A probe into leptophilic scalar dark matter

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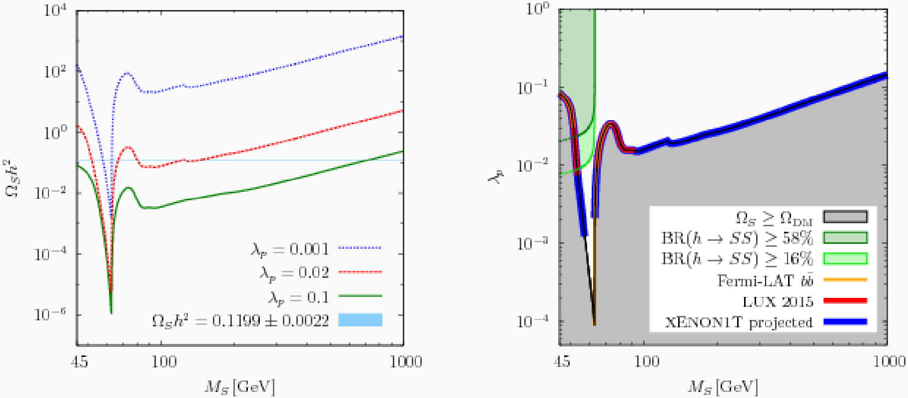
based on

I. *SC and R. Islam*, Phys. Rev. D 101 (2020) 115034, arXiv : 1909.12298

II. *SC and R. Islam*, arXiv : 2007.13719.

Status of scalar singlet dark matter

- Scalar singlet DM is excluded by DD bounds except around $m_{DM} \sim m_h/2$.
- The Higgs portal coupling being very restricted, the search strategy of scalar DM in the colliders are very limited.



JHEP06(2016)152

Extensions of scalar singlet dark matter

extra singlet lepton

- Internal bremsstrahlung
  - Giacchino, Lopez-Honorez and Tytgat, JCAP **10** (2013), 025
  - Toma, Phys. Rev. Lett. **111** (2013), 091301
- Long-lived fermions
  - Khoze, Plascencia and Sakurai, JHEP **06** (2017), 041

extra vectorlike quarks

- Giacchino, Ibarra, Lopez Honorez, Tytgat and Wild, JCAP **02** (2016), 002
- Baek, Ko and Wu, JHEP **10** (2016), 117
- Biondini and Vogl, JHEP **11** (2019), 147

extra scalar

- Wang, Han and Zhu, Phys. Rev. D **98** (2018) no.3, 035024
- Bandyopadhyay, Chun and Mandal, Phys. Lett. B **779** (2018), 201

Case I : *SC and R. Islam*, Phys. Rev. D 101 (2020) 115034

	ℓ_L	e_R	H	Δ	Ψ	ϕ
$SU(2)_L$	**2**	**1**	**2**	**3**	**2**	**1**
$U(1)_Y$	$-1/2$	-1	$1/2$	1	$-1/2$	0
$\mathbb{Z}_2$	$+$	$+$	$+$	$+$	$-$	$-$

$$\Psi = \begin{pmatrix} \psi^0 \\ \psi^- \end{pmatrix}$$

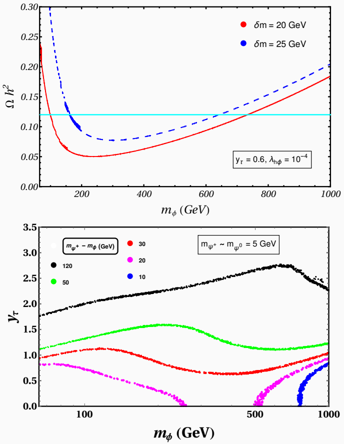
- Interaction Lagrangian

$$\mathcal{L}_{\rm int} = -\frac{\lambda_{h\phi}}{2}(H^\dagger H)\phi^2 - \frac{1}{\sqrt{2}}\left[y_\Delta \bar{\Psi}^c \; i\tau_2 \Delta \Psi + {\rm h.c}\right] - \left[y_j(\bar{\ell}_{jL}\Psi)\phi + {\rm h.c}\right]$$

- The mass splitting between the dark lepton fields in the doublet

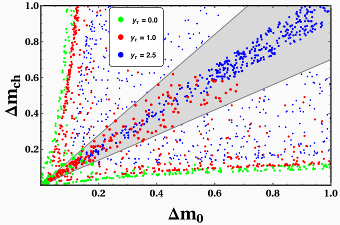
$$\delta = |m_{\psi^0} - m_{\psi^+}| = y_\Delta v_\Delta, \;\; , v_\Delta \rightarrow triplet\;\; vev.$$

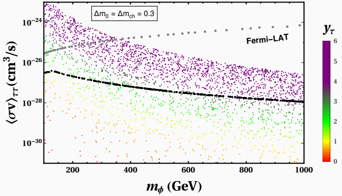
Case I : Transition between regime



- **Pair annihilation** : $\phi\phi \to$ SM SM
- **Coannihilation** : $\phi X \to$ SM SM, $\langle \sigma v \rangle_{\rm eff} \propto e^{-\Delta m}$
- **Mediator annihilation** : $XX \to$ SM SM, $\langle \sigma v \rangle_{\rm eff} \propto e^{-2\Delta m}$ where $X = \psi^{0\pm}$ and $\Delta m = (m_X - m_\phi)/m_\phi$.
- The strength of pair annihilation and coannihilation is controlled by $y_\tau \bar{\ell}_L \Psi \phi$. The mediator annihilation channels are Gauge mediated.
- Depending on y_τ and Δm's, the most efficient number changing process can change from one to another.

Case I : Allowed Parameter space and search strategies





- ρ parameter restricts the triplet vev. So, mass splitting between the components of the lepton doublet becomes restricted. Reduces cross-section for multi-lepton signals in colliders.
- From DM dynamics, one cannot possibly distinguish between the neutral and charged component of the doublet.
- The pair annihilation channel pair produces τ pairs, the flux of which can be detected in indirect search experiments.

Case II : *SC and R. Islam*, arXiv : 2007.13719

	ℓ_L	e_R	H	ξ	Ψ	ϕ
$SU(2)_L$	**2**	**1**	**2**	**1**	**2**	**1**
$U(1)_Y$	$-1/2$	-1	$1/2$	1	$-1/2$	0
$\mathbb{Z}_2$	$+$	$+$	$+$	$-$	$-$	$-$

$$\Psi = \begin{pmatrix} \psi^0 \\ \psi_1^- \end{pmatrix}$$

$$\psi = c_\alpha \psi_1 + s_\alpha \xi$$
$$\chi = -s_\alpha \psi_1 + c_\alpha \xi$$

- Interaction Lagrangian

$$\mathcal{L}_{\rm int} = -\frac{\lambda_{h\phi}}{2}(H^\dagger H)\phi^2 - \left[y_j^D (\bar{\ell}_{jL}\Psi)\phi + y_j^S (\bar{e}_{jR}\xi)\phi + y(\bar{\Psi}H)\xi + \text{h.c}\right]$$

- y and m_{ψ^0} are dependent on other parameters

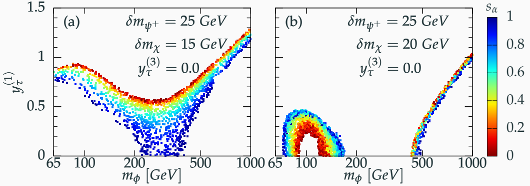
$$y = \frac{(m_\psi - m_\chi)\, s_{2\alpha}}{\sqrt{2}\, v} \qquad m_{\psi^0} = m_\psi\, c_\alpha^2 + m_\chi\, s_\alpha^2$$

- The mass splitting between the dark lepton fields in the doublet is arbitrary

Case I shortcomings addressed by Case II

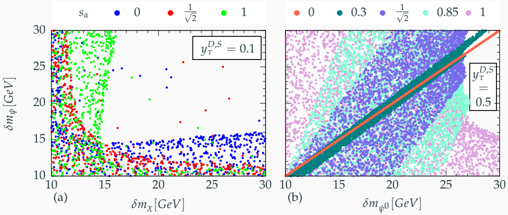
- The mass splitting between the charged and neutral dark leptons was constrained ($\lesssim$ 10 GeV), so in the collider probe, the W boson was highly off shell ($\psi^+ \to \psi^0 W^{+*}$) , giving rise to small multilepton cross-section and signal profile overshadowed the background.
- Some handle is required which could distinguish between the dark leptons of different electric charge.
- These issues are addressed in Case II with the introduction of a charged dark lepton singlet ξ in place of the triplet in Case I. Two DM-SM interaction terms now $y_\tau^{(1)} \bar{\ell}_L \Psi \phi$ and $y_\tau^{(3)} \bar{e}_R \xi \phi$.
- Interaction of charged dark leptons with W boson now plays an important role in the distinction between the neutral and charged leptons.

Case II : Mixing plays key role in dark matter dynamics

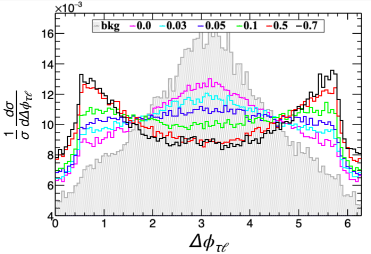


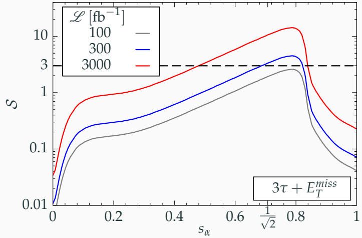
- The mixing angle and the mass splitting between DM and the charged dark leptons (δm's) dictate the dominant annihilation channels.

- Coannihilation is the suitable choice to demonstrate mixing effects : mixed states appear in the initial as well the propagator in the calculation of $\langle \sigma v \rangle$.
- Mixing relaxes the parameter space.



Case II : Mixing plays key role in the search strategies

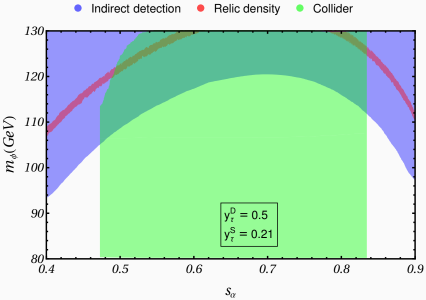


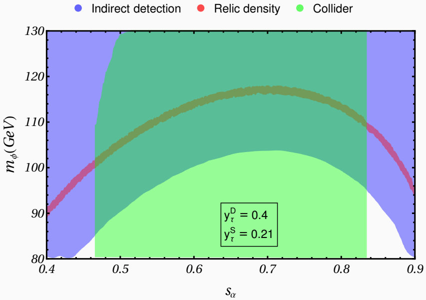


- We studied the mixing effects $3\tau + E_T^{miss}$ and $\ell\,\tau + E_T^{miss}$ channels for LHC at $\sqrt{s} = 13$ TeV.
- The variation with mixing is a contant feature in distributions, independent of other free parameters.
- Mixing dictates the dominant production channel(s).
- Statistical significance is best around the value $s_\alpha = \frac{1}{\sqrt{2}}$.
- $3\tau + E_T^{miss}$ shows better prospect for a collider probe.
- It allows large region of mixing to come under scrutiny.
- Mixing affects ID as a mixed charged lepton is in the propagator of the pair annihilation.
- For low DM mass, a finite mixing relaxes bound on the upper limit of Yukawa coupling.

Case II : Combined parameter region for best detectability

- A combined scan shows that for fixed values of the dark sector masses, it is indeed possible to exclude a portion of parameter space, but this can be tuned with the proper choice of DM-SM couplings.





Summary

- We studied a leptophilic extension of scalar dark matter.
- Direct search bound is at bay due to small Higgs-portal couplings.
- Interaction with the dark leptons relax the parameter space and make way for interesting search strategies.
- Mixing between the dark charged leptons adds an additional feature in the phenomenology. It significantly dictates the dominant channels controlling the relic density, as well as search prospects in indirect detection and colliders.
- Various multi-lepton signatures have a good prospect of detection for future luminosities at LHC.

Thank you!

Backup slides : Possible DM annihilation

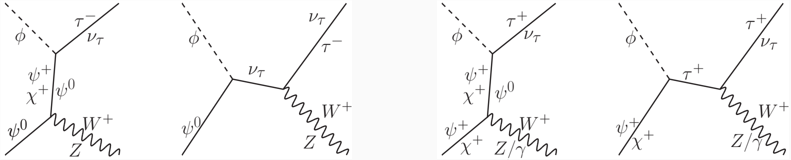


Figure 1: Coannihilation possibilites

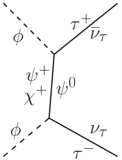


Figure 2: Pair annihilation possibilities

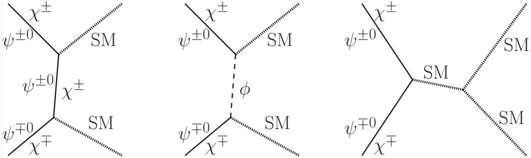
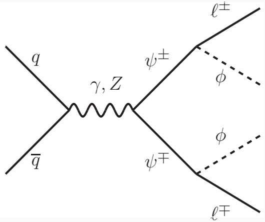
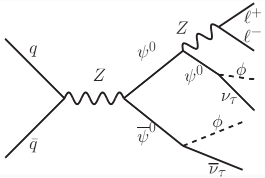


Figure 3: Mediator annihilation possibilities

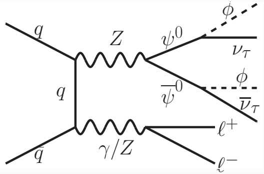
Backup slides : Case I : Collider probe



(a)



(b)



(c)

Figure 4: Feynman diagrams contributing to the dilepton channels.

Backup slides : Case II : Collider probe

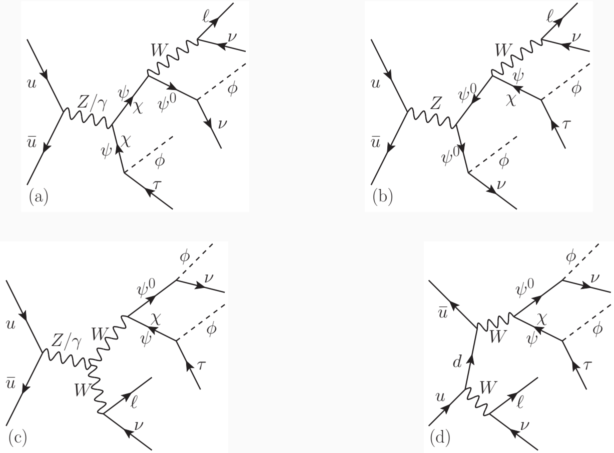


Figure 5: Feynman diagrams contributing to the $\ell\,\tau\,2\nu\,2\phi$ channel at the LHC.

Backup slides : Case II : Mixing affects indirect search prospects

	m_ϕ [GeV]	$m_{\psi^\pm}$ [GeV]	m_χ [GeV]	y_τ^D	y_τ^S	s_α	$\langle \sigma v \rangle_{\tau\tau}$ [cm^3/s]
BP1	100	600	110	2.5	0.0	0.03	8.64×10^{-28}
BP2	105	600	130	2.0	0.0	0.45	6.23×10^{-27}
BP3	125	300	140	1.75	0.03	0.25	1.39×10^{-27}
BP4	150	400	175	2.5	0.0	0.27	5.98×10^{-27}