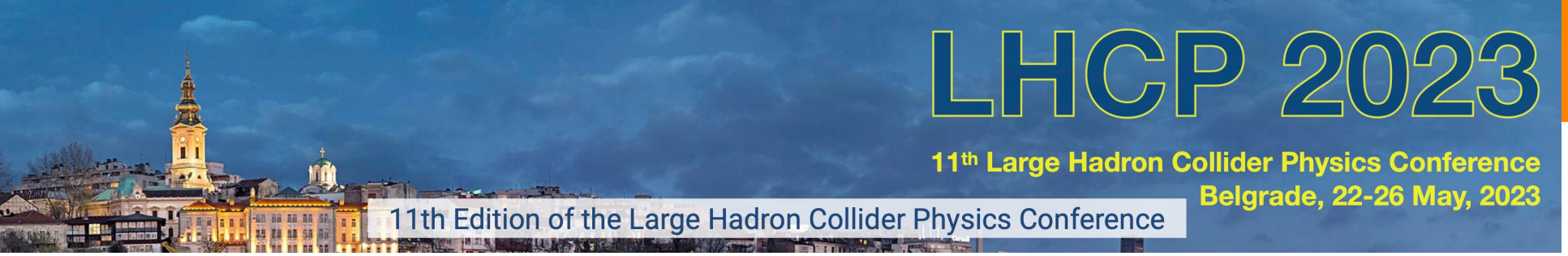


24th - May -2023

Measurement of ttbar and single top quark production in the ATLAS experiment

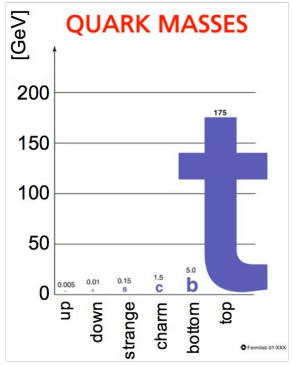
Mohammed Faraj (Udine-ICTP ATLAS group)
On behalf of the ATLAS collaboration

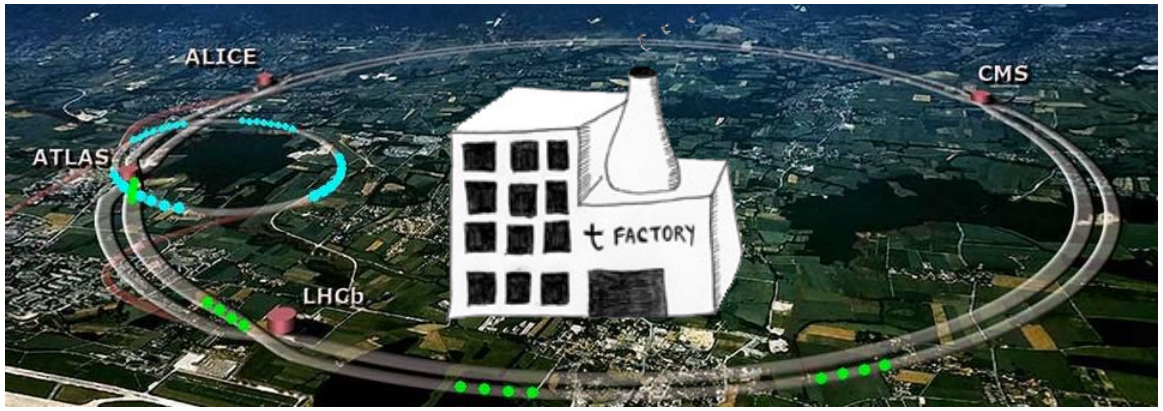
ICTP

INFN
Istituto Nazionale di Fisica Nucleare

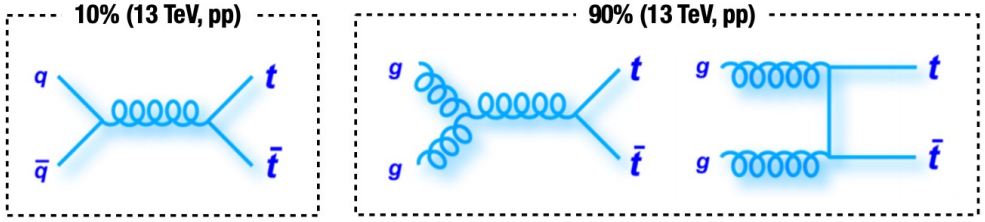
ATLAS EXPERIMENT

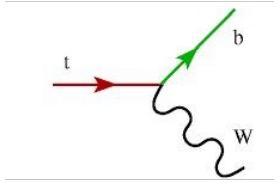
The top quark



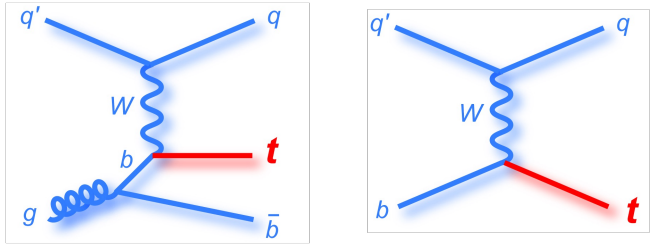


- The heaviest elementary particle:
  - With mass scale close to the EW Symmetry Breaking
  - Large coupling to the Higgs boson, $y_t \sim 1$
- Myriad production at the Large Hardon Collider
  - Top pair production (Strong)
  - Single top (antitop) production (EW): t-, s- and Wt-channels
  - Top production in association with gauge bosons, quarks: $t\bar{t}+\gamma/W/Z/H$, $t\bar{t}+b\bar{b}, t\bar{t}+t\bar{t}$ ...etc
- Decays (before Hadronisation)
  - Almost 100% to Wb



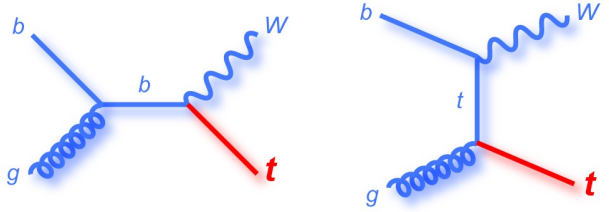


t-channel (~73% at LHC)

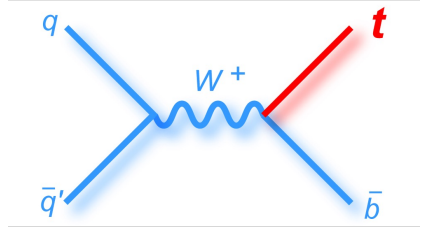


Golden Channel

Wt-channel (~24% at LHC)



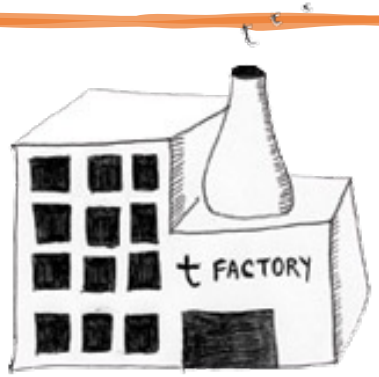
s-channel (~3% at LHC)



Challenging Channel AT LHC

The top quark

- Top (Strong & EW) production cross-sections and mass measurements are entering the high-precision regime at the LHC => LHC turning to the top precision factory.
- However, more efforts are required to control and improve several sources of systematics uncertainties:
  - Experimental
    - B-tagging
    - Lepton selection efficiencies
    - Jet energy scale
    - Luminosity
  - Theoretical Modelling
    - Kinematics for Top quark pair
    - Top-quark decay
    - Parton-shower evolution
    - b-quark fragmentation
    - Higher order calculation and including EW effects



arXiv:2212.09379

Improved Luminosity determination at ATLAS:
Now Lumi uncert. **±0.83%** for Run 2 at $\sqrt{s} = 13$TeV

For today:
Presenting some of the most recent $t\bar{t}$ and single top production in ATLAS

$t\bar{t}$ cross-section in $e\mu$ events at $\sqrt{s} = 13$TeV

New

arXiv:2303.15340

- Using full Run 2 pp data in the $e\mu$ decay channel
  - Inclusive $\sigma_{t\bar{t}}$ at $\sqrt{s} = 13$TeV (total and fiducial) + differential several kinematic variables for lepton.
  - Cross-section obtained using the **b-tag counting method**:
    - Minimize jet and b-tagging systematics.

$$N_1^i = \mathcal{L}\sigma_{t\bar{t}}^i G_{e\mu}^i 2\epsilon_b^i\left(1 - \epsilon_b^i C_b^i\right) + N_{1,bkg}^i$$

$$N_2^i = \mathcal{L}\sigma_{t\bar{t}}^i G_{e\mu}^i 2\left(\epsilon_b^i\right)^2 C_b^i + N_{2,bkg}^i$$

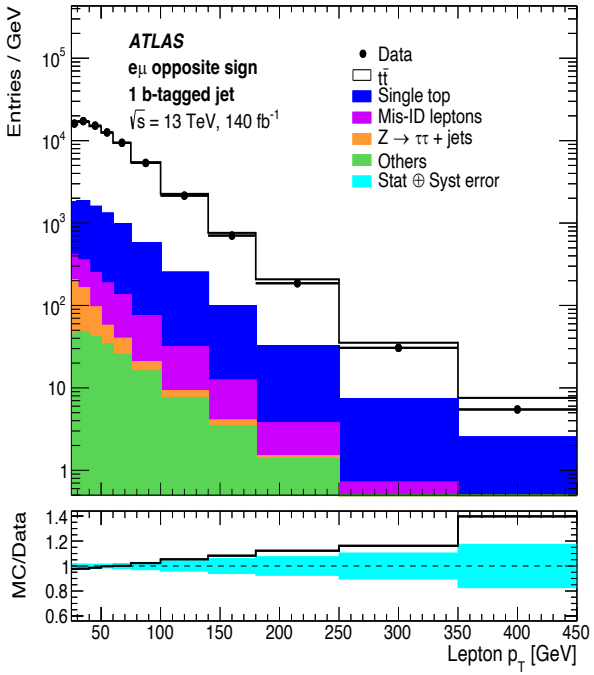
Number of data events with either one or two b-tagged jets in each bin

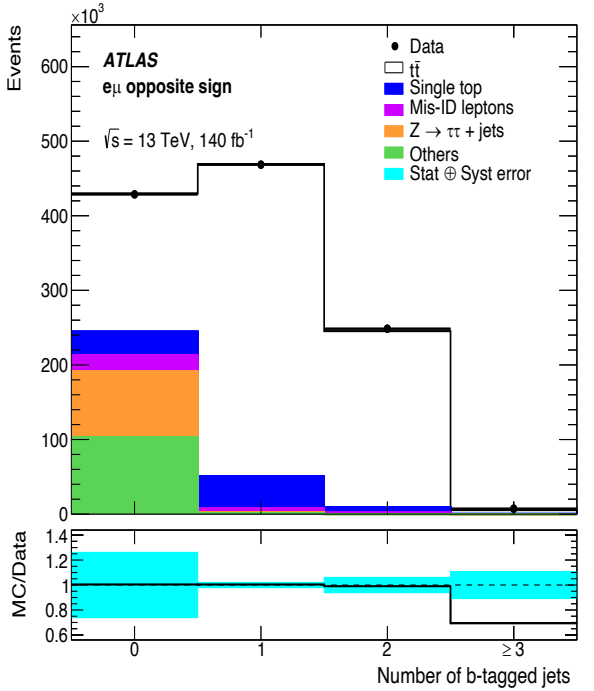
ϵ_b: Effective b-jet selection efficiency

- Dominated **systematics**:
  - Luminosity (0.93%)
  - Wt bkg. (0.6%)
  - Top pT rew. (0.6%)
  - Electron Isolation (0.5%)
  - PDF (0.43%)

$$\sigma_{t\bar{t}} = 829 \pm 1(stat) \pm 13(syst) \pm 8(Lumi) \pm 2(beam)\ pb\ [1.8\%]$$

Theory (NNLO+NNLL): $833.9\ (scale)^{+20.5}_{-30}(PDF + \alpha_s)^{+21}_{-21}(mTop)^{+23.2}_{-22.5}\ pb$ Ref

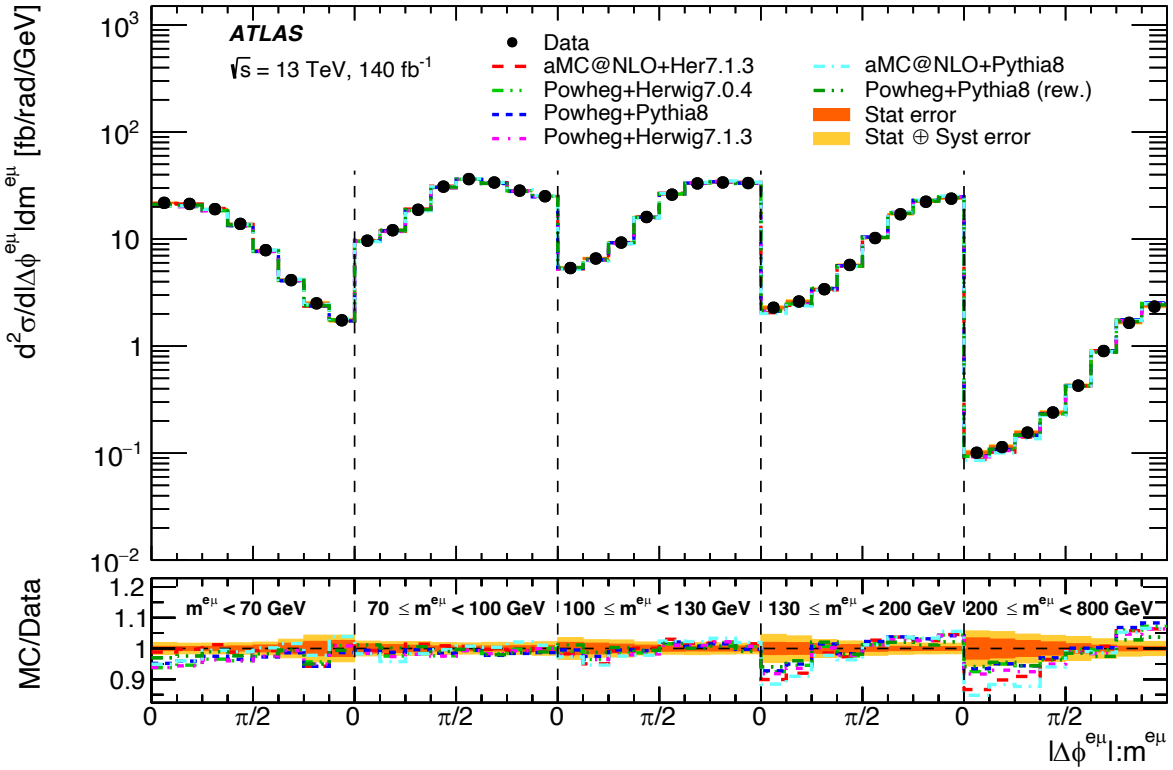


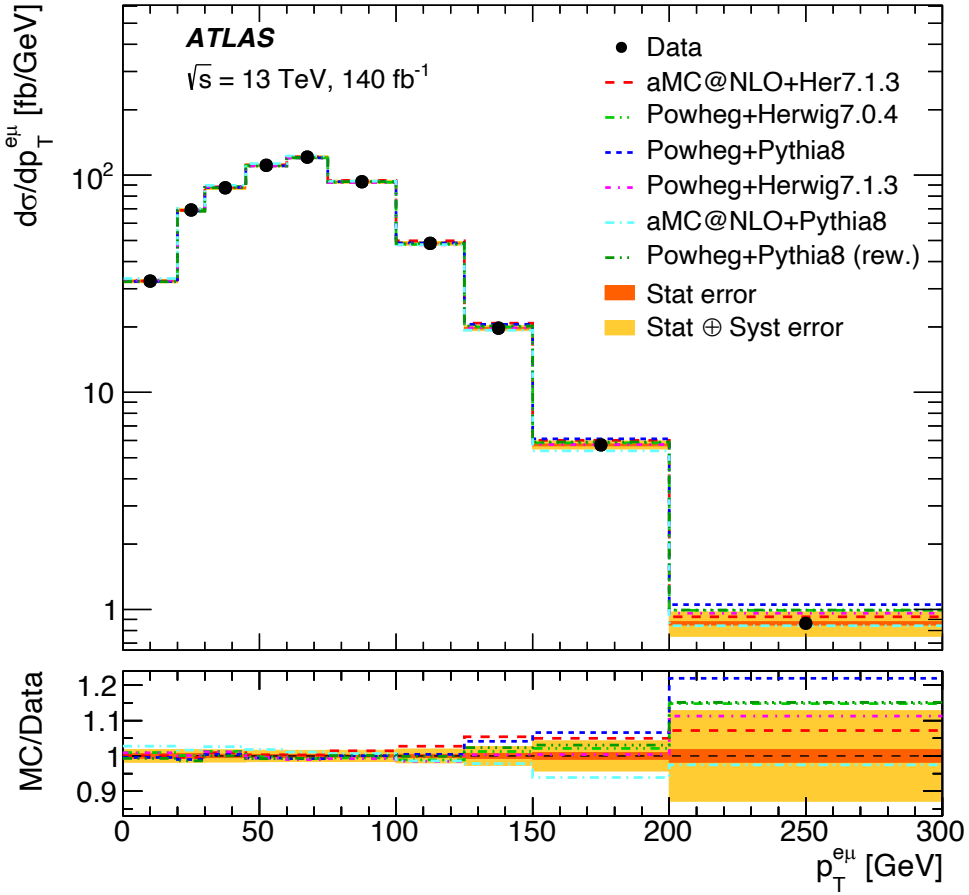


$t\bar{t}$ cross-section in $e\mu$ events at $\sqrt{s} = 13$TeV

arXiv:2303.15340 **New**

- Using full Run 2 pp data in the ***eμ*** decay channel
  - Differential (Single and double $\sigma_{t\bar{t}}^{diff}$) several kinematic variables for lepton.
    - $p_T^l, |\eta_l|, m_{e\mu}, p_T^{e\mu}, |y^{e\mu}|, E^e + E^\mu, p_T^e + p_T^\mu, \Delta\phi^{e\mu}$
  - Cross-section obtained using the **b-tag counting method**
    - Minimize jet and b-tagging systematics.
  - **Good** Data/MC agreements for various predictions
    - Still not that perfect at the tails, e.g. for **High** lepton pT.



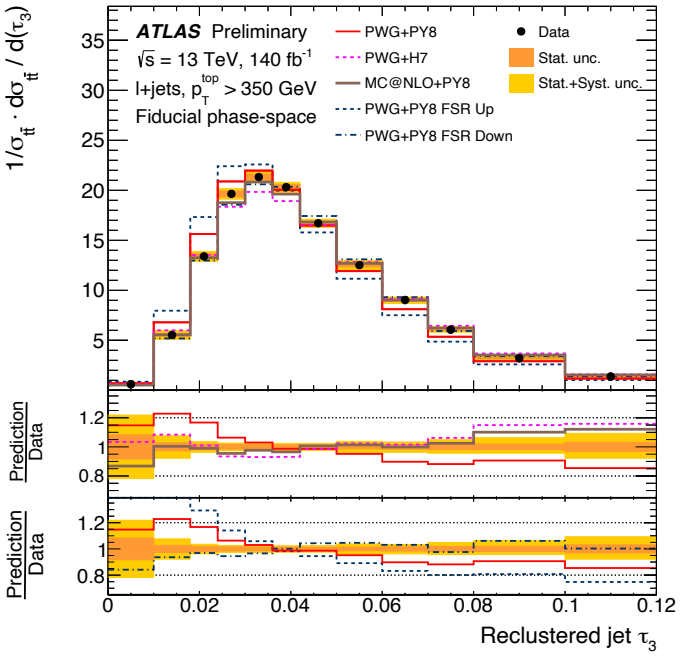


Measurement of Jet Substructure in boosted $t\bar{t}$ events at $\sqrt{s} = 13$TeV

New

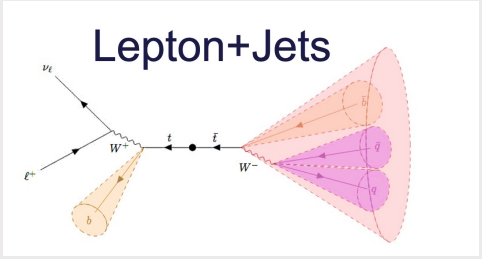
ATLAS-CONF-2023-027

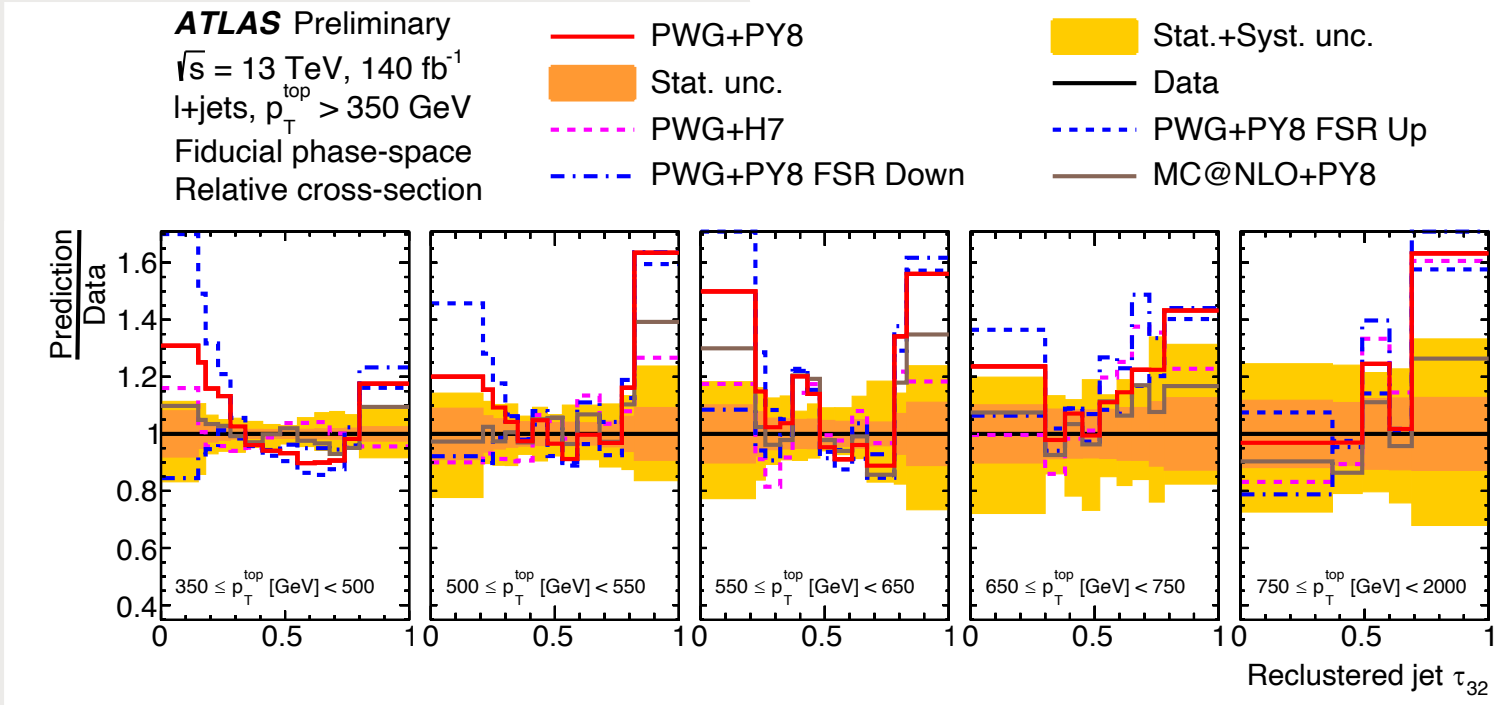
- Poor modeling of Jet substructure in data by the current MC and the analytic description is challenging.
- Using full Run 2 pp data in the semi-leptonic and all hadronic decay channels to study the substructure of jets arising from light-, b-quarks, gluons, and jets from the top-quark decay.
  - One- and two-dimensional differential $\sigma_{t\bar{t}}$ for eight substructure variables defined using only the charged components of the Jets (compared to several MC predictions).



L+jets Channel:

- Electron or Muon
- m_T^W > 20 GeV, E_T^{miss} > 15 GeV and $m_T^W + E_T^{miss}$ > 60 GeV"to reduce Fake lep" to supress Fake leptons
- Hadronically-decaying top reconstructed as reclustered RC large-R jet
- No required b-matching on the measured jets.





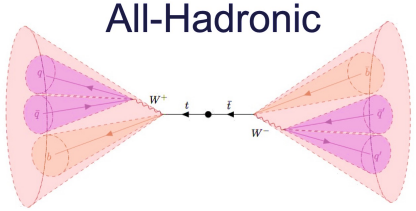
Measurement of Jet Substructure in boosted $t\bar{t}$ events at $\sqrt{s} = 13$TeV

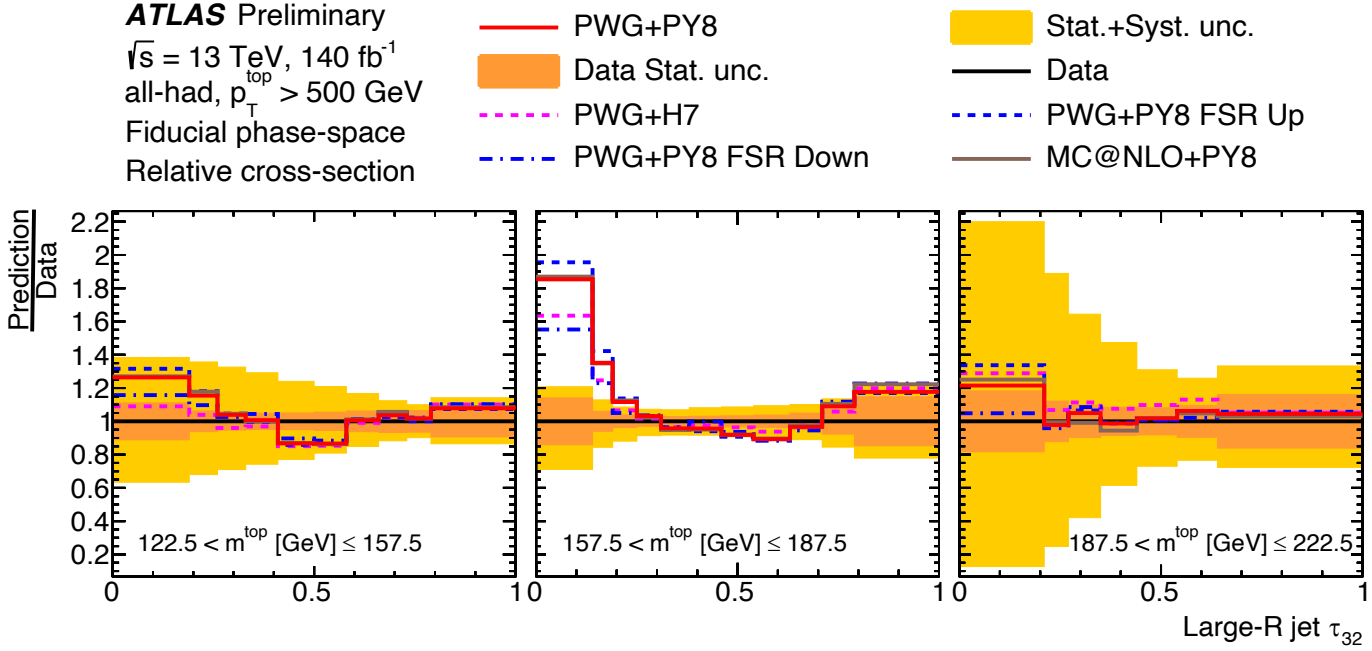
New

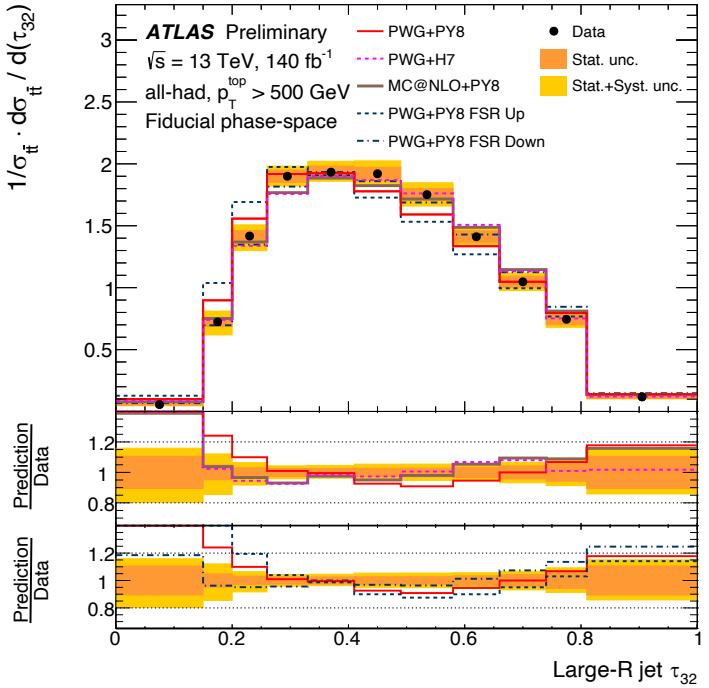
ATLAS-CONF-2023-027

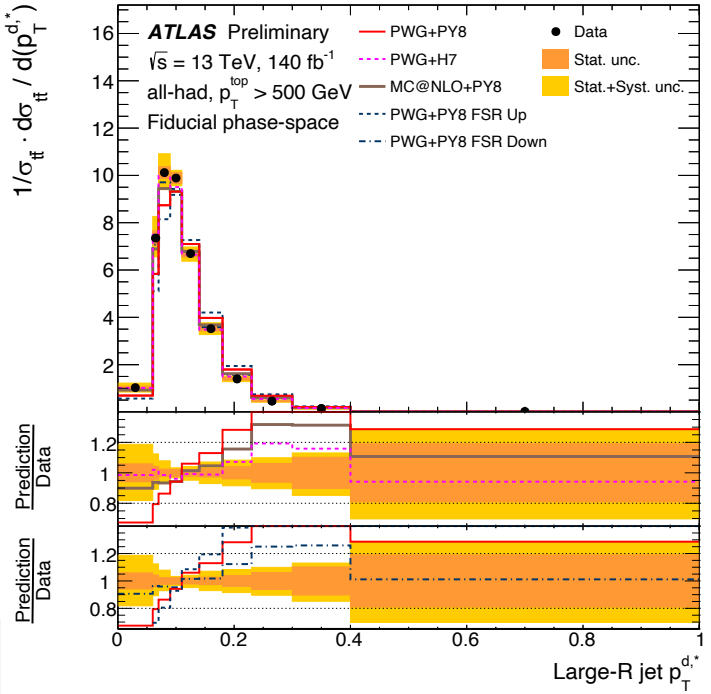
All-Hadronic Channel:

- Zero leptons
- Hadronically-decaying top reconstructed as large-R jet
  - two large-R jets
  - $122.4 < m_{jet} < 222.5$ GeV
  - (sub)Leading jet pT > (350) 500 GeV
- Required b-matching on the measured jets to suppress multijet.
- DNN top-tag on the non-probe large-R jet









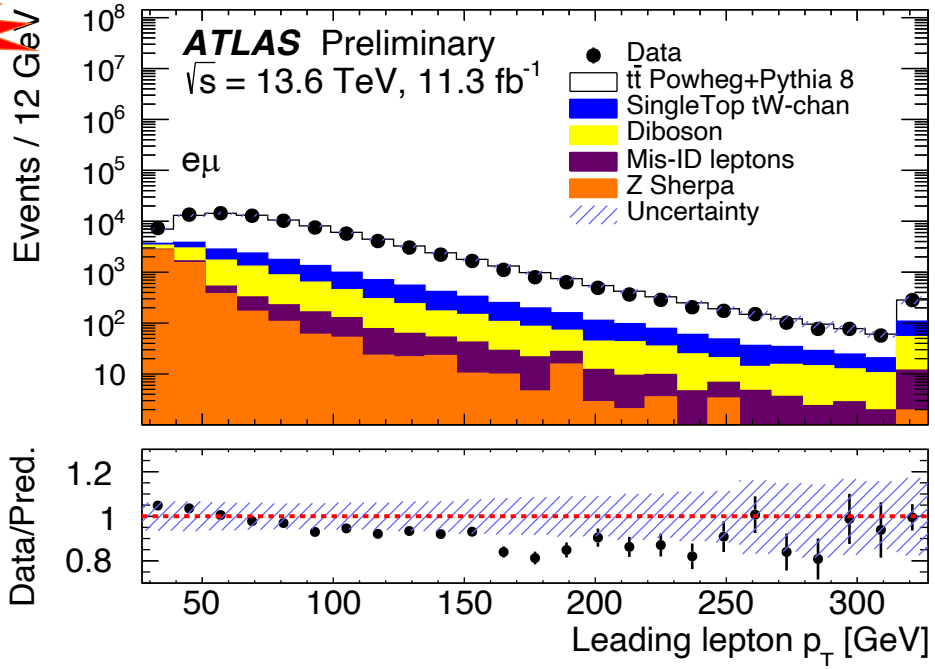
$t\bar{t}$ cross-section in $e\mu$ events at $\sqrt{s} = 13.6$ TeV

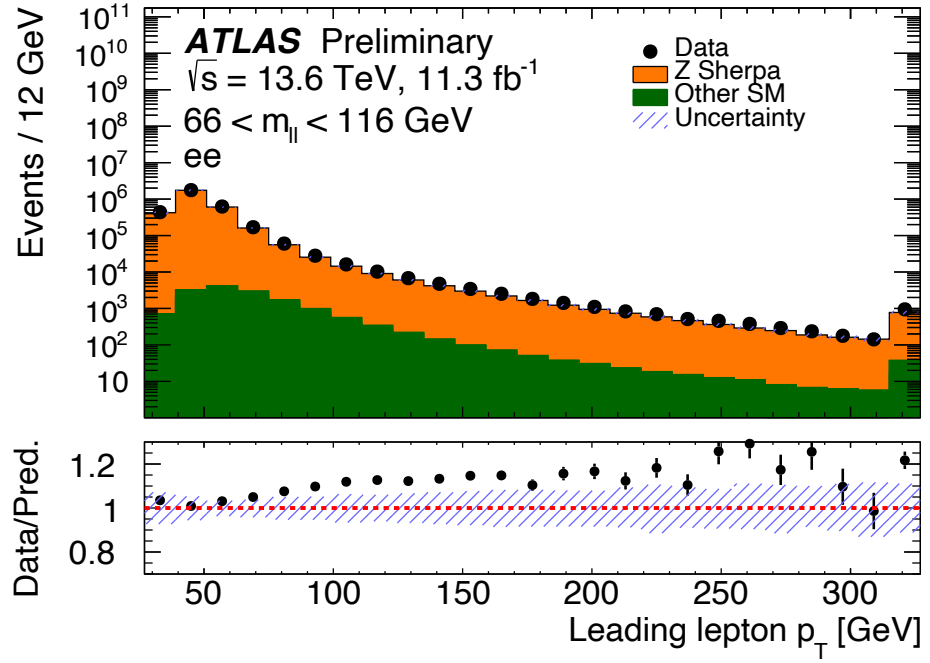
New

ATLAS-CONF-2023-006

- Various quick measurements have been carried out after the successful start of Run3 in 2022 with pp collisions at 13.6 TeV
  - To validate and test several well-known processes (those precisely measured in **Run1** and **Run2**) predicted by the Standard Model, for example, top quark pair production, Higgs production in the $\gamma\gamma$ decay channel ..etc.
  - Verify the **detector** and **reconstruction** performance for all physics objects (e, μ, γ, jets)

- Simultaneous measurement of inclusive $\sigma_{t\bar{t}}$ in $e\mu$ and $\sigma^{fid}_{Z\to ll}$ in ee&$\mu\mu$, also Ratio R $= \sigma_{t\bar{t}}/\sigma^{fid}_{Z\to ll}$ using data collected at 13.6 TeV with integrated $\mathcal{L} = 11.3\ fb^{-1}$
  - MC, detector + software validation
  - In ratio R:
    - Reduction of uncertainties, Luminosity uncertainty cancelled (+ partially lepton-related systematics)
    - Sensitive to the gluon/quark PDFs.





$t\bar{t}$ cross-section in $e\mu$ events at $\sqrt{s} = 13.6$ TeV

New

ATLAS-CONF-2023-006

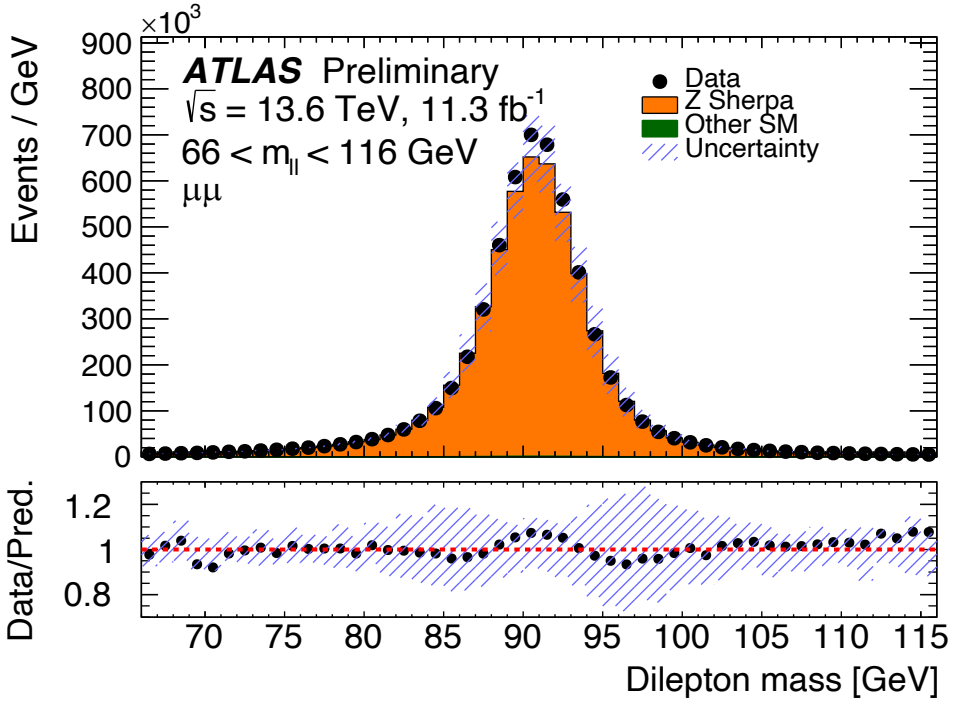
- Simultaneous measurement of inclusive $\sigma_{t\bar{t}}$ in $e\mu$ and σ_Z in ee&$\mu\mu$, also Ratio R $= \sigma_{t\bar{t}}/\sigma_Z$ using data collected at 13.6 TeV with integrated $\mathcal{L}$ $= 11.3\ fb^{-1}$
- b-tag counting method was used to measure $\sigma_{t\bar{t}}$ in $e\mu$
- Dominated systematics:
  - Luminosity (2.3%)
  - Lepton reco. (1.8%)
  - $t\bar{t}$ PS&had (1.1%)
  - Pile-up (1.1%)

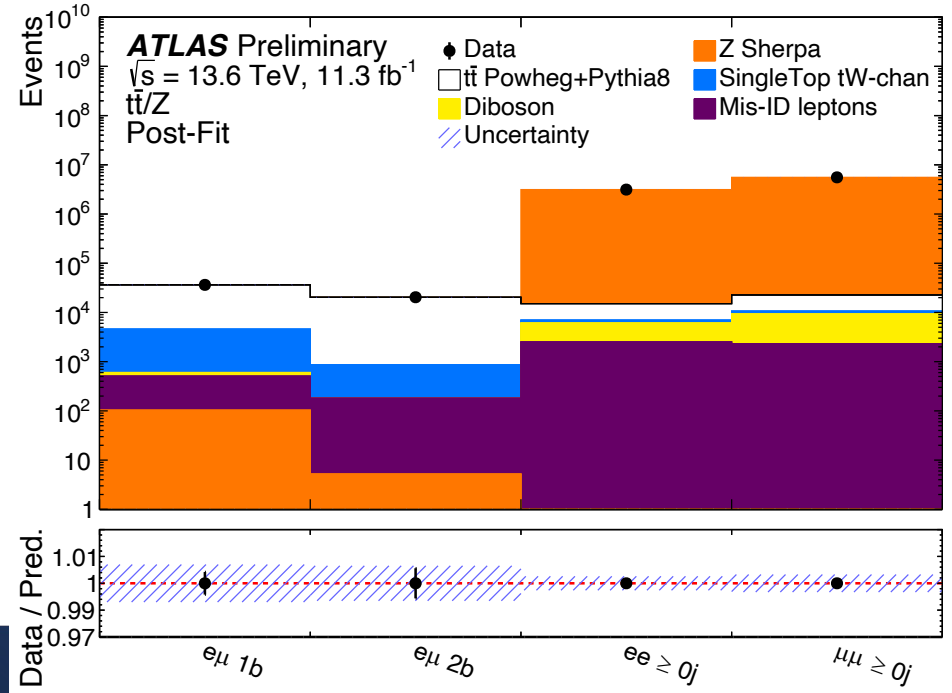
$$\sigma_{t\bar{t}} = 859 \pm 4(stat) \pm 22(syst) \pm 19(Lumi)\ pb\ [3.5\%]$$
$$\sigma^{fid}_{Z\to ll} = 751 \pm 0.3(stat) \pm 15(syst) \pm 17(Lumi)\ pb$$
$$R_{t\bar{t}/Z\to ll} = 1.144 \pm 0.006(stat) \pm 0.004(syst) \pm 0.001(Lumi)$$

Theory predictions

$$\sigma_{t\bar{t}} = 923.6\ (scale)^{+22.6}_{-33.4}(PDF + \alpha_s)^{+22.8}_{-22.8}(mTop)^{+24.6}_{-25.4} pb$$
$$\sigma^{fid,Theory}_{Z\to ll} = 741 \pm 15(scale + PDF) pb$$
$$R_{t\bar{t}/Z\to ll} = 1.245 \pm 0.076(scale + PDF)$$

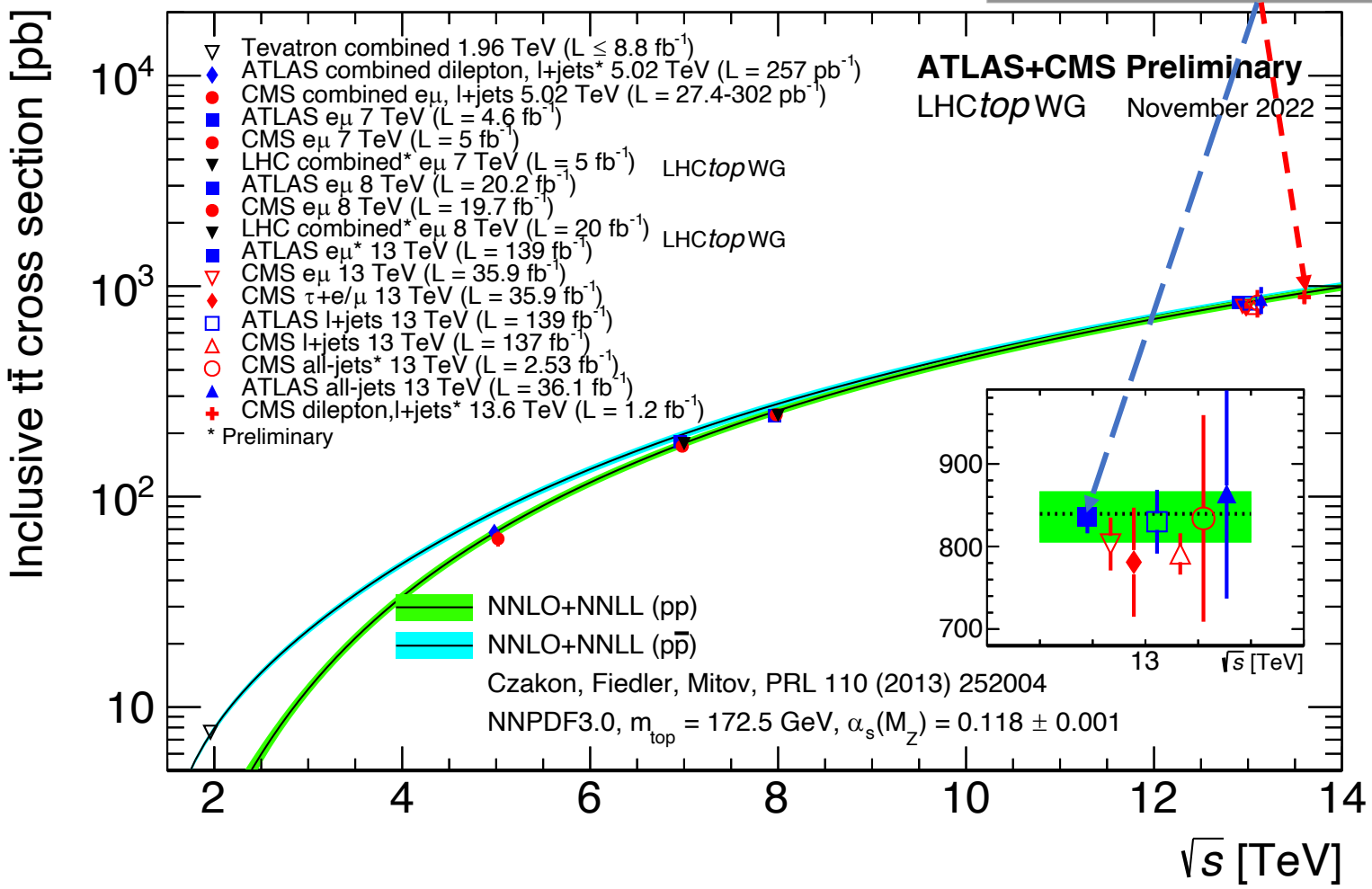
Ref

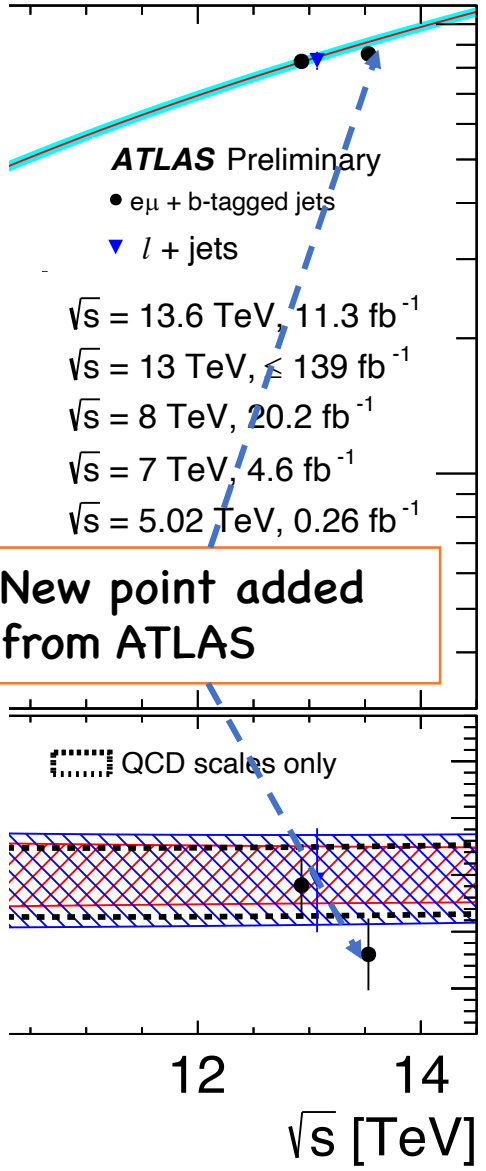




$t\bar{t}$ cross-section summary

Points from ATLAS and CMS have been updated





New point added from ATLAS

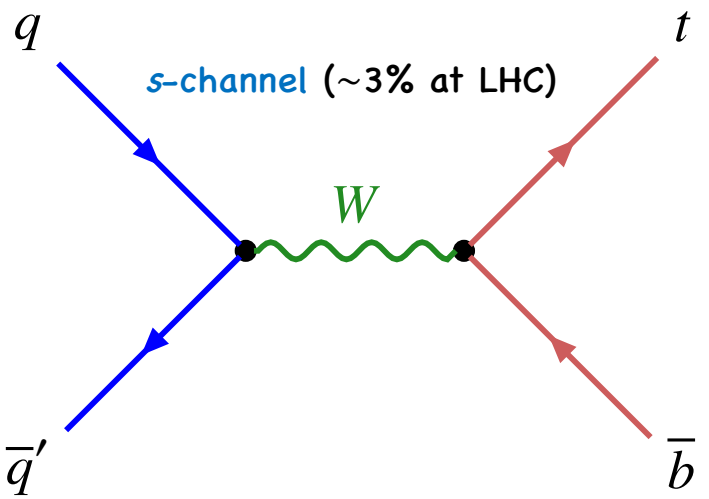
LHCTopWG Summary Plots

Evidence of S-Channel single-top production at $\sqrt{s} = 13$ TeV

New

arXiv:2209.08990

- Using **data collected** at 13 TeV with integrated $\mathcal{L} = 139\ fb^{-1}$ on events with:
  - Electron or Muon
  - Missing transverse momentum (MET)
  - **Exactly** two b-tagged jets
    - One b-hadron originating from the decay of the top quark
    - Another one comes from the Wtb **vertex** producing the top quark.
- **Matrix-element-method** (MEM) is used to derive the signal probability per event from the theoretical calculations. This technique was used in $p\bar{p}$ at the Tevatron.

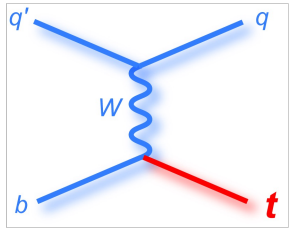


S-Ch NLO Theory predictions

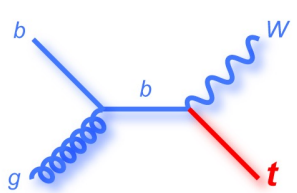
$$\sigma_{\bar{t}} = 3.97\ (scale)^{+0.11}_{-0.09}(PDF + \alpha_s)^{+0.15}_{-0.15}(mTop)^{-0.09}_{+0.09}\ pb$$
$$\sigma_{t} = 6.35\ (scale)^{+0.18}_{-0.15}(PDF + \alpha_s)^{+0.14}_{-0.14}(mTop)^{-0.07}_{+0.07}\ pb$$
$$\sigma_{t+\bar{t}} = 10.32\ (scale)^{+0.29}_{-0.24}(PDF + \alpha_s)^{+0.27}_{-0.27}(mTop)^{-0.23}_{+0.22}\ pb$$

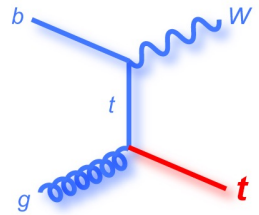
singleTop_NLO_XSecRef singleTop_NNLO_XSecRef

t-channel (~73% at LHC)



Wt-channel (~24% at LHC)





Evidence of S-Channel single-top production at $\sqrt{s} = 13$ TeV

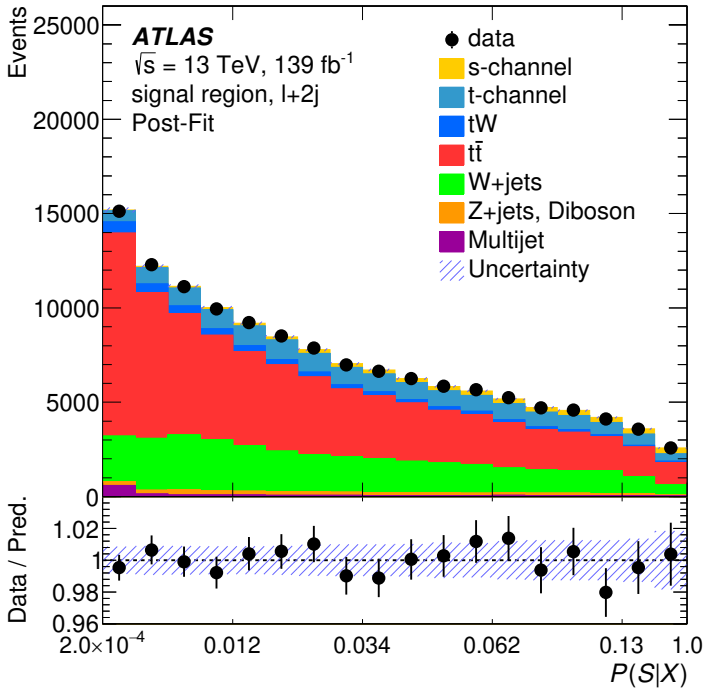
New

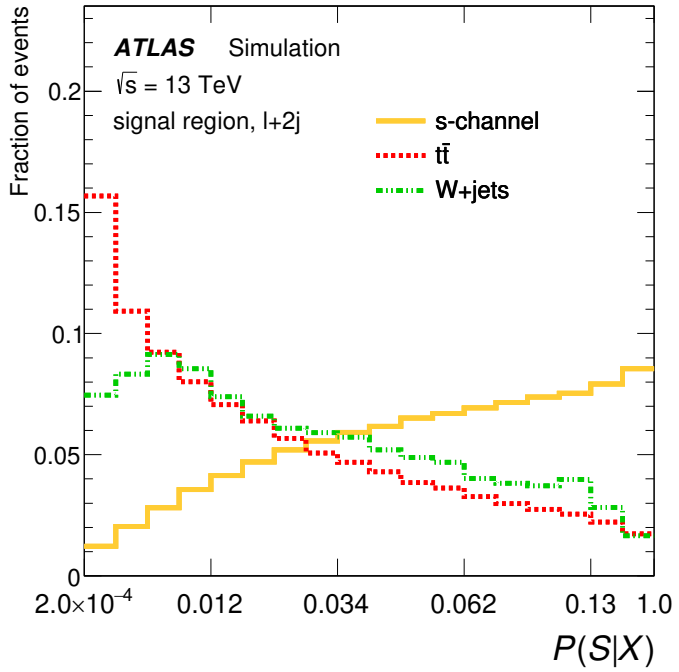
arXiv:2209.08990

- **Signal Region** (SR):
  - two b-tagged jets with pT > 30GeV and at **least one** with pT > 40GeV
  - **Veto** on events with an additional lepton with 10 < pT < 30 GeV "to reduce top-quark pair decaying into dilep"
  - W-boson transverse mass (m_T^W) > 30 GeV "to reduce multijet"
- Three Control Regions (CRs):
  - W+jets: Exactly two b-jets (one loose and one tight) with pT > 30GeV
  - $t\bar{t} \rightarrow 2\mathrm{lep}$: Exactly three or four jets, of which at least two are b-tagged jets.
- Dominated **systematics**:
  - $t\bar{t}$ norm. (24%)
  - $t\bar{t}$ and s-channel single top Modelling uncer. (18%)
  - Jet energy resolution (JER) and Jet energy scale (JES)
- Observed (Expected) signal significance over B-Only hypothesis: 3.3(3.9) Standard deviations.

$$\sigma_{s-ch} = 8.2 \pm 0.6(stat)^{+3.4}_{-2.8}(syst) = 8.2^{+3.5}_{-2.9}\, pb$$

Theory (NLO): $\sigma_{t+\bar{t}} = 10.32\ (scale)^{+0.29}_{-0.24}(PDF + \alpha_s)^{+0.27}_{-0.27}(mTop)^{+0.23}_{-0.22} pb$





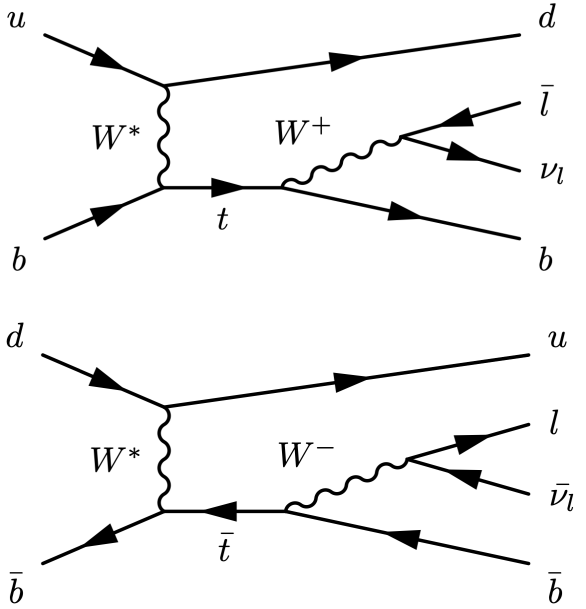
Measurement of t-Channel single-top production at $\sqrt{s} = 13$ TeV

New

ATLAS-CONF-2023-026

- Measurement of σ_{tq}, $\sigma_{\bar{t}q}$, $\sigma_{t+\bar{t}}$ and the $R_t = \sigma_{tq}/\sigma_{\bar{t}q}$ using **data collected** at 13 TeV with integrated $\mathcal{L} = 140\ fb^{-1}$ on events with:
  - Electron or Muon
  - High Missing transverse momentum (MET)
  - **Exactly** two jets with high pT
    - One b-hadron originating from the decay of the top quark
    - Another jet produced in the forward direction, high pseudorapidity (η).
- **Separete** measurements of tq and $\bar{t}q$ production prodvide sensitivity to the PDFs of u- and d-quarks.
- Ratio R_t gives better precision since common uncer. will be partially canceled.
- **Artificial Neural Network (NN),** which is implemented using the NeuroBayes package, has been used to discriminate signal and background events
  - NN is trained using simulated events consisting of both positively and negatively charged leptons.

t-channel (~73% at LHC)



t-Ch NNLO Theory predictions

$$\sigma_{\bar{t}} = 80.0\ (scale)^{+0.80}_{-0.80}(PDF + \alpha_s)^{+1.6}_{-1.2}(mTop)^{-0.7}_{+0.7} pb$$
$$\sigma_{t} = 134.2\ (scale)^{+1.5}_{-1.1}(PDF + \alpha_s)^{+2.1}_{-1.3}(mTop)^{-1.2}_{+1.0}\ pb$$
$$\sigma_{t+\bar{t}} = 214.2 (scale)^{+2.4}_{-1.7}(PDF + \alpha_s)^{+3.3}_{-2.0}(mTop)^{-1.9}_{+1.7} pb$$

singleTop_NLO_XSec_Ref singleTop_NNLO_XSec_Ref

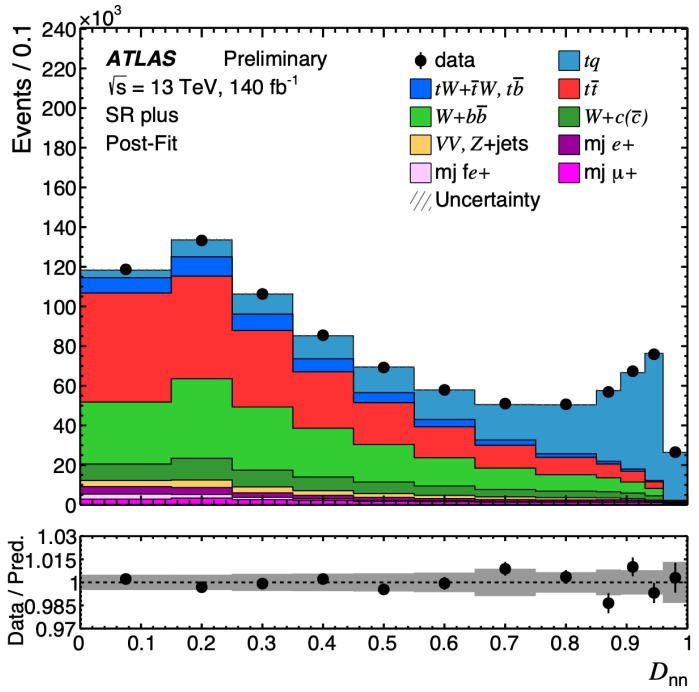
Measurement of t-Channel single-top production at $\sqrt{s} = 13$ TeV

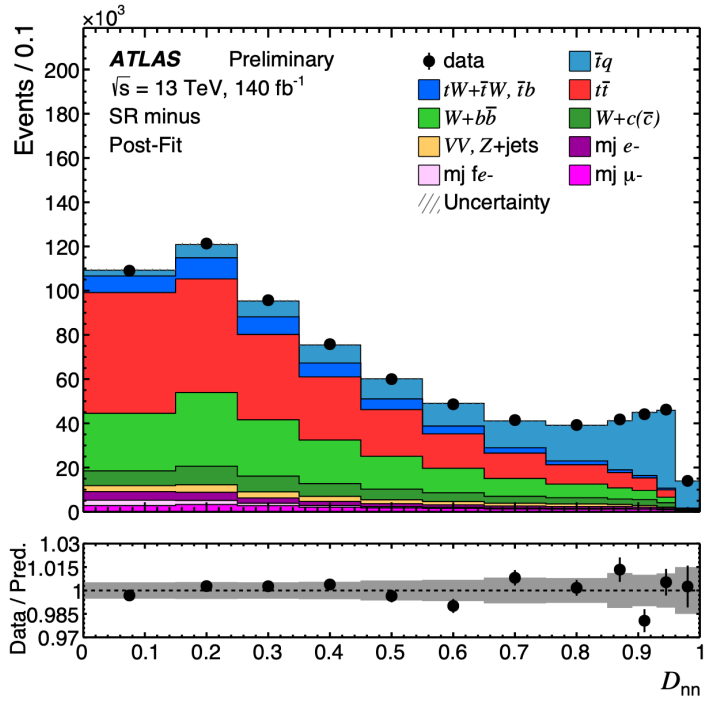
New

ATLAS-CONF-2023-026

- **Two Signal Regions** (SR):
  - Based on the Lepton charge and with pT > 28GeV.
  - Two jets "one of them should be b-jet" with pT > 30GeV and at $|\eta| < 4.5$
  - **Veto** on events with an additional lepton with pT > 10GeV "to reduce top-quark pair decaying into dilep", while m_T^W > 50 GeV and E_T^{miss} > 30GeV "to reduce multijet"
- Dominated **systematics**:
  - tq modelling (Scale, PDF, FSR)
  - Jet energy resolution (JER) and b-tagging NP
  - Background modelling uncer.

$$\sigma_{tq} = 137 \pm 8\, pb, \sigma_{\bar{t}q} = 84^{+6}_{-5}\, pb$$
$$\sigma_{tq+\bar{t}q} = 221 \pm 13\, pb, R_t = 1.636^{+0.036}_{-0.034} pb$$





New

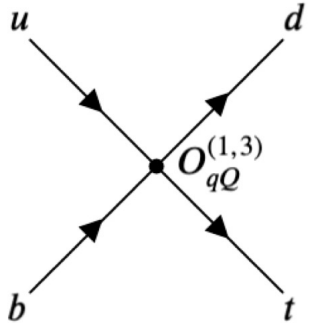
ATLAS-CONF-2023-026

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

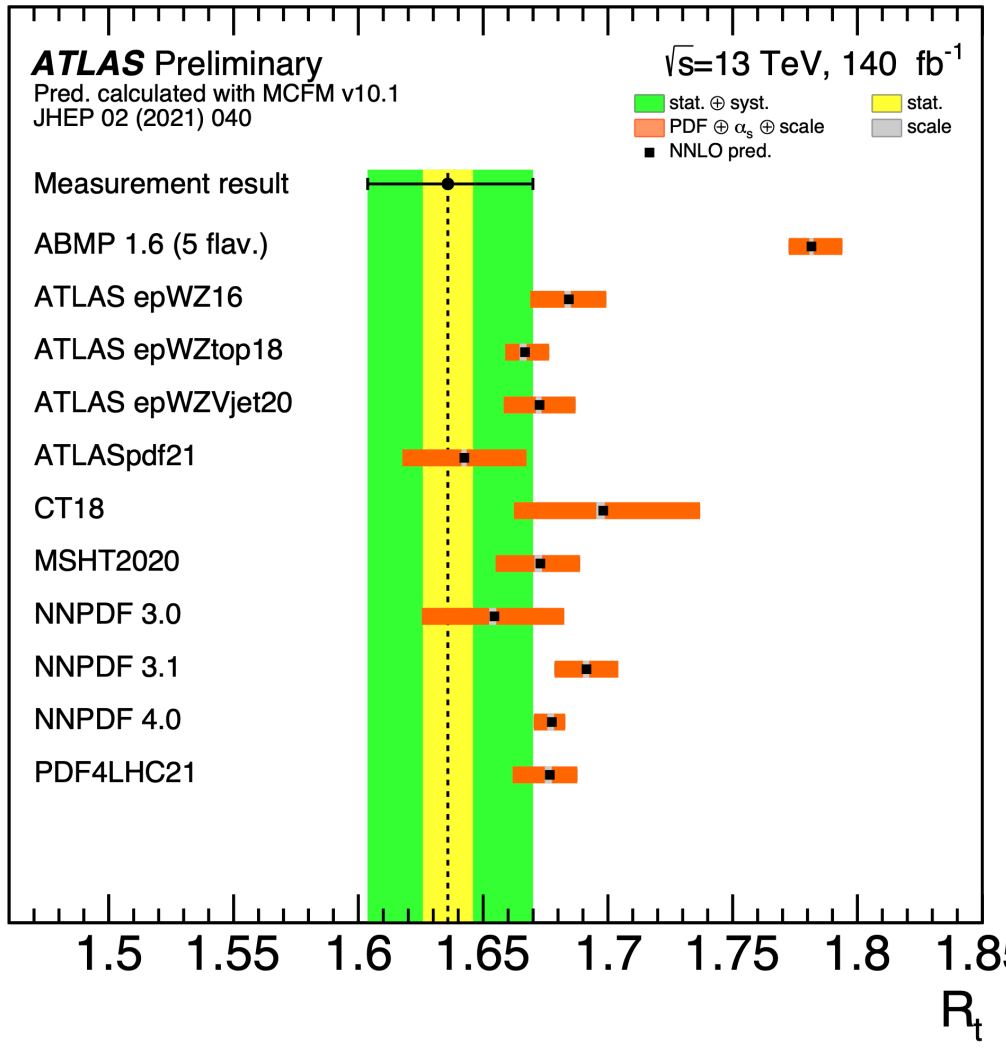
- tq production measurements are interpreted in different ways:
  - R_t is compared to predictions obtained with different PDF sets.
  - Using the DNN output in the SRs, a search for a contribution of a four-quark EFT operator to tq production is performed.

With CL %95: $-0.24 < C_{qQ}^{(1,3)} < 0.14$

$$O_{qQ}^{(1,3)} = (\bar{q}^i \gamma_\mu \tau^I q^j)(\bar{Q} \gamma^\mu \tau^I Q)$$



$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{C_i}{\Lambda^2} O_i + \text{H.c.}$$



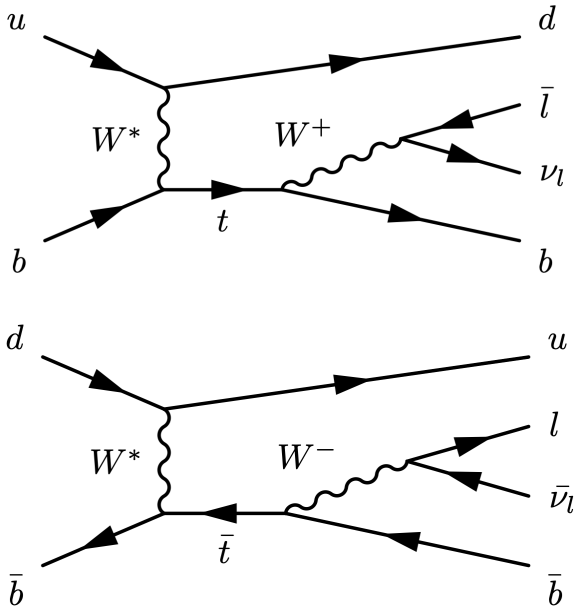
observation of t-Channel single-top production at $\sqrt{s} = 5.02$ TeV

New

ATLAS-CONF-2023-033

- Measurement of inclusive $\sigma_{t+\bar{t}}$ and the $R_t = \sigma_{tq}/\sigma_{\bar{t}q}$ using $257\,pb^{-1}$ pp collision **collected** at 5.02 TeV on events with:
  - Electron or Muon
  - m_T^W > 35 GeV, E_T^{miss} > 15 GeV and $m_T^W + E_T^{miss}$ > 70 GeV "to reduce Fake lep" to supress Fake leptons
  - **Exactly** two jets
    - One b-hadron originating from the decay of the top quark
    - Another jet produced in the forward direction, high pseudorapidity (η).
  - To increase signal purity, $H_T = \sum pT$ of jets, lep, and MET, > 185 GeV
- **Boosted decision trees** (BDTs) has been used to enhance signal and background separation
  - BDT response distribution is used in a binned profile-likelihood fit.
  - The $\sigma_{t+\bar{t}}$ and R_t are determined by a simultaneous fit to the BDT score in l^++jets and l^-+jets

t-channel (~73% at LHC)



t-Ch NNLO Theory predictions

$$\sigma_{\bar{t}} = 10.0\ (scale)^{+0.1}_{-0.1}(PDF + \alpha_s)^{+0.3}_{-0.2}(mTop)^{-0.1}_{+0.3}\ pb$$
$$\sigma_{t} = 20.3\ (scale)^{+0.3}_{-0.2}(PDF + \alpha_s)^{+0.4}_{-0.3}(mTop)^{-0.1}_{+0.2}\ pb$$
$$\sigma_{t+\bar{t}} = 30.3(scale)^{+0.4}_{-0.3}(PDF + \alpha_s)^{+0.6}_{-0.4}(mTop)^{-0.2}_{+0.3}\ pb$$

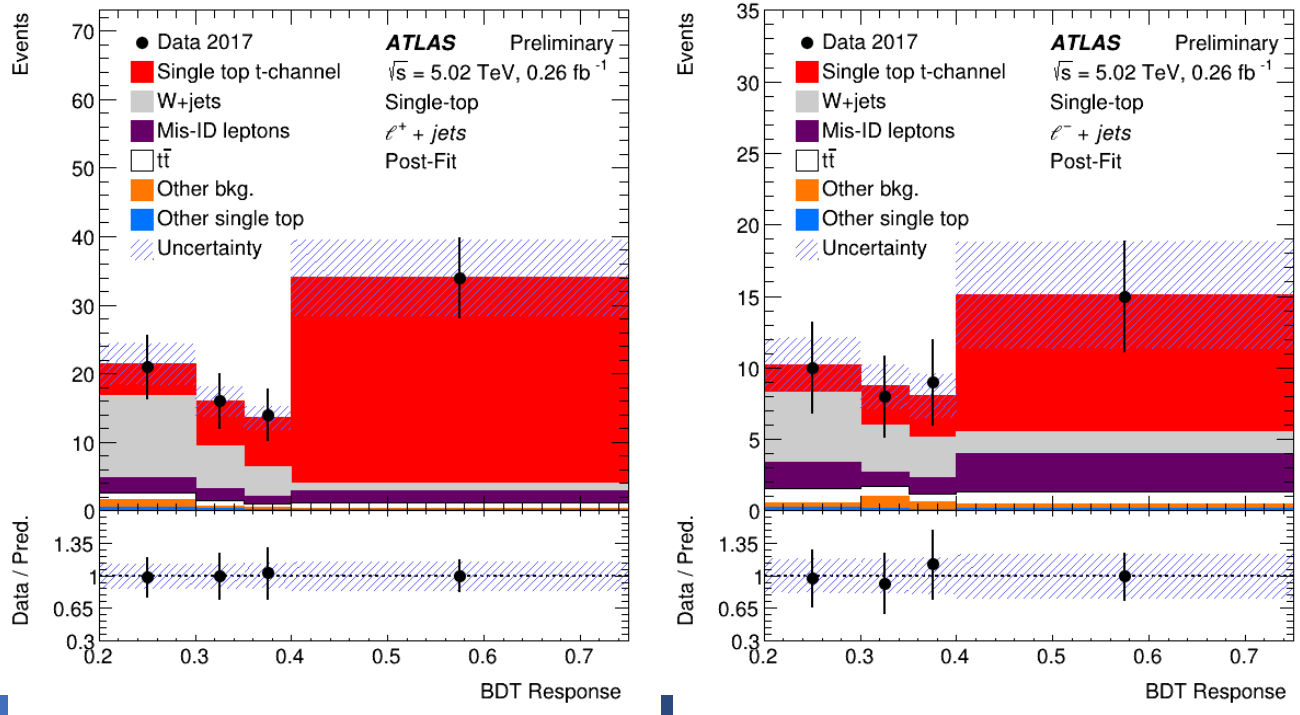
observation of t-Channel single-top production at $\sqrt{s} = 5.02$ TeV

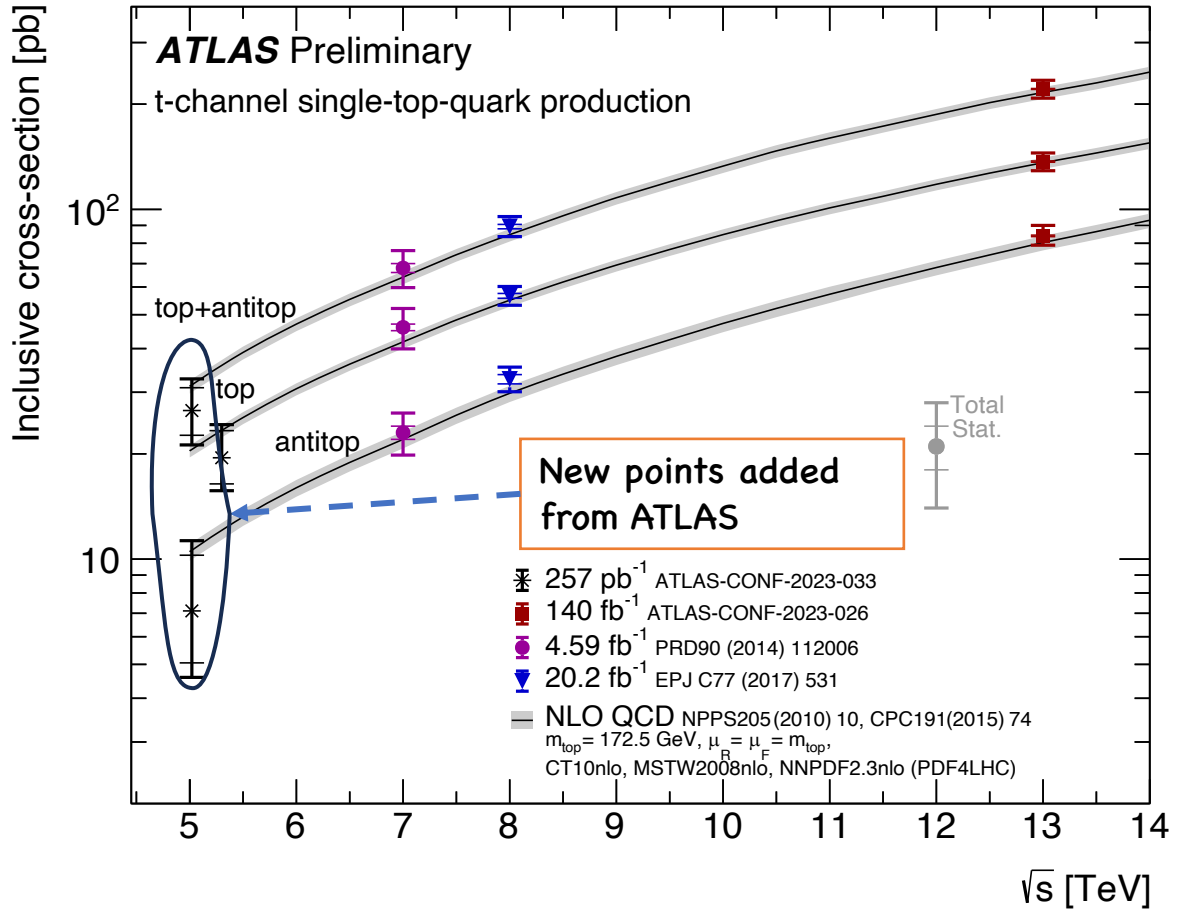
New

ATLAS-CONF-2023-033

- Dominated **systematics:**
  - tq modelling (Scale, PDF, FSR)
  - Mis-ID Leptons
  - Jet energy resolution (JER) and Jet energy scale (JES)
  - Background modelling uncer.
- Observed signal significance over B-Only hypothesis: 6.1

Standard deviations.





$\sigma_{tq} = 19.5^{+3.8}_{-3.1}(stat)^{+2.9}_{-2.2}(syst)pb, \sigma_{\bar{t}q} = 7.1^{+3.2}_{-2.1}(stat)^{+2.8}_{-1.5}(syst)pb$

$\sigma_{tq+\bar{t}q} = 26.6^{+4.4}_{-4.0}(stat)^{+4.4}_{-3.6}(syst)pb, R_t = 2.74^{+1.44}_{-0.83}(stat)^{+1.04}_{-0.29}(syst)\ pb$

Conclusions

- Top-quark pair and single-top production **measurements** in **ATLAS** are reaching **unprecedented** performance.
  - More and more precise measurements have been achieved by using advanced analysis and statistical methods
  - Most measurements **agree** with the SM prediction within modeling and detector uncertainties… until now …
- Analysis of the **Full Run 2** dataset is not yet finished
- Observation or evidence of several rare top quarks processes using **Full Run 2 data**
- First **Run 3** measurements:
  - Top-quark pair production at $\sqrt{s}$ = 13.6 TeV; This is essential to validate the functionality of the detector, the new object recommendations ..etc

- **More public information** and results can be found: ATLAS Top Public Results, CMS Top Public Results, LHC Top WG