Top Quark Properties at the LHC

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Content

• Production:
  – Production cross sections, kinematics
  – Associated production $t\bar{t} + W, Z, \gamma \rightarrow$ 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 $\rightarrow$ see talk by Martin zur Nedden
  $\rightarrow$ only small selection of results shown with focus on most recent ones
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
  - \( \tau_t \approx 0.5 \times 10^{-24} \text{ s} < m_t / \Lambda_{\text{QCD}}^2 \approx 3 \times 10^{-21} \text{ s} \)
  - Study spin correlation properties
- Heaviest particle known: \( m_t \approx 173 \text{ GeV} \)
  - 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
  - $\to W', G, \omega, \phi, \Omega$

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

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

$$A_{FB}^{new} = \frac{N(\Delta y>0) - N(\Delta y<0)}{N(\Delta y>0) + N(\Delta y<0)} \Delta y = y_{\bar{t}} - y_t$$

arxiv:1207.0331
Top quark asymmetries

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

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- 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

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- 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: \(A_C = (1.11 \pm 0.04)\% \)
Top quark asymmetries

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

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

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arXiv:1507.03119, submitted to PLB

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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
    \[ \rho^\pm (X) = \frac{\rho (X) + \rho (-X)}{2} \]
  - 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 \pm 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)%
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(\(t\bar{t}\)) 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
  \[ \frac{1}{N} \frac{d^2 N}{d \cos \theta_1 d \cos \theta_2} = \frac{1}{4} (1 + B_1 \cos \theta_1 + B_2 \cos \theta_2 - C_{helicity} \cos \theta_1 \cos \theta_2) \]
  - 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 \( C = -A\alpha_1\alpha_2 \)
  \[ A_{hel} = 0.315 \pm 0.061 \text{ (stat)} \pm 0.049 \text{ (syst)} \]
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

$-0.053 < \text{Re}(\mu_t) < 0.026$

$-0.068 < \text{Im}(d_t) < 0.067$

Phys. Rev. D93 (2016) 052007

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

- Dominated by: hadronization and ISR/FSR
- $f_{\text{SM}} = 1.20 \pm 0.05 \text{ (stat)} \pm 0.13 \text{ (syst)}$
- 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
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

\[ f = 0.72 \pm 0.08 \ (stat)^{+0.15}_{-0.13} \ (syst) \]

arXiv:1511.06170, submitted to PLB
Top quark spin correlations

### tt Spin Correlation Measurements Summary

| Experiment | Source | f_{SM} ± (stat) ± (syst) |
|------------|--------|--------------------------|
| D0, dilepton + e/\mu+jets | PRL 108 (2012) 032004, \(\sqrt{s}=1.96\text{ TeV}, L_{\text{int}}=5.4\text{ fb}^{-1}\) | 0.85 ± 0.29 |
| CMS, dilepton | PRL 112 (2014) 112001, \(\sqrt{s}=7\text{ TeV}, L_{\text{int}}=5.0\text{ fb}^{-1}\) | 1.02 ± 0.10 ± 0.22 |
| ATLAS, e/\mu+jets | PRL 90 (2014) 112016, \(\sqrt{s}=7\text{ TeV}, L_{\text{int}}=4.6\text{ fb}^{-1}\) | 1.12 ± 0.11 ± 0.22 |
| ATLAS, dilepton | PRL 90 (2014) 112016, \(\sqrt{s}=7\text{ TeV}, L_{\text{int}}=4.6\text{ fb}^{-1}\) | 1.19 ± 0.09 ± 0.18 |
| ATLAS, dilepton | PRL 114 (2015) 142001, \(\sqrt{s}=8\text{ TeV}, L_{\text{int}}=20.3\text{ fb}^{-1}\) | 1.20 ± 0.05 ± 0.13 |
| CMS, \mu+jets | arXiv:1511.06170, \(\sqrt{s}=8\text{ TeV}, L_{\text{int}}=19.8\text{ fb}^{-1}\) | 0.72 ± 0.08 ± 0.15 |
| CMS, dilepton | arXiv:1601.01107, \(\sqrt{s}=8\text{ TeV}, L_{\text{int}}=19.5\text{ fb}^{-1}\) | 1.12 ± 0.06 ± 0.11 |
Flavour-changing neutral current

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

\[ \begin{align*}
B(t \rightarrow H_c) &< 1.16 \% \text{ (obs) at 95\% CL} \\
B(t \rightarrow H_u) &< 1.92 \% \text{ (obs) at 95\% CL}
\end{align*} \]

- \( t \rightarrow Hq \rightarrow b\bar{b}q \) and \( t \rightarrow Wb \rightarrow l\nu b \)

\[ \begin{align*}
B(t \rightarrow H_c) &< 0.47 \% \text{ (obs) at 95\% CL} \\
B(t \rightarrow H_u) &< 0.42 \% \text{ (obs) at 95\% CL}
\end{align*} \]

- \( t \rightarrow Hq \rightarrow \gamma\gamma q \) and \( t \rightarrow Wb \rightarrow l\nu b \) or \( q\bar{q} b \)

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

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

- tt production with
  - $t \to Hq \rightarrow b\bar{b}q$ and $t \to Wb \rightarrow lvb$
- Categories based on jet, b-tag multiplicity
  - $(4j, 3b)$ and $(4j, 4b)$ 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

limit at 95% CL: $B(t \to Hc) < 0.56 \%$ (obs)
$B(t \to Hu) < 0.61 \%$ (obs)
- 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
Charge Asymmetry

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• 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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