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

Runyu Bi

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Introduction

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.

```
\[ q \rightarrow q' \]
\[ W^+ \rightarrow t + b \]
\[ \ell^+ + \nu \]
```

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

```
\[ u \rightarrow W^+ + d \]
\[ \bar{d} \rightarrow W^- + \bar{u} \]
```

**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:**

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

**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: $A_\mu = 0.44$

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.

\[ P_Z = 0.98 \pm 0.10 \]

\[ P_Z > 0.86 \text{ (68\% CL)} \]

\[ P_Z > 0.72 \text{ (95\% CL)} \]
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- In 2017, ATLAS published two polarization measurements at 8TeV. Although different approaches, both analyses demonstrated good consistencies with the SM predictions, where a highly polarized top ensemble is shown.

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

★ 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.
**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.
Introduction

*Template Fit Strategy*

- **Construct templates** in the variable $\cos \theta_I$ 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 $t \to Wb \to lvb$ is:

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

where the $a_{\lambda_W,\lambda_b}$, the coefficients are the transition amplitudes for $t \to Wb$, and $\lambda$’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!
**Template Fit Strategy**

1. **PROTOS** (LO event generator) → **PolManip** → **Pythia8 + AFII (Detector simulation)** → **Templates**
2. **MC Signal** → **Pythia8 + FullSim** → **Simulation** → **Template Fit**
3. **MC Background** → **Pythia8 + FullSim** → **Simulation** → **Template Fit**
4. **ATLAS detector & computing & men & women who make it work** → **Data**
**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.

**Introduction**

**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
- $m_{t,b} < 153$ GeV
- $34$ GeV < $m_{top}$ < 206 GeV
- Trapezoidal Cut on $\eta_{top}$ vs. $\eta_j$
- $m_{j,\text{top}} > 280$ 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.

**Preselection Region (PR):**
- Exactly one tight charged lepton
  - $p_T > 30$ GeV, $|\eta| < 2.5$
  - Vetoing if existing a secondary high-$p_T$ ($p_T > 30$ GeV) charged loose leptons.
- Exactly 2 jets. Exactly 1 b-tagged.
  - $p_T > 30$ GeV ($p_T > 35$ GeV in transition region $2.75 \leq |\eta| < 3.5$ to avoid mis-modeling between the central and forward calorimeters.)
  - Spectator jet ($|\eta| < 4.5$), b-jet (60 %WP (bin selection) within $|\eta| < 2.5$)
- MET > 35 GeV.
  - $m_T(\text{lepton-MET})$ [or MtW] > 60 GeV.
  - Additional multijet rejection (“triangular cut”)

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

<table>
<thead>
<tr>
<th>Process</th>
<th>e-channel</th>
<th>(\mu)-channel</th>
<th>(e+\mu)-channels</th>
</tr>
</thead>
<tbody>
<tr>
<td>(t)-channel</td>
<td>1.06±0.04</td>
<td>1.05±0.06</td>
<td>1.05±0.03</td>
</tr>
<tr>
<td>(W+)jets</td>
<td>0.93±0.03</td>
<td>0.98±0.03</td>
<td>0.954±0.020</td>
</tr>
<tr>
<td>(t\bar{t},Wt,s)-channel</td>
<td>1.008±0.016</td>
<td>0.996±0.017</td>
<td>1.003±0.012</td>
</tr>
</tbody>
</table>

**Scale factors**

**ATLAS Work in Progress**
\(\sqrt{s} = 13\text{ TeV},\ 140.5\text{ fb}^{-1}\)
\(t\bar{t}\) control region (post-fit)

**ATLAS Work in Progress**
\(\sqrt{s} = 13\text{ TeV},\ 140.5\text{ fb}^{-1}\)
\(W+\)jets control region (post-fit)
Control Plots: W+Jets CR

Kinematics

ATLAS Work in Progress
\( \sqrt{s} = 13 \text{ TeV}, 140.5 \text{ fb}^{-1} \)
W+jets Control Region

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\( \sqrt{s} = 13 \text{ TeV}, 140.5 \text{ fb}^{-1} \)
W+jets Control Region

Data
Multijet
Z+jets, Diboson
W+jets
Top
t-channel

MC stat. + multijet norm.

Events
0 50 100 150 200 250 300

Events
0 50 100 150 200 250 300

Data/Pred
0.5 1 1.5

Data/Pred
0.5 1 1.5

\( p_T(l) \) [GeV]

\( E_T^{miss} \) [GeV]

140.5 fb

Work in Progress

ATLAS

W+jets Control Region

Data
Multijet
Z+jets, Diboson
W+jets
Top
t-channel

MC stat. + multijet norm.
Angular Observables

ATLAS Work in Progress
\( \sqrt{s} = 13 \text{ TeV}, 140.5 \text{ fb}^{-1} \)
W+jets Control Region

Data
- Multijet
- Z+jets, Diboson
- W+jets
- Top
- t-channel

MC stat. + multijet norm.

0 \times 10^7

Events

0

ATLAS Work in Progress
\( \sqrt{s} = 13 \text{ TeV}, 140.5 \text{ fb}^{-1} \)
W+jets Control Region

Data
- Multijet
- Z+jets, Diboson
- W+jets
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MC stat. + multijet norm.

0

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\( \sqrt{s} = 13 \text{ TeV}, 140.5 \text{ fb}^{-1} \)
W+jets Control Region

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

Kinematics

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$tt$ Control Region
Angular Observables

ATLAS Work in Progress
\( \sqrt{s} = 13 \) TeV, 140.5 fb\(^{-1} \)
\( \bar{t}t \) Control Region

Events

0
5000
10000
15000
20000
25000
30000
35000
40000

0
0.2
0.4
0.6
0.8
1

Data/Pred

\( \cos(\theta_W) \)

\( l_X \theta \cos(\theta_W) \)

\( l_Y \theta \cos(\theta_W) \)

ATLAS Work in Progress
\( \sqrt{s} = 13 \) TeV, 140.5 fb\(^{-1} \)
\( \bar{t}t \) Control Region
**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: $\vec{P}^t = (0.0, 0.0, +0.9), \vec{P}^\bar{t} = (-0.14, 0.0, -0.86)$

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**Top Polarization Measurement**

<table>
<thead>
<tr>
<th>$P$ components</th>
<th>Expected value: stat.+syst. (stat.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_t^x$</td>
<td>0.00 +0.09 / -0.09 (± 0.02)</td>
</tr>
<tr>
<td>$p_t^y$</td>
<td>0.00 +0.03 / -0.03 (± 0.01)</td>
</tr>
<tr>
<td>$p_t^z$</td>
<td>0.90 +0.13 / -0.13 (± 0.02)</td>
</tr>
<tr>
<td>$\bar{p}_t^x$</td>
<td>-0.14 +0.16 / -0.16 (± 0.03)</td>
</tr>
<tr>
<td>$\bar{p}_t^y$</td>
<td>0.00 +0.04 / -0.04 (± 0.02)</td>
</tr>
<tr>
<td>$\bar{p}_t^z$</td>
<td>-0.86 +0.18 / -0.17 (± 0.04)</td>
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**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.

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

Retrieved the polarization of the Asimov dataset.
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