Recent Top quark properties measurements (excluding mass and asymmetries)
On Behalf of LHC and Tevatron

Michael Homann

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CKM 2016
Outline

- Top Quark Production Properties
  - Spin Correlation
  - Top Polarization
- Top Quark Decay Properties
  - W-Boson Helicity
- Top width
Spin Correlations

- Top lifetime is less than the timescale of QCD interaction
  - Top spin at production is conserved through to the decay

\[
\frac{1}{N} \frac{d^2 N}{d \cos \theta_1 d \cos \theta_2} = \frac{1}{4} \left( 1 + B_1 \cos \theta_1 + B_2 \cos \theta_2 + C_{\text{helicity}} \cos \theta_1 \cdot \cos \theta_2 \right)
\]

- \( C_{\text{helicity}} = -A_{\text{helicity}} \alpha_1 \alpha_2 \)

- \( \alpha \) Spin analyzing power:
  \( \alpha_{\ell^+} = +0.998, \alpha_d = -0.966, \alpha_b = -0.393 \)

- \( A_{\text{helicity}} = \frac{N_{\text{like}} - N_{\text{unlike}}}{N_{\text{like}} + N_{\text{unlike}}} \)

- NLO QCD Prediction \( A = 0.31 \) (dilepton)

- Sensitivity also through \( \Delta \phi \) between leptons
ATLAS: Dilepton $t\bar{t}$ final states at $\sqrt{s} = 7$ TeV
Phys. Rev. D 93, 012002 (2016)

- Reconstruction of $t\bar{t}$ event in dilepton using kinematic constraints
- Angular distribution is unfolded to parton level
- Extract $C_{\text{helicity}}$ and therefore also $A_{\text{helicity}}$:

$$C_{\text{helicity}} = -A_{\text{helicity}} \alpha_1 \alpha_2$$

$$A_{\text{helicity}} = 0.315 \pm 0.061 \text{(stat.)} \pm 0.049 \text{(syst.)}$$
**CMS: Dilepton final states at $\sqrt{s} = 8$ TeV**

PRD 93, 052007 (2016)

**Dilepton Topologies**

- $\Delta \Phi \ell^+ \ell^-$ sensitive to top polarization
  - no need of full reconstruction of $t\bar{t}$ system
- $\phi$ directly sensitive to spin correlations

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<table>
<thead>
<tr>
<th>Variable</th>
<th>$f_{\text{SM}} \pm (\text{stat}) \pm (\text{syst}) \pm (\text{theor})$</th>
<th>Total uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_{\Delta \phi}$</td>
<td>1.14 $\pm 0.06 \pm 0.13 \pm 0.08$</td>
<td>$+0.16$ $-0.11$</td>
</tr>
<tr>
<td>$A_{\cos \phi}$</td>
<td>0.90 $\pm 0.09 \pm 0.10 \pm 0.05$</td>
<td>$+0.15$ $-0.18$</td>
</tr>
<tr>
<td>$A_{c_1c_2}$</td>
<td>0.87 $\pm 0.17 \pm 0.21 \pm 0.04$</td>
<td>$+0.27$ $-0.11$</td>
</tr>
<tr>
<td>$A_{\Delta \phi}$ (vs. $M_{t\bar{t}}$)</td>
<td>1.12 $\pm 0.06 \pm 0.08 \pm 0.08$</td>
<td>$+0.12$ $-0.11$</td>
</tr>
</tbody>
</table>

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Top Properties  
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ATLAS: Spin correlation at 8TeV in Dilepton

Fit to $\Delta \Phi$ Distribution:

$$\Delta \Phi = f_{SM} \cdot SM + (1 - f_{SM}) \cdot no \ corr.$$  

Final Result:

$$f_{SM} = 1.20 \pm 0.05\text{(stat.)} \pm 0.18\text{(syst.)}$$

$$A_{\text{helicity}} = 0.38 \pm 0.04$$

Search for stops with $\tilde{t}_1 \to t\tilde{\chi}_1^0$

Assuming $BR(\tilde{t}_1 \to t\tilde{\chi}_1^0) = 100\%$: top squark masses are excluded between top mass and 191 GeV at 95\% C.L.
CMS: Muon + jets final state at $\sqrt{s} = 8$ TeV
PLB 758, 321 (2016)

- Muon + jets final state
- Using kinematic fit to reduce background

![Graph showing data and background contributions with chi-squared probability]

- Evaluate jet-quark permutations
- Can apply additional quality criteria
- $\chi^2/\text{ndof} < 5$ and $\chi^2$ probability larger than 0.08
Spin Correlation

CMS: Muon+Jets final state at $\sqrt{s} = 8$ TeV

PLB 758, 321 (2016)

Spin Correlation With Matrix Element Method

$$f = 0.72 \pm 0.08\text{(stat.)}^{+0.15}_{-0.13}\text{(syst.)}$$

$$A_{\text{hel}}^{\text{measured}} = 0.23 \pm 0.03\text{(stat.)}^{+0.05}_{-0.04}\text{(syst.)}$$
D0: Dilepton and lepton + jets at $\sqrt{s} = 1.96$ TeV
PLB 757 (2016) 199

Spin Correlation Factor

- Use matrix method
- Spin correlation factor in the off-diagonal basis:

$$O_{\text{off}} = 0.89 \pm 0.16(\text{stat.}) \pm 0.15(\text{syst.})$$

- Main systematic uncertainty: Signal modelling $\pm 0.135$

Event Fraction $f_{\text{gg}}$

Fraction of $t\bar{t}$ events produced by gluon fusion:

$$f_{\text{gg}} = 0.08 \pm 0.12(\text{stat.}) \pm 0.11(\text{syst.})$$

Is in agreement with SM prediction at NLO

Tevatron and LHC measurement are complementary

Spin Correlation Discriminant

$$R(x) = \frac{P_{t\bar{t}}(x, \text{SM})}{P_{t\bar{t}}(x, \text{SM}) + P_{t\bar{t}}(x, \text{null})}$$
Top Quark Polarization

- Single-top: $V - A$ structure of the SM predicts large polarization $P$, along the direction of the momentum of the spectator quark in the top rest frame.

- $t\bar{t}$: Measure Polarisation in Beam, Helicity or transverse base.

$$\frac{1}{\sigma} \frac{d\sigma}{d\cos\theta^*_X} = \left( \frac{1}{2} + A_X \cos\theta^*_X \right)$$

- Here is $A_X = \frac{1}{2} P_t \alpha_X$.

- Top quark polarization can be potentially determined by measuring $\theta^*_X$ distribution.

- Also it can be measured through asymmetries:

$$A_X = \frac{1}{2} P_t \alpha_X = \frac{N(\uparrow) - N(\downarrow)}{N(\uparrow) + N(\downarrow)}$$
D0: $t\bar{t}$ lepton + jets at $\sqrt{s} = 1.96$ TeV

arXiv:1607.07627, subm. to PRL

<table>
<thead>
<tr>
<th>Axis</th>
<th>Measured polarization</th>
<th>SM prediction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam</td>
<td>$+0.070 \pm 0.055$</td>
<td>$-0.002$</td>
</tr>
<tr>
<td>Beam - D0 comb.</td>
<td>$+0.081 \pm 0.048$</td>
<td>$-0.002$</td>
</tr>
<tr>
<td>Helicity</td>
<td>$-0.102 \pm 0.061$</td>
<td>$-0.004$</td>
</tr>
<tr>
<td>Transverse</td>
<td>$+0.040 \pm 0.034$</td>
<td>$+0.011$</td>
</tr>
</tbody>
</table>

Polarizations are consistent with SM predictions
ATLAS: Measurement of the spin density matrix in dilepton final states at $\sqrt{s} = 8$ TeV

Fully bayesian unfolding to extract spin correlation matrix elements

\[ B_+^k = -0.044 \pm 0.038 \pm 0.027 \text{(mass)} \]
\[ B_-^k = -0.064 \pm 0.040 \pm 0.027 \text{(mass)} \]
\[ C(k, k) = 0.296 \pm 0.093 \pm 0.037 \text{(mass)} \]

\( k \) refers to helicity basis

In agreement with NLO SM predictions
\[ B_+^k = 0.0030 \pm 0.0010, \]
\[ B_-^k = 0.0034 \pm 0.0010, \]
\[ C(k, k) = 0.318 \pm 0.003 \]
CMS: Polarization in t-channel single top quark production at $\sqrt{s} = 8$ TeV

JHEP 04 (2016) 073

- $\mu +$ Jets final state
- Use Boosted Decision Tree to separate signal and background
- Extract asymmetries from normalised angular distributions via unfolding

$$A_{\mu}(t) = 0.29 \pm 0.03(\text{stat}) \pm 0.10(\text{syst}) = 0.29 \pm 0.11,$$

$$A_{\mu}(\bar{t}) = 0.21 \pm 0.05(\text{stat}) \pm 0.13(\text{syst}) = 0.21 \pm 0.14,$$

$$A_{\mu}(t + \bar{t}) = 0.26 \pm 0.03(\text{stat}) \pm 0.10(\text{syst}) = 0.26 \pm 0.11,$$

- Measurement is compatible with a $p$-value of 4.6%
W-Boson Helicity and Anomalous Couplings

W-Boson Helicity

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

\[F_0 = 0.687 \pm 0.005 \quad F_L = 0.311 \pm 0.005 \quad F_R = 0.0017 \pm 0.0001\]

at NNLO in SM including electroweak effects for \(m_{\text{top}} = 172.8 \pm 1.3\) GeV


Anomalous Couplings

\[L_{Wtb} = -\frac{g}{\sqrt{2}} \bar{b} \gamma^\mu (V_L P_L + V_R P_R) tW^-_\mu - \frac{g}{\sqrt{2}} \bar{b} \frac{i\sigma^{\mu\nu}}{m_W} q_\nu (g_L P_L + g_R P_R) tW^-_\mu + h.c.\]

- In SM: \(V_L = V_{tb}, \ V_R = g_L = g_R = 0\)
- Deviations would hint to physics beyond the standard model
- Dedicated talk tomorrow
CMS: lepton + jets channel at $\sqrt{s} = 8\,\text{TeV}$
PLB 762 (2016) 512-534

- Full event reconstruction by using $t$ mass and $W$ mass
- Using constrained likelihood fit to improve determination of $p_L^\nu$
- Only using leptonic branch
- Extract helicity fractions from angular distributions
CMS: lepton + jets channel at $\sqrt{s} = 8\,\text{TeV}$

PLB 762 (2016) 512-534

$F_0 = 0.681 \pm 0.012\,\text{(stat.)} \pm 0.023\,\text{(syst.)}$,  
$F_L = 0.323 \pm 0.008\,\text{(stat.)} \pm 0.014\,\text{(syst.)}$,  
and $F_R = -0.004 \pm 0.005\,\text{(stat.)} \pm 0.014\,\text{(syst.)}$

correlation coefficient between $F_0$ and $F_L$: $-0.87$
ATLAS: lepton + jets Channel at $\sqrt{s} = 8$ TeV

Paper in Preparation

- Using Leptonic Branch

$$F_0 = 0.709 \pm 0.012 \text{(stat. + bkg. norm)} \pm 0.015 \text{(syst.)}$$
$$F_R = 0.299 \pm 0.008 \text{(stat. + bkg. norm.)} \pm 0.013 \text{(syst)}$$
$$F_L = -0.008 \pm 0.006 \text{(stat + bkg. norm.)} \pm 0.012 \text{(syst)}$$

- Most sensitive measurement so far.
# Summary $W$-Boson Helicity

## ATLAS+CMS Preliminary LHC topWG Sept 2016

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Luminosity</th>
<th>LHC Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS 2010 single lepton</td>
<td>$\sqrt{s} = 7$ TeV, $L_{\text{int}} = 35$ pb$^{-1}$</td>
<td></td>
</tr>
<tr>
<td>ATLAS 2011 single lepton and dilepton</td>
<td>$\sqrt{s} = 7$ TeV, $L_{\text{int}} = 1.04$ fb$^{-1}$</td>
<td></td>
</tr>
<tr>
<td>CMS 2011 single lepton</td>
<td>$\sqrt{s} = 7$ TeV, $L_{\text{int}} = 2.2$ fb$^{-1}$</td>
<td></td>
</tr>
<tr>
<td>LHC combination, $\sqrt{s} = 7$ TeV</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ATLAS 2012 single lepton</td>
<td>$\sqrt{s} = 8$ TeV, $L_{\text{int}} = 20.2$ fb$^{-1}$</td>
<td></td>
</tr>
<tr>
<td>Paper in preparation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CMS 2011 single lepton</td>
<td>$\sqrt{s} = 7$ TeV, $L_{\text{int}} = 5.0$ fb$^{-1}$</td>
<td></td>
</tr>
<tr>
<td>CMS 2012 single top</td>
<td>$\sqrt{s} = 8$ TeV, $L_{\text{int}} = 19.7$ fb$^{-1}$</td>
<td></td>
</tr>
<tr>
<td>JHEP 01 (2015) 053</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CMS 2012 single lepton</td>
<td>$\sqrt{s} = 8$ TeV, $L_{\text{int}} = 19.8$ fb$^{-1}$</td>
<td></td>
</tr>
<tr>
<td>arXiv:1605.09047</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CMS 2012 dilepton</td>
<td>$\sqrt{s} = 8$ TeV, $L_{\text{int}} = 19.7$ fb$^{-1}$</td>
<td></td>
</tr>
<tr>
<td>CMS-PAS-TOP-14-017</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* superseded by published result

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ATLAS-CONF-2011-037
ATLAS-CONF-2013-033, CMS-PAS-TOP-12-025
JHEP 10 (2013) 167
JHEP 1206 (2012) 088
CMS-PAS-TOP-11-020

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**Theory (NNLO QCD)**

**Data** ($F_R/F_L/F_0$)

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$W$ boson helicity fractions

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Top Properties

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CMS: Measurement of the top width at $\sqrt{s} = 8$ TeV

CMS-TOP-16-019

- Using $t\bar{t}$ and $tW$ decay events with 2 charged leptons
- Reconstruct $M_{\ell b}$ distribution and use for hypothesis tests
- $N_{\text{signal}} = \mu[(1 - x) \cdot N_{\text{SM}} + x \cdot N_{\text{alt}}]
- Measure hypothesis separation with $CL_s$ criterium

- Binary hypothesis test: $0.6 \leq \Gamma_t \leq 2.5$ GeV at the 95% C.L., with expected bounds of $0.6 \leq \Gamma_t \leq 2.4$ GeV with $m_t = 172.5$ GeV
- First direct measurement at LHC and most precise direct bound on top width
Conclusions

- New spin correlation measurements have been presented from both LHC and Tevatron experiments
- Top polarization measurements show no deviation from Standard Model prediction
- Measurement of $W$-Helicity provides probe of $Wtb$ vertex
- Direct searches to probe $Wtb$ vertex and its CP nature
- First measurement of top width with LHC

All measurements getting more precise and the search for the boundaries of the Standard Model continues!
Back Up
ATLAS: Anomalous couplings in the Wtb vertex with single top quarks at $\sqrt{s} = 7$ GeV

JHEP 04 (2016) 023

Normalized double differential angular measurement in $\theta^*$ and $\phi^*$

- $\theta^*$ defined relative to the $W$ boson direction in top rest frame
- $\phi^*$ defined relative to plane containing spectator quark and $W$

- $f_1$: fraction of $W$-Bosons with transverse polarization
- $\delta_-^\perp$: phase between amplitudes for long. and trans. $W$-Bosons produced with left-handed $b$-quarks

Simultaneous parameter extraction:

\[
f_1 = 0.37 \pm 0.05 \text{(stat.)} \pm 0.05 \text{(syst.)}
\]

\[
\delta_-^\perp = -0.014\pi \pm 0.023\pi \text{(stat.)} \pm 0.028\pi \text{(syst.)}
\]

Main uncertainties: Statistics, MC event generator and Jet Energy Scale
ATLAS: Anomalous couplings in the Wtb vertex with single top quarks at $\sqrt{s} = 7$ GeV
JHEP 04 (2016) 023

Assumption: $V_R = g_L = 0$

Limits at 95% C.L:
$\text{Re}[g_R/V_L] \in [-0.36, 0.10]$, $\text{Im}[g_R, V_L] \in [-0.17, 0.23]$, $\rho(\text{Re}[g_R/V_L], \text{Im}[g_R/V_L]) = 0.11$
ATLAS: Probing the $Wtb$ vertex structure with t-channel single top quarks at $\sqrt{s} = 8$ TeV

Using various angular distributions of top decays to extract top and $W$ polarization observables

<table>
<thead>
<tr>
<th>Asymmetry</th>
<th>Angular observable</th>
<th>Polarisation observable</th>
<th>SM prediction</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_{FB}^W$</td>
<td>$\cos \theta_\ell$</td>
<td>$\frac{1}{2} \alpha_\ell P$</td>
<td>0.45</td>
</tr>
<tr>
<td>$A_{FB}^W$</td>
<td>$\cos \theta_W \cos \theta_\ell^*$</td>
<td>$\frac{3}{8} P (F_R + F_L)$</td>
<td>0.10</td>
</tr>
<tr>
<td>$A_{FB}$</td>
<td>$\cos \theta_\ell^*$</td>
<td>$\frac{3}{4} \langle S_3 \rangle = \frac{3}{4} (F_R - F_L)$</td>
<td>-0.23</td>
</tr>
<tr>
<td>$A_{EC}$</td>
<td>$\cos \theta_\ell^*$</td>
<td>$\frac{3}{8} \sqrt{\frac{3}{2}} \langle T_0 \rangle = \frac{3}{16} (1 - 3 F_0)$</td>
<td>-0.20</td>
</tr>
<tr>
<td>$A_{FB}^T$</td>
<td>$\cos \theta_\ell^T$</td>
<td>$\frac{3}{4} \langle S_1 \rangle$</td>
<td>0.34</td>
</tr>
<tr>
<td>$A_{FB}^N$</td>
<td>$\cos \theta_N^*$</td>
<td>$-\frac{3}{4} \langle S_2 \rangle$</td>
<td>0</td>
</tr>
<tr>
<td>$A_{FB}^{T,\phi}$</td>
<td>$\cos \theta_\ell^* \cos \phi_\ell^*$</td>
<td>$-\frac{2}{\pi} \langle A_1 \rangle$</td>
<td>-0.14</td>
</tr>
<tr>
<td>$A_{FB}^{N,\phi}$</td>
<td>$\cos \theta_\ell^* \cos \phi_N^*$</td>
<td>$\frac{2}{\pi} \langle A_2 \rangle$</td>
<td>0</td>
</tr>
</tbody>
</table>

- 4 enrichment cuts $|\eta(j)| > 2$, $\Delta \eta(j, b) > 1.5$, $130 \text{ GeV} < m(l\nu b) < 200 \text{ GeV}$ and $H_T(\ell, j, E_T^{\text{miss}}) > 195 \text{ GeV}$ to improve S/B
ATLAS: Probing the $Wtb$ vertex structure with t-channel single top quarks at $\sqrt{s} = 8$ TeV

ATLAS-CONF-2016-096

- Measured angular distributions are unfolded to parton level (after background substraction)
  - Iterative bayesian unfolding for $A_{FB}^N$ and SM bayesian unfolding for other
- Angular asymmetries extracted from the unfolded distributions
- Results in agreement with Standard Model Prediction
  - Dominant sources of uncertainty: data statistics, modelling of t-channel and $t\bar{t}$, Jet Energy Scale
- Limit on $Im(g_R)$ extracted by using $A_{FB}^N$ and $A_{FB}^I$ distributions

\[ Im(g_R) \in [-0.17, 0.06] \]
(Assumption: $V_L = 1$, $V_R = g_L = 0$)
CMS: $Wtb$ couplings and FCNC in t-channel single top at $\sqrt{s} = 7$ GeV

CMS-PAS-TOP-14-007

- Final states with $\mu +$ jets channel
- After preselection use 3 Bayesian Neural Network for anomalous $Wtb$ couplings
- Observed exclusion limits at 95% C.L.:

$$f_R^{|R|} > 0.34, \quad f_L^{|L|} < 0.09$$

Limits on Branching Ratios:

$$Br(t \to u + g) < 3.55 \times 10^{-4},$$

$$Br(t \to c + g) < 3.44 \times 10^{-3}$$