Dark Matter and Electroweak Symmetry Breaking from $SO(10)$

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Dark Matter

- $4/5$ of matter of unknown nature
- Freezeout – dark matter is a WIMP
- $Z(2)$ to stabilize dark matter

Matter Parity

- $SO(10) \to G_{\mathrm{SM}} \times Z(2)_X$
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- $SO(10) \to G_{\rm SM} \times Z(2)_X$
- $X = 3(B-L) + 4T_{3R}$
- $Z(2)_X \equiv P_M = (-1)^{3(B-L)}$
- Simplest dark matter is a scalar
- SM fermions in **16** are P_M-*odd*
- SM Higgs in **10** is P_M-even
- Dark matter in **16** is P_M-*odd*

Scalar Sector of Our Model

- SM Higgs H_1
- Complex singlet $S = (S_H + iS_A)/\sqrt{2}$
- $H_2 = \begin{pmatrix} H^+ \\ (H_0 + iA_0)/\sqrt{2} \end{pmatrix}$

$SO(10)$ Lagrangian

$$
\begin{aligned}
V = {} & \mu_1^2\, \mathbf{10}\ \mathbf{10} + \lambda_1 (\mathbf{10}\ \mathbf{10})^2 + \mu_2^2\, \overline{\mathbf{16}}\ \mathbf{16} + \lambda_2 (\overline{\mathbf{16}}\, \mathbf{16})^2 \\
& + \lambda_3 (\mathbf{10}\ \mathbf{10})(\overline{\mathbf{16}}\, \mathbf{16}) + \lambda_4 (\mathbf{16}\ \mathbf{10})(\overline{\mathbf{16}}\, \mathbf{10}) \\
& + \frac{1}{2} \left(\lambda_S' \mathbf{16}^4 + \text{h.c.} \right) + \frac{1}{2} \left(\mu_{SH}' \mathbf{16}\ \mathbf{10}\ \mathbf{16} + \text{h.c.} \right)
\end{aligned}
$$

Low Scale Lagrangian

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

Low Scale Lagrangian

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\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}
$$

Soft Portal to Dark Sector

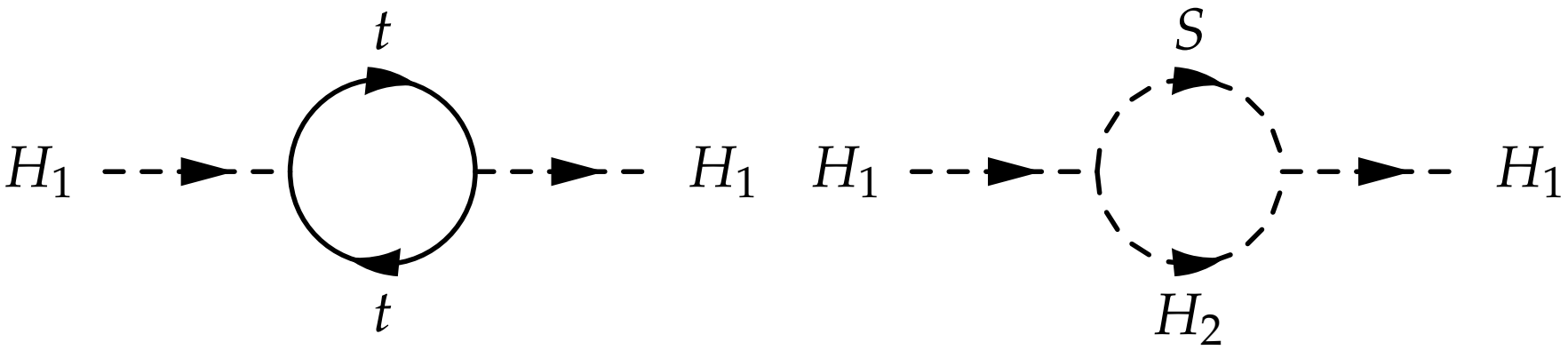
Dimension**ful** coupling

$$\frac{\mu'_{SH}}{2}\left[SH_1^\dagger H_2 + H_2^\dagger H_1 S^\dagger\right]$$

connects dark sector to Standard Model via Higgs
μ'_{SH} can be large:

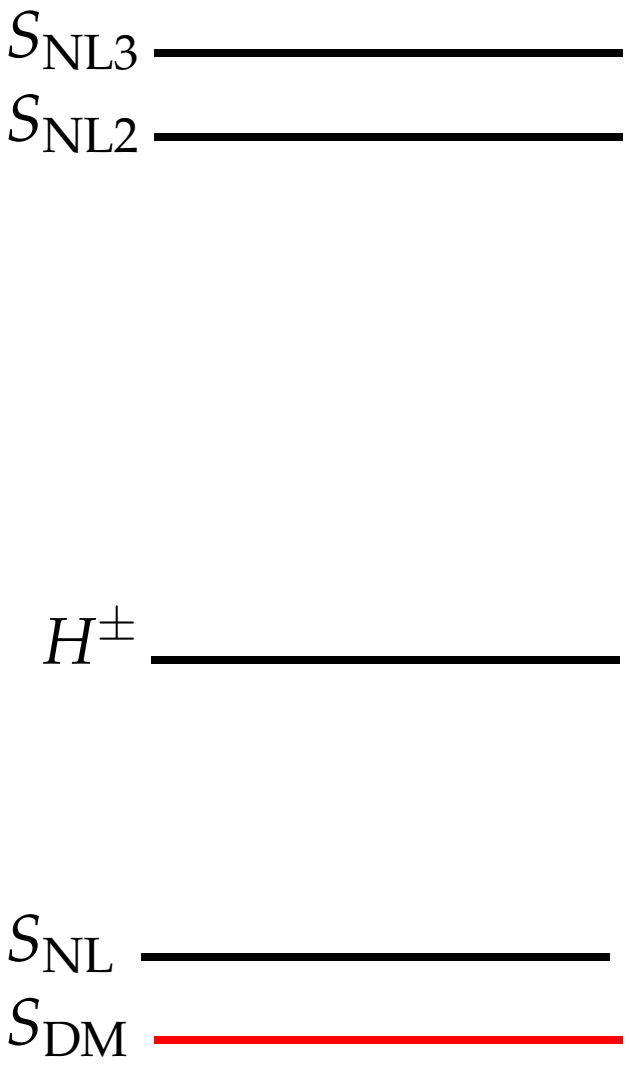
$$\mu'_{SH}/v \gg 1$$

EWSB from



Mass Spectrum

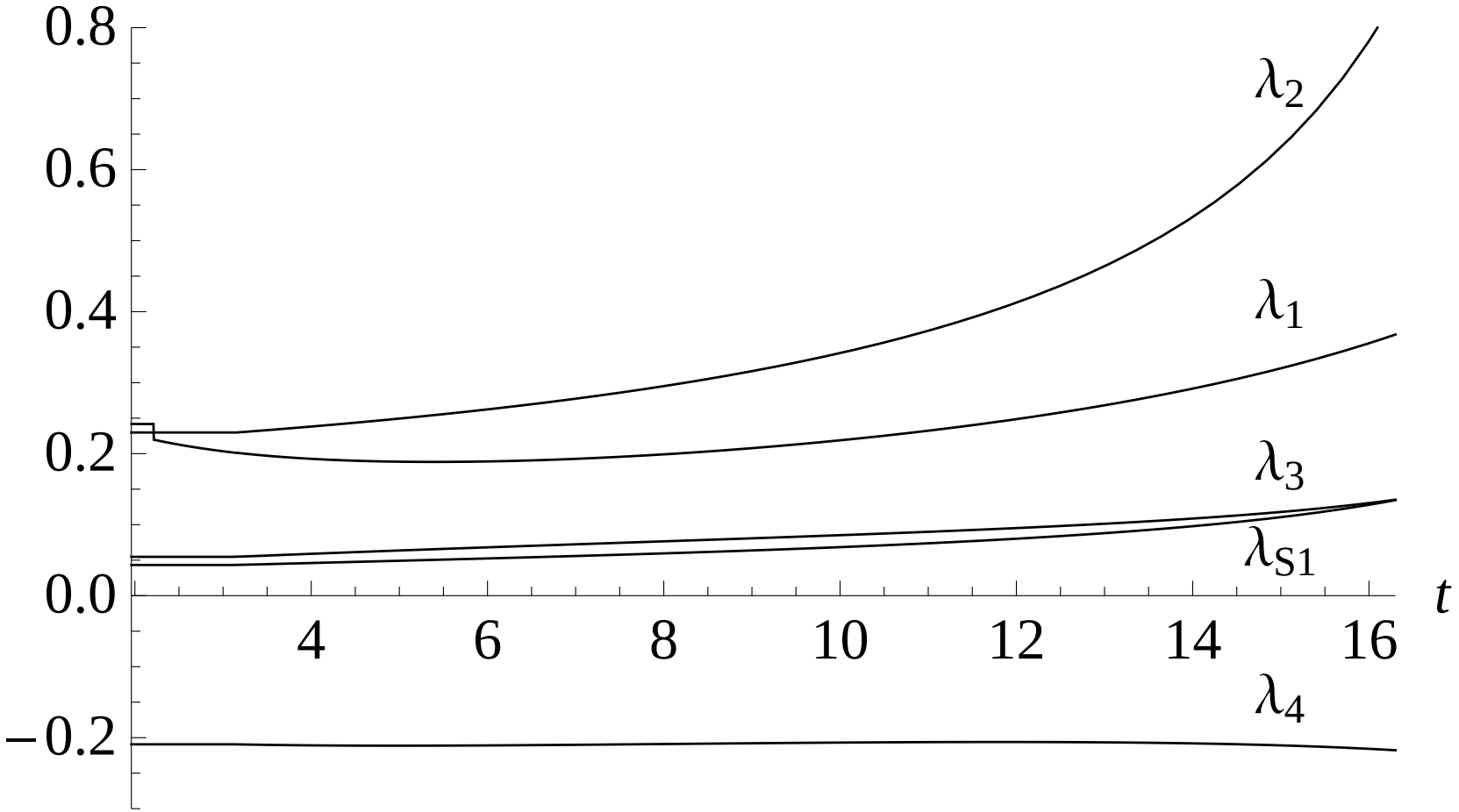
- Physical SM Higgs h
- Charged Higgs H^+
- $S_H, H_0 \to S_{\mathrm{R1}}, S_{\mathrm{R2}}$
- $S_A, A_0 \to S_{\mathrm{I1}}, S_{\mathrm{I2}}$



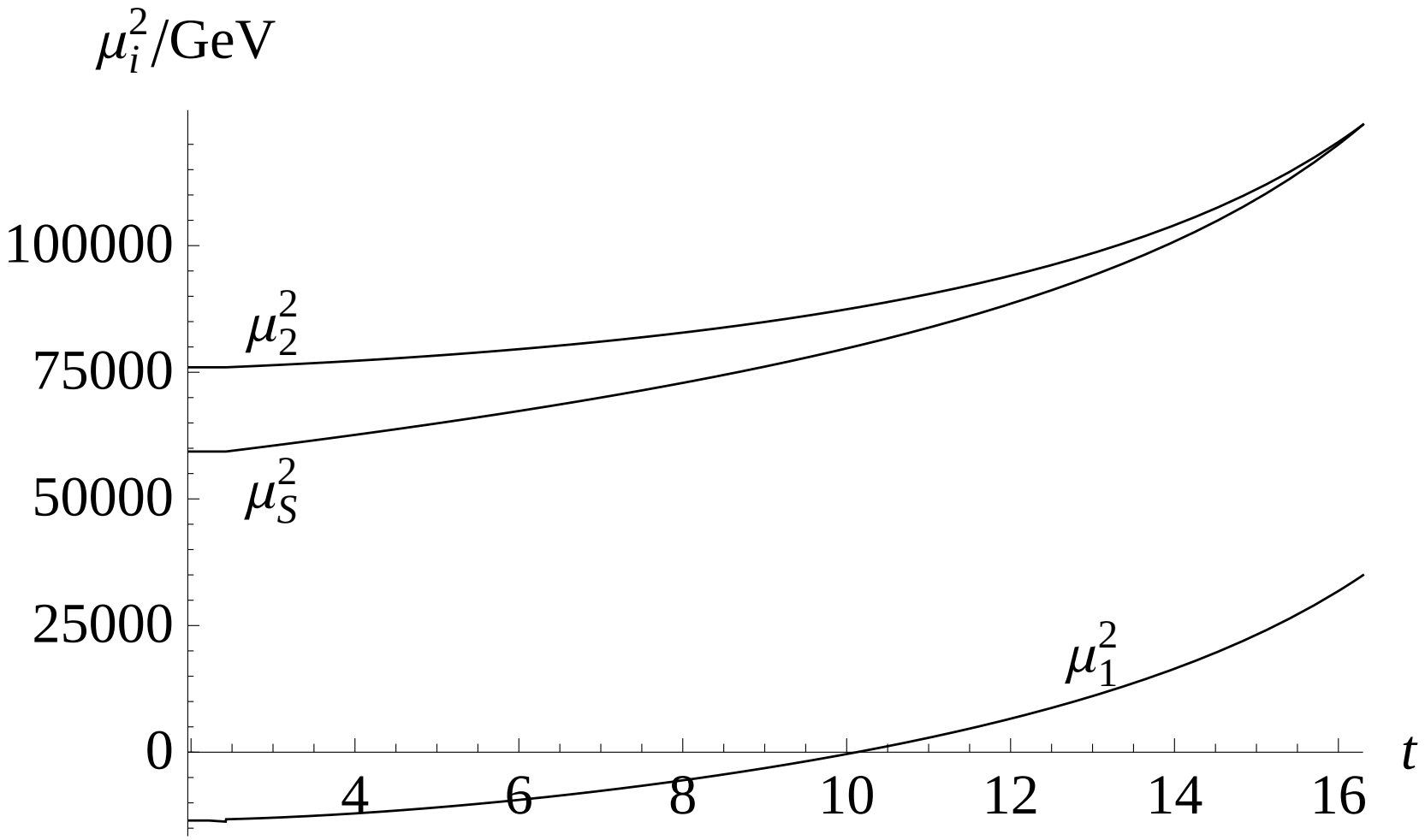
Constraints on the Model

- EW symmetry breaking from dark matter
- Perturbativity $\lambda_i < 4\pi$
- Vacuum stability ($\lambda_1 > 0$ etc.)
- $M_{H^+} > 80$ GeV
- $M_{\mathrm{DM}} > M_Z/2 \approx 45$ GeV
- $0.94 < \Omega_{\mathrm{DM}} < 0.129$
- Have to be satisfied in the full energy range of 90 GeV $\ldots 2 \times 10^{16}$ GeV

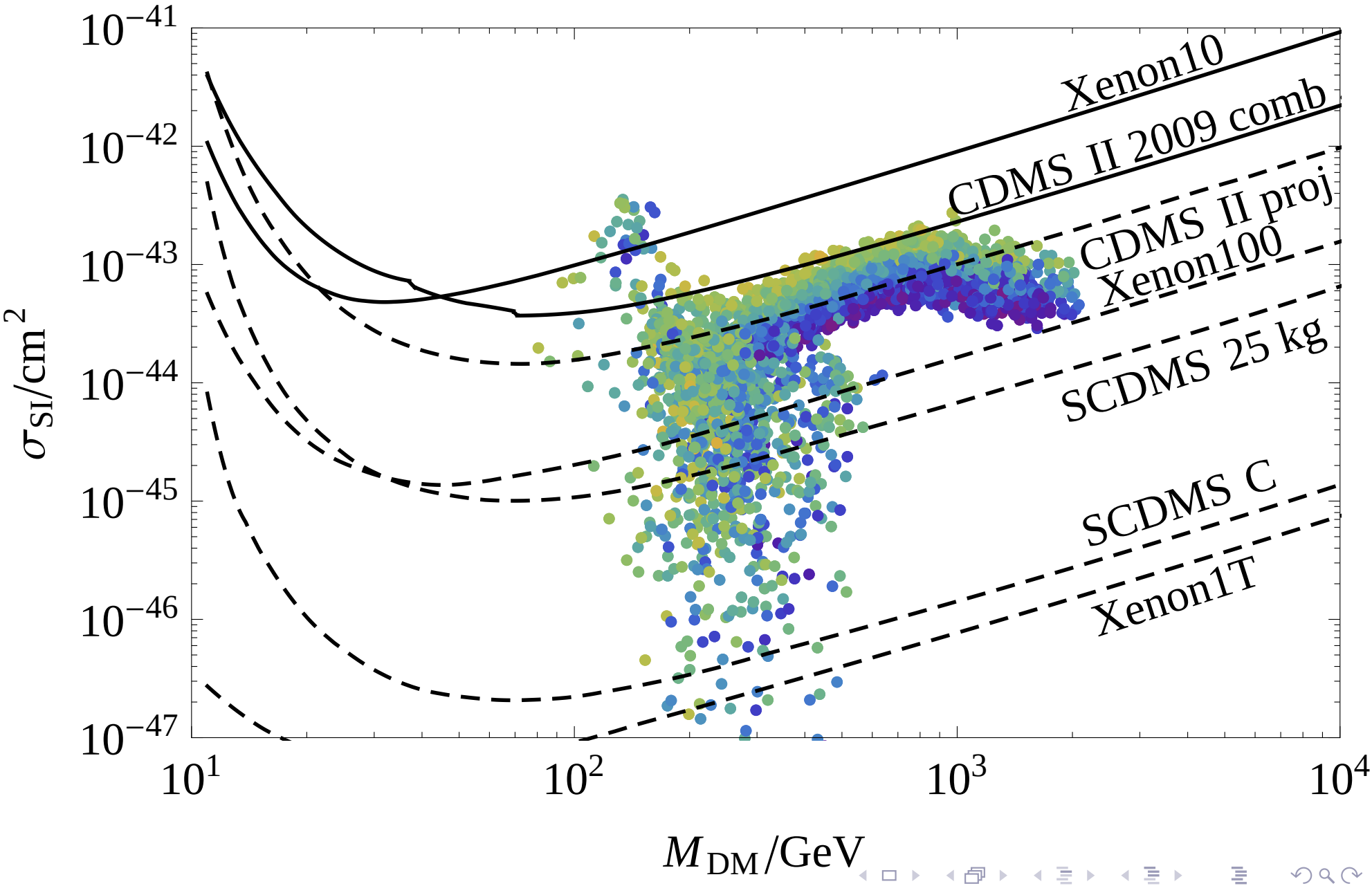
RGE Running of λ_i



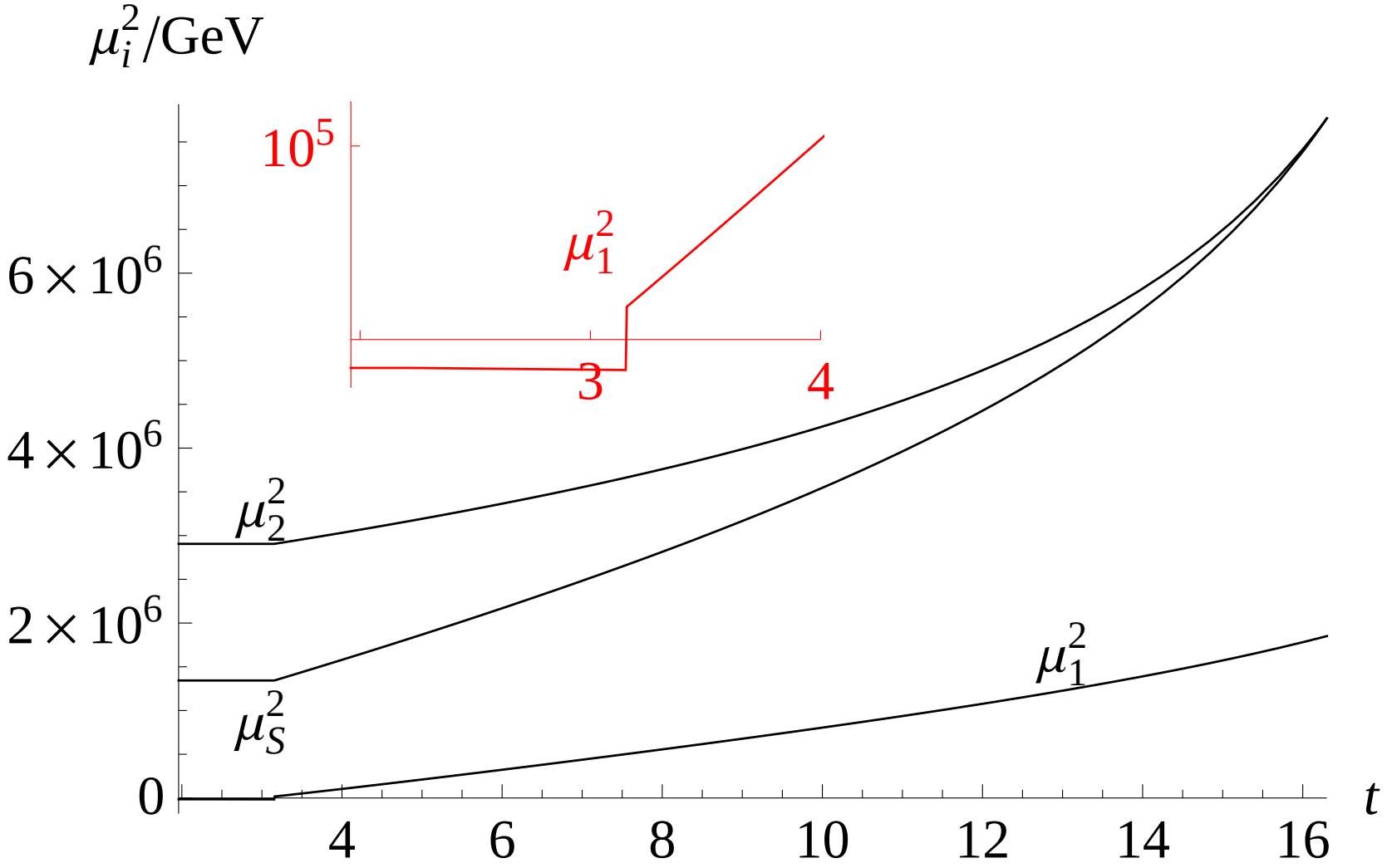
EWSB: $\mu_1^2 < 0$ from RGE Running



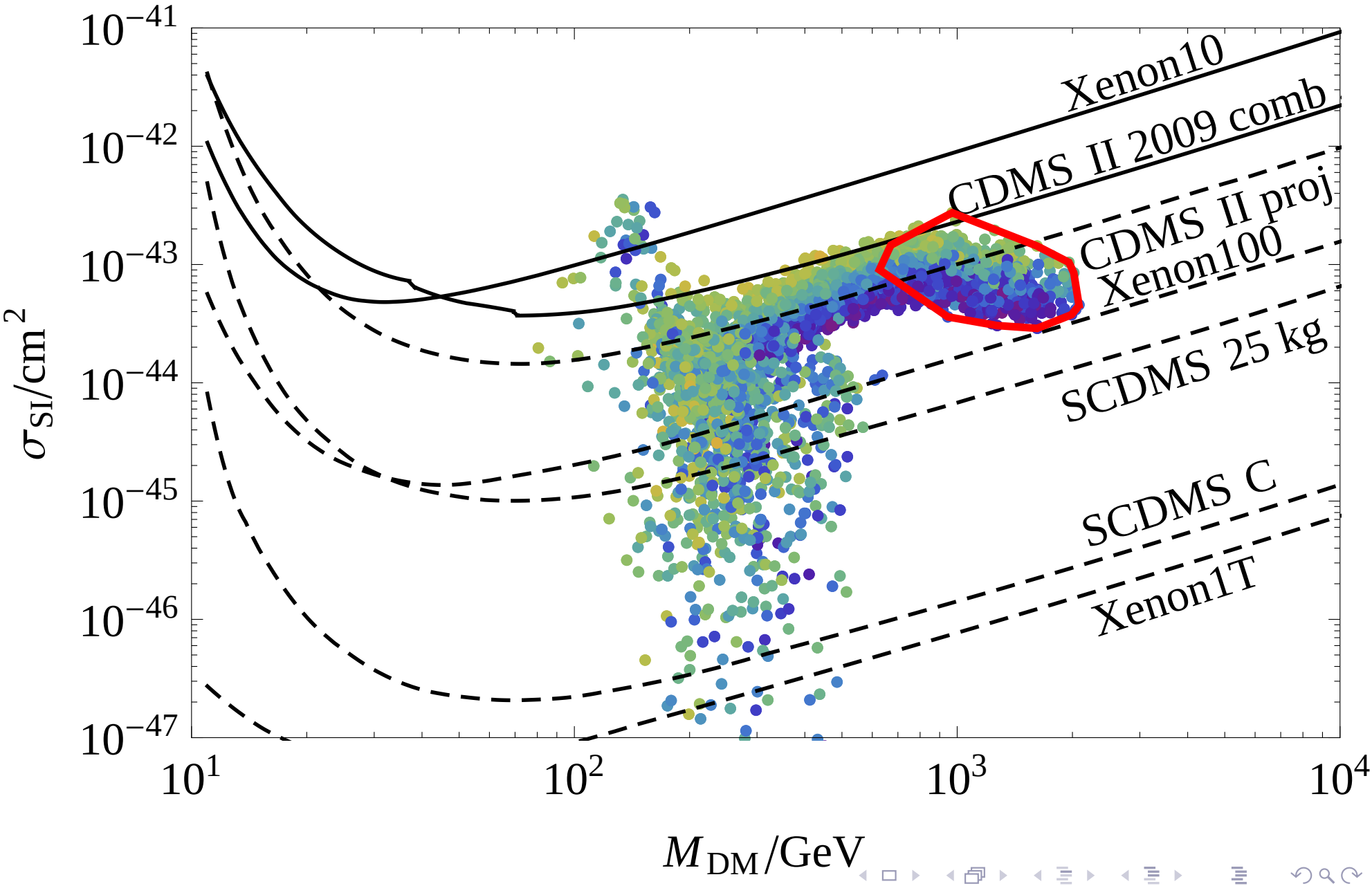
Direct Detection Cross Section



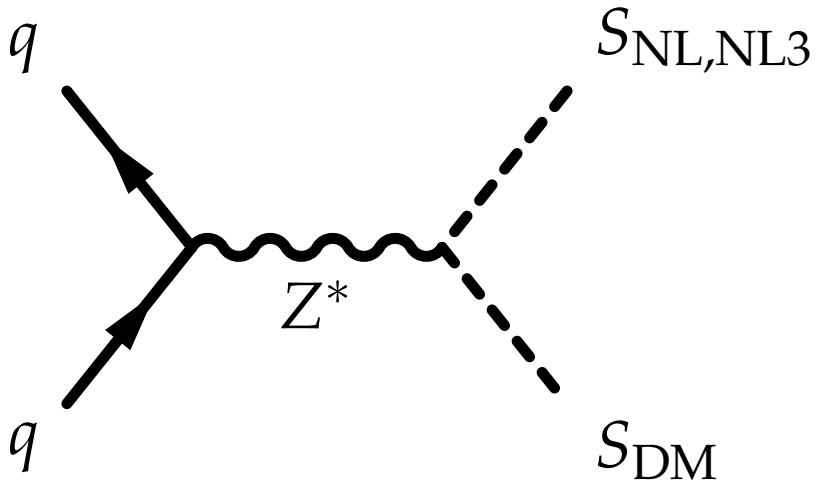
EWSB: $\mu_1^2 < 0$ from Threshold Corrections

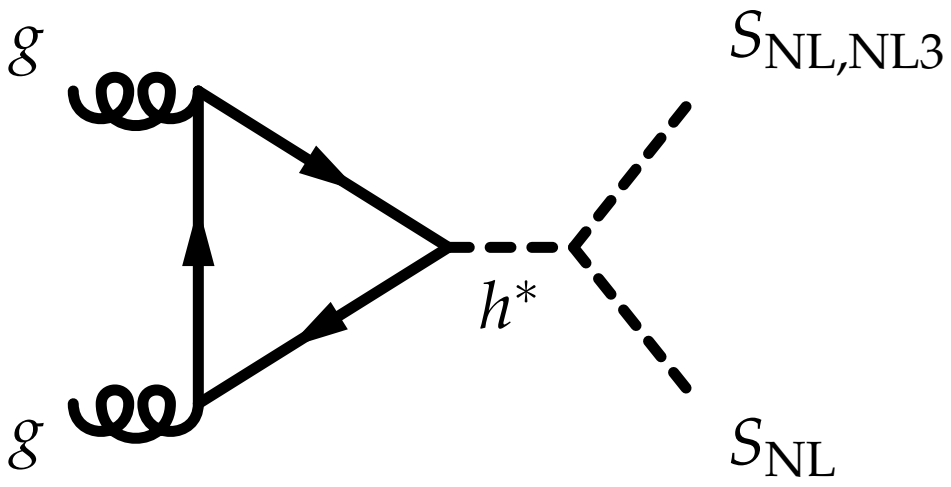


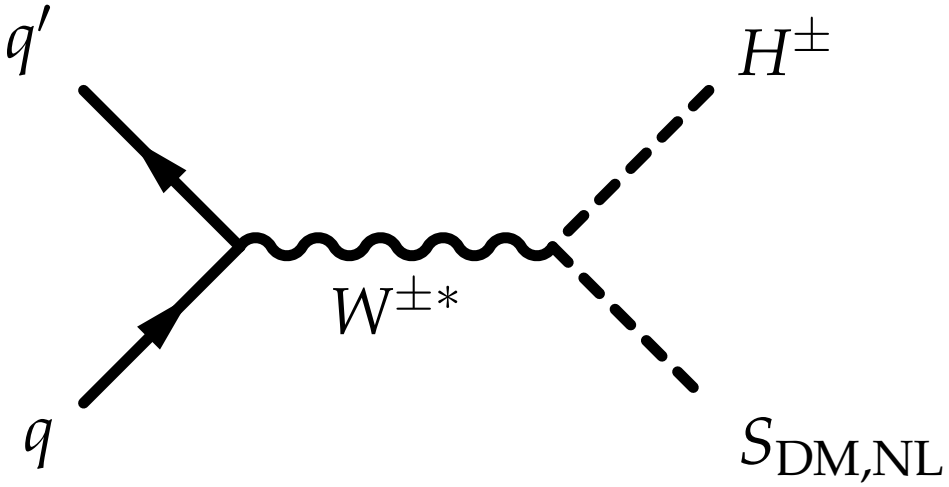
Direct Detection Cross Section



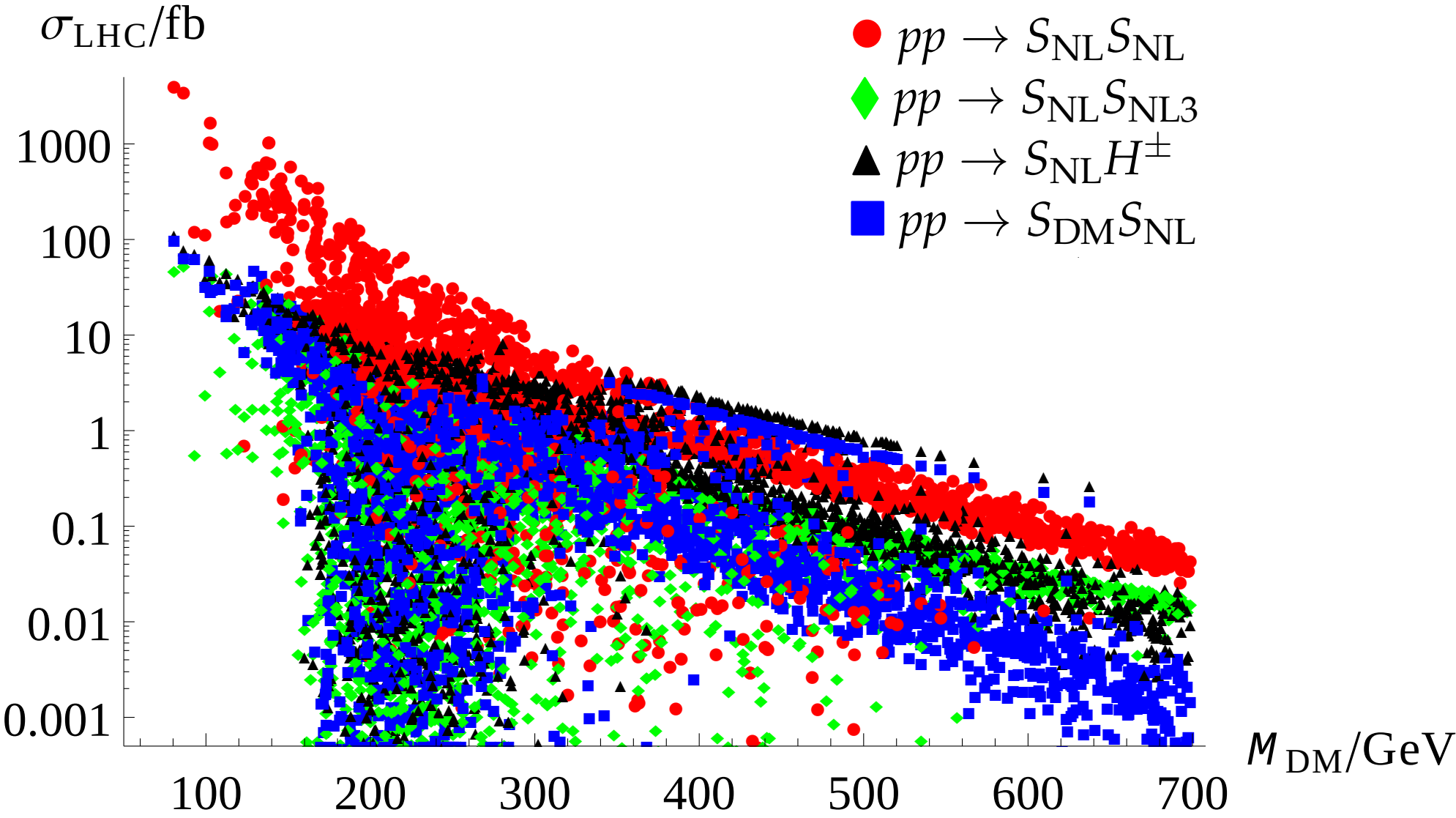
DM Production at LHC



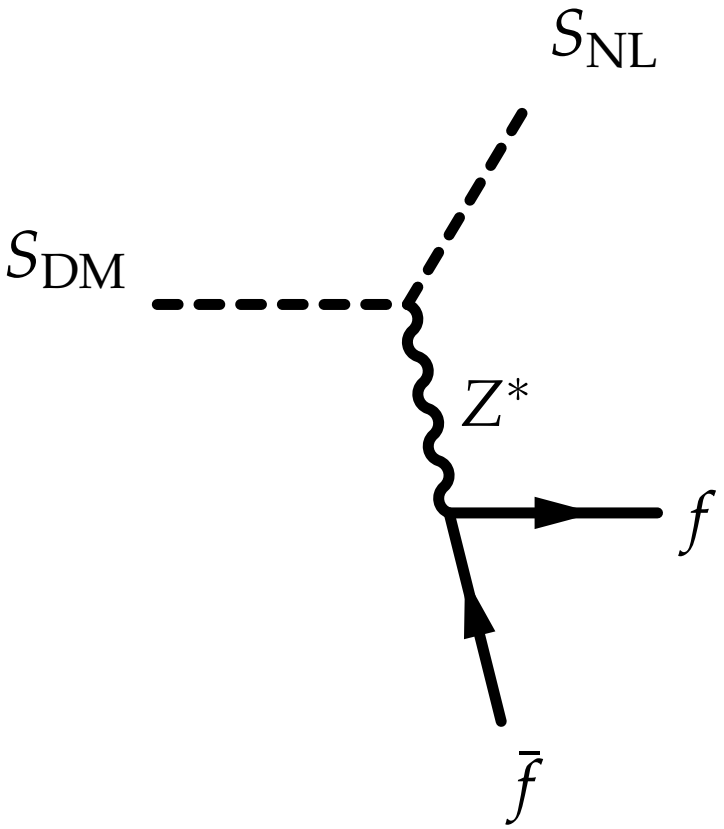




DM Production Cross Section at LHC



Displaced Vertex of S_{NL} Decay



- $\Delta M_{\mathrm{DM}} \equiv M_{\mathrm{NL}} - M_{\mathrm{DM}}$ naturally small
- For $\Delta M_{\mathrm{DM}} \sim$ 0.5 GeV…5 GeV, the displacement is 1 mm…1 m

Conclusions

- Matter parity $(-1)^{3(B-L)}$ from non-SUSY $SO(10)$
- Dark matter in **16** is scalar analogue of SM fermions
- EW symmetry breaking from radiative corrections
- $80\ \text{GeV} < M_{\text{DM}} < 2\ \text{TeV}$
- DM and $H^{\pm}$ can be seen at the LHC with displaced vertex

$SO(10)$ Conditions

$$\mu_1^2(M_{\rm G}) > 0$$
$$\mu_2^2(M_{\rm G}) = \mu_S^2(M_{\rm G}) > 0$$
$$\lambda_2(M_{\rm G}) = \lambda_S(M_{\rm G}) = \lambda_{S2}(M_{\rm G})$$
$$\lambda_3(M_{\rm G}) = \lambda_{S1}(M_{\rm G})$$

$$\mu_S'^2, \mu_{SH}^2 \lesssim \mathcal{O}\left(\frac{M_{\rm G}}{M_{\rm P}}\right)^n \mu_{1,2}^2,$$
$$\lambda_5, \lambda_{S1}', \lambda_{S2}', \lambda_S'' \lesssim \mathcal{O}\left(\frac{M_{\rm G}}{M_{\rm P}}\right)^n \lambda_{1,2,3,4}.$$

Vacuum Stability Conditions

2HDM:

$$\lambda_1 > 0 \qquad \lambda_3 > -2\sqrt{\lambda_1\lambda_2}$$
$$\lambda_2 > 0 \qquad \lambda_3 + \lambda_4 - |\lambda_5| > -2\sqrt{\lambda_1\lambda_2},$$

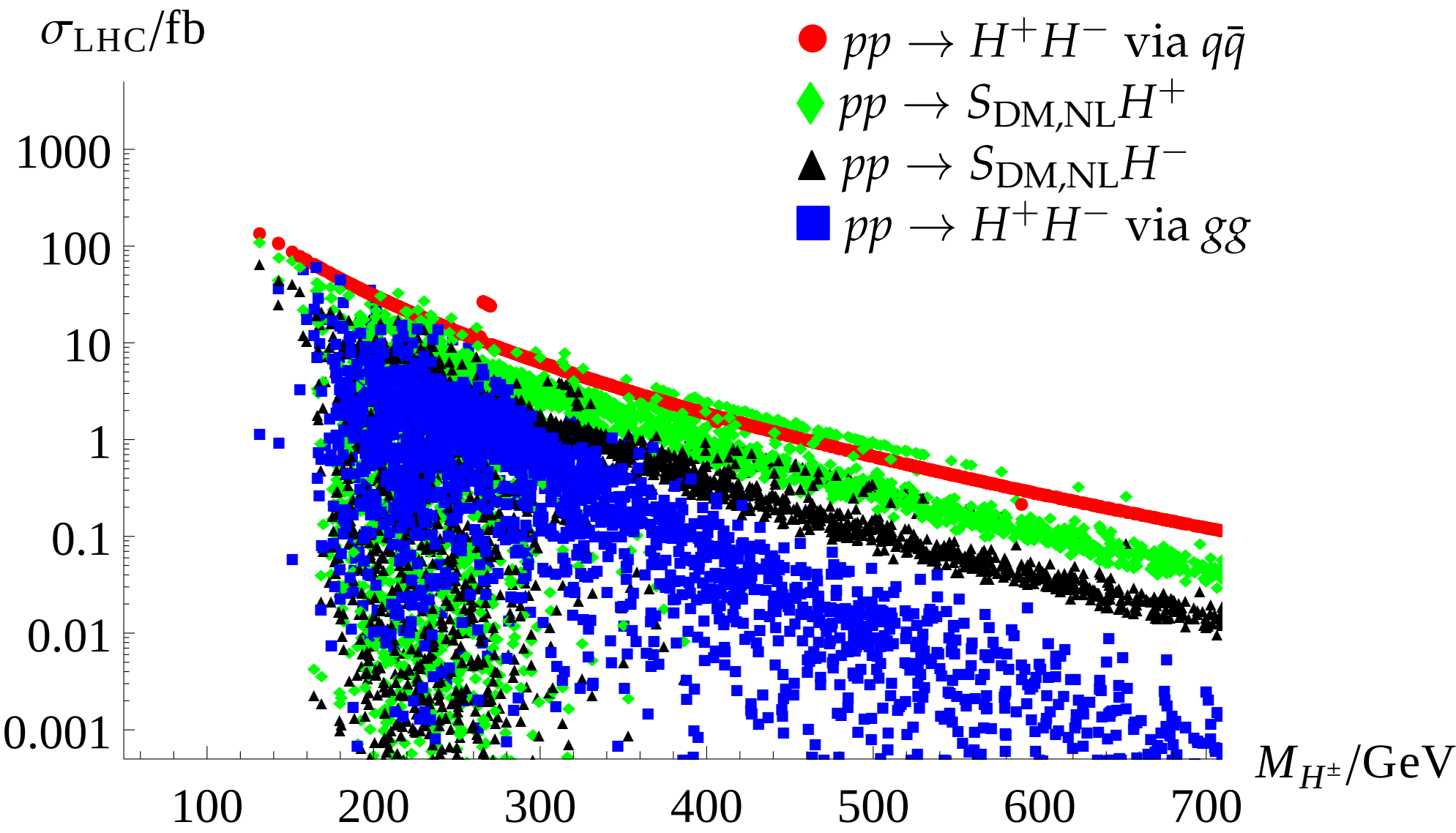
complex singlet:

$$\lambda_S + \lambda_S' > |\lambda_S''| \qquad 8(\lambda_S - \lambda_S')\lambda_S' > \lambda_S''^2,$$

additional:

$$4\lambda_1(\lambda_S + \lambda_S' + \lambda_S'') > (\lambda_{S1} + \lambda_{S1}')^2$$
$$4\lambda_2(\lambda_S + \lambda_S' + \lambda_S'') > (\lambda_{S2} + \lambda_{S2}')^2$$
$$4\lambda_1(\lambda_S + \lambda_S' - \lambda_S'') > (\lambda_{S1} - \lambda_{S1}')^2$$
$$4\lambda_2(\lambda_S + \lambda_S' - \lambda_S'') > (\lambda_{S2} - \lambda_{S2}')^2$$

$H^{\pm}$ Production Cross Section at LHC



$H^{\pm}$ Displaced Vertex at LHC