Spinning Tops: Top quark spin correlations in the dilepton channel at ATLAS (and CMS)

Miriam Watson

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23/05/19
Introduction to top quarks

- Discovered by CDF and DØ collaborations at the Tevatron in 1995

- A unique quark:
  - Lifetime ~5x10^{-25} s
  - Decays before it hadronises
  - No bound states (mesons)

- Largest mass of any fundamental particle
- Yukawa coupling ~ 1
Top quark production at the LHC

**QCD pair production: gg-fusion and q\bar{q} annihilation**

\[ \sim 90 \% \]

**EW production of single top quarks**

**Dominant**

Single top quark production:

- **t-channel**
  - Dominant

- **s-channel**

Associated tW mechanism:

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Overview of $t\bar{t}$ decays

$t$ decays $\sim$100\% to $Wb$

<table>
<thead>
<tr>
<th>BR</th>
<th>Background</th>
<th>$b$ jets</th>
<th>Light jets</th>
<th>Leptons</th>
<th>Neutrinos</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fully hadronic</td>
<td>High</td>
<td>2</td>
<td>4</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Semi-leptonic</td>
<td>High</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Dileptonic</td>
<td>Low</td>
<td>2</td>
<td>0</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

$t$ decays $\sim$100\% to $Wb$

"alljets" 46\%  
$\tau$+jets 15\%  
$\mu$+jets 15\%  
i+jets 15\%  
"lepton+jets"
What we would like to know about top

Production cross section
Resonant production?
Production kinematics
Spin/polarisation

Top mass, width, spin, charge

Wtb coupling, $|V_{tb}|$
W helicity

Anomalous couplings?
Yukawa coupling?

Rare decays
Non-SM decays?
Branching fractions

+ more!
The ATLAS detector
Selection of top events (example)

**Muons:**
Segments in tracker and muon chambers
Isolated track

**Electrons:**
Isolated cluster in EM calorimeter
Matched to track

**Jets:**
Topological calorimeter clusters
Anti-$k_T$ jet finder ($R=0.4$)

**B-tagged jets:**
Displaced tracks, secondary vertex, impact parameters etc.
BDT algorithms

**Missing $E_T$:**
Negative vector sum of $p_T$ for all reconstructed, calibrated objects
Top pair cross-section (lepton+jets)

- Use binned likelihood fit to kinematic distributions

- Selection:
  - Lepton trigger
  - Lepton
  - Jets
  - Missing $E_T$

- Jet energy scale and reconstruction uncertainties dominate
- Most backgrounds determined from data
- Larger background w/o b-tagging, but no tagging uncertainties

14/04/11  M. Watson, Warwick week
Top pair cross-section (dilepton)

- **Cut-based methods**
  - 2 leptons (opp.sign)
  - 2 jets
  - Missing $E_T$, total $E_T$

- **Main systematics**
  - JES
  - Parton shower
  - Fakes

M. Watson, Warwick week 14/04/11
Data-taking at ATLAS 2010-2018

Run 1, 7+8 TeV

Run 2, 2015-18

ATLAS Online Luminosity

- 2010 pp √s = 7 TeV
- 2011 pp √s = 7 TeV
- 2012 pp √s = 8 TeV

Delivered: 156 fb⁻¹
Recorded: 147 fb⁻¹

Today: mostly 2015-16 data, 36 fb⁻¹

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Top physics summary plots: 7, 8 and 13 TeV

Top pair cross-sections (note increase with $\sqrt{s}$)

Single top cross-sections: t-channel, tW production and s-channel

Top quark mass

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ATLAS+CMS Preliminary

Single top-quark production

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ATLAS+CMS Preliminary

LHCtopWG

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Now a “background” to consider!
Spin correlation: overview

- **LHC (pp):** top quarks produced \(\sim\) unpolarised, but…
- …expect **correlations** between spins of top and anti-top in the SM

- Top quarks decay before hadronisation & top lifetime shorter than decorrelation time

Spin information passed directly to decay products

Measure spin information from angular distributions
Spin correlation: beyond the Standard Model

- Measured spin correlation can alter due to
  - Different decays
  - Different production
- Spin correlation: test full chain from production to decay

- Decays: charged Higgs, b', ...
- Production: stop pairs, KK gravitons, Z', Higgs...
Spin correlation: $\Delta \phi$ observable

- Highest spin analysing power: leptons from top decay
- Use dileptonic $tt$ events
- Very clean samples

- Measure spin correlation using angular distributions of decay products (leptons here)
- Spin correlation can be inferred from the $\Delta \phi$ distribution:
  - $\Delta \phi$: difference in azimuthal angle between the leptons, lab frame
- No event reconstruction required
- Excellent lepton resolution
Several measurements by ATLAS and CMS at multiple collision energies

First exclusion of zero spin correlation at >5σ by ATLAS at 7 TeV

Both experiments have observed Δφ to be “steeper” in predictions than the data

Covered by systematic uncertainties at 7 and 8 TeV
Double-differential measurement

- SM spin correlation varies as a function of $m_{tt}$
- Dominated by gluon-gluon fusion at LHC

Double-differential cross-section ($\Delta \phi, m_{tt}$)

- Expect higher sensitivity to SM spin correlations at low $m_{tt}$
- New physics at higher $m_{tt}$?
- Requires $tt$ event reconstruction

Mahlon and Parke
Phys. Rev. D 81, 074024

$g_L g_L, g_R g_R \rightarrow tt$

Like Helicity dominates

$g_L q_R, g_R q_L, g_L g_R \rightarrow tt$

Un-Like Helicity dominates

low $M_{ttbar}$

450 GeV

high $M_{ttbar}$

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13 TeV analysis summary

- 2015 + 2016 data (36 fb$^{-1}$) with a standard dilepton $e\mu$ selection:
  - Exactly 2 opposite-sign leptons (27, 25 GeV)
  - At least one b-jet; >= 2 jets $p_T > 25$ GeV
  - No cuts on MET or on $m(ll)$

- Fiducial particle level:
  - Same kinematic cuts as above
  - “Dressed” leptons with radiated photons
  - Anti-$k_T$ R=0.4 jets with “ghost-matching” for b-tagging

- Parton level, full phase space:
  - Tops defined after radiation, leptons before
  - $e\mu$ channel only (no tau decays)

$\Delta \phi$: in lab. frame
$|\Delta \eta|$: abs. difference in $\eta$ of leptons
Measured distributions: $\Delta\phi$, $\Delta\eta$

- Inclusive selection for simple angular distributions (note: hint of disagreement)
- For $\Delta\phi$ as a function of $m_{tt}$:
  - Require $tt$ event reconstruction
  - Use Neutrino Weighting
Event reconstruction for $m_{tt}$ dependence

- Reconstruct dilepton $tt$ system
  - Two unknowns: $\eta$ of neutrinos

- Constrain system using values of top mass and $W$ mass

- Test many different assumptions for $\eta$ for the two neutrinos

- Give each solution a weight based on observed $E_T^{\text{miss}}$ in the event

- Select solution based on highest weight ("Neutrino Weighting")

- Improving resolution:
  - $M_t$ sampling: [171,174] GeV in 0.5 GeV steps
  - Smear jet $p_T$

Kinematic constraints:

$$ (\ell_{1,2} + \nu_{1,2})^2 = M_W^2 = 80.4^2 $$
$$ (\ell_{1,2} + \nu_{1,2} + b_{1,2})^2 = M_t^2 = 172.5^2 $$

Require 2 b-tagged jets

Weight function:

$$ w_i = \exp\left(\frac{-\Delta E_x^2}{2\sigma_x^2}\right) \cdot \exp\left(\frac{-\Delta E_y^2}{2\sigma_y^2}\right) $$

$E_T^{\text{miss}}$ resolution factor

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The plots display the prediction to data for the three models. The observed distribution is compared to the sum of signal and background using three different background modelling, pile-up modelling and luminosity, but not PDF or signal in quadrature. The systematic uncertainties include contributions from leptons, jets, missing transverse momentum, the statistical uncertainties while the light uncertainty bands represent the statistical and systematic uncertainties added in quadrature.

- Shape differences apparent
- Binning determined by statistical precision and resolution on $m_{tt}$, not $\Delta\phi$
### Selected candidates

<table>
<thead>
<tr>
<th>Process</th>
<th>Inclusive selection $\geq 1$ b-tag</th>
<th>Reconstructed selection $\geq 2$ b-tags</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t\bar{t}$</td>
<td>165 000 $\pm$ 5000</td>
<td>75 000 $\pm$ 4000</td>
</tr>
<tr>
<td>$tW$</td>
<td>8900 $\pm$ 1400</td>
<td>1550 $\pm$ 170</td>
</tr>
<tr>
<td>$t\bar{t}V$ and others</td>
<td>670 $\pm$ 60</td>
<td>233 $\pm$ 22</td>
</tr>
<tr>
<td>Diboson</td>
<td>580 $\pm$ 60</td>
<td>15.1 $\pm$ 2.8</td>
</tr>
<tr>
<td>$Z/\gamma^* \rightarrow \tau^+\tau^-$</td>
<td>420 $\pm$ 70</td>
<td>26 $\pm$ 17</td>
</tr>
<tr>
<td>Fake Lepton</td>
<td>1800 $\pm$ 700</td>
<td>630 $\pm$ 250</td>
</tr>
<tr>
<td><strong>Expected</strong></td>
<td>177 000 $\pm$ 6000</td>
<td>78 000 $\pm$ 4000</td>
</tr>
<tr>
<td><strong>Observed</strong></td>
<td>177 113</td>
<td>75 885</td>
</tr>
</tbody>
</table>

### Nominal $t\bar{t}$ Monte Carlo:
- Powheg-Box next-to-leading order (NLO) matrix-element
- Pythia8 for parton shower and fragmentation
- NNPDF3.0 NLO parton distribution function (PDF)

Recall: This segment, and only 25% of run 2 data

"dileptons"
**Unfolding for detector effects**

- Iterative Bayesian Unfolding is used to correct the data to fiducial Particle or Parton level.

1. **Data**

2. Subtract backgrounds estimated using MC

3. **Data - Background**

4. Bayesian iterative unfolding with $n$ iterations

5. **Unfolded data**

6. Correct for fiducial phase-space acceptance

7. **Fiducial data**

8. or full phase-space

9. Determine cross-section, absolute or normalised

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**Systematic uncertainties**

- **General method:**
  - *unfold shifted sample with nominal response matrix, compare to nominal sample*

- **Detector modelling**
- **Background and luminosity**
- **Signal modelling (dominant):**
  - Parton shower: Pythia8 or Herwig7
  - NLO model: Powheg or aMC@NLO
  - Initial and final state radiation
  - PDF variation

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**ATLAS**

$\sqrt{s} = 13$ TeV, $36.1 \text{ fb}^{-1}$

**Fractional uncertainty size [%]**

**Parton-level $\Delta\phi(l^+,l^+)/\pi$ [rad/$\pi$]**

**Legend:**
- **Background**
- **Lepton**
- **Luminosity and pileup**
- **Jet, b-tagging and $E_T^{\text{miss}}$**
- **$t\bar{t}$ modelling**
Results: $\Delta \phi$ parton level

- Clear slope in the data relative to the MC predictions: none agree well
- Relative cross-sections shift due to acceptance effects when normalising, but shape remains the same
- Systematics are dominant in most bins
The behaviour of the $\Delta \phi$ observable from low $m_{tt}$ to high $m_{tt}$ is clearly seen. Uncertainties are larger here due to the $tt$ reconstruction (jets and $E_T^{\text{miss}}$ become important).
**Results: extracting spin correlation**

- Fraction of SM-like spin correlation ($f_{SM}$) is extracted using a binned maximum likelihood fit with two templates
  - With-spin template: nominal MC (Poweg+Pythia8) with SM spin $\Rightarrow f_{SM} = 1$
  - No-spin template: simulated with the same MC settings, but top quarks decayed using MadSpin with spin correlations between $t$ and $t^{-}$ disabled $\Rightarrow f_{SM} = 0$

- Shallow slope in data is visible

\[
x_i = f_{SM} \cdot x_{\text{spin}, i} + (1 - f_{SM}) \cdot x_{\text{nospin}, i}
\]
Results: extracting spin correlation vs. $m_{\tau\tau}$

- Separation between spin and no-spin templates reduces with $m_{\tau\tau}$
Results: extracting spin correlation vs. $m_{tt}$

- MC parton-level distributions follow theoretical predictions at low $m_{tt}$

![Graph showing distributions and data points for $\Delta \phi(l^+, l')/\pi$]
Results: $f_{\text{SM}}$ values

- The significance of the $f_{\text{SM}}$, relative to the SM template, is calculated using a CL$_{s+b}$ method (effectively the same as counting the number of s.d. away from $f_{\text{SM}} = 1$) c.f. Powheg + Pythia8 with/without scale and PDF uncertainties on templates

<table>
<thead>
<tr>
<th>Region</th>
<th>$f_{\text{SM}}$ ± (stat.,syst.,theory)</th>
<th>Significance (excl. theory uncertainties)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inclusive</td>
<td>$1.249 \pm 0.024 \pm 0.061 \pm 0.040$</td>
<td>3.2 (3.8)</td>
</tr>
<tr>
<td>$m_{t\bar{t}} &lt; 450 \text{ GeV}$</td>
<td>$1.12 \pm 0.04 , ^{+0.12}_{-0.13} \pm 0.02$</td>
<td>0.86 (0.87)</td>
</tr>
<tr>
<td>$450 \leq m_{t\bar{t}} &lt; 550 \text{ GeV}$</td>
<td>$1.18 \pm 0.08 , ^{+0.13}_{-0.14} \pm 0.08$</td>
<td>1.0 (1.1)</td>
</tr>
<tr>
<td>$550 \leq m_{t\bar{t}} &lt; 800 \text{ GeV}$</td>
<td>$1.65 \pm 0.19 , ^{+0.31}_{-0.41} \pm 0.22$</td>
<td>1.3 (1.4)</td>
</tr>
<tr>
<td>$m_{t\bar{t}} \geq 800 \text{ GeV}$</td>
<td>$2.2 \pm 0.9 , ^{+2.5}_{-1.7} \pm 0.7$</td>
<td>0.58 (0.61)</td>
</tr>
</tbody>
</table>

- Slight (but insignificant) increase in $f_{\text{SM}}$ as a function of $m_{t\bar{t}}$
- The inclusive $f_{\text{SM}}$ deviates significantly from the SM prediction in NLO MC
Comparison of $f_{SM}$ values

- When interpreted as spin correlation, shows ~20% more than the spin correlation expectation of the SM (in NLO MC)

- Observed in many other results, with larger uncertainties

- Main differences here:
  - Improved MC generators
  - Improved MC tuning
  - Larger dataset to constrain systematic uncertainties
Further checks

- NLO generators used here (e.g. Powheg + Pythia8):
  - NLO in production
  - Not full NLO in top quark decays
  - Use Narrow Width Approximation (NWA) to factorise production and decay: initial-final state interference effects are neglected
Further checks

- NLO generators used here (e.g. Powheg + Pythia8):
  - NLO in production
  - Not full NLO in top quark decays
  - Use Narrow Width Approximation (NWA) to factorise production and decay: initial-final state interference effects are neglected

- NLO effects in the decays of the top quarks: compare the \( \Delta \phi \) distribution with MCFM (full NLO, including NLO decays) \( \rightarrow \) very close to nominal template
Further checks

- NLO generators used here (e.g. Powheg + Pythia8):
  - NLO in production
  - Not full NLO in top quark decays
  - Use Narrow Width Approximation (NWA) to factorise production and decay: initial-final state interference effects are neglected

- **NWA in the templates:**
  compare with Powheg-Box-Res bb4l for full $tt+tW$
  process **without NWA** $\rightarrow$ no significant differences
Further checks

- NLO generators used here (e.g. Powheg + Pythia8):
  - NLO in production
  - Not full NLO in top quark decays
  - Use Narrow Width Approximation (NWA) to factorise production and decay: initial-final state interference effects are neglected

- Effect of NNLO in production: reweight the top $p_T$ to match fixed-order NNLO predictions or unfolded data from several previous ATLAS measurements

- Deviations reduced slightly but consistent within scale uncertainties already considered
New theoretical predictions: NNLO

- New fixed-order NNLO predictions for $\Delta \phi$ and $\Delta \eta$ directly, with renormalisation and factorisation scale uncertainties
- Closer to parton-level unfolded data, but does not cover observed discrepancy

\[ \pi \]
New theoretical predictions: NNLO inclusive

- Closer to parton-level unfolded data, but does not cover observed discrepancy
- Similar to our results with reweighting to top \( p_T \) for NNLO or data

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The NNLO authors perform a ‘fiducial’ fixed order calculation, similar to ATLAS particle level, by clustering the b-jets with radiation (but not with any parton shower, hadronisation, b-decays etc)

• Larger scale uncertainties, but better agreement with data
New theoretical predictions: NNLO fiducial

- **Author’s conclusion:** There is a problem with the extrapolation of the ATLAS data to the full phase space with NLO/LO MC

- **Comment:** Fiducial cuts are applied to the ‘b-jets’ ($p_T > 25$ GeV, $|\eta| < 2.5$). These are unlikely to be the same for ATLAS particle level jets and fixed-order partons → could sculpt the shape
More theoretical predictions: NLO+weak effects

- **NLO+weak effects**: previous calculation now produced for our binning at 13 TeV
  - NLO QCD + weak corrections
  - Expanded as a ratio to fixed order
  - Less optimal fixed scale choice: \( \mu_{R/F} = m_{\text{top}} \)
  - Different PDF set CT10

- Better agreement with data, but large scale uncertainties
- Gives \( f_{\text{SM}} = 1.03 \pm 0.13 \) (scale)
Aside: renormalisation and factorisation scale choice

\[ \mu_0 \sim m_t, \quad \text{NLO+Weak} \]

\[ \mu_0 \sim m_T = \sqrt{m_t^2 + p_T^2}, \quad \text{PP8} \]

\[ \mu_0 \sim H_T = \sqrt{m_t^2 + p_{T,t}^2 + m_t^2 + p_{T,\bar{t}}^2}, \]

\[ \mu_0 \sim H_T' = \sqrt{m_t^2 + p_{T,t}^2 + m_t^2 + p_{T,\bar{t}}^2 + \sum_i p_{T,i}}, \]

\[ \mu_0 \sim E_T = \sqrt{m_t^2 + p_{T,t}^2} \sqrt{m_t^2 + p_{T,\bar{t}}^2}, \]

\[ \mu_0 \sim H_{T,\text{int}} = \sqrt{(m_t/2)^2 + p_{T,t}^2} + \sqrt{(m_t/2)^2 + p_{T,\bar{t}}^2}, \]

\[ \mu_0 \sim m_{t\bar{t}}, \]

\[ \mu_0 = \begin{cases} 
\frac{m_T}{2} & \text{for: } p_{T,t}, p_{T,\bar{t}} \text{ and } p_{T,t/\bar{t}}, \\
\frac{H_T}{4} & \text{for: all other distributions}
\end{cases} \]
**Δϕ and \( f_{\text{SM}} \) summary**

Table 7: Summary of the extracted spin correlation values in the inclusive \( \Delta \phi \) observable using different hypothesis templates.

<table>
<thead>
<tr>
<th>Generator</th>
<th>Inclusive</th>
<th>( m_{t\bar{t}} &lt; 450 \text{ GeV} )</th>
<th>( 450 \leq m_{t\bar{t}} &lt; 550 \text{ GeV} )</th>
<th>( 550 \leq m_{t\bar{t}} &lt; 800 \text{ GeV} )</th>
<th>( m_{t\bar{t}} \geq 800 \text{ GeV} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( f_{\text{SM}} ) values</td>
<td>( f_{\text{SM}} )</td>
<td>( 1.25 )</td>
<td>( 1.12 )</td>
<td>( 1.18 )</td>
<td>( 1.65 )</td>
</tr>
<tr>
<td>POWHEG + PYTHIA8</td>
<td>( 1.29 )</td>
<td>( 1.14 )</td>
<td>( 1.23 )</td>
<td>( 1.79 )</td>
<td>( 2.0 )</td>
</tr>
<tr>
<td>POWHEG + PYTHIA8 (2.0 ( \mu_F ), 2.0 ( \mu_R ))</td>
<td>( 1.18 )</td>
<td>( 1.09 )</td>
<td>( 1.11 )</td>
<td>( 1.40 )</td>
<td>( 1.3 )</td>
</tr>
<tr>
<td>POWHEG + PYTHIA8 (0.5 ( \mu_F ), 0.5 ( \mu_R ))</td>
<td>( 1.26 )</td>
<td>( 1.13 )</td>
<td>( 1.25 )</td>
<td>( 1.76 )</td>
<td>( 2.2 )</td>
</tr>
<tr>
<td>POWHEG + PYTHIA8 (PDF variations)</td>
<td>( 1.29 )</td>
<td>( 1.15 )</td>
<td>( 1.23 )</td>
<td>( 1.79 )</td>
<td>( 2.0 )</td>
</tr>
<tr>
<td>POWHEG + PYTHIA8 RadLo tune</td>
<td>( 1.32 )</td>
<td>( 1.17 )</td>
<td>( 1.25 )</td>
<td>( 1.79 )</td>
<td>( 2.0 )</td>
</tr>
<tr>
<td>POWHEG + HERWIG7</td>
<td>( 1.20 )</td>
<td>( 1.06 )</td>
<td>( 1.18 )</td>
<td>( 1.40 )</td>
<td>( 0.7 )</td>
</tr>
<tr>
<td>MADGRAPH5_aMC@NLO + PYTHIA8</td>
<td>( 1.03 )</td>
<td>( - )</td>
<td>( - )</td>
<td>( - )</td>
<td>( - )</td>
</tr>
<tr>
<td>NLO (QCD + EW expanded) [35, 81, 82]</td>
<td>( 1.16 )</td>
<td>( - )</td>
<td>( - )</td>
<td>( - )</td>
<td>( - )</td>
</tr>
<tr>
<td>NNLO QCD [80]</td>
<td>( - )</td>
<td>( - )</td>
<td>( - )</td>
<td>( - )</td>
<td>( - )</td>
</tr>
</tbody>
</table>

- This is not a “simple” observable: a lot of effects sculpt the \( \Delta \phi \) shape:
  - Choice of functional form of \( \mu_{R/F} \) e.g. fixed or dynamic scale
  - Parton shower matching/merging
  - Effect of hard radiation (i.e. \( \text{hdamp} \) setting in generators like Powheg)
  - Weak/EW corrections and how they are included
  - Choice of PDF
  - Higher-order NNLO QCD corrections and extrapolation to full phase-space
  - Interplay been kinematic effects and higher order corrections
  - Could also be new physics...

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Supersymmetric top squark pair production

Exclusion contours as a function of $m_{\tilde{\chi}^0_1}$ and $m_{\tilde{t}_1}$

Small region with $m_{\tilde{t}} \sim m_t$

difficult to access in direct searches
Use double differential $\Delta \phi$ in 3 bins of $\Delta \eta$ to set limits on SUSY stop production

More exclusion power comes from $\Delta \eta$ than $\Delta \phi$

Include additional theory uncertainty to cover data-MC difference observed in tt (based on NLO+Weak calculation)
Expected and observed cross-section limits

- Limit is still stronger than expected because the data look very unlike SUSY
- Closes off last hiding place for “stealth stops” with $m_{\tilde{t}} \sim m_t$
Direct spin correlation measurements

- Spin correlation in $\bar{t}t$ is:

$$C = \alpha_1 \cdot \alpha_2 \cdot \frac{N(\uparrow\uparrow) + N(\downarrow\downarrow) - N(\uparrow\downarrow) - N(\downarrow\uparrow)}{N(\uparrow\uparrow) + N(\downarrow\downarrow) + N(\uparrow\downarrow) + N(\downarrow\uparrow)}$$

- Where $\alpha$ is the "spin analysing power" of some decay particle from a top quark ($\sim 1$ for charged leptons so we won’t mention it again for dilepton analyses).
- $\uparrow$ and $\downarrow$ are the direction of $t$ and $\bar{t}$ spin, in some chosen "spin analysing basis"

- There are three orthogonal bases that are most commonly used:
  - The "Helicity" basis: direction of the $t$ in the $\bar{t}t$ rest frame.
  - The "Transverse basis": orthogonal to the plane formed by the $t$ and beam line in $\bar{t}t$ rest frame.
  - The "R-axis": basis orthogonal to the other two.
Direct spin correlation measurements

- Sensitive observables can be readily seen by examining the double differential cross-section as a function of the angular distribution of t and t̅ decay products:

\[
\frac{1}{\sigma} \frac{d^2\sigma}{d \cos \theta^a_+ d \cos \theta^b_-} = \frac{1}{4}(1 + B^a_+ \cos \theta_+^a + B^b_- \cos \theta_-^b - C(a, b) \cos \theta_+^a \cos \theta_-^b)
\]

- By measuring the \(\cos(\theta)\) angles (usually with leptons) we can directly extract the spin correlation parameter \(C\):

\[
B_+ = 3 \cdot < \cos(\theta_+) > \quad C = -9 \cdot < \cos(\theta_+) \cos(\theta_-) >
\]

- ATLAS measured the spin correlation parameter, \(C\), the polarisation parameters \(B\), and cross-correlations (\(\cos(\theta^+\)) and \(\cos(\theta^-)\) using different spin analysing bases) in an 8 TeV paper: JHEP 03 (2017) 113

- But these direct measurements require full t̅ reconstruction in dilepton events and therefore suffer from significant systematic uncertainties and resolution effects.
ATLAS spin observables at 8 TeV

- 15 observables corrected to particle and parton level
- Compared to NLO predictions
- No significant deviation from the SM

\[ s = 8 \text{ TeV} - 20.2 \text{ fb}^{-1} \]

**Spin correlations**
- \( C(k,k) \) 0.296 ± (0.072) ± (0.057)
- \( C(n,n) \) 0.304 ± (0.038) ± (0.047)
- \( C(r,r) \) 0.086 ± (0.075) ± (0.122)

**Polarisations**
- \( B_+ \) -0.044 ± (0.027) ± (0.025)
- \( B^- \) -0.064 ± (0.030) ± (0.023)
- \( B_0 \) -0.018 ± (0.023) ± (0.024)
- \( B_+ \) 0.023 ± (0.024) ± (0.034)
- \( B^- \) 0.039 ± (0.030) ± (0.029)
- \( B_0 \) 0.033 ± (0.029) ± (0.045)
CMS spin/polarisation at 13 TeV

- Distributions corrected to parton level
- Compared to NLO QCD + weak corrections
- Improved regularised unfolding technique

CMS Preliminary

35.9 fb⁻¹ (13 TeV)

- Data
- POWHEGv2 + PYTHIA8
- NLO calculation
- MG5_aMC@NLO + PYTHIA8 [Fx_Fx]

N.b. lab frame

All measurements consistent with the SM

Miriam Watson
CMS spin/polarisation at 13 TeV

- Instead of SUSY contribution, use measurements to constrain the anomalous chromomagnetic dipole moment of the top quark

- Feature of many BSM models, e.g. two-Higgs-doublet models, supersymmetry, technicolor, top quark compositeness models

\[-0.07 < \frac{C_{tG}}{\Lambda^2} < 0.16 \text{ TeV}^{-2}\]
Summary

- Still more to do to understand $t\bar{t}$ spin correlations and QCD!
- Interplay between kinematics, higher order corrections, PDFs and experimental techniques is complicated
- Some hints in calculations (e.g. NNLO, weak corrections, fiducial corrections) but no simple solution

- We can exploit the full Run 2 data (4x the current data), study multidifferential distributions, investigate phase space corrections
- Watch this space!
MC samples

- **Dilepton signal (tt):**
  - Nominal sample: Powheg+Pythia8
  - Radiation high/low: Powheg+Pythia8
  - Parton shower: Powheg+Herwig7
  - Alt. NLO: aMC@NLO+Pythia8

- **Backgrounds:**
  - Z+jets: Sherpa 2.2.1
  - W+jets: Sherpa 2.2.1
  - Diboson: Sherpa 2.2.1 + 2.1
  - Single top: Powheg+Pythia6
  - ttW, ttZ, tWZ: aMC@NLO + Pythia8
  - tZ, ttWW, tttt: MadGraph + Pythia8
  - Fakes from MCTruthClassifier (l+jets tt, W+jets, single top, ttV, other), cross-checked with like-sign leptons
CMS $f_{\text{SM}}$ values

- Correlation term D from opening angle between leptons in parent top rest frames
- Most precise value of $f_{\text{SM}}$
- N.b. all $f_{\text{SM}}$ values determined with Bernreuther-Si NLO QCD+weak predictions

N.b. lab frame
**ATLAS and NNLO $\Delta\eta$**

- Unfolded parton-level distribution
- NNLO corrections appear to follow data trends