Snowmass2021 - Letter of Interest

[Search for Asymmetric Dark Matter model at CEPC by displaced lepton jets]

Thematic Areas: (check all that apply □/■)

□ (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
□ (Other) *[Please specify frontier/topical group]*

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Abstract: Asymmetric Dark Matter (ADM) model makes the generation of dark matter and baryon matter closely related, and thus can naturally explain the coincidence of measured dark matter and baryon abundance, i.e. $\Omega_D : \Omega_B \approx 5 : 1$. We consider a ADM model with net lepton number and dark matter number being generated simultaneously. The following Sphaleron process further transfer net lepton number to baryon number. In this model, dark sector connect to the visible sector through lepton, and thus the expected lepton collider, e.g. CEPC, provides a good chance to search for such ADM model. We find that the main signal of this model is a pair of displaced lepton jets. Such a novel signal can be easily detected, once produced at CEPC.

1 A lepton portal asymmetric dark matter model

Asymmetric Dark Matter (ADM)[1–19] is motivated by the fact that the measured baryon and dark matter abundance happen to be at the same order, i.e. $\Omega_D : \Omega_B \approx 5 : 1$[20]. Here we study a model, which is a mild modification of the model present in[19]. Compared with the model in[19], in our model is connected to the visible sector through leptons. Such a lepton portal ADM model is promising to be searched fo at proposed lepton colliders.

We extend the SM gauge group with a new $SU(3)'$, which is gauge group in the dark sector and generate the mass of dark matter (dark baryon) through a dark confinement. Dark baryon number is carried by dark quark q', and there is a scalar mediator particle which linking dark quark with lepton. Besides, for the generating of baryon and dark baryon number in the early universe, we need to introduce other new particles.

	N_i	Y_1	Y_2	Φ	$l_R(e_R,\ \mu_R,\ \tau_R)$	q'_L
$SU(3)$	1	1	1	1	1	1
$SU(3)'$	1	3	3	3	1	3
$U_Y(1)$	0	-1	2	-1	1	0
Spin	1/2	0	0	0	1/2(right-hand)	1/2(right-hand)

Table 1: Particle content. Here l means e, μ, and τ.

In Tab. 1 we present all the particles that are related to baryon and dark baryon generation. And we assume a mass hierarchy:

$$m_{N_1} \gg m_{Y_1} > m_{Y_2} > m_\Phi \gg m_{l_R},\ m_{q'_L} \tag{1}$$

Relevant interaction Lagrangian is:

$$\mathcal{L} \supset k_i \overline{Y}_1 \Phi N_i + \lambda_1 \Phi \overline{Y}_1^c Y_2 + \lambda_2 \sum_{l=e,\mu,\tau} \Phi \overline{Y}_2 l_R + \lambda_3 \sum_{l=e,\mu,\tau} \Phi \bar{q'}_L l_R + h.c. \tag{2}$$

with k_i being complex and λ_i being real.

Following is the thermal history of baryon and dark baryon generation

- Out of equilibrium decay of heavy Majorana fermion N_1 generate net number density of Φ^* and Y_1, provided Im$[k_1 k_2^*]^2$ is not zero:

$$n_{\Phi^*} = n_{Y_1} \propto \text{Im}[k_1 k_2^*]^2 \tag{3}$$

- Y_1 decay to Φ^* and $\overline{Y}_2$:

$$n_{\Phi^*} = 2n_{Y_1}\ ,\ n_{\overline{Y}_2} = n_{Y_1} \tag{4}$$

- $\overline{Y}_2$ decay to Φ^* and anti-leptons:

$$n_{\Phi^*} = 3n_{Y_1}\ ,\ n_{B-L} = n_{-L} = n_{Y_1} \tag{5}$$

- Φ^* decay to dark quark q' and anti-leptons. Then rapid Sphaleron process and Yukawa interaction transfer anti-lepton to baryon number[21]:

$$n_D = \frac{1}{3} n_{\Phi^*} = n_{Y_1}\ ,\ n_B = \frac{28}{79} n_{B-L} = \frac{28}{79}(n_{Y_1} + n_{\Phi^*}) = \frac{28}{79}(4n_{Y_1}) \tag{6}$$

Finally we obtain the number density ratio between baryon and dark baryon:

$$\frac{n_D}{n_B} = \frac{79}{112} \tag{7}$$

Then the abundance relationship $\Omega_D : \Omega_B \approx 5 : 1$ can be used to estimate the dark confinement scale:

$$\Lambda_D \approx 5\frac{n_B}{n_D}\Lambda_{QCD} \approx 2 \text{ GeV} \tag{8}$$

2 Signal at lepton collider

By integrating mediator Φ, interaction $\lambda_3 \Phi \bar{q'}_L l_R$ induce a dimension 6 operator which couples lepton pairs to dark quark pair:

$$\frac{\lambda_3^2}{m_\Phi^2}(\bar{q'}_L l_R)(\bar{l}_R q'_L) = \frac{\lambda_3^2}{m_\Phi^2}(\bar{q'}_L \gamma_\mu q'_L)(\bar{l}_R \gamma^\mu l_R) \tag{9}$$

Thus dark quark pair can be produced at lepton collider through this dimension 6 operator. Then the generated energetic dark quarks shower dark partons and finally evolve to 2 jet-like objects, which are composed by dark pion π_D. Dark pion π_D is constructed by $\bar{q'}_L q'_L$, and thus can decay to lepton pairs through the same dimension 6 operator. Decay width and proper lifetime of π_D can be estimated by[22]:

$$\Gamma(\pi_D \to \bar{l}l) = \frac{\lambda_3^4}{32\pi m_\Phi^4} f_{\pi_D}^2 m_l^2 m_{\pi_D} \tag{10}$$

$$c\tau_0 \approx 8cm \times \frac{1}{\lambda_3^4}\left(\frac{2\text{GeV}}{f_{\pi_D}}\right)^2\left(\frac{100\text{MeV}}{m_l}\right)^2\left(\frac{2\text{GeV}}{m_{\pi_D}}\right)\left(\frac{m_\Phi}{1\text{TeV}}\right)^4 \tag{11}$$

Considering GeV scale dark pion mass m_{π_D} and its decay constant f_{π_D}. The mean decay length of π_D is around $\mathcal{O}$(10 cm), provided the mediator mass m_Φ is around TeV scale and λ_3 is around $\mathcal{O}$(1). Besides, the main decay channel of π_D is muon pair. Thus the signal of our ADM model is two bunches of displaced muons. Such a novel signal can be easily detected once produced.

Production cross section of $\bar{q'}_L q'_L$ at electron positron collider with central energy s is about $\mathcal{O}(\lambda_3^4 s^2/m_\Phi^4)$. So for en e-p collider with central energy 250 GeV and integral luminosity 1 ab^{-1}, we can estimate a total event signal number around $\mathcal{O}(10^7)$.

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