Matter parity, scalar dark matter and LHC

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Cold Dark Matter does exist!

What we know:

- $\Omega_{DM}/\Omega_b \approx 5$.
  DM *should* be non relativistic.

What we don't know:

- What is DM?
  Neutralino, gravitino, axion, axino, KK state, **scalar singlet, scalar doublet**, ...
- Why is it stable?
  R-parity, T-parity, ...

(See McCullough, Albornoz, Frandsen, McCabe, Marsh, Panotopoulos, Weller, Sokolowska ...)

Popular example

Inert Scalar Models:

- Inert Singlet Model
- Inert Doublet Model

(See Sokolowska)

Motivated by the Higgs portal paradigm: the Higgs boson is the only SM particle that couples to hidden sector.

Limits:

- Why singlet/doublet?
- Z_2 symmetry imposed by hand

Matter Parity P_M

Gauge group:

- $SO(10) \to \cdots \to G \times U(1)_X \to \cdots \to G_{SM} \times P_M$
- $P_M = Z(2)_X = (-1)^{3(B-L)}$

Matter content (NO SUSY):

- SM fermions in **16** of $SO(10) \to P_M$ odd
- Higgs in **10** of $SO(10) \to P_M$ even

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Matter content (NO SUSY):

- SM fermions in **16** of $SO(10) \to P_M$ odd
- Higgs in **10** of $SO(10) \to P_M$ even
- Dark Matter in **16** of SO(10) $\to P_M$ odd
  Higgs portal paradigm

$\Rightarrow$ DM is stable

$SO(10)$ Lagrangian

Matter content:

- $\mathbf{10} \ni$ SM Higgs
- $\mathbf{16} \ni$ DM

$$V = \mu_1^2\, \mathbf{10}\,\mathbf{10} + \lambda_1(\mathbf{10}\,\mathbf{10})^2 + \mu_2^2\, \overline{\mathbf{16}}\,\mathbf{16} + \lambda_2(\overline{\mathbf{16}}\,\mathbf{16})^2 + \lambda_3(\mathbf{10}\,\mathbf{10})(\overline{\mathbf{16}}\,\mathbf{16}) + \lambda_4(\mathbf{16}\,\mathbf{10})(\overline{\mathbf{16}}\,\mathbf{10}) + \frac{1}{2}\left(\lambda'_S \mathbf{16}^4 + \mathrm{h.c.}\right) + \frac{1}{2}\left(\mu'_{SH}\mathbf{16}\,\mathbf{10}\,\mathbf{16} + \mathrm{h.c.}\right)$$

Low energy Lagrangian

Matter content:

- H_1: Higgs $\in$ **10**, P_M even
- H_2, S: DM $\in$ **16**, P_M odd

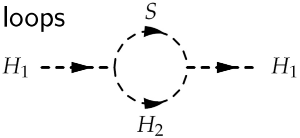
$$H_2 = \begin{pmatrix} H^+ \\ (H_0 + iA_0)/\sqrt{2} \end{pmatrix}$$
$$S = (S_H + iS_A)/\sqrt{2}$$

$$V \simeq \mu_1^2 H_1^\dagger H_1 + \lambda_1 (H_1^\dagger H_1)^2 + \mu_2^2 H_2^\dagger H_2 + \lambda_2 (H_2^\dagger H_2)^2 + \mu_S^2 S^\dagger S + \lambda_S (S^\dagger S)^2 + \frac{\lambda'_S}{2}\left[S^4 + (S^\dagger)^4\right] + \lambda_{S1}(S^\dagger S)(H_1^\dagger H_1) + \lambda_{S2}(S^\dagger S)(H_2^\dagger H_2) + \lambda_3 (H_1^\dagger H_1)(H_2^\dagger H_2) + \lambda_4 (H_1^\dagger H_2)(H_2^\dagger H_1) + \frac{\mu'_{SH}}{2}\left[S H_1^\dagger H_2 + H_2^\dagger H_1 S^\dagger\right]$$

CSDMM

Main Features:

- GUT scale initial conditions $\rightarrow$ RG evolution down to EW scale: **Constrained Scalar Dark Matter Model**
- Natural embedding of Inert Singlet/Doublet Model
- Radiative EWSB induced by DM loops (soft portal μ'_{SH})

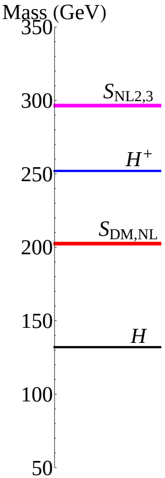


Some Constraints:

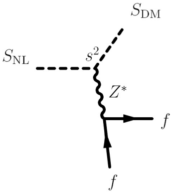
- Perturbativity $\lambda_i < 4\pi$
- Vacuum Stability $\lambda_1 > 0$, $\lambda_2 > 0$, ...
- $M_{DM} > M_Z/2$
- $0.94 \lesssim \Omega_{DM} \lesssim 0.129$

Scalar Mass Spectrum

- Physical SM Higgs: H
- Charged Inert Higgs: H^+
- 4 new neutral scalars:
  - $S_H, S_A, H_0, A_0 \to S_{DM}, S_{NL}, S_{NL2}, S_{NL3}$
  - Dark Matter: S_{DM}, S_{NL}, usually singlet-like
  - (S_{DM}, S_{NL}) and (S_{NL2}, S_{NL3}) degenerate

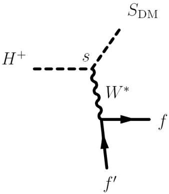


Displaced vertices



$S_{\rm NL} \to S_{\rm DM} f\bar{f}$

- $\Delta M_{NL} = M_{NL} - M_{DM}$ naturally small.
  S_{NL} and S_{DM} belong to the same multiplet.
- $\Gamma_{S_{\rm NL} \to S_{\rm DM} f\bar{f}} \sim s^4$

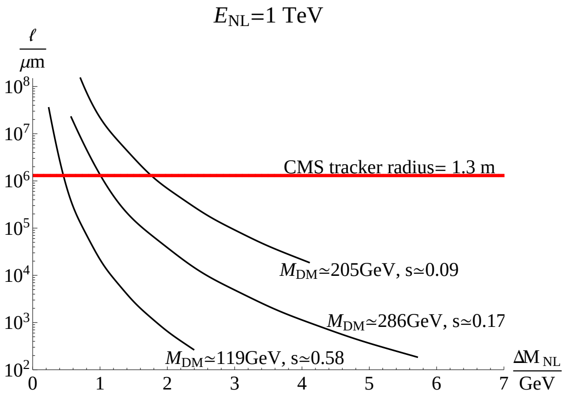


$H^+ \to S_{\rm DM} f\bar{f}'$

- $\Delta M_{H^+} = M_{H^+} - M_{DM}$ accidentally small.
  $\sim 30\%$ of low mass ($M_{H^+} < 300$ GeV) points.
- $\Gamma_{H^+ \to S_{\rm DM} f\bar{f}'} \sim s^2$

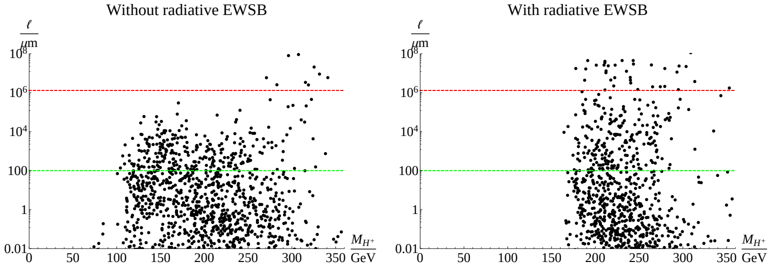
s: sin of the mixing angle
s tiny since $S_{\rm NL}, S_{\rm DM}$ usually singlet-like.

$S_{NL} \to S_{DM} f \bar{f}$



ΔM_{NL} as free parameter, $\ell = \gamma\beta c/\Gamma$

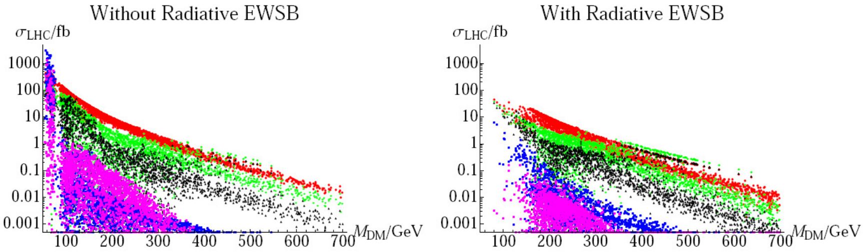
$H^+ \to S_{DM} f\bar{f}'$



$$E_{H^+} = 1\ \text{TeV},\ \ell = \gamma\beta c/\Gamma$$

LHC production cross sections

$$\sqrt{s} = 14 \quad \text{TeV}$$



$pp(q\bar{q}) \to H^+H^-$ (red), $pp(gg) \to H^+H^-$ (magenta),
$pp(gg) \to S_{DM,NL}S_{DM,NL}$ (blue),
$pp(q\bar{q}) \to S_{DM,NL}H^+$ (green), $pp(q\bar{q}) \to S_{NL}S_{DM}$ (black)

Conclusions

- $P_M = (-1)^{3(B-L)}$ from non-SUSY $SO(10)$
- DM in **16** is scalar analogue of SM fermion
- EWSB can be induced by DM radiative corrections
- DM and H^+ can be seen at LHC with displaced vertex
- $q\bar{q} \to H^+H^-$ usually dominant
- $gg \to H^+H^-, S_{\rm NL}S_{\rm NL}$ can be dominant in the non-radiative case for $M_{\rm DM} < 100$ GeV

Thank you!

Low energy Lagrangian

Matter content: H_1 (Higgs), H_2, S (DM)

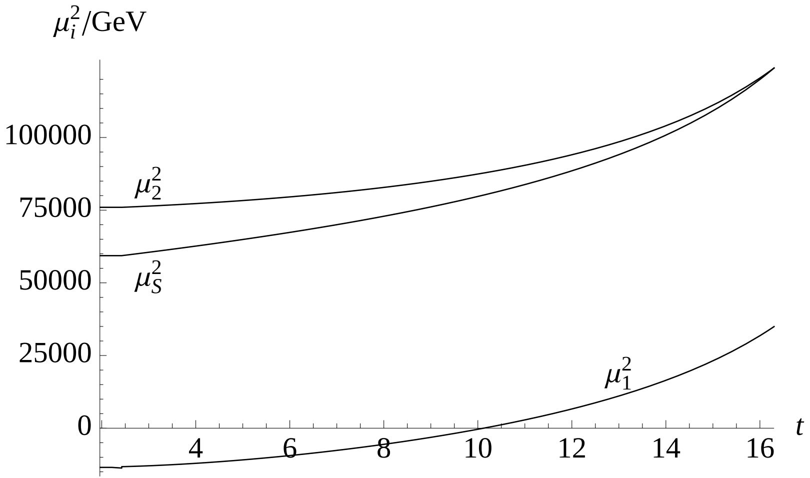
$$\begin{aligned} V = &\mu_1^2 H_1^\dagger H_1 + \lambda_1 (H_1^\dagger H_1)^2 + \mu_2^2 H_2^\dagger H_2 + \lambda_2 (H_2^\dagger H_2)^2 \\ &+ \mu_S^2 S^\dagger S + \frac{\mu_S'^2}{2}\left[S^2 + (S^\dagger)^2\right] \\ &+ \lambda_S (S^\dagger S)^2 + \frac{\lambda_S'}{2}\left[S^4 + (S^\dagger)^4\right] + \frac{\lambda_S''}{2}(S^\dagger S)\left[S^2 + (S^\dagger)^2\right] \\ &+ \lambda_{S1}(S^\dagger S)(H_1^\dagger H_1) + \lambda_{S2}(S^\dagger S)(H_2^\dagger H_2) \\ &+ \frac{\lambda_{S1}'}{2}(H_1^\dagger H_1)\left[S^2 + (S^\dagger)^2\right] + \frac{\lambda_{S2}'}{2}(H_2^\dagger H_2)\left[S^2 + (S^\dagger)^2\right] \\ &+ \lambda_3 (H_1^\dagger H_1)(H_2^\dagger H_2) + \lambda_4 (H_1^\dagger H_2)(H_2^\dagger H_1) + \frac{\lambda_5}{2}\left[(H_1^\dagger H_2)^2 + (H_2^\dagger H_1)^2\right] \\ &+ \frac{\mu_{SH}}{2}\left[S^\dagger H_1^\dagger H_2 + H_2^\dagger H_1 S\right] + \frac{\mu_{SH}'}{2}\left[S H_1^\dagger H_2 + H_2^\dagger H_1 S^\dagger\right] \end{aligned}$$

Low energy Lagrangian

$\mu_S'^2, \mu_{SH}^2, \lambda_5, \lambda_{S1}', \lambda_{S2}', \lambda_S''$: Planck scale suppressed operators

$$
\begin{aligned}
V = {} & \mu_1^2 H_1^\dagger H_1 + \lambda_1 (H_1^\dagger H_1)^2 + \mu_2^2 H_2^\dagger H_2 + \lambda_2 (H_2^\dagger H_2)^2 \\
& + \mu_S^2 S^\dagger S + \frac{\mu_S'^2}{2}\left[S^2 + (S^\dagger)^2\right] \\
& + \lambda_S (S^\dagger S)^2 + \frac{\lambda_S'}{2}\left[S^4 + (S^\dagger)^4\right] + \frac{\lambda_S''}{2}(S^\dagger S)\left[S^2 + (S^\dagger)^2\right] \\
& + \lambda_{S1}(S^\dagger S)(H_1^\dagger H_1) + \lambda_{S2}(S^\dagger S)(H_2^\dagger H_2) \\
& + \frac{\lambda_{S1}'}{2}(H_1^\dagger H_1)\left[S^2 + (S^\dagger)^2\right] + \frac{\lambda_{S2}'}{2}(H_2^\dagger H_2)\left[S^2 + (S^\dagger)^2\right] \\
& + \lambda_3 (H_1^\dagger H_1)(H_2^\dagger H_2) + \lambda_4 (H_1^\dagger H_2)(H_2^\dagger H_1) + \frac{\lambda_5}{2}\left[(H_1^\dagger H_2)^2 + (H_2^\dagger H_1)^2\right] \\
& + \frac{\mu_{SH}}{2}\left[S^\dagger H_1^\dagger H_2 + H_2^\dagger H_1 S\right] + \frac{\mu_{SH}'}{2}\left[S H_1^\dagger H_2 + H_2^\dagger H_1 S^\dagger\right]
\end{aligned}
$$

Radiative EWSB



Tree level mass matrices

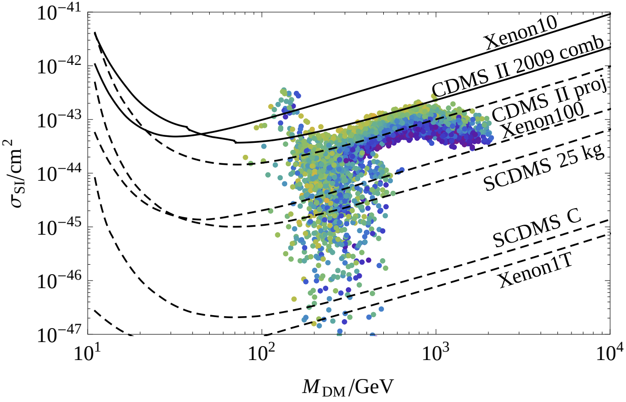
$$m^2_{\mathrm{R}1} = \frac{1}{4}\left[2\mu_2^2 + 2\mu_S^2 + 2(\mu'_S)^2 + v^2(\lambda_3 + \lambda_4 + \lambda_5 + \lambda_{S1} + \lambda'_{S1}) \right.$$
$$\left. - \sqrt{2(\mu_{SH} + \mu'_{SH})^2 v^2 + [2\mu_2^2 - 2\mu_S^2 - 2(\mu'_S)^2 + v^2(\lambda_3 + \lambda_4 + \lambda_5 - \lambda_{S1} - \lambda'_{S1})]^2}\right]$$

$$m^2_{\mathrm{I}1} = \frac{1}{4}\left[2\mu_2^2 + 2\mu_S^2 - 2(\mu'_S)^2 + v^2(\lambda_3 + \lambda_4 - \lambda_5 + \lambda_{S1} - \lambda'_{S1}) \right.$$
$$\left. - \sqrt{2(\mu_{SH} - \mu'_{SH})^2 v^2 + [2\mu_2^2 - 2\mu_S^2 - 2(\mu'_S)^2 + v^2(\lambda_3 + \lambda_4 - \lambda_5 - \lambda_{S1} + \lambda'_{S1})]^2}\right]$$

$$m^2_{\mathrm{R}2} = \frac{1}{4}\left[2\mu_2^2 + 2\mu_S^2 + 2(\mu'_S)^2 + v^2(\lambda_3 + \lambda_4 + \lambda_5 + \lambda_{S1} + \lambda'_{S1}) \right.$$
$$\left. + \sqrt{2(\mu_{SH} + \mu'_{SH})^2 v^2 + [2\mu_2^2 - 2\mu_S^2 - 2(\mu'_S)^2 + v^2(\lambda_3 + \lambda_4 + \lambda_5 - \lambda_{S1} - \lambda'_{S1})]^2}\right]$$

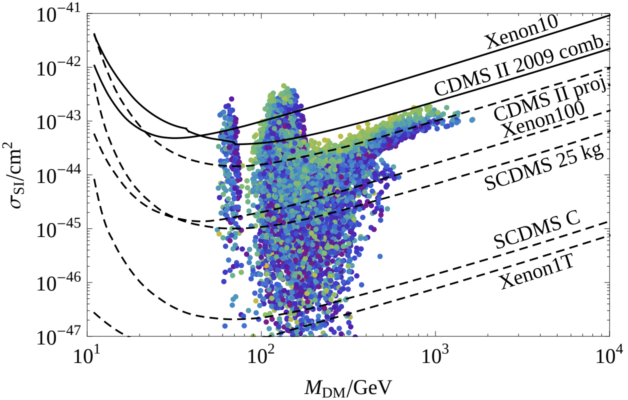
$$m^2_{\mathrm{I}2} = \frac{1}{4}\left[2\mu_2^2 + 2\mu_S^2 - 2(\mu'_S)^2 + v^2(\lambda_3 + \lambda_4 - \lambda_5 + \lambda_{S1} - \lambda'_{S1}) \right.$$
$$\left. + \sqrt{2(\mu_{SH} - \mu'_{SH})^2 v^2 + [2\mu_2^2 - 2\mu_S^2 - 2(\mu'_S)^2 + v^2(\lambda_3 + \lambda_4 - \lambda_5 - \lambda_{S1} + \lambda'_{S1})]^2}\right]$$

DM direct detection:Radiative EWSB



$$\sigma \approx \frac{1}{\pi} f_N^2 \left(\frac{\lambda_{\rm eff} v}{v M_{\rm DM}}\right)^2 \left(\frac{M_N}{M_h}\right)^4 \qquad \lambda_{\rm eff}\, v = \frac{1}{2}(-\sqrt{2} s\, c\, \mu'_{SH} + 2s^2(\lambda_3+\lambda_4)v + 2c^2\lambda_{S1} v)$$

DM direct detection:Without Radiative EWSB



$$\sigma \approx \frac{1}{\pi} f_N^2 \left(\frac{\lambda_{\rm eff} v}{v M_{\rm DM}}\right)^2 \left(\frac{M_N}{M_h}\right)^4 \qquad \lambda_{\rm eff}\, v = \frac{1}{2}(-\sqrt{2} s\, c\, \mu'_{SH} + 2s^2(\lambda_3+\lambda_4)v + 2c^2\lambda_{S1} v)$$

LHC production. Diagrams