Measurement of top-quark $\vec{p}$olarization in t-channel single top-quark production using pp collisions at $\sqrt{s}$ =13TeV with the ATLAS detector

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University of Pittsburgh

❋Top polarization

- **Spin polarization**: represented by a polarization vector in 3D phase space, $\vec{P}$. The polarization depends upon the specific top quark(antiquark) sample.

- **Single Top**: t-channel in electroweak interaction produces highly polarized top quarks due to V-A nature.

- **Detectable**: Because of top's large mass, it decays before hadronization to an on-shell W boson. The decay products preserve the spin information of the top.

t-channel (dominant @LHC)
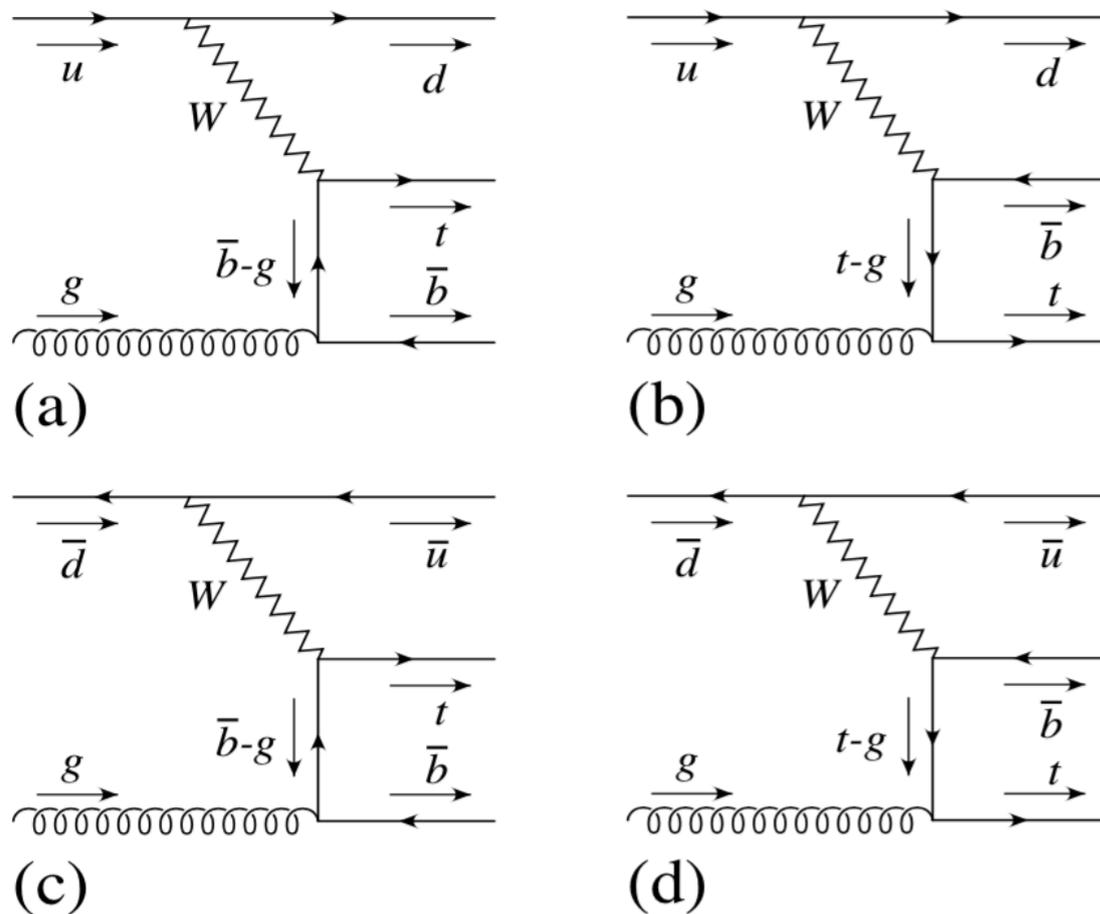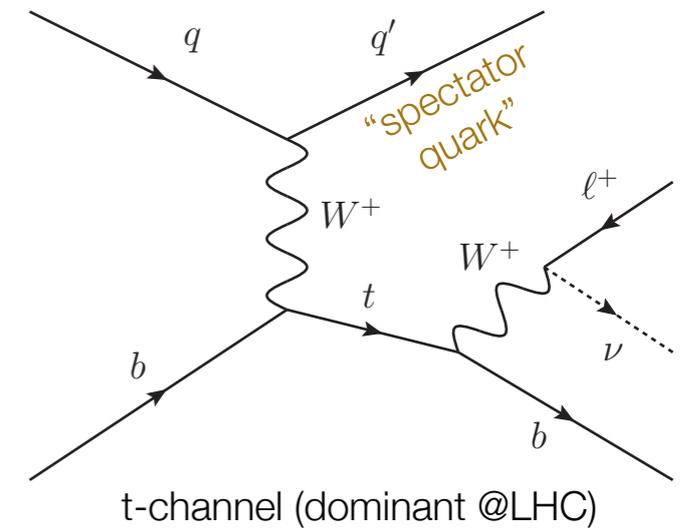
- **Interesting phenomenology**: pp collision at LHC results a large degree of polarization.

Dominant subprocess
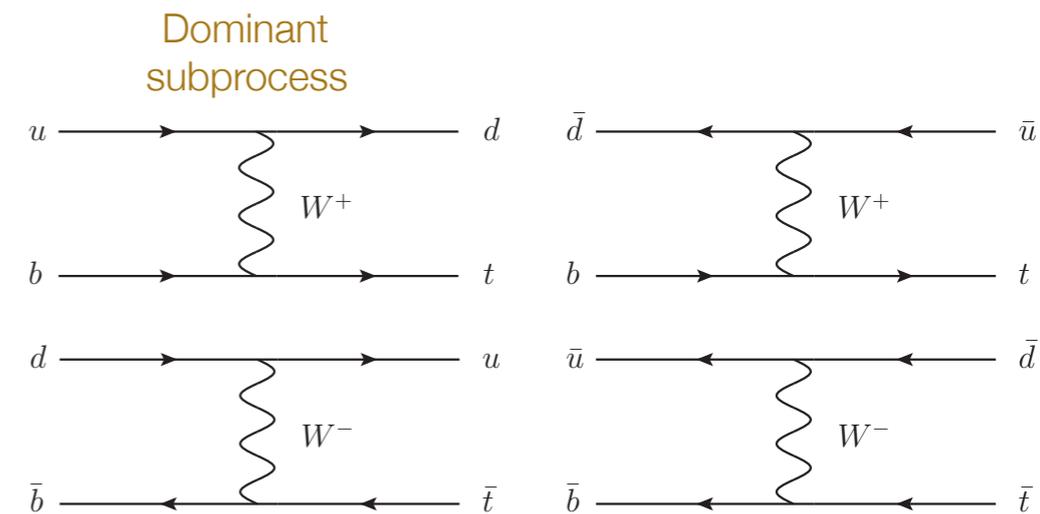
arXiv:hep-ph/0011349

Introduction

❋Motivations

- **Large lumi @LHC**: from 9.7 fb^{-1} to **140.5 fb^{-1}**.

- **Never measured**: the proposed fiducial measurement at reconstruction level of the single top polarization is a first. Proposed experimental measurement strategy: Eur. Phys. J. C77 (2017) 200

- **High polarization expected**: Mahlon, Parke (Phys.Lett.B 476(2000)) predicated a high polarized top ensemble in LHC, with a set of cuts comparable to our selection criteria.

- **Sensitive to new physics**:
  - Four-fermion operator, top couplings
  - CP violation if existing a nonzero P$_y$ component.

Rev. Mod. Phys. 90, 035001

❋ Motivations — Previous Analyses

- In 2016, CMS published the first measurement at 8TeV of the top polarization in t-channel, represented by a differential distribution of the top cross section as a function of the leptonic angle, $\cos\theta_l$. A smaller than prediction measurement was shown.
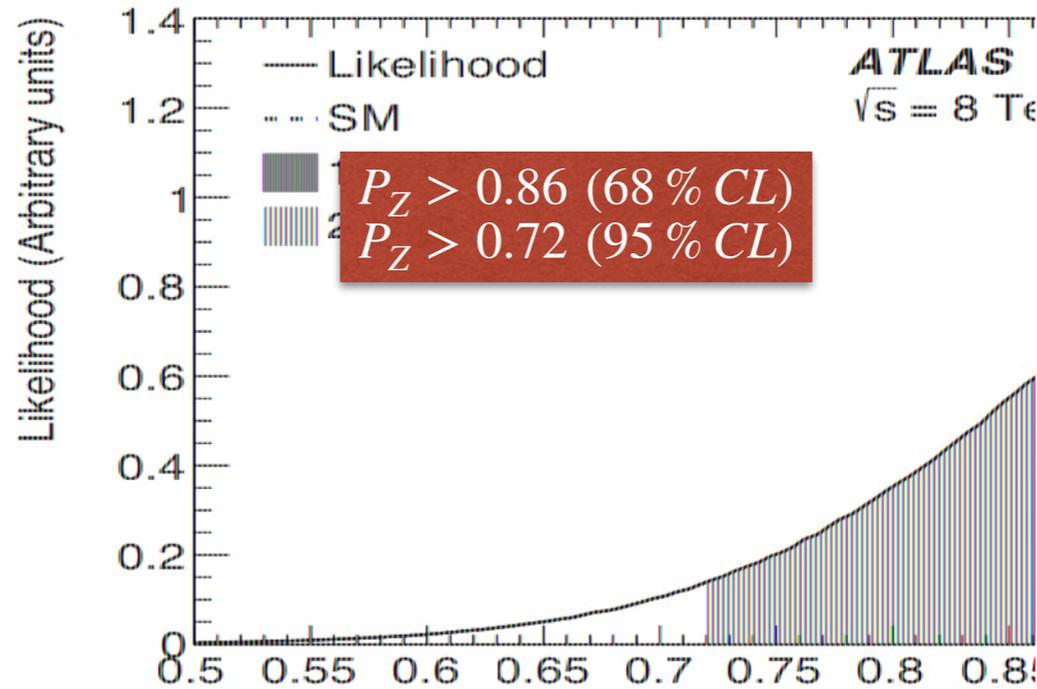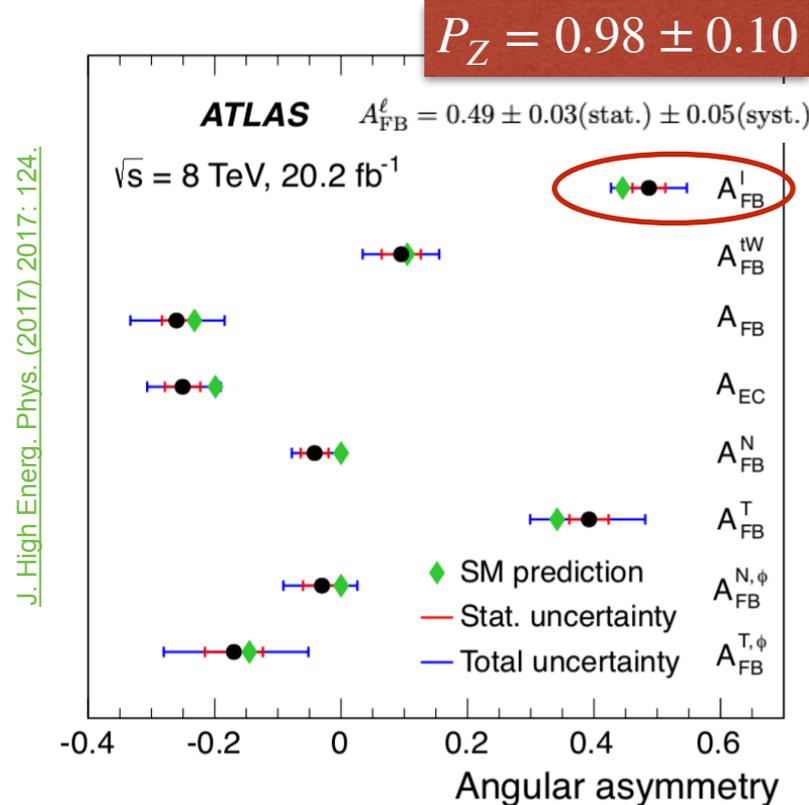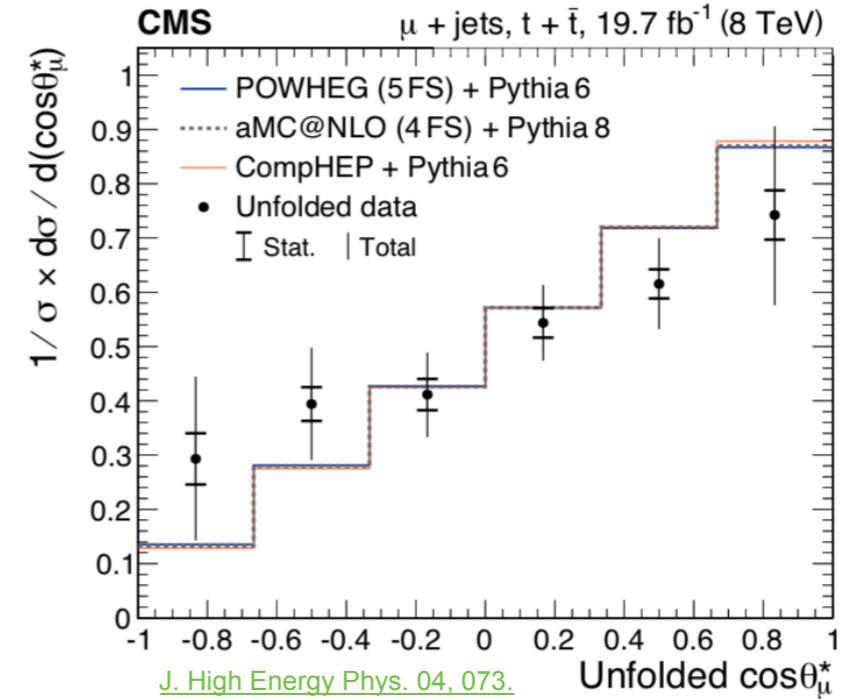
$$A_\mu = 0.26 \pm 0.03 \text{ (stat)} \pm 0.10 \text{ (syst)}$$

$\Rightarrow P_Z = 0.52 \pm 0.20$

Prediction: $A_\mu = 0.44$

$\Rightarrow P_Z = 0.88$

- In 2017, ATLAS published two polarization measurements at 8TeV. Although different approaches, both analyses were consistent with a high value of polarization with the SM predictions.
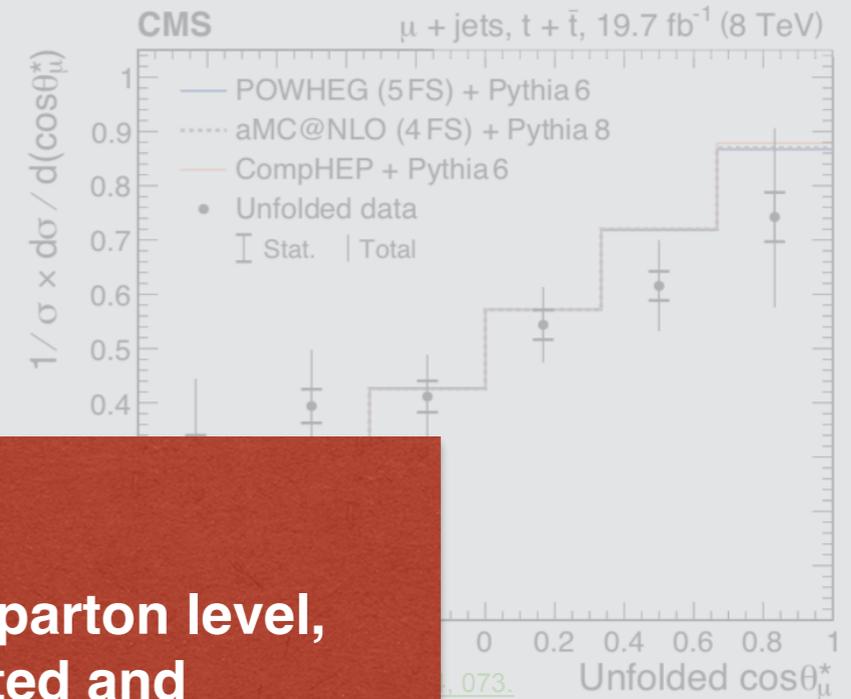
$P_Z = 0.98 \pm 0.10$

J. High Energy Phys. 04, 073.

J. High Energ. Phys. (2017) 2017: 124.

$P_Z > 0.86 \ (68\% \ CL)$
$P_Z > 0.72 \ (95\% \ CL)$

J. High Energ. Phys. (2017) 2017: 17.

❈ Motivations — Previous Analyses

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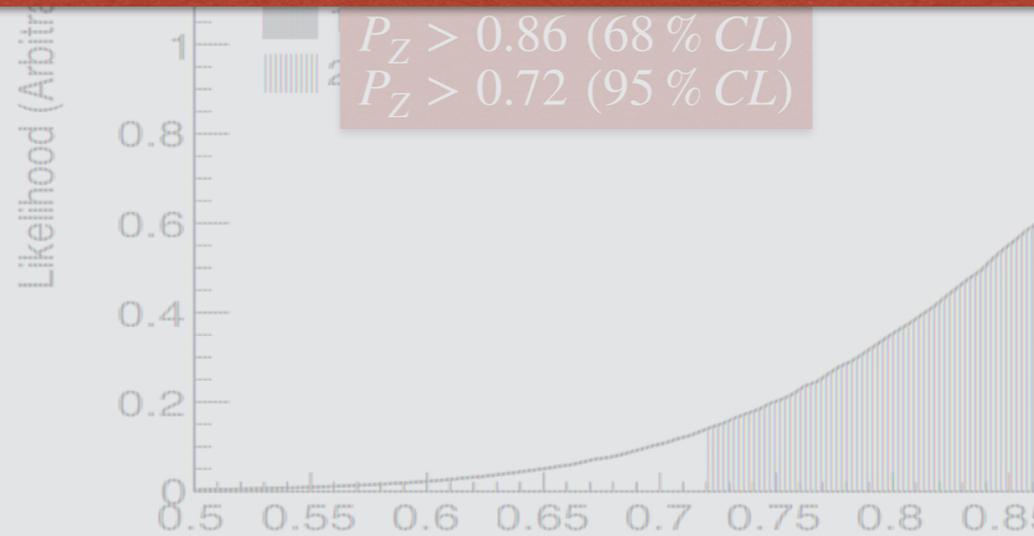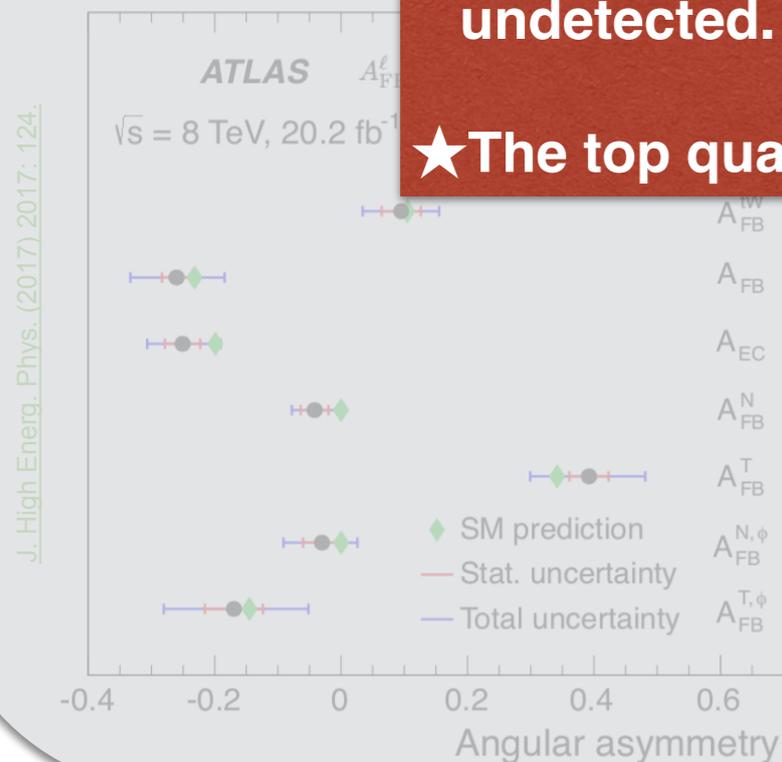
$$A_\mu = 0.26 \pm 0.03 \text{ (stat)} \pm 0.10 \text{ (syst)} \quad \Longrightarrow P_Z = 0.52 \pm 0.20$$

- In 2017, ATLAS published two polarization measurements at 8 TeV. Although different approaches, both a... where a highly pola...

CMS $\quad \mu + \text{jets}, t + \bar{t}, 19.7 \text{ fb}^{-1}$ (8 TeV)

- POWHEG (5 FS) + Pythia 6
- aMC@NLO (4 FS) + Pythia 8
- CompHEP + Pythia 6
- Unfolded data
- Stat. | Total

$1/\sigma \times d\sigma/d(\cos\theta_\mu^*)$

Unfolded $\cos\theta_\mu^*$

★Only the z-components were measured.

★All three measurements were unfolded onto the parton level, measuring the top quark polarization both detected and undetected.

★The top quark and anti-quark data were not separated.

ATLAS A_{FB}^{ℓ}

$\sqrt{s} = 8 \text{ TeV}, 20.2 \text{ fb}^{-1}$

A_{FB}^{lW}
A_{FB}
A_{EC}
A_{FB}^{N}
A_{FB}^{T}
$A_{FB}^{N,\phi}$
$A_{FB}^{T,\phi}$

♦ SM prediction
— Stat. uncertainty
— Total uncertainty

Angular asymmetry

$P_Z > 0.86 \ (68\% \ CL)$
$P_Z > 0.72 \ (95\% \ CL)$

Likelihood (Arbit...

J. High Energ. Phys. (2017) 2017: 124.

J. High Energ. Phys. (2017) 2017: 17.

❋Analysis Goal

- The polarization of the top quark can be determined through the angular distribution of its decay products.

$$\frac{1}{\Gamma}\frac{d\Gamma}{d(\cos\theta_l)} = \frac{1}{2}(1 + \alpha_l P \cos\theta_l)$$

- Performing a cut-based fiducial measurement of the single top polarization in t-channel with full ATLAS Run II dataset at 13TeV (expected 140.2 fb^{-1}).

- We have devised a template fit method to simultaneously measure the polarization vector in terms of three orthogonal axes: (P_x,P_y,P_z).

- The polarization of the top quark and anti-quark will be measured **separately**.

- The results will then be compared to the theoretical predictions, which are (SM LO).
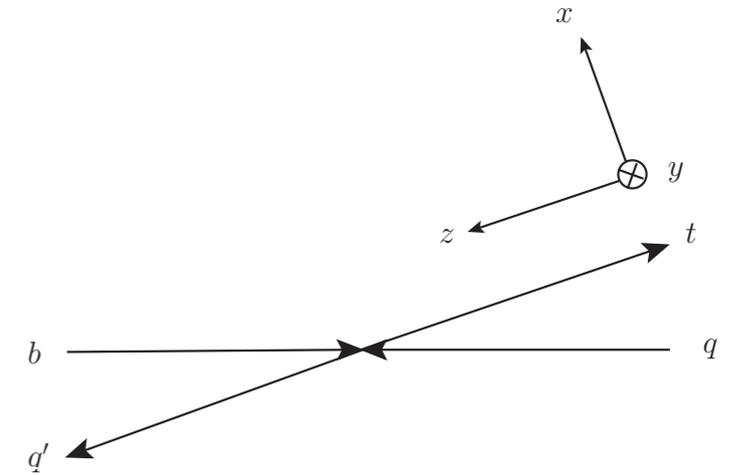
❋Definitions

- In this analysis, we follow the listed choices to define our angular observables. They are:

  - Spectator quark (the untagged light jet) momentum as the top spin axis.

  - Lepton as the primary analyzer ($\alpha_l = 1$).

  - Top quark and W boson are fully reconstructed.

  - Lepton momentum in the top rest frame is determined.
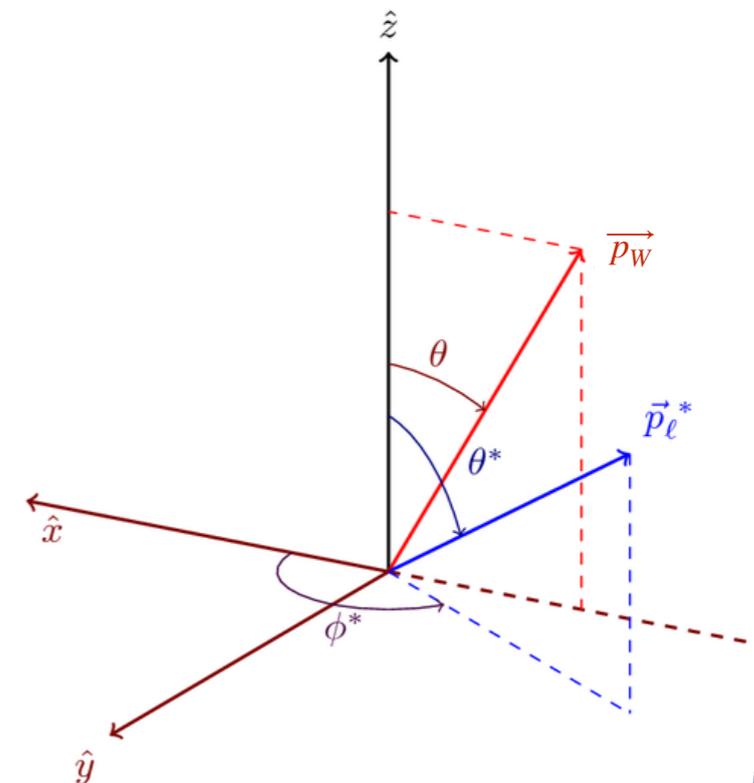
❈Template Fit Strategy

- **Construct templates** in the variable $\cos\theta_l$ for pure polarized ensembles: $P_Z = \pm 1, P_X = \pm 1, P_Y = \pm 1$.
  - Six templates needed to fully cover the differential cross section coming from all spin configurations + interference terms.

- **Obtain dataset for arbitrary polarizations** as a linear combination of these.

- Fit the coefficients to obtain the polarization in real/simulated data.

- The full expression of the differential decay distribution of $t \to Wb \to lvb$ is:

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\Omega d\Omega^*} = \frac{3}{64\pi^2}\frac{1}{\mathcal{N}}\left\{\left[|a_{1\frac{1}{2}}|^2(1+\lambda\cos\theta^*)^2 + 2|a_{0-\frac{1}{2}}|^2\sin^2\theta^*\right]\left(1+\vec{P}\cdot\vec{u}_L\right)\right.$$
$$+ \left[2|a_{0\frac{1}{2}}|^2\sin^2\theta^* + |a_{-1-\frac{1}{2}}|^2(1-\lambda\cos\theta^*)^2\right]\left(1-\vec{P}\cdot\vec{u}_L\right)$$
$$+ \lambda 2\sqrt{2}\left[\mathrm{Re}(a_{0\frac{1}{2}}a^*_{1\frac{1}{2}}e^{-i\phi^*})(1+\lambda\cos\theta^*)\right.$$
$$+ \left.\mathrm{Re}(a_{-1-\frac{1}{2}}a^*_{0-\frac{1}{2}}e^{-i\phi^*})(1-\lambda\cos\theta^*)\right]\sin\theta^*\vec{P}\cdot\vec{u}_T$$
$$+ \lambda 2\sqrt{2}\left[\mathrm{Im}(a_{0\frac{1}{2}}a^*_{1\frac{1}{2}}e^{-i\phi^*})(1+\lambda\cos\theta^*)\right.$$
$$+ \left.\left.\mathrm{Im}(a_{-1-\frac{1}{2}}a^*_{0-\frac{1}{2}}e^{-i\phi^*})(1-\lambda\cos\theta^*)\right]\sin\theta^*\vec{P}\cdot\vec{u}_N\right\}.$$

Eur. Phys. J. C (2017) 77: 200.

where the a_{λ_W,λ_b} the coefficients are the transition amplitudes for $t \to Wb$, and λ's are helicities. The unit vectors are:

- $\vec{u}_L = (\sin\theta\cos\phi, \sin\theta\sin\phi, \cos\theta)$ in the direction of the W boson momentum in the top quark rest frame,

- $\vec{u}_T = (\cos\theta\cos\phi, \cos\theta\sin\phi, -\sin\theta)$, $\vec{u}_N = (\sin\phi, -\cos\phi, 0)$ are two orthonormal vectors.

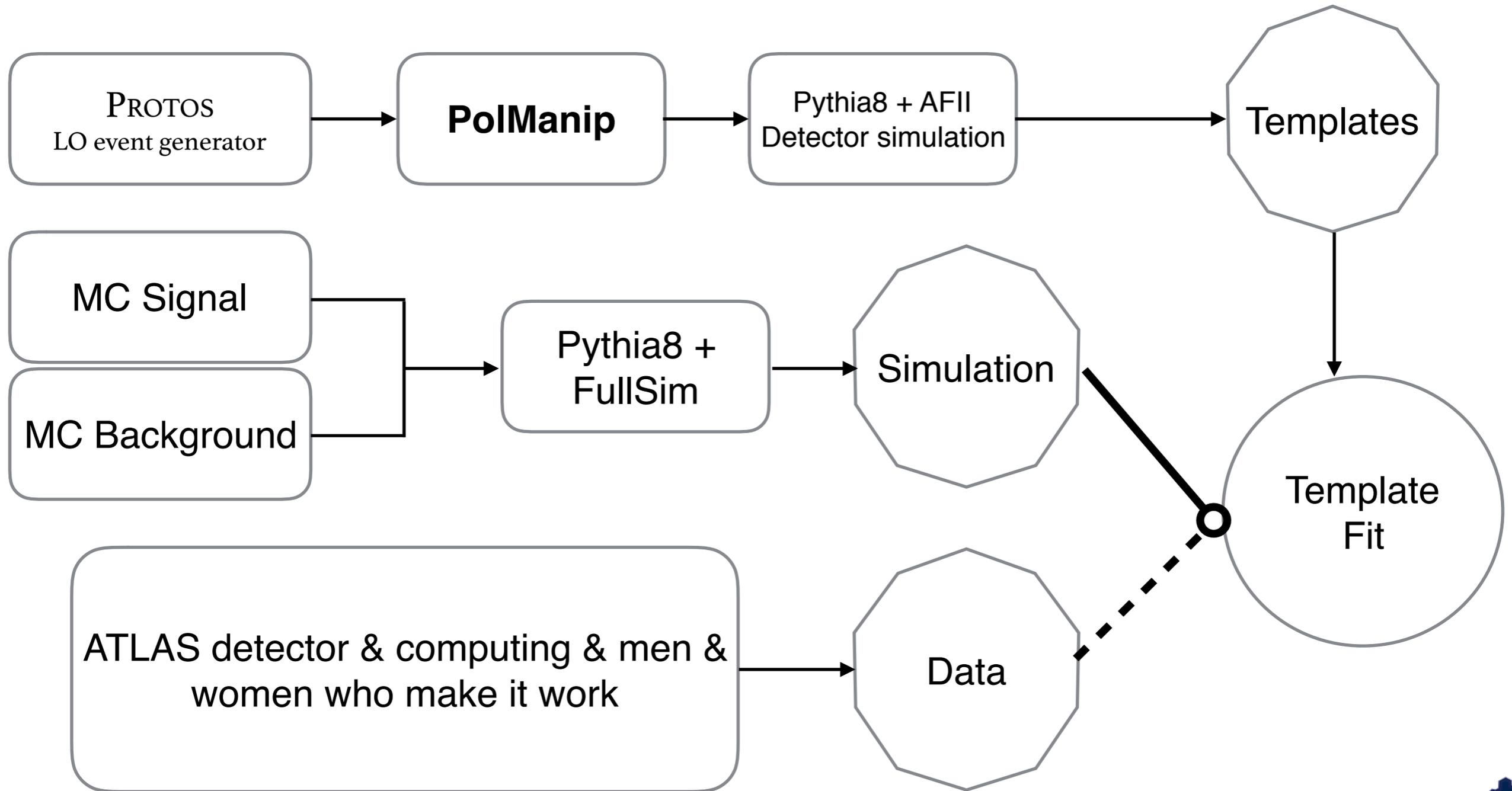- $\lambda = 1$ for top quarks, $\lambda = -1$ for top antiquarks.

PolManip package!
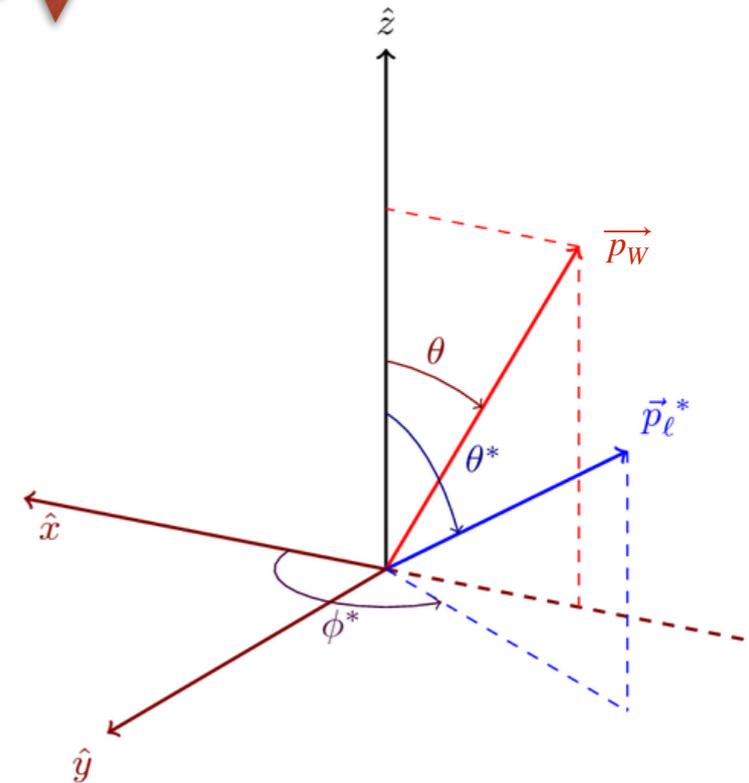
An illustration of angles that were used to define the top decay process. θ and ϕ are the polar and azimuthal angles of the W boson momentum in top rest frame, and θ^* and ϕ^* are the polar and azimuthal angles of the charged lepton momentum in W rest frame.

❋**Template Fit Strategy**
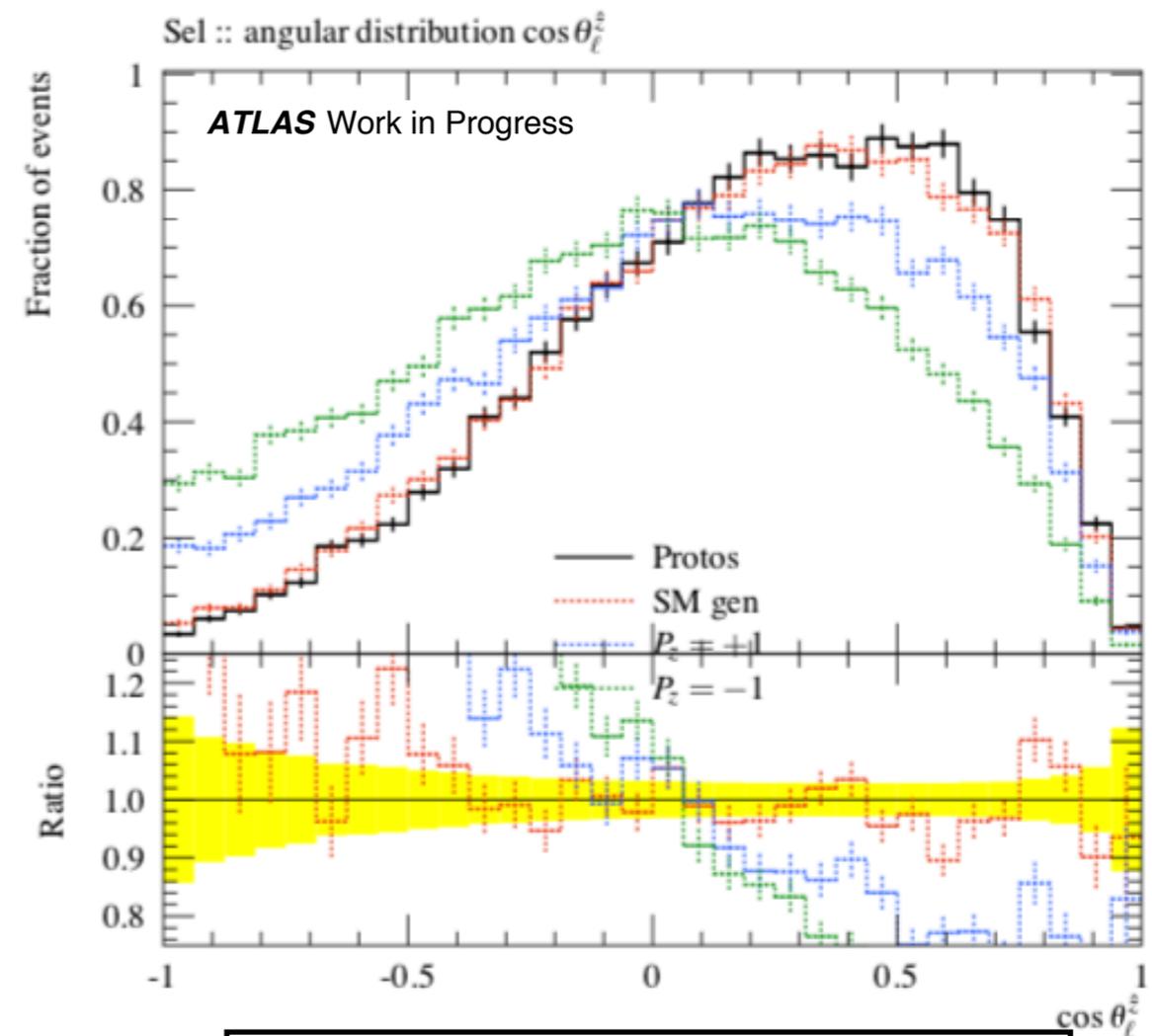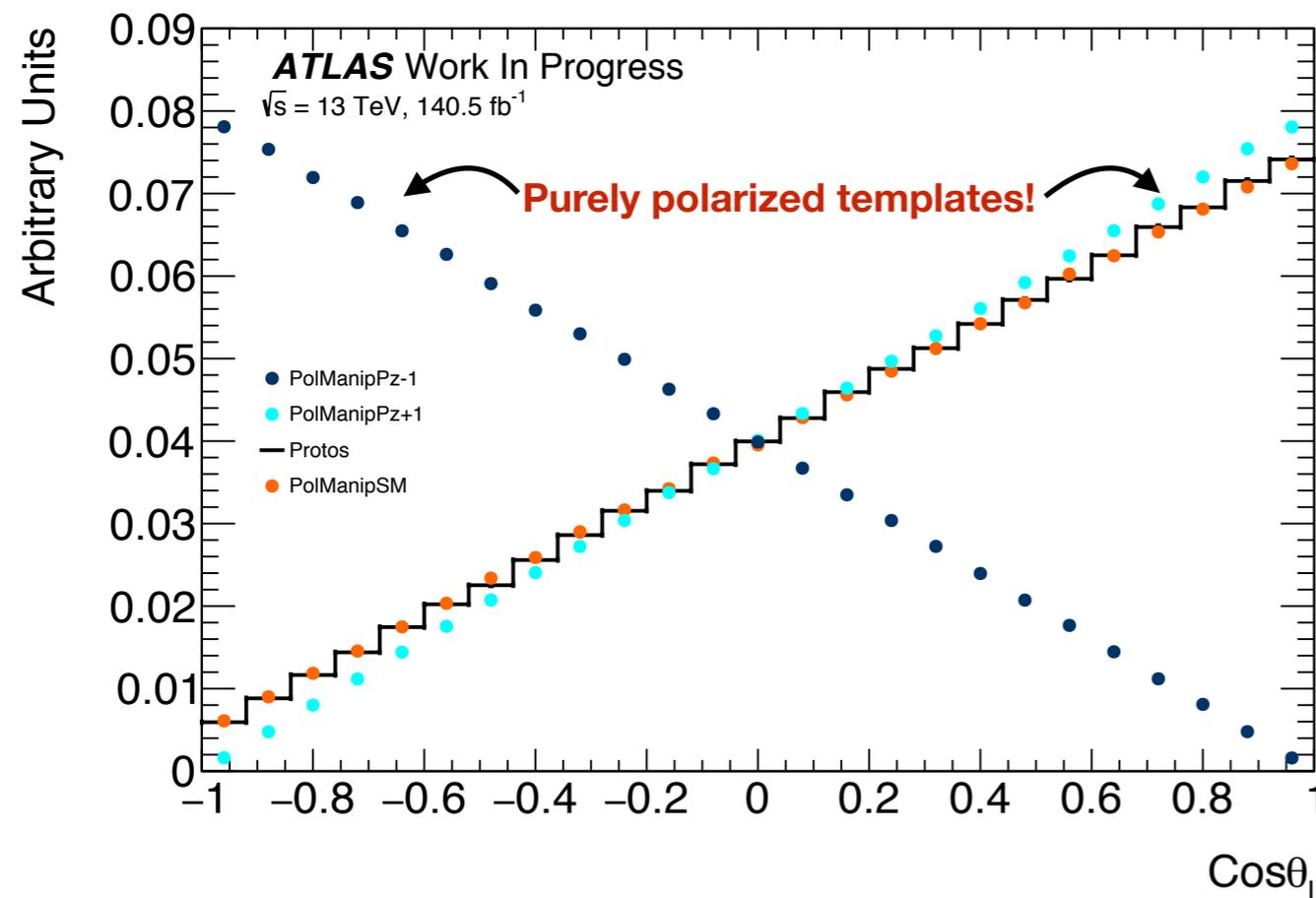
❋PolManip

- **A decay model for top quarks that modifies the polarization**: It takes the output of a single top event generator (i.e. Protos: LHE file), and re-decays the top quark into a lepton, neutrino and b quark according to a user-specified polarization state.

- **Convenient output**

- **Validated in ATLAS.**

Validation plots: comparisons are made between the original Photos sample (Protos), and the PolManip SM sample (SM gen).

❊Event Selection Criteria — 4 regions

- **Selection Region (SR)**:
  - ◉ PR
  - ◉ $m_{l,b} <$ 153 GeV
  - ◉ 34 GeV $< m_{top} <$ 206 GeV
  - ◉ Trapezoidal Cut on η_{top} vs. η_j
  - ◉ $m_{j,top} >$ 280 GeV (select real top)
  - ◉ $H_T >$ 170 GeV (discriminate against W+jets with softer jets)

- **W+jets CR == Anti-selection Region** :
  - ◉ Enriched by selecting events passing the PR criteria, but vetoing all SR requirements.
  - ◉ PR-SR.

- **t̄t CR**
  - ◉ Passing all SR requirements, but requiring 2 b-tagged jets.
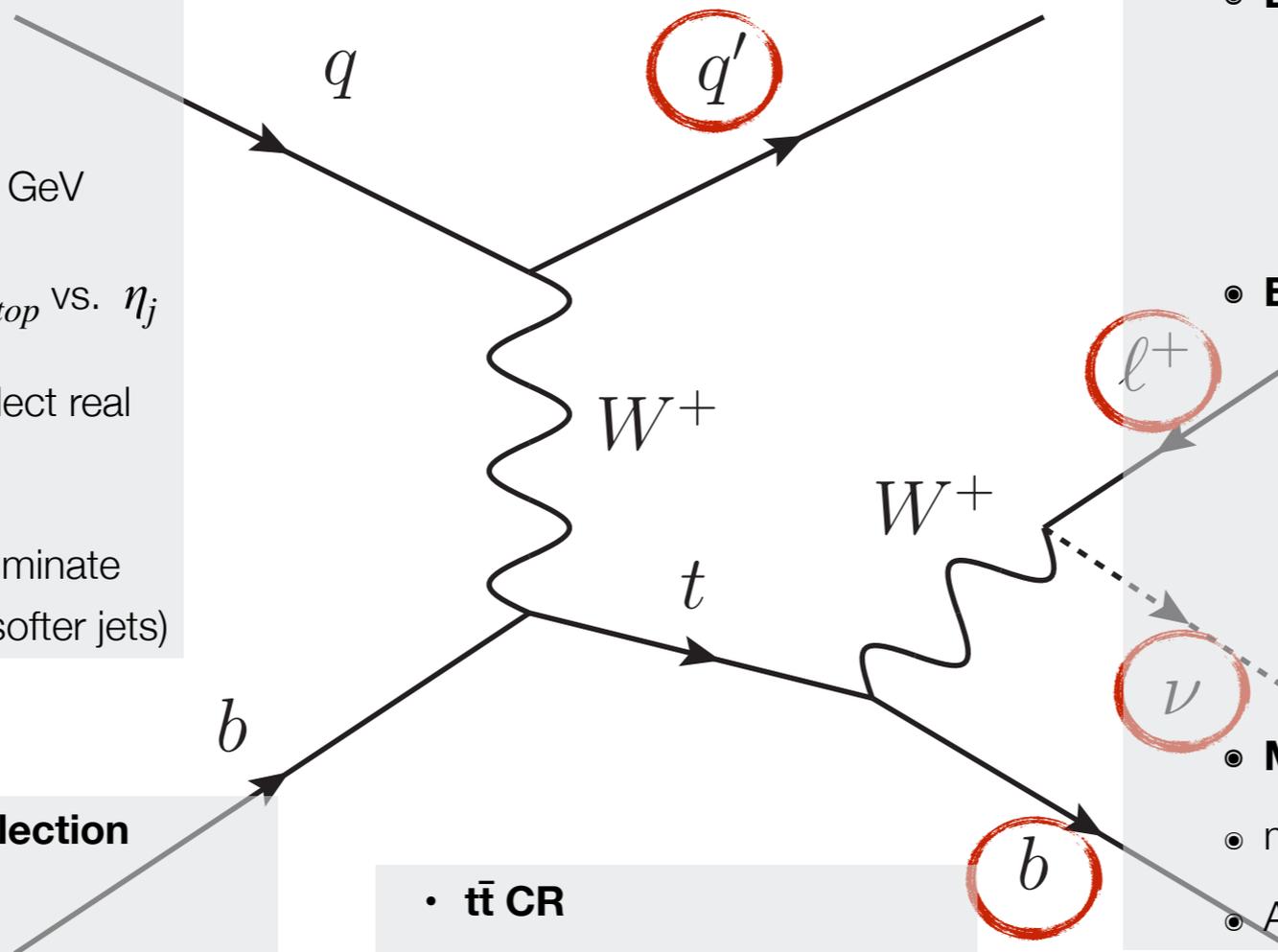
- **Preselection Region (PR)**:
  - ◉ **Exactly one tight charged lepton**
    - ◉ pT > 30 GeV, |η| < 2.5
    - ◉ Vetoing if existing a secondary high-pT (pT > 30 GeV) charged loose leptons.
  - ◉ **Exactly 2 jets. Exactly 1 b-tagged.**
    - ◉ pT > 30 GeV (pT>35 GeV in transition region 2.75<= |η| <3.5 to avoid mis-modeling between the central and forward calorimeters.)
    - ◉ Spectator jet (|η| < 4.5), b-jet (60 %WP (bin selection) within |η| < 2.5)
  - ◉ **MET > 35 GeV.**
  - ◉ mT(lepton-MET) [or MtW] > 60 GeV.
  - ◉ Additional multijet rejection ("triangular cut")

❋Event Selection
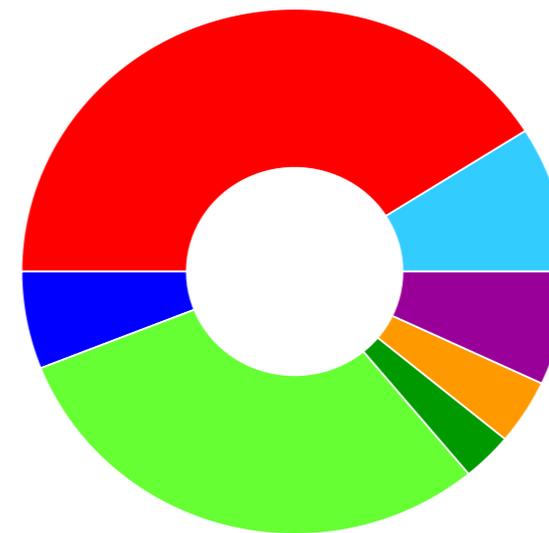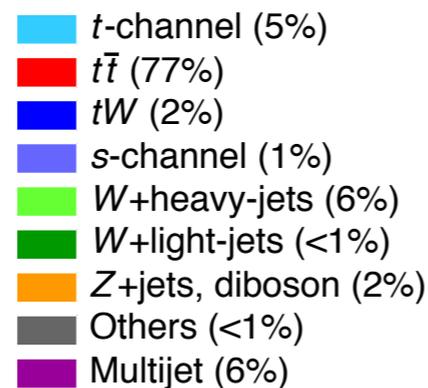
- **Multijet estimation**

  - ◉ Approach with data-driven methods.

  - ◉ Data-driven jet-electron model and generic simulated di-jet events in the electron channel.

  - ◉ Data-driven anti-muon model in the muon channel.
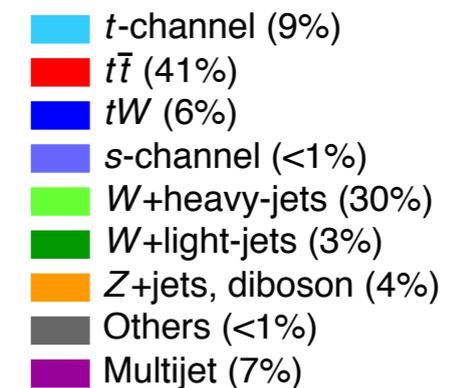
Scale factors

Process	e-channel	μ-channel	$e+\mu$-channels
t-channel	1.06±0.04	1.05±0.06	1.05±0.03
W+jets	0.93±0.03	0.98±0.03	0.954±0.020
$t\bar{t}, Wt, s$-channel	1.008±0.016	0.996±0.017	1.003±0.012
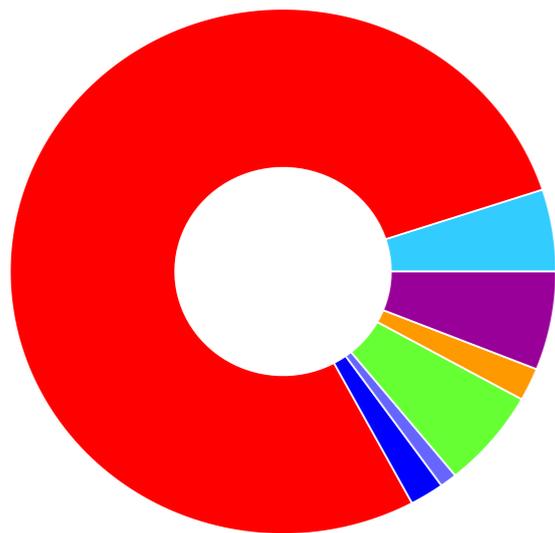
ATLAS Work in Progress
$\sqrt{s}$ = 13 TeV, 140.5 fb^{-1}
$t\bar{t}$ control region (post-fit)

- t-channel (5%)
- $t\bar{t}$ (77%)
- tW (2%)
- s-channel (1%)
- W+heavy-jets (6%)
- W+light-jets (<1%)
- Z+jets, diboson (2%)
- Others (<1%)
- Multijet (6%)

ATLAS Work in Progress
$\sqrt{s}$ = 13 TeV, 140.5 fb^{-1}
W+jets control region (post-fi

- t-channel (9%)
- $t\bar{t}$ (41%)
- tW (6%)
- s-channel (<1%)
- W+heavy-jets (30%)
- W+light-jets (3%)
- Z+jets, diboson (4%)
- Others (<1%)
- Multijet (7%)
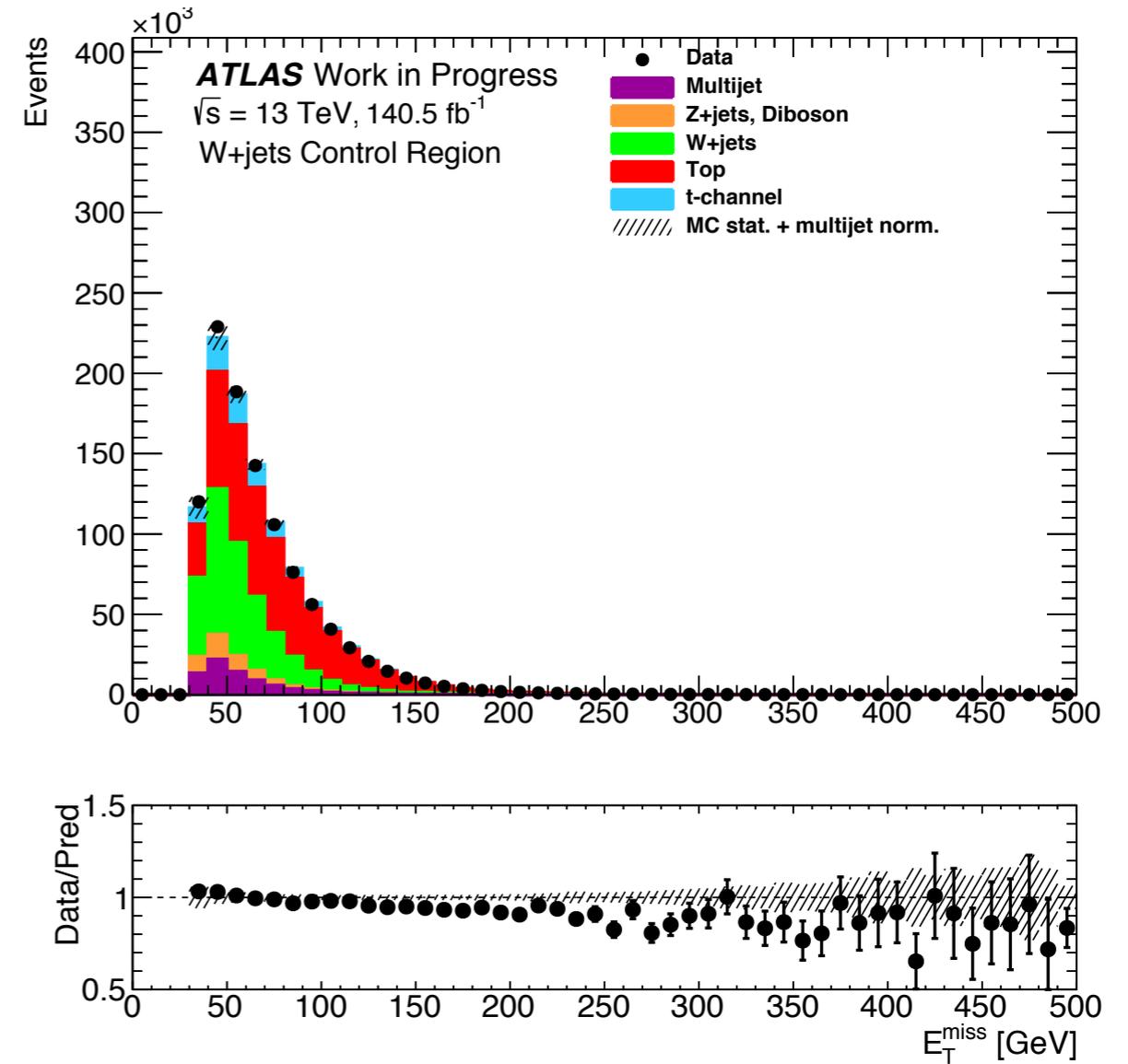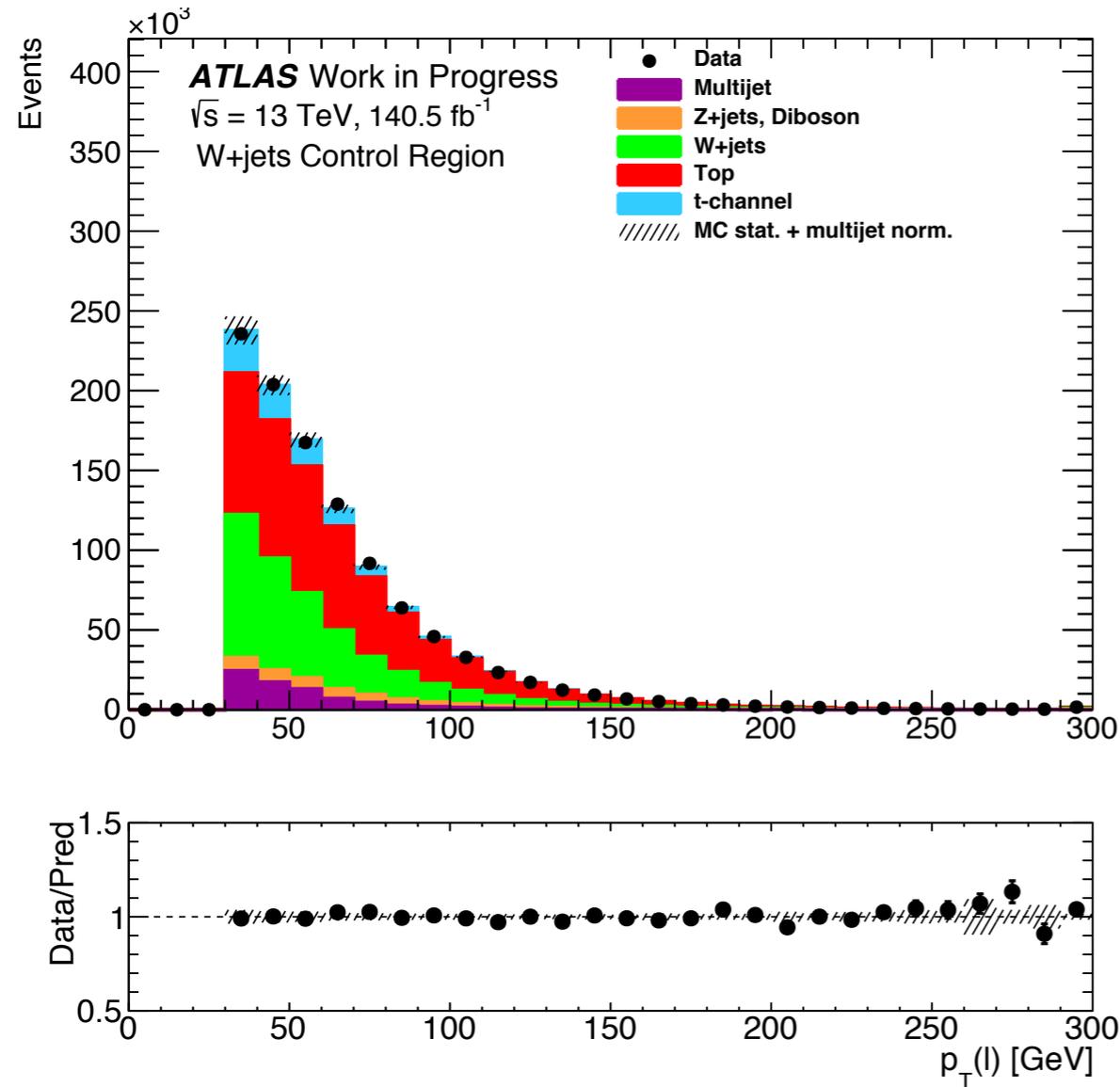
Kinematics

Angular Observables

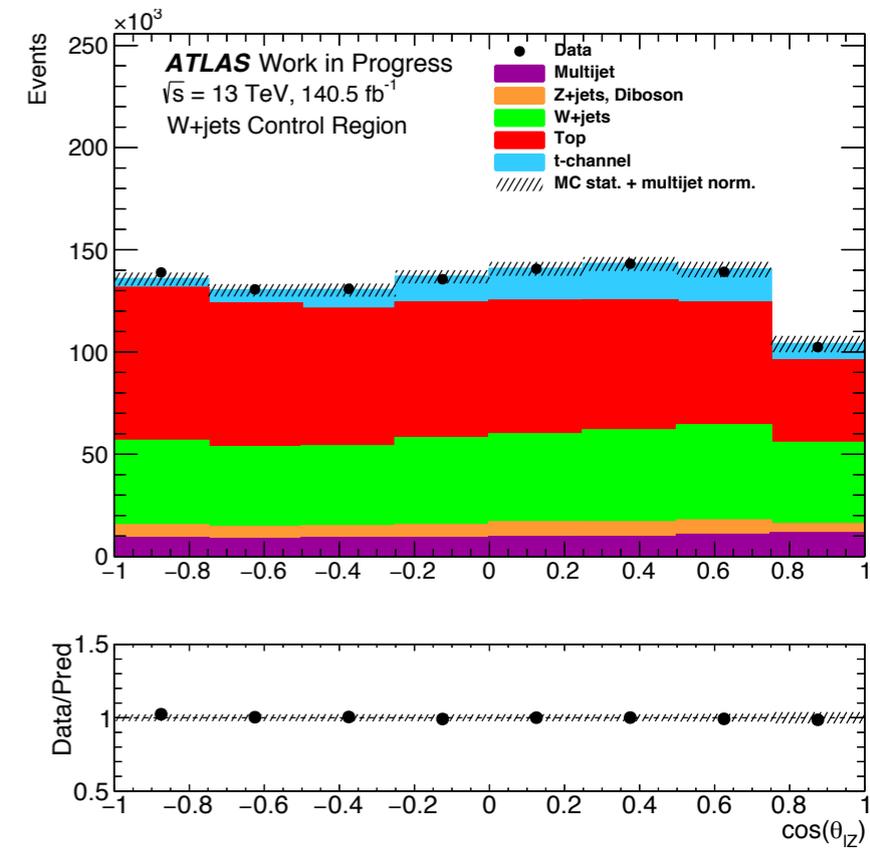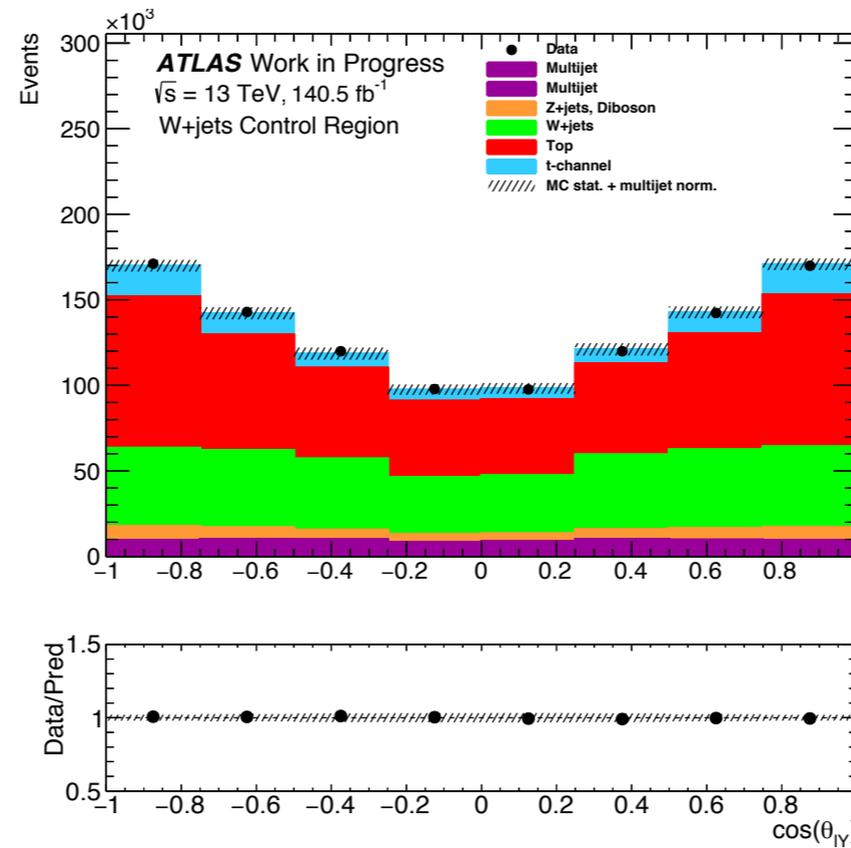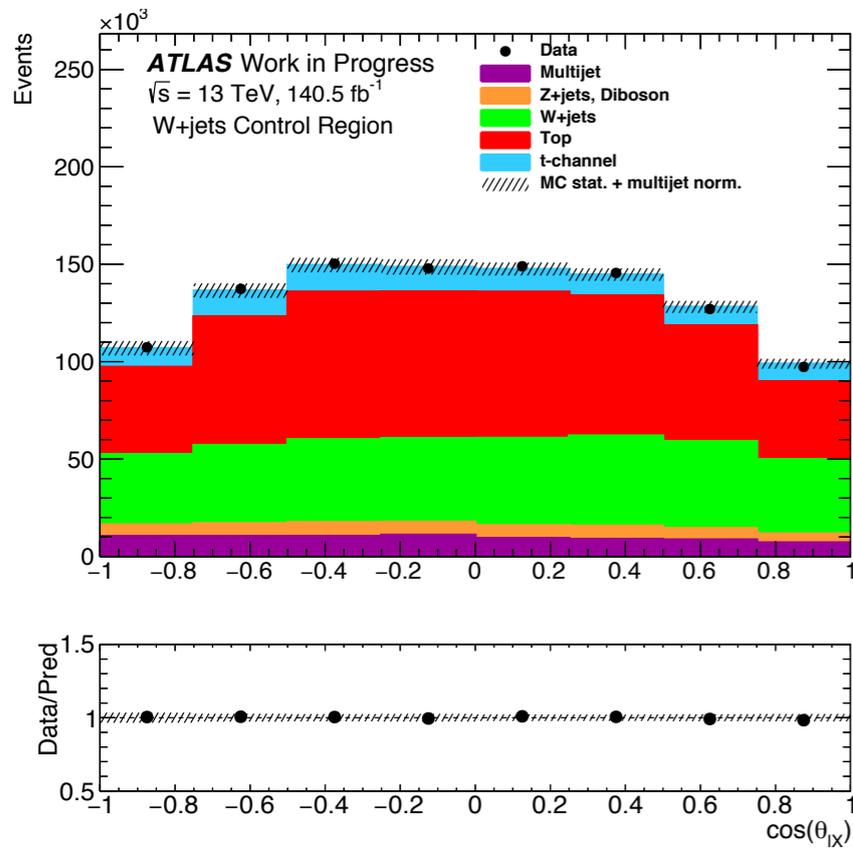# Control Plots: t̄t CR

Kinematics

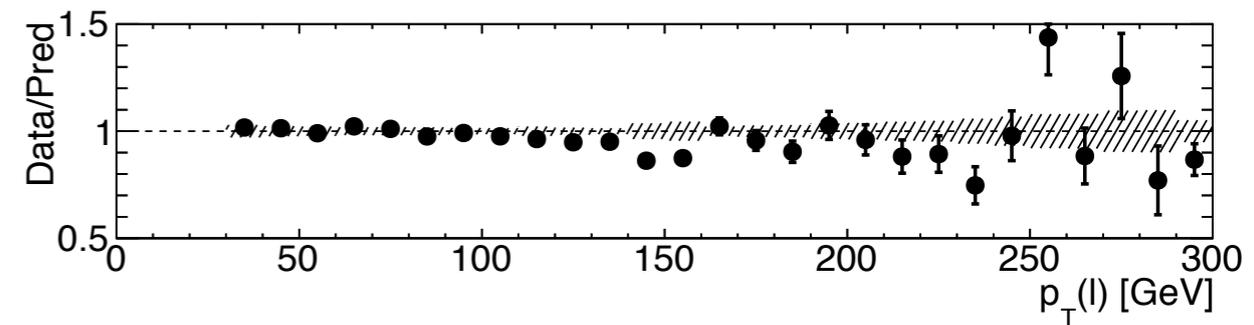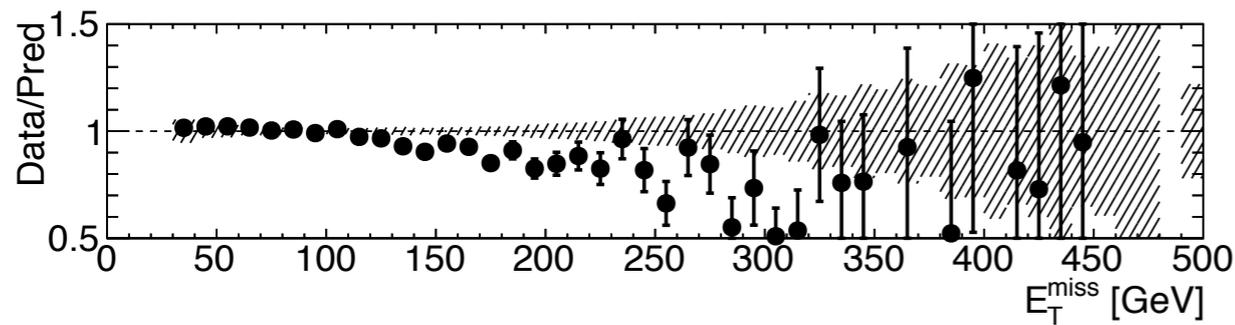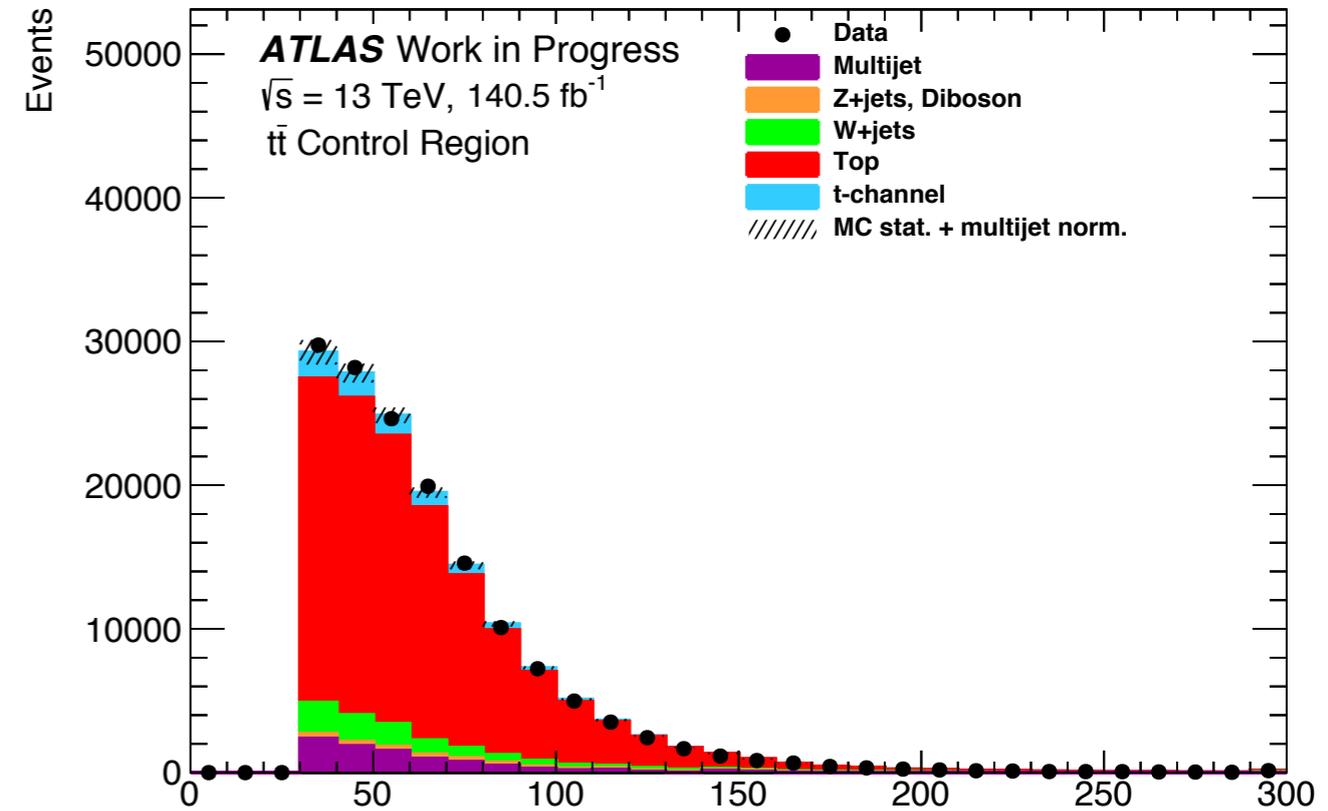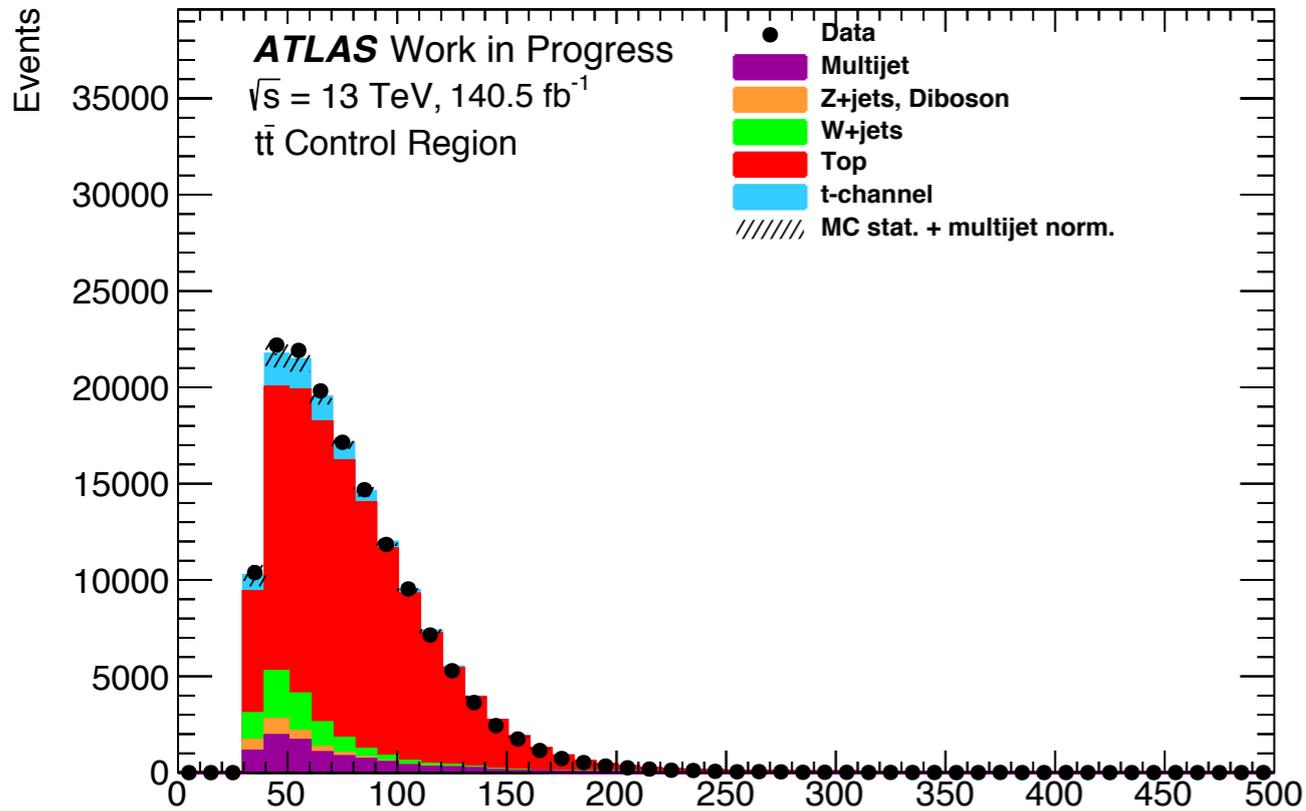## Angular Observables
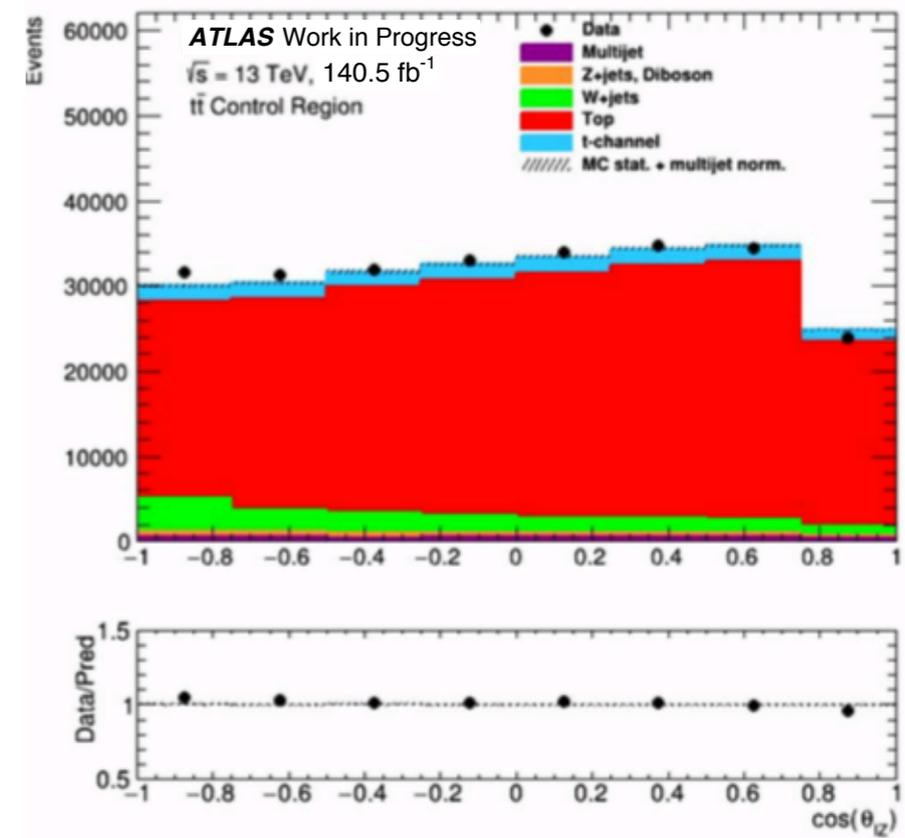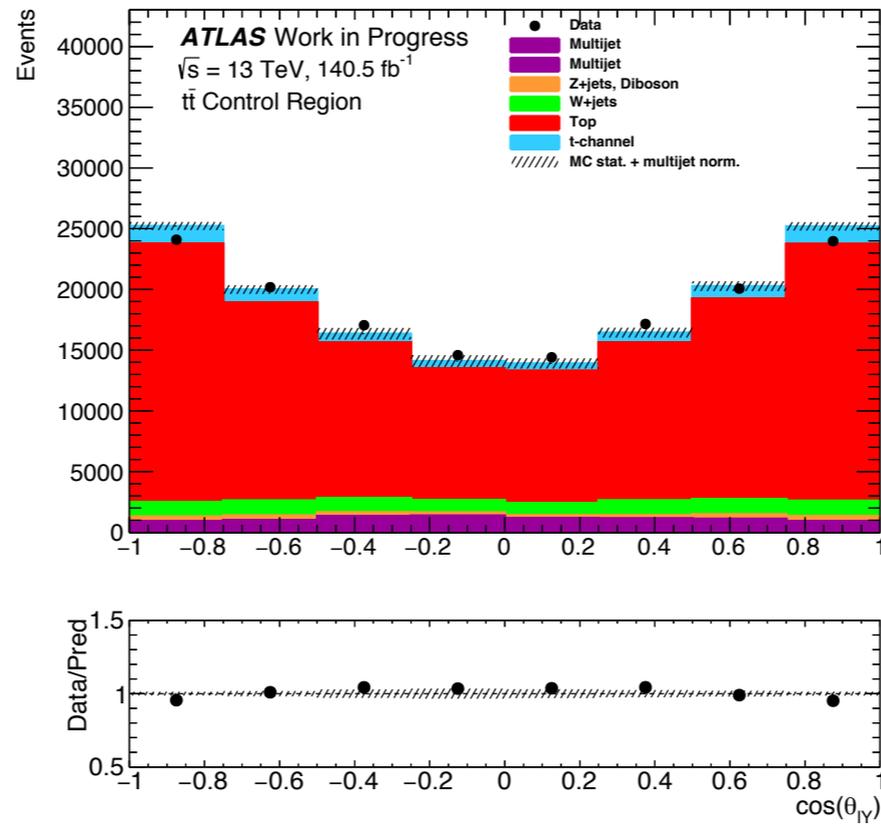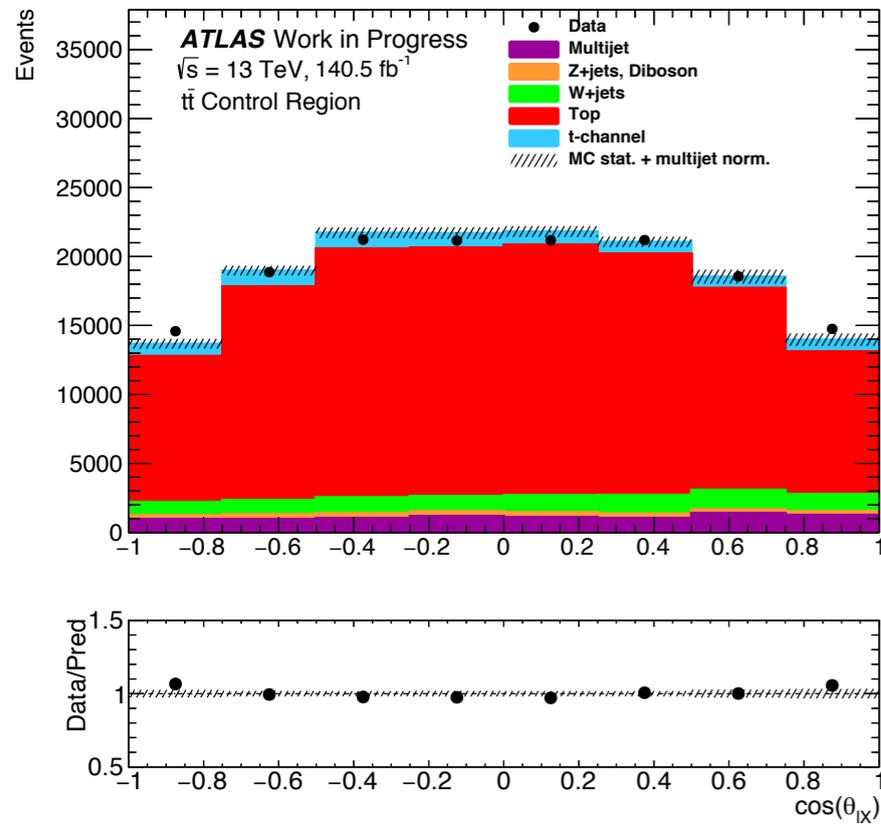
❋Template Fit

- **Octant Fit**: We slice the three-dimensional polarization phase space into 8 octants, and perform a template fit on the populations of the 8 $\cos\theta_l$ bins in these regions.

- **Asimov dataset** with an SM polarization is set up to develop the fitting procedure, and to predict the statistical and systematic uncertainties of the fit.

  - Asimov dataset: PolManip SM gen + total background (**no real data!**)

  - Input polarization: $\overrightarrow{P^t} = (0.0, 0.0, +0.9)$, $\overrightarrow{P^{\bar{t}}} = (-0.14, 0.0, -0.86)$
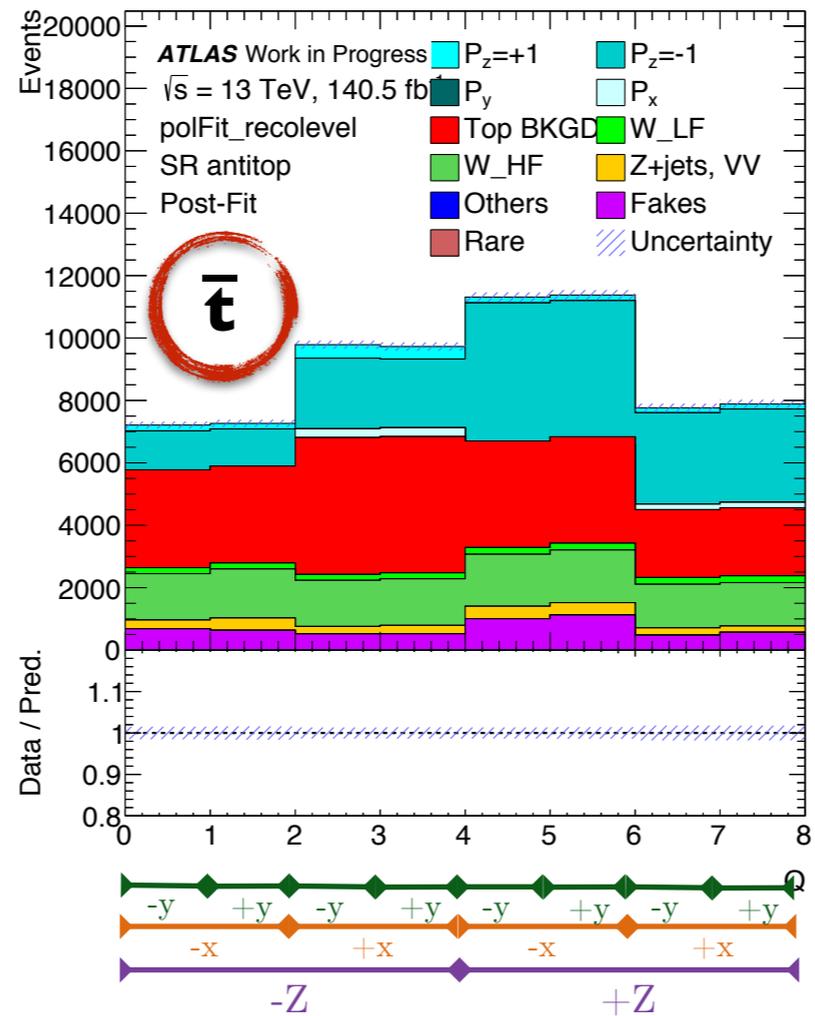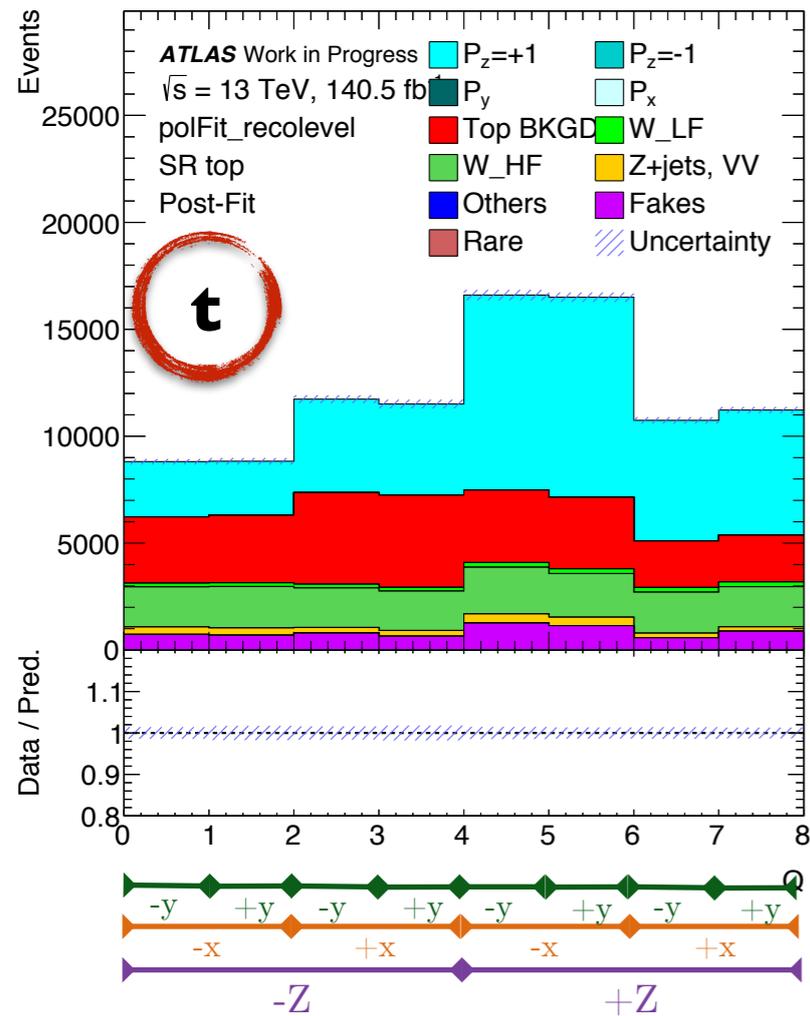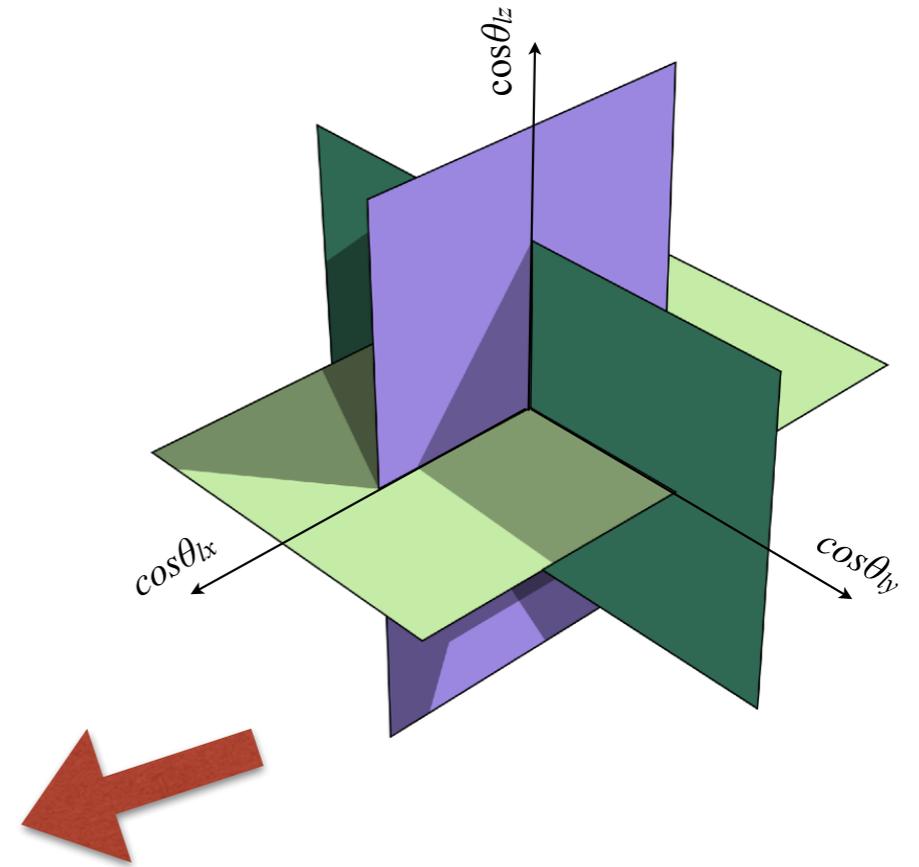
P components	Expected value: stat.+syst. (stat.)
P_x^t	0.00 +0.09 / -0.09 (± 0.02)
P_y^t	0.00 +0.03 / -0.03 (± 0.01)
P_z^t	0.90 +0.13 / -0.13 (± 0.02)
$P_x^{\bar{t}}$	-0.14 +0.16 / -0.16 (± 0.03)
$P_y^{\bar{t}}$	0.00 +0.04 / -0.04 (± 0.02)
$P_z^{\bar{t}}$	-0.86 +0.18 / -0.17 (± 0.04)

❋ Template Fit

- **Systematics dominated measurement**: JES,JER and MET are the main sources of the systematic uncertainties. This is expected because:

  - Spectator jet defines our spin axis.

  - Top quark rest frame is reconstructed from both jets and the neutrino, which means the systematics JET JER and MET have a major impact on this determination.

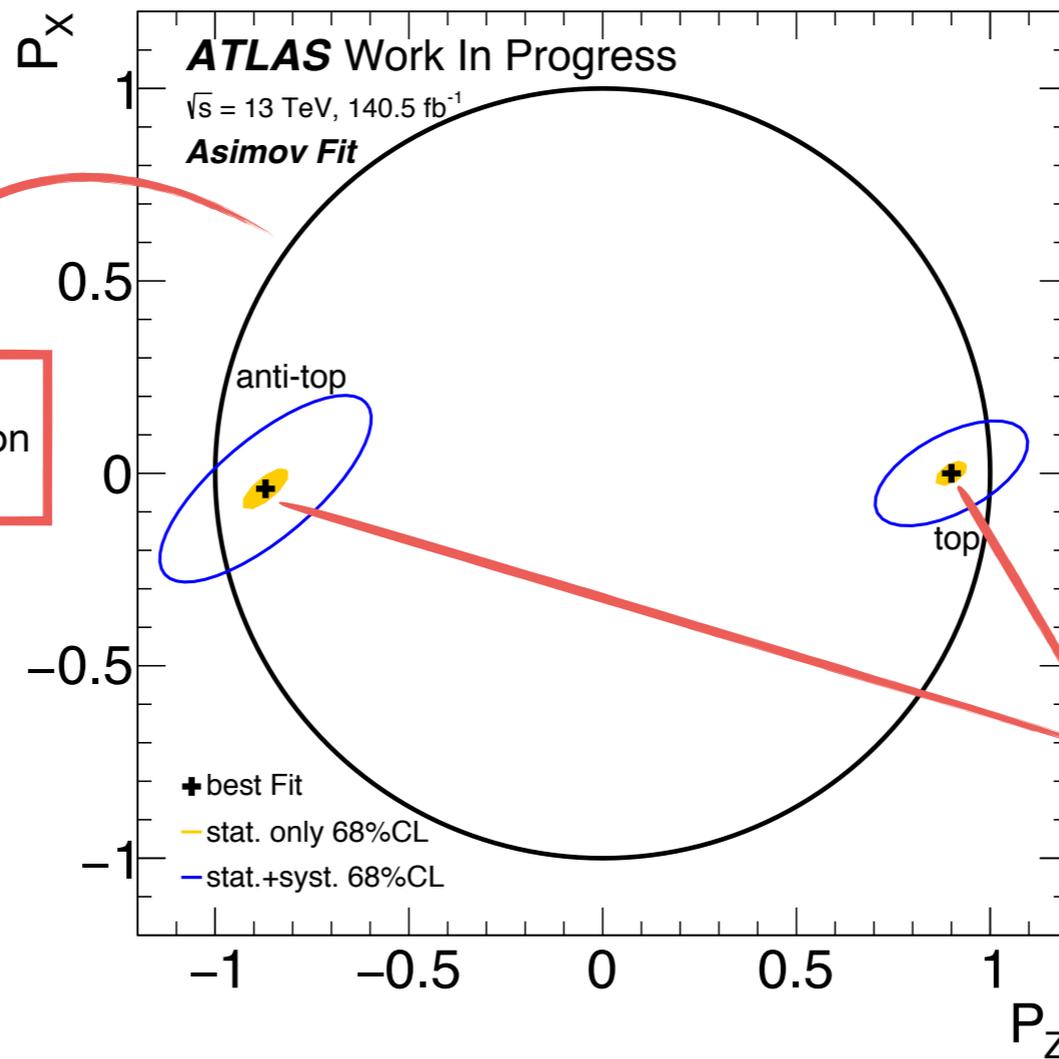| P components	Expected value: stat.+syst. (stat.)
P_x^t	0.00 +0.09 / -0.09 (± 0.02)
P_y^t	0.00 +0.03 / -0.03 (± 0.01)
P_z^t	0.90 +0.13 / -0.13 (± 0.02)
$P_x^{\bar{t}}$	-0.14 +0.16 / -0.16 (± 0.03)
$P_y^{\bar{t}}$	0.00 +0.04 / -0.04 (± 0.02)
$P_z^{\bar{t}}$	-0.86 +0.18 / -0.17 (± 0.04)

Polarization vector should be located inside the physical region represented by this unit circle.

Retrieved the polarization of the Asimov dataset

ATLAS Work In Progress
$\sqrt{s}$ = 13 TeV, 140.5 fb^{-1}
Asimov Fit

anti-top

top

+ best Fit
— stat. only 68%CL
— stat.+syst. 68%CL

P_x

P_z

- A polarization measurement of the top quark and antiquark (separately) based on template fit method with full Run II data is presented.

- Signal and background are well modelled.

- The fitting procedure has shown to be robust through fitting Asimov dataset. Looking forward to unblinding.

- Results with Run II 13 TeV data expected soon!

Thank you!

Backup