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

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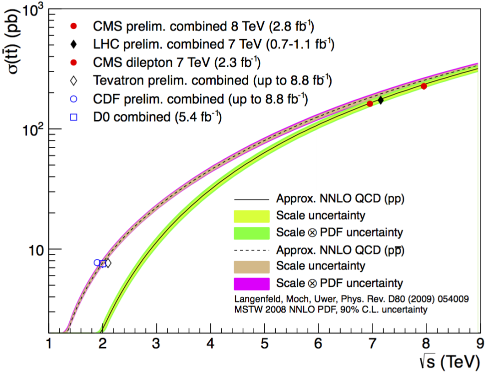
Taller de Altas Energías
Benasque, September 24 2013

Introduction

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

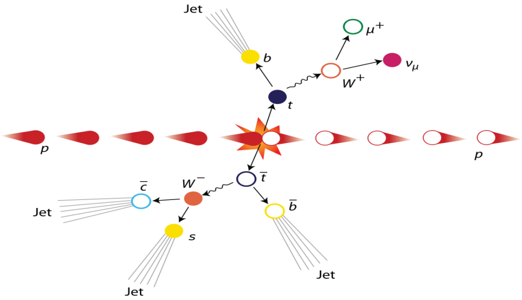
- The top quark was discovered in Tevatron in 1995
- But in the LHC we have many more $t\bar{t}$ pairs:



- It is one of the least explored sectors of the SM, with sensitivity to New Physics
- $m_t \simeq 173$ 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

This presentation is focused in the semi-leptonic decay of the $t\bar{t}$ pair,
$t\bar{t} \rightarrow W^+ bW^- \bar{b} \rightarrow b\bar{b}q\bar{q}' l\nu$, l standing either for muon or electron
2011 data, $\mathcal{L}_{int} = 5\ \mathrm{fb}^{-1}$, $\sqrt{s} = 7$ TeV[1]:
2012 data, $\mathcal{L}_{int} = 19.6\ \mathrm{fb}^{-1}$, $\sqrt{s} = 8$ TeV (only μ chanel)[2]:



Backgrounds:

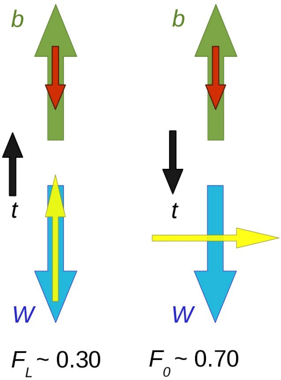
- Non-semileptonic $t\bar{t}$
- W + jets
- Drell-Yan + jets
- Single top

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

[1] arXiv:1308.3879v1 [hep-ex]
[2] *Physics Analysis Summary* **CMS-PAS-TOP-13-008** (2013)

Definitions

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.

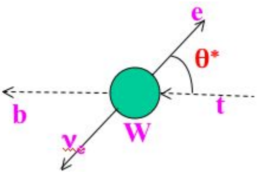


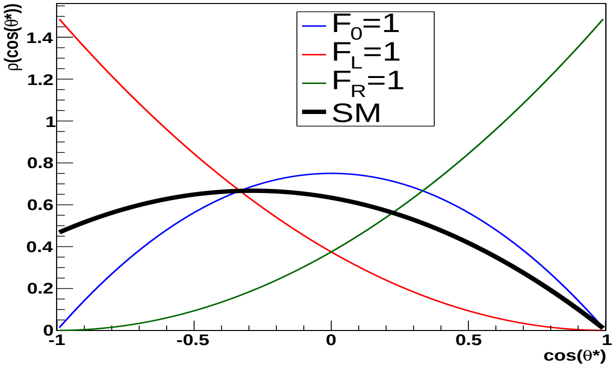
- The helicity fractions are $F_{L,R,0} \equiv \Gamma_{L,R,0}/\Gamma$
- By construction, $F_L + F_R + F_0 = 1$
- $F_R \simeq 0$: V-A character of the W coupling and $m_b \to 0$
- In the SM, the fractions are calculated as a function of m_t, m_W and m_b
- At NLO/NNLO, the predicted values are $F_0 \simeq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

Definitions

Helicity angle θ^*

Assuming a top rest frame, the angle between the down-type fermion three-momentum in the W rest frame and the W momentum in the top rest frame.





In the hadronic side q and $\bar{q}'$ are indistinguishable $\Rightarrow |\cos^{had}\theta^*|$ distribution used instead

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

Anomalous couplings

- 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[3]:

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

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

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

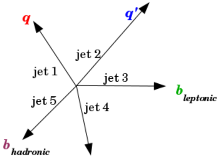
Event selection

In order to have a $t\bar{t}$ enriched sample, and reduce the background, the following cuts are applied (slight changes for 8 TeV analysis):

- One isolated muon(electron) with p_T >25(30) GeV/c and $|\eta|$ <2.1(2.5)
- Veto: additional muon(electron) with p_T >10(15) GeV/c
- $\geq$ 4 jets with $p_T > 30$ GeV/c^2 and $|\eta| < 2.4$
- $M_T = \sqrt{2 p_T E_T^{miss}(1 - \cos(\Delta\phi))} > 30$ GeV/c^2
  - Transverse component of the W-boson invariant mass
  - Cut to reject background from DY+jets
- $M_T < 200$ GeV/c^2
  - Reject background from non-semileptonic $t\bar{t}$ and QCD
- bTagging
  - Identification of b-jets based on the long life-time of the bottom quark
  - Reduces background coming from W+jets
  - At least two of the selected jets must be tagged
- In the 8 TeV analysis
  - Muon $p_T > 26$ GeV/c (official prescription for 8 TeV)
  - Jets $p_T > 55, 45, 35, 20$ GeV/c (use of cross triggers in electron analysis)

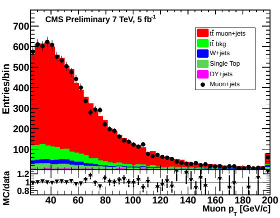
Event reconstruction

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:

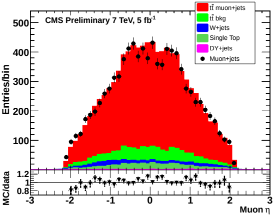


- To find the best jet assignment that matches the $t\bar{t}$ kinematic configuration:
- Tries every combination of measured jets and performs a χ^2 calculation in each one
- It uses the central values $m_{W(lep)} = 80.4$ GeV$/c^2$, $m_{W(had)} = 80.4$ GeV$/c^2$, $m_{top,DATA} = 173.3$ GeV$/c^2$, and $m_{top,MC} = 172.5$ 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

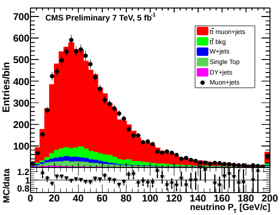
Data/MC comparison @ 7 TeV



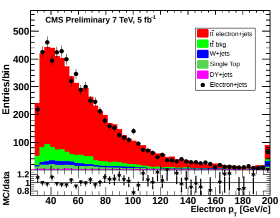
Muon p_T



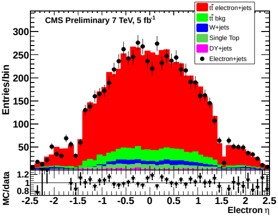
Muon η



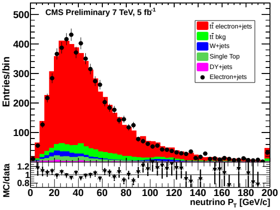
Neutrino p_T (μ channel)



Electron p_T



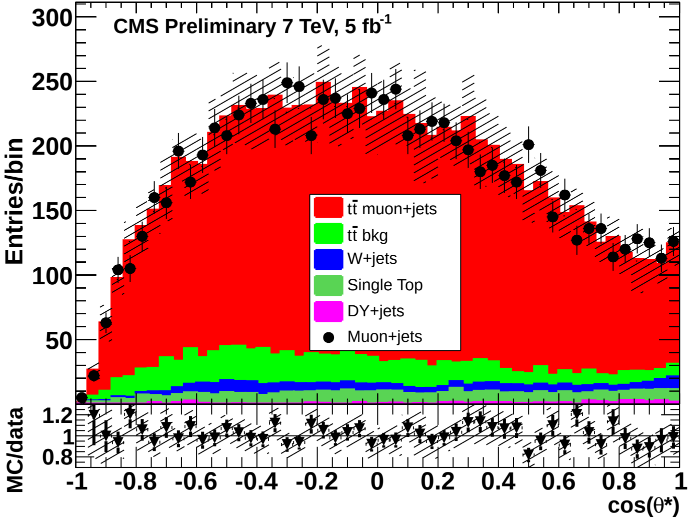
Electron η



Neutrino p_T (e channel)

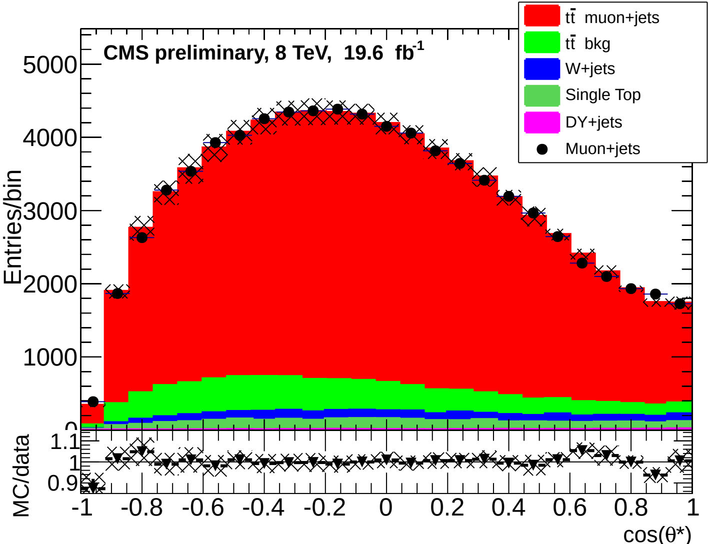
$\cos\theta^*$ distribution @ 7 TeV

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



$\cos\theta^*$ distribution @ 8 TeV

Some improvements can be seen in the 8 TeV analysis: more statistics, greater signal-over-background ratio...

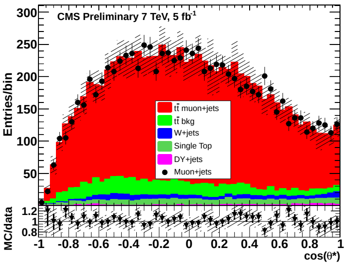


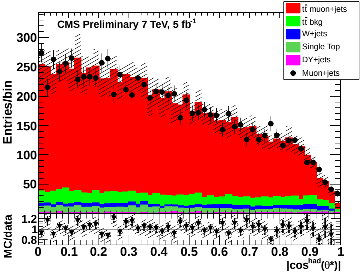
Fitting method

Fitting:

- We use an event-by-event reweighting method implemented with MINUIT
- Functional dependency of the distribution known exactly
- Gen. level $\rightarrow$ RW $\rightarrow$ 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 @ 7 TeV

Two measurements are presented:

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

Leptonic branch: $\cos\theta^*$				
Fit	Channel	$F_0 \pm$ (stat.) $\pm$ (syst.)	$F_L \pm$ (stat.) $\pm$ (syst.)	$F_R \pm$ (stat.) $\pm$ (syst.)
A	μ+jets	0.674±0.039±0.035	0.314±0.028±0.022	0.012 ±0.016±0.020
A	e+jets	0.688±0.045±0.042	0.310±0.033±0.037	0.002 ±0.017±0.023
B	μ+jets	0.698±0.021±0.019	0.302±0.021±0.019	fixed at 0
B	e+jets	0.691±0.025±0.047	0.309±0.025±0.047	fixed at 0
Hadronic branch: $\lvert\cos^{\text{had}}\theta^*\rvert$				
Fit	Channel	$F_0 \pm$ (stat.) $\pm$ (syst.)	$F_L \pm$ (stat.) $\pm$ (syst.)	$F_R \pm$ (stat.) $\pm$ (syst.)
B	μ+jets	0.651±0.060±0.084	0.349±0.060±0.084	fixed at 0
B	e+jets	0.629±0.060±0.093	0.371±0.060±0.093	fixed at 0

SM fractions

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

Systematic uncertainties

- Jet Energy Scale (CMS given) and Jet Energy Resolution (oversmearing)
- MC statistics (reweighting method)
- Data/MC discrepancies
  - Lepton efficiency (*tag* & *probe*)
  - b-Tag efficiency
  - Pileup
- Theoretical
  - PDF
  - Top Q^2 scale→Dedicated MC sample produced
  - Top mass (± 1.4 GeV/c^2)→Dedicated MC sample produced
  - Kinematic scale to match jets to partons in $t\bar{t}$ MC→Dedicated MC sample produced
- Background normalization
  - DY and W+jets: data driven
  - With uncertainty of 30% and 100%, respectively
  - Single top: t and tW-channels
  - Variation of $\pm$15% and $\pm$40%, respectively
- Only @ 8 TeV
  - E_T^{miss} shape
  - $t\bar{t}$ p_T reweighting

Systematic uncertainties with 7 TeV data

Systematics	μ+jets ($\cos\theta^*$)			e+jets ($\cos\theta^*$)			ℓ+jets ($\cos\theta^*$)		
	Fit A		Fit B	Fit A		Fit B	Fit A		Fit B
	$\pm\,\Delta F_0$	$\pm\,\Delta F_L$	$\pm\,\Delta F_0$	$\pm\,\Delta F_0$	$\pm\,\Delta F_L$	$\pm\,\Delta F_0$	$\pm\,\Delta F_0$	$\pm\,\Delta F_L$	$\pm\,\Delta F_0$
b-tag eff.	0.001	0.001	$< 10^{-3}$	$< 10^{-3}$	$< 10^{-3}$	0.001	0.001	$< 10^{-3}$	$< 10^{-3}$
Single-t bkg.	0.004	$< 10^{-3}$	0.003	0.004	$< 10^{-3}$	0.004	0.004	0.001	0.003
DY+jets bkg.	0.002	0.001	0.001	0.001	$< 10^{-3}$	0.001	0.001	$< 10^{-3}$	0.001
W+jets bkg.	0.019	0.007	0.006	0.009	0.006	0.022	0.013	0.004	0.006
Lepton eff.	0.001	0.001	0.001	0.009	0.012	0.015	0.001	0.002	0.002
JES	0.005	0.003	0.001	0.006	0.002	0.003	0.006	0.003	0.001
$t\bar{t}$ scales	0.013	0.009	0.007	0.015	0.018	0.030	0.009	0.009	0.011
JER	0.009	0.005	0.001	0.014	0.009	0.003	0.011	0.007	0.001
Top-quark mass	0.011	0.008	0.007	0.025	0.018	0.014	0.016	0.011	0.019
Pileup	0.013	0.011	0.008	0.008	0.007	0.005	0.002	$< 10^{-3}$	0.008
$t\bar{t}$ match. scale	0.004	0.001	0.006	0.010	0.013	0.016	0.011	0.010	0.008
PDF	0.002	0.001	0.003	0.004	0.002	0.002	0.002	$< 10^{-3}$	0.003
MC statistics	0.016	0.012	0.009	0.019	0.015	0.012	0.016	0.012	0.010

Systematics compared

Systematics	$\pm\,\Delta F_0$	$\pm\,\Delta F_L$
JES	0.002	<0.001
JER	0.004	0.003
Lepton eff.	0.001	<0.001
b-tag eff.	0.001	<0.001
Pileup	<0.001	0.001
Single-t bkg.	0.002	<0.001
DY+jets bkg.	0.001	<0.001
W+jets bkg.	0.009	<0.001
MC statistics	0.003	0.002
Top-quark mass	0.012	0.008
$t\bar{t}$ scales	0.012	0.012
$t\bar{t}$ match. scale	0.012	0.008
$t\bar{t}$ p_{T} reweig.	0.001	<0.001
$E_{\mathrm{T}}^{\mathrm{miss}}$ shape	0.004	0.018
Total syst.	0.023	0.024

Systematics	μ+jets ($\cos\theta^*$)		
	Fit A		Fit B
	$\pm\,\Delta F_0$	$\pm\,\Delta F_L$	$\pm\,\Delta F_0$
b-tag eff.	0.001	0.001	$< 10^{-3}$
Single-t bkg.	0.004	$< 10^{-3}$	0.003
DY+jets bkg.	0.002	0.001	0.001
W+jets bkg.	0.019	0.007	0.006
Lepton eff.	0.001	0.001	0.001
JES	0.005	0.003	0.001
$t\bar{t}$ scales	0.013	0.009	0.007
JER	0.009	0.005	0.001
Top-quark mass	0.011	0.008	0.007
Pileup	0.013	0.011	0.008
$t\bar{t}$ match. scale	0.004	0.001	0.006
PDF	0.002	0.001	0.003
MC statistics	0.016	0.012	0.009

Results

Combined results with 7 TeV data:

Fit	Channel(s)	Branch	Fraction ± (stat.) ± (syst.) [total]	
A	ℓ+jets	l	F_0	0.682 ±0.030±0.033 [0.045]
			F_L	0.310 ±0.022±0.022 [0.032]
			F_R	0.008 ±0.012±0.014 [0.018]
B	μ+jets	l+h	F_0	0.694 ±0.020±0.025 [0.032]
			F_L	0.306 ±0.020±0.025 [0.032]
B	e+jets	l+h	F_0	0.674 ±0.025±0.028 [0.037]
			F_L	0.326 ±0.025±0.028 [0.037]
B	ℓ+jets	l+h	F_0	0.685 ±0.017±0.021 [0.027]
			F_L	0.315 ±0.017±0.021 [0.027]

CMS preliminary, μ+jets, 8 TeV:

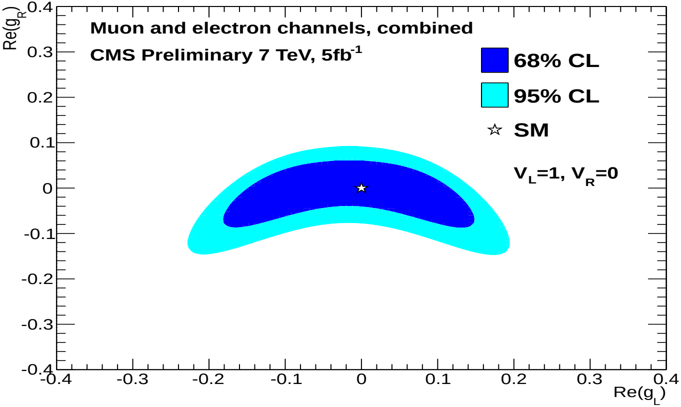
Fit	Fraction ± (stat.) ± (syst.)	
A	F_0	0.659 ±0.015±0.023
	F_L	0.350 ±0.010±0.024
	F_R	0.008 ±0.012±0.014

Precision achieved $\sim$ 10% **in** F_L **and** $\sim$ 5% **in** F_0

Limits on anomalous couplings with 7 TeV data

Two cases considered:

- From Fit B: $F_R = 0$, $V_L = 1$ and $V_R = g_L = 0$:
  - Gives $\mathrm{Re}(g_R) = -0.008 \pm 0.024(\mathrm{stat.})^{+0.029}_{-0.030}(\mathrm{syst.})$
- CP-conserving; F_R =FREE, $V_L = 1$; $V_R = 0$:
  - Results from plot



Conclusions & prospects

Conclusions

- W helicity fractions in $t\bar{t}$ decays measured using 5 fb^{-1} of CMS pp collisions data at $\sqrt{s} = 7$ TeV and 20 fb^{-1} at $\sqrt{s} = 8$ TeV
- Results in agreement with Standard Model
- Limits on anomalous couplings g_R and g_L obtained
- Analysis with 2012 data to be complemented with the addition of electron channel, but some improvements already visible:
  - At $\sqrt{s} = 8$ TeV greater signal over background ratio

The end

Thank you very much

But wait

Back up

Formulae

Fractions in the SM

$$
\begin{aligned}
F_0 &= \frac{(1-y^2)^2 - x^2(1+y^2)}{(1-y^2)^2 + x^2(1-2x^2+y^2)} \\
F_L &= \frac{x^2(1-x^2+y^2+\sqrt{\lambda})}{(1-y^2)^2 + x^2(1-2x^2+y^2)} \\
F_R &= \frac{x^2(1-x^2+y^2-\sqrt{\lambda})}{(1-y^2)^2 + x^2(1-2x^2+y^2)}
\end{aligned}
$$

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:

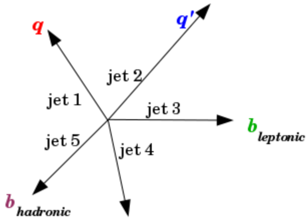
$$
\begin{aligned}
A = \; & \left(\frac{M_t^2}{M_W^2} - 1\right) + (g_L^2 + g_R^2)\left(1 - \frac{M_W^2}{M_t^2}\right) - 4\frac{M_b}{M_t} g_L g_R \\
& -2\frac{M_t}{M_W} g_R\left(1 - \frac{M_W^2}{M_t^2}\right) + 2\frac{M_b}{M_W} g_L\left(1 + \frac{M_W^2}{M_t^2}\right) \\
B_0 = \; & \left(1 - \frac{M_W^2}{M_t^2}\right)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

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

Kinematic Fitter

Using TopQuarkAnalysis/TopKinFitter package

$$\chi^2 = \sum_i^{jets,lep} \frac{(p_i - p_i^{meas.})^2}{\sigma^2(p_i)} +$$
$$\sum_m^{t,W} \frac{(M_m - M(p_k))^2}{\sigma^2(M_m)} +$$
$$\sum_j^{jets} -2\log p(disc_j|flav_j)$$



- 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

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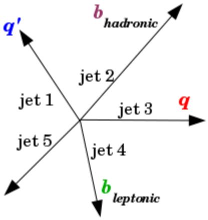

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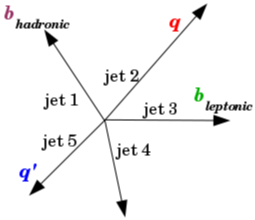

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- The combination with the minimum χ^2 is selected

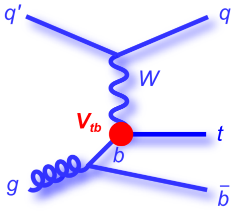
B-Tagging

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

Results from single-t

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



In single top production, CMS has obtained results[4] 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 the SM

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