Singlet-Doublet Majorana Dark Matter and Neutrino Mass in a minimal Type-I Seesaw Scenario

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(arXiv: 2009.00885 [hep-ph], Manoranjan Dutta, Subhaditya Bhattacharya, Purusottam Ghosh, Narendra Sahu)

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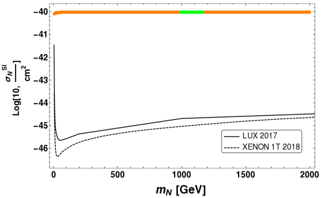
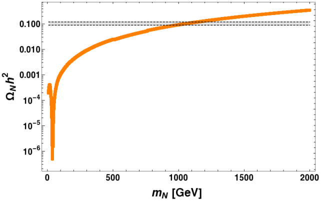
Motivation towards Singlet-Doublet Majorana Dark Matter

- Simplest of Z-mediated Scalar and Vector Dark Matter models are ruled out by direct search and invisible Z width.
- Dirac DM with a vector coupling to the Z is ruled out for DM mass nearly upto 6 TeV.
- The only scenarios which remain viable at this time are those with a fermionic dark matter candidate with a nearly pure axial coupling to the Z and with a mass that lies within either a few GeV of the Z pole or that is heavier than 200 GeV.

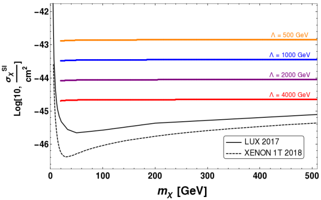
Motivation towards Singlet-Doublet Majorana Dark Matter

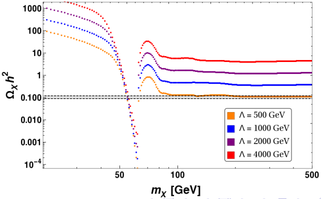
Vector-like Leptonic Doublet DM: (S. Bhattacharya, P. Ghosh, N. Sahoo, and N. Sahu, *Front. in Phys.* **7** (2019) 80.)





Vector-like Leptonic Singlet DM: $\mathcal{L} = \overline{\chi}(i\gamma^\mu \partial_\mu - m_\chi)\chi - \frac{1}{\Lambda}(H^\dagger H - \frac{v^2}{2}\overline{\chi}\chi)$





Singlet-Doublet Majorana Dark Matter: The Model Lagrangian

Fields		$SU(3)_C$	$\otimes SU(2)_L$	$\otimes U(1)_Y$	$\otimes \mathcal{Z}_2$
VLFd	$\Psi = \begin{pmatrix} \psi^0 \\ \psi^- \end{pmatrix}$	1	2	-1	-
RHNs	N_{R_1}	1	1	0	-
	N_{R_2}	1	1	0	+
	N_{R_3}	1	1	0	+
Higgs doublet	$H = \begin{pmatrix} w^+ \\ \frac{h+v+iz}{\sqrt{2}} \end{pmatrix}$	1	2	1	+

$$\mathcal{L} = \mathcal{L}_{SM} + \overline{\Psi}\left(i\gamma^\mu D_\mu - M\right)\Psi + \overline{N_{R_i}} i\gamma^\mu \partial_\mu N_{R_i} - \left(\frac{1}{2} M_{R_i} \overline{N_{R_i}} \left(N_{R_i}\right)^c + h.c\right) + \mathcal{L}_{yuk}.$$

where, $D_\mu = \partial_\mu - i\frac{g}{2}\tau.W_\mu - ig'\frac{Y}{2}B_\mu$

$$-\mathcal{L}_{yuk} = \left[\frac{Y_1}{\sqrt{2}}\overline{\Psi}\tilde{H}\left(N_{R_1} + (N_{R_1})^c\right) + h.c\right] + \left(Y_{j\alpha}\overline{N_{R_j}}\tilde{H}^\dagger L_\alpha + h.c.\right).$$

where $\alpha = e, \mu, \tau$ and $j = 2, 3$.

The Mass Matrix of the Dark sector

After the SM Higgs acquires vev,

$$-\mathcal{L}_{mass} = M\overline{\psi_L^0}\psi_R^0 + \frac{1}{2}M_{R_1}\overline{N}_{R_1}(N_{R_1})^c + \frac{m_D}{\sqrt{2}}(\overline{\psi_L^0}N_{R_1} + \overline{\psi_R^0}(N_{R_1})^c) + h.c.$$

The Mass matrix for Dark Sector in the basis $((\psi_R^0)^c, \psi_L^0, (N_{R_1})^c)^T$,

$$\mathcal{M} = \begin{pmatrix} 0 & M & \frac{m_D}{\sqrt{2}} \\ M & 0 & \frac{m_D}{\sqrt{2}} \\ \frac{m_D}{\sqrt{2}} & \frac{m_D}{\sqrt{2}} & M_{R_1} \end{pmatrix}$$

Can be diagonalized by $\mathcal{U}.\mathcal{M}.\mathcal{U}^T$ where,

$$\mathcal{U} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\pi/2} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \frac{1}{\sqrt{2}}\cos\theta & \frac{1}{\sqrt{2}}\cos\theta & \sin\theta \\ \frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} & 0 \\ -\frac{1}{\sqrt{2}}\sin\theta & -\frac{1}{\sqrt{2}}\sin\theta & \cos\theta \end{pmatrix}$$

Mass EigenValues and EigenVectors

$$
\begin{aligned}
m_{\chi_1} &= M\cos^2\theta + M_{R_1}\sin^2\theta + m_D\sin 2\theta\,, \\
m_{\chi_2} &= M, \\
m_{\chi_3} &= M_{R_1}\cos^2\theta + M\sin^2\theta - m_D\sin 2\theta\,.
\end{aligned}
$$

where the mixing angle,

$$\tan 2\theta = \frac{2m_D}{M - M_{R_1}}$$

In the small mixing ($\theta \to 0$) limit ,

$$
\begin{aligned}
m_{\chi_1} &\approx M + \frac{m_D^2}{M - M_{R_1}}\,, \\
m_{\chi_2} &= M, \\
m_{\chi_3} &\approx M_{R_1} - \frac{m_D^2}{M - M_{R_1}}\,.
\end{aligned}
$$

χ_3 becomes the stable DM candidate. Using $\mathcal{U}.\mathcal{M}.\mathcal{U}^T = \mathcal{M}_{Diag.}$,

$$Y_1 = \frac{\sqrt{2}\,\Delta M\,\sin 2\theta}{v},$$

$$M = m_{\chi_1}\cos^2\theta + m_{\chi_3}\sin^2\theta,\quad M_{R_1} = m_{\chi_3}\cos^2\theta + m_{\chi_1}\sin^2\theta;$$

$$\text{Dark Parameters}: \quad \{\, m_{\chi_3}, \Delta M = (m_{\chi_1} - m_{\chi_3}) \approx (m_{\chi_2} - m_{\chi_3}),\ \sin\theta \,\}.$$

Relic Abundance of Singlet-Doublet Majorana DM

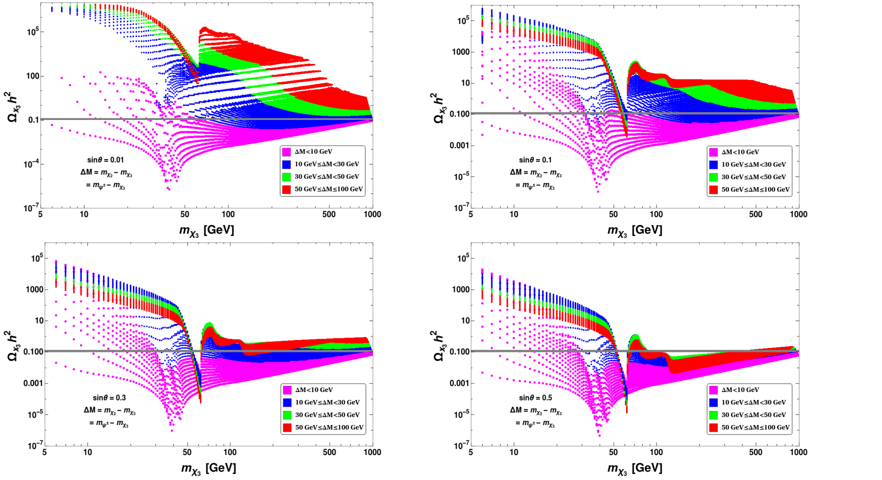
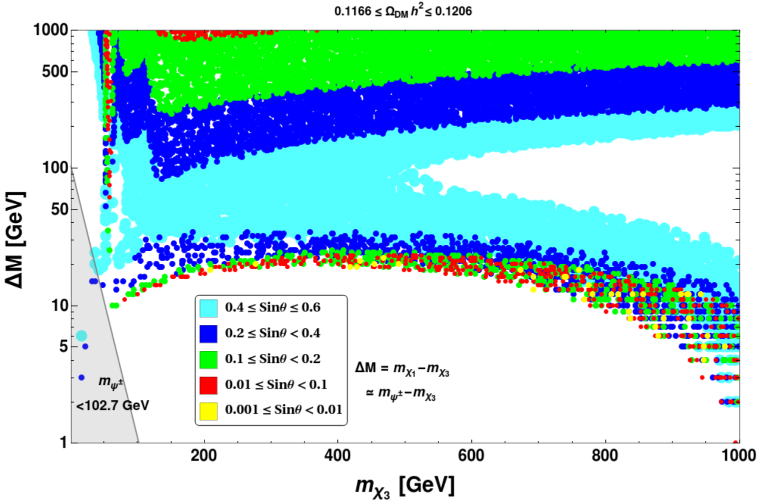
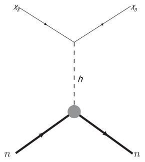


Figure: Variation of DM relic density with different ranges of mixing parameter $\sin\theta$.

Relic density allowed parameter space in $\Delta M - m_{\chi_3}$ plane

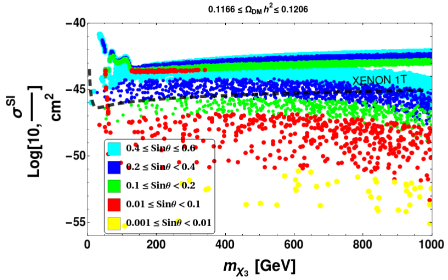


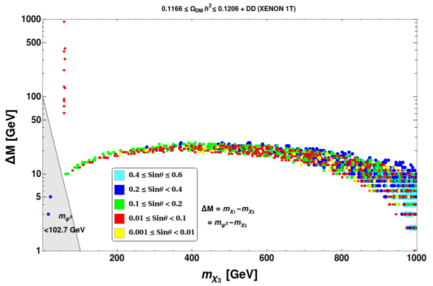
Relic and Direct Detection constraints combined



Effective coupling strength:

$$\alpha_q = \frac{Y_1 \sin 2\theta}{M_h^2}\,\frac{m_q}{v} = \frac{\Delta M\ \sin^2 2\theta\, m_q}{v^2 M_h^2}$$





Gauged $U(1)_{B-L}$ Extension of the Model

Fields		$SU(3)_C$	$\otimes SU(2)_L$	$\otimes U(1)_Y$	$\otimes U(1)_{B-L}$	$\otimes \mathcal{Z}_2$
VLFd	$\Psi = \begin{pmatrix} \psi^0 \\ \psi^- \end{pmatrix}$	1	2	-1	-1	-
RHNs	N_{R_1}	1	1	0	-1	-
	$N_{R_{2/3}}$	1	1	0	-1	+
Higgs doublet	$H = \begin{pmatrix} w^+ \\ \frac{h+v+iz}{\sqrt{2}} \end{pmatrix}$	1	2	1	0	+
Scalar Singlet	$\Phi_{BL} = \frac{\phi+v_{BL}+iz_\phi}{\sqrt{2}}$	1	1	0	-2	+

$$\mathcal{L} = \overline{\Psi}(i\not{D} - M)\Psi + \overline{N}_{R_i} i\tilde{\not{D}} N_{R_i} + \mathcal{L}_{yuk} + \mathcal{L}_{Gauge} + \mathcal{L}_{\rm scalar} + \mathcal{L}_{SM};$$

where,

$$D_\mu = \partial_\mu - i\frac{g}{2}\tau.W_\mu - ig'\frac{Y}{2}B_\mu - ig_{BL}Y_{BL}Z_{BL},$$

$$\tilde{D}_\mu = \partial_\mu - ig_{BL}Y_{BL}(Z_{BL})_\mu.$$

$$-\mathcal{L}_{yuk} = \left[Y_1\overline{\Psi}\tilde{H}N_{R_1} + h.c\right] + \left(Y_{j\alpha}\overline{N_{R_j}}\tilde{H}^\dagger L_\alpha + h.c.\right) + \left[\frac{y_i'}{2}\Phi_{BL}\overline{N_{R_i}}\left(N_{R_i}\right)^c + h.c.\right];$$

$$\mathcal{L}_{Gauge} = -\frac{1}{4}(Z_{BL})_{\mu\nu}Z_{BL}^{\mu\nu} - \frac{\epsilon}{2}(Z_{BL})_{\mu\nu}B^{\mu\nu};$$

The Scalar Sector

$$\mathcal{L}_{\rm scalar} = |\mathcal{D}_\mu H|^2 + |\mathfrak{D}_\mu \Phi_{BL}|^2 - V(H, \Phi_{BL})$$

where,

$$\mathcal{D}_\mu = \partial_\mu - i\frac{g}{2}\tau . W_\mu - ig'\frac{Y}{2}B_\mu$$

$$\mathfrak{D}_\mu = \partial_\mu - ig_{BL}Y_{BL}(Z_{BL})_\mu$$

The scalar potential is given by,

$$V(H, \Phi_{BL}) = -{\mu_H}^2\left(H^\dagger H\right) + \lambda_H\left(H^\dagger H\right)^2 - {\mu_\Phi}^2\left({\Phi_{BL}}^\dagger \Phi_{BL}\right) + \lambda_\Phi\left({\Phi_{BL}}^\dagger \Phi_{BL}\right)^2 + \lambda_{H\Phi}(H^\dagger H)\left({\Phi_{BL}}^\dagger \Phi_{BL}\right)$$

$$\mathcal{L}^{\rm mass}_{\rm scalar} = \frac{1}{2}\begin{pmatrix} h & \phi \end{pmatrix}\begin{pmatrix} 2\lambda_H v^2 & \lambda_{H\Phi} v v_{BL} \\ \lambda_{H\Phi} v v_{BL} & 2\lambda_\Phi v_{BL}^2 \end{pmatrix}\begin{pmatrix} h \\ \phi \end{pmatrix} = \frac{1}{2}\begin{pmatrix} h_1 & h_2 \end{pmatrix}\begin{pmatrix} m_{h_1}^2 & 0 \\ 0 & m_{h_2}^2 \end{pmatrix}\begin{pmatrix} h_1 \\ h_2 \end{pmatrix}.$$

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} \cos\beta & \sin\beta \\ -\sin\beta & \cos\beta \end{pmatrix}\begin{pmatrix} h \\ \phi \end{pmatrix}$$

Scalar Sector Parameters: m_{h_2}, v_{BL}, $\sin\beta$,
However, $M_{Z_{BL}} = g_{BL}v_{BL}$;
Combined Scalar-Gauge sector:
m_{h_2}, g_{BL}, $M_{Z_{BL}}$, $\sin\beta$

The Mass Matrix and the Eigenvalues

$$-\mathcal{L}_{mass} = M\overline{\psi_L^0}\psi_R^0 + \frac{1}{2}M_{R_1}\overline{N}_{R_1}(N_{R_1})^c + m_D\overline{\psi_L^0}N_{R_1} + h.c.\,,$$

In the basis $((\psi_R^0)^c, \psi_L^0, (N_{R_1})^c)^T$,

$$\mathcal{M} = \begin{pmatrix} 0 & M & 0 \\ M & 0 & m_D \\ 0 & m_D & M_{R_1} \end{pmatrix}.$$

Diagonalization upto $\mathcal{O}(\frac{m_D^2}{M+M_{R_1}})$ by: $\mathcal{M}_{\rm diag} = U.\mathcal{M}.U^T$, where $U = U_{13}.U_{23}.U_{12}$.

Assuming $m_D << M, M_{R_1}$,

$$m_{\chi_1} \approx M + \frac{m_D^2}{2(M - M_{R_1})},$$

$$m_{\chi_2} \approx -\left(M + \frac{m_D^2}{2(M + M_{R_1})}\right),$$

$$m_{\chi_3} \approx M_{R_1}\left(1 - \frac{m_D^2}{M^2 - M_{R_1}^2}\right).$$

We assume $m_{\chi_1} > m_{\chi_2} > m_{\chi_3}$, so that χ_3 serves as a stable dark matter candidate.

$$\theta_{12} = \frac{\pi}{4}, \quad \tan 2\theta_{23} = \frac{-\sqrt{2}m_D}{M + M_{R_1}},$$

$$\tan 2\theta_{13} = \left(\frac{\sqrt{2}m_D}{M - M_{R_1} - \frac{m_D^2}{2(M+M_{R_1})}}\right)\cos\theta_{23}\,.$$

In the limit $m_D << M, M_{R_1}$,

$$Y_1 \approx \frac{\Delta M \sin 2\theta_{13}}{v},$$

$$\text{Dark Parameters}: \quad \{m_{\chi_3}, \Delta M, \sin\theta_{13}\}, \text{ or } \{M_{R_1}, M, \sin\theta_{13}\}.$$

Relic Abundance of Singlet-Doublet Majorana DM

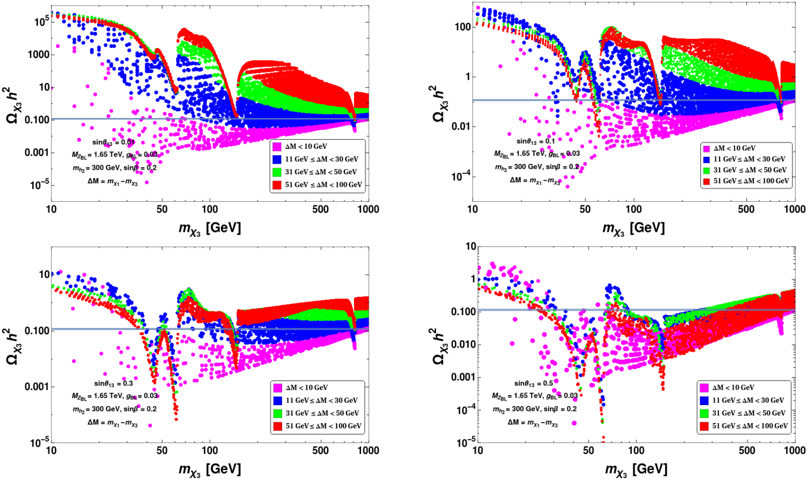
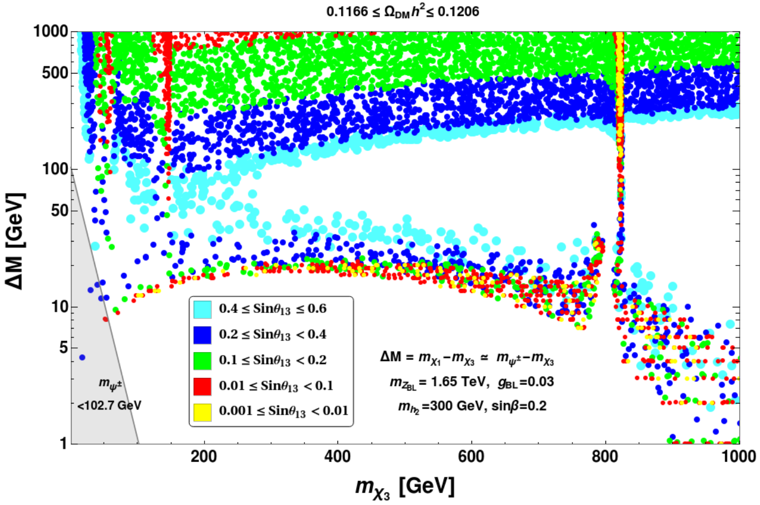
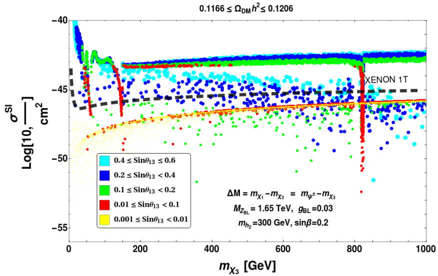


Figure: Variation of DM relic density with different ranges of mixing parameter $\sin\theta_{13}$.

Relic density allowed parameter space in $\Delta M - m_{\chi_3}$ plane



Relic and Direct Detection constraints combined



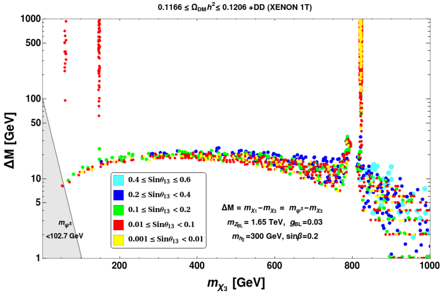


Figure: [Left]: Spin-independent direct detection cross section of DM (χ_3) with nucleon as function of DM mass (in GeV) for $U(1)_{B-L}$ model confronted with XENON-1T data (E. Aprile et. al., XENON-1T Collaboration, *Phys. Rev. Lett., 121,* **11***, 2018)* over and above relic density constraint from PLANCK (P. A. R. ade et. al., Planck collaboration,*Astron. Astrophys. 571*, **A16**, 2014); [Right]: Correct DM relic density allowed parameter space of the model in $\Delta M - m_{\chi_3}$ plane constrained by XENON-1T bound. Different coloured points indicate different ranges of $\sin\theta_{13}$ as mentioned in the figure inset. The parameters kept fixed for the scan are $M_{Z_{BL}} = 1.65\ \mathrm{TeV}$, $g_{BL} = 0.03$, $m_{h_2} = 300\ \mathrm{GeV}$, $\sin\beta = 0.2$. The shaded region in the bottom left corner of right hand plot is ruled out by LEP exclusion bound on charged fermion mass, $m_{\psi^\pm} = M > 102.7$ GeV.

ATLAS bound on $g_{BL} - M_{Z_{BL}}$

$$\left\{ \begin{array}{l} 1 \text{ GeV} \leq m_{\chi_3} \leq 2000 \text{ GeV}, \;\; 1 \text{ GeV} \leq \Delta M \leq 1000 \text{ GeV}, \;\; 20 \text{ GeV} \leq M_{Z_{BL}} \leq 4000 \text{ GeV} \\ 0.001 \leq \sin\theta_{13} \leq 0.6, 0.001 \leq g_{BL} \leq 0.3, \;\; \sin\beta = 0.2, \;\; m_{h_2} = 300 GeV \end{array} \right.$$

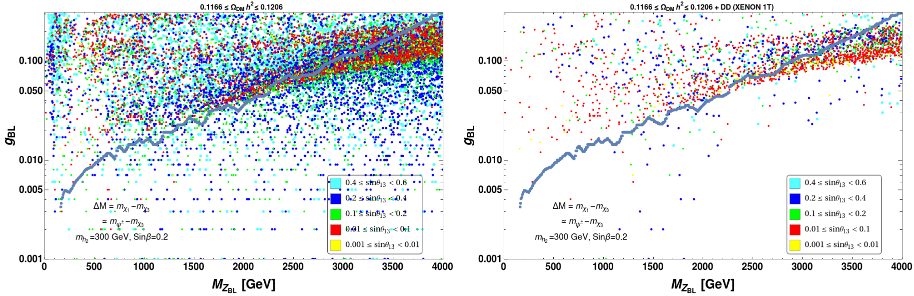
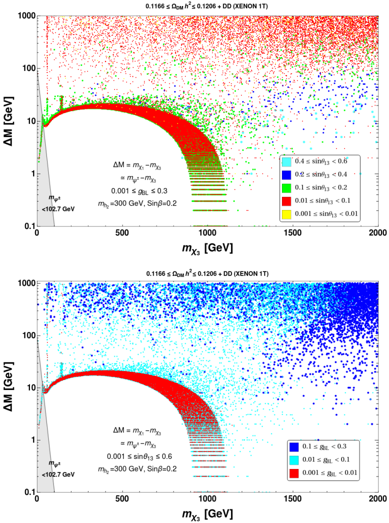
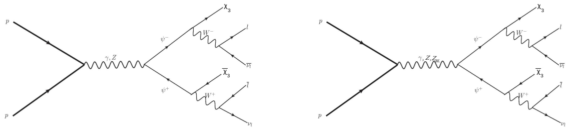


Figure: [Left]:Parameter space satisfying relic density constraint from PLANCK in the plane of $g_{BL} - M_{Z_{BL}}$, [Right]: Parameter space satisfying both relic density constraint from PLANCK and direct detection constraint from XENON-1T in the plane of $g_{BL} - M_{Z_{BL}}$. The thick silver line shows the ATLAS bound on g_{BL} for corresponding $M_{Z_{BL}}$ (Aaboud et. al., ATLAS Collaboration, *JHEP* 10, **182**, 2017).

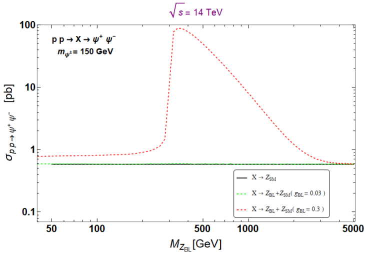
Parameter Space in light of varying $M_{Z_{BL}}$ and ATLAS bound on g_{BL}

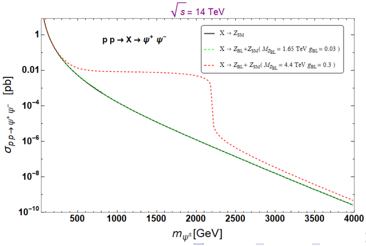


Collider Signatures



$$OSD + \not{E}_T : \quad p\, p \to \psi^+ \, \psi^-, \; (\psi^- \to \ell^- \, \overline{\nu_\ell} \, \chi_3), \;\; (\psi^+ \to \ell^+ \, \nu_\ell \, \chi_3); \;\; \ell = \{e, \mu\} \, .$$





Non-Zero Neutrino Mass

The Lagrangian,

$$-\mathcal{L}^{\nu}_{mass} \supset Y_{j\alpha}\overline{N_{R_j}}\tilde{H}^{\dagger}L_{\alpha} + \frac{1}{2}M_{R_j}\overline{N}_{R_j}(N_{R_j})^c + h.c. \, ;$$

where,

$$M_R = Diag(0, M_{R_2}, M_{R_3})$$

In this basis, under Type-I See-Saw,

$$m_\nu = -m_D M_R^{-1} m_D^T$$

which can be diagonalised by,

$$(m_\nu)^{diag} = U^T \; m_\nu \; U$$

where, $(m_\nu)^{diag} = Diag(m_1, m_2, m_3)$ contains at least one zero eigenvalue.

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} U_{ph}$$

where,

$$U_{ph} = Diag(1, e^{-i\alpha/2}, 1)$$

Non-Zero Neutrino Mass

Using Casas-Ibarra Parametrization (Casas, J.A. and Ibarra, A., *Nucl. Phys. B* 168, 171-204, 2001),

$$(m_D)_{j\alpha} = \sqrt{M_{R_j}} R_{ji} \sqrt{m_i} U^\dagger_{i\alpha}$$

since M_{R_1} is decoupled from the spectrum,

$$\begin{aligned} Y_{1\alpha} &= \frac{1}{v}(\sqrt{M_{R_1}} R_{1i} \sqrt{m_i} U^\dagger_{i\alpha}) \\ &= \frac{1}{v}(\sqrt{M_{R_1}} R_{11} \sqrt{m_1} U^\dagger_{1\alpha} + \sqrt{M_{R_1}} R_{12} \sqrt{m_2} U^\dagger_{2\alpha} + \sqrt{M_{R_1}} R_{13} \sqrt{m_3} U^\dagger_{3\alpha}) = 0 \end{aligned}$$

- **Normal Hierarchy (NH):**

$$\begin{cases} m_1 = 0 \\ m_2 = \sqrt{\Delta m^2_\odot} \ll m_{\chi_3} = \sqrt{\Delta m^2_{\mathrm{atm}}} \end{cases}$$

$$R = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos z & -\sin z \\ 0 & \sin z & \cos z \end{pmatrix}$$

- **Inverted Hierarchy (IH):**

$$\begin{cases} m_3 = 0 \\ m_1 = \sqrt{\Delta m^2_{\mathrm{atm}} - \Delta m^2_\odot} \simeq m_2 = \sqrt{\Delta m^2_{\mathrm{atm}}} \end{cases}$$

$$R = \begin{pmatrix} 0 & 0 & 1 \\ \cos z & -\sin z & 0 \\ \sin z & \cos z & 0 \end{pmatrix}$$

$$m_D = v \begin{pmatrix} 0 & 0 & 0 \\ Y_{2e} & Y_{2\mu} & Y_{2\tau} \\ Y_{3e} & Y_{3\mu} & Y_{3\tau} \end{pmatrix}$$

Charged Lepton Flavour Violation: $\mu \to e\gamma$ Branching Ratio

The branching ratio of $\mu \to e\gamma$ is given by (R. Alonso et. al., JHEP 01, **118**, 2013; A. Ilakovac and A. Pilaftsis, *Nucl. Phys. B* 437, **491**, 1995; F Deppisch and J. W. F. Valle, *Phys. Rev. D* 72, 036001, 2005; Marcano et. al., hep-ph/1710.08032),

$$Br(\mu \to e\gamma) = \frac{\alpha_W^3 s_W^2}{256\pi^2}\frac{m_\mu^4}{M_W^4}\frac{m_\mu}{\Gamma_\mu}|G_\gamma^{\mu e}|^2$$

$$G_\gamma^{\mu e} = \sum_i U_{ei}U_{\mu i}^* G_\gamma(x_i) = \sum_j U_{eN_j}U_{\mu N_j}^* G_\gamma(x_{N_j})$$

where, $x_i = \frac{m_{\nu_i}^2}{M_W^2}$ and $x_{N_j} = \frac{m_{N_j}^2}{M_W^2}$ and $G_\gamma(x) = -\frac{x(2x^2+5x-1)}{4(1-x^3)} - \frac{2x^3}{2(1-x^4)} ln(x)$

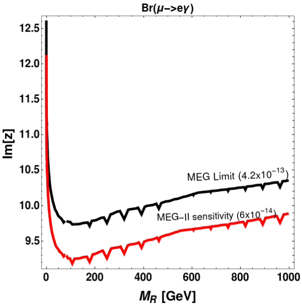
After some mathematics,

$$Br(\mu \to e\gamma) = \frac{\alpha_W^3 s_W^2}{256\pi^2}\frac{m_\mu^4}{M_W^4}\frac{m_\mu}{\Gamma_\mu}\frac{4}{M_R^4}G_\gamma^2(x_N)|(m_D^\dagger m_D)_{e\mu}|^2$$

where,

$$\begin{aligned}(m_D^\dagger m_D)_{e\mu}\Big|_{NH} &= M_R\big[(m_2 U_{e2}U_{\mu 2}^* + m_3 U_{e3}U_{\mu 3}^*)\cosh(2Im[z]) \\ &\quad + i\sqrt{m_2}\sqrt{m_3}(U_{e3}U_{\mu 2}^* - U_{e2}U_{\mu 3}^*)\sinh(2Im[z])\big] \\ (m_D^\dagger m_D)_{e\mu}\Big|_{IH} &= M_R\big[(m_1 U_{e1}U_{\mu 1}^* + m_2 U_{e2}U_{\mu 2}^*)\cosh(2Im[z]) \\ &\quad + i\sqrt{m_1}\sqrt{m_2}(U_{e2}U_{\mu 1}^* - U_{e1}U_{\mu 2}^*)\sinh(2Im[z])\big]\end{aligned}$$

$\mu \to e\gamma$ Branching Ratio



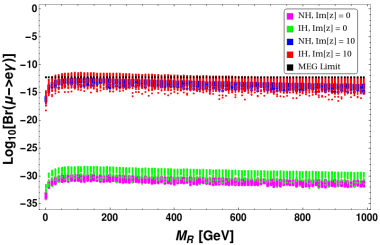


Figure: [Left]: $Br(\mu \to e\gamma)$ in $M_R - Im[z]$ plane; [Right]: $Log[Br(\mu \to e\gamma)]$ for $Im[z] = 0, 10$ for both NH and IH. The black dashed line represents the MEG limit.

Naturalness and vacuum stability bounds can also be applied (G. Bambhaniya, , P.S. Bhupal Dev, S. Goswami, S. Khan and W. Rodejohann, *Phys. Rev. D* 95, **9**, 2017), however these bounds are extremely weaker for M_R upto TeV scale.

Summary

- The SM has been extended by a vector-like fermionic doublet and three right handed neutrinos. After diagonalization, we get three Majorana states as dark sector particles, the lightest one being the Dark Matter.
- We studied the Relic abundance and Direct Detection of the DM candidate and the same has been confronted with recent experiments like PLANCK and XENON-1T. We showed the favourable points satisfying both relic density constraints from PLANCK and direct detection bounds from XENON-1T in the $\Delta M_{23} - m_3$ plan.
- The model is also extended to an anomaly free gauged $U(1)_{B-L}$ symmetry to get new signatures in Relics as well as in Direct Detection.
- We show that for singlet-doublet Majorana DM, the mixing can be pretty large ($\sin\theta \sim 0.6$ for 1 TeV DM) since it escapes the Z-mediated direct search, in constrast to singlet-doublet Dirac DM, where the mixing is restricted to $\sin\theta \sim 0.2$.
- The tiny neutrino mass has been explained in a Type-I see-saw framework. In the $U(1)_{B-L}$ model, we can treat the right handed neutrino mass as a bridging ligand of the model.

Sincerely,
Manoranjan

Back-Up Slides

DM-SM Interactions

$$\mathcal{L}_{int}^{Gauge} = \overline{\Psi} i\gamma^\mu(-i\frac{g}{2}\tau.W_\mu - ig'\frac{Y}{2}B_\mu)\Psi$$
$$= \left(\frac{e}{2sin\theta_W cos\theta_W}\right)\overline{\psi^0}\gamma^\mu Z_\mu \psi^0 + \frac{e}{\sqrt{2}sin\theta_W}(\overline{\psi^0}\gamma^\mu W_\mu^+\psi^- + \psi^+\gamma^\mu W_\mu^-\psi^0)$$
$$- e\psi^+\gamma^\mu A_\mu \psi^- - \left(\frac{e}{2sin\theta_W cos\theta_W}\right)cos2\theta_W \psi^+\gamma^\mu Z_\mu \psi^-$$

In mass bases,

$$\mathcal{L}_{int}^{Gauge} = \left(\frac{e}{2sin\theta_W cos\theta_W}\right)(-\cos\theta\overline{\chi_{1L}}i\gamma^\mu Z_\mu \chi_{2L} - \sin\theta\overline{\chi_{2L}}i\gamma^\mu Z_\mu\chi_{3L} + h.c.)$$
$$+ \frac{e}{\sqrt{2}\sin\theta_W}(\cos\theta\overline{\chi_1}\gamma^\mu W_\mu^+\psi^- + \overline{\chi_2}i\gamma^\mu W_\mu^+\psi^- - \sin\theta\overline{\chi_3}\gamma^\mu W_\mu^+\psi^-)$$
$$+ \frac{e}{\sqrt{2}\sin\theta_W}(\cos\theta\psi^+\gamma^\mu W_\mu^-\chi_1 - \psi^+ i\gamma^\mu W_\mu^-\chi_2 - \sin\theta\psi^+\gamma^\mu W_\mu^-\chi_3)$$
$$- e\psi^+\gamma^\mu A_\mu\psi^- - (\frac{e}{2sin\theta_W cos\theta_W})cos2\theta_W\psi^+\gamma^\mu Z_\mu\psi^-$$

$$-\mathcal{L}_{DM-Higgs} = \frac{Y_1}{\sqrt{2}}\left(\sin 2\theta(\overline{\chi_1}h\chi_1 - \overline{\chi_3}h\chi_3) + \cos 2\theta(\overline{\chi_1}h\chi_3 + \overline{\chi_3}h\chi_1)\right)$$

Annihilation Channels

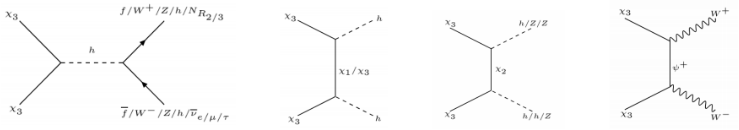


Figure 1: Annihilation channels to SM through which the DM (χ_3) density depletes.

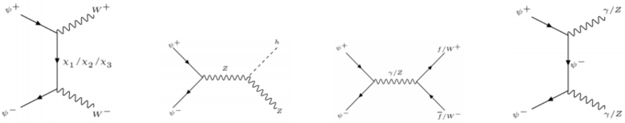
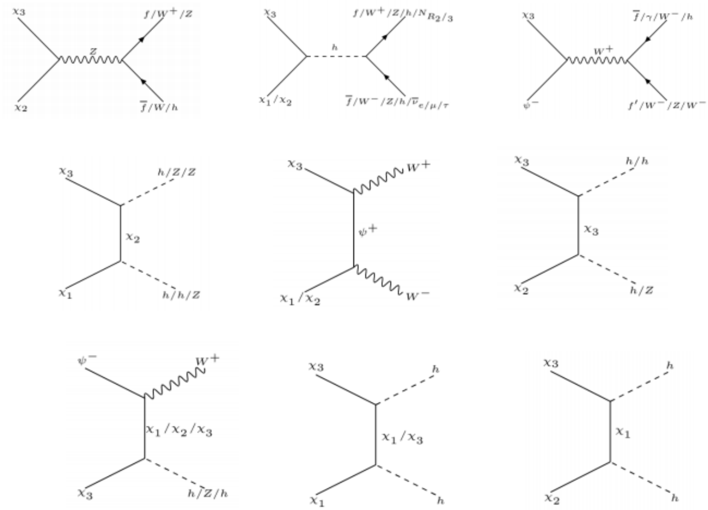


Figure 3: Annihilation channels of ψ^+ and ψ^- that contributes to coannihilation of DM (χ_3).

Coannihilation Channels



Theoretical and Experimental constraints

- **Perturbativity:** In order to maintain Perturbativity of the model, Yukawa couplings should satisfy the following limits:

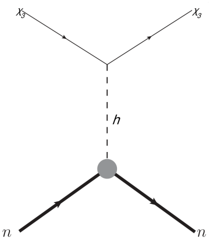
$$|Y_1| < \sqrt{4\pi}, \quad |Y_{\alpha j}| < \sqrt{4\pi} \quad .$$

- **LEP Limit:** LEP exclusion bound on charged fermion mass, $m_{\psi^\pm} = M > 102.7$ GeV.
(Abdallah et. al., DELPHI collaboration, *Eur. Phys. J. C*, **31**, 2003.)

- **Relic Density:** The observed number density of DM is constrained by the combined WMAP and PLANCK data as: $0.1166 \leq \Omega_{DM} h^2 \leq 0.1206$.
(Hinshaw et. al., WMAP Collaboration, *Astrophys. J. Suppl. 208*, **19**, 2013; P. A. R. ade et. al., Planck collaboration,*Astron. Astrophys. 571*, **A16**, 2014.)

- **Direct Detection:** For direct search, we have used the current stringent bounds from XENON-1T.
(E. Aprile et. al., XENON-1T Collaboration, *Phys. Rev. Lett., 121,* **11**, *2018.)*

Direct Detection of Singlet-Doublet Majorana DM



$$\sigma_{SI} = \frac{1}{\pi A^2} \mu_r^2 |\mathcal{M}|^2$$

where,

$$\mathcal{M} = \Big[Z f_P + (A - Z) f_n \Big]$$

Here,

$$f_{p,n} = \sum_{q=u,d,s} f_{Tq}^{p,n} \alpha_{(p,n)} \frac{m_{(p,n)}}{m_q} + \frac{2}{27} f_{TG}^{p,n} \sum_{q=c,b,t} \alpha_q \frac{m_{(p,n)}}{m_q}$$

where,

$$\alpha_q = \frac{Y_1 \sin 2\theta}{M_h^2} \frac{m_q}{v} = \frac{\Delta M \ \sin^2 2\theta m_q}{v^2 M_h^2}$$

Finally,

$$\sigma_{SI} = \frac{4 Y^2 \sin^2 2\theta}{\pi A^2 \mu_r^2 M_h^4} \Big[\frac{m_p}{v} \Big(f_{Tu}^p + f_{Td}^p + f_{Ts}^p + \frac{2}{9} f_{TG}^p + \frac{m_n}{v} \Big(f_{Tu}^n + f_{Td}^n + f_{Ts}^n + \frac{2}{9} f_{TG}^n \Big) \Big]^2$$

DM-SM Interactions in gauged $U(1)_{B-L}$ case

$$\begin{aligned}
\mathcal{L}_{int} &= \overline{\Psi} i\gamma^\mu(-i\frac{g}{2}\tau.W_\mu - ig'\frac{Y}{2}B_\mu - ig_{BL}Y_{BL}(Z_{BL})_\mu)\Psi + \overline{N_{R_1}} i\gamma^\mu(-ig_{BL}Y_{BL}(Z_{BL})_\mu)N_{R_1} \\
&= \Big(\frac{e}{2sin\theta_W cos\theta_W}\Big)\overline{\psi^0}\gamma^\mu Z_\mu \psi^0 + \frac{e}{\sqrt{2}sin\theta_W}(\overline{\psi^0}\gamma^\mu W^+_\mu \psi^- + \psi^+\gamma^\mu W^-_\mu \psi^0) \\
&- e\psi^+\gamma^\mu A_\mu \psi^- - \Big(\frac{e}{2sin\theta_W cos\theta_W}\Big)cos2\theta_W \psi^+\gamma^\mu Z_\mu \psi^- \\
&- g_{B-L}\Big(\overline{\psi^0}\gamma^\mu (Z_{BL})_\mu \psi^0 + \psi^+\gamma^\mu (Z_{BL})_\mu \psi^- + \overline{N_{R_1}}\gamma^\mu (Z_{BL})_\mu N_{R_1}\Big)
\end{aligned}$$

In physical bases,

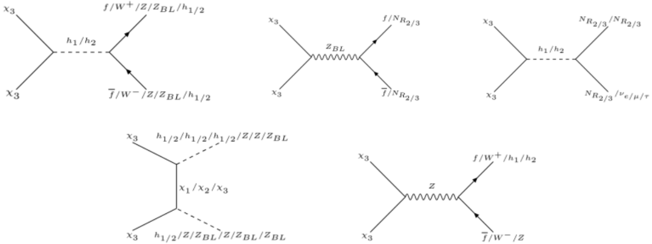
$$\begin{aligned}
\mathcal{L}^{Gauge}_{DM-SM} &= (\frac{e}{2sin\theta_W cos\theta_W})\Big[(2s_{23}s_{13}c_{13})(\overline{\chi_{3L}}\gamma^\mu Z_\mu \chi_{3L} - \overline{\chi_{1L}}\gamma^\mu Z_\mu \chi_{1L}) \\
&+ (c_{23}c_{13}\overline{\chi_{1L}}\gamma^\mu Z_\mu \chi_{2L} - c2_{13}s_{23}\overline{\chi_{1L}}\gamma^\mu Z_\mu \chi_{3L} - s_{13}c_{23}\overline{\chi_{2L}}\gamma^\mu Z_\mu \chi_{3L} + h.c.)\Big] \\
&+ \frac{e}{\sqrt{2}sin\theta_W}\Big[\frac{1}{\sqrt{2}}\Big((c_{13} - s_{13}s_{23})\overline{\chi_{1L}} + c_{23}\overline{\chi_{2L}} - (s_{13} + s_{23}c_{13})\overline{\chi_{3L}}\Big)\gamma^\mu W^+_\mu \psi^-_L \\
&+ \frac{1}{\sqrt{2}}\Big((c_{13} + s_{13}s_{23})\overline{\chi_{1L}} - c_{23}\overline{\chi_{2L}} - (s_{13} - s_{23}c_{13})\overline{\chi_{3L}}\Big)\gamma^\mu W^+_\mu \psi^-_R + h.c.\Big] \\
&- e\psi^+\gamma^\mu A_\mu \psi^- - \Big(\frac{e}{2sin\theta_W cos\theta_W}\Big)cos2\theta_W \psi^+\gamma^\mu Z_\mu \psi^-
\end{aligned}$$

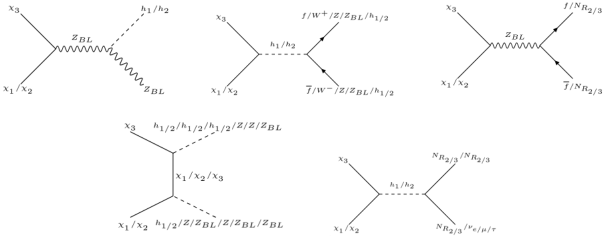
DM-SM Interactions in gauged $U(1)_{B-L}$ case

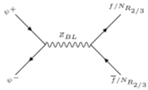
$$
\begin{aligned}
\mathcal{L}_{DM-Z_{BL}} = & -g_{BL}\Big(s_{23}s2_{13} + c_{13}^2 c_{23}^2)(\overline{\chi_{3L}}\gamma^\mu (Z_{BL})_\mu \chi_{3L} \\
& + (s_{13}^2 c_{23}^2 - s_{23}s2_{13})\overline{\chi_{1L}}\gamma^\mu (Z_{BL})_\mu \chi_{1L} + s_{23}^2\overline{\chi_{2L}}\gamma^\mu (Z_{BL})_\mu \chi_{2L} \\
& + (\frac{1}{2}s2_{23}s_{13} + c_{23}c_{13})(\overline{\chi_{1L}}\gamma^\mu (Z_{BL})_\mu \chi_{2L} + h.c) \\
& + (\frac{1}{2}s2_{13}c_{23}^2 - c2_{13}s_{23})(\overline{\chi_{1L}}\gamma^\mu (Z_{BL})_\mu \chi_{3L} + h.c.) \\
& + (\frac{1}{2}s2_{23}c_{13} - s_{13}c_{23})\overline{\chi_{2L}}\gamma^\mu (Z_{BL})_\mu \chi_{3L} + h.c.)\Big) \\
& - g_{BL}\psi^+\gamma^\mu (Z_{BL})_\mu \psi^-
\end{aligned}
$$

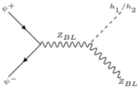
$$
\begin{aligned}
-\mathcal{L}_{DM-Higgs} = & \frac{Y_1}{2}(h_1\cos\beta - h_2\sin\beta)\Big[\Big((c_{13} - s_{13}s_{23})\overline{\chi_{1L}} + c_{23}\overline{\chi_{2L}} - (s_{13} + s_{23}c_{13})\overline{\chi_{3L}}\Big) \\
& \Big(s_{13}c_{23}(\chi_{1L})^c + s_{23}(\chi_{2L})^c + c_{13}c_{23}(\chi_{3L})^c\Big) + h.c.\Big] \\
& + \frac{y_1'}{2\sqrt{2}}(h_2\cos\beta + h_1\sin\beta)\Big[\Big(s_{13}c_{23}\overline{(\chi_{1L})^c} + s_{23}\overline{(\chi_{2L})^c} + c_{13}c_{23}\overline{(\chi_{3L})^c}\Big) \\
& \Big(s_{13}c_{23}\chi_{1L} + s_{23}\chi_{2L} + c_{13}c_{23}\chi_{3L}\Big) + h.c.\Big]
\end{aligned}
$$

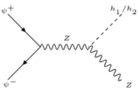
Additional Annihilation and coannihilation channels in light of $U(1)_{B-L}$

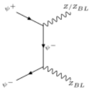





ψ+
ψ−
Z_BL
f/N_R2/3
f̄/N_R2/3


ψ+
ψ−
Z_BL
h1/h2
Z_BL


ψ+
ψ−
Z
h1/h2
Z


ψ+
ψ−
Z/Z_BL
ψ−
Z_BL

Theoretical and Experimental constraints

- **Stability of potential:**

$$\lambda_H \geq 0, \quad \lambda_\Phi \geq 0 \;\; \text{and} \;\; \lambda_{H\Phi} + 2\sqrt{\lambda_H \lambda_\Phi} \geq 0.$$

- **Perturbativity:**

$$|\lambda_H| < 4\pi, \quad |\lambda_\Phi| < 4\pi, \quad |\lambda_{H\Phi}| < 4\pi \;\; ;$$
$$|Y_1| < \sqrt{4\pi}, \quad |Y_{\alpha j}| < \sqrt{4\pi}, \quad |g_{BL}| < \sqrt{4\pi} \;\; .$$

- **LEP limits:** LEP exclusion bound on charged fermion mass, $m_{\psi^\pm} = M > 102.7$ GeV
- **Constrained on $M_{Z_{BL}}$:** LEP II: $M_{Z_{BL}}/g_{BL} \geq 7$ TeV. (Cacciapaglia, G et. al., *Phys. Rev. D* 74, 033011, 2006)

ATLAS and CMS at LHC Run 2: $M_{Z_{BL}} > 4.3$ TeV for $g_{BL} \sim$ SM coupling.

(Aaboud et. al., ATLAS Collaboration, *JHEP* 10, **182**, 2017; Sirunyan et. al., CMS Collaboration, *JHEP* 08, **130**, 2018.)

- **Bounds on scalar singlet:**

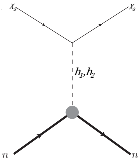
i) For W mass corrections at NLO : $0.2 \leq \sin\beta \leq 0.3$ for $250 GeV \leq m_{h_2} \leq 850 GeV$.

(López-Val, D. and Robens, *Phys. Rev. D* 90, 114018, 2014.)

ii) For the requirement of perterbative unitarity : $\sin\beta \leq 0.2$ for $m_{h_2} \geq 850 GeV$.
iii) Direct search measurement of Higgs signal strength at LHC:$|\sin\beta| < 0.36$.

(T.Robens et. al.,*Eur. Phys. J. C* 76, **5**, 2668, 2016)

Direct Detection of Singlet-Doublet Majorana DM in $U(1)_{B-L}$ case



$$\alpha_q = \frac{m_q}{v}\left(\frac{\lambda_a \cos\beta}{m_{h_1}^2} - \frac{\lambda_b \sin\beta}{m_{h_2}^2}\right),$$

where

$$\lambda_a = \frac{Y_1}{2}(s_{13} + s_{23}c_{13})c_{13}c_{23}\cos\beta - \frac{y_1'}{2\sqrt{2}}c_{13}^2 c_{23}^2 \sin\beta\,,$$

$$\lambda_b = -\frac{Y_1}{2}(s_{13} + s_{23}c_{13})c_{13}c_{23}\sin\beta - \frac{y_1'}{2\sqrt{2}}c_{13}^2 c_{23}^2 \cos\beta\,.$$

$$\sigma^{SI} = \frac{\mu_r^2}{\pi A^2}\left(\frac{\lambda_a \cos\beta}{m_{h_1}^2} - \frac{\lambda_b \sin\beta}{m_{h_2}^2}\right)^2 \Big[Z\frac{m_p}{v}\left(f_{Tu}^p + f_{Td}^p + f_{Ts}^p + \frac{2}{9}f_{TG}^p\right.$$

$$\left. + (A-Z)\frac{m_n}{v}\left(f_{Tu}^n + f_{Td}^n + f_{Ts}^n + \frac{2}{9}f_{TG}^n\right)\right]^2$$