The Compact Muon Solenoid Experiment

Conference Report

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19 May 2010 (v3, 31 May 2010)

Searches for New Heavy Quarks with the CMS Detector at the LHC

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Abstract

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Presented at *BEYOND 2010: Fifth International BEYOND 2010 Conference on Beyond the Standard Models of Particle Physics, Cosmology and Astrophysics*

SEARCHES FOR NEW HEAVY QUARKS WITH THE CMS DETECTOR AT THE LHC

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We review the capability of the CMS experiment to address the experimental searches for New Heavy Quarks at the LHC. In particular, we concentrate on the first year(s) of LHC operations, since new physics at the TeV scale may manifest itself even in modest data samples of the order of a few hundreds pb^{-1} . A few example searches for New Heavy Quarks are discussed, with emphasis on processes characterized by clean final states with electrons and muons.

Keywords:

Keywords: LHC, CMS, luminosity, physics reach, searches, new physics, beyond Standard Model, New Heavy Quarks

1. Introduction

The possible existence of new heavy fermions is going to be fully tested at the Large Hadron Collider. Already with the first data it will be possible to entirely explore the interesting range allowed for their mass values, from the existing experimental bounds up to the limits set by unitarity conditions.

Here we present two independent scenarios analyzed by the CMS experiment: new physics with a fourth generation of elementary quarks, b' and t' , and with exotic partners of the top quark. In both cases a significance above three standard deviations can be reached at the LHC with integrated luminosities between 100 pb^{-1} and 1 fb^{-1} . Stringent limits can be also set with early data.

This note is structured as follows: after an introduction on the Large Hadron Collider (Section 2), Section 3 contains a description of the CMS detector, while Section 4 is dedicated to the CMS performances with the first data. The searches for fourth generation quarks are addressed in Section 5. Finally Section 6 deals with the searches for exotic partners of the top quark.

2. The Large Hadron Collider

The Large Hadron Collider (LHC) has become operational in 2009. High-energy physics runs are taking place in 2010,¹ with proton-proton collisions at a center-of-

mass energy of 7 TeV and peak values of the instantaneous luminosity that will soon reach $10^{30} - 10^{31} \text{ cm}^{-2} \text{ s}^{-1}$. The design energy of 14 TeV and the design luminosity of $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ are expected to be attained after a few years of operation. Each LHC experiment will collect an integrated luminosity up to about 1 fb^{-1} under the initial conditions, and up to about hundreds fb^{-1} per year when the design luminosity will be reached.

Six experiments are currently operating at the LHC: two so-called omni-purpose detectors, ATLAS² and CMS,^{3,8} which are performing a general research program, two dedicated detectors, ALICE⁴ and LHCb,⁵ specifically designed for heavy-ion physics and b-physics, respectively, and two special purpose experiments: TOTEM⁶ and LHCf.⁷

3. The CMS detector

The central feature of the Compact Muon Solenoid (CMS) detector⁸ is a superconducting solenoid, of 6 m internal diameter, providing a field of 3.8 T. Within the field volume are the silicon pixel and strip tracker, the lead-tungstate crystal electromagnetic calorimeter (ECAL), and the brass/scintillator hadron calorimeter (HCAL). Muons are measured in gas-ionization detectors embedded in the steel return yoke. In addition to the barrel and endcap detectors, CMS has extensive forward calorimetry, assuring very good hermeticity with pseudorapidity coverage up to high values ($|\eta| < 5$). CMS has an overall length of 22 m, a diameter of 15 m, and weighs 12 500 tonnes.

The electromagnetic calorimeter (ECAL) contains 75 848 lead tungstate (PbWO_4) crystals (25.8 X_0 long in the barrel, 24.7 X_0 long in the endcaps). Scintillating crystals are the most precise calorimeters for energy measurements and they provide excellent energy resolution over a wide range, as well as high detection efficiency for low energy electrons and photons. The ECAL has an energy resolution of better than 0.5 % above 100 GeV. The 15K-channel HCAL, when combined with the ECAL, measures jets with a resolution $\Delta E/E \sim 100\%/\sqrt{E} \oplus 5\%$.

Muons with pseudorapidity in the range $|\eta| < 2.4$ are measured with detection planes made of three technologies: Drift Tube chambers (DT), Cathode Strip Chambers (CSC) and Resistive Plate Chambers (RPC). The readout has nearly 1 million electronic channels. Matching the muons to the tracks measured in the silicon tracker should result in a transverse momentum (p_T) resolution between 1 and 5 %, for p_T values up to 1 TeV/c.

The inner tracker measures charged particles within the $|\eta| < 2.5$ pseudorapidity range. It consists of 1440 silicon pixel and 15 148 silicon strip detector modules, chosen for their radiation hardness and small amount of material, corresponding to about 30% of the radiation length X_0 . The tracking system provides an impact parameter resolution of the order of 5 μm and a transverse momentum resolution of about 1.5 % for 100 GeV/c particles.

The first level (Level-1) of the CMS trigger system, composed of custom hard-

ware processors, is designed to select the most interesting events in about $1\ \mu\text{s}$ using information from the calorimeters and muon detectors. The High Level Trigger (HLT) processor farm further decreases the event rate from up to 100 kHz to 100 Hz (initial DAQ system is 50 kHz), before data storage. On the Worldwide LHC Computing GRID (WLCG), some 50k cores dedicated to CMS run more than 2M lines of source code.

4. Detector Performance with Data and Prospects for Searches

The data collected during the first proton-proton collisions have shown that the performance of the CMS detector is according to design expectations and the first data distributions agree well with Monte Carlo simulation.⁹ As an example, Figure 1 show the K_S^0 and Λ invariant mass distributions, in agreement with the PDG¹⁰ values at the 10^{-4} level.

5. Searches for Fourth Generation b' Quarks

In this Section we consider two benchmark channels for the search for heavy bottom-like fourth generation quark pairs in proton-proton collisions with the CMS detector, $pp \rightarrow b'\bar{b}'$:

- (1) Searches for light b' quarks
- (2) Searches for heavy b' quarks, above the tW threshold.

A wider discussion can be found in.^{11,12} The center-of-mass energy assumed in those analyses is 10 TeV.

The existence of a fourth generation of elementary fermions, a new replica of the known three generations of chiral matter, may provide a sufficiently large CP violation and may account as well for the asymmetry between matter and antimatter. Provided the mass difference between the fourth generation quarks t' and b' is lower than the W mass, their existence is not excluded by precision electroweak measurements. Furthermore, within the framework of the Standard Model, the t' and b' masses are constrained to be below approximately $550\ \text{GeV}/c^2$ by unitarity conditions. The possible phenomenology of fourth generation quarks is extensively discussed in.¹³

The present b' and t' mass limits have been obtained by the CDF experiment¹⁴ assuming, in case of light b' quark, a 100% decay branching fraction into the Flavor Changing Neutral Current (FCNC) decay channel $b' \rightarrow bZ$. For the b' quark, mass values below $268\ \text{GeV}/c^2$ and $325\ \text{GeV}/c^2$, respectively, are excluded at 95% confidence level by the light b' and heavy b' analyses. For the t' quark, the current CDF limit is $311\ \text{GeV}/c^2$. The integrated luminosities considered in those analyses are between 1.1 and $2.7\ \text{fb}^{-1}$.

Searches for fourth generation quarks at the LHC will benefit from the higher center-of-mass energy, providing larger possible b' (or t') production cross sections

ranging from ~ 1 pb for masses of about $500 \text{ GeV}/c^2$, to ~ 100 pb for masses of $200 \text{ GeV}/c^2$.

5.1. Light b'

For b' mass values lower than tW mass threshold the decay $b' \rightarrow tW$ is kinematically suppressed.

The leading charged current process is the doubly Cabibbo-suppressed $b' \rightarrow cW$, which suffers from high background contamination. For this reason, this analysis considers the possibility, for one of the two pair-produced b' quarks, of a sizable FCNC decay channel $b' \rightarrow bZ$ (an electroweak penguin loop process) with a branch-

Fig. 1. Top: $\pi^+\pi^-$ invariant mass distribution, obtained with CMS 900 GeV and 2.36 TeV data. The reconstructed K_S^0 mass is in agreement with the PDG value at the 10^{-4} level: $m_K/m_{PDG} = 1 - (0.7 \pm 1.4) \cdot 10^{-4}$. Bottom: $p\pi^-$ (+c.c.) invariant mass distribution, from 900 GeV and 2.36 TeV data. The reconstructed Λ mass results : $m_\Lambda/m_{PDG} = 1 + (1.9 \pm 0.9) \cdot 10^{-4}$.

ing ratio BR between 5% and 20%. With this assumption the signal is relatively clean and one can fully reconstruct the b' in the leptonic decay channel of the vector bosons.

The process $b'\bar{b}' \rightarrow bZcW$, followed by leptonic decays of the Z and W bosons, gives rise to a tri-leptonic final state plus two jets. The main background is represented by Z+jets, WZ+jets and $t\bar{t}$ events. Further background rejection is achieved by requiring the presence of exactly one Z and one W and isolation between jets and lepton candidates.

The results are shown in Figure 2 for $\sqrt{s} = 10\text{TeV}$. Assuming a BR ($b' \rightarrow bZ$) = 10%, b' mass values up to about 190 GeV can be excluded with 200 pb^{-1} of data. With 1 fb^{-1} of data, we can exclude light b' quark masses up to $235\text{ GeV}/c^2$.

Fig. 2. b' cross section as a function of the b' mass, for different values of the BR ($b' \rightarrow bZ$) = 5% - 20 %. Upper limits at 95% C.L. are provided for 200 pb^{-1} and 1 fb^{-1} . The center-of-mass energy is 10 TeV.

5.2. Heavy b'

In this analysis the mass of the b' quark is assumed to be above the tW threshold, i.e. above approximately 255 GeV. The dominant decay mode is expected to be $b'\bar{b}' \rightarrow tW^- \bar{t}W^+$, hence producing a four W boson plus two b-jets final state.

Each W boson can decay either leptonically ($W \rightarrow l\nu$) or hadronically ($W \rightarrow \text{di-jet}$). Among the possible final states of the four W boson decay chain, the ones with low Standard Model background are selected, i.e. trilepton and same-sign dilepton processes, with multijets. The event selection requires at least one energetic and isolated lepton with transverse momentum $p_T > 35\text{ GeV}/c$ and at least one hard jet with $p_T > 85\text{ GeV}/c$.

For the same-sign dileptonic channel, exactly two same-charge leptons (either electron or muon) and at least four jets are requested. For the trileptonic channel,

events with three leptons are selected, with two or more jets. Lepton-jet separation is required to suppress additional leptons from jets. In addition, background from doubly reconstructed muons or electrons, where a radiative photon is reconstructed as a lepton candidate of the same charge, is rejected by requiring lepton-lepton isolation. Finally, the invariant mass of two muons or electrons of any charge should not be within a window of $10 \text{ GeV}/c^2$ around the Z-boson mass. The above selection criteria are optimized assuming a $b' \rightarrow tW$ signal of $400 \text{ GeV}/c^2$.

The analysis results are summarized in Figure 3, assuming an integrated luminosity of 200 pb^{-1} at 10 TeV for the search reach and the exclusion limits. The main background sources are $t\bar{t}$, $t\bar{t} + W/Z + jets$ and $W/Z + jets$ events. Three typical benchmark points are discussed in this analysis, corresponding to b' masses of 300, 400, and $500 \text{ GeV}/c^2$, and production cross sections at the leading order¹⁷ in pp collisions at $\sqrt{s} = 10 \text{ TeV}$ of 13.6 pb, 2.80 pb, and 0.78 pb, respectively.

With a data set of 200 pb^{-1} , evidence of a $b'b' \rightarrow ttWW$ signal can be obtained with a significance of 3.7 standard deviations for a b' mass of $400 \text{ GeV}/c^2$. If no signal is observed in the data, b' quarks with a mass less than $485 \text{ GeV}/c^2$ can be excluded at the 95% confidence level.

Fig. 3. b' cross-section upper limits as a function of the b' mass, for 60 pb^{-1} and 200 pb^{-1} . The center-of-mass energy assumed in this analysis is 10 TeV. For comparison, the Pythia¹⁷ leading-order production cross section is shown as a function of the b' mass.

6. Searches for Exotic Partners of the Top Quark

In this Section we address the searches for heavy fermionic partners of the top quark and refer to¹⁵ for a detailed discussion. The center-of-mass energy considered in this analysis is 10 TeV.

Natural, non-supersymmetric solutions of the hierarchy problem generally require fermionic partners of the top quark, with masses not much heavier than

$500\text{GeV}/c^2$, i.e. in the mass range accessible with early LHC data. This analysis searches for pair production of the two top partners with electric charge $Q=5/3$ (the $T_{5/3}$) and $Q=-1/3$ (the B), that are predicted in models¹⁶ where the Higgs particle is a pseudo-Goldstone boson. Both kinds of new fermions decay to Wt , leading to $t\bar{t}W^+W^-$. With the subsequent decay of the top quarks to bW , as shown in Figure 4, the final state is given $b\bar{b}WWWW$. For this study $T_{5/3}$ and B are assumed to be degenerate in mass.

The golden channels for this analyses are the semi-leptonic channels where two of the W bosons in Fig. 4 decay into same-sign leptons and the other two decay into jets. The event selection requires at least five jets with transverse momentum above $30\text{ GeV}/c$, including a leading jet with a p_T of more than $100\text{ GeV}/c$, and two same-sign leptons (two electrons, two muons or one electron and one muon), with transverse momentum larger than $50\text{ GeV}/c$ and $25\text{ GeV}/c$, respectively. A $10\text{ GeV}/c^2$ veto around the Z mass is applied for the two-electron channel. The presence of same-sign dileptons distinguishes this process from $t\bar{t}$, which represents the main Standard Model background, and allows to reduce its contribution. Other background processes, like $t\bar{t}WW$, $t\bar{t}W$, WWW , and WW , have much smaller cross sections. Due to instrumental effects, QCD multi-jets and Z +jets also contribute to the total background.

As the same-sign dileptons come from different B' s, no full mass reconstruction is possible for the B quarks. However, the $T_{5/3}$ mass can be reconstructed in the fully hadronic decay chain, as the dileptons come from the decay of the same heavy fermion. The $T_{5/3}$ mass peak is shown in Fig. 5. An integrated luminosity of about 1.6 fb^{-1} at 10 TeV is needed for a 5σ observation of the tW peak.

Figure 6 shows, as a function of the integrated luminosity, the 95% upper limit on the production cross section (multiplied by the branching ratio into same-sign dileptons) and the discovery potential in terms of signal significance. $T_{5/3}$ and B

Fig. 4. Pair production of $T_{5/3}$ (left) and B (right) quarks, followed by examples of their decays to same-sign dilepton final states. The figures are taken from.¹⁶

expectations are combined. In absence of any observed excess over the expected background, stringent limits can be set at the LHC with early data. Heavy exotic quarks with masses up to $400 \text{ GeV}/c^2$ can be excluded with 80 pb^{-1} , while 340 pb^{-1} are needed for masses of $500 \text{ GeV}/c^2$. For the observation of heavy top partners of mass $400 \text{ GeV}/c^2$, $\sim 115 \text{ pb}^{-1}$ of data are needed for a 5σ observation significance and about 50 pb^{-1} of integrated luminosity for a 3σ evidence. For a heavy top partner of mass $500 \text{ GeV}/c^2$ these numbers increase to about 600 pb^{-1} and 220 pb^{-1} , respectively.

Fig. 5. Invariant mass distribution of the reconstructed tW for a signal of $500 \text{ GeV}/c^2$.

Fig. 6. Left: 95 % C.L. cross-section upper limit $\text{BR}(\text{same-sign dileptons})$ as a function of integrated luminosity. Right: signal significance as a function of integrated luminosity.

7. Conclusions

Evidence of New Physics could be obtained by the CMS experiment already during the low luminosity period of the LHC. A few searches for new heavy quarks have been discussed, which have been performed assuming a center-of-mass energy of 10 TeV. About 200 pb^{-1} , corresponding to the first year of data taking at low luminosity, will allow to observe new heavy quarks up to masses of the order of $400 \text{ GeV}/c^2$.

8. Acknowledgments

Acknowledgments of support of all CMS are given in Ref.⁸ I would like to thank the organizers for their invitation.

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