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Pair production of heavy $Q = 2/3$ singlets at LHC

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Abstract

We examine the LHC discovery potential for new $Q = 2/3$ quark singlets T in the process $gg, qq \to T\bar{T} \to W^+bW^-\bar{b}$, with one W boson decaying hadronically and the other one leptonically. A particle-level simulation of this signal and its main backgrounds is performed, showing that heavy quarks with masses of 500 GeV or lighter can be discovered at the 5σ level after a few months of running, when an integrated luminosity of 3 fb^{-1} is collected. With a luminosity of 100 fb^{-1}, this process can signal the presence of heavy quarks with masses up to approximately 1 TeV. Finally, we discuss the complementarity among $T\bar{T}$, Tj production and indirect constraints from precise electroweak data in order to discover a new quark or set bounds on its mass.

1. Introduction

The Large Hadron Collider (LHC) will be a powerful tool to explore energies up to the scale of a few TeV. It is expected to provide some striking evidence of new physics, for instance, of a light Higgs boson, in its first months of operation [1,2]. Among many promising possibilities for the discovery of new particles, LHC will offer an ideal environment for the production of heavy quarks. New quarks of either charge can be copiously produced in pairs through QCD interactions, namely via gluon fusion and quark–antiquark annihilation, if there is available phase space [3,4]. Up-type quarks T can also be produced in association with light jets, e.g., in the processes $qb \to q'T$, $\bar{q}'b \to \bar{q}T$ (here and throughout this Letter $q = u, c$, $q' = d, s$), provided their mixing with the bottom quark is sizeable. New interactions may also bring about further production mechanisms. The prospects for heavy quark detection depend on the production processes (with their respective cross sections) as well as on the decay modes (and their relevant backgrounds), which are distinctive of the Standard Model (SM) extension considered.

The presence of a fourth sequential generation is disfavoured by naturalness arguments[1] and precision

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[1] For a fourth quark generation, anomaly cancellation requires the simultaneous presence of a lepton doublet. LEP measurement of the

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electroweak data, which leave a small window for the new quark masses consistent with the experimental measurement of the S, T, U parameters [5]. On the other hand, heavy $SU(2)_L$ quark singlets with charges $Q = 2/3$ or $Q = -1/3$ can exist with a moderate mixing of order 10^{-2}–10^{-1} with the SM quarks. Here we are concerned with the first possibility. Models with large extra dimensions with, for example, t_R in the bulk predict the existence of a tower of $Q = 2/3$ singlets $T^{(n)}_{L,R}$. If there is multilocalisation the lightest one $T^{(1)}_{L,R}$ can have a mass of 300 GeV or larger, and a sizeable mixing with the top quark [6]. (The class of extra-dimensional models having a light $Q = 2/3$ singlet mixing with the top quark is enlarged when corrections localised on the branes to the kinetic terms of fermions and bosons are taken into account [7].) Little Higgs models [8] include in their additional spectrum an up-type singlet, which is expected to have a mass of 1 TeV or larger. Quark singlets also appear in some grand unified theories [4,9]. Their effects in low energy and top physics have already been studied [10]. In this Letter we address their direct observation at LHC through pair production $gg, qq \to T\bar{T}$ [11].

We note that for heavy quark masses $m_T \gtrsim 800$ GeV and a coupling to the bottom quark V_{Tb} of the size suggested by the experimental measurement of the T parameter, single T production $pp \to Tj$ has a larger cross section than pair production and can then explore larger mass scales [12,13]. Therefore, Tj production will eventually set more stringent limits (albeit dependent on V_{Tb}) on heavy quark masses if a positive signal is not observed. However, two important points have to be remarked: (i) the Tj cross section is proportional to $|V_{Tb}|^2$, hence for small mixings this process becomes less relevant; (ii) pair production has the best sensitivity to the presence of new quarks having masses of several hundreds of GeV. If new quarks exist in this mass range, $T\bar{T}$ production would allow to observe a signal in a rather short time.

In the following we briefly review the mixing of the new quark, its interactions and decay modes. After summarising the relevant aspects of the signal and background generation, we will present our results for quark masses of 500 GeV and 1 TeV. Finally, the relation between $T\bar{T}$, Tj production and indirect constraints from the T parameter will be discussed.

2. SM extensions with $Q = 2/3$ singlets

The addition of two $SU(2)_L$ singlet fields $T^0_{L,R}$ to the quark spectrum modifies the weak and scalar interactions involving $Q = 2/3$ quarks. (We denote weak eigenstates with a zero superscript, to distinguish them from mass eigenstates which do not bear superscripts.) Using standard notation, these interactions read

$$\begin{aligned}
\mathcal{L}_W &= -\frac{g}{\sqrt{2}}\left[\bar{u}\gamma^\mu V P_L d W^+_\mu + \bar{d}\gamma^\mu V^\dagger P_L u W^-_\mu\right], \\
\mathcal{L}_Z &= -\frac{g}{2c_W}\bar{u}\gamma^\mu\left[X P_L - \frac{4}{3}s_W^2 \mathbb{1}_{4\times 4}\right]u Z_\mu, \\
\mathcal{L}_H &= \frac{g}{2M_W}\bar{u}\left[\mathcal{M}^u X P_L + X\mathcal{M}^u P_R\right]u H, \qquad (1)
\end{aligned}$$

where $u = (u, c, t, T)$, $d = (d, s, b)$ and $P_{R,L} = (1 \pm \gamma_5)/2$. The extended Cabibbo–Kobayashi–Maskawa (CKM) matrix V is of dimension 4×3, $X = VV^\dagger$ is a non-diagonal 4×4 matrix and $\mathcal{M}^u$ is the 4×4 diagonal up-type quark mass matrix. The new mass eigenstate T is expected to couple mostly with third generation quarks t, b, because T^0_L, T^0_R preferably mix with t^0_L, t^0_R, respectively, due to the large top quark mass. V_{Tb} is mainly constrained by the contribution of the new quark to the T parameter [10,14],

$$\begin{aligned}
\mathrm{T} = \frac{N_c}{16\pi s_W^2 c_W^2}\Big\{&|V_{Tb}|^2\left[\theta_+(y_T, y_b) - \theta_+(y_t, y_b)\right] \\
&- |X_{tT}|^2\theta_+(y_T, y_t)\Big\}, \qquad (2)
\end{aligned}$$

where $N_c = 3$ is the number of colours, $y_i = (\bar{m}_i/M_Z)^2$, $\bar{m}_i$ being the $\overline{\mathrm{MS}}$ mass of the quark i at the scale M_Z, $|X_{tT}|^2 \simeq |V_{Tb}|^2(1 - |V_{Tb}|^2)$ and [14]

$$\theta_+(y_1, y_2) = y_1 + y_2 - \frac{2y_1 y_2}{y_1 - y_2}\log\frac{y_1}{y_2}. \qquad (3)$$

The experimental measurement $\mathrm{T} = 0.12 \pm 0.10$ [15], obtained setting $\mathrm{U} = 0$, implies $\mathrm{T} \leqslant 0.28$ with a 95% confidence level (CL), and the corresponding limit $|V_{Tb}| \leqslant 0.26$–0.18 for $m_T = 500$–1000 GeV (see also Ref. [16]).[2] Mixing of T^0_L with u^0_L, c^0_L, especially with

Z invisible width sets the number of light neutrino species to three, and additional neutrinos must be heavier than 45 GeV [5], in sharp contrast with the smallness of the light neutrino masses $m_\nu \lesssim 1$ eV.

[2] The new quark contribution to U is much smaller, of order 10^{-2} [10], thus it makes sense using this value for T. If we take T =