Measurement of the W helicity in top pair production with dileptons at 7 TeV using CMS detector at the LHC

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W-Polarization in Theory

@NNLO, the SM predictions for the W-boson helicity fractions are \((PHYSICAL\ REVIEW\ D\ 81,\ 111503(R)\ (2010))\)

\[ F_0 = 0.687, \quad F_{-1} = 0.311, \quad F_{+1} = 0.0017. \]

This can be understood since in the limit of massless b-quarks, right-handed W-bosons are suppressed.
W-Polarization in Experiment

Find the distribution of $\cos \theta^*$

\[
\frac{1}{\Gamma} \frac{d\Gamma}{d\cos \theta^*} = \frac{3}{8} (1 - \cos \theta^*)^2 F_- + \frac{3}{8} (1 + \cos \theta^*)^2 F_+ + \frac{3}{4} (\sin \theta^*)^2 F_0
\]

$LH$ $RH$ $Long.$

$\theta^*$: the angle in the W-boson rest frame between the direction opposite to the top quark and the direction of lepton.
CMS (Compact Muon Solenoid) Detector

One of the two general-purpose detector of LHC
CMS Detector

One of the two general-purpose detector of LHC

A man for scale!
The only particles that can be seen at the detector are **Electrons, Photons, Muons** and **Hadrons**.
Jet Reconstruction at CMS

- Calorimeter jets: with *calo-towers*
Jet Reconstruction at CMS

- Calorimeter jets: with *calo-towers*

- Jet Plus Track: correct for tracks
Jet Reconstruction at CMS

● Calorimeter jets: with *calo-towers*

● Jet Plus Track: correct for tracks

● Particle Flow: particle candidates
Jet Reconstruction at CMS

● Calorimeter jets: with *calo-towers*

● Jet Plus Track: correct for tracks

● Particle Flow: particle candidates

1. Simple
2. Worst resolution

3. Improving resolution with tracks

4. Best resolution
5. Used in most analysis
$t\bar{t}$ Events Are Selected to Measure W-Polarization

- $t\bar{t}$ events are produced via gluon-gluon fusion
- Almost all the time, a top quark decays to a W and b
- W-boson decays into hadrons (67%)
- W-boson decays into leptons (33%)
Only dilepton $t\bar{t}$ events are chosen.

The probability is found to be $33\% \times 33\% \sim 11\%$.

Very small probability, but still very clean sample at the end.
**$t\bar{t}$ Dilepton Events: Characteristics**

- **2 neutrinos**
- **6 unknown parameters!**
- **2 leptons**
- **low backgrounds**
- **2 b-quark jets**

**4 mass constraints from:**
- **2 top quarks**
- **2 W bosons**
- **low production rate (11%)**
Finding $\nu$ and $\bar{\nu}$ Four-Vectors

The four-vector of neutrinos are found by solving the 6 equations:

$$\begin{align*}
(E^\text{miss}_T)_x &= p_{\nu x} + p_{\bar{\nu} x}; \\
(E^\text{miss}_T)_y &= p_{\nu y} + p_{\bar{\nu} y}.
\end{align*}$$

\[
\begin{align*}
m^2_{W^+} &= (E_{l^+} + E_\nu)^2 - (p_{l^+} + p_{\nu x})^2 - (p_{l^+} + p_{\nu y})^2 - (p_{l^+} + p_{\nu z})^2; \\
m^2_{W^-} &= (E_{l^-} + E_{\bar{\nu}})^2 - (p_{l^-} + p_{\bar{\nu} x})^2 - (p_{l^-} + p_{\bar{\nu} y})^2 - (p_{l^-} + p_{\bar{\nu} z})^2; \\
m^2_t &= (E_{b} + E_{l^+} + E_\nu)^2 - (p_{b} + p_{l^+} + p_{\nu x})^2 - (p_{b} + p_{l^+} + p_{\nu y})^2 - (p_{b} + p_{l^+} + p_{\nu z})^2; \\
m^2_{\tilde{t}} &= (E_{\bar{b}} + E_{l^-} + E_{\bar{\nu}})^2 - (p_{\bar{b}} + p_{l^-} + p_{\bar{\nu} x})^2 - (p_{\bar{b}} + p_{l^-} + p_{\bar{\nu} y})^2 - (p_{\bar{b}} + p_{l^-} + p_{\bar{\nu} z})^2.
\end{align*}
\]

Polynomial equation of degree 4

Maximally four solutions for the $\nu$

Maximally four solutions for the $\bar{\nu}$

The ambiguity should be resolved!

The solution minimizing the mass of top pair system
# List of Samples

<table>
<thead>
<tr>
<th>SUMMER11 MC Samples</th>
<th>XSection (pb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TTJets_TuneZ2_7TeV-madgraph</td>
<td>157.5</td>
</tr>
<tr>
<td>WJetsToLNu_TuneZ2_7TeV-madgraph-tauola</td>
<td>31314.0</td>
</tr>
<tr>
<td>DYJetsToLL_TuneZ2_M-50_7TeV-madgraph-tauola</td>
<td>2475.0</td>
</tr>
<tr>
<td>DYJetsToLL_M-10To50_TuneZ2_7TeV-madgraph-tauola</td>
<td>9611.0</td>
</tr>
<tr>
<td>T_TuneZ2_tW-channel-DR_7TeV-powheg-tauola</td>
<td>7.8</td>
</tr>
<tr>
<td>Tbar_TuneZ2_tW-channel-DR_7TeV-powheg-tauola</td>
<td>7.8</td>
</tr>
<tr>
<td>WWJetsTo2L2Nu_TuneZ2_7TeV-madgraph-tauola</td>
<td>4.65</td>
</tr>
<tr>
<td>WZJetsTo3LNu_TuneZ2_7TeV-madgraph-tauola</td>
<td>0.6</td>
</tr>
<tr>
<td>ZZ_TuneZ2_7TeV_pythia6_tauola</td>
<td>4.65</td>
</tr>
<tr>
<td>T_TuneZ2_t-channel_7TeV-powheg-tauola</td>
<td>42.5</td>
</tr>
<tr>
<td>Tbar_TuneZ2_t-channel_7TeV-powheg-tauola</td>
<td>22.0</td>
</tr>
</tbody>
</table>

## 2011 Data

<table>
<thead>
<tr>
<th></th>
<th>Run2011A</th>
<th>Run2011B v1</th>
<th>Total data</th>
</tr>
</thead>
<tbody>
<tr>
<td>DoubleElectron</td>
<td>2.044 fb⁻¹</td>
<td>2.485 fb⁻¹</td>
<td>4.529 fb⁻¹</td>
</tr>
<tr>
<td>DoubleMuon</td>
<td>1.993 fb⁻¹</td>
<td>2.466 fb⁻¹</td>
<td>4.459 fb⁻¹</td>
</tr>
<tr>
<td>MuEG</td>
<td>2.123 fb⁻¹</td>
<td>2.508 fb⁻¹</td>
<td>4.631 fb⁻¹</td>
</tr>
</tbody>
</table>
### Cut Flow Table

Several cuts are applied to select signal events

$\sim 5 \, fb^{-1}$ of CMS data from pp collisions at 7 TeV was analyzed

With this amount of data, about 788k $t \bar{t}$ events have been recorded by the CMS detector

<table>
<thead>
<tr>
<th>Dataset</th>
<th>Njets</th>
<th>MET</th>
<th>NBjets</th>
<th>$N_{t\bar{t}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t\bar{t}$</td>
<td>13569.6±50.4</td>
<td>12160.2±47.7</td>
<td>9075.0±42.3</td>
<td>8692.3±32.7</td>
</tr>
<tr>
<td>SingleTop $tW$</td>
<td>708.2±7.9</td>
<td>631.4±7.4</td>
<td>410.4±6.2</td>
<td>357.3±4.5</td>
</tr>
<tr>
<td>DY $M_{ll} &gt; 10 GeV$</td>
<td>16193.2±106.7</td>
<td>2841.3±41.7</td>
<td>206.9±11.8</td>
<td>167.0±9.5</td>
</tr>
<tr>
<td>WW</td>
<td>399.4±2.6</td>
<td>353.1±2.4</td>
<td>32.0±0.7</td>
<td>22.8±0.5</td>
</tr>
<tr>
<td>SingleTop $t$</td>
<td>14.6±1.0</td>
<td>12.4±0.9</td>
<td>7.8±0.8</td>
<td>6.5±0.6</td>
</tr>
<tr>
<td>WJets</td>
<td>553.3±32.2</td>
<td>448.2±28.8</td>
<td>33.0±7.4</td>
<td>17.0±4.4</td>
</tr>
<tr>
<td>WZ</td>
<td>89.6±0.4</td>
<td>70.6±0.4</td>
<td>3.9±0.1</td>
<td>2.7±0.1</td>
</tr>
<tr>
<td>ZZ</td>
<td>69.3±0.6</td>
<td>15.4±0.3</td>
<td>2.2±0.1</td>
<td>1.6±0.0</td>
</tr>
<tr>
<td>Total(Simulation)</td>
<td>31597.3±122.7</td>
<td>16532.7±70.0</td>
<td>9771.3±45.0</td>
<td>9267.3±34.7</td>
</tr>
<tr>
<td>Data</td>
<td>29982</td>
<td>16257</td>
<td>9888</td>
<td>9341</td>
</tr>
</tbody>
</table>
Data-MC Comparison

CMS Preliminary, 4.6 fb⁻¹ at \( \sqrt{s} = 7 \text{TeV} \)
Constructing Angular Distribution
Fit Method

A likelihood function is introduced

$$\mathcal{L}(\vec{F}) = \prod_{\text{bin } i} \frac{N_{\text{MC}}(i; \vec{F})}{(N_{\text{data}}(i))!} \frac{N_{\text{data}}(i)}{\exp(-N_{\text{MC}}(i; \vec{F}))},$$

where

$$N_{\text{MC}}(i; \vec{F}) = N_{\text{BKG}}(i) + N_{\ttbar}(i; \vec{F})$$

$$N_{\ttbar}(i; \vec{F}) = \mathcal{F}_{\ttbar} \left[ \sum_{\ttbar \text{ events, bin } i} W(\cos \theta^*_{\text{gen}}; \vec{F}) \right]$$

$$N_{\text{BKG}}(i) = N_{W+\text{jets}}(i) + N_{\text{Drell-Yan+jets}}(i) + N_{\text{QCD}}(i) + N_{\text{Single-Top}}(i)$$

and the weight function is defined as

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

The $W$-boson helicity fractions are those which maximize the likelihood function.
The helicity fractions of W bosons from top quark decays are found from the fit method

\[ F_0 = 0.698 \pm 0.057 \]
\[ F_- = 0.288 \pm 0.035 \]
\[ F_+ = 0.014 \pm 0.027 \]

They are in agreement with the SM expectations

No BSM effect is found

Several statistical tests are performed to check if the method works fine

- **Linearity test:** the central values are truly estimated
- **Pull distribution:** there is no bias on uncertainties
# W-Polarization: Systematics

<table>
<thead>
<tr>
<th>Systematic Source</th>
<th>$\pm \delta F_L$</th>
<th>$\pm \delta F_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top QScale</td>
<td>0.027</td>
<td>0.051</td>
</tr>
<tr>
<td>Top Mass</td>
<td>0.016</td>
<td>0.003</td>
</tr>
<tr>
<td>WZQScale</td>
<td>0.013</td>
<td>0.026</td>
</tr>
<tr>
<td>DY XSection</td>
<td>0.009</td>
<td>0.014</td>
</tr>
<tr>
<td>W XSection</td>
<td>0.000</td>
<td>0.002</td>
</tr>
<tr>
<td>SingleTopTW XSection</td>
<td>0.002</td>
<td>0.008</td>
</tr>
<tr>
<td>JES</td>
<td>0.01</td>
<td>0.006</td>
</tr>
<tr>
<td>Pile Up</td>
<td>0.014</td>
<td>0.017</td>
</tr>
<tr>
<td>PDF</td>
<td>0.004</td>
<td>0.005</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>0.040</strong></td>
<td><strong>0.063</strong></td>
</tr>
</tbody>
</table>
Summary

- W-polarization fractions from top quark decay in dilepton $t\bar{t}$ events are measured
- Full 2011 data collected by the CMS experiment from proton-proton collisions at 7 TeV is analyzed
- The presented results are approved by the CMS
- Measured helicity fractions of the W bosons are in agreement with the SM prediction
- No new physics is observed
Plan

- To update this analysis using 8 TeV datasets collected at 2012 corresponding to about 20 fb⁻¹
- To study any possible anomalous Wtb couplings
- Two new PhD students have already been joined to the team, Mr Behnamian & Mr Naseri
- Seems still more work is needed!
BACK-UP
W-Boson Decay from Theory

A massive spin-1 boson traveling along the z-axis

\[ \epsilon_-^\mu = \frac{1}{\sqrt{2}} (0, 1, -i, 0); \quad \epsilon_L = \frac{1}{m} (p_z, 0, 0, E); \quad \epsilon_+^\mu = -\frac{1}{\sqrt{2}} (0, 1, i, 0) \]

\( S_z = -1 \)  
\( S_z = 0 \)  
\( S_z = +1 \)

transverse  
longitudinal  
transverse

Want to calculate W boson decay rate
W-Boson Decay from Theory

Matrix element for $W^- \rightarrow e^- \bar{v}_e$ is

$$-iM_{fi} = \epsilon_\mu (p_1) . \bar{u}(p_3) . -i \frac{g_W}{\sqrt{2}} \gamma^\mu \frac{1}{2} (1 - \gamma^5) . v(p_4)$$

which can be written as

$$M_{fi} = \frac{g_W}{\sqrt{2}} \epsilon_\mu (p_1) . j^\mu$$

$\epsilon^\mu = \frac{1}{\sqrt{2}} (0, 1, -i, 0)$

$\epsilon_L = (0, 0, 0, 1)$

$\epsilon^\mu = -\frac{1}{\sqrt{2}} (0, 1, i, 0)$

$J^\mu = \bar{u}(p_3) \gamma^\mu \frac{1}{2} (1 - \gamma^5) v(p_4)$
W-Decay: The Lepton Current

Working in the COM frame

\[ p_1 = (m_W, 0, 0, 0); \]
\[ p_3 = (E, E \sin \theta, 0, E \cos \theta) \]
\[ p_4 = (E, -E \sin \theta, 0, -E \cos \theta) \], where \( E = \frac{m_W}{2} \)

In the ultra-relativistic limit, the lepton current is found to be

\[
    j^\mu = \bar{u}(p_3) \gamma^\mu \frac{1}{2} (1 - \gamma^5) v(p_4) = \bar{u}_\downarrow(p_3) \gamma^\mu v_\uparrow(p_4) \]
\[
    = 2E(0, -\cos \theta, -i, \sin \theta) \]
Helicity Amplitudes

Matrix element for the different polarization states

\[
M_- = \frac{g_w}{\sqrt{2}} \frac{1}{\sqrt{2}} (0, 1, -i, 0).m_W (0, -\cos \theta, -i, \sin \theta) = \frac{1}{2} g_w m_W (1 + \cos \theta)
\]

\[
M_L = \frac{g_w}{\sqrt{2}} (0, 0, 0, 1).m_W (0, -\cos \theta, -i, \sin \theta) = -\frac{1}{\sqrt{2}} g_w m_W \sin \theta
\]

\[
M_+ = -\frac{g_w}{\sqrt{2}} \frac{1}{\sqrt{2}} (0, 1, i, 0).m_W (0, -\cos \theta, -i, \sin \theta) = \frac{1}{2} g_w m_W (1 - \cos \theta)
\]

\[
|M_-|^2 = g_w^2 m_W^2 \frac{1}{4} (1 + \cos \theta)^2
\]

\[
|M_L|^2 = g_w^2 m_W^2 \frac{1}{2} \sin^2 \theta
\]

\[
|M_+|^2 = g_w^2 m_W^2 \frac{1}{4} (1 - \cos \theta)^2
\]
**Total W-Boson Decay Rate**

The Differential decay rate obtained from
\[
\frac{d\Gamma}{d\Omega} = \frac{|p^*|}{32\pi^2m^2_W} |M|^2
\]
where \( p^* = \frac{m_W}{2} \)

For a sample of unpolarized W-boson each polarization state is equally likely
sum over all possible matrix elements and average over the three initial polarization states
\[
\langle |M_{fi}|^2 \rangle = \frac{1}{3}(|M_-|^2 + |M_L|^2 + |M_+|^2)
\]
\[
= \frac{1}{3}g_w^2m_W^2 \left[ \frac{1}{4}(1 + \cos \theta)^2 + \frac{1}{2}\sin^2 \theta + \frac{1}{4}(1 - \cos \theta)^2 \right]
\]
\[
= \frac{1}{3}g_w^2m_W^2
\]

Total decay rate is found to be
\[
\Gamma(W^- \rightarrow e^-\bar{\nu}) = \frac{g_w^2m_W}{48\pi}
\]
Differential W-Boson Decay Rate

From \( \frac{d\Gamma}{d\Omega} = \frac{|p^*|}{32\pi^2m_W^2} |M|^2 \) and using total decay rate, one can derive

\[
\frac{1}{\Gamma} \frac{d\Gamma}{d\cos\theta^*} = \frac{3}{8} (1 - \cos\theta^*)^2 F^- + \frac{3}{8} (1 + \cos\theta^*)^2 F^+ + \frac{3}{4} (\sin\theta^*)^2 F_0
\]
Differential W-Boson Decay Rate

From

\[
\frac{d\Gamma}{d\Omega} = \frac{|p^*|}{32\pi^2 m_W^2} |M|^2
\]

and using total decay rate, one can derive

\[
\frac{1}{\Gamma} \frac{d\Gamma}{d\cos \theta^*} = \frac{3}{8} (1 - \cos \theta^*)^2 F^- + \frac{3}{8} (1 + \cos \theta^*)^2 F^+ + \frac{3}{4} (\sin \theta^*)^2 F_0
\]
Data-Driven Bkg Estimation of DY

- To reduce the DY contribution to a dilepton data sample, events with $76 < M_{ll} < 106$ are excluded.
- A scale factor (SF) between DY events predicted by simulation and measured in data is computed in the control region.
- This SF is used to normalize the predictions of the simulation outside the veto region expressed here:
  \[ N_{DY}^{out\ (est)} = \frac{N_{DY\ DATA}^{in}}{N_{DY\ MC}^{in}} \cdot N_{DY\ MC}^{out} \]
- Assumed the control region is dominated by DY.
- In reality, we should deal with bkgs when measuring $N_{DY\ DATA}^{in}$. 
Data-Driven Bkg Estimation of DY

Two different types of bkgs

Peaking bkg
WZ and ZZ give a peak at the Z mass in the dilepton invariant mass distribution, if both selected leptons come from the Z in the case of WZ, or the same Z in the case of ZZ.

Neglected because of small contribution

Non-peaking bkg
WW, tt, tW and W+jets give a flat contribution in the dilepton invariant mass distribution, which must be estimated from data.

Measure number of events in the control region in the e-mu final state
Two different types of bkg's

**Peaking bkg**
WZ and ZZ give a peak at the Z mass in the dilepton invariant mass distribution, if both selected leptons come from the Z in the case of WZ, or the same Z in the case of ZZ.

Neglected because of small contribution

**Non-peaking bkg**
WW, tt, tW and W+jets give a flat contribution in the dilepton invariant mass distribution, which must be estimated from data.

Measure number of events in the control region in the e-mu final state

\[ K_{ee, (\mu\mu)} = \sqrt{\left( \frac{N_{\text{in}}^{\text{data, ee}(\mu\mu)}}{N_{\text{in}}^{\text{data, \mu\mu}(ee)}} \right)} \times \frac{1}{2} \]

\[ N_{DY \text{ DATA}}^{in} = (N_{ll \text{ DATA}}^{in} - k \cdot N_{e\mu \text{ DATA}}^{in}) \]
We've found the following DY scale factors

\[\text{ee: } 1.56 \pm 0.042\]
\[\text{\(\mu\mu\): } 1.09 \pm 0.037\]

For DY in e-mu channel, most of the DY contribution is coming from the Z->tau tau

The X-section is much lower than inclusive DY, hence small bkg contamination

In addition, because of the presence of neutrinos coming from tau decays, the dilepton invariant mass is not compatible with the known Z mass and the Z mass peak is shifted to the low masses

It is rather difficult to estimate the DY contamination in the e-mu channel from data