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Enhancement of new physics signal sensitivity with mistagged charm quarks

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ABSTRACT

We investigate the potential for enhancing search sensitivity for signals having charm quarks in the final state, using the *sizable* bottom-mistagging rate for charm quarks at the LHC. Provided that the relevant background processes contain light quarks instead of charm quarks, the application of b-tagging on charm quark-initiated jets enables us to reject more background events than signal ones due to the relatively small mistagging rate for light quarks. The basic idea is tested with two rare top decay processes: i) $t \to ch \to cb\bar{b}$ and ii) $t \to bH^+ \to b\bar{b}c$ where h and H^+ denote the Standard Model-like higgs boson and a charged higgs boson, respectively. The major background source is a hadronic top quark decay such as $t \to bW^+ \to b\bar{s}c$. We test our method with Monte Carlo simulation at the LHC 14 TeV, and find that the signal-over-background ratio can be increased by a factor of $\mathcal{O}(6\text{–}7)$ with a suitably designed (heavy) flavor tagging algorithm and scheme.

1. Introduction

The discovery of the Higgs particle at the Large Hadron Collider (LHC) [1,2] reaffirms that the Standard Model (SM) is a successful description of fundamental particles and their interactions in nature. Nevertheless, the detailed mechanism of protecting its mass scale from large quantum corrections is still unexplained by the SM, and new physics beyond the Standard Model (BSM) is anticipated to address this puzzle. Since the corrections are dominantly contributed by the top quark, the top quark sector has been regarded as a promising host to accommodate and reveal new physics signatures. Furthermore, the LHC, dubbed a "top factory", is capable of copiously producing top quarks in pairs via the strong interaction, and it can therefore be taken as a great venue to discover new physics phenomena using top quarks.

We emphasize that although many physical properties of the top quark have been measured with great precision since its discovery, its decays are relatively poorly-measured; typical errors in the top quark decays are of $\mathcal{O}(10\%)$ mostly coming from systematics in the measurement of the t-channel single top quark cross section [3,4]. Hence, any new physics effects emerging in the top quark decay channels are, in principle, less constrained by current experimental data.

One of the rare top decay examples to be considered here is $t \to ch$ via a flavor changing neutral current (FCNC) [5–8] followed by the dominant decay mode of the higgs of 125 GeV, i.e., $h \to b\bar{b}$. In principle, nothing precludes the top quark from decaying in this manner. Nevertheless, the SM prediction on the branching ratio (Br) of this process is extremely small due to the famous Glashow–Iliopoulos–Maiani mechanism and second-third generation mixing suppression, which results in $\text{Br}(t \to ch)_{\text{SM}} \approx 10^{-13} - 10^{-15}$ [5–7]. Therefore, a significant excess from such a small SM expectation could be a convincing sign of the existence of new physics. In fact, once new physics is introduced, the aforementioned suppressions can be relaxed, and thus fairly larger branching fractions can be anticipated, e.g., $\text{Br}(t \to ch)_{\text{BSM}} \approx 10^{-3} - 10^{-6}$ depending on the details of the BSM models of interest [7], which is comparable with the recent experimental bound reported by the CMS collaboration [9].

Another exciting scenario to be considered here is $t \to bH^+$ where the charged higgs sequentially decays into a charm quark and an anti-bottom quark unlike the typical decay mode of $H^+ \to c\bar{s}$. A sizable branching fraction of $H^+ \to c\bar{b}$ arises in a few mod-

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els with two or more higgs doublets: for example, multi-higgs doublet models (MHDM) [10], flipped two-higgs doublet models (2HDM) [11–13] with "natural flavor conservation", and Aligned-2HDM [14]. Depending on the model details, $\mathrm{Br}(H^+ \to c\bar{b})$ could be as large as $\sim 80\%$ [15]. Although existing experimental searches of $t \to bH^+ \to b\bar{s}c$ done by the CDF [16] and ATLAS [17] collaborations could be applied to the decay of $H^+ \to c\bar{b}$ [12], an enhanced branching ratio motivates more dedicated searches to discover a new phenomenon or directly constrain the parameter space in the relevant physics models.

For the purpose of concreteness we focus on the collider signatures in the context of pair-produced top quarks, and assume that one of the top quarks decays into two bottom and one charm quarks via the decay sequences described above while the other follows the regular leptonic decay cascade. Provided with the visible final state defined by the signal processes, obviously, the dominant SM background is semi-leptonic top quark pair production. Since there exist three bottom quarks for the signal process vs. two bottom quarks for the background one, the requirement of three bottom-tagged jets can substantially reduce background events. It is noteworthy that this event selection enables us to have the hadronic top quark decaying into $b\bar{s}c$ (i.e., $t \to bW^+ \to b\bar{s}c$) as a main background source because the b-mistagging rate for charm quarks is rather sizable. We henceforth take it as the major background unless specified otherwise.

We point out that, remarkably enough, the high mis-tagging rate for charm quarks can be useful for a further improvement in the relevant signal-over-background ratio (S/B). More specifically, if one demands an additional bottom-tagged jet, then signal events can be selected by tagging the remaining charm quark as a bottom quark, whereas background events can be selected by tagging the remaining strange quark as a bottom quark for which the corresponding mis-tagging rate is typically far smaller than that for charm quarks. Therefore, we expect that the relevant signal sensitivity gets increased so that it is possible to probe smaller branching fractions of signal processes.[1] Of course, a non-negligible reduction in the signal acceptance due to the additional b-jet requirement could be an issue. Given an immense production cross section of top pairs and a large expected integrated luminosity, for example, $\mathcal{L} = 300$ fb^{-1} at the 14 TeV LHC, adequate statistics can be nevertheless achieved in these search channels.

2. Expected enhancement and potential issues

To develop intuition on the basic idea described thus far, we provide a rough estimation of the expected enhancement by parameterizing pertinent efficiencies. As mentioned before, a way to enhance the S/B (before any posterior analysis using kinematic variables) is to require one more b-tagged jet in the final state, utilizing the sizable mistagging rate of charm-induced jets. For more systematic comparison, we begin with (would-be) conventional selection scheme (denoted by 3b), that is, three bottom jets, one regular jet, and a W gauge boson. Since the W is irrelevant to the later discussion, we drop it for convenience. We first define some of the efficiencies with respect to the identification of bottom-initiated jets; b_b as b-tagging efficiency of b quark, b_c as b-mistagging efficiency of c quark, and b_s as b-mistagging efficiency of s quark (light quarks). With this set of definitions and S being the number of signal events before the tagging procedure, the expected number of signal events in the 3b scheme ($S_{3\mathrm{b}}$) is given by

$$S_{3\mathrm{b}} = S\left\{\mathrm{b}_b^3(1-\mathrm{b}_c) + 3\mathrm{b}_b^2\mathrm{b}_c(1-\mathrm{b}_b)\right\}, \tag{1}$$

where the first term represents the leading contribution while the second term represents the subleading contribution such as the case where c-induced jet is mistagged while one of the b-induced jets is not tagged. When it comes to the major background, the leading contribution comes from a hadronic W decaying into c and s as mentioned earlier. Therefore, the expected number of background events in the 3b scheme ($B_{3\mathrm{b}}$) is

$$B_{3\mathrm{b}} = B\mathrm{b}_b^2\left\{\mathrm{b}_c(1-\mathrm{b}_s) + \mathrm{b}_s(1-\mathrm{b}_c) + \frac{2\mathrm{b}_c\mathrm{b}_s}{\mathrm{b}_b}(1-\mathrm{b}_b)\right\}, \tag{2}$$

where B denotes the number of background events before the tagging procedure. We then have the S/B in the 3b scheme as

$$\left(\frac{S}{B}\right)_{3\mathrm{b}} = \left(\frac{S}{B}\right)\frac{\mathrm{b}_b(\mathrm{b}_b - 4\mathrm{b}_b\mathrm{b}_c + 3\mathrm{b}_c)}{\mathrm{b}_b\mathrm{b}_c + \mathrm{b}_b\mathrm{b}_s + 2\mathrm{b}_c\mathrm{b}_s - 4\mathrm{b}_b\mathrm{b}_c\mathrm{b}_s}. \tag{3}$$

Here we assume that the expected number of background events originating from $t \to b\bar{d}u$ is negligible because two light quarks are involved.

On the other hand, if we modify the aforementioned selection scheme by requiring an additional b-tagged jet instead of a regular jet (denoted by 4b), the expected numbers of signal and background events ($S_{4\mathrm{b}}$ and $B_{4\mathrm{b}}$, respectively) are expressed as

$$S_{4\mathrm{b}} = S\mathrm{b}_b^3\mathrm{b}_c\,, \tag{4}$$

$$B_{4\mathrm{b}} = B\mathrm{b}_b^2\mathrm{b}_c\mathrm{b}_s\,, \tag{5}$$

from which the relevant S/B is simply given by

$$\left(\frac{S}{B}\right)_{4\mathrm{b}} = \left(\frac{S}{B}\right)\frac{\mathrm{b}_b}{\mathrm{b}_s}\,, \tag{6}$$

where a small portion from $t \to b\bar{d}u$ is neglected again in computing $B_{4\mathrm{b}}$. Defining the improvement of the 4b scheme with respect to the 3b scheme as I, we have

$$I = \frac{(S/B)_{4\mathrm{b}}}{(S/B)_{3\mathrm{b}}} = \frac{\mathrm{b}_b\mathrm{b}_c + \mathrm{b}_b\mathrm{b}_s + 2\mathrm{b}_c\mathrm{b}_s - 4\mathrm{b}_b\mathrm{b}_c\mathrm{b}_s}{\mathrm{b}_s(\mathrm{b}_b - 4\mathrm{b}_b\mathrm{b}_c + 3\mathrm{b}_c)}. \tag{7}$$

Since tagging efficiencies vary in the transverse momentum of jets, it is interesting to investigate the dependence of I according to the P_T of b-jets, which is explicitly shown by red dots in Fig. 1. As an example tagging scheme, the CSVM tagger of the CMS collaboration has been adopted, and relevant efficiencies are applied based upon the values reported in Ref. [18] wherein they have measured the data using $t\bar{t}$ events. To understand this behavior more intuitively, it is worthwhile to rewrite I using the leading contributions (i.e., the first terms) in eqs. (1) and (2):

$$I \approx \frac{\mathrm{b}_c(1-\mathrm{b}_s)}{\mathrm{b}_s(1-\mathrm{b}_c)}. \tag{8}$$

One can easily see that the value of I is solely governed by b_c and b_s. More specifically, this is an increasing function as b_c (b_s) increases (decreases) so that a large gap between b_c and b_s is favored to attain a large improvement. In fact, it turns out that heavy flavor quarks are less tagged as b-jets while light quarks fake b-jets more often in the high P_T region. The reason is that jets with a large P_T are typically collimated so that errors in particle tracking, which is involved in the tagging algorithm, are likely to increase. As a consequence, less significant improvement is shown in the high P_T region.

[1] In general, the basic idea can be applied to the cases where the signal comes along with charm-induced jet(s) in the final state, whereas the counterparts in the background are light quark-induced jet(s).