Top quark physics with the ATLAS experiment at the LHC

Marino Romano
(INFN – Bologna)
On behalf of the ATLAS Collaboration

DISCRETE2022
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Top quark ID card

Name: Top quark

Discovery: Tevatron, 1995
(CDF, PRL 74 p. 2626 and
D0, PRL 74 p. 2422)

Mass: 173.34 ± 0.76 GeV
(Tevatron – LHC combination
arXiv:1403.4427)

Charge: +2/3e

Generation: Third

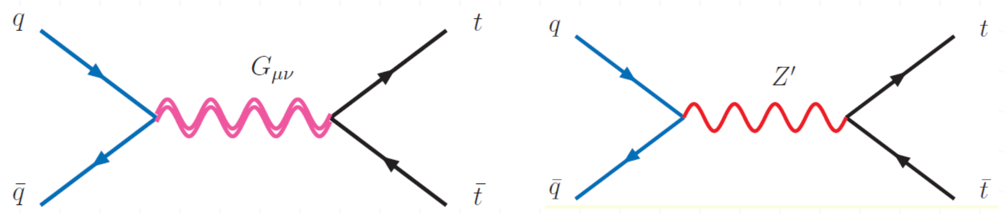
Decays: Wb (~100%)

Why top quark physics?

- Most massive known fundamental particle
  - Large Yukawa coupling: $Y_t > 0.9$
  - Production time < Lifetime < Hadronization time < Spin decorrelation time:

$$\frac{1}{m_t} < \frac{1}{\Gamma_t} < \frac{1}{\Lambda_{\text{QCD}}} < \frac{m_t}{\Lambda^2_{\text{QCD}}}$$

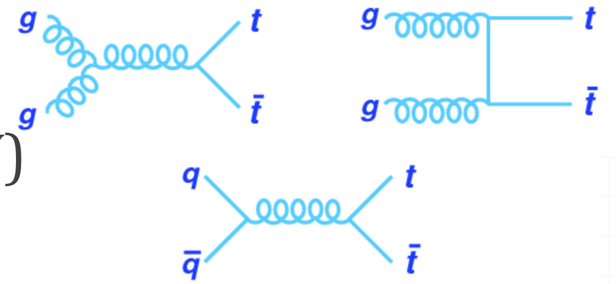
  unique opportunity to study a “bare” quark
- Production and decay rates are strong tests for SM predictions
- Background to Higgs and new physics (SUSY,...)
- (In)Direct coupling to new physics in many scenarios



Top quark pair production and decays

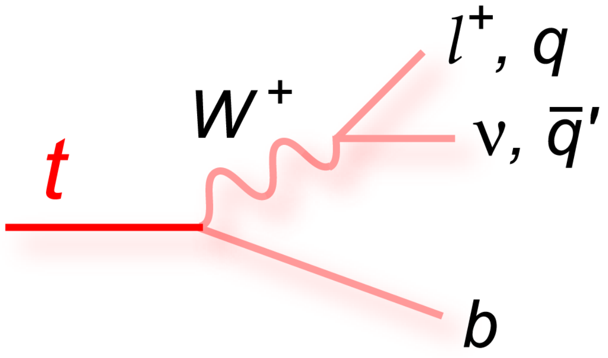
Pair production mechanisms at LHC

- Gluon-gluon fusion (>90% @ 13 TeV)
- Quark-antiquark annihilation



Decays

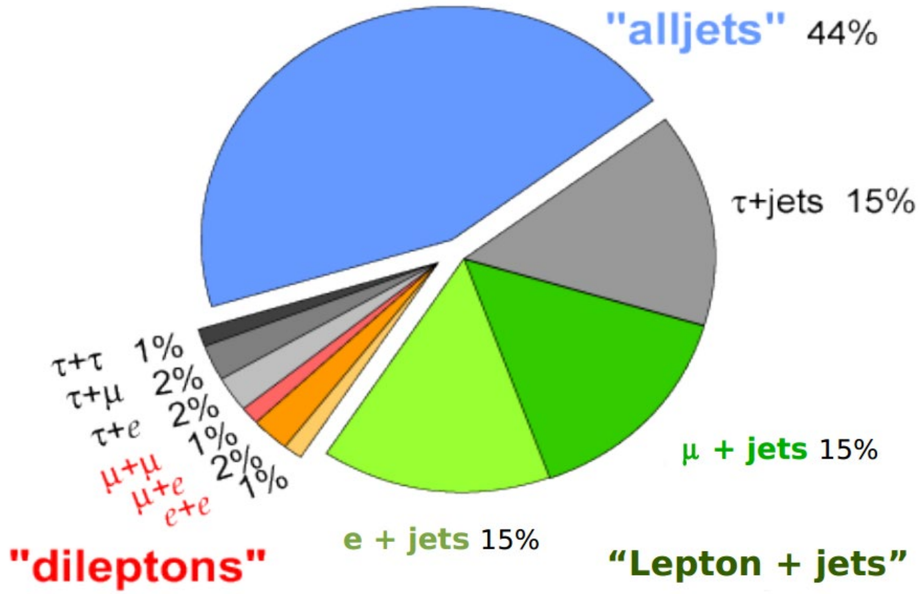
- $t \to Wb(\sim 100\%)$



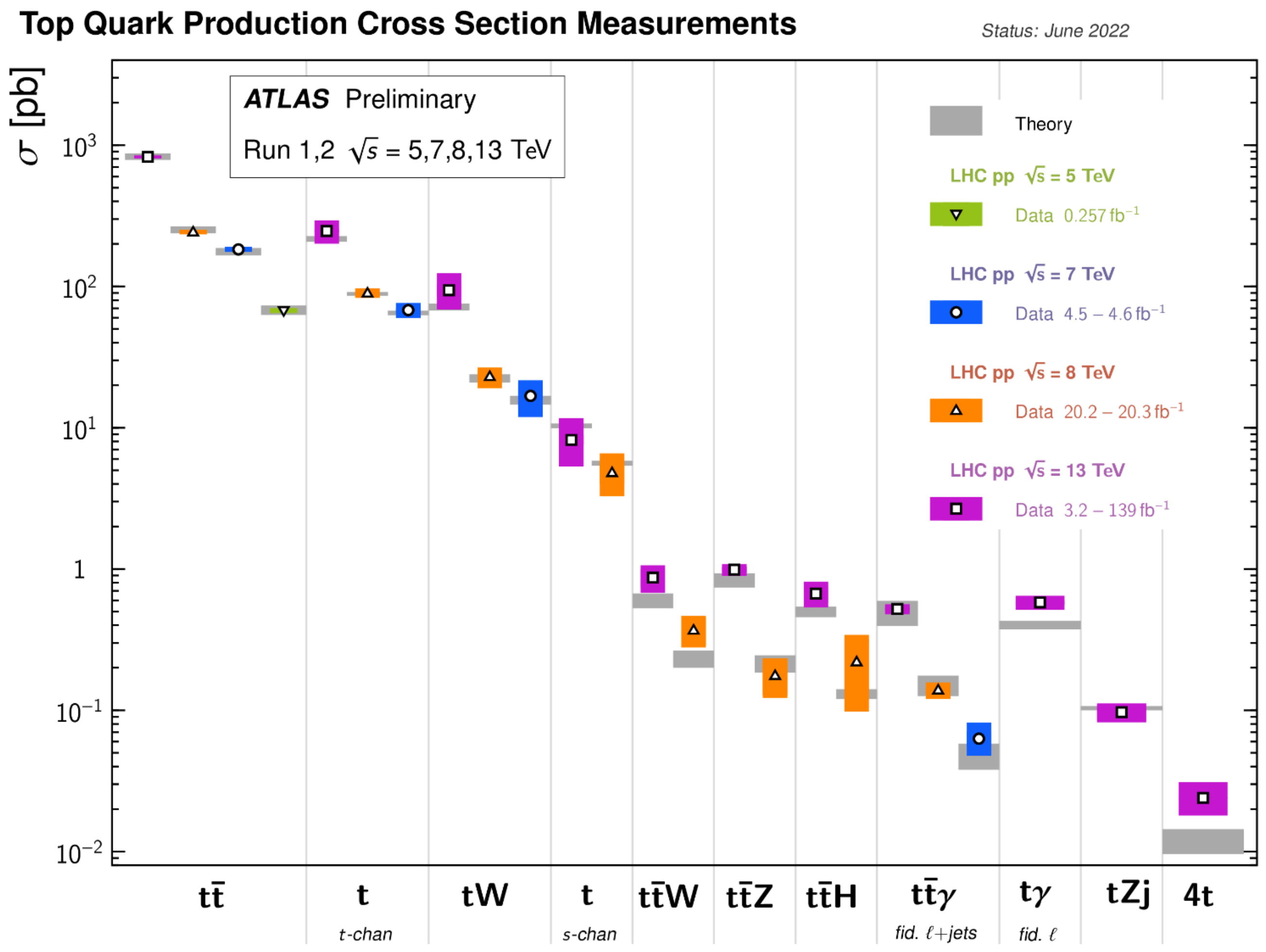
$W \to l\nu_l \sim 33\%$

$W \to q\overline{q}' \sim 66\%$

Top pair final states



Top quark production (...not only in pairs!)

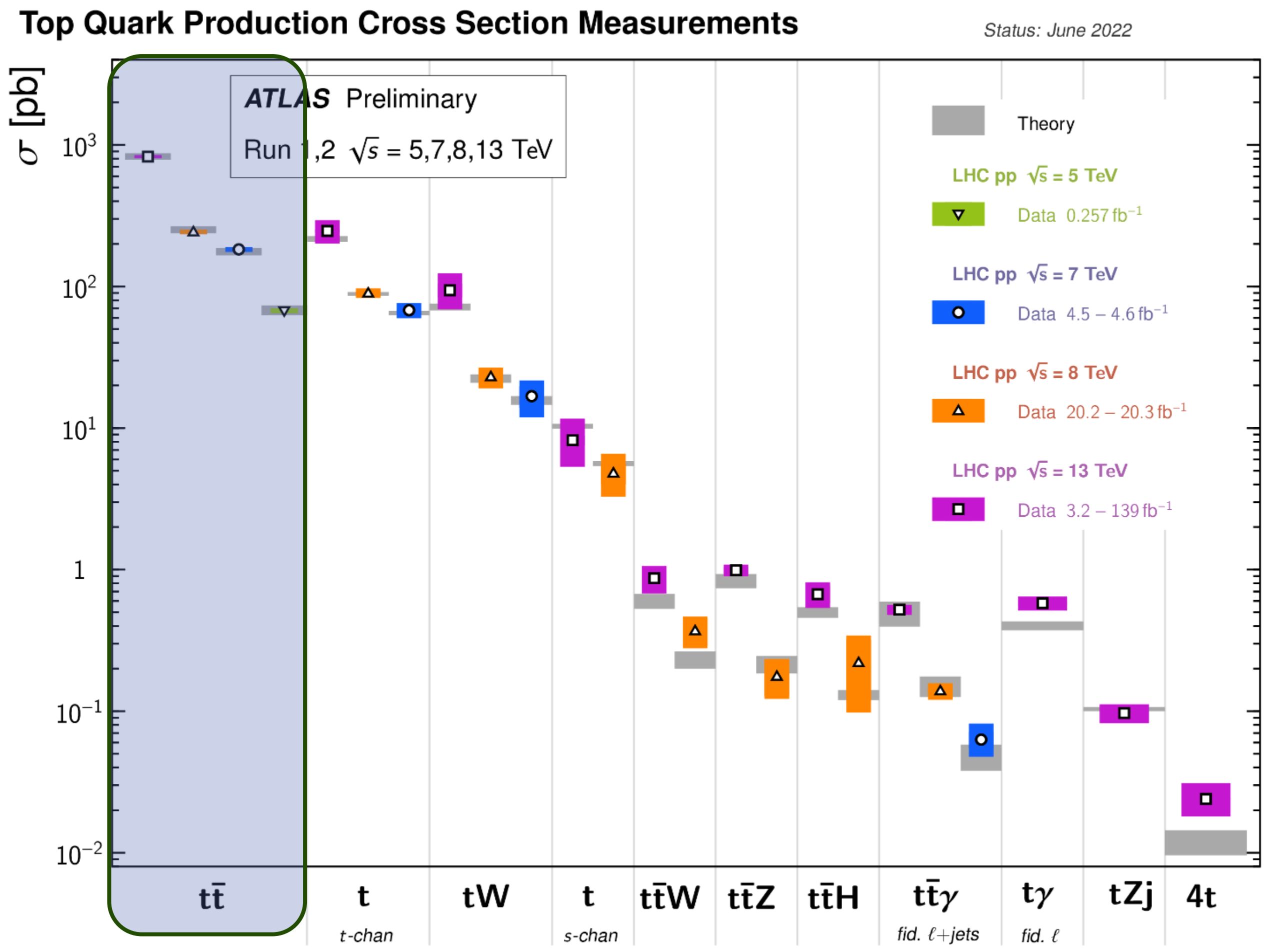


LHC is a ***top factory***

Top quarks can be measured in a wide range of production modes

This talk will focus on a selection of recent results

Top pair production



Top pair inclusive cross section

arXiv:2207.01354 [hep-ex]

$\sqrt{s} = 5.02$ TeV, $L = 257$ pb^{-1}

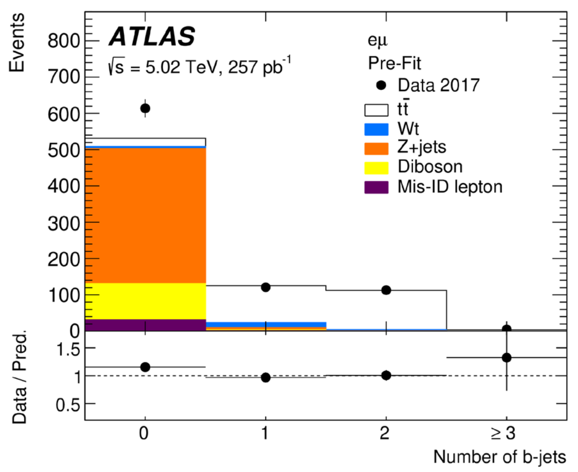
Lepton+jets, Dilepton

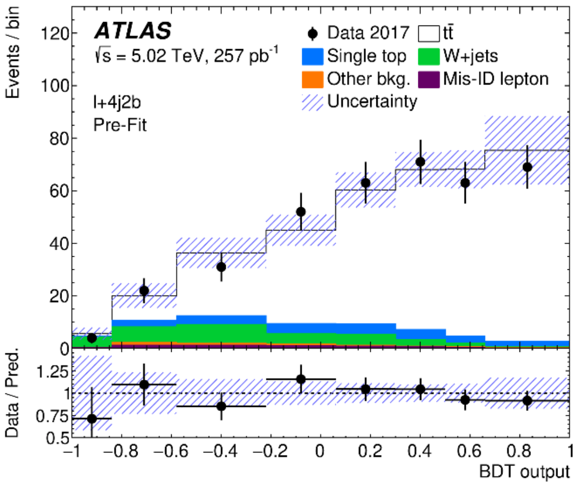
Challenging and *interesting* new measurement

- Lower production cross section (~1 order of magnitude wrt 13 TeV) + lower recorded integrated luminosity
- Possibility of new PDF constraints thanks to higher $q\bar{q}$ fraction wrt 13 TeV (and higher x required)

Cross section measured in the dilepton and lepton+jets channels

- Dilepton: *bjet counting method* (simultaneous fit of σ_{tt} and b-jet identification efficiency ε_b)
  - Stat. limited (~7%)
- L+jets: *profile likelihood fit* of BDT discriminants
  - Syst. limited ($t\bar{t}$ and V+jets modelling, b-tag, JES, lepton efficiency and scale)





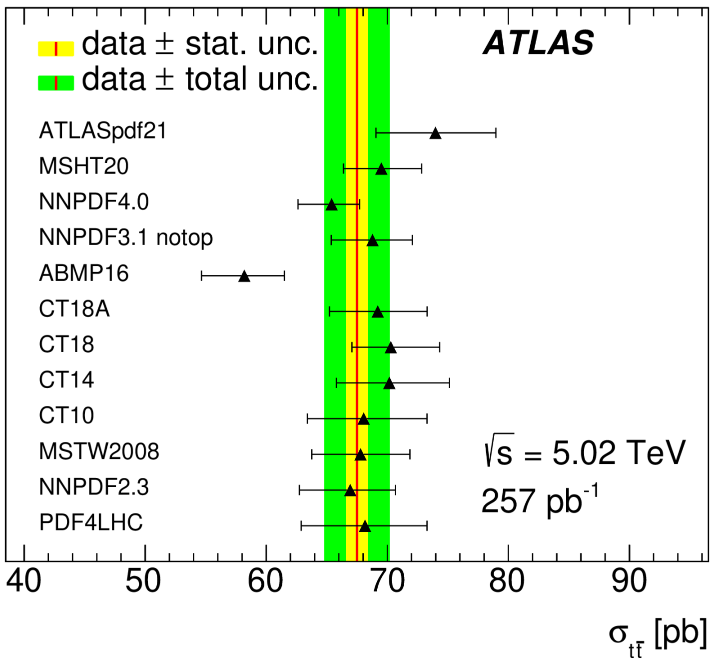
Top pair inclusive cross section

arXiv:2207.01354 [hep-ex]
$\sqrt{s} = 5.02$ TeV, $L = 257$ pb^{-1}
Lepton+jets, Dilepton

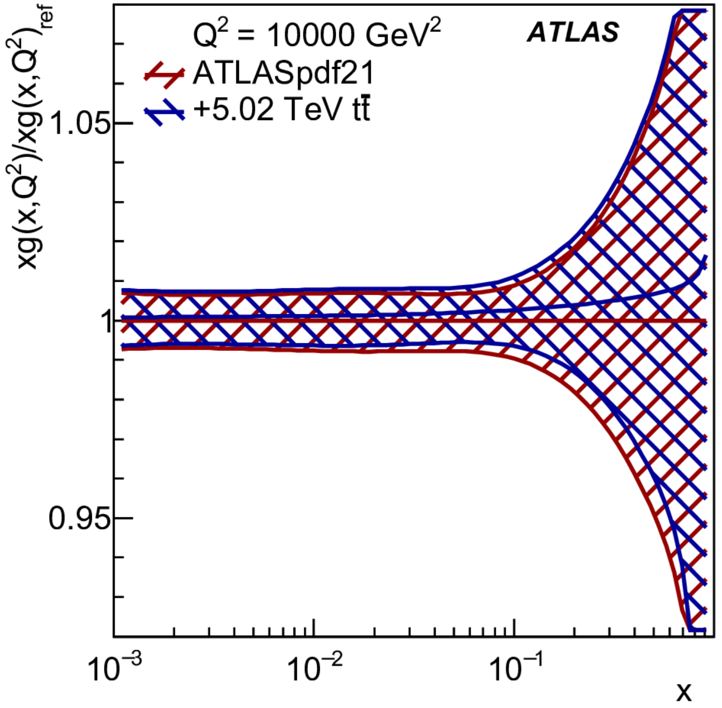
L+jets and dilepton channels combined using the Convino tool. Final uncertainty is 3.8%:

$$\boldsymbol{\sigma_{t\bar{t}} = 67.5 \pm 0.9(\text{stat.}) \pm 2.3(\text{syst.}) \pm 1.1(\text{lumi.}) \pm 0.2(\text{beam})\ \text{pb}}$$

In excellent agreement with the NNLO QCD prediction (Top++, $m_t = 172.5$ GeV): $\sigma_{t\bar{t}}^{th} = 68.2^{+5.2}_{-5.3}$ pb



The addition of this new measurement improves the precision of the fits for the gluon PDF of 5% at $x \sim 0.1$



Top pair differential cross section

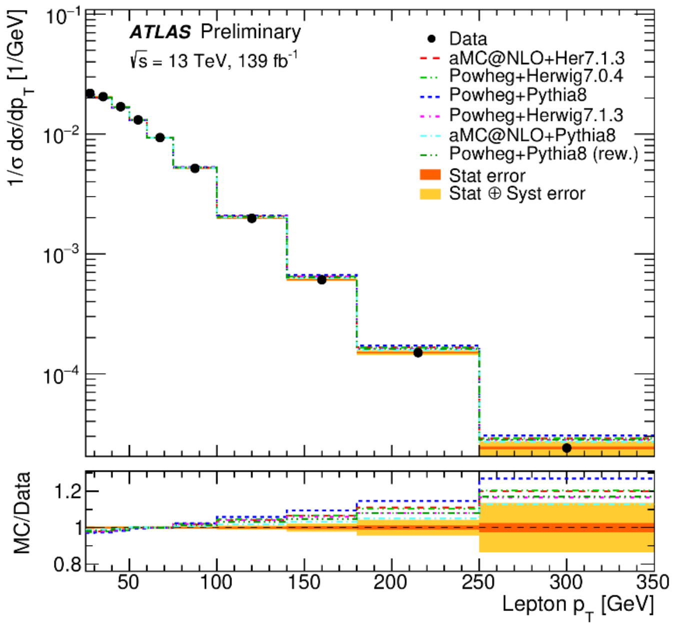
ATLAS-CONF-2022-061

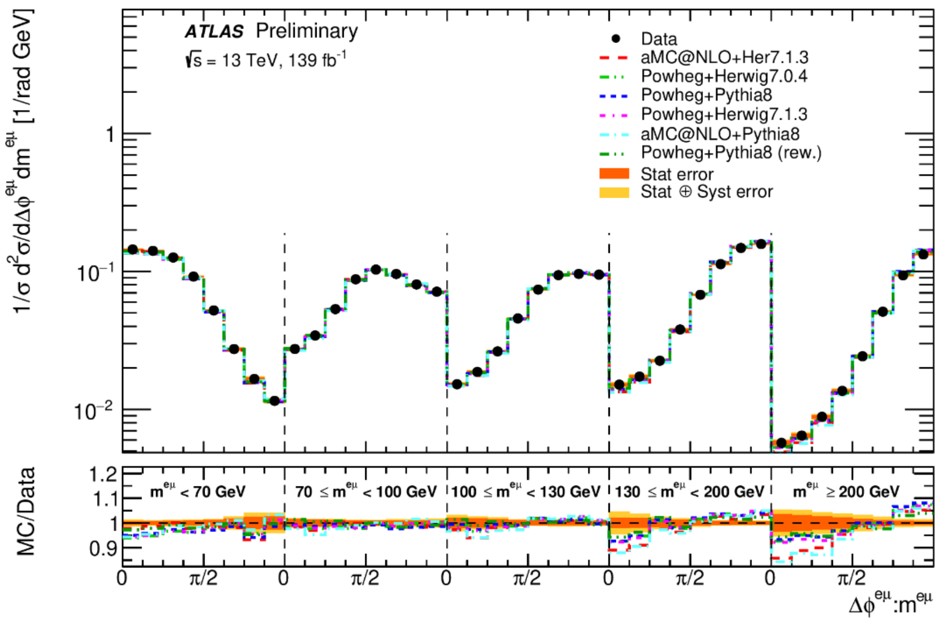
$\sqrt{s} = 13$ TeV, $L = 139$ fb^{-1}

Dilepton

Total $\sigma_{t\bar{t}}$ measurements show very good agreement with the SM, but new physics phenomena can still affect the shape of $\frac{d\sigma_{t\bar{t}}}{dX}$

- Single and double differential cross sections measured for 8 lepton kinematic variables in a fiducial phase space
- Analysis technique based on a generalization of the bjet counting technique
- Main uncertainties: luminosity, tW modelling (at high p_T^{lep})





Poor agreement to the data is observed for several MC generators

NLO MC generators predict harder p_T^{lep} spectrum

- Reweighing PWG+PY8 to reproduce the NNLO p_T^t prediction leads to a *general* better agreement with the data

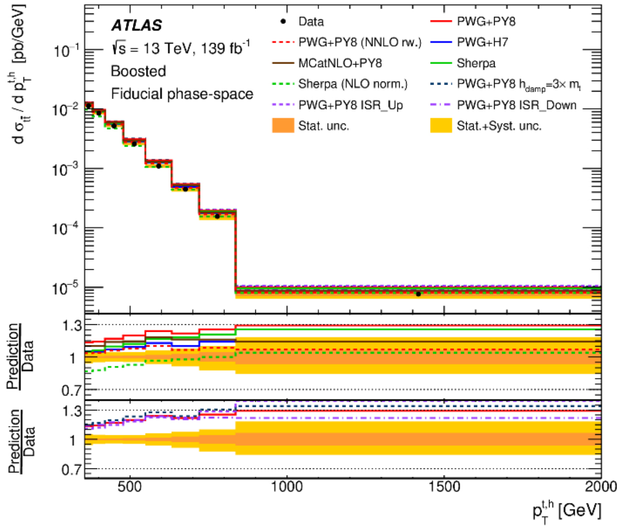
Boosted pair differential cross section

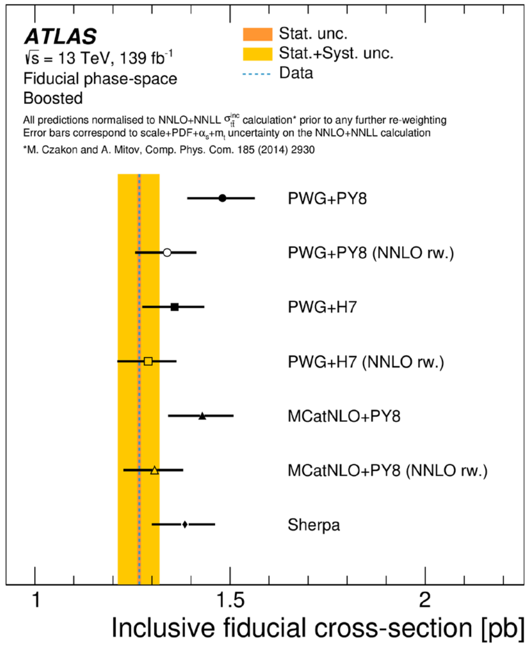
JHEP 06 (2022) 063

$\sqrt{s} = 13$ TeV, $L = 139$ fb^{-1}

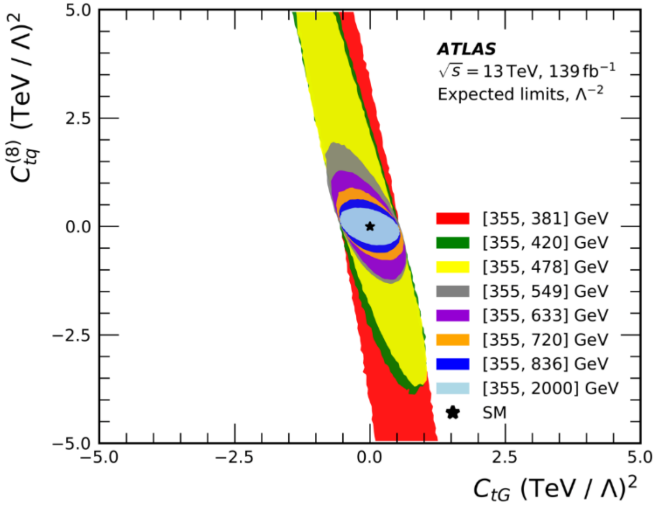
Lepton+jets

- Single and double-differential cross sections as a function of kinematic variables of the top quark and additional jets
- Boosted top quark identified using large-radius jets
- Main uncertainty: Signal modeling
  - JES uncertainty highly reduced via additional calibration using the top quark mass

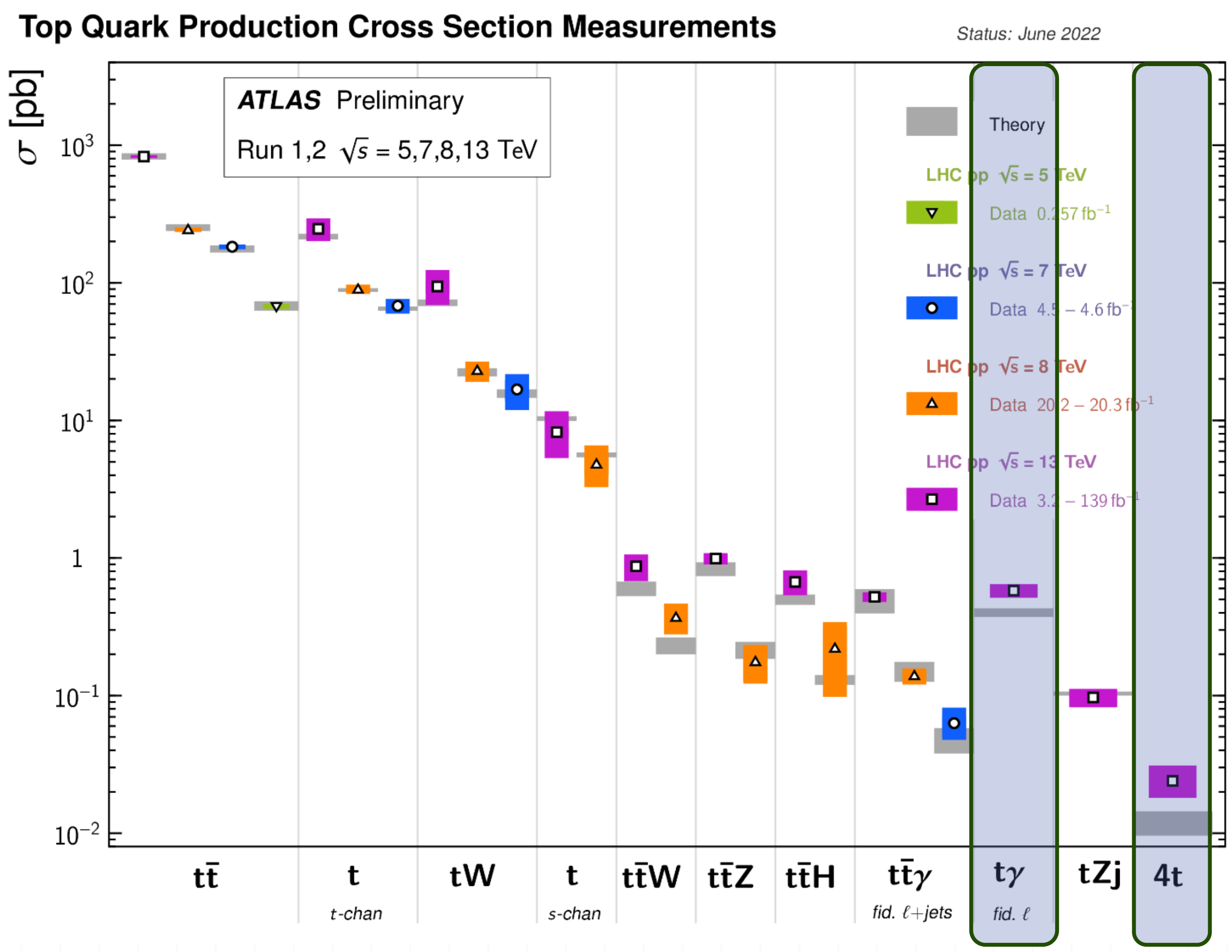


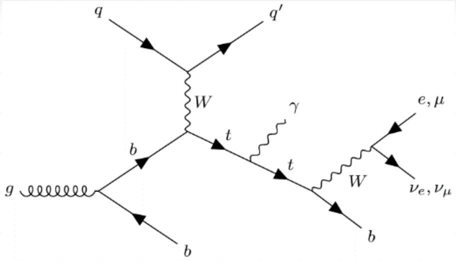


- SMEFT interpretation to constrain Wilson coefficients C_{tG} and $C_{tq}^{(8)}$
  - Enhanced sensitivity in the top p_T specturm
- Obtained similar limits on $C_{tq}^{(8)}$ as in the recent global fit arXiv:2105.00006



Rare top production

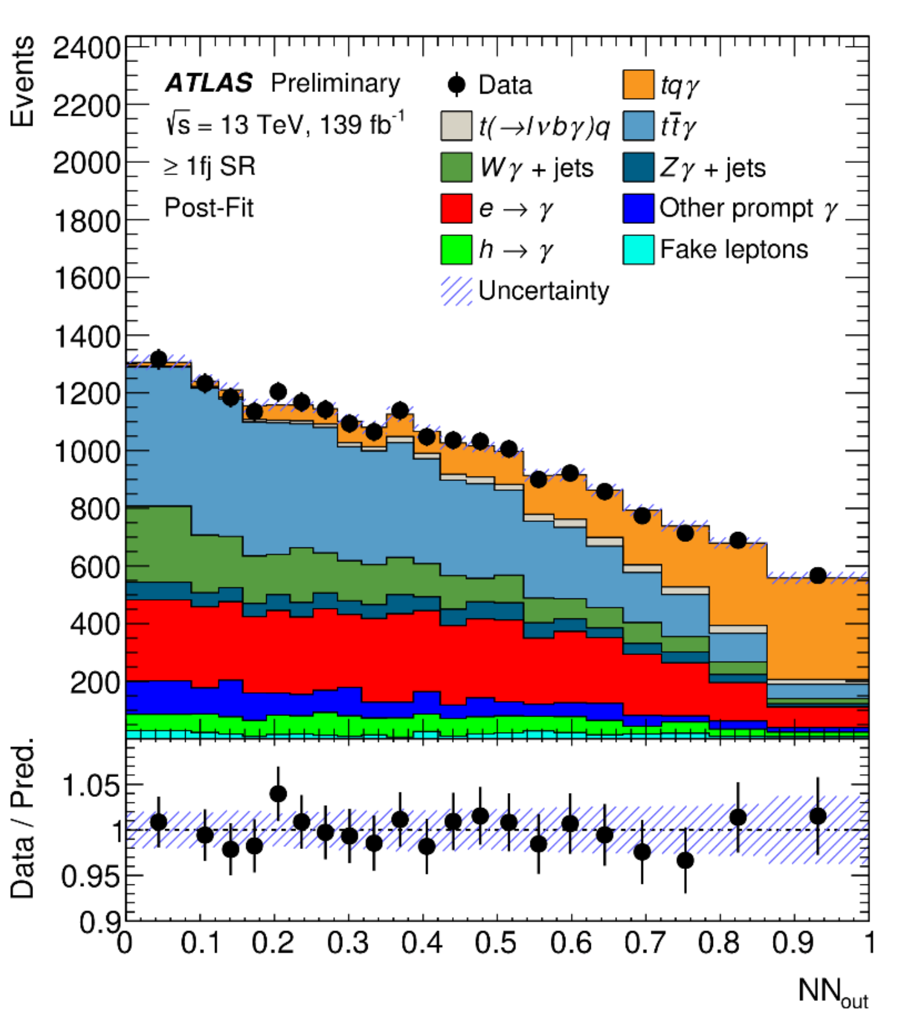




Observation of $tq\gamma$

ATLAS-CONF-2022-013

$\sqrt{s} = 13$ TeV, $L = 139$ fb^{-1}



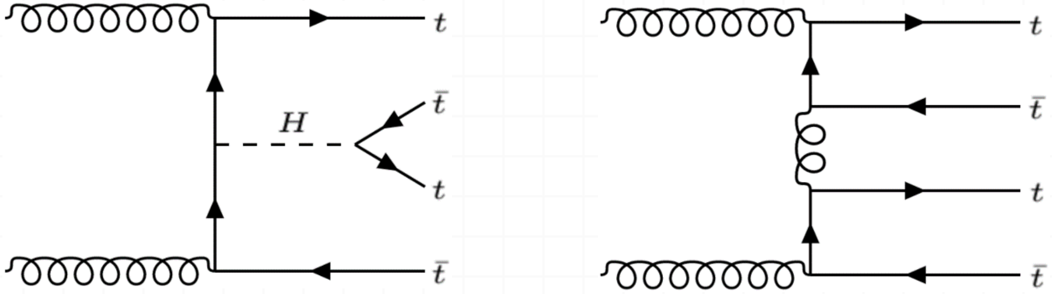
Standard Model t-channel single top production in association with a photon

- Very rare process: $\sigma_{tq\gamma}^{SM} \times B(t \to l\nu b) = 406^{+25}_{-32}$fb
- Sensitive to EW couplings of the top
- Final state with exactly 1lepton (e/μ), 1-bjet, 1photon
    - Profile likelihood fit of a NN discriminant
    - Two signal regions: with/without a forward jet
    - Control regions for $tt\gamma$ and $W\gamma$
- Main uncertainties from tt and $tt\gamma$ background modelling and MC statistics

***tqγ* observation with measured (expected) significance of 9.1 (6.7)σ**

- Parton level: $\sigma_{tq\gamma} \times B(t \to l\nu b) = 580 \pm 19(\text{stat.}) \pm 63(\text{syst.})$fb
- Particle level: $\sigma_{tq\gamma} \times B(t \to l\nu b) + \sigma_{t(\to l\nu b\gamma)} = 287 \pm 8(\text{stat.}) \pm 31(\text{syst.})$fb

Evidence of $4t$ production



JHEP 11 (2021) 118

$\sqrt{s} = 13$ TeV, $L = 139$ fb^{-1}

Extremely rare process: $\sigma_{4t}^{SM} = 12 \pm 2.4$ fb

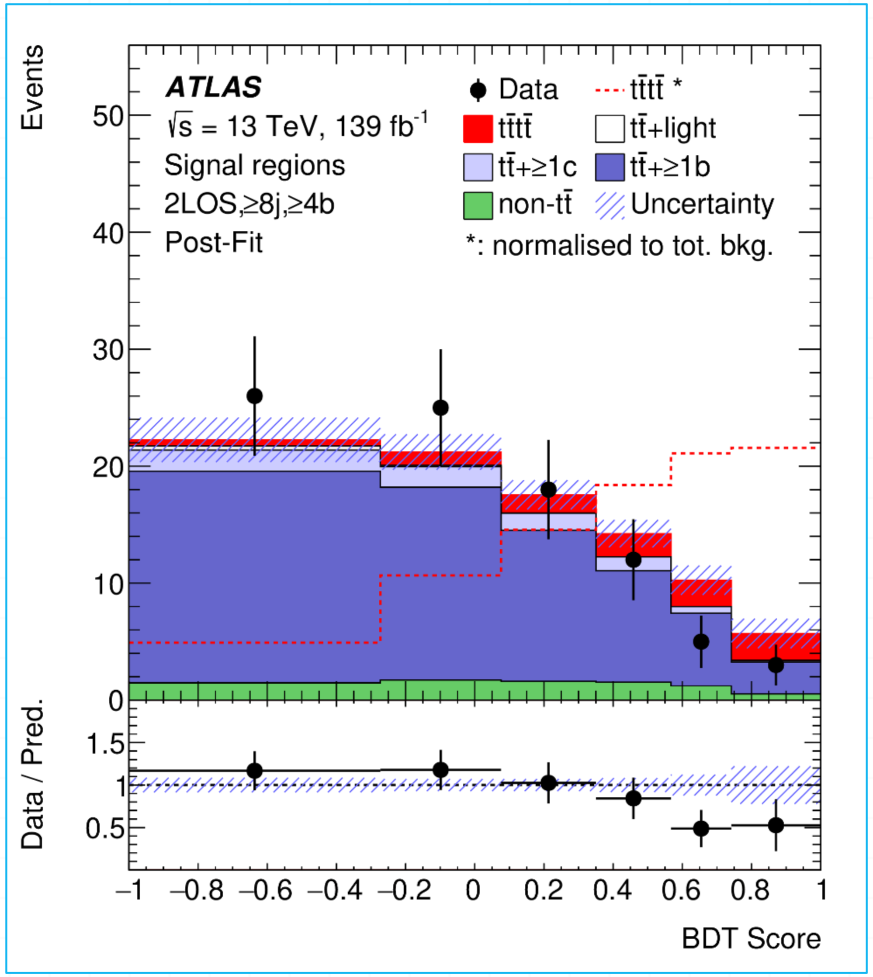
- Never observed by ATLAS or CMS yet
- Sensitive to the magnitude and CP properties of the top-Higgs Yukawa coupling

Measurements performed in all leptonic final states

- Same sign dilepton and multi-lepton channels (SSML): EPJC 80 (2020)
- Single lepton and opposite sign dilepton (1LOS) + combination with SSML: JHEP 11 (2021) 118

Final state with high jet and b-jet multiplicities

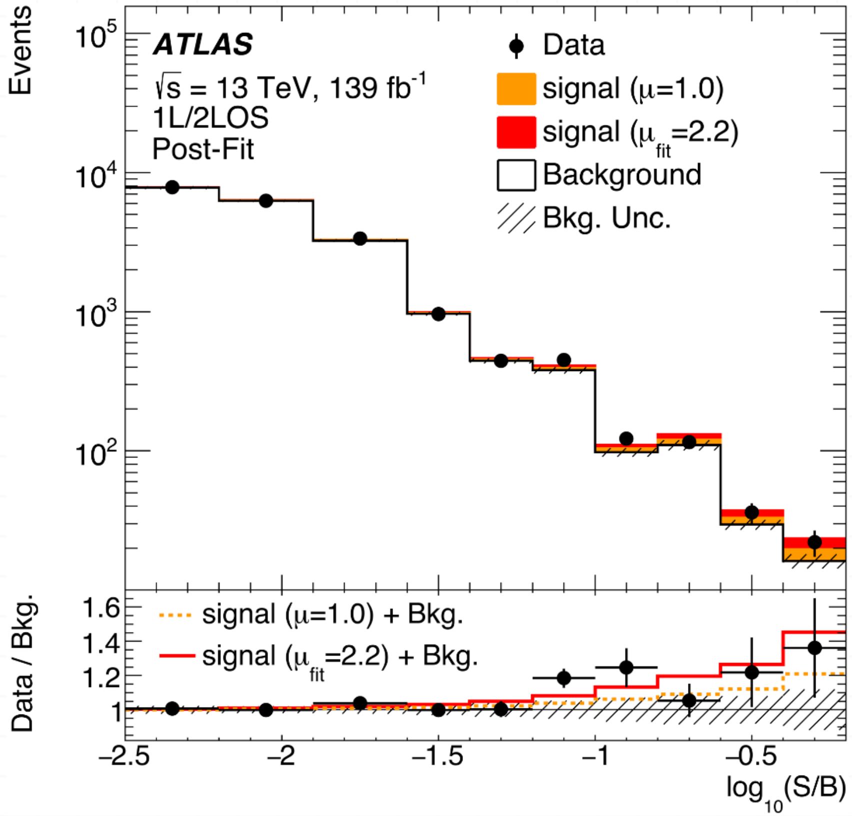
- 10(8) jets in 1L(2LOS) + 4 b-jets expected in typical 4top events
- Measurement extracted via a profile likelihood fit of a BDT discriminant

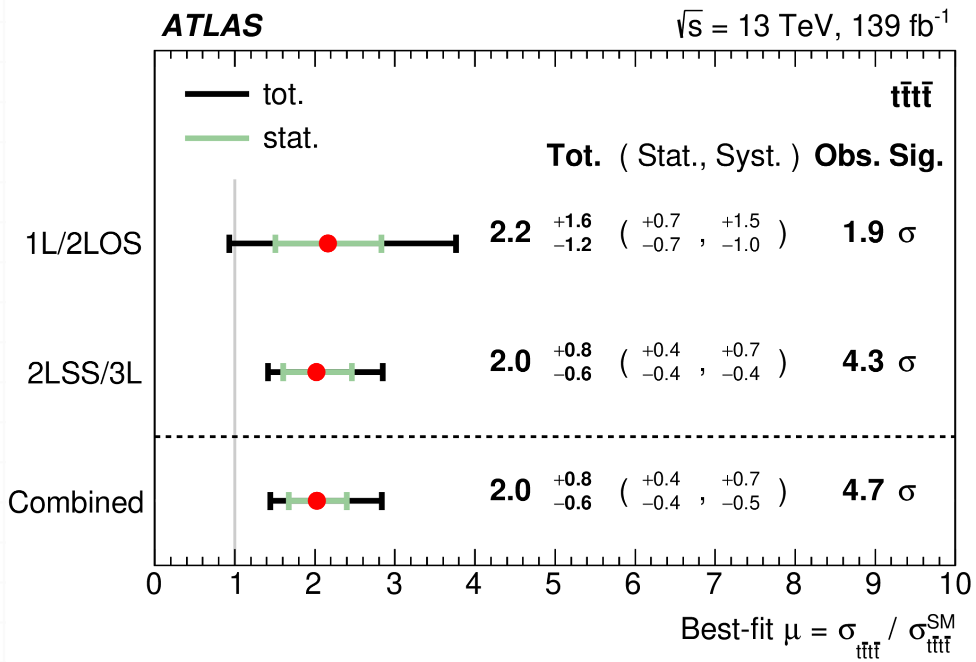


Evidence of 4t production

JHEP 11 (2021) 118

$\sqrt{s} = 13$ TeV, $L = 139$ fb^{-1}





Measured cross section for 1LOS: $\sigma_{4t} = 26^{+17}_{-15}$ fb

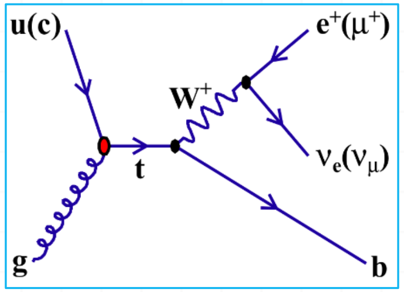
- Observed (expected) significance: 1.9 (1.0)σ
- Uncertainties dominated by 4-top and $t\bar{t}$+HF modelling

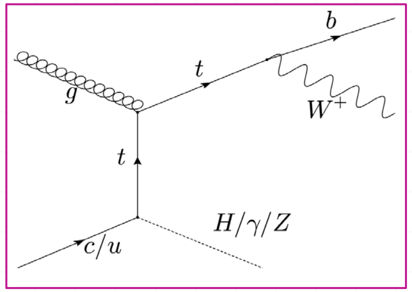
Combined cross section for 1LOS+SSML: $\sigma_{4t} = 24^{+7}_{-6}$ fb

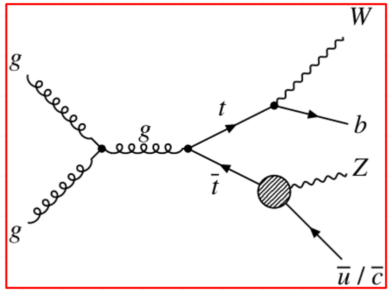
- Observed (expected) significance: 4.7 (2.6)σ

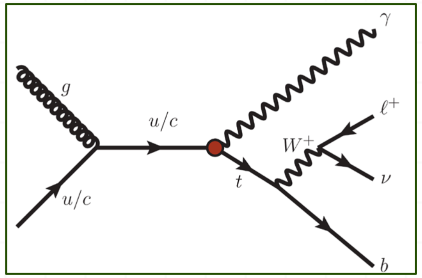
FCNC ($tqg/tqZ/tqH/tq\gamma$)

EPJC 82 (2022) 334
ATLAS-CONF-2021-049
ATLAS-CONF-2022-014
arXiv:2205.0253
$\sqrt{s} = 13$ TeV, $L = 139$ fb^{-1}

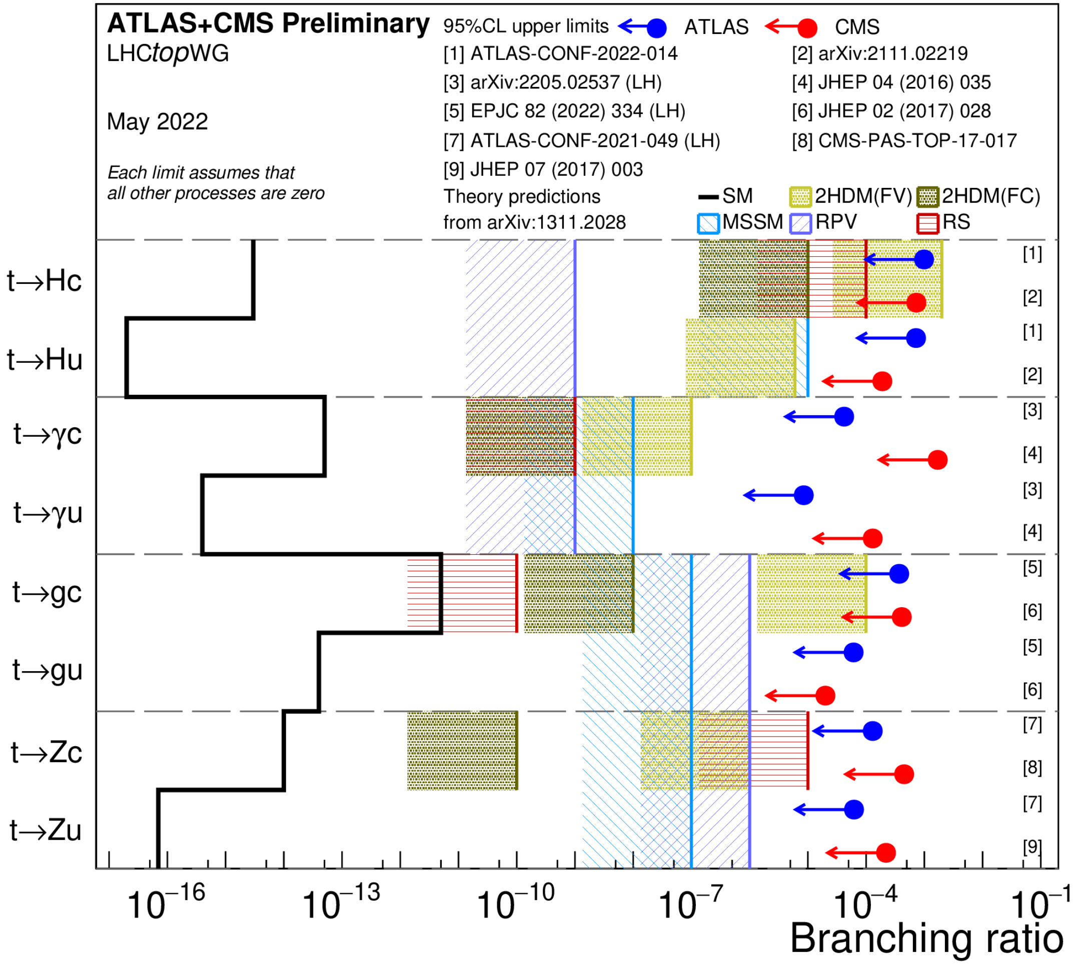








ATL-PHYS-PUB-2022-030



Flavour Changing Neutral Currents (FCNC) forbidden at tree level and suppressed at higher orders in the SM

- FCNC can be enhanced via BSM processes and EFT extensions of the SM

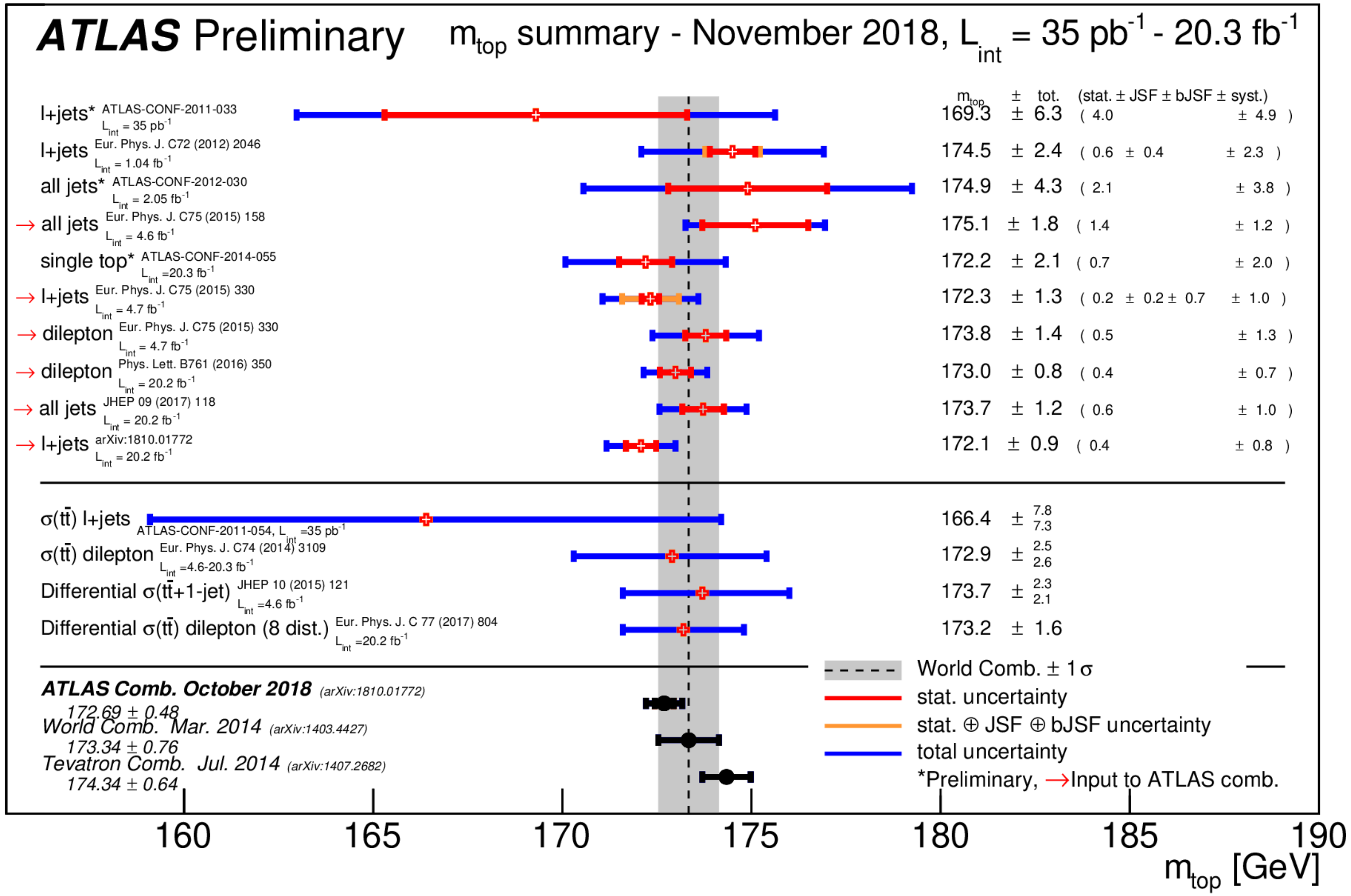
FCNC probed both in top production ($tqg/tqZ/tqH/tq\gamma$) and decay ($tqZ/tqH/tq\gamma$)

Upper limits are set for branching ratios $B(t \to q\gamma/H/g/Z)$ and Wilson coefficients

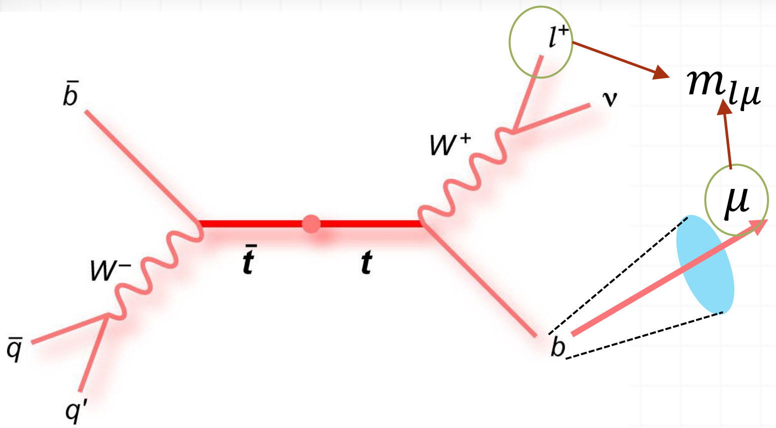
ATL-PHYS-PUB-2022-032

Top quark mass

Precision on m_t measurement at LHC is constantly improving and reached the level of precision achieved at Tevatron



Top mass with SMT



arXiv:2209.00583

$\sqrt{s} = 13$ TeV, $L = 36.1$ fb^{-1}

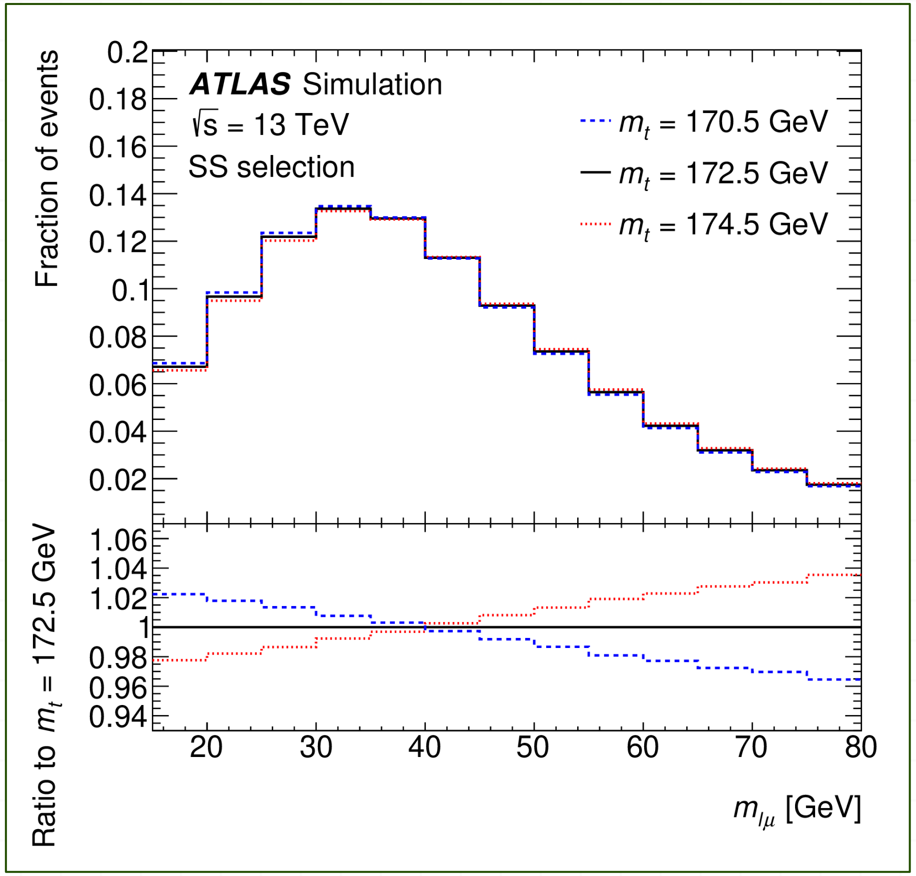
Lepton+jets

Identify semi-leptonic decay of the B-hadron: $B \to \cdots \to \mu\nu^{\mu} + X$

- **S**oft **m**uon **b**-tagging: $\Delta R(\mu, jet) < 0.4$

Exploit the dependence of $m_{l\mu}$ on m_t

- Purely leptonic observable, less affected by uncertainties on the jets



Simultaneous fit of templates in the OS and SS regions

$m_t = \mathbf{174.41} \pm 0.39(\text{stat.}) \pm 0.66(\text{syst.}) \pm 0.25(\text{recoil})$ GeV (**0.46% unc.**)

Dominant uncertainties:

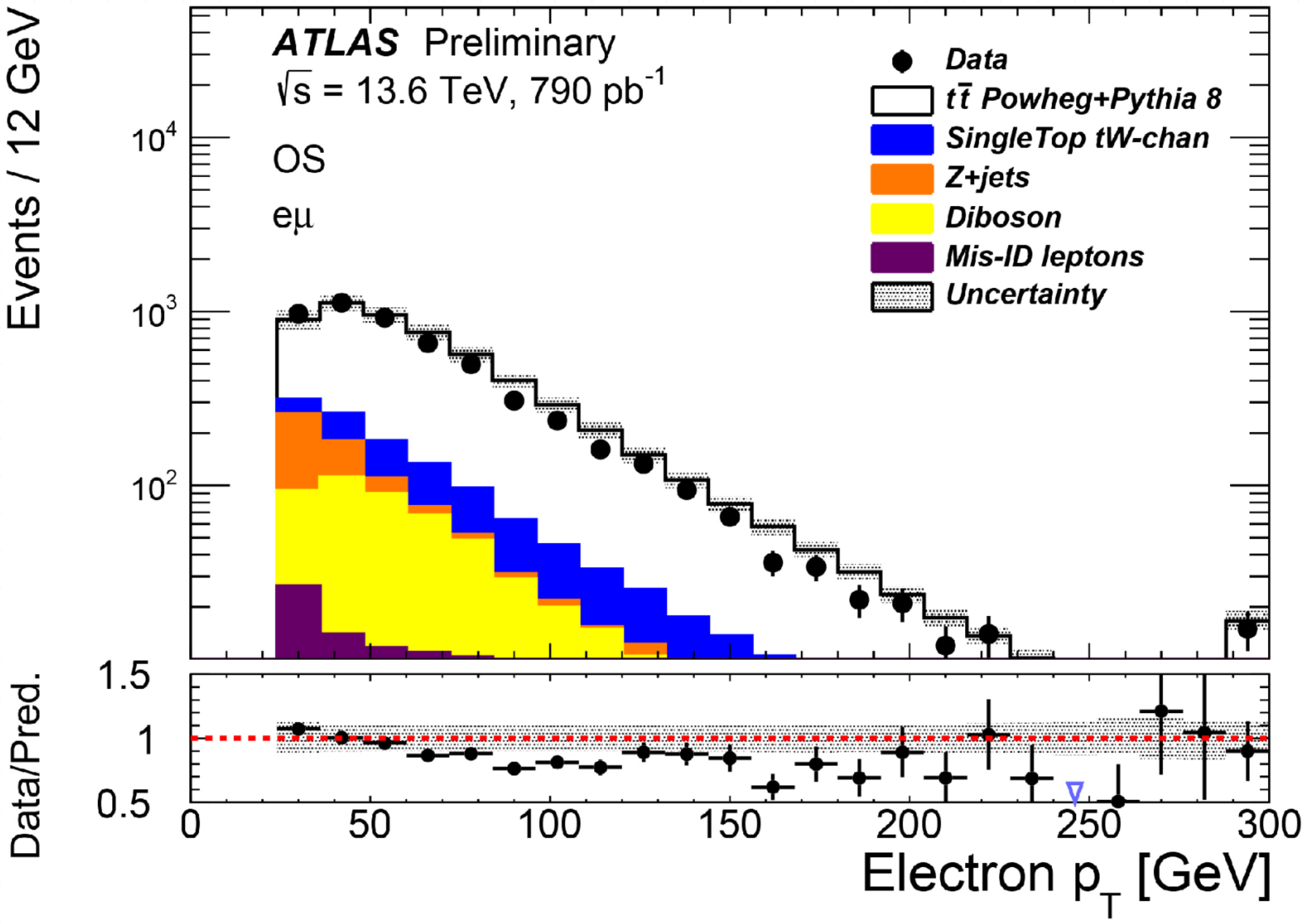
- signal modeling (b fragmentation and decay, $t\bar{t}$ production)

Outlook

FTAG-2022-003

- **Top analyses are in full swing** thanks to the combined performance of LHC & detectors: **a very rich program is under way.**
- ATLAS is ready to analyze the data from the newly started Run3

  So… stay tuned!



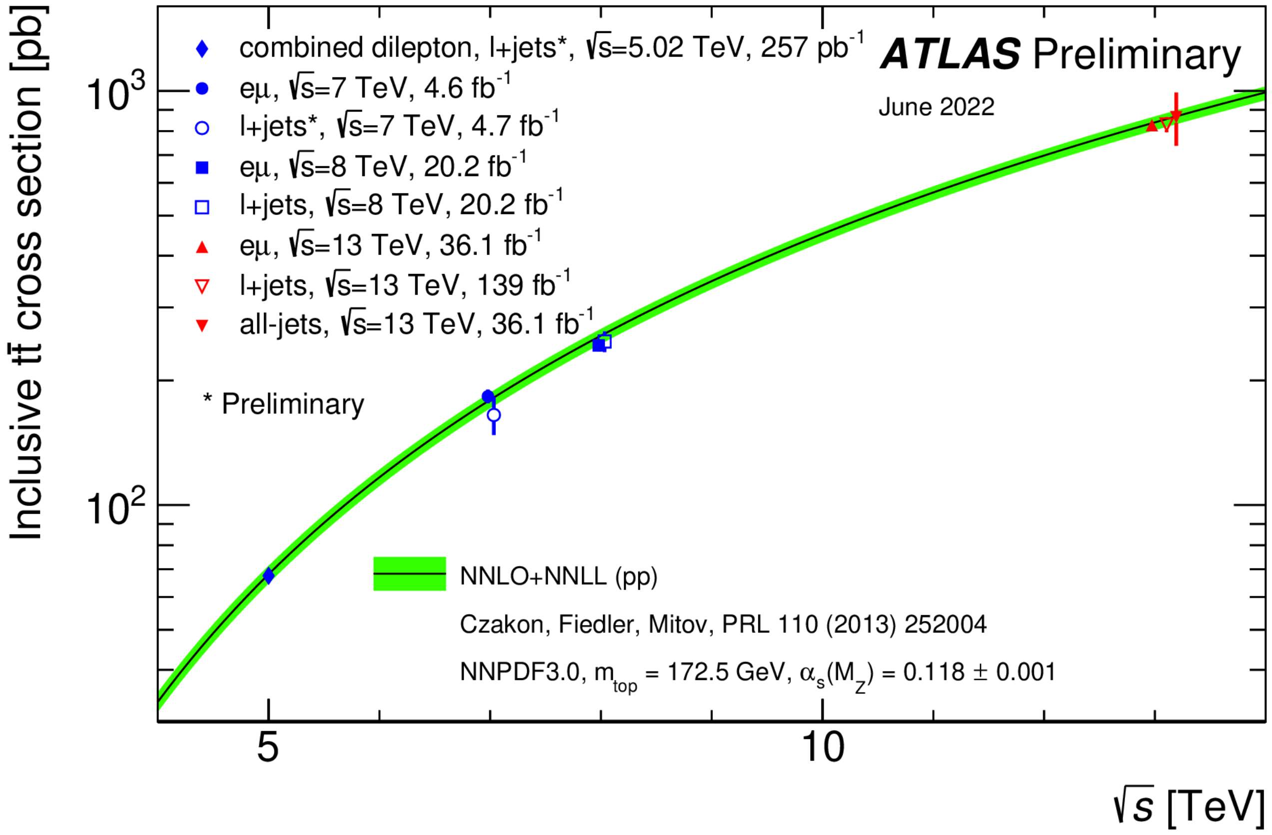
Summary

- **A lot of interesting results produced by ATLAS** thanks to the combined performance of LHC & detectors
  - Presented today only a small selection of recent results
    - Many more can be found in the ATLAS Top Public page*
  - **Top strong and electroweak inclusive production has been measured with exceptional precision**
  - Differential cross sections measurements test SM $t\bar{t}$ production and complement new physics searches in completely new phase space
  - New energy domains and rare top production processes are now accessible thanks to the LHC top quark factory, allowing to set **stronger limits to extensions of the SM**

*: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults

Backup

Top quark pair inclusive cross section: summary



ATL-PHYS-PUB-2022-031

Wide range of measurements by ATLAS in different decay channels

Good agreeement of all measurements with SM predictions

Experimental uncertainties already comparable with theoretical ones

Measurements in eμ and lepton+jets channels are outstanding

Common limitation: uncertainty on integrated luminosity (~2.3%)

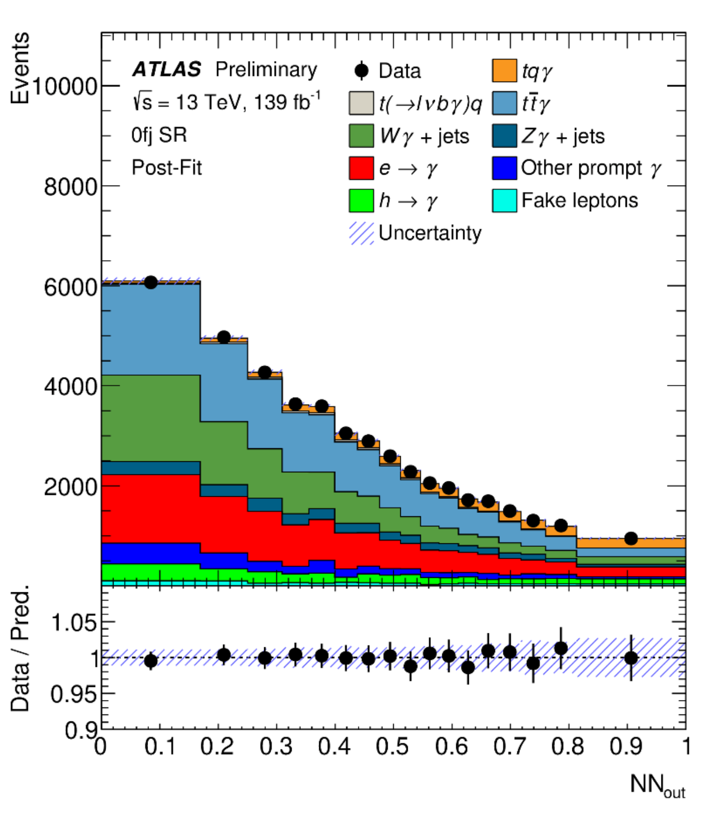
Observation of $tq\gamma$

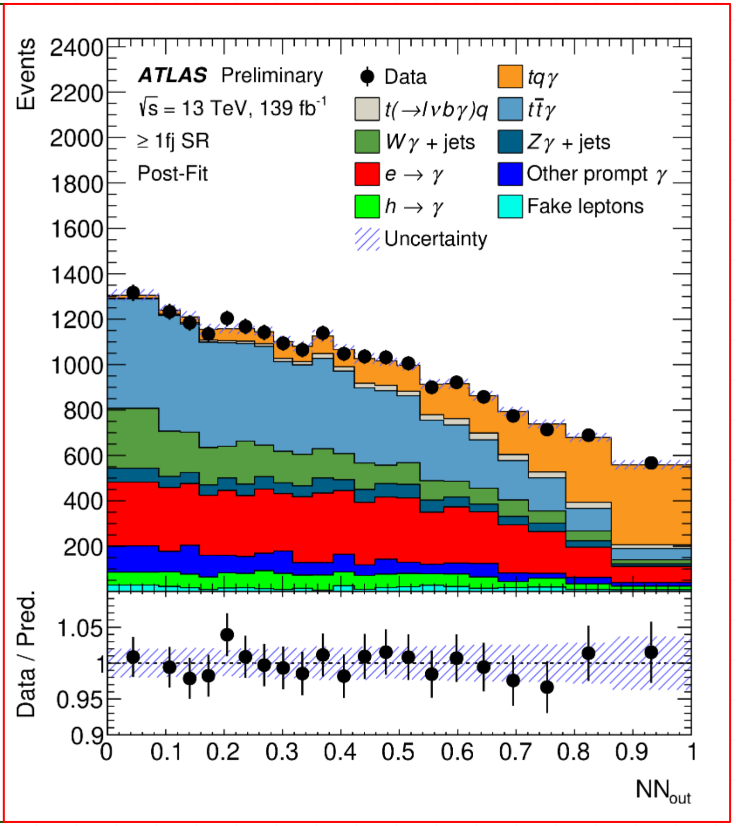
ATLAS-CONF-2022-013

$\sqrt{s} = 13$ TeV, $L = 139$ fb^{-1}

Standard Model t-channel single top production in association with a photon

- Very rare process: $\sigma^{SM}_{tq\gamma} \times B(t \to l\nu b) = 406^{+25}_{-32}$fb
- Sensitive to EW couplings of the top quark (esp. top-γ vertex)
- Final state with exactly 1lepton (e/μ), 1-bjet, 1photon
  - Profile likelihood fit of a NN discriminant
  - Two signal regions: with/without a forward jet
  - Two control regions for $tt\gamma$ and $W\gamma$
- Cross section measured in a fiducial phase space at parton and particle level
  - At particle level process made up of two contributions
    - $pp \to t(\to bl\nu)q\gamma$ (~80%)
    - $pp \to t(\to \gamma bl\nu)q$ (~20%)
- Main uncertainties from tt and $tt\gamma$ background modelling and MC statistics





***tqγ* observation with measured (expected) significance of 9.1 (6.7)σ**

- Parton level: $\sigma_{tq\gamma} \times B(t \to l\nu b) = 580 \pm 19(\text{stat.}) \pm 63(\text{syst.})$fb
- Particle level: $\sigma_{tq\gamma} \times B(t \to l\nu b) + \sigma_{t(\to l\nu b\gamma)} = 287 \pm 8(\text{stat.}) \pm 31(\text{syst.})$fb