Measurement of the W-Helicity in $t\bar{t}$ Events Using CMS Detector at the LHC

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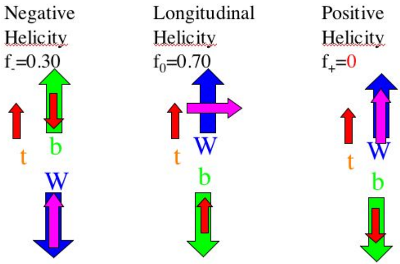
W-Polarization in Theory

- At NNLO, the SM predictions for the W-boson helicity fractions are[1]
  - $F_0 = 0.687 \pm 0.005$
  - $F_L = 0.311 \pm 0.005$
  - $F_R = 0.0017 \pm 0.0001$
- This can be understood since in the limit of massless b-quarks, right-handed W-bosons are suppressed



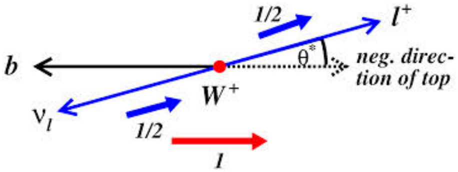
[1] Phys.Rev.D81:111503,2010

W-Polarization in Experiment

- In order to estimate the W-boson helicity fractions from experimental data, one needs to find the distribution of $\cos\theta^*$

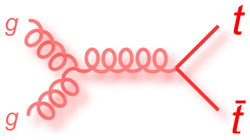
$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta^*} = \frac{3}{8}(1-\cos\theta^*)^2 F_L + \frac{3}{8}(1+\cos\theta^*)^2 F_R + \frac{3}{4}\sin^2\theta^* F_0$$

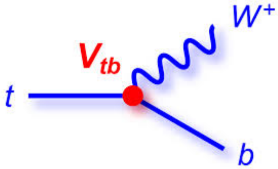
- θ^* is defined as the angle in the W-boson rest frame between the direction opposite to the top-quark and the direction of lepton

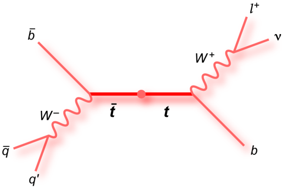


$t\bar{t}$ Events Are Selected to Measure W-Helicity Fractions

- At the LHC, $t\bar{t}$ events are mainly produced via gluon-gluon fusion
- Since $V_{tb} \sim 1$, almost all the time a top-quark decays to a W-boson and a b-quark
- W-boson decays into hadrons in 67% and into leptons in 33%

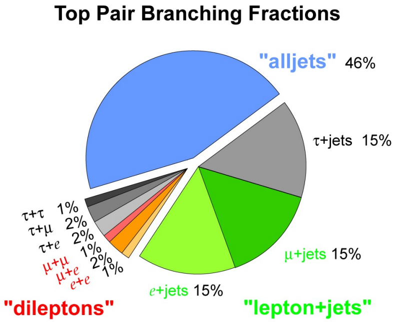






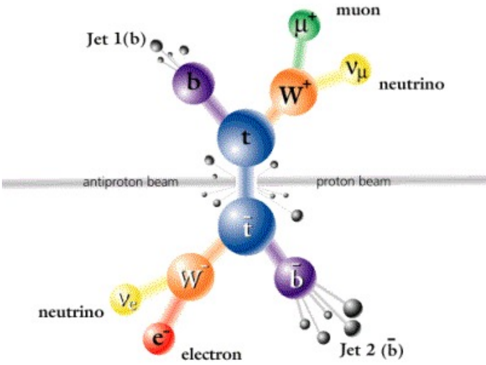
Probability for a $t\bar{t}$ Event Decaying into Di-Leptons

- In this analysis, di-lepton $t\bar{t}$ events are selected
- The probability for a top-pair event decaying into di-leptons is found to be 33%×33%∼11%
- Despit of very small probability, but still very clean sample at the end



Signatures of Di-Lepton $t\bar{t}$ Decay

- 2 neutrinos ➡ yields to a large Missing Transverse Energy (MET) containing 6 unknown parameters
- 2 leptons ➡ low QCD backgrounds
- 2 b-quark ➡ 2 b-quark jets at detector-level ➡ low W+jets backgrounds
- 4 mass constraints
  - 2 top-quark mass constraints
  - 2 W-boson mass constraints
- Low production rate (11%) ➡ but still clean signature



Finding ν and $\bar{\nu}$ Four-Vectors from Kinematic Constraints

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

$$
\begin{aligned}
(E_T^{\text{miss}})_x &= p_{\nu_x} + p_{\bar{\nu}_x} \\
(E_T^{\text{miss}})_y &= p_{\nu_y} + p_{\bar{\nu}_y} \\
m_{W^+}^2 &= (E_{l^+} + E_{\nu})^2 - \Sigma_{i=x,y,z}(p_{l_i^+} + p_{\nu_i})^2 \\
m_{W^-}^2 &= (E_{l^-} + E_{\bar{\nu}})^2 - \Sigma_{i=x,y,z}(p_{l_i^-} + p_{\bar{\nu}_i})^2 \\
m_t^2 &= (E_b + E_{l^+} + E_{\nu})^2 - \Sigma_{i=x,y,z}(p_{b_i} + p_{l_i^+} + p_{\nu_i})^2 \\
m_{\bar{t}}^2 &= (E_{\bar{b}} + E_{l^-} + E_{\bar{\nu}})^2 - \Sigma_{i=x,y,z}(p_{\bar{b}_i} + p_{l_i^-} + p_{\bar{\nu}_i})^2
\end{aligned}
$$

- Polynomial equation of degree 4 ⇨ maximally four solutions for the ν and $\bar{\nu}$
- The ambiguity is resolved by choosing the solution minimizing the mass of top pair system

Data and MC Samples

- Summer11 MC data sets

Sample Name	σ^{NLO} (pb)
TTJets_TuneZ2_7TeV-madgraph	157.5
WJetsToLNu_TuneZ2_7TeV-madgraph-tauola	31314.0
DYJetsToLL_TuneZ2_M-50_7TeV-madgraph-tauola	3048.0
DYJetsToLL_M-10To50_TuneZ2_7TeV-madgraph	9611.0
T_TuneZ2_tW-channel-DR_7TeV-powheg-tauola	7.8
Tbar_TuneZ2_tW-channel-DR_7TeV-powheg-tauola	7.8
WWJetsTo2L2Nu_TuneZ2_7TeV-madgraph-tauola	4.65
WZJetsTo3LNu_TuneZ2_7TeV-madgraph-tauola	0.6
ZZ_TuneZ2_7TeV_pythia6_tauola	4.65
T_TuneZ2_t-channel_7TeV-powheg-tauola	42.5
Tbar_TuneZ2_t-channel_7TeV-powheg-tauola	22

- Run2011A and Run2011B data are analyzed, corresponding to an amount equal to 4.6 fb^{-1}

Selection Cuts

- 1 good vertex is required
- At least 2 opposit-charge leptons with $p_T > 20$ GeV within the tracker acceptance
- Same-flavour events under the Z-peak $76 < M_{ll} < 106$, are vetoed
- At least 2 PF jets with $p_T > 30$ GeV within the tracker acceptance
- Same(Opposit)-flavour events should have $E_T^{\text{miss}} > 30(20)$ GeV
- At least one of the jets should be tagged as b-jet

Cut Flow Table

- Various scale factors are applied, including pile-up reweighting, b-tagging, trigger and lepton efficiencies
- DY normalization factor obtained after cutting on $E_T^{\rm miss}$ is also taken into account
- The cut flow results for all three di-lepton channels are combined and can be found in the table below

Dataset	Njets	$E_T^{\rm miss}$	NBjets	$N_{t\bar{t}}$
$t\bar{t}$	13569.6±50.4	12160.2±47.7	9075.0±42.3	8692.3±32.7
Single top tW	708.2±7.9	631.4±7.4	410.4±6.2	357.3±4.5
DY $M_{ll} > 10GeV$	16193.2±106.7	2841.3±41.7	206.9±11.8	167.0±9.5
WW	399.4±2.6	353.1±2.4	32.0±0.7	22.8±0.5
Single top t	14.6±1.0	12.4±0.9	7.8±0.8	6.5±0.6
W+jets	553.3±32.2	448.2±28.8	33.0±7.4	17.0±4.4
WZ	89.6±0.4	70.6±0.4	3.9±0.1	2.7±0.1
ZZ	69.3±0.6	15.4±0.3	2.2±0.1	1.6±0.0
Total(Simulation)	31597.3±122.7	16532.7±70.0	9771.3±45.0	9267.3±34.7
Data	29982	16257	9888	9341

Data-Driven Estimation of Drell-Yan(DY) Backgrounds

- To reduce the DY contribution in a di-lepton data sample, events with $76 < M_{ll} < 106$ GeV are excluded from the analysis
- The predicted simulation outside the veto region is normalized by the fraction of data over prediction inside the control region

$$N_{DY}^{out\ (est)} = \frac{N_{DY\ Data}^{in}}{N_{DY\ MC}^{in}} \times N_{DY\ MC}^{out}$$

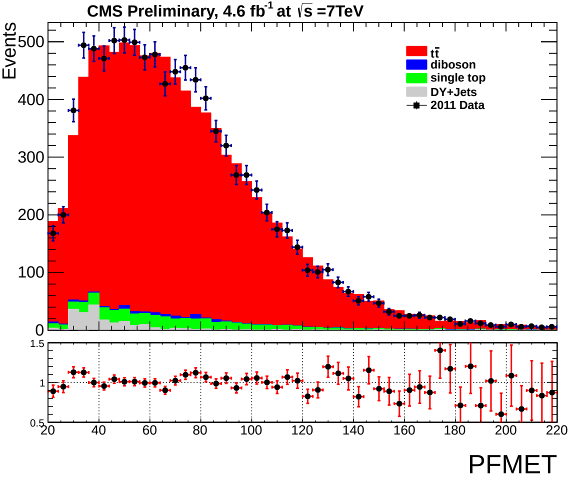
- Inside the control region, non-DY data events which is estimated from $e\mu$ channel, should be subtracted from DY data events

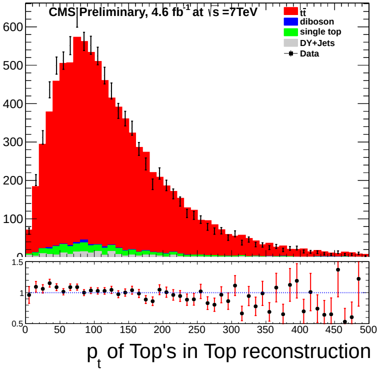
$$N_{DY\ Data}^{in} = (N_{ee(\mu\mu)\ Data}^{in} - N_{e\mu\ Data}^{in} \times \frac{1}{2}\sqrt{(\frac{N_{ee(\mu\mu)\ Data}^{int}}{N_{\mu\mu(ee)\ Data}^{int}}}))$$

- The correction factor multiplied by $N_{e\mu\ Data}^{in}$ is due to the difference in efficiency to reconstruct and select a muon compared to an election
- The obtained results are 1.56±0.04(ee), 1.09±0.04($\mu\mu$) and 1.31±0.06(eμ)

Data-MC Comparison

- bottom plot: distribution of E_T^{miss} after applying all kinematics cuts

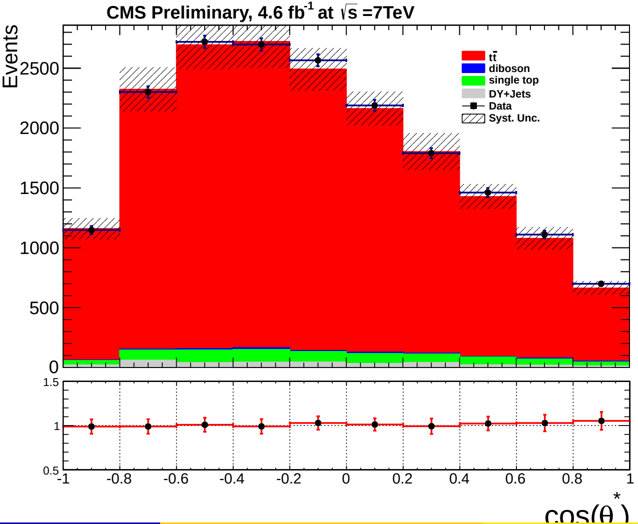




- top plot: distribution of top quark p_T in positive branch of di-lepton $t\bar{t}$ events after running neutrino solver

Constructing Angular Distribution

- Combined distribution of $\cos\theta^*$ for all di-lepton channels



Fit Method

- A likelihood function is introduced

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

- where

$$\begin{aligned} N_{MC}(i;\vec{F}) &= N_{t\bar{t}}(i;\vec{F}) + N_{BKG}(i) \\ N_{t\bar{t}}(i;\vec{F}) &= \mathcal{F}_{t\bar{t}}[\sum_{t\bar{t}\ \ events, bin\ \ i} W(\cos\theta^*_{gen};\vec{F})] \\ N_{BKG}(i) &= N_{DY}(i) + N_{W+jets}(i) + N_{di-bosons}(i) + N_{single\ \ top}(i) \end{aligned}$$

- and the weight function is defined as

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

- The W-boson helicity fractions are those which maximize the likelihood function

Measured W-Heliciy Fractions in Di-Leptonic $t\bar{t}$ Events

W-heliciy @ 7 TeV, di-leptonic channel

$$F_L = 0.288 \pm 0.035(\text{stat}) \pm 0.040(\text{sys})$$
$$F_0 = 0.698 \pm 0.057(\text{stat}) \pm 0.063(\text{sys})$$
$$F_R = 0.014 \pm 0.027(\text{stat}) \pm 0.042(\text{sys})$$
$$\mathcal{F}_{t\bar{t}} = 1.034 \pm 0.016$$

- The F_R is found from the constraint $F_L + F_0 + F_R = 1$
- 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

	Fitting F_L, F_0	
Systematic Source	$\pm\delta F_L$	$\pm\delta F_0$
Top QScale	0.027	0.051
Top Mass	0.016	0.003
WZ QScale	0.013	0.026
DY XSection	0.009	0.014
W XSection	0.000	0.002
Single top TW XSection	0.002	0.008
JES	0.01	0.006
Pile Up	0.014	0.017
PDF	0.004	0.005
Total	0.040	0.063

Selection Cuts in $t\bar{t}$ Events with Lepton+Jets [1]

- Exactly one tight lepton, where tight muons(electrons) have $p_T > 25(30)$ Gev and $|\eta| < 2.1(2.5)$
- Veto events with additional looser leptons
- At least 4 jets with $p_T > 30$ GeV within the tracker acceptance
- At least one (or at least two) jets passing the b-tag CVSM criteria for the 1 btag (2 btags) analysis
- Requiring leptonic W transverse mass $30 < M_T < 200$ GeV [2]

[2] No explicit cut on E_T^{miss} is applied since it has a strong correlation with $\cos\theta^*$. An explicit requirement on E_T^{miss} would imply a loss in efficiency at high values of $\cos\theta^*$, which is the most sensitive region for the determination of F_R.

[1] TOP-11-020

Analysis Overview: Neutrino Solution and Jet Combination

- Two(Three) jets are assigned to the W(top), if the invariant mass of the two(three)-jet system is compatible with the W(top) mass
- A value of neutrino p_z is searched so that the invariant mass formed with the neutrino four-vector, comprising of $E_T^{\rm miss}$ with unknown p_z component, and the lepton is compatible with the W mass
- A χ^2 method is used to select a best jet combination

$$\chi^2_{\rm comb} = \left(\frac{m_t - m_t^{\rm ref}}{\sigma_{m_t}}\right)^2 + \left(\frac{m_{\bar{t}} - m_t^{\rm ref}}{\sigma_{m_{\bar{t}}}}\right)^2 + \left(\frac{M_W^{\rm lep} - 80.4}{\sigma_{M_W^{\rm lep}}}\right)^2 + \left(\frac{M_W^{\rm had} - 80.4}{\sigma_{M_W^{\rm had}}}\right)^2$$
$$+ \sum_{i=1,4} -2\ln p_i(disc|f)$$

- The term $p_i(disc|f)$ is build for each jet as the probability of the given jet with flavour f, given its measured value of CSV discriminant
- The configuration of lepton, neutrino and jets minimizing $\chi^2_{\rm comb}$ is used to reconstruct $t\bar{t}$ system

Analysis Overview: Kinematic Fitter

- Once the best combination is found, a constrained kinematic fit is perfomed leading to a better determination of the unmeasured neutrino p_z and a more accurate reconstruction of the $t\bar{t}$ system
- The fitted four-momentum of the lepton $p^{\mathrm{fit,lep}}$ and jets $p^{\mathrm{fit,jet}}$ are obtained minimizing a χ^2

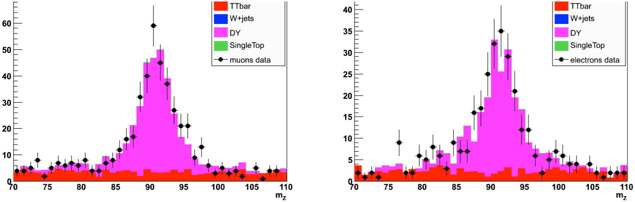
$$\chi^2 = \left(\frac{m_t - m_t^{\mathrm{ref}}}{\sigma_{m_t}}\right)^2 + \left(\frac{m_{\bar{t}} - m_t^{\mathrm{ref}}}{\sigma_{m_{\bar{t}}}}\right)^2 + \left(\frac{M_W^{\mathrm{lep}} - 80.4}{\sigma_{M_W^{\mathrm{lep}}}}\right)^2 + \left(\frac{M_W^{\mathrm{had}} - 80.4}{\sigma_{M_W^{\mathrm{had}}}}\right)^2$$

$$+ \sum_i \left(\frac{p_i^{\mathrm{fit,lep}} - p_i^{\mathrm{lep}}}{\sigma_{p_i^{\mathrm{lep}}}}\right)^2 + \sum_j \sum_i \left(\frac{p_i^{\mathrm{fit,jet_j}} - p_i^{\mathrm{jet_j}}}{\sigma_{p_i^{\mathrm{jet_j}}}}\right)^2 ,$$

- The same reweighting technique, as described before, is used to extract W-helicity fractions

Data-Driven Background Estimation: DY

- A control sample is defined applying the same selection criteria, except that events containing an additional lepton of the same flavour and opposite charge are selected instead
- The distribution of the invariant mass of the dilepton system for data and simulation in the control region is shown for electrons and muons



- The normalization of the DY simulated sample was fitted to the data inside a window of 20 GeV around the Z mass
- The predicted normalization factor for the DY sample is 1.002 ± 0.113(electrons) and 0.996 ± 0.093(muons)

Data-Driven Background Estimation: W+jets

- The contribution from W+jets is determined from the charge asymmetry $N(l^+) - N(l^-)$
- The total number of W+jets events in the sample can be estimated as

$$(N_+ + N_-)^{W+jets}_{\mathrm{data-driven}} = R^W_{\pm(\mathrm{MC})} \times (N_+ - N_-)_{\mathrm{data}}$$

  where $(N_+ - N_-)_{\mathrm{data}}$ is measured in data (after subtracting single top contamination from simulation)
- $R^W_{\pm(\mathrm{MC})}$ is estimated using simulated events as

$$R_{\pm(\mathrm{MC})} = \frac{(N_+^{\mathrm{W+jets}} + N_-^{\mathrm{W+jets}})}{(N_+^{\mathrm{W+jets}} - N_-^{\mathrm{W+jets}})}$$

- This method is applied in two bins of jet multiplicity and for events with at least 1-btagged or 2-btagged jets
- The estimated scale factors in, e.g. events with exactly 4 jets, are compatible with one

Cut Flow Table in $t\bar{t}$ Events with Lepton+Jets

- Table below presents the number of data events used in lepton+jets analysis, and predictions from simulation for the $t\bar{t}$ signal and background process for both one and two b-tagged jets requirement
- A very good agreement between data and expected yields is found for both channels, if either 1 or 2 btags are applied

Sample	Electrons				Muons			
	1 tag		2 tags		1 tag		2 tags	
	Selec	KF	Selec	KF	Selec	KF	Selec	KF
W+jets	1647.1	1352.5	234.3	203.3	2179.8	1779.3	350.9	282.0
Single top	721.6	613.2	265.0	223.1	1012.5	872.4	371.9	318.6
DY	221.2	182.2	42.5	33.7	247.4	217.6	42.8	38.3
$t\bar{t}$ bkg	1343.5	1156.8	628.6	546.8	1979.1	1749.8	928.3	827.8
Sum bkg	3933.4	3304.7	1170.4	1006.9	5418.8	4619.2	1694.0	1466.8
$t\bar{t}$ sig	11542.1	10958.4	5390.6	5179.2	16185.3	15434.7	7596.7	7321.3
Simulation	15475.4	14263.1	6561.0	6186.1	21604.1	20053.9	9290.7	8788.1
Data	15319	14019	6526	6135	21818	20221	9268	8772

Measured W-Heliciy Fractions in Semi-Leptonic $t\bar{t}$ Events

W-heliciy @ 7 TeV, semi-leptonic channel at least 1 b-tagged jets

$$F_L = 0.322 \pm 0.017(\text{stat}) \pm 0.022(\text{sys})$$
$$F_0 = 0.656 \pm 0.024(\text{stat}) \pm 0.035(\text{sys})$$
$$F_R = 0.022 \pm 0.013(\text{stat}) \pm 0.019(\text{sys})$$

W-heliciy @ 7 TeV, semi-leptonic channel at least 2 b-tagged jets

$$F_L = 0.308 \pm 0.022(\text{stat}) \pm 0.012(\text{sys})$$
$$F_0 = 0.686 \pm 0.031(\text{stat}) \pm 0.025(\text{sys})$$
$$F_R = 0.006 \pm 0.015(\text{stat}) \pm 0.015(\text{sys})$$

Measured W-Heliciy Fractions in Semi-Leptonic $t\bar{t}$ Events [1]

W-heliciy @ 8 TeV, semi-leptonic channel

$$F_L = 0.354 \pm 0.011(\text{stat}) \pm 0.025(\text{sys})$$
$$F_0 = 0.655 \pm 0.015(\text{stat}) \pm 0.018(\text{sys})$$
$$F_R = -0.009 \pm 0.006(\text{stat}) \pm 0.020(\text{sys})$$
$$\mathcal{F}_{t\bar{t}} = 1.034 \pm 0.016$$

[1] TOP-13-008

Summary

- The W-helicity measuements in top pair production using 7 TeV and 8 TeV data collected by CMS experiment were presented
- The studies were performed on either single-lepton or di-lepton products of top pair events
- The update on W-helicity measurement using 8 TeV data in di-lepton channel is ongoing
- Measured helicity fractions are in good agreement with predicted Standard Model values