Spin Correlation and W Helicity in Top Events with ATLAS

Markus Jüngst
on behalf of the ATLAS collaboration

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Motivation

- Sensitive test of perturbative QCD and the SM prediction of top-quark decays
  - understanding of important background for many BSM and SM Higgs searches
  - as decays before hadronisation (lifetime $5 \cdot 10^{-25}$ s) it gives access to a bare quark
- Top quark events are produced (mostly gg-fusion) in abundance at the LHC
  - allows precision measurements of several SM quantities
  - can also be used for calibration (e.g. b-tagging)
- Some of the most basic quantities of the elementary particles are their mass (lifetime), charge and spin and also their couplings
Polarisation Power

- Spin information can be accessed via the angular momentum of the top quark decay products

\[ \frac{1}{N} \frac{dN}{d \cos(\theta_i)} = \frac{1}{2} \left[ 1 + \alpha_i \cos(\theta_i) \right] \]

- Amount of spin information a daughter particle carries from the parent top is encoded in \( \alpha_i \)

<table>
<thead>
<tr>
<th></th>
<th>b-quark</th>
<th>( W^+ )</th>
<th>( l^+ )</th>
<th>d/s quark</th>
<th>u/c quark</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \alpha(\text{LO}) )</td>
<td>-0.41</td>
<td>0.41</td>
<td>1</td>
<td>1</td>
<td>-0.31</td>
</tr>
<tr>
<td>( \alpha(\text{NLO}) )</td>
<td>-0.39</td>
<td>0.39</td>
<td>0.998</td>
<td>0.93</td>
<td>-0.31</td>
</tr>
</tbody>
</table>

- Largest fractions are carried by leptons and down-type quarks
  - dilepton channel: simple to tag leptons, but event reconstruction required to define spin basis
  - lepton+jets channel: event reconstruction less challenging but critical to tag the down-type quark with high efficiency
Spin Correlation

- Short lifetime → can access spin via decay particles
- Strength of the correlation may differ for BSM models (e.g. \( H^+ \) contribution)
- For spin-1/2 top particles two states possible → \( ^1S_0 \) and \( ^3S_1 \)

\[
\begin{align*}
^1S_0 & \quad \text{beam axis as spin quantisation axis} \\
^3S_1 & \quad \text{tt pairs close to the threshold}
\end{align*}
\]

\[
\text{dominated by } qq \text{ annihilation}
\]


- In gg-fusion at threshold top pair produced in \( ^1S_0 \) state (\( tLtL \) and \( tRtR \))
  - at high energies dominant production is \( ^3S_1 \) state (\( tLtR \) and \( tRtL \))
- In qq-annihilation produced in \( ^3S_1 \) state
- Asymmetry parameter, \( A \), describing difference between like and unlike spin configuration depends on quantization axis

\[
A = \frac{N_{\text{like}} - N_{\text{unlike}}}{N_{\text{like}} + N_{\text{unlike}}} = \frac{N(\uparrow\uparrow) + N(\downarrow\downarrow) - N(\uparrow\downarrow) - N(\downarrow\uparrow)}{N(\uparrow\uparrow) + N(\downarrow\downarrow) + N(\uparrow\downarrow) + N(\downarrow\uparrow)}
\]

- At the LHC no axis for 100% correlation
  - for helicity basis \( A \) is predicted to be \( A_{\text{hel}} \approx 0.326 \)
  - complementary to Tevatron measurement

\[
\frac{1}{\sigma} \frac{d^2\sigma}{d\cos\theta_1 d\cos\theta_2} = \frac{1}{4} \left( 1 - C \cos\theta_1 \cos\theta_2 \right)
\]

where \( C = A \alpha_1 \alpha_2 \)

Markus Jüngst
### Template Fit

- In dilepton channel almost 100% of correlation carried by the two leptons
- Opening angle between leptons carry information about spin correlation
  

- Template fit separately performed for the three dilepton channels and in a combined fit

\[
f_{\text{SM}} = \frac{N_{\text{SM}}}{N_{\text{SM}} + N_{\text{UC}}} \]

\[
A_{\text{SM}} = A_{\text{SM, theo}} \times f_{\text{SM}}
\]

- Combined result gives correction factor of \( f = 1.30 \) to the input SM correlation

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**Graphs:**
- **ee channel**
- **\( \mu\mu \) channel**
- **\( e\mu \) channel**
The data are **inconsistent with zero** (or negative) spin correlation with a significance of **5 standard deviations** → first observation of spin correlation!
Helicity

- Top quarks decay as left-handed fermions through the V-A weak interaction
- Helicity of W boson in the decay is constraint to 0, +1, -1 (massive particles have 2S+1 states)

- Angular momentum conservation → only left handed and longitudinal W helicity configuration allowed

\[ F_L = \frac{\Gamma(t \rightarrow W_{(h=-1)}b)}{\Gamma(t \rightarrow Wb)} \quad \text{(Negative helicity)} \quad \sim 30\% \]
\[ F_0 = \frac{\Gamma(t \rightarrow W_{(h=0)}b)}{\Gamma(t \rightarrow Wb)} \quad \text{(Zero helicity)} \quad \sim 70\% \]
\[ F_R = \frac{\Gamma(t \rightarrow W_{(h=+1)}b)}{\Gamma(t \rightarrow Wb)} \quad \text{(Positive helicity)} \quad \sim 0\% \]

- Sensitivity to anomalous (non-SM) couplings

W-Helicity Templates

- The Wtb vertex is defined by the electroweak interaction and has V-A structure
- W bosons are produced as real particles → polarisation can be longitudinal-, left- and right-handed

\[
\frac{1}{\Gamma} \frac{d\Gamma}{d \cos \theta^*} = \frac{3}{8}(1 + \cos \theta^*)^2 F_R + \frac{3}{8}(1 - \cos \theta^*)^2 F_L + \frac{3}{4} \sin^2 \theta^* F_0
\]

\[\Gamma \equiv \Gamma(t \rightarrow W^+ b) = \Gamma_R + \Gamma_L + \Gamma_0\]

- angle between lepton and negative top quark direction

- Two different methods used:
  1. template fit using distributions for different signal and background contributions
  2. counting events after bkg subtraction above and below \(z = \pm (1-2^{2/3})\) in unfolded distribution

\[
A_z = \frac{N(\cos \theta^* > z) - N(\cos \theta^* < z)}{N(\cos \theta^* > z) + N(\cos \theta^* < z)}
\]
Helicity - Combined Results

• Results of four measurements combined using BLUE method:

<table>
<thead>
<tr>
<th>Combined Result</th>
<th>NNLO</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F_0$</td>
<td>0.67±0.03 (stat+syst)</td>
</tr>
<tr>
<td>$F_L$</td>
<td>0.32±0.02 (stat+syst)</td>
</tr>
<tr>
<td>$F_R$</td>
<td>-0.01±0.01 (stat+syst)</td>
</tr>
</tbody>
</table>

• Main systematics from lepton ID, JES and from method-specific uncertainties

No significant deviations from NNLO QCD predictions observed supporting the model of a pure V-A structure of the Wtb vertex → Most precise measurement of hel. fractions!
Effective Lagrangian

- New physics can be parametrized in terms of an effective Lagrangian (above the electroweak symmetry breaking scale of $v=246$ GeV)

\[
L_{Wtb} = -\frac{g}{\sqrt{2}} \bar{b} \gamma^\mu (V_L P_L + V_R P_R) t W_\mu^- - \frac{g}{\sqrt{2}} \bar{b} \frac{i\sigma^{\mu\nu} q_\nu}{M_W} (q_L P_L + q_R P_R) t W_\mu^- + \text{h.c.},
\]

where

\[
V_L = V_{tb} + C_{\phi q}^{(3,3+3)} \frac{v^2}{\Lambda^2}, \quad V_R = \frac{1}{2} C_{\phi q}^{33*} \frac{v^2}{\Lambda^2}, \quad g_L = \sqrt{2} C_{dW}^{33*} \frac{v^2}{\Lambda^2}, \quad g_R = \sqrt{2} C_{uW}^{33} \frac{v^2}{\Lambda^2}.
\]

- couplings $V_R$, $g_L$ and $G_R$ absent in the SM at tree-level

- Measured limits at 95 % CL are:

\[
\begin{align*}
\text{Re}(V_R) &\in [-0.20, 0.23] \rightarrow \text{Re}\left(C_{\phi q}^{33}\right) \frac{1}{\Lambda^2} \in [-6.7, 7.8] \text{ TeV}^{-2} \\
\text{Re}(g_L) &\in [-0.14, 0.11] \rightarrow \text{Re}\left(C_{dW}^{33}\right) \frac{1}{\Lambda^2} \in [-1.6, 1.2] \text{ TeV}^{-2} \\
\text{Re}(g_R) &\in [-0.08, 0.04] \rightarrow \text{Re}\left(C_{uW}^{33}\right) \frac{1}{\Lambda^2} \in [-1.0, 0.5] \text{ TeV}^{-2} \\
\end{align*}
\]

\[
\frac{\text{Re}\left(C_{uW}^{33}\right)}{\Lambda^2} \in [-0.9, 2.3] \text{ TeV}^{-2} \quad (F_L=0)
\]
Summary

• Top physics (at the LHC) provides the possibility to test the SM in various ways

• Two analysis from top properties presented:
  1. “Observation of spin correlation in tt events from pp collisions at $\sqrt{s} = 7$ TeV using the ATLAS detector”
  2. “Measurement of the W boson polarization in top quark decays with the ATLAS detector”

• No significant deviation from SM prediction observed
  1. hypothesis of zero spin correlation excluded with 5 sigma
  2. helicity measurements supports model of pure V-A Wtb vertex structure

Thanks for your attention!
Backup
proton proton collisions at $\sqrt{s} = 7$ TeV

- More than 5 fb$^{-1}$ recorded in 2011
- Will present analyses with 2.1/1 fb$^{-1}$
- Both using 7 TeV (we have 8 TeV in 2012)
• Single lepton and dilepton events selected by lepton triggers and require to have a good primary vertex (at least 5 tracks associated to it)

**Lepton+jets**

- One lepton
  - $p_T > 25$ (20) GeV
  - $|\eta| < 2.5$ (and transition cuts for e)
- At least four Jets (anti-kt $R=0.4$)
  - $p_T > 20$ GeV
  - $|\eta| < 2.5$
- Background Rejection
  - (e): $E_{T}^{\text{Miss}} > 35$ GeV and $m_T^W > 25$
  - (μ): $E_{T}^{\text{Miss}} > 20$ GeV and $E_{T}^{\text{Miss}} + m_T^W > 60$ GeV

**Dilepton**

- Two oppositely charged leptons
  - $p_T > 20$ (25) GeV
  - $|\eta| < 2.5$ (2.47 and transition cuts)
- At least two Jets (anti-kt $R=0.4$)
  - $p_T > 25$ GeV
  - $|\eta| < 2.5$
- Background Rejection
  - (ee, μμ): $E_{T}^{\text{Miss}} > 60$ GeV, $m_\ll > 15$ GeV and $|m_\ll - m_Z| > 10$ GeV
  - (eμ): $H_T > 130$ GeV
  - (Tl): $E_{T}^{\text{Miss}} > 60$ GeV, $H_T > 150$ GeV and $|m_{Tl} - m_Z| > 10$ GeV
Event Reconstruction

- To associate reconstructed objects to truth partons and to determine event kinematic full event reconstruction necessary
  - for some analysis like W helicity or spin correlation reference frame has to be defined for boosting
- In lepton+jets channel missing information (z-component) of the neutrino can be reconstructed using MET and constraints from known top and W masses
- For more clean dilepton environment system is under constraint and in general several solutions exist

<table>
<thead>
<tr>
<th>Lepton+Jets</th>
<th>Dilepton</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutrino momentum unknown</td>
<td>Two neutrino momenta unknown</td>
</tr>
<tr>
<td>→ use constraints from</td>
<td>→ same constraints as for lepton+jets</td>
</tr>
<tr>
<td>1. transverse momentum (MET)</td>
<td>Up to four remaining solutions due to under-constraint system</td>
</tr>
<tr>
<td>2. Top mass</td>
<td>Take solution with minimal product of neutrino momenta</td>
</tr>
<tr>
<td>3. W mass</td>
<td>Alternative is ME approach .....</td>
</tr>
<tr>
<td>(and additional input from b-tagging for jet-permutations)</td>
<td></td>
</tr>
<tr>
<td>Use chi2 minimization or kinematic likelihood fit to find best solution</td>
<td></td>
</tr>
</tbody>
</table>
| \[ \chi^2 = \frac{(m_{\ell\nu_ja} - m_t)^2}{\sigma_t^2} + \frac{(m_{j_{b}j_{c}j_{d}} - m_t)^2}{\sigma_t^2} + \frac{(m_{\ell\nu} - m_{W})^2}{\sigma_W^2} + \frac{(m_{j_{c}j_{d}} - m_{W})^2}{\sigma_W^2} \] | \[ p_{x1}^2 + p_{x2}^2 = E_x, \]
| | \[ p_{y1}^2 + p_{y2}^2 = E_y, \]
| | \[ (p_{\ell_1} + p_{\nu_1})^2 = m_{W}^2, \]
| | \[ (p_{\ell_2} + p_{\nu_2})^2 = m_{W}^2, \]
| | \[ (p_{\nu_1} + p_{j_1})^2 = m_t^2, \]
| | \[ (p_{\nu_2} + p_{j_2})^2 = m_t^2. \]
Background Estimate

- Due to cut on two good leptons main background is from Z decay or from events with at least one fake lepton
- To evaluate the Z/γ*+jets background the MC prediction for the number of events in the SR is normalized to the data using the events measured in CR (|m_ℓℓ-m_Z|<10 GeV and E_T^{Miss}>30 (35) GeV)
- The yield of fake leptons is determined from data using a matrix-method (put dileptons into four categories using loose and tight definitions for both leptons)
Background Enriched Control Plots

- Control plots for background enriched (mainly DY) region
  - $E_T^{miss}$ for events with at least two jets for ee inside the Z mass window
  - Number of jets with same Z mass window cut and $E_T^{miss}<60$ GeV
  - Invariant dilepton mass for events with at least two jets and $E_T^{miss}< 60$ GeV
Spin Basis

- Number of unlike spin combinations of the top pair depends on choice of spin basis
- Spin correlation strength ($A$) depends on collision energy
- For Tevatron off-diagonal basis is best choice, where up to 90% of top pairs have unlike-sign spin
- For LHC beam-line and off-diagonal basis have very poor strength
- Helicity (or more complicated maximal) basis provide possibility to extract spin correlation
- Center-of-mass dependence is not very large

Beam-Axis (Tevatron): NLO QCD: $A = 0.78$

Helicity-Axis (LHC): NLO QCD: $A = 0.32$

maximal basis requires matrix solving (eigenvectors of spin density matrix)
Spin Correlation - BSM

- Several BSM scenarios predict different top decay/production mechanisms yielding in a different spin polarization

Higgs, KK gravitons, Z', stop pairs, ...

charged Higgs, b', ...

Higgs, KK gravitons, Z', stop pairs, ...
Spin Correlation - Channels

\[ \int L_{dt} = 2.1 \text{ fb}^{-1} \]

\[ \text{ee channel} \]

\[ \int L_{dt} = 2.1 \text{ fb}^{-1} \]

\[ \text{\( \mu \mu \) channel} \]

\[ \int L_{dt} = 2.1 \text{ fb}^{-1} \]

\[ \text{\( e\mu \) channel} \]

\[ \int L_{dt} = 2.1 \text{ fb}^{-1} \]
## Spin Correlation - Systematics

<table>
<thead>
<tr>
<th>Uncertainty source</th>
<th>$\Delta f_{\text{SM}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data statistics</td>
<td>±0.14</td>
</tr>
<tr>
<td>MC simulation template statistics</td>
<td>±0.09</td>
</tr>
<tr>
<td>Luminosity</td>
<td>±0.01</td>
</tr>
<tr>
<td>Lepton</td>
<td>±0.01</td>
</tr>
<tr>
<td>Jet energy scale, resolution and efficiency</td>
<td>±0.12</td>
</tr>
<tr>
<td>NLO generator</td>
<td>±0.08</td>
</tr>
<tr>
<td>Parton shower and fragmentation</td>
<td>±0.08</td>
</tr>
<tr>
<td>ISR/FSR</td>
<td>±0.07</td>
</tr>
<tr>
<td>PDF uncertainty</td>
<td>±0.07</td>
</tr>
<tr>
<td>Top quark mass</td>
<td>±0.01</td>
</tr>
<tr>
<td>Fake leptons</td>
<td>+0.16/−0.07</td>
</tr>
<tr>
<td>Calorimeter readout</td>
<td>±0.01</td>
</tr>
<tr>
<td>All systematics</td>
<td>+0.27/−0.22</td>
</tr>
<tr>
<td>Statistical + Systematic</td>
<td>+0.30/−0.26</td>
</tr>
</tbody>
</table>
Helicity - Asymmetry Method

- Extracting information about the polarization states of the W bosons evaluating angular asymmetries
  \[ A_z = \frac{N(\cos \theta^* > z) - N(\cos \theta^* < z)}{N(\cos \theta^* > z) + N(\cos \theta^* < z)} \]

- For z=0 this transforms into forward-backward asymmetry which is directly related to the helicity fractions by
  \[ A_{FB} = \frac{3}{4}[F_R - F_L] \]

- Using the normalization constraint it is possible to define two independent asymmetries which fully constrain the three fractions (with \( \beta = 2^{1/3} - 1 \))

  \[ F_R = \frac{1}{1 - \beta} + \frac{A_\beta - A_{-\beta}}{3\beta(1 - \beta^2)} \]

  \[ F_L = \frac{1}{1 - \beta} - \frac{A_{-\beta} - A_\beta}{3\beta(1 - \beta^2)} \]

  \[ F_0 = -\frac{1 + \beta}{1 - \beta} + \frac{A_\beta - A_{-\beta}}{3\beta(1 - \beta^2)} \]

- This provides an alternative method to extract helicity fractions
## W Helicity - Systematics

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainties</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$F_0$</td>
<td>$F_L$</td>
<td>$F_R$</td>
<td></td>
</tr>
<tr>
<td><strong>Signal and background modelling</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Generator choice</td>
<td>0.012</td>
<td>0.009</td>
<td>0.004</td>
<td></td>
</tr>
<tr>
<td>ISR/FSR</td>
<td>0.015</td>
<td>0.008</td>
<td>0.007</td>
<td></td>
</tr>
<tr>
<td>PDF</td>
<td>0.011</td>
<td>0.006</td>
<td>0.006</td>
<td></td>
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<tr>
<td>Top quark mass</td>
<td>0.016</td>
<td>0.009</td>
<td>0.008</td>
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<tr>
<td>Misidentified leptons</td>
<td>0.020</td>
<td>0.013</td>
<td>0.007</td>
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</tr>
<tr>
<td>W+jets</td>
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<td>0.008</td>
<td>0.008</td>
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<tr>
<td>Other backgrounds</td>
<td>0.006</td>
<td>0.003</td>
<td>0.003</td>
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<tr>
<td><strong>Method-specific uncertainties</strong></td>
<td>0.031</td>
<td>0.016</td>
<td>0.035</td>
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<tr>
<td><strong>Detector modelling</strong></td>
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<tr>
<td>Lepton reconstruction</td>
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<tr>
<td>Jet energy scale</td>
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<td>0.014</td>
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<tr>
<td>Jet reconstruction</td>
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<tr>
<td>$b$-tagging</td>
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<td>0.004</td>
<td></td>
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<tr>
<td>Calorimeter readout</td>
<td>0.009</td>
<td>0.005</td>
<td>0.004</td>
<td></td>
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<tr>
<td>Luminosity and pileup</td>
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<td>0.004</td>
<td>0.005</td>
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<tr>
<td><strong>Total systematic uncertainty</strong></td>
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<td>0.03</td>
<td>0.04</td>
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</table>