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EXOTIC QUARKS FROM COMPOSITE MODELS

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Abstract

We investigate the phenomenology at the CERN LHC of the exotic quarks appearing in composite models considering weak isospin multiplets $I_W = 1$ and $I_W = 3/2$. We focus on $pp \to Qj \to W^+jj \to \ell^+ \not{p}_T jj$ process and then perform a fast simulation of the detector reconstruction based on DELPHES. We study the statistical significance and we estimate a bound on the excited quark mass by recasting an experimental search.

1 Introduction

The composite models represent one of the possible theories beyond the standard model. In this scenario quarks and leptons are assumed not to be elementary particles, but to be bound states of some as yet unknown entities. One consequence of this scenario is that excited quarks and leptons are expected [1, 2, 3, 4, 5]. In general the following parameters are introduced: m_*, the mass of the excited states, and Λ, the energy scale at which the internal substructure becomes manifest (compositeness scale). In our study we will use the parametrization $m_* = \Lambda$. In particular we will take in consideration the extended weak-isospin model [6].

2 Extended weak-isospin model

This model tries to find some properties of excited fermions through the weak isospin spectroscopy without reference to a particular internal structure. This approach is in analogy with the strong isospin symmetry, that allowed to discover baryon and meson resonances before the observation of quarks and gluons.

The standard model fermions have $I_W = 0, 1/2$ and the electroweak bosons have $I_W = 0, 1$, so we can consider fermionic excited states with $I_W \leq 3/2$. The multiplets with $I_W = 1$ (triplet) and $I_W = 3/2$ (quadruplet) of the hadronic sector include ordinary charged excited quarks, U and D, and exotically charged excited quarks, U^+ of charge 5/3 and D^- of charge -4/3:

$$U = \begin{pmatrix} U^+ \\ U \\ D \end{pmatrix}, \quad D = \begin{pmatrix} U \\ D \\ D^- \end{pmatrix}, \quad \Psi = \begin{pmatrix} U^+ \\ U \\ D \\ D^- \end{pmatrix}$$

These multiplets contribute solely to the iso-vector current and do not contribute to the hypercharge current. The exotically charged excited quarks interact with the standard model fermions only via W^+ and W^- gauge bosons, while the ordinary charged excited quarks via W^+, W^-, Z and γ. Because all gauge fields carry no hypercharge Y, a given multiplet couples through the gauge field to light multiplet with the same Y. In order to conserve the $SU(2)$ currents, the couplings between excited and ordinary fermions are magnetic moment type transition couplings. The lagrangians describing these couplings are

$$\mathcal{L}^{(I_W=3/2)} = \frac{gf_{3/2}}{\Lambda} \sum_{M,m,m'} C(\frac{3}{2}, M|1, m; \frac{1}{2}, m') \times (\bar{\Psi}_M \sigma_{\mu\nu} q_{Lm'}) \partial^\nu (W^m)^\mu + h.c. \quad (1)$$

$$\mathcal{L}^{(I_W=1)} = \frac{gf_1}{\Lambda} \sum_{m=-1,0,1} \left[(\bar{U}_m \sigma_{\mu\nu} u_R) + (\bar{D}_m \sigma_{\mu\nu} d_R) \right] \partial^\nu (W^m)^\mu + h.c. \quad (2)$$

where g is the $SU(2)$ coupling, F_1 and $f_3/2$ are dimensionless couplings assumed to be equal to 1, C are the Clebsch-Gordan coefficients and we consider $m_* = \Lambda$.

3 Production and decay of excited quarks

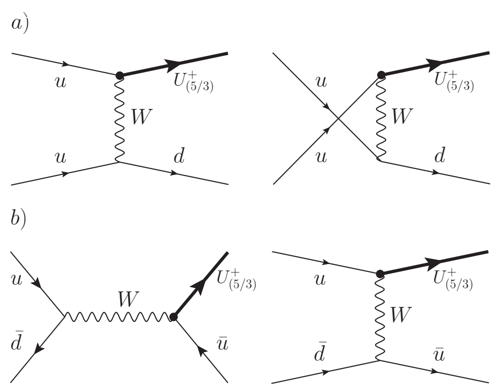

Figure 1: *Feynman diagrams of U^+ resonant production in pp collisions.*

The U^+ quark can be produced through the Feynman diagrams shown in fig.1. The partonic sub-processes cross sections for $I_W = 1$ are characterized by the absence of interference between the kinematical channels and they are

$$\left(\frac{d\hat{\sigma}}{d\hat{t}}\right)^{I_W=1}_{uu\to U^+d} = \frac{1}{4\hat{s}^2 m_*^2} \frac{g^4 f_1^2}{16\pi} \frac{\hat{t}}{(\hat{t} - M_W^2)^2} \left[m_*^2(\hat{t} - m_*^2) + 2\hat{s}\hat{u} + m_*^2(\hat{s} - \hat{u}) \right]$$
$$+ \frac{1}{4\hat{s}^2 m_*^2} \frac{g^4 f_1^2}{16\pi} \frac{u}{(\hat{u} - M_W^2)^2} \left[m_*^2(\hat{s} - m_*^2) + 2\hat{t}\hat{u} + m_*^2(\hat{t} - \hat{u}) \right]$$

$$\left(\frac{d\hat{\sigma}}{d\hat{t}}\right)^{I_W=1}_{u\bar{d}\to U^+\bar{u}} = \frac{1}{4\hat{s}^2 m_*^2}\frac{g^4 f_1^2}{16\pi}\frac{\hat{s}}{(\hat{s}-M_W^2)^2}\left[m_*^2(\hat{s}-m_*^2)+2\hat{t}\hat{u}+m_*^2(\hat{t}-\hat{u})\right]$$
$$+\frac{1}{4\hat{s}^2 m_*^2}\frac{g^4 f_1^2}{16\pi}\frac{\hat{t}}{(\hat{t}-M_W^2)^2}\left[m_*^2(\hat{t}-m_*^2)+2\hat{s}\hat{u}+m_*^2(\hat{s}-\hat{u})\right]$$

The ones for $I_W = 3/2$ have nonzero interference and they are

$$\left(\frac{d\hat{\sigma}}{d\hat{t}}\right)^{I_W=3/2}_{uu\to U^+d} = \frac{1}{4\hat{s}^2 m_*^2}\frac{g^4 f_{3/2}^2}{16\pi}\frac{\hat{t}}{(\hat{t}-M_W^2)^2}\left[m_*^2(\hat{t}-m_*^2)+2\hat{s}\hat{u}-m_*^2(\hat{s}-\hat{u})\right]$$
$$+\frac{1}{4\hat{s}^2 m_*^2}\frac{g^4 f_{3/2}^2}{16\pi}\frac{\hat{u}}{(\hat{u}-M_W^2)^2}\left[m_*^2(\hat{u}-m_*^2)+2\hat{s}\hat{t}-m_*^2(\hat{s}-\hat{t})\right]$$
$$+\frac{1}{4\hat{s}^2 m_*^2}\frac{g^4 f_{3/2}^2}{16\pi}\frac{1}{(\hat{u}-M_W^2)}\frac{1}{(\hat{t}-M_W^2)}\left(\hat{s}\hat{t}\hat{u}+\frac{3}{8}\hat{u}\hat{t}m_*^2\right)$$

$$\left(\frac{d\hat{\sigma}}{d\hat{t}}\right)^{I_W=3/2}_{u\bar{d}\to U^+\bar{u}} = \frac{1}{4\hat{s}^2 m_*^2}\frac{g^4 f_{3/2}^2}{16\pi}\frac{\hat{s}}{(\hat{s}-M_W^2)^2}\left[m_*^2(\hat{s}-m_*^2)+2\hat{t}\hat{u}-m_*^2(\hat{t}-\hat{u})\right]$$
$$+\frac{1}{4\hat{s}^2 m_*^2}\frac{g^4 f_{3/2}^2}{16\pi}\frac{\hat{t}}{(\hat{t}-M_W^2)^2}\left[m_*^2(\hat{t}-m_*^2)+2\hat{s}\hat{u}-m_*^2(\hat{s}-\hat{u})\right]$$
$$+\frac{1}{4\hat{s}^2 m_*^2}\frac{g^4 f_{3/2}^2}{16\pi}\frac{1}{(\hat{s}-M_W^2)}\frac{1}{(\hat{t}-M_W^2)}\left(\hat{s}\hat{t}\hat{u}+\frac{3}{8}\hat{s}\hat{t}m_*^2\right)$$

For the production of D^- quark we have a similar situation, while for the production of U and D quarks we have analogous diagrams, but involving all the gauge bosons.

For the U^+ and D^- quarks the only decay channel is Wq, while the U and D quarks can decay to all the gauge bosons. In our study we consider the production and decay chain $pp \to Qj \to W^+jj \to \ell^+\not{p}_T$ jj, where Q can be U^+, $\bar{D}^-$, U or $\bar{D}$, with all the excited quarks considered to be mass degenerate.

4 Signal and background

The main standard model backround for our signature is the process $pp \to Wjj \to \ell^+\not{p}_T jj$. From the study of the kinematical distribution of signal and background we found that the background can be drastically reduced by applying the cuts

$$p_T(j1) \geq 180 \text{ GeV}, \quad p_T(j2) \geq 100 \text{ GeV}$$

We note that we cannot exactly reconstruct the excited quark mass, because one of its decay product is a neutrino, for which it is not possible to reconstruct the longitudinal momentum. However we can reconstruct the transverse mass defined as

$$M_T^2 = \left(\sqrt{p_{TW}^2 + M_W^2} + p_{Tj1}\right)^2 - (p_{TW} + p_{Tj1})^2 \quad (3)$$

This distribution shows a peak with a relatively sharp end-point at $M_T \approx m_*$ (fig.2, left).

Actually we can still reconstruct the excited quark invariant mass to some degree of accuracy starting from the four-momentum conservation: $M_W^2 = (p_\ell + p_\nu)^2$. From it we obtain a second order equation for the longitudinal momentum of the neutrino and, among the two solutions, we select the one that gives the more central W. Now we have all the quantities to reconstruct the invariant mass $M_{\ell\nu j1}$. This distribution has a clear peak in correspondence of the excited quark mass (fig.2, right).

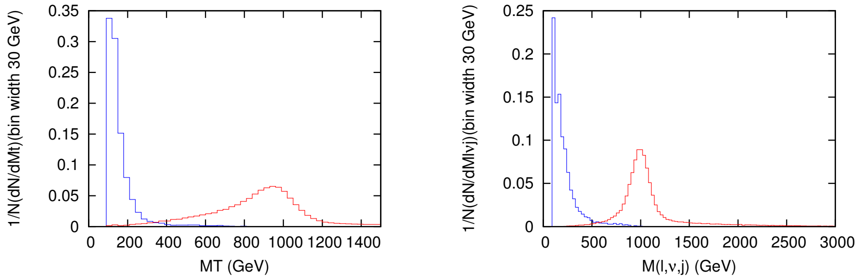

Figure 2: *Transverse mass (left) and invariant mass (right) distribution obtained for an excited quark mass of 1000 GeV. The red line is the signal and the blue line is the background.*

5 Fast detector simulation and reconstructed objects

In order to take into account the detector effects, we have interfaced the LHE output of CalcHEP with the software DELPHES, that simulates the response of a generic detector; we used a CMS-like parametrization. From these simulations we have evaluated the reconstruction efficiencies for signal and background (ϵ_s, ϵ_b); once we have them, it is possible to evaluate the statistical significance as:

$$S = \frac{N_s}{\sqrt{N_s + N_b}}, \quad \text{with} \quad N_s = L\sigma_s\epsilon_s, \quad N_b = L\sigma_b\epsilon_b$$

Finally we can evaluate the luminosity needed to have a given S:

$$L = \frac{S^2}{\sigma_s\epsilon_s}\left[1 + \frac{\sigma_b\epsilon_b}{\sigma_s\epsilon_s}\right]$$

The luminosity curves as function of the excited quark for $S = 3$ and $S = 5$ are reported in fig.3. We

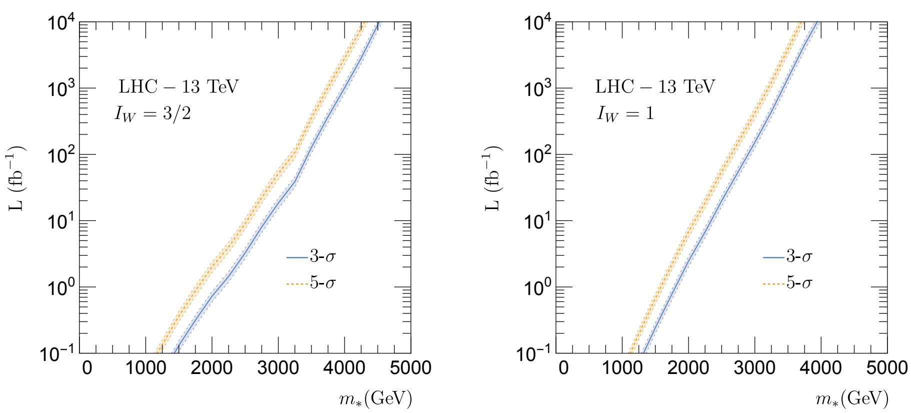

Figure 3: *Luminosity curves at 3-σ (solid) and 5-σ (dashed) level for $\sqrt{s} = 13$ TeV as a function of the excited quark mass, for $I_W = 1$ (left) and $I_W = 3/2$ (right). The shaded bands represent the statistical uncertainties.*

give an estimate of the bound on the excited quark mass by recasting a CMS analysis that search for exotic light flavour quark partner performed at $\sqrt{s} = 8$ TeV [7]. We compare the observed limit on $\sigma(pp \to Dq) \times \mathcal{B}(D \to Zq)$ with the prediction of our model. The results are shown in fig.4.

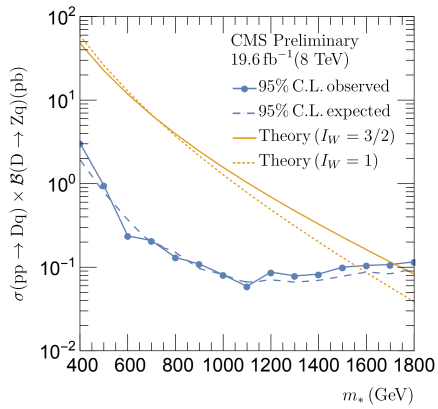

Figure 4: *95% Confidence level limits observed (solid line with disk markers) and expected (dashed line) as reported by a CMS search* [7] *for light flavour quark partners in the Zqq channel are compared with the prediction of our model for* $I_W = 3/2$ *(solid line) and* $I_W = 1$ *(dotted line)*

6 Discussions and conclusions

We have presented the first study of the production at the CERN LHC of exotic quark states which appear in composite models when considering higher isospin multiplets $I_W = 1$ and $I_W = 3/2$. The results obtained are quite interesting and, in our opinion, warrant more detailed studies. For instance the two dimensional parameter space could be fully explored and the effect of the expected contact interaction should be taken into account.

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