Measurement of the W boson helicity using top pair events in the dilepton final state

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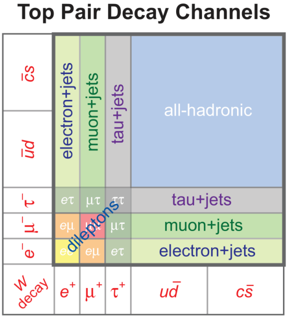
October 20, 2017

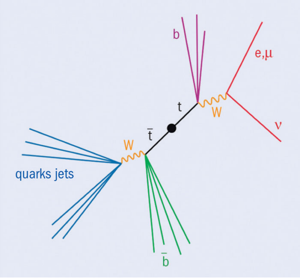
Overview

Based on the results in CMS PAS TOP-14-017

W Polarization

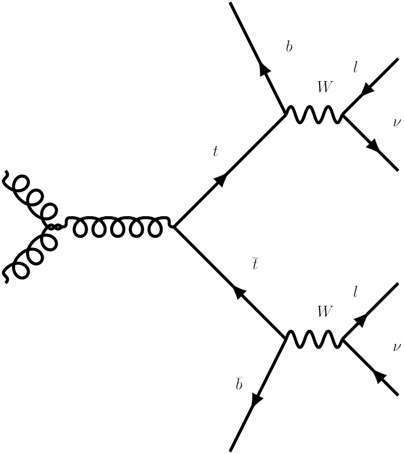
- Top quark decays almost exclusively into a b-quark and a W-boson via the weak interaction
- AT the LHC, $t\bar{t}$ events are produced mainly via gluon-gluon fusion
- W-boson decays into hadrons (67%) and leptons (33%)





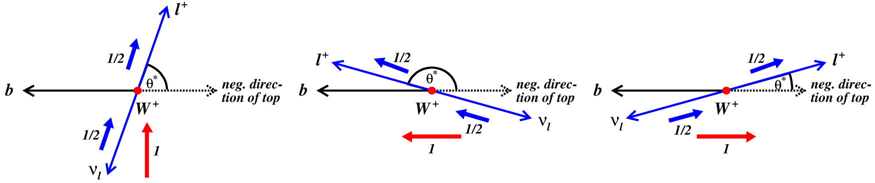
$t\bar{t}$ dilepton event characteristics

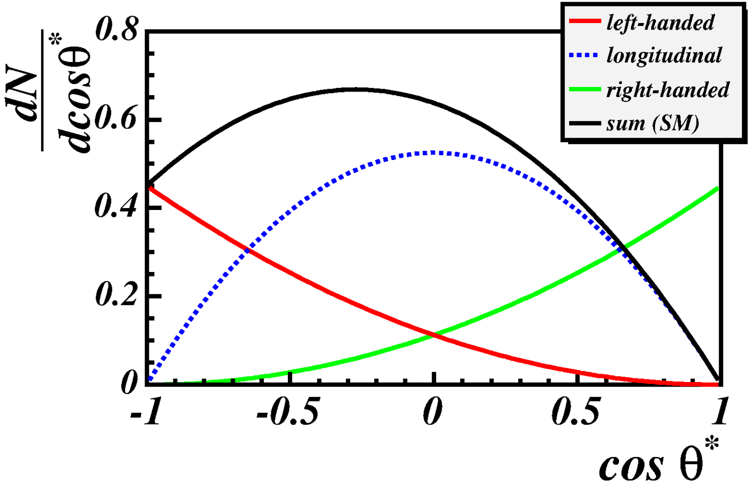
- → 2 neutrinos
  - ∘ 6 unknown parameters
- → 2 leptons
  - ∘ Low backgrounds
  - ∘ Low production rate (11%)
- → 2 b-quark jets
- → 4 mass constrains from:
  - ∘ 2 top quark
  - ∘ 2 W bosons



Helicity Fractions

- The W-boson helicity fractions are defined as the partial width of the top quark decaying into W-boson with different polarizations
- The angular distribution of the top quark decay width is parametrized as:
$\frac{1}{\Gamma}\frac{d\Gamma}{dcos\theta^*} = \frac{3}{8}(1 - cos\theta^*)^2 F_L + \frac{3}{8}(1 + cos\theta^*)^2 F_R + \frac{3}{8}(1 - cos^2\theta^*)F_0$
- θ^* is the angle between the 3-momentum of the charged lepton in the W-boson rest frame and the 3-momentum of the W-boson in the top quark rest frame.




left-handed
longitudinal
right-handed
sum (SM)
dN/dcosθ*
0.8
0.6
0.4
0.2
0
-1
-0.5
0
0.5
1
cos θ*

Backgrounds

- **Z+jets**
- $t\bar{t}$ **from semileptonic,hadronic and tau decay**
- **W+jets**
- **Multi-jet QCD**
- **Diboson**
- **Single Top**

Data and Simulated Samples

- Data corresponds to 19.7 fb^{-1} Integrated luminosity at 8 TeV from CMS experiment
- $t\bar{t}$ sample generated with MADGRAPH 5.1.48 interfaced with PYTHIA 6.426 for hadronization and showering, TAUOLA for τ decays($m_t = 172.5 GeV$, $\sigma(NNLO) = 252.9 \pm 16.4 pb$)
- DY+jets, W+jets and WW are generated with MADGRAPH.
- Single-Top generated with POWHEG interfaced with PYTHIA 6.426
- QCD multijet, WZ, and ZZ generated with PYTHIA 6.426
- The PYTHIA $Z2^*$ tune is used and GEANT 4 is used for detector simulations

Event Selection

- At least one good primary vertex.
- Triggers corresponding to the presence of two charged leptons with $p_T > 17\ GeV(lead)\ and\ 8\ GeV(subleading)$
- p_T cut of 20 GeV and $|\eta| < 2.4(2.5)$ imposed on leptons; muons (electrons).
- $I_{rel} < 0.2(0.15)$ relative isolation cut is enforced on muons (electrons).
- Jets with $p_T > 30\ GeV$ and $|\eta| < 2.5$ not containing a lepton in their 0.5 ΔR cone. CSV (CMS-PAS-BTV-11-004) is used for b-tagging (80% b-tag eff. & 0.1 mistag rate).
- Two oppositely charged leptons , MET, and two b tagged jets.

Reconstruction of a Top System

$t\bar{t} \to W^+ b W^- \bar{b} \to l^+ \nu b l^- \bar{\nu} \bar{b}$

$\to$ 6 particles, 4 known.

$\to E_T^{miss}$ for 2 neutrinos, 6 unknowns.

$\to$ 6 constraints.

- Missing Energy:

$$\not{E}_x = p_{\nu,x} + p_{\bar{\nu},x}$$
$$\not{E}_y = p_{\nu,y} + p_{\bar{\nu},y}$$

- W mass constraints:

$$m_{W^+} = (E_{l^+} + E_\nu)^2 - (p_{x,l^+} + p_{x,\nu})^2 - (p_{y,l^+} + p_{y,\nu})^2 - (p_{z,l^+} + p_{z,\nu})^2$$
$$m_{W^-} = (E_{l^-} + E_{\bar{\nu}})^2 - (p_{x,l^-} + p_{x,\bar{\nu}})^2 - (p_{y,l^-} + p_{y,\bar{\nu}})^2 - (p_{z,l^-} + p_{z,\bar{\nu}})^2$$

- Top mass constraints:

$$m_t = (E_{l^+} + E_\nu + E_b)^2 - (p_{x,l^+} + p_{x,\nu} + p_{x,b})^2 - (p_{y,l^+} + p_{y,\nu} + p_{y,b})^2 - (p_{z,l^+} + p_{z,\nu} + p_{z,b})^2$$

$$m_{\overline{t}} = (E_{l^-} + E_{\overline{\nu}} + E_{\overline{b}})^2 - (p_{x,l^+} + p_{x,\overline{\nu}} + p_{x,\overline{b}})^2 - (p_{y,l^-} + p_{y,\overline{\nu}} + p_{y,\overline{b}})^2 - (p_{z,l^-} + p_{z,\overline{\nu}} + p_{z,\overline{b}})^2$$

- Neglecting the b-quark and lepton mass

$$0 = \sum_{i=0}^{4} c_i(m, p_{l^+}, p_{l^-}, p_b, p_{\overline{b}})p_i(\nu)$$

The Analytic Mass Weighing Technique

- A proper weight is assigned to each solution (see PhysRevD.45.1531) :

$$w(\vec{X}, m_t) = \left\{ \sum_{InitialPartons} F(x_1, Q)F(x_2, Q)p(E_{l^+}|m_t)p(E_{l^-}|m_t) \right\}$$

  at $Q = m_t$

- The probability density for observing lepton with energy E in rest frame of the top quark with mass m_t is defined as

$$p(E_l|m_t) = \frac{4m_t E(m_t^2 - m_b^2) - 2m_t E}{(m_t^2 - m_b^2)^2 + m_W^2(m_t^2 - m_b^2) - 2m_W^4}$$

- Solution with the highest weight is selected.

DY Background Estimation

The contribution of DY is estimated using the data driven method as follows:

- The excluded region around the Z mass is used as a control region.
- $N_{out}^{l^+l^-, Z+jets\ \ data} = R_{out/in}^{l^+l^-}(N_{in}^{l^+l^-, data} - 0.5 N_{in}^{e\mu, data} k_{ll})$
- $R_{out/in}^{l^+l^-} = \frac{N_{out}^{l^+l^-, Z+jets\ \ MC}}{N_{in}^{l^+l^-, Z+jets\ \ MC}}$
- $k_{ee} = \sqrt{\frac{N^{e^+e^-, in, loose}}{N^{\mu^+\mu^-, in, loose}}}$
- $k_{\mu\mu} = \sqrt{\frac{N^{\mu^+\mu^-, in, loose}}{N^{e^+e^-, in, loose}}}$
- $SF_{Z+jets} = \frac{N_{out}^{l^+l^-, Z+jets\ \ data}}{N_{out}^{l^+l^-, Z+jets\ \ MC}}$

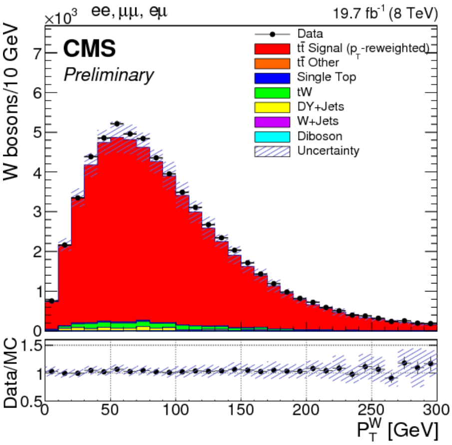


Figure: Distributions of the transverse momentum of the reconstructed W bosons

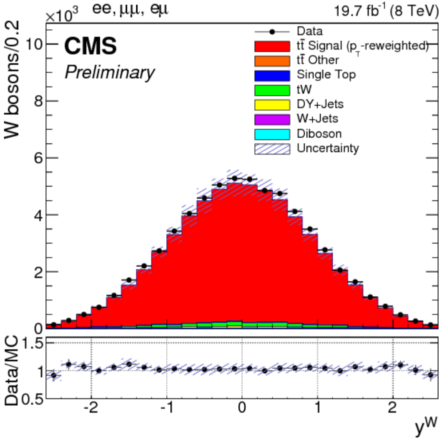


Figure: Distributions of rapidity of the reconstructed W bosons

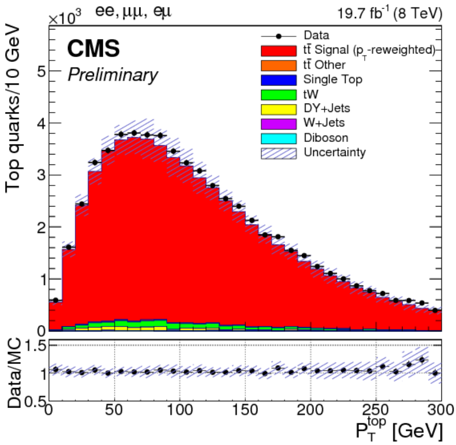


Figure: Distributions of the transverse momentum of the reconstructed top quarks

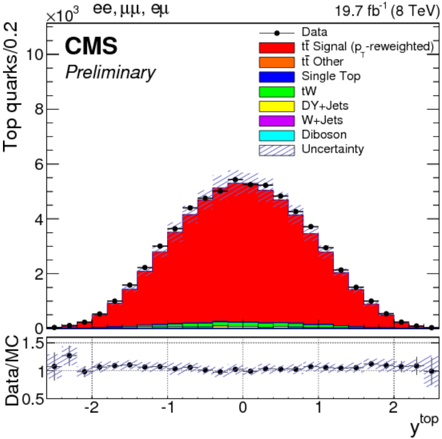


Figure: Distributions of the rapidity of the reconstructed top quarks

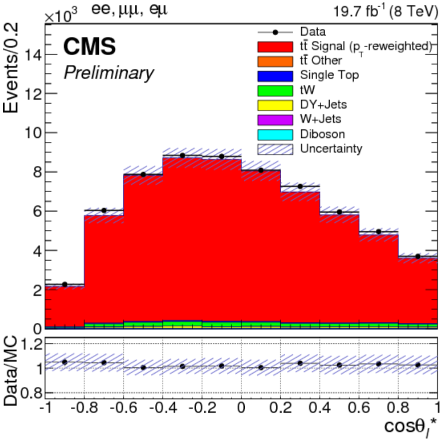


Figure: Distribution of the $cos\theta^*$ for the e^+e^-, $\mu^+\mu^-$, and $e^\pm\mu^\pm$ channel summed

Fitting Method

- In order to extract the W boson helicity fractions, a re-weighting technique is used (CMS-PAS-TOP-13-008).
- Each top quark pair event is re-weighted according to, $W_{l^+l^-}(cos\theta^*_{gen};\vec{F}) = W_{l^+}(cos\theta^*_{gen};\vec{F}) \times W_{l^-}(cos\theta^*_{gen};\vec{F})$ where

$$W_{l\pm}(cos\theta^*_{gen};\vec{F}) = \frac{\frac{3}{8}(1-cos\theta^*_{l,gen})^2F_L+\frac{3}{8}(1+cos\theta^*_{l,gen})^2F_R+\frac{3}{8}(1-cos^2\theta^*_{l,gen})F_0}{\frac{3}{8}(1-cos\theta^*_{l,gen})^2F_L^{SM}+\frac{3}{8}(1+cos\theta^*_{l,gen})^2F_R^{SM}+\frac{3}{8}(1-cos^2\theta^*_{l,gen})F_0^{SM}}$$

- A binned Poisson likelihood function is introduced to extract the helicity fractions,

$$\mathcal{L}(\vec{F}) = \prod_{i\epsilon bins} \frac{N_{MC(i;\vec{F})}^{N_{data(i)}}}{N_{data(i)}!} \times \exp^{-N_{MC(i;\vec{F})}}$$

- the index i denotes the i'th bin of the measured $cos\theta^*_{rec}$.

- $N_{data}(i)$ is the number of observed data in the i'th bin and
- $N_{MC}(i;\vec{F}) = N_{BKG}(i) + N_{t\bar{t}}(i;\vec{F})$
- $N_{t\bar{t}}(i;\vec{F}) = \mathcal{F}_{t\bar{t}}[\sum_{t\bar{t}\ \ events;i'th\ \ bin} W_{l^+l^-}(cos\theta^*_{gen};\vec{F})]$

  $N_{BKG}(i) = N_{single-top}(i) + N_{DY}(i) + N_{diboson}(i) + N_{W+jets}(i) + N_{t\bar{t}\ \ other}(i)$
- The variable $\mathcal{F}_{t\bar{t}}$ free parameter covering biases(detector inefficiencies, luminosity estimation, tagging efficiencies, acceptance of cuts and theory uncertainties.)
- A 3-parameter fit is performed by minimizing the $-2\ln\mathcal{L}(\vec{F})$ function using the MINUIT2 package.

Systematic uncertainties (absolute) Summary Table

Systematics uncertainty	ΔF_L	ΔF_0
Lepton ID and trigger	< 0.001	< 0.001
b tagging	0.001	0.001
Background normalisations	0.002	0.005
Jet energy resolution	0.003	0.002
Jet energy scale	0.002	0.009
Top p_T reweighting	0.007	0.01
Factorization/renormalization scales (signal)	0.013	0.01
Factorization/renormalization scales (DY)	0.004	0.007
Hadronization model	0.006	0.008
Jet-parton matching	0.017	0.012
Top mass ($\pm$1GeV)	0.004	0.005
Pileup	0.001	0.001
PDF	< 0.001	< 0.001
Integrated luminosity	0.001	< 0.001
Limited simulated signal statistics	0.003	0.004
Total uncertainty	0.025	0.024

Results

Channel	Results
$\mu\mu$	$F_0 = 0.636 \pm 0.033(stat) \pm 0.038(syst)$ $F_L = 0.337 \pm 0.020(stat) \pm 0.033(syst)$ $F_R = 0.027 \pm 0.016(stat) \pm 0.038(syst)$
ee	$F_0 = 0.617 \pm 0.037(stat) \pm 0.065(syst)$ $F_L = 0.330 \pm 0.022(stat) \pm 0.048(syst)$ $F_R = 0.053 \pm 0.019(stat) \pm 0.047(syst)$
$e\mu$	$F_0 = 0.665 \pm 0.020(stat) \pm 0.022(syst)$ $F_L = 0.329 \pm 0.012(stat) \pm 0.032(syst)$ $F_R = 0.007 \pm 0.009(stat) \pm 0.026(syst)$
combined	$F_0 = 0.653 \pm 0.016(stat) \pm 0.024(syst)$ $F_L = 0.329 \pm 0.009(stat) \pm 0.025(syst)$ $F_R = 0.018 \pm 0.008(stat) \pm 0.026(syst)$
SM (Phys.Rev.D81,111503(R))	$F_0 = 0.687 \pm 0.005$ $F_L = 0.311 \pm 0.005$ $F_R = 0.0017 \pm 0.0001$

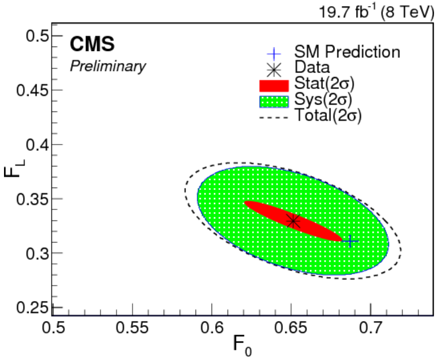


Figure: The 95% region in the (F_0, F_L) plane obtained from the fit to data. The measured and theoretical values of the W boson helicity fractions are shown as well.

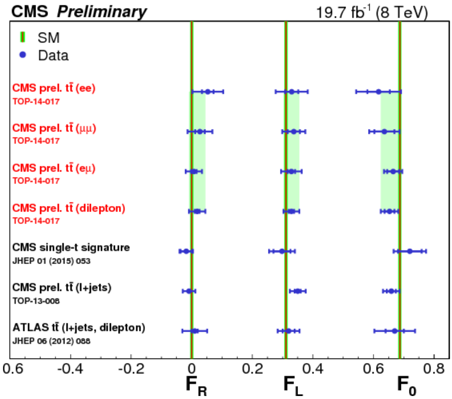


Figure: Measured W boson helicity fractions in the tt dilepton compared with results in different final states from the CMS experiment(CMS-TOP-11-020,CMS-PAS-TOP-13-008,CMS-TOP-12-020) and from the ATLAS experiment(JHEP06(2012)088)

Conclusion

- The measurement is based on 19.7 fb^-1 of data collected with the CMS detector at the LHC at a center of mass energy of 8 TeV.
- The W boson helicity fractions, obtained from a fit to the reconstructed distributions of $cos\theta^*$ are
  $F_L = 0.329 \pm 0.029$, $F_0 = 0.653 \pm 0.026$, and $F_R = 0.018 \pm 0.027$.
- These results are in agreement with the SM predictions at NNLO within 2σ uncertainties.
- There is an ongoing measurement of the helicity fractions at 13 TeV center of mass energy; which will hopefully further our understanding of the top properties and the precision of our results on helicity fractions.