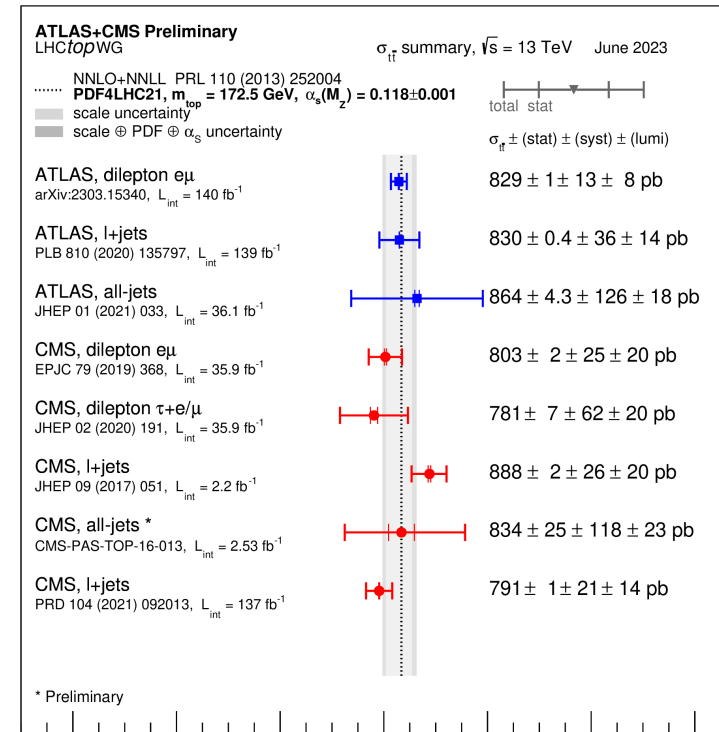
17 - 21 July 2023

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Introduction

- ▶ The top quark is the heaviest known elementary particle, with a mass of $172.76 \pm 0.30 \text{ GeV}$
- ▶ At LHC an unprecedented number of top-quark events is being collected
- ▶ Since 2010, the large center-of-mass energy, $\sqrt{s} = 5, 7, 8, 13, 13.6 \text{ TeV}$, and luminosity of LHC has enabled many precise and differential cross-section measurements for SM processes
- ▶ Due to its large mass, the top quark has a large coupling to the SM Higgs boson. Predicted large couplings to hypothetical new particles in BSM processes
- ▶ Plots with summary of $t\bar{t}$ production cross-section measurements, (top) LHC results at 13 TeV compared to NNLO QCD calculation and NNLL resummation; (bottom) results from LHC and Tevatron obtained at different \sqrt{s} compared to NNLO QCD calculation and NNLL resummation
- ▶ Plot shows latest ATLAS $t\bar{t} e\mu$ cross-section measurement obtained using 13.6 TeV data collected in 2022 with $\sigma_{t\bar{t}} = 859 \pm 4 \text{ (stat.)} \pm 22 \text{ (syst.)} \pm 19 \text{ (lumi.) pb}$ ATLAS-CONF-2023-006
- ▶ All measurements agree with SM predictions

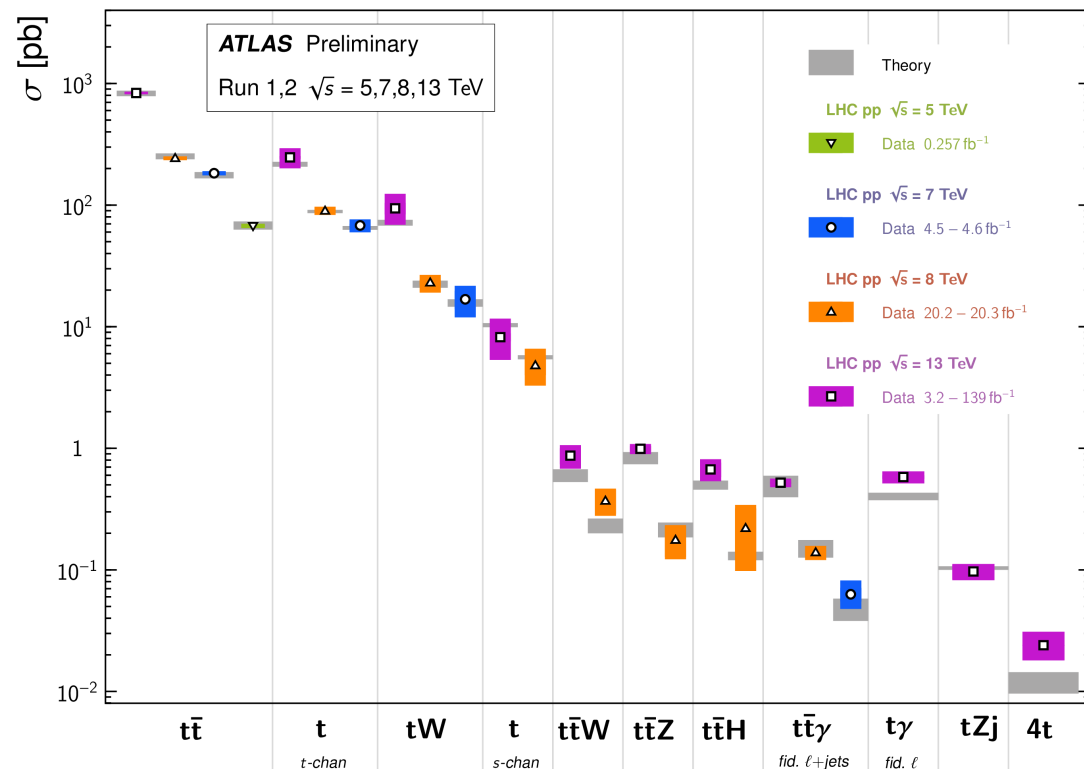


Top quark production

- ▶ Rare processes involving the top quark are relevant to study
- ▶ Allow tests of the electroweak couplings of the top quark to bosons
- ▶ Give the possibility to test, improve and understand the modeling of our Monte Carlo (MC) simulations and the higher order calculations methods behind them
- ▶ Enhance the possibility to do $t\bar{t}$ asymmetry studies in processes like: $t\bar{t}\gamma$ and $t\bar{t}W$
- ▶ Allow further Effective Field Theory (EFT) interpretations and look for BSM effects
- ▶ The associate production of $t\bar{t} + X$ processes, where X is a boson (W , Z , γ), are irreducible background to several BSM phenomena and also to important measurements like $t\bar{t}H$ and $t\bar{t}t\bar{t}$
- ▶ Plot on the right-hand-side shows most recent top quark production cross-section results obtained in ATLAS @ LHC
- ▶ In the following recent highlights of $t\bar{t}$ cross sections and properties measurements performed with the ATLAS experiment are presented

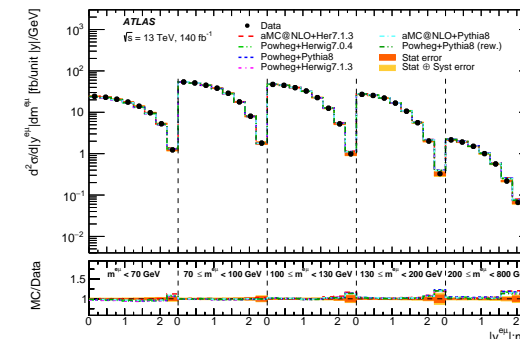
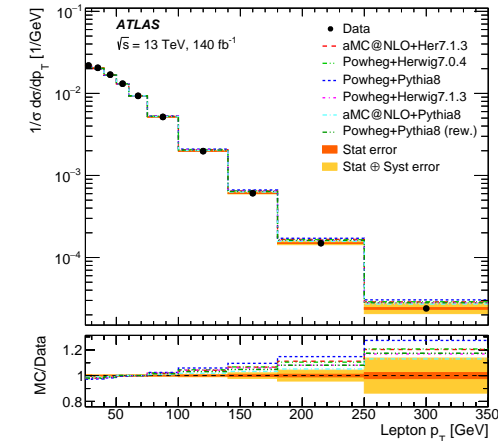
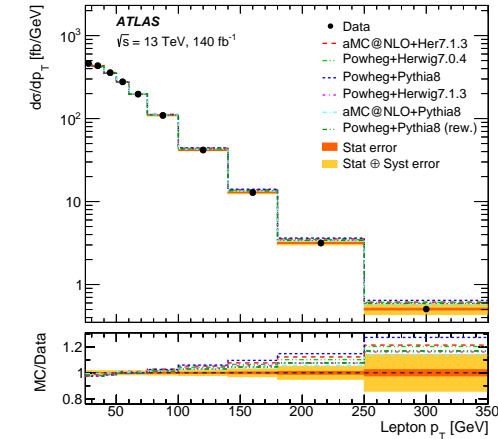
Top Quark Production Cross Section Measurements

Status: November 2022



Inclusive and diff. cross-sections in dilepton $t\bar{t}$

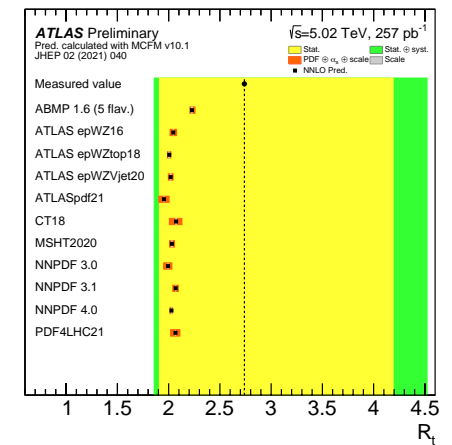
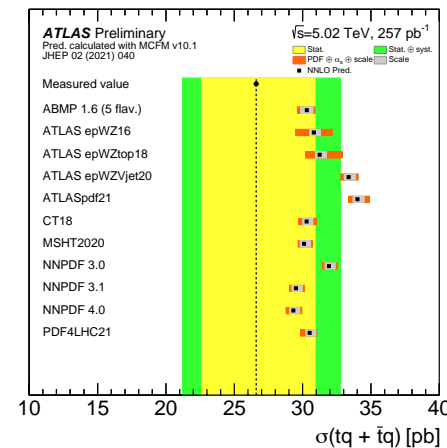
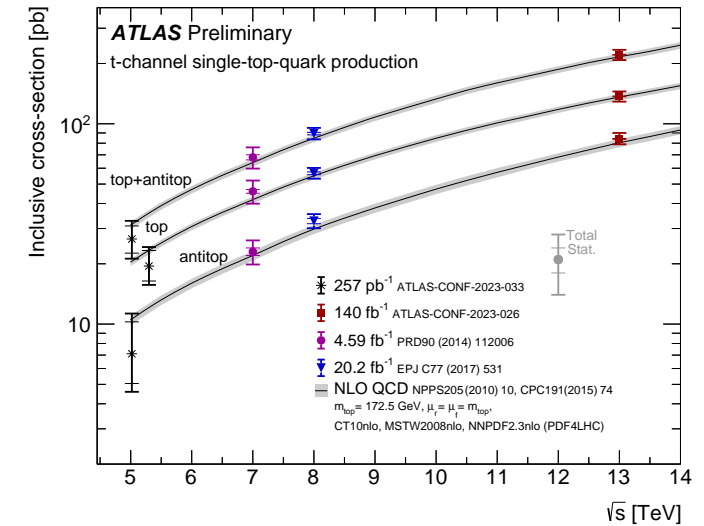
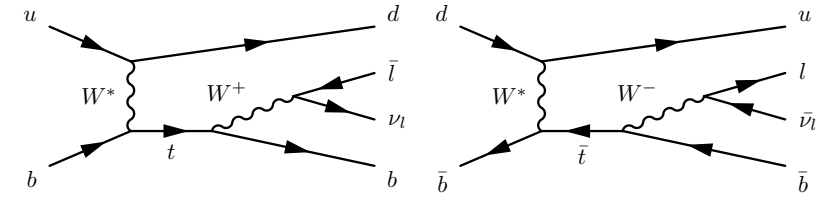
- Precise measurements of $t\bar{t}$ production allow sensitive test of QCD, particularly allow test of PDFs
- Analysis report measurement of $t\bar{t}$ inclusive and differential cross-sections using ATLAS data at 13 TeV using $\int \mathcal{L} 140 \text{ fb}^{-1}$ arXiv:2303.15340
- Events contain an e , a μ , and either 1 or 2 b-tagged jets
- Fiducial cross section measured at particle level:
 $\sigma_{t\bar{t}}^{\text{fid}} = 10.53 \pm 0.02 \text{ (stat.)} \pm 0.13 \text{ (syst.)} \pm 0.10 \text{ (lumi.)} \pm 0.02 \text{ (beam.) pb}$
- Inclusive cross section measurement: $\sigma_{t\bar{t}} = 829 \pm 1 \text{ (stat.)} \pm 13 \text{ (syst.)} \pm 8 \text{ (lumi.)} \pm 2 \text{ (beam.) pb}$
- $t\bar{t}$ absolute and normalized differential cross-section measured for 8 different variables: $p_T^{e\mu}$, $p_T^e + p_T^\mu$, etc.
- Measured four double-differential cross-sections
- Absolute (normalized) differential cross-sections measured with a typical 2% (1%) precision
- Measurements compared with several MC $t\bar{t}$ models. No model describes all the measurements within their uncertainties



Observation of single-top-quark @ 5.02 TeV

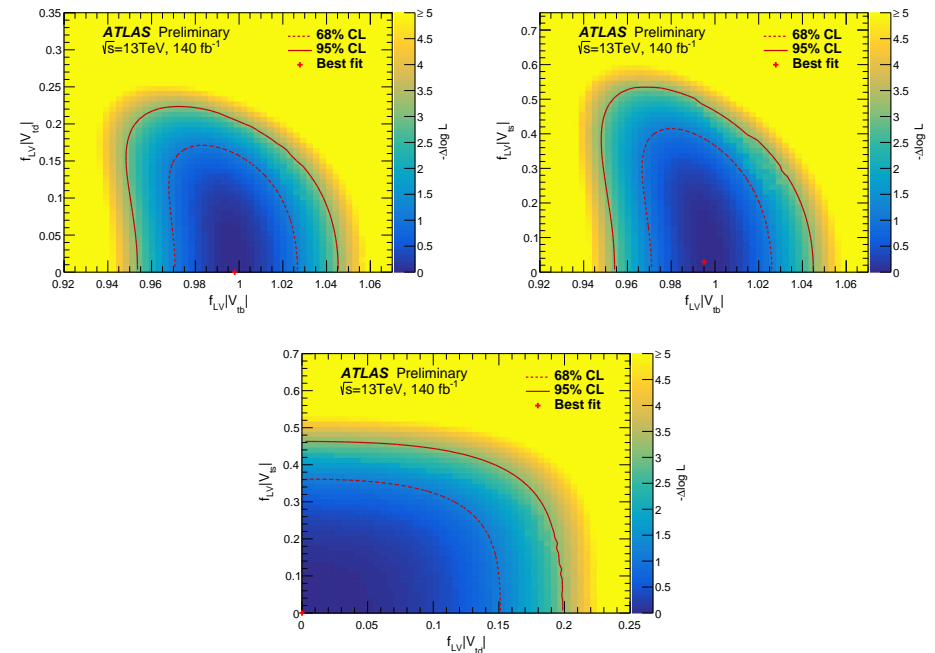
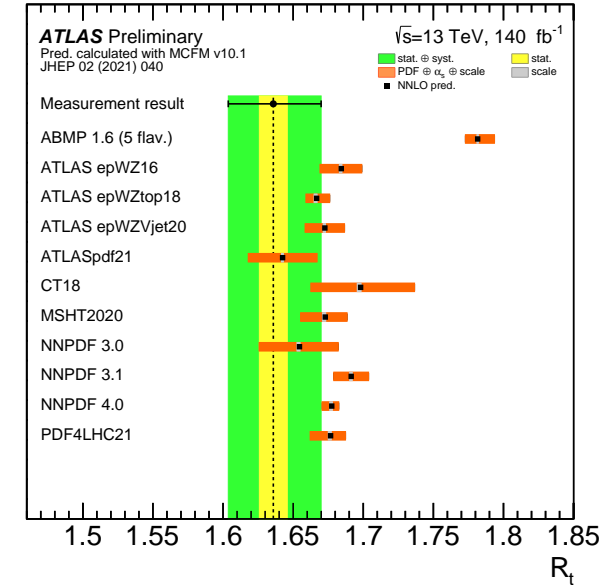
- Single-top-quark (single tq) produced @ LHC via electroweak interaction. Single tq measurements allow studies of the unitarity CKM matrix, tests of higher-order corrections from QCD, and constraints on PDFs
- Analysis report **observation of single tq production** in dominant t-channel mode using ATLAS data at 5.02 TeV using $\int \mathcal{L} 257 \text{ pb}^{-1}$ ATLAS-CONF-2023-033
- Single-top-quark t-channel production already measured at $\sqrt{s} = 7, 8, 13 \text{ TeV}$. This measurement allows further SM tests with different levels of backgrounds and instrumental uncertainties. Final state include leptonic W boson decay in top quark, two jets, one is a b-tagged jet
- Cross section measured with profile likelihood fit

$$\sigma(tq + \bar{t}\bar{q}) = 26.6^{+4.3}_{-4.0}(\text{stat.})^{+4.4}_{-3.6}(\text{syst.}) \text{ pb}$$
- Measured $R_t = 2.74^{+1.44}_{-0.83}(\text{stat.})^{+1.04}_{-0.29}(\text{syst.})$
- Observed single tq production with significance: 6.1σ**
- Extracted $V_{tb} = 0.94 \pm^{+0.08}_{-0.07}(\text{stat.})^{+0.08}_{-0.06}(\text{syst.})$
- All results in agreement with SM



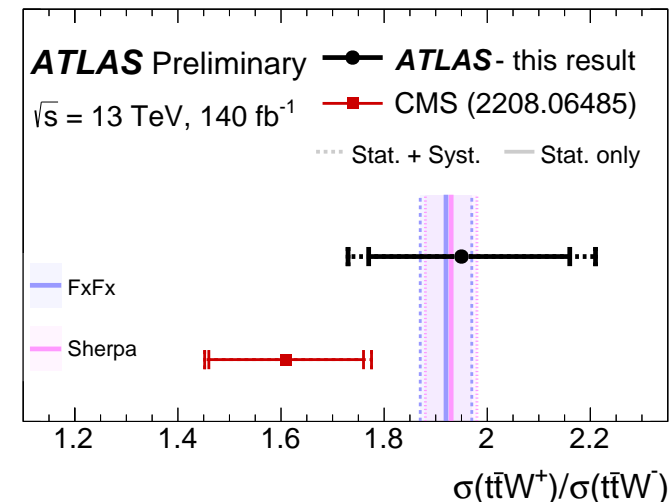
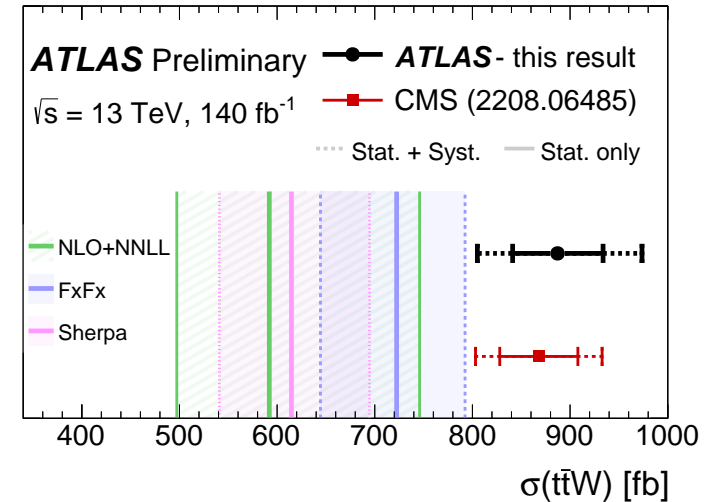
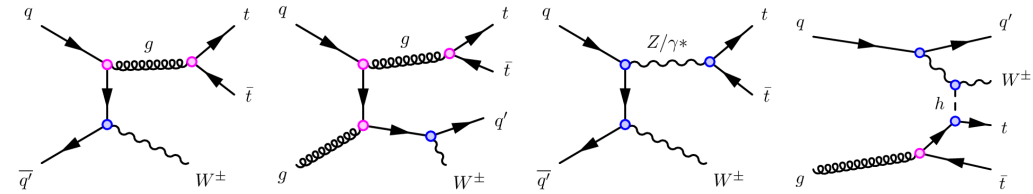
Measurement of single-top-quark @ 13 TeV

- Measurement of single tq production in dominant t-channel mode using ATLAS full Run2 data at 13 TeV with a $\int \mathcal{L} 140 \text{ fb}^{-1}$ ATLAS-CONF-2023-026 (previous analysis JHEP 04 (2017) 086)
- This measurement significantly improve the precision due to statistical uncertainty, better detector calibration and usage of advanced object reconstruction Events include leptonic W boson decay in top quark, two jets, one is a b-tagged jet
- Cross section measured $\sigma(tq + \bar{t}\bar{q}) = 221 \pm 13 \text{ pb}$
- Measured ratio of $\sigma(qt)$ to $\sigma(\bar{t}\bar{q})$: $R_t = 1.636^{+0.036}_{-0.034}$
- From measured $\sigma(qt + \bar{t}\bar{q})$ extracted $V_{tb} > 0.95$ at 95% CL
- The $\sigma(tq)$ and $\sigma(\bar{t}\bar{q})$ interpreted in an EFT approach, setting limits on the strength of the 4-quark operator $O_{qQ}^{(1,3)}$: $-0.25 < c_{qQ}^{(1,3)} < 0.12$ at 95% CL
- Confidence contours determined in the $f_{LV}|V_{tb}|$ -versus- $f_{LV}|V_{td}|$, $f_{LV}|V_{tb}|$ -versus- $f_{LV}|V_{ts}|$, $f_{LV}|V_{ts}|$ -versus- $f_{LV}|V_{td}|$
- All results in agreement with NNLO calculation



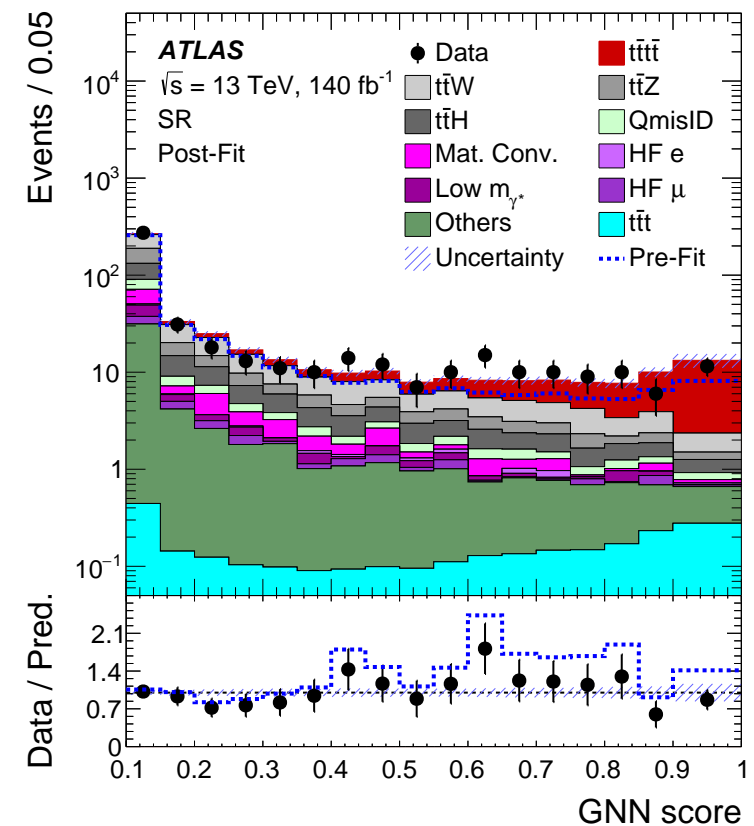
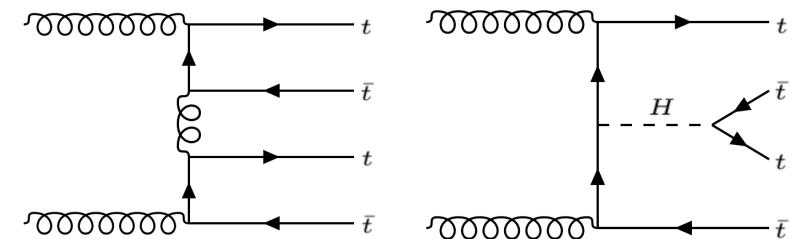
$t\bar{t}W$: total and differential cross-section

- $t\bar{t}W$ cross-section calculations are complex, higher powers of the strong and weak couplings corrections needed. $t\bar{t}W$ measurements allow testing predictions of the QCD and the EW sector of the SM. This process is background for BSM and SM processes, e.g. $t\bar{t}H$ and $t\bar{t}t\bar{t}$
- Performed $t\bar{t}W$ inclusive cross-section measurement using ATLAS data at 13 TeV with events having 2 same-sign, $2\ell SS$, or three isolated leptons, 3ℓ see ATLAS-CONF-2023-019
- Best-fit value give: $\sigma(t\bar{t}W) = 890 \pm 50(\text{stat.}) \pm 70(\text{syst.}) \text{ fb} = 890 \pm 80 \text{ fb}$
- Result compatible within 1.5σ with SM prediction
- First absolute differential $t\bar{t}W$ cross-section measurements made as a function of 7 observables: N_{jets} , $H_{T,\text{jets}/\text{lep}}$... No significant disagreement found between data and MC
- Measured ratio $\sigma(t\bar{t}W^+)/\sigma(t\bar{t}W^-)$:
 $R(t\bar{t}W) = 1.95^{+0.21}_{-0.18}(\text{stat.})^{+0.16}_{-0.13}(\text{syst.})$
 and charge asymmetry:
 $A_C^{\text{rel}} = 0.32 \pm 0.05(\text{stat.}) \pm 0.03(\text{syst.})$
 in agreement with the prediction



Observation of $t\bar{t}t\bar{t}$ production

- $t\bar{t}t\bar{t}$ important final state. Its cross-section can be enhanced in many BSM processes. $t\bar{t}t\bar{t}$ measurements can constrain the top-Higgs Yukawa coupling and its CP properties. In the EFT framework it is sensitive to 4-fermion interactions and the Higgs oblique parameters
- **First observation of $t\bar{t}t\bar{t}$ production:** re-analysis of ATLAS data at 13 TeV using $\int \mathcal{L} 140 \text{ fb}^{-1}$, see Eur. Phys. J. C 83, 496 (2023)
- Selected $t\bar{t}t\bar{t}$ events with 2 same-sign, $2\ell\text{SS}$, or 3 leptons (e or μ) 3ℓ . Signal events have ≥ 6 jets, ≥ 2 b-tagged jets, $H_T > 500 \text{ GeV}$, a Graph Neural Network (GNN) separates signal from background events (mainly $t\bar{t}W$, $t\bar{t}H$, $t\bar{t}Z$ events)
- $t\bar{t}t\bar{t}$ production observed significance: 6.1σ
- Measured cross-section: $\sigma(t\bar{t}t\bar{t}) = 22.5^{+6.6}_{-5.5} \text{ fb}$, compatible within 1.5 or 1.8σ with SM
- Data used to set limits on the $t\bar{t}$ cross section, to constrain the top-Higgs Yukawa coupling, and to constrain EFT operator coefficients
- M. Vos's will talk further on the observation of $t\bar{t}t\bar{t}$ production. CMS $t\bar{t}t\bar{t}$ results just presented



Observation of $tq\gamma$ production

- Rare associated-production processes of the top quark crucial to constrain non resonant contributions from physics BSM, parameterised in the SMEFT framework. The γ radiation before top-quark decay sensitive to top- γ coupling, process called $tq\gamma$
- Analysis reports **first observation of $tq\gamma$ production** in the dominant t-channel mode using ATLAS data at 13 TeV and a $\int \mathcal{L} 139 \text{ fb}^{-1}$ arXiv:2302.01283
- Events have a γ , an e or μ , missing transverse momentum, w/o forward-jet characteristic of t-channel production
- Cross section measured in fiducial phase space at **parton level**:

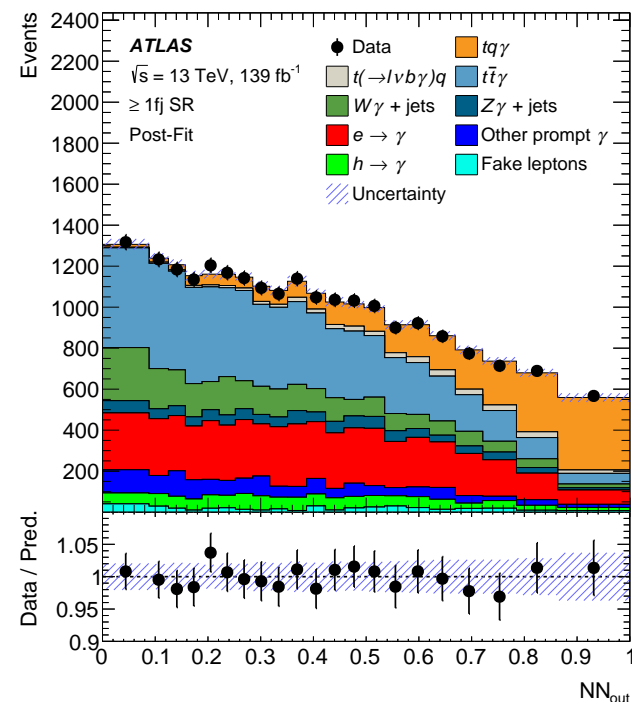
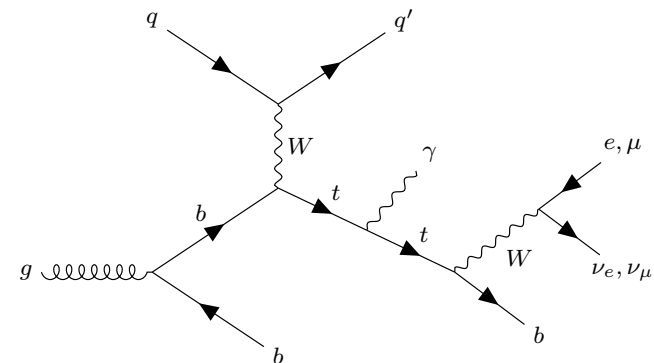
$$\sigma_{tq\gamma} \times \text{BR}(t\ell b) = 688 \pm 23(\text{stat.})^{+75}_{-71}(\text{syst.}) \text{ fb}$$

$$(\sigma_{qt\gamma}^{\text{QCD}+\text{EW NLO}} = 515^{+36}_{-42} \text{ fb})$$
- Fiducial cross section measured at **particle level**:

$$\sigma_{tq\gamma} \times \text{BR}(t\ell b) + \sigma_{t \rightarrow \ell \nu b \gamma q} =$$

$$303 \pm 9(\text{stat.})^{+33}_{-32}(\text{syst.}) \text{ fb}$$

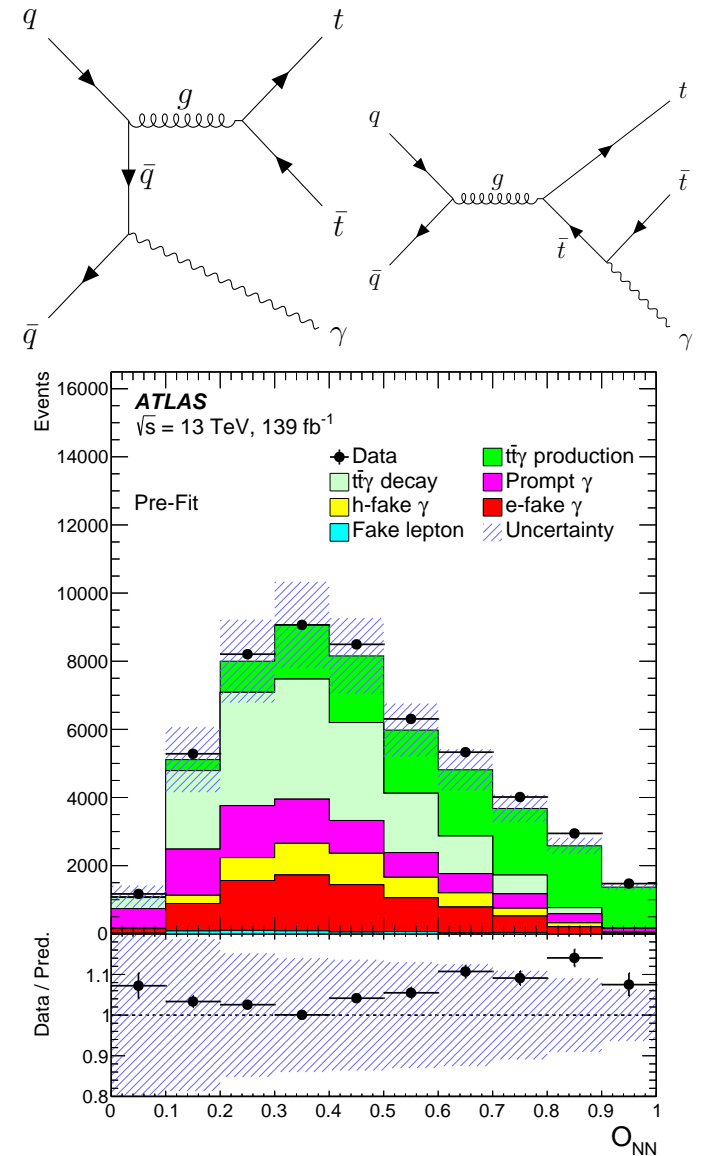
$$(\sigma_{qt\gamma}^{\text{QCD}+\text{EW NLO}} = 217^{+27}_{-15} \text{ fb})$$
- SM compatible within 2.1 (2.0) σ at parton (particle) level
- **Observed (expected) significance: 9.1(6.7) σ**
- See M. Vos's talk for further information on $tq\gamma$ production



First measurement of A_C in $t\bar{t}\gamma$ production

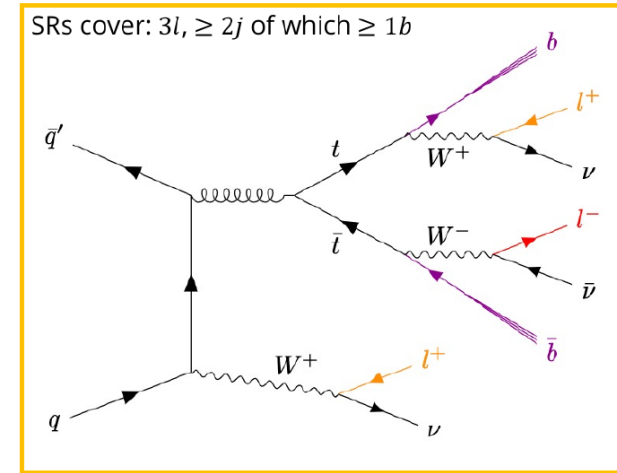
- Measurements of top-quark properties are important for testing theoretical calculations and to look for deviations from the SM. A relevant property is the slight difference between the rapidity distributions in $t\bar{t}$ pairs, the charge asymmetry A_C
- $t\bar{t}$ asymmetry is diluted at LHC, is enhanced when the fraction of quark-antiquark initiated production is larger, e.g. in associate production of $t\bar{t}\gamma$
- ATLAS performed the **first measurement of A_C in $t\bar{t}\gamma$ production** using data at 13 TeV with a $\int \mathcal{L} 139 \text{ fb}^{-1}$, see Phys. Lett. B 843 (2023) 137848
- Select lepton+jets $t\bar{t}$ events and exactly one high- p_T , isolated γ . Neural network is used to discriminate $t\bar{t}\gamma$ production from all types of backgrounds.
- Measured

$$A_C = -0.003 \pm 0.024(\text{stat.}) \pm 0.017(\text{syst.}) = -0.003 \pm 0.029$$
- Measurement dominated by stat. uncertainty



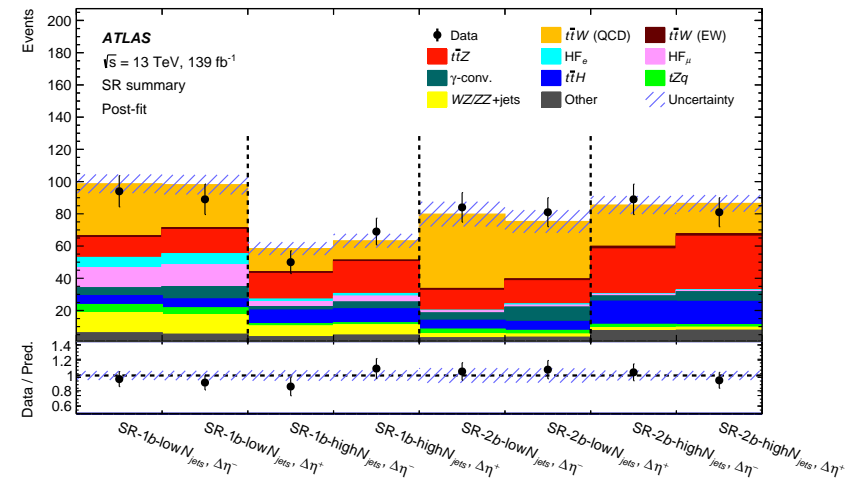
First measurement of $A_C^{\ell\ell}$ in $t\bar{t}W$ production

- At pp collision at LHC $t\bar{t}$ has a small A_C of the order of 1% In $t\bar{t}W$ production, the qq' initial state leads to larger A_C than in $t\bar{t}$ production. The W in $t\bar{t}W$ is radiated from initial qq' state and act as event polarization, enhancing the asymmetry between the $t\bar{t}$
- Measurement of A_C in $t\bar{t}W$ production using ATLAS data at 13 TeV with a $\int \mathcal{L} 139 \text{ fb}^{-1}$, see arXiv:2301.04245
- Analysis uses events in final state with exactly 3 charged leptons (e or μ), 3ℓ . Signal and control regions (SRs and CRs) defined by requirements on number of jets and b-tagged jets
- Simultaneous fit to the numbers of observed events in the SRs and CRs define the leptonic $A_C^{\ell\ell}$
- At reconstruction level measured:
 $A_C^{\ell\ell} = -0.123 \pm 0.136(\text{stat.}) \pm 0.051(\text{syst.})$
 $(A_{\text{CSM}}^{\ell\ell} = -0.084^{+0.005}_{-0.003}(\text{scale}) \pm 0.006(\text{MC stat.})$
 SHERPA)
- After unfolding at particle level and fiducial phase space as in reco level: $A_C^{\ell\ell} = -0.112 \pm 0.170(\text{stat.}) \pm 0.055(\text{syst.})$
 $(A_{\text{CSM}}^{\ell\ell} = -0.063^{+0.007}_{-0.004}(\text{scale}) \pm 0.004(\text{MC stat.})$
 SHERPA)



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

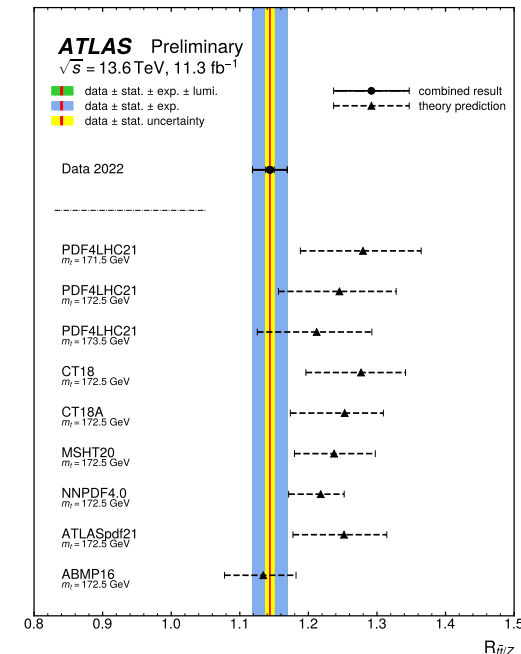
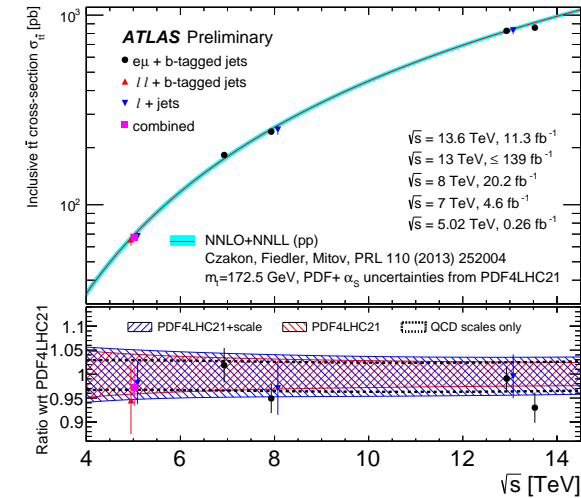
[From M. Miralles]



$t\bar{t}$ and Z-boson cross-sections @ 13.6 TeV

- Precise measurements of $t\bar{t}$ and Z-boson production cross-sections allow tests of QCD, of EW, and PDFs
- Analysis report measurement of $t\bar{t}$ inclusive cross-section, and fiducial Z boson cross-section using 2022 ATLAS data at 13.6 TeV using $\int \mathcal{L} 11.3 \text{ fb}^{-1}$ ATLAS-CONF-2023-006
- $t\bar{t}$ events contain an e and a μ with opposite sign (OS) and 1 or 2 b-tagged jets. Events same-flavor channels (ee , $\mu\mu$) used for reconstruction the Z-boson
- Inclusive cross section measured:

$$\sigma_{t\bar{t}} = 859 \pm 4 \text{ (stat.)} \pm 22 \text{ (syst.)} \pm 19 \text{ (lumi.) pb}$$
- Fiducial cross section measurement: $\sigma_{Z \rightarrow \ell\ell}^{\text{fid}} = 751 \pm 0.3 \text{ (stat.)} \pm 15 \text{ (syst.)} \pm 17 \text{ (lumi.) pb}$
- The fitted value for the ratio of $R_{t\bar{t}/Z} = 1.114 \pm 0.006 \text{ (stat.)} \pm 0.022 \text{ (syst.)} \pm 0.003 \text{ (lumi.)}$
- Absolute cross-section measurements limited by luminosity and lepton efficiency uncertainties
- $R_{t\bar{t}/Z}$ measured with 2.2% uncertainty
- Measurements consistent with the SM prediction using PDF4LHC21 PDF set



Conclusions

- ▶ Presented highlights of recent $t\bar{t}$ cross section and top quark properties measurements made with ATLAS experiment at LHC using data $\sqrt{s} = 13 \text{ TeV}$ and $\sqrt{s} = 13.6 \text{ TeV}$
- ▶ Precise measurements of $t\bar{t}$ production performed with the large data set at LHC allow sensitive tests of QCD, EW, and test of PDFs
- ▶ The A_C measurements in the $t\bar{t}\gamma$ and $t\bar{t}W$ processes are dominated by statistical uncertainty
- ▶ ATLAS performed measurement of jet substructure in boosted $t\bar{t}$ events using data at 13 TeV , results available at ATLAS-CONF-2023-027
- ▶ Rare processes on the path of precision regime
- ▶ ATLAS first observation of $tq\gamma$ final state and $t\bar{t}t\bar{t}$ production will be further presented by Marcel Vos in his talk, see also Poster presented by Harish Potti