Dark Hypercharge Symmetry

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Outline

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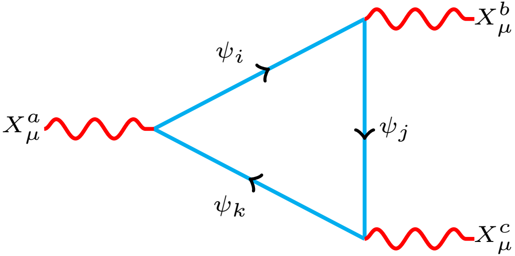
- Despite its many successes, Standard Model (SM) is an incomplete theory
- New physics Beyond Standard Model (BSM) is needed to explain Neutrino mass and mixing, Dark Matter, Matter - Antimatter Asymmetry, Vacuum Stability, Hierarchy Problem etc
- $U(1)_X$ gauge theories are one of the simplest extensions of SM
- They naturally occur in many popular BSM extensions e.g. GUTs, Left-Right Symmetry etc
- In recent times there is a growing interest in using $U(1)_X$ symmetries to explain various phenomenon
- In addition to its simplicity $U(1)_X$ theories are highly predictive: Gauge charges of SM and BSM fermions can be fixed by anomaly cancellation conditions

- Anomalies: Whenever a symmetry of the classical theory which does not survive to the quantum theory
- Anomalies can potentially occur whenever a classically invariant field theory with a continuous symmetry is quantized
- Historically they were first discovered in context of $\pi^0 \to \gamma\gamma$ decay[1]
- Especially for gauge symmetries presence of anomalies can have serious consequences and can make the theory nonunitary and nonrenormalizable.
- Thus any gauge theory should always be anomaly free.
- A pure gauge theories with no "matter fields" or a gauge theory with only scalar matter fields is always anomaly free
- However one has to be careful when the gauge theory also has fermionic matter fields like SM

[1] S. L. Adler, Phys. Rev. 177 (5), 2426–2438 (1969); J. S. Bell, R. Jackiw, Nuovo Cimento A. 60 (1): 47–61 (1969)

- The "gauge anomalies" in field theory are induced by the triangle diagrams



- For a gauge theory to be anomaly free, the total contribution of all such diagrams must vanish
- For theories with multiple gauge symmetries such as SM: All triangle diagrams with odd number of non-abelian gauge bosons attached to the vertices vanish
- Thus, one has to worry about anomaly only when the theory also has abelian $U(1)$ gauge symmetries like the case of SM

Outline

- SM is a theory with:
  - An abelian gauge symmetry $U(1)_Y$
  - Its fermions are also "chiral" i.e. the left and right counterpart fields do not have same charge under both $SU(2)_L$ and $U(1)_Y$
  - SM can be potentially anomalous

- All anomalies must be cancelled for SM to be a unitary and renormalizable field theory

- The complete set of anomaly cancellation conditions for SM are:

$$[SU(3)_C]^2 U(1)_Y = \sum_i Y_{Q^i} - \sum_j Y_{q^j} \,, \tag{1a}$$

$$[SU(2)_L]^2 U(1)_Y = \sum_i Y_{L^i} + 3\sum_j Y_{Q^j} \,, \tag{1b}$$

$$[U(1)_Y]^3 = \sum_{i,j} (Y^3_{L^i} + 3Y^3_{Q^j}) - \sum_{i,j} (Y^3_{l^i} + 3Y^3_{q^j}), \tag{1c}$$

$$[G]^2 U(1)_Y = \sum_{i,j} (Y_{L^i} + 3Y_{Q^j}) - \sum_{i,j} (Y_{l^i} + 3Y_{q^j}). \tag{1d}$$

- Let's first consider only one generation of SM fermions
- For SM to be anomaly free the $U(1)_Y$ charges of SM fermions should be such that all anomalies cancel
- Canonical SM hypercharge assignment for fermions is

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

- One can check explicitly that it cancels all the anomalies.
- The usual choice for Y is either $Y = 1$ or $Y = 1/2$ depending on how you defined relation between hypercharge (Y) and electric charge (Q)
    - If you define $Q = T_3 + Y/2$; T_3 being the third component of $SU(2)_L$, then $Y = 1$
    - If you define $Q = T_3 + Y$, then $Y = 1/2$
- Is this hypercharge assignment unique?
- NO!

- One can find other solutions for SM fermion hypercharge assignments which also cancel anomalies
- One more solution can be found simply by interchanging the hypercharges of $u_{\rm R}$ and $d_{\rm R}$ i.e. $Y_{u_{\rm R}} = \frac{-2Y}{3}$ and $Y_{d_{\rm R}} = \frac{4Y}{3}$
- Another solution is $Y_{u_{\rm R}} + Y_{d_{\rm R}} = 0$ and $Y_L = Y_Q = Y_{e_{\rm R}} = 0$.
- However, all these other solutions have problems
  - Most serious problem is that none of these solutions give correct electric charges of the SM fermions
  - It is also not possible to define a new relation between Y and Q that gives correct electric charges for all SM fermions
  - Mass generation of all fermions cannot be achieved with only the SM Higgs. One will need more scalars.
- In summary for one generation of SM fermions, the anomaly cancellation conditions alone don't give an unique solution
- The additional requirement that the hypercharge assignment must lead to correct electric charges of SM fermions, makes the assignment unique.

- What happens with full three generations of SM fermions?
- The canonical choice is to give all generations of a given type of fermion the same hypercharge

Q^i	u^i_R	d^i_R	L^i	e^i_R	Φ
$\frac{Y}{3}$	$\frac{4Y}{3}$	$\frac{-2Y}{3}$	$-Y$	$-2Y$	Y

- Thus with the canonical choice the SM hypercharges, the anomalies cancel generation by generation
- Are there other options?
- Yes! All other solutions discussed before can also work in a similar way. They all again will have the same problems so we have to again reject them
- In addition one can have new solutions

- One new solution is obtained when:

$$Y_{Q^i} = -Y_{Q^j} = Y, \ \ Y_{Q^k} = 0 \qquad Y_{u^l_{\rm R}} = -Y_{u^m_{\rm R}} = Y^{'}, \ \ Y_{u^n_{\rm R}} = 0$$
$$Y_{d^r_{\rm R}} = -Y_{d^s_{\rm R}} = Y^{''}, \ \ Y_{d^t_{\rm R}} = 0 \qquad Y_{L^i} = Y_{e^i_R} = 0$$

- Another solution is obtained when

$$Y_{L^i} = -Y_{L^j} = Y, \ \ Y_{L^k} = 0 \qquad Y_{e^l_{\rm R}} = -Y_{e^m_{\rm R}} = Y', \ \ Y_{e^n_{\rm R}} = 0$$
$$Y_{Q^i} = Y_{u^i_{\rm R}} = Y_{d^i_{\rm R}} = 0$$

- Again both these solutions have same problem as other solutions and hence should be rejected

- In summary, even with full three generations of SM fermions, the canonical hypercharge assignment is unique modulo an overall normalization factor.

Outline

$U(1)_X$ Anomaly Cancellation Conditions

- If we want to add a new $U(1)_X$ gauge symmetry to the SM then one has to ensure that it is also not anomalous
- The extra anomaly cancellations needed are:

$$[SU(3)_C]^2[U(1)_X] = \sum_i X_{Q'^i} - \sum_j X_{q'^j}. \tag{2a}$$

$$[SU(2)_\mathrm{L}]^2[U(1)_X] = \sum_i X_{L'^i} + 3\sum_j X_{Q'^j}. \tag{2b}$$

$$[U(1)_Y]^2[U(1)_X] = \sum_{i,j}(Y^2_{L'^i} X_{L'^i} + 3Y^2_{Q'^j} X_{Q'^j}) - \sum_{i,j}(Y^2_{l'^i} X_{l'^i} + 3Y^2_{q'^j} X_{q'^j}). \tag{2c}$$

$$[U(1)_Y][U(1)_X]^2 = \sum_{i,j}(Y_{L'^i} X^2_{L'^i} + 3Y_{Q'^j} X^2_{Q'^j}) - \sum_{i,j}(Y_{l'^i} X^2_{l'^i} + 3Y_{q'^j} X^2_{q'^j}). \tag{2d}$$

$$[U(1)_X]^3 = \sum_{i,j}(X^3_{L'^i} + 3X^3_{Q'^j}) - \sum_{i,j}(X^3_{l'^i} + 3X^3_{q'^j}). \tag{2e}$$

$$[G]^2[U(1)_X] = \sum_{i,j}(X_{L'^i} + 3X_{Q'^j}) - \sum_{i,j}(X_{l'^i} + 3X_{q'^j}). \tag{2f}$$

- There are many solutions to these anomaly cancellation conditions
- $\mathbf{L_i - L_j}$ **Solutions:** One of the popular solution which is very well studied
- The charges of SM fermions under $U(1)_X$ symmetry are given by[2]

$$X_{L^i} = -X_{L^j} = X, X_{L^k} = 0; \qquad i,j,k = 1,2,3 \;\&\; i \neq j \neq k$$
$$X_{e^l_R} = -X_{e^m_R} = X, \;\; X_{e^n_R} = 0; \qquad l,m,n = 1,2,3 \;\&\; l \neq m \neq n$$
$$X_{Q^i} = X_{q^j} = 0; \quad i,j = 1,2,3 \;\; \forall \; i,j.$$

- This is a vector solution with $U(1)_X$ charges of left and right handed fermions being same.
- One unique feature of this solution is that no new BSM fermion is needed to cancel the anomalies

[2] X. G. He, G. C. Joshi, H. Lew, and R. R. Volkas; Phys. Rev. D. 43 (1991) 22-24

- There are several known solutions which require presence of new BSM fermions (typically right handed neutrinos) to cancel anomalies

- **B − L Solution:** The $B-L$ solution is one of the oldest and most popular solution

- The charges of SM and right handed BSM fermion (f_i; $i = 1, 2, 3$) are given by

$$\begin{aligned} X_{Q^i} &= X_{q^j} = 1/3; \quad i, j, k = 1, 2, 3\,, \\ X_{L^i} &= X_{l^j} = X_{f^i} = -1; \quad \forall\ i, j. \end{aligned}$$

- Notice that again its a vector solution with $U(1)_X$ charges of the BSM fermion f_i being same as that of SM neutrinos.

- Its also a "flavor blind" symmetry with $B-L$ charges of each generation being same.

- During phenomenology part of the talk, I will use the equivalent results of the $B-L$ case as the reference to compare with our results

$U(1)_X$ Anomaly Cancellation Conditions: Other Solutions

- There are several other solutions: I will just list some of the other popular ones
  - **$\mathbf{B-3L_i}$**: Charges are[3]

$$X_{Q^i} = X_{q^j} = 1/3; \quad i,j = 1,2,3\,,$$
$$X_{L^i} = X_{l^i} = X_f = -3,\ X_{L^k} = X_{l^k} = 0; \quad i,k = 1,2,3\ \&\ i \neq k.$$

  - **$\mathbf{B_i-3L_j}$**: Charges are[4]

$$X_{Q^i} = X_{q^i} = 1,\ X_{Q^j} = X_{q^j} = 0; \quad i,j = 1,2,3\ \&\ i \neq j\,,$$
$$X_{L^j} = X_{l^j} = X_f = -3,\ X_{L^k} = X_{l^k} = 0; \quad j,k = 1,2,3\ \&\ j \neq k.$$

  - Variants such as $B-2L_i-L_j$, $B-\frac{3}{2}(L_i+L_j)$, $B_1-yB_2+(y-3)B_3+L_i+L_j$ etc. are also possible
- One common feature of all these solutions is that they are all vector solutions i.e. the $U(1)_X$ charges of left and right handed fermions of a given type are same
- Are chiral solutions analogous to hypercharge solution in SM case possible?

[3] E. Ma, Phys. Lett. B 433 (1998) 74–81,

[4] C. Bonilla, T. Modak, R. Srivastava, and J. W. F. Valle, Phys. Rev. D 98 no. 9, (2018) 095002

Outline

$U(1)_X$ Anomaly Cancellation Conditions: Chiral Solutions

- The chiral solutions have not been explored much in literature
- One of the known chiral solutions is for the $B - L$ symmetry[5] where the BSM fermions $f_i;\ i = 1, 2, 3$ have $U(1)_X$ charges of $+4, +4, -5$
- We also found that one can also have chiral solutions for gauged Baryon ($U(1)_B$) and Lepton ($U(1)_L$) symmetries
- All these solutions although chiral, are very limited in their chirality
- In all of them the SM fermions are still vector under $U(1)_X$ symmetry and only BSM fermions have exotic $U(1)_X$ charges
- This is in contrast of the SM hypercharge case where the left and right counterpart of all types are fermions have different hypercharges
- Are similar solutions for $U(1)_X$ symmetries possible?

[5] J. C. Montero and V. Pleitez; Phys. Lett. B 675 (2009) 64–68; E. Ma and R. Srivastava, Phys. Lett. B 741 (2015) 217–222; E. Ma and R. Srivastava, Mod. Phys. Lett. A 30 no. 26, (2015) 1530020, E. Ma, N. Pollard, R. Srivastava, and M. Zakeri, Phys. Lett. B 750 (2015) 135–138

- Such solutions are indeed possible.
- In fact we have found a whole class of hithero unknown solutions, all completely chiral in their $U(1)_X$ charge assignments [6]
- We call them Dark Hypercharge Solutions:
- Like Hypercharge, left and right handed couterparts of all fermions have different $U(1)_X$ charges
- They require addition of SM gauge singlet BSM fermions f_i
- These BSM fermions can belong to the dark sector with the lightest of them being a good dark matter symmetry
- The associated gauge boson Z' connects the dark sector to visible sector: Hence Dark Hypercharge

[6] H. Prajapati, R.S., Manuscript under preparation

- 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

$U(1)_X$ Anomaly Cancellation Conditions: Dark Hypercharge Symmetry

- 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
$\frac{-X_L}{3}$	$\frac{2X_L}{3} - X_{e_R}$	$\frac{-4X_L}{3} + X_{e_R}$	X_L	X_{e_R}	k	$-k$	$2X_L - X_{e_R}$	$X_L - X_{e_R}$

- 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	$-k$	$-X_L$
$\frac{-X_L}{3}$	$\frac{2X_L}{3} - X_{e_R}$	$\frac{-4X_L}{3} + X_{e_R}$	X_L	X_{e_R}	0	$2X_L - X_{e_R}$	$2X_L - X_{e_R}$	$X_L - X_{e_R}$

$U(1)_X$ Anomaly Cancellation Conditions: Dark Hypercharge Symmetry

- For three generation (S(III)) 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	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	$-(\kappa-\frac{3}{s})$
$-\frac{X_L}{3}$	$\frac{-4X_L}{3}-\frac{s^2-1}{8}$	$\frac{2X_L}{3}+\frac{s^2-1}{8}$	X_L	$2X_L+\frac{s^2-1}{8}$	$\frac{1}{8}(-4s^2+3s+\frac{1}{s})$	$\frac{1}{8}(5s^2+3)$	$-\frac{1}{8}(4s^2+3s+\frac{1}{s})$	$-(X_L+\frac{s^2-1}{8})$
$-\frac{X_L}{3}$	$\frac{-4X_L}{3}+\frac{s^2-1}{8}$	$\frac{2X_L}{3}-\frac{s^2-1}{8}$	X_L	$2X_L-\frac{s^2-1}{8}$	$\frac{1}{8}(3s^2+5)$	$-\frac{1}{8}(s^3+3s+4)$	$\frac{1}{8}(s^3+3s-4)$	$-X_L+\frac{s^2-1}{8}$

- 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

$U(1)_X$ Anomaly Cancellation Conditions: Dark Hypercharge Symmetry

- In all cases all fermions have completely chiral $U(1)_X$ charges
- We always need three dark sector fermions to cancel anomalies
- Only SM Higgs is enough to generate mass of all SM fermions
- 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

Outline

- The covariant derivative is defined as

$$D_\mu = \partial_\mu + ig_s T_g^a G_\mu^a + igT_w^a W_\mu^a + ig'\frac{Y}{2}B_\mu + ig_x XC_\mu \,. \qquad (3)$$

where

$$\langle\phi\rangle = \frac{1}{\sqrt{2}}\begin{bmatrix}0\\ v\end{bmatrix}, \qquad \langle\chi_i\rangle = \frac{v_i}{\sqrt{2}} \,. \qquad (4)$$

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

$$(D_\mu)^\dagger D^\mu + (D_\mu\chi_i)^\dagger D^\mu\chi_i \;, \qquad (5)$$

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

$$\mathcal{M}_v^2 = \frac{v^2}{4}\begin{pmatrix} g'^2 & -gg' & 2g'X_\phi g_x \\ -gg' & g^2 & -2gX_\phi g_x \\ 2g'X_\phi g_x & -2gX_\phi g_x & 4u^2g_x^2 \end{pmatrix}, \qquad (6)$$

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

Gauge Boson Masses and ρ parameter

- The mass eigen states are given by

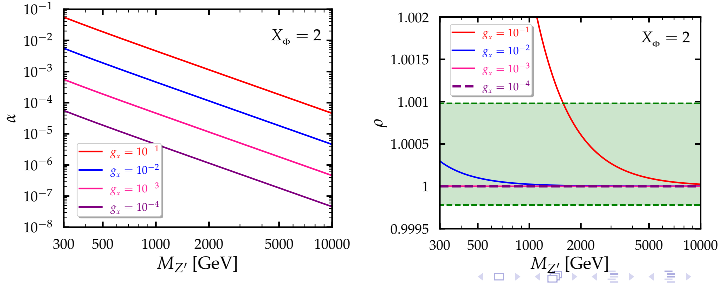
$$m^2 = \frac{v^2}{8}\left(A_0 - \sqrt{B_0^2 + C_0^2}\right),\ M^2 = \frac{v^2}{8}\left(A_0 + \sqrt{B_0^2 + C_0^2}\right), \qquad (7)$$

where $A_0 = g^2 + g'^2 + 4u^2 g_x^2$, $B_0 = 4X_\phi g_x \sqrt{g^2 + g'^2}$, $C_0 = 4u^2 g_x^2 - (g^2 + g'^2)$.
And the W boson mass is given as $M_W^2 = (gv)^2/4$.

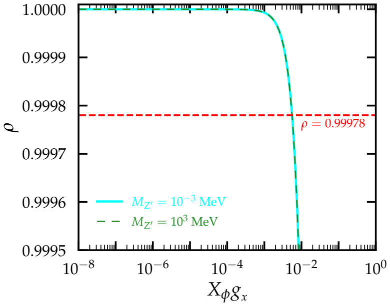
- The ratio of gauge boson masses is measured through the parameter

$$\rho' = \frac{\rho}{\cos^2\alpha + \left(\frac{M_{Z'}}{M_Z}\right)^2 \sin^2\alpha} = 1.\quad \rho - 1 = \left[\left(\frac{M_{Z'}}{M_Z}\right)^2 - 1\right]\sin^2\alpha.$$

- For the case of $M_{Z'}[g_x, u_\chi] > M_Z[g_x, u_\chi]$



- For the case of $M_{Z'}[g_x, u_\chi] < M_Z[g_x, u_\chi]$
  - The ρ parameter could be approximated as, $\rho \approx \left(1 + \frac{4X_\phi^2 g_x^2}{g^2+g'^2}\right)^{-1}$
  - This implies that the ρ parameter is independent of $M_{Z'}$



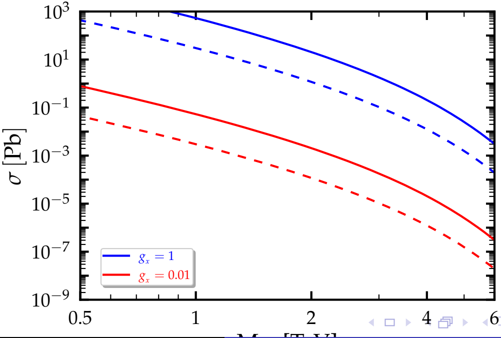
- In the low mass limit of $M_{Z'}$, $X_\phi g_x \lesssim 5.5 \times 10^{-3}$ is adequate to satisfy the ρ parameter, $M_{Z'} \approx u_\chi g_x$.

Production and decays of Z'

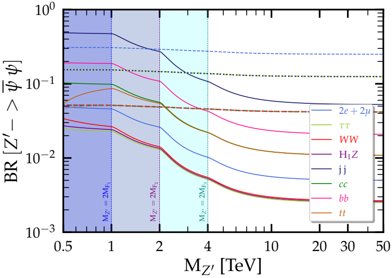
- To be concrete henceforth we take one of the models of the S(III) type to do the phenomenological studies. The charges of particles are

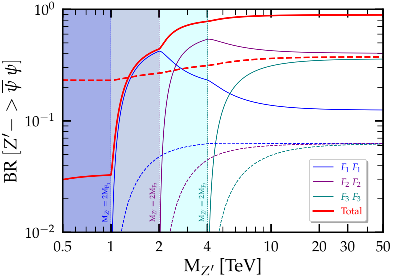
$U(1)$	Q	u_R	d_R	L	e_R	f_1	f_2	f_3	Φ	χ_0
$U(1)_Y$	$\frac{1}{3}$	$\frac{4}{3}$	$\frac{-2}{3}$	-1	-2	0	0	0	1	0
$U(1)_X$	$-\frac{1}{3}$	$\frac{5}{3}$	$-\frac{7}{3}$	1	-1	10	-18	17	2	-6

- In hadronic colliders the most efficient process involving Z' production is Drell-Yan $q\,\bar{q} \longrightarrow Z'$,

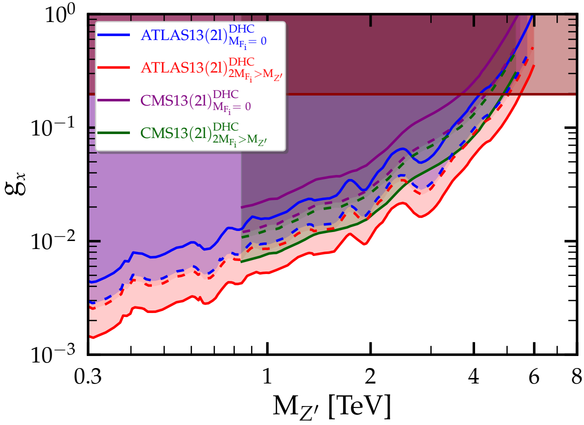


- In the DHC symmetry, the total branching fraction of invisible decay is approximately 90% when the branching fraction saturates. In contrast, in the $B - L$ symmetry, it is about 38%.
- In the fermionic decay modes, the dileptonic branching fraction, is much smaller in DHC (0.5%) compared to say $B - L$ (25%).





- We used the ATLAS[7] and CMS[8] search for Z' in Dilepton resonance at pp collisions with ($\sqrt{s} = 13$) TeV and an integrated luminosity of 139 fb^{-1} .

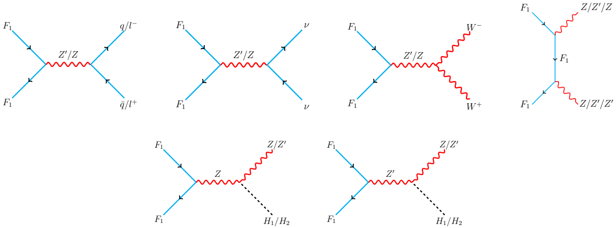


[7] ATLAS Collaboration, Phys. Lett. B 796 (2019) 68–87,
[8] CMS Collaboration, JHEP 07 (2021) 208

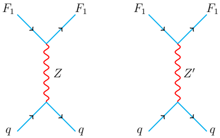
Outline

Dark Matter Constraints

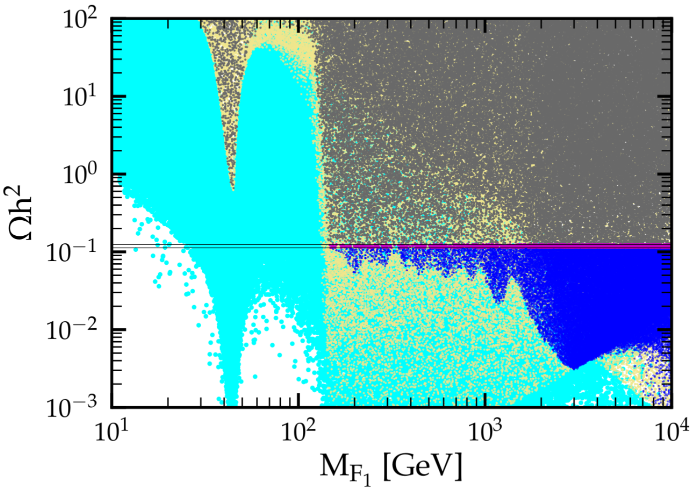
- As mentioned before, the BSM fermions f_i; $i = 1, 2, 3$ belong to the dark sector and the lightest of them can be dark matter
- The charges and interaction strength of the dark matter to all SM particles is completely fixed by the anomaly cancellation conditions. This makes the model highly predictive
- Feynman diagram contributing to DM annihilation



- Feynman Diagrams Contributing to DM-nucleon Scattering

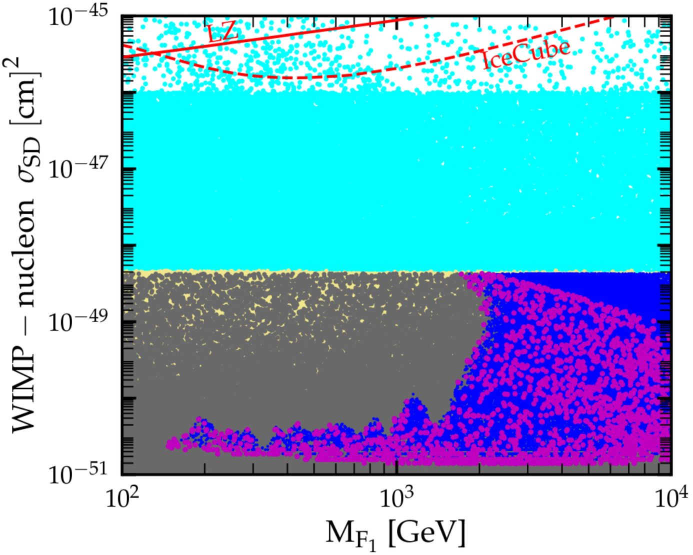


- Measured Relic Abundance[9] $0.1126 \leq \Omega h^2 \leq 0.1246$.



[9] Planck Collaboration, 641 (2020) A6

- Direct Detection Constraints[10]



[10] IceCube Collaboration, Eur. Phys. J. C 77 no. 3, (2017) 146
LUX-ZEPLIN Collaboration, Phys. Rev. Lett. 131 no. 4, (2023) 041002

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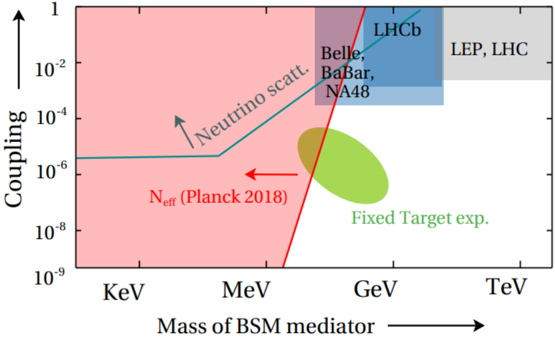
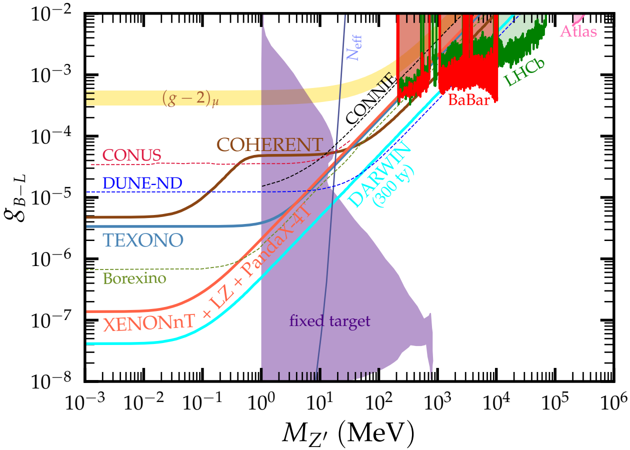
- Light Z' can be constrained from different experiments like Direct Detection Experiments, Fixed target experiments, Supernovae Cooling, N_{eff} etc.

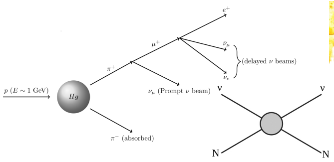


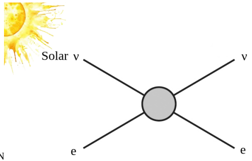
- As an example the parameter space for coupling and mass of the Z' from gauged $B-L$ has been constrained through various experiments[11]

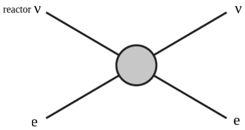


[11] Anirban Majumdar, Dimitrios K. Papoulias, Hemant Prajapati, Rahul Srivastava; Manuscript under preparation

CEνNS and EνES constraints on Light Z' from Dark HyperCharge Symmetry







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

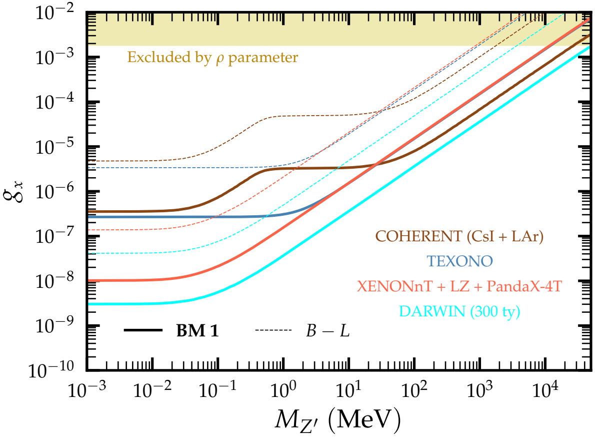
- **Experiment: XENONnT, LZ, PandaX-4T, and DARWIN** (future sensitivity)
- ν Source: Solar ν_e
- Target: LXe TPC
- Relevant Interaction: **EνES**

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

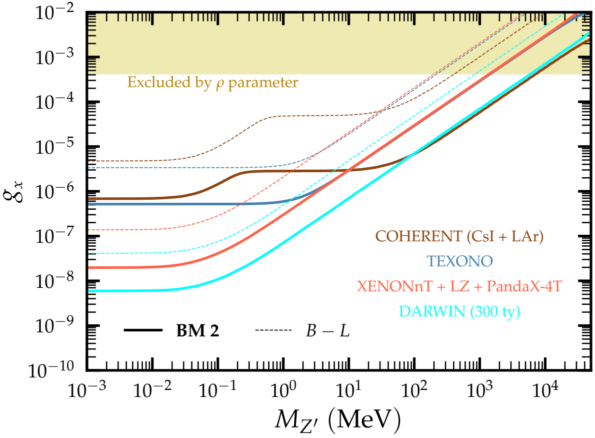
Benchmark Dark Hypercharge Models

Fields	Hypercharge (Y)	Weak Isospin (T^3)	$U(1)_X$ Charge			
			BM 1	BM 2	BM 3	B - L
u_L	1/3	1/2	-13/3	-3	-1/3	1/3
u_R	4/3	0	-4/3	10	5/3	1/3
d_L	1/3	-1/2	-13/3	-3	-1/3	1/3
d_R	-2/3	0	-22/3	-16	-7/3	1/3
e_L	-1	-1/2	13	9	1	-1
e_R	-2	0	10	-4	-1	-1
ν_L	-1	1/2	13	9	1	-1
f^1	0	0	16	-110	10	-1
f^2	0	0	16	88	-18	-1
f^3	0	0	16	88	17	-1
ϕ	1	-	3	13	2	0

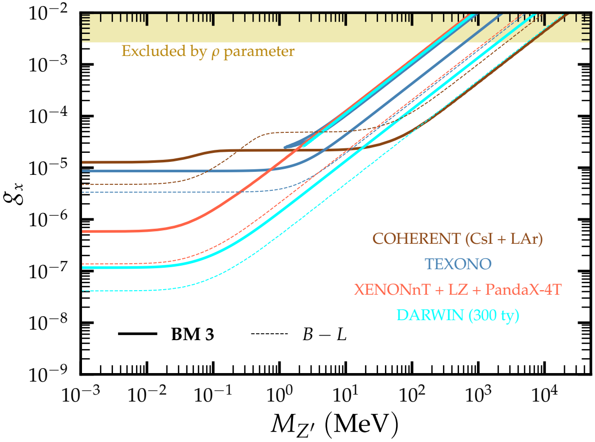
CEνNS and EνES constraints on Z' from BM 1



CEνNS and EνES constraints on Z' from BM 2



CEνNS and EνES constraints on Z' from BM 3



Outline

Conclusions

- Extensions of the Standard Model with $U(1)_X$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 both heavy and light Z' cases.
- These dark hypercharge models can be tested in various experiments.

Thank You