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Monotops at the LHC

J. Andrea,[1] B. Fuks,[1] and F. Maltoni[2]

[1]*Institut Pluridisciplinaire Hubert Curien/Département Recherches Subatomiques, Université de Strasbourg/CNRS-IN2P3, 23 Rue du Loess, F-67037 Strasbourg, France*

[2]*Center for Cosmology, Particle Physics and Phenomenology (CP3), Université Catholique de Louvain, B-1348 Louvain-la-Neuve, Belgium*

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We explore scenarios where top quarks may be produced singly in association with missing energy, a very distinctive signature, which, in analogy with monojets, we dub *monotops*. We find that monotops can be produced in a variety of modes, typically characterized by baryon number-violating or flavorchanging neutral interactions. We build a simplified model that encompasses all the possible (tree-level) production mechanisms and study the LHC sensitiveness to a few representative scenarios by considering fully hadronic top decays. We find that constraints on such exotic models can already be set with 1 fb^{-1} of integrated luminosity collected at $\sqrt{s} = 7$ TeV.

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I. INTRODUCTION

With the LHC running, the TeV scale has just begun to be explored. The search, in particular, of new phenomena, interactions, and/or particles, motivated by several theoretical arguments as well as current precision data, moves in several directions. The most beaten path is a top-down approach: a theory is conceived so that it extends the standard model (SM), addresses one or more open issues (such as the hierarchy problem or neutrino mass generation), and predictions can be made through perturbation theory or symmetries. In general, some or many new parameters enter, they cannot be fixed by the present constraints and yet determine the expected signatures at colliders.

The most famous example is supersymmetry (SUSY), and more especially its minimal version [1,2], which, in its general form at TeV energies, might feature up to a hundred of free parameters. Benchmark choices are then made that simplify the analyses and typical signatures can be identified. For example, in SUSY, same sign leptons are typically connected to the Majorana nature of some of new states, multijets with missing energy to heavy colored states decaying to partons and to a stable neutral weakly interacting state (possibly a dark matter candidate), and multiphotons with missing energy to gravitinos.

While widely used, this theory-driven approach has notable limitations. The first is that signatures are neither typical of a given benchmark nor of a model itself. Universal extra dimensions [3] and SUSY can have, for instance, very similar signatures. The second and most important limitation is that the top-down approach can lead to strong biases in the final state signatures studied in the experimental analyses.

In this paper, we follow an alternative approach, i.e., we propose a final state signature, a top quark in association with missing transverse energy, dubbed *monotop*, that no process in the standard model can lead to at tree-level, the dominant production mode being suppressed both by a loop factor and by two powers of nondiagonal Cabibbo-Kobayashi-Maskawa matrix elements. We are inspired by the monojet and missing energy final state used to probe gravitons, where the missing energy can be related to weakly interacting states leaving no visible traces in the detectors. Having a top quark in the final state, however, gives a signature much clearer and easier to discriminate than just a light jet. From the theoretical point of view, asking for a top gives a further advantage in that it fixes the flavor of the final state and restricts the possibilities for partons in the initial state. As a result, we find that there are only two classes of processes leading to such a final state signature, through baryon number-violating and flavor-changing neutral interactions. In both cases the key assumption is the existence of an enhanced coupling between the first and third generation. Interestingly enough, both these phenomena are not very much constrained for the top quark [4] and room appears for the LHC to make a discovery or set bounds.

II. BEYOND THE STANDARD MODEL EXPLORATIONS

At the tree level, monotop production can occur via two main mechanisms. Either the top quark is produced (resonantly or not) in association with missing energy of a fermionic nature or through a flavor-changing interaction with an invisible bosonic state, as illustrated on the left and right panels of Fig. 1, respectively.

In the first class of models, the top quark is produced in association with an undetected fermionic particle χ via s, t, u-channel exchanges of a scalar (S) or vector (V) field lying in the (anti-) fundamental representation of $SU(3)_c$. As an example, consider the s-channel resonant case

$$\bar{d}_i \bar{d}_j \to S \quad \text{or} \quad V \to t\chi,$$

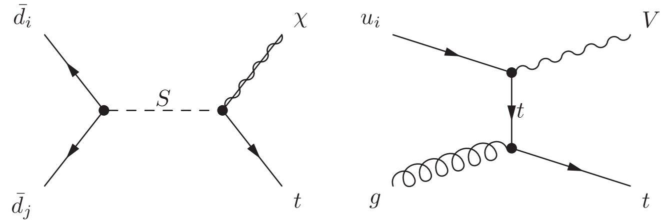

FIG. 1. Representative Feynman diagrams leading to monotop signatures, through the resonant exchange of a colored scalar field S (left) and via a flavor-changing interaction with a vector field V (right). In these two examples, the missing energy is carried by the V and χ particles. More diagrams with, for example, t-channel and s-channel exchanges for the two type of processes, respectively, are possible.

where d_k denotes a down-type quark of generation k. Such processes occur in R-parity-violating SUSY [5] where, similarly to the case discussed in Ref. [6], the intermediate particle is a (possibly on shell) squark and χ the lightest neutralino ($\bar{d}\,\bar{s} \to \tilde{u}_i \to t\tilde{\chi}_1^0$, where $\tilde{u}_i$ are any of the up squarks), or in $SU(5)$ theories where a vector leptoquark V decays into a top quark and a neutrino ($\bar{d}\,\bar{d} \to V \to t\bar{\nu}$). The key difference between these two examples is the mass of the invisible fermionic state inducing different transverse-momentum (p_T) spectrum for the top quark. In the limit of a very heavy resonance, monotops can be seen as being produced through a baryon number-violating effective interaction ($\bar{d}\,\bar{s} \to t\bar{\chi}$), after having included the possible t- and u-channel exchanges of a heavy field [7,8]. Let us note that the fermionic particle could also be a Rarita-Schwinger field, as in SUSY theories containing a spin-3/2 gravitino field, or a multiparticle state (with a global half-integer spin), as in hylogenesis scenarios for dark matter [9]

In the second class of models, the top quark is produced in association with a neutral bosonic state, either long-lived or decaying invisibly, from quark-gluon initial states undergoing a flavor-changing interaction, as discussed, e.g., in Ref. [10]. Missing energy consists either in a two-fermion continuous state, as in R-parity conserving SUSY [11], or in a spin-0 (S), spin-1 (V), or spin-2 (G) particle,

$$ug \to \tilde{u}_i\tilde{\chi}_1^0 \to t\tilde{\chi}_1^0\tilde{\chi}_1^0, \qquad ug \to tS, \qquad tV \quad \text{or} \quad tG.$$

III. EFFECTIVE THEORY FOR MONOTOPS

The top quark kinematic distributions depend both on the partonic initial state and on the nature of the undetected recoiling object (scalar, massive or massless fermion, vector or tensor), as well as on the possible presence of an intermediate resonant state. This suggests a model-independent analysis where we account for all cases within a single simplified theory, in the same spirit as Ref. [12]. Assuming QCD interactions to be flavor-conserving, as in the SM, the flavor-changing neutral interactions are coming from the weak sector. We denote by ϕ, χ and V the possible scalar, fermionic and vectorial missing energy particles, respectively, and by φ and X scalar and vector fields lying in the fundamental representation of $SU(3)_c$ which could lead to resonant monotop production.[1] In addition, we obtain a simplified modeling of four-fermion interactions through possible s, t, u exchanges of heavy scalar fields φ and $\tilde{\varphi}$. The corresponding effective Lagrangian in terms of mass eigenstates reads

$$\begin{aligned}\mathcal{L} = {} & \mathcal{L}_{\rm SM} + \phi\bar{u}[a^0_{FC} + b^0_{FC}\gamma_5]u + V_\mu\bar{u}[a^1_{FC}\gamma^\mu + b^1_{FC}\gamma^\mu\gamma_5]u \\ & + \epsilon^{ijk}\varphi_i\bar{d}^c_j[a^q_{SR} + b^q_{SR}\gamma_5]d_k + \varphi_i\bar{u}^i[a^{1/2}_{SR} + b^{1/2}_{SR}\gamma_5]\chi \\ & + \epsilon^{ijk}\tilde{\varphi}_i\bar{d}^c_j[\tilde{a}^q_{SR} + \tilde{b}^q_{SR}\gamma_5]u_k + \tilde{\varphi}_i\bar{d}^i[\tilde{a}^{1/2}_{SR} + \tilde{b}^{1/2}_{SR}\gamma_5]\chi \\ & + \epsilon^{ijk}X_{\mu,i}\bar{d}^c_j[a^q_{VR}\gamma^\mu + b^q_{VR}\gamma^\mu\gamma_5]d_k \\ & + X_{\mu,i}\bar{u}^i[a^{1/2}_{VR}\gamma^\mu + b^{1/2}_{VR}\gamma^\mu\gamma_5]\chi + \text{H.c.},\end{aligned} \qquad (1)$$

where the superscript c stands for charge conjugation, i, j, k are color indices in the fundamental representation, and flavor indices are understood. The matrices (in flavor space) $a^{\{0,1\}}_{FC}$ and $b^{\{0,1\}}_{FC}$ contain quark interactions with the bosonic missing-energy particles ϕ and V, while $a^{1/2}_{\{S,V\}R}$ and $b^{1/2}_{\{S,V\}R}$ are the interactions between up-type quarks, the invisible fermion χ and the new colored states φ and X. The latter also couple to down-type quarks with a strength given by $a^q_{\{S,V\}R}$ and $b^q_{\{S,V\}R}$. Because of the symmetry properties of the ϵ^{ijk} tensor, identical quark couplings to the scalar field φ vanish and so do their axial couplings to the vector field X. In the case of four-fermion interactions, we also need to introduce additional $\tilde{a}^q_{SR}$, $\tilde{b}^q_{SR}$, $\tilde{a}^{1/2}_{SR}$ and $\tilde{b}^{1/2}_{SR}$ interaction matrices, assuming heavy masses for the φ and $\tilde{\varphi}$ fields.

IV. MODEL-INDEPENDENT SEARCHES

The main signatures associated with monotop production can be classified according to the top quark decays,

$$pp \to t + \not{E}_T \to bW + \not{E}_T \to bjj + \not{E}_T \quad \text{or} \quad b\ell + \not{E}_T,$$

where j and b denote (parton-level) light/c- and b-jets, respectively, ℓ a charged lepton, and $\not{E}_T$ missing transverse energy. In this paper, we consider the simpler hadronic signatures of one b-jet and two light jets, typically lying in the same hemisphere. While monotop signatures with leptonically decaying top quarks are expected to be more

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[1] For simplicity, we neglect spin-2 gravitons, as their flavor-changing couplings are loop-induced and thus very small [13], as well as any of their excitations, which, even if they have, on the one hand, typically flavor-violating couplings at tree level, do not lead, on the other hand, to a missing energy signature. On the same footing, we do not consider spin-3/2 fields since their couplings are, at least in SUSY theories, in general suppressed by the SUSY-breaking scale.

challenging, they have been widely investigated in the past in the context of R-parity-violating SUSY [14,15]. Top quark mass reconstruction is a powerful tool to reject electroweak or QCD backgrounds at low as well as at high transverse momentum. In the latter case, boosted top reconstruction techniques could be also exploited to reconstruct fully hadronic top candidates with a good purity [16].

The only source of irreducible SM background to hadronic monotop production consists in the associated production of an invisibly decaying Z-boson with three jets (one being a b jet). Other sources of background, related to detector effects, consist, first, in QCD multijet events where misreconstructed jets produce large (fake) $\not{E}_T$, then in W plus jets, $t\bar{t}$ and diboson events where the W and Z bosons decay to nonreconstructed leptons, and finally in single top events including non- or misreconstructed jets. A proper investigation of those instrumental backgrounds requires not only parton showering, hadronization, and realistic detector simulation, but also data-driven methods. It is therefore preferable to resort to the available experimental studies, e.g., [17,18]. In a recent analysis performed by the CMS collaboration with the 7 TeV data [17], it has been shown that simple selection cuts on the missing transverse momentum (>150 GeV) and on the p_T (>50 GeV) of the three jets reconstructed with a high quality as well as on their scalar sum (>300 GeV) allow to keep a good control of the backgrounds. This leads to comparable amounts of selected QCD, Z, W and $t\bar{t}$ events, while the contamination from diboson and single top backgrounds is further reduced by about 1 order of magnitude. In addition, the presence of a top quark can be exploited by demanding two non-b-jets with an invariant mass compatible with the W-boson mass, one b-tagged jet, and a three-jet invariant mass compatible with the top quark mass. Hence, all instrumental backgrounds are expected to be strongly suppressed after selection. We therefore base our estimate of the monotop sensitivity at the LHC taking into account the irreducible background related to the production of an invisibly decaying Z-boson in association with three jets.

Event simulation is performed for the LHC at $\sqrt{s} = 7$ TeV and for a luminosity of $1\ \text{fb}^{-1}$ using the Monte Carlo generator MADGRAPH 5 [19]. We employ the CTEQ6L1 set of parton densities [20] and identify renormalization and factorization scales to the value of the top quark mass, $M_t = 172$ GeV for the signal (as well as for the background). We have implemented the Lagrangian of Eq. (1) into MADGRAPH via FEYNRULES [21]. In this prospective study, we present results based on a parton-level simulation for the signal as well as for the main irreducible background, $Z + 3$ jets, computed at the tree level in the five-flavor scheme.

To illustrate the main features of the monotop production, we consider simplified scenarios where all axial couplings involving new particles vanish ($b = \tilde{b} = 0$). Furthermore, we only retain the interactions that can be enhanced by parton density functions, and set $(a^0_{FC})_{13} = (a^0_{FC})_{31} = (a^1_{FC})_{13} = (a^1_{FC})_{31} = (a^q_{SR})_{12} = -(a^q_{SR})_{21} = (a^{1/2}_{SR})_3 = (a^q_{VR})_{11} = (a^{1/2}_{VR})_3 = a = 0.1$. In the four-fermion interaction limit, the heavy mass is set to $M_\varphi = M_{\tilde{\varphi}} = 3$ TeV and the corresponding nonvanishing interaction are $(a^q_{SR})_{12} = -(a^q_{SR})_{21} = (\tilde{a}^q_{SR})_{\{1,2\}3} = (\tilde{a}^{1/2}_{SR})_{\{1,2\}} = a = 0.1$. Within the above settings, we define five scenarios: a scalar (vector) resonant monotop production with $m_\chi = 50$ (300) GeV, flavor-changing neutral production with a 300 GeV scalar (50 GeV vector) invisible state and, finally, a scenario including four-fermion interactions with a massless invisible state χ. The values for the masses of the invisible states are inspired by present collider data and lie right above the lower bound on the mass of the lightest neutralino in typical SUSY scenarios and of the lightest Kaluza-Klein excitation in extra-dimensional scenarios, respectively [4]. In the case of resonant monotop production, we assume the branching ratio $X, \varphi \to t\chi$ equal to one, our analysis being thus insensitive to $a^q_{\{SR,VR\}}$, and we fix the resonance mass to 500 GeV. In Fig. 2, we present the missing transverse-momentum ($\not{p}_T$) spectrum associated with the five monotop scenarios presented above and with the irreducible $Z + 3$ jet background. We require three jets with $p_T > 50$ GeV, rapidity $|\eta| < 2.5$, and relative distance $\Delta R > 0.5$. All event samples being normalized to one, we compare the shapes of the distributions. As expected, we observe a typical resonant behavior for the first two scenarios, the spectrum showing an edge at a value depending on the masses of the resonance and of the invisible produced fermion. On the other hand, the distributions related to flavor-changing monotop production are flatter, peaking

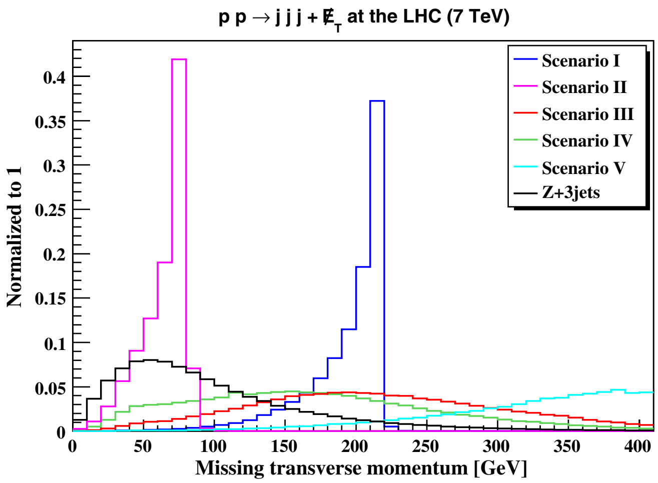

FIG. 2 (color online). Missing transverse-momentum spectrum for monotop production ($t + \bar{t}$) at the LHC (7 TeV) for the five considered scenarios and for the $Z + 3$ jet background. Selection cuts are given in the text. The distributions are normalized to unity.

at higher $\not{p}_T$ values with respect to the background. Finally, monotop production through four-fermion interactions leads to a $\not{p}_T$-distribution monotonically growing with the energy, thus fully distinguishable from the SM background if the number of signal events is large enough.

In summary, $\not{p}_T$ distributions are characteristic of the monotop production mode. However, in all cases, simple cuts on the missing transverse momentum allow us to get rid of the major background contributions and keep a good fraction of the signal. We define three basic possible cuts on the required $\not{p}_T$: "loose", "standard" and "tight" cut corresponding to $\not{p}_T > 65$, 150, 250 GeV, respectively. The first is suitable for resonant monotop production when the resonance mass is close to the monotop production threshold. The latter leaves an almost background-free sample, useful in the production via four-fermion interactions. For all intermediate cases, we employ the standard cut. Our leading-order estimate of the cross section for the Z (invisible) $+3$ jet background within the jet cuts mentioned above and the additional $\not{p}_T > 65$ GeV cut gives 4.9 pb. In the context of an analysis including parton showering, hadronization, and detector simulation, as well as all instrumental backgrounds, events containing isolated leptons should be rejected and exactly three jets required. In so doing, background from single top and $t\bar{t}$ events becomes negligible and combinatorial issues for the top candidate reconstruction are minimized, at a price of a lower signal selection efficiency. In more refined analysis, the p_T-threshold could be further tuned to optimize over extra radiation possibly present in the events. We only retain events with a single b-tagged jet, estimating a b-tagging efficiency of about 60% for a charm/light flavor mistagging rate of 10%/1%. In addition, the two non-b-tagged jets invariant mass is required to lie in a $M_W \pm 20$ GeV range while the three-jet invariant mass is required to be in a $M_t \pm 30$ GeV interval. In order to include resolution effects, the (parton-level) invariant-mass distributions have been smeared using Gaussian functions with a width of 15 GeV in the dijet and 20 GeV in the three-jet cases.

In Table I the signal cross sections and the corresponding sensitivities at LHC $\sqrt{s} = 7$ TeV with 1 fb^{-1} accumulated luminosity are shown for the five representative scenarios.

TABLE I. Signal cross sections in the five selected scenarios corresponding to the choice $a = 0.1$. In scenarios I and II the branching ratios of intermediate resonances is set to unity. In the last column the minimal values of the effective couplings $a_{\min}$ leading to sensitivities $s = S/\sqrt{S+B} \geq 5$, assuming 1 fb^{-1} of collected luminosity at LHC ($\sqrt{s} = 7$ TeV) are given.

Scenario	$\not{p}_T$ cut [GeV]	$\sigma(t+\bar{t})$ [pb]	$a_{\min}$
I	150	3.99	0.042
II	65	32.1	0.043
III	150	0.322	0.14
IV	150	24.3	0.017
V	250	$1.08 \cdot 10^{-4}$	4.9

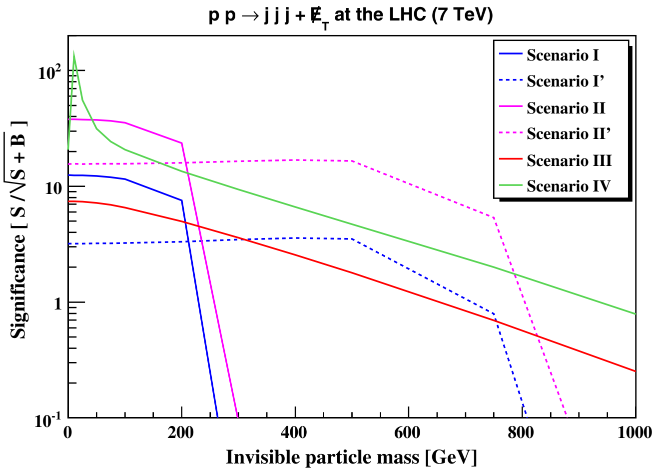

FIG. 3 (color online). Significance in the five selected scenarios as a function of the invisible state mass, assuming 1 fb^{-1} of collected luminosity at LHC ($\sqrt{s} = 7$ TeV). Selection cuts are described in the text.

In Fig. 3, we estimate the sensitivity of the LHC to monotop discovery. Starting from the five scenarios presented above, we vary the mass of the missing energy particle and calculate in each case the significance, using the standard $\not{p}_T$ cut of 150 GeV. The benchmark scenarios I' and II' are variations of the two first scenarios where the mass of the resonant particle is taken at 1 TeV. Flavor-changing monotop production appears to be the most optimistic case, especially in the low mass region, due to the enhancement given by the parton densities. On the other hand, in the case of resonant monotop production, the accessible mass region depends strongly on the resonance mass, with heavier resonances allowing to probe a larger invisible mass.

V. CONCLUSIONS

In this paper, we have proposed a novel signature, which we dubbed monotop, involving the production of a top in association with missing energy. We have analyzed it through a simplified theory approach and argued that couplings of order one or smaller can be strongly constrained at the LHC for the different production modes, just by using a basic set of cuts. Our results motivate further studies, possibly including more complete simulations and advanced analysis techniques, e.g., the use of boosted top reconstruction algorithms, as well as a thorough analysis of the indirect constraints coming from lower energy experiments and flavor physics.

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