Signatures of TeV Higgs Portal Vector Dark Matter for PAMELA and AMS02

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OUTLINE

- Introduction
  - Evidences for DM, Global Symmetry
- $U_X(1)$ vector dark matter
- Effective Operators
- Phenomenology
  - Relic density, direct detection, indirect signatures,…
- Summary

Evidences for Dark Matter

- Rotation Curves of Galaxies
- Gravitational Lensing
- Large Scale Structure
- CMB anisotropies
- ……

Some Features

- Interactions with standard model particles need to be weak,
- Stable, if it decays, its lifetime must be long, even longer than the age of Universe. Longevity is usually associated with global symmetry.
- Z_2 symmetry $\phi \to -\phi$

$$\mathcal{L} = \frac{1}{2}\partial^\mu\phi\partial_\mu\phi - \frac{1}{2}m^2\phi^2 - \lambda\phi^4 - \lambda_{\phi H}\phi^2 H^\dagger H + \mathcal{L}_{\rm SM}$$

Global Symmetry

- There are some reasons to expect that global symmetries are not respected by non-perturbative quantum gravity.
- Global charges can be absorbed by black holes which then evaporate.

R.Kallosh, A.Linde, D.Linde and L.Susskind, hep-th/9502069

- There is no global symmetry in string theory, symmetry must be gauged.

T.Banks and N.Seiberg, arXiv:1011.5120

Scalar Dark Matter

- Scalar dark matter with Z_2 symmetry, $\phi \to -\phi$

$$\mathcal{L} = \frac{1}{2}\partial^\mu\phi\partial_\mu\phi - \frac{1}{2}m^2\phi^2 - \lambda\phi^4 - \lambda_{\phi H}\phi^2 H^\dagger H + \mathcal{L}_{\rm SM}$$

- Z_2 violating terms lead to decay

$$\delta\mathcal{L}_{\rm eff} = \frac{g}{M_{\rm pl}}\phi\mathcal{O}_{\rm SM},\ \mathcal{O}_{\rm SM} = F_{\mu\nu}F^{\mu\nu},\ \bar{f}\gamma\cdot Df,\ \bar{f}_L f_R H, \ldots$$

- Lifetime $\Gamma \sim \frac{g^2}{16\pi}\frac{m^3}{M_{\rm pl}^2} \simeq g^2\left(\frac{m}{1\rm TeV}\right)^3 \times 10^{-29}\rm GeV$

$$\Rightarrow \tau \sim \frac{1}{g^2}\left(\frac{1\rm TeV}{m}\right)^3 \times 10^4\rm s \qquad t_0 \sim 10^{18}s$$

$U(1)_X$ gauge symmetry

Minimal extension, a complex scalar Φ and a gauge boson X_μ

$$\mathcal{L} = -\frac{1}{4}X_{\mu\nu}X^{\mu\nu} + (D_\mu\Phi)^\dagger(D^\mu\Phi) - \lambda_\Phi\left(\Phi^\dagger\Phi - \frac{v_\Phi^2}{2}\right)^2$$

$$-\lambda_{H\Phi}\left(H^\dagger H - \frac{v_H^2}{2}\right)\left(\Phi^\dagger\Phi - \frac{v_\Phi^2}{2}\right) - \lambda_H\left(H^\dagger H - \frac{v_H^2}{2}\right)^2 + \mathcal{L}_{\mathrm{SM}}.$$

With $D_\mu\Phi = (\partial_\mu + ig_X Q_\Phi X_\mu)\Phi,$

Spontaneous breaking

$$\Phi = \frac{1}{\sqrt{2}}\left(v_\Phi + \varphi\right),$$

Mixing with Higgs

- Mass Eigenstates

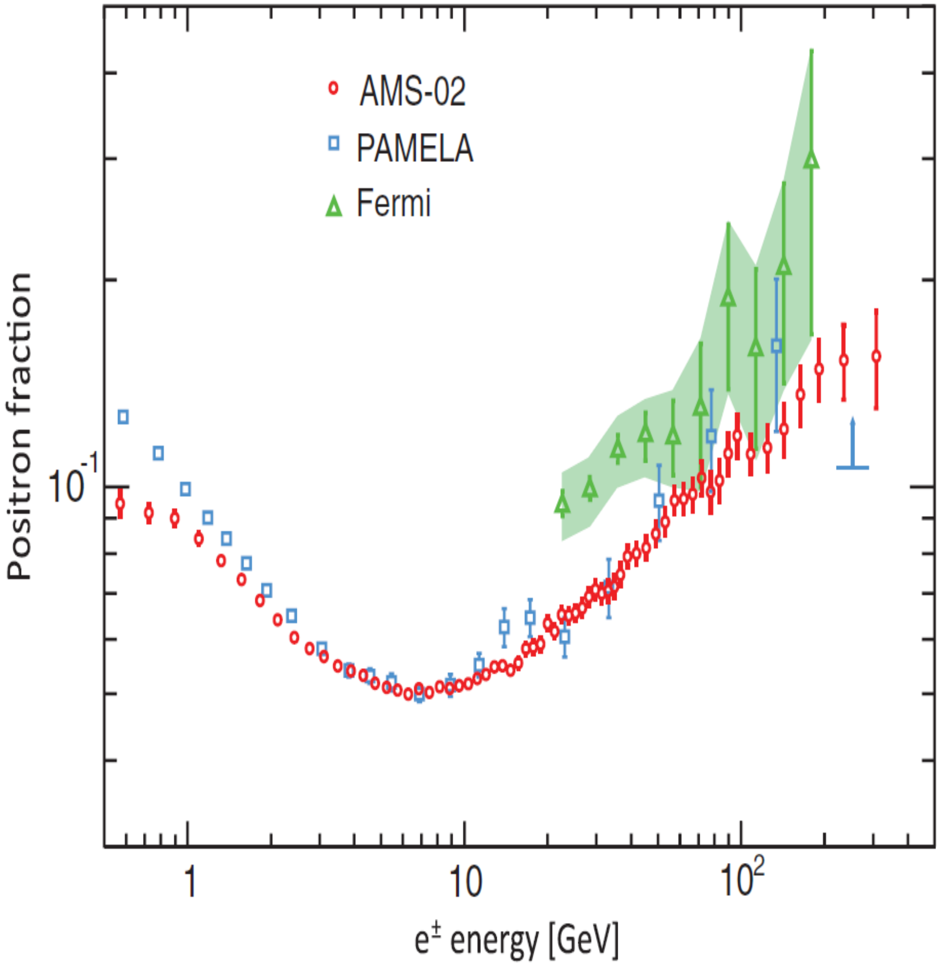
$$\begin{pmatrix} h \\ \varphi \end{pmatrix} = \begin{pmatrix} c_\alpha & s_\alpha \\ -s_\alpha & c_\alpha \end{pmatrix} \begin{pmatrix} H_1 \\ H_2 \end{pmatrix}$$

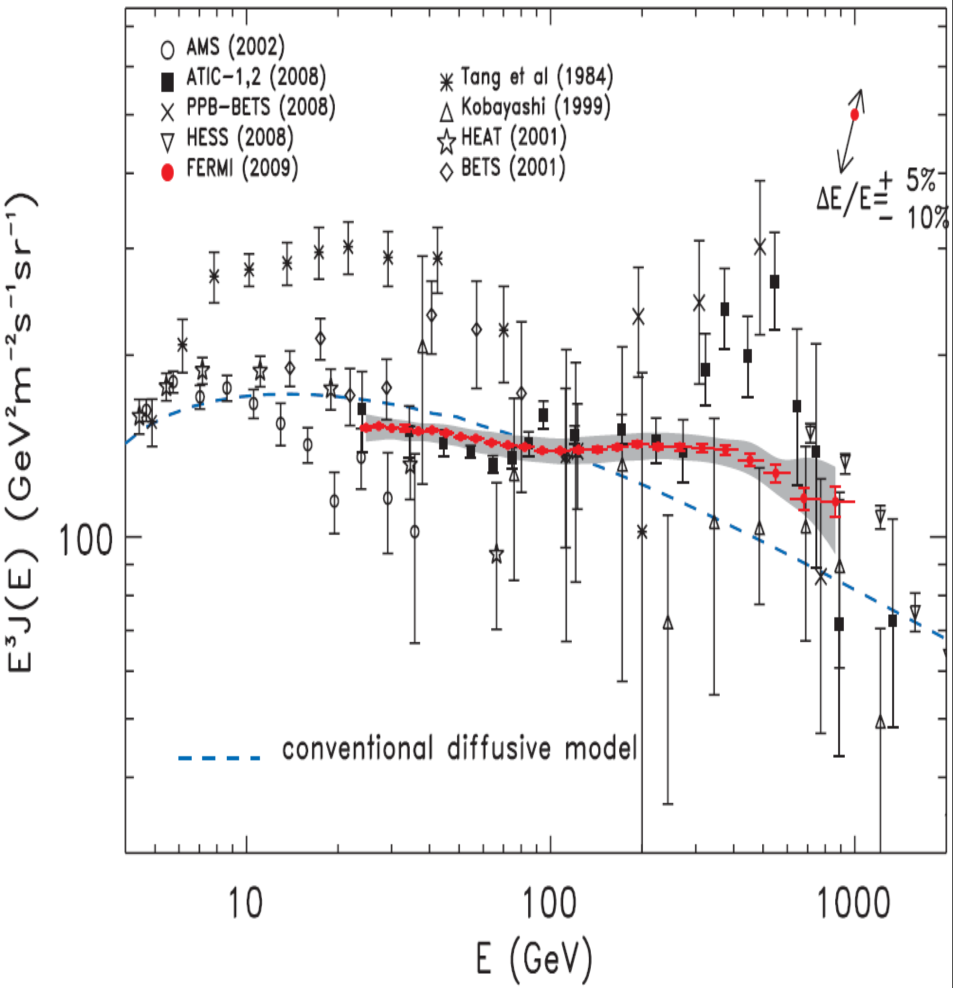
$$\begin{pmatrix} M_{H_1}^2 c_\alpha^2 + M_{H_2}^2 s_\alpha^2 & \left(M_{H_2}^2 - M_{H_1}^2\right) s_\alpha c_\alpha \\ \left(M_{H_2}^2 - M_{H_1}^2\right) s_\alpha c_\alpha & M_{H_1}^2 s_\alpha^2 + M_{H_2}^2 c_\alpha^2 \end{pmatrix} \equiv \mathcal{M}$$

$$\tan 2\alpha = \frac{2\mathcal{M}_{12}}{\mathcal{M}_{22} - \mathcal{M}_{11}}, \text{ or } \sin 2\alpha = \frac{2\lambda_{H\Phi} v_H v_\Phi}{M_{H_2}^2 - M_{H_1}^2}.$$

- Higgs' couplings to SM particles are universally scale by cosα.
- New Parameters $M_X,\ M_{H_2},\ g_X,\ \sin\alpha$

Positron Excess





Leptophilic model, TeV DM

Possible Explanations

- DM annihilation $\langle \sigma v \rangle \sim 10^{-23}\mathrm{cm}^3/\mathrm{s} \gg 10^{-26}\mathrm{cm}^3/\mathrm{s}$
  - Sommerfeld Enhancement
  - Breit-Wigner resonance
- DM decay, $\tau_{\mathrm{DM}} \sim 10^{26}\mathrm{s}$
- …

Decaying Dark Matter

- High dimensional operators can induce DM decay,

$$\mathcal{L} = -\frac{g_\Lambda^2}{\Lambda^2}\mathcal{O}_6$$

gives

$$\Gamma \sim \frac{g_\Lambda^4 M^5}{\Lambda^4},$$

for $\tau_{\rm DM} \sim 10^{26}{\rm s}$, we have

$$\Lambda \sim g_\Lambda \left(M^5 \tau_{\rm DM}\right)^{\frac{1}{4}} \simeq 2 g_\Lambda \times 10^{16}{\rm GeV}$$

Effective Operators

Gauge invariant building blocks in dark sector

$$\Phi^\dagger\Phi,\ \Phi^\dagger i\overleftrightarrow{D}_\mu\Phi,\ X^{\mu\nu},\ \tilde{X}^{\mu\nu}.$$

where

$$\Phi^\dagger\overleftrightarrow{D}_\mu\Phi = \Phi^\dagger D_\mu\Phi - \left(D_\mu\Phi\right)^\dagger\Phi$$

then independent dimension-6 operators are

$$\left(\Phi^\dagger\Phi\right)^3,\ \left(\Phi^\dagger\Phi\right)\Box\left(\Phi^\dagger\Phi\right),\ \left(\Phi^\dagger D^\mu\Phi\right)^\dagger\left(\Phi^\dagger D^\mu\Phi\right),$$

$$\Phi^\dagger\Phi X_{\mu\nu}X^{\mu\nu},\ \Phi^\dagger\Phi\tilde{X}_{\mu\nu}X^{\mu\nu}.$$

Other operators can be reduced to the above ones by equation of motion.

Effective Operators

- Building components in the SM

$$H^\dagger H,\ H^\dagger i\overleftrightarrow{D}_\mu H,\ B^{\mu\nu},\ \tilde{B}^{\mu\nu},\ \bar{L}_i R_j H,\ \bar{f}_i\gamma^\mu f_j,$$
$$\left(\bar{L}_i\sigma^{\mu\nu}R_j\right)H,\ H^\dagger\tau^I H W^I_{\mu\nu},\ H^\dagger\tau^I H\tilde{W}^I_{\mu\nu},$$

- Operators involves both DM sector and SM

$$\left(\Phi^\dagger\Phi\right)^2 H^\dagger H,\ \Phi^\dagger\Phi\left(H^\dagger H\right)^2,\Phi^\dagger\Phi\Box H^\dagger H,\ \left(\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi\right)\left(H^\dagger i\overleftrightarrow{D}_\mu H\right),$$
$$\Phi^\dagger\Phi\left(\bar{L}_i R_j H + h.c\right),\ \left(\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi\right)\left(\bar{L}_i\gamma^\mu L_j + \bar{R}_i\gamma^\mu R_j\right),\ \left(\bar{L}_i\sigma^{\mu\nu}R_j\right)HX^{\mu\nu}$$
$$\Phi^\dagger\Phi B_{\mu\nu}X^{\mu\nu},\ \Phi^\dagger\Phi\tilde{B}_{\mu\nu}X^{\mu\nu},H^\dagger H B_{\mu\nu}X^{\mu\nu},\ H^\dagger H X_{\mu\nu}X^{\mu\nu},$$
$$H^\dagger H\tilde{X}_{\mu\nu}X^{\mu\nu},\ H^\dagger H\tilde{B}_{\mu\nu}X^{\mu\nu},\ H^\dagger\tau^I H W^I_{\mu\nu}X^{\mu\nu},\ H^\dagger\tau^I H\tilde{W}^I_{\mu\nu}X^{\mu\nu}.$$

DM decay

After the symmetry breaking, DM can decay induced by these effective operators,

$$\left(\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi\right)\left(H^\dagger i\overleftrightarrow{D}^\mu H\right) \Rightarrow X^\mu \to \varphi/h + \gamma/Z,$$

$$\left(\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi\right)\left(\bar{f}\gamma^\mu f\right),\ \bar{L}\sigma_{\mu\nu}RHX^{\mu\nu} \Rightarrow X^\mu \to \bar{f} + f,$$

$$\Phi^\dagger\Phi B_{\mu\nu}X^{\mu\nu},\ \Phi^\dagger\Phi\tilde{B}_{\mu\nu}X^{\mu\nu}, (\Phi \to H) \Rightarrow X^\mu \to \varphi/h + \gamma/Z,$$

$$H^\dagger\tau^I HW^I_{\mu\nu}X^{\mu\nu},\ H^\dagger\tau^I H\tilde{W}^I_{\mu\nu}X^{\mu\nu} \Rightarrow X^\mu \to \varphi/h + \gamma/Z,$$

An illustrative example

Effective operator

$$-\frac{g_\Lambda^2}{\Lambda^2}\left(\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi\right)\left(\bar{f}\gamma^\mu f\right),$$

can be induced from the following UV complete theory,

$$\mathcal{L}=\left(D'_\mu\Phi\right)^\dagger D'^\mu\Phi+\bar{f}i\gamma^\mu D'_\mu f-\frac{1}{4}F'^{\mu\nu}F'_{\mu\nu}+\left(D'_\mu\phi\right)^\dagger D'^\mu\phi-V\left(\phi^\dagger\phi\right),$$

$$\begin{aligned}D'_\mu\Phi&=\left(\partial_\mu+ig_XQ_XX_\mu+ig'Q'_\Phi A'_\mu\right)\Phi,\\ D'_\mu\phi&=\left(\partial_\mu+ig'Q'_\phi A'_\mu\right)\phi,\\ D'_\mu f&=\left(D_\mu^{\rm SM}+ig'Q'_fA'_\mu\right)f.\end{aligned}$$

with the replacement

$$\Lambda\to M_{A'},\ g_\Lambda\to g'$$

An illustrative example

- The previous symmetry can be identified as the lepton number.
- It can also serve as the source for type-I seesaw mechanism.
- If it is only associated with one generation of leptons, DM then decays solely to that generation lepton pair, $X^\mu \to l^+ l^-$.

Indirect Signatures

- DM decay can provide additional source,

$$Q\left(E,\vec{r}\right)=\frac{\rho\left(\vec{r}\right)}{M_{\mathrm{DM}}\tau_{\mathrm{DM}}}\frac{dN^{e^{\pm}}}{dE}$$

micrOMEGAs_3.1

- We use the NFW density profile for DM in Milky Way

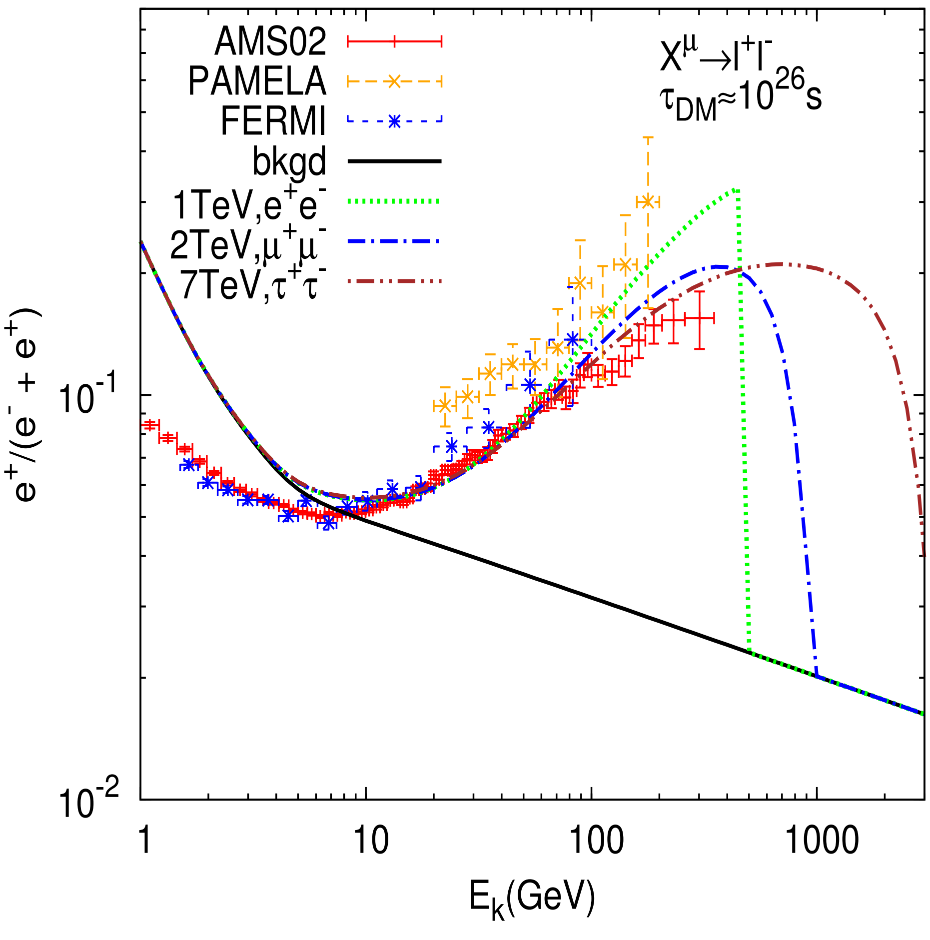
$$\rho\left(\vec{r}\right)=\rho_{\odot}\left[\frac{r_{\odot}}{r}\right]\left[\frac{1+\left(r_{\odot}/r_c\right)}{1+\left(r/r_c\right)}\right]^2 .$$

And

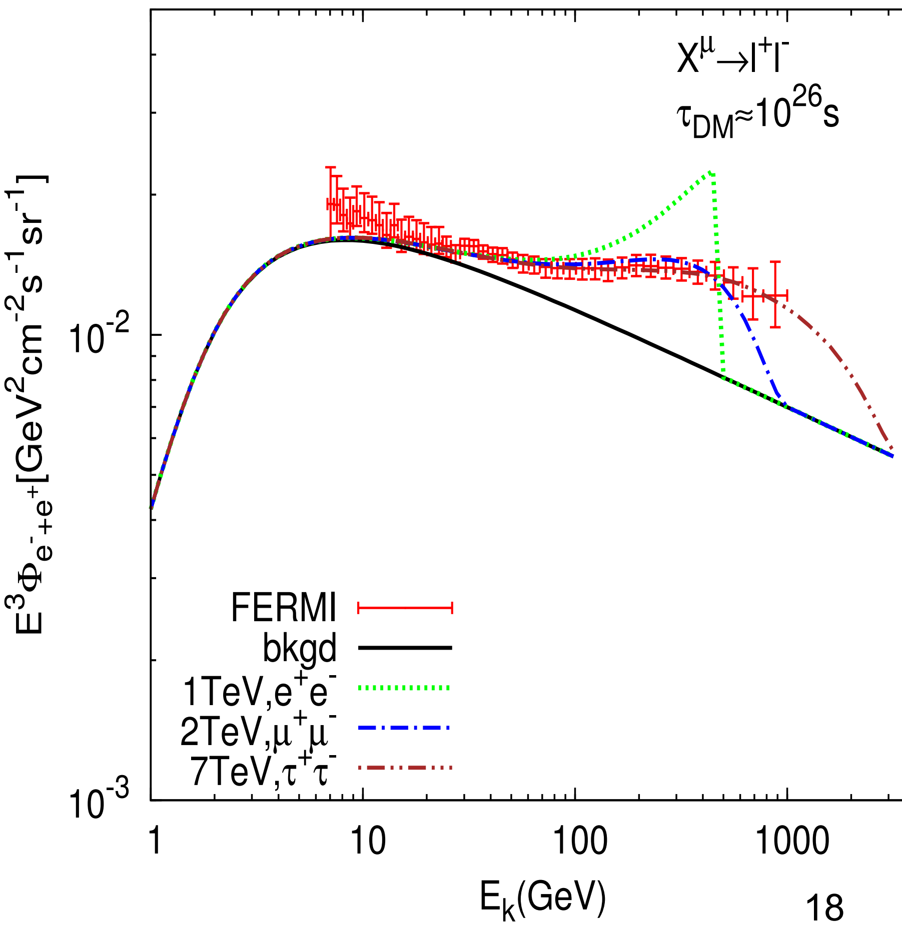
$$\rho_{\odot}\simeq 0.3\mathrm{GeV/cm}^3,\ r_{\odot}\simeq 8.5\mathrm{kpc}\ \mathrm{and}\ r_c\simeq 20\mathrm{kpc}$$

Spectra from $X^\mu \to l^+ l^-$

positron fraction



total flux



Some Remarks

- E<10GeV can be affected by solar wind significantly.
- The spectrum from $X^{\mu} \to e^{+}e^{-}$ is hard and very sharp near the end point.
- The spectrum from $X^{\mu} \to \mu^{+}\mu^{-}$ is softer than the electron case due to the three-body decay,

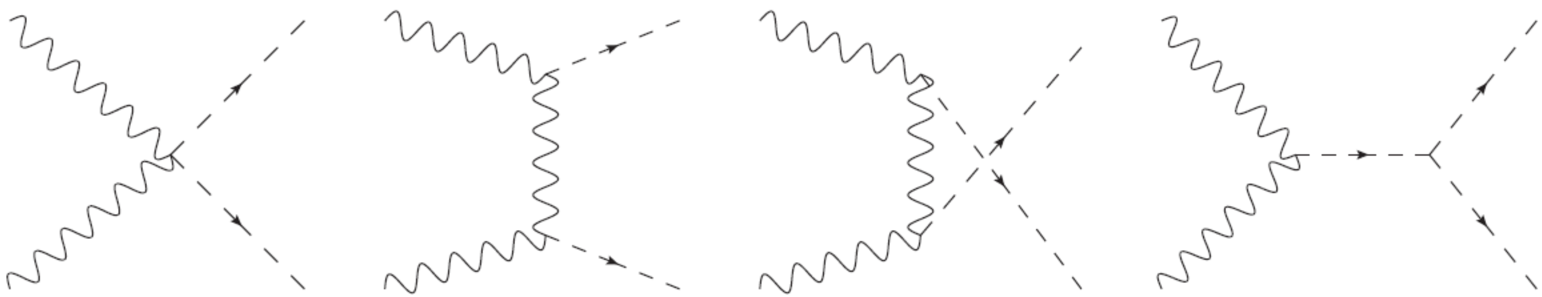
$$\mu^{\pm} \to e^{\pm} + \nu_e + \nu_{\mu},$$

- Tau final states give even softer spectra since only 1/3 taus decay to light leptons directly, the rest mainly to mesons and then to pions, followed by,

$$\pi^{\pm} \to \mu^{\pm} + \nu_{\mu} \text{ and } \pi^{0} \to 2\gamma.$$

Constraints and Other Signatures for TeV X_μ

Relic density

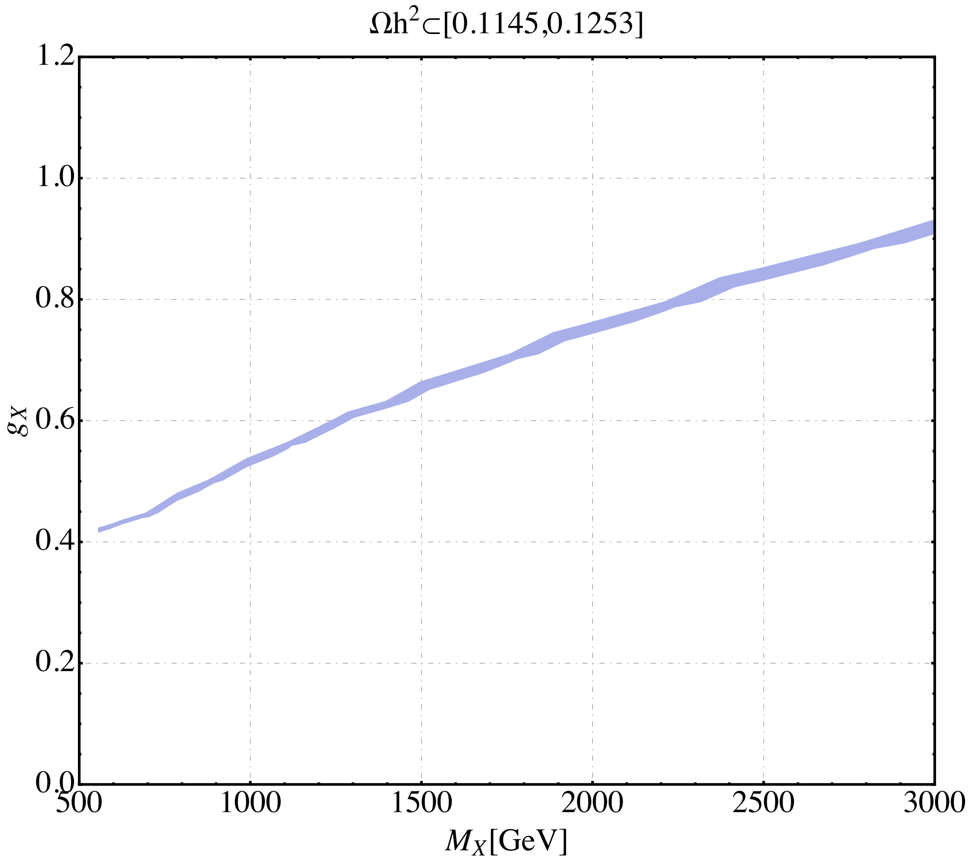


$$\sigma v \simeq \frac{g_X^4}{144\pi M_X^2}\left[3-\frac{8\left(M_{H_2}^2-4M_X^2\right)}{M_{H_2}^2-2M_X^2}+\frac{16\left(M_{H_2}^4-4M_{H_2}^2M_X^2+6M_X^4\right)}{\left(M_{H_2}^2-2M_X^2\right)^2}\right]$$

relic density requires

$$\sigma v \simeq 3\times 10^{-26}\mathrm{cm}^3/\mathrm{s} \Rightarrow\ g_X \sim 0.57\times\left(\frac{M_X}{1\mathrm{TeV}}\right)^{\frac{1}{2}}$$

Relic density



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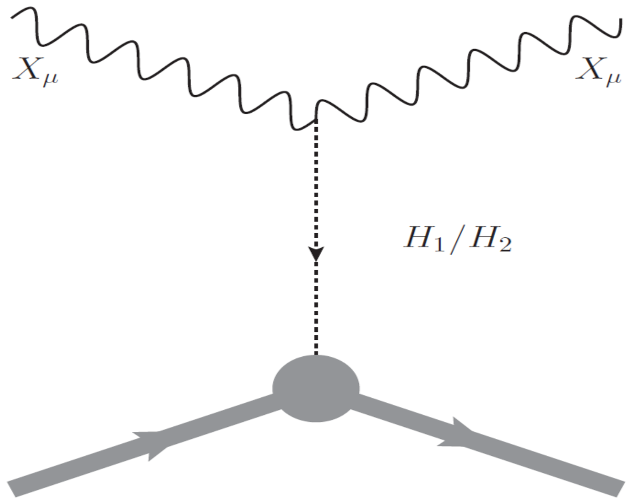
- Planck gives

$$\Omega h^2 = 0.1199 \pm 0.0027$$

- approximation

$$g_X \sim 0.57 \times \left(\frac{M_X}{1\mathrm{TeV}}\right)^{\frac{1}{2}}$$

Direct detection

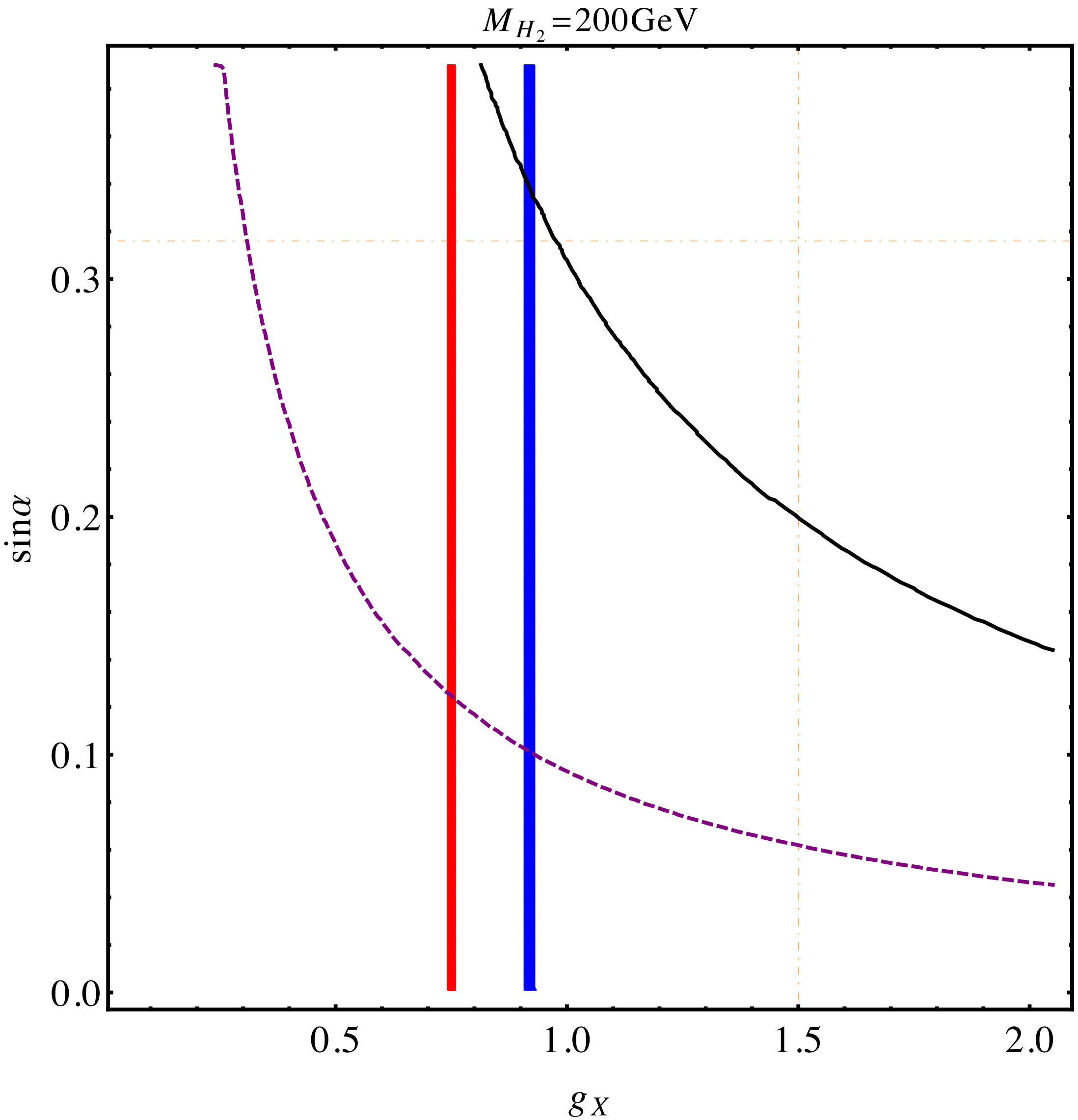


The cross section of dark matter scattering off a nucleon is

$$\sigma\left(X_\mu N \to X_\mu N\right) = \frac{1}{16\pi} g_X^4 \sin^2 2\alpha \frac{f^2 m_N^2}{v_H^2} \left(\frac{1}{m_{H_2}^2} - \frac{1}{m_{H_1}^2}\right)^2 \left(\frac{M_X m_N}{M_X + m_N}\right)^2 .$$

Cancellation occurs when masses are degenerate.

Parameter Limits



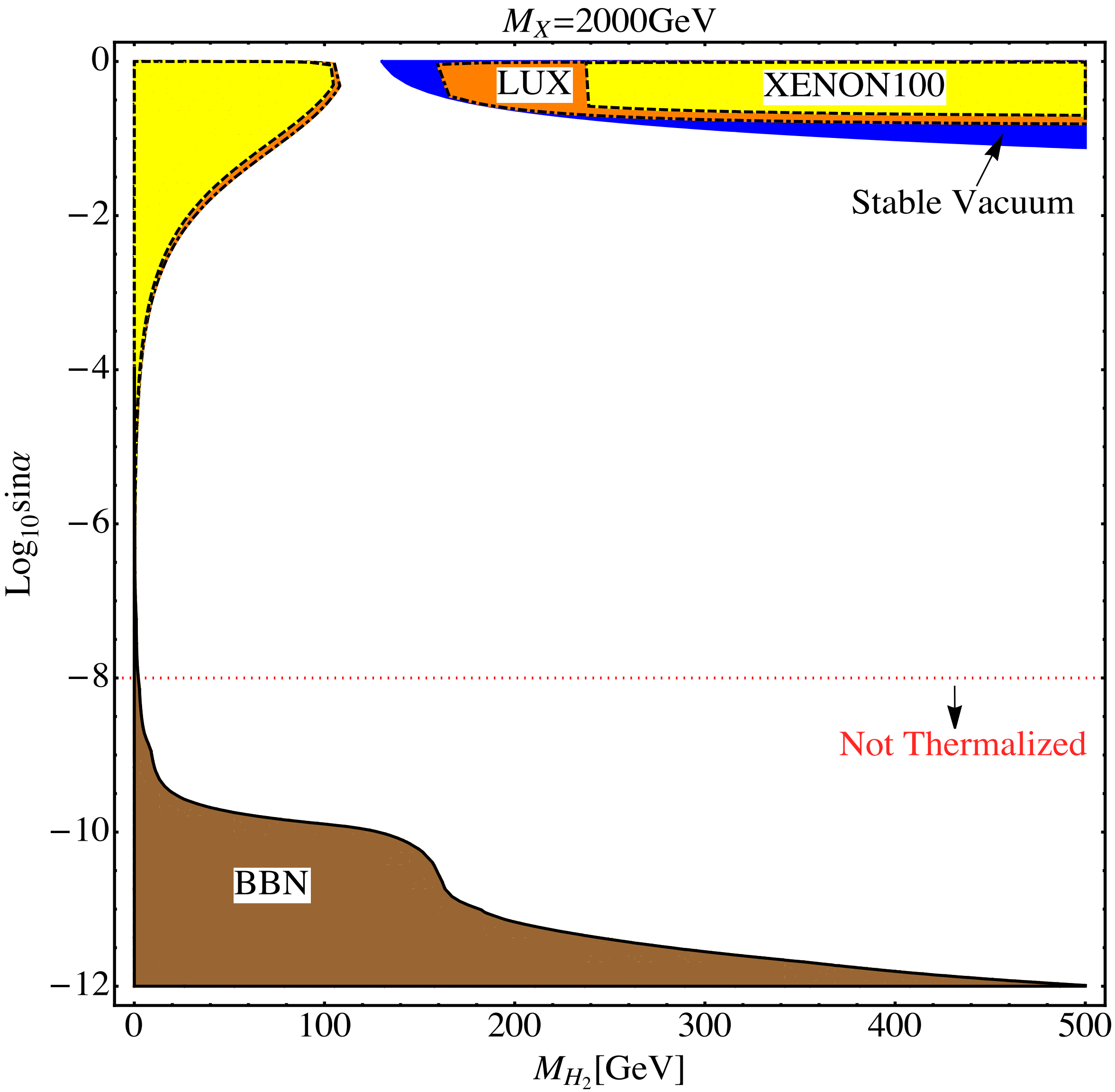
The blue band is for 3TeV VDM, and red one for 2TeV.

The solid(dashed) curves corresponds

$$\sigma_{XN} = 10^{-44}\left(10^{-45}\right)\mathrm{cm}^2$$

For different mass of H_2, we can constrain the mixing angle.

Limits on the mixing angle



Yellow(Orange) regions are excluded by XENON100(LUX).

Lowest bounds are set by thermalization and BBN constraints on the lifetime of H_2.

Blue region gives the stable vacuum.

Some Estimations

The LHC higgs data give constraint on the mixing angle, roughly $\sin^2\alpha \lesssim 0.1$, then

$$\sin\alpha = \frac{\lambda_{H\Phi} v_H v_\Phi}{M_{H_2}^2 - M_{H_1}^2}.$$

take for example

$$M_X \sim 2\mathrm{TeV},\ g_X \simeq 0.7,\ M_{H_2} \sim 500\mathrm{GeV}$$

we have

$$\lambda_{H\Phi} \sim \frac{\sin\alpha\left(500^2 - 125^2\right)}{246 \times 2000} \sim 0.5 \times \sin\alpha,$$

$$\lambda_\Phi \sim \frac{500^2}{2 \times 2000^2} = 0.03,$$

$$\lambda_H = \frac{125^2 + \left(500^2 - 125^2\right)\sin^2\alpha}{2 \times 246^2} \simeq 0.13 + 2\sin^2\alpha.$$

Perturbativity

Since we need no more new physics below Λ, the theory should be perturbative up to Λ.

$$\frac{d\lambda_H}{d\ln\mu} = \frac{1}{16\pi^2}\left[24\lambda_H^2 + \lambda_{H\Phi}^2 - 6y_t^4 + \frac{3}{8}\left(2g_2^2 + \left(g_1^2 + g_2^2\right)^2\right) - \lambda_H\left(9g_2^2 + 3g_1^2 - 12y_t^2\right)\right],$$

$$\frac{d\lambda_{H\Phi}}{d\ln\mu} = \frac{1}{16\pi^2}\left[2\lambda_{H\Phi}\left(6\lambda_H + 4\lambda_\Phi + 2\lambda_{H\Phi}\right) - \lambda_{H\Phi}\left(\frac{9}{2}g_2^2 + \frac{3}{2}g_1^2 - 6y_t^2 + 6g_X^2\right)\right],$$

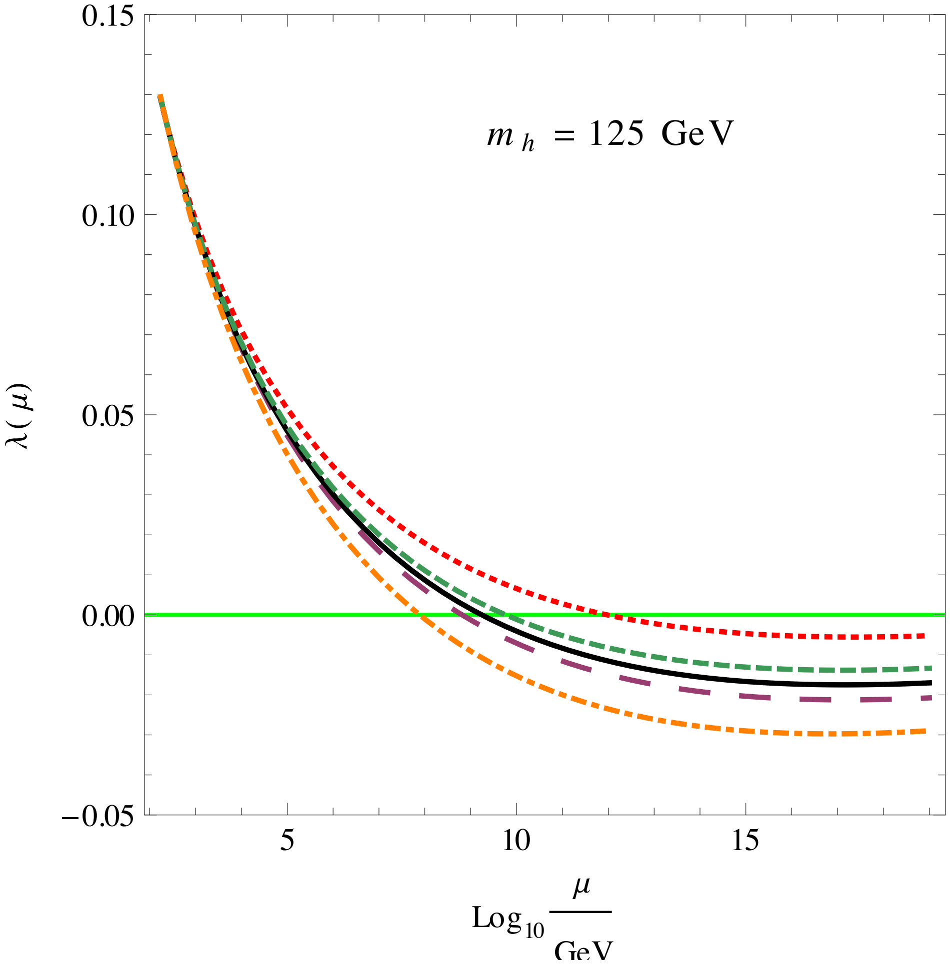
$$\frac{d\lambda_\Phi}{d\ln\mu} = \frac{1}{16\pi^2}\left[2\left(\lambda_{H\Phi}^2 + 10\lambda_\Phi^2 + 3g_X^4\right) - 12\lambda_\Phi g_X^2\right],$$

$$\frac{dg_X}{d\ln\mu} = \frac{1}{16\pi^2}\frac{1}{3}g_X^3\ .$$

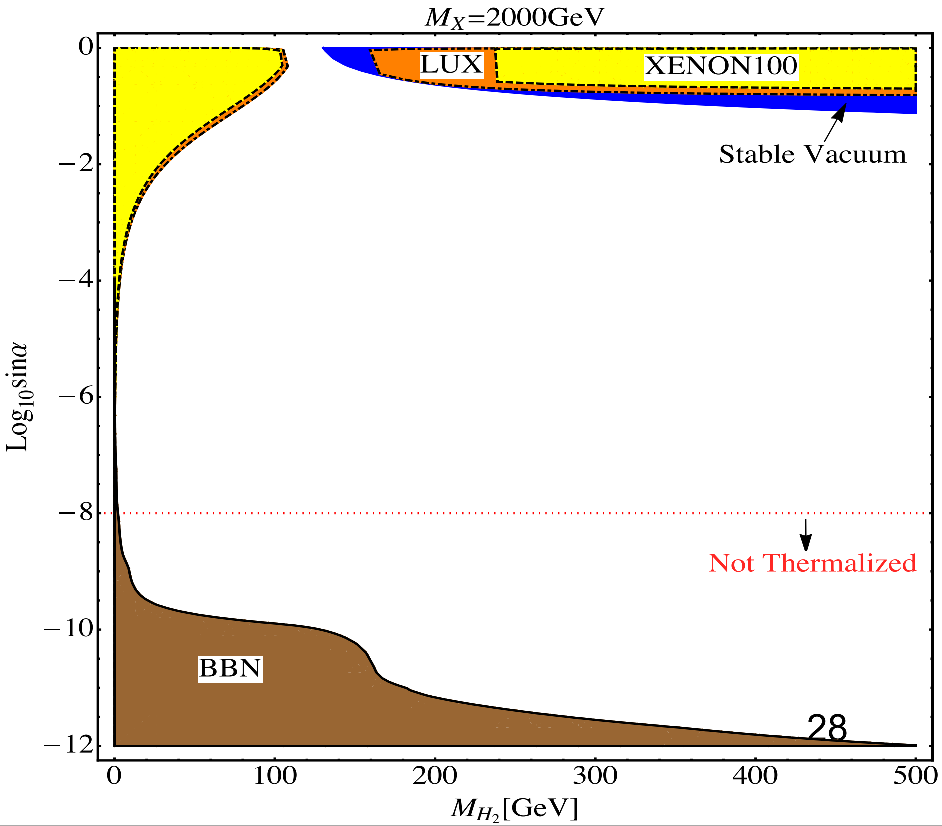
$$\lambda_\Phi(\Lambda) \lesssim 4\pi \Rightarrow g_X \lesssim 1.5$$

Vacuum Stability

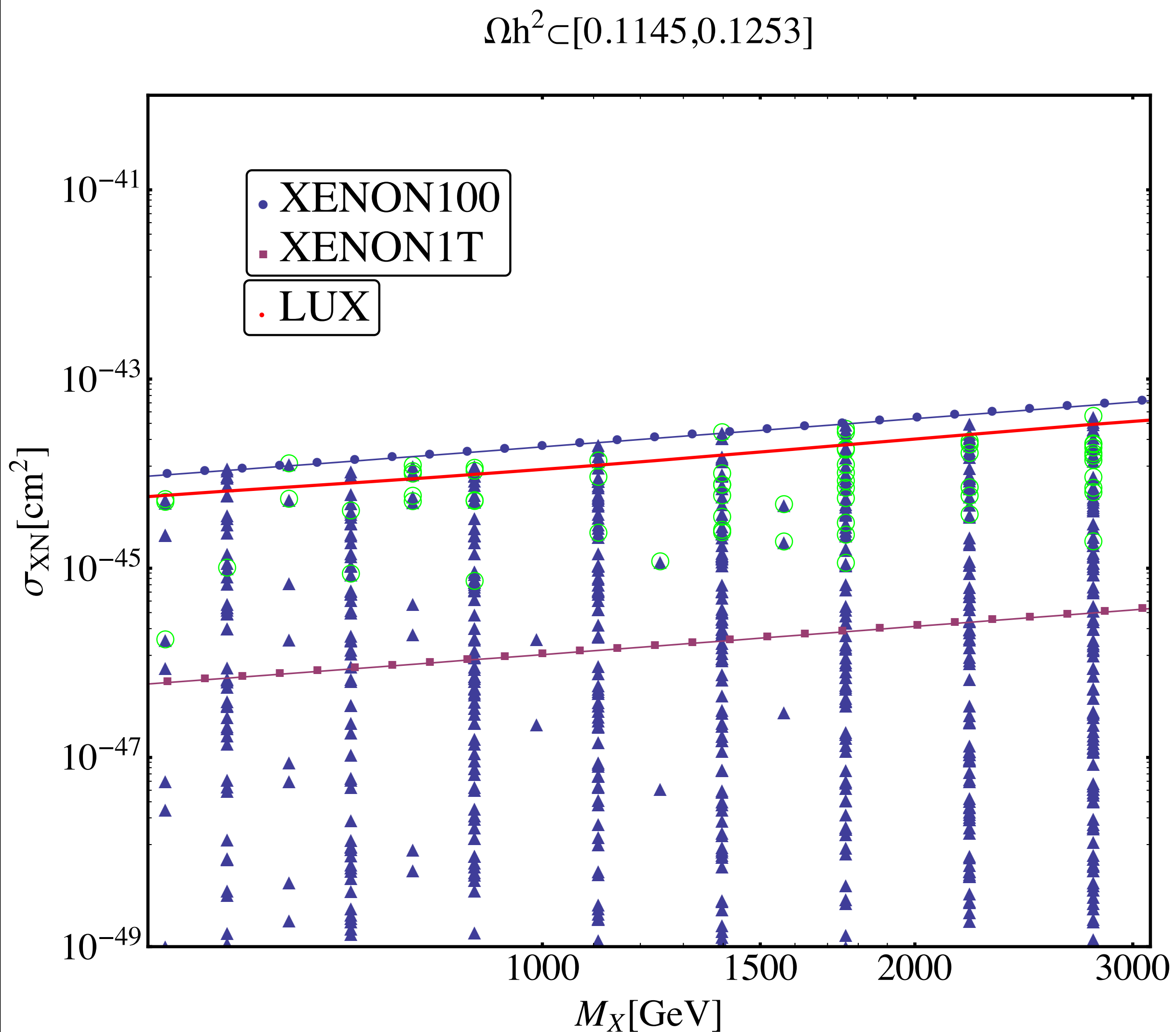
$$\frac{d\lambda_H}{d\ln\mu} = \frac{1}{16\pi^2}\left[24\lambda_H^2 + \lambda_{H\Phi}^2 - 6y_t^4 + \frac{3}{8}\left(2g_2^2 + \left(g_1^2 + g_2^2\right)^2\right) - \lambda_H\left(9g_2^2 + 3g_1^2 - 12y_t^2\right)\right]$$



$$\lambda_H = \frac{M_{H_1}^2\cos^2\alpha + M_{H_2}^2\sin^2\alpha}{2v_H^2} \gtrsim 0.14.$$



Experimental Searches

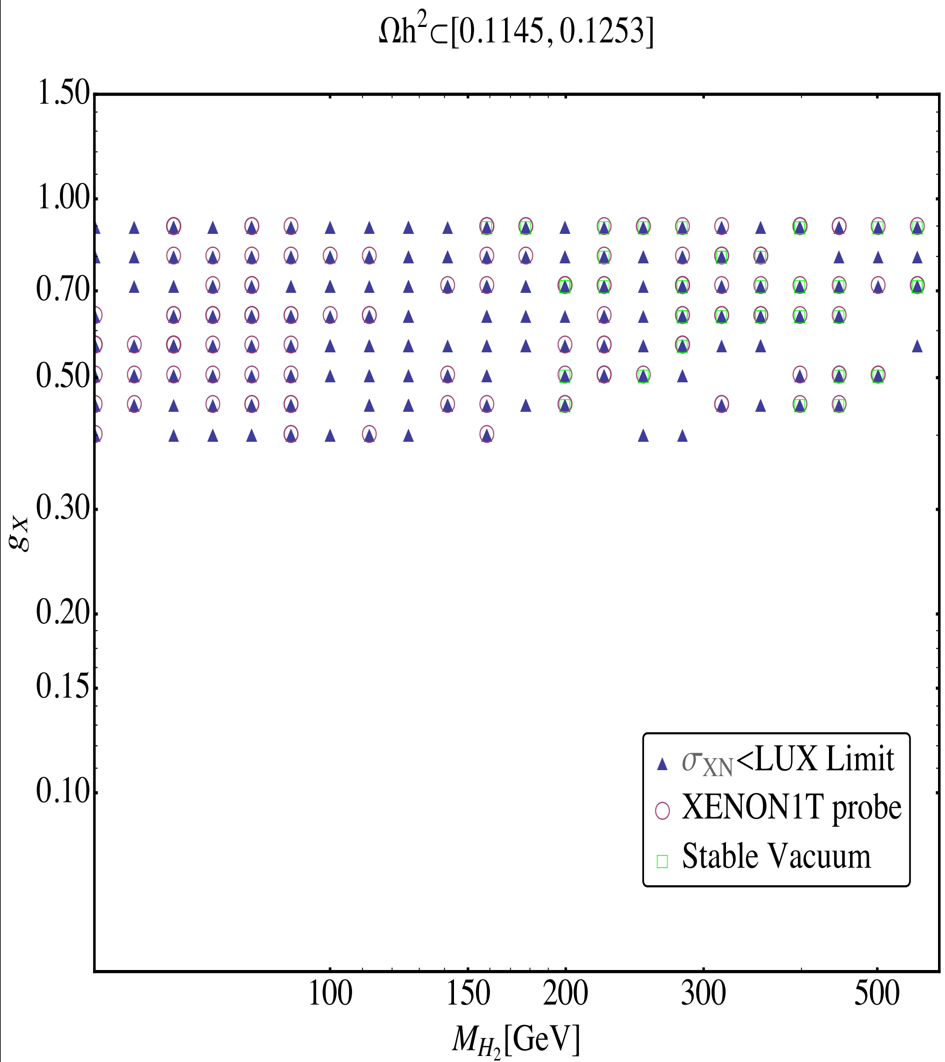


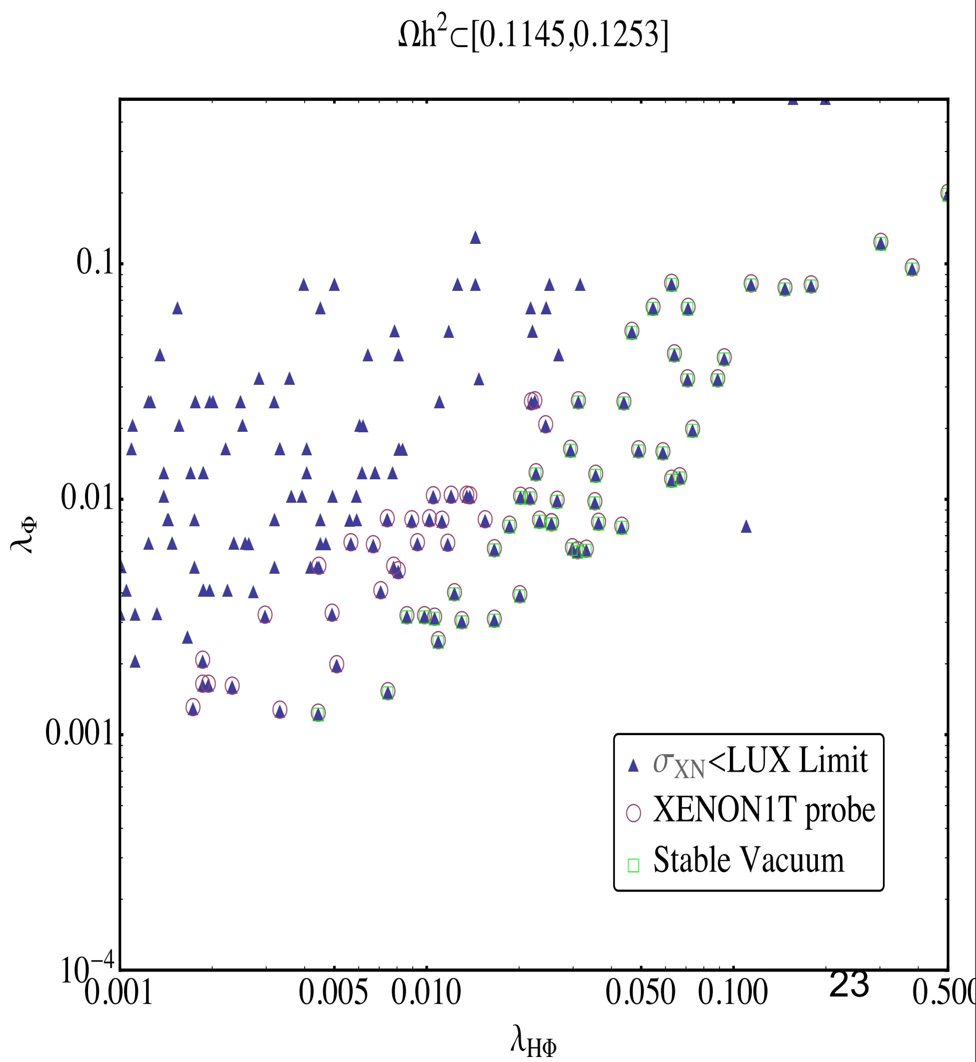
Blue line is the latest XENON100 limit.

Red line is LUX limit.

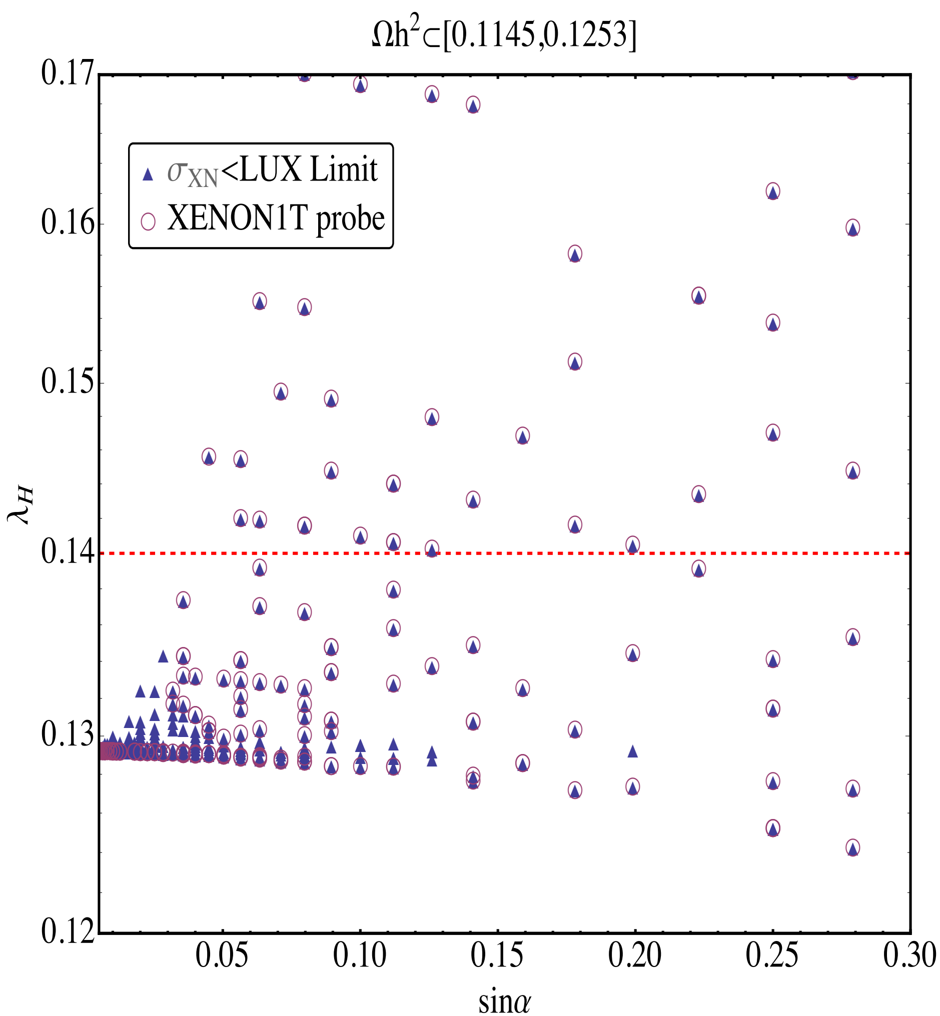
Purple line shows the expected limit from XENON1T.

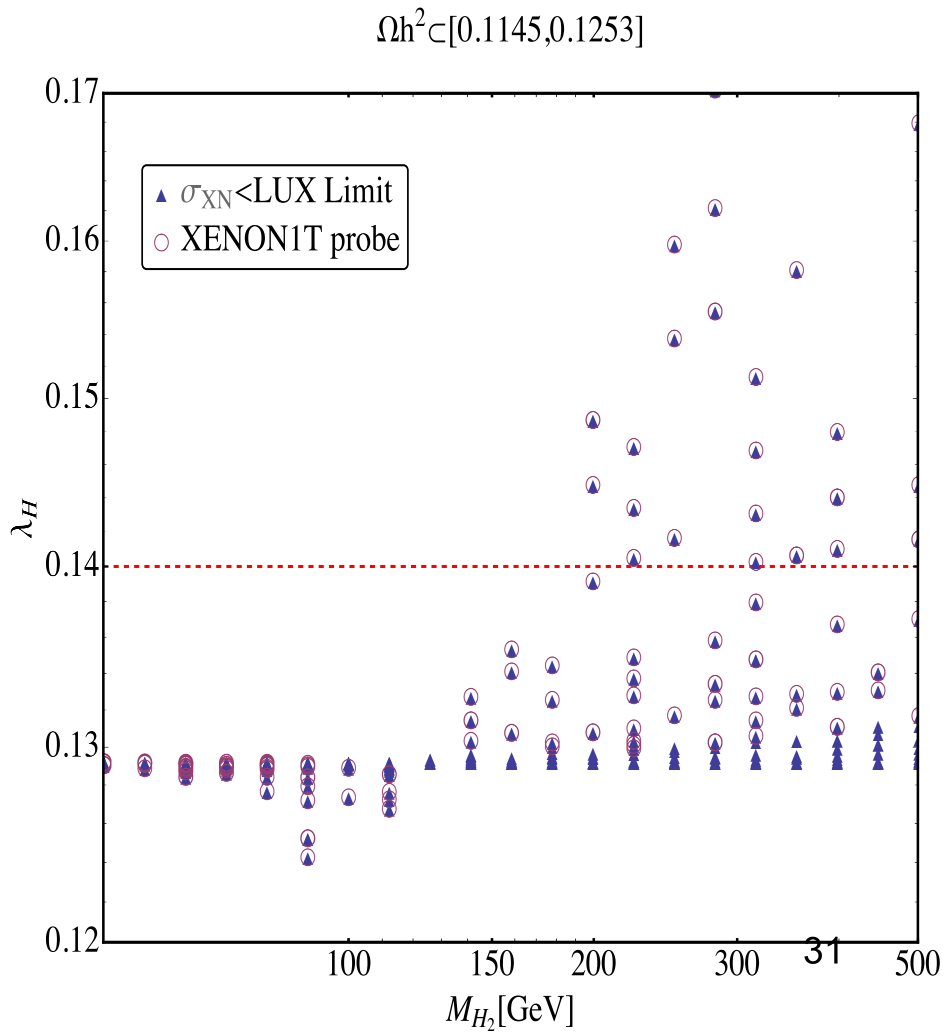
Parameter Space





Higgs self-coupling λ_H





Summary

- We have investigated a simple extension of SM, higgs portal VDM model.
- Higher dimensional operators can induce VDM decay. An illustrative example is given to explain the positron excess.
- Various constraints are analyzed and viable parameter space can be probed by future experiments.

Summary

$$\mathcal{L}_{\rm VDM} = \mathcal{L}_{\rm ren}(Z_2 \text{ conserving}) + \mathcal{L}_{\rm non-ren}(Z_2 \text{ breaking})$$

- Thermal relic density
- Direct detection cross section
- Indirect signatures from pair annihilations of VDM's
- Higgs phenomenology (an additional scalar)

- Suppressed by $1/\Lambda^2$
- $\tau(VDM) \sim 10^{26}$ sec
- Indirect signature from VDM decays : positron excess observed by PAMELA, Fermi and AMS02

$$M_{H_2},\ \sin\alpha \longleftarrow g_X \xleftarrow{\Omega_{\rm DM}h^2} M_X$$

Direct Searches
Higgs self-coupling
Collider production