Measurement of the properties of top quarks in decays
(includes top quark and W polarisation, top quark charge and couplings)

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CIEMAT - Madrid

on behalf of the CMS Collaboration

EPS2013 - Stockholm
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• **W** helicity in top decays

• **Electroweak couplings:**
  • associated $tt+\gamma$ production
  • associated $tt+Z$ and $tt+W$ production

• Branching ratio: $R = \frac{B(t \to Wb)}{B(t \to Wq)}$

• **FCNC**
W helicity in top decays

- Very sensitive to additional contributions: (BSM or “anomalous”) couplings - **important test of Wtb structure**

- W helicity fractions measured from angular distributions:
  - $\cos(\theta^*)$: in t rest frame - **angle between down-type fermion momentum in W rest frame and W momentum in top rest frame**
  
  \[
  \frac{1}{\Gamma} \frac{d\Gamma}{d\cos \theta^*} = \frac{3}{8} (1 - \cos \theta^*)^2 F_L + \frac{3}{8} (1 + \cos \theta^*)^2 F_R + \frac{3}{4} \sin^2 \theta^* F_0
  \]

- General vertex langrangian:
  
  \[
  \mathcal{L}_{Wtb} = -\frac{g}{\sqrt{2}} \bar{b} \gamma^\mu (V_L P_L + V_R P_R) t W^-_\mu - \frac{g}{\sqrt{2}} \bar{b} \frac{i \sigma^{\mu\nu} q_\nu}{M_W} (g_L P_L + g_R P_R) t W^-_\mu + \text{H.c.}
  \]

  In the SM: $V_L = V_{tb} = 1$  $V_R, g_L, g_R$ are all =0

  - Straightforward to interpret fractions in terms of anomalous couplings:
    - simple polynomial dependence

  - Saavedra et al.
W helicity in top decays

Single-top topology

Data: pp@ 7 TeV (1.14 fb⁻¹) / 8 TeV (5.3 fb⁻¹)

Selection for 7 / 8 TeV:

1 muon $p_T > 20 / p_T > 26$ GeV

Exactly 2 jets $p_T > 30 / p_T > 60$ GeV

Exactly 1 tagged as b

$M_T > 40 / M_T > 50$ GeV (W transverse mass)

ll+jets

Data: pp@ 7 TeV (4.6 fb⁻¹)

2 isolated leptons (e/μ) $p_T > 20$ GeV

In ee and μμ channels: reject evt in Z mass window $76 < M_{ll} < 106$ GeV

At least 2 jets $p_T > 30$ GeV

At least 1 tagged as b

$E_T^{miss} > 30$ (ee/μμ) or $E_T^{miss} > 20$ (eμ) GeV

l+jets

Data: pp@ 7 TeV (5.0 fb⁻¹)

Exactly 1 lepton

$p_T > 26$ (muon) or $p_T > 30$ (electron channel) GeV

At least 4 jets $p_T > 30$ GeV

At least 2 jets tagged as b

$M_T > 30$ GeV
W helicity: single-top topology

- Large contribution from top pairs, specially at 8 TeV
- Measurement from both single-top and top pairs
- Shape and normaliz. of W+jets:
  - data control samples

\[ F_0 = 0.713 \pm 0.114 \pm 0.023 \]
\[ F_L = 0.293 \pm 0.069 \pm 0.030 \]
\[ F_R = -0.006 \pm 0.057 \pm 0.027 \]

Combined results:

7 and 8 TeV
W helicity in top decays (ll+jets):

- Measurement from \( \cos(\theta^*) \) both sides
- Very low backgrounds: estimated using MC

\[
F_0 = 0.698 \pm 0.057 \pm 0.063 \\
F_L = 0.288 \pm 0.035 \pm 0.040 \\
F_R = 0.014 \pm 0.027 \pm 0.042
\]
W helicity in top decays (l+jets)

- $\cos(\theta^*)$: needs to identify **down-type fermion**
- Leptonic branch: $d$-fermion = lepton (ok!)
- Hadronic branch: $d$-type quark can not be identified: only $|\cos_{\text{had}}(\theta^*)|$ information

New results: TOP-11-020 updated, to be submitted to JHEP

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**Muon channel**

**Electron channel**

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W helicity in top decays (l+jets)

- Treating leptonic/hadronic branches independently
- "3D": fit $F_0$, $F_L$, and $t\bar{t}$ normalization
  take $F_R=1-F_0-F_L$ (as in single top and $t\bar{t}$)
- "2D": set $F_R=0$
- $W$+jets and DY+jets normalization and shape from control regions

(estimated in data)

New results: TOP-11-020 updated

<table>
<thead>
<tr>
<th>Systematics</th>
<th>$\mu$+jets ($\cos \theta^*$)</th>
<th>$e$+jets ($\cos \theta^*$)</th>
<th>$\ell$+jets ($\cos \theta^*$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3D fit</td>
<td>2D fit</td>
<td>3D fit</td>
</tr>
<tr>
<td></td>
<td>$\Delta F_0$</td>
<td>$\Delta F_L$</td>
<td>$\Delta F_0$</td>
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<tr>
<td>b-tag eff.</td>
<td>0.001</td>
<td>0.001</td>
<td>$&lt;10^{-3}$</td>
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<tr>
<td>Single-t bkg.</td>
<td>0.004</td>
<td>$&lt;10^{-3}$</td>
<td>0.003</td>
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<tr>
<td>DY+jets bkg.</td>
<td>0.002</td>
<td>0.001</td>
<td>0.001</td>
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<tr>
<td>W+jets bkg.</td>
<td>0.019</td>
<td>0.007</td>
<td>0.006</td>
</tr>
<tr>
<td>Lepton eff.</td>
<td>0.001</td>
<td>0.001</td>
<td>0.01</td>
</tr>
<tr>
<td>JES</td>
<td>0.005</td>
<td>0.003</td>
<td>0.001</td>
</tr>
<tr>
<td>$t\bar{t}$ scales</td>
<td>0.013</td>
<td>0.009</td>
<td>0.007</td>
</tr>
<tr>
<td>JER</td>
<td>0.009</td>
<td>0.005</td>
<td>0.001</td>
</tr>
<tr>
<td>Top-quark mass</td>
<td>0.011</td>
<td>0.008</td>
<td>0.007</td>
</tr>
<tr>
<td>Pileup</td>
<td>0.013</td>
<td>0.011</td>
<td>0.008</td>
</tr>
<tr>
<td>$t\bar{t}$ match. scale</td>
<td>0.004</td>
<td>0.001</td>
<td>0.006</td>
</tr>
<tr>
<td>PDF</td>
<td>0.002</td>
<td>0.001</td>
<td>0.003</td>
</tr>
<tr>
<td>MC statistics</td>
<td>0.016</td>
<td>0.012</td>
<td>0.009</td>
</tr>
</tbody>
</table>
W helicity in top decays (l+jets)

New results: TOP-11-020
updated

World’s most precise:
(with no $F_R=0$ assumption)

$F_0 = 0.682\pm0.030\pm0.033$
$F_L = 0.310\pm0.022\pm0.022$
$F_R = 0.008\pm0.012\pm0.014$

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Anomalous couplings from W helicity

- Fix $V_L=1$ and $V_R=0$ to SM predictions
  1) fix also $g_L=0 \rightarrow$ set limits on $g_R$ (independent on $F_R$):
    - Use measurement setting $F_R=0$, more precise $F_0$
    - Limit: $\text{Re}(g_R) = -0.008 \pm 0.024\text{(stat.)}^{+0.029}_{-0.030}\text{(syst.)}$
  2) set limits on $\text{Re}(g_R)$ vs $\text{Re}(g_L)$
    - Use most precise “3D” measurement:

![Graph showing limits on Re(g_R) vs Re(g_L)](image)

From single-top (TOP-12-020):
Highly disfavored by single-top cross sections measurements
LHC measurements are crucial: ttV cross section very low to be seen at Tevatron

- tt → l+jets and Z→ ll
- Three-lepton final state, event selection:
  2 isolated leptons p_T>20 GeV in Z window
  3rd lepton p_T>10 GeV
  at least 3 jets p_T>20 GeV, 2 b-tags
  H_T = ∑p_T(jets)>120 GeV

σ_{ttZ} = 0.28^{+0.14}_{-0.11}(stat)^{+0.06}_{-0.03}(syst) pb

significance: 3.3 σ, (p-value 0.0004) (NLO pred: 0.137 pb)
• Selecting 2 same-sign leptons

\[
pp \to t\bar{t}W \to (t \to b\ell^\pm\nu)(t \to b\bar{b}j)(W \to \ell^\pm\nu) \\
pp \to t\bar{t}Z \to (t \to b\ell^\pm\nu)(t \to b\bar{b}j)(Z \to \ell^\pm\ell^\mp)
\]

**Event selection**

2 leptons $p_T > 55$ (30) GeV

veto over $ttZ$ selection (3 leptons)

3 jets $p_T > 20$ GeV

1 $b$-tag

$H_T > 100$ GeV

• 16 events (9.2±2.6 expected bkg only)

\[
\sigma_{ttV} = 0.43^{+0.17}_{-0.15}^{(\text{stat})} +0.09_{-0.07}^{(\text{syst})} \text{ pb}
\]

significance: 3.0 $\sigma$

(p-value 0.002)

(NLO pred: 0.306 pb)

**Background sources**

Mis-reconstruction (charge id, fakes)

Rare SM: WZ, ZZ, Wγ, WW(++,--), VVV

PRL 110(2013) 172002 (PAS:TOP 12-014)
Cross sections slightly above but consistent with the Standard Model predictions
Branching ratio:
\[ R = \frac{\mathcal{B}(t \rightarrow Wb)}{\mathcal{B}(t \rightarrow Wq)} \quad q=b,s,d \]

* Key issues: correctly identify b/light-quark jets and its parent top *

- Data: pp @ 8 TeV (2012), 16.7 fb\(^{-1}\)
- Dilepton channel, event selection:
  2 isolated leptons \( p_T > 20 \) GeV
  \(|M_{ll}-M_Z| > 15 \) GeV (Z bkg removal) for ee/\(\mu\mu\)
  \(M_{ll} > 12 \) GeV
  \(E_T^{\text{miss}} > 40 \) GeV for ee/\(\mu\mu\)
  At least two jets separated from leptons \( \Delta R \geq 0.3 \)

- b-tagging: for the analysis, crucial to know efficiency of
  - correctly identifying b-jets using btag (\(\epsilon_b, \pm \sim 1-3\%\))
  - accepting light jets passing btag (mistags: \(\epsilon_q \sim 14\%, \pm \sim 11\%\))
Jet assignment to its parent top:
- use invariant mass (lepton-jet)
- normalize at high mass region

Measured in data
- remove from data $f_{\text{corr}} \sim 0.25$

<table>
<thead>
<tr>
<th>Category</th>
<th>$f_{\text{MC correct}}$</th>
<th>$f_{\text{data correct}}$</th>
<th>data/MC</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 jets</td>
<td>0.265 ± 0.002</td>
<td>0.28 ± 0.01 ± 0.01</td>
<td>1.05 ± 0.04 ± 0.04</td>
</tr>
<tr>
<td>ee</td>
<td>0.211 ± 0.002</td>
<td>0.21 ± 0.02 ± 0.01</td>
<td>0.99 ± 0.09 ± 0.05</td>
</tr>
<tr>
<td>3 jets</td>
<td>0.173 ± 0.002</td>
<td>0.18 ± 0.02 ± 0.02</td>
<td>1.04 ± 0.12 ± 0.12</td>
</tr>
<tr>
<td>4 jets</td>
<td>0.3475 ± 0.0009</td>
<td>0.35 ± 0.01 ± 0.01</td>
<td>1.00 ± 0.02 ± 0.02</td>
</tr>
<tr>
<td>ee</td>
<td>0.2539 ± 0.0008</td>
<td>0.26 ± 0.01 ± 0.01</td>
<td>1.01 ± 0.04 ± 0.04</td>
</tr>
<tr>
<td>4 jets</td>
<td>0.2114 ± 0.0010</td>
<td>0.20 ± 0.01 ± 0.01</td>
<td>0.94 ± 0.05 ± 0.05</td>
</tr>
<tr>
<td>2 jets</td>
<td>0.269 ± 0.001</td>
<td>0.27 ± 0.01 ± 0.01</td>
<td>0.97 ± 0.04 ± 0.04</td>
</tr>
<tr>
<td>$\mu\mu$</td>
<td>0.214 ± 0.001</td>
<td>0.22 ± 0.01 ± 0.01</td>
<td>1.05 ± 0.05 ± 0.05</td>
</tr>
<tr>
<td>4 jets</td>
<td>0.172 ± 0.002</td>
<td>0.18 ± 0.02 ± 0.01</td>
<td>1.06 ± 0.12 ± 0.06</td>
</tr>
</tbody>
</table>
Branching ratio

- From $f_{\text{corr}} \Rightarrow$ get $N$, nr of correctly reconstructed and selected tops (thus, of bjets!)

- Given $N$, from $\varepsilon_b$, $\varepsilon_q \Rightarrow$ model the nr expected events for each b-tag multiplicity

Extract $R$ from a likelihood fit to the model entirely based on data
Branching ratio

- **Systematic uncertainties**

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Statistical</td>
<td>0.4</td>
</tr>
<tr>
<td>Systematic</td>
<td>3.4</td>
</tr>
<tr>
<td><strong>Individual contributions:</strong></td>
<td></td>
</tr>
<tr>
<td><em>b</em>-tagging efficiency</td>
<td>1.9</td>
</tr>
<tr>
<td>$f^{\text{stat}}_t\bar{t}$</td>
<td>0.5</td>
</tr>
<tr>
<td>Mistag rate</td>
<td>0.9</td>
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<tr>
<td>$B(W \to \ell \nu)$</td>
<td>0.2</td>
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<tr>
<td>DY</td>
<td>0.3</td>
</tr>
<tr>
<td>Fake leptons</td>
<td>0.1</td>
</tr>
<tr>
<td>JER</td>
<td>0.9</td>
</tr>
<tr>
<td>JES</td>
<td>1.0</td>
</tr>
<tr>
<td>Luminosity</td>
<td>0.2</td>
</tr>
<tr>
<td><strong>ME-PS</strong></td>
<td>1.2</td>
</tr>
<tr>
<td>Pileup</td>
<td>0.2</td>
</tr>
<tr>
<td>$Q^2$</td>
<td>1.1</td>
</tr>
<tr>
<td>Selection efficiency</td>
<td>0.2</td>
</tr>
<tr>
<td>Signal</td>
<td>0.2</td>
</tr>
<tr>
<td>Simulation stat.</td>
<td>0.2</td>
</tr>
<tr>
<td>Single top cross section</td>
<td>0.1</td>
</tr>
<tr>
<td>$f^{\text{stat}}_t\nu$</td>
<td>1.1</td>
</tr>
<tr>
<td>Extra sources of heavy flavors</td>
<td>0.9</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>3.4</td>
</tr>
</tbody>
</table>

- **Likelihood fit:**

R = 1.023$^{+0.036}_{-0.034}$
R > 0.945 @ 95% CL

At 7 TeV (TOP 11-029) with 2.2 fb$^{-1}$:
R = 0.98$^{+0.04}_{-0.04}$, R > 0.85 @ 95% CL
FCNC in top pairs

- SM: $t \rightarrow Wb \ \text{almost 100\%}$
- Direct search for flavor changing neutral currents $t\bar{t} \rightarrow Wb + Zq \rightarrow l\nu b + l\ell q$
- $t \rightarrow Zq$ is highly suppressed ($BF \sim 10^{-14}$), not visible at the LHC unless new physics occurs
- Tri-lepton final state, event selection ($19.5 \text{ fb}^{-1} \ pp @ 8 \text{ TeV}$)

3 isolated leptons $p_T > 20 \text{ GeV}$
Z mass window: $78 < M_{ll} < 102 \text{ GeV}$
$p_T(Z) > 35 \text{ GeV}$
3rd lepton $p_T > 10 \text{ GeV}$
at least 2 jets $p_T > 30 \text{ GeV}$
exactly 1 btag
$E_T^{miss} > 30 \text{ GeV}$

- Backgrounds from data: classified by nr of b-tags
  - 0 b-tag: diboson, Drell-Yan, QCD
  - 1 b-tag: signal
  - 2 b-tags: $tt, tbZ, Wtt, Ztt$

<table>
<thead>
<tr>
<th>Selection</th>
<th>data-driven estimation</th>
<th>SM MC prediction</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t \rightarrow Zq$</td>
<td>$B = 0.1%$</td>
<td>$6.36 \pm 0.08 \pm 1.27$</td>
</tr>
<tr>
<td>$WZ$</td>
<td></td>
<td>$0.87 \pm 0.10 \pm 0.62$</td>
</tr>
<tr>
<td>$ZZ$</td>
<td></td>
<td>$0.07 \pm 0.01 \pm 0.05$</td>
</tr>
<tr>
<td>Drell-Yan</td>
<td></td>
<td>$0.00 \pm 0.03 \pm 0.02$</td>
</tr>
<tr>
<td>$tt$</td>
<td></td>
<td>$0.74 \pm 0.70 \pm 0.52$</td>
</tr>
<tr>
<td>$Zt\bar{t}$</td>
<td></td>
<td>$1.09 \pm 0.13 \pm 0.77$</td>
</tr>
<tr>
<td>$Wt\bar{t}$</td>
<td></td>
<td>$0.09 \pm 0.05 \pm 0.06$</td>
</tr>
<tr>
<td>$tbZ$</td>
<td></td>
<td>$0.33 \pm 0.02 \pm 0.23$</td>
</tr>
<tr>
<td>Total background</td>
<td></td>
<td>$3.14 \pm 4.97 \pm 1.17$</td>
</tr>
<tr>
<td>Observed events</td>
<td>1</td>
<td>$3.19 \pm 0.72 \pm 2.26$</td>
</tr>
<tr>
<td>Expected limit</td>
<td>$B(t \rightarrow Zq) &lt; 0.1%$</td>
<td>—</td>
</tr>
<tr>
<td>Observed limit</td>
<td>$B(t \rightarrow Zq) &lt; 0.07%$</td>
<td>—</td>
</tr>
</tbody>
</table>

1 event observed (3.14 expected)

$BF < 0.05\% \ \text{@95\%CL}$
Summary and conclusions

- Important tests of the Standard Model validity on 2011 and 2012 LHC data:
  - $W$ helicity in top decays measured with unprecedented precision
    - Stringent constraints on anomalous couplings
  - Measurements of $ttV$ ($V=Z,W$) cross sections presented
    - $ttV$ in hadron colliders: unique for LHC
    - first steps towards understanding structure of electroweak couplings to tops
  - $R=B(t\to Wb)/B(t\to Wq) > 0.85$ at 95%CL
  - Limits on FCNC in top pairs were set ($BF<0.05\%$ at 95%CL)
  - Consistency with the Standard Model in all measurements

All results can be found in https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP
Additional slides
Likelihood fit with

\[ \mathcal{L}(\vec{F}) = \prod_{\text{bin } i} \frac{N_{MC}(i; \vec{F}) N_{data}(i)}{(N_{data}(i))!} \exp\left(-N_{MC}(i; \vec{F})\right). \]

- \( N_{MC}(i, \vec{F}) = N_{BKG}(i) + N_{tt}(i; \vec{F}) \)
- \( N_{tt}(i; \vec{F}) = \mathcal{F}_{tt} \left[ \sum_{\text{tt events, bin } i} W(\cos \theta^*_{gen}; \vec{F}) \right] \)
- \( N_{BKG}(i) = N_{W+jets}(i) + N_{Drell-Yan+jets}(i) + N_{Single-Top}(i) \)

Number of expected \( tt \) for different helicity configurations \( \vec{F} \) obtained by reweighting

\[ W(\cos \theta^*_{gen}; \vec{F}) = \rho(\cos \theta^*_{gen}) \rho^{SM}(\cos \theta^*_{gen}) = \frac{3}{8} F_L (1 - \cos \theta^*_{gen})^2 + \frac{3}{4} F_0 \sin^2 \theta^*_{gen} + \frac{3}{8} F_R (1 + \cos \theta^*_{gen})^2 \]

\[ = \frac{3}{8} F^{SM}_L (1 - \cos \theta^*_{gen})^2 + \frac{3}{4} F^{SM}_0 \sin^2 \theta^*_{gen} + \frac{3}{8} F^{SM}_R (1 + \cos \theta^*_{gen})^2 \]
Electroweak couplings: gauge-boson associated $t\bar{t}$ production

- Important Standard Model test: new physics modifies the structure of the electroweak couplings, described by

$$\Gamma_{\mu}^{t\bar{t}V}(k^2, q, \bar{q}) = -ie \left\{ \gamma_{\mu} \left( F_{1V}^V(k^2) + \gamma_5 F_{1A}^V(k^2) \right) + \frac{\sigma_{\mu\nu}}{2m_t} (q + \bar{q})^\nu \left( iF_{2V}^V(k^2) + \gamma_5 F_{2A}^V(k^2) \right) \right\}$$

- $t\bar{t}$ production via intermediate $V$ very difficult
  - small correction to a QCD dominated process
  - Instead, measure cross-sections: $t\bar{t}Z$, $t\bar{t}W$ production

- Tests of the electroweak sector in top physics specially interesting
  - LHC measurements are crucial: $t\bar{t}V$ cross section very low to be seen at Tevatron

see e.g. U.Baur et al., PRD71 (2005) 054013

Precision measurements on $t\bar{t}V$ final states sensitive to anomalous couplings
Top quark charge

- SM - electroweak isospin partner of b quark (of q=-1e/3): charge = +2e/3
- Other possible decay to W and b quark: exotic particle charge -4e/3

* Key issue: to identify b-quark jet and its charge *

- **Identification of b-initiated jets** (b-tagging): long lifetime of B hadrons, jets with large impact parameter; soft (low-p_T) muons from B decays

- **Identification of b quark charge** ➔ more complicated! Methods:
  1. from the charge of the soft muon (same sign as B-hadron in direct decays)
     - smeared by flavour oscillations of neutral B mesons
     - smeared by B-hadron cascades through charmed hadrons
  2. from the momentum-weighted charge of all charged particles in the jet

\[
Q_{b\text{jet}} = \frac{\sum_i q_i \sqrt{\vec{J} \cdot \vec{p}_i}}{\sum_i \sqrt{\vec{J} \cdot \vec{p}_i}},
\]

K MC derived parameter = 0.5

i runs over all tracks
Top quark charge

PAS: TOP 11-031
4.6 fb$^{-1}$ $tt\rightarrow \mu \nu +$jets

exactly 1 isolated muon $p_T>26$ GeV
$\geq 4$ jets $p_T>30$ GeV
2 btags

Soft lepton: +1 $\mu$ within jet ($p_T>4$ GeV)

Systematic uncertainties

<table>
<thead>
<tr>
<th>Category</th>
<th>Rel. Sys. Uncertainty on $P_{signal}$</th>
<th>Rel. Sys. Uncertainty on $A$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Matching Threshold</td>
<td>5%</td>
<td>23%</td>
</tr>
<tr>
<td>b Charge MisID</td>
<td>2.5%</td>
<td>12%</td>
</tr>
<tr>
<td>Top Mass</td>
<td>2%</td>
<td>8%</td>
</tr>
<tr>
<td>JES</td>
<td>1%</td>
<td>7%</td>
</tr>
<tr>
<td>$Q^2$</td>
<td>0.5%</td>
<td>3%</td>
</tr>
<tr>
<td>Fragmentation Model</td>
<td>0.6%</td>
<td>3%</td>
</tr>
<tr>
<td>JER</td>
<td>0.1%</td>
<td>3%</td>
</tr>
<tr>
<td>b-tagging</td>
<td>0.2%</td>
<td>2%</td>
</tr>
<tr>
<td>Pileup</td>
<td>0.4%</td>
<td>2%</td>
</tr>
</tbody>
</table>

* Exotic scenario excluded at 5 $\sigma$ *

Friday, July 19, 2013