Top quark property measurements at CMS

The 9th Workshop of TeV Physics Working Group in 2014

Yanjun Tu
Heaviest elementary particle known

- Produced at the LHC predominantly through strong interactions - high production rate
- Decays predominantly through $t \rightarrow bW$
- Decays before hadronization - access spin information via its decay products

Test Standard Model predictions

- Mass, couplings, and other properties have been measured precisely at the LHC

Probe to new physics

- Large couplings to the Higgs boson
- Special role in the EW symmetry breaking in many new physics scenarios

Outline:

- Top mass
- TTbar spin correlation and top polarization
- Top pair charge asymmetry
- W helicity in top decays
- Search for anomalous couplings
- TTbar association production with photon
Top mass at 7 TeV - hadronic

- 2011 dataset at $\sqrt{s} = 7$ TeV: 3.54 fb
- At least 6 jets, at least two of them are b-tagged
- Kinematic fit with the constraints that the reconstructed masses of two tops are equal and the mass of both W bosons is 80.4 GeV
- Cuts on the goodness of fit probability and separation of the two b jets are applied
- Ideogram method uses a likelihood function that allows the determination of the JES and the top quark mass simultaneously by a joint fit to all events in data

2D Fit Results: $m_t = 174.28 \pm 1.00\text{(stat+JES)} \pm 1.23\text{(syst)}$ GeV and $\text{JES} = 0.991 \pm 0.008\text{(stat)} \pm 0.013\text{(syst)}$
Top mass at 8 TeV - single lepton

- **Full 2012 dataset at $\sqrt{s} = 8$ TeV: 19.7/fb**
- One isolated lepton, at least 4 jets, two of them are b-tagged, MET
- A kinematic fit of the decay products to a ttbar hypothesis
- Ideogram method: 2D likelihood functions for each event to estimate simultaneously the top-quark mass and the jet energy scale (JSF)

$$mt = 172.04\pm0.19\text{(stat+JSF)}\pm0.75\text{(syst)} \text{ GeV}$$

$$\text{JSF} = 1.007\pm0.002\text{(stat)}\pm0.012\text{(syst)}$$
Top mass at 7 TeV - dilepton

- Full 2011 dataset at $\sqrt{s} = 7$ TeV: 5.0/fb
- Two isolated leptons, at least two jets (at least one b-tagged jet), MET
- Analytical Matrix Weighting Technique: the kinematic equations are solved many times per event using a series of top-quark mass hypotheses between 100 and 400 GeV in 1 GeV steps.

- Each solution is weighted according to top mass hypothesis and lepton momenta

For each event, the mass hypothesis with maximum weight is chosen

For each value of $M_t$, a likelihood is computed by comparing the reconstructed mass distribution in data with the expectation in simulation

$M_t = 172.5 \pm 0.4\,\text{(stat)} \pm 1.5\,\text{(syst)}$ GeV
Top mass and $\alpha_s$ extracted from $t\bar{t}$bar cross section

- **2011 dataset at $\sqrt{s} = 7$ TeV:** 2.3/fb
- The measured inclusive cross section for top-quark pair production is compared to the QCD prediction at NNLO to determine top pole mass or the strong coupling $\alpha_s$

---

Observed cross section in the dilepton channel with 2.3/fb: $161.9 \pm 6.7$ pb

With the PDF set NNPDF2.3, $M_t = 176.7^{+3.8}_{-3.4}$ GeV when constraining $\alpha_s(M_Z) = 0.1184$

$\alpha_s(M_Z) = 0.1151^{+0.0033}_{-0.0032}$ when constraining $M_t = 173.2$ GeV
Top mass new combinations

Tevatron+LHC $m_{top}$ indiv. comb. - March 2014, $L_{int} = 3.5 \text{ fb}^{-1} - 8.7 \text{ fb}^{-1}$

ATLAS + CDF + CMS + D0 Preliminary

<table>
<thead>
<tr>
<th>Individual Combinations</th>
<th>$m_{top}$ [GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t!+!j$</td>
<td>$173.29 \pm 0.80$ (0.23 ± 0.24 ± 0.72)</td>
</tr>
<tr>
<td>di-lepton</td>
<td>$172.74 \pm 1.15$ (0.43 ± 0.06 ± 1.07)</td>
</tr>
<tr>
<td>all jets</td>
<td>$173.17 \pm 1.20$ (0.65 ± 0.30 ± 0.96)</td>
</tr>
<tr>
<td>$E_T^{miss}$ +jets</td>
<td>$173.93 \pm 1.85$ (1.26 ± 1.05 ± 0.86)</td>
</tr>
<tr>
<td>CDF</td>
<td>$173.19 \pm 1.00$ (0.52 ± 0.44 ± 0.73)</td>
</tr>
<tr>
<td>D0</td>
<td>$174.85 \pm 1.48$ (0.78 ± 0.48 ± 1.16)</td>
</tr>
<tr>
<td>ATLAS</td>
<td>$172.65 \pm 1.44$ (0.31 ± 0.41 ± 1.34)</td>
</tr>
<tr>
<td>CMS</td>
<td>$173.58 \pm 1.03$ (0.29 ± 0.28 ± 0.95)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Previous Comb.</th>
<th>$m_{top}$ [GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tevatron</td>
<td>$173.58 \pm 0.94$ (0.44 ± 0.36 ± 0.74)</td>
</tr>
<tr>
<td>LHC</td>
<td>$173.28 \pm 0.94$ (0.22 ± 0.26 ± 0.88)</td>
</tr>
<tr>
<td>World comb. 2014</td>
<td>$173.34 \pm 0.76$ (0.27 ± 0.24 ± 0.67)</td>
</tr>
<tr>
<td>Tevatron March 2013 (Run I+II)</td>
<td>$173.20 \pm 0.87$ (0.51 ± 0.36 ± 0.61)</td>
</tr>
<tr>
<td>LHC September 2013</td>
<td>$173.29 \pm 0.95$ (0.23 ± 0.26 ± 0.88)</td>
</tr>
</tbody>
</table>
Top spin correlation and polarization in ttbar

- Full 2011 dataset at $\sqrt{s} = 7$ TeV: 5/fb
- Dilepton channel, **top kinematics reconstructed** using analytical matrix weighting technique
- An “**unfolding**” procedure is employed to correct acceptance and resolution effects

Where $c_1 = \cos(\theta_{l+})$ and $c_2 = \cos(\theta_{l-})$,

\[
A_P = \frac{N(\cos(\theta_\ell) > 0) - N(\cos(\theta_\ell) < 0)}{N(\cos(\theta_\ell) > 0) + N(\cos(\theta_\ell) < 0)}
\]

\[
A_{\Delta \phi} = \frac{N(\Delta \phi_\ell^+ \ell^- > \pi/2) - N(\Delta \phi_\ell^+ \ell^- < \pi/2)}{N(\Delta \phi_\ell^+ \ell^- > \pi/2) + N(\Delta \phi_\ell^+ \ell^- < \pi/2)}
\]

\[
A_{c_1c_2} = \frac{N(c_1 \cdot c_2 > 0) - N(c_1 \cdot c_2 < 0)}{N(c_1 \cdot c_2 > 0) + N(c_1 \cdot c_2 < 0)}
\]

<table>
<thead>
<tr>
<th>Asymmetry</th>
<th>Data (unfolded)</th>
<th>MC@NLO</th>
<th>NLO (SM, correlated)</th>
<th>NLO (uncorrelated)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_{\Delta \phi}$</td>
<td>0.113 ± 0.010 ± 0.007 ± 0.012</td>
<td>0.110 ± 0.001</td>
<td>0.115 ± 0.004 ± 0.0016</td>
<td>0.210 ± 0.003 ± 0.008</td>
</tr>
<tr>
<td>$A_{c_1c_2}$</td>
<td>-0.021 ± 0.023 ± 0.027 ± 0.010</td>
<td>-0.078 ± 0.001</td>
<td>-0.078 ± 0.006</td>
<td>N/A</td>
</tr>
<tr>
<td>$A_P$</td>
<td>0.005 ± 0.013 ± 0.020 ± 0.008</td>
<td>0.000 ± 0.001</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>
Full 2011 dataset at $\sqrt{s} = 7$ TeV: 5.0/fb

CMS dilepton channel
$A_C = -0.010 \pm 0.017$(stat)$
$\pm 0.008$(syst)

$A_C^{\text{lep}} = 0.009 \pm 0.010$(stat)$
$\pm 0.006$(syst)

ATLAS+CMS: single lepton channel
$A_C = 0.005 \pm 0.007$(stat)$\pm 0.006$(syst);
NLO: $0.0115 \pm 0.0006$;  
JHEP 1201 (2012) 063
Inclusive measurement: $0.005 \pm 0.007 \text{(stat)} \pm 0.006 \text{(syst)}$

NLO: $0.0111 \pm 0.0004$  


**W helicity in top events**

- W boson helicity fraction in top-quark decays are sensitive to the Wtb couplings
- Measure W helicity fractions ($F_R$, $F_L$, and $F_0$) using $\cos(\theta^*)$ distribution in $t\bar{t}$ events
- NNLO predictions in the SM: $F_L = 0.311 \pm 0.05$, $F_0 = 0.687 \pm 0.005$, $F_R = 0.0017 \pm 0.0001$

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

### 7 TeV

| Lepton+jets | FL = 0.310 ± 0.022 (stat.) ± 0.022 (syst.), FR = 0.008 ± 0.012 (stat.) ± 0.014 (syst.), F0 = 0.682 ± 0.030 (stat.) ± 0.033 (syst.) | JHEP 10 (2013) 167 |
| Dilepton | FL = 0.288 ± 0.035 (stat) ± 0.040 (sys), FR = 0.014 ± 0.027 (stat) ± 0.042 (sys), F0 = 0.698 ± 0.057 (stat) ± 0.063 (sys) | CMS PAS TOP-12-015 |
| Single top | FL = 0.293 ± 0.069 (stat.) ± 0.030 (syst.), FR = −0.006 ± 0.057 (stat.) ± 0.027 (syst.), F0 = 0.713 ± 0.114 (stat.) ± 0.023 (syst.) | CMS PAS TOP-12-020 |
| Atlas+CMS combination Lepton+jets and dilepton | FL = 0.359 ± 0.021 (stat.) ± 0.028 (syst.), FR = 0.015 ± 0.034, F0 = 0.626 ± 0.034 (stat.) ± 0.048 (syst.) | CMS PAS TOP-12-025 |

### 8 TeV

| Lepton+jets | FL = 0.350 ± 0.010 (stat.) ± 0.024 (syst.), FR = −0.009 ± 0.006 (stat.) ± 0.020 (syst.), F0 = 0.659 ± 0.015 (stat.) ± 0.023 (syst.) | CMS PAS TOP-13-008 |

**References:**
- JHEP 10 (2013) 167
Search for FCNC in top decays

- **Full 2012 dataset at √s = 8 TeV:** 19.7/fb
- t→Zq suppressed in SM but can be enhanced in new physics models
- 3 isolated leptons + at least two jets (exactly one is b-tagged)+missing transverse momentum

<table>
<thead>
<tr>
<th>Process</th>
<th>Estimation from data</th>
<th>MC prediction</th>
</tr>
</thead>
<tbody>
<tr>
<td>t→Zq (B = 0.1%)</td>
<td>—</td>
<td>6.4 ± 0.1 ± 1.3</td>
</tr>
<tr>
<td>Total background</td>
<td>3.1 ± 0.8 ± 0.8</td>
<td>3.2 ± 1.2 ± 1.5</td>
</tr>
<tr>
<td>Observed events</td>
<td>1</td>
<td>—</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>B(t → Zq)</th>
<th>8 TeV</th>
<th>7 TeV + 8 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expected upper limit</td>
<td>&lt;0.10%</td>
<td>&lt;0.09%</td>
</tr>
<tr>
<td>Observed upper limit</td>
<td>&lt;0.06%</td>
<td>&lt;0.05%</td>
</tr>
<tr>
<td>1 σ boundary</td>
<td>0.06–0.13%</td>
<td>0.06–0.13%</td>
</tr>
<tr>
<td>2 σ boundary</td>
<td>0.05–0.20%</td>
<td>0.05–0.18%</td>
</tr>
</tbody>
</table>

CERN-PH-EP-2013-208, accepted by PRL
**TTbar + photon cross section**

- **Full 2012 dataset at $\sqrt{s} = 8$ TeV: 19.7/fb**
- one muon, at least four jets (at least one b-tagged), one $\gamma$
- quantity of correctly identified prompt photons is estimated using a binned maximum likelihood template fit

---

**CMS preliminary L=19.7 fb$^{-1}$ at $\sqrt{s}=8$ TeV**

\[ R = \frac{\sigma_{tt+\gamma}}{\sigma_{tt}} \]

\[ = (1.07 \pm 0.07 \text{(stat.)} \pm 0.27 \text{(syst.)}) \cdot 10^{-2} \]

\[ \sigma_{tt+\gamma} = R \cdot \sigma_{tt}^{\text{CMS}} \]

\[ = 2.4 \pm 0.2 \text{(stat.)} \pm 0.6 \text{(syst.)} \text{pb} \]

\[ \sigma_{tt+\gamma}^{\text{SM}} = 1.8 \pm 0.5 \text{pb} \]
Conclusions

- As a top factory, LHC allows precision measurements of many top properties - they are not only the tests for the SM, but also good probes to new physics

- CMS latest results of top property measurements have been presented - all presented results are in good agreement with SM predictions
Top polarization in t-channel single-top production

- **Full 2012 dataset at $\sqrt{s} = 8$ TeV: 19.7/fb**
- One isolated lepton, two jets (one b-tagged), MET
- In t-channel single-top production, top quarks are almost 100% polarized through the V-A coupling structure
- New physics models may alter the coupling structure which affects the top quark polarization

\[
A_l = \frac{N(\cos \theta^*_{\text{unfolded}} > 0) - N(\cos \theta^*_{\text{unfolded}} < 0)}{N(\cos \theta^*_{\text{unfolded}} > 0) + N(\cos \theta^*_{\text{unfolded}} < 0)}. 
\]

\[
P = \frac{1}{2} \cdot P_T \cdot \alpha_l
\]

Polarization: $0.82 \pm 0.12\text{(stat)} \pm 0.32\text{(syst)}$

Asymmetry:

\[
A^\mu_l = 0.42 \pm 0.07\text{(stat.)} \pm 0.15\text{(syst.)},
A^\ell_l = 0.31 \pm 0.11\text{(stat.)} \pm 0.23\text{(syst.)}.
\]
Top mass at 7 TeV - dilepton

- Full 2011 dataset at $\sqrt{s} = 7$ TeV: 5.0/fb
- Two isolated leptons, at least two b-tagged jets, MET
- Technique is based on edges of $M_{T2}$ distributions
- $M_{\nu}^2$, $M_w$ and $M_t$ are obtained in a simultaneous fit to three endpoints

\[ M_t = 173.9 \pm 0.9 \text{(stat)}^{+1.7}_{-2.1} \text{(syst)} \text{ GeV} - \text{fixed } M_w \text{ and } M_{\nu}^2 \]
Measurement of $B(t \to W_b)/B(t \to W_q)$, \(q=d,s,b\)

- **Full 2012 dataset at \(\sqrt{s} = 8\) TeV: 19.7 fb**
- Dilepton channel, purity of the signal sample is quantified by measuring the cross section
- In the SM, the top decays predominantly into \(W_b\): \(R \sim 1\)
- \(R\) value is measured by fitting the observed \(b\)-tagged jet distribution with a parametric model

\[
R = 1.014 \pm 0.003{\text{(stat)}} \pm 0.032{\text{(syst)}}
\]

At 95% C.L., \(R > 0.955\), assuming \(R \leq 1\).
\(|V_{tb}| > 0.975\), assuming the unitarity of CKM matrix

Indirect measurement on top total decay width \(1.36 \pm 0.02{\text{(stat)}}^{+0.14}_{-0.11}{\text{(syst)}}\) GeV