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

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Abstract

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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: 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 $10^{30}$ cm$^{-2}$ s$^{-1}$. The design energy of 14 TeV and the design luminosity of $10^{34}$ cm$^{-2}$ 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, ATLAS$^2$ and CMS,$^3,8$ which are performing a general research program, two dedicated detectors, ALICE$^4$ and LHCb,$^5$ specifically designed for heavy-ion physics and b-physics, respectively, and two special purpose experiments: TOTEM$^6$ and LHCf.$^7$

3. The CMS detector

The central feature of the Compact Muon Solenoid (CMS) detector$^8$ 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 $\Delta E/E \sim 100\%/\sqrt{E} \pm 5\%$.

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 $\mu$m 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 μs 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. As an example, Figure 1 show the $K^0_S$ and $Λ$ invariant mass distributions, in agreement with the PDG 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, $pp \rightarrow b'b'$:

1. Searches for light $b'$ quarks
2. Searches for heavy $b'$ quarks, above the $tW$ threshold.

A wider discussion can be found in. 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 GeV/$c^2$ by unitarity conditions. The possible phenomenology of fourth generation quarks is extensively discussed in.

The present $b'$ and $t'$ mass limits have been obtained by the CDF experiment 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 GeV/$c^2$ and 325 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 GeV/$c^2$. The integrated luminosities considered in those analyses are between 1.1 and 2.7 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 \( \sim 1 \text{ pb} \) for masses of about 500 GeV/\( c^2 \), to \( \sim 100 \text{ pb} \) for masses of 200 GeV/\( c^2 \).

5.1. Light \( b' \)

For \( b' \) mass values lower than \( tW \) mass threshold the decay \( b' \to tW \) is kinematically suppressed.

The leading charged current process is the doubly Cabibbo-suppressed \( b' \to cW \), 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 \( b' \to bZ \) (an electroweak penguin loop process) with a branch-
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 $b'b' \rightarrow bZcW$, 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 $\sqrt{s} = 10$ 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 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.](image)

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 $b'b' \rightarrow tW^−tW^+$, 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 ($W \rightarrow dijet$). 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 $p_T > 35$ GeV/$c$ and at least one hard jet with $p_T > 85$ 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 $200 \text{ pb}^{-1}$ at 10 TeV for the search reach and the exclusion limits. The main background sources are $t\bar{t}$, $t\bar{t} + W/Z + \text{jets}$ and $W/Z + \text{jets}$ 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 order 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 $200 \text{ pb}^{-1}$, evidence of a $b'b' \rightarrow t\bar{t}WW$ 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$^{-1}$.](image)

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 to\textsuperscript{15} 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 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 models\textsuperscript{16} where the Higgs particle is a pseudo-Goldstone boson. Both kinds of new fermions decay to Wt, leading to t\bar{t}W^+W^-\bar{t}. With the subsequent decay of the top quarks to bW, as shown in Figure 4, the final state is given bbWWWW. 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 GeV/c, including a leading jet with a \( p_T \) of more than 100 GeV/c, and two same-sign leptons (two electrons, two muons or one electron and one muon), with transverse momentum larger than 50 GeV/c and 25 GeV/c, respectively. A 10 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 tt, which represents the main Standard Model background, and allows to reduce its contribution. Other background processes, like ttWW, ttW, 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 5 \( \sigma \) observation of the t\bar{t}W 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
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 $80 \text{ pb}^{-1}$, while $340 \text{ pb}^{-1}$ 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 $5 \sigma$ observation significance and about $50 \text{ pb}^{-1}$ of integrated luminosity for a $3 \sigma$ evidence. For a heavy top partner of mass $500 \text{ GeV}/c^2$ these numbers increase to about $600 \text{ pb}^{-1}$ and $220 \text{ pb}^{-1}$, respectively.

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

![Fig. 6. Left: 95 % C.L. cross-section upper limit BR(same-sign dileptons) as a function of integrated luminosity. Right: signal significance as a function of integrated luminosity.](image)
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 GeV/c\(^2\).

8. Acknowledgments

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References

1. The Large Hadron Collider home page: http://lhc.web.cern.ch/lhc/ contains also general and outreach information. The LHC schedule can be found here: http://lhc-commissioning.web.cern.ch/lhc-commissioning/.
An overview of results obtained with the 2009 run can be found here: http://indico.cern.ch/conferenceOtherViews.py?view=standard&confId=73860.


