Distinguishing Standard Model Extensions using Monotop Chirality at the LHC

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We present two minimal extensions of the standard model that gives rise to baryogensis and include heavy color-triplet scalars interacting with a light Majorana fermion that can be the dark matter (DM) candidate. The electroweak charges of the new scalars govern their couplings to quarks of different chirality, which leads to different collider signals. These models predict monotop events at the LHC and the energy spectrum of decay products of highly polarized top quarks can be used to establish the chiral nature of the interactions involving the heavy scalars and the DM.

I. INTRODUCTION

The monojet final states have attracted a lot of attention as of late since they can probe many extensions of the standard model (SM) that can explain dark matter (DM) [1]. Along the same line, the monotop final state is also under investigation as a probe of DM models [2].

Recently, a minimal extension to the SM has been proposed [3] that explains the proximity of baryon and DM abundances [4] by introducing baryon number violating interactions via (a set of) heavy color-triplet scalars X_α and a light singlet Majorana fermion. The fermion becomes stable,and hence a viable DM candidate, when its mass is almost equal to the proton mass. Since no new discrete symmetry is needed to protect the DM particle against decay, this model naturally predicts monojet signals at the LHC with a characteristic resonance [5] that features a Jacobian peak in the jet's transverse momentum distribution. The model in addition produces, dijet, dijet+missing energy, 4 jet + missing energy final states.

For successful baryogenesis, the TeV X fields can couple to quarks of any generation and chirality. While largely leaving the same imprint on eartly universe, the couplings to different generations can potentially lead to very different signals at the LHC. The first-generation quark couplings enhance production rate of X, while the third-generation coupling yields a monotop final state with a sizeable missing transverse energy ($\not{E}_T$). Moreover, when monotop events are present, the top polarization can be a useful probe of the chiral property of the new interactions in the model. In this paper, we discuss two models where the X couples to either a purely right-handed or a purely left-handed top quark. In the literature, effective theory Lagrangian has been considered where the monotop signal involves interactions that contain both chiralities of the tops [2]. Investigating the energy and transverse momentum distributions of the top quark decay products, we show how the top chirality can be a useful handle in distinguishing these models at the LHC.

The rest of the paper is organzied as follows. We discuss models with isospin singlet and doublet X fields in Section II, collider monotop signals from these models in Section III, top chirality discrimination in Section IV, and then conclude in Section V.

II. MODELS WITH EXPLICIT ISOSPIN STRUCTURE

In this section, we introduce two minimal extensions of the SM that include color-triplet scalar fields with baryon number violating interactions. The first model (Model 1) includes two iso-singlet color-triplet scalars $X_{1,2}$ with hypercharge $+4/3$ and a singlet fermion N with the following Lagrangian,

$$\mathcal{L}_1 = \lambda_1^{\alpha,i} X_\alpha^* N u_i^c + \lambda_2^{\alpha,ij} X_\alpha d_i^c d_j^c + \text{h.c.} \qquad (1)$$
$$+ \frac{1}{2} m_N N N + m_\alpha^2 |X_\alpha|^2 .$$

Here α denote coupling to different X_α, and i, j are flavor indices (color indices are omitted for simplicity), and we note that λ_2 is antisymmetric under $i \leftrightarrow j$.

The second model (Model 2) includes iso-doublet color-triplets $X_{1,2}$ with hypercharge $+1/3$, iso-doublet fermions Y and $\bar{Y}$ with hypercharge $+1$ and -1 respectively, and a singlet fermion N with the following Lagrangian

$$\begin{aligned}
\mathcal{L}_2 &= y_1^{\alpha,i} X_\alpha^* Q_i N X_\alpha + y_2^{\alpha,i} X_\alpha \bar{Y} d_i^c \\
&+ y_3^{\alpha,i} X_\alpha Y u_i^c + \text{h.c.} \\
&+ m_Y \bar{Y}Y + \frac{1}{2} m_N NN + m_\alpha^2 |X_\alpha|^2.
\end{aligned} \tag{2}$$

We note the $Xd^c d^c$ term, which leads to an s-channel resonance enhancement of X production at the LHC, is not present in Model 2 due to electroweak charge assignment. Another important difference between these models is that in Model 1 X interacts with only *right handed* up-type quaks, while in Model 2 it interacts with the *left handed* up-type quarks. We will exploit this feature to distinguish these models at the LHC.

In Model 1, the exchange of X particles leads to $\Delta B = 2$ processes like double proton decay $pp \rightarrow K^+ K^+$ and neutron $n - \bar{n}$ oscillations. Experimental limits on these processes set stringent constraints on the model parameters (for a detailed discussion, see [3]. An interesting aspect of Model 2 is that it does not result in proton decay or $n-\bar{n}$ oscillations. The tightest limits on this model arise from processes like $K^0 - \bar{K}^0$ and $B^0 - \bar{B}^0$ mixing.

As pointed out in [3], the fermion N becomes a viable DM candidate in Model 1 provided that $m_p - m_e \leq m_N \leq m_p + m_e$, where m_p and m_e are the proton mass and electron mass respectively. In Model 2, N becomes stable, hence a DM candidate, if $m_N < m_Y$. The measured value of the Z width requires that $m_Y > m_Z/2$. As the current LHC bound on weakly produced doublets is very weak [6] and heavily depends on leptonic final states, the iso-doublets Y and $\bar{Y}$ of a few hundred GeV mass can easily evade the current collider searches. For direct comparison between the two models, we consider the case when $m_N \approx 1$ GeV in Model 2 as well[1]. The prospects for direct and indirect detection of N DM in Model 1 have been discussed in [3].

It is interesting to note that both models can explain the DM and baryon abundances, and produce a monojet signal at colliders. The X interacts with opposite chiral currents of the u-type quark between the two models.

III. MONOTOPS AT THE LHC

The phenomenological difference between the singlet and doublet X scenarios can be better constrained by the LHC in the following ways:
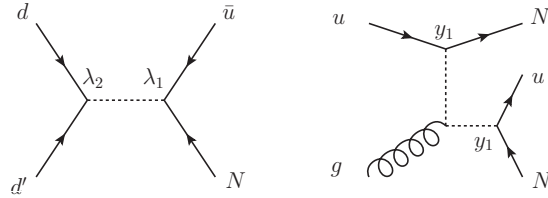

FIG. 1: Feynman diagrams for single X production at the LHC in the singlet (left) and doublet (right) scenarios.

(1) The X single production is a resonant s-channel process in the singlet model.

(2) When coupled to the 3rd generation quarks, the top chirality from X decay is opposite between the singlet and doublet cases.

While X can be singly produced in both models, as shown in Fig. 1, the $Xd^c d^c$ term in the iso-singlet scenario would allow a resonant $dd' \rightarrow X \rightarrow uN$ monojet process at the LHC, leading to a tight constraint on flavor-blind λ_1 and λ_2 couplings as $|\lambda_1 \lambda_2| \leq 10^{-2}$ and a corresponding *pre-cut* signal cross-section of 30 fb for a TeV X resonance. If the top couplings $\lambda_1^{\alpha,3}$ is also $\mathcal{O}(10^{-1})$, a monotop signal of similar cross-section will be expected, which is allowed by current LHC data [7]. In the iso-doublet model, the resonant production is absent and the heavy X in the t-channel would yield a smaller production cross section. Generally, if λ and y couplings have comparable sizes, the singlet case would be easier to probe at the LHC. Nevertheless, baryogenesis can work for a range of parameter values, the doublet case may also provide a competitive collider signal if y is larger than the singlet coupling.

If monotop signals are present in one or both of the models, the chirality of decay products of X will provide a useful tool to distinguish between the two models. Due to a large mass gap between $m_N \approx 1$ GeV and $m_X \sim 1$ TeV, the top quark from X decay gets a significant Lorentz boost and statistically leaves the imprint of its polarization in its decay products. The iso-singlet X decays to a purely right-handed up-type quark, while the iso-doublet X decays to purely left-handed. When X couplings to light quarks are taken into account, the $pp \rightarrow t + \not{E}_T$ process becomes a perfect channel to probe the chiral nature of the X coupling to quarks.

IV. TOP CHIRALITY AS A DISCRIMINATOR

Due to the enhancement from a large top Yukawa coupling, the top quark mostly decays into a longitudinal W, and the b spin aligns with the parent top spin in the center-of-mass frame. As W only couples to the left-handed current, the direction of b quark momentum would be anti-parallel to the spin and align against the Lorentz boost if the top is right-handed. Similarly in the left-handed top decay, b momentum would be along

the Lorentz boost and become more energetic in the lab frame. The top polarization can be clearly distinguished with a model-independent observable in the b energy ratio, which is constructed from the top sub-system in the final state:

$$\eta \equiv \frac{\Delta N_+ + \Delta N_-}{N_{\text{total}}} \qquad (3)$$

where

$$\Delta N_+ = \int_{x_0}^1 \left(\frac{dN}{dx} - \frac{dN^U}{dx} \right) dx \qquad (4)$$
$$\Delta N_- = \int_0^{x_0} \left(\frac{dN^U}{dx} - \frac{dN}{dx} \right) dx,$$

where N denotes the monotop event number distribution over the bottom quark energy fraction $x \equiv E(b)/E(t)$, not to be confused with the DM candidate. dN^U/dx denotes the spectrum from unpolarized tops and $\Delta N_\pm$ are the deviations above/below the cross-over point x_0 at about half the maximum energy fraction, where the pure left/right handed spectra meet. As shown in Fig. 2, a positive(negative) η value indicates enhanced left(right)-handed chirality among the top sample. The shape of the left and right handed spectra depends on the size of the boost and both distinguish from a flat unpolarized spectrum.
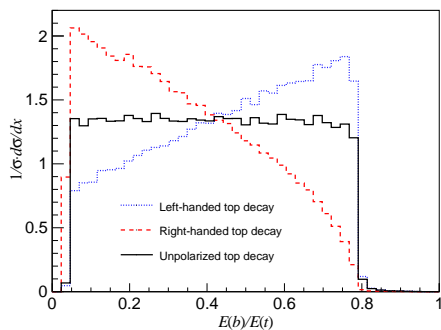

FIG. 2: Normalized parton level b energy fraction from left-handed (dotted) and right-handed (dashed) top decays. The flat distribution from unpolarized (solid) top decay is shown in black. $E_t = 500$ GeV in this figure.

At the LHC, the top energy can be fully constructed when the top decay hadronically. When the b jet is successfully tagged, the top energy is $E(b) + E(j_1) + E(j_2)$ and j denotes leading non-b jets. The sizeable missing energy $\not{E}_T \sim p_T(t)$ in such events can help reducing SM backgrounds. It is worth notice the SM single-top production is mostly left-handed via the W interaction, while the unpolarized QCD-dominated top pair production differs in both top energy/transverse momentum distributions as well as a much more crowded final state. A discovery-level study at limited statistics against SM backgrounds and/or a non-polarized top would involve

more sophisticated spectral analyses than the naive discriminator in Eq. 3, and is beyond the scope of the current paper. The semi-hadonic decay of the top also yield different kinematic patterns, especially lepton angular correlations in $t\bar{t}$ searches [8]. Here we include the combination of lepton and b-jet energy fractions as a complementary to the fully hadronic channel.
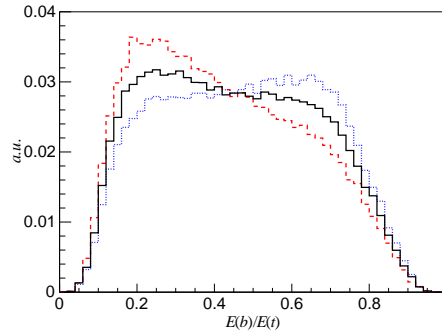

FIG. 3: Normalized b energy fraction spectrum from left-handed (dotted) and right-handed (dashed) top decays. The unpolarized (solid) spectrum is shown in black.

Difficulty may arise from instrumental effects with the detectors. In order to study a feasibility of the proposed method of the top quark chirality determination, we provide the results with a detector simulation. The monotop events are prepared with MadGraph5 v1.5 [9] for parton-level generation followed by Pythia 8.2 [10] for parton showering and Delphes 3.2 [11] for a fast detector simulation. In this study we use a default CMS detector card. The jets are reconstructed with FastJet [12] package using anti-k_T algorithm for $p_T > 20$ GeV. The efficiency of the b-jet tagging is set to be $\sim 70\%$ in the barrel part of the detector ($|\eta| < 1.2$) and $\sim 60\%$ in the endcaps ($1.2 < |\eta| < 2.5$). These numbers correspond to the ones used in the Snowmass workshop [13]. The fully hadronic events are selected with $p_T(b) > 60$ GeV and at least two jets with $p_T(j) > 20$ GeV. The invariant mass of two light flavor jets is required to be within 20 GeV from the W mass. The semileptonic events are selected with $p_T(b) > 30$ GeV and a lepton with $p_T(\ell) > 30$ GeV.

The results of the simulation are presented in Fig. 3 for the fully hadronic final state, and in Fig. 4 for the leptonic case in which we define the chirality observable as $p_T(b)/[p_T(b) + p_T(l)]$. A clear separation between three representative chirality states (left, right and unpolarized) is seen. Due to b-tagging requirements, jet reconstruction may under-evaluate the energy of non-isolated b jets in boosted top system, resulting in softer $E(b)/E(t)$ fraction. As the result the distributions of $E(b)/e(t)$ or related variables at the reconstructed objects level become slightly tilted comparing to the generator-level ones. Both ATLAS and CMS experiments will need to calibrate the reconstruction efficiency to extract a proper physics conclusion.

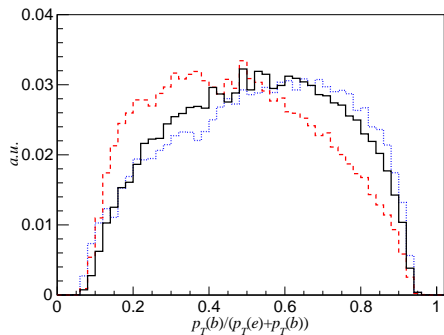Obtained results show good prospects on the top-quark

FIG. 4: Normalized b+lepton transverse momentum fraction spectrum from the semileptonic decay of left-handed (dotted) and right-handed (dashed) tops. The unpolarized (solid) spectrum is shown in black.

chirality reconstruction at the LHC experiments. We see that even after the inclusion of the detector simulation, it is possible to distinguish models with left and right handed tops.

V. CONCLUSION

We have discussed minimal extensions of the SM by color-triplet scalars X_i that give rise to baryogenesis and a light DM candidate, and lead to highly polarized monotops at the LHC. Polarization of the top quark depends on the electroweak charge assignment of X. In the first model, X is an isospin singlet that couples to the right-handed up-type quarks. In the second model, X is an isopspin doublet that couples to the left-handed up-type quarks, as well as new color-singlet iso-doublet field(s).

Unlike the colored superpartners in supersymmetyric extensions of the SM, the colored scalars X can be singly produced in both of our models. The models can lead to potentially interesting monotop events where top energy is about half of the X mass, although the monotop production mechanism is different in two models. The large mass of X leads to boosted tops whose polarization affects the energy distribution of the decay products. The top polarization can therefore serve as a good probe of the isospin of colored scalars and help us differentiate between the two models.

We have presented a detector level simulation and found that the energy and transverse momentum distributions of b quark, both in fully hadronic top decays and in combination with the visible lepton momentum in semileptonic decays, can distinguish tops of different polarizations from each other, and also from unpolarized tops.

As chiral couplings between the DM and quarks are often present in beyond SM theories, the search for the top chirality can be a very useful probe for establishing such models. Also, while monotop+$\not{E}_T$ events are often smoking-gun signal for new physics, the spectral analyses of top polarization can be readily applied to $t\bar{t}$ pairs if the two tops can be separately reconstructed, for instance, in the pair production of the X mediators or heavy top-partners in other beyond SM cases.

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