Physics Letters B 740 (2015) 80–82

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Dark matter with flavor symmetry and its collider signature

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ARTICLE INFO

Article history:
Received 23 October 2014
Received in revised form 16 November 2014
Accepted 17 November 2014
Available online 20 November 2014
Editor: J. Hisano

ABSTRACT

The notion that dark matter and standard-model matter are connected through flavor implies a generic collider signature of the type 2 jets $+ \mu^\pm + e^\mp +$ missing energy. We discuss the theoretical basis of this proposal and its verifiability at the Large Hadron Collider.

A generic framework [1] has been proposed for understanding how dark matter (DM) and flavor are connected through the 125 GeV particle [2,3] discovered at the Large Hadron Collider (LHC). It is assumed to be the one Higgs boson h of the standard model (SM), but its couplings to some of the SM fermions are forbidden at tree level by a flavor symmetry such as A_4, and occur only in one loop by the soft breaking of this flavor symmetry in the dark sector. A verifiable consequence is the possible deviation [4] of the Higgs Yukawa coupling from the SM prediction of m_f/v, where m_f is the mass of the fermion and $v = 246$ GeV is the vacuum expectation value of h. Here we consider a generic collider signature from the new particles of this proposal.

Our specific starting point is the radiative generation of charged-lepton and d quark masses as proposed in Ref. [1].

In Figs. 1 and 2, η^+ is part of a scalar electroweak doublet (η^+, η^0) first introduced in Ref. [5]. It is distinguished from the SM Higgs doublet (ϕ^+, ϕ^0) by an exactly conserved (dark) discrete Z_2 symmetry, under which (η^+, η^0) is odd and (ϕ^+, ϕ^0) is even. The scalar singlet χ^+ is also odd. There are three neutral singlet Dirac fermions $N_{1,2,3}$ which are odd under Z_2 as well. The scalar color triplet $\xi^{-1/3}$ is part of an electroweak doublet $(\xi^{2/3}, \xi^{-1/3})$ and $\zeta^{-1/3}$ is an electroweak singlet. They are also odd under Z_2. Hence all the particles in the loop are distinguished from those of the SM by this dark Z_2 symmetry. If desired, Z_2 may be promoted to a gauged $U(1)_D$ as shown in Ref. [6]. In this scheme, flavor is being carried by the neutral singlet fermions $N_{1,2,3}$, the lightest of which, say N_1, is a DM candidate.

The usual tree-level SM Yukawa couplings, i.e. $\phi^0 \bar{l}_L l_R$ and $\phi^0 \bar{d}_L d_R$, are assumed to be forbidden by a flavor symmetry [1]. This flavor symmetry is then broken softly by the 3×3 $\bar{N}_L N_R$ mass matrix, allowing the loop to be connected. Flavor is thus carried by the dark matter fermions $N_{1,2,3}$. The flavor structure of dark matter is transmitted to the visible sector through the radiative mass-generating mechanism, using the one Higgs doublet of the standard model. The color-triplet scalars ξ and ζ are analogs of the scalar quarks of supersymmetry (SUSY), but there is only one copy of each and they do not carry flavor. Because they are colored, they are produced copiously in pairs by gluons at the Large Hadron Collider (LHC). To see how they may be detected, consider the following scenario with the simplifying assumed interactions:

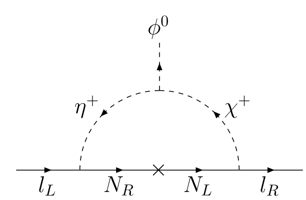

Fig. 1. One-loop generation of charged-lepton mass.

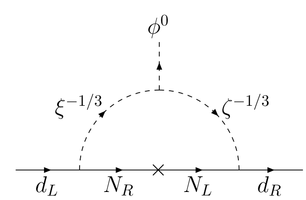

Fig. 2. One-loop generation of d quark mass.

$$\mathcal{L}_{int} = f(\bar{d}_R N_{1L} + \bar{s}_R N_{2L})\zeta^{-1/3} + f'(\bar{e}_R N_{1L} + \bar{\mu}_R N_{2L})\chi^- + H.c. \quad (1)$$

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http://dx.doi.org/10.1016/j.physletb.2014.11.032

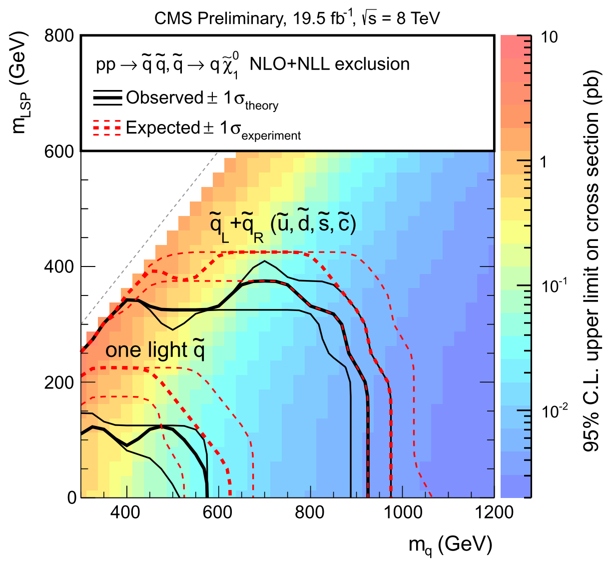

Fig. 3. Results of squark searches at the LHC of squark decay to quark + LSP at 8 TeV from CMS-PAS-SUS-13-019 [17].

Assume further that $m_\zeta > m_{N_2} > m_\chi > m_{N_1}$, then ζ decays to sN_2 and dN_1. Whereas N_1 is stable, N_2 decays to $\mu^\pm\chi^\mp$, and $\chi^\mp$ decays to $e^\mp N_1$. This implies a signature of the type 2 jets + $\mu^\pm + e^\mp$ + missing energy ($E_T^{\rm miss}$) at the LHC, and is rather distinct because of the different charged leptons in the final state. In supersymmetry, flavor is organized from quark to squark and lepton to slepton. Here it is organized through the flavored DM particles $N_{1,2,3}$.

In the following we take the above simplified model, and see how it may be probed at the LHC. The color-triplet ζ behaves as a squark, so it couples to gluons, but since there is no gluino, it has no connection to quarks except through Eq. (1) which always involves $N_{1,2,3}$. As such, the branching fractions of $\zeta \to dN_1$ and $\zeta \to sN_2$ are roughly equal, i.e. 0.5 each. The mass of the charged scalar χ is constrained to be greater than 70 GeV from LEP data [16]. However, after analyzing the model with a range of masses, we find that the best scenarios of optimizing the ratio of the cross sections of the signal divided by background under various cuts are those for $m_{N_2} = 400$ GeV and $m_\chi = 200$ GeV. For the results below, we use the specific mass scheme of $m_\zeta > m_{N_2} > m_\chi > m_{N_1}$, as already mentioned.

Our model is implemented in CalcHEP [7] to generate parton-level events using the CTEQ6M parton distribution functions (PDF) [8], which are then analyzed with PYTHIA 8 [9,10] to produce leading-order (LO) results. The LO production cross section of the squark analogs (hereby referred to simply as squarks) is verified through the Feynrules [11] interface with Madgraph 5 [12], producing a cross section consistent with CalcHEP. Whereas the main signature of this model is distinct from that of SUSY squarks, SUSY models with only one light family of squark and the gluinos decoupled (called simplified topologies) will have the same production cross section as the squarks here. Most importantly, the masses excluded by the LHC are much lower for such models as seen in Fig. 3. This scenario is used for the expected 13 TeV data where the production cross sections of the squarks are compared to simplified topology models of SUSY squarks, which are calculated at Next-To-Leading-Order (NLO) and Next-Leading-Log (NLL) by C. Borschensky et al. [13]. The comparison of our LO calculation to these results is used to obtain a k-factor in order to approximate the NLO contributions to the squark production. For the opposite-sign opposite-flavor dilepton events, the main background is from $t\bar{t}$ pairs, unlike the same-flavor case which has significant contribution from Drell–Yan production [14]. For the expected 13 TeV data, only the $t\bar{t}$ background is generated with CalcHEP, using a k-factor to scale to the NLO production cross section for $t\bar{t}$ [15], and analyzed with PYTHIA 8.

In addition to the opposite-sign opposite-flavor dilepton + 2 jets + $E_T^{\rm miss}$ signature, it is also possible for each squark to decay directly to DM and a quark, thus producing two jets and missing energy, without any lepton. As a result, SUSY searches at 7 TeV and 8 TeV for this signature in simplified SUSY topologies offer useful constraints on our model. The searches at 8 TeV [17] are presented in Fig. 3. For our model, the 7 TeV (not shown) and 8 TeV (Fig. 3) data are taken into account by ensuring the cross section for ζ decaying directly to dN_1 is lower than the upper limit observed at the LHC for a single squark (in a simplified topology) decaying directly to a quark + LSP. After these constraints are taken into account, the results from the 7 TeV [18] and 8 TeV [14] searches looking for events with 2 leptons, 2 jets, and missing energy do not provide any further constraints. Additionally, it is possible for the squark to be produced through a t-channel process directly with DM producing a monojet signal, however this production cross section is a smaller contributor to an LHC signal than the dijet + $E_T^{\rm miss}$. Such a monojet + $E_T^{\rm miss}$ signature for DM has been investigated in a model independent way (see [19–22]). When taking into account the monojet signature, the upper bound of allowed events in the 8 TeV data [20] is taken into account, at LO, if a squark mass above 400 GeV is assumed. Additionally, studies on DM that can interact with a colored scalar have explored the constraints from relic abundance and direction detection of DM, which are potentially more restrictive than the LHC [19,21,22]. In particular, XENON100 is able to probe down to 10^{-45} cm^2 for a DM mass of 100 GeV [22], which would rule out much of the parameter space if f is of order unity. However, to yield the proper down quark mass a value of $f \approx 0.01$ must be used and the spin dependent, direct detection, cross section for Dirac fermion dark matter [22] can be of order 10^{-45} cm^2 for a squark mass of 400 GeV and a DM mass of 100 GeV.

We now present our analysis for the expected 13 TeV run. Six cuts are applied to the signal and background events in PYTHIA, with four of the cuts corresponding to the cut regions from [18], while the last two cut regions are found to be effective for our model based on our analysis. All of the six cuts are described in Table 1 below, with the resulting $t\bar{t}$ decay cross section in each cut region. Each cut is implemented in PYTHIA 8 and applied to both the signal events, and the background events from $t\bar{t}$ decays. A signal-to-background (SB) ratio of the resulting cross sections is calculated for each choice of squark and DM mass. In Figs. 4 and 5 we show the regions in which the choice of DM mass and squark mass satisfies $SB > 5$ for various cuts. Two of the cut regions, R1 and R4, do not have any mass choice for which $SB > 5$, and so do not appear in Figs. 4 and 5.

As seen in Figs. 4 and 5, the cuts R5 and R2 allow fewer mass choices to have a large SB ratio. This can be understood after consulting the resulting background cross sections in Table 1, which show that the background cross section for these cuts is larger than the cuts R6 and R3, so while fewer background events survive these more stringent cuts, the background events are cut down even further producing the results seen in the figures.

In conclusion, the model outlined in this paper could be observed at the LHC during the 13 TeV run, and has a signature distinct from SUSY. The major difference between this model and SUSY is that the signature is produced solely in the opposite-flavor channel, however, same-sign searches use the opposite-flavor events to estimate the flavor symmetric background [14],

Table 1
Cuts applied to the signal and background for opposite-sign opposite-flavor dileptons + 2 jets + missing energy (E_T^{miss}). The values of E_T^{miss}, H_T (the scalar sum of transverse jet momentum), and transverse momentum of jets and leptons (p_T) are in GeV. Also shown are the resulting SM background cross section after the cuts are applied in PYTHIA.

Cut:	E_T^{miss}	H_T	p_T^j (p_T^l)	$\|\eta_j\|$ upper-limit	$\|\eta\|$ e (μ) upper-limit	$\sigma_{post-cut}$ (fb)
R1	275	300	30 (20)	3.00	2.40 (2.50)	10.0
R2	200	600	30 (20)	3.00	2.40 (2.50)	0.5
R3	275	600	30 (20)	3.00	2.40 (2.50)	0.4
R4	200	> 125, < 300	30 (20)	3.00	2.40 (2.50)	33.1
R5	200	350	30 (20)	3.00	2.40 (2.50)	7.1
R6	200	350	150 (25)	3.00	2.40 (2.50)	1.2

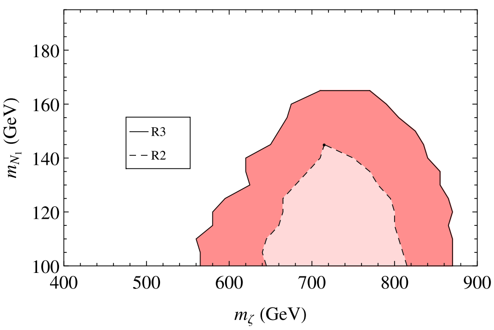

Fig. 4. Masses for N_1 and ζ that could produce a signal-to-background ratio, when compared to $t\bar{t}$ decays, larger than 5 in the opposite-sign opposite-flavor dilepton + 2 jets + missing energy signature, under the R2 and R3 cuts.

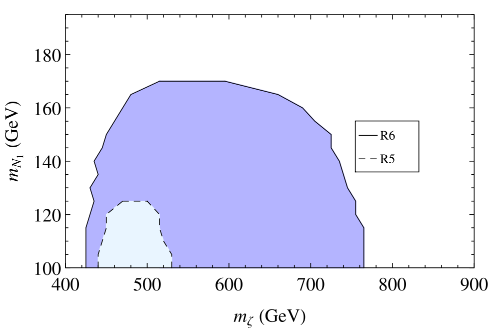

Fig. 5. Masses for N_1 and ζ that could produce a signal-to-background ratio, when compared to $t\bar{t}$ decays, larger than 5 in the opposite-sign opposite-flavor dilepton + 2 jets + missing energy signature, under the R5 and R6 cuts.

and subtract it from the observed same-sign background to obtain a signal for SUSY [14]. Given a similar search strategy, our model would predict a significant negative signal in same-flavor searches. As a result, any large, positive, signal in the same-flavor channel could potentially rule out or heavily constrain our model. For example the mass choices that produce large SB ratios would be ruled out in such a scenario. In addition, searches at 13 TeV for ζ decaying directly to dN_1 will provide further constraints.

Acknowledgement

This work is supported in part by the U.S. Department of Energy under Grant No. DE-SC0008541.

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