Constraining low scale dark hypercharge symmetry at spallation, reactor and dark matter direct detection experiments .

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NEUTRINO PHYSICS VẬT LÝ NEUTRINOS

Hemant Kumar Prajapati

(In collaboration with A. Majumdar, D. K. Papoulias and R. Srivastava)

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Introduction

The Standard Model (SM) has proven to be an extremely successful theory as it effectively accounts for the fundamental forces between particles up to the energy scales examined in recent research.
However, there are sufficient reasons to believe that The SM is not the final theory and it is just an effective theory in the low energy regime.

- Evidence for the existence of Dark Matter.
- Matter–antimatter asymmetry.
- Experimental evidense of Neutrino oscillation.
- Hierarchy problem.
- Muon's anomalous magnetic dipole moment.
- Strong CP problem.

New gauged symmetries beyond the SM (BSM) are motivated by these desire to explain observations that go beyond the SM.

- The simplest and highly motivated one is an extra $U(1)_X$ gauge symmetry. New $U(1)$ symmetry is highly inspired by Grand unified theories (GUT).
- Some symmetries higly explored in literatures are $B-L$, $L_\mu - L_\tau$, $B-3L_\mu$, $B-3L_\tau$, etc. [arXiv: 2202.11002]

Gauge Anomalies

- An anomaly is a symmetry of the classical theory which does not survive to the quantum theory.
- Gauge symmetry plays a crucial role in establishing unitarity and renormalizability in gauge theories. An anomaly in the gauge symmetry would have severe consequences, leading to what is termed a gauge anomaly.

$$
\begin{aligned}
[SU(3)_C]^2 U(1)_Y &= \sum_q Y_{q_\mathrm{L}} - \sum_q Y_{q_\mathrm{R}} \\
[SU(2)_L]^2 U(1)_Y &= \sum_l Y_{l_\mathrm{L}} + 3\sum_q Y_{q_\mathrm{L}} \\
[U(1)_Y]^3 &= \sum_{l,q} (Y^3_{l_\mathrm{L}} + 3Y^3_{q_\mathrm{L}}) - \sum_{l,q} (Y^3_{l_\mathrm{R}} + 3Y^3_{q_\mathrm{R}}) \\
[G]^2 U(1)_Y &= \sum_{l,q} (Y_{l_\mathrm{L}} + 3Y_{q_\mathrm{L}}) - \sum_{l,q} (Y_{l_\mathrm{R}} + 3Y_{q_\mathrm{R}})
\end{aligned}
\tag{1}
$$

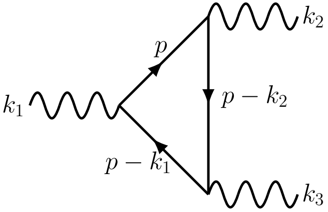

Figure: A triangle diagram.

The uniqueness of SM Hypercharge.

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- Hypercharges of all the SM fermions adds up in way to cancel these anomalies. However, these anomaly cancellation conditions solely does not fix the SM hypercharge uniquely.

Let us first consider only one generation of SM fermions:

- $Y_L = Y_Q = Y_{e_R} = Y_{u_R} + Y_{d_R} = 0.$
- The second solution is the standard SM chiral hypercharge assignment.

Q	u_R	d_R	L	e_R	Φ
$\frac{-Y}{3}$	$\frac{-4Y}{3}$	$\frac{2Y}{3}$	Y	$2Y$	$-Y$

- One more solution can be found by interchanging the hypercharges of u_R and d_R i.e. $Y_{u_R} = \frac{2Y}{3}$ and $Y_{d_R} = \frac{-4Y}{3}$.

Only standard solutions leads to correct electric charges of all fermions

- Another way to fix hypercharges uniquely : Mass generation mechanism.

$$-\mathscr{L}_Y = Y_e\overline{L}\varphi e_R + Y_u\overline{Q}\tilde{\varphi}u_R + Y_d\overline{Q}\varphi d_R + \text{h.c.}\,. \quad (2)$$

- $$Y_{u_{\rm R}} = Y_Q + Y_L - Y_{e_{\rm R}}\,, \text{ and } Y_{d_{\rm R}} = Y_Q - Y_L + Y_{e_{\rm R}}\,. \quad (3)$$

Three generations of SM fermions :

$$Y_{Q^i} = -Y_{Q^j} = Y,\ \ Y_{Q^k} = 0; \quad i,j,k = 1,2,3 \ \& \ i \neq j \neq k$$
$$Y_{u^l_{\rm R}} = -Y_{u^m_{\rm R}} = Y',\ \ Y_{u^n_{\rm R}} = 0; \quad l,m,n = 1,2,3 \ \& \ l \neq m \neq n$$
$$Y_{d^r_{\rm R}} = -Y_{d^s_{\rm R}} = Y'',\ \ Y_{d^t_{\rm R}} = 0; \quad r,s,t = 1,2,3 \ \& \ r \neq s \neq t$$
$$Y_{L^i} = Y_{l^j} = 0; \quad i,j = 1,2,3 \ \forall\, i,j.$$

$$Y_{L^i} = -Y_{L^j} = Y, Y_{L^k} = 0; \quad i,j,k = 1,2,3 \ \& \ i \neq j \neq k$$
$$Y_{e^l_{\rm R}} = -Y_{e^m_{\rm R}} = Y',\ \ Y_{e^n_{\rm R}} = 0; \quad l,m,n = 1,2,3 \ \& \ l \neq m \neq n$$
$$Y_{Q^i} = Y_{q^j} = 0; \quad i,j = 1,2,3 \ \forall\, i,j.$$

- Some solutions lead to correct mass generation (but not mixing) for the fermions. But no solution lead to correct electric charge.
- The standard SM hypercharge assignment remains unique even with three generations of SM

$U(1)_X$ anomaly cancellation

$$[SU(3)_C]^2[U(1)_X] = \sum_q X_{q_\mathrm{L}} - \sum_q X_{q_\mathrm{R}} \tag{4}$$

$$[SU(2)_\mathrm{L}]^2[U(1)_X] = \sum_l X_{l_\mathrm{L}} + 3\sum_q X_{q_\mathrm{L}} \tag{5}$$

$$[U(1)_Y]^2[U(1)_X] = \sum_{l,q}(Y_{l_\mathrm{L}}^2 X_{l_\mathrm{L}} + 3Y_{q_\mathrm{L}}^2 X_{q_\mathrm{L}}) - \sum_{l,q}(Y_{l_\mathrm{R}}^2 X_{l_\mathrm{R}} + 3Y_{q_\mathrm{R}}^2 X_{q_\mathrm{R}}) \tag{6}$$

$$[U(1)_Y][U(1)_X]^2 = \sum_{l,q}(Y_{l_\mathrm{L}} X_{l_\mathrm{L}}^2 + 3Y_{q_\mathrm{L}} X_{q_\mathrm{L}}^2) - \sum_{l,q}(Y_{l_\mathrm{R}} X_{l_\mathrm{R}}^2 + 3Y_{q_\mathrm{R}} X_{q_\mathrm{R}}^2) \tag{7}$$

$$[U(1)_X]^3 = \sum_{l,q}(X_{l_\mathrm{L}}^3 + 3X_{q_\mathrm{L}}^3) - \sum_{l,q}(X_{l_\mathrm{R}}^3 + 3X_{q_\mathrm{R}}^3) \tag{8}$$

$$[G]^2[U(1)_X] = \sum_{l,q}(X_{l_\mathrm{L}} + 3X_{q_\mathrm{L}}) - \sum_{l,q}(X_{l_\mathrm{R}} + 3X_{q_\mathrm{R}}) \tag{9}$$

- **Vector Solutions :** In the BSM scenarios, while gauging new $U(1)_X$ symmetries, vector charges are typically assigned to the SM particles. This is done to ensure the invariance of the Yukawa structure.
- $B-L$, $B-3L_\tau$, $L_\mu - L_\tau$ etc.
- **Chiral Solutions :** Chiral solutions are those in which SM fermions behave non-trivially under $U(1)_X$, meaning that SM fermions are chiral under this symmetry.
- In this study, we explored these chiral solutions. We will show that the induced gauge anomalies can be cancelled by adding right-handed dark fermions (DFs).

Dark Hypercharge Symmetry

We have obtained class of solutions of under three different scenarios :

- **S(I) :** Only one generation of SM fermions is charged under $U(1)_X$ $(X_{\psi^i} = X_{\psi^j} = 0, X_{\psi^k} = X, \quad i, j, k = 1, 2, 3 \;\&\; i, j \neq k)$.
- **S(II) :** Two generations share the same charge under $U(1)_X$, while one generation remains uncharged $(X_{\psi^i} = X_{\psi^j},\ X_{\psi^k} = 0, \quad i, j, k = 1, 2, 3 \;\&\; i, j \neq k)$.
- **S(III) :** All three generations of SM fermions are charged under the new symmetry, and their charges are identical across generations $(X_{\psi^i} = X_{\psi^j} = X_{\psi^k}, \quad i, j, k = 1, 2, 3)$.

In addition we demand that the masses of SM fermions are generated through the SM Higgs boson itself. No BSM scalar needed for SM fermion mass generation

$$X_\Phi = X_L - X_{e_R} = X_Q - X_{d_R} = X_{u_R} - X_Q. \tag{10}$$

- **For one generation (S(I)) case we get only one solution:**

Q	u_{R}	d_{R}	L	e_{R}	f_1	f_2	f_3	Φ
$\frac{-X_L}{3}$	$\frac{2X_L}{3} - X_{e_{\mathrm{R}}}$	$\frac{-4X_L}{3} + X_{e_{\mathrm{R}}}$	X_L	$X_{e_{\mathrm{R}}}$	k	$-k$	$2X_L - X_{e_{\mathrm{R}}}$	$X_L - X_{e_{\mathrm{R}}}$

- **For two generation (S(II)) case we get following solutions :**

Q	u_{R}	d_{R}	L	e_{R}	f_1	f_2	f_3	Φ
$\frac{-X_L}{3}$	$\frac{-4X_L}{3}$	$\frac{2X_L}{3}$	X_L	$2X_L$	0	k	$-k$	$-X_L$
$\frac{-X_L}{3}$	$\frac{2X_L}{3} - X_{e_{\mathrm{R}}}$	$\frac{-4X_L}{3} + X_{e_{\mathrm{R}}}$	X_L	$X_{e_{\mathrm{R}}}$	0	$2X_L - X_{e_{\mathrm{R}}}$	$2X_L - X_{e_{\mathrm{R}}}$	$X_L - X_{e_{\mathrm{R}}}$

For three generation (S(III)) case we get following solutions :

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Q	u_R	d_R	L	e_R	f_1	f_2	f_3	Φ
$\frac{-X_L}{3}$	$\frac{-4X_L}{3}$	$\frac{2X_L}{3}$	X_L	$2X_L$	0	κ	$-\kappa$	$-X_L$
$-\frac{X_L}{3}$	$-\frac{4X_L}{3}+\kappa$	$\frac{2X_L}{3}-\kappa$	X_L	$2X_L-\kappa$	κ	κ	κ	$\kappa-X_L$
$\frac{1}{s}$	$-(\kappa-\frac{4}{s})$	$\kappa-\frac{2}{s}$	$-\frac{3}{s}$	$\kappa-\frac{6}{s}$	5κ	-4κ	-4κ	$-(\kappa-\frac{3}{s})$
$-\frac{X_L}{3}$	$\frac{-4X_L}{3}-\frac{s^2-k^2}{8}$	$\frac{2X_L}{3}+\frac{s^2-k^2}{8}$	X_L	$2X_L+\frac{s^2-k^2}{8}$	$\frac{1}{8}(-4s^2+3sk+\frac{k^3}{s})$	$\frac{1}{8}(5s^2+3k^2)$	$-\frac{1}{8}(4s^2+3sk+\frac{k^3}{s})$	$-(X_L+\frac{s^2-k^2}{8})$

- As you can see, $U(1)_X$ charges of all fermions are chiral
- We need three dark sector BSM fermions f_i; $i = 1, 2, 3$ to cancel anomalies
- Mass of all SM fermions can be generated just with the SM Higgs boson
- In all cases all fermions have completely chiral $U(1)_X$ charges
- To make the dark sector gauge boson massive, we need to add another SM singlet scalar
- Masses of dark sector fermions can also be generated by addition of SM gauge singlet scalars

- **Let's now look at the phenomenological aspects of the Dark Hypercharge Symmetry**

Dark Hypercharge Symmetry: Gauge Sector

- The covariant derivative is defined as

$$D_\mu = \partial_\mu + ig_s T_g^a G_\mu^a + ig T_w^a W_\mu^a + ig' \frac{Y}{2} B_\mu + ig_x X C_\mu \,. \tag{11}$$

where

$$\langle \varphi \rangle = \frac{1}{\sqrt{2}} \begin{bmatrix} 0 \\ v \end{bmatrix}, \quad \langle \chi_i \rangle = \frac{v_i}{\sqrt{2}} \,. \tag{12}$$

- The mass spectrum of the gauge bosons are generated by the expansion of the kinetic terms of the scalars, as given below

$$(D_\mu)^\dagger D^\mu + (D_\mu \chi_i)^\dagger D^\mu \chi_i \,, \tag{13}$$

- We can write the mass matrix of the gauge bosons in the basis (B^μ, W_3^μ, C^μ) as

$$\mathcal{M}_V^2 = \frac{v^2}{4} \begin{pmatrix} g'^2 & -gg' & 2g' X_\varphi g_x \\ -gg' & g^2 & -2g X_\varphi g_x \\ 2g' X_\varphi g_x & -2g X_\varphi g_x & 4u^2 g_x^2 \end{pmatrix} \,, \tag{14}$$

where $u^2 = X_\varphi^2 + u_\chi^2/v^2$, and u_χ is defined as $u_\chi = \sqrt{\sum_i (X_{\chi_i}^2 v_i^2)}$.

Gauge Boson Masses and ρ parameter

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$$\begin{bmatrix} A^\rho \\ Z^\rho \\ Z'^\rho \end{bmatrix} = \begin{bmatrix} \cos\theta_W & \sin\theta_W & 0 \\ -\cos\alpha\sin\theta_W & \cos\alpha\cos\theta_W & -\sin\alpha \\ -\sin\alpha\sin\theta_W & \sin\alpha\cos\theta_W & \cos\alpha \end{bmatrix} \begin{bmatrix} B^\rho \\ W_3^\rho \\ C^\rho \end{bmatrix}. \tag{15}$$

Following this, one mass eigenstate becomes zero which is identified as the photon, while the remaining two mass eigenstates read

$$M_{Z'}^2 = \frac{v^2}{8}(A_0 - \sqrt{B_0^2 + C_0^2}), \qquad M_Z^2 = \frac{v^2}{8}(A_0 + \sqrt{B_0^2 + C_0^2}), \tag{16}$$

with A_0, B_0 and C_0 defined as

$$A_0 = g^2 + g'^2 + 4u^2 g_x^2\,, B_0 = \quad 4X_\varphi g_x \sqrt{g^2 + g'^2}\,, C_0 = g^2 + g'^2 - 4u^2 g_x^2\,. \tag{17}$$

The rotation angles are defined as

$$\tan\theta_W = \frac{g'}{g}, \quad \tan 2\alpha = \frac{4X_\varphi g_x \sqrt{g^2 + g'^2}}{|g^2 + g'^2 - 4u^2 g_x^2|} = \frac{2X_\varphi g_x v M_Z^{SM}}{|(M_Z^{SM})^2 - [v^2 X_\varphi^2 + u_\chi^2] g_x^2|}\,, \tag{18}$$

And the W boson mass is given as $M_W^2 = (gv)^2/4$.

- The ratio of gauge boson masses is measured through the parameter
$$\rho' = \frac{\rho}{\cos^2\alpha + \left(\frac{M_{Z'}}{M_Z}\right)^2 \sin^2\alpha} = 1\,.\quad \rho - 1 = \left[\left(\frac{M_{Z'}}{M_Z}\right)^2 - 1\right]\sin^2\alpha.$$

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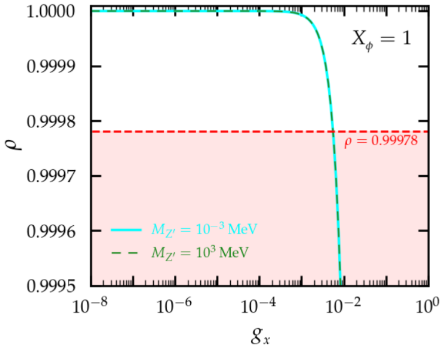
- For the case of $M_{Z'}[g_x, u_\chi] < M_Z[g_x, u_\chi]$. The ρ parameter could be approximated as, $\rho \approx \left(1 + \frac{4X_\varphi^2 g_x^2}{g^2 + g'^2}\right)^{-1}$
- In the low mass limit of $M_{Z'}$, $X_\varphi g_x \lesssim 5.5 \times 10^{-3}$ is adequate to satisfy the ρ parameter, $M_{Z'} \approx u_\chi g_x$, $\alpha \approx 2.67 X_\varphi g_x$.



Constraining Light Z'

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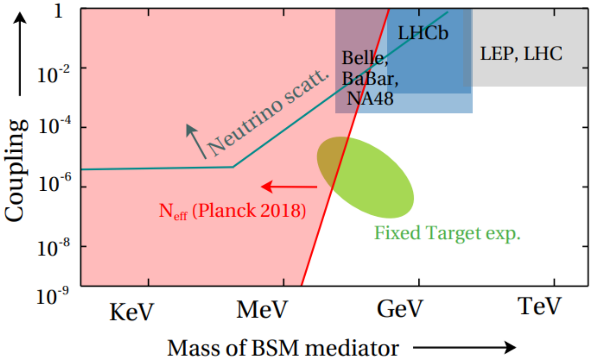
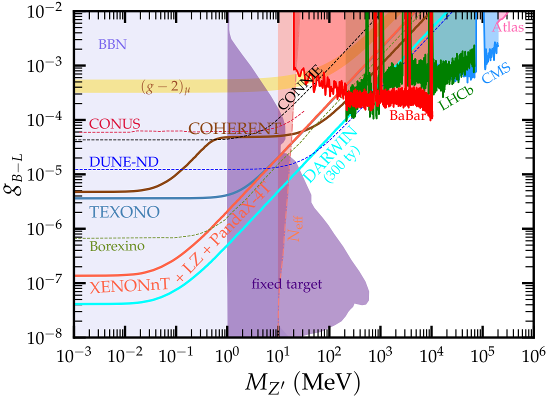
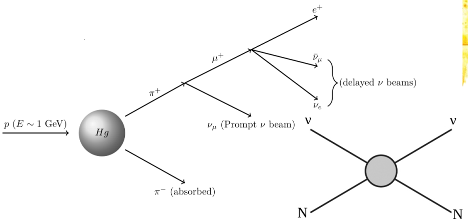
- Light Z' can be constrained from different experiments like Direct Detection Experiments, Fixed target experiments, Supernovae Cooling, N_{eff} etc.

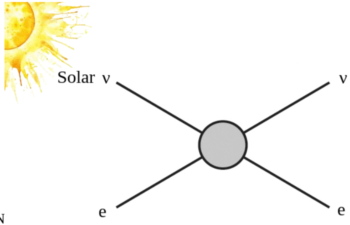


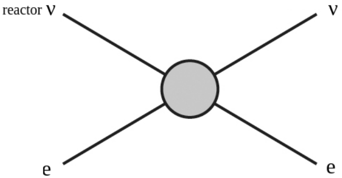
- As an example the parameter space for coupling and mass of the Z' from gauged $B-L$ has been constrained through various experiments[1]



[1] Anirban Majumdar, Dimitrios K. Papoulias, Hemant Prajapati, Rahul Srivastava; Phys.Rev.D 111 (2025) 7, 073006 • e-Print: 2411.04197 [hep-ph]







- **Experiment: COHERENT**
- ν Source: π-DAR, μ-DAR
- Target: LAr (2020 data), CsI (2021 data)
- Relevant Interaction: **CEνNS, EνES**

- **Experiment: XENONnT, LZ, PandaX-4T, and DARWIN** (future sensitivity)
- ν Source: Solar ν_e
- Target: LXe TPC
- Relevant Interaction: **EνES**

- **Experiment: TEXONO**
- ν Source: Reactor $\bar{\nu}_e$
- Target: CsI
- Relevant Interaction: **EνES**

Interactions between fermions and Z'

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$$\mathscr{L}_{\text{int}} \subset -\frac{g}{\cos\theta_W}\overline{\psi}\gamma^{\rho}\left(g^{z}_{\psi_{\mathrm{L}}}\,\mathrm{L} + g^{z}_{\psi_{\mathrm{R}}}\,\mathrm{R}\right)\psi Z_{\rho} - \overline{\psi}\gamma^{\rho}\left(g^{z'}_{\psi_{\mathrm{L}}}\,\mathrm{L} + g^{z'}_{\psi_{\mathrm{R}}}\,\mathrm{R}\right)\psi\, Z'_{\rho}\,, \tag{19}$$

$$g^{z}_{\psi_{\mathrm{L}}} = \left(T^{3}_{\psi_{\mathrm{L}}} - Q_{\psi_{\mathrm{L}}}\sin^{2}\theta_W\right)\cos\alpha - \frac{X_{\psi_{\mathrm{L}}}g_x}{g}\sin\alpha\cos\theta_W\,, \tag{20a}$$

$$g^{z}_{\psi_{\mathrm{R}}} = -Q_{\psi_{\mathrm{R}}}\sin^{2}\theta_W\cos\alpha - \frac{X_{\psi_{\mathrm{R}}}g_x}{g}\sin\alpha\cos\theta_W\,, \tag{20b}$$

(20c)

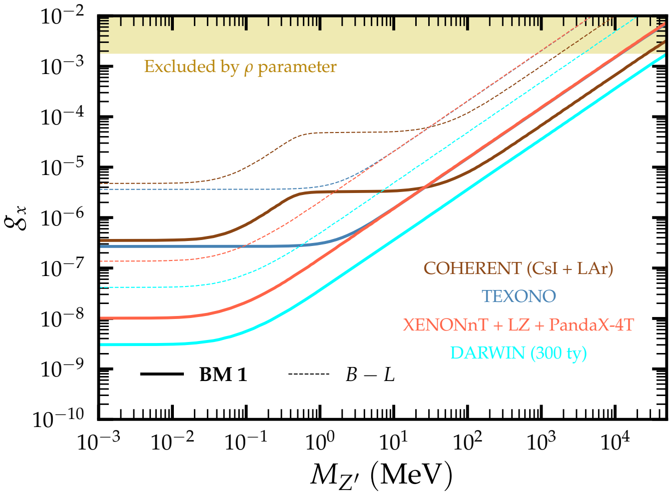
$$g^{z'}_{\psi_{\mathrm{L}}} = \left(gT^{3}_{\psi_{\mathrm{L}}}\cos\theta_W - \frac{g'\,Y_{\psi_{\mathrm{L}}}}{2}\sin\theta_W\right)\sin\alpha + X_{\psi_{\mathrm{L}}}g_x\cos\alpha\,, \tag{20d}$$

$$g^{z'}_{\psi_{\mathrm{R}}} = -\frac{g'\,Y_{\psi_{\mathrm{R}}}}{2}\sin\theta_W\sin\alpha + X_{\psi_{\mathrm{R}}}g_x\cos\alpha\,. \tag{20e}$$

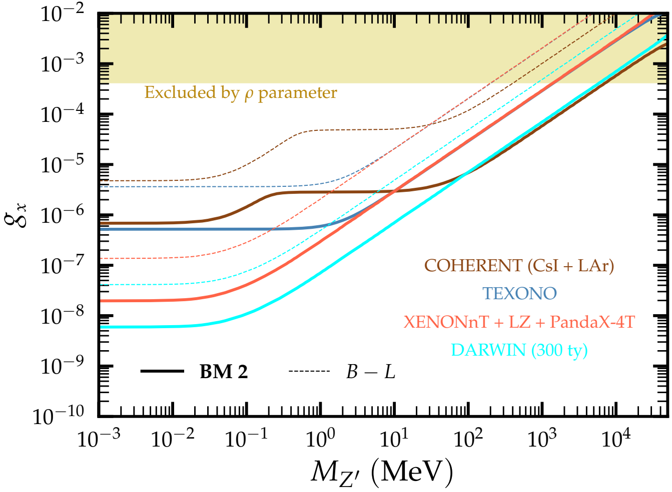
CEνNS and EνES constraints on Z' For Bench Mark Charges

$U(1)_X$ **Models**	Q	u_R	d_R	L	e_R	f^1	f^2	f^3	φ
BM 1	-13/3	-4/3	-22/3	13	10	16	16	16	3
BM 2	-3	10	-16	9	-4	-110	88	88	13
BM 3	-1/3	5/3	-7/3	1	-1	10	-18	17	2
$B-L$	1/3	1/3	1/3	-1	-1	-1	-1	-1	0

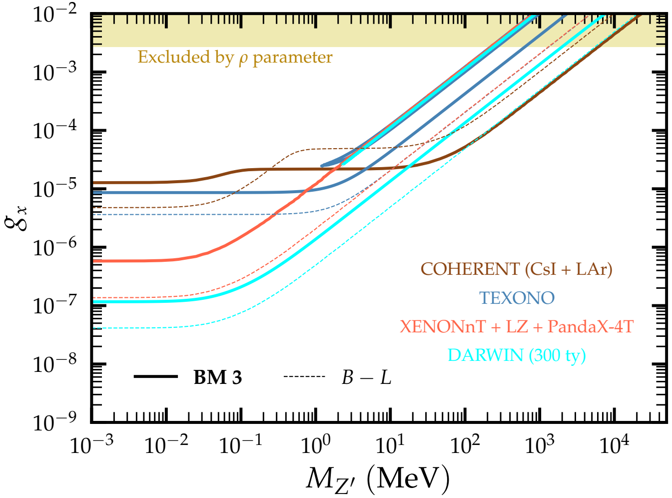
CEνNS and EνES constraints on Z' from BM 1



CEνNS and EνES constraints on Z' from BM 2



CEνNS and EνES constraints on Z' from BM 3



Conclusions

- Extensions of the Standard Model with $U(1)_X$ gauge symmetries are strongly motivated.
- The charges of SM fermions are constrained by anomaly cancellation conditions, making $U(1)_X$ models highly predictive.
- I discussed a new class of models where all SM fermions have chiral charges under the $U(1)_X$ symmetry.
- The anomaly cancellation necessitates need to add three BSM fermions which can be identified as dark fermions with the lightest of them being a good dark matter candidate.
- I also discussed the phenomenological signatures of certain Benchmark Models for light Z' cases.
- The charges of leptons and quarks can differ significantly depending on the specific anomaly cancellation solution. As a result, different models exhibit distinct phenomenological signatures and can be constrained through various experiments.
- We analyze the recent data from the COHERENT experiment, along with results from dark matter (DM) direct detection experiments such as XENONnT, LUX-ZEPLIN, and PandaX-4T, and place new constraints on three benchmark models. Additionally, we set constraints from a performed analysis of TEXONO data and discuss the prospects of improvement in view of the next-generation DM direct detection DARWIN experiment.

Thank You