The search for rare top production and decay processes with the ATLAS experiment at the LHC

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on behalf of the ATLAS Collaboration

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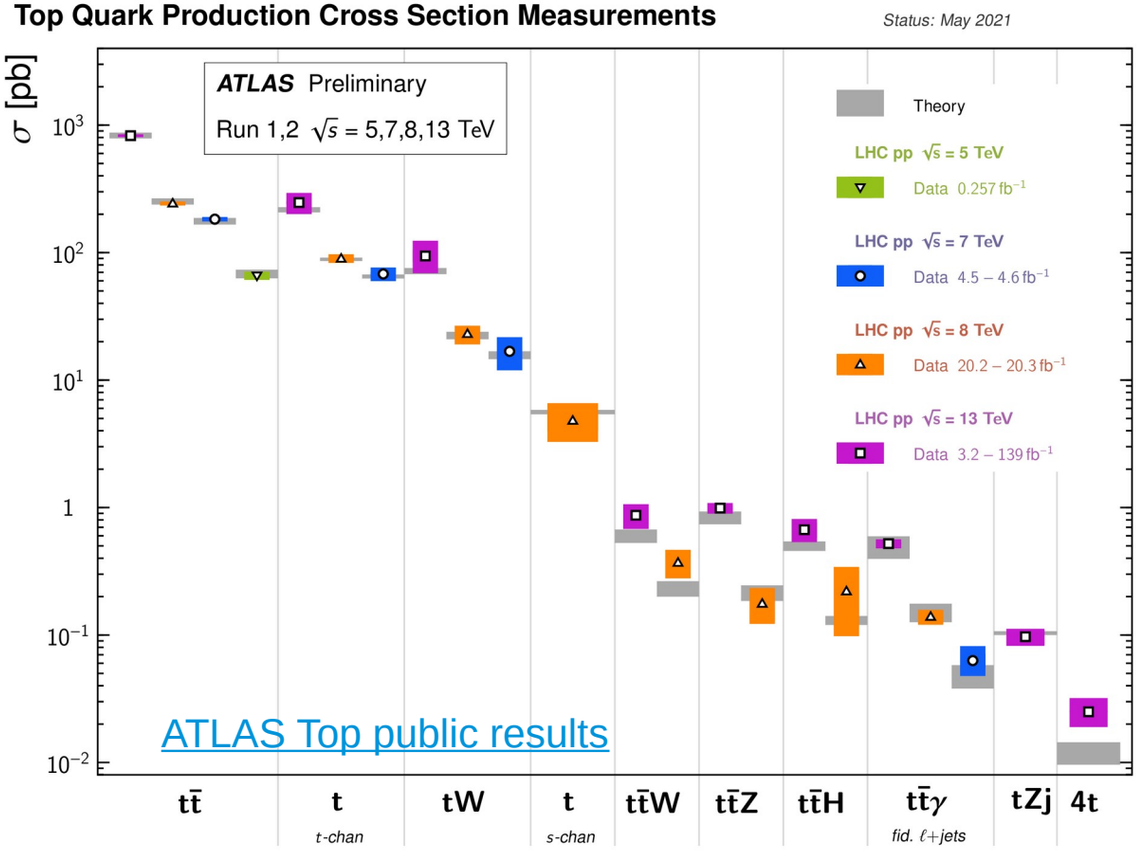
Introduction

- The most massive elementary particle ~172 GeV
- Strongest interaction with the Higgs boson
- LHC is a top quark factory
  - ➔ Over 200 million top quark pairs in LHC Run 2 13 TeV data

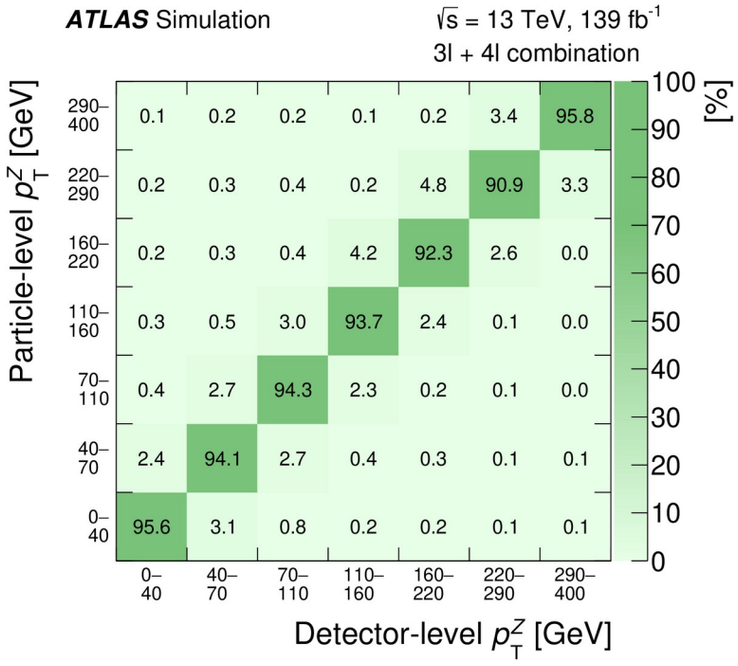


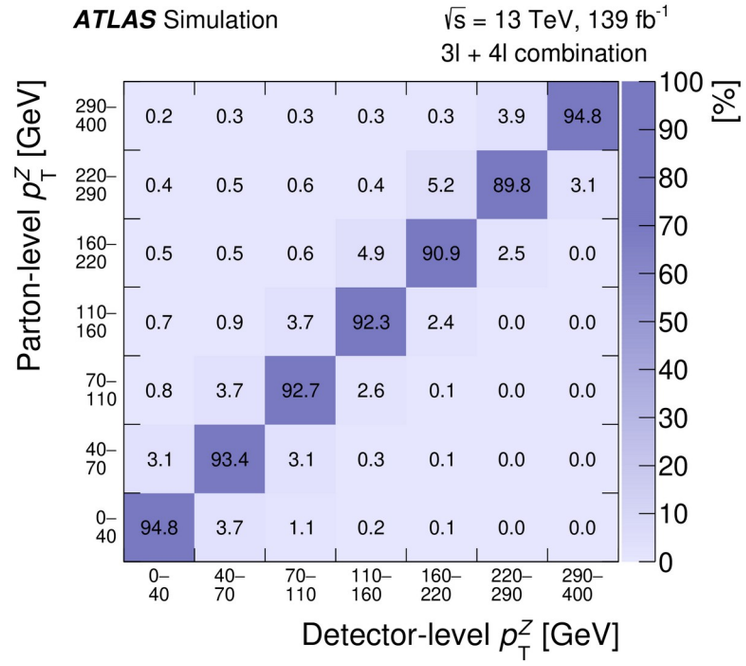
- The top quark sector offers many opportunities to search for FCNC interactions beyond the SM
- Run 2 data allowed searches for rare top quark production processes.
  - ➔ Measurement of tt̄Z
  - ➔ Measurement of tt̄ɣ
  - ➔ Observation of tZq
  - ➔ First evidence of tt̄tt̄

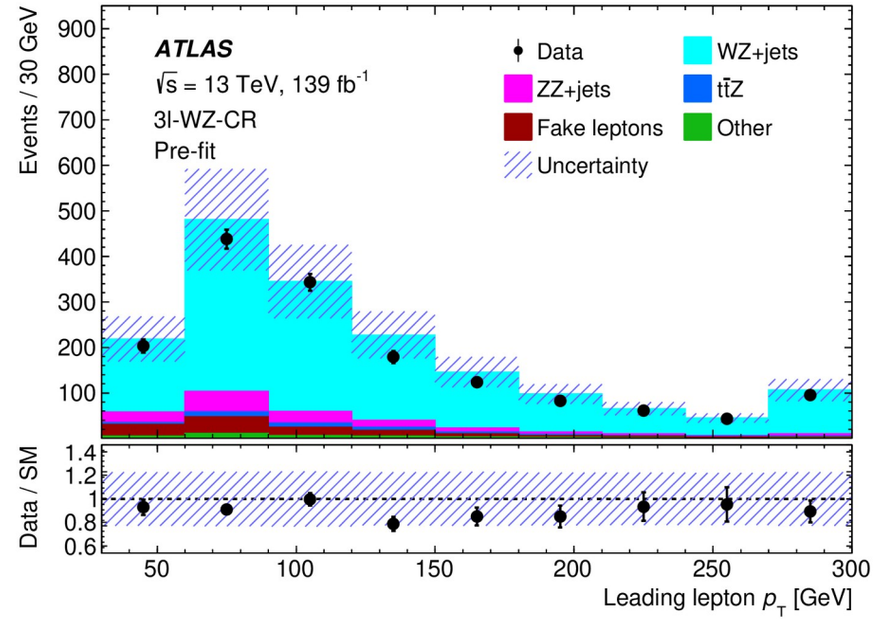
$t\bar{t}Z$ Production in 3ℓ/4ℓ Final State

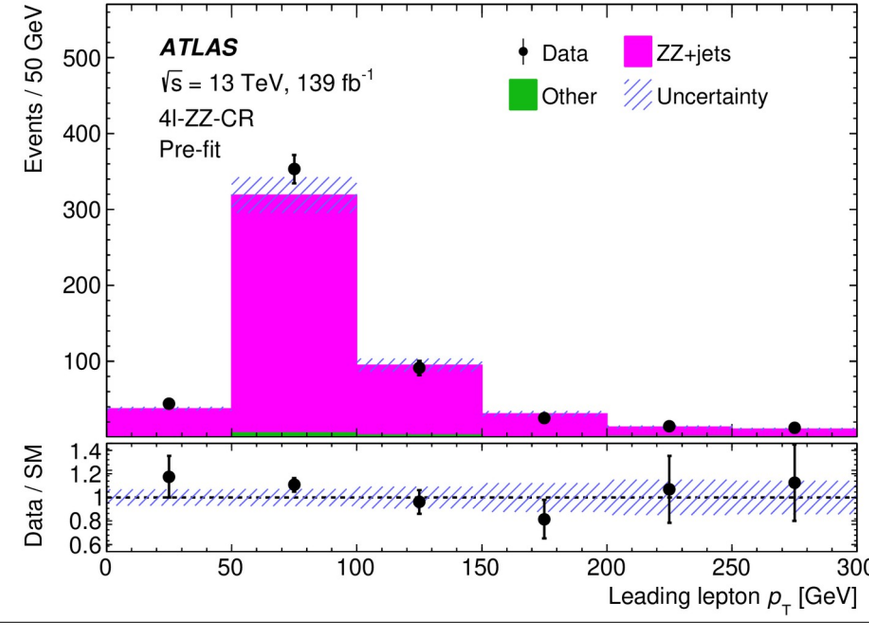
arXiv:2103.12603

- Measurement of $t\bar{t}Z$ with full Run 2 data
- Trilepton channels – different selection in incl./diff.:
  - One b-tag region for unfolding → maximum statistics
  - Two b-tag regions for inclusive measurement → maximum precision & WZ background suppression
- Tetralepton channels – four signal regions:
  - Same-flavour/opposite-flavour lepton pairing
  - Different b-tag multiplicities
- Control regions for ZZ and WZ backgrounds
- Unfolding done to both parton and particle level









$t\bar{t}Z$ Production in 3ℓ/4ℓ Final State

arXiv:2103.12603

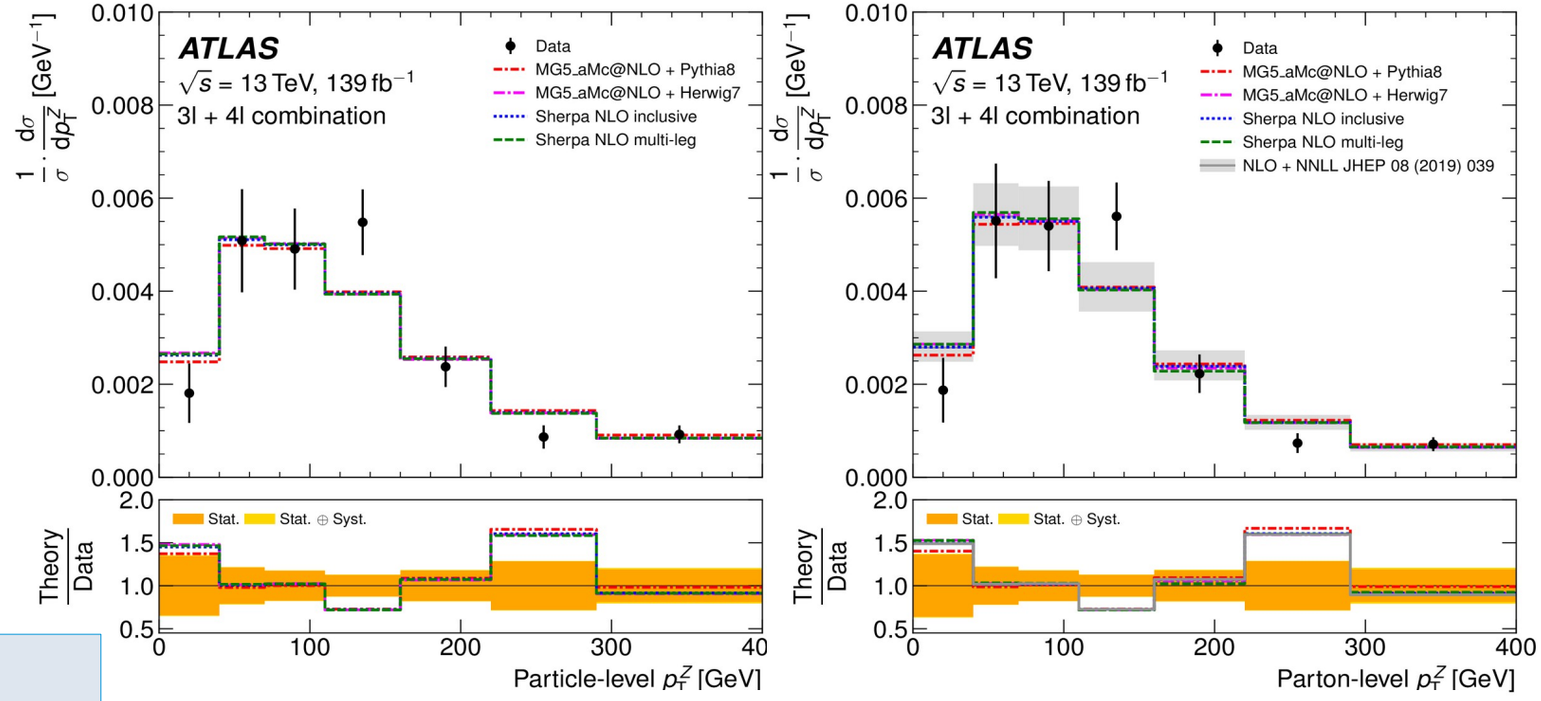
- Simultaneous profile likelihood fit of all trilepton and tetralepton signal regions + WZ and ZZ control regions
- Differential results dominated by statistical uncertainties and those on signal modelling and b-tagging
- In agreement with NLO+NNLL prediction [Eur Phys. J. C 80 (2020) 428]:

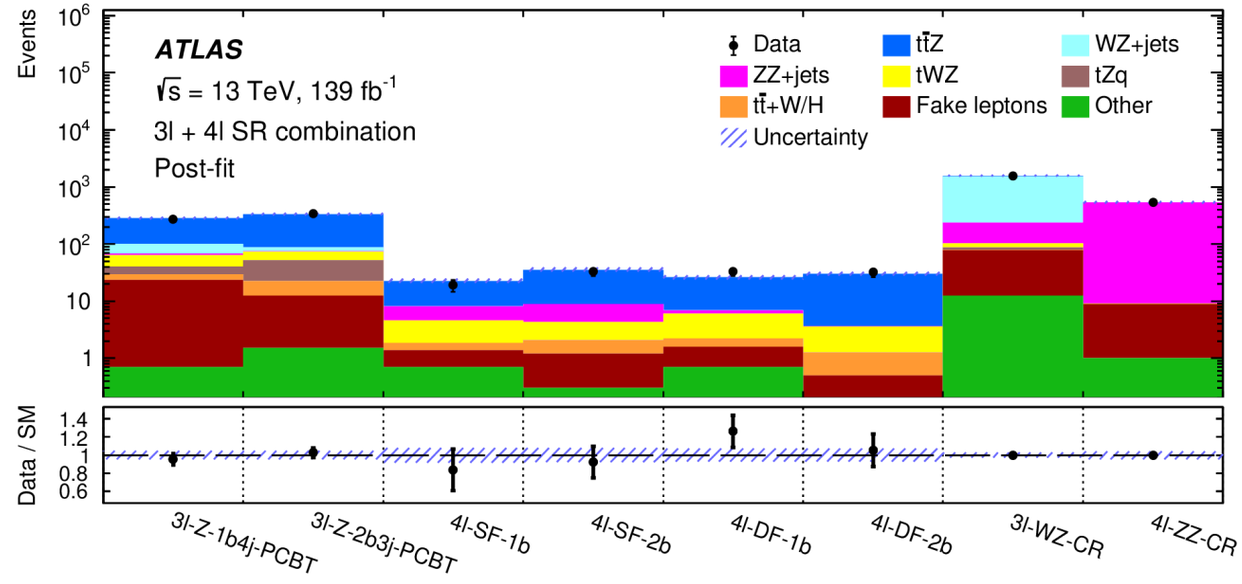
$$0.86^{0.09}_{-0.1}(\text{scale}) \pm 0.02(\text{PDF} + \alpha_s)\ \text{pb}$$

The measured cross section:

$$\sigma = 0.99 \pm 0.05(\text{stat}) \pm 0.08(\text{syst.})\,\text{pb}$$

Channel	$\mu_{t\bar{t}Z}$
Trilepton	$1.17 \pm 0.07\,(\text{stat.})\,^{+0.12}_{-0.11}\,(\text{syst.})$
Tetralepton	$1.21 \pm 0.15\,(\text{stat.})\,^{+0.11}_{-0.10}\,(\text{syst.})$
Combination $(3\ell + 4\ell)$	$1.19 \pm 0.06\,(\text{stat.}) \pm 0.10\,(\text{syst.})$

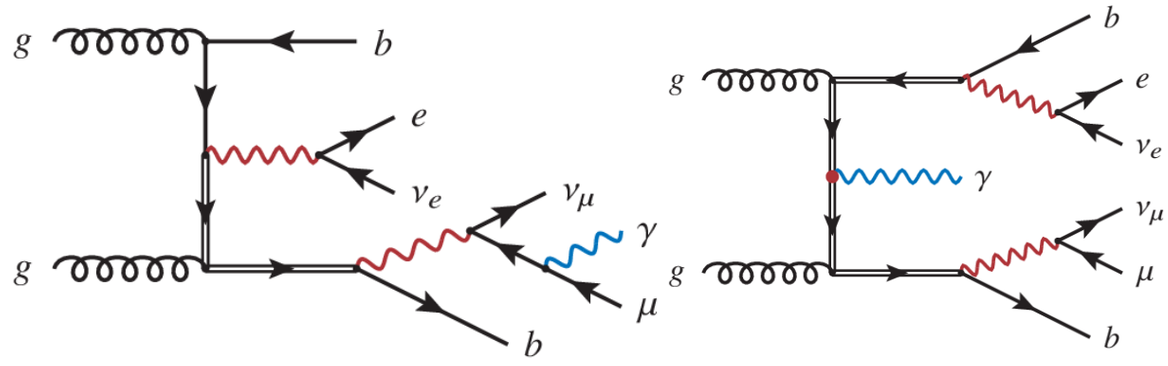




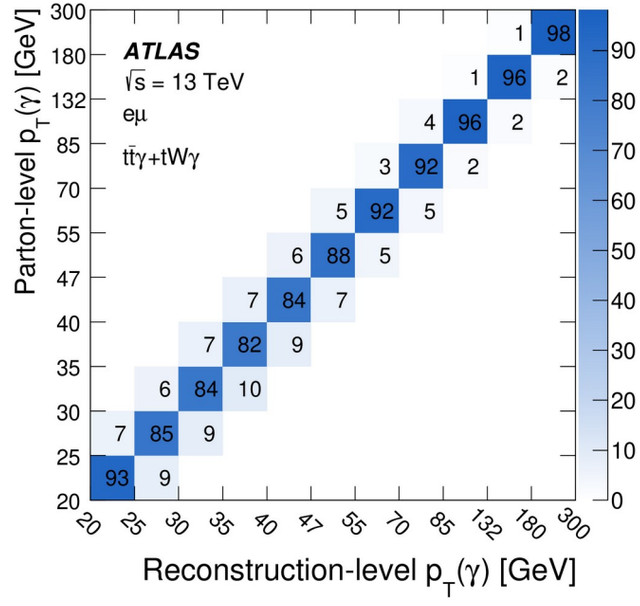
$t\bar{t}\gamma$ and $tW\gamma$ Production in the $e\mu$ Channel

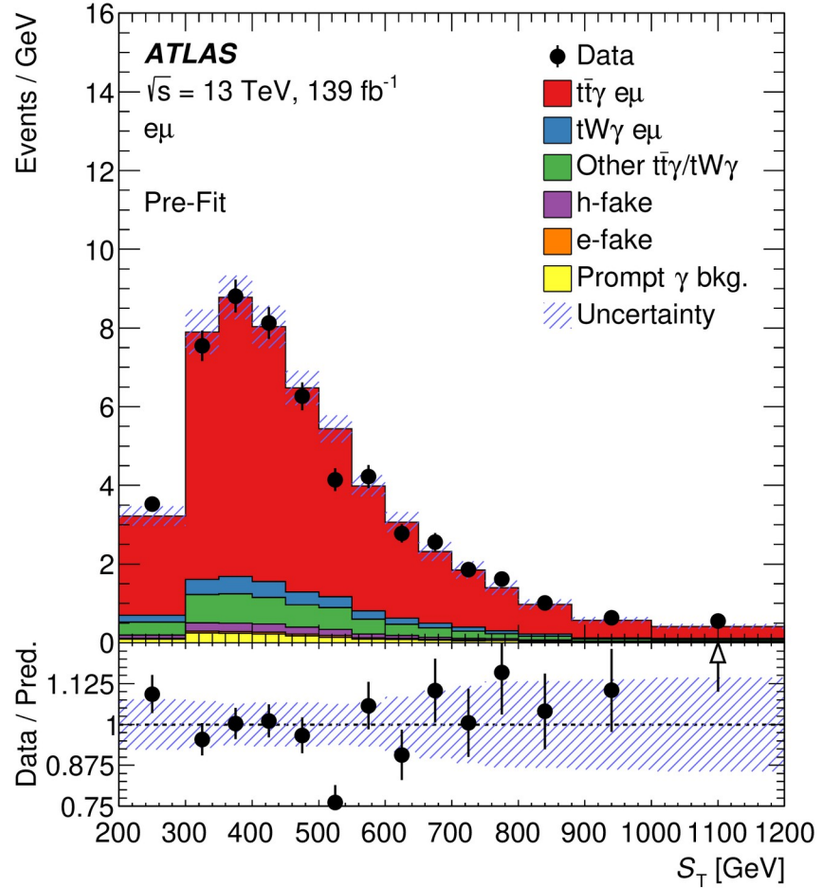
JHEP 09 (2020) 049

- Top-photon coupling accessible in production of $t\bar{t}\gamma$ final states
- The measurements are performed in a fiducial phase space.
- Event selection:
  - One electron, one muon (pT> 25 GeV)
  - >=2 jets (>= 1bjet)
  - 1 photon ($\Delta R(l,\gamma) > 0.4$)
- The differential measurement is obtained applying an iterative unfolding procedure.



	Events
$t\bar{t}\gamma\ e\mu$	2391 ± 130
$tW\gamma\ e\mu$	156 ± 15
Other $t\bar{t}\gamma/tW\gamma$	279 ± 15
h-fake	78 ± 40
e-fake	23 ± 12
Prompt γ bkg.	87 ± 40
Total	3014 ± 160
Data	3014





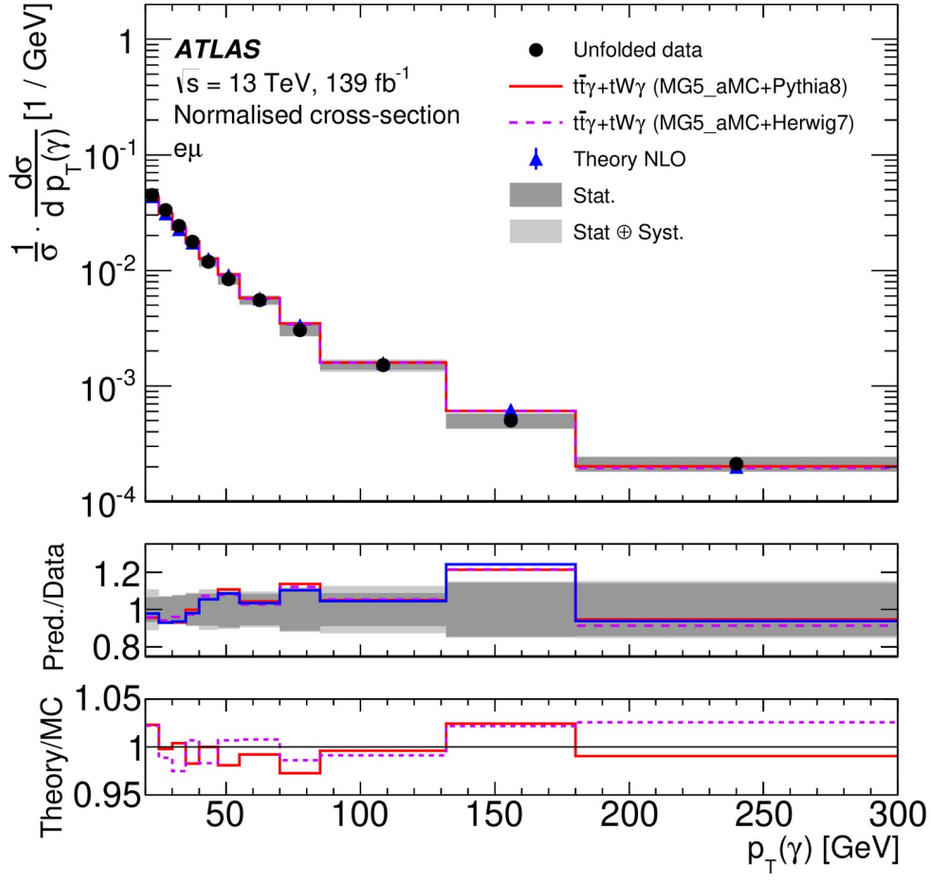
$t\bar{t}\gamma$ and $tW\gamma$ Production in the eμ Channel

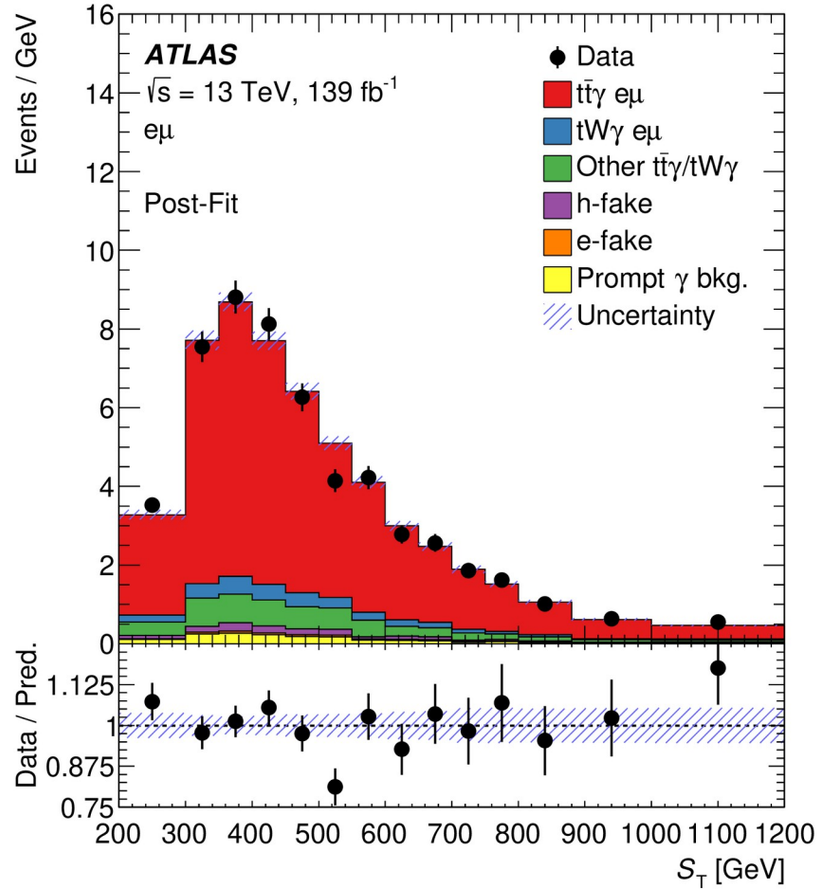
JHEP 09 (2020) 049

- ATLAS data unfolded to parton level
- Main uncertainty coming from signal and background modelling
- Good agreement is observed between the LO MC and NLO differential distributions and the expectations.
- In agreement with NLO cross section [JHEP 10 (2018) 158]: $38.5^{0.56}_{-2.18}\,(\text{scale})^{1.04}_{-1.18}\,(\text{PDF})$

The measured fiducial inclusive cross section: $\sigma = 39.6 \pm 0.8\,(\text{stat})^{+2.6}_{-2.2}\,(\text{syst}) = 39.6^{+2.7}_{-2.3}\,\text{fb}$

Category	Uncertainty
$t\bar{t}\gamma/tW\gamma$ modelling	3.8%
Background modelling	2.1%
Photons	1.9%
Luminosity	1.8%
Jets	1.6%
Pile-up	1.3%
Leptons	1.1%
Flavour-tagging	1.1%
MC statistics	0.4%
Soft term $E_{\text{T}}^{\text{miss}}$	0.2%
$tW\gamma$ parton definition	2.8%
Total syst.	6.3%

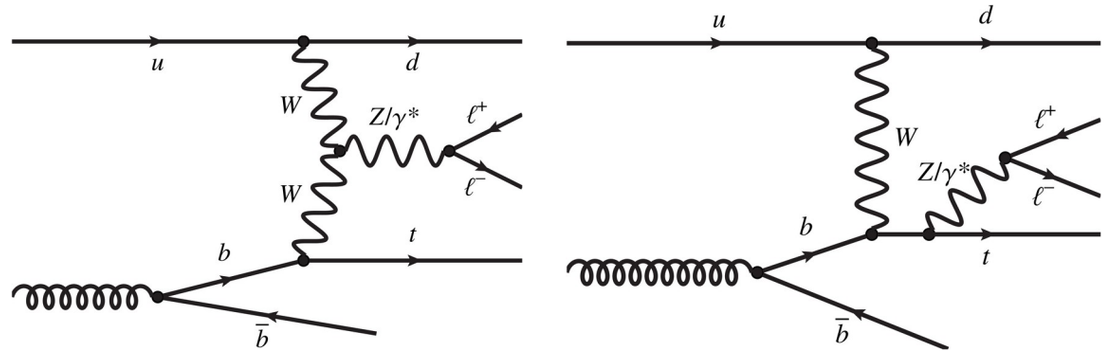


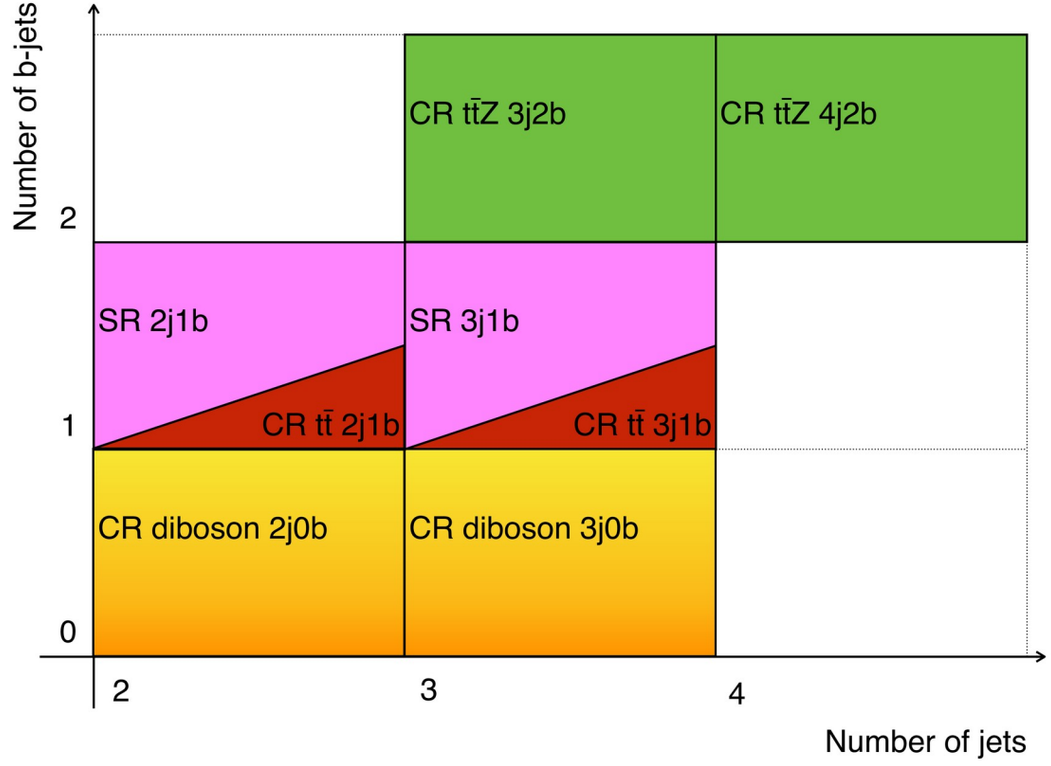


Observation of tZq Production

JHEP 07 (2020) 124

- Measurement of a single top quark in association with a Z boson (tZq production)
  - ➔ Allow for the study of tZ and WZ couplings.
  - ➔ Small NLO QCD corrections
  - ➔ Small deviations from the SM can be interpreted in the SMEFT
- Best signal significance in the trilepton channel
  - ➔ One pair should build a Z mass peak
- Include non-resonant lepton pairs
- Two signal regions (2j1b, 3j1b) plus additional control regions for the largest backgrounds (tt̄Z, diboson, tt̄)
- Event selection:
  - ➔ 3 leptons (pT> 28,20,20 GeV)
  - ➔ At least 1 jet (pT> 35 GeV)
  - ➔ 1 btagged jet





Observation of tZq Production at √s=13 TeV

JHEP 07 (2020) 124

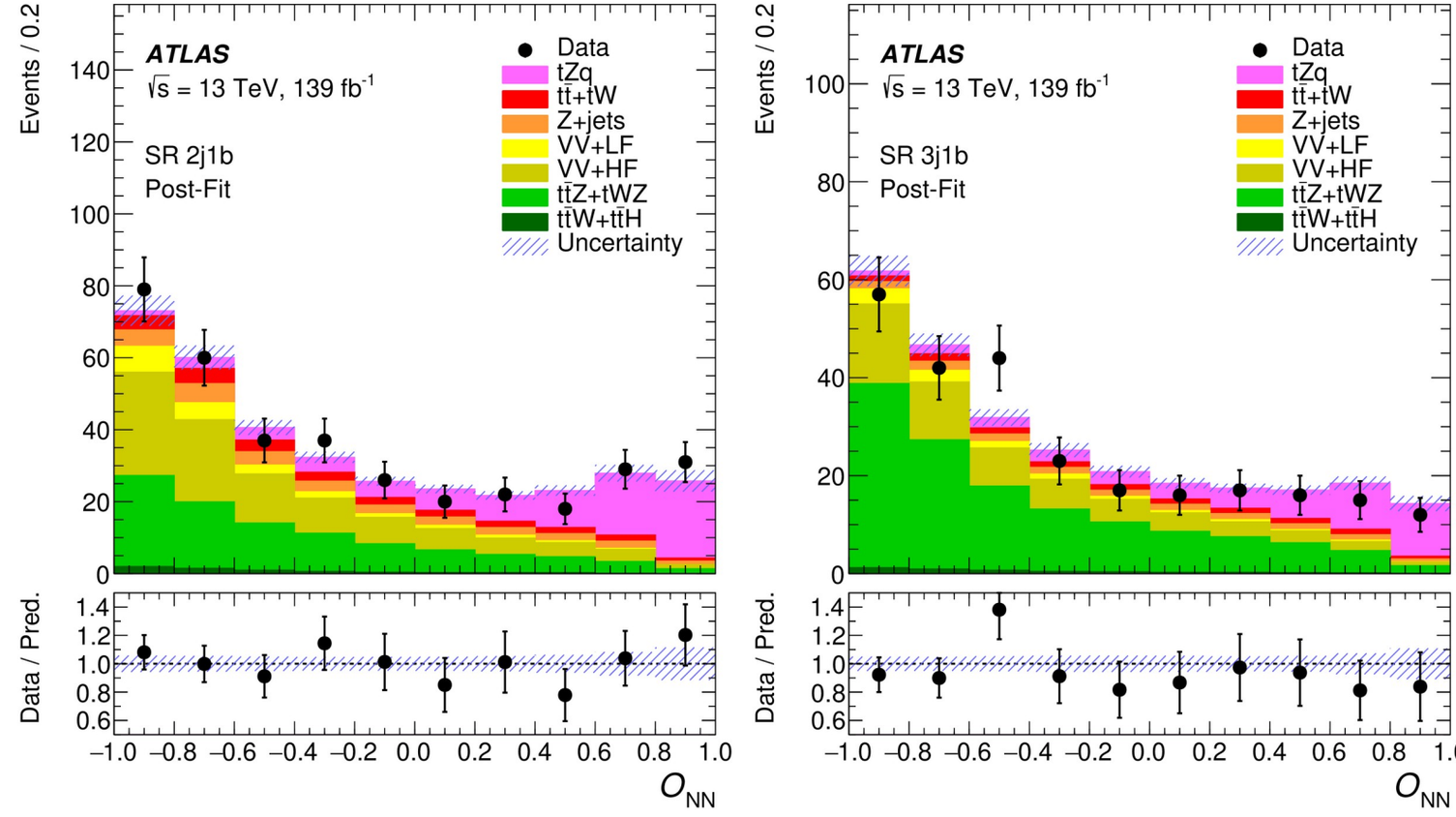
- Cross section extracted using a binned maximum likelihood fit performed on the NN output in SRs and Crs
- Observation with > 5σ

$$\sigma_{tZq} = 97 \pm 13\,(\text{stat}) \pm 7\,(\text{syst})\,\text{fb}$$

Consistent with the SM expectation of

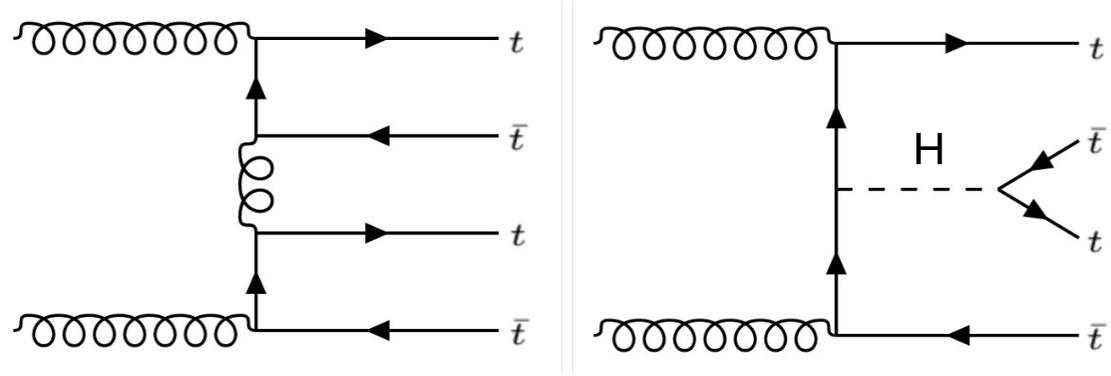
$$102^{+5.2\%}_{-1.3\%}\,(\text{scale}) \pm 1.0\%\,(\text{PDF})\,\text{fb}$$

Uncertainty source	$\Delta\sigma/\sigma$ [%]
Prompt-lepton background modelling and normalisation	3.3
Jets and $E_{\mathrm{T}}^{\mathrm{miss}}$ reconstruction and calibration	2.0
Lepton reconstruction and calibration	2.0
Luminosity	1.7
Non-prompt-lepton background modelling	1.6
Pile-up modelling	1.2
MC statistics	1.0
tZq modelling (QCD radiation)	0.8
tZq modelling (PDF)	0.7
Jet flavour tagging	0.4
Total systematic uncertainty	7.0
Data statistics	12.6
$t\bar{t} + tW$ and Z + jets normalisation	2.1
Total statistical uncertainty	12.9

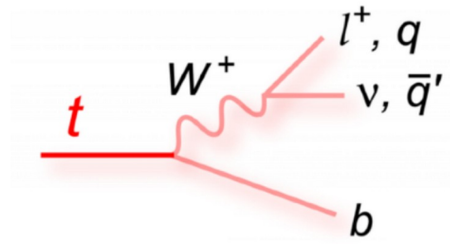


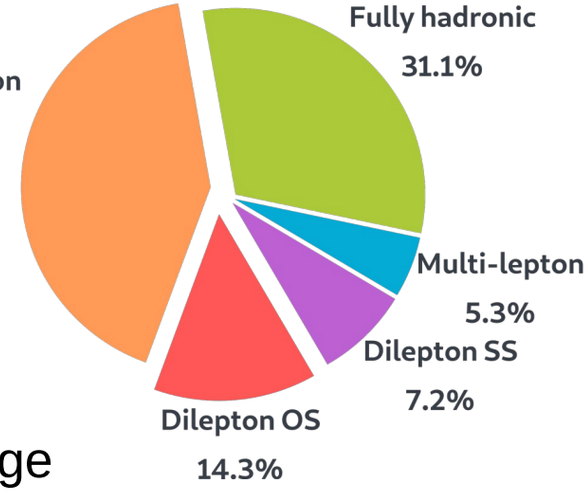
$t\bar{t}t\bar{t}$ Production

- Four top production: $pp \rightarrow t\bar{t}t\bar{t}$, is a rare and theoretically challenging process
  - $\sigma^{NLO}(tttt) = 12.0 \pm 2.4$ fb at NLO QCD+EW at 13 TeV arXiv:1711.02116 [hep-ph]



- Extremely high energy scale production makes it naturally sensitive to many BSM models, e.g.
  - Gluino pair production in SUSY
  - Heavy pseudoscalar/scalar boson in 2HDM
  - Four-fermion contact interaction within EFT





- **Signatures:**
  - **2ℓSS / 3ℓ :**
    - Low branching fraction, but small background (ttW, ttZ, non-prompt leptons, charge misidentification)
    - Eur. Phys. J. C (2020) 80:1085
  - **1ℓ / 2ℓOS :**
    - Dominant branching fraction, but large background from tt+jets
    - ATLAS-CONF-2021-013

Analysis Strategy

SS/ML

- Process characterised by leptonic signatures creating a cleaner signal
  - ➔ Main challenge is handling of dominant $t\bar{t}W$+jets background
    - Mismodelled at high jet multiplicities
    - Dedicated CR for proper $t\bar{t}W$+jets estimation
  - ➔ Further CRs for Fake/Non-prompt lepton background estimations
  - ➔ Data-driven charge misassignment background estimation
  - ➔ 1 inclusive SR with a BDT distribution

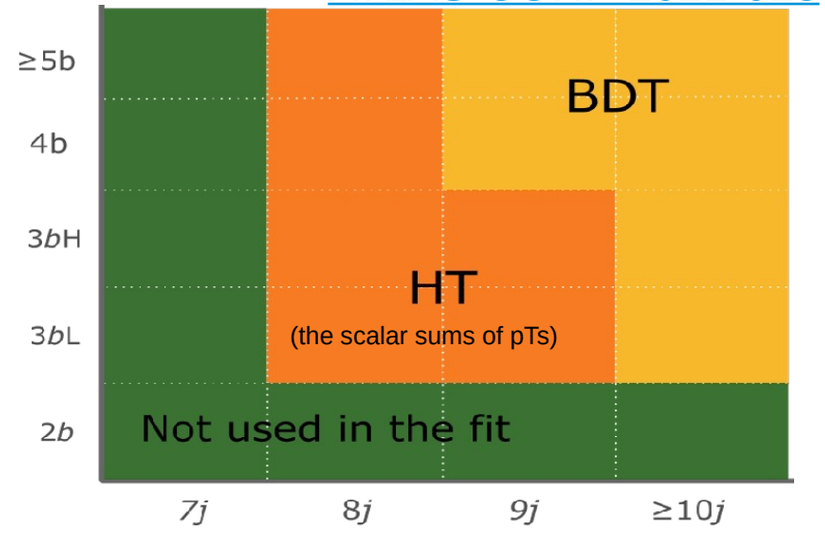
Eur. Phys. J. C 80 (2020) 1085

Region	Channel	N_j	N_b	Other requirements	Fitted variable
SR	2LSS/3L	≥ 6	≥ 2	$H_T > 500$	BDT
CR Conv.	$e^{\pm}e^{\pm}\|\|e^{\pm}\mu^{\pm}$	$4 \leq N_j < 6$	≥ 1	$m_{ee}^{CV} \in [0, 0.1\ \text{GeV}]$ $200 < H_T < 500$ GeV	m_{ee}^{PV}
CR HF e	$eee \,\|\|\, ee\mu$	-	= 1	$100 < H_T < 250$ GeV	counting
CR HF μ	$e\mu\mu \,\|\|\, \mu\mu\mu$	-	= 1	$100 < H_T < 250$ GeV	counting
CR ttW	$e^{\pm}\mu^{\pm}\|\|\mu^{\pm}\mu^{\pm}$	≥ 4	≥ 2	$m_{ee}^{CV} \notin [0, 0.1\ \text{GeV}]$, $\|\eta(e)\| < 1.5$ for $N_b = 2$, $H_T < 500$ GeV or $N_j < 6$ for $N_b \geq 3$, $H_T < 500$ GeV	Σp_T^{ℓ}

1ℓ/2ℓOS

- Event signature characterized by one or two OS leptons and high jet multiplicity and b-jet multiplicities
- Main background: tt+jets (incl heavy-flavor) production, which is challenging to model accurately by the MC simulation
- Signal extracted via profile likelihood fit across all event categories including for a complex model of systematic uncertainties

ATLAS-CONF-2021-013



First Evidence of $t\bar{t}t\bar{t}$ Production

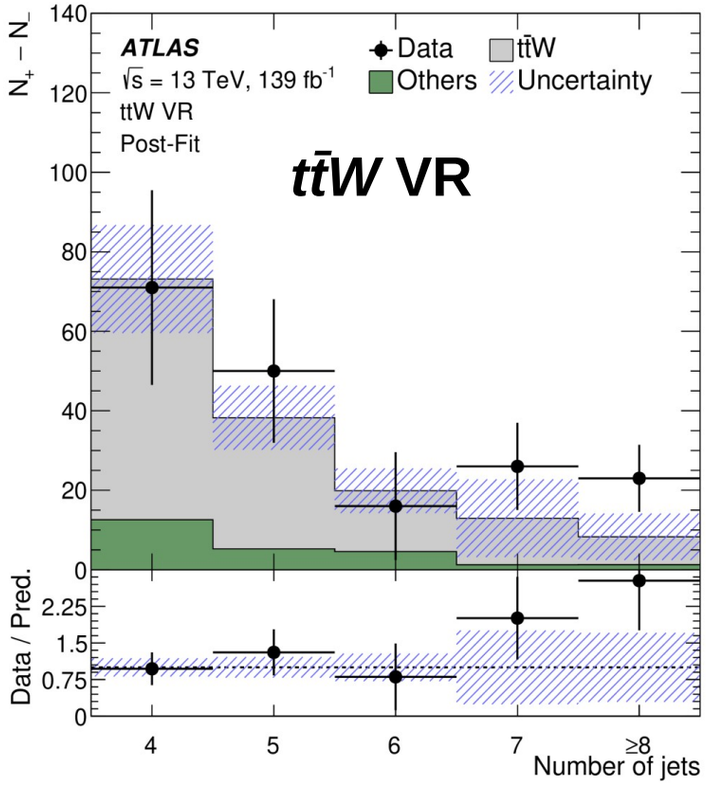
[Eur. Phys. J. C 80 (2020) 1085]

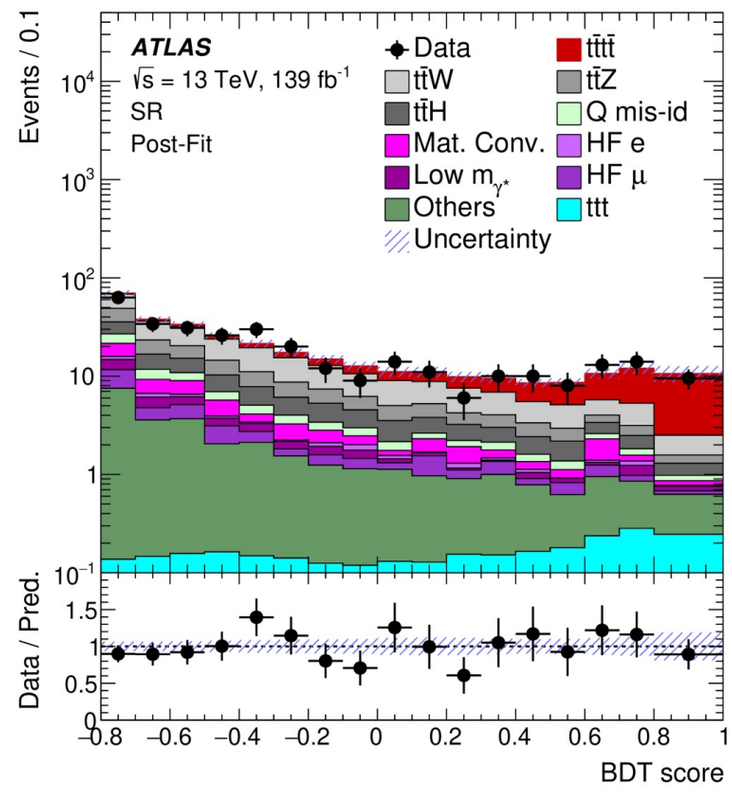
- First evidence of $t\bar{t}t\bar{t}$ production in SSML at ATLAS, observed (expected) significance 4.3(2.4)σ

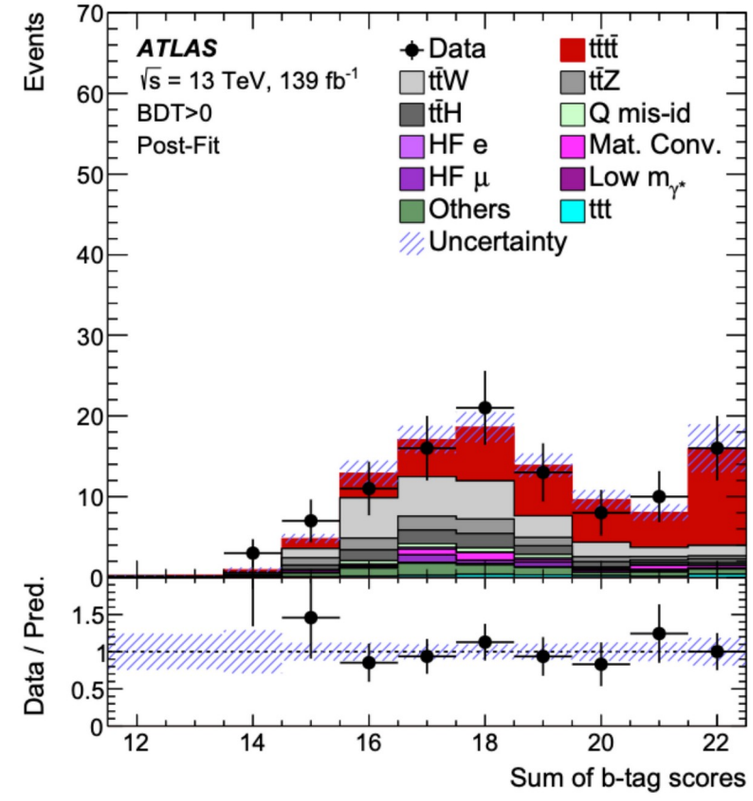
$$\mu = 2.0^{+0.4}_{-0.4}(\text{stat})^{+0.7}_{-0.4}(\text{syst}) = 2.0^{0.8}_{-0.6}$$

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

Parameter	$NF_{t\bar{t}W}$	$NF_{\text{Mat. Conv.}}$	$NF_{\text{Low } m_{\gamma^*}}$	$NF_{\text{HF } e}$	$NF_{\text{HF } \mu}$
Value	1.6 ± 0.3	1.6 ± 0.5	0.9 ± 0.4	0.8 ± 0.4	1.0 ± 0.4







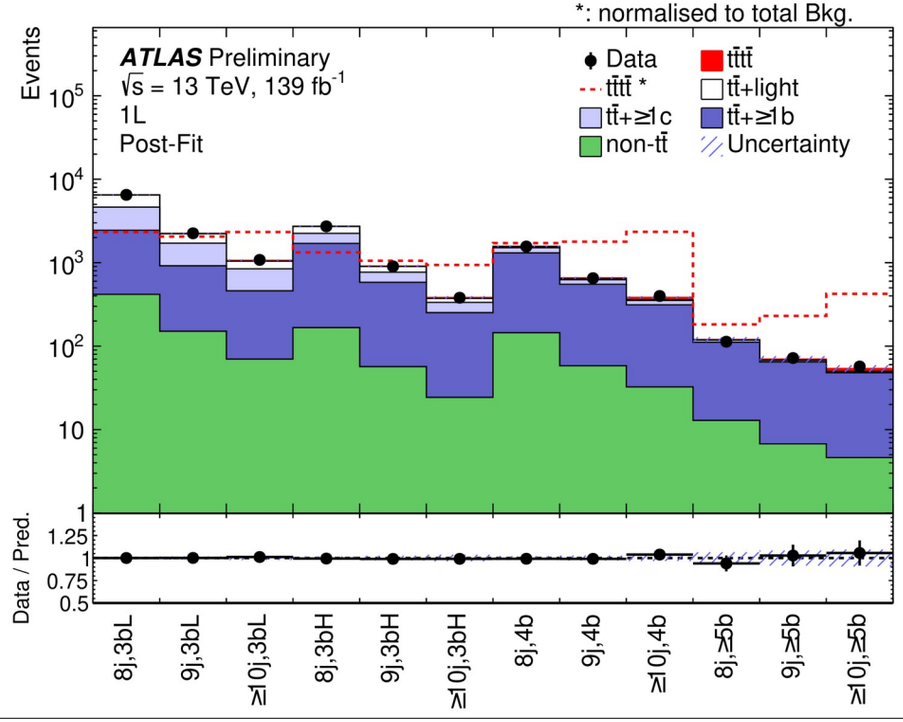
1ℓ/2ℓOS Result and Combination with SSML Channel

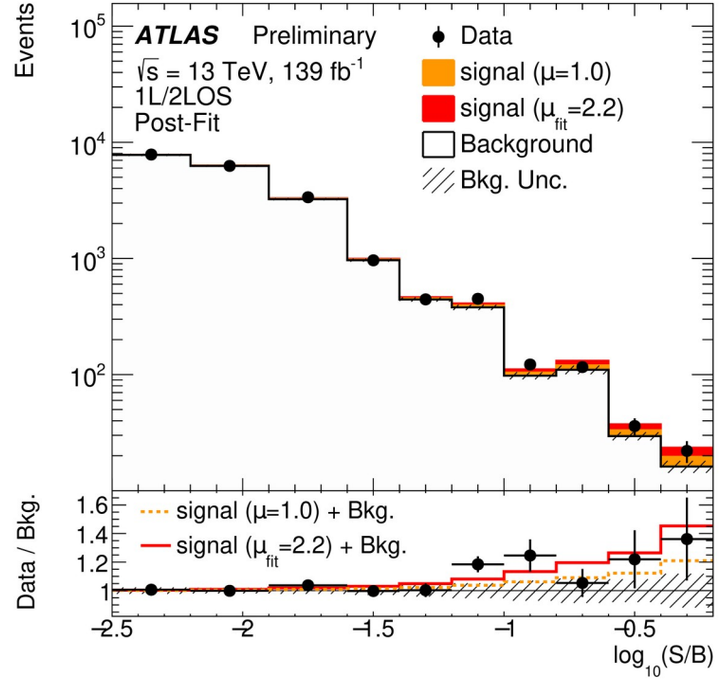
ATLAS-CONF-2021-013

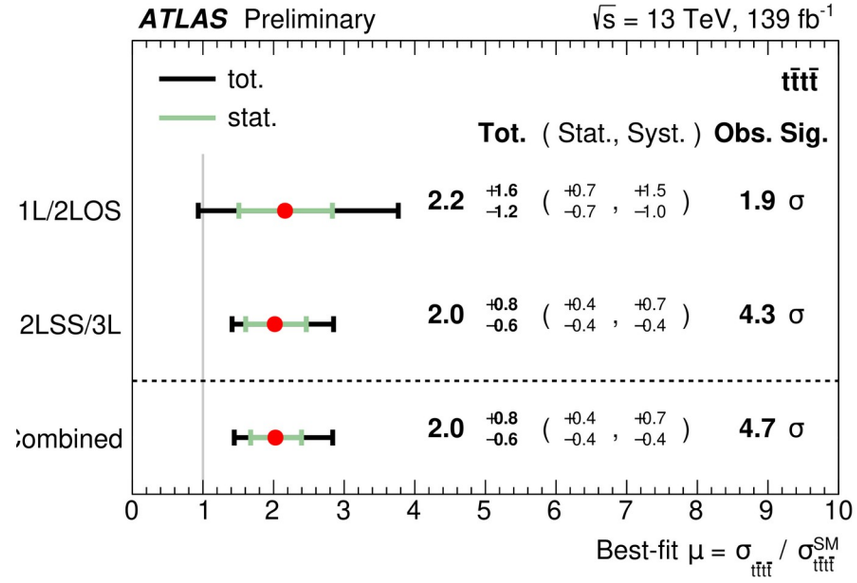
- Good agreement obtained between data and post-fit prediction
- Dominant uncertainties on signal strength from tttt theoretical cross-section and modelling, and from tt+>=1b modelling.
- The extracted signal strength for 1L/2LOS: $\mu = 2.2^{+0.7}_{-0.7}\,(\text{stat})^{+1.5}_{--1.0}\,(\text{syst}) = 2.2^{1.6}_{-1.2}$
- The combined four-top-quark production cross section is measured to be with a corresponding observed (expected) signal significance of 4.7 (2.6) standard deviations over background-only hypothesis

$$\sigma_{t\bar{t}t\bar{t}} = 25^{+7}_{-6}\ \text{fb} \qquad \sigma^{SM}_{t\bar{t}t\bar{t}} = 12.0 \pm 2.4\ \text{fb}$$

- Consistent within 2.0 standard deviations with the Standard Model expectation



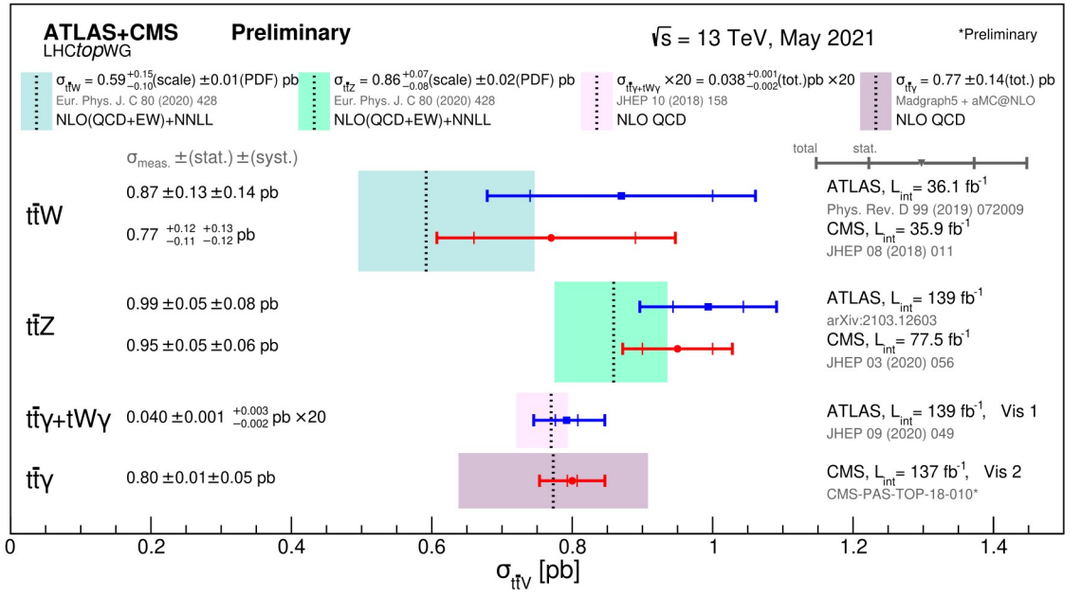


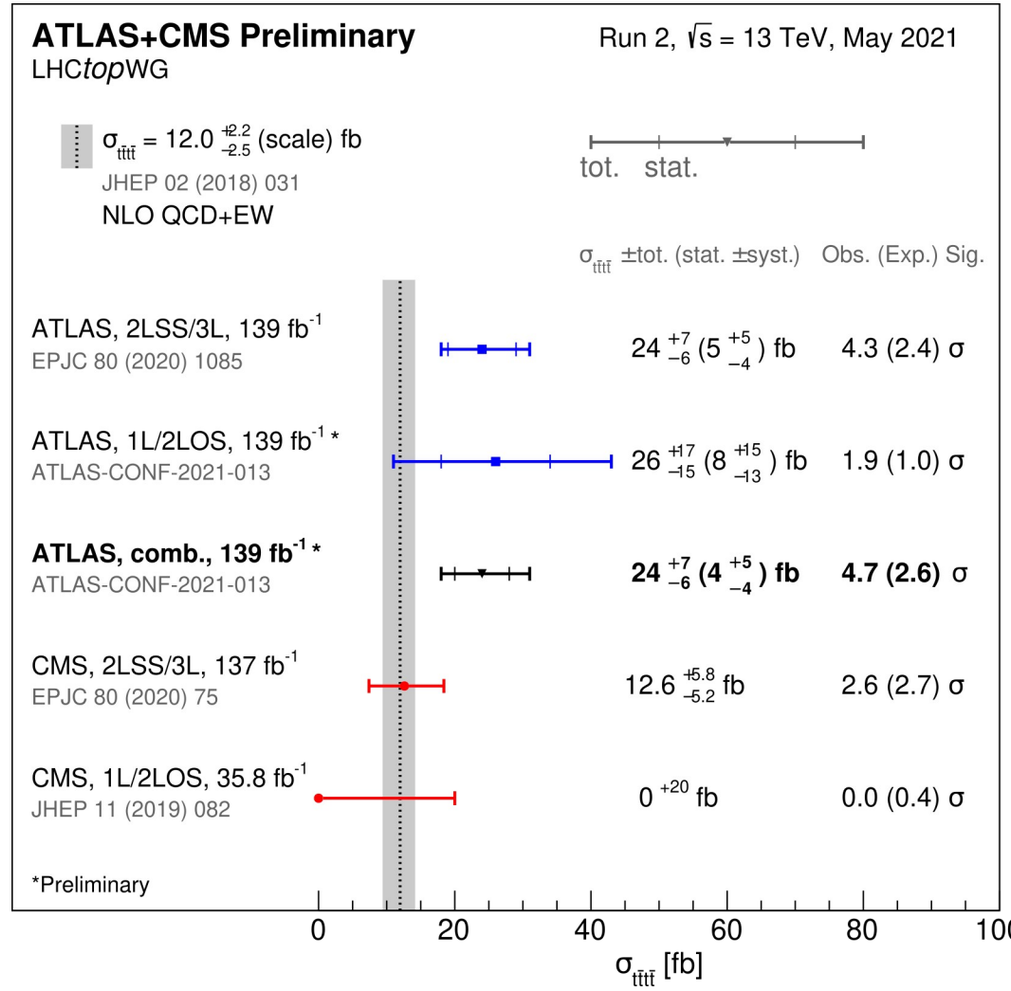


Summary

- LHC has made measurements from precision to rarity using top quarks
  - ATLAS performs the first **differential measurement** in $t\bar{t}Z$, important for new physics searches via anomalous couplings between top and weak bosons
  - Precision measurements in inclusive $t\bar{t}\gamma$ cross section reaching **2.4%** precision in eμ
  - **Observation** of tZq process at ATLAS
  - **Evidence** for four-top quark production established at ATLAS

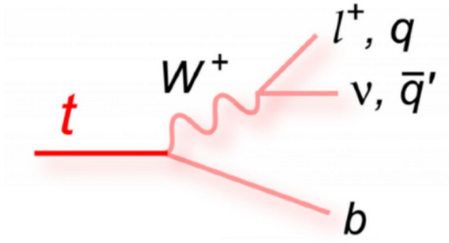
Stay tuned !



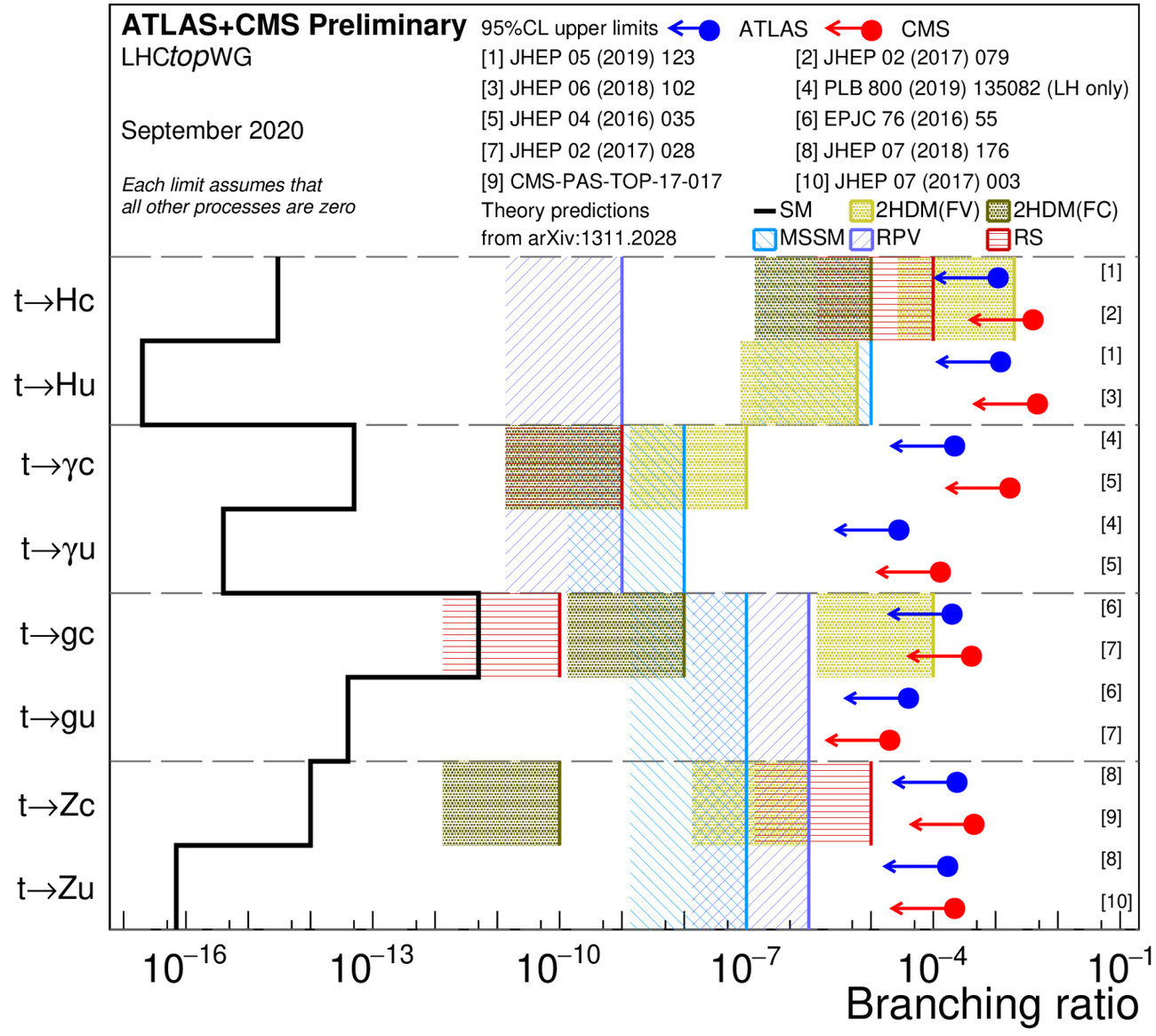


BACKUP

FCNC Searches at the LHC



- Flavor changing neutral current decays can occur at one-loop level, but highly suppressed by GIM mechanism in SM
- GIM suppression can be relaxed in several BSM scenarios, leads to various single top production and top decay processes [arXiv:hep-ph/0409342]
- The rarity of such kinds of decays in SM would provide a clear indirect signal of new physics
  - ➔ 2HDM w/ and w/o flavor conservation
  - ➔ Minimal Supersymmetric Standard Model
  - ➔ R-parity violation
  - ➔ Extra dimensions



Analysis Strategy (SS/ML Channel)

Eur. Phys. J. C 80 (2020) 1085

- Process characterised by leptonic signatures creating a cleaner signal
  - ➔ Main challenge is handling of dominant $t\bar{t}W$+jets background
    - Mismodelled at high jet multiplicities
    - Dedicated CR and VR for proper $t\bar{t}W$+jets estimation
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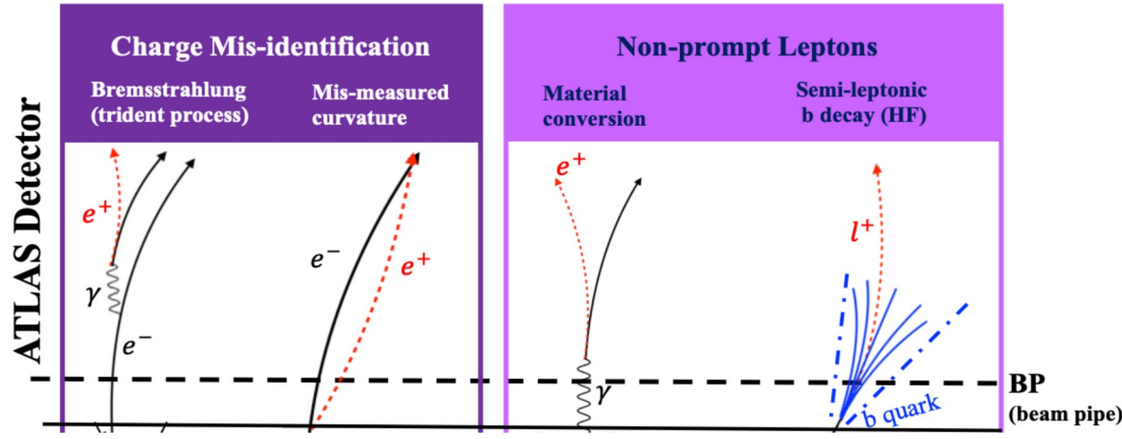

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CR HF e	$eee \ \| \| \ ee\mu$	-	$= 1$	$100 < H_T < 250$ GeV	counting
CR HF μ	$e\mu\mu \ \| \| \ \mu\mu\mu$	-	$= 1$	$100 < H_T < 250$ GeV	counting
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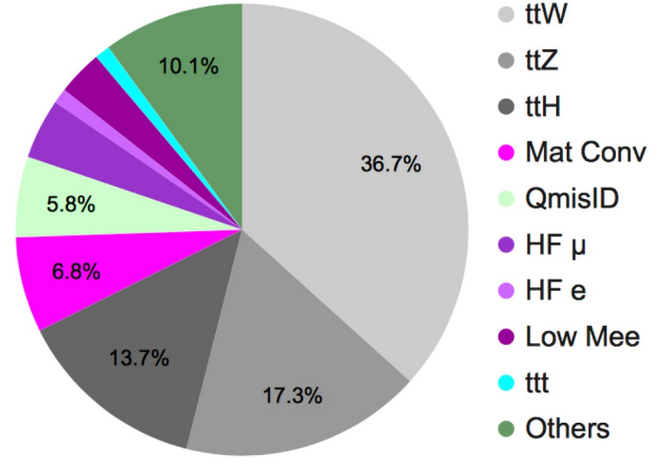
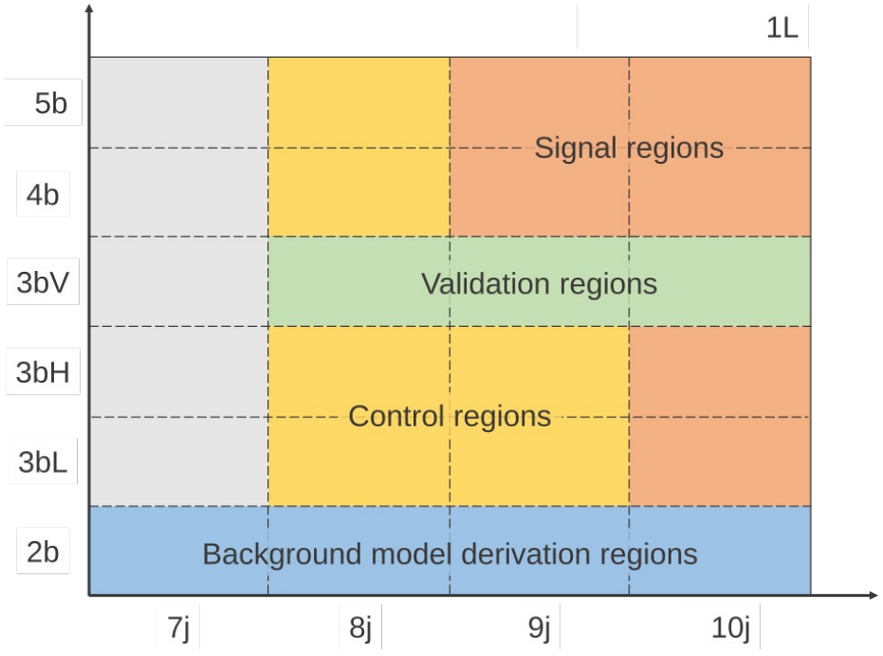
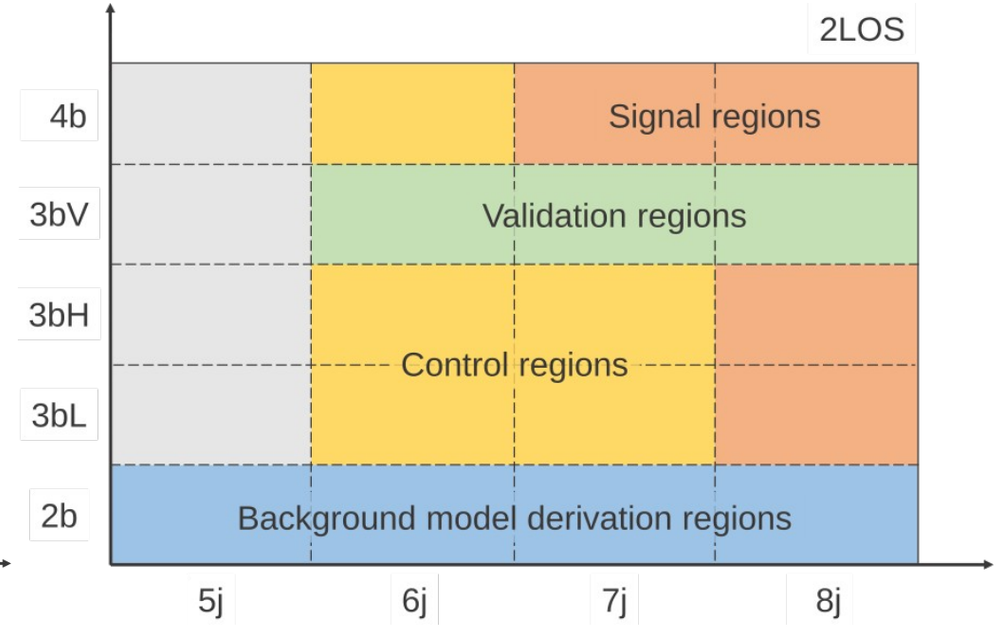
Backgrounds:

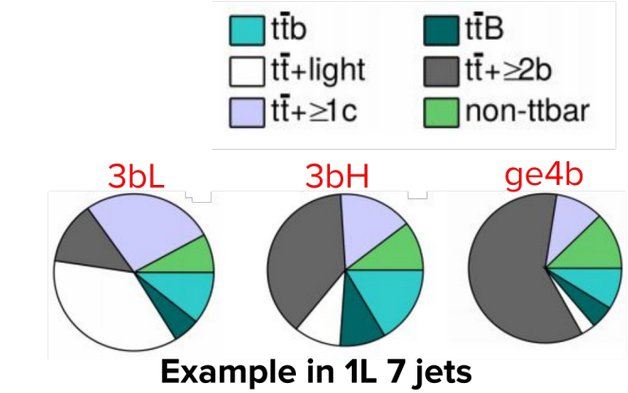


Analysis Strategy (1L/2LOS Channel)





Nb@70%	Nb@60%	Nb@85%	Name
=3	≤2	-	3bL
=3	=3	≥4	3bH
≥4	-	-	ge4b



Example in 1L 7 jets

Analysis Strategy (1ℓ/2ℓOS Channel)

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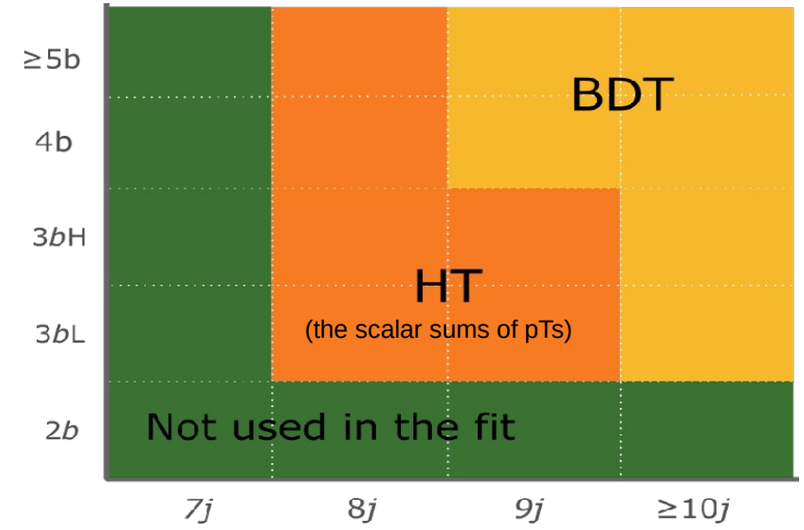
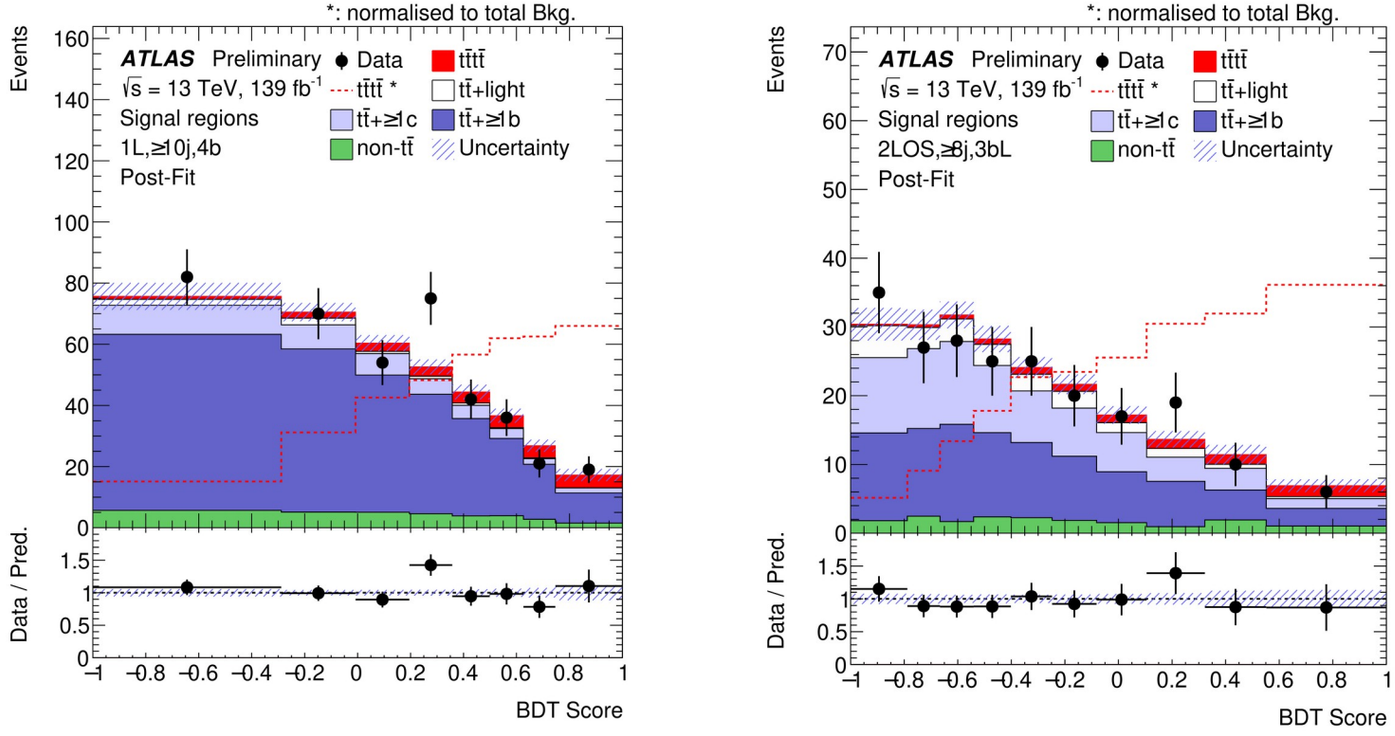
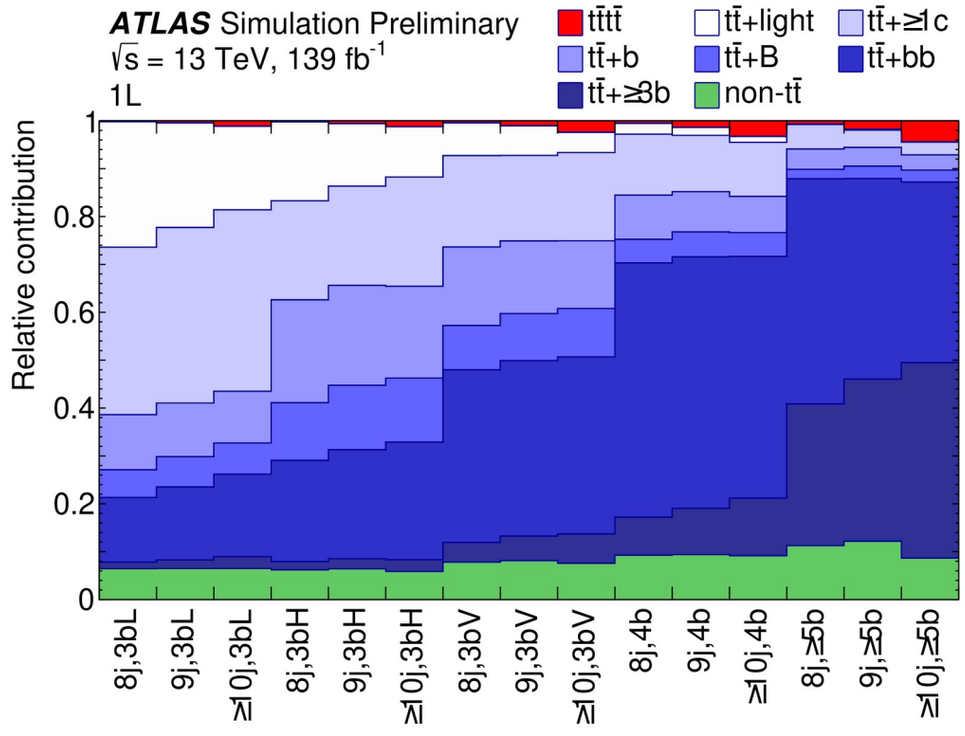
- Event signature characterized by one or two OS leptons and high jet multiplicity and b-jet multiplicities
- Main background: tt+jets (incl heavy-flavor) production, which is challenging to model accurately by the MC simulation
- Signal extracted via profile likelihood fit across all event categories including for a complex model of systematic uncertainties

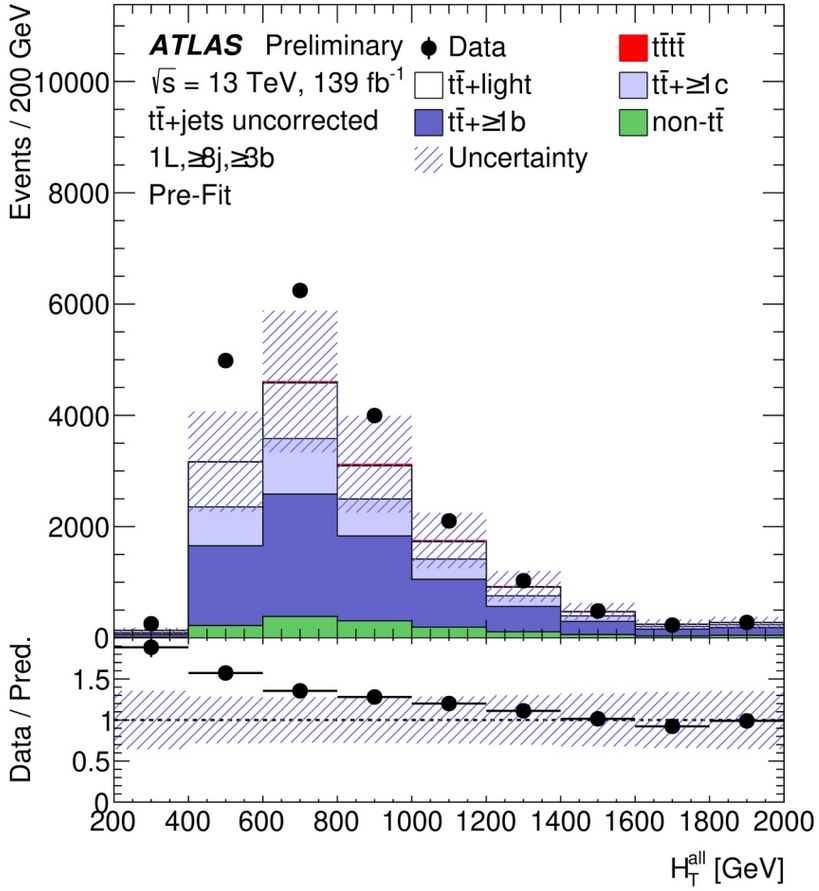


Example BDTs

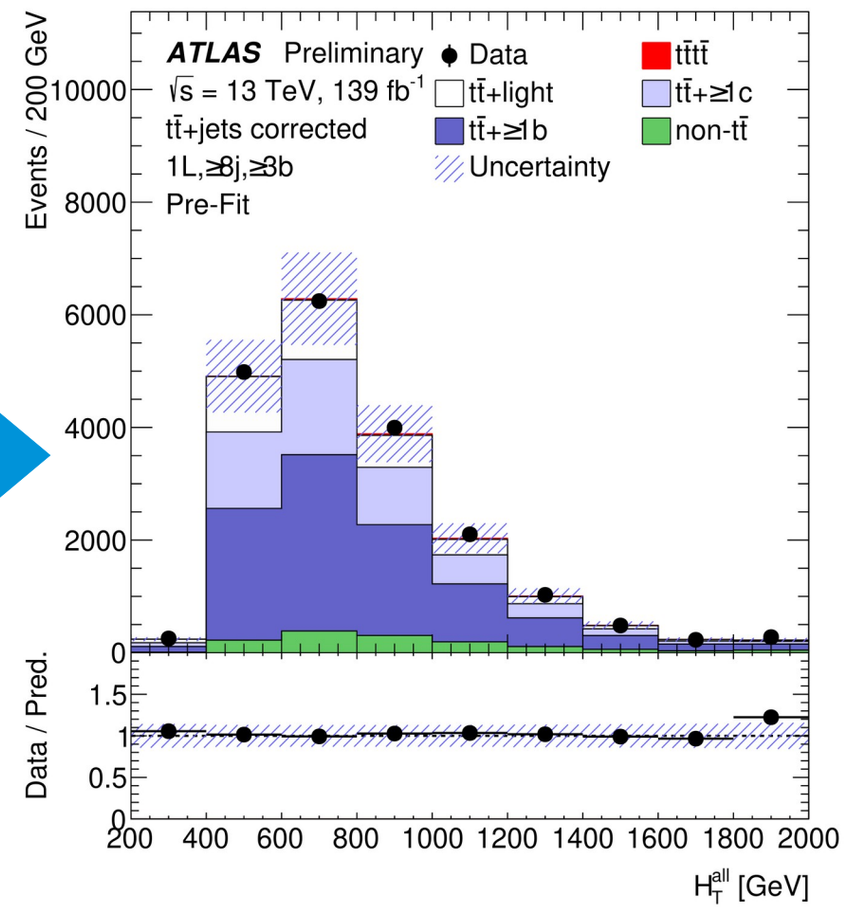




Analysis Strategy (1L/2LOS Channel) ATLAS-CONF-2021-013



Reweighting



Systematic Uncertainties ATLAS-CONF-2021-013

Uncertainty source	σ_μ	
Signal Modelling		
$t\bar{t}t\bar{t}$ cross section	+0.75	-0.20
$t\bar{t}t\bar{t}$ modelling	+0.66	-0.27
Background Modelling		
$t\bar{t}$+≥1b modelling	+0.72	-0.59
$t\bar{t}$+≥1c modelling	+0.41	-0.31
$t\bar{t}$+jets reweighting	+0.30	-0.25
Other background modelling	+0.30	-0.24
$t\bar{t}$+light modelling	+0.15	-0.12
Experimental		
Jet energy scale and resolution	+0.49	-0.30
b-tagging efficiency and mis-tag rates	+0.38	-0.26
MC statistical uncertainties	+0.21	-0.19
Luminosity	+0.07	-0.03
Other uncertainties	+0.05	-0.03
Total systematic uncertainty	+1.45	-1.04
Statistical uncertainty	+0.67	-0.65