Snowmass2021 - Letter of Interest

Sharing but not Caring at colliders

EF Topical Groups:

☐ (EF01) EW Physics: Higgs Boson properties and couplings
☐ (EF02) EW Physics: Higgs Boson as a portal to new physics
☐ (EF03) EW Physics: Heavy flavor and top quark physics
☐ (EF04) EW Precision Physics and constraining new physics
☐ (EF05) QCD and strong interactions: Precision QCD
☐ (EF06) QCD and strong interactions: Hadronic structure and forward QCD
☐ (EF07) QCD and strong interactions: Heavy Ions
■ (EF08) BSM: Model specific explorations
☐ (EF09) BSM: More general explorations
■ (EF10) BSM: Dark Matter at colliders
■ (TF07) Collider phenomenology
■ (Other) (CF1) Dark Matter: Particle-like

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Abstract: We consider the collider phenomenology of asymmetric Dark Matter (DM) scenarios where DM carries baryon or lepton numbers, which can be defined if there exist operators connecting the dark to the visible sector. In particular, we focus on minimal models where Standard Model (SM) and DM particles *share* a common asymmetry through effective operators at early time in the Universe, and later on decouple from each other (*not care*). Once the DM mass is specified, the Wilson coefficients of these operators are fixed by the requirement of the correct transfer of the asymmetry. This EFT operators can be searched and constrained at hadron colliders looking at the following processes: $i)$ Jet(s) + MET, $ii)$ jet(s) + lepton + MET, $iii)$ di-lepton + di-jet + MET. Besides effective operators, it is also possible to constrain the parameter space of some representative ultraviolet complete models by using additional lepton collider measurements, like photon + MET.

Main: The idea of asymmetric DM is a few decades old [1–3] and has seen a renewed interest in recent years resulting in a plethora of new ideas (see some recent review articles [4–7]). Following Ref. [8], we will consider a scenario where DM X is a SM singlet but carries either nonzero baryon B and/or lepton number L and couples to the SM particles through the following effective operators

$$\frac{1}{\Lambda^{n-p}}\bar{X}^2\mathcal{O}^{(n)}, \tag{1}$$

where $p = 1, 2$ for X being a complex scalar or a Dirac fermion, respectively, and their stability is ensured by either being odd under a $\mathbb{Z}_2$ or charged under a dark $U(1)$ symmetry. $\mathcal{O}^{(n)}$ are operators of mass dimension $n > 4$ carrying nonzero B and/or L and composed of only the SM particles. Such operators have mass dimension 5 and 6, and are given, respectively, by [9, 10]:

$$\mathcal{O}^{(5)}_{\alpha\beta} = \epsilon_{ik}\epsilon_{jl}\left(\ell^i_{L_\alpha}\ell^j_{L_\beta}\right)H^k H^l, \tag{2}$$

and

$$\mathcal{O}^{(6)\mathrm{I}}_{\alpha\beta\delta\gamma} = \epsilon_{abc}\epsilon_{ij}\left(q^{ia}_{L_\alpha}\ell^j_{L_\beta}\right)\left(d^b_{R_\delta}u^c_{R_\gamma}\right), \tag{3}$$

$$\mathcal{O}^{(6)\mathrm{II}}_{\alpha\beta\delta\gamma} = \epsilon_{abc}\epsilon_{ij}\left(q^{ia}_{L_\alpha}q^{jb}_{L_\beta}\right)\left(u^c_{R_\delta}e_{R_\gamma}\right), \tag{4}$$

$$\mathcal{O}^{(6)\mathrm{III}}_{\alpha\beta\delta\gamma} = \epsilon_{abc}\epsilon_{il}\epsilon_{jk}\left(q^{ai}_{L_\alpha}q^{jb}_{L_\beta}\right)\left(q^{kc}_{L_\delta}\ell^l_{L_\delta}\right), \tag{5}$$

$$\mathcal{O}^{(6)\mathrm{IV}}_{\alpha\beta\delta\gamma} = \epsilon_{abc}\left(d^a_{R_\alpha}u^b_{R_\beta}\right)\left(u^c_{R_\delta}e_{R_\gamma}\right). \tag{6}$$

The basic idea is that a nonzero $B - L$ is generated at some high scale and at lower scale, the asymmetry is shared between the SM and the dark sector through $B - L$ or B conserving operators above. The parameter space consistent with scenarios such that the charge asymmetry in $B - L$ [before electroweak sphaleron (EWSp) processes freeze out through operator (2)] or B [after EWSp processes freeze out through operators (3)-(6)] are properly shared between the SM and the dark sectors in accordance with observations are explored in Ref. [8].

In Ref. [11], we carried out relevant searches for signatures in the collider experiments. For studies relevant to collider searches, we consider all the SM fermions to be the first-generation ones and focus on the following operators

$$\frac{1}{\Lambda^{5-p}}\bar{X}\bar{X}\epsilon_{ij}\epsilon_{kl}(\bar{\ell}^c_{Li}\ell_{Lk})H_j H_l\,, \tag{7}$$

$$\frac{1}{\Lambda^{6-p}}\bar{X}\bar{X}\epsilon_{ij}(\bar{q}^c_{Li}\ell_{Lj})(\bar{d}^c_R u_R)\,. \tag{8}$$

The possible signatures for hadron collider are shown in figure 1.

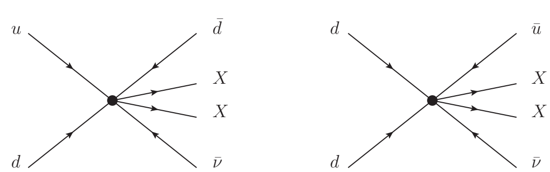

Figure 1: Feynman diagrams for $pp \to j\nu XX$ production at the LHC from the operator in Eq. (8).

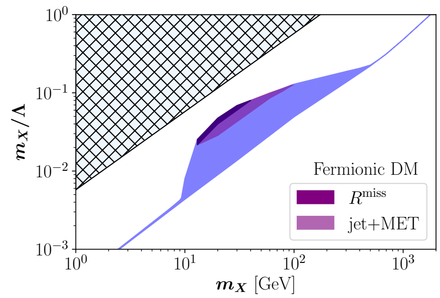

Figure 2: Exclusion regions for fermionic DM, obtained from the LHC recasting of jet + MET searches [12] (pink) and $R^{\rm miss}$ measurements [13] (purple), at $\sqrt{s} = 13$ TeV and 3.2 fb^{-1}.

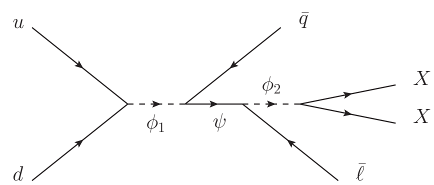

Figure 3: Example of simplified UV model giving rise to operator (8).

For the effective field theory (EFT) operators to be valid at the collider studies, we retain at generator level only events that satisfy the following EFT validity cut

$$\sqrt{s} < \begin{cases} g\,\Lambda & \text{for scalar DM,} \\ g^{4/5}\Lambda & \text{for fermionic DM.} \end{cases} \tag{9}$$

Figure 2 shows with the (blue) region of $(m_X,\, \Lambda)$ plane characterized by the fact that the measured baryon asymmetry of the Universe and the DM relic abundance can be reproduced simultaneously, in the case of fermionic Dirac DM (current data cannot yet exclude any parameter space of the scalar DM scenario), and for the scenarios where the transfer of the asymmetry is efficient after the freeze-out of the EWSp processes. In the upper left hatched regions, Λ is smaller than the Higgs vev. The exclusion regions obtained from the LHC recasting of jet + MET searches [12] (pink) and $R^{\rm miss}$ measurements [13] (purple), at $\sqrt{s} = 13$ TeV and 3.2 fb^{-1}.

Due to the restriction from the applicability of the EFT operators, we further consider several simplified UV models in Ref. [11] for instance, in Fig. 3. ϕ_1 being a colored particle can be explored through di-jets event $pp \to \phi_1 \to jj$. On the other hand, ψ being a $SU(2)_L$ doublet which couple to lepton doublet and singlet ϕ can result in mono-photon even $e^+e^- \to \phi_2\phi_2^*\gamma$ as illustrated in Fig. 4. While current data is not able to exclude this class of sharing scenarios [11], we look forward to future hadron and lepton colliders to do the job.

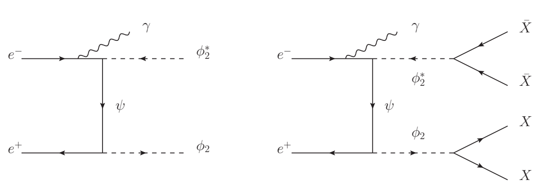

Figure 4: Feynman diagrams for $e^+e^- \to \phi_2\phi_2^*\gamma$ and $e^+e^- \to XX\bar{X}\bar{X}\gamma$.

References

[1] S. Nussinov, *Technocosmology: Could a Technibaryon Excess Provide a 'Natural' Missing Mass Candidate?*, *Phys. Lett.* **B165** (1985) 55.

[2] E. Roulet and G. Gelmini, *Cosmions, Cosmic Asymmetry and Underground Detection*, *Nucl. Phys.* **B325** (1989) 733.

[3] S.M. Barr, R.S. Chivukula and E. Farhi, *Electroweak Fermion Number Violation and the Production of Stable Particles in the Early Universe*, *Phys. Lett.* **B241** (1990) 387.

[4] H. Davoudiasl and R.N. Mohapatra, *On Relating the Genesis of Cosmic Baryons and Dark Matter*, *New J. Phys.* **14** (2012) 095011 [1203.1247].

[5] K. Petraki and R.R. Volkas, *Review of asymmetric dark matter*, *Int. J. Mod. Phys.* **A28** (2013) 1330028 [1305.4939].

[6] K.M. Zurek, *Asymmetric Dark Matter: Theories, Signatures, and Constraints*, *Phys. Rept.* **537** (2014) 91 [1308.0338].

[7] S.M. Boucenna and S. Morisi, *Theories relating baryon asymmetry and dark matter: A mini review*, *Front. Phys.* **1** (2014) 33 [1310.1904].

[8] N. Bernal, C.S. Fong and N. Fonseca, *Sharing but not Caring: Dark Matter and the Baryon Asymmetry of the Universe*, *JCAP* **1609** (2016) 005 [1605.07188].

[9] S. Weinberg, *Baryon and Lepton Nonconserving Processes*, *Phys. Rev. Lett.* **43** (1979) 1566.

[10] S. Weinberg, *Varieties of Baryon and Lepton Nonconservation*, *Phys. Rev.* **D22** (1980) 1694.

[11] N. Bernal, C.S. Fong and A. Tonero, *Sharing but not Caring: Collider Phenomenology*, *JHEP* **08** (2018) 037 [1806.00482].

[12] ATLAS collaboration, *Search for new phenomena in final states with an energetic jet and large missing transverse momentum in pp collisions at* $\sqrt{s}$ *=13 TeV using the ATLAS detector*, *Phys. Rev.* **D94** (2016) 032005 [1604.07773].

[13] ATLAS collaboration, *Measurement of detector-corrected observables sensitive to the anomalous production of events with jets and large missing transverse momentum in pp collisions at* $\sqrt{s}$ *=13 TeV using the ATLAS detector*, *Eur. Phys. J.* **C77** (2017) 765 [1707.03263].