Higgs Portal Vector Dark Matter and its Indirect Signatures

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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

- Interaction with standard model particles need to be weak,
- Stable, if it decay, its lifetime must be long, even longer than the age of Universe. Usually associated with global symmetry.
- R-parity in MSSM, new physics models
- 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 nonperturbative 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, $\phi \to -\phi$

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

- Z_2 violating terms lead to decay

$$\delta \mathcal{L}_{\mathrm{eff}} = \frac{g}{M_{pl}} \phi \mathcal{O}_{\mathrm{SM}}, \ \mathcal{O}_{\mathrm{SM}} = F_{\mu\nu} F^{\mu\nu}, \ \bar{f} \gamma \cdot D f, \ \bar{f}_L f_R H + h.c, ...$$

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

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

$$t_0 \sim 10^{18} \ \mathrm{s}$$

$U(1)_X$ gauge symmetry

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

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

With D_μ on Φ is defined as

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

Spontaneous breaking

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

Mixing with Higgs

- Mass Eigenstates

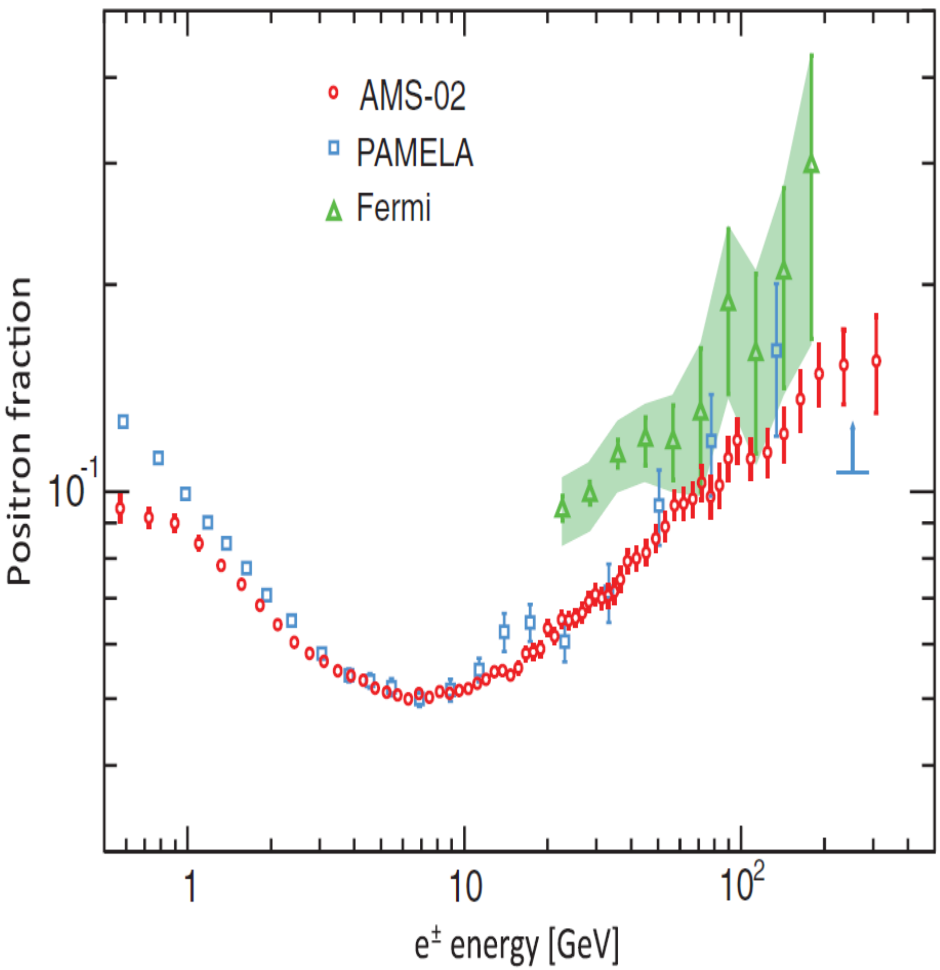
$$\begin{pmatrix} h \\ \varphi \end{pmatrix} = \begin{pmatrix} c_\alpha & s_\alpha \\ -s_\alpha & c_\alpha \end{pmatrix} \begin{pmatrix} H_1 \\ H_2 \end{pmatrix}$$

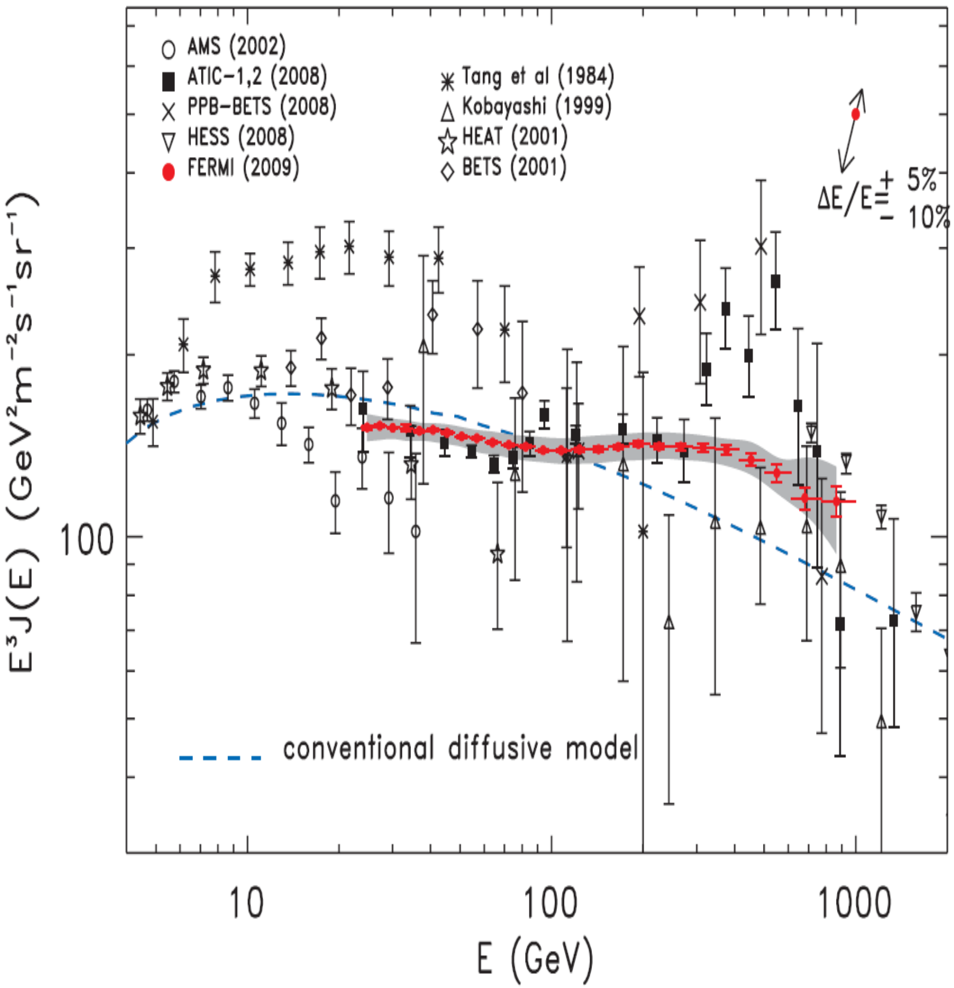
$$\begin{pmatrix} 2\lambda_H v_H^2 & \lambda_{H\Phi} v_H v_\Phi \\ \lambda_{H\Phi} v_H v_\Phi & 2\lambda_\Phi v_\Phi^2 \end{pmatrix} = \begin{pmatrix} m_1^2 c_\alpha^2 + m_2^2 s_\alpha^2 & (m_2^2 - m_1^2)\, s_\alpha c_\alpha \\ (m_2^2 - m_1^2)\, s_\alpha c_\alpha & m_1^2 s_\alpha^2 + m_2^2 c_\alpha^2 \end{pmatrix}$$

$$\tan 2\alpha = \frac{2\mathcal{M}_{12}}{\mathcal{M}_{11} - \mathcal{M}_{22}}, \text{ or } \sin 2\alpha = \frac{2\lambda_{H\Phi} v_H v_\Phi}{m_2^2 - m_1^2}.$$

- Higgs' coupling to SM particle are universally scaled by sinα.

Positron Excess





Leptonphilic, TeV dark Matter

Possible Explanations

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

Decaying Dark Matter

- High dimensional operators can induce DM decay

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

$$\Gamma \sim \frac{g_\Lambda^4 M^5}{\Lambda^4},\ \tau = \frac{\hbar}{\Gamma} \sim 10^{26}\mathrm{s} \Rightarrow \Gamma \sim 6 \times 10^{-51}\mathrm{GeV}$$

$$\Lambda \sim g_\Lambda \left(\frac{M^5\tau}{\hbar}\right)^{\frac{1}{4}} = g_\Lambda \left(\frac{10^{15}\mathrm{GeV}^5 \times 10^{26}\mathrm{s}}{6.583 \times 10^{-25}\mathrm{GeV\ s}}\right)^{\frac{1}{4}} \sim 2g_\Lambda \times 10^{16}\mathrm{GeV}$$

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

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

then dimension-6 operators are

$$(\Phi^\dagger\Phi)^3,\ (\Phi^\dagger\Phi)\Box(\Phi^\dagger\Phi),\ (\Phi^\dagger D^\mu\Phi)^\dagger(\Phi^\dagger D^\mu\Phi),$$
$$\Phi^\dagger\Phi X_{\mu\nu}X^{\mu\nu},\ \Phi^\dagger\Phi\tilde{X}_{\mu\nu}X^{\mu\nu},$$

Effective Operators

- Building components in the SM

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

- Operators involves both DM sector and SM

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

DM decay

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

$$\left(\Phi^\dagger i \overleftrightarrow{D}_\mu \Phi\right)\left(H^\dagger i \overleftrightarrow{D}^\mu H\right)$$

$$\Rightarrow X^\mu \rightarrow \varphi + Z,$$

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

$$\Rightarrow X^\mu \rightarrow \bar{f} + f,$$

DM decay

$$\Phi^\dagger \Phi B_{\mu\nu} X^{\mu\nu},\ \Phi^\dagger \Phi \tilde{B}_{\mu\nu} X^{\mu\nu}, (\Phi \to H)$$

$$\Rightarrow X^\mu \to \varphi/h + \gamma/Z,$$

$$H^\dagger \tau^I H W^I_{\mu\nu} X^{\mu\nu},\ H^\dagger \tau^I H \tilde{W}^I_{\mu\nu} X^{\mu\nu}$$

$$\Rightarrow X^\mu \to \varphi/h + \gamma/Z,$$

Three body decay

$$\Phi^\dagger \Phi B_{\mu\nu} X^{\mu\nu} \Rightarrow X^\mu \to \varphi + \varphi + \gamma/Z.$$

Phenomenology

Some Estimations

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

$$\sin\alpha \simeq \frac{\lambda_{H\Phi} v_H v_\Phi}{m_2^2 - m_1^2}$$

take for example

$$M_X = 2\mathrm{TeV},\ g_X \simeq 1,\ \text{and}\ M_{H_2} = 200\mathrm{GeV}$$

we have

$$\lambda_{H\Phi} \sim \frac{\sin\alpha\,(200^2 - 125^2)}{246 \times 2000} \sim 0.1 \times \sin\alpha$$

$$\lambda_\Phi \sim \frac{200^2}{2 \times 2000^2} = 0.005,\ \ \lambda_H = \frac{125^2}{2 \times 246^2} \sim 0.13.$$

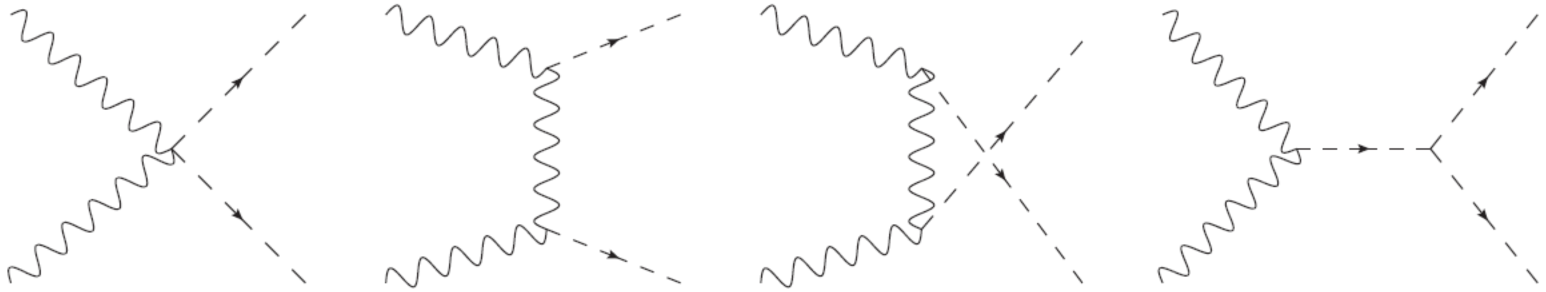
Perturbativity

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

$$\begin{aligned}
\frac{d\lambda_H}{d\ln\mu} &= \frac{1}{16\pi^2}\left[24\lambda_H^2 + \lambda_{H\Phi}^2 - 6y_t^4 + \frac{3}{8}\left(2g_2^2 + \left(g_1^2+g_2^2\right)^2\right) - \lambda_H\left(9g_2^2 + 3g_1^2 - 12y_t^2\right)\right] \\
\frac{d\lambda_{H\Phi}}{d\ln\mu} &= \frac{1}{16\pi^2}\left[2\lambda_{H\Phi}\left(6\lambda_H + 4\lambda_\Phi + 2\lambda_{H\Phi}\right) - \lambda_{H\Phi}\left(\frac{9}{2}g_2^2 + \frac{3}{2}g_1^2 - 6y_t^2 + 6g_X^2\right)\right], \\
\frac{d\lambda_\Phi}{d\ln\mu} &= \frac{1}{16\pi^2}\left[2\left(\lambda_{H\Phi}^2 + 10\lambda_\Phi^2 + 3g_X^4\right) - 12\lambda_\Phi g_X^2\right], \\
\frac{dg_X}{d\ln\mu} &= \frac{1}{16\pi^2}\frac{1}{3}g_X^3.
\end{aligned}$$

$$\lambda_\Phi\left(\Lambda\right) < 4\pi \Rightarrow \quad g_X \leq 1.5$$

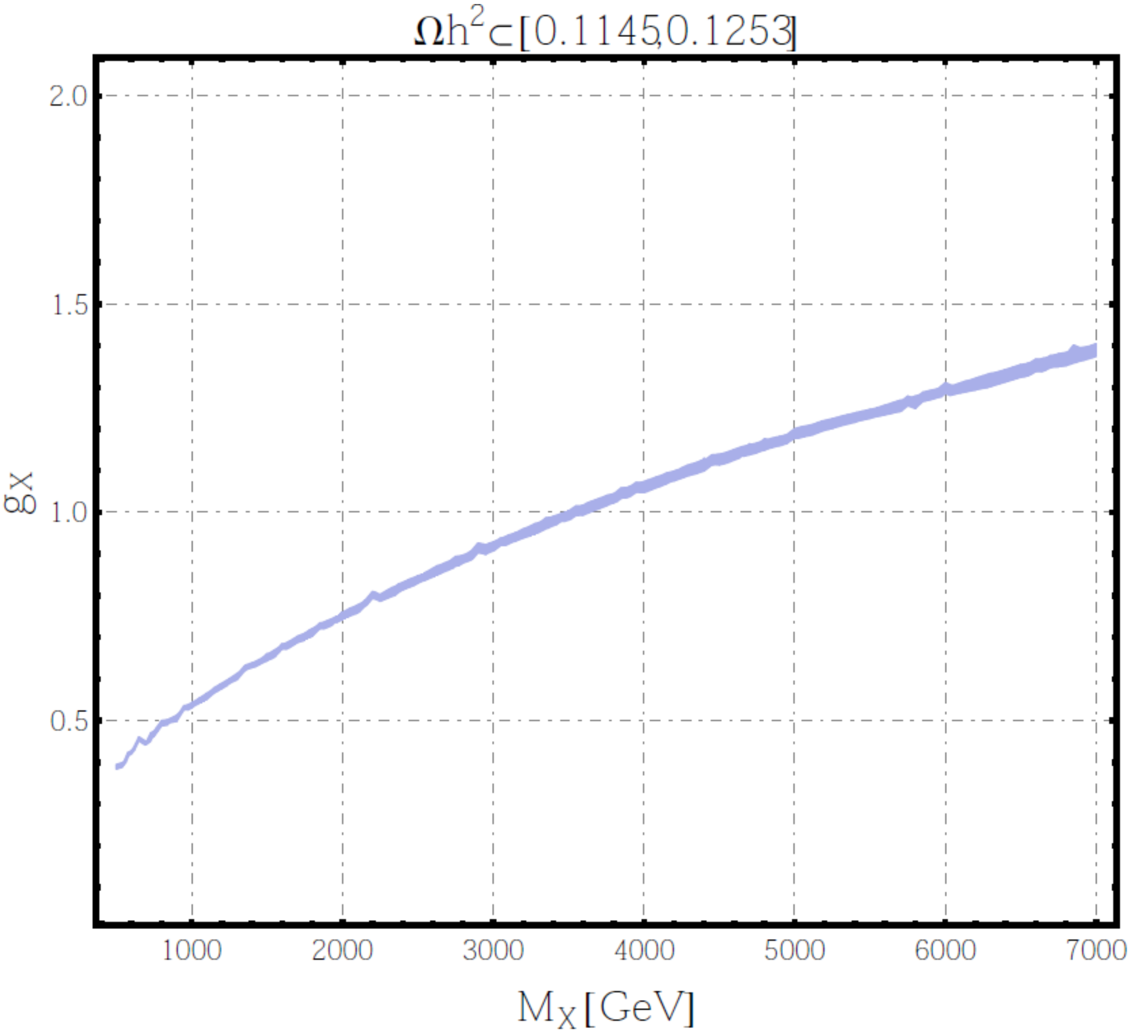
Relic density



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

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

Relic density



micrOMEGAs_3.1

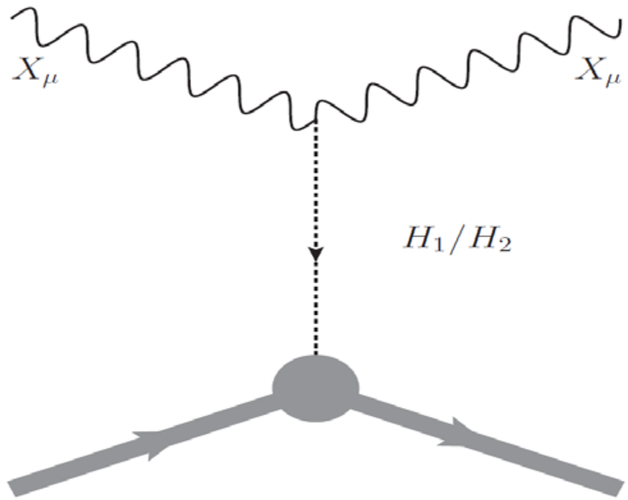
- Planck gives

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

- approximation

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

Direct detection

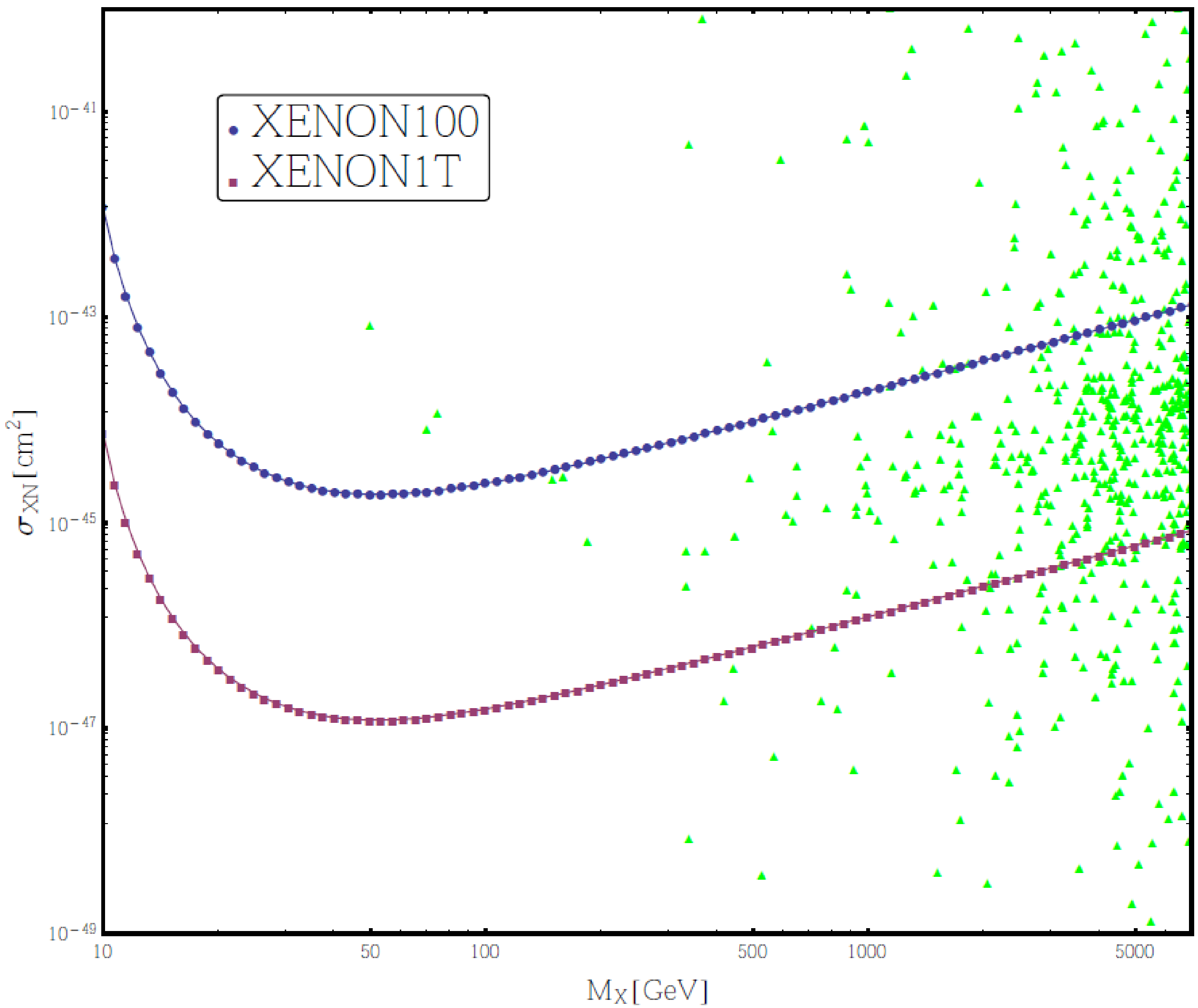


The cross section of dark matter scattering of a nucleon

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

$$m_{H_2} = m_{H_1},\ \sigma = 0$$

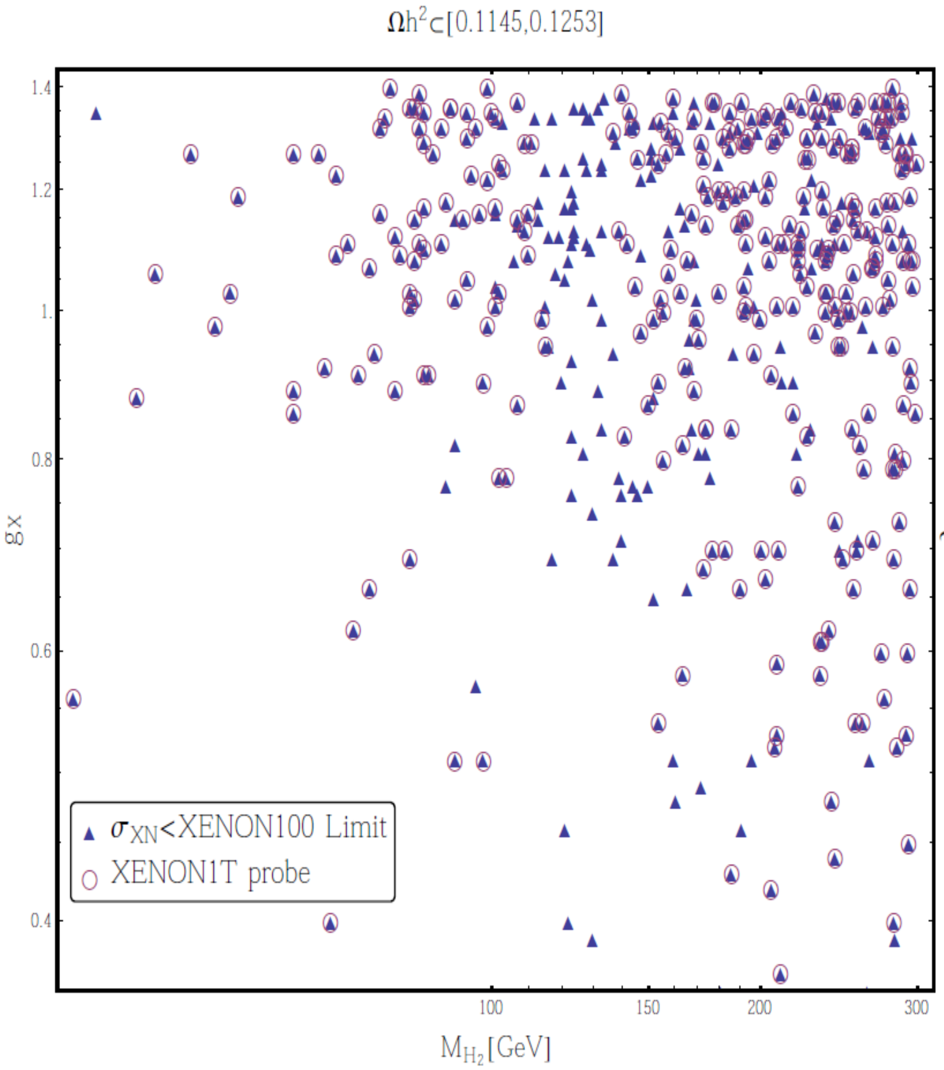
XENON Limits

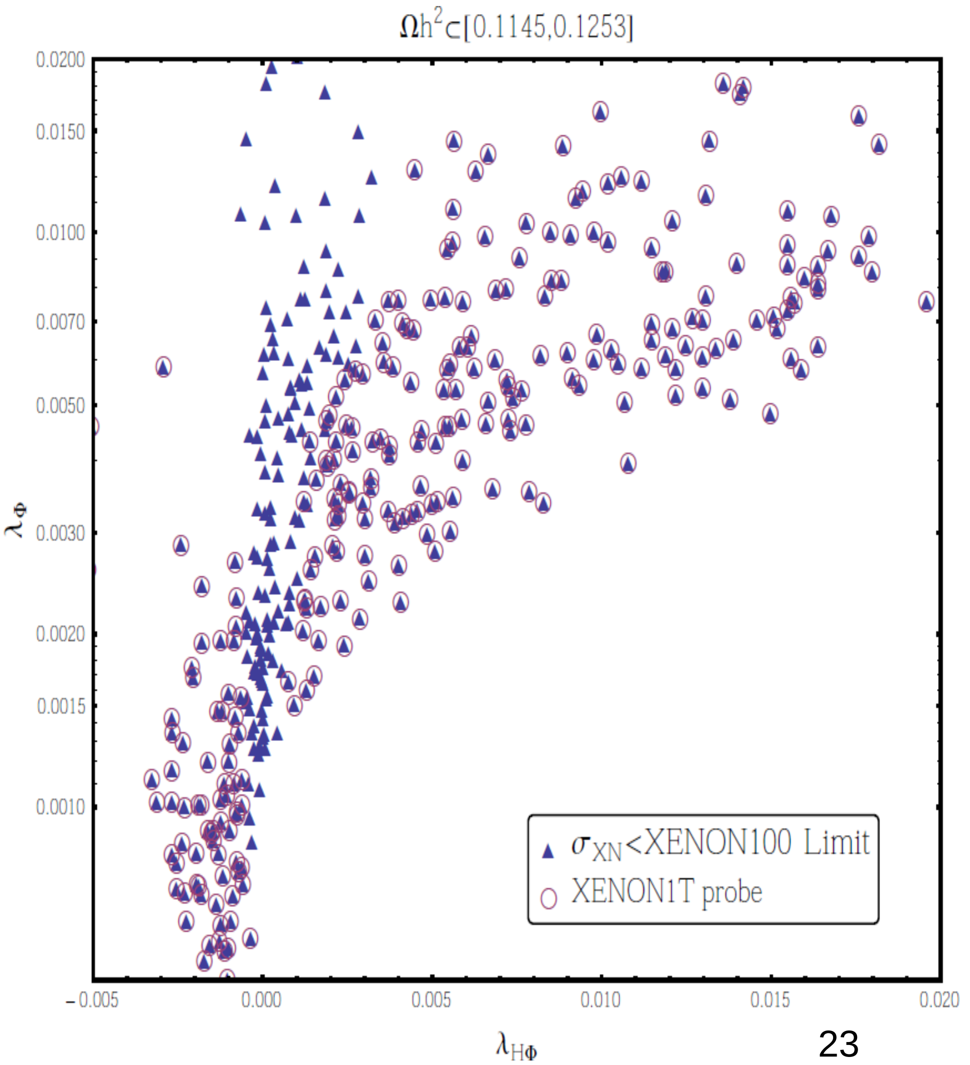


Blue line is the latest XENON100 limit.

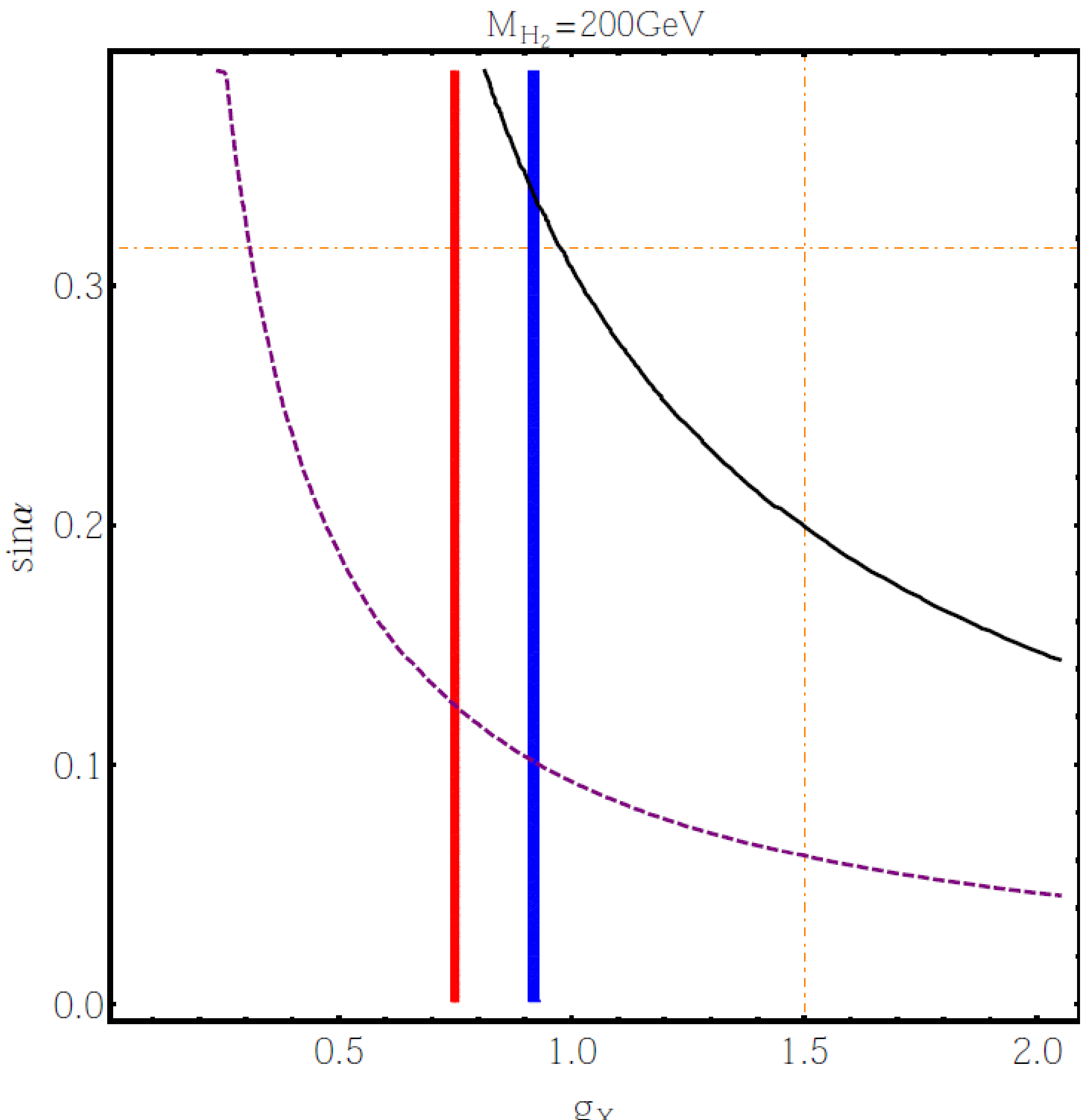
Purple line shows the expected limit from XENON1T.

Parameter Space



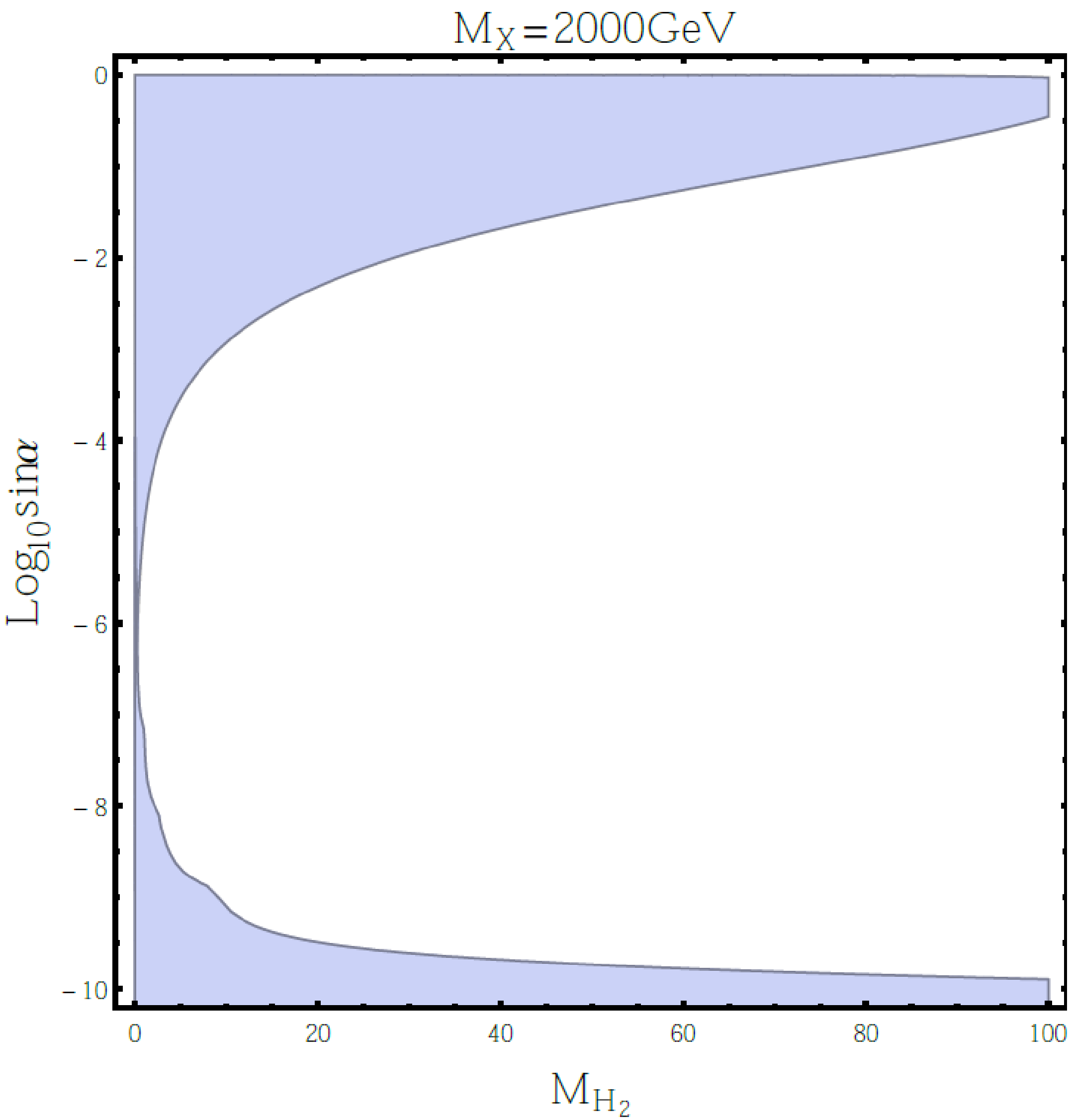


Parameter Limits



- Blue band is for 2000GeV DM, and red one for 1000GeV.

Limits on the Mixing angle



- Upper bound:

From XENON100 direct detection.

- Lower bound:

Lifetime should not be too long to spoil BBN.

Decaying DM
and
Indirect Signatures

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,

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

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

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

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.

Indirect Signatures

- DM decay can provide additional source,

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

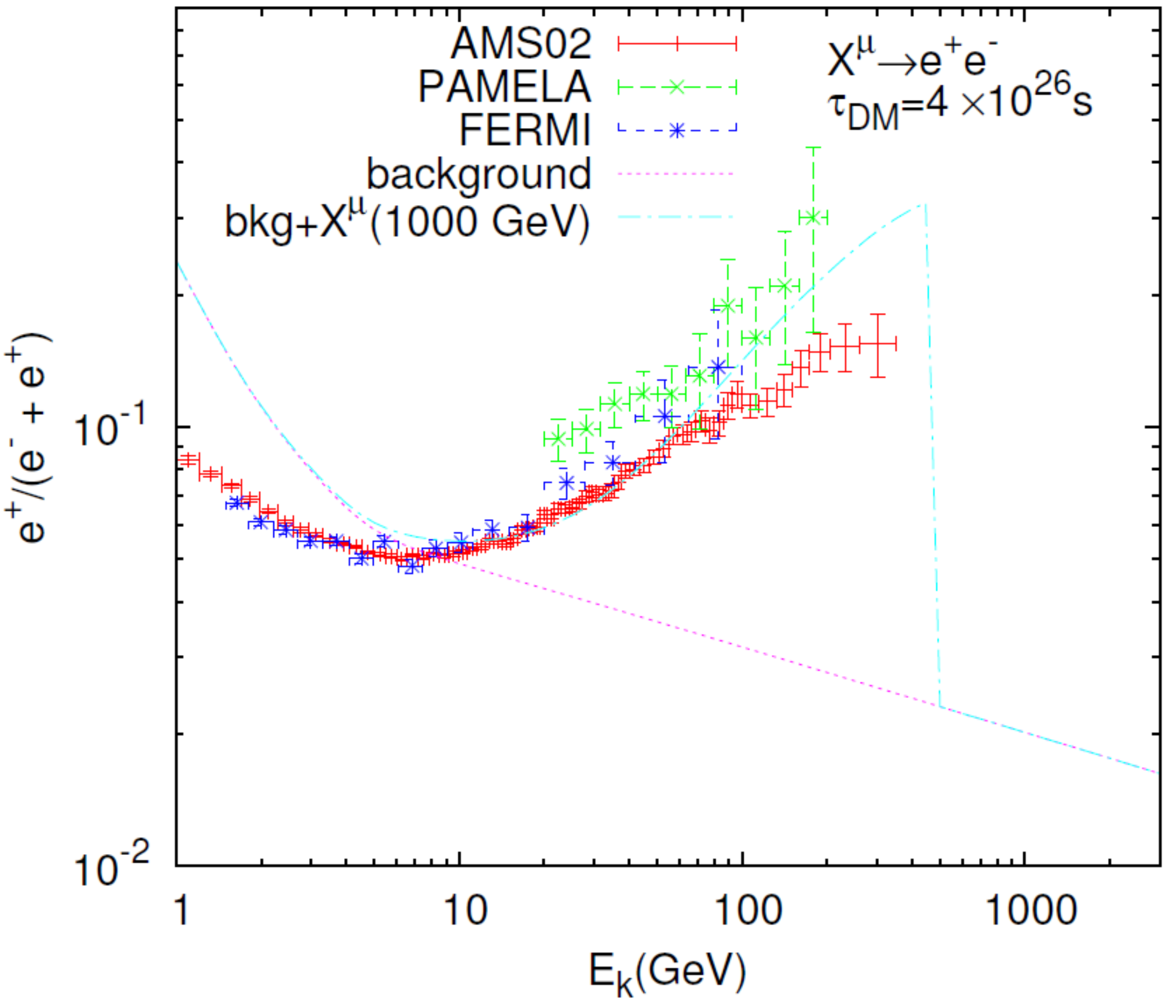
micrOMEGAs_3.1

- We use the NFW density profile

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

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

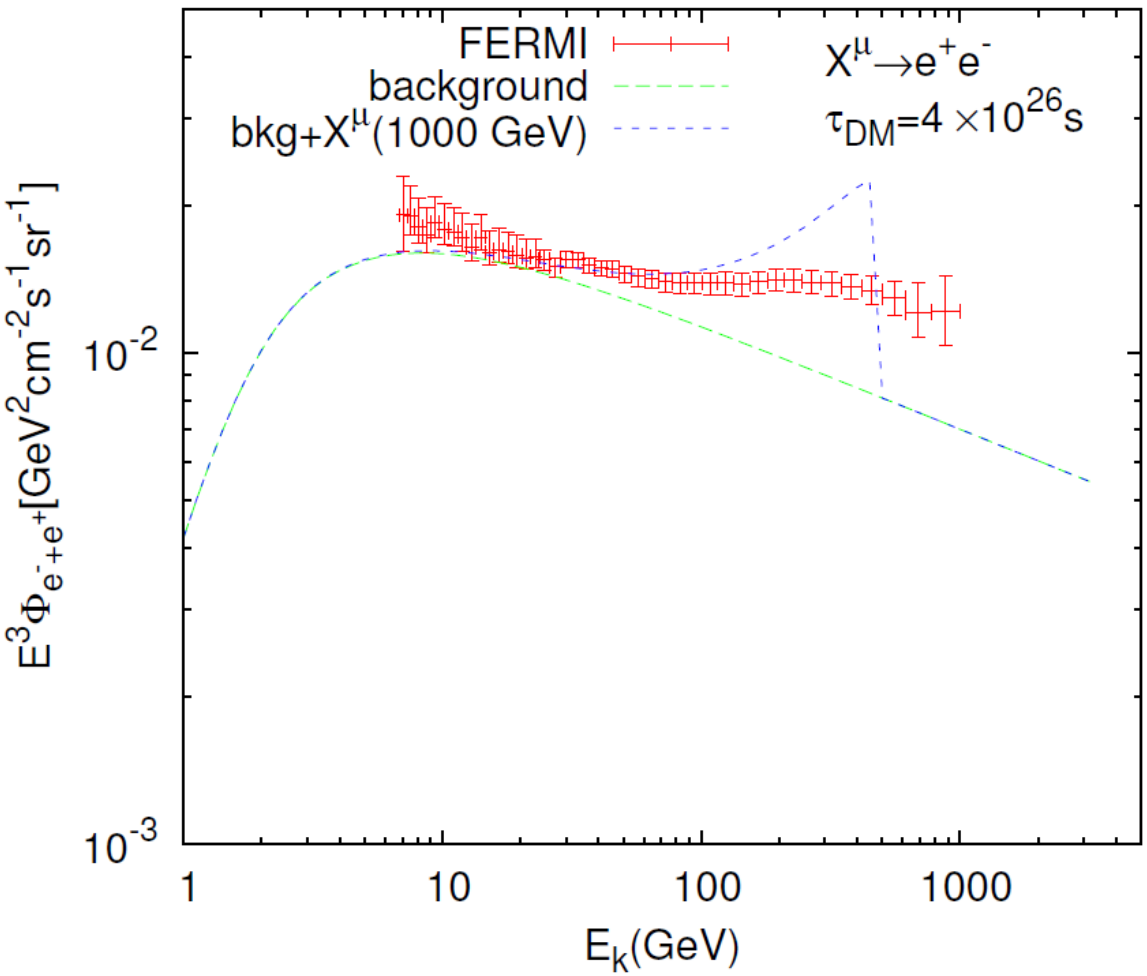
$X^\mu \to e^+e^-$



E<10GeV can be affected by solar wind significantly.

The spectrum is very sharp near the end point.

$$X^\mu \to e^+ e^-$$

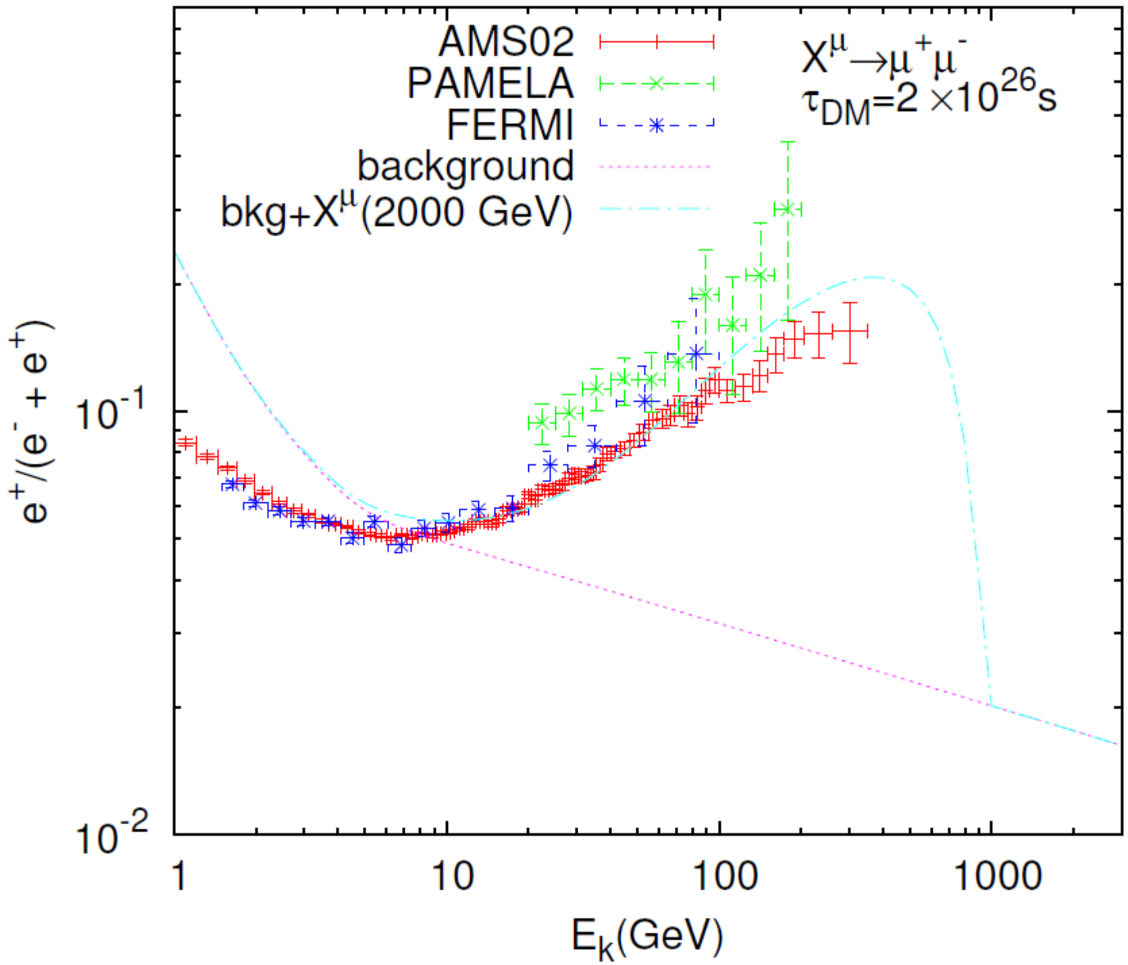


FERMI
background
bkg+X^μ(1000 GeV)
X^μ→e^+e^-
τ_DM=4 ×10^26s
E^3Φ_{e^-+e^+}[GeV^2cm^-2s^-1sr^-1]
10^-2
10^-3
1
10
100
1000
E_k(GeV)

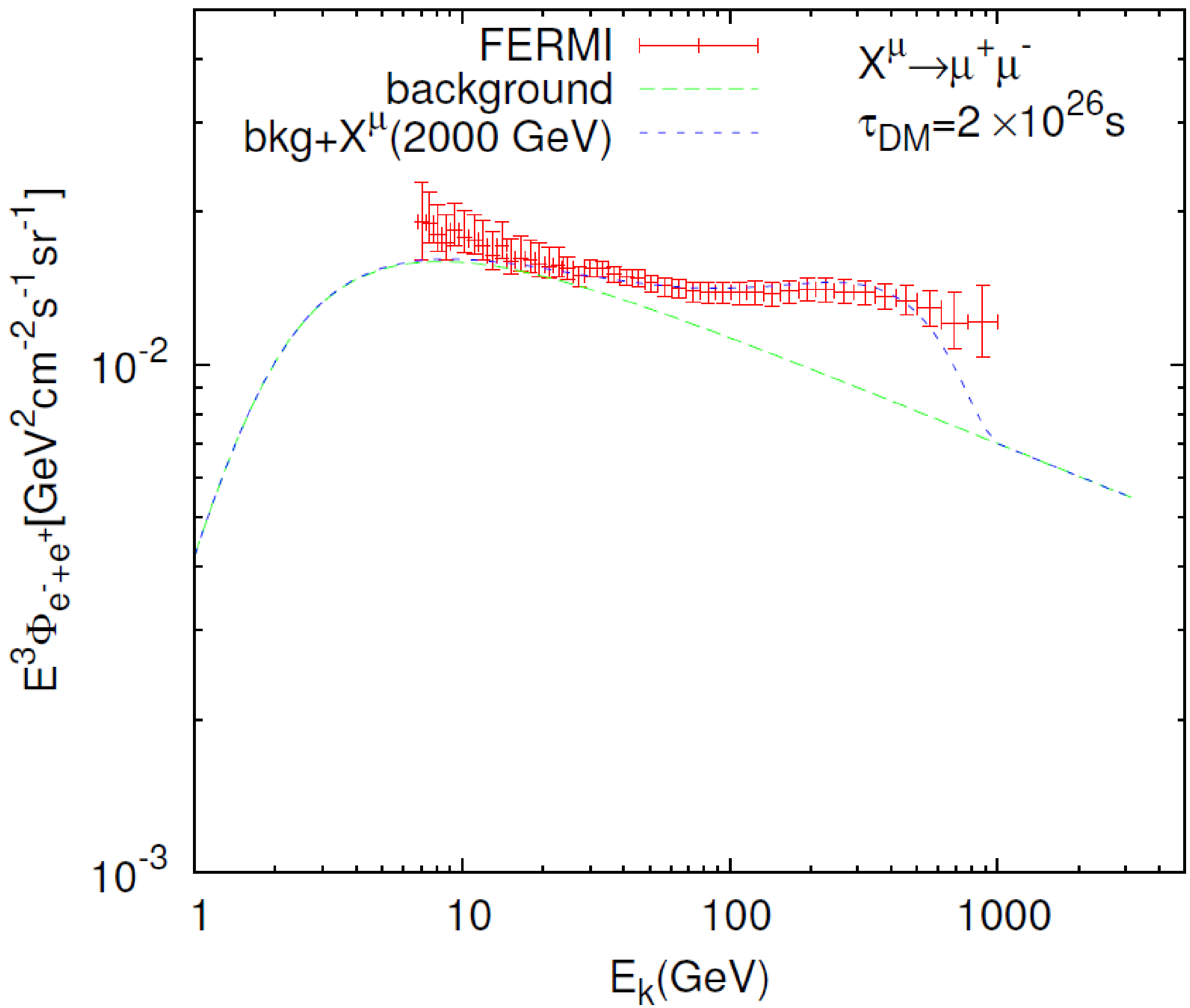
$X^\mu \to \mu^+\mu^-$

- The spectrum is softer than the $X^\mu \to e^+e^-$ case.
- Muons decay

$$\mu^\pm \to e^\pm + \nu_e + \nu_\mu$$

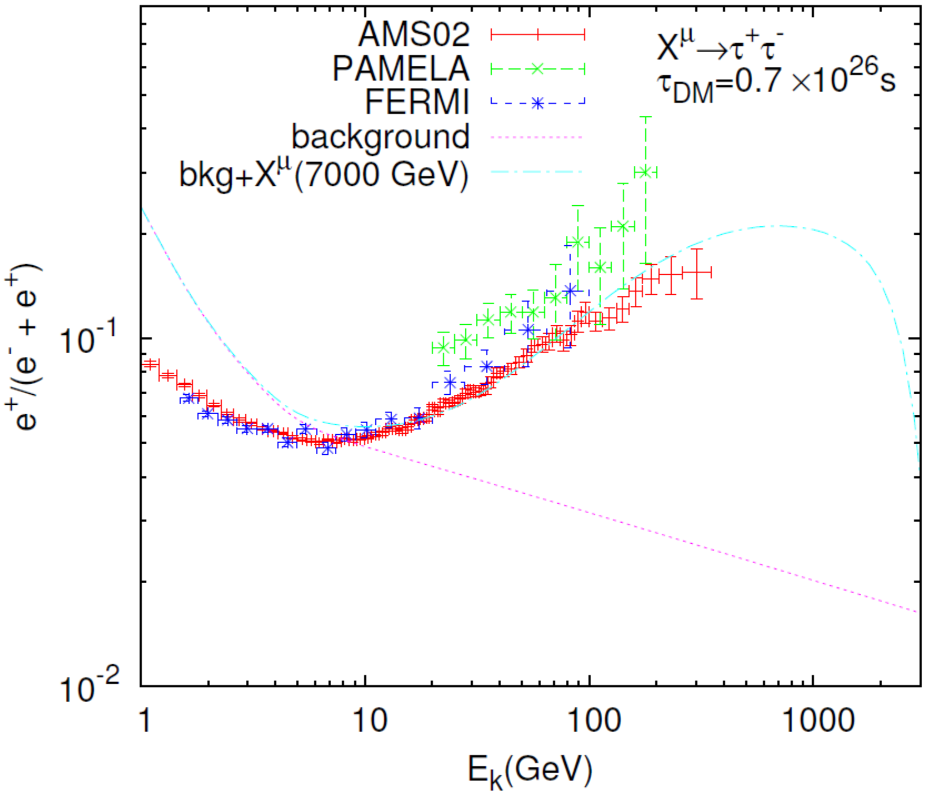


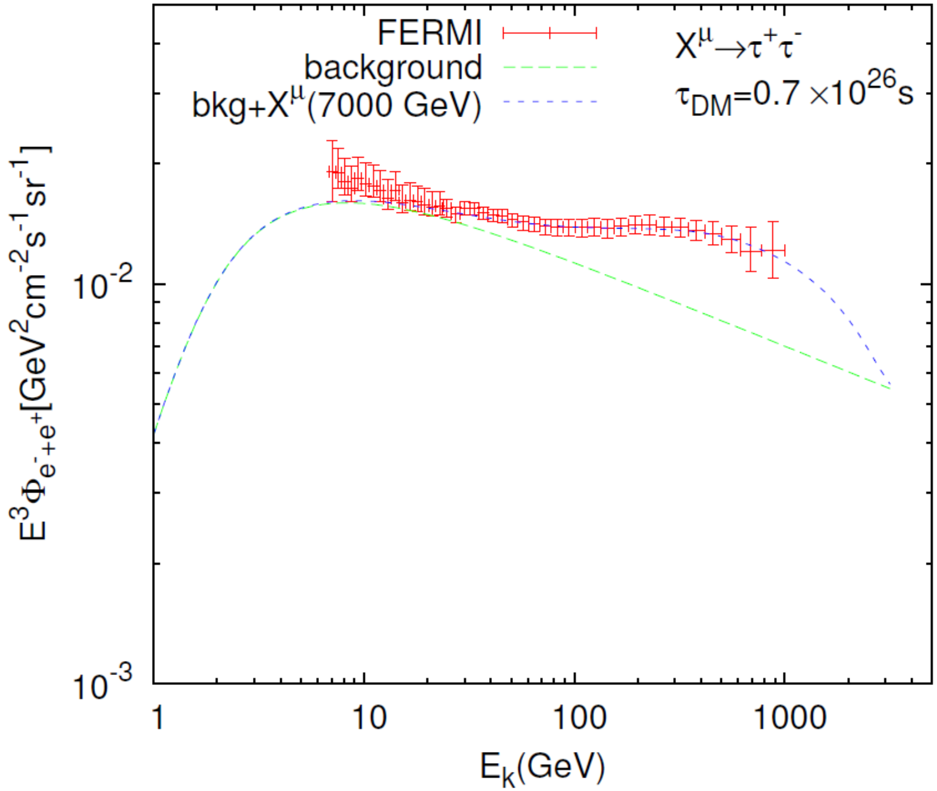
$$X^\mu \to \mu^+\mu^-$$



FERMI
background
bkg+X^μ(2000 GeV)
X^μ→μ^+μ^-
τ_DM=2 ×10^26s
E^3Φ_e^-+e^+[GeV^2cm^-2s^-1sr^-1]
10^-2
10^-3
1
10
100
1000
E_k(GeV)

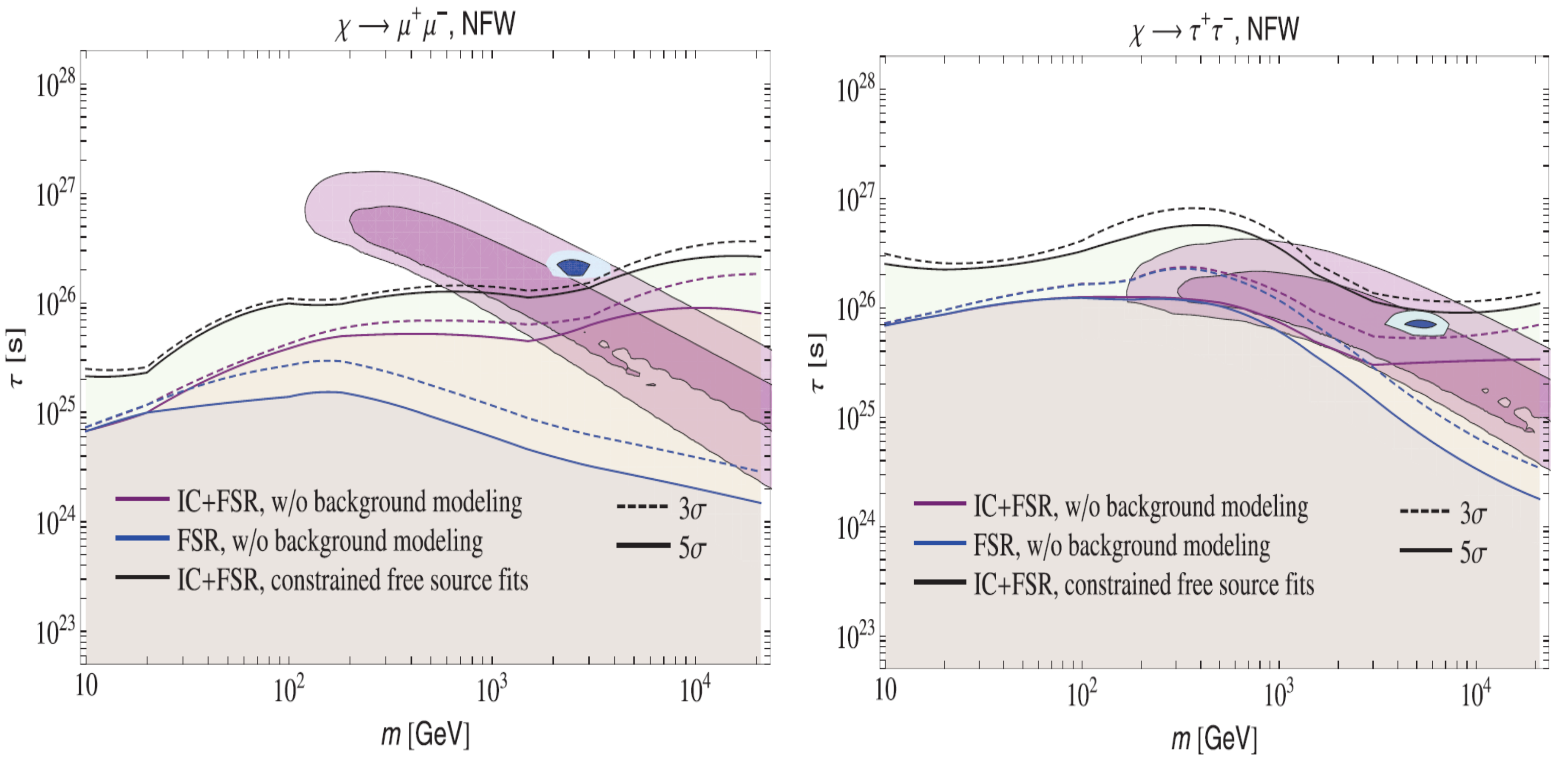
$$X^\mu \to \tau^+\tau^-$$





Only 1/3 taus decay to light leptons, the rest mainly to pions, $\pi^\pm \to \mu^\pm + \nu_\mu$ and $\pi^0 \to 2\gamma$

Fermi-LAT Constraints



Fermi-LAT, **arXiv:1205.6474**

Summary

- We have investigated a simple extension of SM, $U_X(1)$ VDM model.
- Higher dimensional operators can induce the DM decay.
- Phenomenological constraints are shown.
- An illustrative example is given to explain the positron excess.