Measurement of the W boson polarization in semi-leptonic top-pair decays with the CMS detector at the LHC

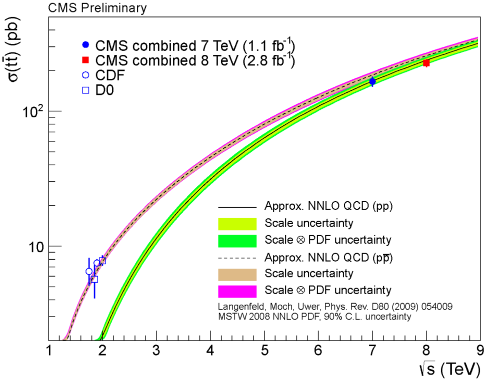
Adrián Quintario Olmeda, CMS Collaboration

IV CPAN Days - Granada
November 26-28, 2012

Introduction

Why study the $t\bar{t}$ production

- The top quark was discovered in Tevatron in 1995
- But in the LHC we have many more $t\bar{t}$ pairs:

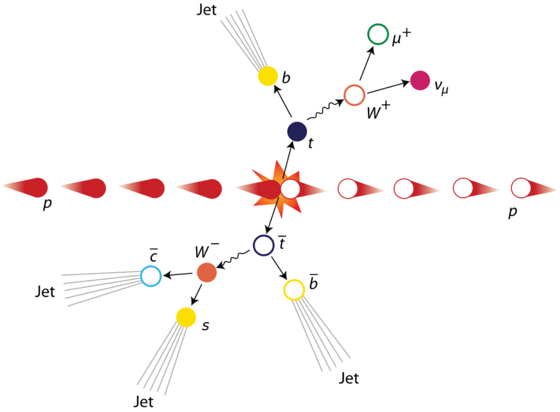


- It is one of the least explored sectors of the SM, with sensitivity to New Physics
- $m_t \simeq 173\ \text{GeV}/c^2$, $\tau_t \simeq 10^{-2}\tau_{QCD}$
- Decays almost exclusively into a W-boson and a bottom quark
- Unique opportunity to study the general structure of the Wtb vertex

Introduction

2011 data, $\sqrt{s}$= 7 TeV. $\mathcal{L}_{int}$= 2.2 fb^{-1}

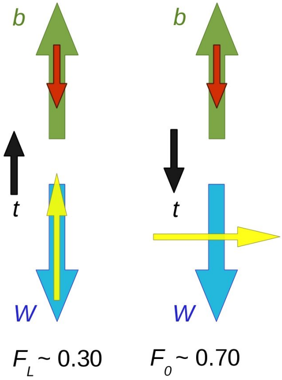
This presentation is focused in the semi-leptonic decay of the $t\bar{t}$ pair, with a muon in its final state, $t\bar{t} \rightarrow W^+ bW^- \bar{b} \rightarrow b\bar{b}q\bar{q}' \mu\nu_\mu$



One W decays into two quarks and the other into a muon and a neutrino, which escapes the detection, leaving an apparent imbalance of energy-momentum

Introduction

The helicity, the projection of the spin over the momentum, of the W produced in a $t \to Wb$ decay may be longitudinal, left- or right-handed.

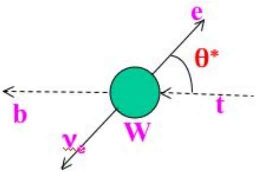


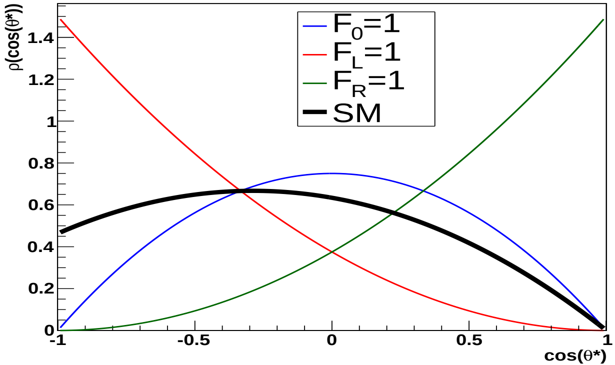
- The helicity fractions are $F_{L,R,0} \equiv \Gamma_{L,R,0}/\Gamma$
- By construction, $F_L + F_R + F_0 = 1$
- $F_R \simeq 0$: V-A character of the W coupling and $m_b \to 0$
- In the SM, the fractions are calculated as a function of m_t, m_W and m_b
- At NLO/NNLO, the predicted values are $F_0 \simeq 0.69$, $F_L \simeq 0.31$, $F_R \simeq 0.002$

Introduction

Helicity angle θ^*

Assuming a top rest frame, the angle between the charged lepton three-momentum in the W rest frame and the W momentum in the top rest frame.





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

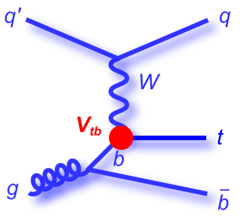
Introduction

- If measured fractions are different from SM predictions, the result will be interpreted in terms of **anomalous couplings**
- The general Lagrangian that describes the Wtb vertex is[1]:

$$\mathcal{L}_{Wtb} = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}(V_L P_L + V_R P_R)tW_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_{\nu}}{m_W}(g_L P_L + g_R P_R)tW_{\mu}^{-} + h.c.$$

- Being V_L, V_R, g_L and g_R complex constants
- In the SM $V_L = V_{tb} \simeq 1$ and $V_R = g_L = g_R = 0$

Alternatively to $t\bar{t}$ production, we access the Wtb vertex via single-t production, whose cross section is proportional to $|V_{tb}|^2$



[1] J. Aguilar-Saavedra and J. Bernabeu, "W polarisation beyond helicity fractions in top quark decays", Nucl.Phys. B840 (2010) 349378, arXiv:1005.5382

Event selection

In order to have a $t\bar{t}$ enriched sample, reducing the background, the following cuts are applied:

- ≥ 4 jets with $p_T > 30$ GeVc and $|\eta| < 2.4$
- Only one good muon with $p_T > 25$ GeVc and $|\eta| < 2.1$
- $M_T = \sqrt{2 p_T E_T^{miss}(1 - \cos(\Delta\phi))} > 30$ GeV$/c^2$
  - Transverse component of the W-boson invariant mass
  - Cut to reject background from DY and QCD
- bTagging
  - Identification of b-jets based on the long life-time of the bottom quark
  - Reduces background coming from QCD and W+jets

Data:

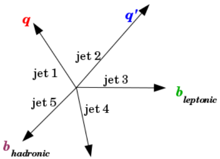
- p-p collisions data at $\sqrt{s}$=7 TeV, collected during the first half of 2011, $2.2\mathrm{fb}^{-1}$

MC

- MADGRAPH was used to simulate the $t\bar{t}$ (using $m_t = 172.5$ GeV$/c^2$) and background coming from W+jets and DY
- POWHEG was used to simulate single-t
- PYTHIA was used to simulate QCD

Event reconstruction

A good identification of the 4-momenta of all the final particles in the $t\bar{t}$ event is mandatory to calculate the helicity angle θ^*. Our two main tools for the reconstruction are b-tagging and kinematic fitter. This one:



- To find the best jet assignment that matches the $t\bar{t}$ kinematic configuration:
- Tries every combination of measured jets and performs a χ^2 calculation in each one
- It uses the central values $m_{W(lep)} = 80.4$ GeV$/c^2$, $m_{W(had)} = 80.4$ GeV$/c^2$, and $m_{top(had)} = 172.5$ GeV$/c^2$.
- The momenta of final state particles are free to vary within its resolution
- Finds the undetectable components of the neutrino 4-momentum, E and η

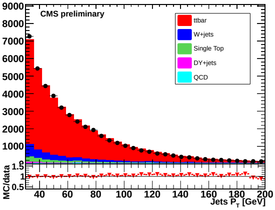
Event yields

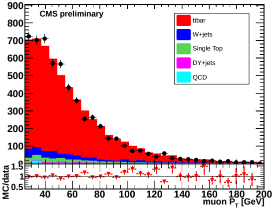
Process	Evt. passing selection cuts	Evt. kinematic fitter converges
Signal: $t\bar{t}$	7175.0	4570.3
W+jets	889.2	389.2
DY+jets	95.2	50.6
Single-t (t+tW-ch)	387.5	242.5
QCD	19.4	19.4
Total predicted	8566.4	5272.1
Data	9307	5712

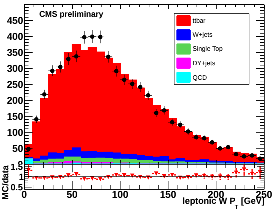
Central column: number of events selected according to the criteria mentioned above
Right column: subsample of selected events in which a $t\bar{t}$ pair is reconstructed
Event yields from MC samples are scaled to the luminosity
(Latest luminosity and efficiency corrections not included)

Data/MC comparison

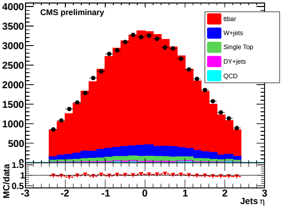
p_T

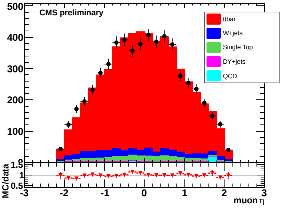


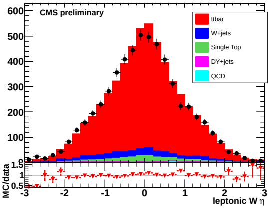




η



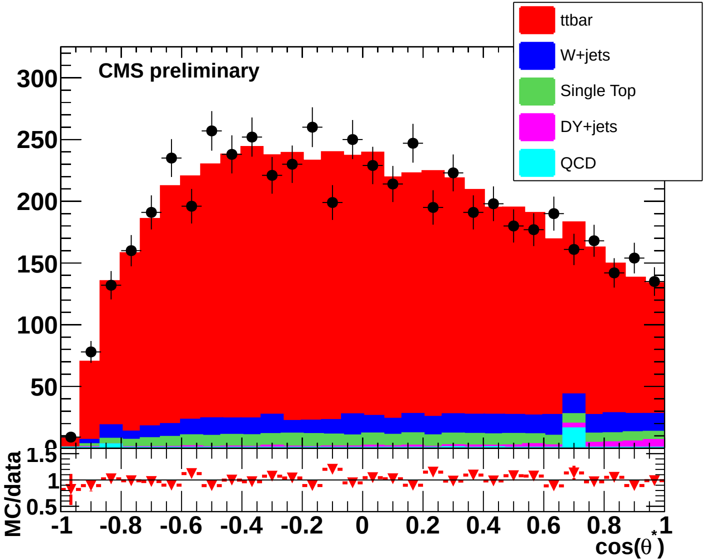




JETS MUON LEPTONIC W

cos θ^* distribution

SM already describes the data reasonably well
Main backgrounds: W+jets and single-t

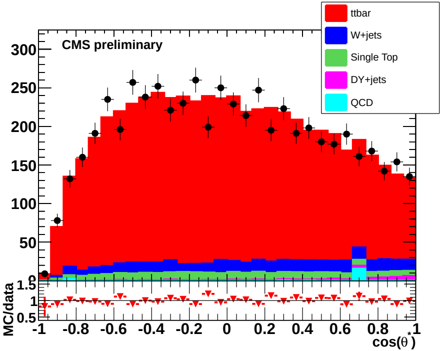


Fitting method

Fitting:

- We use an event-by-event reweighting method implemented with MINUIT
- Functional dependency of the distribution known exactly
- Gen. level → RW → Any configuration

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



Results

Two measurements are presented:

- Fit A: fit F_0 and F_L and extract $F_R = 1 - F_0 - F_L$
- Fit B: assume $F_R = 0$, fit F_0 and extract $F_L = 1 - F_0$.

Fit A

$F_0 =$
$0.567 \pm 0.074(stat.) \pm 0.047(syst.)$
$F_L =$
$0.393 \pm 0.045(stat.) \pm 0.029(syst.)$
$F_R =$
$0.040 \pm 0.035(stat.) \pm 0.044(syst.)$

Fit B

$F_0 =$
$0.643 \pm 0.034(stat.) \pm 0.050(syst.)$
$F_L =$
$0.357 \pm 0.034(stat.) \pm 0.050(syst.)$

SM fractions

$F_0 \simeq 0.69,\ F_L \simeq 0.31,\ F_R \simeq 0.002$

Systematic uncertainties

Systematics uncertainties sources

- Jet Energy Scale (CMS given)
- Data/MC discrepancies
  - Lepton efficiency (*tag* & *probe*)
  - b-Tag efficiency
- Theoretical
  - PDF
  - Top Q^2 scale$\rightarrow$Dedicated MC sample produced
  - DY, W+jets Q^2 scale$\rightarrow$Dedicated MC sample produced
  - Top mass (± 3 GeV/c^2)$\rightarrow$Dedicated MC sample produced
- Background normalization
  - DY, W+jets, QCD and single-t normalization
  - Obtained by varying norm. $\pm 100\%$
  - Covers errors coming from ISR/FSR

Only shape-changing systematics are to be taken into account

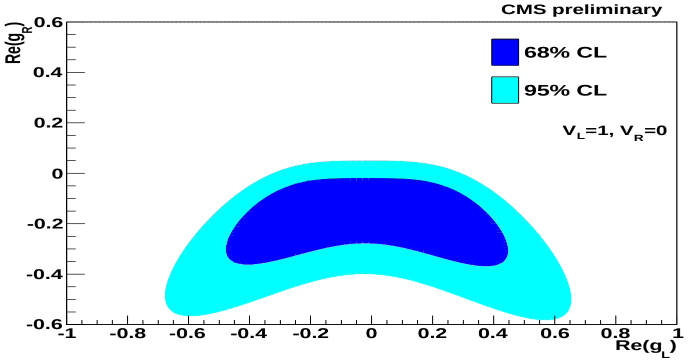
Systematic uncertainties

Systematic check	Fitting F_0 and F_L **Fit A**		Fitting F_0 **Fit B**
	$\pm$ Unc. F_0	$\pm$ Unc. F_L	$\pm$ Unc. F_0
b-Tag ($\frac{\epsilon_{\mathrm{b-tag}}^{DATA}}{\epsilon_{\mathrm{b-tag}}^{MC}}$)	0.007	0.009	0.010
QCD Norm	0.007	0.002	0.003
Single-t Norm	0.003	0.007	0.010
DY Norm	**0.018**	**0.003**	**0.010**
W+jet Norm	**0.020**	**0.006**	**0.029**
muon (no $\frac{\epsilon_{\mu}^{DATA}}{\epsilon_{\mu}^{MC}}$)	0.002	0.003	0.003
PDF	0.001	0.001	0.002
JES scale	**0.018**	**0.011**	**0.005**
top Q^2 scale	0.014	0.007	0.021
DY,W Q^2 scale	**0.022**	**0.003**	**0.014**
top mass ($\pm$3 GeV/c^2)	**0.019**	**0.021**	**0.025**

Limits on anomalous couplings

Two cases considered:

- From Fit B: $F_R = 0$, $V_L = 1$ and $V_R = g_L = 0$:
    - Gives $\mathrm{Re}(g_R) = -0.070 \pm 0.053(\mathrm{stat.})^{+0.073}_{-0.081}(\mathrm{syst.})$
- CP-conserving; F_R =FREE, $V_L = 1$; $V_R = 0$:
    - Results from plot



Results from single-t

In single top production, CMS has obtained results[2] 2011 data ($\sqrt(s) = 7$ TeV) amounting up to integrated luminosities of 1.17 fb^{-1} for the muon channel and 1.56 fb^{-1} for the electron channel. The measurement of the production cross section yields the following value for the V_L coupling:

$$|V_L| = \sqrt{\frac{\sigma_{t\text{-ch.}}}{\sigma^{\text{th}}_{t\text{-ch.}}}} = 1.020 \pm 0.046 \text{ (exp.)} \pm 0.017\text{(theor.)}$$

Which is in agreement with SM

[2] The CMS Collaboration, "Measurement of the single-top-quark t-channel cross section in pp collisions at $\sqrt(s) = 7$ TeV", arXiv:1209.4533v1

Conclusions & prospects

Conclusions

- W helicity fractions in $t\bar{t}$ decays measured using 2.2 fb^{-1} of CMS pp collision data at $\sqrt{s} = 7$ TeV
- Results in agreement with Standard Model
- Limits on anomalous coupling g_R, g_L obtained
- Conservative estimate of systematic uncertainties

Prospects (or ongoing)

- Study with full statistics
- Inclusion of electron channel
- Improvement of systematics using data-driven methods
- Combination with results from di-leptonic channel, single-t and ATLAS measurements

The end

Thank you very much

But wait

Back up

Formulae

Fractions in the SM

$$F_0 = \frac{(1-y^2)^2 - x^2(1+y^2)}{(1-y^2)^2 + x^2(1-2x^2+y^2)}$$

$$F_L = \frac{x^2(1-x^2+y^2+\sqrt{\lambda})}{(1-y^2)^2 + x^2(1-2x^2+y^2)}$$

$$F_R = \frac{x^2(1-x^2+y^2-\sqrt{\lambda})}{(1-y^2)^2 + x^2(1-2x^2+y^2)}$$

where $x = m_W/m_t$, $y = m_b/m_t$, $\lambda = 1 + x^4 + y^4 - 2x^2y^2 - 2x^2 - 2y^2$

Anomalous couplings and fractions:

$$\begin{aligned}
A = \; & (\frac{M_t^2}{M_W^2} - 1) + (g_L^2 + g_R^2)(1 - \frac{M_W^2}{M_t^2}) - 4\frac{M_b}{M_t} g_L g_R \\
& -2\frac{M_t}{M_W} g_R (1 - \frac{M_W^2}{M_t^2}) + 2\frac{M_b}{M_W} g_L (1 + \frac{M_W^2}{M_t^2}) \\
B_0 = \; & (1 - \frac{M_W^2}{M_t^2}) + (g_L^2 + g_R^2)(\frac{M_t^2}{M_W^2} - 1) - 4\frac{M_b}{M_t} g_L g_R \\
& -2\frac{M_t}{M_W} g_R (1 - \frac{M_W^2}{M_t^2}) + 2\frac{M_b}{M_W} g_L (1 + \frac{M_W^2}{M_t^2}) \\
B_1 = \; & -1 + (g_L^2 + g_R^2)\frac{M_t^2}{M_W^2} + 2\frac{M_t}{M_W} g_R + 2\frac{M_b}{M_t} g_L
\end{aligned}$$

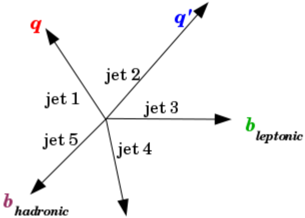
$$\begin{aligned}
\Gamma_0 &= A \\
\Gamma_L &= B_0 - (1 - \frac{M_W^2}{M_t^2})B_1 \\
\Gamma_R &= B_0 + (1 - \frac{M_W^2}{M_t^2})B_1
\end{aligned}$$

Kinematic Fitter

Using TopQuarkAnalysis/TopKinFitter package

$$\chi^2 = \sum_{comps} \frac{\Delta y^2}{\sigma_y^2}$$

$$L = \chi^2 + \sum \lambda_j f_j$$



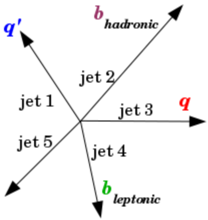
- y stands for the measurable quantities, σ their uncertainties, f_i are the constraints we are imposing and λ_i the Lagrange multipliers
- $M_{W(lep)} = 80.4$, $M_{W(had)} = 80.4$ and $M_{top(had)} = 172.5$ GeV.
- Measurable 4-momenta allowed to vary within their resolutions
- Neutrino p_z and η initialized at 0 and allowed to vary
- If the fit converges, for that combination it outputs:
  - χ^2
  - Neutrino p_z
  - Neutrino η
- The combination with the minimum χ^2 is selected

Kinematic Fitter

Using TopQuarkAnalysis/TopKinFitter package

$$\chi^2 = \sum_{comps} \frac{\Delta y^2}{\sigma_y^2}$$

$$L = \chi^2 + \sum \lambda_j f_j$$



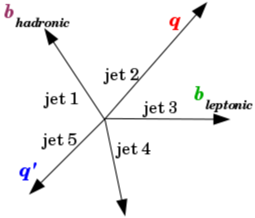
- y stands for the measurable quantities, σ their uncertainties, f_i are the constraints we are imposing and λ_i the Lagrange multipliers
- $M_{W(lep)} = 80.4$, $M_{W(had)} = 80.4$ and $M_{top(had)} = 172.5$ GeV.
- Measurable 4-momenta allowed to vary within their resolutions
- Neutrino p_z and η initialized at 0 and allowed to vary
- If the fit converges, for that combination it outputs:
  - χ^2
  - Neutrino p_z
  - Neutrino η
- The combination with the minimum χ^2 is selected

Kinematic Fitter

Using TopQuarkAnalysis/TopKinFitter package

$$\chi^2 = \sum_{comps} \frac{\Delta y^2}{\sigma_y^2}$$

$$L = \chi^2 + \sum \lambda_j f_j$$



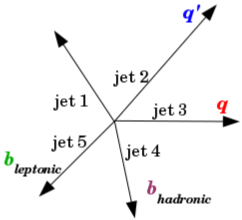
- y stands for the measurable quantities, σ their uncertainties, f_i are the constraints we are imposing and λ_i the Lagrange multipliers
- $M_{W(lep)} = 80.4$, $M_{W(had)} = 80.4$ and $M_{top(had)} = 172.5$ GeV.
- Measurable 4-momenta allowed to vary within their resolutions
- Neutrino p_z and η initialized at 0 and allowed to vary
- If the fit converges, for that combination it outputs:
    - χ^2
    - Neutrino p_z
    - Neutrino η
- The combination with the minimum χ^2 is selected

Kinematic Fitter

Using TopQuarkAnalysis/TopKinFitter package

$$\chi^2 = \sum_{comps} \frac{\Delta y^2}{\sigma_y^2}$$

$$L = \chi^2 + \sum \lambda_j f_j$$



- y stands for the measurable quantities, σ their uncertainties, f_i are the constraints we are imposing and λ_i the Lagrange multipliers
- $M_{W(lep)} = 80.4$, $M_{W(had)} = 80.4$ and $M_{top(had)} = 172.5$ GeV.
- Measurable 4-momenta allowed to vary within their resolutions
- Neutrino p_z and η initialized at 0 and allowed to vary
- If the fit converges, for that combination it outputs:
  - χ^2
  - Neutrino p_z
  - Neutrino η
- The combination with the minimum χ^2 is selected

B-Tagging

The algorithm used to identify b-jets is known as "combined secondary vertex". It calculates, for every jet, a likelihood value from the next variables:

- The vertex category (real, pseudo, or no vertex)
- 2D flight distance significance
- Vertex mass
- Number of tracks at the vertex
- Ratio of the energy carried by tracks at the vertex with respect to all tracks in the jet
- The pseudo-rapidity of the tracks at the vertex with respect to the jet axis
- 2D IP significance of the first track that raises the invariant mass above the charm threshold of 1.5 GeV when subsequently summing up tracks ordered by decreasing IP significance
- Number of tracks in the jet
- 3D signed IP significances for all tracks in the jet