Phenomenology of Singlet-doublet VLF Dark Matter

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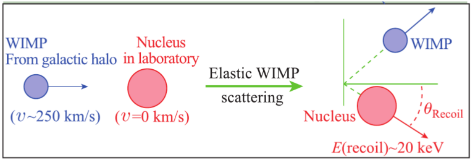
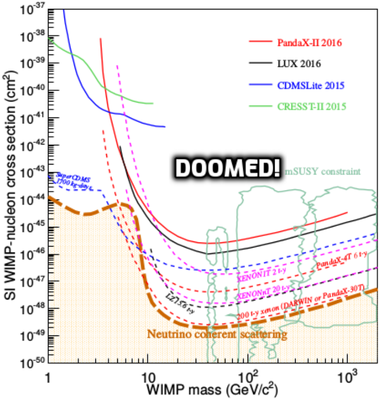
Plan of talk

- Introduction & Motivation
- Phenomenology of singlet-doublet DM
  - Fermion DM with scalar triplet at direct and collider searches (based on: Phys. Rev. D 100, 015027 (2019))
  - Flavoured gauge extension of singlet-doublet fermionic DM: neutrino mass, high scale validity and collider signatures (based on: JHEP 1910 (2019) 275)
  - Singlet-Doublet Fermionic DM and Gravitational Wave in 2HDM (based on: Phys.Rev.D 101 (2020) 5, 055028)
- Conclusions

Direct Search: The Grim Reaper





- Strong bound on WIMP-like DM models from non-observation in direct search expts.
- No significant excess @ colliders $\sim$ TeV scale.
- Alternatives $\Longrightarrow$ FIMP (0911.1120), SIMP (1402.5143), ELDER (1706.05381)...typically sub-GeV DM.
- *'Rennervate!'* Possible way to evade DD $\Longrightarrow$ Singlet-doublet mixing.

Singlet-doublet VLF: Pros and cons

- Pure singlet does not have enough annihilation (only $\frac{\chi\chi HH}{\Lambda}$).
- What about direct search?
  - The effective operator $\left(\overline{\psi}\gamma^{\mu}\psi\right)\left(\overline{q}\gamma_{\mu}q\right)$ is generated via Z exchange for a pure doublet.
    - Mixing reduces the size of the coupling to Z.
      (0706.0918, 1109.2604, 1505.03867, 1509.05323, 1510.02760, 1601.01569, 1704.03417, 1812.06505)
- This operator vanishes if DM is Majorana.
  - But if Dirac $\rightarrow$ makes the DM dominantly singlet to evade σ^{SI}.
    (Yaguna,1510.06151)
    - ✓ Split the Dirac state into *pseudo-Dirac* states $\implies$ kinematically forbid the inelastic Z mediation.
- VLFs do not contribute to the gauge anomaly.

VLF DM+triplet scalar

SB,PG,SK,NS & BB, Phys. Rev. D 100, 015027 (2019)

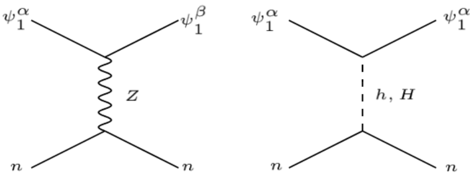
Particles	$SU(3)_c$	$SU(2)$	$U(1)_Y$	$\mathcal{Z}_2$
$\psi^T : \left(\psi^0, \psi^-\right)$	1	2	-1	-1
χ^0	1	1	0	-1
Δ	1	3	2	+1
H	1	2	1	+1

$$-\mathcal{L}_{yuk} \supset \frac{1}{\sqrt{2}}\left[(y_L)_{ij}\overline{L^c}_i i\sigma^2 \Delta L_j + y_\psi \overline{\psi^c} i\sigma^2 \Delta\psi\right] + \underbrace{Y}_{\frac{\Delta M \sin 2\theta}{\sqrt{2}\langle H\rangle}} \overline{\psi}\widetilde{H}\chi^0 + h.c.$$

$$\underbrace{M_{\psi_1}(\text{Lightest } Z_2 \text{ odd}), \sin\theta, \Delta M = M_{\psi^\pm} - M_{\psi_1} \approx M_{\psi_2} - M_{\psi_1}}_{\text{Free parameters}}$$

- ν mass (Type-II): $\mathcal{R} = \left(\frac{(y_L)_{\alpha\beta}}{y_\psi \sin^2\theta}\right) \leq 10^{-6}$
- EWPO: $\Delta T \simeq \frac{(\delta m)^2}{3\pi s_w^2 m_W^2} < 0.2 \implies m_{H^{\pm\pm}} - m_{H^\pm} \leq 50 \text{ GeV}$ (1604.08099)
- Collider limits: are lose if $\langle\Delta\rangle > 10^{-4}$ GeV.

Pseudo-Dirac state



$\sigma_{SI} \sim 10^{-40} \sin^4\theta < 10^{-50}$ cm^2 $\Longrightarrow$ $\sin\theta < \mathcal{O}(10^{-3})$ $\Longrightarrow$ small ΔM $\Longrightarrow$ co-annihilation

Basis: $\{\psi^c, \psi\}$

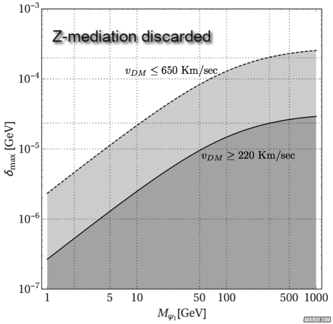
$$\begin{pmatrix} M_\psi & m \\ m & M_\psi \end{pmatrix}$$

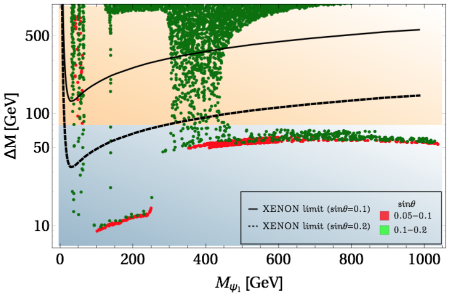
pseudo-Dirac splitting: $\psi_1 \to \{\psi_1^\alpha, \psi_1^\beta\} \Longrightarrow \delta m = y_\psi \sin^2\theta \langle\Delta^0\rangle$

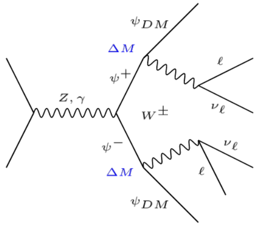
Off-diagonal Z-mediation:

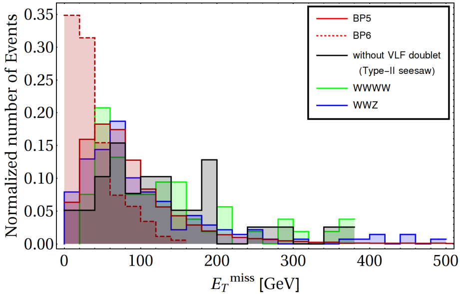
$$\mathcal{L} \supset i\overline{\psi_1}\left(\partial\!\!\!/ - i g_z \gamma_\mu Z^\mu\right)\psi_1 \Longrightarrow \overline{\psi_1^\alpha} i\partial\!\!\!/ \psi_1^\alpha + \overline{\psi_1^\beta} i\partial\!\!\!/ \psi_1^\beta + g_z \overline{\psi_1^\alpha}\gamma_\mu \psi_1^\beta Z^\mu$$

Forbidding Z-mediation: $\delta_{max} > \frac{\beta^2}{2}\frac{M_{\psi_1} M_N}{M_{\psi_1}+M_N}$ (hep-ph/0101138)









VLF DM in SM $\otimes\, U(1)_{B-3L_\tau}$

DB,PG,AKS & BB : JHEP 1910 (2019) 275

Particles	$SU(3)_c$	$SU(2)$	$U(1)_Y$	$U(1)_{B-3L_\tau}$
$\mathcal{S}$	1	1	0	3
Φ	1	1	0	-3/2
$N_{R_{1,2}}$	1	1	0	0
N_{R_3}	1	1	0	-3
χ	1	1	0	3/4
$\psi^T : \left(\psi^0, \psi^-\right)$	1	2	-1/2	3/4

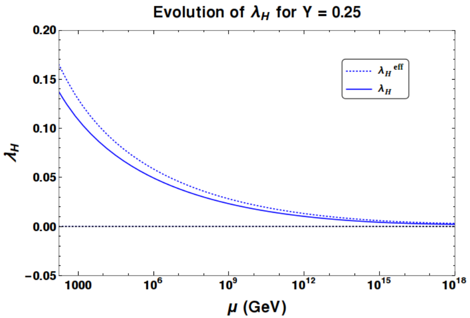
$$-\mathcal{L}_{yuk} \supset \sum_{i=1}^{2} \sum_{\alpha=e,\mu} y_{\alpha i}\, \overline{L_\alpha} \widetilde{H} N_{R_i} + y_{\tau 3} \overline{L_3} \widetilde{H} N_{R_3} + \underbrace{Y}_{\frac{\Delta M \sin 2\theta}{\sqrt{2} v_d}} \overline{\psi} \widetilde{H} \chi + \text{h.c.}$$

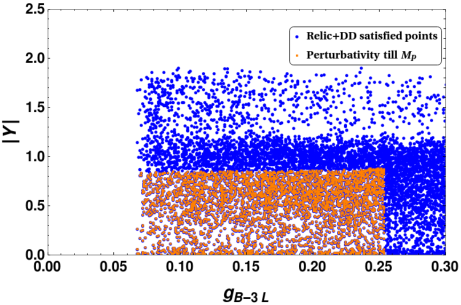
- Lose collider bound: $M_{Z'} > 2.42$ TeV for *ditau* final state (CMS:1611.06594, ATLAS:1709.07242)
- NSI: $M_{Z'}/g' > 4.8$ TeV (1812.04067)
- New scalars $(m_i \sim 300$ GeV$, \sin\theta_{ij} \sim 0.1)$:
  - $\rightarrow$ break $U(1)_{B-3L_\tau}$
  - $\rightarrow$ pseudo-Dirac splitting via $\Longrightarrow\ y_\chi \overline{\chi^c} \chi \Phi$
  - $\rightarrow$ ν mass generation (Type-I)
- No ad-hoc symmetry || $\left\{ \textit{Free parameters: } \{\overbrace{M_{\psi_1}, \Delta M, \sin\theta}^{\textit{same as before}}, g_{B-3L_\tau}, \widetilde{v} = v_S/v_\Phi\} \right\}$

High scale stability and Collider search

- $\lambda_i > 0$ (BFB) & $|\lambda_i|, |y_i|, |g_i| \leq 4\pi$ (perturbative).
- Radiatively corrected 1-loop effective potential $V_h^{\text{eff}} = \frac{\lambda_H^{\text{eff}}}{4} h^4$ with:

$$\lambda_H^{\text{eff}} = \lambda_H^{\text{SM, eff}} + \underbrace{\lambda_H^{(S,\Phi),\text{ eff}} + \lambda_H^{(\psi,\chi),\text{ eff}}}_{\text{due to new fields}} > 0$$

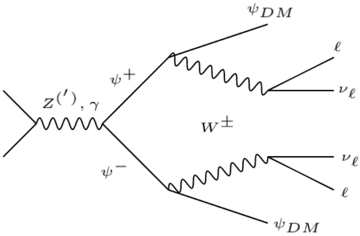


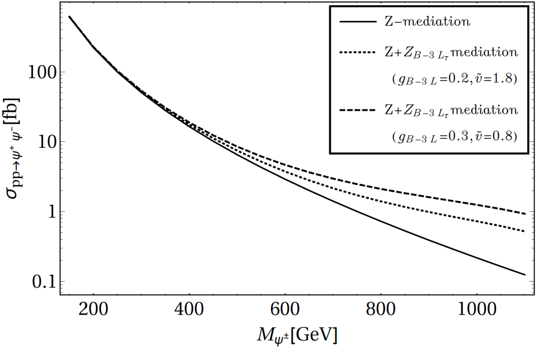


High scale stability and Collider search

Large $\Delta M \rightarrow \ell^+\ell^- + \not{E}_T$

$\Delta M < m_W \rightarrow$ stable charged track





For a sizeable enhancement $M_{\psi^\pm} > 800$ GeV $\Longrightarrow$ production x-section reduces.

VLF DM+2HDM

ADB,AP & BB : Phys.Rev.D 101 (2020) 5, 055028

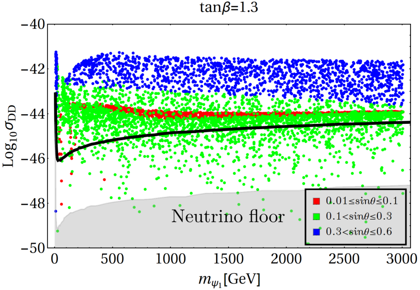
Particles	$SU(3)_c$	$SU(2)$	$U(1)_Y$	$\mathcal{Z}_2$	$\mathcal{Z}_2^{'}$
$\psi^T : \left(\psi^0, \psi^-\right)$	1	2	1	+	-
χ^0	1	1	0	+	-
Φ_2	1	2	1	+	+
Φ_1	1	2	1	-	+

$$V(\Phi_1,\Phi_2) \supset m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2 - m_{12}^2\left(\Phi_1^\dagger\Phi_2 + H.c\right) + \frac{\lambda_1}{2}\left(\Phi_1^\dagger\Phi_1\right)^2 + \frac{\lambda_2}{2}\left(\Phi_2^\dagger\Phi_2\right)^2 + \lambda_3\Phi_1^\dagger\Phi_1\,\Phi_2^\dagger\Phi_2 + \lambda_4\Phi_1^\dagger\Phi_2\,\Phi_2^\dagger\Phi_1 + \frac{\lambda_5}{2}\left[\left(\Phi_1^\dagger\Phi_2\right)^2 + H.c.\right]; \quad -\mathcal{L}_{yuk} \supset Y\left(\overline{\psi}\widetilde{\Phi}_2\chi^0 + H.c.\right)$$

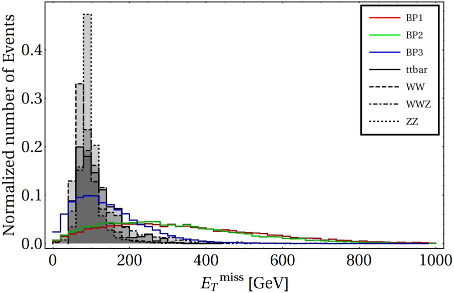
Second Higgs $\begin{cases}\text{Surviving DD bound}\\ \text{Stochastic GW due to SFOPT}\end{cases}$

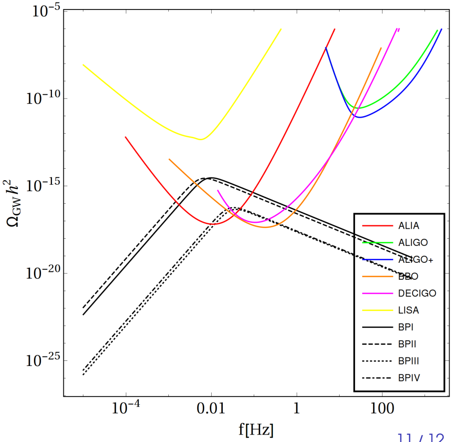
$$\underbrace{m_{H^\pm} \approx m_A \sim 600\ \text{GeV}, m_{H^\pm} - m_H \geq v_{\text{EW}}, \tan\beta \sim 1}_{\text{SFOPT (1611.05874,1712.08430)}}$$

A complementarity of searches (ADB,AP & BB : Phys.Rev.D 101 (2020) 5, 055028)



$$\Omega_{GW}h^2 = \underbrace{\Omega_{col}h^2}_{\text{bubble collision}} + \underbrace{\Omega_{sw}h^2}_{\text{sound wave}} + \underbrace{\Omega_{turb}h^2}_{\text{turbulance}}$$





Conclusion

- Pseudo-Dirac splitting helps the singlet-doublet Dirac DM to survive direct search guillotine.
- In presence of new annihilation channels several complementary signatures manifest.
- Extended scalar sector stabilizes the EW vacuum, also constraints the model parameter space by constraining different couplings.
- Interesting correlations can be made between DM and neutrino sector.

Thank you!
Questions/Comments/Critique?

Backup Slides

Type-II seesaw

Coupling of SM leptons with triplet:

$$(m_\nu)_{ij} = \frac{1}{2}(y_L)_{ij}\langle\Delta\rangle \simeq (y_L)_{ij}\ \frac{\mu v_d^2}{2\sqrt{2}\mu_\Delta^2},$$

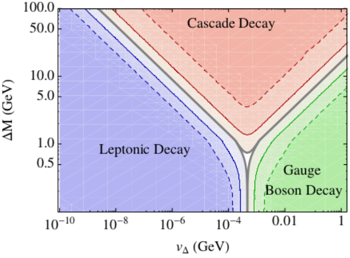
$\langle\Delta\rangle$ induces Majorana mass term for ψ:

$$m = \frac{1}{2}y_\psi \sin^2\theta\langle\Delta\rangle \sim \mathcal{O}(100\ \mathrm{keV}).$$

Trading off $\langle\Delta\rangle$, $m_\nu \sim \mathcal{O}(0.1\ \mathrm{eV})$

$$(m_\nu)_{ij} = \left(\frac{(y_L)_{\alpha\beta}}{y_\psi \sin^2\theta}\right) m \implies \left(\frac{(y_L)_{\alpha\beta}}{y_\psi \sin^2\theta}\right) \leq 10^{-6}.$$

- EWPO: $\Delta T \simeq \frac{(\delta m)^2}{3\pi s_w^2 m_W^2} < 0.2 \implies m_{H^{\pm\pm}} - m_{H^{\pm}} \leq 50\ \mathrm{GeV}$ (1604.08099)
- Collider bounds (hep-ex/0303026, 1710.09748, 1803.00677):
  - $H^{\pm\pm} \to \ell^{\pm\pm}\ell^{\pm\pm} \implies m_{H^{\pm\pm}} > 100\ \mathrm{GeV}$ (LEP-II).
  - Pair-production: $m_{H^{\pm\pm}} > 870\ \mathrm{GeV}$ (ATLAS).
  - Limits are valid if $v_\Delta < 10^{-4}\ \mathrm{GeV}$ (Plot from:1108.4416).



- Invisible decay: easily evaded due to small mixing.

VLF mass mixing

$$\begin{pmatrix} M_{\psi_1} & 0 \\ 0 & M_{\psi_2} \end{pmatrix} = \mathcal{U}^{\mathcal{T}} \begin{pmatrix} M_\psi & \frac{Y\langle H\rangle}{\sqrt{2}} \\ \frac{Y\langle H\rangle}{\sqrt{2}} & M_\chi \end{pmatrix} \mathcal{U}$$

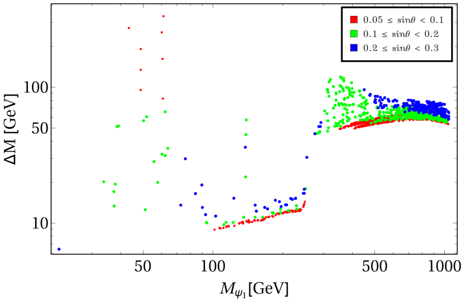
Lightest charge neutral $\mathcal{Z}_2$ odd $\implies \psi_1 \implies DM$

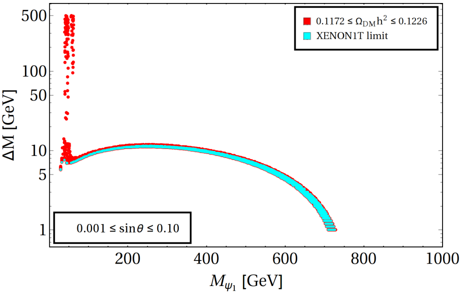
$$M_{\psi^\pm} = M_{\psi_1}\sin^2\theta + M_{\psi_2}\cos^2\theta \approx M_{\psi_2}.$$

$$Y = \frac{(M_{\psi_2} - M_{\psi_1})\sin 2\theta}{\sqrt{2}v_d} = \frac{\Delta M \sin 2\theta}{\sqrt{2}v_d}$$

Presence vs absence of triplet

Left: with triplet, Right: without triplet (1812.06505)





Advantage of triplet $\Longrightarrow$ large ΔM $\Longrightarrow$ improved collider signal.

Scalar potential & gauge boson mass

$$V\left(H,\Phi,\mathcal{S}\right)=\mu_H^2\left(H^\dagger H\right)+\lambda_H\left(H^\dagger H\right)^2+\mu_\Phi^2|\Phi|^2+\lambda_\Phi|\Phi|^4+\mu_{\mathcal{S}}^2|\mathcal{S}|^2$$
$$+\lambda_{\mathcal{S}}|\mathcal{S}|^4+\lambda_1\left(H^\dagger H\right)|\Phi|^2+\lambda_{\mathcal{S}\Phi}|\Phi|^2|\mathcal{S}|^2+\lambda_2\left(H^\dagger H\right)|\mathcal{S}|^2$$
$$+\mu\left(\mathcal{S}\Phi\Phi+H.c\right).$$

$$H=\begin{pmatrix}G^+\\ \frac{h+v_d+iz_1}{\sqrt{2}}\end{pmatrix},\ \Phi=\frac{1}{\sqrt{2}}\left(\phi+v_\Phi+iz_2\right),\mathcal{S}=\frac{1}{\sqrt{2}}\left(s+v_{\mathcal{S}}+iz_3\right).$$

$$m^2_{Z_{B-3L_\tau}}=\frac{9}{4}v_\Phi^2g^2_{B-3L_\tau}\left(1+4\widetilde{v}^2\right).$$

Interaction Lagrangian

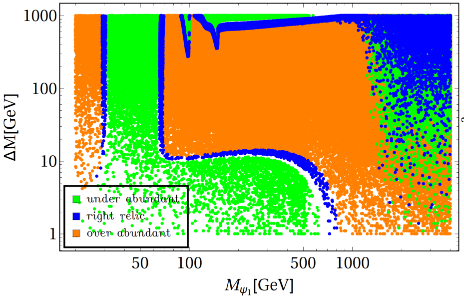
$$\mathcal{L}_f = \overline{\psi} \not{D} \psi + \overline{\chi} \not{D} \chi + \sum_{j=1}^{3} \overline{N^j} \not{D} N^j - M_\psi \overline{\psi} \psi - M_\chi \overline{\chi} \chi - \frac{1}{2} \sum_{i,j=1,2} M_{ij} \overline{(N_i)^c} N_j$$

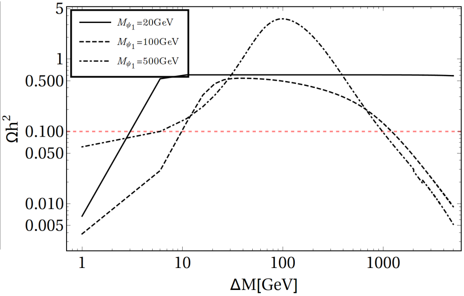
$$- \sum_{i=1,2} \frac{1}{2} y_{i3} \overline{(N_3)^c} N_i \mathcal{S} - \underbrace{y_\chi \overline{(\chi)^c} \chi \Phi}_{\text{pseudo-Dirac splitting}} + \text{h.c.},$$

$$-\mathcal{L}_{yuk} = \sum_{i=1}^{2} \sum_{\alpha=e,\mu} y_{\alpha i} \, \overline{L_\alpha} \widetilde{H} N_{R_i} + y_{\tau 3} \overline{L_3} \widetilde{H} N_{R_3} + \underbrace{Y}_{\frac{\Delta M \sin 2\theta}{\sqrt{2} v_d}} \overline{\psi} \widetilde{H} \chi + \text{h.c.}$$

$$D_\mu \equiv \left(\partial_\mu - i g_2 \frac{\tau^a}{2} W^a_\mu - i g_1 Y B_\mu - \underbrace{i g_{B-3L_\tau} Y_{B-3L_\tau} Z_{(B-3L_\tau)\mu}}_{\text{new gauge boson}} \right).$$

Parameter space for $\sin\theta = 0.2$





- For a fixed DM mass relic is satisfied for two values of ΔM
  - Small $\Delta M \implies$ Co-annihilation
  - Large $\Delta M \implies$ larger Y

$$
\begin{aligned}
T^{\mathrm{VLF}} = &\frac{g_2^2}{16\pi m_W^2}\left(-2\sin^2\theta\ \Pi(M_\psi, M_{\psi_1})\right) \\
&- \frac{g_2^2}{16\pi m_W^2}\left(2\cos^2\theta\ \Pi(M_\psi, M_{\psi_2})\right) \\
&+ \frac{g_2^2}{16\pi m_W^2}\left(2\cos^2\theta\sin^2\theta\ \Pi(M_{\psi_1}, M_{\psi_2})\right),
\end{aligned}
$$

where

$$
\begin{aligned}
\Pi(m_i, m_j) = &-\frac{1}{2}\left(m_i^2 + m_j^2\right)\left(\mathrm{div} + \log\left(\frac{\mu_{EW}^2}{m_i m_j}\right)\right) \\
&+ m_i m_j\left(\mathrm{div} + \frac{\left(m_i^2 + m_j^2\right)\log\left(\frac{m_j^2}{m_i^2}\right)}{2\left(m_i^2 - m_j^2\right)} + \log\left(\frac{\mu_{EW}^2}{m_i m_j}\right) + 1\right) \\
&- \frac{1}{4}\left(m_i^2 + m_j^2\right) - \frac{\left(m_i^4 + m_j^4\right)\log\left(\frac{m_j^2}{m_i^2}\right)}{4\left(m_i^2 - m_j^2\right)},
\end{aligned}
$$

$$\hat{S} = \frac{g_2^2}{16\pi^2}\left(\tilde{\Pi}'\left(M_{\psi^\pm}, M_{\psi^\pm}, 0\right) - \cos^4\theta\tilde{\Pi}'\left(M_{\psi_1}, M_{\psi_1}, 0\right) - \sin^4\theta\tilde{\Pi}'\left(M_{\psi_2}, M_{\psi_2}, 0\right)\right) \\ - \frac{g_2^2}{16\pi^2}\left(2\sin^2\theta\cos^2\theta\tilde{\Pi}'\left(M_{\psi_2}, M_{\psi_1}, 0\right)\right), \tag{33}$$

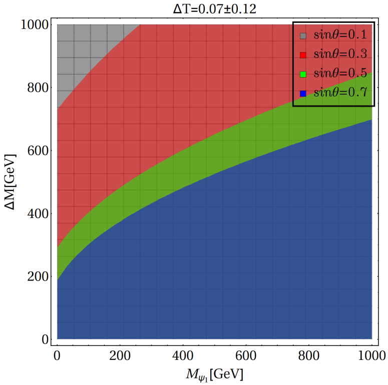
where g_2 is the $SU(2)_L$ gauge coupling. The expression for vacuum polarization for identical masses (at $q^2 = 0$) [79]:

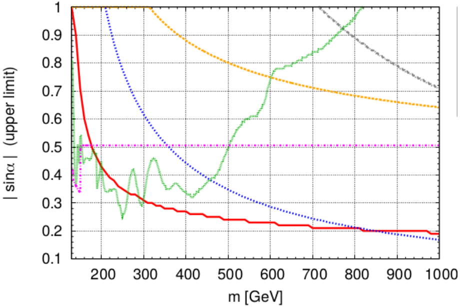
$$\tilde{\Pi}'\left(m_i, m_i, 0\right) = \frac{1}{3}\text{div} + \frac{1}{3}\ln\left(\frac{\mu_{EW}^2}{m_i^2}\right). \tag{34}$$

For two different masses ($m_i \neq m_j$) the expression for vacuum polarization reads [79]:

$$\tilde{\Pi}'\left(m_i, m_j, 0\right) = \left(\frac{1}{3}\text{div} + \frac{1}{3}\ln\left(\frac{\mu_{EW}^2}{m_i m_j}\right)\right) + \frac{m_i^4 - 8m_i^2 m_j^2 + m_j^4}{9\left(m_i^2 - m_j^2\right)^2} \\ + \frac{\left(m_i^2 + m_j^2\right)\left(m_i^4 - 4m_i^2 m_j^2 + m_j^4\right)}{6\left(m_i^2 - m_j^2\right)^3}\ln\left(\frac{m_j^2}{m_i^2}\right) \\ + m_i m_j\left(\frac{1}{2}\frac{m_i^2 + m_j^2}{\left(m_i^2 - m_j^2\right)^2} + \frac{m_i^2 m_j^2}{\left(m_i^2 - m_j^2\right)^3}\ln\left(\frac{m_j^2}{m_i^2}\right)\right). \tag{35}$$

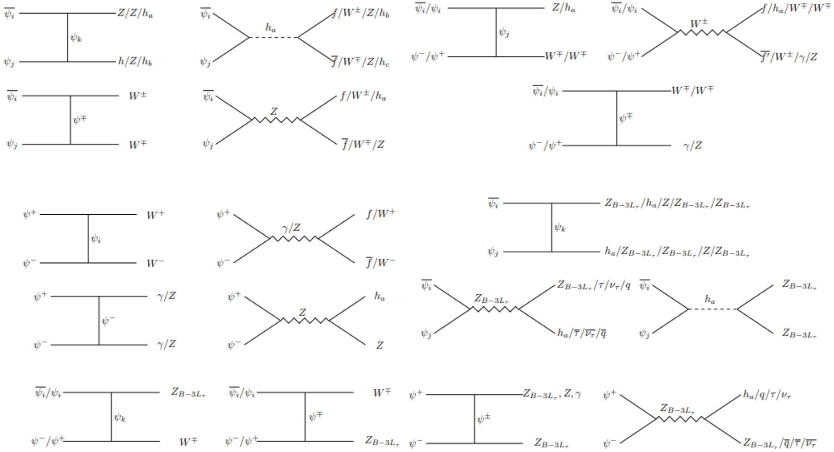
- EWPO: Small $\sin\theta \implies$ large ΔM.





- Scalar mixing: $\sin\theta_m < 0.3$ for $m_S > 250$ GeV $\implies$ W-mass correction (plot from 1501.02234). We take $\sin\theta_m \sim 0.1$ & $m_S \sim 200$ GeV.

Dominant annihilation channels



Constraints

- Neutrino mass:

$$M_\nu = -M_D M_R^{-1} (M_D)^T \,,$$

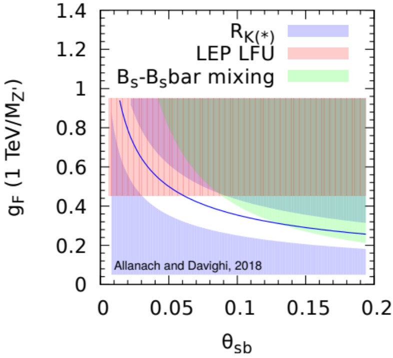
where

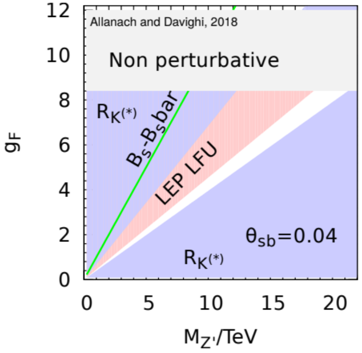
$$M_D = \begin{pmatrix} y_{e_1} v_d & y_{e_2} v_d & 0 \\ y_{\mu_1} v_d & y_{\mu_2} v_d & 0 \\ 0 & 0 & y_{\tau_3} v_d \end{pmatrix}$$

$$M_R = \begin{pmatrix} M_{11} & M_{12} & y_{13} v_{\mathcal{S}} \\ M_{12} & M_{22} & y_{23} v_{\mathcal{S}} \\ y_{13} v_{\mathcal{S}} & y_{23} v_{\mathcal{S}} & 0 \end{pmatrix}$$

- We choose: $v_{\mathcal{S}} \sim \mathcal{O}\,(\mathrm{TeV})$, $y_l \simeq y_{\tau_3} \sim \mathcal{O}(10^{-7})$, $y_{13} = y_{23} = y \sim 0.1$, $M \simeq 1$ TeV $\implies \mathrm{m}_\nu \sim \mathcal{O}(0.1\ \mathrm{eV})$
  - These Yukawas do not appear in DM/collider pheno.

1809.01158 (flavour),1812.04067 (NSI)

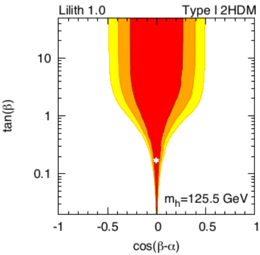


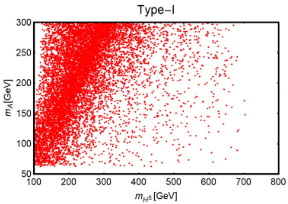


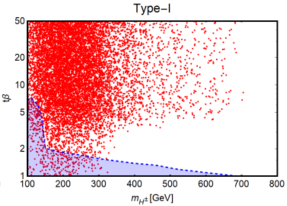
$U(1)_X$	$\epsilon^{p+n}_{ee} - \epsilon^{p+n}_{\mu\mu}$	$\epsilon^{p+n}_{\tau\tau} - \epsilon^{p+n}_{\mu\mu}$	$M_{Z'}/\lvert g'\rvert$
$B - 3L_\tau$	0	$-\frac{3(g')^2}{\sqrt{2}G_F M^2_{Z'}}$	$> 4.8\,\text{TeV}$
$B - \frac{3}{2}(L_\mu + L_\tau)$	$+\frac{3(g')^2}{2\sqrt{2}G_F M^2_{Z'}}$	0	$> 360\,\text{GeV}$
$B - 3L_\mu$	$+\frac{3(g')^2}{\sqrt{2}G_F M^2_{Z'}}$	$+\frac{3(g')^2}{\sqrt{2}G_F M^2_{Z'}}$	$> 1.0\,\text{TeV}$

Constraints on Type-I 2HDM parameters

(Plots from: 1507.06424,1807.04930)







- $m_{H^\pm} > 80$ GeV (LEP).
- $b \to s$ transition $\implies m_{H^\pm} > 400$ GeV for $\tan\beta \approx 1$.

We are strictly following the *alignment limit* here.

Thermal parameters

BP	m_{11}^2 in GeV^2	m_{22}^2 in GeV^2	m_{12} in GeV	λ_1	λ_2	λ_3	λ_4	λ_5	$\tan\beta$
I	27511.8	18531.5	176	6.05	2.00	6.63	-8.27	-8.27	1.3
II	36668.7	18503.2	185	0.79	0.45	11.54	-5.80	-5.80	1.3
III	70301.2	-4698.75	125	3.87	0.26	11.37	-5.63	-5.63	5
IV	76676.2	-4443.75	130	1.13	0.26	11.26	-5.52	-5.52	5

BP	T_c (GeV)	ξ	v_n (GeV)	T_n (GeV)	α'	$\frac{\beta'}{H}$
I	71.36	1.71	125.73	66.86	0.26	3527
II	49.34	1.74	88.82	46.22	0.26	3571.17
III	62.39	1.17	75.87	61.33	0.12	14078.9
IV	58.88	1.21	73.74	57.79	0.13	13190.8