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CMS CR-2008/053

The Compact Muon Solenoid Experiment

Conference Report

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13 July 2008

Top properties: prospects at CMS

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Abstract

With about 10 millions top-pair events per year at low luminosity the Large Hadron Collider will be a Top Factory. Precision measurements in the top quark sector will be performed allowing for detailed study on electroweak (and flavor) symmetry breaking mechanism and also will help in constraining the Standard Model. A review of the measurements of the top quark properties is given, together with indications about the potential of CMS.

Presented at *Top2008 International Workshop on Top Quark Physics,May 18-24, 2008,Biodola,Italy*

Top properties: prospects at CMS

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Summary. — With about 10 millions top-pair events per year at low luminosity the Large Hadron Collider will be a Top Factory. Precision measurements in the top quark sector will be performed allowing for detailed study on electroweak (and flavor) symmetry breaking mechanism and also will help in constraining the Standard Model. A review of the measurements of the top quark properties is given, together with indications about the potential of CMS.

1. – Introduction

The top quark is a fermion with electric charge 2/3; it is the weak-isospin partner of the bottom quark, and together with the bottom quark forms the third generation of quark families. The top quark is the heaviest known elementary particle and it is approximately forty times heavier than its partner. The top quark lifetime $\tau_t \simeq 0.4 \times 10^{-24}s$, is smaller than the the tpypical time for the QCD bound state formation ($\simeq 3 \times 10^{-24}s$) hence it decays before hadronization and there are no top hadrons. [1]

The Large Hadron Collider (LHC), with the expected large amount of $t\bar{t}$ pairs (about eight millions per year), will provide the opportunity to measure many top properties with a precision never reached before.

Most of the top quarks at the LHC will be produced as $t\bar{t}$ pairs. The $t\bar{t}$ production cross section is estimated to be 830 pb at NLO and the dominant production mechanisms are gluon-gluon fusion ($\sim$ 90%) and quark-anti-quark annihilation (10%).
Within the Standard Model the top quark decays almost exclusively to a W boson and a b quark. The decays of the $t\bar{t}$ system are then classified according to the decays of the W^+W^- system as dileptonic, semi-leptonic or fully hadronic. Neglecting QCD corrections, branching fractions are 1/9 for the dileptonic, 4/9 for the semi-leptonic and 4/9 for the fully hadronic.

CMS [2] will extensively study the top quark sector, to search for new physics and probing the SM. Moreover, $t\bar{t}$ events will provide an excellent environment for calibration of the jet energy scale and b-tagging algorithms.

This paper reports on spin correlation measurement and Flavour Changing Neutral Currents (FCNC) studies.

2. – Spin Correlation

Since there is no hadronization, the top quark does not loose its spin information before its decay. The study of the angular correlation between the decay products (b-jet, leptons or light quarks from W boson) of the top and the anti-top gives the opportunity to measure the top quark spin correlation, which has never been observed. These angular distributions allow for the determination of the top quark spin and search for possible deviations from the Standard Model couplings.

2·1. *Analysis strategy.* – The spin correlation in the $t\bar{t}$ semileptonic decay channel can be measured via the asymmetry A of a double differential lepton and quark angular distribution, which (neglecting higher order QCD corrections) is given by

$$\frac{1}{N}\frac{d^2N}{d\cos\theta_l d\cos\theta_q} = \frac{1}{4}(1 - \mathcal{A}_{\mathcal{K}_l\mathcal{K}_q}\cos\theta_l\cos\theta_q) \tag{1}$$

where the two observables are the angle $\theta_l(\theta_q)$ between the top (anti-top) direction in the $t\bar{t}$ center-of-mass frame and the lepton (quark) direction of flight in the top (anti-top) rest frame. $\mathcal{K}_i$ represents the spin analyzer of the top particle, defined as the degree to which the daughter particle is correlated with the top spin. The correlation coefficient

$$\mathcal{A} = \frac{N(t_L\bar{t}_L + t_R\bar{t}_R) - N(t_L\bar{t}_R + t_R\bar{t}_L)}{N(t_L\bar{t}_L + t_R\bar{t}_R) + N(t_L\bar{t}_R + t_R\bar{t}_L)} \tag{2}$$

which is the asymmetry of finding top and anti-top in the same or different polarization state, can be extracted by fitting eq. 1 to data.

2·2. *Results.* – The analysis developed within CMS [3] considers the distributions of two angle combinations: θ_l versus θ_b and θ_l versus $\theta_{q(lower\ energy)}$, denoted as $b{-}tl{-}t$ and $q{-}tl{-}t$ respectively. The measurement results in a total relative uncertainty dominated

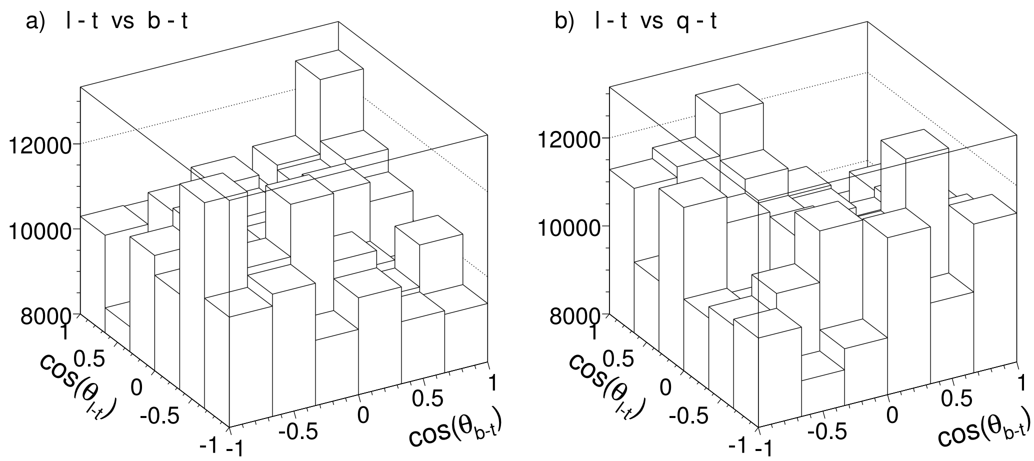

Fig. 1. – Double differential distribution of the cosine of lepton and quark in the helicity basis: a l-t angle θ_{l-t} versus b-t angle θ_{b-t}, b) l-t angle θ_{l-t} versus jet^{min} angle θ_{q-t}

by systematic uncertainties of 27% $\mathcal{A}_{b-tl-t}$ and of 17% $\mathcal{A}_{q-tl-t}$ considering an integrated luminosity of $10 fb^{-1}$ (fig 1).

3. – Top Branching Ratio

The large top-production is crucial to explore the top sector of the Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix, which is at the moment the most unknown. The matrix elements $|V_{td}|$ and $|V_{ts}|$ are indirectly estimated and $|V_{tb}|$ is deduced (0.9989 0.9993 at 90% CL) by a global fit, with the additional assumptions of having only three generations and unitarity [4].

The ratio of top branching fractions

$$R = \frac{B(t \to Wb)}{B(t \to Wq)} \tag{3}$$

where q can be a d, s and a b quark, allow for the direct determination of $|V_{tb}|^2/(|V_{ts}|^2 + |V_{td}|^2 + |V_{tb}|^2)$ corresponding to $|V_{tb}|^2$in the SM assumption.

In minimal extensions of the standard model with extra heavy quarks, the unitarity constraints are much weaker. A possible measurement of the ratio R significantly less than the unity would lead to an experimental evidence of a fourth generation of quarks [5]. Both the CDF and DØ previously measured R. The measurements result in the lower limit $|V_{tb}| > 0.78$ at 95% CL [6, 7] which leave still open the possibility that $|V_{tb}|$ is sizeably smaller than one.

The proposed approach within CMS still under discussion is to derive the ratio R from the relative number of b-jet found in the selected $t\bar{t}$ events in semi leptonic decay. The probability ϵ_i to count i b-tag jets in each $t\bar{t}$ selected event can be expressed as a function of b-tag efficiency B, mis-tag probability M and the ratio R as follow:

$$\epsilon_i(R; B, M) = R^2 P_i(t\bar{t} \to bb) + 2R(1-R)P_i(t\bar{t} \to bq) + (1-R)^2 P_i(t\bar{t} \to qq) \tag{4}$$

where q can represent a quark b, s or d and each P_i depends on B and M.
Fitting eq. 4 to the distribution of b-tagged jets, divided in five non overlapping bins, (corresponding to the 5 possibility to tag 0,1..4 b-jets), may allow to extract the unknown parameter R.
In case of background events, low values of a mass χ^2, defined from the masses of the expected top and W's particles, are due to combinatorial effects. In this assumption the background distribution can be modelled trying to replicate the combinatorial on real data, as an example by artificially changing the direction of one of the selected jets.

The key point is that starting from the same data sample, both *Normal* and *Flipped* ([1]) distribution of b-tag jets could be computed and the background events contribution can be subtracted by subtracting the *Flip* distribution to the *Normal* one, before the extraction of R.
The proposed method is fully independent from the MonteCarlo parametrization, a crucial aspect especially at the LHC start-up.

([1]) *Normal* distribution is computed assuming the correct jet sample, *Flipped* is the same but computed using the jet sample where the direction of one jet is inverted

4. – Search for new physics: Flavour changing neutral currents

In the Standard Model, $t \to Wb$ is by far the dominant decay mode ($> 99.9\%$) while others decay widths are very small (BR($t \to Ws$) $\sim 10^{-3}$,BR($t \to Wd$)$\sim 10^{-4}$). Flavor Changing Neutral Current (FCNC) decays $t \to qV$ ($V = Z, \gamma, g$) are suppressed in SM and their expected BR are very small (of the order of 10^{-11} to 10^{-13}). In new physics scenarios these branching ratios may rise higer values. Any experimental evidence for a top quark FCNC interaction would be an indication of new physics.

4·1. *CMS sensitivity to FCNC*. – CMS studies [8] have been based on the observability of the non-SM signals $t \to Zq$ and $t \to \gamma q$ (where q represents c or u quarks). A cut-based analysis has been developed where the selection procedure includes an extensive set of quality requirements on the final state lepton candidates and is heavily reliant on good b-tagging capabilities. This approach has been shown to be very effective in reducing the large background contributions from Standard Model $t\bar{t}$, QCD multi-jet and Z^0 production in association with a $b\bar{b}$ pair, while retaining a reasonable selection efficiency and minimising the impact of systematic uncertainties.
Referring to an integrated luminosity L = 10 fb^{-1} an upper limit of 11.4×10^{-4} has been determined for the $t \to Zq$ decay channel and 5.7×10^{-4} for the $t \to \gamma q$ decay channel.

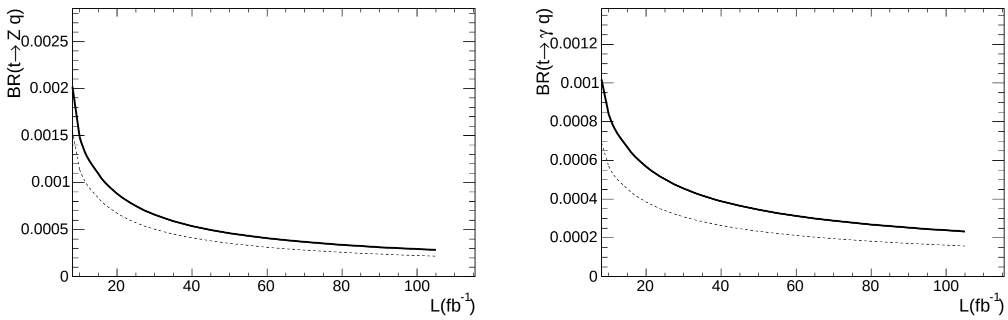

Fig. 2. – The branching ratios of FCNC top decays as a function of integrated luminosity assuming a 5-sigma discovery level for an integrated luminosity of L=10fb^{-1}. Left $t \to qZ$ and right $t \to q\gamma$. The two curves represent the branching ratios including (solid line) and excluding (dashed line) the contribution from systematic uncertainties.

5. – Conclusion

The LHC experiments will rapidly collect large samples of $t\bar{t}$ events that will be used for precision studies of the top properties. CMS is ready to exploit the first top events to tests the SM and to the search for new physics.

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