Top quarks measurements with the ATLAS detector

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- The top quark is the **heaviest** known elementary particle described by SM

- The top quark has a mass close to the EW symmetry breaking scale, and in many BSM models it is predicted to have a **very large coupling** to new resonances

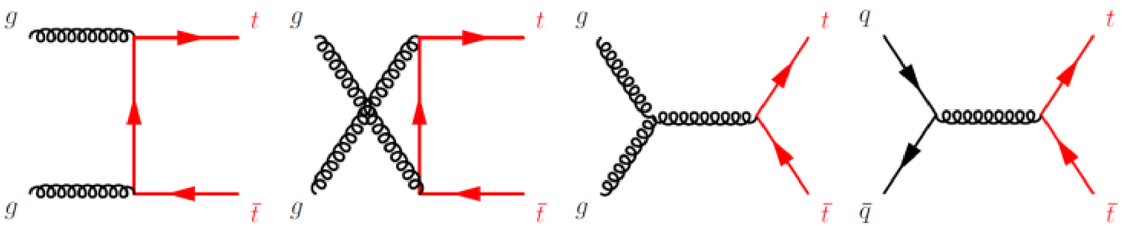
- Due to its large mass, the predicted top quark lifetime (~ 5 x 10^{-25} s) implies that it **decays before** forming hadrons

- The ATLAS and CMS experiments at the LHC have accumulated millions of top quark events (~ 500 tt-pairs per minute), sustained by data from the LHCb experiment in forward kinematic regions

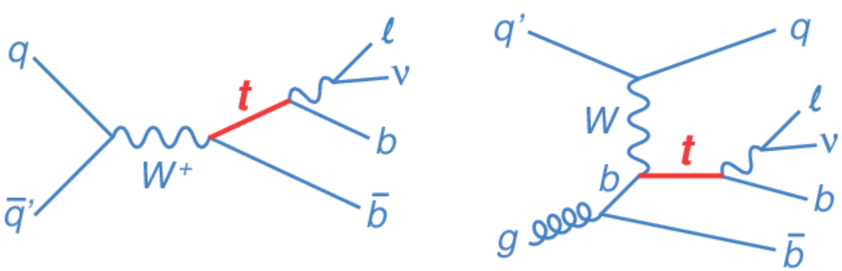
- Large number of results produced by the ATLAS experiment, **today** will focus on a selection of latest measurements concerning:
  i. top quark mass
  ii. single top and top-pair cross-section (inclusive and differential)
  iii. top quark spin correlations
  iv. rare processes with top quarks (tt+X)

- Apologies if your preferred search is not included due to lack of time

- Top quark pair production governed by **strong** interaction:



- Single top production proceeds via **EW** interaction:



- The top quark decays almost 100% to a W-boson and b-quark (V_{tb} ~ 1):
  - final state topology is given W-boson decays: $W \rightarrow l\nu$ (~ 30%) / qq' (~ 70%)

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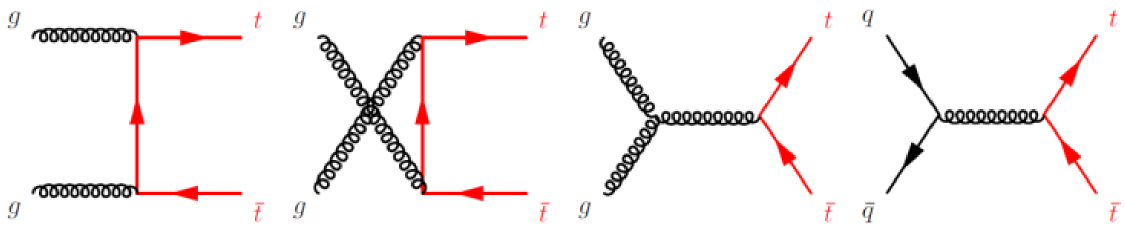

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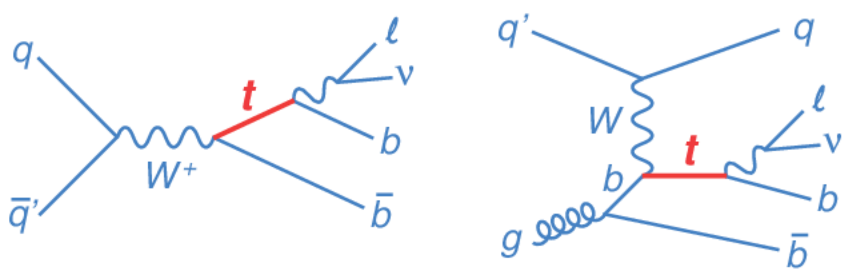

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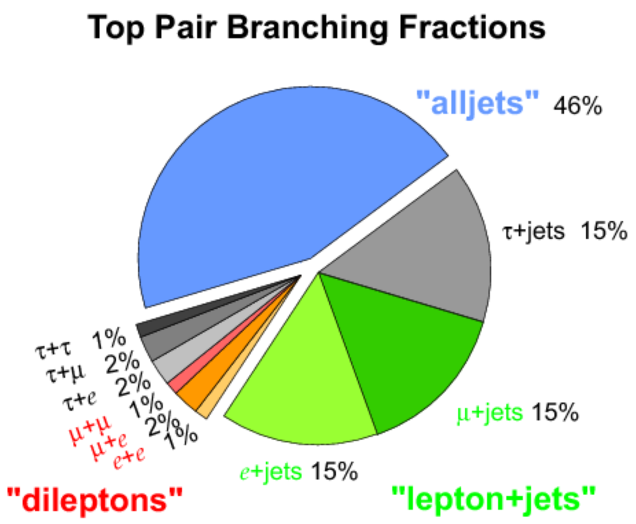
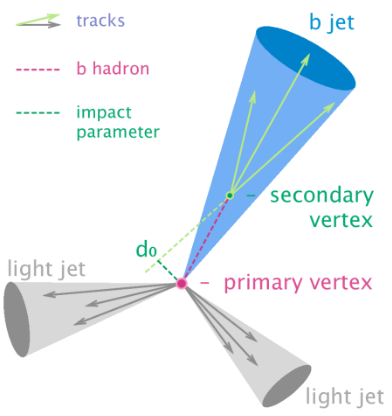


Final states:

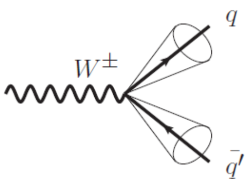
- **Single-lepton**: large statistics and large background
- **Dilepton**: cleanest signature but lower statistics
- **All-hadronic:** large uncert. due to multijet background

- Very **peculiar** experimental signature
  - jets and *b*-jets, charged leptons, MET (neutrino)



- **Algorithms** built to identify b-jets
  - b-hadron long lifetimes (e.g. 1.5ps for B^0) can travel few millimetres before they decay
  - based on displaced vertex and jet shape information
  - multivariate discriminant used to discriminate *b*-, *c*- and *light*-jets

- **Boosted** object tagging:



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  - jets and *b*-jets, charged leptons, MET (neutrino)

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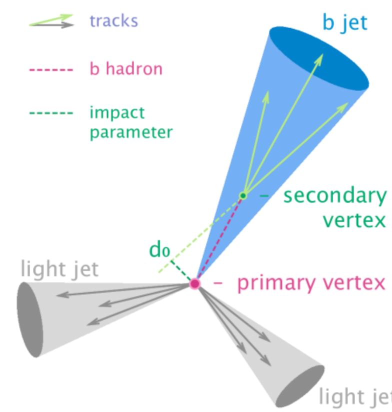

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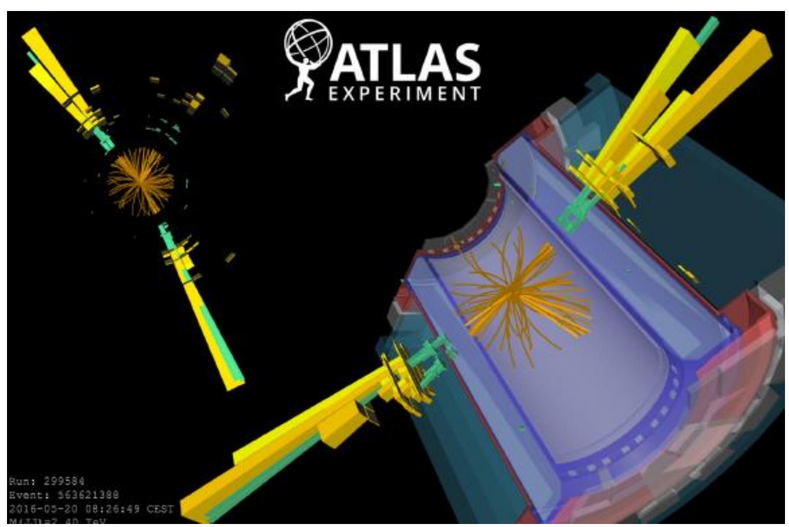

Summary of top mass measurements

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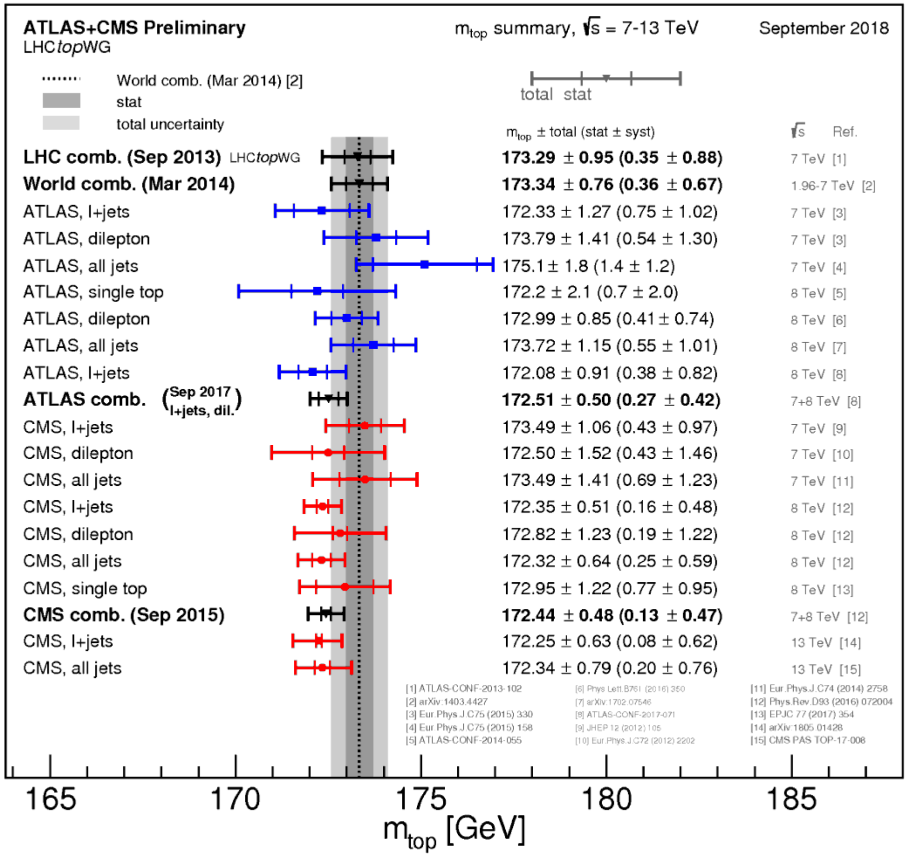
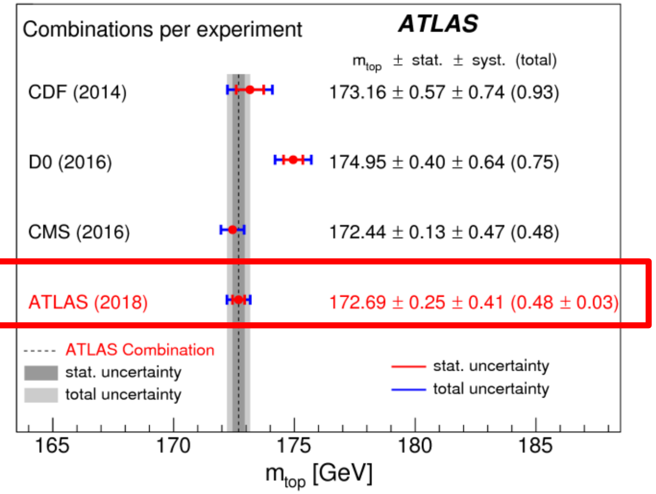


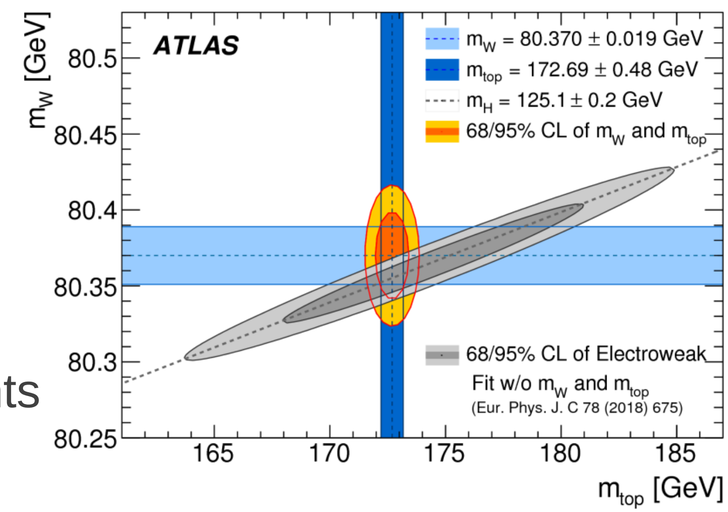
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/TOP/

Latest combined ATLAS 2018 result:

CERN-EP-2018-238



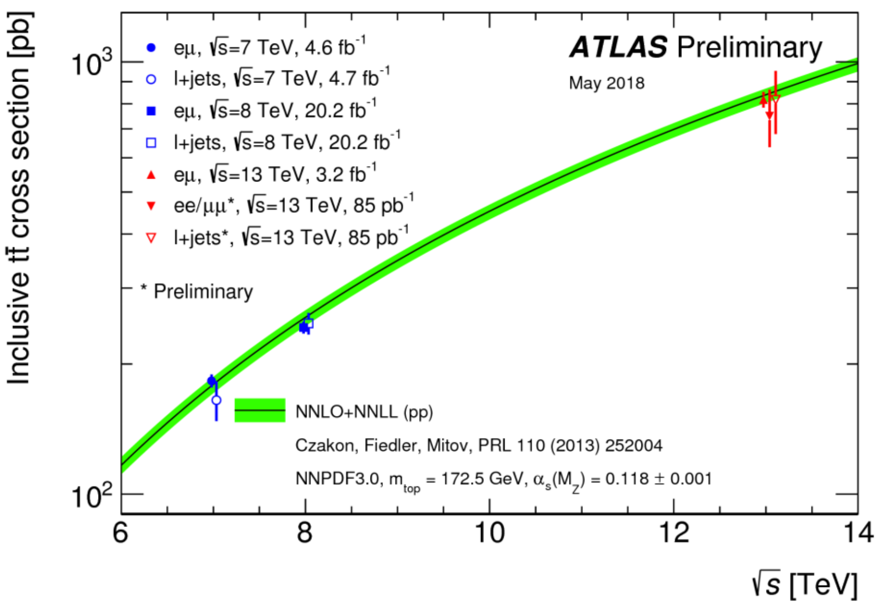
Relative precision of **0.28%**

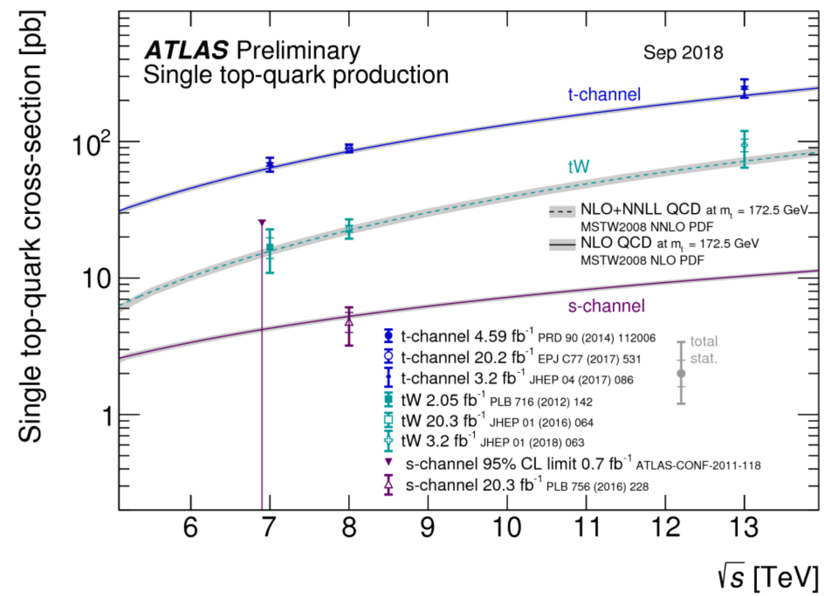


Good **agreement** between ATLAS measurements and indirect mass determinations by the EW fit

Summary of inclusive top cross-section measurements

- Top cross-section can **constrain** parameters such as top mass, α_S and PDFs
- All measurement consistent with the SM prediction





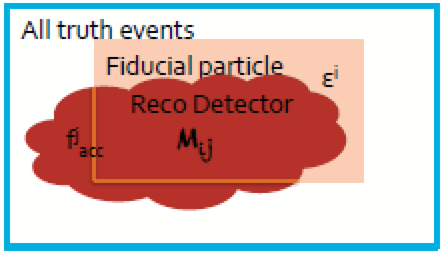
- Theory (NNLO+NNLL): ~ **5.5%** precision
- ATLAS (eμ channel): **4%** precision at 7/8 TeV
- **7%** precision at 13 TeV (lumi uncert.)

- Measured total cross section converted to CKM matrix element Vtb, achieving **5%** precision
- s-channel challenging @13 TeV

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/TOP/

Fiducial and differential cross-section measurements

- Test global properties of top-quark pair events by measuring top quark observables in both fiducial (particle) and full (parton) phase space



- Comparison of different generator setups and radiation tunes
- Precision limited by: data statistics, generator uncertainties, jet energy scale and resolution

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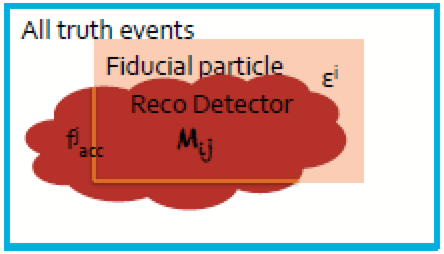

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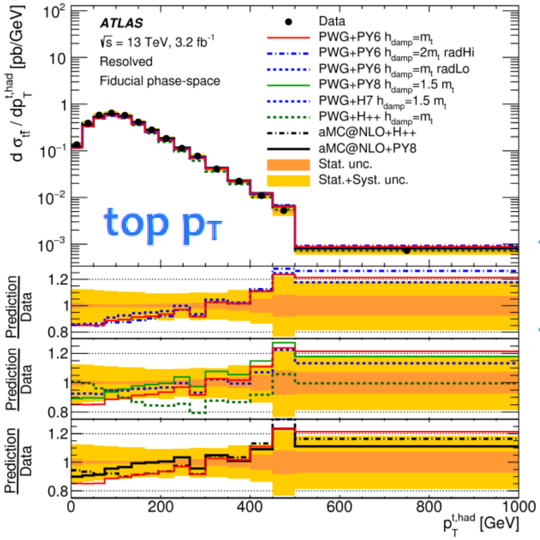
- All **three final states** studied: MC simulations predict harder top p_T than data

Single-lepton resolved



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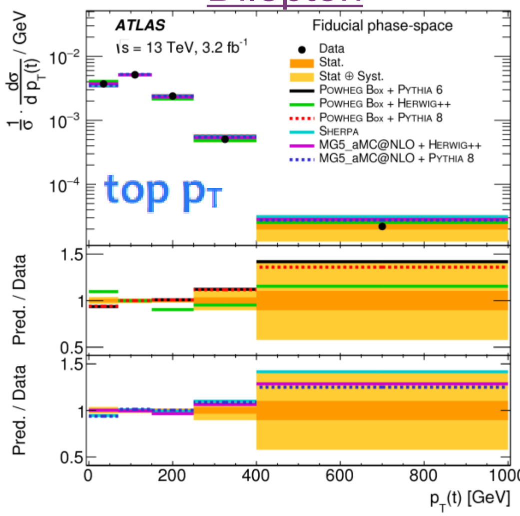
Dilepton



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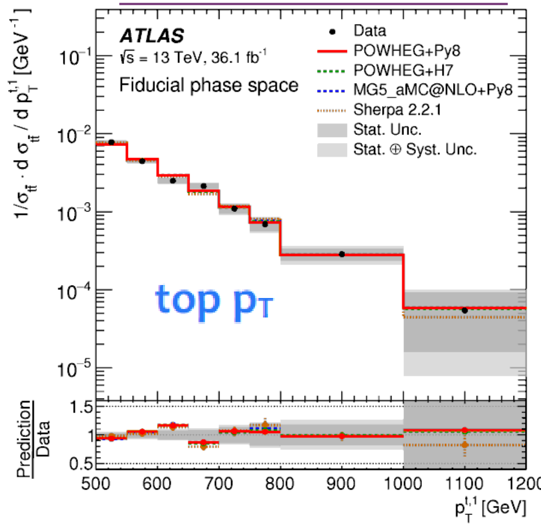
All-hadronic boosted



PRD 98 (2018) 012003

- MC simulations predict harder top p_T than data, NNLO agrees better

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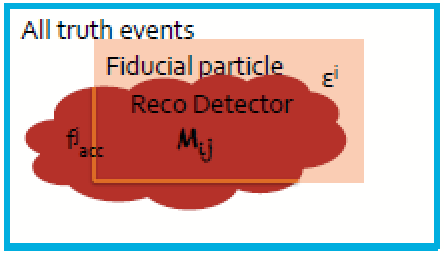

- Comparison of different generator setups and radiation tunes
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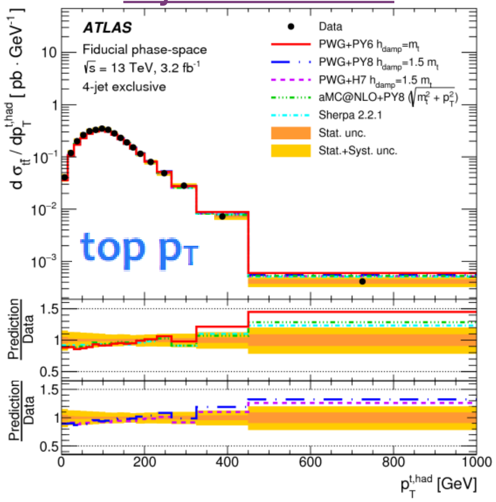
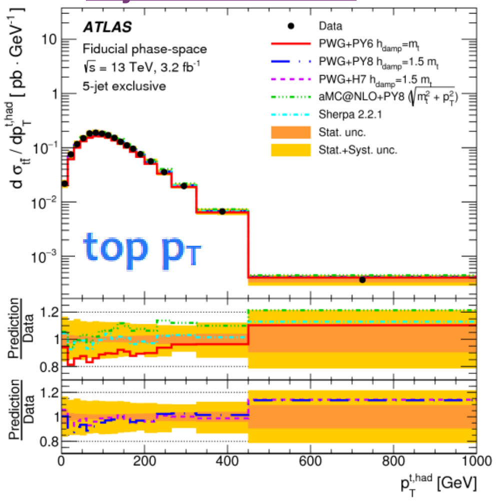
- Single-lepton final state with **additional jets** (sensitive to gluon radiation):

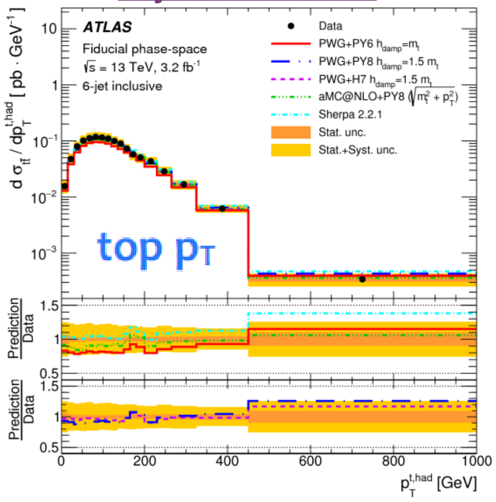
4-jet exclusive



5-jet exclusive



6-jet inclusive



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- MC simulations predict harder top p_T than data, NNLO agrees better

Fiducial and differential cross-section measurements

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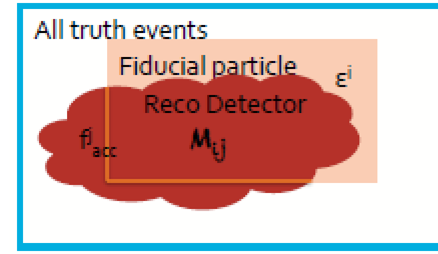
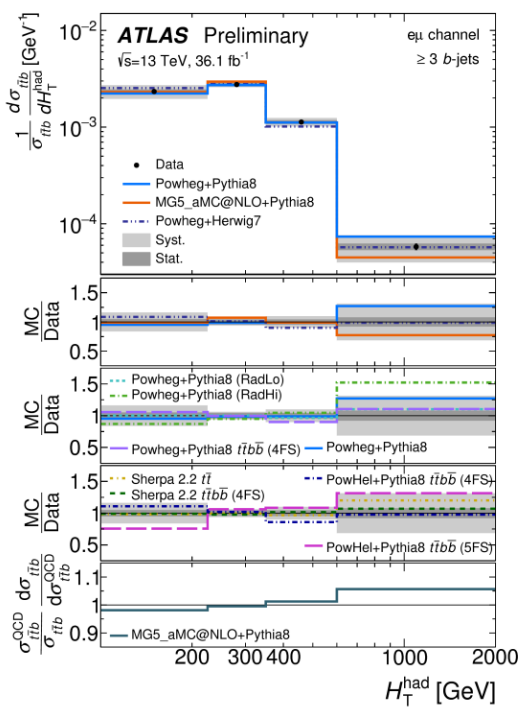
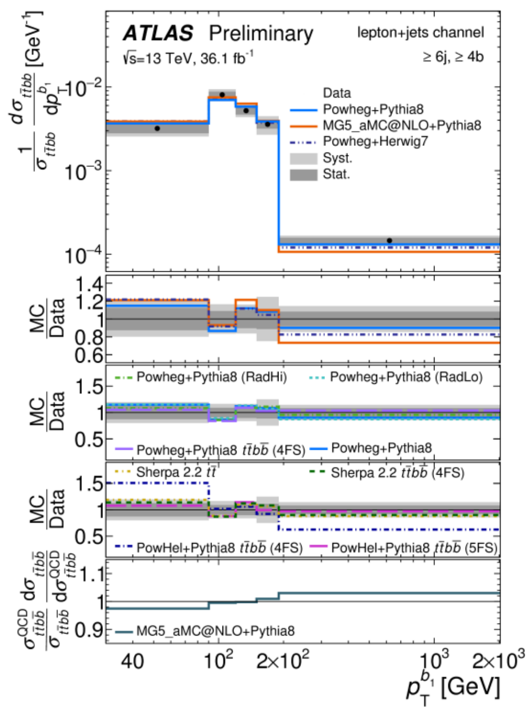


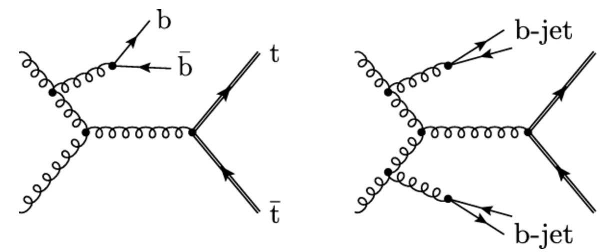
- Comparison of different generator setups and radiation tunes
- Precision limited by: data statistics, generator uncertainties, jet energy scale and resolution

- tt + additional **heavy-flavour jets**





ATLAS-CONF-2018-029



- MC predictions where additional b-jets are dominantly produced by the parton shower predict too few events

Fiducial and differential cross-section measurements

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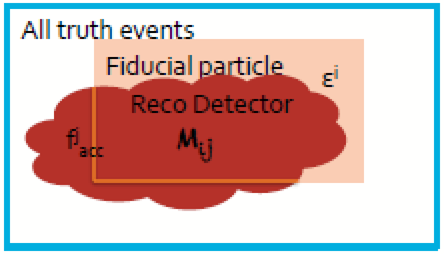

- Comparison of different generator setups and radiation tunes
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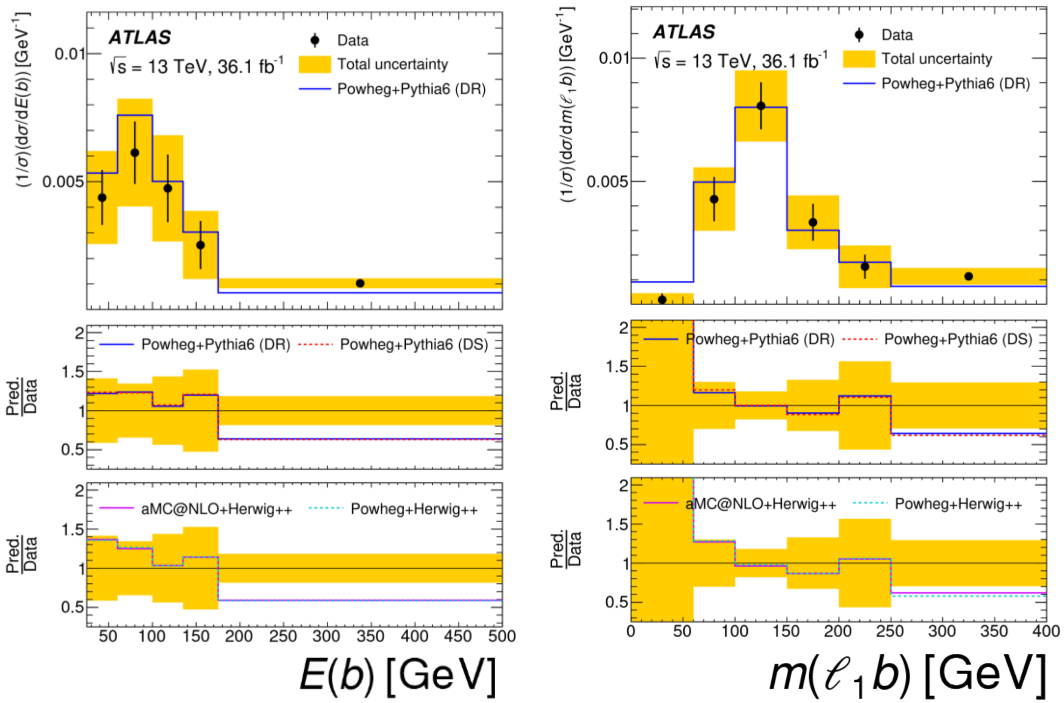
- Differential cross-section in **single top** production



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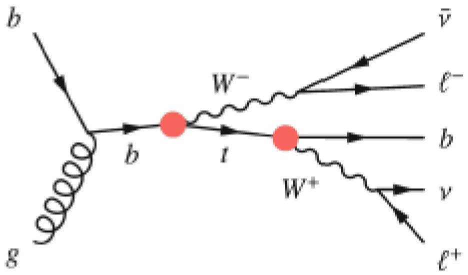


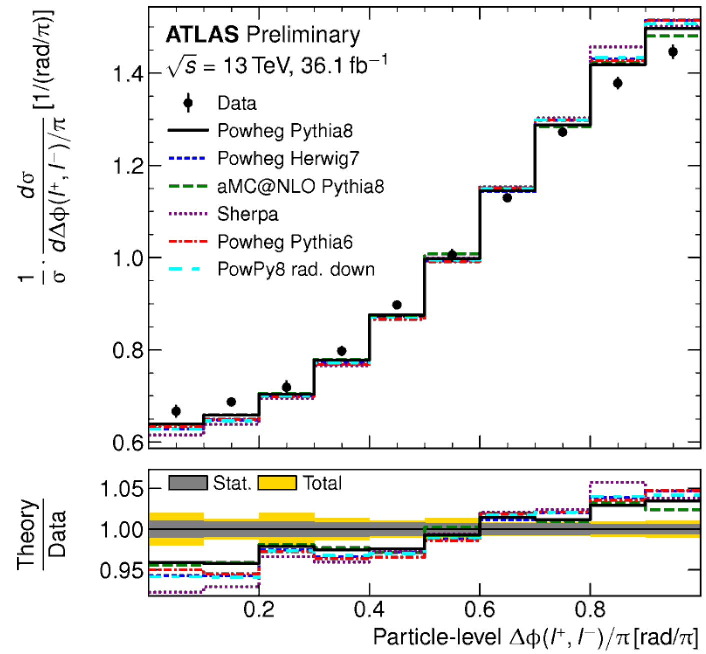
- Most of the MC models show fair agreement, however there are more events with high-pT final-state objects than several of the MC models predict

ATLAS-CONF-2018-027

- SM predicts top quark and anti-quark spins to be correlated in tt-pairs
- Spin information is carried by the top quark decay products, particularly accessible in charged leptons
- Measure unfolded |Δϕ| = |Δϕ|(e,μ) differential cross section in dileptonic channel
- Extract the fraction of SM-like spin correlation f_{SM} at parton level:

$$n_i = f_{\mathrm{SM}} \cdot n_{\mathrm{spin}} + (1 - f_{\mathrm{SM}}) \cdot n_{\mathrm{nospin}}$$

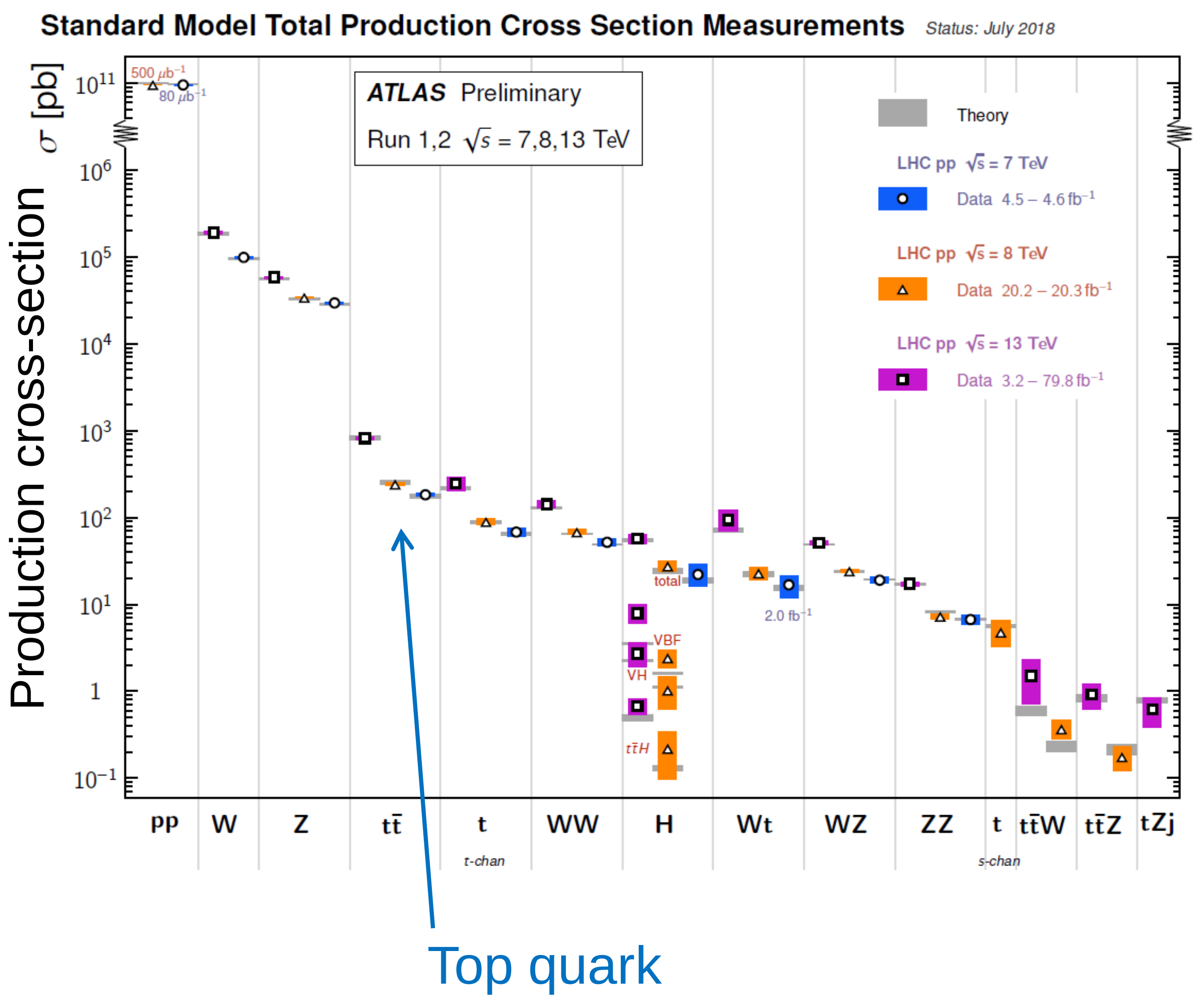
- Measure the azimuthal opening angle as a function of the invariant mass of the tt-system: spin correlation increases
- None of the studied MC generators is able to reproduce the data within uncertainties



Region	f_{SM}	Significance (incl. theory uncertainties)
$m_{t\bar{t}} < 450$ GeV	$1.11 \pm 0.04 \pm 0.13$	0.85 (0.84)
$450 < m_{t\bar{t}} < 550$ GeV	$1.17 \pm 0.09 \pm 0.14$	1.00 (0.91)
$550 < m_{t\bar{t}} < 800$ GeV	$1.60 \pm 0.24 \pm 0.35$	1.43 (1.37)
$m_{t\bar{t}} > 800$ GeV	$2.2 \pm 1.8 \pm 2.3$	0.41 (0.40)
inclusive	$1.250 \pm 0.026 \pm 0.063$	3.70 (3.20)

Production of rare phenomena with top quarks

- With increasing energy and integrated luminosity, the ability to study **rare SM phenomena** becomes possible



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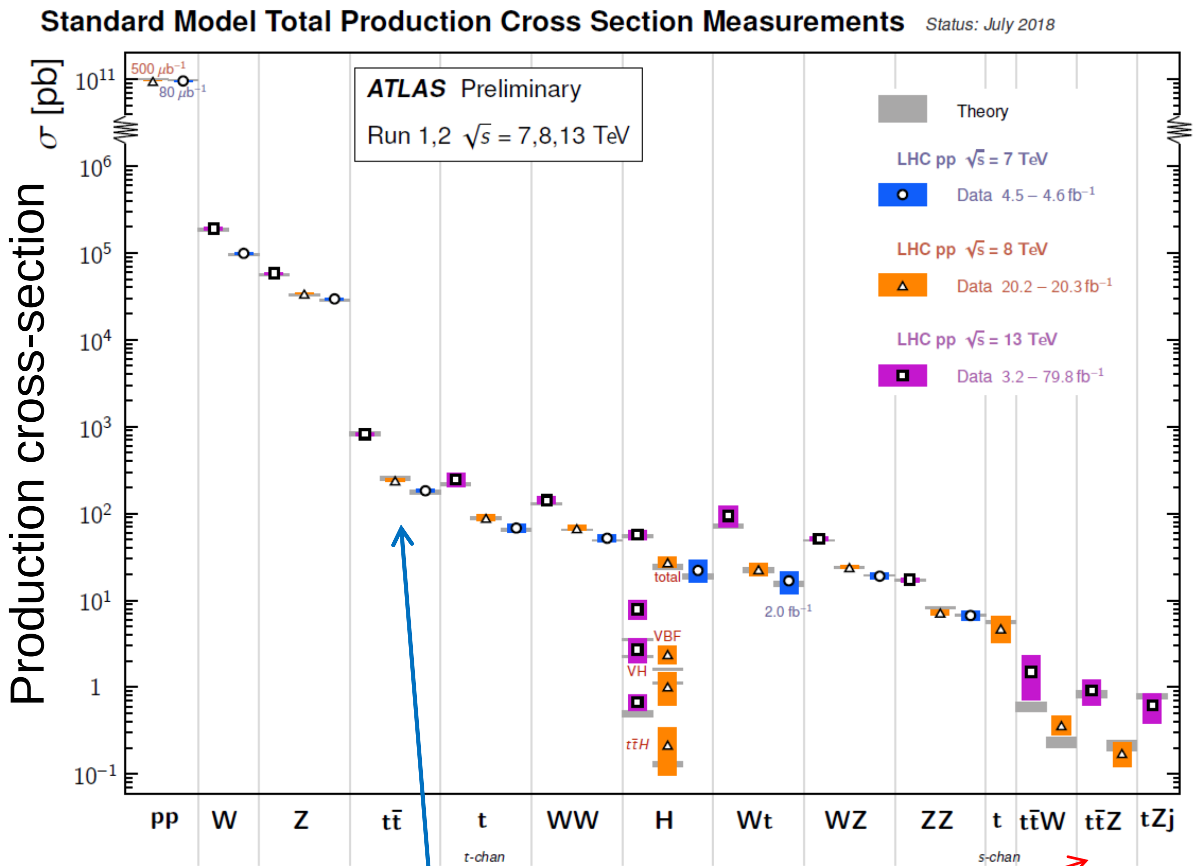
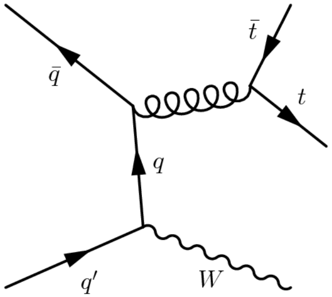
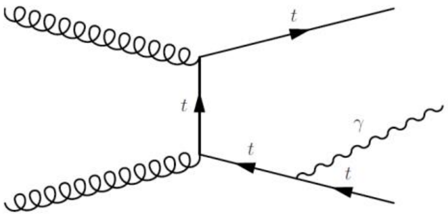


Top quark + X

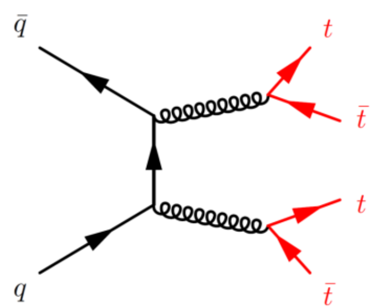
tt+V (W/Z)



tt+γ



tt+tt

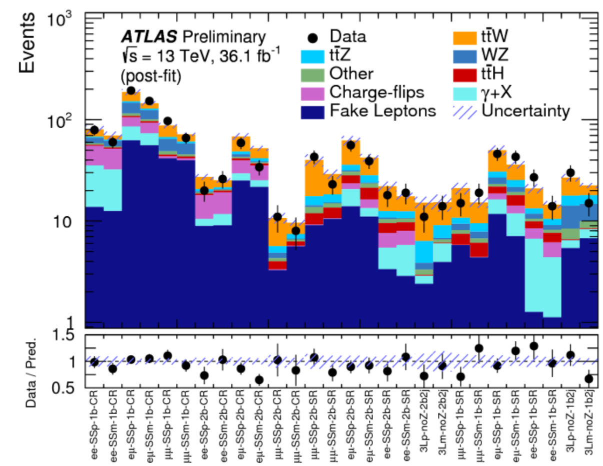


ATLAS-CONF-2018-047

- Measurement of tt+Z and tt+W cross-section at 13 TeV using a dataset of 36.1 fb^{-1} pp events
  - direct probe of weak coupling to top quark
  - important background in many searches with multilepton final states (SUSY, tt+H,..)

Process	$t\bar{t}$ decay	Boson decay	Channel
$t\bar{t}W$	$(\ell^{\pm}\nu b)(q\bar{q}b)$	$\ell^{\pm}\nu$	SS dilepton
	$(\ell^{\pm}\nu b)(\ell^{\mp}\nu b)$	$\ell^{\pm}\nu$	Trilepton
$t\bar{t}Z$	$(q\bar{q}b)(q\bar{q}b)$	$\ell^{+}\ell^{-}$	OS dilepton
	$(\ell^{\pm}\nu b)(q\bar{q}b)$	$\ell^{+}\ell^{-}$	Trilepton
	$(\ell^{\pm}\nu b)(\ell^{\mp}\nu b)$	$\ell^{+}\ell^{-}$	Tetralepton

- Events are selected in channels with two same- or opposite-sign, three or four leptons (electrons or muons) and each channel is further divided into multiple regions



Top quark pair + vector boson

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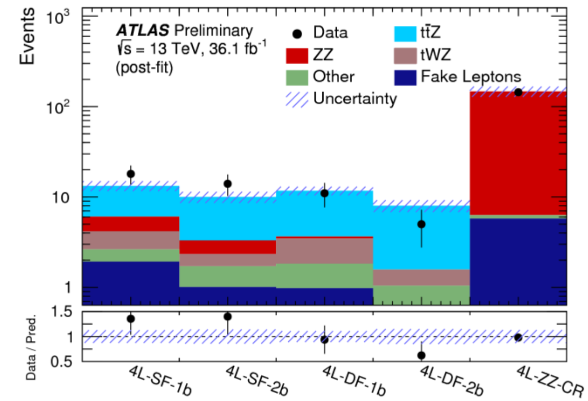
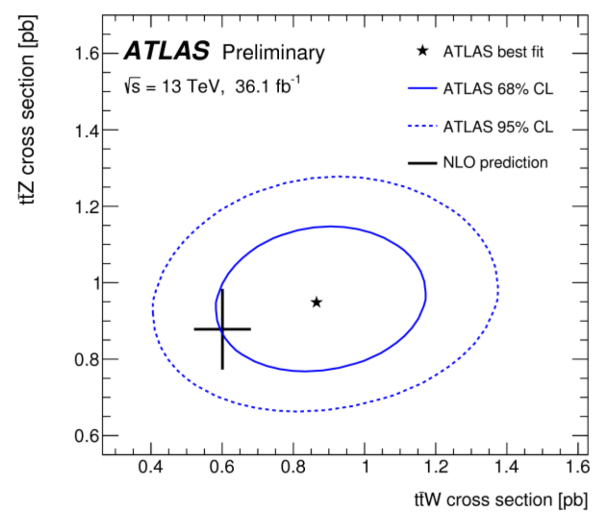


- Events are selected in channels with two same- or opposite-sign, three or four leptons (electrons or muons) and each channel is further divided into multiple regions

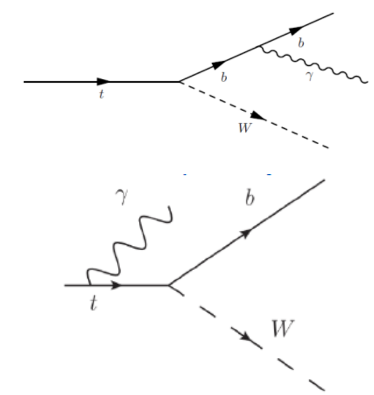
- Yielding significance of ttW: **4.3σ** (**3.4σ**) observed (expected) and ttZ > **5σ**, with dominant systematic uncertainties: modelling, sample statistics

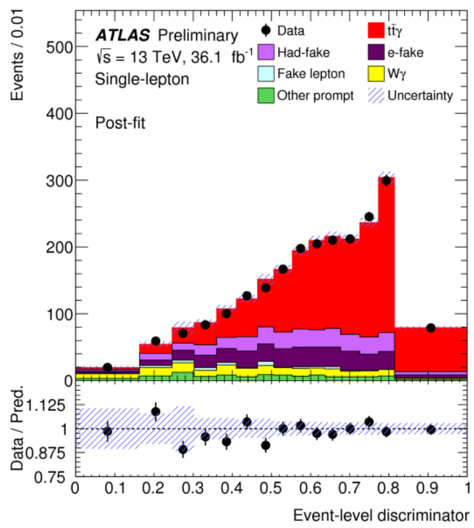


- Interpretations of the inclusive cross section measurement in terms of EFT, constrain operators which modify ttZ vertex

ATLAS-CONF-2018-048

- Measurement of tt+γ inclusive and differential cross-section at 13 TeV using a dataset of 36.1 fb^{-1} pp events
  - direct probe of EM coupling of the top quark
  - no attempt to separate but reduce the contribution of photons being radiated from top quark decays
- Events are selected in single-lepton and dilepton channels, and exactly one photon
- Tag-and-probe method are used to correct the number of fake photons predicted by MC samples
- Hadronic fake background via ABCD method inverting isolation/identification criteria
- Object-level and event-level neural networks improve the separation and sensitivity





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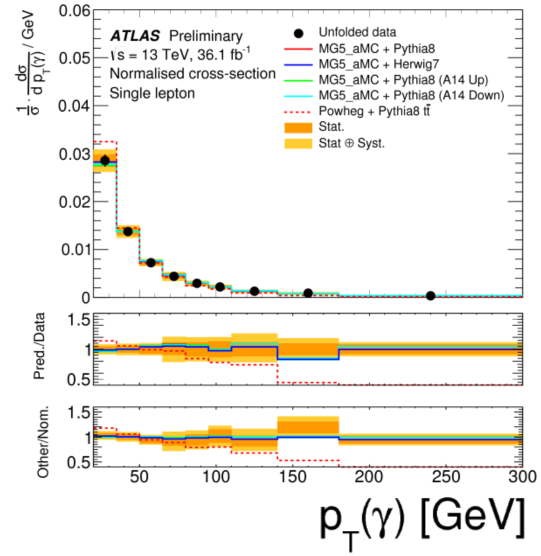
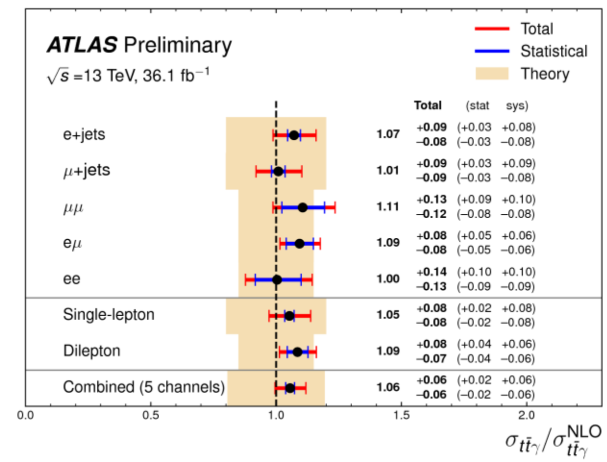
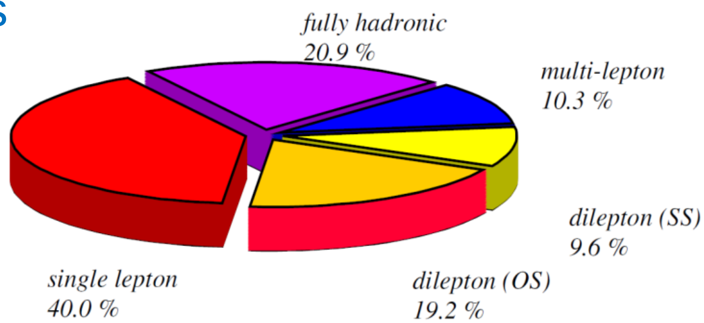
- Object-level and event-level neural networks improve the separation and sensitivity
- Normalised differential crosssections are measured as a function of the photon kinematics
- All measurements are in agreement with NLO predictions





- SM four-top-quarks (tttt) cross-section ~9.2 fb (NLO in QCD)
- Powerful probe for many signatures of BSM physics



- Can be studied in a variety of final states, given by the decays of each W-boson ($t \to Wb$)

4 tops in SS dilepton/trilepton events

CERN-EP-2018-171

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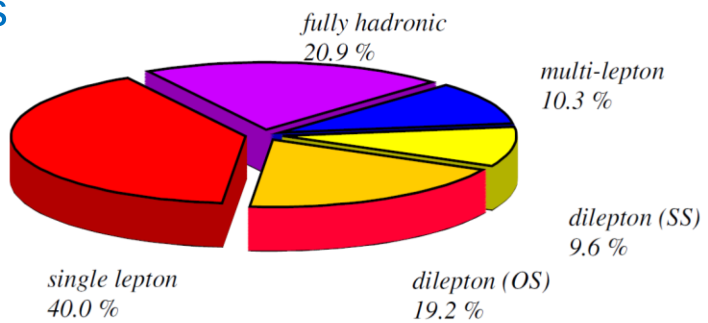
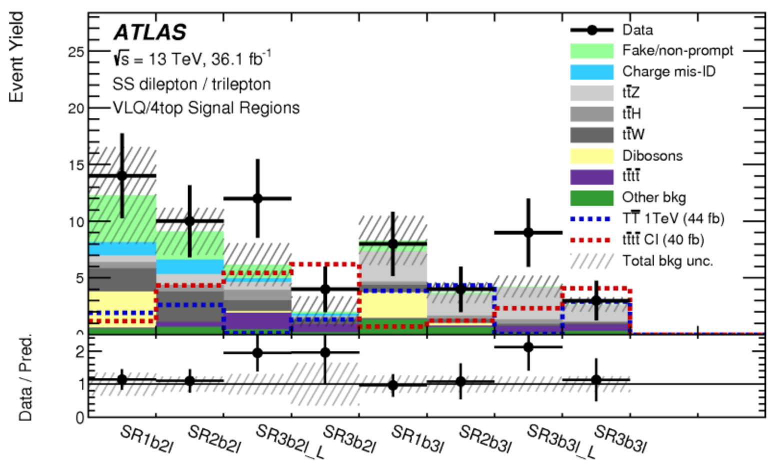


- Can be studied in a variety of final states, given by the decays of each W-boson ($t \rightarrow Wb$)

- Cut & count in 6 (8) validation (signal) regions with selection on MET, HT, number of leptons, jets and b-jets: achieve very low SM background



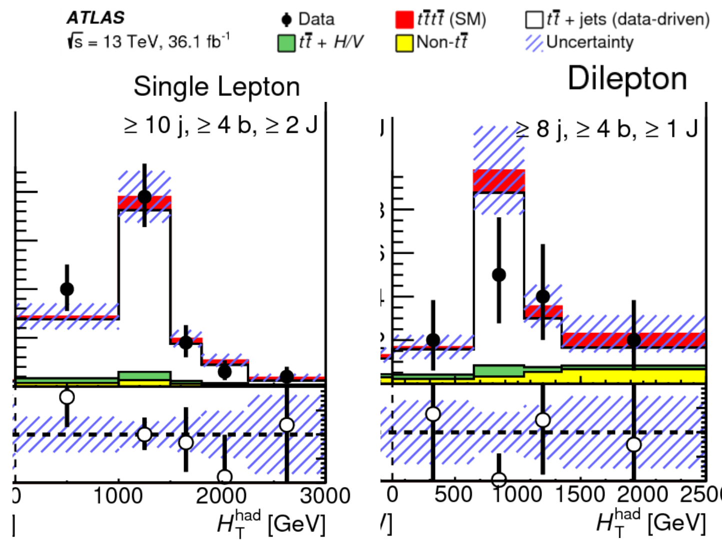
- Data-driven backgrounds:
  - ✓ Fake/non-prompt e/μ backgrounds estimated using a matrix method
  - ✓ Charge mis-ID backgrounds (for SS dilepton events) estimated via rate measured in data

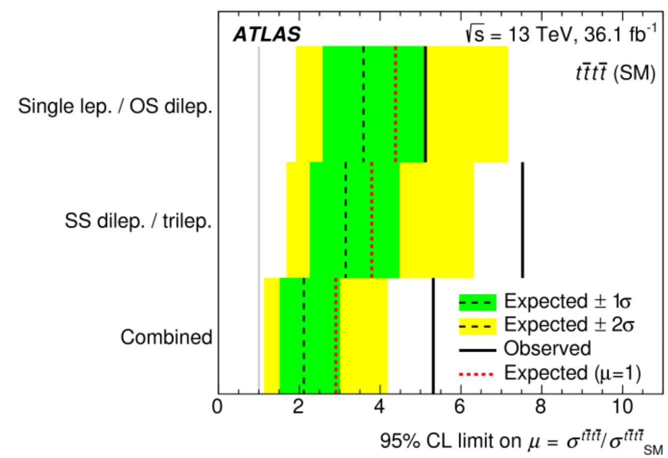
- SM four-top-quark production cross-section upper limit obtained (expected) of **69** (**29**) **fb**

4 tops in single lepton / OS dilepton events

- Search for four-top-quark production in 1L / 2OSL final states: small signal on top of large tt+jets bkg
- Probe extreme regions: go to up to 10 jets, up to 4 b-jets and up to 2 large-R jets
- MC simulation not expected to model well the high multiplicity regions: data-driven tt+jets
- Simultaneous fit to HT_{had} in 20 signal regions using data-driven estimation of tt+jets
- Results combined with ATLAS SS dilepton / trilepton search: excess of events over the SM background prediction observed with a significance of **2.8σ** (**1.0σ**).
- Assuming no signal, obs. (exp.) 95% CL upper limit of 5.3 (2.1) times SM expectation

CERN-EP-2018-174





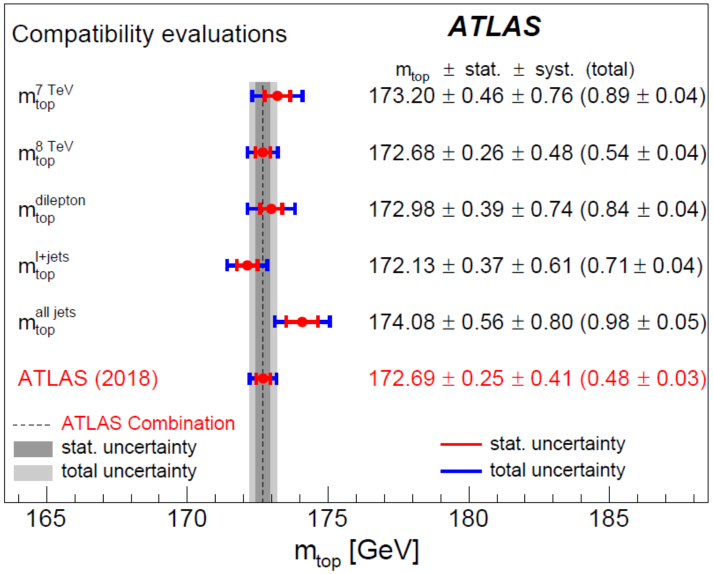
- Top quark: a laboratory for precisely testing theory predictions and perform high-precision measurements, and a window into BSM physics
- ATLAS has a broad program using top/b-quarks with many public results: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults
- Challenging and rare decay modes are exploited:
    - measurements using all possible top-quark pair final states
    - dedicated resolved/boosted channels
    - jet substructure and jet reclustering
    - event categorisation/background rejection using MVAs
    - combination of searches and various interpretations of the results
- Looking forward to new results using full Run 2 data thanks to LHC great performance
- Muchas gracias por su atención!

BACK-UP

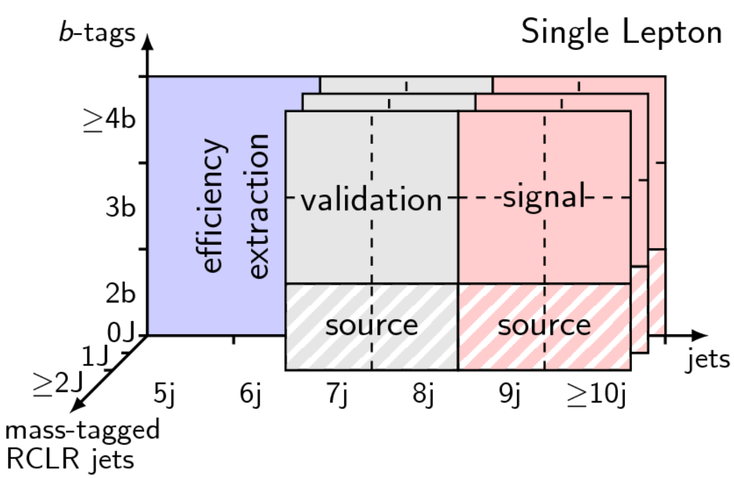
Summary of top mass measurements

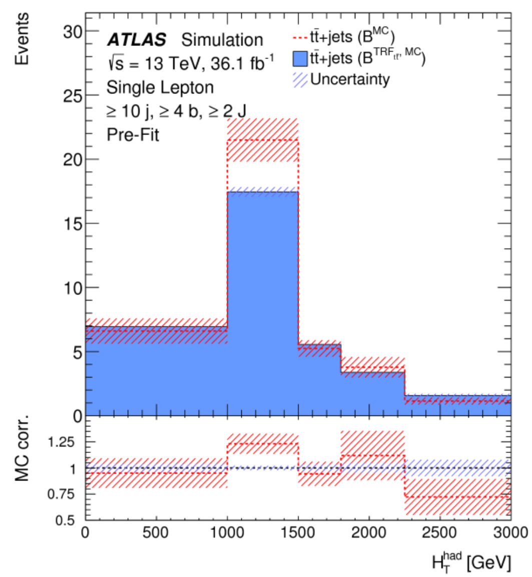
CERN-EP-2018-238

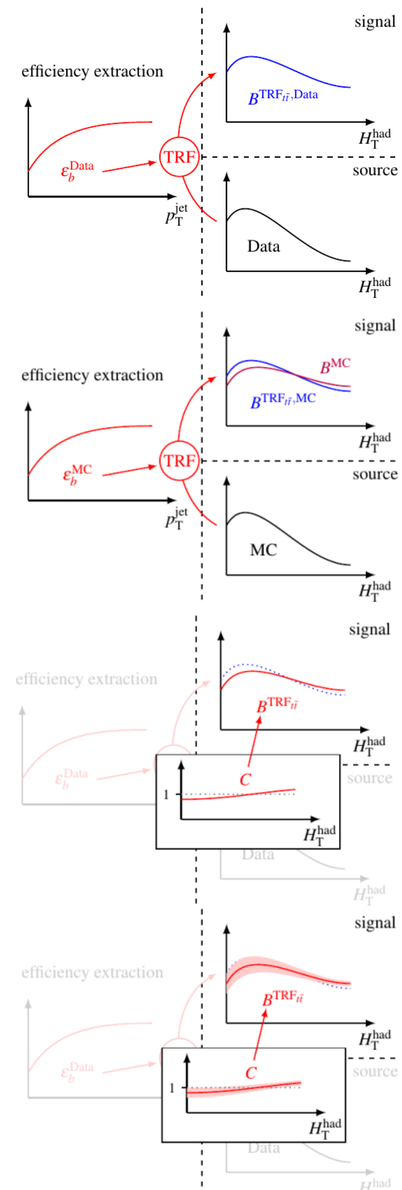
Uncertainty	Δm_{top}^{up} [GeV]	Δm_{top}^{dw} [GeV]	Δm_{top} [GeV]
Signal Monte Carlo generator		**0.16 ± 0.17**	
POWHEG-BOX - MC@NLO (HERWIG)			−0.161 ± 0.168
Hadronization		**0.15 ± 0.10**	
POWHEG+PYTHIA - POWHEG+HERWIG			+0.146 ± 0.098
Initial- and final-state QCD radiation		**0.08 ± 0.11**	
less I/FSR - more I/FSR	+0.086	−0.075	+0.080 ± 0.111
Underlying event		**0.08 ± 0.15**	
P2012 - P2012 MPIHI			−0.080 ± 0.153
Colour reconnection		**0.19 ± 0.15**	
P2012 - P2012 LOCR			+0.191 ± 0.154
Background normalization		**0.08 ± 0.00**	
Z+jets norm.	+0.007	−0.015	+0.011 ± 0.000
W+jets norm.	−0.017	−0.061	−0.061 ± 0.000
Fake lepton norm.			+0.046 ± 0.000
W/Z+jets shape		**0.11 ± 0.00**	
W+jets HF0	−0.001	−0.070	−0.070 ± 0.000
W+jets HF1	−0.005	−0.087	−0.087 ± 0.000
Jet reconstruction efficiency		**0.02 ± 0.01**	
nominal - 0.23% drop			+0.022 ± 0.013
Jet vertex fraction		**0.09 ± 0.01**	
	+0.077	−0.112	0.095 ± 0.009
Leptons		**0.16 ± 0.01**	
Electron energy scale	+0.025	−0.006	+0.016 ± 0.006
Electron energy resolution	−0.152	−0.145	−0.152 ± 0.013
Muon resolution (muon spectrometer)			+0.027 ± 0.000
Muon resolution (inner detector)			+0.023 ± 0.000
Muon scale	−0.013	+0.015	−0.014 ± 0.000
Lepton trigger SF	−0.005	−0.003	−0.005 ± 0.001
Lepton identification SF	+0.005	−0.011	+0.008 ± 0.001
Lepton reconstruction SF	+0.003	−0.008	+0.005 ± 0.000
Missing transverse momentum(E_T^{miss})		**0.05 ± 0.01**	
E_T^{miss} (resolution soft term)	+0.003	+0.012	+0.012 ± 0.018
E_T^{miss} (scale soft term)	+0.054	−0.039	+0.047 ± 0.009



- Data-driven tt+jets
  - ✓ assume probability of b-tagging a jet in tt+jets event is independent of number of extra jets
  - ✓ extract effective b-tagging efficiencies from low Nj, reweight the data and predict tt+jets in signal regions with same Nj/NJ, but larger Nb
  - ✓ correction factor C for each considered bin
  - ✓ full set of syst. uncert. by repeating the procedure on MC simulated events with syst. variations applied







- Excess info: More than half of the excess is observed in events with two muons, three b-tagged jets and HT around 700 GeV.

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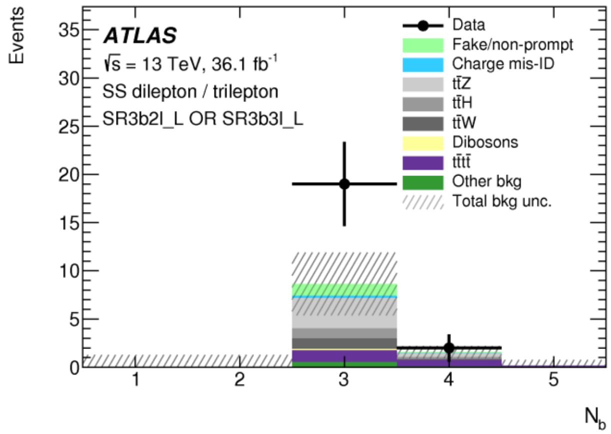
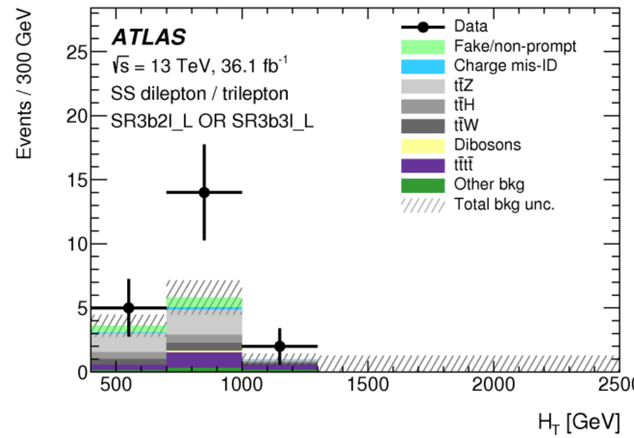
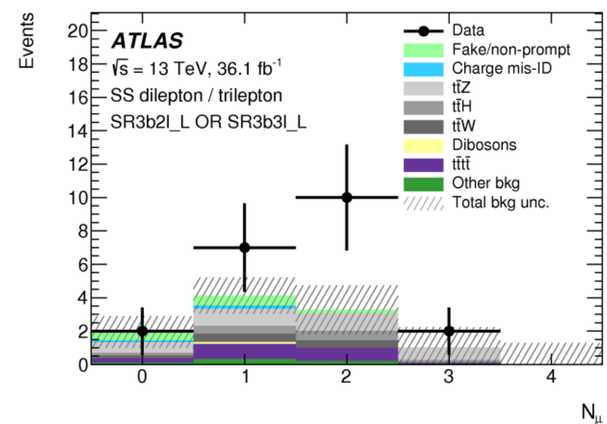
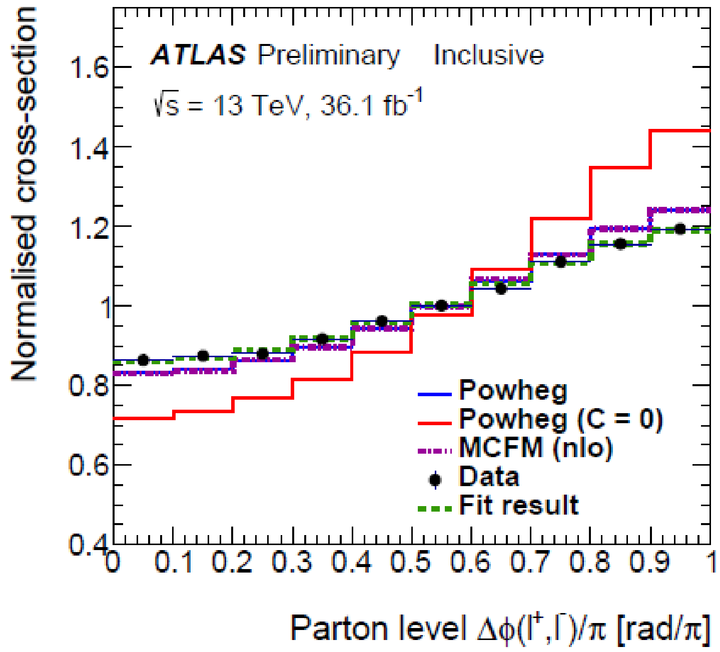




Region name	N_j	N_b	N_ℓ	Lepton charges	Kinematic criteria
VR1b2ℓ	≥ 1	1	2	++ or −−	$400 < H_T < 2400$ GeV or $E_T^{miss} < 40$ GeV
SR1b2ℓ	≥ 1	1	2	++ or −−	$H_T > 1000$ GeV and $E_T^{miss} > 180$ GeV
VR2b2ℓ	≥ 2	2	2	++ or −−	$H_T > 400$ GeV
SR2b2ℓ	≥ 2	2	2	++ or −−	$H_T > 1200$ GeV and $E_T^{miss} > 40$ GeV
VR3b2ℓ	≥ 3	≥ 3	2	++ or −−	$400 < H_T < 1400$ GeV or $E_T^{miss} < 40$ GeV
SR3b2ℓ_L	≥ 7	≥ 3	2	++ or −−	$500 < H_T < 1200$ GeV and $E_T^{miss} > 40$ GeV
SR3b2ℓ	≥ 3	≥ 3	2	++ or −−	$H_T > 1200$ GeV and $E_T^{miss} > 100$ GeV
VR1b3ℓ	≥ 1	1	3	any	$400 < H_T < 2000$ GeV or $E_T^{miss} < 40$ GeV
SR1b3ℓ	≥ 1	1	3	any	$H_T > 1000$ GeV and $E_T^{miss} > 140$ GeV
VR2b3ℓ	≥ 2	2	3	any	$400 < H_T < 2400$ GeV or $E_T^{miss} < 40$ GeV
SR2b3ℓ	≥ 2	2	3	any	$H_T > 1200$ GeV and $E_T^{miss} > 100$ GeV
VR3b3ℓ	≥ 3	≥ 3	3	any	$H_T > 400$ GeV
SR3b3ℓ_L	≥ 5	≥ 3	3	any	$500 < H_T < 1000$ GeV and $E_T^{miss} > 40$ GeV
SR3b3ℓ	≥ 3	≥ 3	3	any	$H_T > 1000$ GeV and $E_T^{miss} > 40$ GeV



ATLAS-CONF-2018-027



Generator	inclusive	$m_{t\bar{t}} < 450$ GeV	$450 < m_{t\bar{t}} < 550$ GeV	$550 < m_{t\bar{t}} < 800$ GeV	$m_{t\bar{t}} > 800$ GeV
f_{SM} values					
Powheg + Pythia 8	1.25	1.11	1.17	1.60	2.19
Powheg + Pythia 8 (2.0 μ_F, 2.0 μ_R)	1.29	1.14	1.21	1.70	1.70
Powheg + Pythia 8 (0.5 μ_F, 0.5 μ_R)	1.18	1.09	1.11	1.40	1.30
Powheg + Pythia 8 (PDF variations)	1.26	1.12	1.24	1.69	2.19
Powheg + Pythia 8 RadLo tune	1.29	1.14	1.21	1.40	1.70
Powheg + Herwig 7	1.32	1.16	1.23	1.70	1.70
MadGraph5_aMC@NLO + Pythia 8	1.20	1.06	1.17	1.40	0.70

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$$\mathcal{L}_{\rm SM} = \mathcal{L}_{\rm SM}^{(4)} + \frac{1}{\Lambda}\sum_k C_k^{(5)} Q_k^{(5)} + \frac{1}{\Lambda^2}\sum_k C_k^{(6)} Q_k^{(6)} + \mathcal{O}\left(\frac{1}{\Lambda^3}\right),$$

Operator	Expression
$O_{\phi Q}^{(3)}$	$i\frac{1}{2}(\phi^\dagger \overleftrightarrow{D}^I_\mu \phi)(\bar{Q}\gamma^\mu \tau^I Q)$
$O_{\phi Q}^{(1)}$	$i\frac{1}{2}(\phi^\dagger \overleftrightarrow{D}_\mu \phi)(\bar{Q}\gamma^\mu Q)$
$O_{\phi t}$	$i\frac{1}{2}(\phi^\dagger \overleftrightarrow{D}_\mu \phi)(\bar{t}\gamma^\mu t)$
O_{tW}	$y_t g_w (\bar{Q}\sigma^{\mu\nu}\tau^I t)\tilde{\phi} W^I_{\mu\nu}$
O_{tB}	$y_t g_Y (\bar{Q}\sigma^{\mu\nu} t)\tilde{\phi} B_{\mu\nu}$

$$\sigma_{tot,i} = \sigma_{SM} + \frac{C_i}{(\Lambda/1\mathrm{TeV})^2}\sigma_i^{(1)} + \frac{C_i^2}{(\Lambda/1\mathrm{TeV})^4}\sigma_{ii}^{(2)},$$

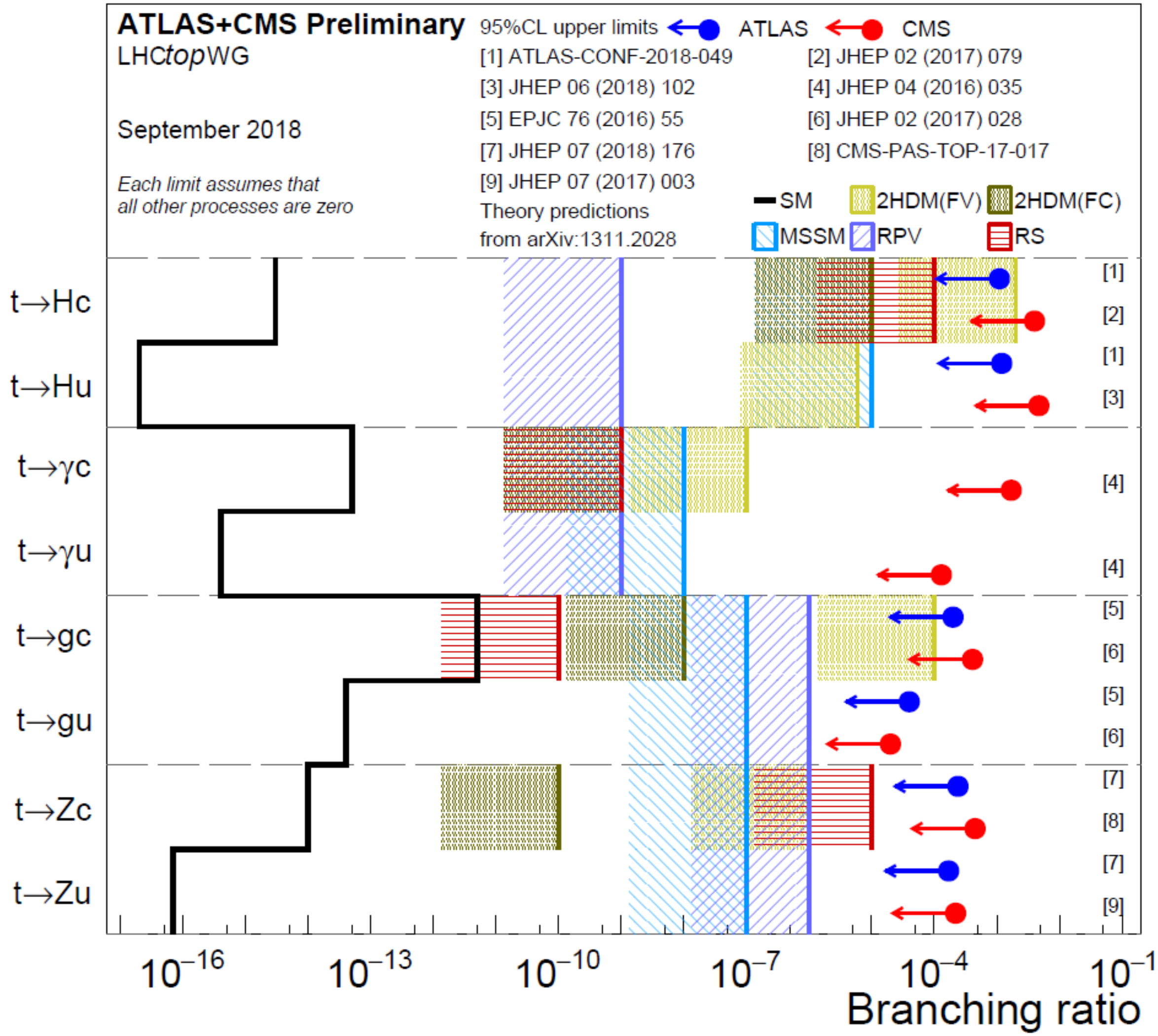
Table 10: The expected and observed 68% and 95% confidence intervals that include the value 0, on C_i/Λ^2 for the EFT coefficients $C_{\phi Q}^{(3)}$, $C_{\phi Q}^{(1)}$, $C_{\phi t}$, C_{tB} and C_{tW}. The measurement is sensitive only to the difference $C_{\phi Q}^{(3)} - C_{\phi Q}^{(1)}$. All results are given in units of $1/\mathrm{TeV}^2$. Previous 95% confidence level constraints as summarized in Ref. [6] are quoted in the last column.

Coefficient	Expected limits at 68% and 95 % CL	Observed limits at 68% and 95 % CL	Previous constraints at 95 % CL
$(C_{\phi Q}^{(3)} - C_{\phi Q}^{(1)})/\Lambda^2$	[-2.1, 1.9], [-4.6, 3.7]	[-1.0, 2.7], [-3.4, 4.3]	[-3.4, 7.5]
$C_{\phi t}/\Lambda^2$	[-3.8, 2.8], [-23, 5.0]	[-2.0, 3.6], [-27, 5.7]	[-2.0, 5.7]
C_{tB}/Λ^2	[-8.3, 8.6], [-12, 13]	[-11, 10], [-15, 15]	[-16, 43]
C_{tW}/Λ^2	[-2.8, 2.8], [-4.0, 4.1]	[-2.2, 2.5], [-3.6, 3.8]	[-0.15, 1.9]

Flavor-changing neutral currents (FCNC) are forbidden at tree level and strongly suppressed at higher order in SM, ex.

$$t \to Hq, (q = u, c)$$

Large enhancements in branching ratio are possible in some beyond Standard Model (SM) scenarios, $\mathcal{B}(t \to Hc) \sim 0.1\%$ ($\sim 10^{-15}$ in SM)



https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/TOP/