Top Quark Properties at the LHC

Kelly Beernaert (DESY)
for the ATLAS & CMS collaborations

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Content

• Production:
  - Production cross sections, kinematics
  - Associated production $t\bar{t} + W, Z, \gamma$ → see talk by Markus Seidel
  - Spin correlations
  - Polarization
  - Production Asymmetries

• Decay:
  - Branching ratios
  - Anomalous couplings
  - Flavour-changing neutral currents
  - W helicity

• Results in single top channel → see talk by Martin zur Nedden

• CP violation in top pairs → see back-up
  → only small selection of results shown with focus on most recent ones
Introduction

- Why study top quark properties?
  - Top quark decays before it can form bound states
    - Study “bare” quark properties using the decay products
  - Top quark decays before the spin decorrelates
    - $\tau_t \sim 0.5 \times 10^{-24} \text{ s} < m_t / \Lambda_{QCD}^2 \sim 3 \times 10^{-21} \text{ s}$
    - Study spin correlation properties
  - Heaviest particle known: ($m_t \sim 173$ GeV)
    - Large coupling to Higgs boson, plays significant role in EWSB
  - Properties measurements test SM and probe new physics
    - Increasing levels of precision and COM energy at LHC → sensitivity of several BSM models coming within reach
Top quark asymmetries

- Measurement of $A_{FB}$ at Tevatron and $A_C$ at LHC are complementary to evaluate new physics models
  - Various models still allowed
  - $\rightarrow W', G, \omega, \varphi, \Omega$

- Evaluate asymmetry based on fully reconstructed top quarks or leptons in dilepton channel

$$A_C = \frac{N(\Delta |y|>0) - N(\Delta |y|<0)}{N(\Delta |y|>0) + N(\Delta |y|<0)} \quad \Delta |y| \equiv |y_t| - |y_{\bar{t}}|$$

$$A_{FB} = \frac{N(\Delta y>0) - N(\Delta y<0)}{N(\Delta y>0) + N(\Delta y<0)} \quad \Delta y \equiv y_t - y_{\bar{t}}$$
Top quark asymmetries

ATLAS, 8 TeV, 20.3 fb\(^{-1}\), lepton+jets channel


- Boosted regime: \(m(t\bar{t}) > 0.75\) TeV
  - Leptonic decay resolved
  - Hadronic decay reconstructed as large R jet with substructure
- Full Bayesian unfolding
- Differential in \(m(t\bar{t})\)

\[ A_C = (4.2 \pm 3.2)\% \text{ (stat + syst)} \]

SM pred: \(A_C = (1.6 \pm 0.04)\%\) for \(m(t\bar{t}) > 0.75\) TeV


- 3 signal regions: 0, 1, 2 b-tag
- Likelihood fit to reconstruct \(t\bar{t}\)
- Full Bayesian unfolding
- Differential in \(m(t\bar{t}), \beta_z(t\bar{t}), p_T(t\bar{t})\)

\[ A_C = (0.9 \pm 0.5)\% \text{ (stat + syst)} \]

SM pred: \(A_C = (1.11 \pm 0.04)\%\)

A. C. = (4.2 ± 3.2) % (stat + syst)  
SM pred: A. C. = (1.6 ± 0.04) %  
for m(t\bar{t}) > 0.75 TeV

A. C. = (0.9 ± 0.5)% (stat + syst)  
SM pred: A. C. = (1.11 ± 0.04)%
Top quark asymmetries

ATLAS, 8 TeV, 20.3 fb$^{-1}$, lepton+jets channel

CMS, 8 TeV, 19.7 fb$^{-1}$, lepton+jets channel


arXiv:1507.03119, submitted to PLB

Good agreement with SM
Top quark asymmetries

CMS, 8 TeV, 19.7 fb\(^{-1}\), lepton+jets channel

- Template method:
  - Use symmetric and asymmetric version of MC template to fit
    \[ \rho^\pm (X) = [\rho (X) \pm \rho (-X)] / 2 \]
  - Smaller statistical uncertainty than unfolding, larger model dependence
  - Observable needs to be bounded:
    \[ Y_{t\bar{t}} = \tanh \Delta |y|_{t\bar{t}} \]

- Fit to \( Y_{t\bar{t}} \) distribution: fit parameter \( \alpha \) of relative contribution from symmetric and anti-symmetric templates

\[ A_C = [0.33 \pm 0.42 \text{(stat+syst)}] \% \]

SM pred: (1.11 ± 0.04)\%
Top quark asymmetries

CMS, 8 TeV, 19.7 fb⁻¹, dilepton channel

- Asymmetry defined with decay leptons and reconstructed tops
  \[
  A_{C}^{\text{lep}} = \frac{N(\Delta|\eta_{l}|>0) - N(\Delta|\eta_{l}|<0)}{N(\Delta|\eta_{l}|>0) + N(\Delta|\eta_{l}|<0)}
  \]

- Top reconstruction using matrix weighting technique

- Regularised unfolding to parton level

- Differential measurement in \(m(\bar{t}t), |y(\bar{t}t)|, p_{T}(\bar{t}t)\)

\[
A_{C} = [1.1 \pm 1.3 \text{ (stat+syst)}] \%
\]
SM pred: (1.11 ± 0.04)%

\[
A_{C}^{\text{lep}} = [0.3 \pm 0.7 \text{ (stat+syst)}] \%
\]
SM pred: (0.64 ± 0.03)%

arXiv:1603.06221, sub. to PLB
Top quark asymmetries

- Good agreement between theory and experiment
- NNLO predictions are being finalized
- On experiment side: statistical and systematic uncertainties are comparable in size
- Several differential distributions available + results in high $m(\bar{t}t)$ region where asymmetry is enhanced
Top quark spin correlations

- Top quark spins are correlated in the SM
dilepton channel, 7 TeV, reconstruction of \( tt \) final state
\[
\frac{1}{N} \frac{d^2 N}{d \cos \theta_1 d \cos \theta_2} = \frac{1}{4} \left( 1 + B_1 \cos \theta_1 + B_2 \cos \theta_2 - C_{\text{helicity}} \cos \theta_1 \cos \theta_2 \right)
\]
- with \( \theta \) angle between lepton direction in top parent rest frame and top parent in \( tt \) rest frame

- Bayesian unfolding to parton level

- Dominated by:
  unfolding uncertainties, theoretical modeling, jet reconstruction

- Direct extraction of \( C = -A \alpha_1 \alpha_2 \)

\[
A_{\text{hel}} = 0.315 \pm 0.061 \text{ (stat)} \pm 0.049 \text{ (syst)}
\]
Top quark spin correlations

- dilepton channel, 8 TeV, reconstruction of ttbar final state
- Regularized unfolding to parton level
- Using asymmetries (also differentially) → direct measurement of spin correlation strength and polarization
- Dominated by: top $p_T$ modeling & JES

Search for top chromomagnetic couplings using differential cross sections, limit on CMDM $\text{Re}(\mu_t)$ and CEDM $\text{Im}(d_t)$ at 95% CL

$$-0.053 < \text{Re}(\mu_t) < 0.026$$
$$-0.068 < \text{Im}(d_t) < 0.067$$

First result on $\text{Im}(d_t)$
Top quark spin correlations

- Dominated by: hadronization and ISR/FSR
- $f_{SM} = 1.20 \pm 0.05 \text{ (stat)} \pm 0.13 \text{ (syst)}$
- Top squarks in MSSM with 100% $t \rightarrow t\chi^0$ with mass close to $m_t$

→ Excluded masses between $m_t$ and 191 GeV at 95% CL

PRL 114 142001 (2015)
Top quark spin correlations

- Reconstruction in the muon+jets channel with 4,5 jets using kinematic fitter
- LO Matrix Element Method for event likelihoods (MadWeight) under SM or uncorrelated
- Hypothesis testing + fit to likelihood ratio distribution
- Dominated by: hadronization uncertainty

\[ f = 0.72 \pm 0.08 \, (stat) + 0.15 \, (syst) \]

arXiv:1511.06170, submitted to PLB
Top quark spin correlations
Flavour-changing neutral current

- SM: no FCNC at tree level (GIM suppression),
  \( BR \sim O(10^{-12} \rightarrow 10^{-17}) \)
- \( t \rightarrow u/c + X, X = g, \gamma, Z \) and \( H \)
- BSM: 2HDM, MSSM, … → enhanced couplings → \( BR \) as high as \( 10^{-5} \)

\[ B(t \rightarrow Hc) < 1.16 \% \text{ (obs) at 95\% CL} \]
\[ B(t \rightarrow Hu) < 1.92 \% \text{ (obs) at 95\% CL} \]

- \( t \rightarrow Hq \rightarrow \bar{b}bq \) and \( t \rightarrow Wb \rightarrow lvb \)

\[ B(t \rightarrow Hc) < 0.74 \% \text{ (obs) at 95\% CL} \]
\[ B(t \rightarrow Hu) < 0.42 \% \text{ (obs) at 95\% CL} \]

- \( t \rightarrow Hq \rightarrow \gamma\gamma q \) and \( t \rightarrow Wb \rightarrow lvb \) or \( qqb \)

\[ B(t \rightarrow Hc) < 0.93 \% \text{ (obs) at 95\% CL} \]

- \( t \rightarrow Hq \rightarrow ZZq \) or \( WWq \) and \( t \rightarrow Wb \rightarrow lvb \)
Flavour-changing neutral current

- \( \bar{t}t \) production with
- \( t \to Hq \rightarrow b\bar{b}q \) and \( t \to Wb \rightarrow l\nu b \)
- Categories based on jet, b-tag multiplicity → (4 j, 3 b) and (4 j, 4 b) most sensitive
- Signal/background discriminant:

\[
D(x) = \frac{P^{\text{sig}}(x)}{P^{\text{sig}}(x) + P^{\text{bkg}}(x)}
\]

with \( P^{\text{sig}} \), \( P^{\text{bkg}} \) PDFs using the resonances and jet flavour content of final state

<table>
<thead>
<tr>
<th>( BR(t \to Hc) ) [%]</th>
<th>Total Stat. Syst.</th>
</tr>
</thead>
<tbody>
<tr>
<td>( H \to WW, \tau \tau )</td>
<td>( 0.27 \pm 0.27 (\pm 0.18 \pm 0.21) % )</td>
</tr>
<tr>
<td>( H \to \gamma \gamma )</td>
<td>( 0.22 \pm 0.28 (\pm 0.26 \pm 0.10) % )</td>
</tr>
<tr>
<td>( H \to b \bar{b} )</td>
<td>( 0.17 \pm 0.21 (\pm 0.12 \pm 0.17) % )</td>
</tr>
<tr>
<td>Combined</td>
<td>( 0.22 \pm 0.14 (\pm 0.10 \pm 0.10) % )</td>
</tr>
</tbody>
</table>

limit at 95% CL: \( B(t \to Hc) < 0.56 \% \) (obs)
\( B(t \to Hu) < 0.61 \% \) (obs)
Flavour-changing neutral current

combined summary plots

- All analyses presented assume all anomalous couplings are zero, but one
- Still far above SM prediction, but sensitivity to certain BSM models getting closer or even already reached
Conclusions and outlook

- High precision measurements, dominated by systematic uncertainties → focus on improving **signal modeling, generator and theory uncertainties**

- Top charge asymmetry:
  - no deviations from SM observed
  - Measurements becoming dominated by systematic uncertainty

- FCNC: sensitivity to certain BSM models (almost) within reach

- No observation of New Physics or deviations from the SM from LHC Run I

Only a small selection of results is shown, for more information:

  ATLAS Top Web pages
  CMS Top Web pages

Thank you!
Back up
CP violation in top pairs

- 8 TeV, semi-leptonic ttbar channel
- CP violation clear sign of new physics, SM predicts 0 asymmetry
- Asymmetries based on T-odd triple products

\[ A_{CP}(O_i) = \frac{N_{events}(O_i > 0) - N_{events}(O_i < 0)}{N_{events}(O_i > 0) + N_{events}(O_i < 0)} \]

\[ O_2 = Q_\ell e(P, p_b + p_\bar{b}, p_\ell, p_{j1}) \xrightarrow{lab} \propto Q_\ell (\vec{p}_b + \vec{p}_\bar{b}) \cdot (\vec{p}_\ell \times \vec{p}_{j1}) \]

\[ O_3 = Q_\ell e(p_b, p_\bar{b}, p_\ell, p_{j1}) \xrightarrow{b\bar{b} CM} \propto Q_\ell \vec{p}_b \cdot (\vec{p}_\ell \times \vec{p}_{j1}) \]

\[ O_4 = Q_\ell e(P, p_b - p_\bar{b}, p_\ell, p_{j1}) \xrightarrow{lab} \propto Q_\ell (\vec{p}_b - \vec{p}_\bar{b}) \cdot (\vec{p}_\ell \times \vec{p}_{j1}) \]

\[ O_7 = q \cdot (p_b - p_\bar{b}) e(P, q, p_b, p_\bar{b}) \xrightarrow{lab} \propto (\vec{p}_b - \vec{p}_\bar{b})_z (\vec{p}_b \times \vec{p}_\bar{b})_z \]

<table>
<thead>
<tr>
<th>( A'_{CP}(O_i) )</th>
<th>e+jets</th>
<th>( \mu )+jets</th>
<th>( \ell )+jets</th>
</tr>
</thead>
<tbody>
<tr>
<td>( O_2 )</td>
<td>-0.01 ± 0.61 ± 0.01</td>
<td>+0.50 ± 0.56 ± 0.02</td>
<td>+0.27 ± 0.41 ± 0.01</td>
</tr>
<tr>
<td>( O_3 )</td>
<td>-0.34 ± 0.61 ± 0.02</td>
<td>-1.03 ± 0.56 ± 0.04</td>
<td>-0.71 ± 0.41 ± 0.03</td>
</tr>
<tr>
<td>( O_4 )</td>
<td>-0.24 ± 0.61 ± 0.02</td>
<td>-0.49 ± 0.56 ± 0.04</td>
<td>-0.38 ± 0.41 ± 0.03</td>
</tr>
<tr>
<td>( O_7 )</td>
<td>-0.42 ± 0.61 ± 0.00</td>
<td>+0.46 ± 0.56 ± 0.01</td>
<td>-0.06 ± 0.41 ± 0.01</td>
</tr>
</tbody>
</table>
Charge Asymmetry


Flavour-changing neutral current

combined summary plots

- All analyses presented assume all anomalous couplings are zero, but one
- Many channels are covered → consider pursuing global approach, considering mixing of various anomalous couplings at NLO

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