IL NUOVO CIMENTO Vol. 35 C, N. 3 Maggio-Giugno 2012
DOI 10.1393/ncc/i2012-11256-y

Colloquia: TOP2011

Inclusive search for a fourth generation of quarks

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ricevuto l' 1 Marzo 2012
pubblicato online il 5 Giugno 2012

Summary. — We present a search for a fourth generation chiral quarks of the up- and down-type in 7 TeV proton collisions recorded by the CMS experiment at the LHC. Final state topologies with b' and t' quarks produced singly or in pairs are studied in the 2011 data corresponding to an integrated luminosity of $1.1\,\text{fb}^{-1}$. Degenerate masses are assumed for the fourth generation quarks. The inclusive search is performed in the decay channel where one isolated muon with a high transverse momentum is identified and results in model dependent limits on the mass of the chiral quarks and the relevant CKM4 matrix elements. For minimal off-diagonal mixing between the third and the fourth generation, a limit $m_{t'} > 490\,\text{GeV}/c^2$ is obtained at 95% CL.

PACS `14.65.Jk` – Other quarks (*e.g.* 4th generations).

1. – Introduction and theoretical model

Previous searches at hadron colliders have only considered pair production of one of the fourth-generation quarks. The CMS experiment performed an inclusive search for fourth-generation up-type t' and down-type b' quarks, produced singly or in pairs [1].

The cross section of the electroweak processes and the decay of the produced fourth-generation quarks depend on the values of the CKM4 matrix elements in a fourth-generation model. The unitary CKM4 matrix can be conveniently described with one free parameter A as follows:

$$\text{CKM4} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} & V_{ub'} \\ V_{cd} & V_{cs} & V_{cb} & V_{cb'} \\ V_{td} & V_{ts} & V_{tb} & V_{tb'} \\ V_{t'd} & V_{t's} & V_{t'b} & V_{t'b'} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & \sqrt{A} & \sqrt{1-A} \\ 0 & 0 & \sqrt{1-A} & \sqrt{A} \end{pmatrix}. \tag{1}$$

For simplicity, degenerate masses are assumed for the fourth-generation up and down-type quarks, hence $m_{t'} = m_{b'} = m_{q'}$. The model of the fourth-generation quark sector allows for a parametrisation of the cross sections of the relevant processes with only two variables, namely the CKM4 matrix parameter A and the mass of the fourth-generation quarks $m_{q'}$. Therefore, the limit will be a function of $m_{q'}$ and $A = |V_{tb}|^2$.

Given the described model, the branching fractions of the $t' \to bW$ and the $b' \to tW \to (bW)W$ decays are 100% if $A \neq 1$. The final-state topologies that are expected are thus

– $t'b \to bWb$,

– $b't \to tWbW \to bWWbW$,

– $t'\bar{t'} \to bWbW$,

– $b'\bar{b'} \to tWtW \to bWWbWW$.

These decay chains imply that for both singly and pair produced fourth-generation quarks, two b-jets are expected in the final state. Additionally, one to four W-bosons are present in the decay of each signal event. The different production processes can be classified according to the number of observed W bosons. The combined search for b' and t' quarks in these subsamples reflects an inclusive search over all dominant production mechanisms.

2. – Event selection and classification

A dataset corresponding to $1.093 \pm 0.045\,\mathrm{fb}^{-1}$ recorded with the CMS experiment [2] was analyzed. Events are selected with a single isolated muon trigger with a transverse momentum (p_T) threshold of $17\,\mathrm{GeV}/c$. At least one high quality isolated muon with a p_T exceeding $40\,\mathrm{GeV}/c$ is required in the acceptance region $|\eta| < 2.1$. This muon should be isolated by $\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2} > 0.3$ from jets in the tracker acceptance ($|\eta| < 2.4$) with $p_T > 30\,\mathrm{GeV}/c$. A veto for a second loosely isolated muon with $p_T > 10\,\mathrm{GeV}/c$ is applied in the acceptance region $|\eta| < 2.5$. No isolated electron with $p_T > 20\,\mathrm{GeV}/c$ is allowed in the acceptance region of $|\eta| < 2.5$. To reduce the rate of multi-jet events, a missing transverse energy of at least $40\,\mathrm{GeV}$ is required.

Events are classified according to the number of b-tagged jets and the number of hadronically decaying W boson candidates. A W boson candidate is found as the jet couple (j_1, j_2), that fulfills best the constraint $|m_{j1,j2} - m_W^{fit}| < \sigma_{m_W}^{fit}$, where m_W^{fit} is the expectation value, and $\sigma_{m_W}^{fit}$ the width of the reconstructed W-boson mass distribution obtained from a Gaussian fit of the simulated distribution of di-jet masses of correctly assigned $W \to q\bar{q}$ topologies. The procedure is repeated until no more hadronically decaying W-boson candidates are found.

In total six exclusive subsamples are defined. In the case of two and three or more hadronically decaying W-bosons, two or more b-tagged jets are required. For the subsamples with zero and one hadronically decaying W boson, both the subsamples with one and two or more b-tagged jets are used.

3. – Discriminating variable and fit

The H_T variable is used as discriminating variable and is defined as the sum of the missing transverse energy, the transverse momenta of the muon, the b-jet(s) and the reconstructed hadronically decaying W-boson candidates. The distribution of this variable is sensitive to the presence of fourth-generation quarks as shown in fig. 1.

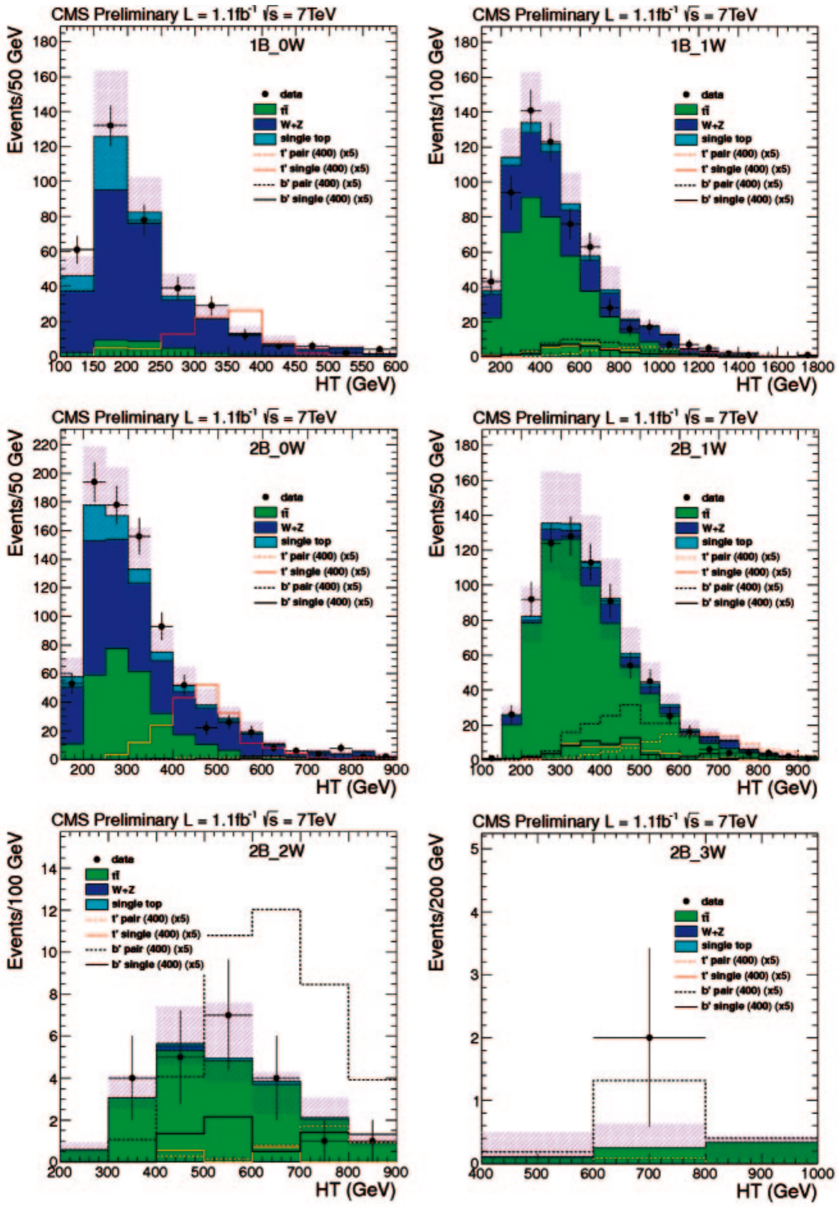

Fig. 1. – The distributions of H_T in each of the different subsamples defined by the number of b-tagged jets and the number of hadronically decaying W-boson candidates. The top plots have a one b-tagged jet and a W-boson count of zero (left) and one (right), the middle plots have two b-tagged jets and a W-boson count of zero (left) and one (right), the lower plots have a W-boson count of two (left) and three or more (right). The last bins include the overflow events. The hashed band shows the quadratic sum of the systematic uncertainties and the various signal processes are shown for $m_{t'} = m_{b'} = 400\,\text{GeV}/c^2$.

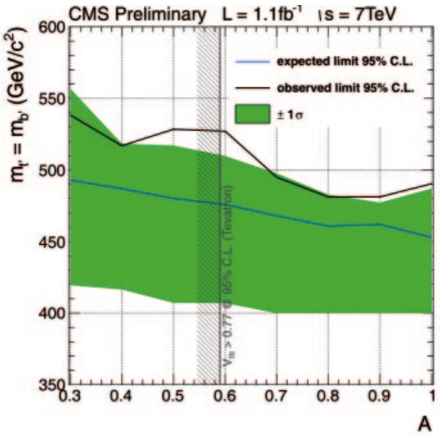

Fig. 2. – Expected and observed exclusion limits for $m_{t'} = m_{b'}$ as a function of the CKM4 parameter $A = V_{tb}^2 = V_{t'b'}^2 = 1 - V_{t'b}^2 = 1 - V_{tb'}^2$. The parameter values below the solid black line are excluded at 95% CL.

The effect of processes with fourth-generation quarks would appear in the high tails of the H_T distribution. The six subsamples are simultaneously used in a fit for the presence of fourth-generation quarks in the data. Systematic uncertainties are taken into account by nuisance parameters. The CLs method is used to determine the 95% CL upper limit on the combined signal cross section as a function of the CKM4 parameter A.

4. – Result and conclusion

The expected and observed limits are shown in fig. 2. These limits indicate a 95% CL lower bound on the degenerate mass of the fourth-generation b' and t' quarks, $m_{q'}$, as a function of the CKM4 parameter A within the simplified model we have assumed. When the value of A approaches one, the standard model single-top process reaches its maximal cross section. When the value of parameter A decreases, the expected cross section of the single t' and single b' processes increases. Therefore, the single t' and single b' processes are expected to enhance the sensitivity for fourth-generation quarks when the parameter A decreases. This is visible in fig. 2, where both the expected and observed limits on $m_{q'}$ are more stringent for smaller values of A.

For minimal off-diagonal mixing ($A \simeq 1$) between the third and the fourth generation, the observed limit $m_{t'} = m_{b'} > 490\,\text{GeV}/c^2$ at 95% CL is obtained (the expected limit is $453\,\text{GeV}/c^2$). A non-zero cross section for the single fourth-generation quark production processes, corresponding to a value of $A < 1$ in our CKM4 model clearly raises both the expected and observed 95% CL exclusion limit.

REFERENCES

[1] The CMS Collaboration, CMS-PAS-EXO-11-054, 2011.
[2] The CMS Collaboration, *JINST*, **3** (2008) S08004, doi=10.1088/1748-0221/3/08/S08004.