Probing New Top Physics at the LHCb Experiment

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(Received 15 April 2011; published 16 August 2011)

We suggest that top quark physics can be studied at the LHCb experiment and that top quark production could be observed. Since LHCb covers a large pseudorapidity region in the forward direction, it has unique abilities to probe new physics in the top quark sector. Furthermore, we demonstrate that LHCb may be able to measure a $t\bar{t}$ production rate asymmetry and, thus, indirectly probe an anomalous forward-backward $t\bar{t}$ asymmetry in the forward region, a possibility suggested by the enhanced forward-backward asymmetry reported by the CDF experiment.

DOI: 10.1103/PhysRevLett.107.082003 PACS numbers: 14.65.Ha

Introduction.—In the standard model (SM) the top quark induces the most severe hierarchy problem. Furthermore, in most natural models it is linked to electroweak symmetry breaking. Consequently, there is strong motivation to search for new physics (NP) effects associated with top quark physics. Recently, the CDF Collaboration has reported evidence for a large forward-backward asymmetry in top quark pair production [1]. Interestingly, there is also an indication that the asymmetry increases significantly with the rapidity difference:

$$A^{t\bar{t}}_{\Delta y>1} = \frac{N(\Delta y > 1) - N(\Delta y < -1)}{N(\Delta y > 1) + N(\Delta y < -1)} = 0.611 \pm 0.256, \tag{1}$$

where N is the number of events with a given rapidity difference Δy between the top quark and the top antiquark. This result motivates extensions of the SM that enhance top quark production in the very forward region. In fact, it is well known that this is a feature of a wide class of new physics models, i.e., those in which top quark production proceeds via t-channel exchange of a new low mass particle, due to forward peaking in the differential cross section. Regardless of any specific theoretical scenario, it is very important to have an experimental probe of this forward region. Below, we argue that the LHCb experiment, by virtue of its high pseudorapidity detector capabilities, may provide a unique opportunity for such a study. The LHCb detector is far from being Hermetic. Thus, substantial event information, e.g., missing energy, is not available. Nevertheless, we propose that the LHCb detector can study SM top quark pair production. In addition, it may be sensitive to new physics dynamics where the rate for top quark pair or single top quark production is enhanced in the forward direction. We further demonstrate that this would allow for a probe of the top quark forward-backward asymmetry in the high pseudorapidity region.

Signal and backgrounds.—In order to identify top quarks at LHCb, we use their decay $t \to Wb$, $W \to \mu\nu$, where both the muon and b have to be in the acceptance of the detector, defined by the approximate pseudorapidity range $2 < \eta < 5$ [2]. LHCb provides enhanced detection of muons with respect to electrons, so in the following for this first study we consider only final state muons from W decay. We consider events with large invariant mass and transverse momenta p_T. Throughout, the muon is required to have $p_T > 20$ GeV and a moderate isolation cut of $\Delta R = 0.4$ is imposed, where $\Delta R^2 = \Delta\eta^2 + \Delta\phi^2$ with ϕ being the muon's azimuthal angle. Thus, all of these events pass the LHCb trigger requirement. Finally, a cut of $p_T > 50$ GeV is imposed on the b jet, which retains most of the signal events. In Fig. 1, we show the resulting SM $t\bar{t}$ signal (thick full black line) as a function of the b-μ

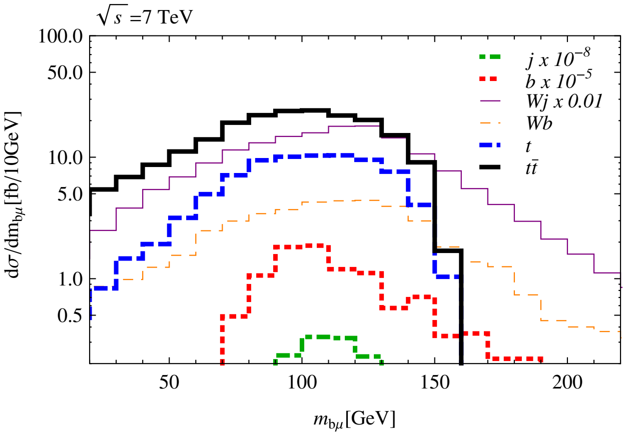

FIG. 1 (color online). The $t\bar{t}$ signal and background distributions as a function of the invariant mass of the candidate b and muon $m_{b\mu}$; see the text for details. The curves from top to bottom (at $m_{b\mu} = 100$ GeV) are for $t\bar{t}$, Wj, single top quark, Wb, bb, and jj.

invariant mass $m_{b\mu}$. The signal, as well as the Wj, Wb, and single top quark backgrounds (see below), was obtained at leading order, by using MADGRAPH/MADEVENT 4.4.57 [3], at the partonic level and using CTEQ6L1 parton distribution functions [4]. The signal curve has been rescaled by a K factor of 1.7, corresponding to an inclusive $t\bar{t}$ cross section of 150 pb, within the range obtained at NLO + NNLL order in Refs. [5,6] and consistent with recent LHC measurements [7,8]. The LHCb detector response is not included in any of our simulations.

We divide the backgrounds broadly into two categories: The first one includes a genuine hard muon from a W decay, and the second one involves either a fake or secondary isolated muon from a light flavor jet j (including charm) or a b quark. In Fig. 1, we also show the Wx backgrounds belonging to the first category, where $x = b, j$ (x corresponds to the leading jet), and the backgrounds are plotted as functions of m_{xl} (thin dashed orange and full purple lines, respectively). A cut of $p_T > 50$ GeV is imposed on x. The ATLAS Collaboration has recently reported an inclusive Wj cross section times leptonic branching ratio of 0.84 nb [9]. We have rescaled the Wx curves by a K factor of 1.2, which reproduces the central value of the measurement under the same set of cuts. A signal to background ratio above 1 can be obtained for the Wj background, if a $j \to b$ mistag rate of 1:100 can be achieved, while maintaining a large b jet detection efficiency. The fact that this is in the ballpark of the mistag rates found by ATLAS and CMS [10,11] (for a b-tagging efficiency of 50%) is encouraging. For charm jets, the Wc background can be brought to a level at or below the top quark signal with a far more modest mistag rate (consistent with Refs. [10,11]). The *a priori* worrisome Wb irreducible background lies well below the signal.

Single top quark production, due to its forward nature, is another relevant irreducible background for the $t\bar{t}$ signal. As shown in Fig. 1 (thick dashed blue line), within the SM and with the cuts described above, a signal to background ratio of a few is expected. Our leading order curve for the sum of single top quark and top antiquark production corresponds to an inclusive cross section of 62 pb, consistent with a recent approximate next-to-next-to-leading-order analysis [12] and a prior next-to-leading-order analysis [13] (we have checked that the Wt contribution [14] to the single top quark signal is negligible). Note that single top quark measurements at ATLAS and CMS, particularly at the high end of their pseudorapidity reach, $\eta \sim 2$, will be useful for calibrating single top quark production in the various Monte Carlo tools. A detailed study of the differences between single top quark and $t\bar{t}$ events, e.g., the presence of a second b jet in the forward direction, may allow a further reduction of the single top quark background. It is important to note that the LHCb is sensitive to models in which single top quark production receives a large forward enhancement (see [15] for a recent discussion).

Backgrounds in the second category consist of QCD production of $b\bar{b}$ as well as light jets, where one jet inside the detector is mistagged as an isolated muon and the other one is identified with a b quark. We have simulated these backgrounds by using MADGRAPH interfaced with PYTHIA 6.4.14 [16] for showering and hadronization. FASTJET [17] has been employed for jet clustering using the anti-k_t [18] algorithm with $R = 0.4$. Cuts of $p_T > 50$ GeV are imposed on the leading b or light jet. We have checked that our leading order Monte Carlo simulations of the $b\bar{b}$ invariant mass and p_T spectra are ~30% larger than those recently measured by ATLAS and CMS [19]. Therefore, we are confident that we are not underestimating the $b\bar{b}$ background at LHCb.

For the jj background we assume a $j \to b$ mistag rate of 1:100, as discussed above. Fake $j \to \mu$ muons originate from calorimeter punchthrough and also from early leptonic decays of pions and kaons. The former can be removed with a cut on the maximum energy deposited in the hadronic calorimeters [20]. The muons originating from decay in flight can be efficiently rejected by requiring an isolation cut. We estimate the rejection power by requiring that the subleading jet in p_T contains only a single particle (pion or kaon). In addition, we employ an early leptonic decay rate of 10^{-3}, as obtained with a full detector simulation in Ref. [20]. Combining the two yields a rejection power of 1:10^6. For the $b \to \mu$ fake rate we require that one b decays (semi)leptonically and apply a $\Delta R = 0.4$ isolation cut on the emitted muon, resulting in a rejection power of 1:10^5. In Fig. 1, the raw jj and bb backgrounds (thick dot-dashed green and dotted red lines, respectively) are multiplied by 10^{-8} and 10^{-5}, respectively, demonstrating that they are reduced to levels well below the signal using our estimates.

As Fig. 1 shows, after the cuts described above and with a $j \to b$ mistag rate of 1:100, a signal to background ratio near 1 is expected. However, the largest background, due to Wj, could be well measured given a precise determination of the $j \to b$ mistag rate at LHCb. Consequently, with enough statistics the $t\bar{t}$ signal can be extracted. For instance, with the above cuts more than 100 $t\bar{t}$ events are expected for 1 fb^{-1}.

Forward-backward asymmetry.—At the LHC there is *a priori* no preferred direction of collisions due to the symmetric nature of the initial state. In principle, one can measure a forward-backward asymmetry based on the fact that on average the proton's valence quarks carry larger momentum fractions. Hence, the event boost is correlated with the initial quark direction, leading to a physical axis with respect to which an asymmetry could be measured. Unfortunately, full reconstruction of the event and its boost is not possible at LHCb due to the detector's limited angular coverage. Instead, we propose a way to indirectly measure the forward-backward asymmetry. In the absence of an asymmetry, the $t\bar{t}$ pseudorapidity distribution is

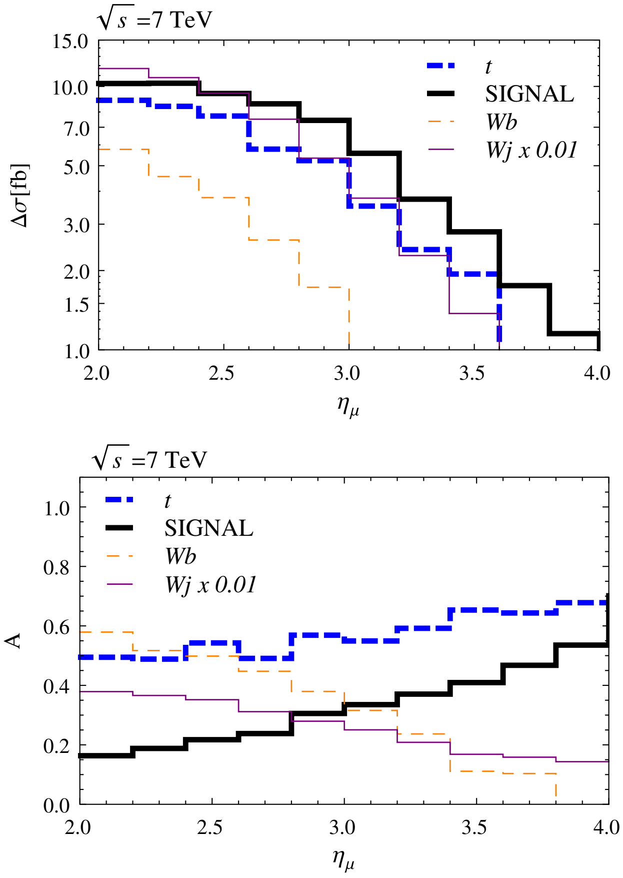

FIG. 2 (color online). The signal and background top quark top antiquark cross section differences (upper panel) and individual rate asymmetries (lower panel), as functions of η_μ. See the text for details.

symmetric; i.e., there is no difference between the top quark and top antiquark distributions as functions of η. However, a positive forward-backward asymmetry would imply that the top quark direction is correlated with the u or d parton direction from the hard part of the interaction. Hence it is expected to be more boosted and forward on average, compared to the top antiquark. Thus, one would expect the forward-backward asymmetry to generate a $t\bar{t}$ rate asymmetry at given pseudorapidity

$$A_\eta^{t\bar{t}} = \left(\frac{d\sigma^t/d\eta - d\sigma^{\bar{t}}/d\eta}{d\sigma^t/d\eta + d\sigma^{\bar{t}}/d\eta}\right)_{\eta\in 2\text{–}5}, \qquad (2)$$

resulting in a different number of top quarks vs top antiquarks in the LHCb detector. This is demonstrated in Fig. 2, where the difference between the top quark and top antiquark cross sections (numerator of $A_\eta^{t\bar{t}}$), as well as the rate asymmetry, is plotted as a function of the muon pseudorapidity η_μ (alternatively, one could also study the dependence on the b pseudorapidity). For illustration, the NP signal (thick full black line) is due to t-channel Z' exchange (see Jung *et al.* in Ref. [21]), with parameters chosen to yield a sizable forward-backward asymmetry in the forward region ($A_{\Delta y>1}^{t\bar{t}} = 0.43$ at leading order in QCD). The SM leading order contribution is symmetric, consistent with no rate asymmetry.

The Wj, Wb, and single top quark backgrounds also yield a rate asymmetry. Their impact is included in Fig. 2 (thin full purple, dashed orange, and thick dashed blue lines, respectively), where the actual rate differences and the individual asymmetries are shown in the upper and lower panel, respectively. The largest background to the top quark top antiquark cross section difference is due to Wj (again we have assumed a $j \to b$ mistag rate of 1:100). However, the underlying Wj cross section asymmetry should be well measured by LHCb, due to the large statistics that will be available in Wj. Thus, precise knowledge of the $j \to b$ mistag rate would accurately determine this background for $A_\eta^{t\bar{t}}$. Sizable contributions to $A_\eta^{t\bar{t}}$ are also expected to arise from single top quark production; see Fig. 2. Our single top quark simulation corresponds to inclusive cross sections of 41 pb (t) and 21 pb ($\bar{t}$), consistent with Refs. [12,13]. Note that precise ATLAS and CMS measurements of the Wj and single top quark cross section asymmetries at lower pseudorapidities will again be useful for calibrating the relevant Monte Carlo tools.

We emphasize that our analysis does not aim to replace a state of the art experimental effort, including optimization of cuts and detector effects. We merely wish to point out that such an analysis may be feasible and worthwhile, especially if the NP leads to anomalous top quark kinematics in the forward direction. Finally, we note that the p_T and pseudorapidty distributions of the muon [22], which is known to be a perfect top quark-spin analyzer, may provide LHCb with sensitivity to differences between the polarization of the top quark produced in the SM and in its extensions. Moreover, a measurement of the top quark polarization could shed light [23] on the origin of a large top quark charge asymmetry in the forward region. This is particularly interesting in view of the fact that flavor physics constraints favor couplings of the NP to right-handed top quarks.

We thank Ohad Silbert for useful discussions. A. L. K. is supported by DOE Grant No. FG02-84-ER40153. J. F. K. is supported in part by the Slovenian Research Agency. G. P. is supported by the Israel Science Foundation (Grant No. 1087/09), EU-FP7 Marie Curie, IRG fellowship, Minerva and G. I. F., the German–Israeli Foundations, and the Peter & Patricia Gruber Foundation. S. S. thanks the U.S. National Science Foundation for support.

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