Measurements of the top quark properties at production with CMS

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on behalf of CMS collaboration

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Introduction

- Some top quark properties are predicted by the SM, some are not (e.g. mass, $V_{tq}$)
  - precision measurements can reveal signs of new physics
  - unique opportunity to measure properties of "bare" quark

In this talk:
- latest measurements of top quark properties in $t\bar{t}$ production with CMS detector
- study of dilepton and lepton+jets final states

Also see talks for other properties:
- by J. E. Palencia Cortezon: CMS Measurements of the top quark mass and width
- by J. Andrea: Measurement of single top quark production with CMS
- by A. Castro: Measurements of the top quark properties at decay with CMS
Spin correlations and polarization

- In SM, top quarks from pair production are almost unpolarized, but have correlated spins.
- Top quark lifetime (~10^{-25}s) is much shorter than the spin decorrelation time scale (~10^{-21}s).
  - angular distributions of top quark decay products provide access to spin of top quark.
- Study spin correlation strength $A$ and coefficient $f_{SM}$ shows its relation to SM correlation:

  $$A = \frac{(N_{\uparrow\uparrow} + N_{\downarrow\downarrow}) - (N_{\uparrow\downarrow} + N_{\downarrow\uparrow})}{(N_{\uparrow\uparrow} + N_{\downarrow\downarrow}) + (N_{\uparrow\downarrow} + N_{\downarrow\uparrow})}$$

  $$f_{SM} = \frac{N_{SM}^{t\bar{t}}}{N_{SM}^{t\bar{t}} + N_{uncorrelated}^{t\bar{t}}}$$
Spin correlations & polarization in dileptons

- Probing spin density matrix and extraction of $f_{SM}$
- Using asymmetries in angular observables of two leptons
  - $\Delta \phi(\ell^+\ell^-)$: difference in azimuthal angles in the laboratory frame
  - $\cos \theta^*(\ell^\pm)$ and $\cos \theta^*(\ell^+)$·$\cos \theta^*(\ell^-)$: dependent from helicity angles $\theta^*(\ell)$
  - $\cos \varphi$: angle between leptons measured in rest frames of parental top quarks
- Inclusive and differential measurements of asymmetries
  - in bins of $m_{t\bar{t}}$, $|y_{t\bar{t}}|$, $p_T^{t\bar{t}}$
- Setting limits on chromo-magnetic and chromo-electric dipole moments

[Graphs and plots showing data comparison and asymmetry measurements]
Spin correlations in muon+jets

- Consistency check of spin correlation strength in $t\bar{t}$ with the SM
- Test of two hypothesis behind $t\bar{t}$ production in data
  - spin correlation predicted by SM
  - no spin correlation
  - event probabilities $P$ estimated via matrix element method
  - separation power given by sample likelihood ratio $\lambda$

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Spin correlations in muon+jets

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  - no spin correlation: within 2.9σ

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- Template fit for extraction of $f_{SM}$ and background fraction
  - using distribution of event likelihood ratio $\lambda$
  - SM contribution: $f_{SM} = 0.72 \pm 0.08 \text{ (stat.)} ^{+0.15}_{-0.13} \text{ (syst.)}$
  - spin correlation strength:

$$A_{hel}^{\text{measured}} = f_{SM} \cdot A_{hel}^{SM, MC} = 0.23 \pm 0.03 \text{ (stat.)} ^{+0.05}_{-0.04} \text{ (syst.)}$$
Good agreement between SM predictions and both experiments
Charge asymmetry

- Non-zero charge asymmetry in $t\bar{t}$ production through $q\bar{q}$ interaction beyond LO

- At LHC, different centrality in rapidity for top quarks and anti-quarks

- Measure charge asymmetry $A_C$ using observable $\Delta|y_t| = |y_t| - |y_{\bar{t}}|

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

- Enhanced by BSM scenarios, e.g. axigluons, $Z'$
Charge asymmetry in dileptons

- Inclusive and differential measurements of $A_C$

- Also measure observable $A_C^{\text{lep}}$ using $\Delta|\eta_\ell| = |\eta_{\ell^+}| - |\eta_{\ell^-}|$
  - better resolution and independent from top reconstruction
  - carries info about top quark polarization

<table>
<thead>
<tr>
<th>Variable</th>
<th>Data</th>
<th>MC@NLO</th>
<th>NLO (QCD+EW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_C$</td>
<td>$0.011 \pm 0.011 \pm 0.007$</td>
<td>$0.006 \pm 0.001$</td>
<td>$0.0111 \pm 0.0004$</td>
</tr>
<tr>
<td>$A_C^{\text{lep}}$</td>
<td>$0.003 \pm 0.006 \pm 0.003$</td>
<td>$0.004 \pm 0.001$</td>
<td>$0.0064 \pm 0.0003$</td>
</tr>
</tbody>
</table>

- Extraction from unfolded spectrum in bins of $m_{\tilde{t}\tilde{t}}$, $|y_{\tilde{t}\tilde{t}}|$, $p_T^{\tilde{t}\tilde{t}}$

All results in agreement with SM
Unfolding method

Inclusive and differential measurement of $A_C$
- unfolding of $\Delta|y_t|$ back to parton level after background subtraction
- presented in full and fiducial phase space
- also as a function of $m_{t\bar{t}}$, $|y_{t\bar{t}}|$, $p_T^{t\bar{t}}$
Charge asymmetry in lepton+jets

- **Unfolding method**
  - Inclusive and differential measurement of $A_C$
    - unfolding of $\Delta |y_t|$ back to parton level after background subtraction
    - presented in full and fiducial phase space
    - also as a function of $m_{t\bar{t}}$, $|y_{t\bar{t}}|$, $p_T^{t\bar{t}}$
  - **Template method**
    - Transformed rapidity observable: $Y_{t\bar{t}} = tanh \Delta |y_t|$
    - Extract $A_C$ via template fit of reconstructed $Y_{t\bar{t}}$
      - using (anti)symmetric $x^{(\pm)}$ components of probability density for $Y_{t\bar{t}}$ from base model (SM)

$$\chi^2_{\alpha}^{data} = \chi^2_{+\,rec}^{+} + \alpha \cdot \chi^2_{-\,rec}$$

[Graphs and plots showing data and theoretical predictions for $A_C$]
Charge asymmetry in lepton+jets

Results in agreement with SM predictions

![Graph showing CMS results and comparison with other models.](image)
CP violation in $t\bar{t}$ production and decay

- Very small in SM, but may be enhanced by potential new physics
- Search for effects induced by CP-violating anomalous top quark couplings
- Sizable deviations from the SM may shed light on the matter-antimatter asymmetry of the universe
Search for CP violation in $t\bar{t}$ production and decay

- First measurement of CP-violating asymmetries in $t\bar{t}$
- Construct four T-odd observables $O_i$
  - use spin or momentum vectors of decay products in $t\bar{t}\rightarrow \ell+\text{jets}$ final state
- Non-zero asymmetry as an evidence of CP violation:
  $$A_{CP}(O_i) = \frac{N_{\text{events}}(O_i > 0) - N_{\text{events}}(O_i < 0)}{N_{\text{events}}(O_i > 0) + N_{\text{events}}(O_i < 0)}$$
- Up-to 8% CPV effects are expected in $A_{CP}(O_i)$ depending on theory model
- Consistent with SM, thus no observation of CP violating effects
Summary

- Probing nature with several measurements of top quark properties at production with CMS
  - spin correlation and polarization: unfolding and MEM methods
  - charge asymmetry: unfolding and template methods
  - CP violation

- All results are in agreement with SM and no evidence of new physics

- Next generation of new exciting results to come with study of latest 13 TeV data from LHC
Summary

- Probing nature with several measurements of top quark properties at production with CMS
  - spin correlation and polarization: unfolding and MEM methods
  - charge asymmetry: unfolding and template methods
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THANK YOU FOR YOUR ATTENTION
Event selection

Lepton+jets:
- Exactly 1 high-p$_T$ isolated lepton (e or $\mu$)
  - $p_T >$ around 30 GeV (analysis dependent), $|\eta| < 2.1$
- ≥ 4 jets: $p_T >$ 30 GeV, $|\eta| < 2.4$
- ≥ 2 b-tagged jets

Dileptons:
- ≥ 2 OS, high-p$_T$ isolated leptons (ee, $\mu\mu$, $\mu e$)
  - $p_T >$ 20 GeV, $|\eta| < 2.4$
- QCD veto: $m_{ll} > 20$ GeV
- ≥ 2 jets: $p_T >$ 30 GeV, $|\eta| < 2.4$
- ≥ 1 b-tagged jets
- ee, $\mu\mu$ channels: $E_T^{\text{miss}} > 40$ GeV
  - Z veto: $|m_Z - m_{ll}| > 15$ GeV

In addition: kinematic reconstruction of $t\bar{t}$ system
Spin correlations in muon+jets

- Consistency check of spin correlation strength in $t\bar{t}$ with the SM

- Test of two hypothesis behind $t\bar{t}$ production in data
  - **spin correlation predicted by SM**: agrees within 2.2σ
  - **no spin correlation**: within 2.9σ
  - event probabilities $P$ estimated via matrix element method
  - separation power given by sample likelihood ratio

\[-2 \ln \lambda_{\text{sample}} = - \sum 2 \ln \lambda_{\text{event}} \propto \frac{P_{\text{uncorrelated}}}{P_{\text{correlated}}}\]

- Template fit for extraction of $f_{\text{SM}}$ and background fraction
  - using distribution of event likelihood ratio
  - SM contribution: $f_{\text{SM}} = 0.72 \pm 0.08 \text{(stat.)}^{+0.15}_{-0.13} \text{(syst.)}$
  - spin correlation strength:

\[A_{\text{hel, measured}} = f_{\text{SM}} \cdot A_{\text{hel, MC}} = 0.23 \pm 0.03 \text{(stat.)}^{+0.05}_{-0.04} \text{(syst.)}\]
Spin correlations & polarization in dileptons

- Search for hypothetical top quark anomalous couplings
  - setting limits on chromo-magnetic and chromo-electric dipole moments
  - parameters interfere with SM $t\bar{t}$ production
  - fit of new physics contributions or extraction from spin coefficients

- No evidence of new physics

\[
(1/\sigma \, d\sigma/d|\Delta \phi_{t\bar{t}}|)_{\text{NP}}
\]

- LO NP ($\mu_R = \mu_F = m_t$) [4]
- Parametrization

\[
1/\sigma \, d\sigma/d|\Delta \phi_{t\bar{t}}|
\]

- CMS
- 19.5 fb$^{-1}$ (8 TeV)
- Data
- Fit
- NLO SM ($\mu_R = \mu_F = m_t$)
- NLO SM ($\mu_R = \mu_F = 2 m_t$)
- NLO SM ($\mu_R = \mu_F = m_t/2$)
- Unfolding method
  - Inclusive and differential measurement of $A_C$
    - unfolding of $\Delta|y_t|$ back to parton level after background subtraction
    - presented in full and fiducial phase space
    - also as a function of $m_{t\bar{t}}$, $|y_{t\bar{t}}|$, $p_T^{t\bar{t}}$

- Template method
  - Transformed rapidity observable: $Y_{t\bar{t}} = tanh \Delta|y_t|$
  - Extract $A_C$ via template fit of reconstructed $Y_{t\bar{t}}$
    - using (anti)symmetric ($x^+$ and $x^-$) components of probability density for $Y_{t\bar{t}}$ from base model (SM)
    - connected with fit parameter $\alpha$

\[ A_C^{data} = \alpha \cdot A_C^{model} \quad \Leftrightarrow \quad x_\alpha^{data} = x^{+,\text{rec}} + \alpha \cdot x^{-,\text{rec}} \]
First measurement of CP-violating asymmetries in $t\bar{t}$

- Construct four T-odd observables $O_i$ of the form $\vec{u}_1 \cdot (\vec{u}_2 \times \vec{u}_3)$
  - use spin or momentum vectors of decay products in $t\bar{t} \to \ell + \text{jets}$ final state
  - also CP-odd, if CPT conservation is valid
  - e.g., $O_2 \propto (\vec{p}_b + \vec{p}_{\bar{b}}) \cdot (\vec{p}_\ell \times \vec{p}_{j_1})$

- Non-zero asymmetry as an evidence of CP violation:
  \[ A^{\text{CP}}(O_i) = \frac{N_{\text{events}}(O_i > 0) - N_{\text{events}}(O_i < 0)}{N_{\text{events}}(O_i > 0) + N_{\text{events}}(O_i < 0)} \]

- Up-to 8% CPV effects are expected in $A^{\text{CP}}(O_i)$ depending on theory model

- Consistent with SM, thus no observation of CP violating effects
Search for CP violation in $t\bar{t}$ production and decay

- Results are presented as $A'_{CP}$ (raw) and $A_{CP}$ (corrected for detector effects) asymmetries
  - after background subtraction (determined from fit)
  - systematic uncertainty mostly arises from estimation of possible detector bias

- Consistent with SM, thus no observation of CP violating effects