

Dirac fermion dark matter

with Dirac neutrino masses



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1803

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Focus on

1812.05523 [PRD] and 1905.NNNNN

In collaboration with

Carlos Yaguna (UPTC), Julian Calle, Oscar Zapata, Andrés River (UdeA), Walter Tangarife (Loyola University Chicago)

3 broad classes of DM models:

Simplicity



Effective Field Theories

- We don't know what the higher-scale physics is, but we can integrate it out.

"Simplified Models"

- We introduce a few additional degrees of freedom, but don't try to make statements about the complete theory.

Complete Theories

- We add a full set of new DoF's and expect them to explain everything (e.g. SUSY).



Completeness

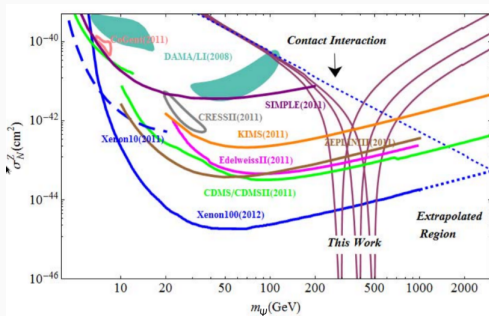
Dirac fermion dark matter

Isosinglet dark matter candidate

ψ as a isosinglet Dirac dark matter fermion charged under a local $U(1)_X$ (SM) couples to a SM-singlet vector mediator X as

$$\mathcal{L}_{\text{int}} = -g_\psi \bar{\psi} \gamma^\mu \psi X_\mu - \sum_f g_f \bar{f} \gamma^\mu f X_\mu,$$

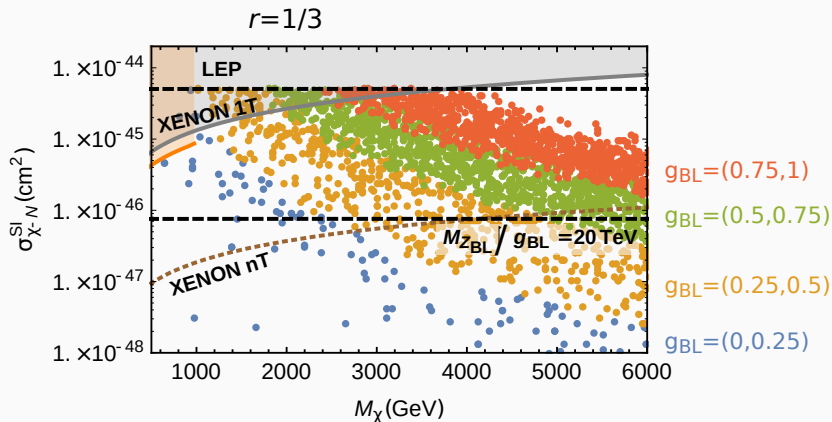
where f are the Standard Model fermions



Isosinglet Dirac fermion dark matter model

Left Field	$U(1)_{B-L}$
$(\nu_{R1})^\dagger$	+1
$(\nu_{R2})^\dagger$	+1
$(\nu_{R2})^\dagger$	+1
ψ_L	$-r$
$(\psi_R)^\dagger$	r
ϕ	2

$$\chi = \begin{pmatrix} \psi_L \\ \psi_R \end{pmatrix}$$



Duerr et al: 1803.07462 [PRD]

Singlet-Doublet Dirac Dark matter Model (SD³M)

The model extends the standard model (SM) particle content with Dirac Fermions: from SU(2) doublets of Weyl fermions: $\Psi_L = (\Psi_L^0, \Psi_L^-)^T$, $\widetilde{(\Psi_R)} = ((\Psi_R^-)^\dagger, -(\Psi_R^0)^\dagger)^T$ and singlet Weyl fermions ψ_{LR} that interact among themselves and with the SM fields

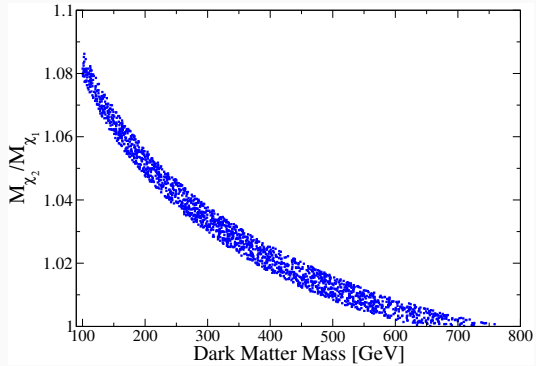
$$\mathcal{L} \supset \textcolor{red}{M}_\psi (\psi_R)^\dagger \psi_L + \textcolor{red}{M}_\Psi \widetilde{(\Psi_R)} \cdot \Psi_L + \textcolor{red}{y}_1 (\psi_R)^\dagger \Psi_L \cdot H + \textcolor{red}{y}_2 \widetilde{(\Psi_R)} \cdot \tilde{H} \psi_L + \text{h.c} \quad (1)$$

Four free parameters:

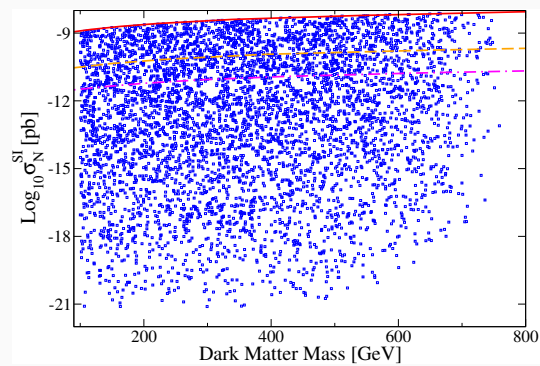
$$\textcolor{red}{M}_\psi, \textcolor{red}{M}_\Psi < 2 \text{ GeV}, \quad \textcolor{red}{y}_1, \textcolor{red}{y}_2 > 10^{-6} \quad (2)$$

Two neutral Dirac fermion eigenstates:

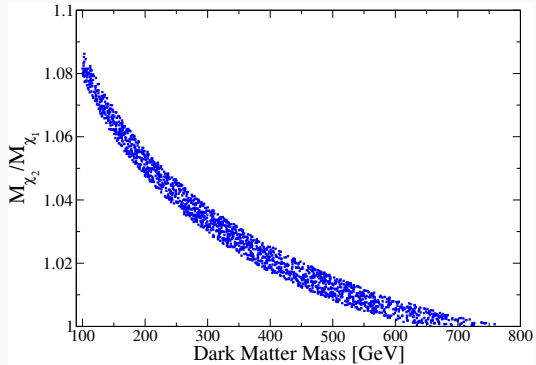
$$M = \begin{pmatrix} \textcolor{red}{M}_\psi & \textcolor{red}{y}_2 v / \sqrt{2} \\ \textcolor{red}{y}_1 v / \sqrt{2} & \textcolor{red}{M}_D \end{pmatrix}, \quad M_{\text{diag}} = \begin{pmatrix} M_{\chi_1} & 0 \\ 0 & M_{\chi_2} \end{pmatrix} = U_L^\dagger M U_R \quad (3)$$



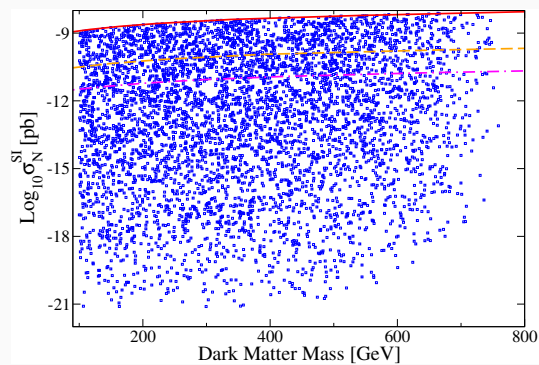
Compressed spectra region



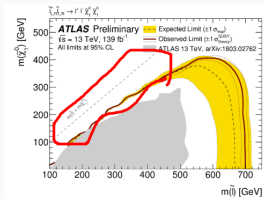
LUX - XENON1T - LZ



Compressed spectra region

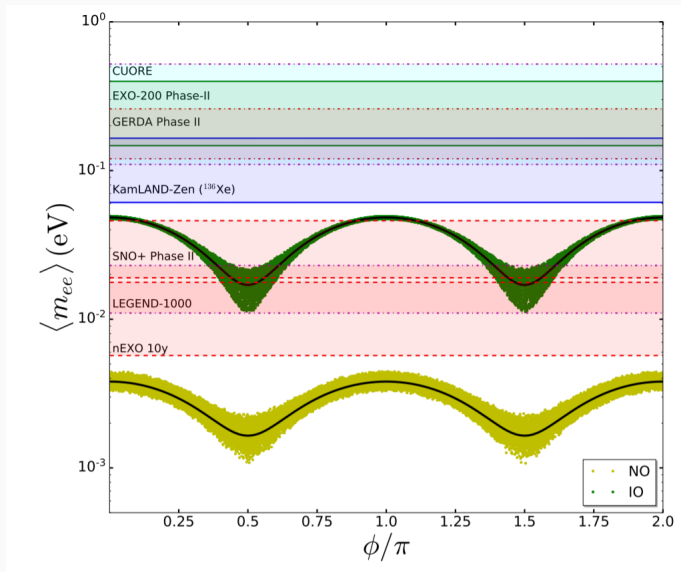


LUX - XENON1T - LZ



Neutrino masses

- Lepton number (L) is an accidental discrete or Abelian symmetry of the standard model (SM).
- Without neutrino masses L_e , L_μ , L_τ are also conserved.
- The processes which violate individual L are called Lepton flavor violation (LFV) processes.
- All the neutrino mass models predict, to some extent, LFV processes
- Only models with Majorana neutrinos predict processes with total $L = L_e + L_\mu + L_\tau$ violation, like **neutrino less doublet beta decay** (NLDBD).
- NLDBD is experimentally challenging, specially if there is a massless neutrino in the spectrum.



Total lepton number: $L = L_e + L_\mu + L_\tau$

Majorana $\cancel{U(1)}_L$

Field	$Z_2 \ (\omega^2 = 1)$
SM	1
L	ω
$(e_R)^\dagger$	ω
$(\nu_R)^\dagger$	ω

$$\mathcal{L}_\nu = h_D (\nu_R)^\dagger L \cdot H + \textcolor{red}{M_R} \nu_R \nu_R + \text{h.c.}$$

$$h_D \sim \mathcal{O}(1)$$

Dirac $U(1)_L$

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SM	1
L	ω
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SM	1
L	ω
$(e_R)^\dagger$	ω^2
$(\nu_R)^\dagger$	ω^2

$$\mathcal{L}_\nu = h_D (\nu_R)^\dagger L \cdot H + \text{h.c.}$$

$$h_D \sim \mathcal{O}(10^{-11})$$

Explain smallness ala Peccei-Quinn:

$$U(1)_{B-L} \xrightarrow{\langle S \rangle} Z_N, \quad N \geq 3.$$

Small Dirac neutrino masses

To explain the **smallness** of Dirac neutrino masses choose $U(1)_{B-L}$ which:

- Forbids tree-level mass (TL) term ($Y(H) = +1/2$)

$$\begin{aligned}\mathcal{L}_{\text{T.L}} &= h_D \epsilon_{ab} (\nu_R)^\dagger L^a H^b + \text{h.c.} \\ &= h_D (\nu_R)^\dagger L \cdot H + \text{h.c.}\end{aligned}$$

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- Realizes of the 5-dimension operator which conserves lepton number in $SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$:

$$\mathcal{L}_{5-D} = \frac{h_\nu}{\Lambda} (\nu_R)^\dagger L \cdot H \textcolor{red}{S} + \text{h.c}$$

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See E. Ma, Rahul Srivastava: arXiv:1411.5042 [PLB] for tree-level realization

One-loop realization of \mathcal{L}_{5-D} with
total L

Dirac neutrino masses

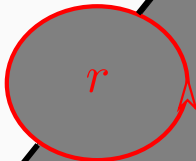
$U(1)_X$
+

Dirac fermion dark matter



L

ν_R



Dirac neutrino masses

$$\nu_R \nu_R$$

$$(\nu_R)^\dagger L H$$

$$\nu_R \psi_R$$

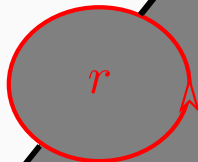
$$(\psi_L)^\dagger \nu_R$$

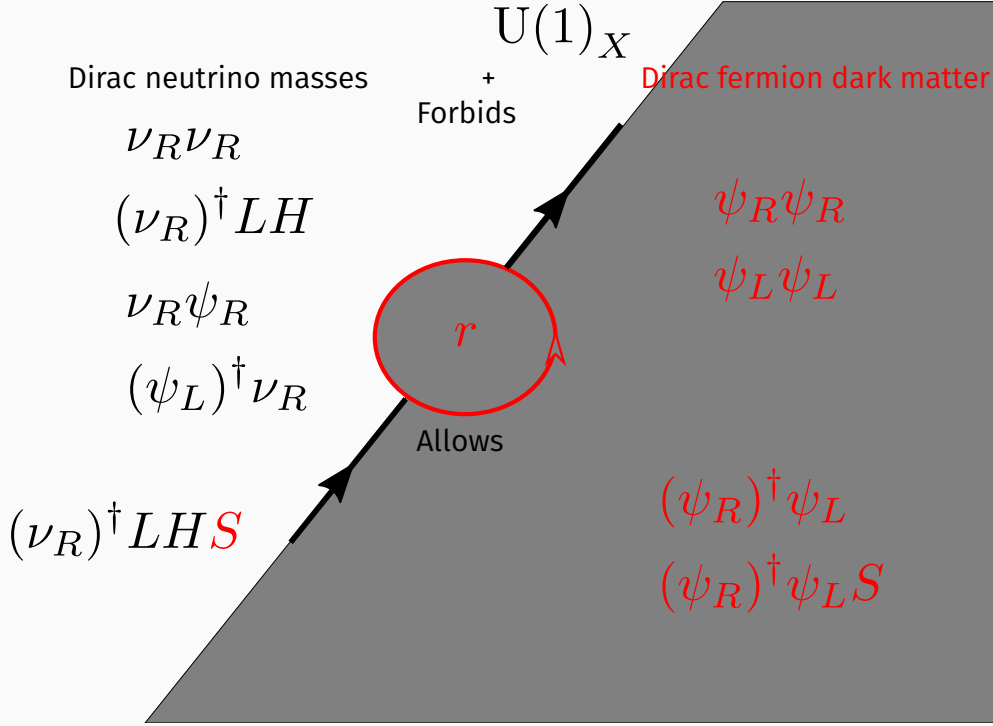
$U(1)_X$
+
Forbids

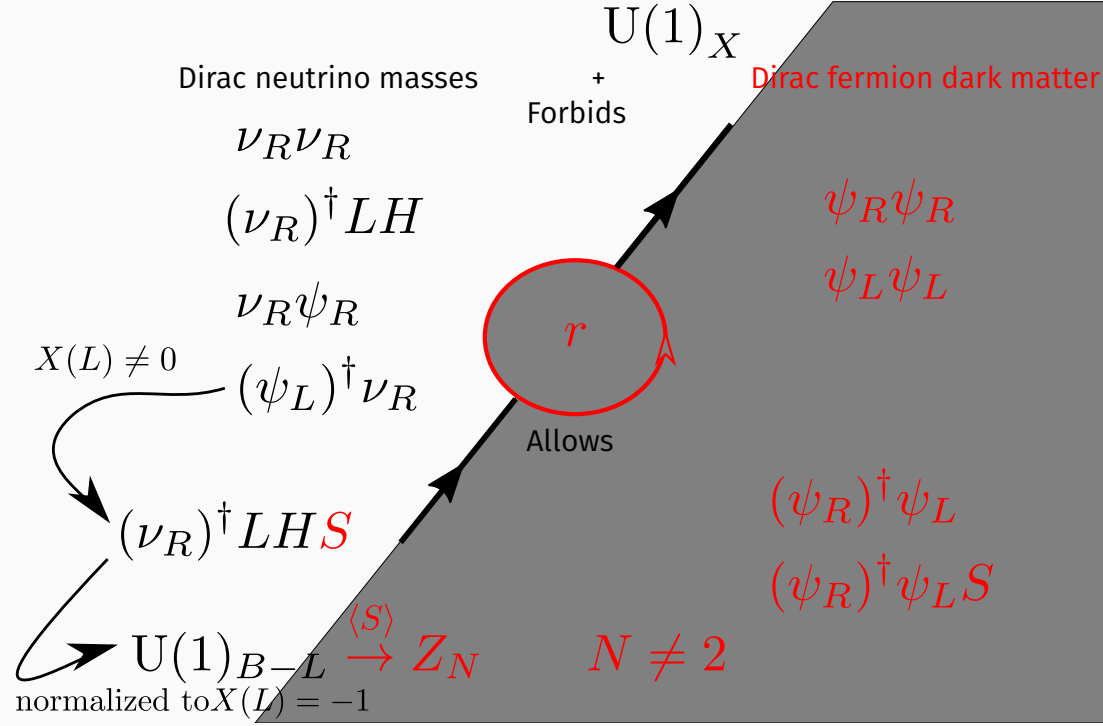
Dirac fermion dark matter

$$\psi_R \psi_R$$

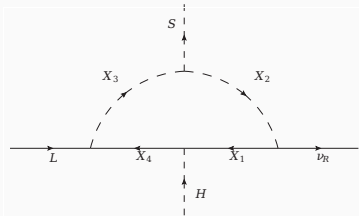
$$\psi_L \psi_L$$



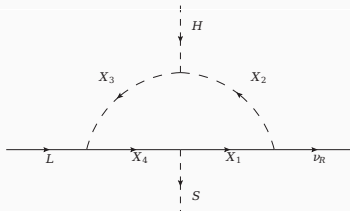




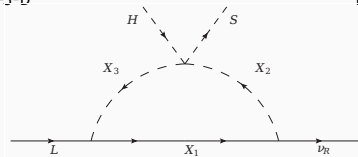
One loop topologies $U(1)_{B-L} \oplus Z_2 \oplus Z_2$



T1-3-D

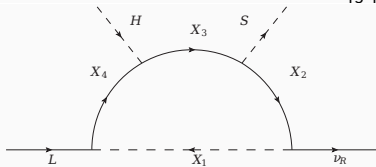


T1-3-E

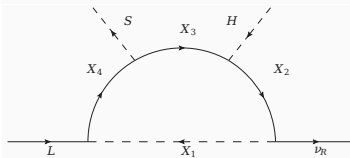


T3-1-A

Chang-Yuan Yao and Gui-Jun Ding, arXiv:1802.05231 [PRD]

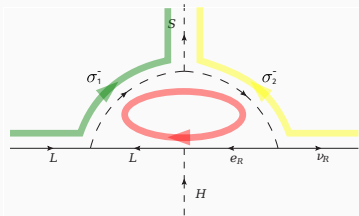


T1-2-A

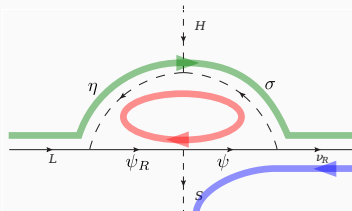


T1-2-B

One loop topologies $U(1)_{B-L}$ only!

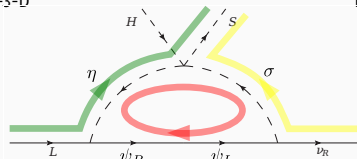


T1-3-D



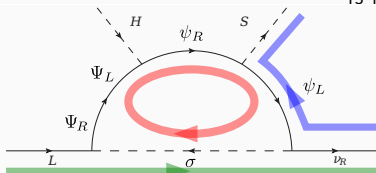
T1-3-E

$\psi_{L,R} \rightarrow$ Singlet fermions
 $\Psi_{L,R} \rightarrow$ Doublet fermions
 $\sigma \rightarrow$ Singlet scalar
 $\eta \rightarrow$ Doublet scalar

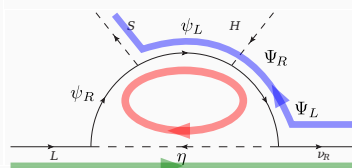


T3-1-A

with J. Calle, C. Yaguna, and O. Zapata, arXiv:1812.05523 [PRD]

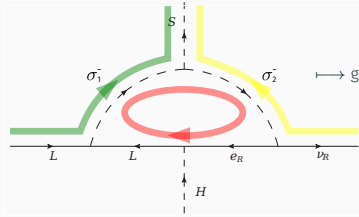


T1-2-A



T1-2-B

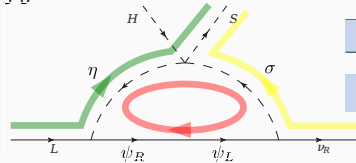
One loop topologies $U(1)_{B-L}$ only!



→ generalization to two and three loops: Shaikh Saad arXiv:1902.07259

T1-3-D

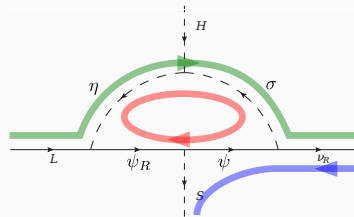
- $\psi_{L,R} \rightarrow$ Singlet fermions
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T3-1-A

Fields	$(\nu_{Ri})^\dagger$	$(\nu_{Rj})^\dagger$	$(\nu_{Rk})^\dagger$	ψ_L	$(\psi_R)^\dagger$	S
(A)	+4	+4	-5	-r	r	+3

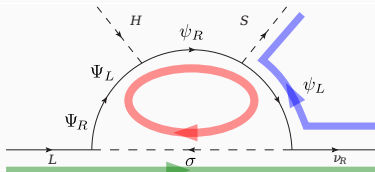
One loop topologies $U(1)_{B-L}$ only!



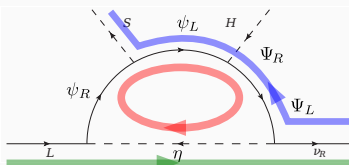
T1-3-E

Fields	$(\nu_{Ri})^\dagger$	$(\nu_{Rj})^\dagger$	$(\nu_{Rk})^\dagger$	ψ_L	$(\psi_R)^\dagger$	S
(A)	+4	+4	-5	-r	r	+3
(B)	$+\frac{8}{5}$	$+\frac{8}{5}$	$+\frac{2}{5}$	$\frac{7}{5}$	$-\frac{10}{5}$	$+\frac{3}{5}$

- $\psi_{L,R} \rightarrow$ Singlet fermions
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T1-2-A

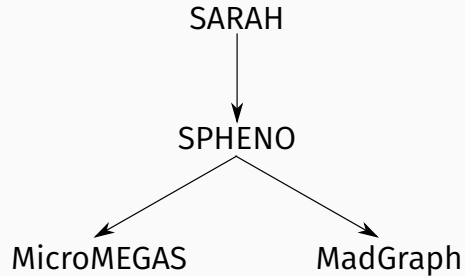
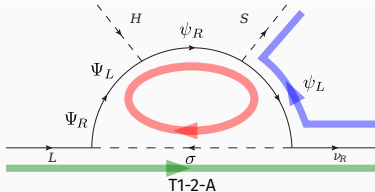


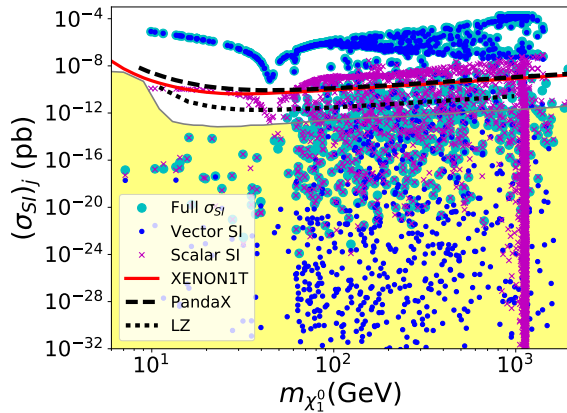
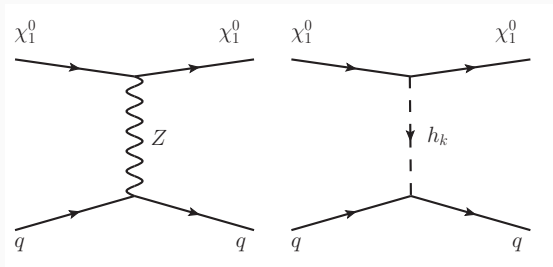
T1-2-B

$$M_\psi = h_1 \langle S \rangle, y_2 = 0:$$

$$\mathcal{L} = \mathcal{L}_{\text{SD}^3\text{M}} + h_3^{ia} \widetilde{(\Psi_R)} \cdot L_i \sigma_a + h_2^{\beta a} (\nu_{R\beta})^\dagger \psi_L \sigma_a^* - V(\sigma_a, S, H).$$

with A.F Rivera, W. Tangarife, arXiv:1905.NNNNN





Vector SI (blue points) and scalar SI (green points)

A single $U(1)$ symmetry to explain both the smallness of Dirac neutrino masses and the stability of Dirac fermion dark matter

A single $U(1)$ symmetry to explain both the smallness of Dirac neutrino masses and the stability of Dirac fermion dark matter

Dirac neutrino masses and DM

- Spontaneously broken $U(1)_{B-L}$ generates a radiative Dirac neutrino masses
- A remnant symmetry makes the lightest field circulating the loop stable and good dark matter candidate.
- For T1-2-A: Either Singlet Doublet Dirac Dark Matter or Singlet Scalar Dark Matter with extra scalar and vector portal
- With relaxed direct detection constraints

Thanks!