A probe into leptophilic scalar dark matter

ANOMALIES 2021, November 10

Based on

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

II. *SC and R. Islam*, JHEP 03 (2021) 032

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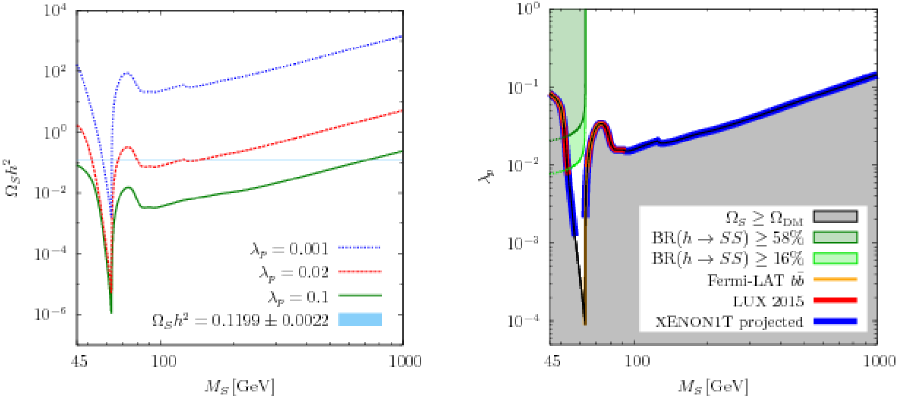
Status of scalar singlet dark matter

- 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.



Duerr, Pérez and Smirnov, JHEP 06 *(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

Leptophilic extension of scalar singlet DM

	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

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

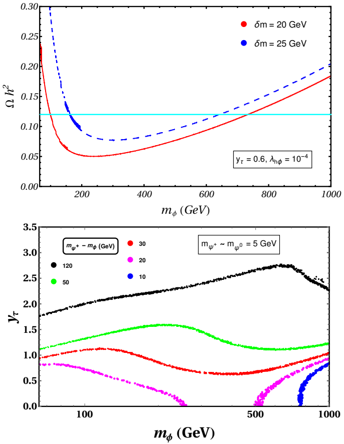
The mass splitting between the dark lepton fields in the doublet

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

- Dark leptonic doublet is introduced to improve the search prospect in colliders. Multilepton final state is not constrained by $(g-2)_{\mu/e}$ measurements here unlike singlet leptonic addition.

SC and R. Islam, Phys. Rev. D 101 (2020) 115034

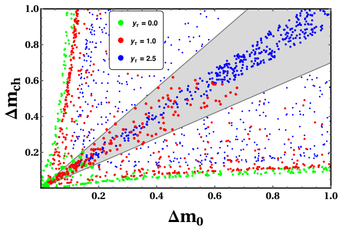
Transition between different regime in dark sector



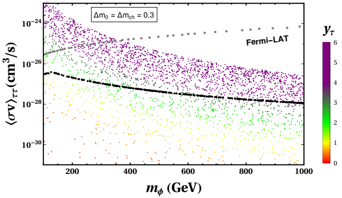
New annihilation channels

- **Pair annihilation** : $\phi\phi \rightarrow$ SM SM with dark leptons in t-channel
- **Coannihilation** : $\phi X \rightarrow$ SM SM, $\langle \sigma v \rangle_{\rm eff} \propto e^{-\Delta m}$
- **Mediator annihilation** : $XX \rightarrow$ 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.

Pros and cons of possible search strategies



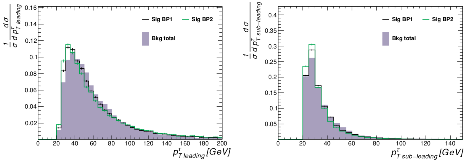
- ρ parameter restricts the triplet vev. So, mass splitting between the components of the lepton doublet becomes too restricted. Off-shell W reduces cross-section for multi-lepton signals in colliders ☹
- From DM dynamics, one cannot possibly distinguish between the neutral and charged component of the doublet ☹

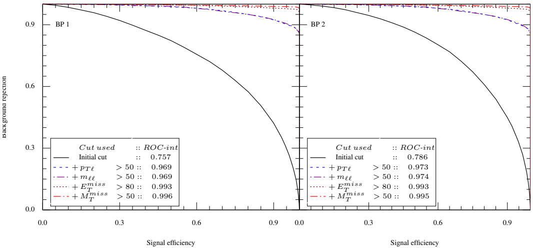


- The pair annihilation channel pair produces τ pairs, the flux of which can be detected in indirect search experiments ☺

Selection parameter	$p_T^{\ell\ (\ j\ )}$	$\lvert\eta_{\ell\ (\ j\ )}\rvert$	ΔR_{ik}
Cut value	10 (20) GeV	5	0.4

- Extra dark leptons introduce new multi-leptonic final states + MET in the colliders. These channels have negligible cross-section for simple scalar singlet DM case, due to feeble Higgs coupling with the light SM leptons.
- Mass splitting between the charged and neutral dark leptons was constrained ($\lesssim$ 10 GeV), whcih makes W boson was highly off-shell ($\psi^+ \to \psi^0 W^{+*}$) : small multilepton cross-section and signal profile overshadowed the background





	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

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

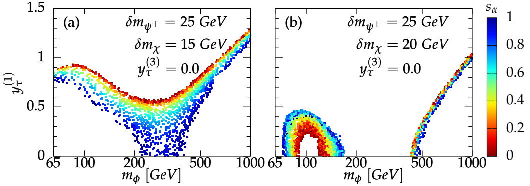
- y and m_{ψ^0} are dependent on other parameters

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

SC and R. Islam, JHEP 03 (2021) 032

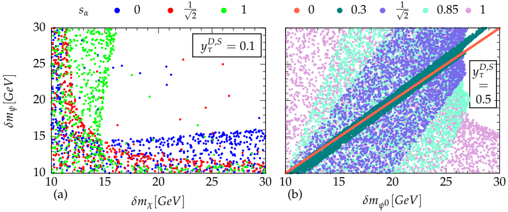
Improvements over previous study : naive guess

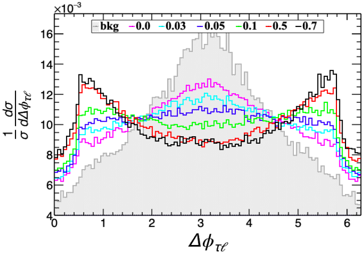
- The mass splitting between the dark lepton fields in the doublet is now arbitrary, so multilepton cross-sections are improved ☺
- Mixing between the same charged dark leptons adds interesting handle in the collider phenomenology and dictates the DM number changing processes ☺
- Interaction of charged dark leptons with W boson now plays an important role in the distinction between the neutral and charged leptons ☺

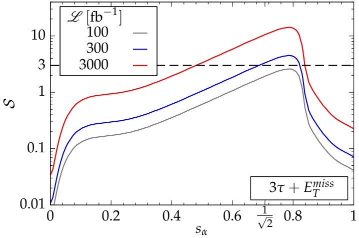


- The mixing angle and the mass splitting between DM and the charged dark leptons (δm's) dictate the dominant annihilation channels.

- 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.







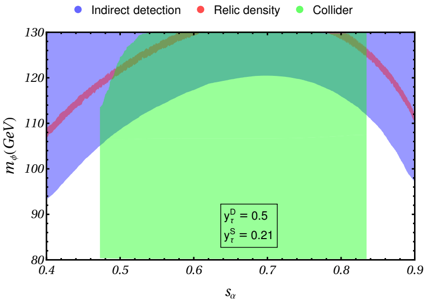
- We studied the mixing effects $3\tau + E_T^{miss}$ and $\ell\tau + E_T^{miss}$ channels for LHC at $\sqrt{s} = 13$ TeV.

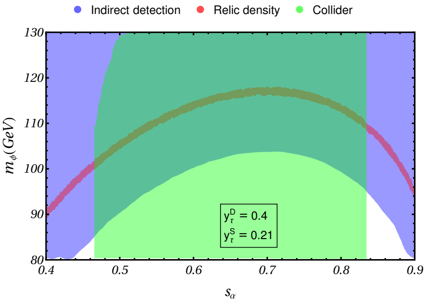
Selection parameter	$p_T^{\ell\,(\,j\,)}$	$\lvert\eta_{\ell\,(\,j\,)}\rvert$	ΔR_{ik}
Cut value	10 (20) GeV	5	0.4

- 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.

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.





Projection at HL-LHC with $\mathcal{L} = 3000\ fb^{-1}$

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.
- Compressed dark sector in coannihilation can be tested with metastable signatures such as *disappearing tracks* or *displaced leptons*
- 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.

Thank you!

Backup slides : Possible DM annihilation

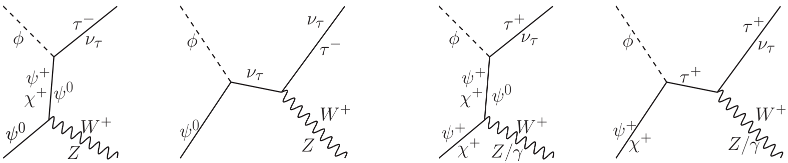


Figure 1: Coannihilation possibilites

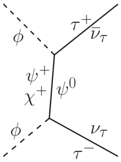


Figure 2: Pair annihilation possibilities

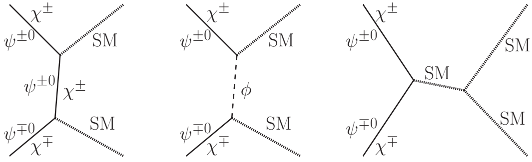
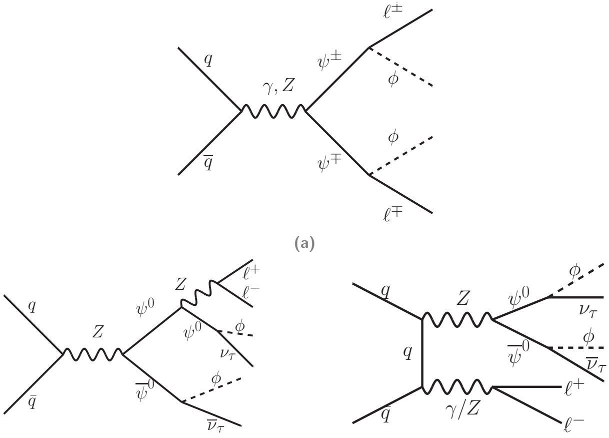


Figure 3: Mediator annihilation possibilities



(a) (b) (c)

Figure 4: Feynman diagrams contributing to the dilepton channels.

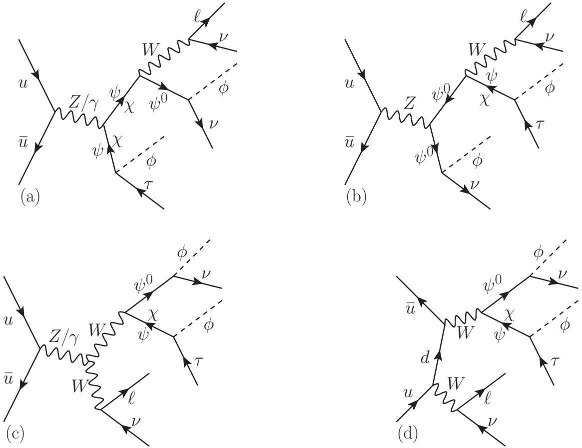


Figure 5: Feynman diagrams contributing to the $\ell\,\tau\,2\nu\,2\phi$ channel at the LHC.

	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}