Top-quark polarization in single top t-channel

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4th Red LHC Workshop

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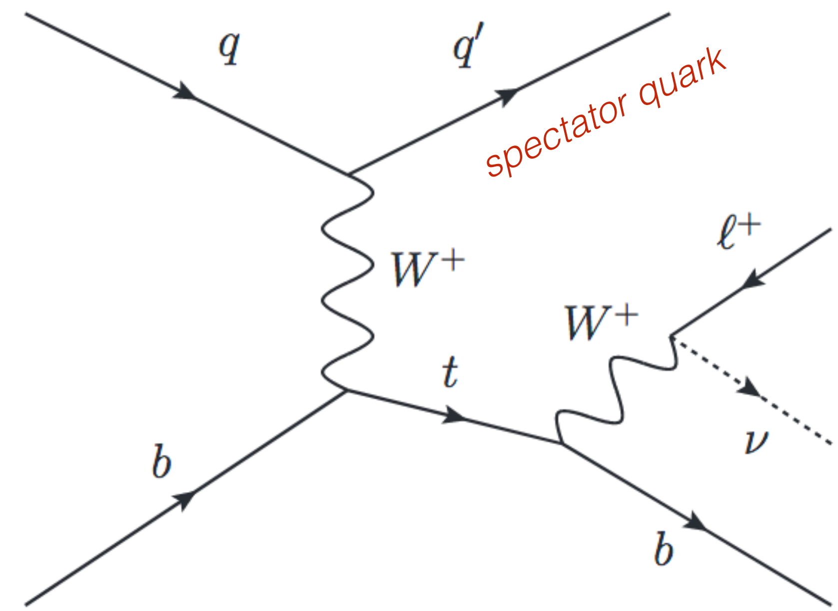
OVERVIEW

- Introduction.
- Signal and control regions definition.
- Overall normalisation constraints.
- Angular distributions at reconstruction level.
- Results: Unfolded differential measurements.
- Conclusions.

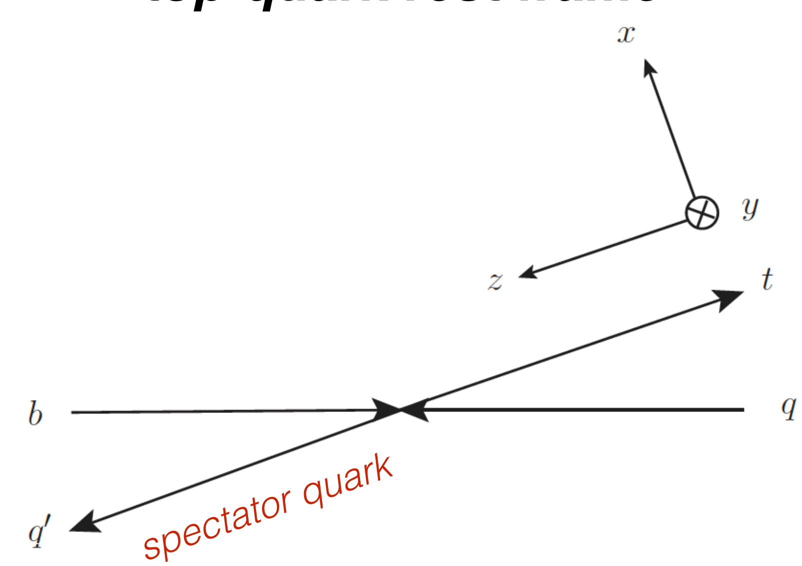
INTRODUCTION

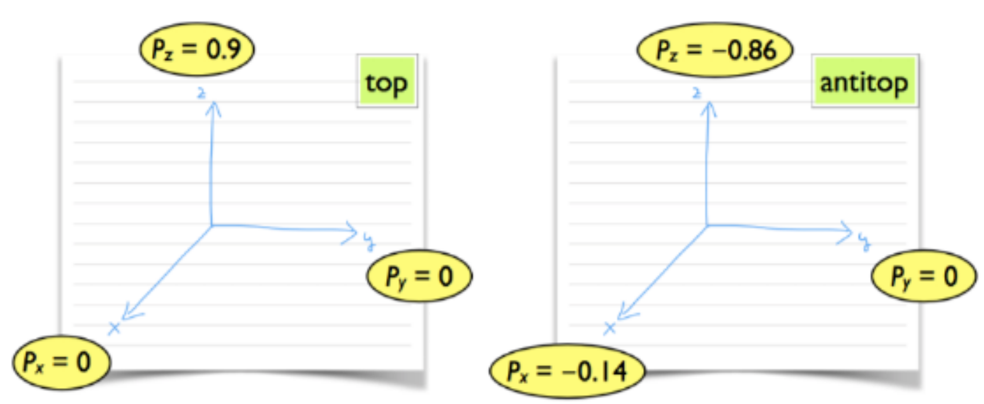
- First measurement of all the top-quark polarisation components at 13 TeV.
- In the t-channel at LO single top quarks are produced with their spin aligned along the direction of the down-type quarks (Phys. Rev.D55(1997) 7249).
- Polarisation accessible in the angular distributions of the decaying charged lepton in the top quark rest frame.
- Using a proper coordinate system (Phys. Rev. D89 (2014) 114009) one can obtain the differential angular distributions associated with the three different polarisation components.
    - Differential measurements carried out separately for top and antitop quarks at particle level in a fiducial region.
    - Direct measurement of the polarisation components $\{P_X, P_Y, P_Z\}$ using a template fit (not covered in this talk).
- Deviations from SM predictions can give hints of physics beyond the SM.
    - Measurement can be interpreted within an EFT framework.

t-channel



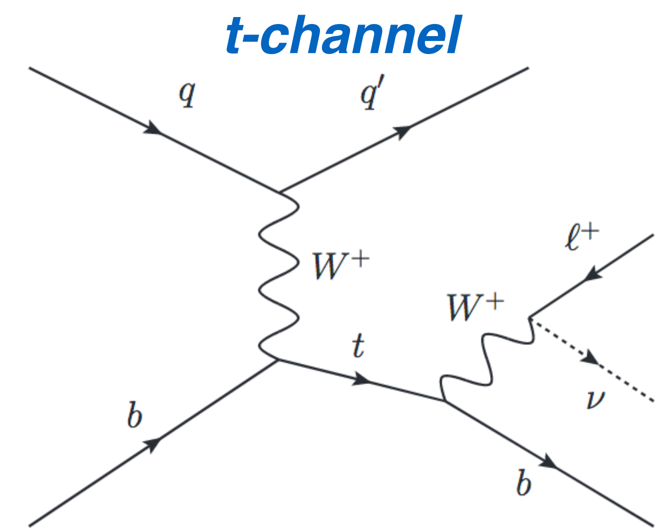
top-quark rest frame

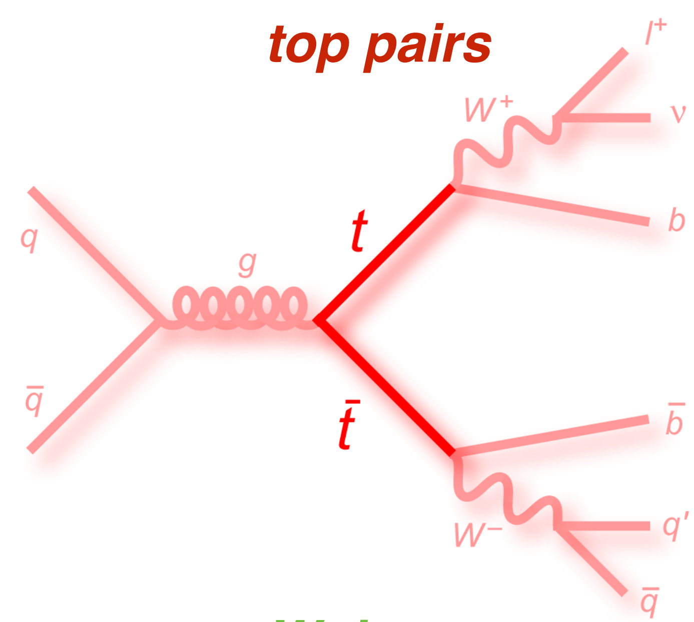


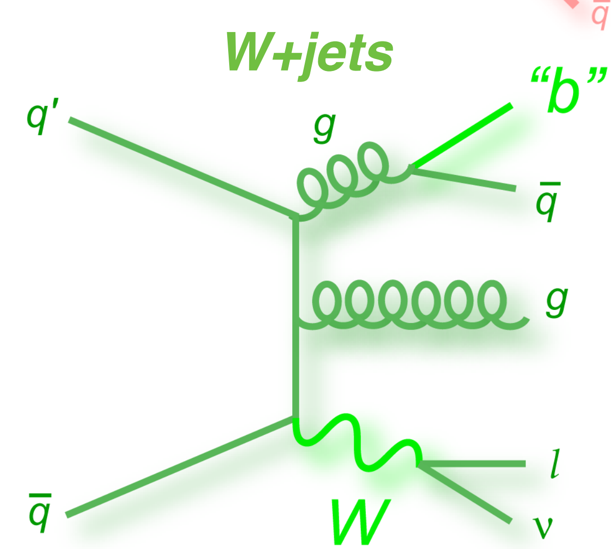


SIGNAL AND BACKGROUNDS

- This analysis is performed at **13 TeV** using the full Run2 dataset, corresponding to 2015-2018 (~**139.0 fb^{-1}**)
- Signal and background processes are all simulated using different MC generators (except multijet).
- **Signal**: Single top-quark t-channel (Powheg)
- **Main backgrounds**:
  - top-quark pair production (Powheg)
  - W+jets (Sherpa)
- **Other backgrounds:**
  - Z+jets (Sherpa)
  - Diboson (Sherpa)
  - Other single top-quark processes (s-channel, tW) (Powheg)
  - Multijet
  - Other minor backgrounds (top pair and single top-quark productions associated with vector and Higgs bosons).
- All backgrounds (except multijet) are normalised to their respective cross-sections and to the total luminosity used in this analysis.



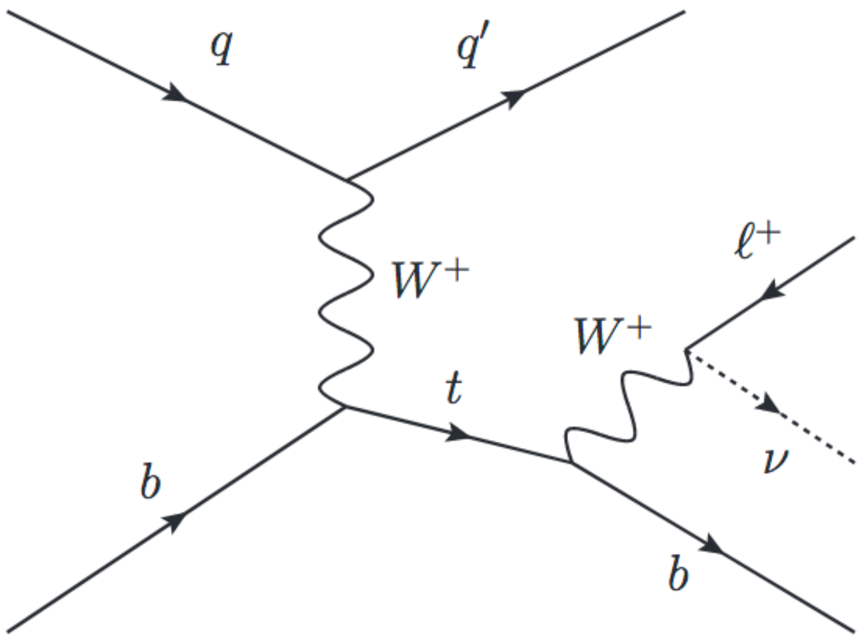




SIGNAL AND CONTROL REGIONS

- **Pre-selection (PR):**
  - Exactly one tight charged lepton (electron or muon).
  - Exactly 2 jets, exactly one b-tagged.
  - MET > 35 GeV
  - $M_T(W) > 60$ GeV → $m_T(\ell E_T^{miss}) = \sqrt{2 p_T(\ell) E_T^{miss} \left(1 - \cos\Delta\phi(p_T(\ell), E_T^{miss})\right)}$
  - Additional multijet rejecting cut →

$$p_T(l) > 50 \left(1 - \frac{\pi - |\Delta\Phi(l, j)|}{\pi - 1}\right)$$



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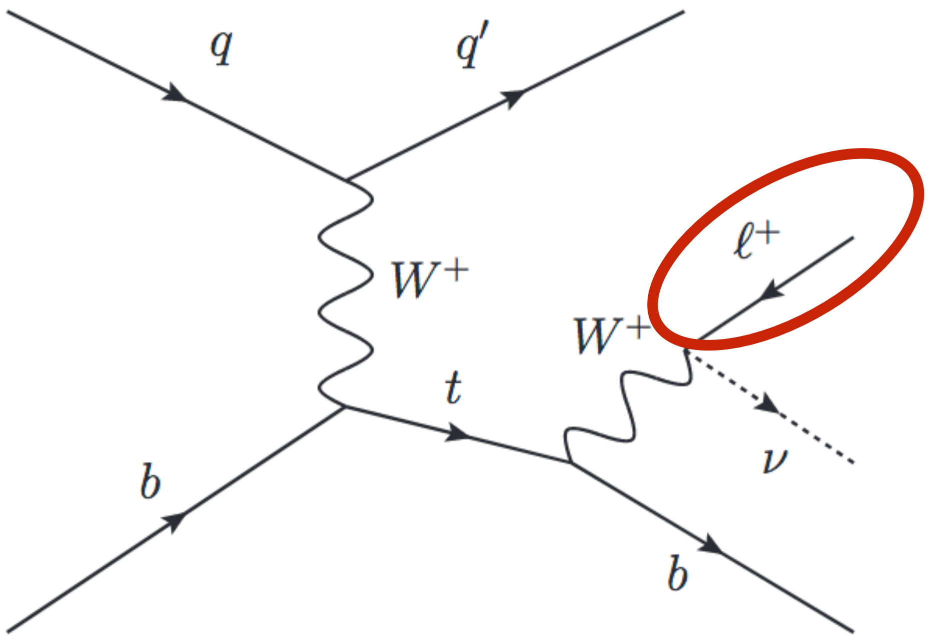

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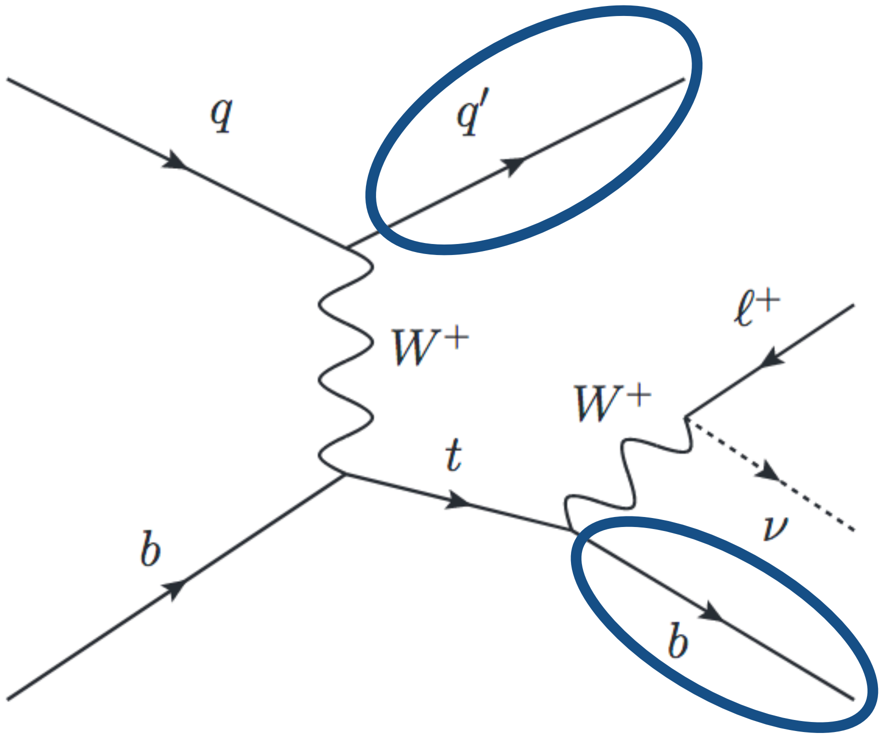

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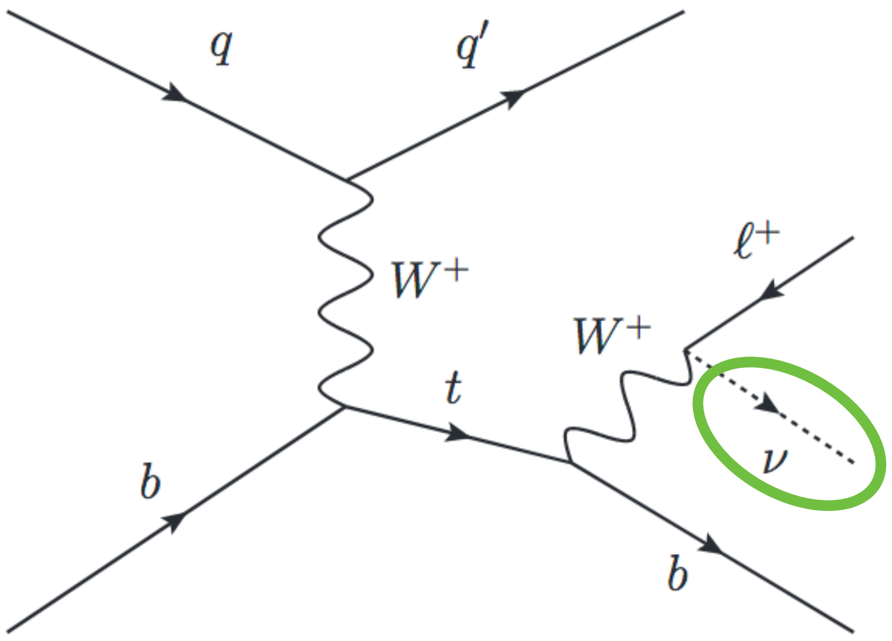

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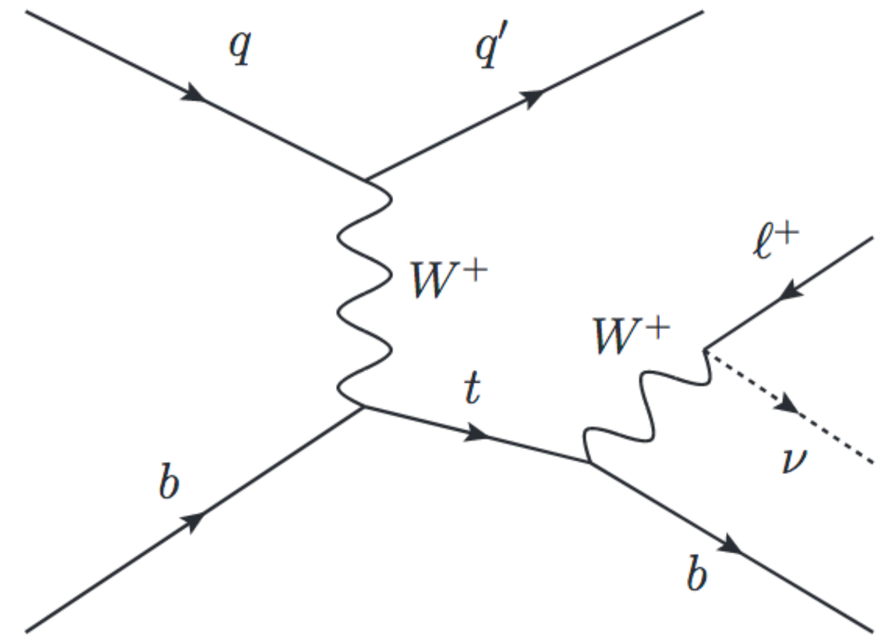
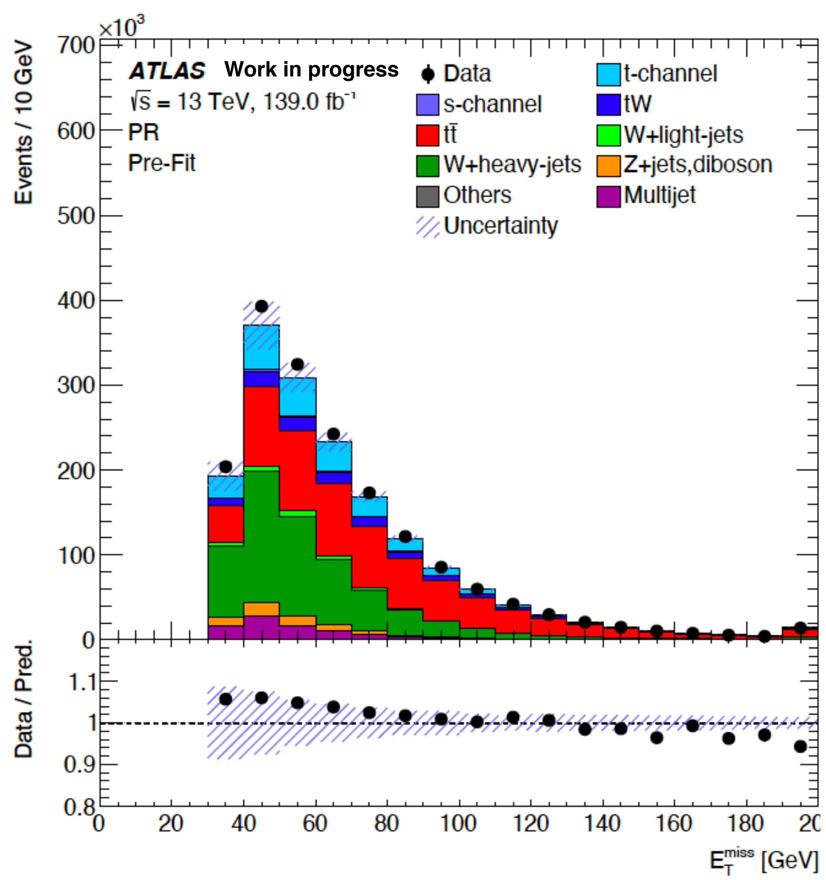
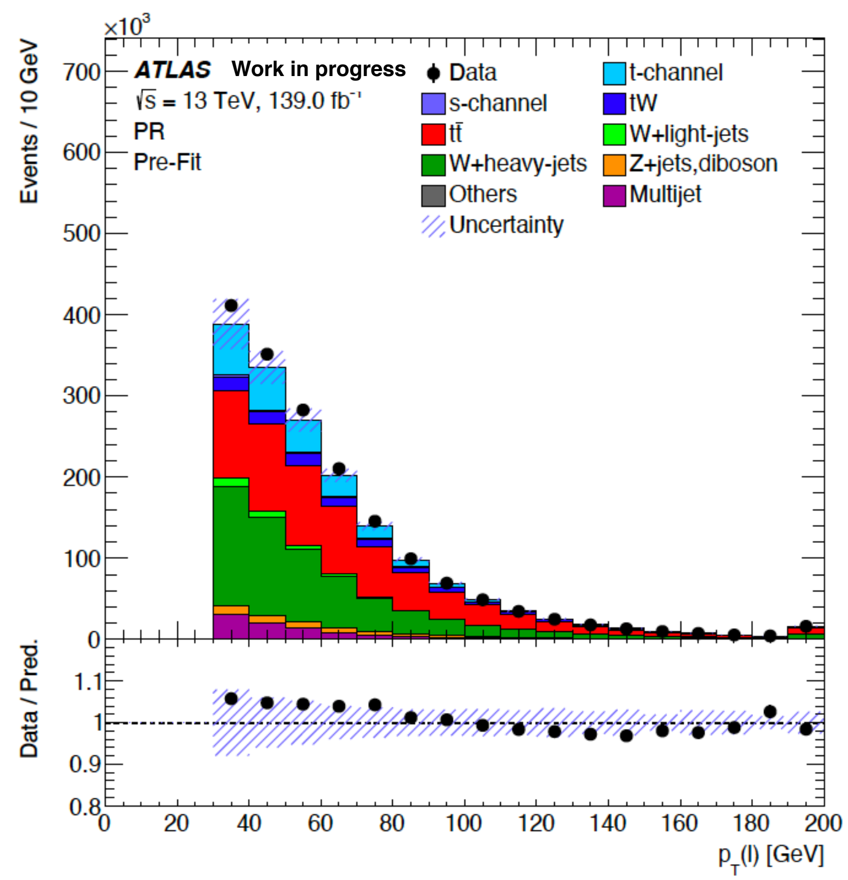
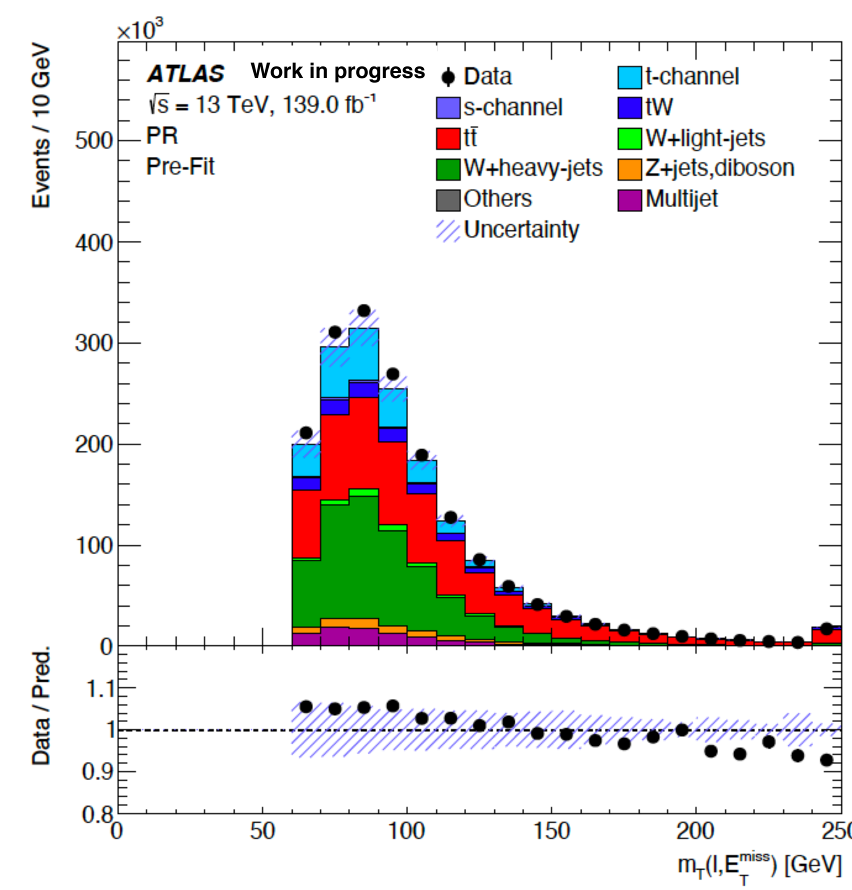


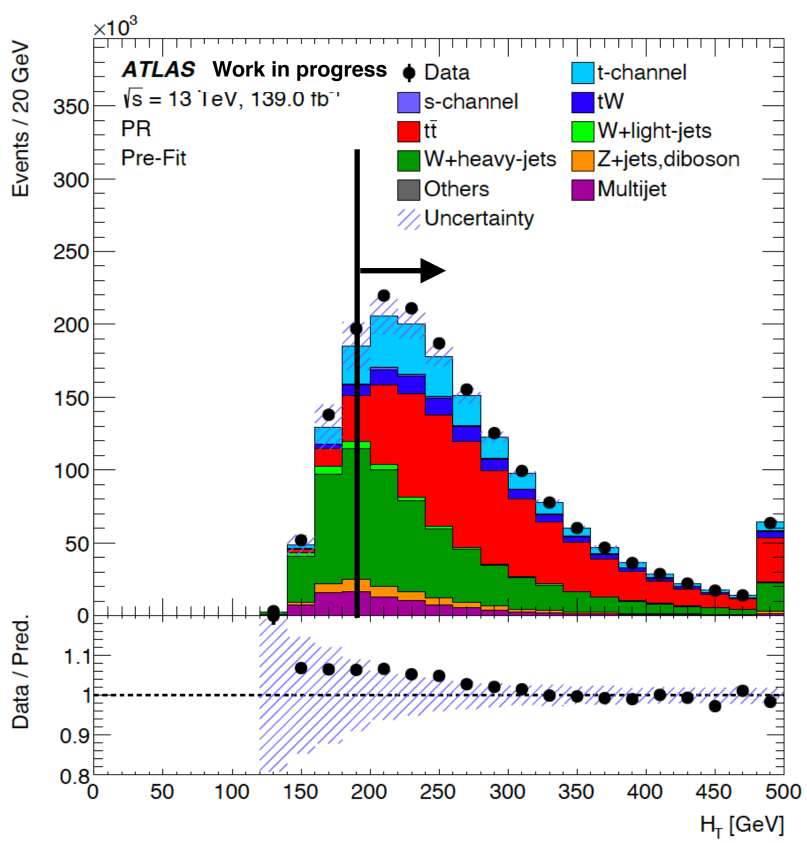


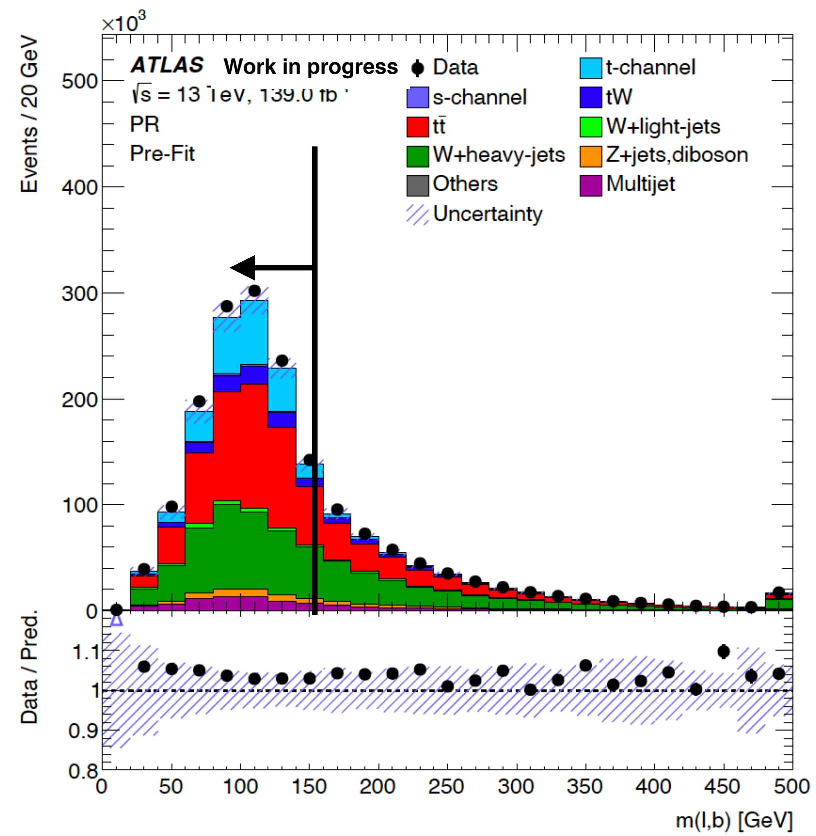


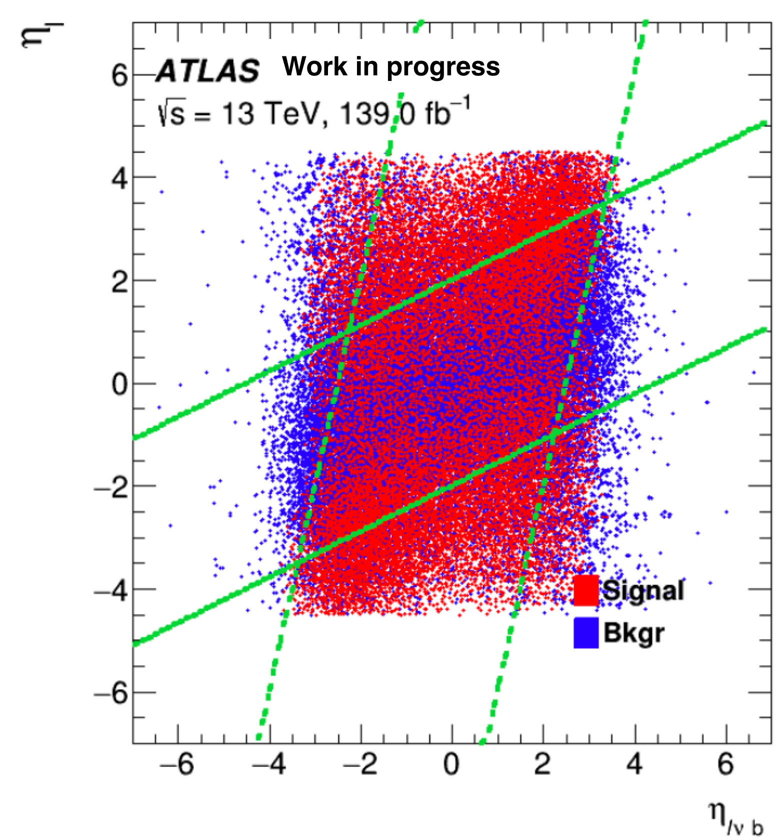


SIGNAL AND CONTROL REGIONS

- **Signal region (SR):**
  - $m_{lb} < 153$ GeV
    - Exclude events in which the top-quark of the t-channel is off-shell.
  - $120.6 < m_{top} < 234.6$ GeV
    - Reject background events from processes not involving top quarks.
  - $m_{j,top} > 320$ GeV
    - Reject background events from processes not involving top quarks.
  - Trapezoidal cut*: a = 10, b = 2
    - Reject events with central reconstructed top-quarks and leptons in the central region.
  - $H_T > 190$ GeV
    - The backgrounds peak lower in the H_T distribution.



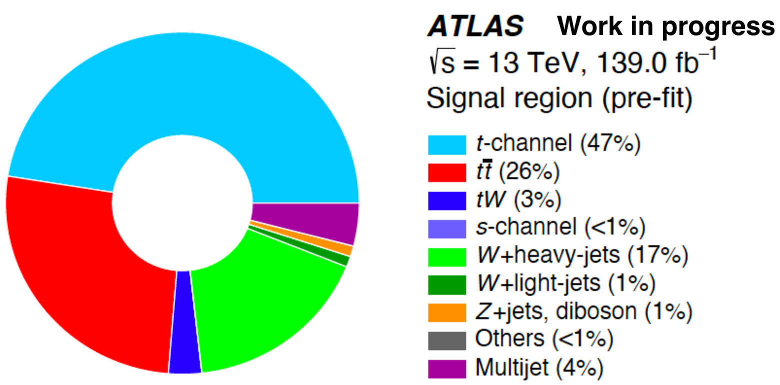




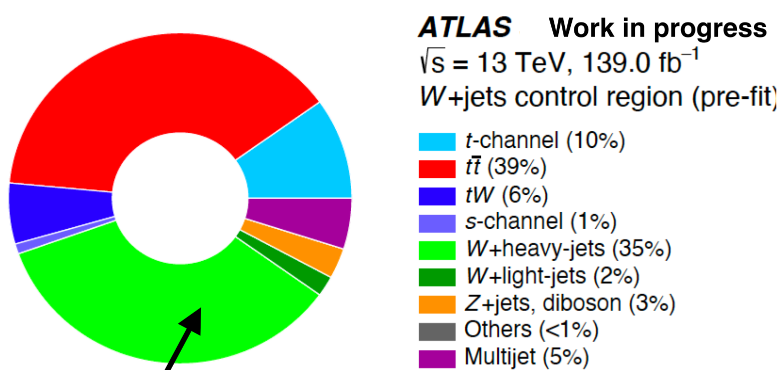
$$* \left(\eta_j < (4\,\eta_{\ell E_T^{miss} b} + a) \cap \eta_j > (4\,\eta_{\ell E_T^{miss} b} - a)\right) \cap \left(\eta_j > (0.44\,\eta_{\ell E_T^{miss} b} + b) \cup \eta_j < (0.44\,\eta_{\ell E_T^{miss} b} - b)\right)$$

SIGNAL AND CONTROL REGIONS

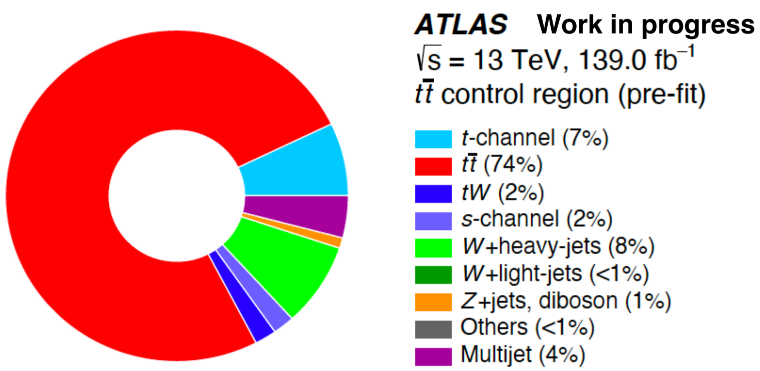
- **Control regions**:
  - W+jets CR: PR-SR (events that pass pre-selection cuts but not signal region cuts)
  - $t\bar{t}$ CR: Same as PR, but with 2 b-jets and no light jets.



(b) Signal region



(d) W+jets control region

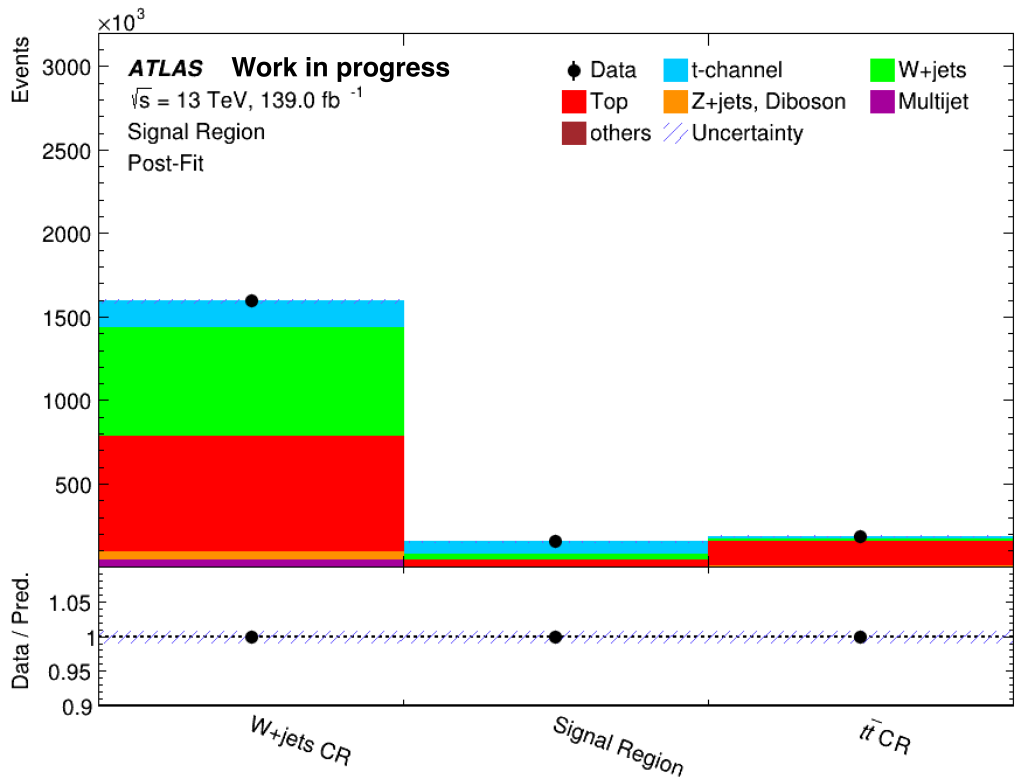


(c) $t\bar{t}$ control region

✓ *Same W+jets flavour composition as in signal region*

OVERALL NORMALISATION CONSTRAINTS

- The normalisation of the different backgrounds and the t-channel signal events has theoretical normalisation uncertainties (4% t-channel, 6% $t\bar{t}$, 20% W+jets).
- The overall normalisations of the W+jets and top-quark background ($t\bar{t}$, single top *Wt* and *s*-channel) contributions and the *t*-channel signal is constrained in this analysis.
- A data-driven method, based on a maximum-likelihood fit of the numbers of data events obtained in the $t\bar{t}$ and W+jets control regions and in the signal region, is applied to derive scale factors for the three processes.

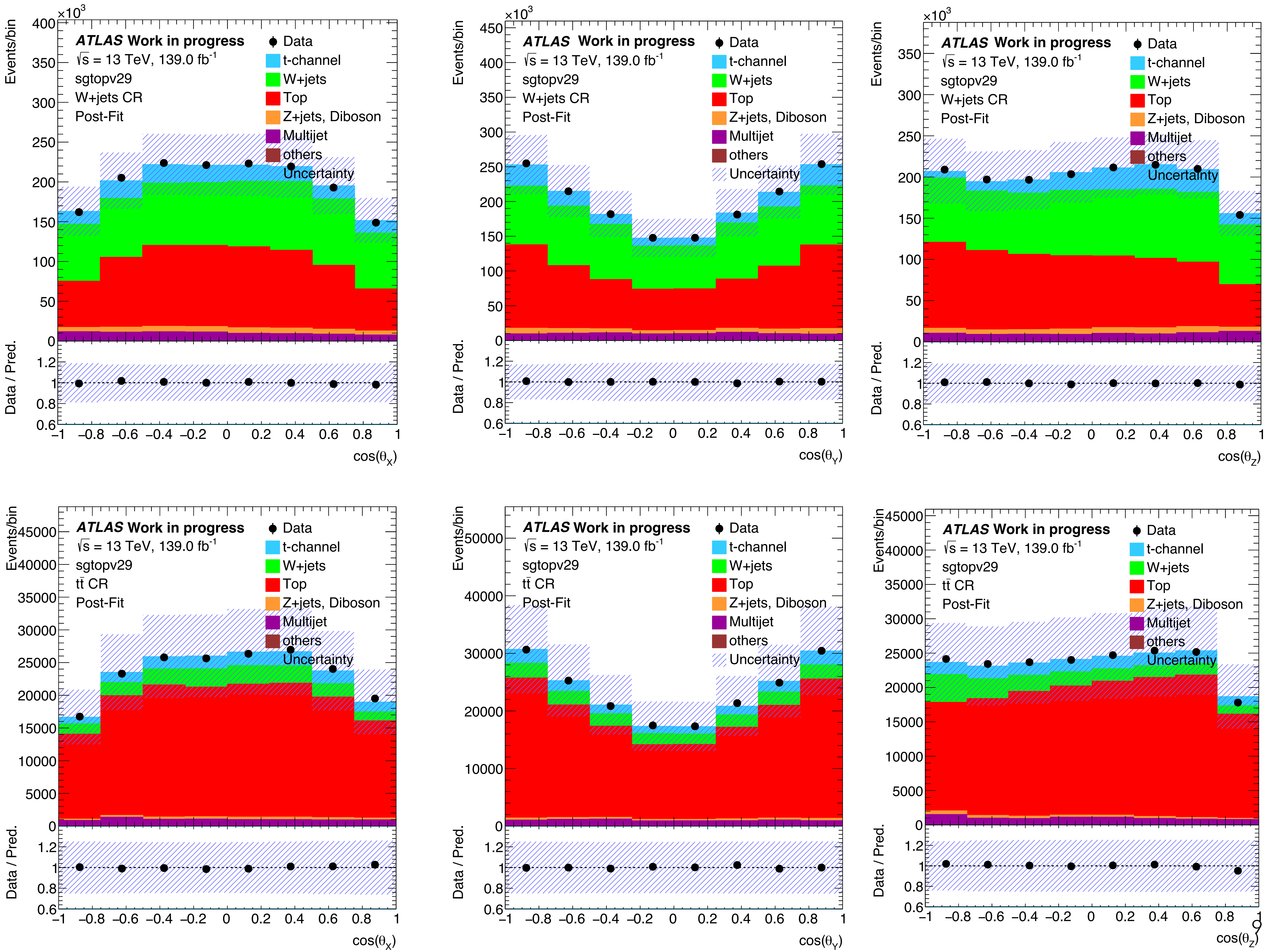


Process	e-channel (stat.)	μ-channel (stat.)	e+μ-channels (stat.+syst.)
t-channel	1.087 ± 0.017	1.059 ± 0.017	1.073 ± 0.012 ± 0.288
W+jets	1.138 ± 0.013	1.168 ± 0.011	1.153 ± 0.009 ± 0.601
$t\bar{t}$,Wt,s-channel	0.990 ± 0.008	1.003 ± 0.006	0.996 ± 0.005 ± 0.321

ANGULAR DISTRIBUTIONS IN THE CONTROL REGIONS

W+jets CR

$t\bar{t}$ CR



ANGULAR DISTRIBUTIONS IN THE CONTROL REGIONS

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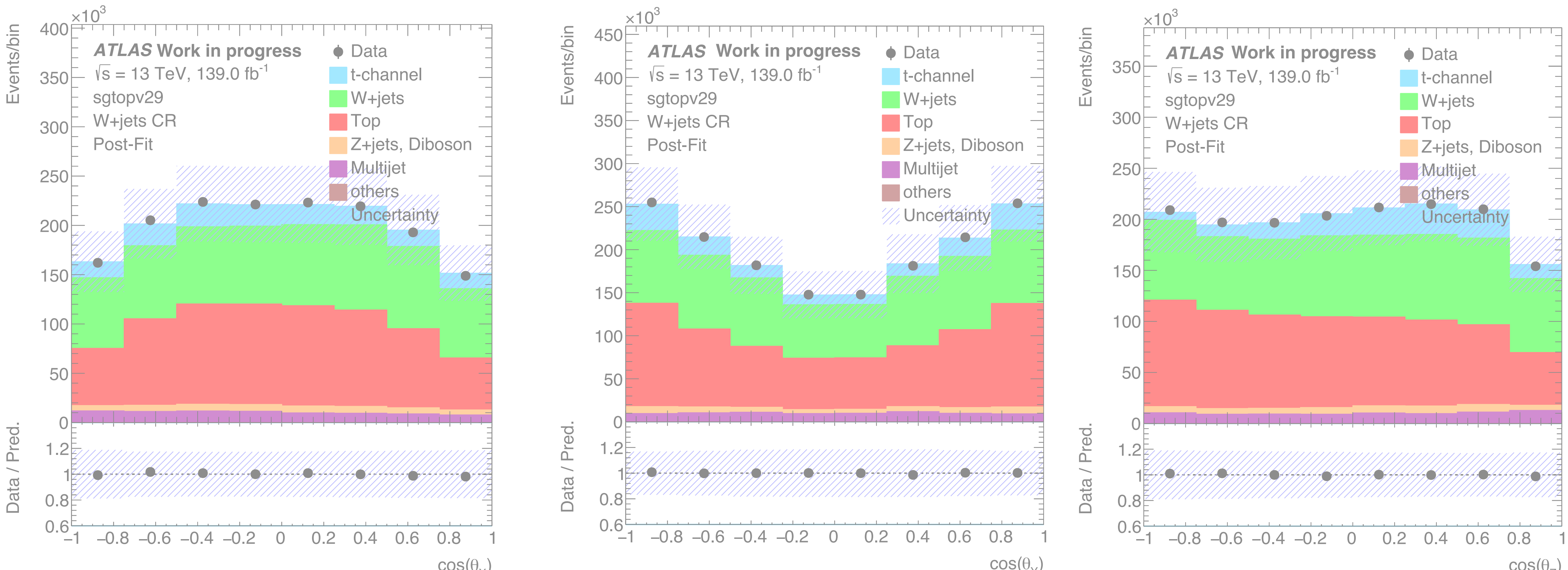
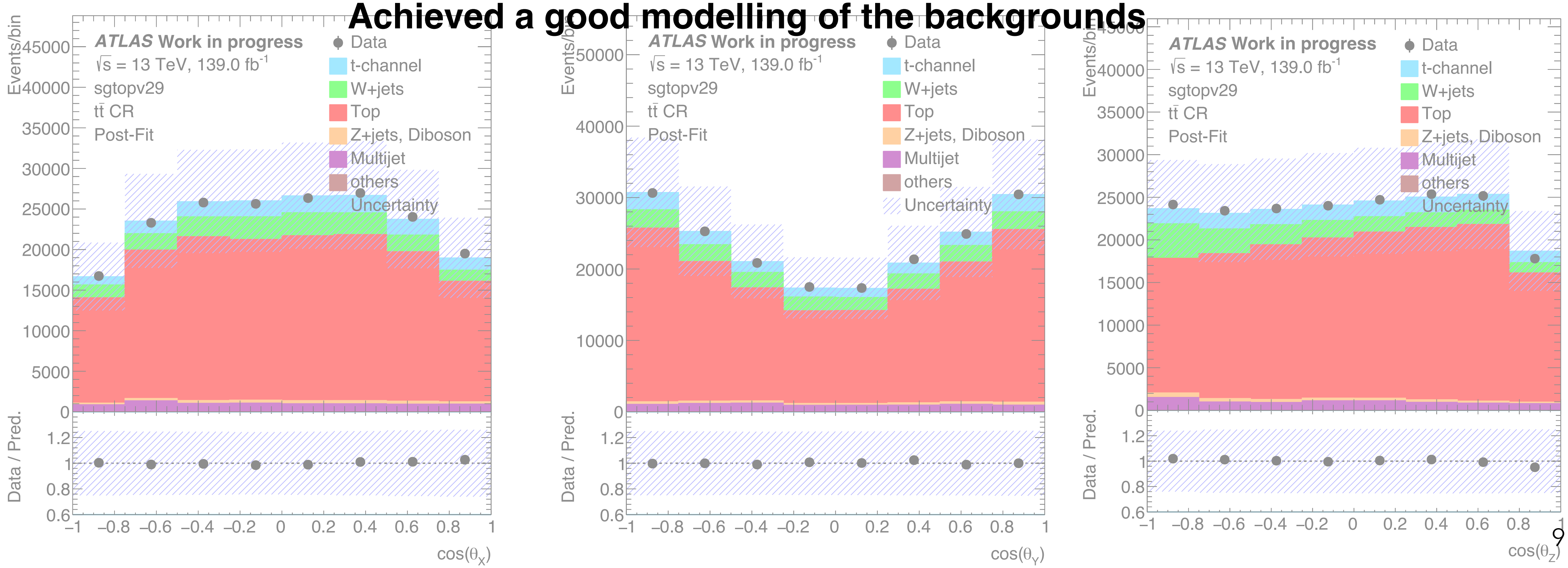


Uncertainty bands include statistical and all systematic uncertainties

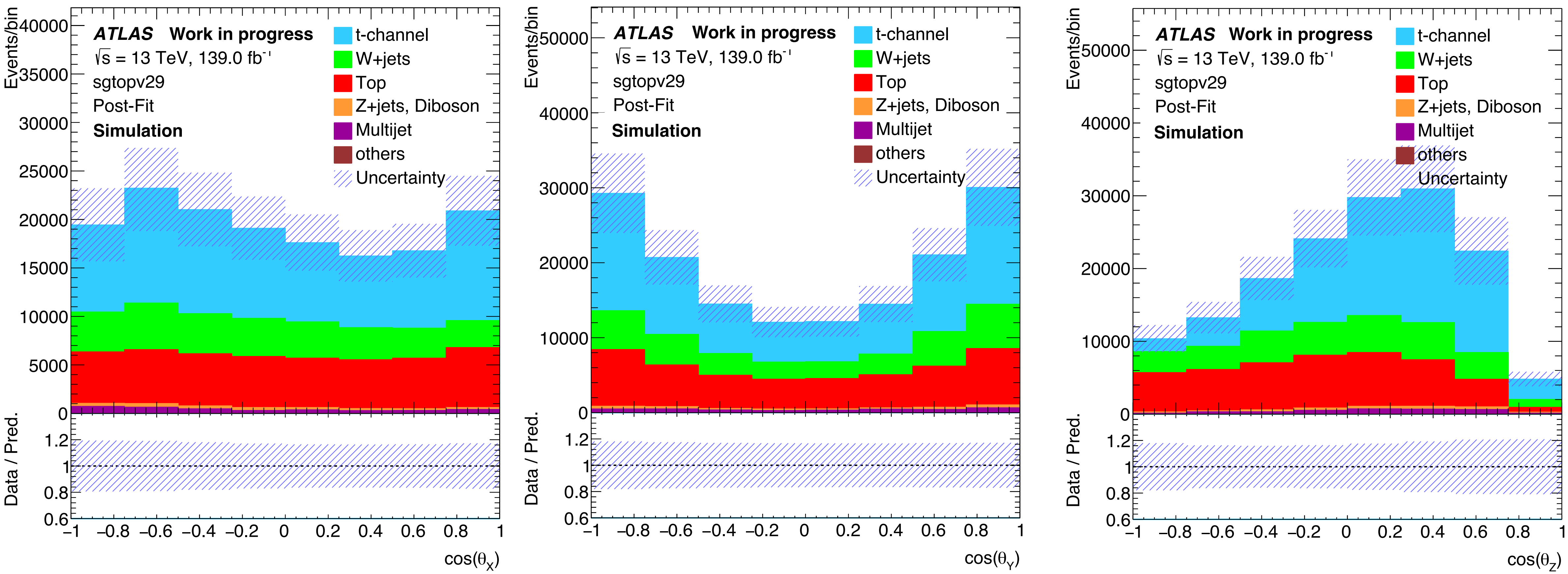
Achieved a good modelling of the backgrounds

$t\bar{t}$ CR



UNFOLDED DIFFERENTIAL MEASUREMENTS: METHOD

Signal region



- The different contributing backgrounds are subtracted to the data so that we only stay with events expected to be t-channel signal events.
- The t-channel expected distribution is normalised to measure differential distributions.
- These differential angular distributions (*reconstruction level*) are distorted by detector inefficiencies and acceptance effects.
- To correct this, the detector effects are **unfolded** to *particle level** in a fiducial region. Then the measured angular differential distributions can be compared to theoretical predictions.
- The fiducial region at particle level is defined applying the same requirements used to define the signal region to particle level objects.

**Objects do not take into account any detector effect.*

UNFOLDED DIFFERENTIAL MEASUREMENTS: METHOD

- An iterative Bayesian approach implemented in RooUnfold is used with additional correction factors.
- The correction factors and unfolding matrices are computed using t-channel single top events generated with Powheg+Pythia 8 at NLO.
- Convergence, closure and linearity tests have been performed.

$$N_k^{\text{particle}} = C_k^{\text{particle!reco}} \sum_j M_{jk}^{-1} C_j^{\text{reco!particle}} (N_k^{\text{reco}}),$$

with $C_k^{\text{particle!reco}} = \frac{S_k^{\text{particle}} - S_k^{\text{particle!reco}}}{S_k^{\text{particle}}}$ and $C_j^{\text{reco!particle}} = \frac{S_j^{\text{reco}} - S_j^{\text{reco!particle}}}{S_j^{\text{reco}}}$

UNFOLDED DIFFERENTIAL MEASUREMENTS: METHOD

- 8 bins used for θ_X and θ_Y, 4 bins used for θ_Z (ensure > 70% of events in diagonal elements of the migration matrix and not a very large number of iterations).

Migration matrix from reco. to particle level

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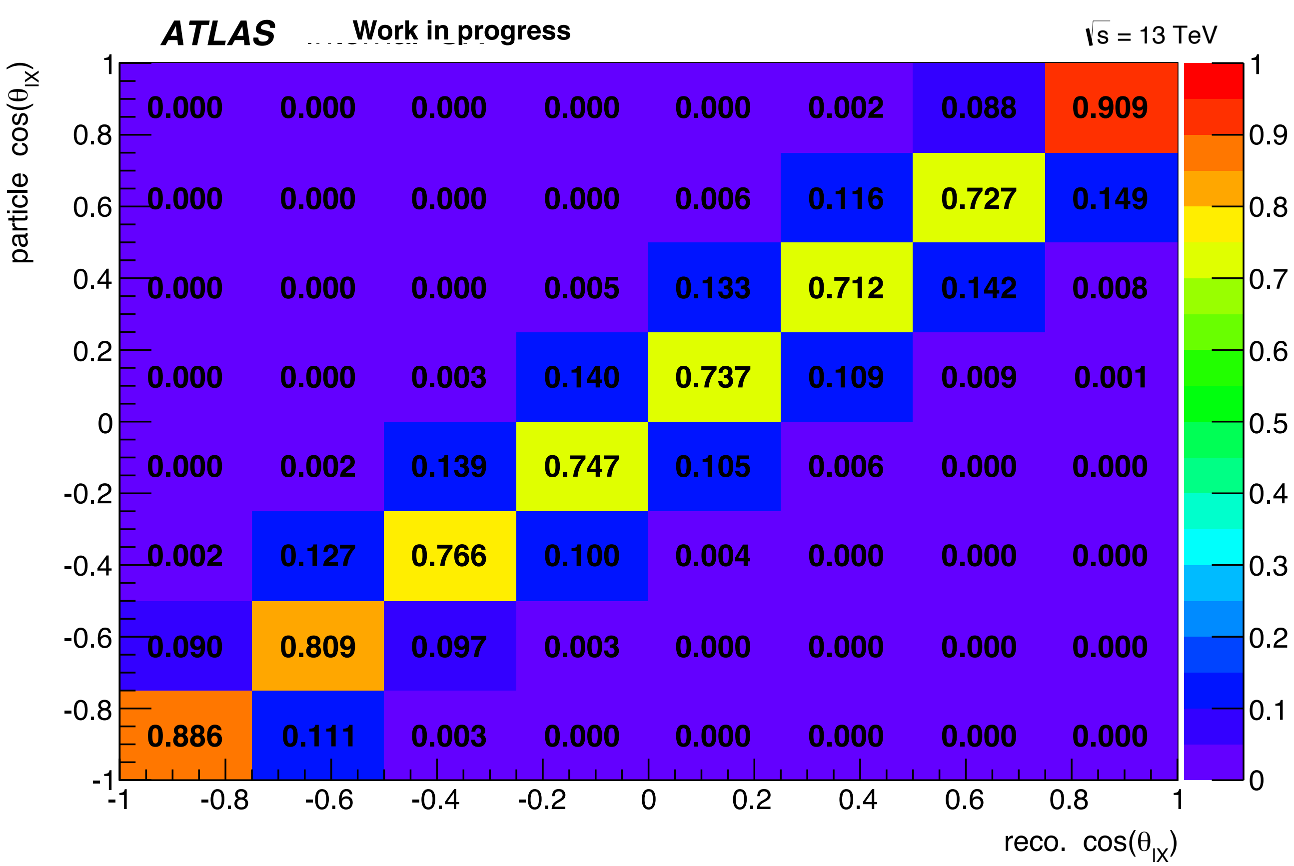

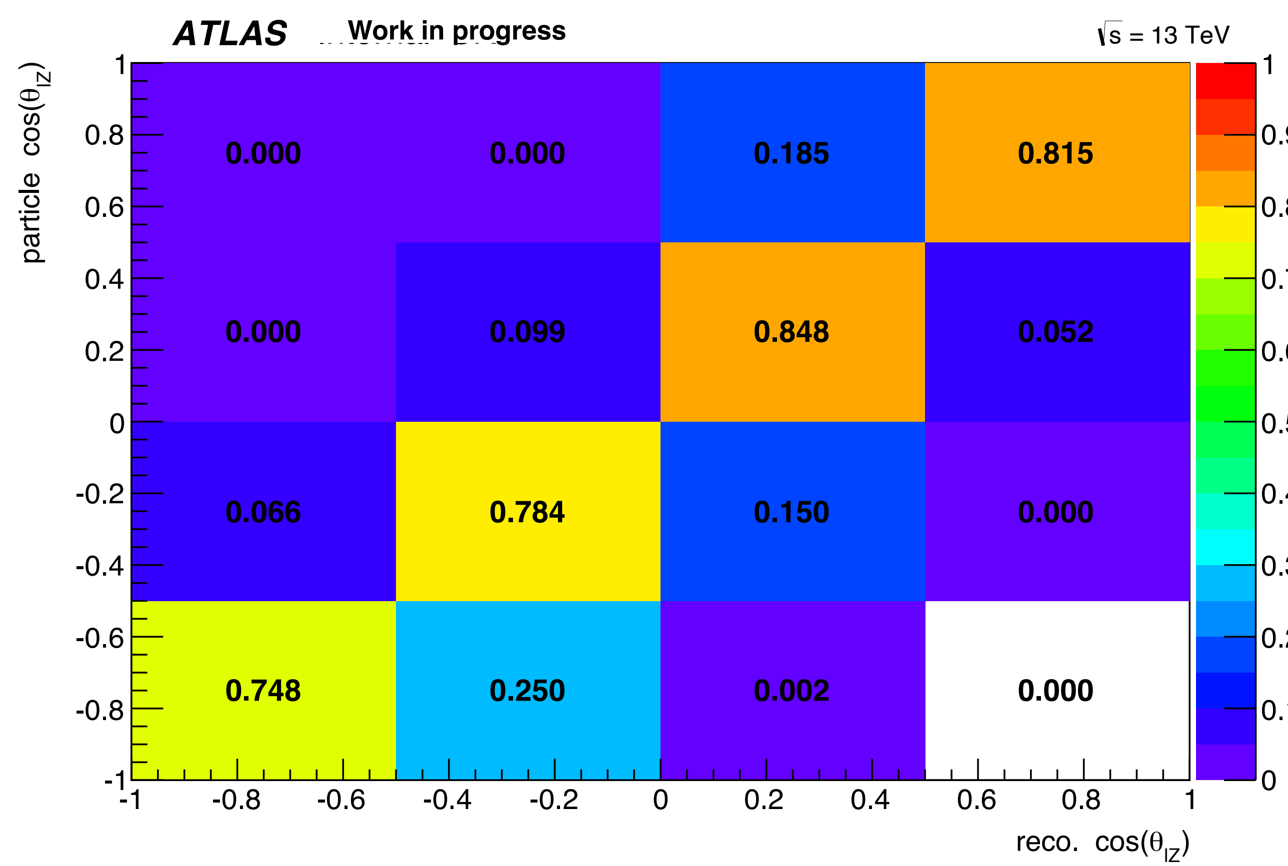

UNFOLDED DIFFERENTIAL MEASUREMENTS: METHOD

Correction factors: Events that pass particle level cuts and not reconstruction level cuts

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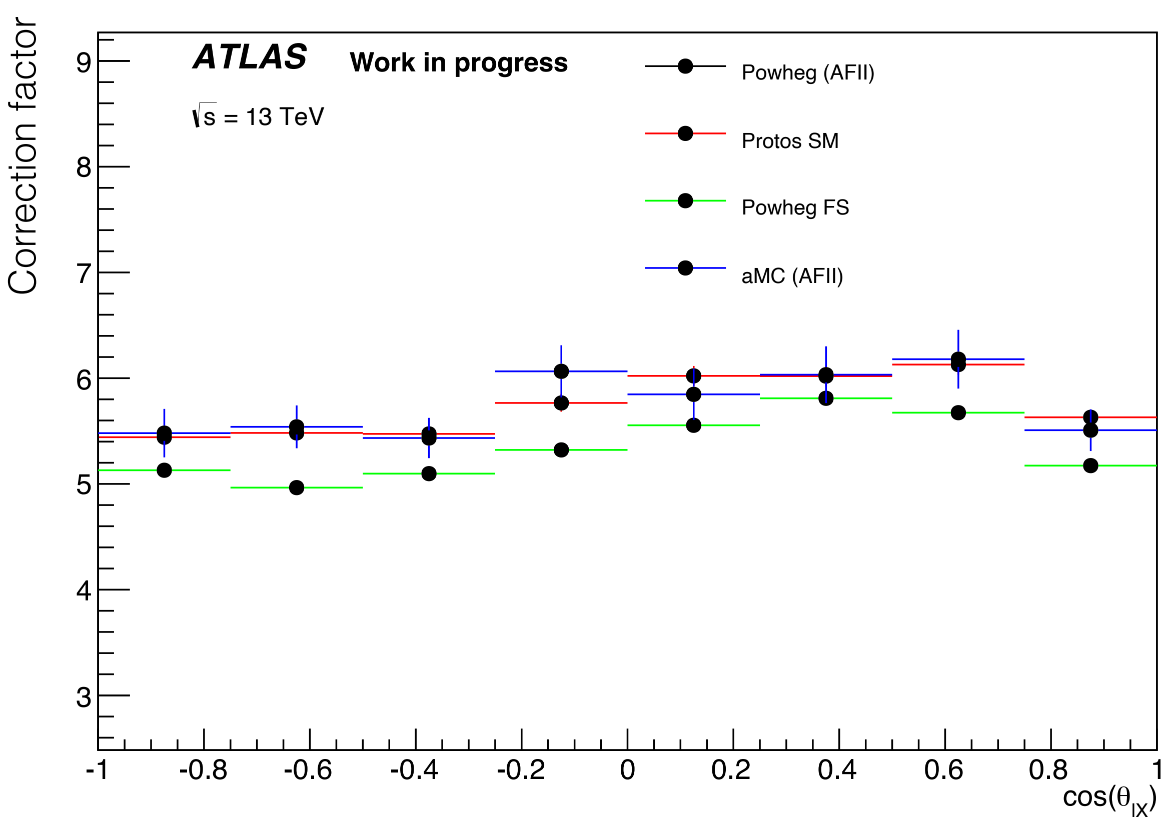
$C^{\text{part!reco}}$



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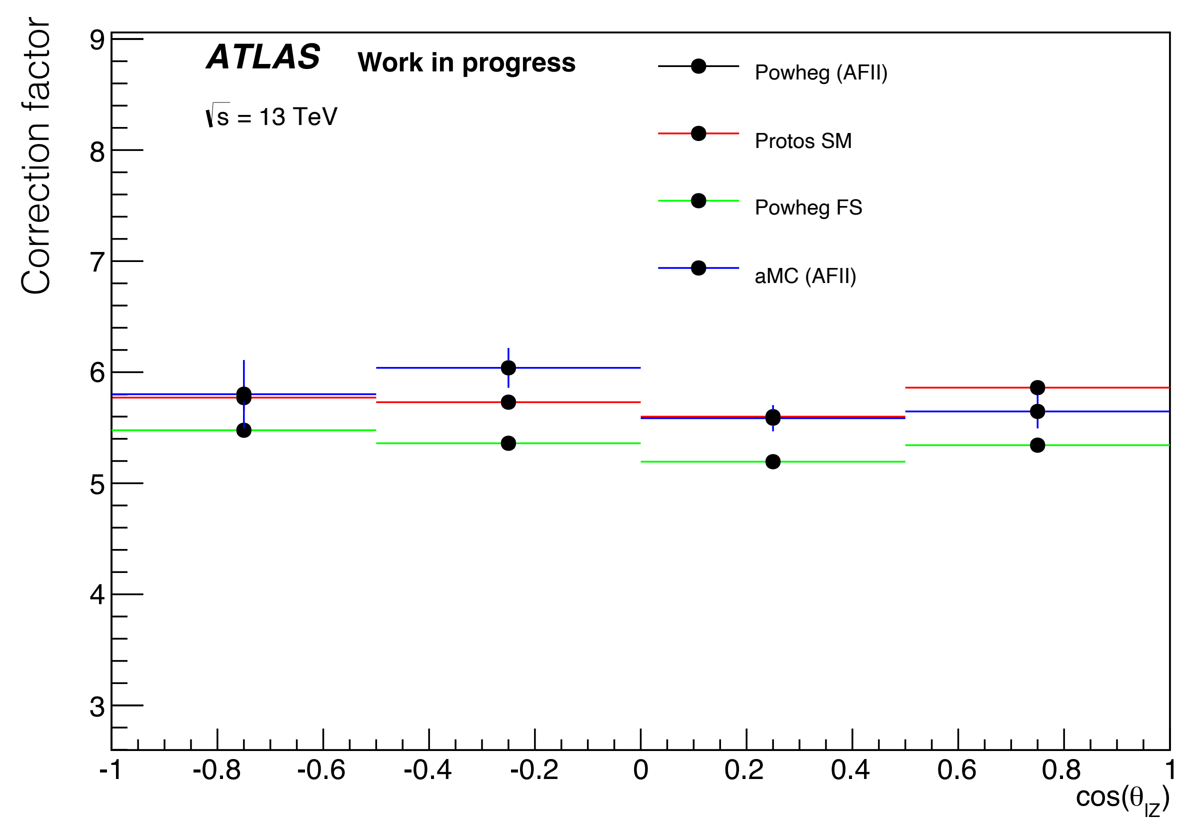
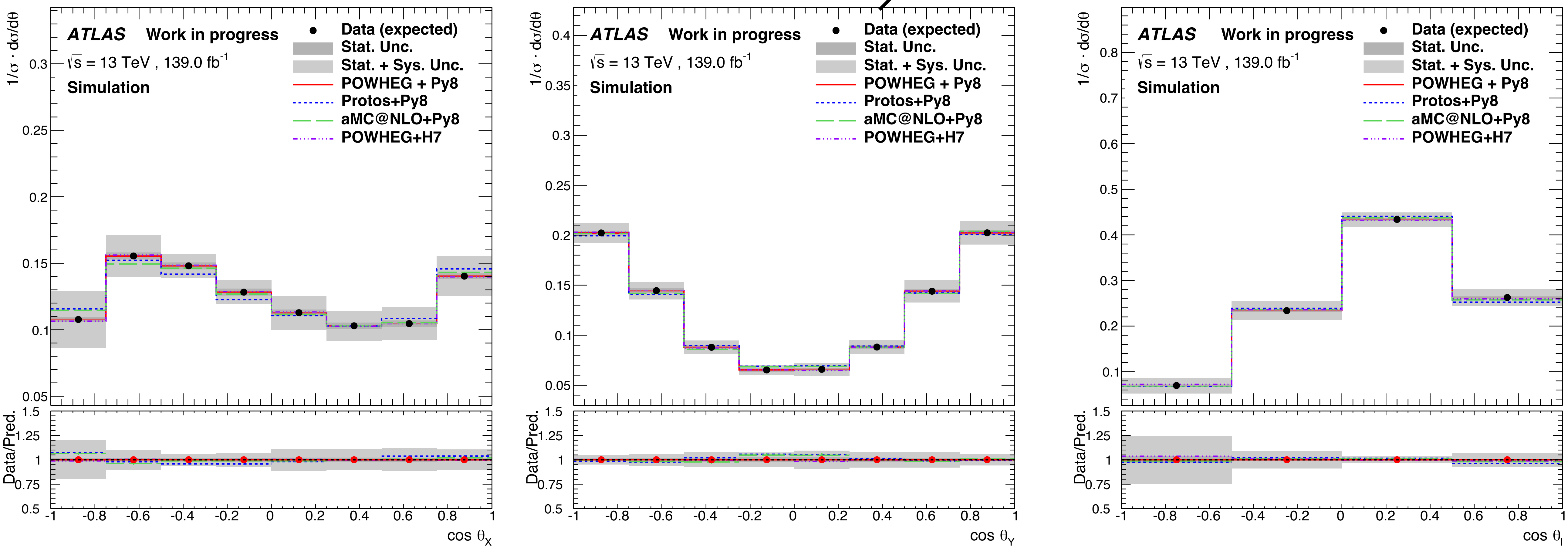


**All generators interfaced with Pythia8.*

EXPECTED RESULTS AT PARTICLE LEVEL IN THE FIDUCIAL REGION

- **Inclusive measurement (top+antitop):**

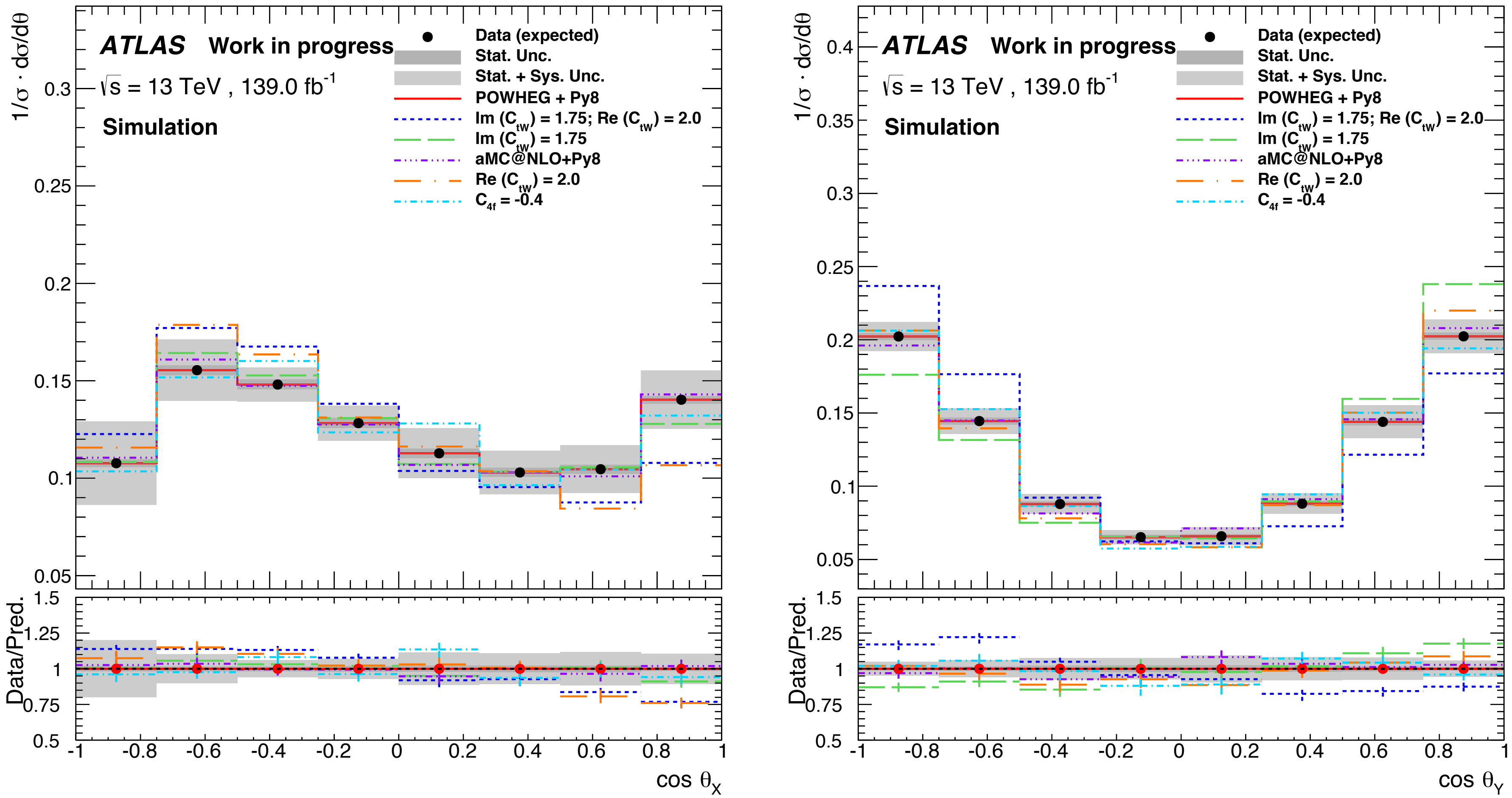
Asimov dataset



- Comparisons with different MC predictions at particle level in the fiducial region are provided:
  - Different MC generators: Powheg (NLO), aMC@NLO (NLO), Protos (LO)
  - Different parton shower simulators: Pythia8, Herwig7
- <u>Uncertainty sources</u>: Mainly dominated by systematic uncertainties.

EXPECTED RESULTS AT PARTICLE LEVEL IN THE FIDUCIAL REGION

- **Inclusive measurement (top+antitop). Interpretation in an EFT framework:**



$$\mathcal{L}_{\rm SM} + \sum_i \frac{C_i}{\Lambda^2} O_i^{[6]} + \text{hermitian conjugate}$$

$$O_{\varphi Q}^{(3)} = i\frac{1}{2}y_t^2 \left(\varphi^\dagger \overleftrightarrow{D}^I_\mu \varphi\right)\left(\bar{Q}\gamma^\mu \tau^I Q\right)$$

$$O_{tW} = y_t g_w (\bar{Q}\sigma^{\mu\nu}\tau^I t)\tilde{\varphi} W^I_{\mu\nu}$$

$$O_{qQ,rs}^{(3)} = \left(\bar{q}_r \gamma^\mu \tau^I q_s\right)\left(\bar{Q}\gamma_\mu \tau^I Q\right)$$

- These measurements will be used to set constraints on *tWb* anomalous couplings or Wilson coefficients within an EFT framework.
- cos θx sensitive to Re(Ctw), cos θy sensitive to Im(Ctw).
  - cos θy sensitive to CP violation effects which can not be accessed in top pair production!

SUMMARY

- Normalised differential measurements of angular distributions sensitive to the top quark polarisation are being measured in the t-channel production.
- First measurement of the top-quark polarisation at 13 TeV with the full Run 2 dataset.
- Measurements provided at particle level in a fiducial region to ensure model independence.
- These measurements will be used to set constraints on tWb anomalous couplings or Wilson coefficients within an EFT framework.

BACKUP

PARTICLE LEVEL OBJECTS DEFINITION

- Particle-level objects are constructed from stable particles of the MC event record (ME+PS) with a lifetime > $0.3 \cdot 10^{-10}$ s within the observable pseudorapidity range.
- These objects do not take into account any detector effect or any additional pp interactions (pile-up).
- More info: https://twiki.cern.ch/twiki/bin/view/LHCPhysics/ParticleLevelTopDefinitions

Object construction

The objects considered in the event record are stable particles (mean lifetime > 0.3×10^{-10}s) within the observable pseudorapidity range.

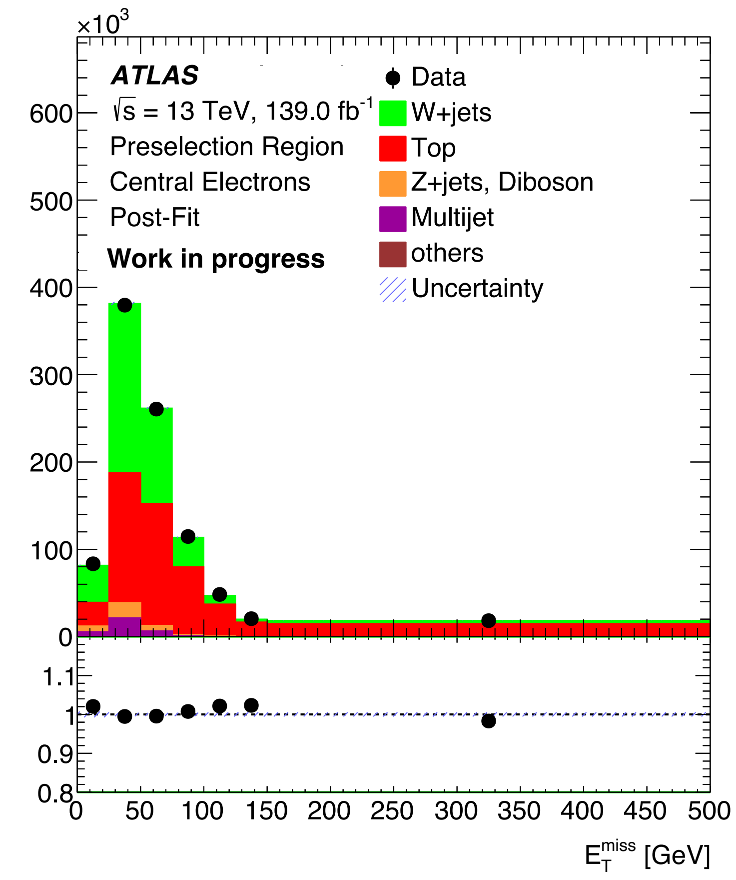
- **Photons**: photons used for final state definitions and for the definition of leptons (electron & muon) should not be from hadron decays. These removes the dependency on the underlying event.
- **Electron**: define 4-momentum from photons and electron within an anti-k_t R=0.1, where leptons (electron & muons) are considered for jet clustering. No isolation condition is imposed. In order to choose prompt leptons from W/Z decay in a way safe for all generators currently under consideration, the parent of the electron is required not to be a hadron or quark (u-b). (Expect that future sanitisation of generator record will remove the need for the quark requirement.)
- **Muon**: define 4-momentum from photons and muon within an anti-k_t R=0.1, where leptons (electron & muons) and photons are considered for jet clustering. No isolation condition is imposed. In order to choose prompt leptons from W/Z decay in a way safe for all generators currently under consideration, the parent of the muon is required not to be a hadron or quark (u-b). (Expect that future sanitisation of generator record will remove the need for the quark requirement.)
- **ETmiss/Neutrinos**: As an event level variable the missing transverse energy is calculated as the 4-vector sum of neutrinos from W/Z-boson decays. Tau decays are included. A neutrino is treated as a detectable particle and is selected for consideration in the same way as electrons or muons, i.e. the parent is required not to be a hadron or quark (u-b). (Expect that future sanitisation of generator record will remove the need for the quark requirement.)
- **Jets**: define with anti-k_t algorithm. Loop over all stable particles excluding the electrons, muons, neutrinos, and photons used in the definition of the selected leptons. This includes non-prompt muons and neutrinos for a proper b-jet energy scale. Use specific R parameter chosen by experiment: R=0.4 for ATLAS and R=0.5 for CMS.
- **b-jets**: A jet is a b-jet if any rescaled B-hadron is included in the jet. A rescaled B-hadron is treated as a stable B-hadron (that does not oscillate or decay to another B-hadron) for which the 4-momentum is scaled down by to the limit of floating point precision and added to the list of particles for jet-clustering as described above. Only B-hadrons with an initial p_T > 5 GeV are considered. This prescription provides an unambiguous way to associate a single jet with a B-hadron.
- **Further cuts in the event**: overlap removal, such as applied to reconstructed objects, does not make sense when the selected leptons are not included within jets. Instead, events where the leptons overlap with the selected jets should be discarded. For example, for a anti-k_t radius parameter of 0.4, events with dR(jet,el/mu) < 0.4 should be discarded.

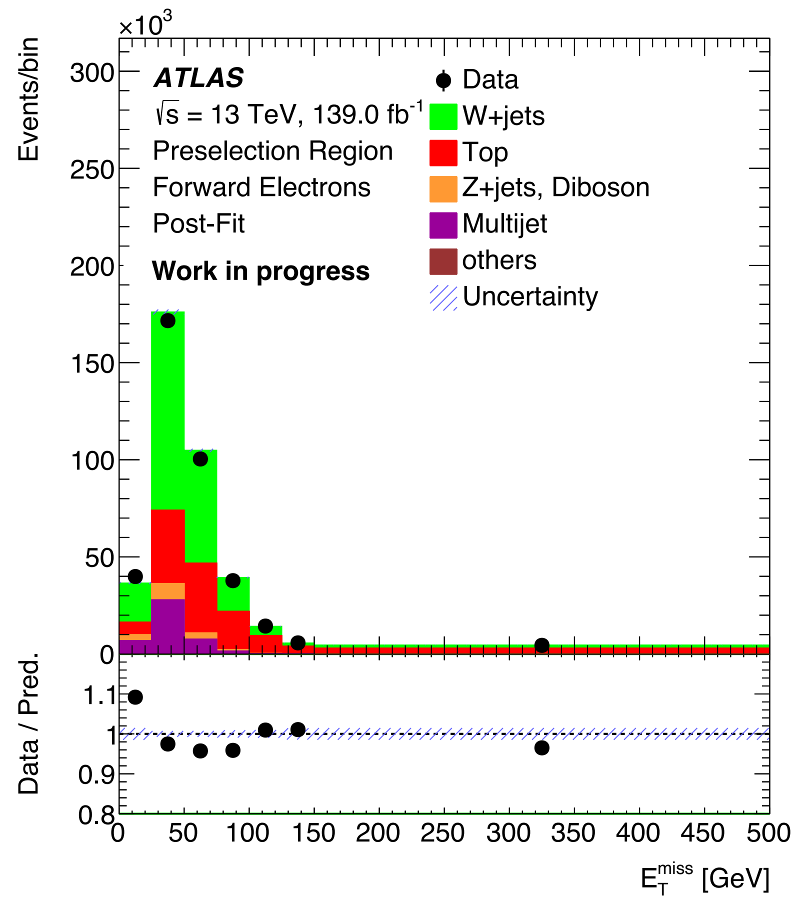
MULTIJET BACKGROUND ESTIMATION

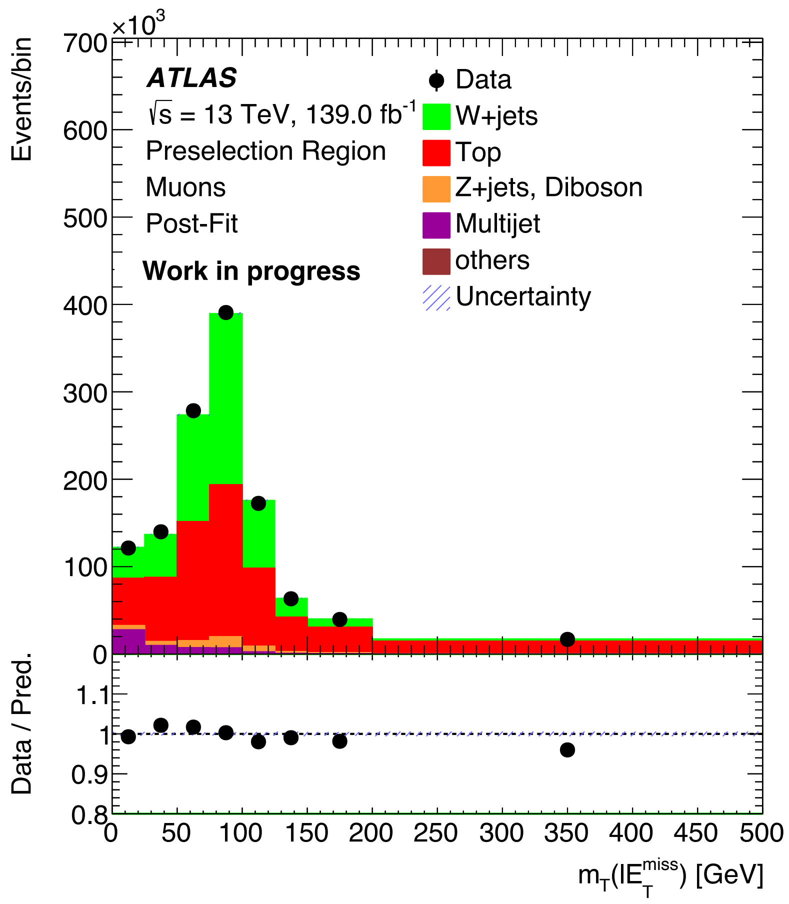
- Multijet is a non-negligible background coming from fake and non-prompt leptons.
- Shape of the multijet contributions being modelled using:
  - Jet-electron model (MC simulated) and generic simulated dijet events in the electron channel (ATLAS-CONF-2014-058)
  - Data-driven anti-muon model in the muon channel. (ATLAS-CONF-2014-058)
- Multijet normalisation (for central electrons, forward electrons and muons) extracted from a likelihood fit to the data.
- Simultaneous fit to the MET (electrons) and the MTW (muons) distributions in regions enhanced in multijet:
  - Electron channel: Removing the MET and the multijet rejecting cut.
  - Muon channel: Removing the MTW and the multijet rejecting cut.
- Two fits are performed:
  - Fit in extended pre-selection region: Multijet normalisation for signal region and W+jets CR.
  - Fit in extended tt CR: Multijet normalisation for the tt CR.

MULTIJET BACKGROUND ESTIMATION

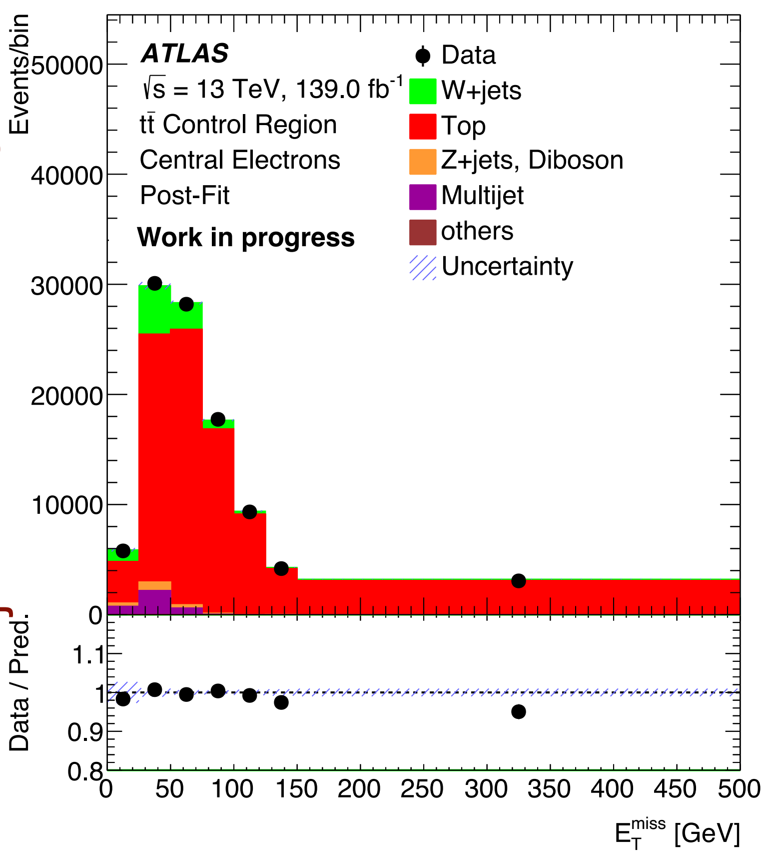
Multijet enriched pre-selection

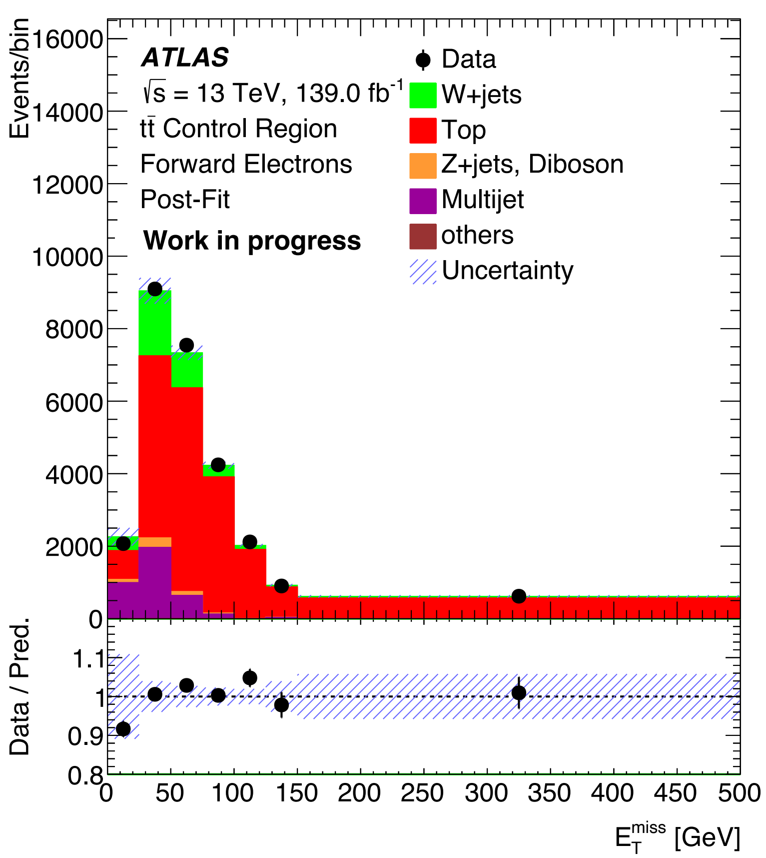


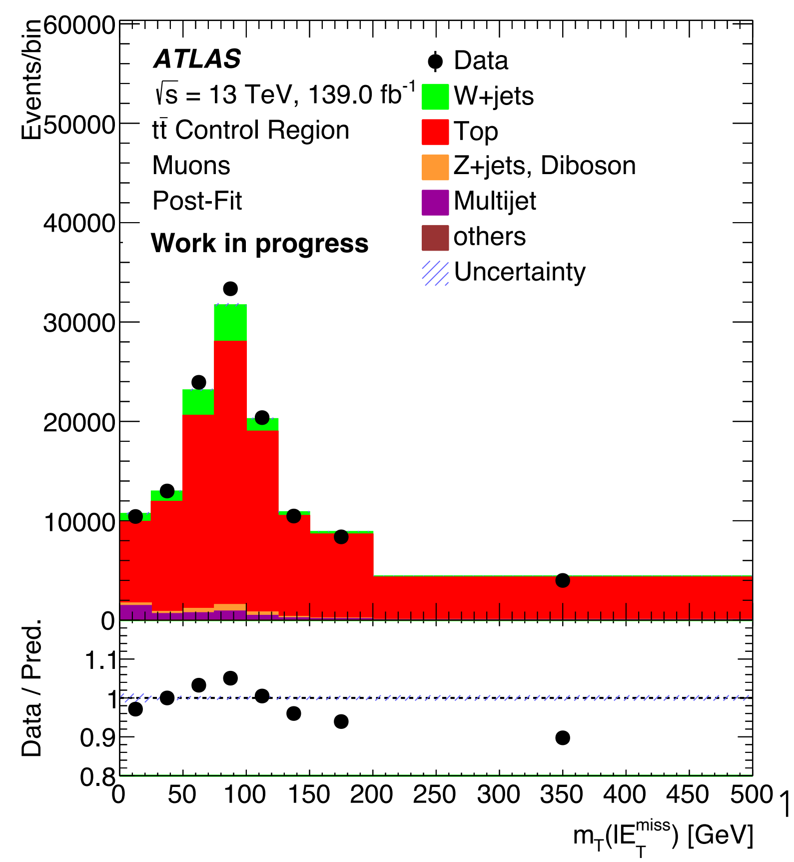




Multijet enriched tt CR

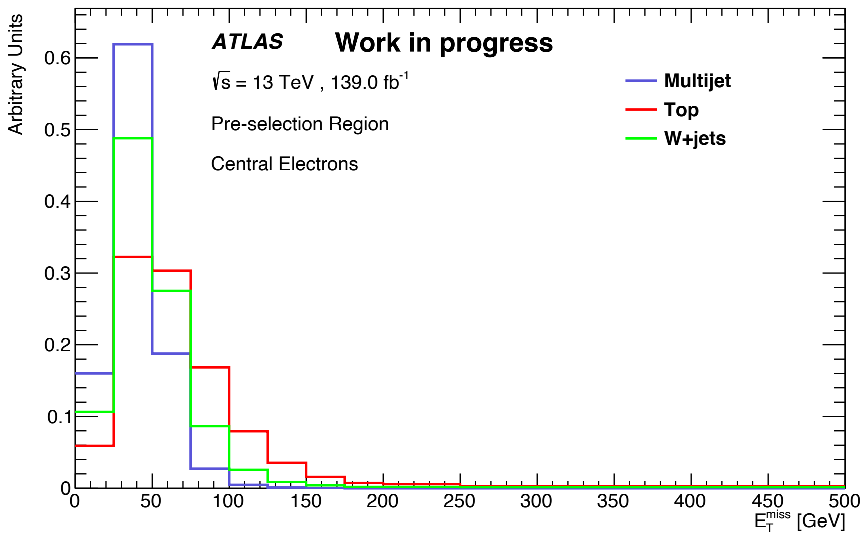


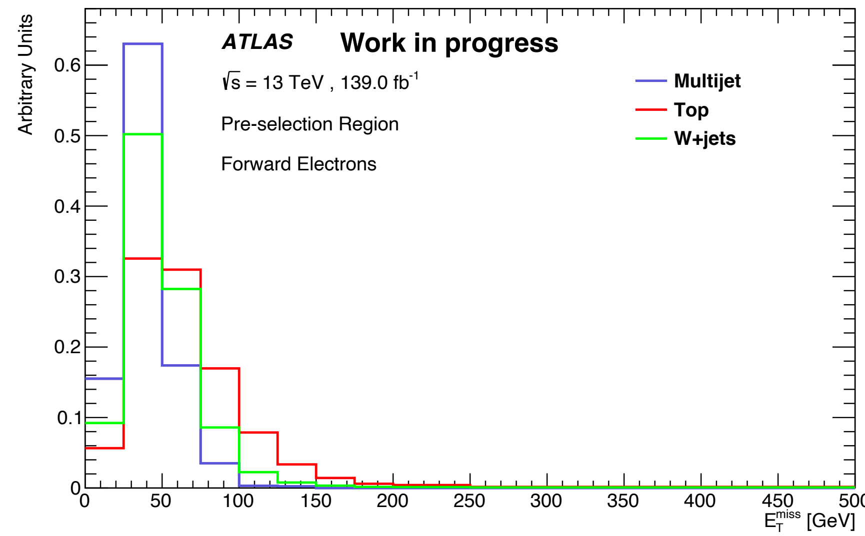


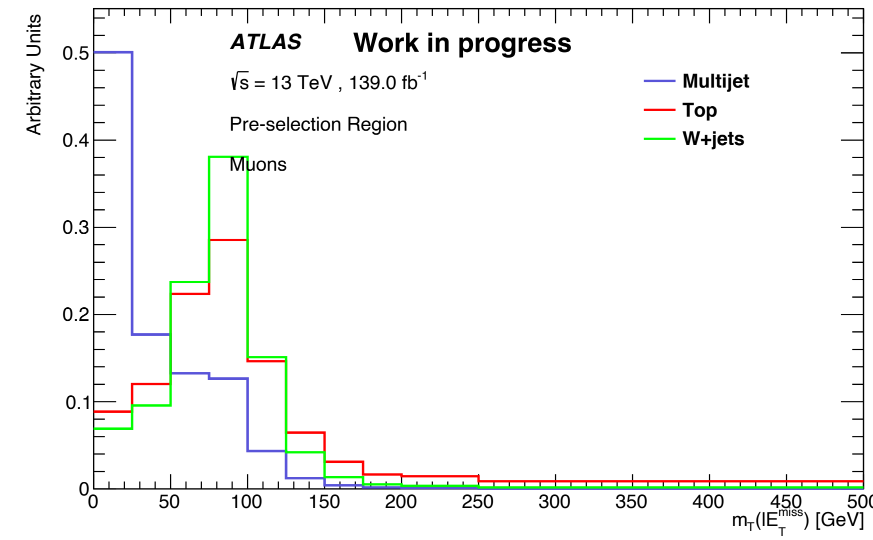


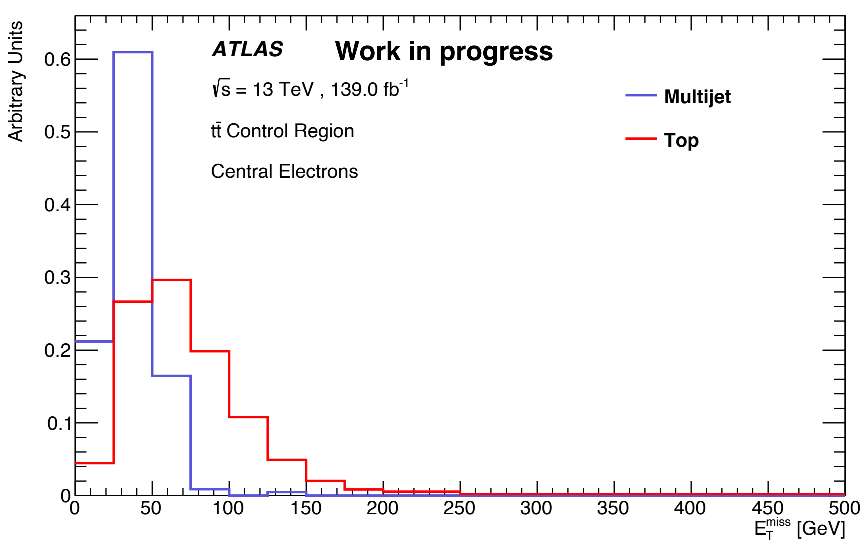
MULTIJET BACKGROUND ESTIMATION: NORMALISATION

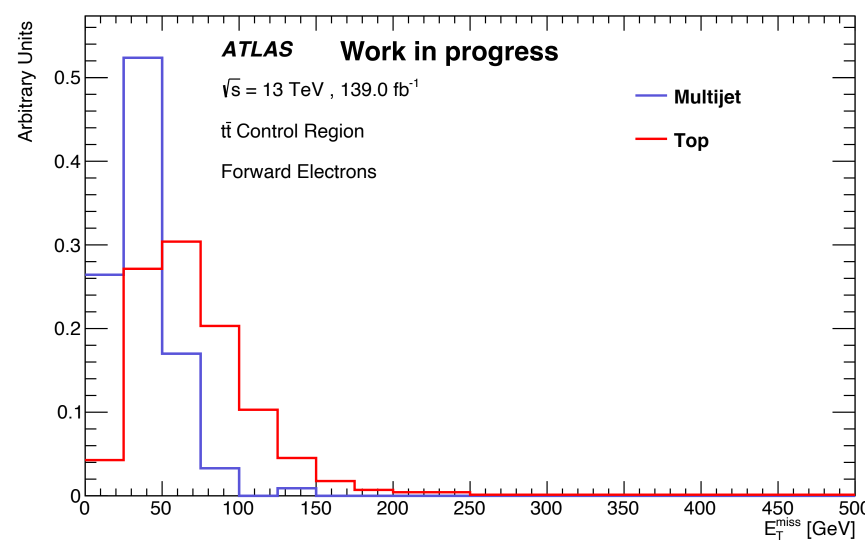
- In order to have a reliable fit, the shape of the fitted kinematic variable has to be **discriminant** enough between the multijet and the other fitted background sources.
- The MET was found to be a good candidate in the electron channel, and the MTW was found to be a good candidate in the muon channel:

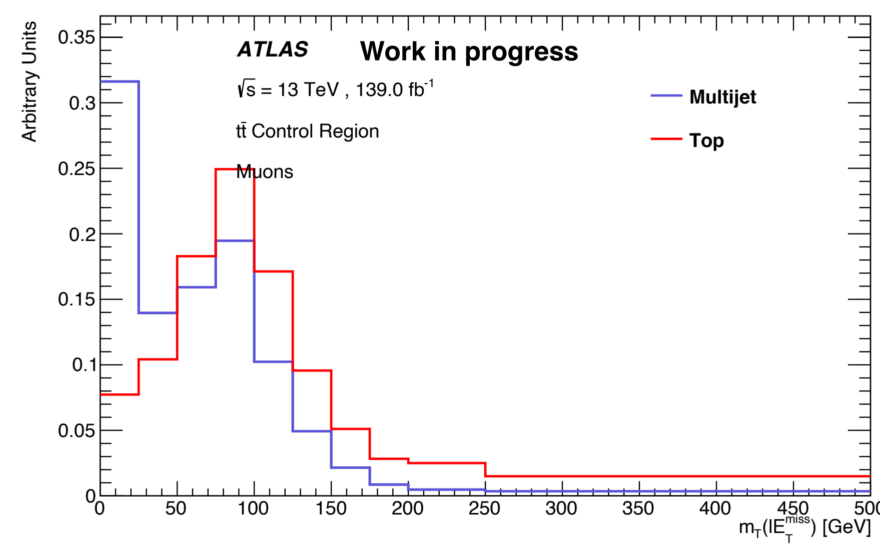






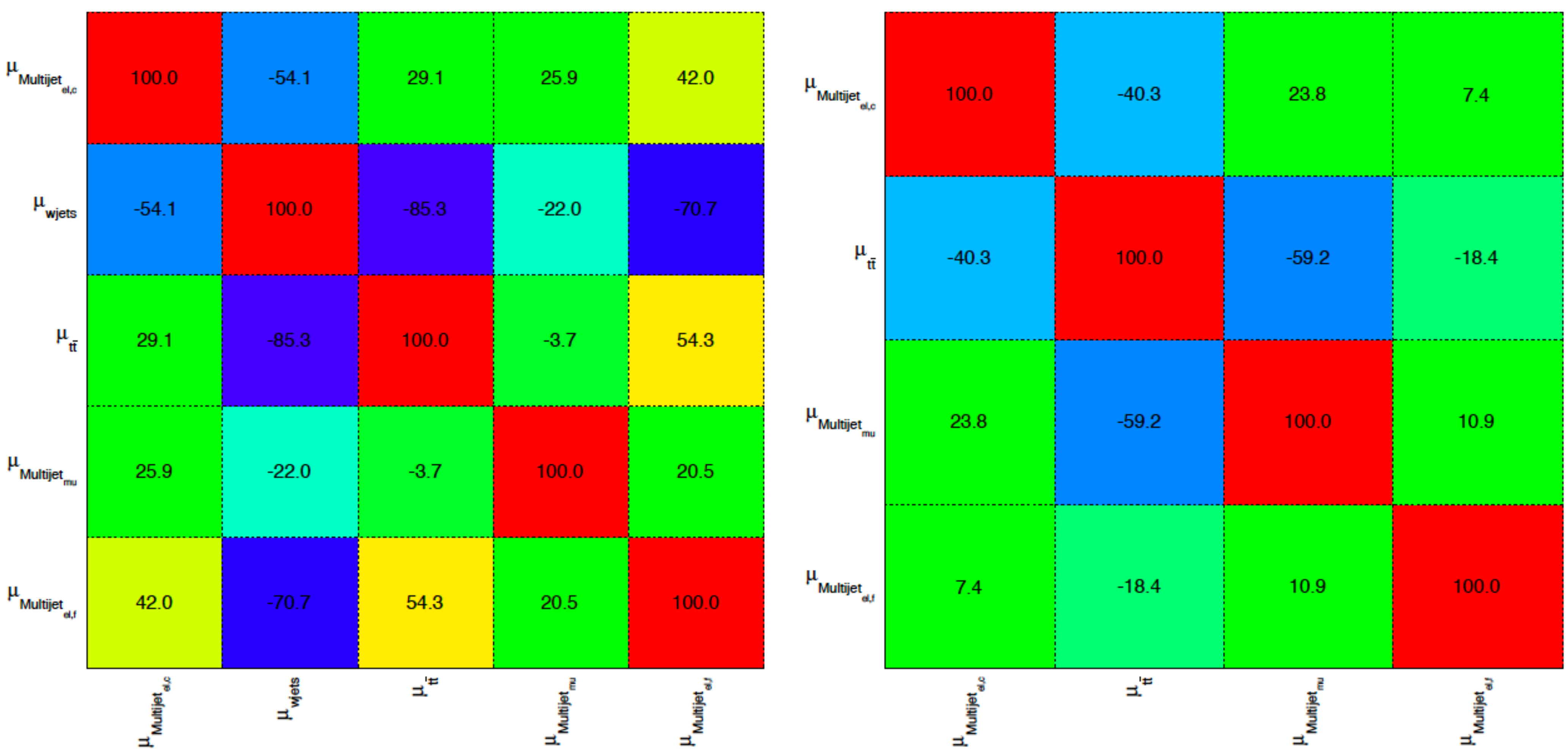






MULTIJET BACKGROUND ESTIMATION: NORMALISATION

- In order to have a reliable fit, the shape of the fitted kinematic variable has to be **discriminant** enough between the multijet and the other fitted background sources.
- The MET was found to be a good candidate in the electron channel, and the MTW was found to be a good candidate in the muon channel.
- The statistical correlation between the different fitted parameters validates this statement:



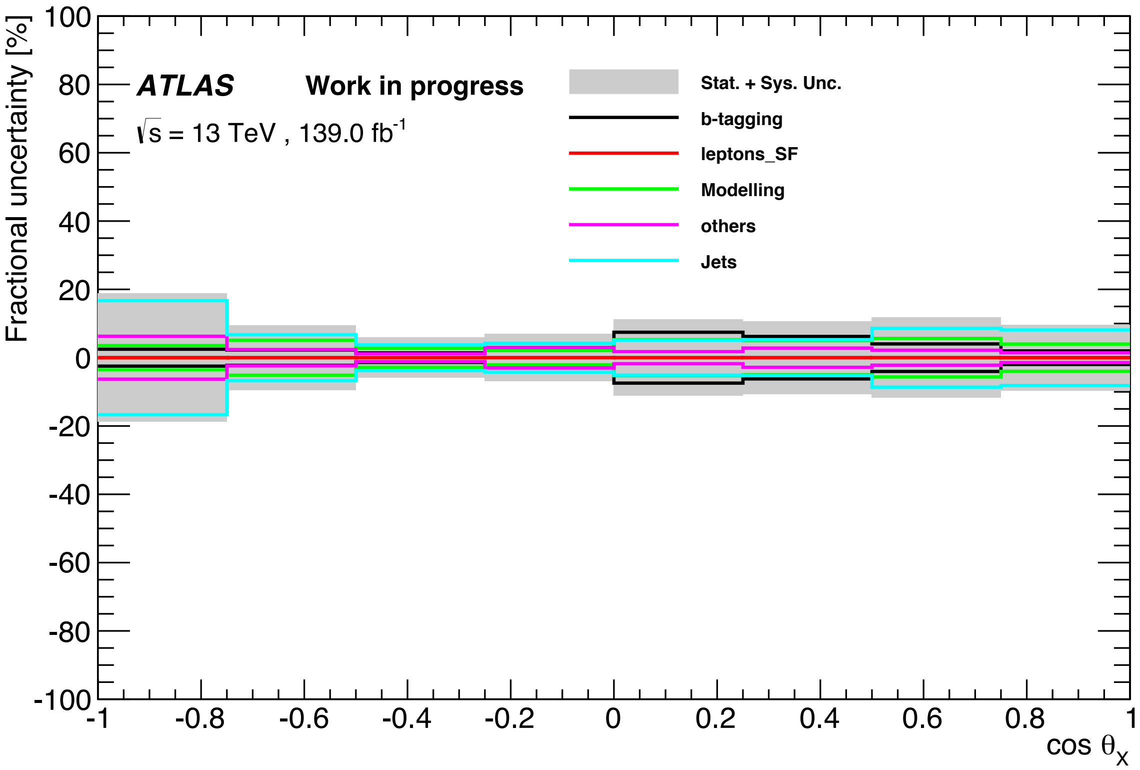
(a) (b)

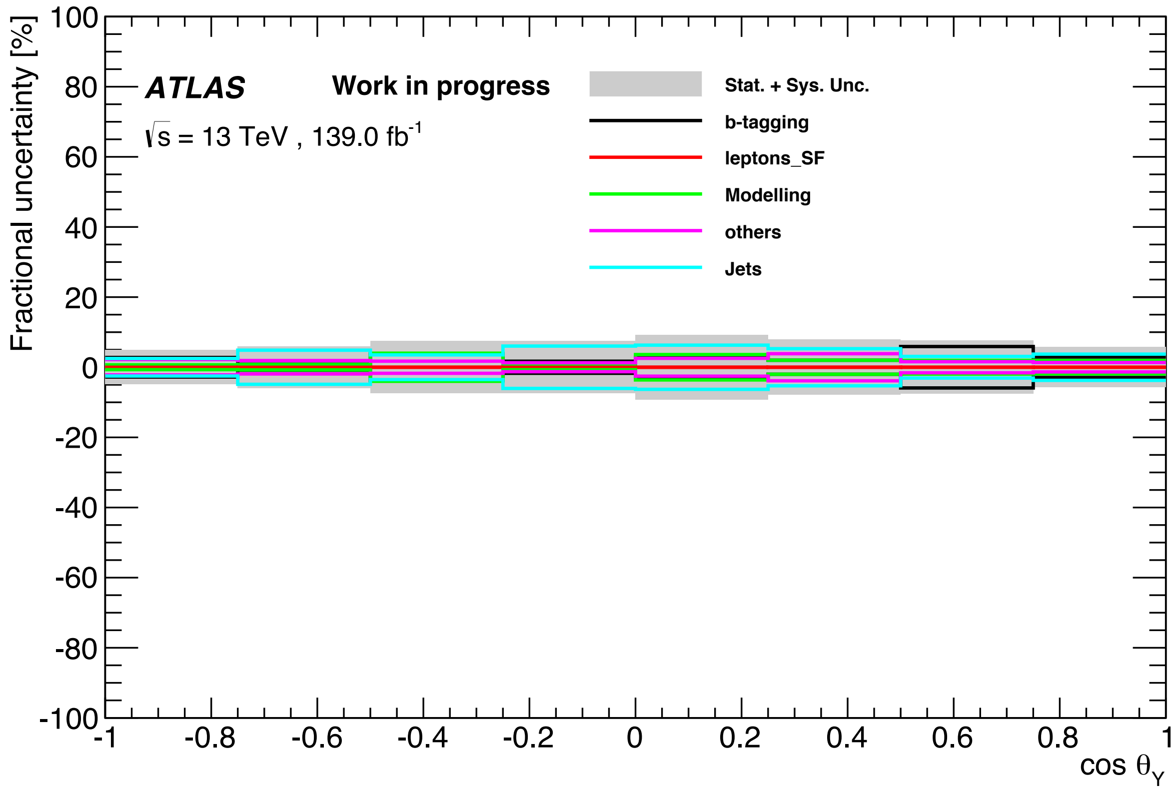
Figure 132: Correlation factors of the different fitted parameters using the baseline approach for (a) the multijet-enriched preselection region and (b) the multijet-enriched $t\bar{t}$ control region.

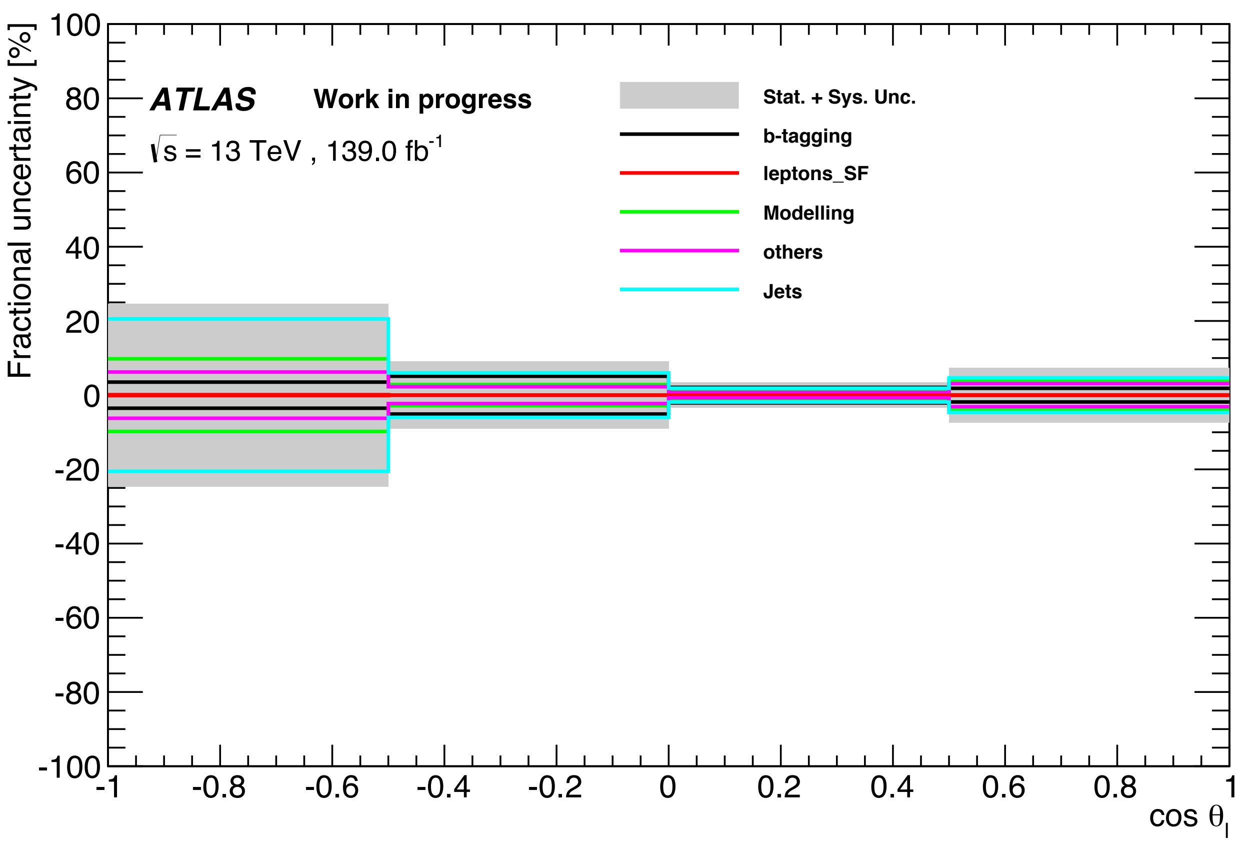
STATISTICAL AND SYSTEMATIC UNCERTAINTIES

- In this analysis both statistical and systematic (theoretical and experimental) uncertainties are considered.
- **Statistical uncertainties** are computed using pseudo-experiments.
  - In each pseudo-experiment, the content of each bin is varied according to its expected statistical uncertainty through Poisson fluctuations.
  - Each pseudo-experiment is unfolded and the spread (RMS) of the result in each bin is taken as the measure of the statistical uncertainty.
- **Systematic uncertainties** are computed using varied template distributions.
  - Template distributions are obtained with fully simulated pseudo-data corresponding to a given systematic uncertainty effect.
  - For each systematic effect, a new background normalisation estimation is performed before subtraction.
  - After background subtraction, the nominal unfolding corrections are used to unfold the template distributions of each source of systematic uncertainty.
  - In general, the systematic uncertainties are evaluated as the difference between the nominal angular distribution values and the ones measured using the varied normalisations and shapes.

SYSTEMATICS BREAKDOWN



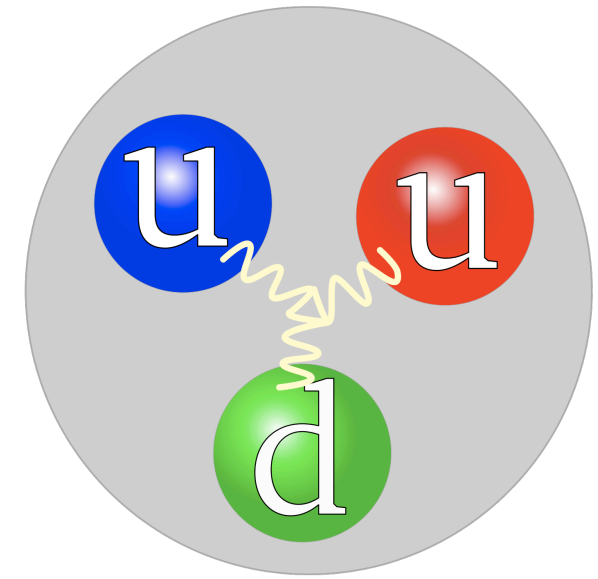


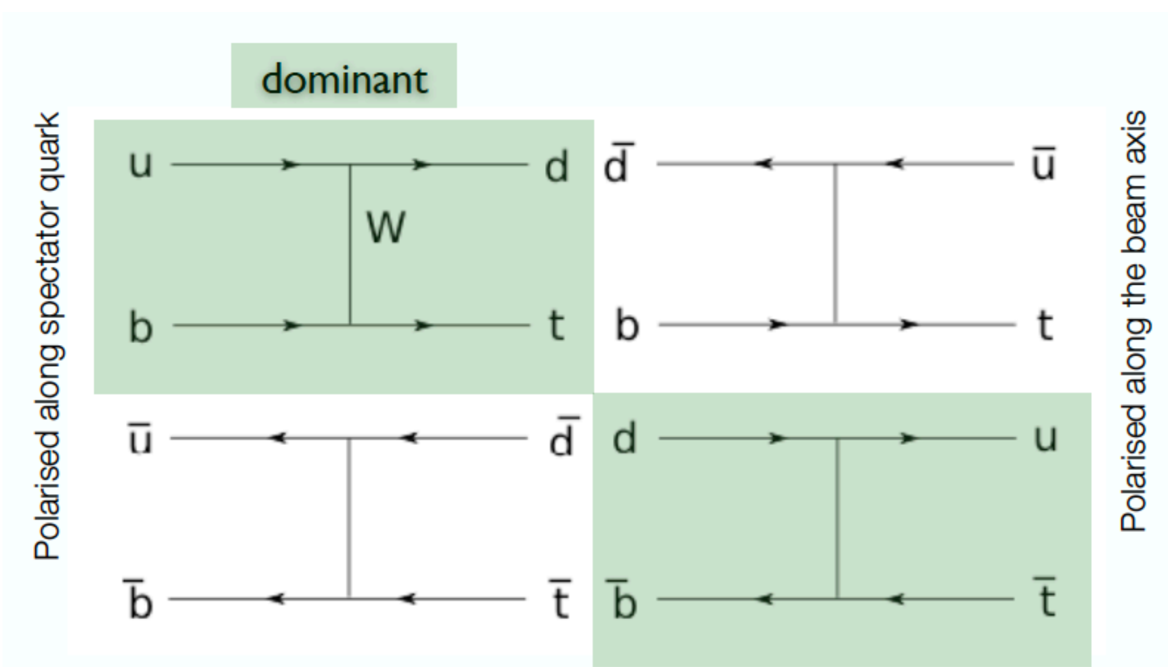


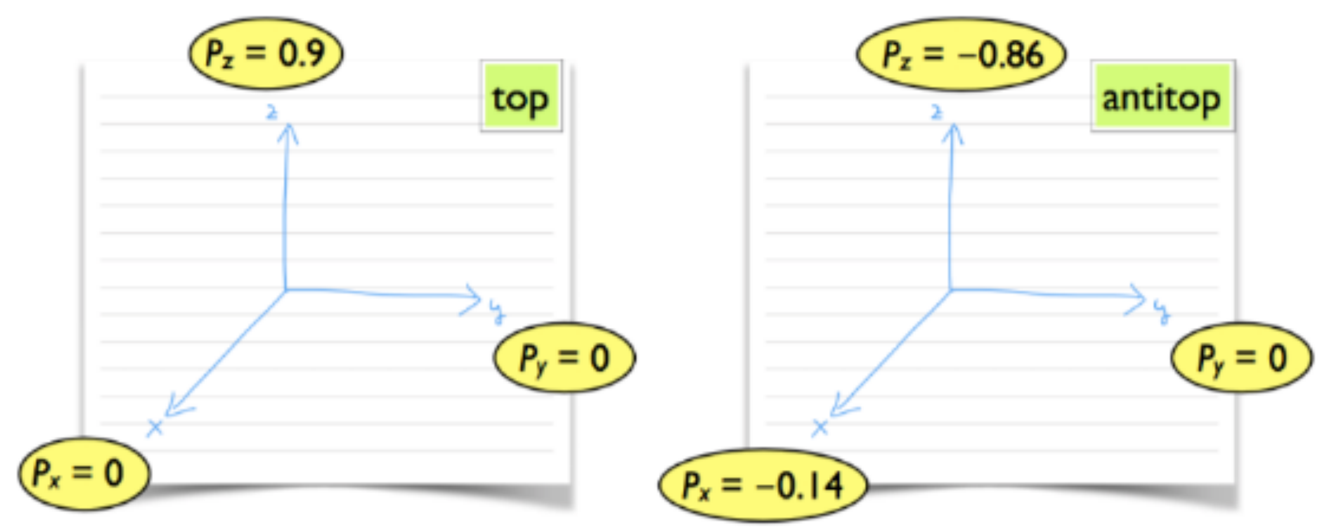
TOP QUARK VS ANTIQUARK

Unfolded differential measurements for top quarks and antiquarks

- In *pp* collisions, both the production cross-section and the polarisation of top quarks and top antiquarks differ owing to the predominance of *u*-type quarks in the proton.
- Theoretical predictions at LO (Phys. Rev. D89 (2014) 114009) predict different polarisations in the different projections for top quarks and antiquarks.
- This analysis also provides a straight comparison between the differential cross section for top quarks and top antiquarks to check for any deviations from the theoretical predictions which could be related with new physics.



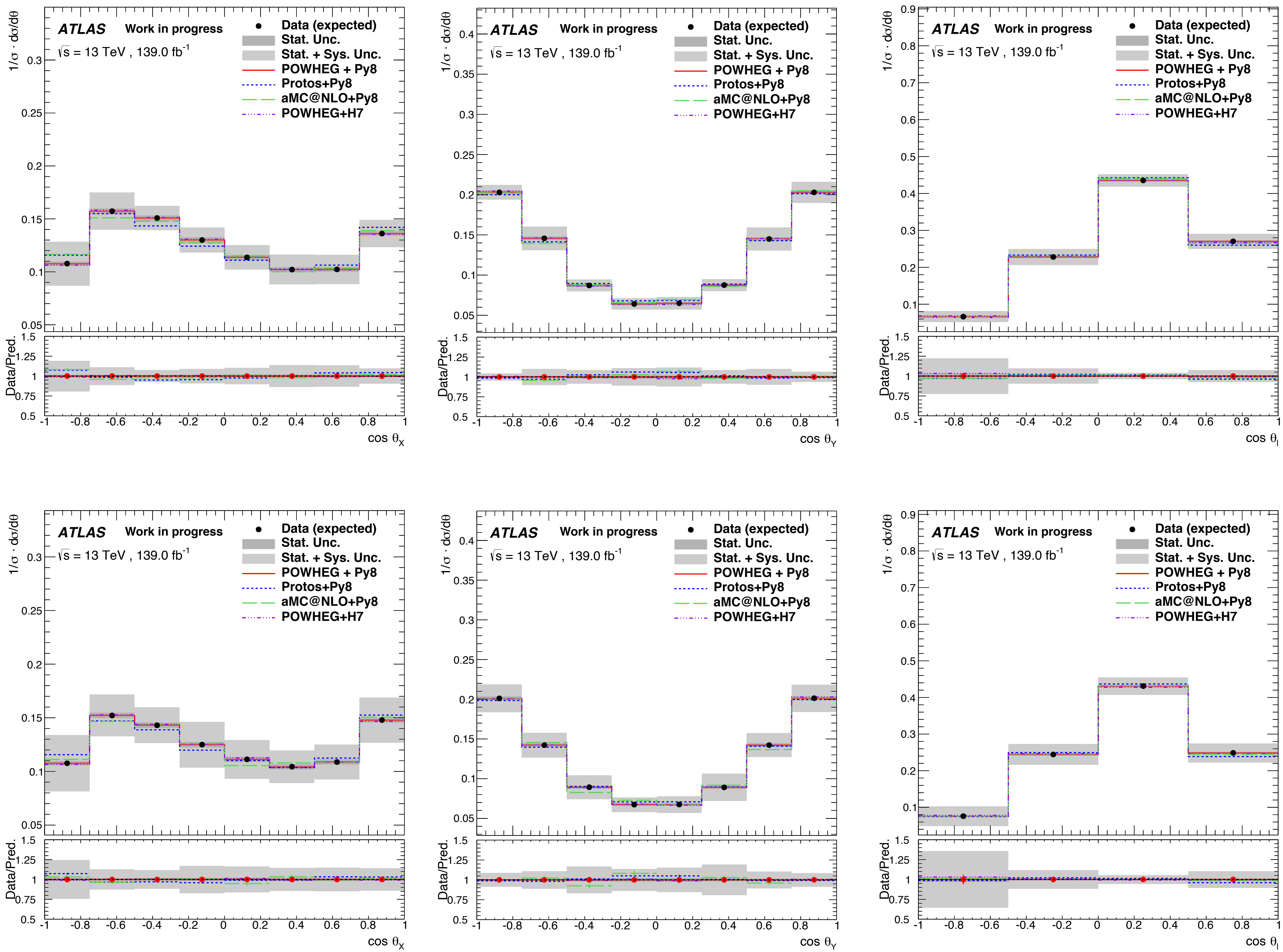




TOP QUARK VS ANTIQUARK

TOP

ANTITOP



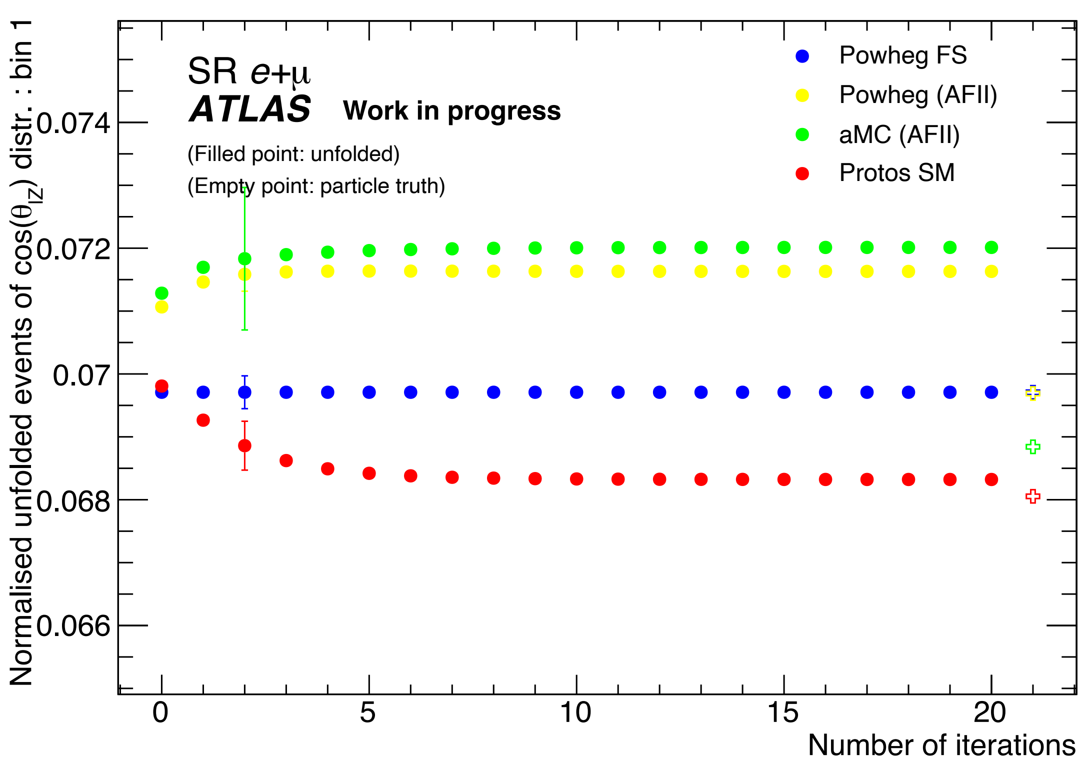
CONVERGENCE TEST TO FIX THE NUMBER OF ITERATIONS

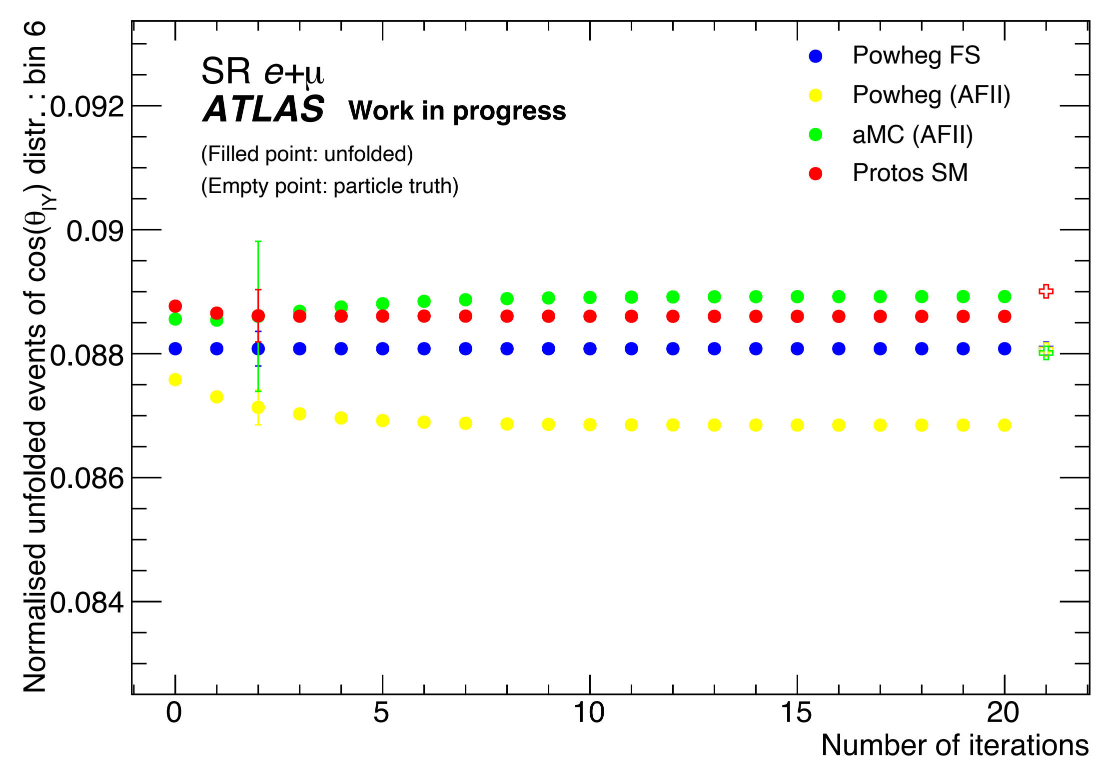
Convergence test:

- The unfolding procedure is considered to have converged when the absolute change between two successive steps becomes negligible (difference < 0.001 between successive iterations for all samples) and when a stable convergent state is reached (no further divergence, the difference in the results obtained with the chosen number of iterations and with 15 more iterations should not exceed 0.0015).
- Different generators are considered:
  - Powheg (+Pythia8)
  - Protos (+Pythia8)
  - aMc@NLO (+Pythia8)

Angular distribution	Number of iterations
$\cos\theta_{\ell x}$	5
$\cos\theta_{\ell y}$	3
$\cos\theta_{\ell z}$	3

- For each angular distribution, convergence is reached when the convergence criteria are satisfied for all bins.

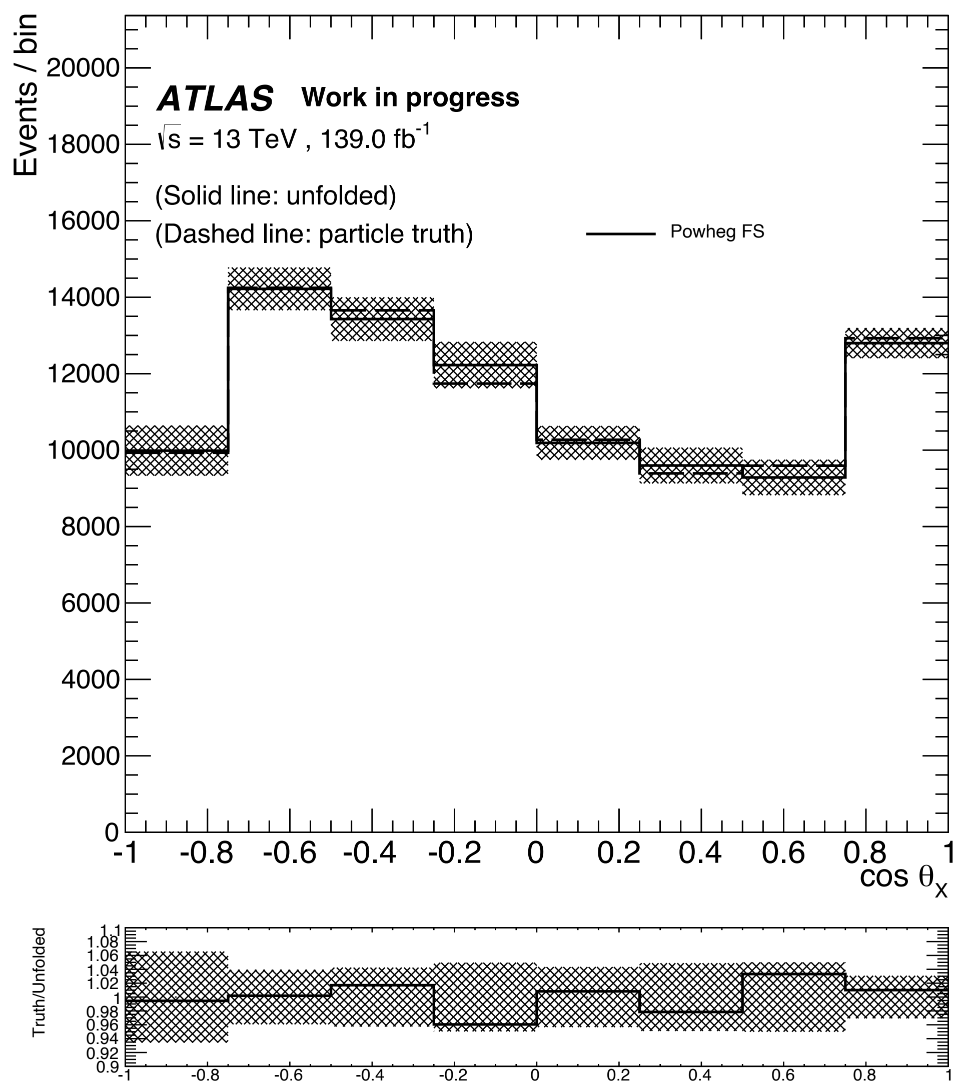




CLOSURE AND LINEARITY TESTS

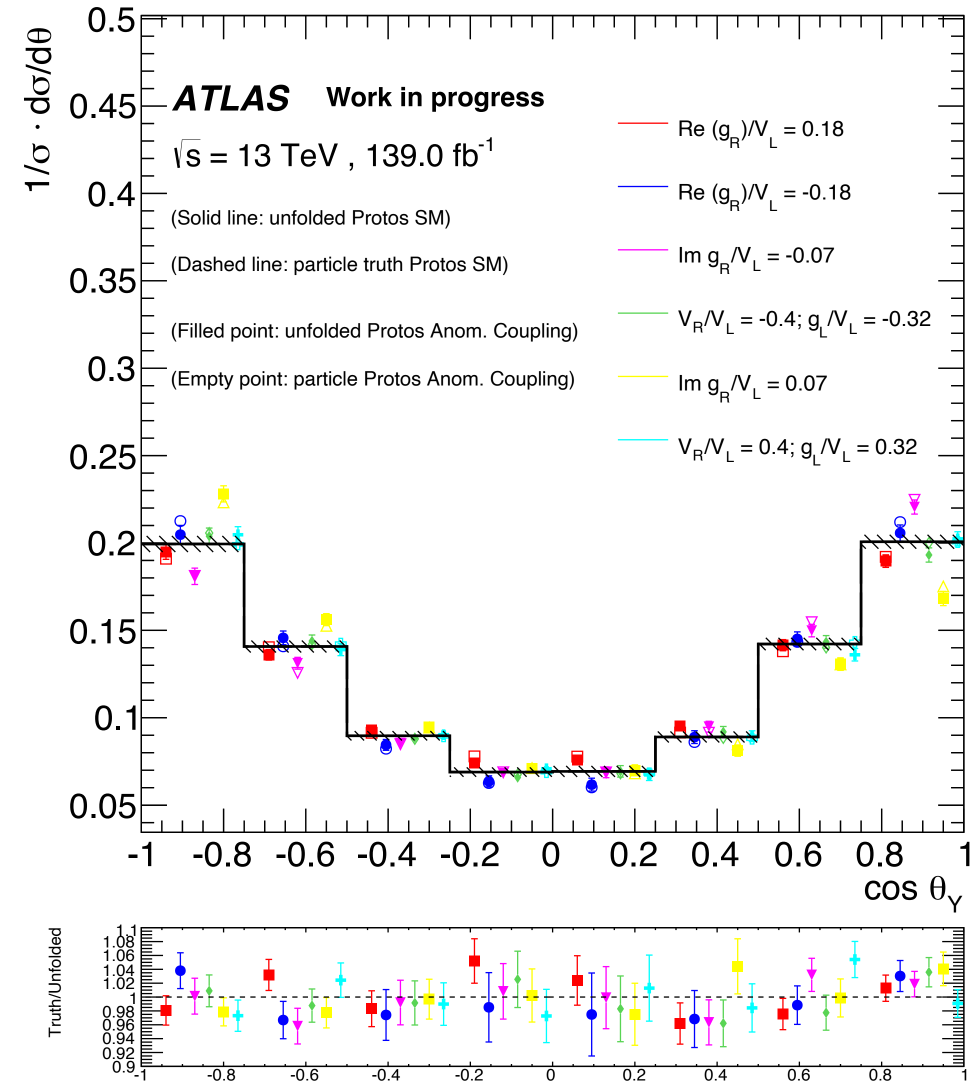
Closure test:

- Baseline Powheg+Pythia8 (FS) sample is split into two subsets of same size.
- The former sub-set is used to determine the migration matrix and the correction factors.
- These migration matrix and correction factors are applied to the latter sub-set to compare the unfolded distribution with the actual particle level distribution.



Linearity test:

- Performed with samples generated with Protos+Pythia8 with different anomalous couplings settings (BSM effects)
- The angular distributions predicted by these simulated samples are unfolded using the resolution and efficiency corrections calculated with the Protos SM sample.
- The extracted histograms are compared to the particle-level distributions of each sample.



SIGNAL REGION AND CONTROL REGIONS DEFINITION

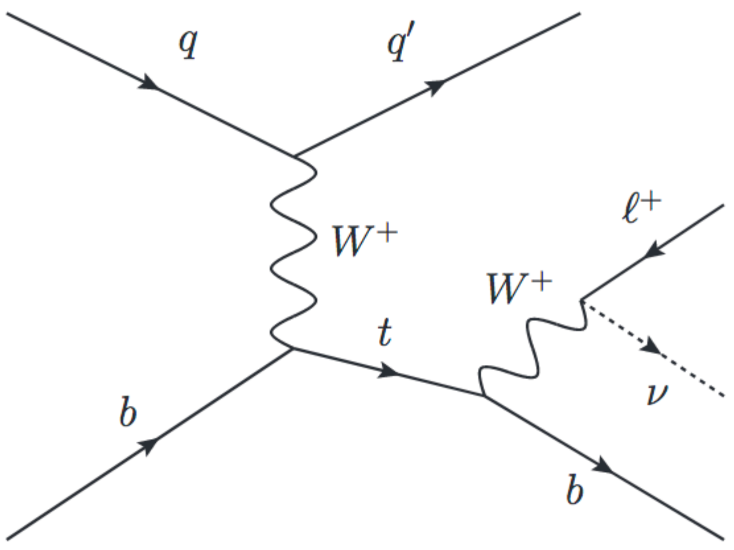
- This analysis is performed at **13 TeV** using the full Run2 dataset, corresponding to 2015-2018 (**139.0 fb**$^{-1}$)
- **Pre-selection (PR):**
  - Exactly one tight charged lepton (electron or muon).
    - $p_T > 30$ GeV, $|\eta| < 2.5$.
    - Dilepton veto (loose leptons).
  - Exactly 2 jets, exactly one b-tagged:
    - *Spectator jet*: $p_T > 30$ GeV, $|\eta| < 4.5$; *b-jet*: $p_T > 30$ GeV, $|\eta| < 2.5$ (b-tagging WP 60%).
      - ✳ $p_T > 35$ GeV in transition region ($2.75 < |\eta| < 3.5$) to prevent mismodelling
  - MET > 35 GeV
  - MTW > 60 GeV ⟶ $m_T(\ell E_T^{miss}) = \sqrt{2 p_T(\ell) E_T^{miss} \left(1 - \cos\Delta\phi(p_T(\ell), E_T^{miss})\right)}$
  - Additional multijet rejecting cut (a.k.a. triangular cut)

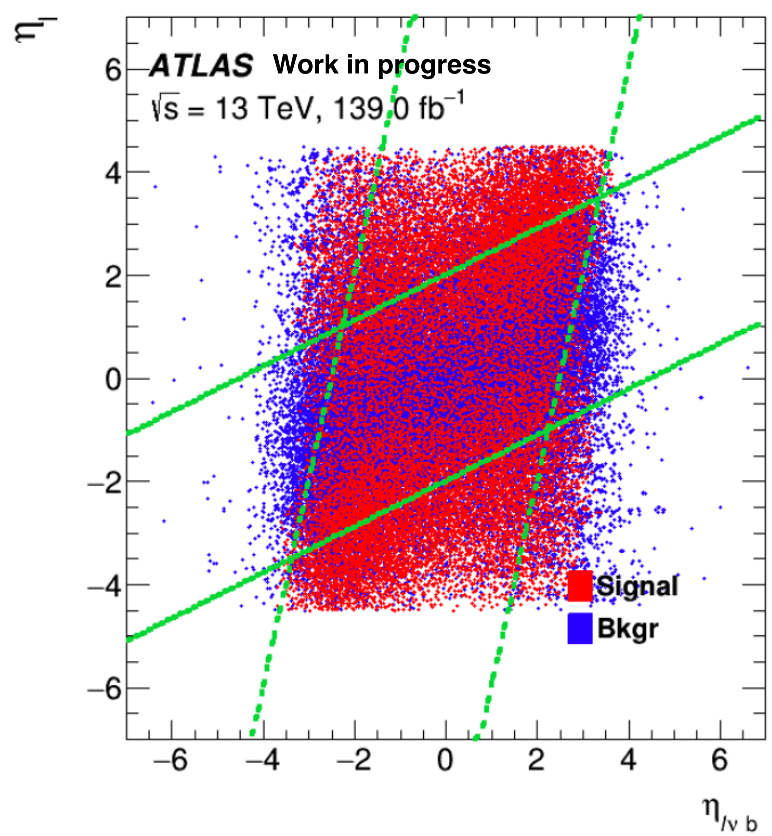
$$p_T(l) > 50\left(1 - \frac{\pi - |\Delta\Phi(l,j)|}{\pi - 1}\right)$$

- **Signal region (SR):**
  - $m_{lb} < 153$ GeV
  - $120.6 < m_{top} < 234.6$ GeV
  - Trapezoidal cut*: a = 10, b = 2
  - $m_{j,top} > 320$ GeV
  - $H_T > 190$ GeV

$$* \quad \left(\eta_j < (4\,\eta_{\ell E_T^{miss} b} + a) \cap \eta_j > (4\,\eta_{\ell E_T^{miss} b} - a)\right) \cap \left(\eta_j > (0.44\,\eta_{\ell E_T^{miss} b} + b) \cup \eta_j < (0.44\,\eta_{\ell E_T^{miss} b} - b)\right)$$

t-channel





INTERPRETATION IN AN EFT FRAMEWORK

- Deviations from SM predictions of the unfolded differential measurements can give hints of physics beyond the SM (the measurement can be interpreted within an EFT framework in terms of *tWb* anomalous couplings or Wilson coefficients).
- In an EFT framework:

$$\mathcal{L}_{\rm SM} + \sum_i \frac{C_i}{\Lambda^2} O_i^{[6]} + \text{hermitian conjugate}$$

- In single-top t-channel production (for massless b-quarks) at LO QCD and at O(1/Λ^2), only three operators with three coefficients are required to parametrize new physics effects:

$$\begin{aligned} O_{\varphi Q}^{(3)} &= i\frac{1}{2}y_t^2 \left(\varphi^\dagger \overleftrightarrow{D}_\mu^I \varphi\right)(\bar{Q}\gamma^\mu \tau^I Q) \\ O_{tW} &= y_t g_w (\bar{Q}\sigma^{\mu\nu}\tau^I t)\tilde{\varphi} W_{\mu\nu}^I \\ O_{qQ,rs}^{(3)} &= \left(\bar{q}_r \gamma^\mu \tau^I q_s\right)\left(\bar{Q}\gamma_\mu \tau^I Q\right) \end{aligned}$$

- In terms of anomalous couplings, the most general effective *tWb* interaction arising from a minimal set of dimension-six effective operators was found to be:

$$g_R = \sqrt{2} C_{uW}^{33} \frac{v^2}{\Lambda^2},$$

$$\begin{aligned} \mathscr{L}_{Wtb} = & -\frac{g}{\sqrt{2}}\bar{b}\gamma^\mu (V_L P_L + V_R P_R)\, t\, W_\mu^- \\ & -\frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_\nu}{M_W}(g_L P_L + g_R P_R)\, t\, W_\mu^- + \text{h.c.} \end{aligned}$$