Relativistic Freeze-in with Scalar Dark Matter in a Gauged $B-L$ Model and Electroweak Symmetry Breaking .

Priyotosh Bandyopadhyay [1], Manimala Mitra [2,3], Abhishek Roy [2,3].

Indian Institute of Technology Hyderabad, Kandi, Telengana, India.[1]

Institute of Physics, Bhubaneswar , Odisha, India.[2,3]

Introduction

The null-results from a number of dark matter direct detection experiments motivate to explore alternate dark matter production mechanism. In freeze-in mechanism [1], the dark matter is feebly coupled with the Standard Model (SM) particles, in general with particles in equilibrium. The suppressed interaction further gives natural explanation for the non-observation of any direct detection signal.

We explore relativistic freeze-in production of scalar dark matter in gauged $B-L$ model, where we focus on the production of dark matter from the decay and annihilation of Standard Model (SM) and $B-L$ Higgs bosons. We consider the Bose-Einstein (BE) and Fermi-Dirac (FD) statistics, along with the thermal mass correction of the SM Higgs boson in our analysis. We show that in addition to the SM Higgs boson, the annihilation and decay of the $B-L$ scalar can also contribute substantially to the dark matter relic density. Potential effects of electroweak symmetry breaking (EWSB) and thermal mass correction in BE framework enhance the dark matter relic substantially as it freezes-in near EWSB temperature via scalar annihilation. However, such effects are not so prominent when the dark matter freezes-in at a later epoch than EWSB, dominantly by decay of scalars. The results of this analysis are rather generic, and applicable to other similar scenarios.

Model

We consider gauged $B-L$ model that contains one SM gauge singlet complex scalar field $\mathcal{S}$ and three heavy right handed neutrinos (RH-neutrinos) N_i. In this framework, the vacuum expectation value (vev) of the gauge singlet scalar field breaks the $B-L$ symmetry. Additionally, we also consider another SM gauge singlet complex scalar field ϕ_D, which we consider to be the dark matter.

	Φ	N	L	Q	u_R	d_R	e_R	$\mathcal{S}$	ϕ_{DM}
Y_{B-L}	0	−1	−1	1/3	1/3	1/3	1	2	q_{DM}

Table 1: $B-L$ charges for all the fields present in the model

The Yukawa Lagrangian involving $\mathcal{S}$, N_i and ϕ_D fields, and the scalar potential are given by,

$$\mathcal{L}_{\rm BSM} = -\mu_S^2|\mathcal{S}|^2 - \mu_h^2|\Phi|^2 - \mu_D^2|\phi_D|^2 - \lambda_{Sh}|\mathcal{S}|^2|\Phi|^2 - \lambda_{SD}|\phi_D|^2|\mathcal{S}|^2 - \lambda_{Dh}|\phi_D|^2|\Phi|^2$$
$$-\lambda_h|\Phi|^4 - \lambda_S|\mathcal{S}|^4 - \lambda_D|\phi_D|^4 - \left(\sum_{i=1}^{3}\lambda_{NS}\mathcal{S}\bar{N}_i^c N_i + \sum_{i,j=1}^{3} y'_{N,ij}\bar{L}_i\tilde{\Phi}N_j + h.c.\right).$$

Freeze-in Production of Dark Matter

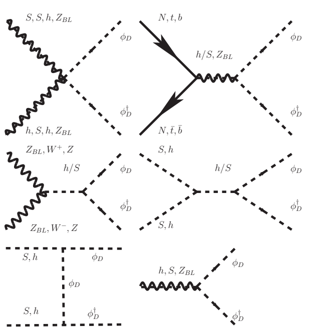
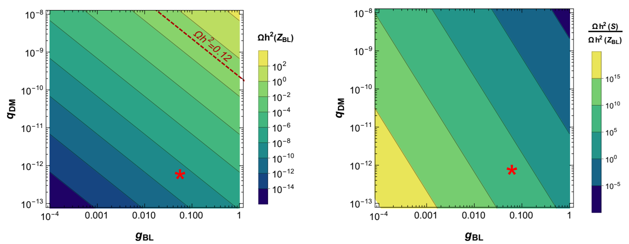


Figure 1: Production channels of dark matter ϕ_D.

When the dark matter is gauged it would quickly thermalise due to potentially larger effective gauge coupling and charge associated with it. In our case such a phenomena can happen as dark matter can be copiously produced in the very early Universe via Z_{BL} decay and/or by the annihilation mediated by Z_{BL} or via contact interaction. The only viable option to maintain the correct dark matter relic is freeze-out [6]. However, to investigate the possibility of relativistic freeze-in scenario which compels us to choose a very small value of q_{DM}. We choose $q_{DM} \approx 10^{-12}$ represented by the red star in Fig 2 where the production of ϕ_D through gauge interaction is negligible and thus we neglect the $B-L$ gauge interaction.



Contours of relic abundance of ϕ_D in the g_{BL} and q_{DM} plane governed by gauge interaction.

Contours of the ratio of relic abundance of ϕ_D from S and Z_{BL} decay.

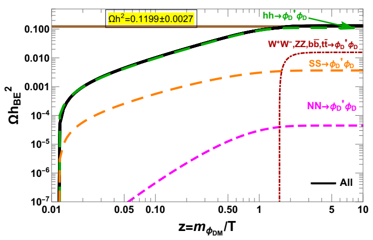
Figure 2: The parameters are as follows, $m_{\phi_{DM}}$=1 GeV, $m_{Z_{BL}}$=5.5 TeV, m_S=200 GeV and $\lambda_{SD} = 10^{-13}$.

Results on dark matter relic abundance

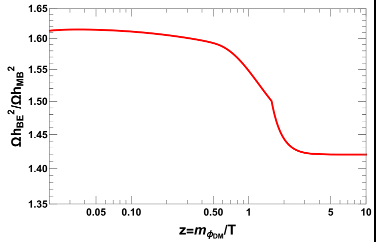
Depending on the primary production mechanism, we sub-divide the entire discussion in different *Cases*, and analyse the production of ϕ_D in detail.

Case-1:- **SM Higgs boson annihilation dominant.**

Case	Masses in GeV			Couplings				
	m_S	m_N	$m_{\phi_{DM}}$	y_N	λ_{SD}	λ_{Sh}	λ_{NS}	λ_{Dh}
1	200	300	250	10^{-7}	5.0×10^{-12}	6×10^{-6}	0.053	1.6×10^{-11}



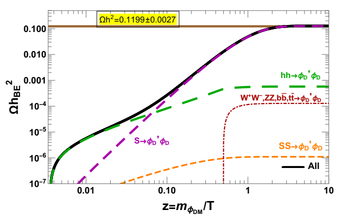
The individual contributions to the relic density, and the total relic density.



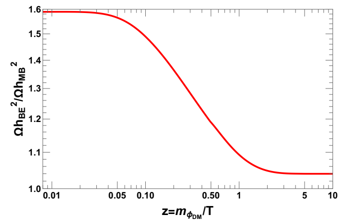
Relative enhancement in the relic density with respect to MB distribution.

Case-2:- **B-L Higgs boson decay dominant.**

Case	Masses in GeV			Couplings				
	m_S	m_N	$m_{\phi_{DM}}$	y_N	λ_{SD}	λ_{Sh}	λ_{NS}	λ_{Dh}
2	200	300	80	10^{-7}	1.28×10^{-13}	6×10^{-6}	0.053	1.414×10^{-12}



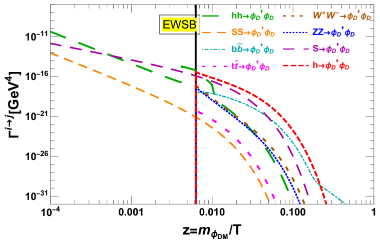
The individual contributions to the relic density, and the total relic density.



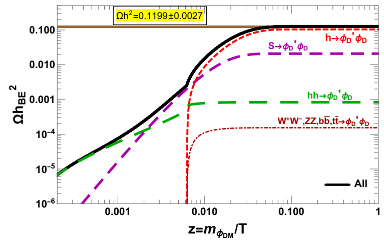
Relative enhancement in the relic density with respect to MB distribution.

Case 3: **SM Higgs boson decay dominant.**

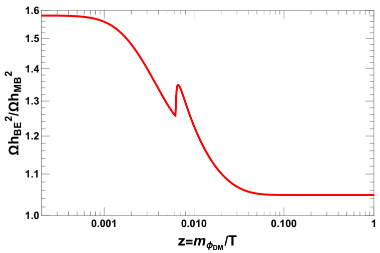
Case	Masses in GeV			Couplings				
	m_S	m_N	$m_{\phi_{DM}}$	y_N	λ_{SD}	λ_{Sh}	λ_{NS}	λ_{Dh}
3	200	300	1	10^{-7}	3.6×10^{-13}	6×10^{-6}	0.053	1.24×10^{-11}



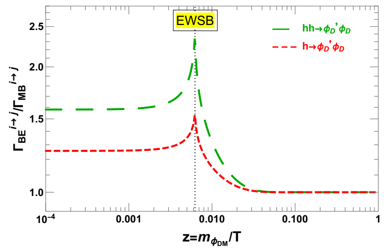
Relativistic reaction rates for the relevant processes.



Individual contributions to the relic density, and the total relic density.



Relative enhancement in the relic density with respect to MB distribution.



Relative enhancement in reaction rates.

The kink appears in the relative enhancement in the relic density is due to the sudden jump in the rates. This is also to note that for the annihilation $hh \to \phi_D^*\phi_D$(via contact) (green line) kink is more pronounced than the decay process $h \to \phi_D^*\phi_D$ (red line) at EWSB.

Conclusion

A comparison between the relic density obtained by using BE statistics, with the one by using MB statistics. We see for the annihilation dominated by SM and $B-L$ Higgs boson dominated, where freeze-in occurs during EWSB, the final ratio of relic density obtained using BE and MB statistics is large, $\mathcal{R} = \frac{\Omega_{\rm BE}h^2}{\Omega_{\rm MB}h^2}$ varies between 1.42-1.62. For the other cases, where the decay of SM and $B-L$ Higgs bosons dominate the relic density and freeze-in occurs at a much later epoch , the enhancement factor is much less $\simeq 1.04$.

We conclude with the observations that quantum statistics, along with the thermal mass correction are essential to capture these enhancement effects in dark matter relic density in freeze-in mechanism, which otherwise would be overlooked.

References

[1] L. J. Hall, K. Jedamzik, J. March-Russell, and S. M. West,Freeze-In Production of FIMP Dark Matter

[2] G. Arcadi, O. Lebedev, S. Pokorski, and T. Toma, Real Scalar Dark Matter:Relativistic Treatment"

[3] Oleg Lebedev et al. In: Phys. Lett. B 798 (2019), p. 134961

[4] Giorgio Arcadi et al. In: :10.1007/JHEP08(2019)050.

[5] Valentina De Romeri et al. In: arXiv e-prints, arXiv: 2003.12606 (2020),

[6] Carlos E. Yaguna. In: 10.1007/JHEP08(2011)060.

[7] P. Bandyopadhyay, M. Mitra, A. Roy.,In: 10.1007/JHEP05(2021)150