Rare top quark production

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On behalf of the ATLAS Collaboration

15th International Workshop on Top-Quark Physics

TOP 2022

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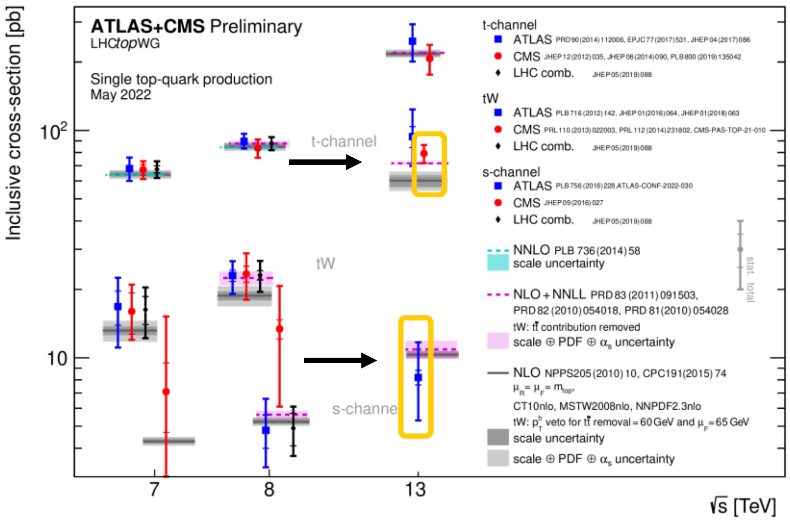
SURPRISE!

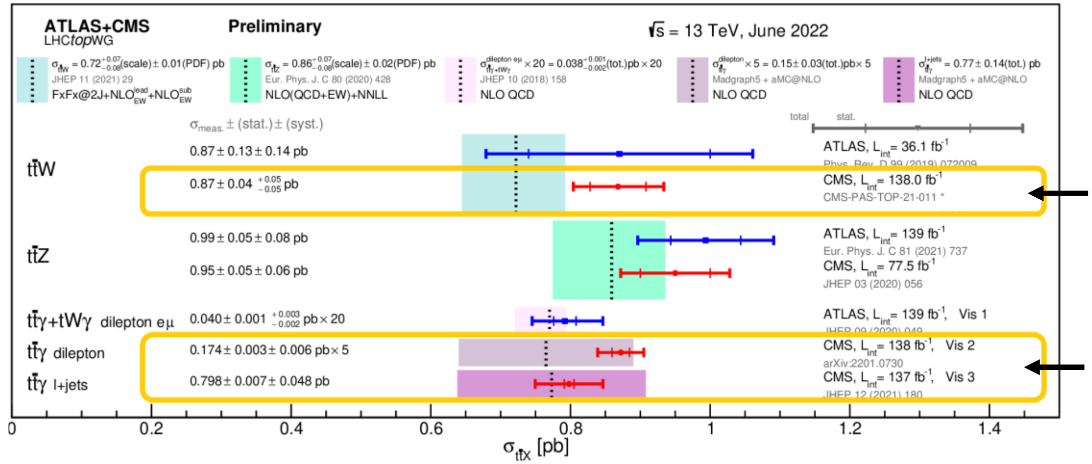
Introduction

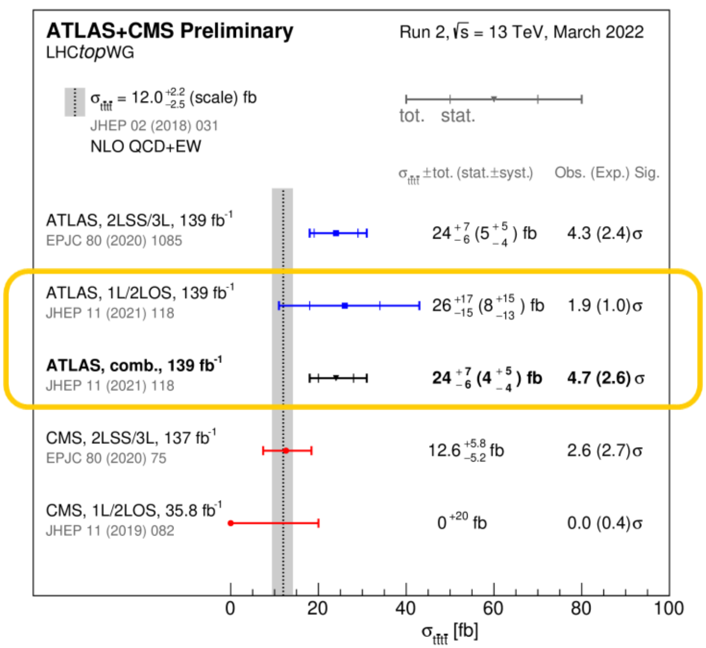
- LHC is in an era of precision top quark measurements
- Rarest processes with the lowest cross sections may be probed
- Stringent tests of the Standard Model
- Tiny anomalies may appear from new physics, and be explored through Effective Field Theory

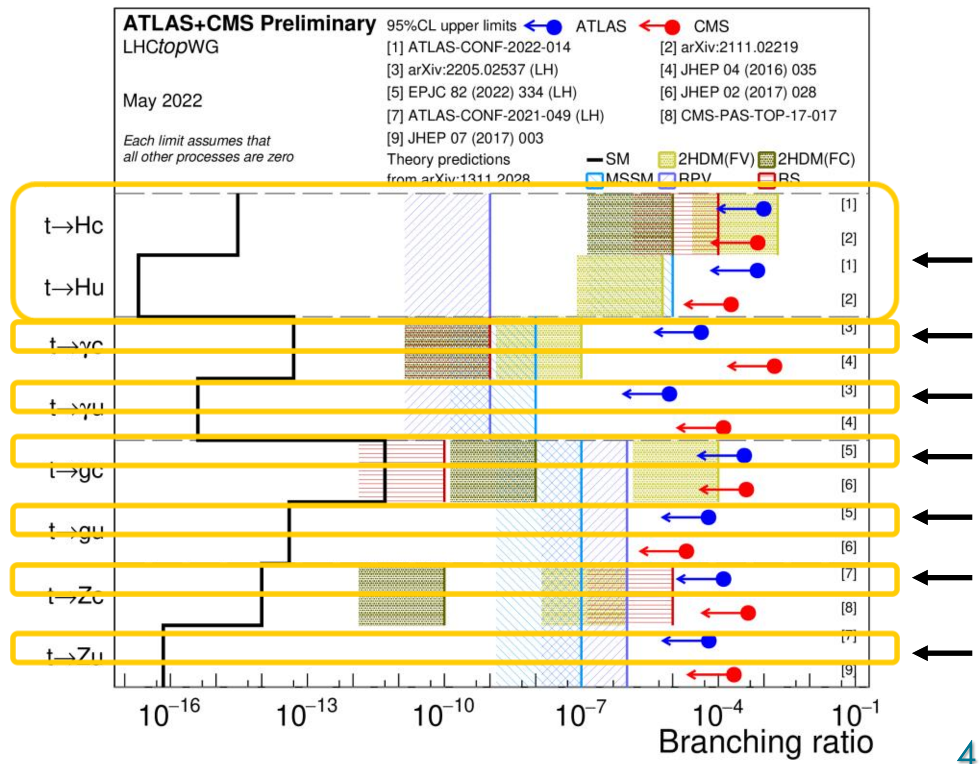
Recent history of Rare Top Processes – 17+ new results in the last year!

ATL-PHYS-PUB-2022-031 ATL-PHYS-PUB-2022-030



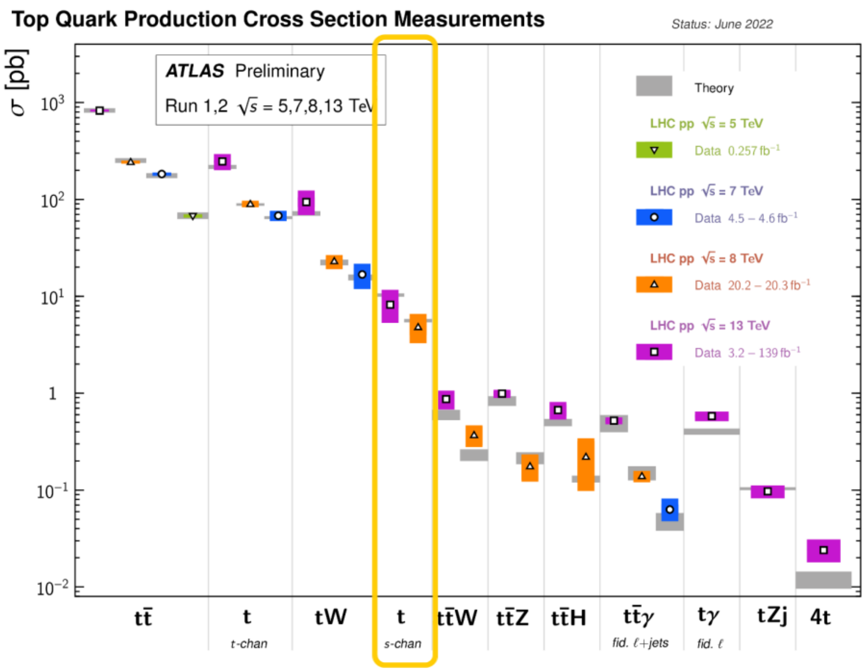






See Jan Van Der Linden's Talk!

Introduction



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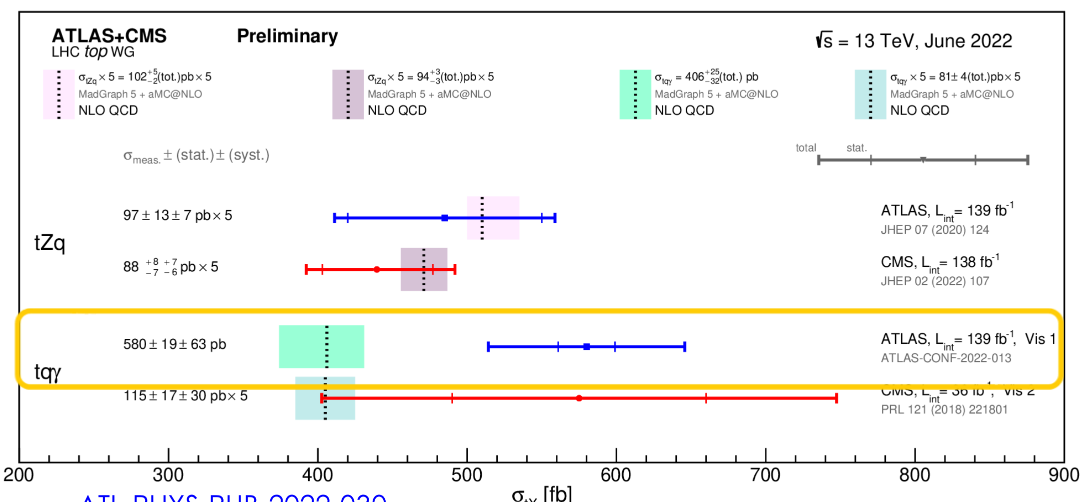

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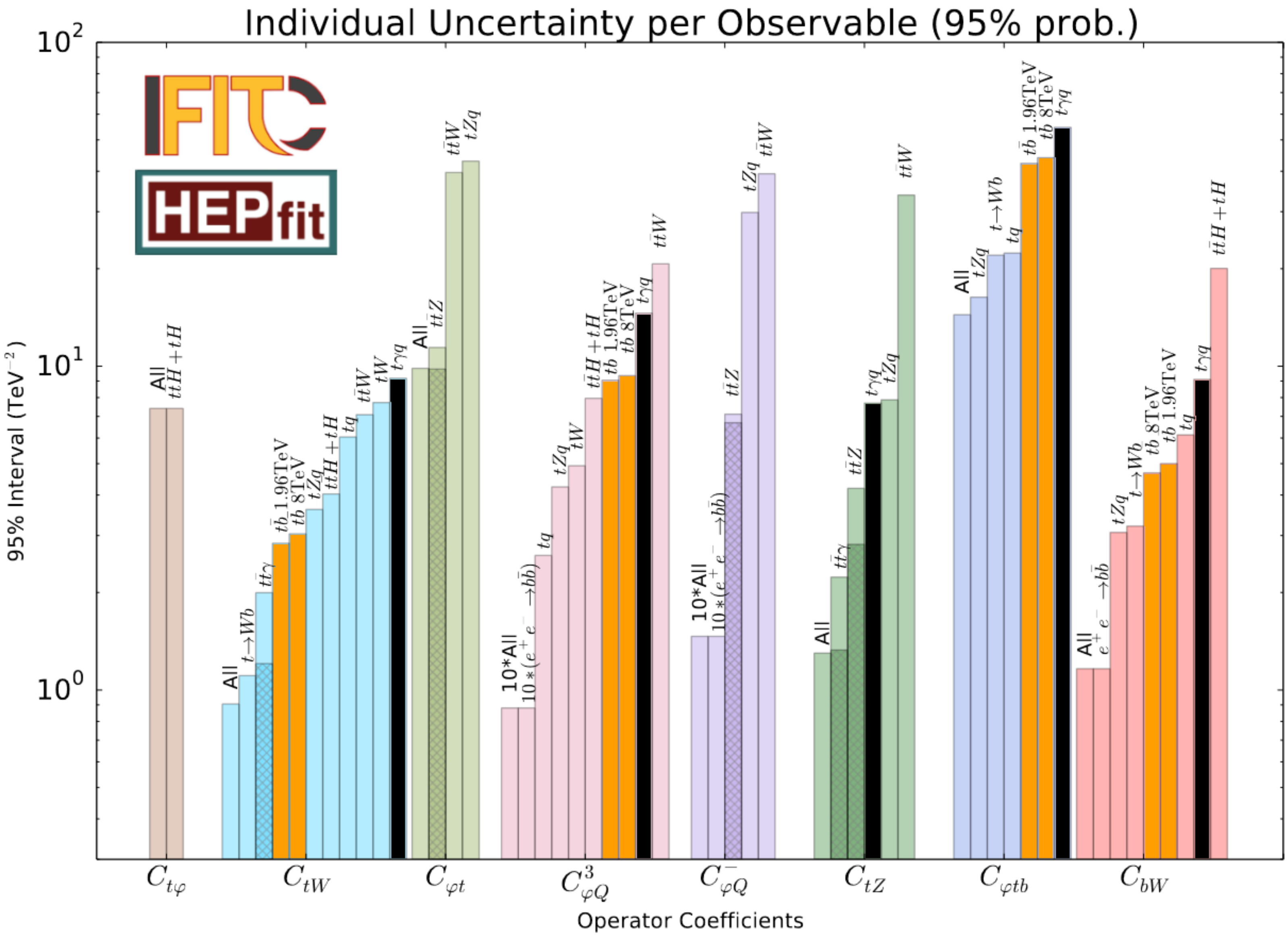
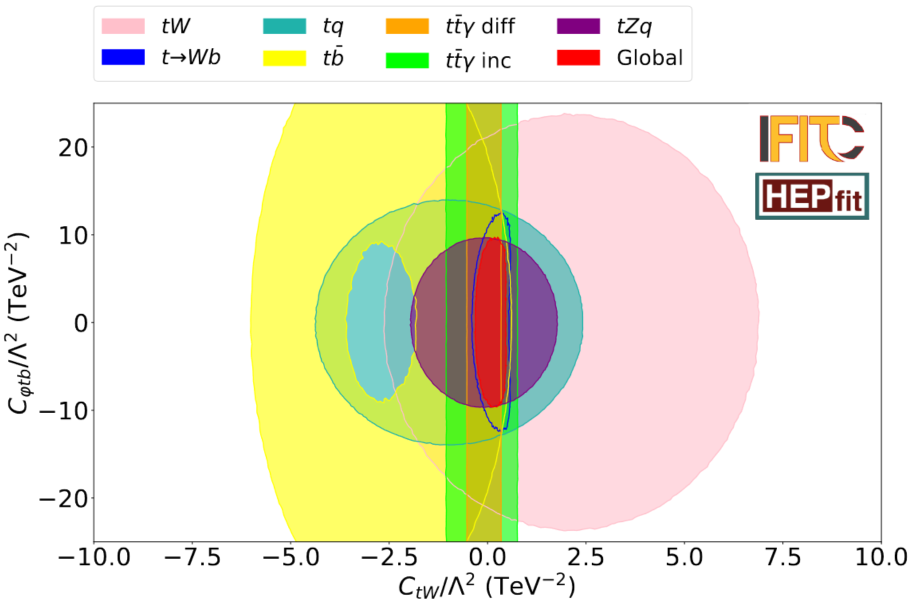
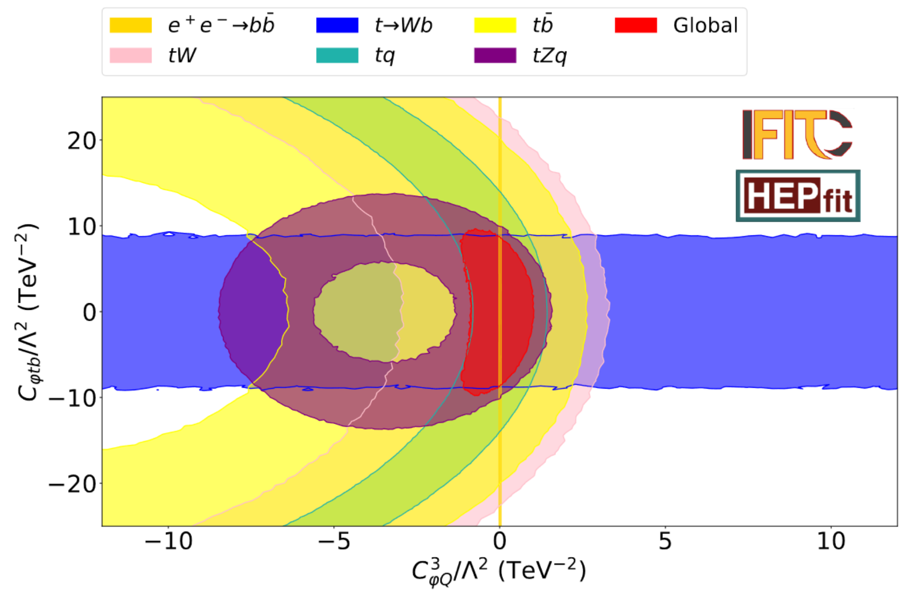
EFT Importance of Rare Top Processes



JHEP 02 (2022) 032

EFT Importance of Rare Top Processes





s-channel and t-channel probe same set of operators but from different 'directions'

Good candidates for combination with tZq and $tq\gamma$
(Essentially t-channel single-top with an additional vertex)

See Josh McFayden, Jonathan Wilson (and many others'!) talks for EFT combinations with rare top processes!

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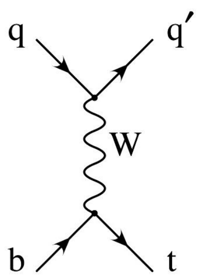
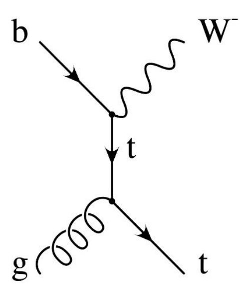
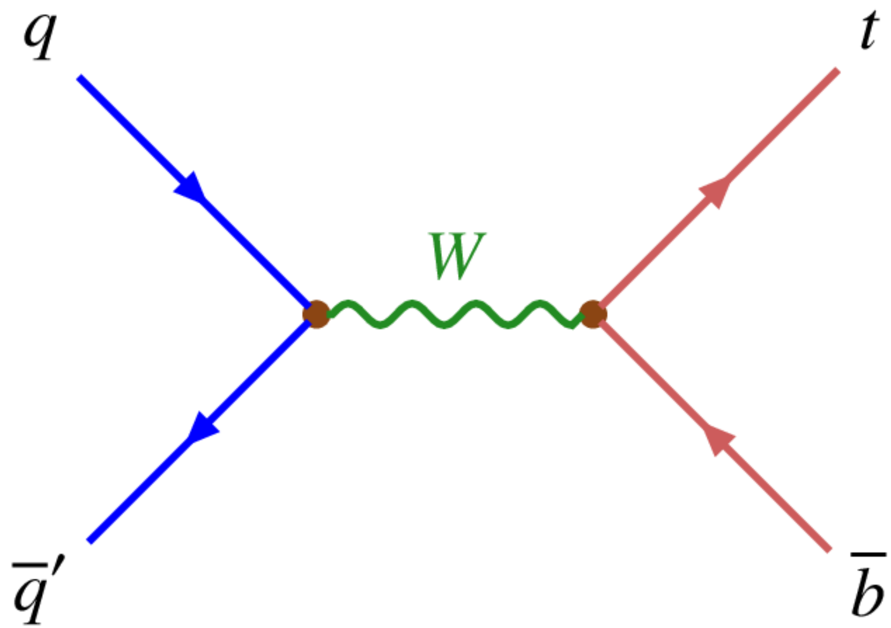
Measurement of single-top *s*-channel

- Single-top quark production via the electroweak interaction, the Wtb vertex
- s-channel has the lowest predicted cross-section of the three leading-order diagrams (compared to t-channel and associated tW)





- Only observed by a combination of results from CDF and D0 collaborations (PRL 112 (2014) 231803) (valence anti-quarks!)
- Sensitive to anomalous couplings

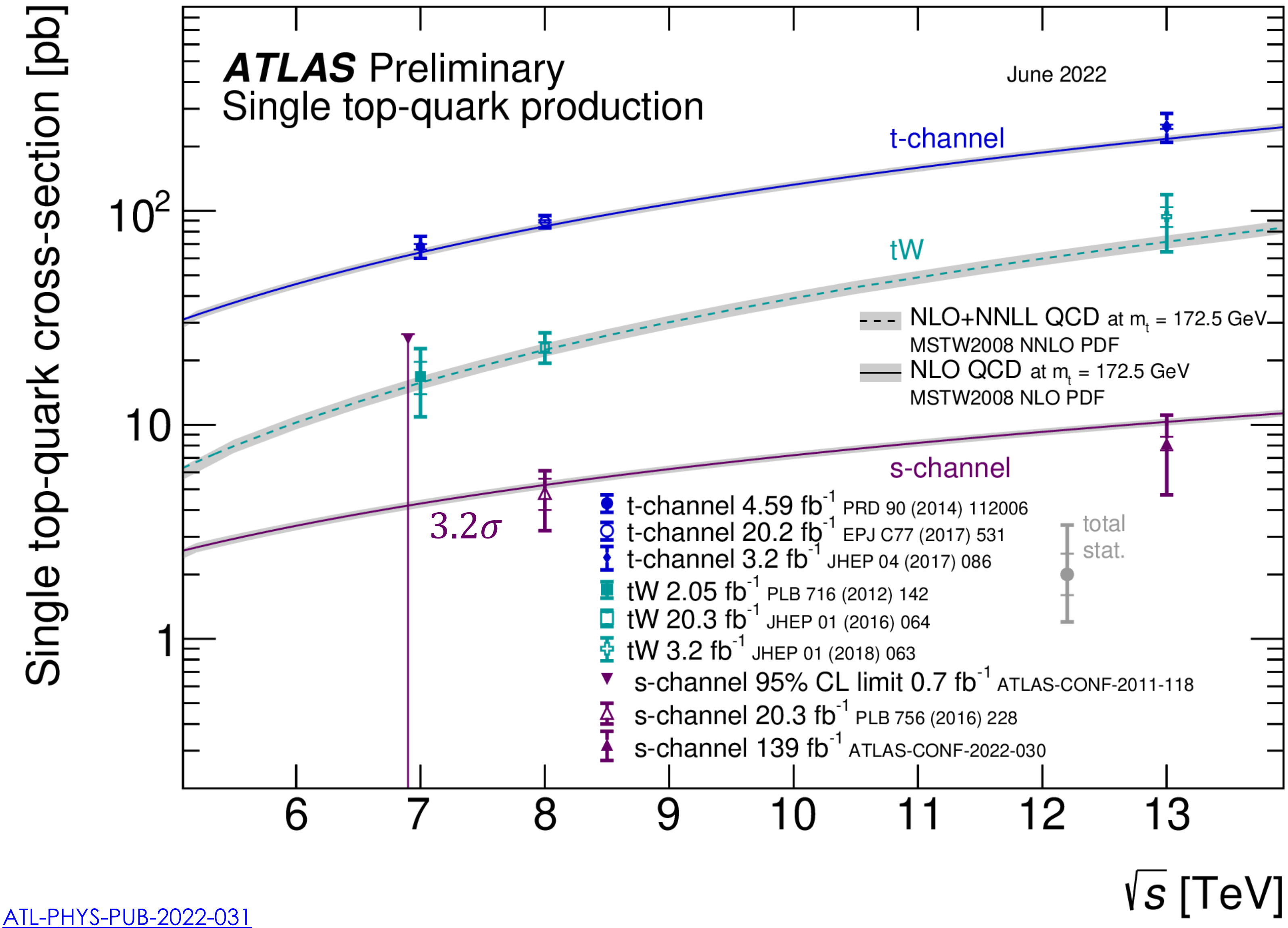


$$\sigma_{\mathrm{SM}} = 10.32^{+0.29}_{-0.24}(\mathrm{scales}) \pm 0.29(\mathrm{PDF} + \alpha_s)\ \mathrm{pb}$$

$$= \mathbf{10.32^{+0.40}_{-0.36}\ pb}$$

Calculated at NLO in QCD with HATHOR

$\mathrm{PDF} + \alpha_s$ uncertainties from PDF4LHC prescription



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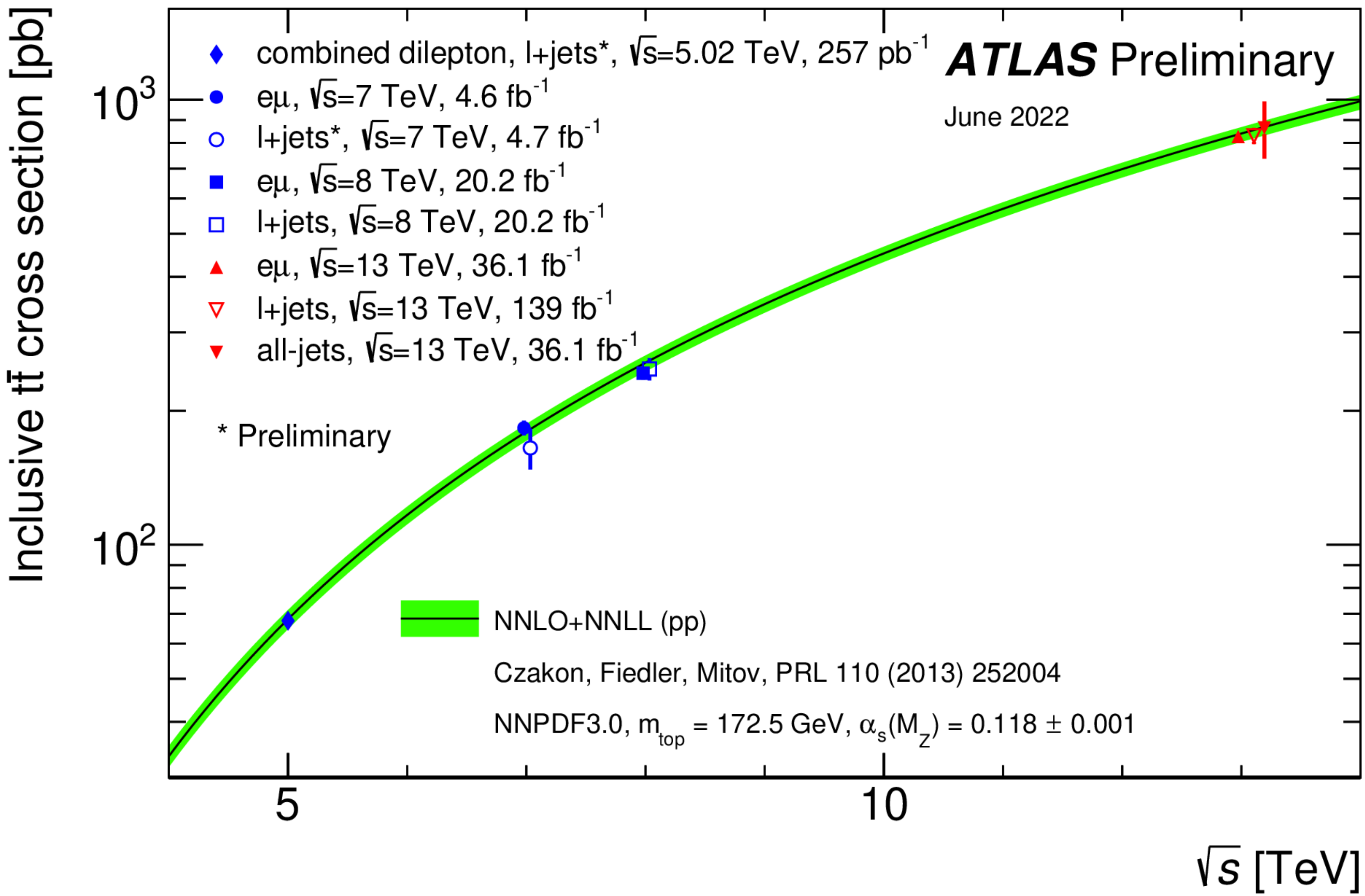

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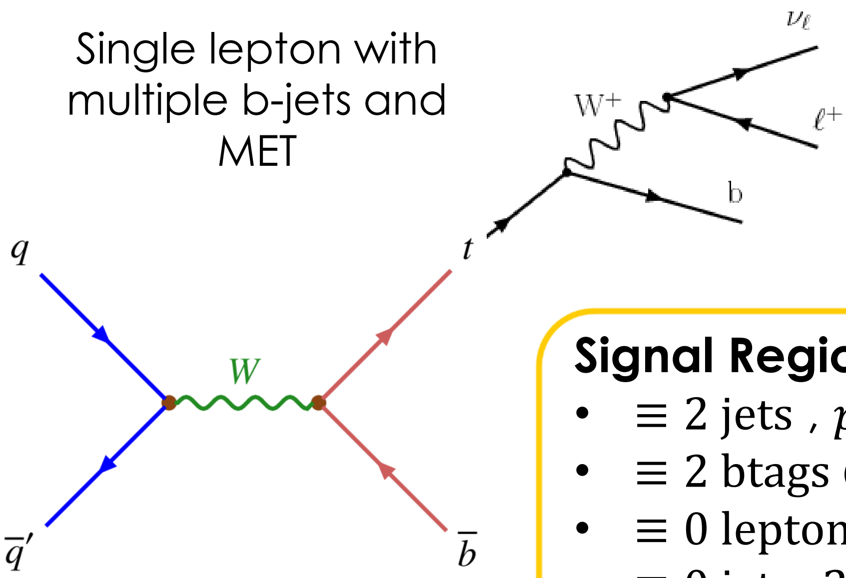
Single lepton with multiple b-jets and MET



Pre-selection

- $\equiv 1\ e/\mu$, $p_T > 30$ GeV
- $E_{\mathrm{T}}^{\mathrm{miss}} > 35$ GeV , $m_{\mathrm{T}}(W) > 30$ GeV
- $\equiv 2$ jets , $p_T > 25$ GeV , $|\eta| < 2.5$

Signal Region

- $\equiv 2$ jets , $p_T > 30$ GeV and ≥ 1 jet , $p_T > 40$ GeV
- $\equiv 2$ btags @ 77% WP
- $\equiv 0$ leptons , 10 GeV $< p_T <$ 30 GeV ($t\bar{t}$ dilepton)
- $\equiv 0$ jets , 20 GeV $< p_T <$ 30 GeV or $|\eta| > 2.5$ (t-channel)

$t\bar{t}$ Validation Regions

- $\equiv 3$ (4) jets , $p_T > 25$ GeV
- $\equiv 2$ btags @ 77% WP

W+jets Validation Region

- $\equiv 2$ jets , $p_T > 30$ GeV
- $\equiv 2$ btags @ 85% WP
- ≥ 1 jet failing btag @ 77% WP
- $\equiv 0$ leptons, 10 GeV $< p_T <$ 30 GeV

Process	Event yield Pre-fit
s-channel	$4\,200 \pm 710$
t-channel	$13\,000 \pm 2\,000$
tW	$3\,680 \pm 970$
$t\bar{t}$	$76\,000 \pm 12\,000$
W+jets	$21\,500 \pm 2\,900$
Z+jets, VV	$2\,400 \pm 1\,400$
Multijet	$2\,150 \pm 650$
Total	$123\,000 \pm 17\,000$

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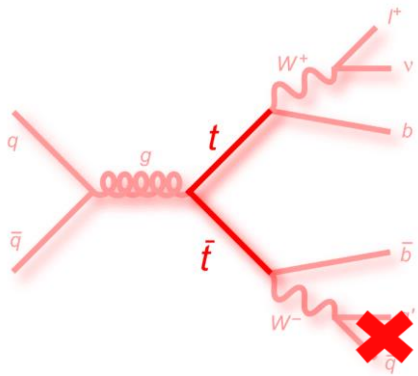
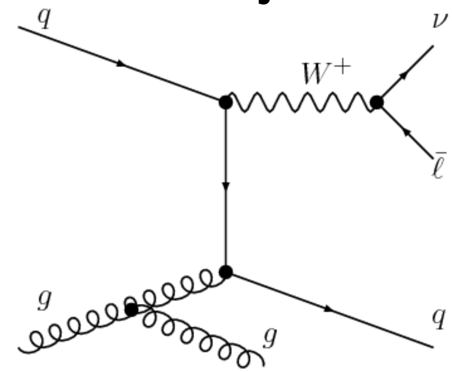
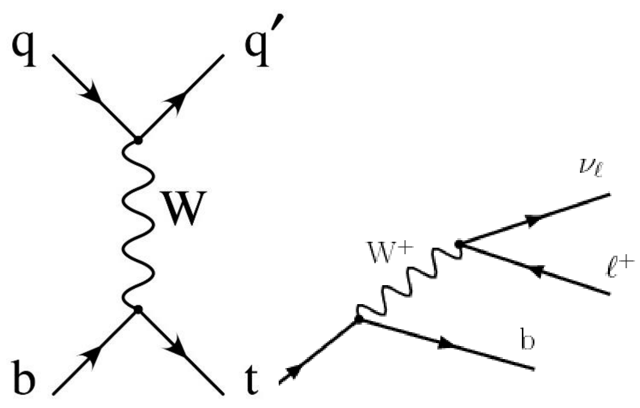
$t\bar{t}$ - 1L or 2L



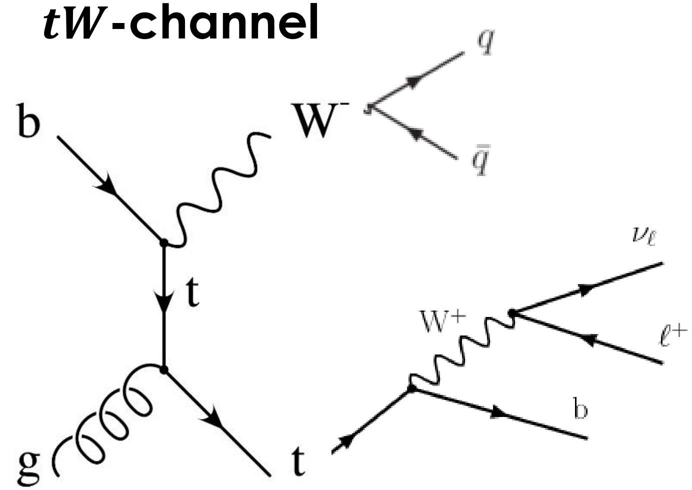
W+jets



t-channel



tW-channel



All modelled by MC simulations

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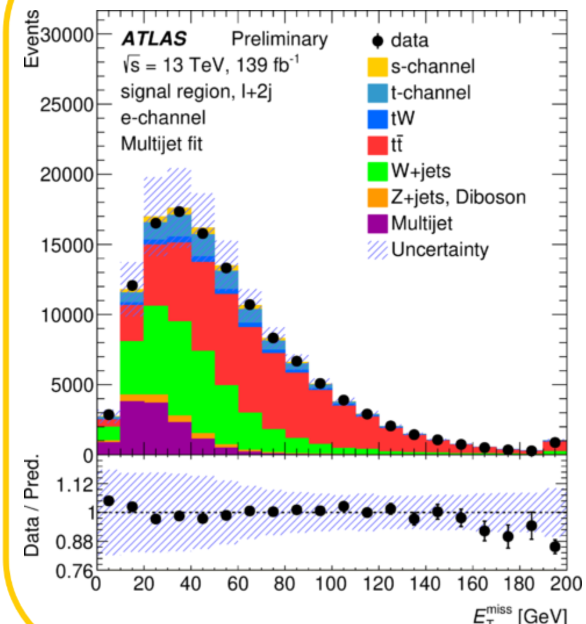
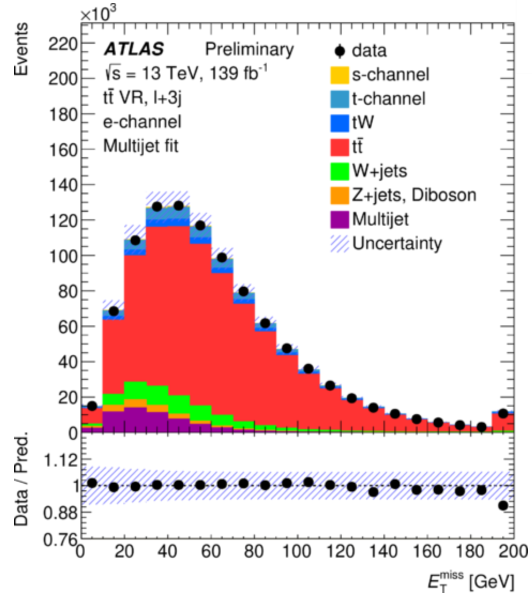
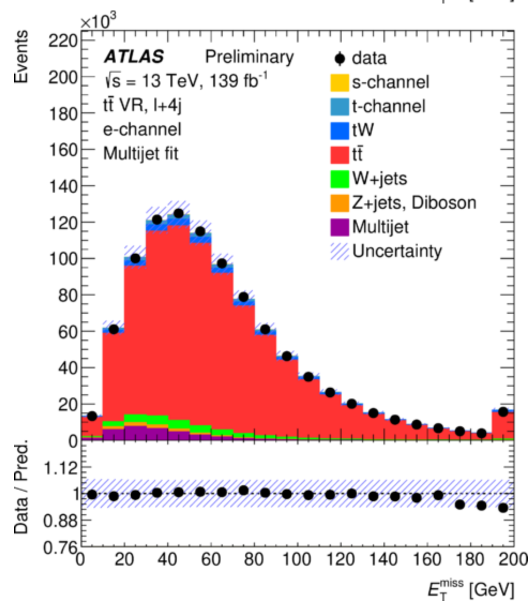
Signal Region

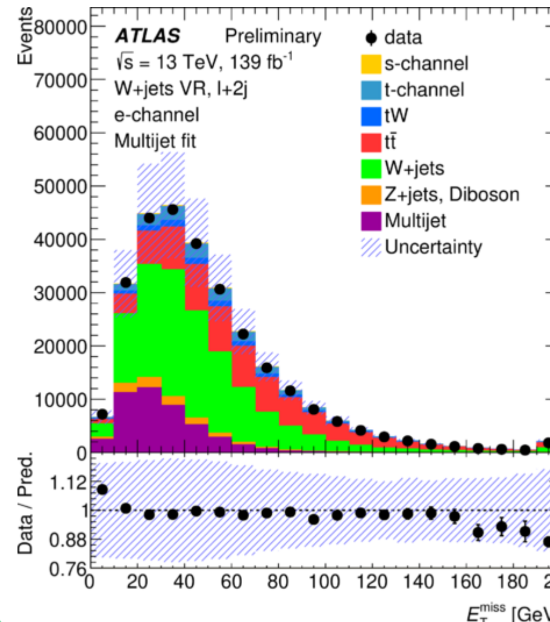


$t\bar{t}$ Validation Regions





W+jets Validation Region



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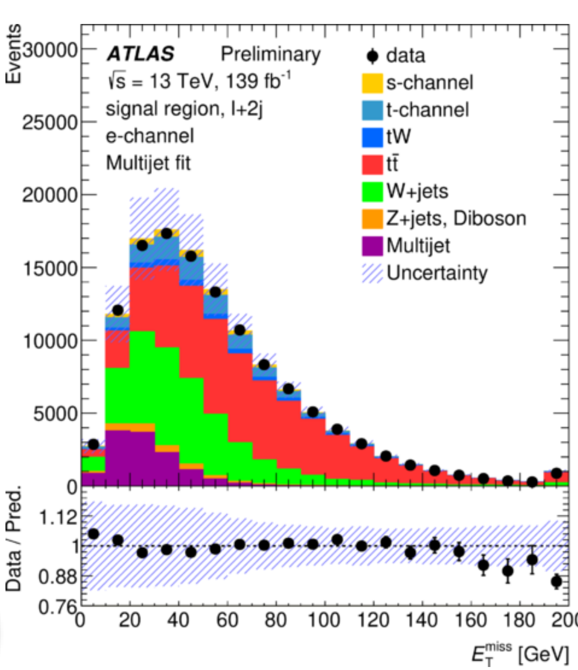
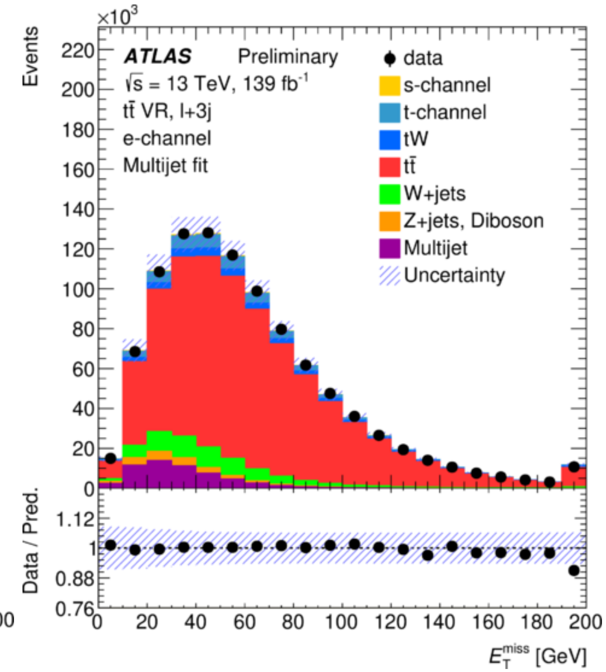
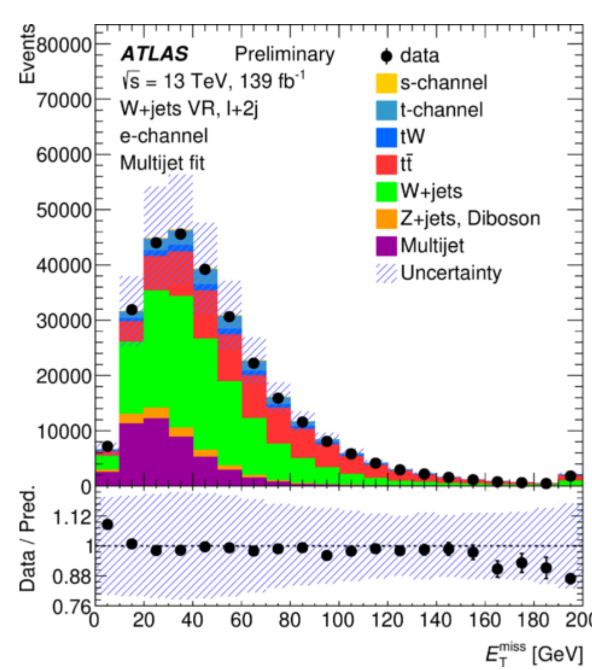
Multijet estimation in electron channel → **The Jet-Electron method**

Jets
Non-prompt leptons (HF decays)
Photon Conversions
} "electron"

- Dedicated selection on dijet events with large EM energy fractions (energy deposition in ECAL), appearing as "electrons" passing quality criteria
- B-tagging and MET requirements dropped to increase statistics
- Multijet normalisation extracted from binned maximum likelihood fit to data in loosened SR (with $t\bar{t}$ and W+jets free-floating) – process repeated in loosened VRs







Measurement of single-top s-channel

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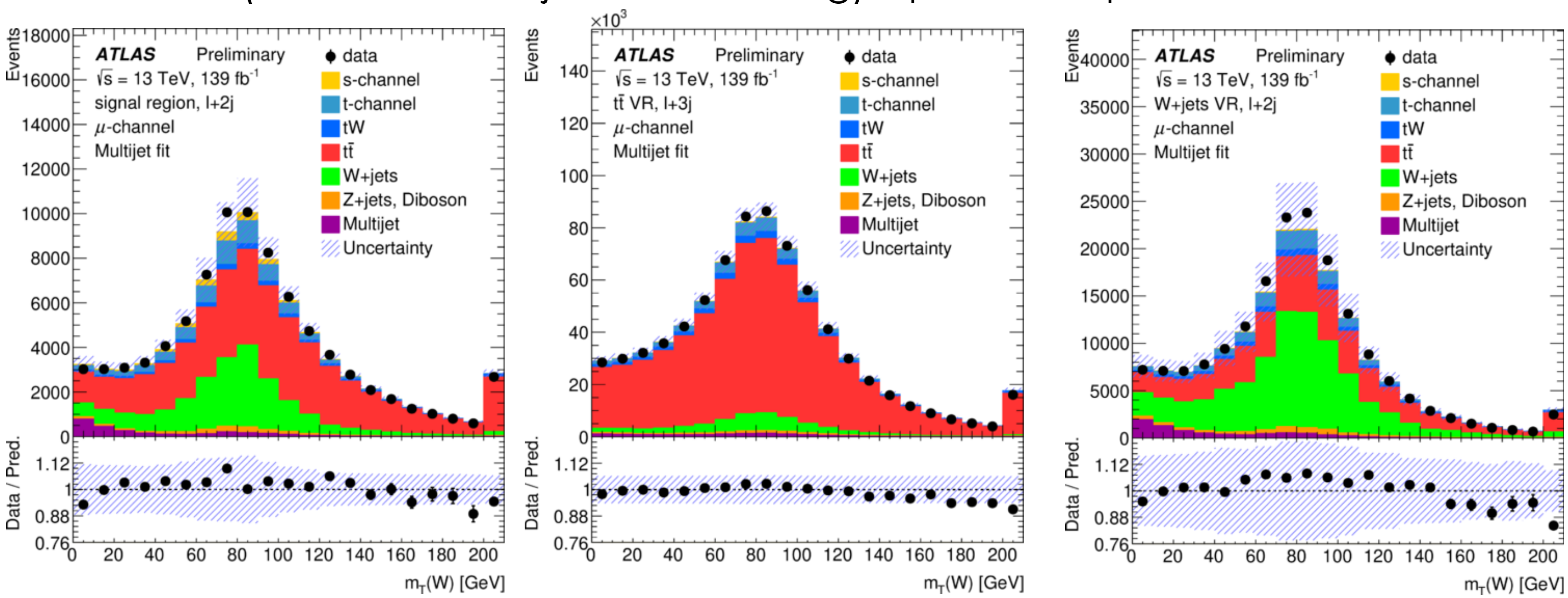
Multijet estimation in muon channel → **The Anti-Muon method**

Jets
Non-prompt leptons (HF decays) } "muon"

- Dedicated selection with inverted/modified muon identification criteria:
  - Calorimeter energy loss
  - Longitudinal impact parameter
  - Tracking and Calorimeter Isolation
- m_{T}^{W} requirements dropped to increase statistics
- Multijet normalisation extracted from binned maximum likelihood fit to data in loosened SR (with $t\bar{t}$ and W+jets free-floating) – process repeated in loosened VRs



Matrix Element Method (MEM) – for Signal and Background separation.
Used at Tevatron, and ATLAS at 8 TeV

$$\mathcal{P}(X \mid H_{\text{proc}}) = \int d\Phi \, \frac{1}{\sigma_{H_{\text{proc}}}} \frac{d\sigma_{H_{\text{proc}}}}{d\Phi} T_{H_{\text{proc}}}(X \mid \Phi)$$

This is a **per-event** likelihood calculation for the **hypothesis that a measured final state X is of a certain process H_{proc}**

The **normalised fully differential cross-section** gives the probability density for a scattering process H_{proc} to lead to a parton-level final state Φ as a function of the four-momenta of all outgoing particles.

The **transfer functions** map between the measured final state X and the parton-level state Φ, accounting for:

- Detector energy resolution
- Reconstruction and b-tagging efficiencies as a function of transverse momenta and pseudorapidities
- Permutations between the partons and the reconstructed objects.

(Likelihood values consider 2 signal and 8 background processes/diagrams which match the final state)

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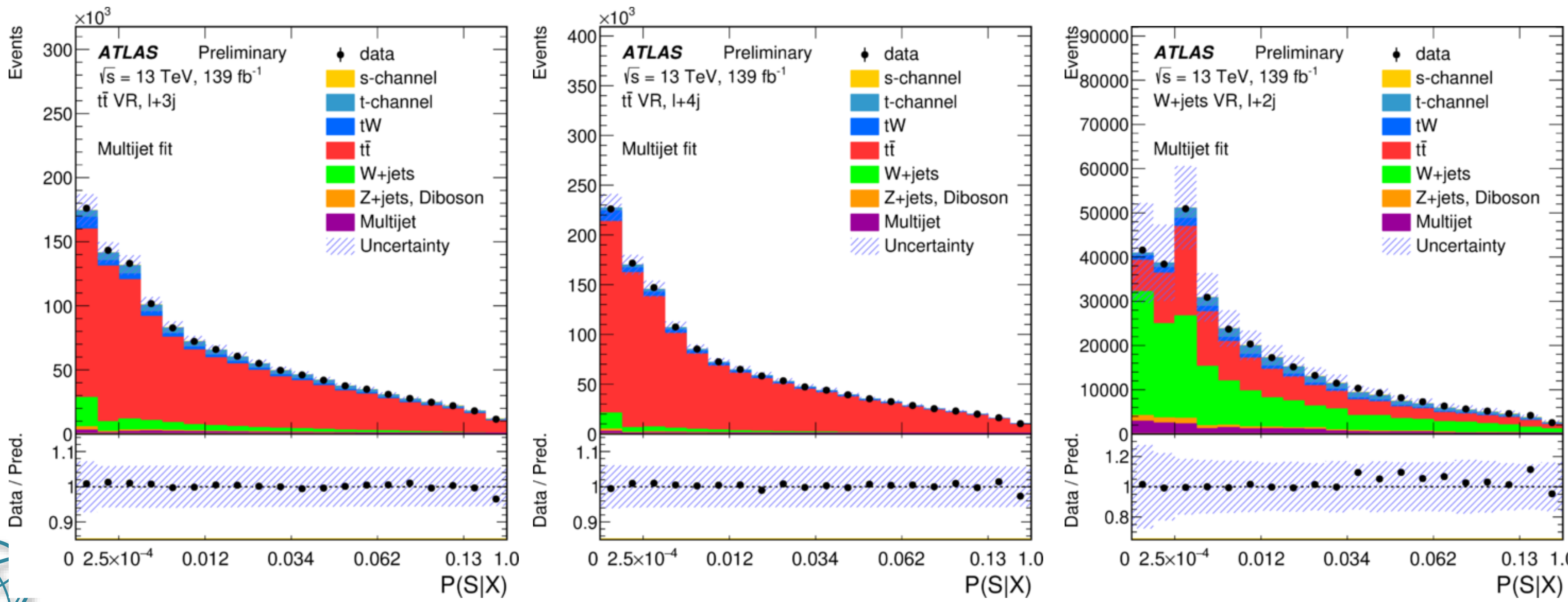
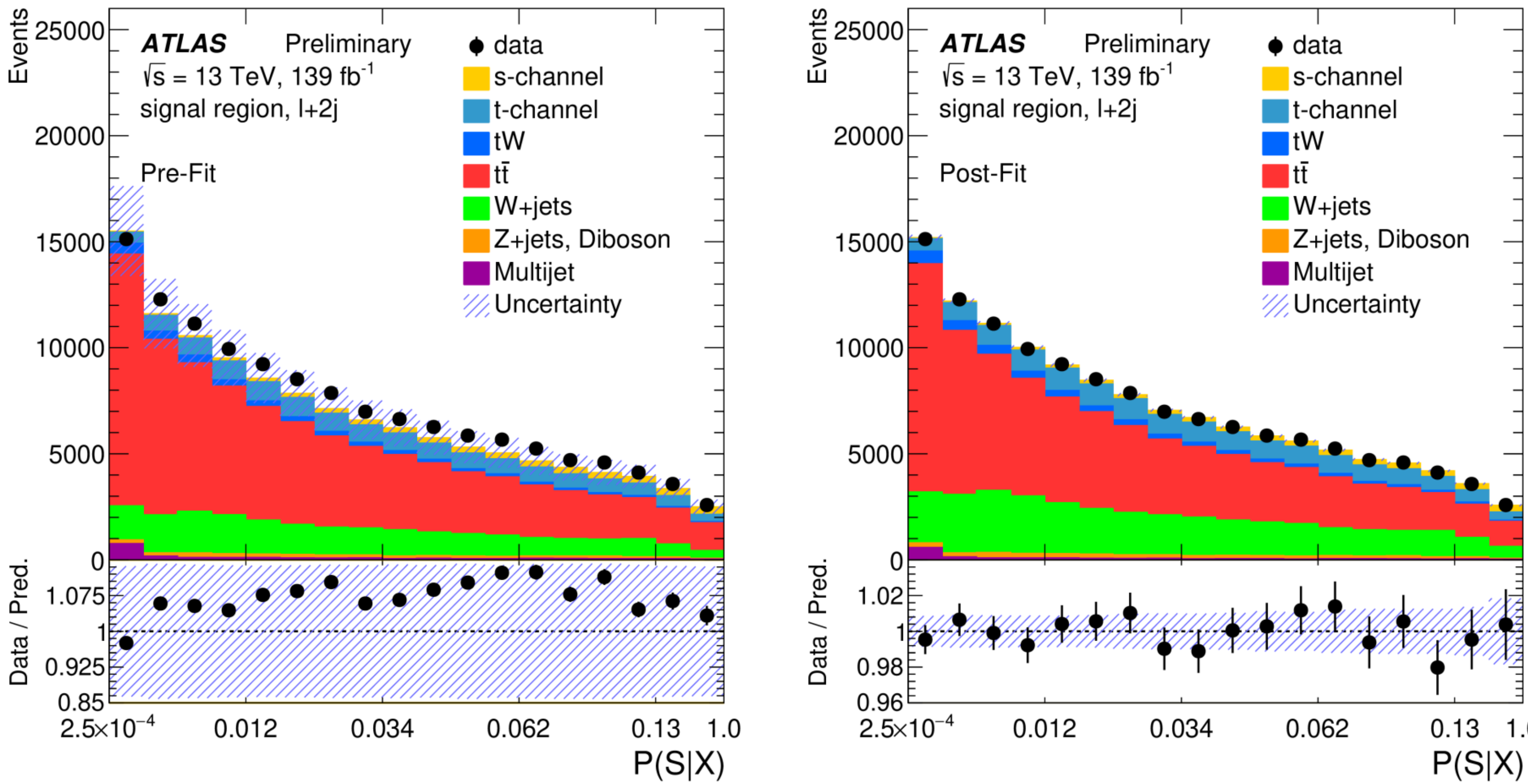
Matrix Element Method – for Signal and Background separation

$$P(S\,|\,X) = \frac{\sum_i P(S_i)\mathcal{P}(X\,|\,S_i)}{\sum_i P(S_i)\mathcal{P}(X\,|\,S_i) + \sum_j P(B_j)\mathcal{P}(X\,|\,B_j)}$$

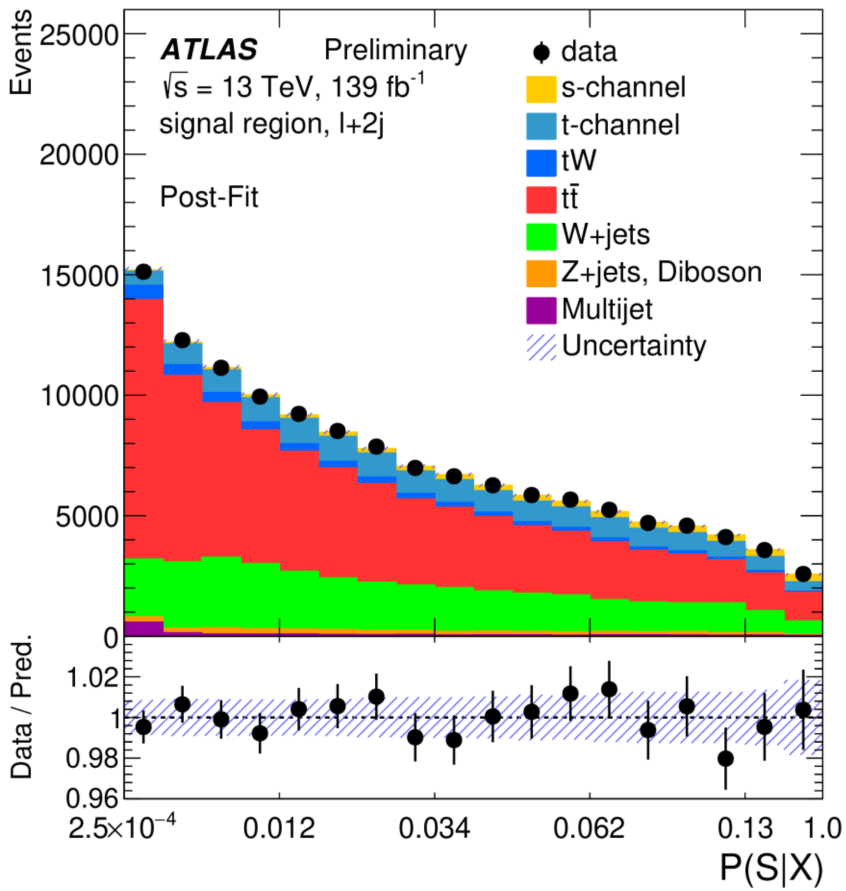
In practice the MEM is utilised through Bayes' theorem to product a discriminant distribution – **the probability for a measured event X to be a signal event S**.

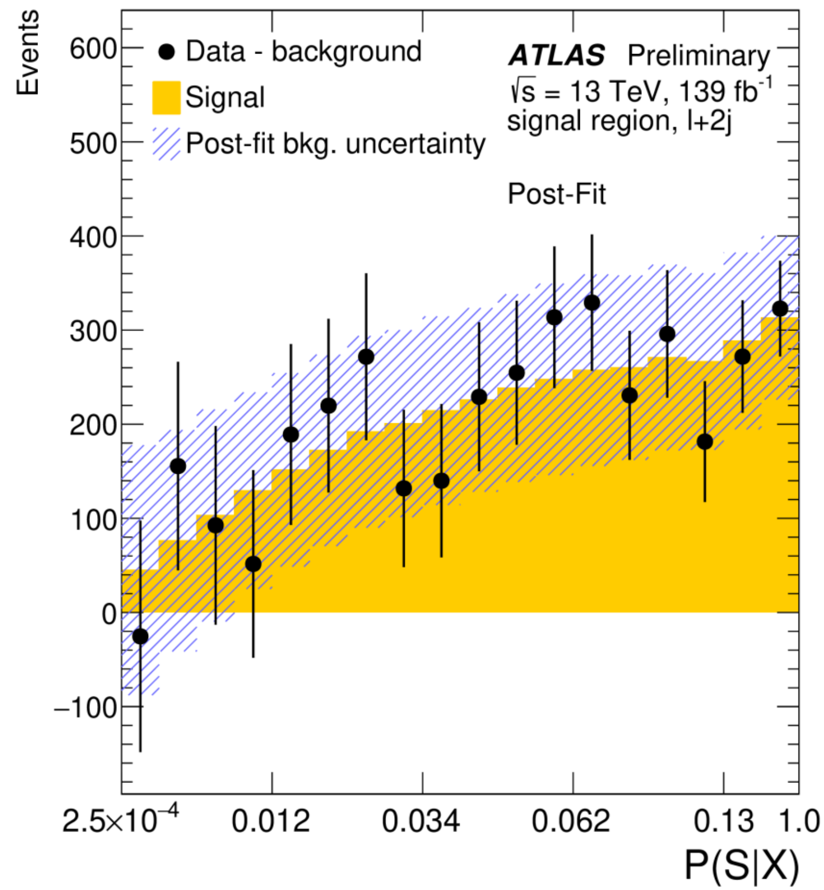


Signal Extraction



Signal Extraction





Measurement of single-top *s*-channel

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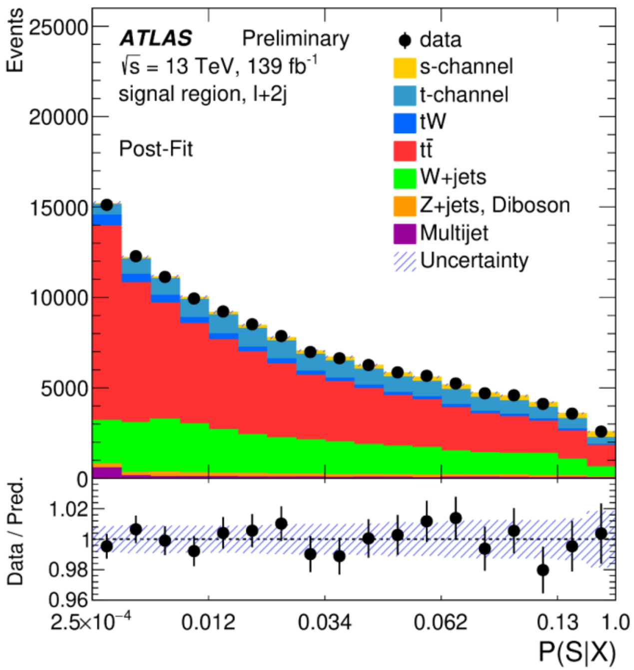

Process	Event yield Pre-fit	Event yield Post-fit
s-channel	$4\,200 \pm 710$	$3\,700 \pm 1\,100$
t-channel	$13\,000 \pm 2\,000$	$15\,000 \pm 2\,300$
tW	$3\,680 \pm 970$	$4\,250 \pm 1\,100$
$t\bar{t}$	$76\,000 \pm 12\,000$	$70\,600 \pm 4\,200$
W+jets	$21\,500 \pm 2\,900$	$32\,200 \pm 5\,000$
Z+jets, VV	$2\,400 \pm 1\,400$	$2\,900 \pm 1\,600$
Multijet	$2\,150 \pm 650$	$1\,700 \pm 540$
Total	$123\,000 \pm 17\,000$	$130\,310 \pm 620$
Data	$130\,310$	

Source	$\Delta\sigma/\sigma$ [%]
$t\bar{t}$ normalisation	$+24/-17$
Jet energy resolution	$+18/-12$
Jet energy scale	$+18/-13$
Other s-channel modelling sources	$+18/-8$
Top-quark processes ISR/FSR	$+13/-11$
MC statistics	$+13/-11$
Other $t\bar{t}$ shape modelling sources	$+12/-10$
Flavour tagging	$+12/-10$
W+jets normalisation	$+11/-8$
Top-quark processes PDFs	$+10/-9$
W+jets μ_R/μ_F shape	$+6/-5$
Other processes normalisation	$+6/-5$
Pileup	$+5/-3$
Other t-channel modelling sources	± 5
Luminosity	$+4/-3$
Other tW modelling sources	$+1/-2$
Missing transverse energy	± 1
Multijet shape modelling	± 1
Other sources	< 1
Systematic uncertainties	$+42/-34$
Data statistics	± 8
Total	$+42/-35$

Precision dominated by multiple systematic uncertainties

$$\sigma_{\text{obs}} = 8.2^{+3.5}_{-2.9}\ \text{pb}$$

$$\sigma_{\text{SM}} = 10.32^{+0.40}_{-0.36}\ \text{pb}$$

3.3σ (3.9σ) observed (expected) significance

Observation of $tq\gamma$

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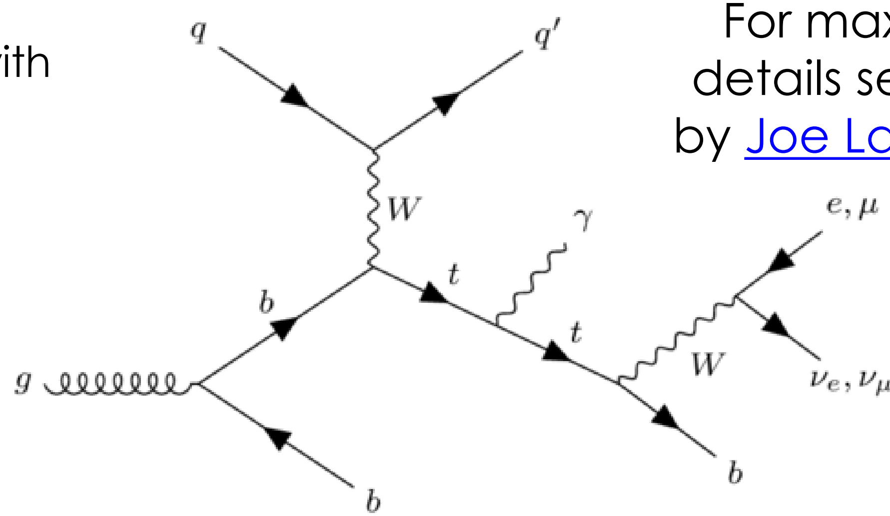
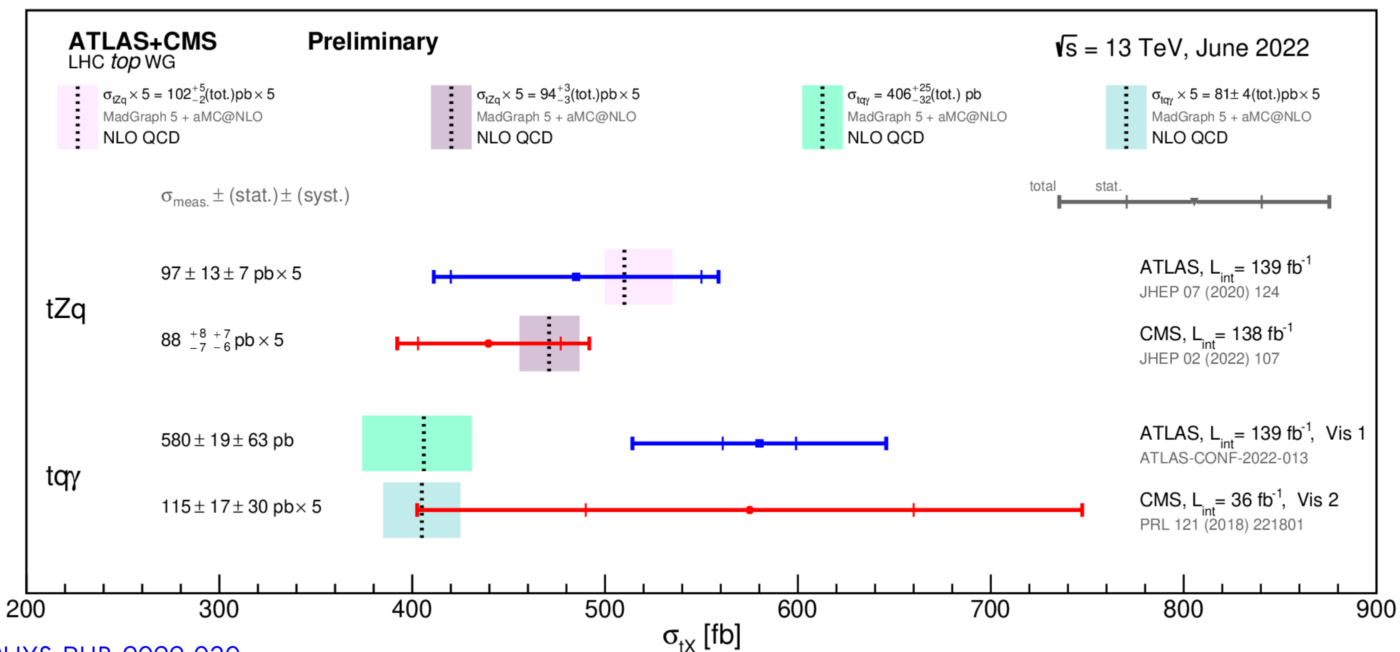
- Associated top quark production with a photon
- t-channel top quark production
- Probes coupling sensitive to EW parameters



For maximal details see talk by Joe Lambert!



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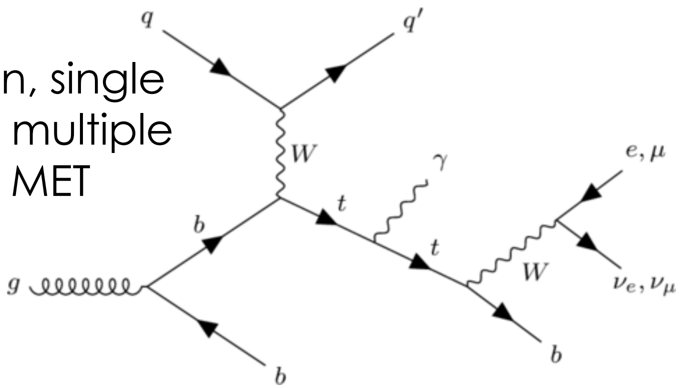
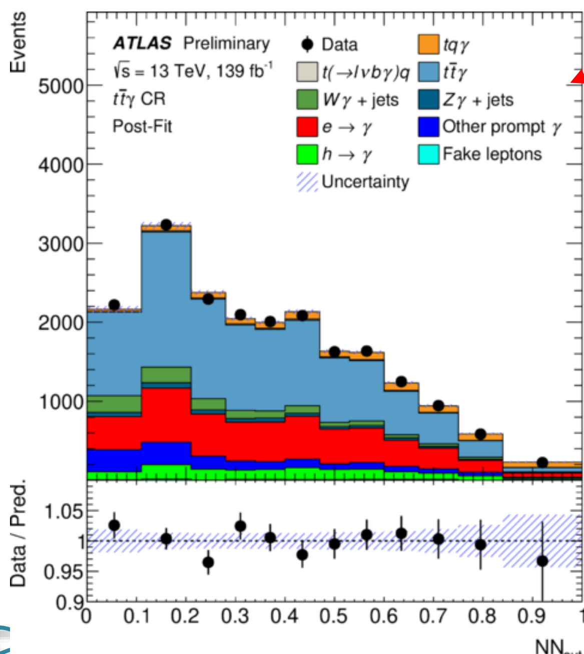
Single lepton, single photon and multiple jets with MET



Signal Regions

- $\equiv 1\ e/\mu$
- $\equiv 1\ \gamma$, $(80\text{ GeV} > m_{e\gamma} < 100\text{ GeV}\ (Zee))$
- $\equiv 1$ \`tight' btag
- $\equiv 0$ \`loose' btags
- $\equiv 0$ forward – jets **OR** ≥ 1 forward – jet $(2.5 < |\eta| < 4.5)$

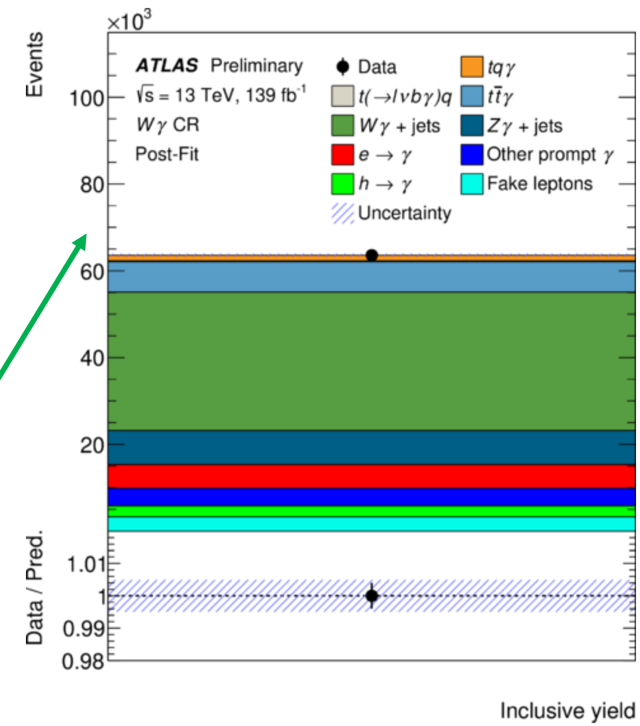


$t\bar{t}\gamma$ Control Region

- SR Selection, except:
  - ≥ 0 forward – jets
  - ≥ 1 \`loose' btags

$W\gamma$ Control Region

- SR Selection, except:
  - ≥ 0 forward – jets
  - ≥ 1 \`loose' btags
  - $\equiv 0$ \`tight' btags



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Electron to "photon" fakes

Tag and probe method employed in dedicated CRs to derive MC scale factors using Z-mass peak

Binned in photon η and reconstruction properties (e.g. track hits)

$$F_{e\to\gamma} = \frac{N(Z \to e(e \to \gamma))}{2 \times N(Z \to ee)}$$

$$SF_{e\to\gamma} = \frac{F_{e\to\gamma}^{\mathrm{Data}}}{F_{e\to\gamma}^{\mathrm{MC}}}$$

Jet to "photon" fakes

ABCD method employed – splitting regions by photon identification and isolation criteria

Binned in photon η , p_T and reconstruction properties (e.g. track hits)

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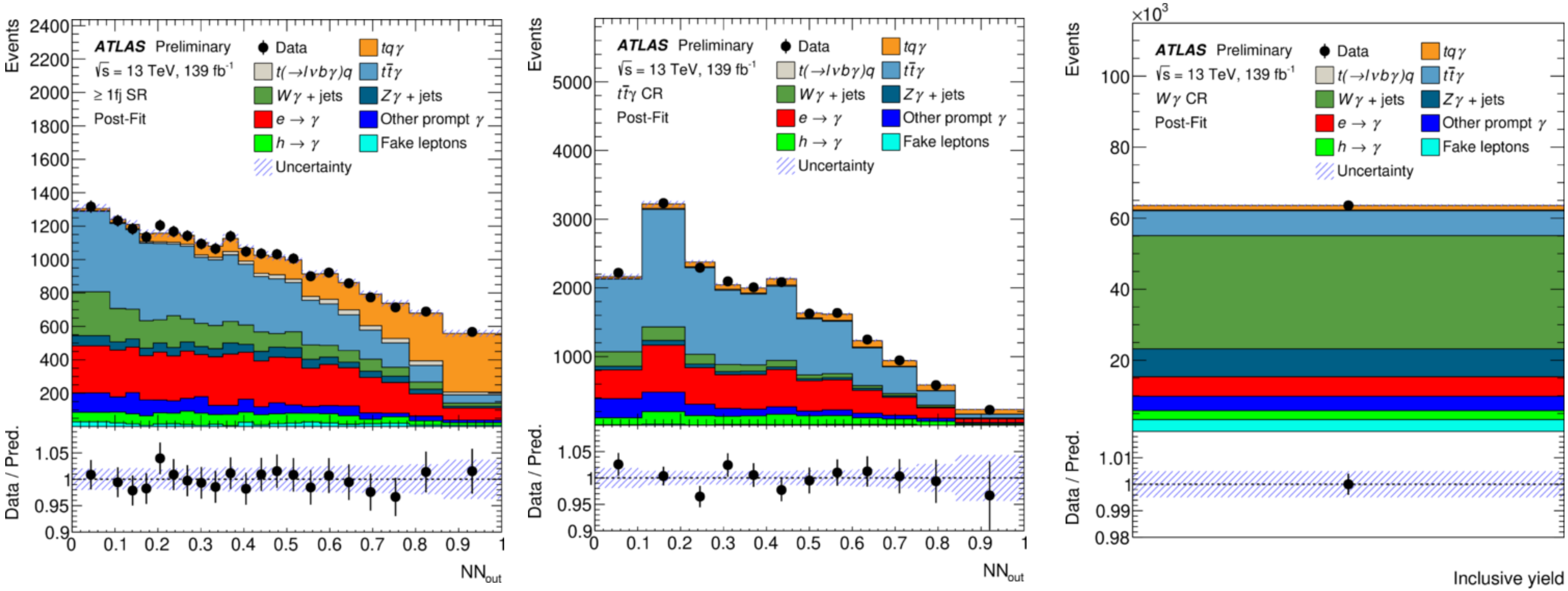
Signal and Background separation and Signal Extraction

- Neural networks are trained using kinematic variables:
  - η, p_T, φ of the photon, lepton, leading b-tagged and forward jets, MET, b-tagging properties, and kinematic combinations
  - Top-quark mass is most useful input variable



- Simultaneous profile-likelihood fit performed across all regions with free-floating $\boldsymbol{t\bar{t}\gamma}$ and $W\gamma$

Observation of $tq\gamma$

Results (in fiducial phase space close to SR)

$$\sigma_{\text{obs}}^{\text{particle}} = 287 \pm 8(\text{stat.})^{+31}_{-31}(\text{syst.})\ \text{fb}$$

$$\sigma_{\text{SM}}^{\text{particle}} = 207^{+26}_{-11}\ \text{fb}$$

1.9σ

$$\sigma_{\text{obs}}^{\text{parton}} = 580 \pm 19(\text{stat.}) \pm 63(\text{syst.})\ \text{fb}$$

$$\sigma_{\text{SM}}^{\text{parton}} = 406^{+25}_{-32}\ \text{fb}$$

2.5σ

Process observed with a significance of 9.1σ! (Expected 6.1σ).

$$\mu_{\text{SM}}^{\text{CMS}} = 1.42 \pm 0.43$$

Uncertainty (parton level)	$\Delta\sigma/\sigma$
$t\bar{t}\gamma$ modelling	±5.6%
Background MC statistics	±3.5%
$t\bar{t}$ modelling	±3.4%
$tq\gamma$ MC statistics	±3.4%
$t(\rightarrow \ell\nu b\gamma)q$ modelling	±1.9%
Additional background uncertainties	±1.9%
$tq\gamma$ modelling	±1.8%
$t(\rightarrow \ell\nu b\gamma)q$ MC statistics	±0.3%
Lepton fakes	±2.2%
$h \rightarrow \gamma$ photon fakes	±2.2%
$e \rightarrow \gamma$ photon fakes	±0.6%
Luminosity	±2.2%
Pileup	±1.2%
Jets and $E_{\text{T}}^{\text{miss}}$	±4.0%
Photons	±2.5%
Leptons	±0.9%
b-tagging	±0.8%
Total systematic uncertainty	±10.9%

$\mu_{\text{SM}}^{\text{ATLAS}}$ consistent with previous CMS result in PhysRevLett.121.221802

Summary

- Measurements of rare top processes are extremely active, making full use of the Run 2 dataset as we begin Run 3
- These processes are extremely important and useful inputs to EFT fits
- s-channel cross section extremely challenging due to large backgrounds, but achieved same sensitivity as 8 TeV result
- First observation of the SM $tq\gamma$ process achieved
- Consistent 'excess' in $tq\gamma$ cross section observed by both ATLAS and CMS

Thanks for your attention

BACKUP

Measurement of single-top s-channel

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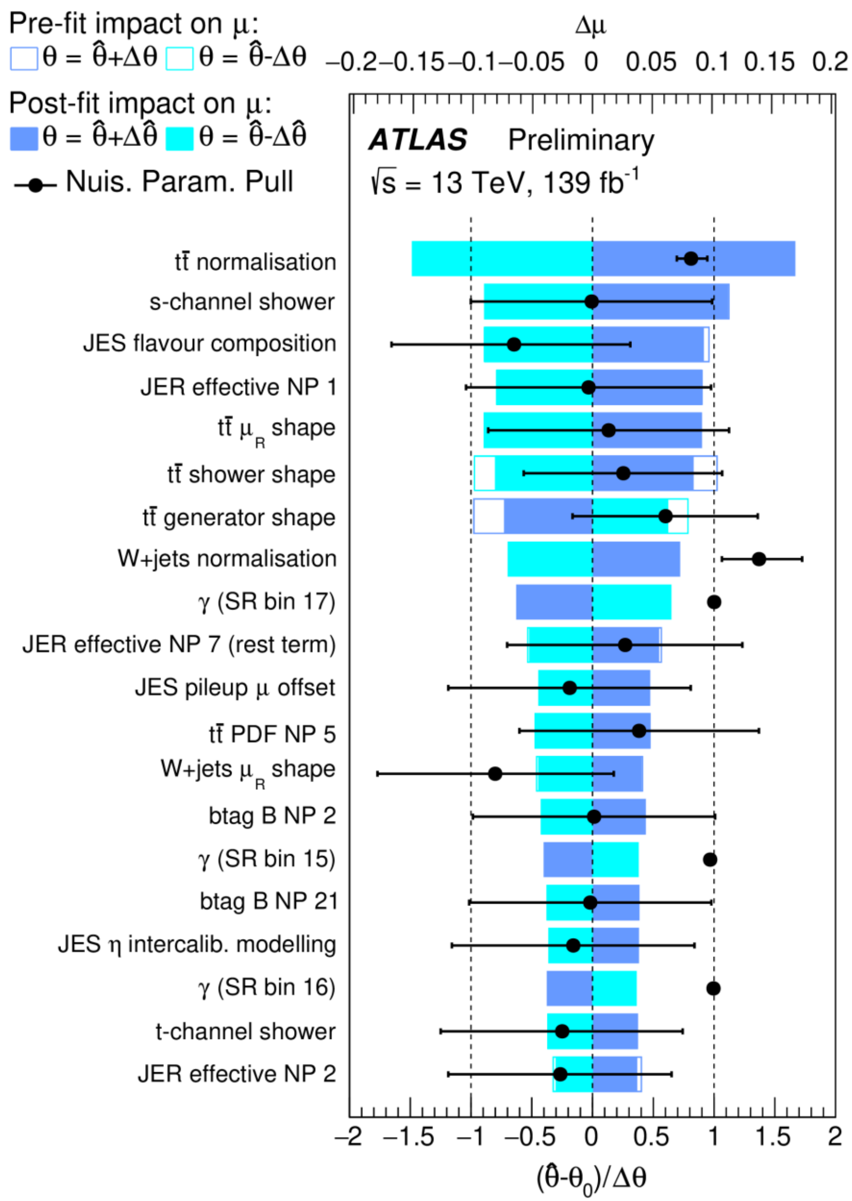

Measurement of single-top s-channel

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ATLAS Preliminary

	JES effective NP modelling 1	JES η intercalib. modelling	JES flavour composition	JES flavour response	JER effective NP 1	JES pileup μ offset	JES pileup ρ topology	btag Light NP 0	multijet normalisation	s-channel shower	$t\bar{t}$ generator shape	$t\bar{t}$ shower shape	$t\bar{t}$ μ_R shape	W+jets μ_R shape	μ	$t\bar{t}$ normalisation	W+jets normalisation
JES effective NP modelling 1	100.0	0.1	0.1	-0.1	-0.4	0.0	-1.5	0.0	0.4	0.6	10.8	6.5	1.7	-5.2	-3.6	13.1	26.8
JES η intercalib. modelling	0.1	100.0	1.6	-0.6	1.2	0.8	0.2	0.4	0.2	0.4	4.2	3.3	0.7	-2.0	13.2	24.0	15.4
JES flavour composition	0.1	1.6	100.0	-1.5	3.1	2.0	0.0	1.2	0.7	1.4	12.5	7.3	2.4	-6.3	32.5	63.7	48.3
JES flavour response	-0.1	-0.6	-1.5	100.0	-1.1	-0.7	-0.2	-0.4	0.1	-0.4	-3.5	-2.8	-0.6	1.5	-11.8	-24.3	-13.5
JER effective NP 1	-0.4	1.2	3.1	-1.1	100.0	1.5	-0.2	1.3	0.2	0.9	3.4	5.9	2.8	-0.4	29.7	30.4	23.5
JES pileup μ offset	0.0	0.8	2.0	-0.7	1.5	100.0	0.3	0.7	0.2	0.5	4.9	4.0	0.9	-2.3	16.3	26.6	23.4
JES pileup ρ topology	-1.5	0.2	0.0	-0.2	-0.2	0.3	100.0	0.2	-1.2	1.6	8.0	3.2	1.9	-3.5	7.8	24.7	16.7
btag Light NP 0	0.0	0.4	1.2	-0.4	1.3	0.7	0.2	100.0	-0.2	0.1	1.1	1.0	0.2	-1.2	11.5	4.2	37.1
multijet normalisation	0.4	0.2	0.7	0.1	0.2	0.2	-1.2	-0.2	100.0	-0.0	-7.4	-5.6	-1.4	-7.9	-10.0	-17.4	22.2
s-channel shower	0.6	0.4	1.4	-0.4	0.9	0.5	1.6	0.1	-0.0	100.0	-2.3	-1.5	-0.7	-1.2	33.1	2.1	2.6
$t\bar{t}$ generator shape	10.8	4.2	12.5	-3.5	3.4	4.9	8.0	1.1	-7.4	-2.3	100.0	-46.6	-9.3	-2.2	-21.6	27.6	13.1
$t\bar{t}$ shower shape	6.5	3.3	7.3	-2.8	5.9	4.0	3.2	1.0	-5.6	-1.5	-46.6	100.0	-4.9	4.9	27.6	27.1	-6.5
$t\bar{t}$ μ_R shape	1.7	0.7	2.4	-0.6	2.8	0.9	1.9	0.2	-1.4	-0.7	-9.3	-4.9	100.0	-0.8	29.6	3.7	0.6
W+jets μ_R shape	-5.2	-2.0	-6.3	1.5	-0.4	-2.3	-3.5	-1.2	-7.9	-1.2	-2.2	4.9	-0.8	100.0	13.7	0.6	-20.2
μ	-3.6	13.2	32.5	-11.8	29.7	16.3	7.8	11.5	-10.0	33.1	-21.6	27.6	29.6	13.7	100.0	54.7	27.0
$t\bar{t}$ normalisation	13.1	24.0	63.7	-24.3	30.4	26.6	24.7	4.2	-17.4	2.1	27.6	27.1	3.7	0.6	54.7	100.0	51.4
W+jets normalisation	26.8	15.4	48.3	-13.5	23.5	23.4	16.7	37.1	22.2	2.6	13.1	-6.5	0.6	-20.2	27.0	51.4	100.0

A fiducial phase space is defined at particle level, close to the SR definitions, requiring one electron or muon with $p_{\mathrm{T}} > 25$ GeV and $|\eta| < 2.5$, at least one photon with $p_{\mathrm{T}} > 20$ GeV and $|\eta| < 2.37$, at least one b-jet with $p_{\mathrm{T}} > 25$ GeV and $|\eta| < 2.5$ and at least one neutrino not from hadron decay. Jets within $\Delta R < 0.4$ of a lepton or a photon are removed, if the p_{T} of charged particles within $\Delta R < 0.3$ of the photon is smaller than 10% of its p_{T}. Events are removed where a photon is close ($\Delta R < 0.4$) to a lepton or a jet. The SM fiducial cross section at particle level times branching ratio is calculated to be $\sigma_{tq\gamma} \times \mathcal{B}(t \to \ell\nu b) + \sigma_{t(\to\ell\nu b\gamma)q} = 207\,^{+26}_{-11}$ fb. The uncertainty includes PDF and scale variations as well as uncertainties in the parton shower model, in the choice of the matrix-element generator and the modeling of initial and final state radiation (ISR/FSR), as detailed below. The $t\,(\to \ell\nu b\gamma)\,q$ process, where the photon is radiated from one of the top-quark decay products, makes up $\approx 20\%$ of the events in the fiducial region.