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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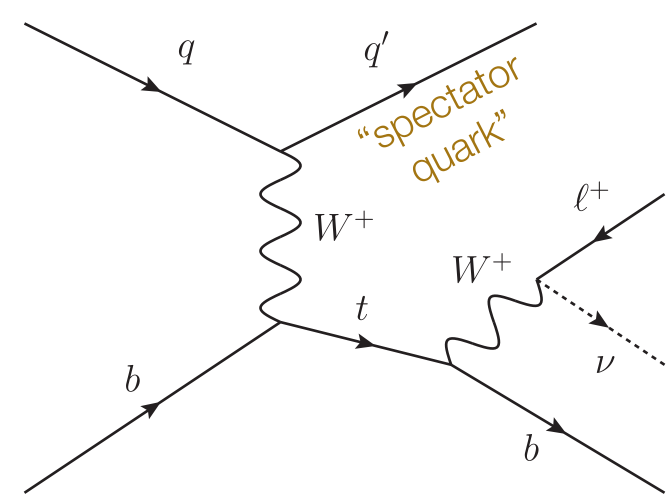
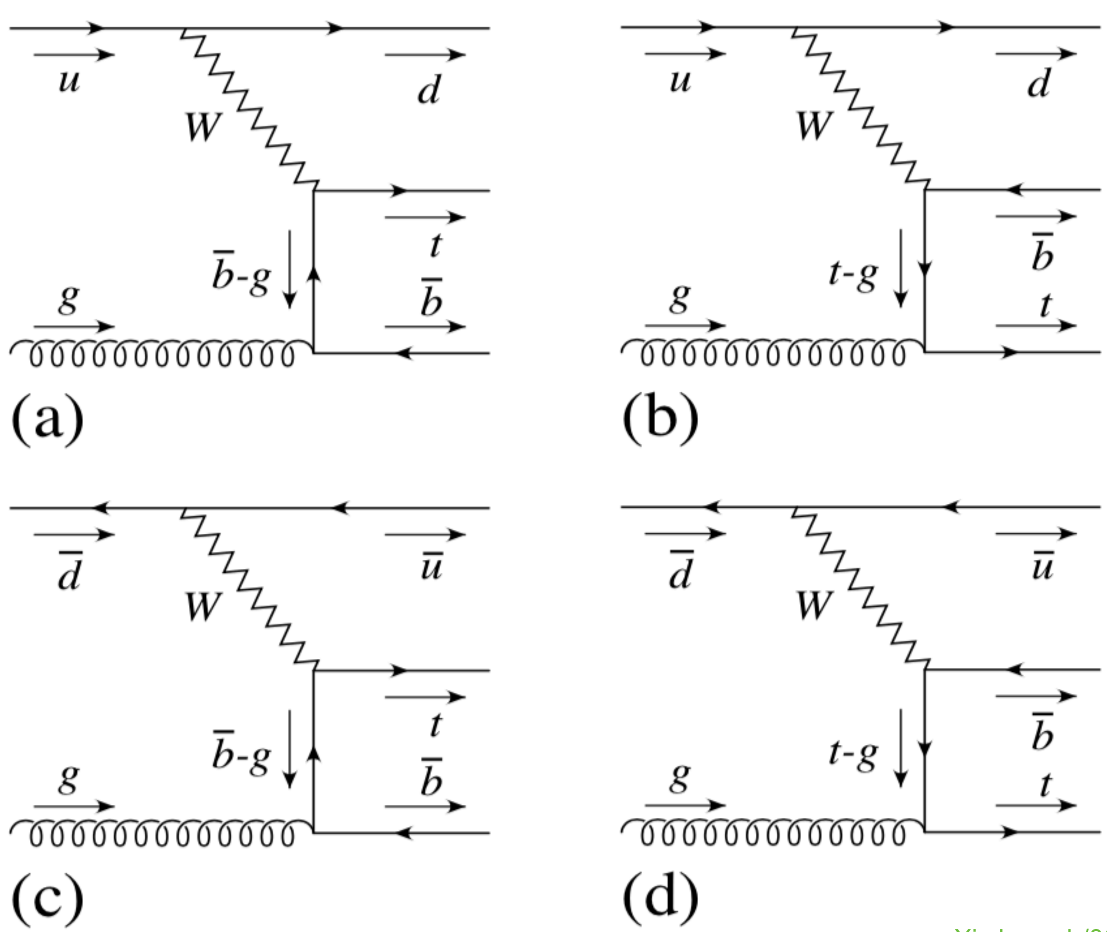
❈Top polarization

- Spin polarization: represented by a polarization vector in 3D phase space, $\overrightarrow{P}$. 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.



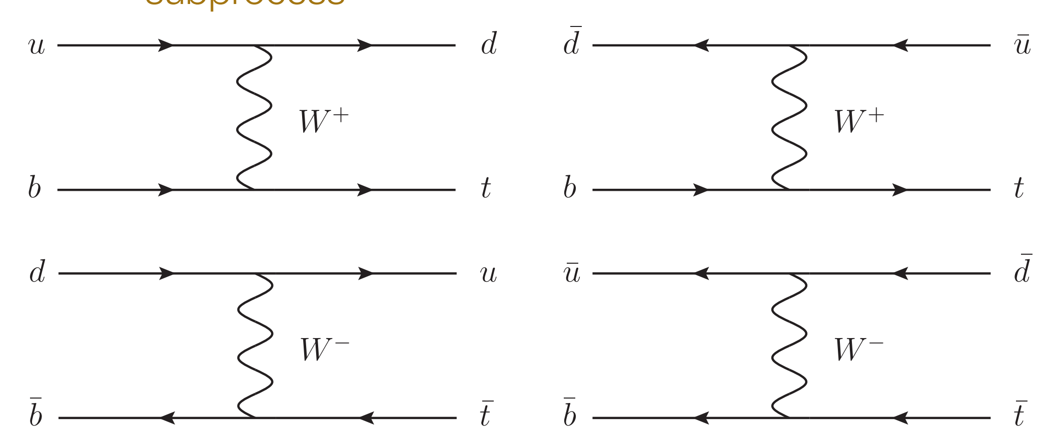
t-channel (dominant @LHC)



arXiv:hep-ph/0011349

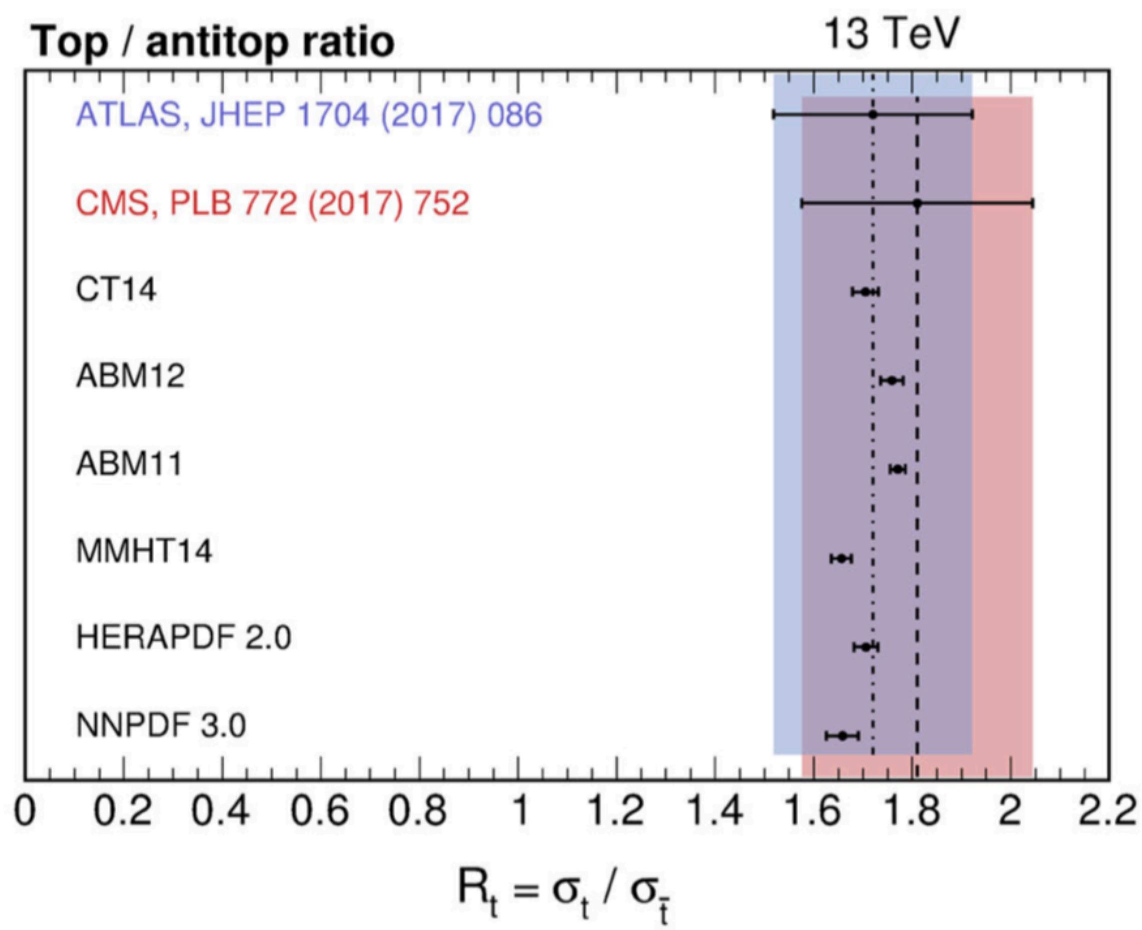
- Interesting phenomenology: pp collision at LHC results a large degree of polarization.

Dominant subprocess



❋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.



Rev. Mod. Phys. 90, 035001

- Sensitive to new physics:
  - Four-fermion operators, top couplings
  - CP violation if existing a nonzero P_y component.

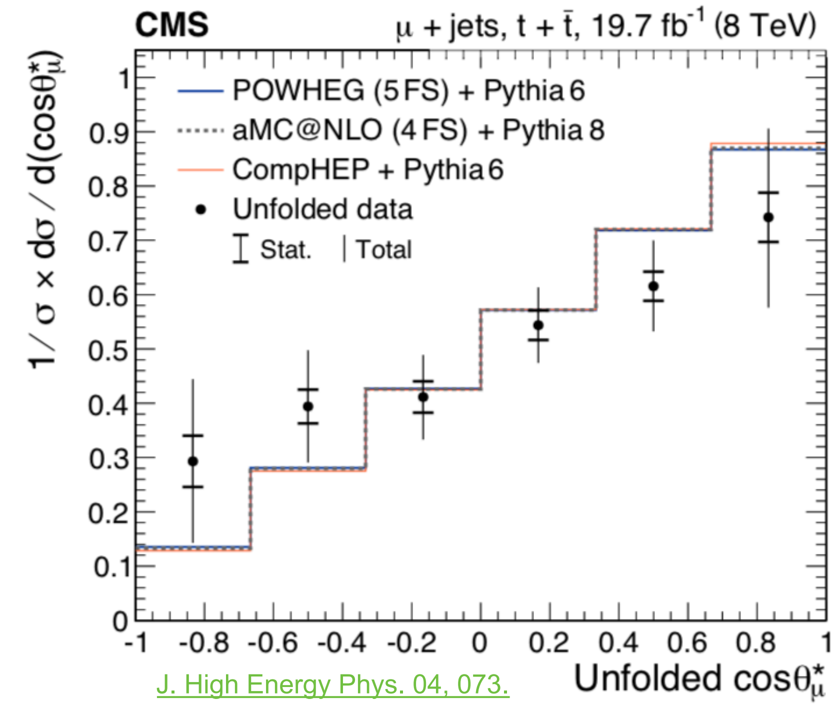
✻Motivations — Previous Analyses

- 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.

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

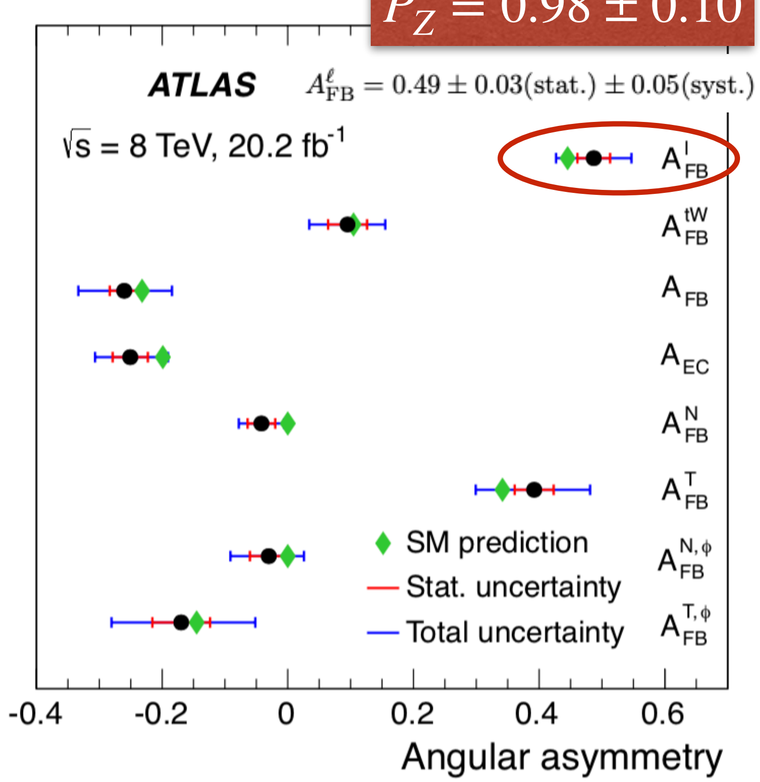
Prediction: $A_\mu = 0.44$ ➡ $P_Z = 0.88$

- 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.

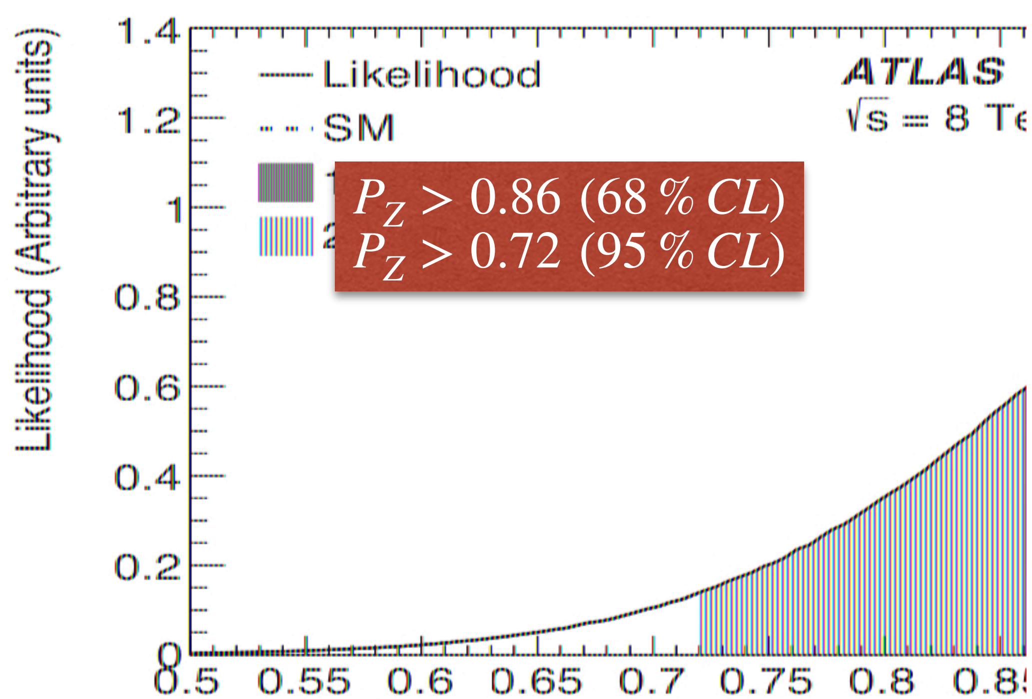


J. High Energy Phys. 04, 073.

$P_Z = 0.98 \pm 0.10$



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



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

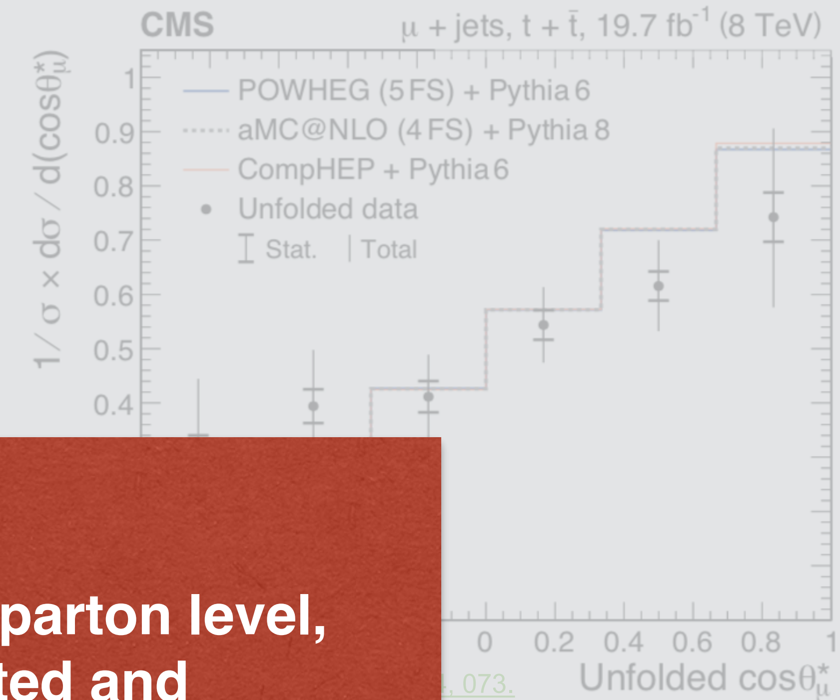
J. High Energ. Phys. (2017) 2017: 17.

Introduction

✵Motivations — Previous Analyses

- In 2016, CMS published the first measurement 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.

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



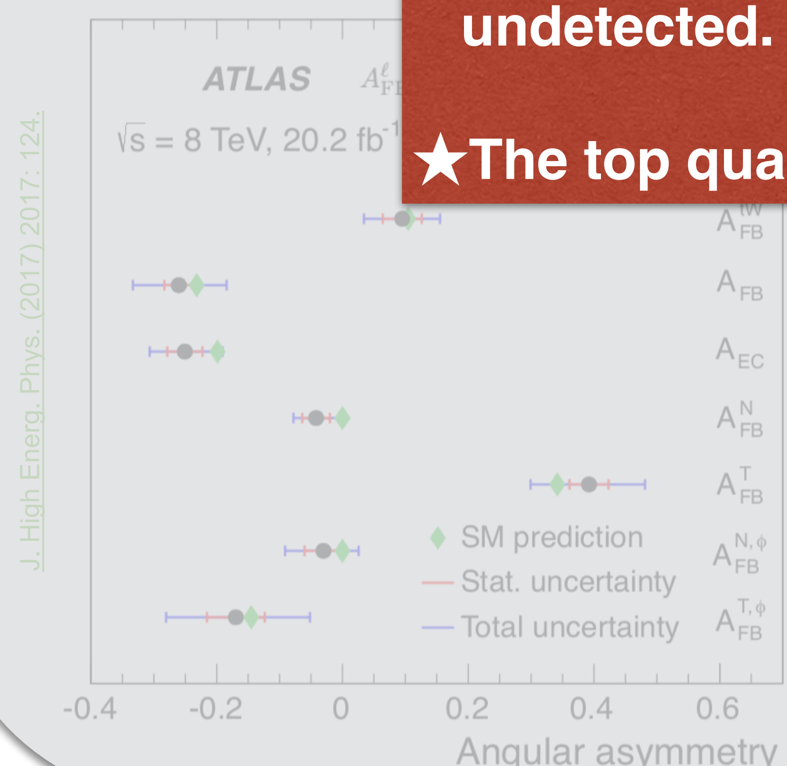
...073.

- In 2017, ATLAS pu[...] approaches, both a[...] where a highly pola[...]

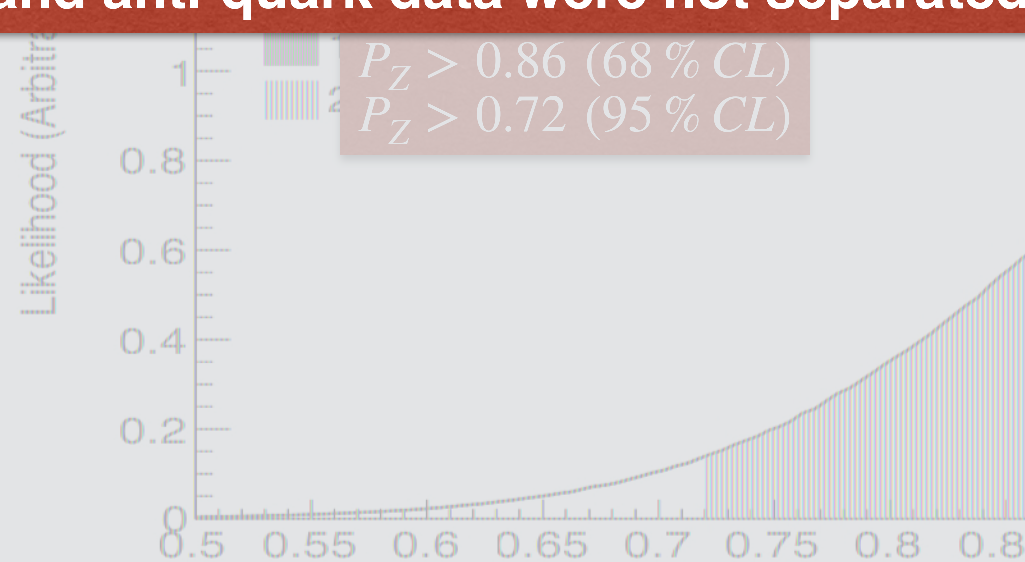
★Only the z-components were measured.

★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.



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

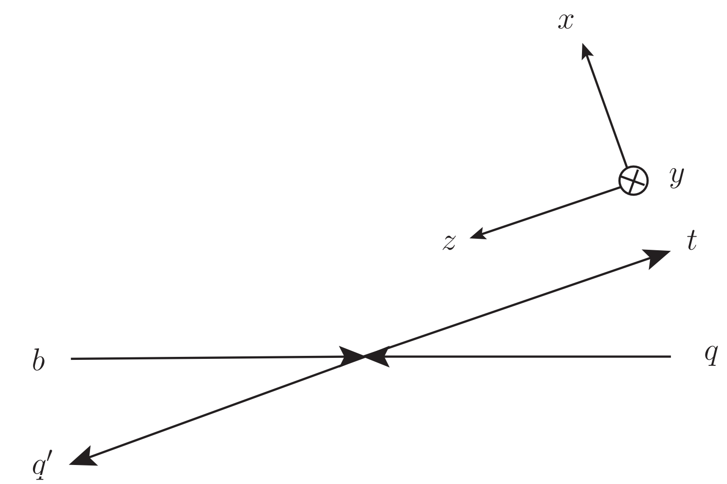


J. High Energ. Phys. (2017) 2017: 17.

✵Analysis Goal

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

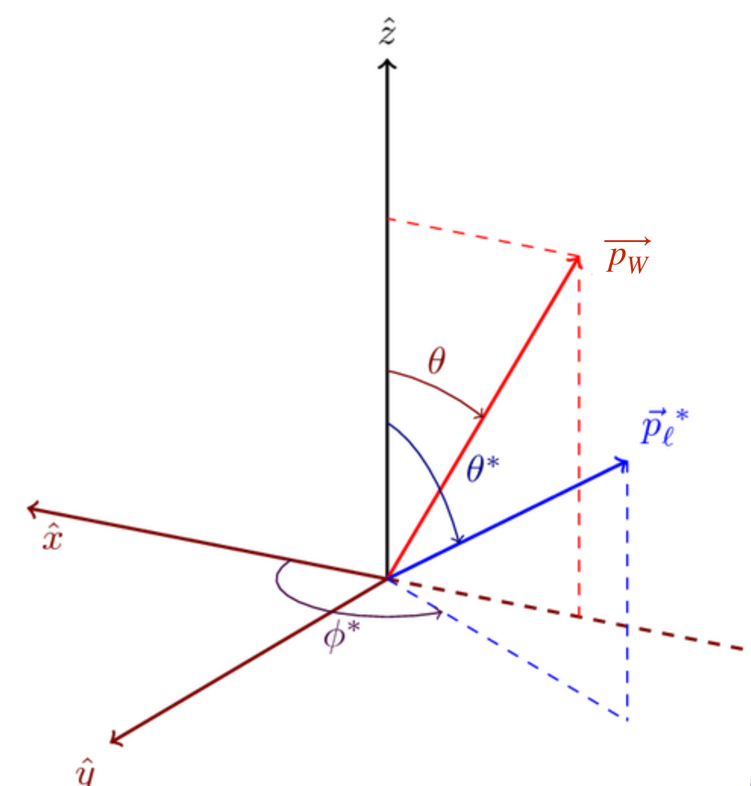
$$\frac{1}{\Gamma}\frac{d\Gamma}{d(\cos\theta_l)} = \frac{1}{2}(1 + \alpha_l P \cos\theta_l)$$



- 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 onto real/simulated data.
- The full expression of the differential decay distribution of $t \to Wb \to l\nu b$ is:

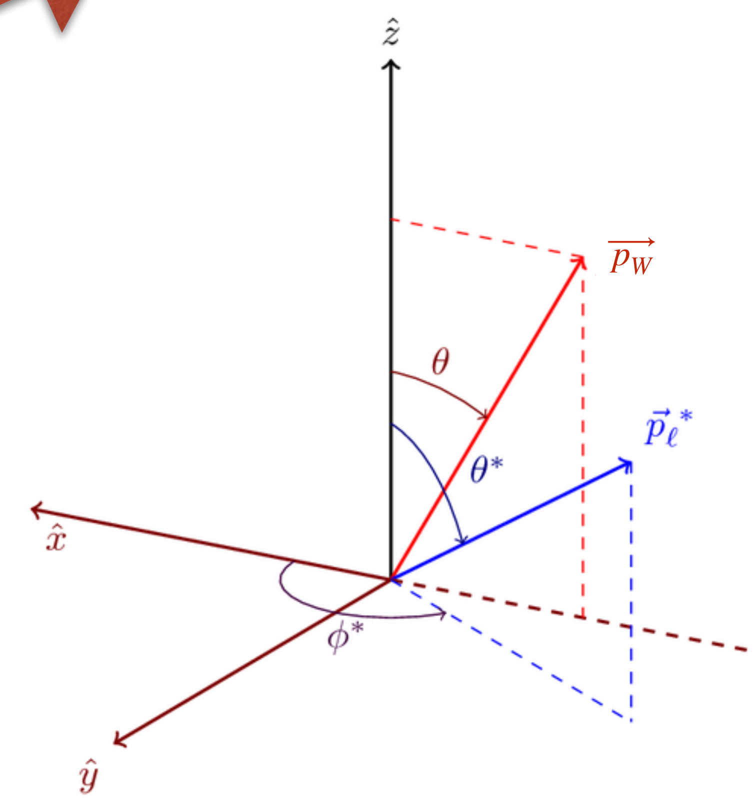
$$
\begin{aligned}
\frac{1}{\Gamma}\frac{d\Gamma}{d\Omega d\Omega^*} = &\frac{3}{64\pi^2}\frac{1}{N}\Big\{\Big[|a_{1\,\frac{1}{2}}|^2(1+\lambda\cos\theta^*)^2 + 2|a_{0\,-\frac{1}{2}}|^2\sin^2\theta^*\Big]\left(1+\vec{P}\cdot\vec{u}_L\right) \\
&+\Big[2|a_{0\,\frac{1}{2}}|^2\sin^2\theta^* + |a_{-1\,-\frac{1}{2}}|^2(1-\lambda\cos\theta^*)^2\Big]\left(1-\vec{P}\cdo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

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:

- $\overrightarrow{u_L} = (\sin\theta\cos\phi, \sin\theta\sin\phi, \cos\theta)$ in the direction of the W boson momentum in the top quark rest frame,
- $\overrightarrow{u_T} = (\cos\theta\cos\phi, \cos\theta\sin\phi, -\sin\theta)$, $\overrightarrow{u_N} = (\sin\phi, -\cos\phi, 0)$ are two orthonormal vectors.
- $\lambda = 1$ for top quarks, $\lambda = -1$ for top antiquarks.

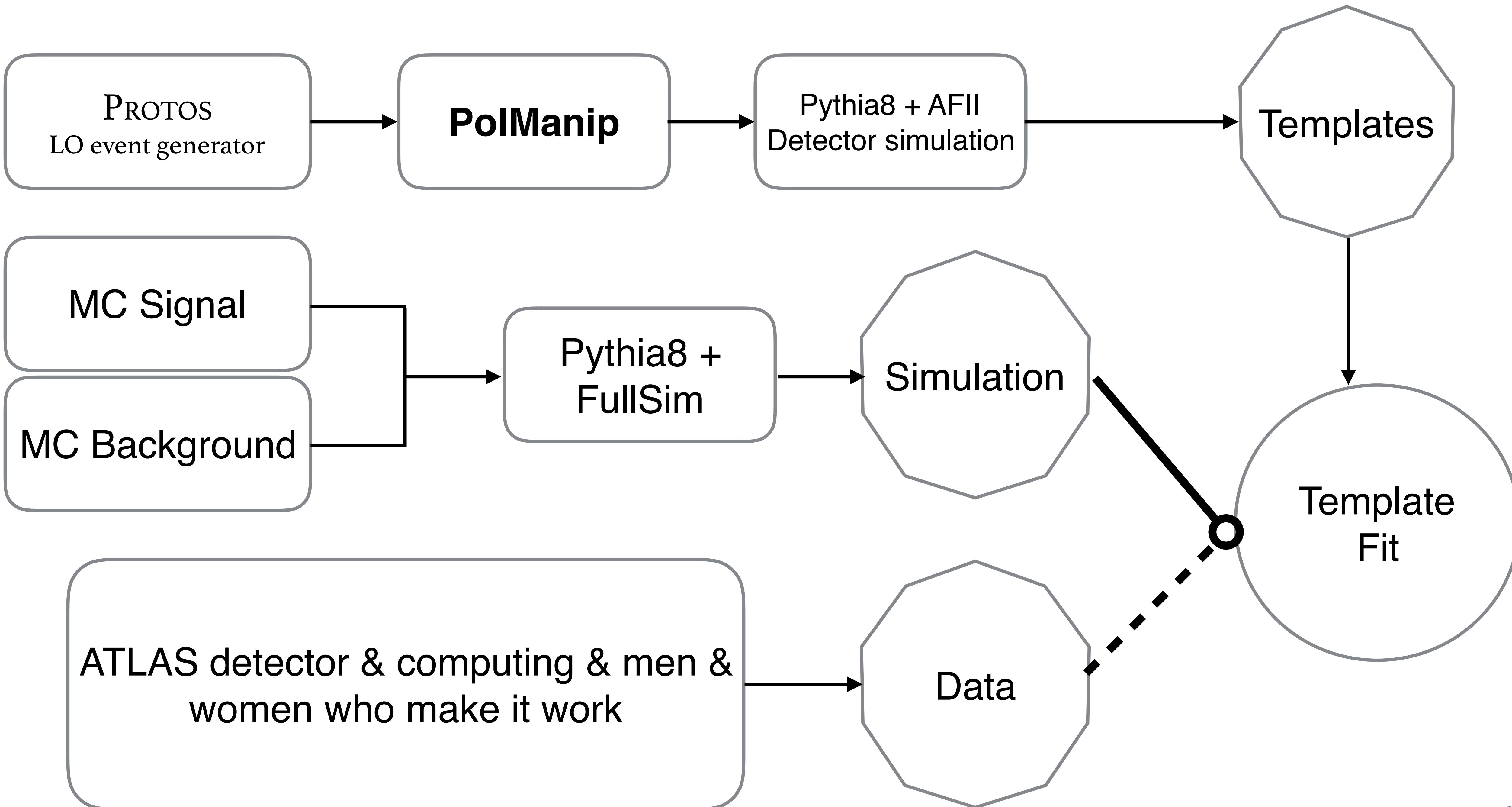
PolManip package!



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.

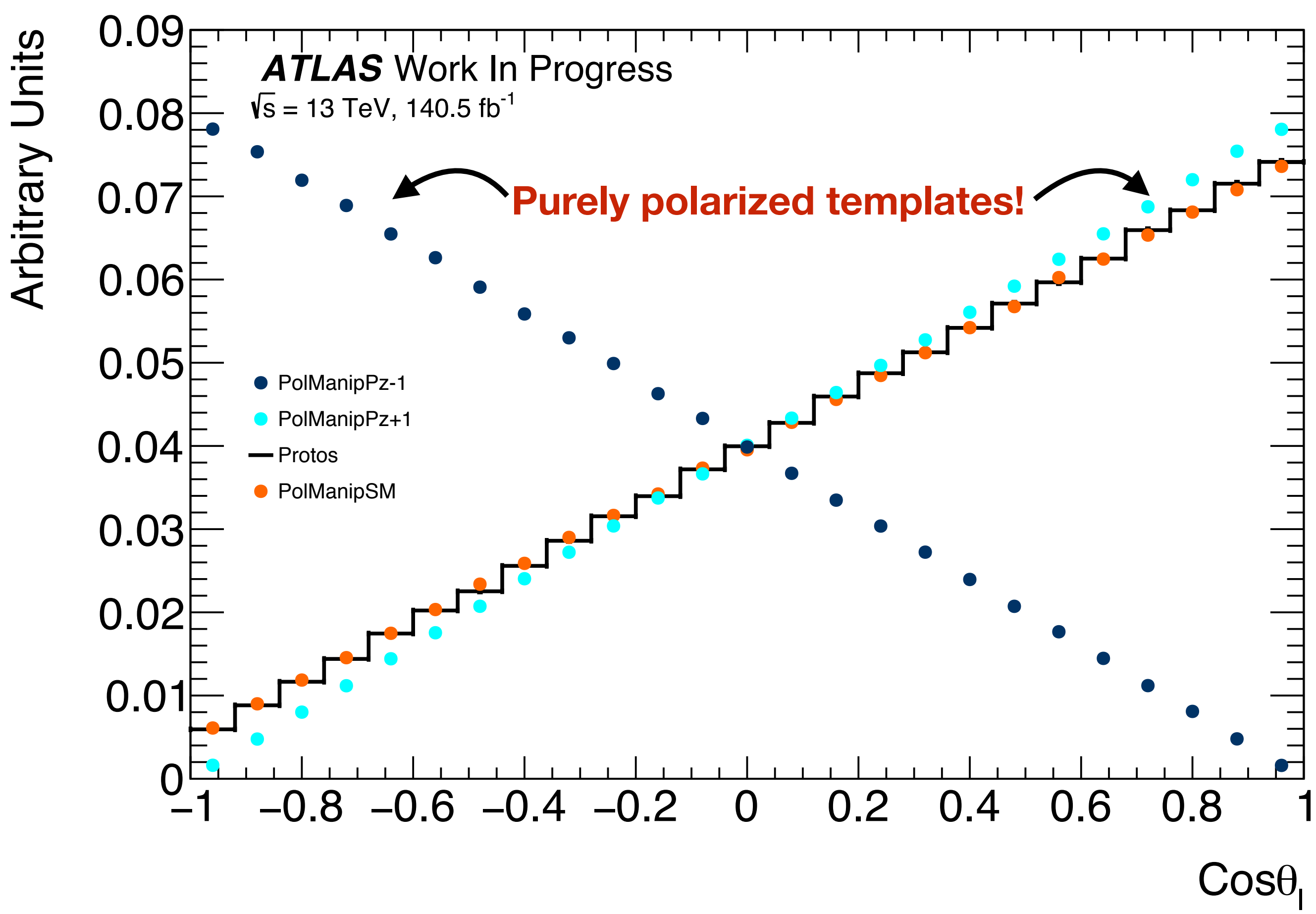
Introduction

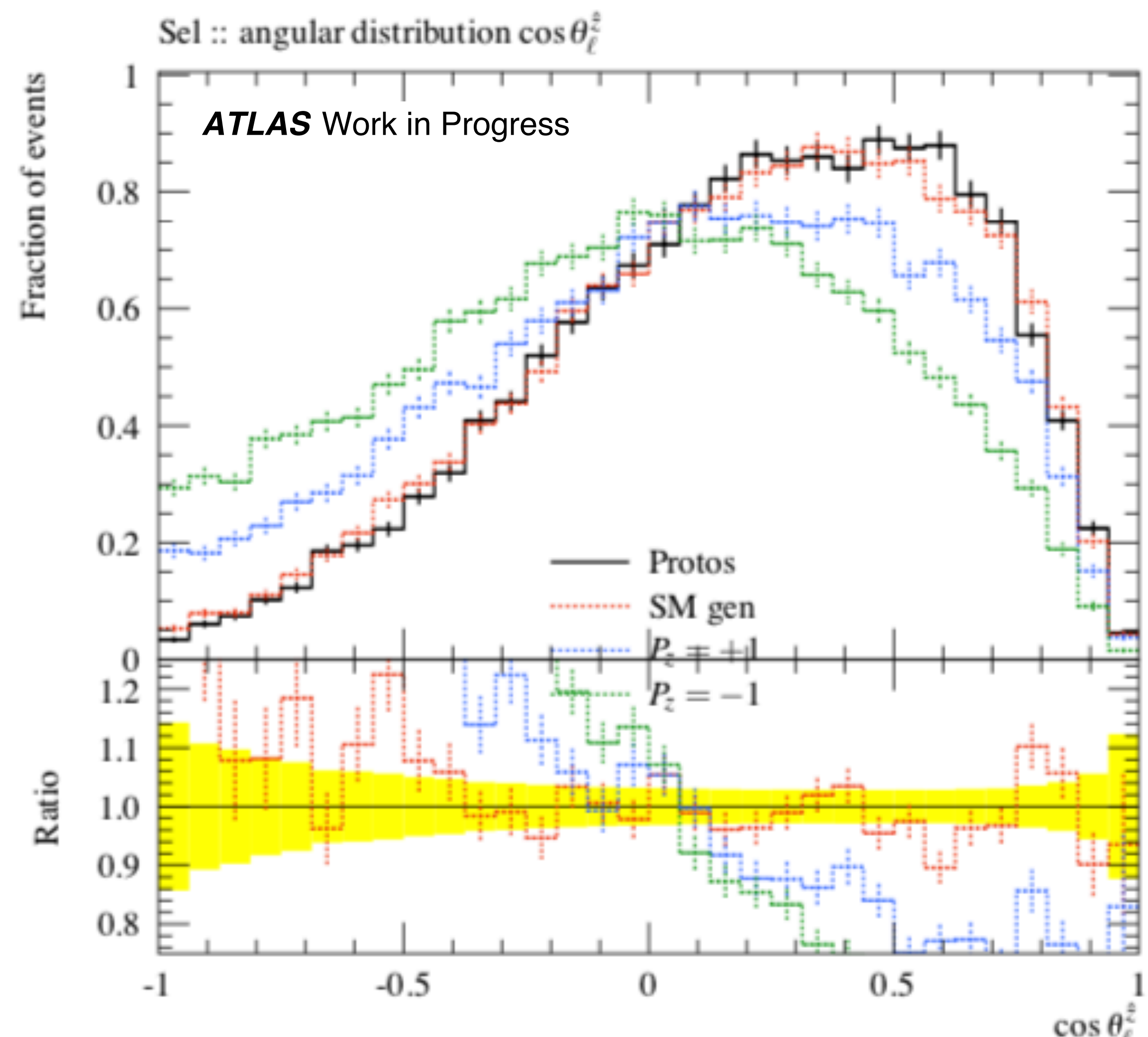
✻Template Fit Strategy



✻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.



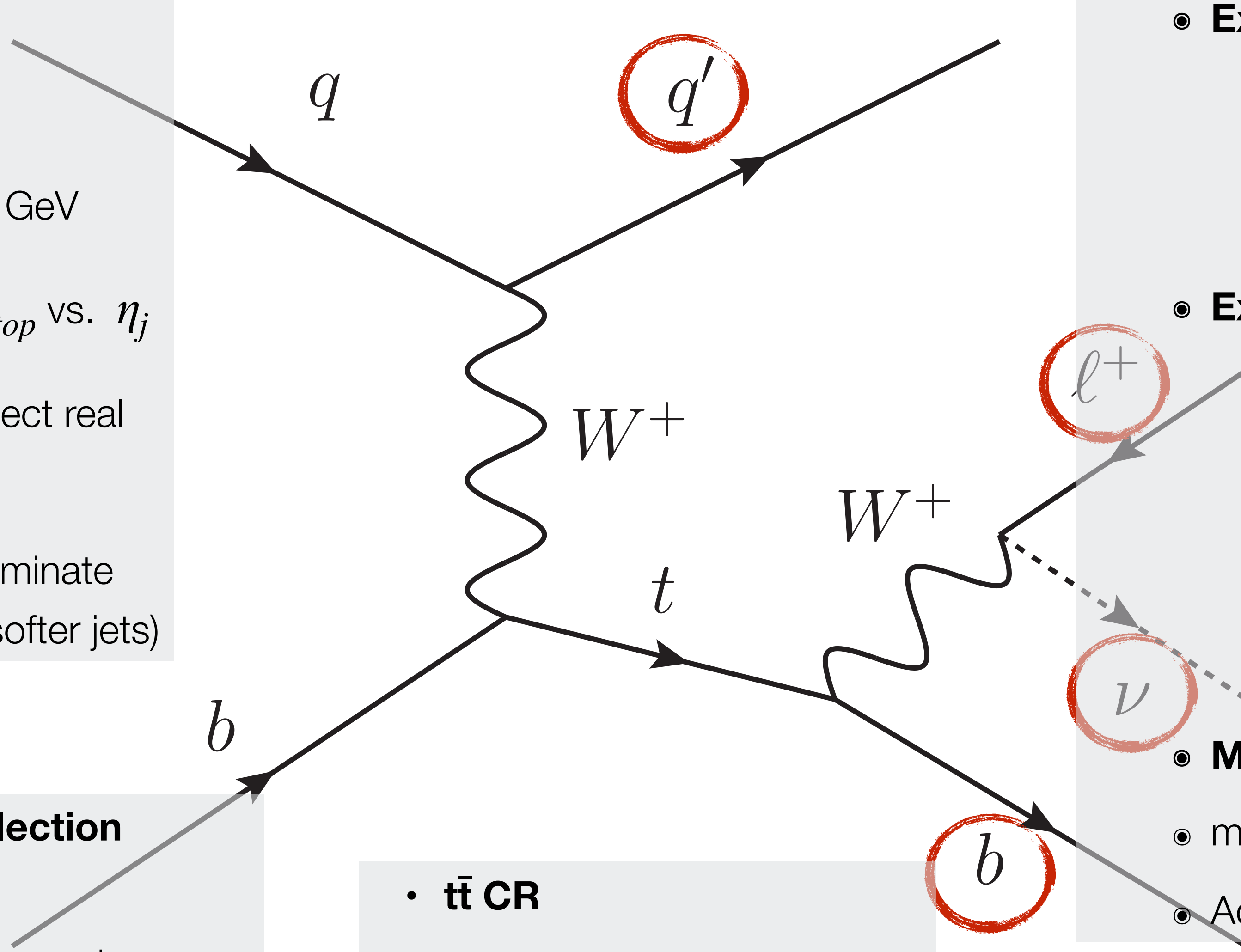


Validation plots: comparisons are made between the original Photos sample (Protos), and the PolManip SM sample (SM gen).

Pitt

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)



- **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")

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

- **tt̄ CR**
  - Passing all SR requirements, but requiring 2 b-tagged jets.

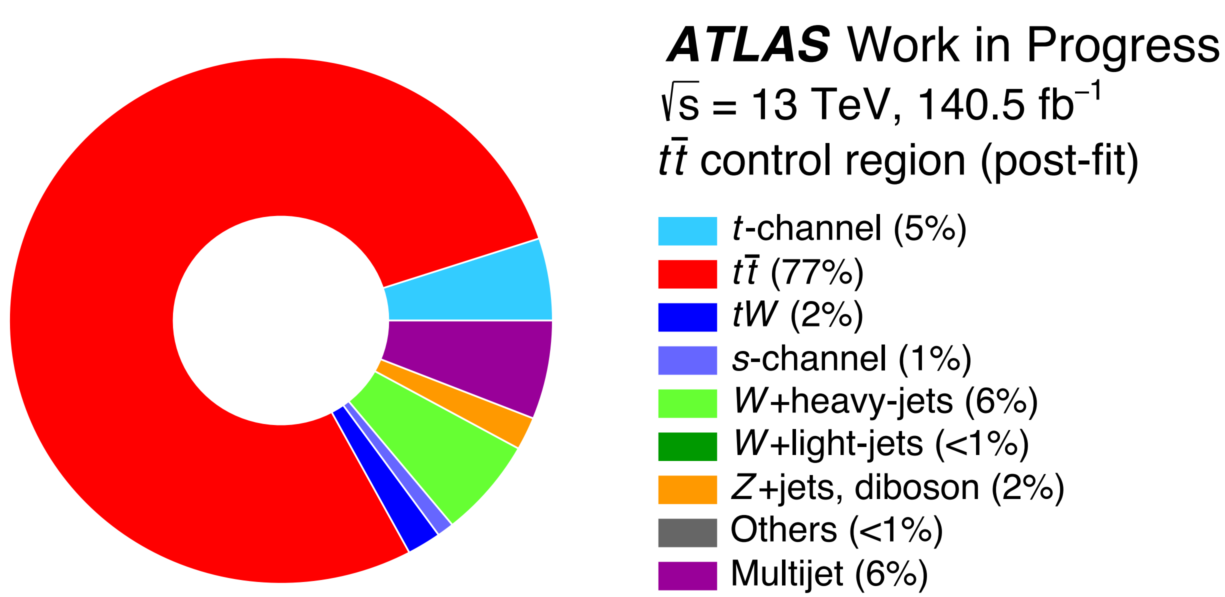
Analysis

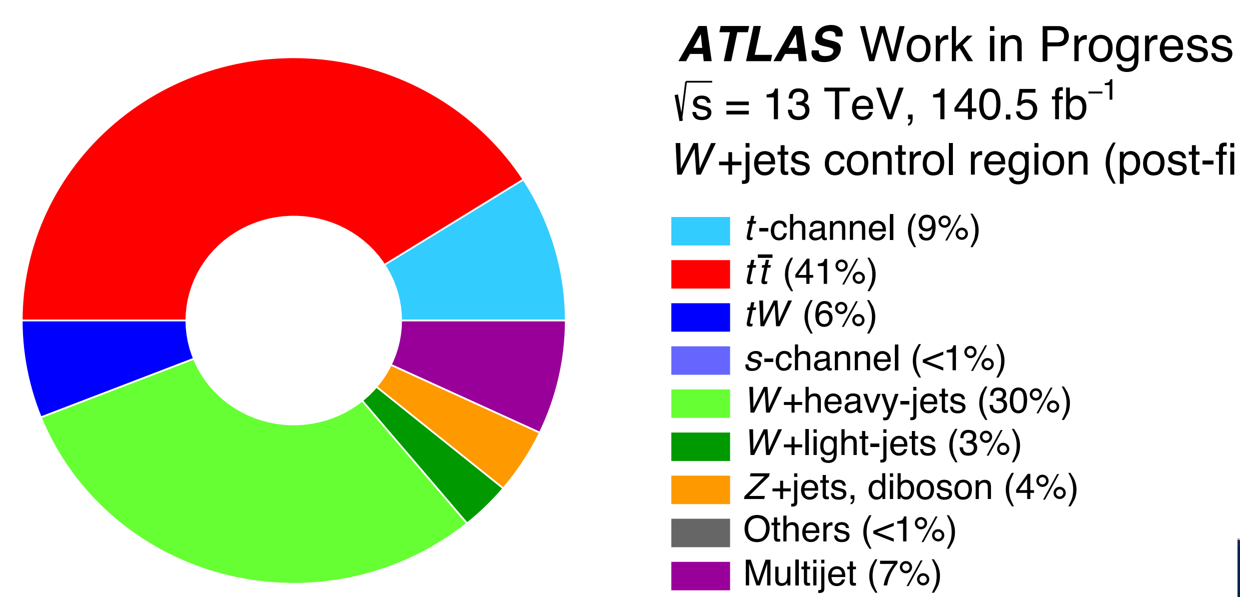
❋Event Selection

- **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

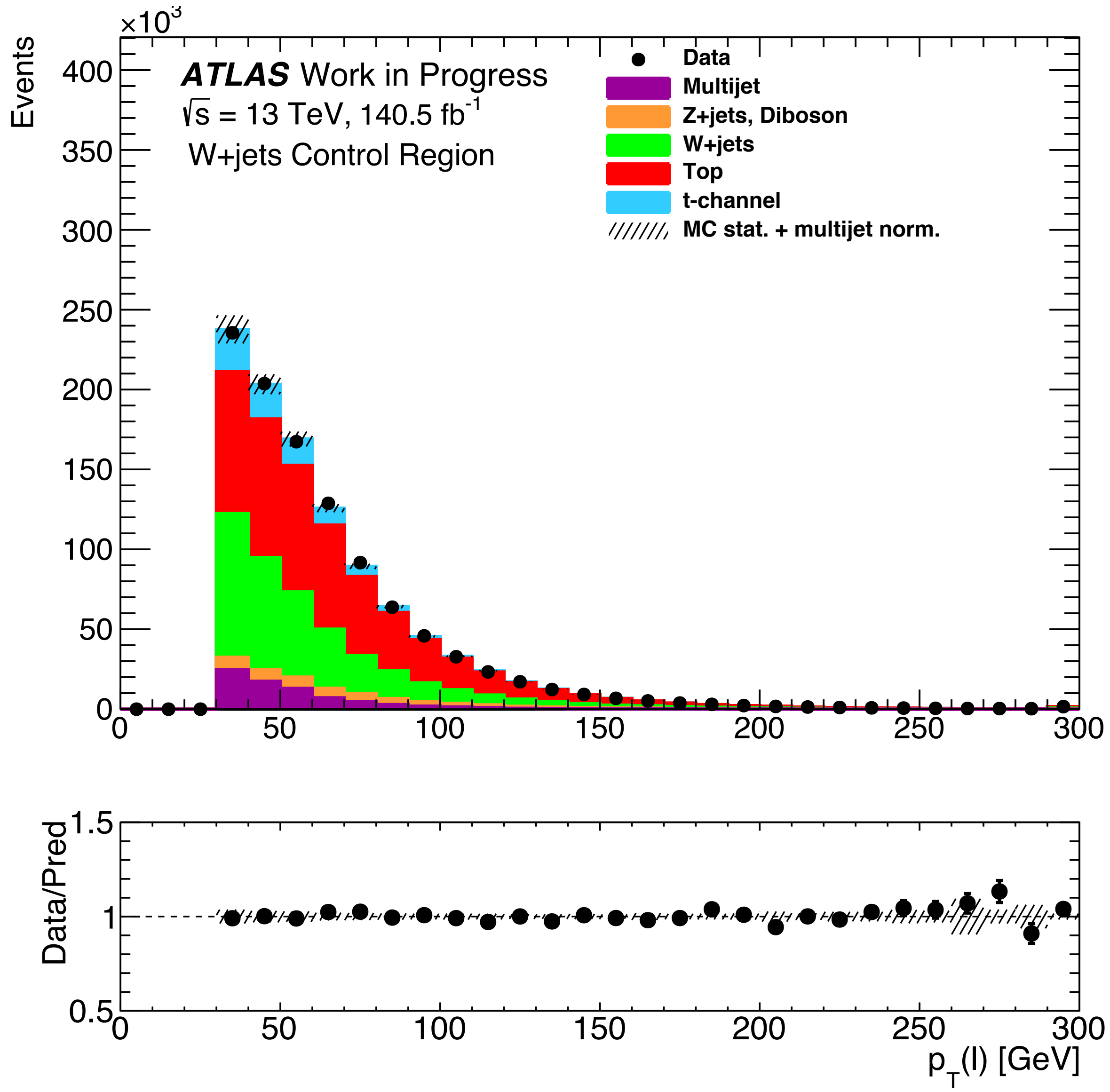
Process	e-channel	μ-channel	e+μ-channels
t-channel	1.06±0.04	1.05±0.06	1.05±0.03
W+jets	0.93±0.03	0.98±0.03	0.954±0.020
$t\bar{t}$,Wt,s-channel	1.008±0.016	0.996±0.017	1.003±0.012

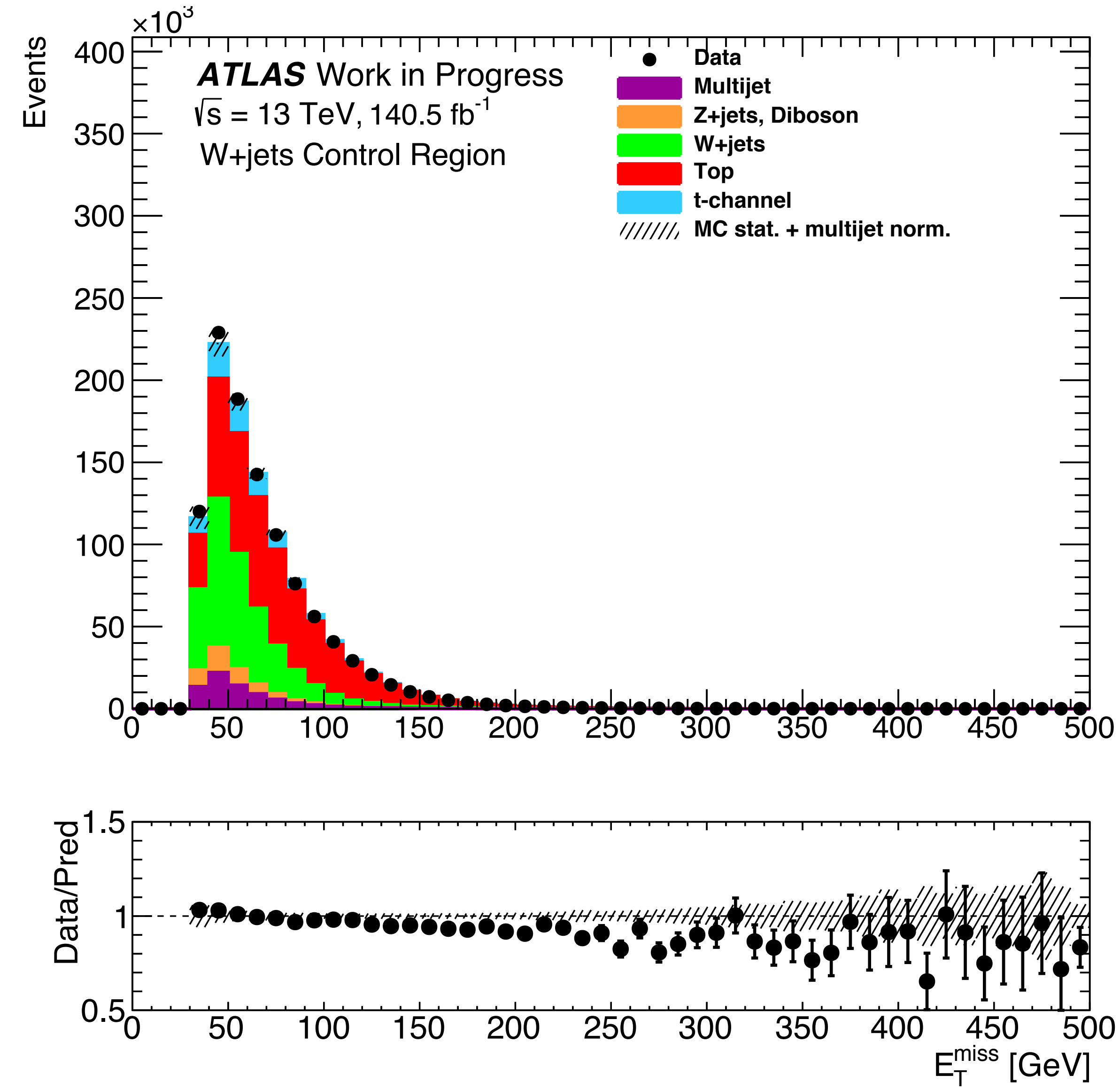




Control Plots: W+Jets CR

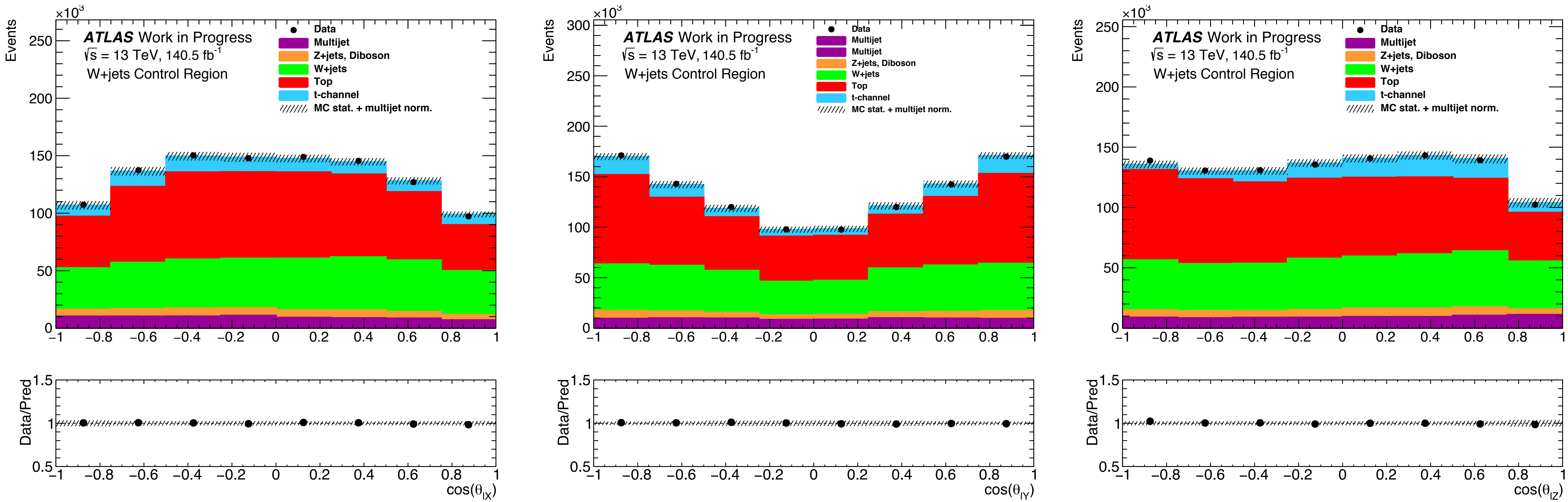
Kinematics





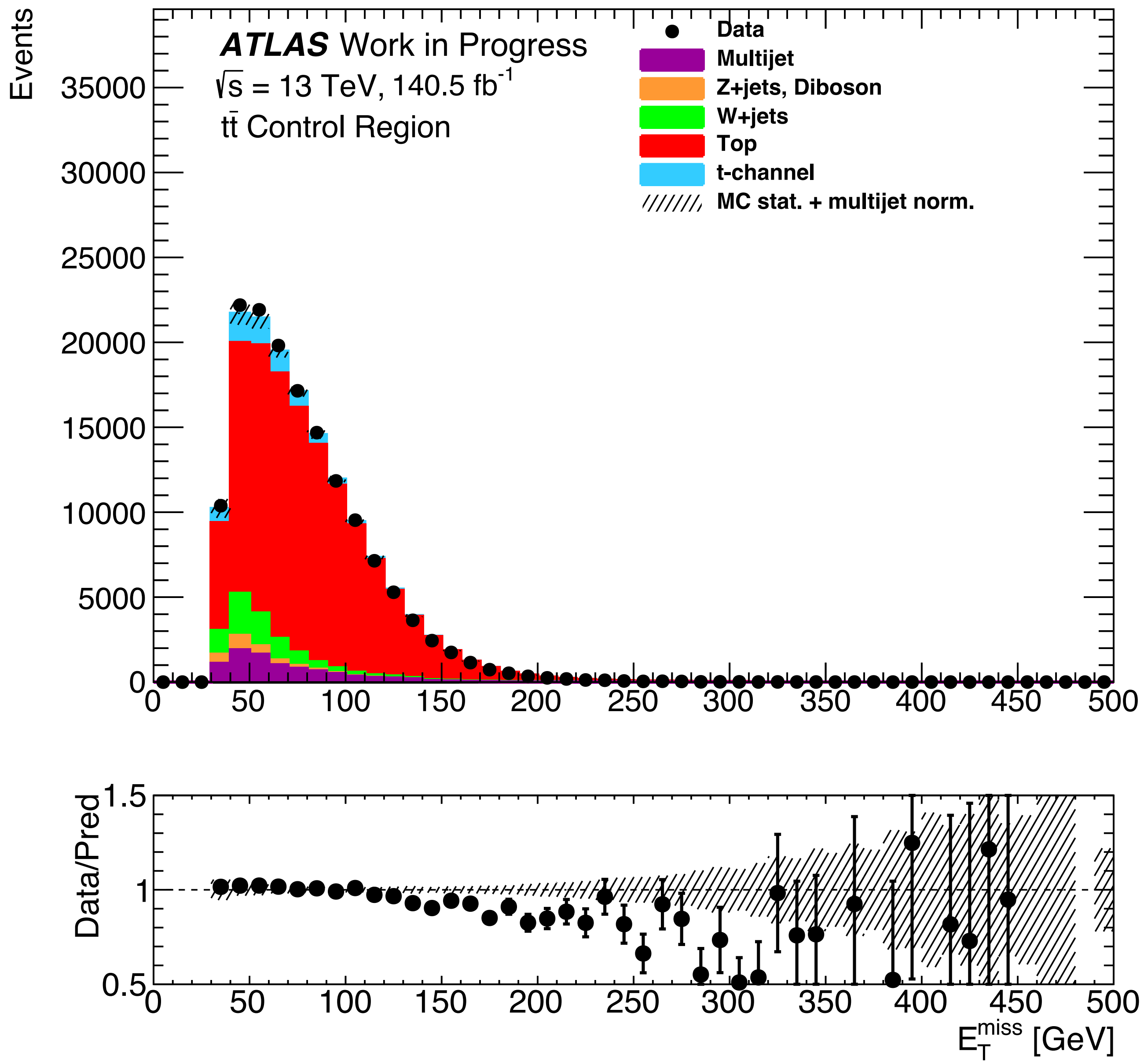
Control Plots: W+Jets CR

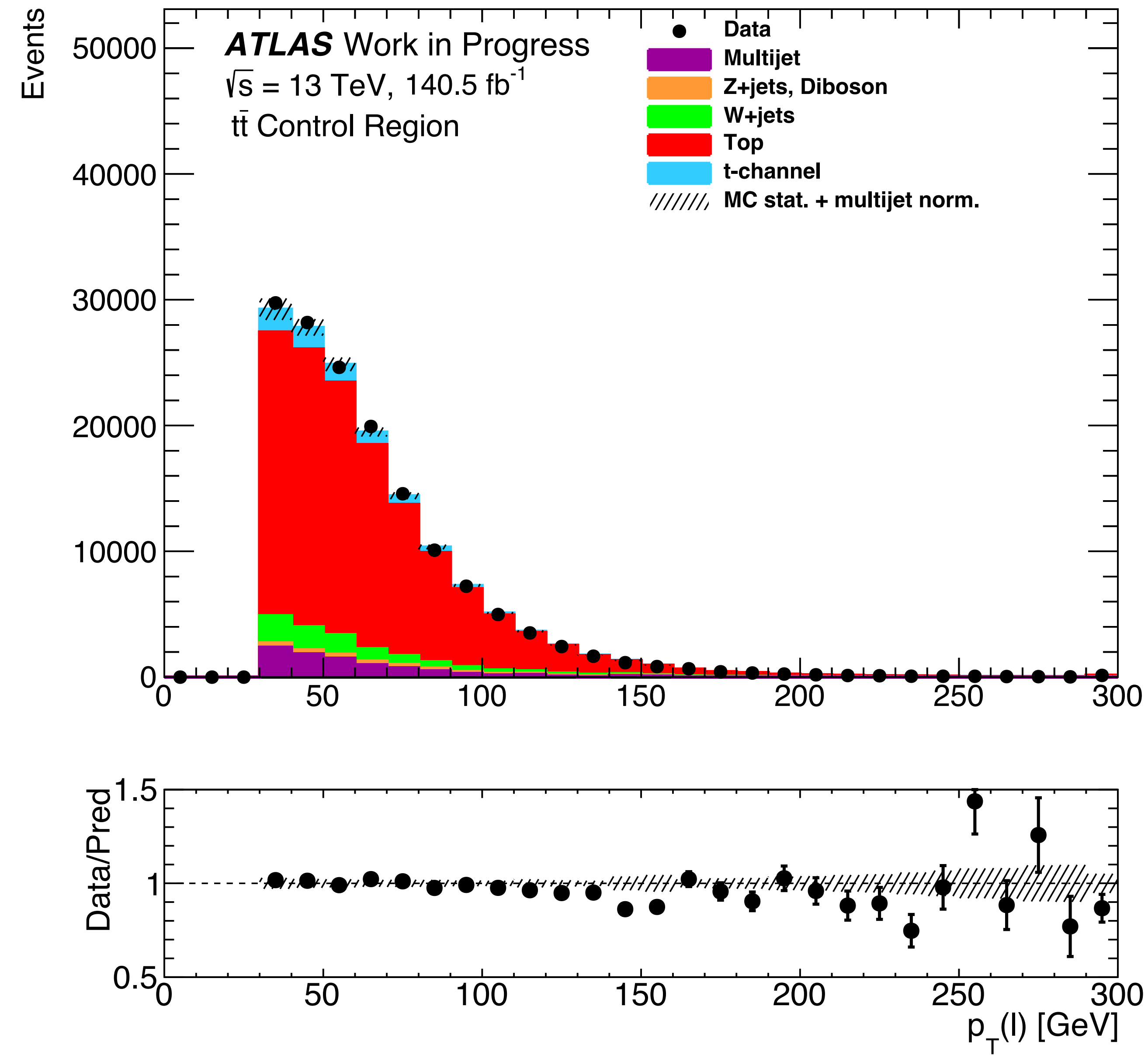
Angular Observables



Control Plots: $t\bar{t}$ CR

Kinematics





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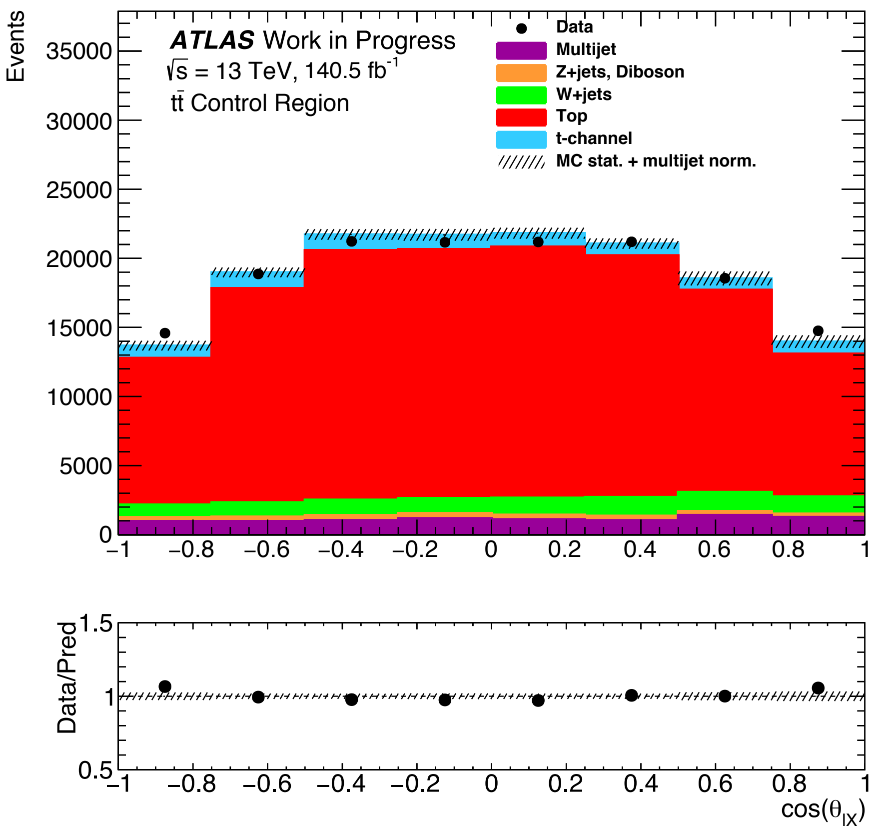
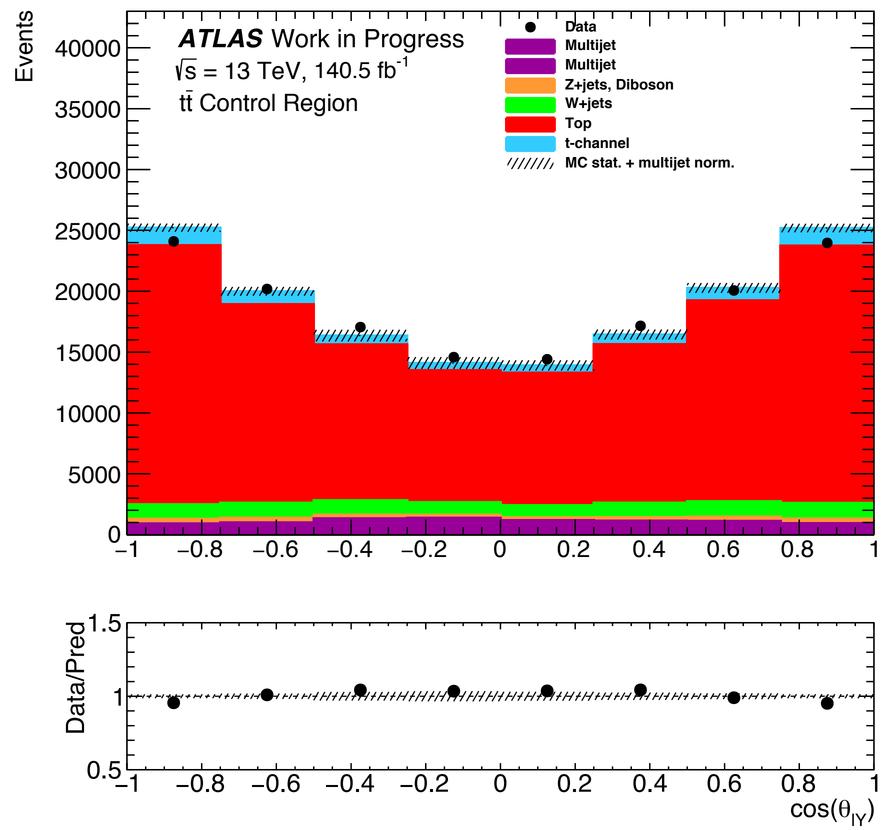
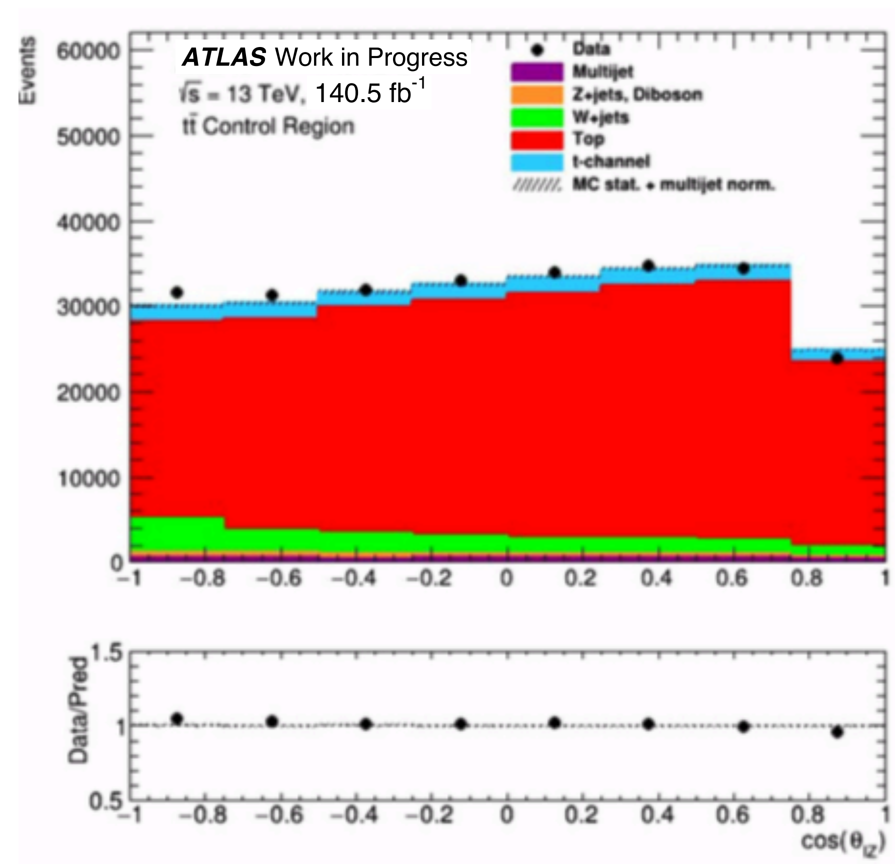


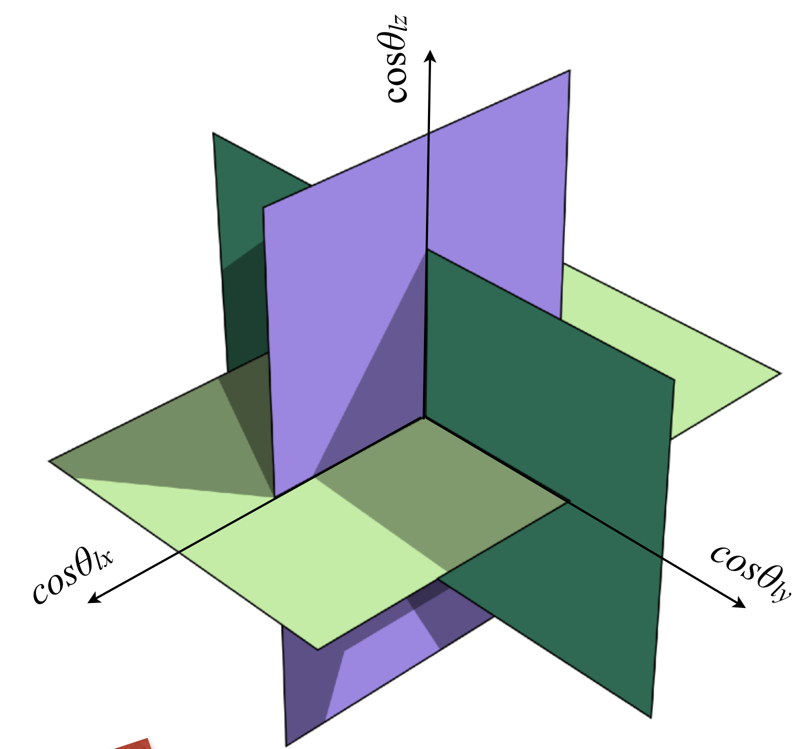


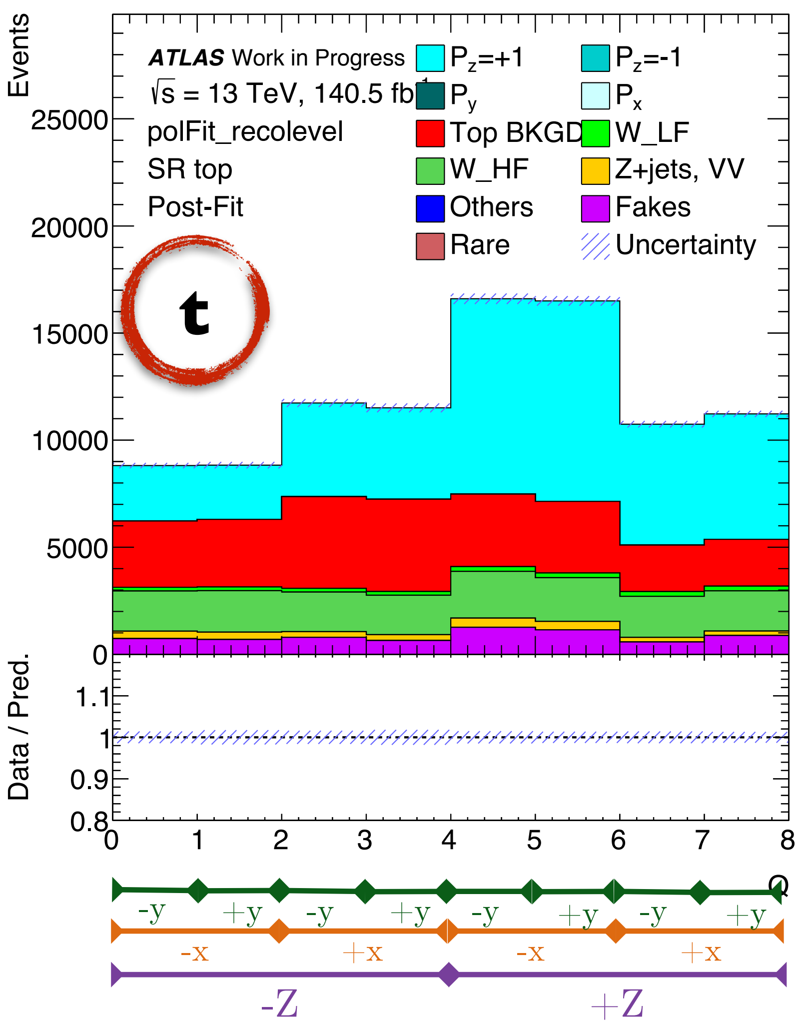


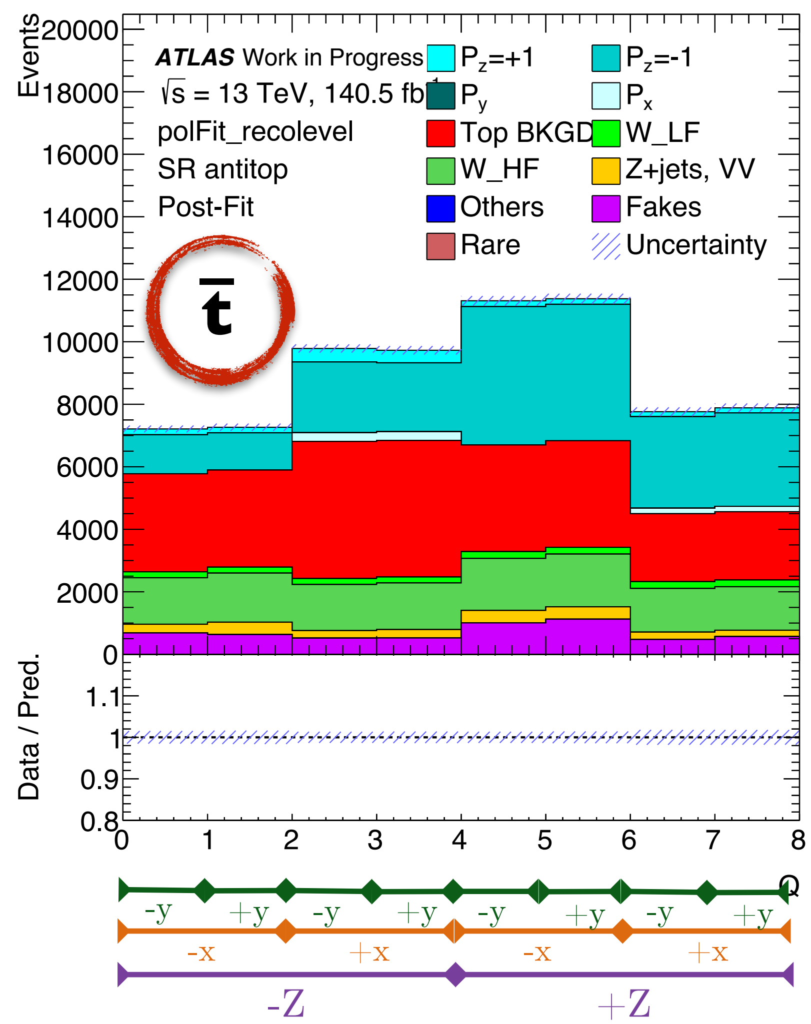
Top Polarization Measurement

❇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: $\overrightarrow{P}^{t} = (0.0,\ 0.0, +0.9)$, $\overrightarrow{P}^{\bar{t}} = (-0.14,\ 0.0, -0.86)$







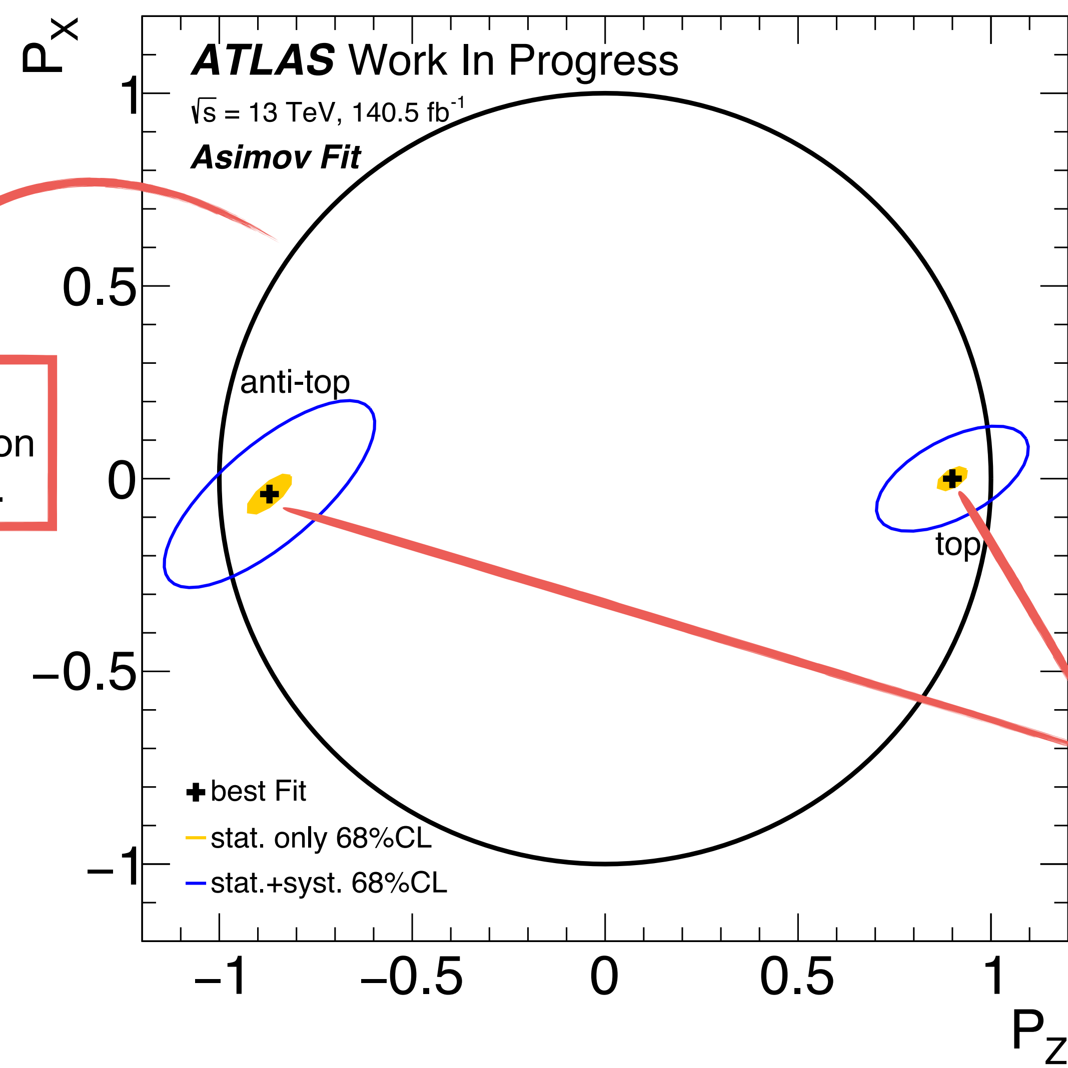
P components	Expected value: stat.+syst. (stat.)
P^t_x	0.00 +0.09 / -0.09 (± 0.02)
P^t_y	0.00 +0.03 / -0.03 (± 0.01)
P^t_z	0.90 +0.13 / -0.13 (± 0.02)
$P^{\bar{t}}_x$	-0.14 +0.16 / -0.16 (± 0.03)
$P^{\bar{t}}_y$	0.00 +0.04 / -0.04 (± 0.02)
$P^{\bar{t}}_z$	-0.86 +0.18 / -0.17 (± 0.04)

Top Polarization Measurement

❇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^t_x	0.00 +0.09 / -0.09 (± 0.02)
P^t_y	0.00 +0.03 / -0.03 (± 0.01)
P^t_z	0.90 +0.13 / -0.13 (± 0.02)
$P^{\bar{t}}_x$	-0.14 +0.16 / -0.16 (± 0.03)
$P^{\bar{t}}_y$	0.00 +0.04 / -0.04 (± 0.02)
$P^{\bar{t}}_z$	-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

Summary

- 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