Minimal Majoronic model for dark matter and dark radiation and its signal at the colliders

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- BSM New phys. are called for: (1) $m_\nu \neq 0$ and (2) $\Omega_{DM} h^2 \sim 0.12$
- (Too) Many models for Majorana ν. The key is the effective Weinberg operator $(LH)^2$ which breaks $U(1)_L$.
- DM: something BSM electrically charge neutral and stable/long-lived.
- Neutrinos decouple at $T \sim 1$MeV. The present relativistic energy density of the universe

$$\rho_{rad} = g_\gamma \frac{\pi^2}{30} T_\gamma^4 + g_\nu \frac{\pi^2}{30} \frac{7}{8} T_\nu^4 = \left[1 + \frac{7}{8} \left(\frac{4}{11} \right)^{4/3} N_{eff} \right] \rho_\gamma$$

- Taking into account the incomplete decoupling, $N_{eff}^{SM} = 3.046$ (Mangano et al. 2005). Nonzero $\triangle N_{eff}$ call for new relativistic DOF beyond the SM, coined as dark radiation.

N_{eff} and Lepton number

- Planck 2015, 1502.01589, $N_{eff} = 3.15(46)$ at 95%CL.
  Although the SM seems OK, the statistical significance to rule out DR is still very poor.
- $\triangle N_{eff} = 0.4 - 1.0$, Riess et el(WFC3 on HST), Astrophys.J. 826 (2016).
- Accidental global $U(1)_L \in$ SM and it connects to m_ν.
  Majorona mass is controlled by the scale of $U(1)_L$ SSB in the type-I/inverse see-saw:

$$y\overline{N}^c N S_L \to m_N = y\langle S_L\rangle$$

- DM is stabilized by the Krauss-Wilczek, $U(1)_L \to Z_2$.
- Global SSB $U(1)_L$ DM-m_ν model: massless Goldstone is built in. It contributes to radiation energy density.

Model

Particle content:

	L, Z_2	$SU(2)$	$U(1)_Y$
S(Singlet)	$2_{SSB,+}$ (2nd Higgs, Majoron)	**1**	**0**
Φ(Singlet)	1_- (DM candidate)	**1**	**0**
H	$0_{SSB,+}$	**2**	$\frac{1}{2}$
N_{iR}	1_-	**1**	**0**
L_i	1_-	**2**	$-\frac{1}{2}$

Renormalizable Lagrangian: (8 new parameters)

$$\mathcal{L}_{scalar} = (D_\mu H)^\dagger (D^\mu H) + (\partial_\mu \Phi)^\dagger (\partial^\mu \Phi) + (\partial_\mu S)^\dagger (\partial^\mu S) - V(H, S, \Phi)$$

$$V(H, S, \Phi) = -\mu^2 H^\dagger H - \mu_s^2 S^\dagger S + m_\Phi^2 \Phi^\dagger \Phi + \lambda_H (H^\dagger H)^2 + \lambda_\Phi (\Phi^\dagger \Phi)^2 + \lambda_s (S^\dagger S)^2 + \lambda_{SH} (S^\dagger S)(H^\dagger H) + \lambda_{\Phi H} (\Phi^\dagger \Phi)(H^\dagger H) + \lambda_{\Phi S} (S^\dagger S)(\Phi^\dagger \Phi) + \frac{\kappa}{\sqrt{2}} \left[(\Phi^\dagger)^2 S + S^\dagger \Phi^2 \right]$$

and we take κ to be real, $m_\Phi^2 > 0$, and define $\bar{\kappa} \equiv \lambda_{\Phi S} v_s + \kappa$.

Model

- After SSB, $\langle S \rangle \neq 0$ and $\langle H \rangle \neq 0$, $\Phi = \frac{1}{\sqrt{2}}(\rho + i\chi)$, $S = \frac{1}{\sqrt{2}}(v_s + s + i\omega)$ and $H = (0, \frac{v+h}{\sqrt{2}})^T$. ω is the massless Goldstone or Singlet Majoron.
- $\langle S \rangle$ is inv. under a $U(1)_L$ $\pi-$rotation, a Z_2 parity remains:

$$s, \omega, h \longrightarrow s, \omega, h$$

$$\rho, \chi \longrightarrow -\rho, -\chi$$

- As in Higgs portal, $h_1 = c_\theta h - s_\theta s \equiv h_{SM}$ with a mass of 125 GeV, and $h_2 = s_\theta h + c_\theta s$ (just call them H and S).
- Once $\{M_S, \theta, \lambda_{SH}\}$ are given, v_S and λ_S are determined.
- No solution found for $M_N < 0.5$TeV, not sensitive otherwise. Take $M_N = 1$TeV as benchmark value.
- leptons interact with the Majoron via

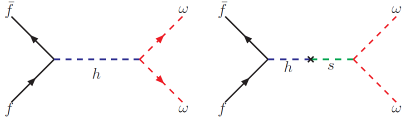
$$\frac{1}{2v_s}(\partial_\mu \omega \, \bar{\psi}_l \gamma^\mu \psi_l)$$

T_{dec} of Majoron

- Very small($\propto m_\nu$) pseudoscalar couplings to u, d, e at 1-loop, no constraints from stellar cooling. However a dim-7 int.

$$\mathcal{L}_{f\omega} = -\frac{\lambda_{HS} m_f}{M_h^2 M_s^2} \bar{f} f \partial^\mu \omega \partial_\mu \omega$$

can be generated through scalar mixing:



- Order of magnitude estimation gives

$$\Gamma(f\bar{f} \leftrightarrow \omega\omega) \sim \frac{\lambda_{HS}^2 m_f^2}{M_H^4 M_S^4} \times T_{\rm dec}^7 \times N_c^f$$

Since $H \sim T_{dec}^2 / M_{pl}$,

$$\frac{N_c \lambda_{HS}^2 m_{eff}^2 T_{\rm dec}^5 M_{Pl}}{M_H^4 M_s^4} \approx 1.$$

$\triangle N_{eff}$ and T_{dec}

- Conservation of Entropy in the co-moving volume give:

$$\triangle N_{eff} = \frac{4}{7}\left(\frac{g_*(T_\nu^+)}{g_*(T_\omega^-)}\right)^{\frac{4}{3}}$$

  where g_* is the effective number of relativistic DOF.
  $\Delta N_{\rm eff} = \{0.39, 0.055, 0.0451, 0.0423\}$ for
  $T_{dec} = \{m_\mu, 1GeV, m_c, m_\tau\}$ respectively.
- Due to scalar mixing, H can always decays into a pair of invisible ω's,

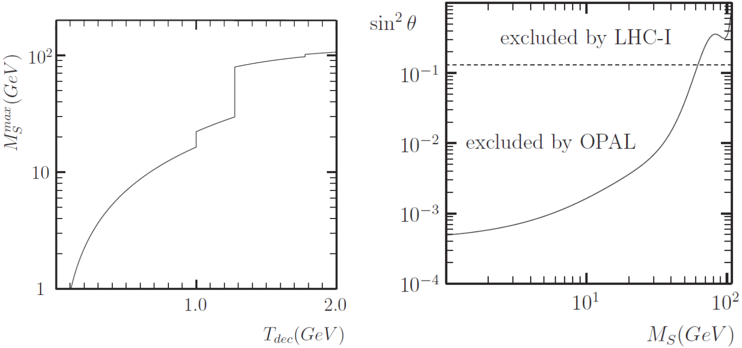
$$\Gamma_{\omega\omega} = \frac{1}{32\pi}\frac{\sin^2\theta M_H^3}{v_S^2}$$

- $\Gamma_{\omega\omega} \leq \Gamma_H^{inv} < 0.8$ MeV gives M_S^{max} via

$$\frac{M_S^4}{(M_H^2 - M_S^2)^2} \leq \cos^2\theta \frac{32\pi m_{eff}^2 T_{\rm dec}^5 M_{pl}}{v_H^2 M_H^7}\Gamma_H^{inv}$$

M_S, T_{dec}, and $\sin\theta^2$

- LHC-I, $\mu = 1.1 \pm 0.11$ gives indirect bound $\sin\theta^2 < 0.13$ at 2 σ. Direct search from OPAL $e^+e^- \to hZ$.



- From rare B decay, $|\theta| < 0.002$ for $M_S < 2$GeV.
- With this, the decoupling condition yields

$$\lambda_{SH} \sim \frac{M_H^2 M_S^2}{T_{dec}^3 \sqrt{T_{dec} M_{pl}}} \ll 1$$

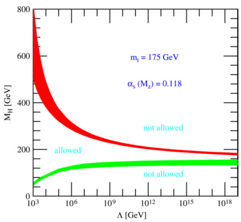
One more thing to be taken into account

- Operational see-saw needs stable vacuum at the $\not{L}$ scale μ_{LV}, or $\mu_{LV} < \mu_{VS}^{SM}$.

$$(\overline{\nu^c}, \overline{\nu_R}) \begin{pmatrix} 0 & y_D v_{SM} \\ y_D v_{SM} & M_N (= y_s v_l) \end{pmatrix} \begin{pmatrix} \nu \\ \nu_R^c \end{pmatrix}$$

- $\mu_{VS}^{SM} \simeq 10^{10-12}$ GeV

A. Djouadi / Physics Reports 457 (2008) 1–216



- For ϕ_A, ϕ_B in $V = \lambda_A \phi_A^4 + \lambda_B \phi_B^4 + \lambda_{AB} \phi_A^2 \phi_B^2 + \ldots$, $\lambda_A > 0$, $\lambda_B > 0$, $\lambda_{AB} > -2\sqrt{\lambda_A \lambda_B}$ at any given energy scale. RGE study is necessary.

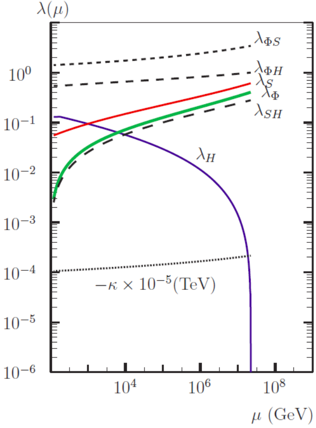
Numerical Scan

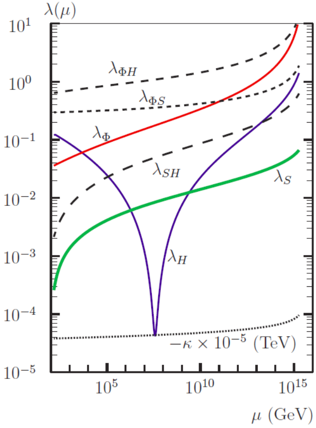
- Comprehensive scan of the whole parameter space. Randomly scan T_{dec}, M_S, θ, M_ρ, $\lambda_{\Phi S}(\in [-4\sqrt{\pi\lambda_S}, 4\pi])$, $\bar{\kappa}$, $\lambda_{\Phi H}$, λ_Φ.
- Requirements and experimental constraints in our search:
  - Improve the SM vacuum stability, $\mu_{VS} > \mu_{VS}^{SM}$ $(\mu_{VS1-loop}^{SM} = 2 \times 10^5\text{GeV})$
  - No Landau pole below μ_{VS}^{SM}
  - $\Gamma_{inv}^H < 0.8$MeV.
  - $T_{dec} \in [m_\mu, 2GeV]$.
  - θ complies with all experimental bounds.
  - relic density $\langle \sigma v \rangle = 2.5(1) \times 10^{-9}(GeV)^{-2}$.
  - Spin-independent direct DM search bound (LUX)
- The largest $R_{VS} \equiv \log_{10} \mu_{VS}/\mu_{VS}^{SM}$ we got ~ 11. New scalar DOF help to go up to GUT scale, but not M_{pl}.
- $T_{dec} > 1.3$GeV, $1.5\text{TeV} < M_\rho < 4\text{TeV}$, $M_S \in [20, 100]$GeV, $v_S, -\kappa \in [2 - 20]$TeV

Numerical Scan: 2 examples

Config.	T_{dec}	M_S	θ	M_ρ	v_S	R_{VS}	$Br(\omega\omega)$	$Br(b\bar{b})$
A	1.94	27.3	-0.03	2.2	6.7	2.1	0.87	0.11
B	1.87	67.6	-0.32	1.8	12.1	10.0	0.07	0.78

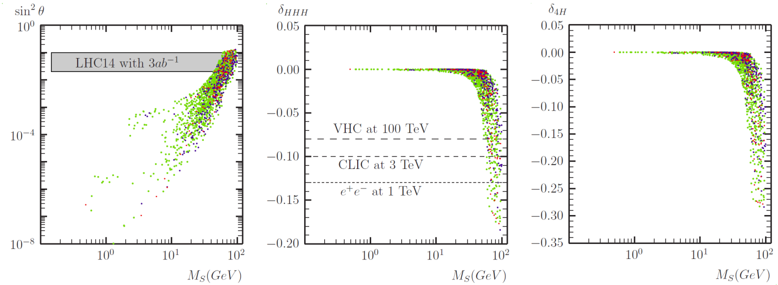
T_{dec} and M_S (M_ρ and v_S) are in GeV (TeV).





Indirect search at LHC (heavy S)

- A universal $\cos^2\theta$ suppression to all signal strengthes due to $H-S$ mixing. $M_S > 40$GeV detectable at LHC14 with $3ab^{-1}$.
- the SM Higgs triple coupling $\lambda^{SM}_{HHH} = 3M_H^2/v_H$ and $\lambda^{SM}_{4H} = 6\lambda_H = 3(M_H/v_H)^2$ will be modified in this model. The XS for triple Higgs production is too small.



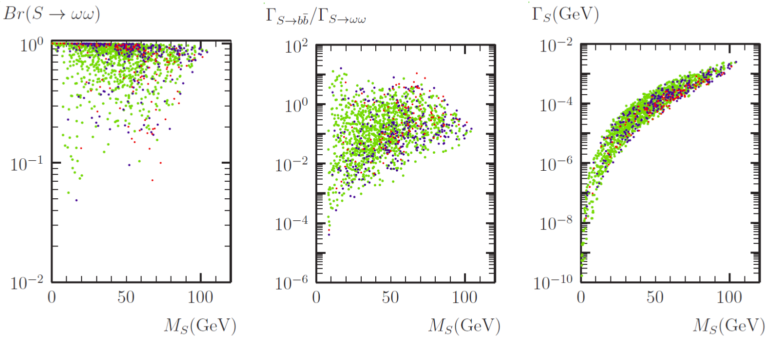
S: A narrow width resonance

- The relevant modes are s into quarks, leptons, and ω's.

$$\Gamma(s \to \omega\omega) = \frac{1}{32\pi}\frac{c_\theta^2 M_s^3}{v_s^2}, \Gamma(s \to f\bar{f}) = \frac{M_s}{8\pi} N_c^f \beta_f^3 \left(\frac{m_f s_\theta}{v}\right)^2$$

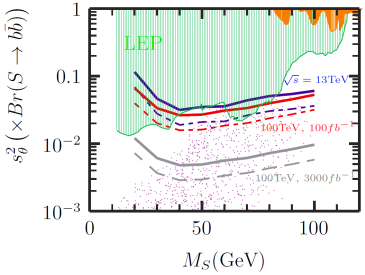
where $\beta_f = (1 - \frac{4m_f^2}{M_s^2})^{1/2}$.

- Dominate decay modes: ω-pair (invisible) or $b\bar{b}(M_S > 2m_b)$.
- Looking for a very narrow resonance.

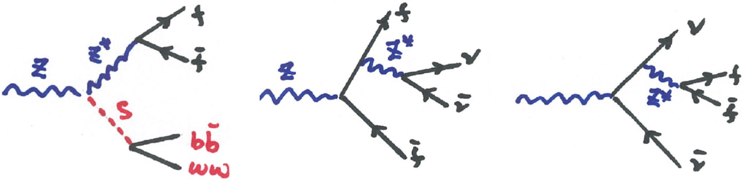


Direct search at LHC

- $S \to 2\omega$ has no significance, only $S \to b\bar{b}$ can be used.
- GF, VBF, VS have huge QCD background. With $4b$-tagged jets $+l+$MET, $t\bar{t}S$ is possible at HL($3ab^{-1}$) LHC14.
- We study the SM background following both ATLAS and CMS collaborations. (details see 1711.05722)
- We also extrapolate to a future 100 TeV hadron collider.



At Z factory

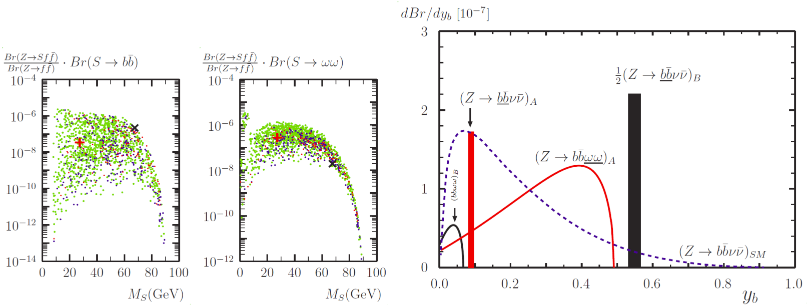


- Future Circular Collider expects to have 10^{12-13} Z bosons at $\sqrt{s} = M_Z$ with multi-ab^{-1} luminosity.
- Defining $y_f = \frac{M^2_{f\bar{f}}}{M_Z^2}$ we obtain

$$\frac{dBr(Z \to Sf\bar{f})}{dy} = \frac{g^2 \sin^2\theta}{192\pi^2 \cos^2\theta_W}\sqrt{y_f^2 - 2y_f(1+r_Z^2) + (1-r_Z^2)^2} \times \frac{\left[y_f^2 + 2y_f(5-r_Z^2) + (1-r_Z^2)^2\right]}{(1-y_f)^2} \times Br(Z \to f\bar{f})$$

where $r_Z = \frac{M_S}{M_Z}$ and $0 \leq y_f \leq (1-r_Z)^2$. The kinematic lower bound can be safely taken to be zero even for y_b.

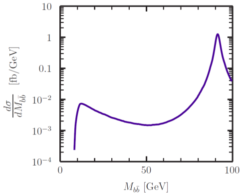
$Z \to f\bar{f}S$

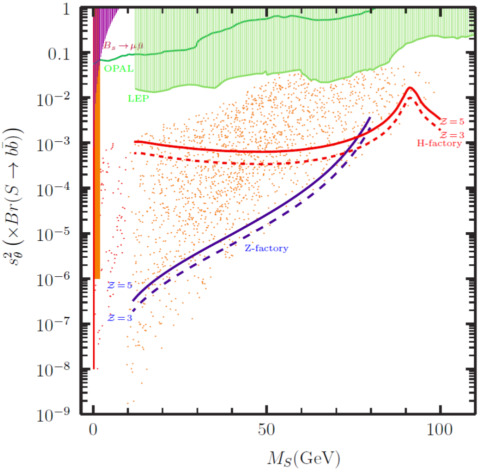


- Note the lower bound for each decay mode.
- $Br(Z \to b\bar{b} \not{E})_{SM} = 5.25 \times 10^{-8}$
- $Z \to S\bar{f}f$ signal stands out from the SM background.

Direct search at e^+e^- machines

- At Higgs factory $e^+e^- \to Z^* \to ZS$.
- The dominant SM BG is the intrinsic t-channel $e^+e^- \to ZZ^*$





Summary

- Minimal Majoron model with SM singlet scalars carrying lepton numbers takes care of DR+DM+m_ν+V.S.
- $\triangle N_{eff} \sim 0.05$, or $T_{dec} > m_c$ is preferred.
- Scalar DM, ρ, of mass $1.5 - 4$ TeV is required by V.S. and an operational type-I see-saw.
- New scalar S with $M_S \in [10, 100]$ GeV, mixing as large as 0.1.
- S mainly decays into $b\bar{b}$ and/or $\omega\omega$(invisible).
- $pp \to t\bar{t}S(b\bar{b})$ is feasible at HL LHC.
- Future Z and Higgs factories can reach much smaller mixing region. Sensitive search will be $Z \to S + f\bar{f}$, followed by S into a pair of Majoron and/or b-quarks.