Fermionic dark matter in the light of positron-fraction excess measured by AMS-02

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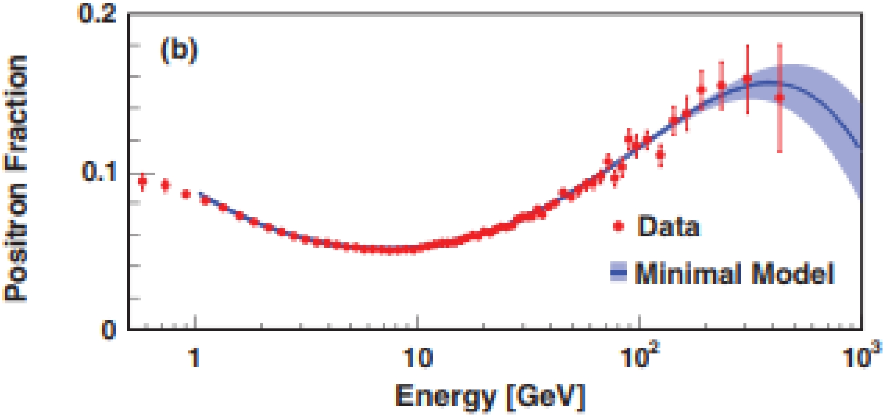
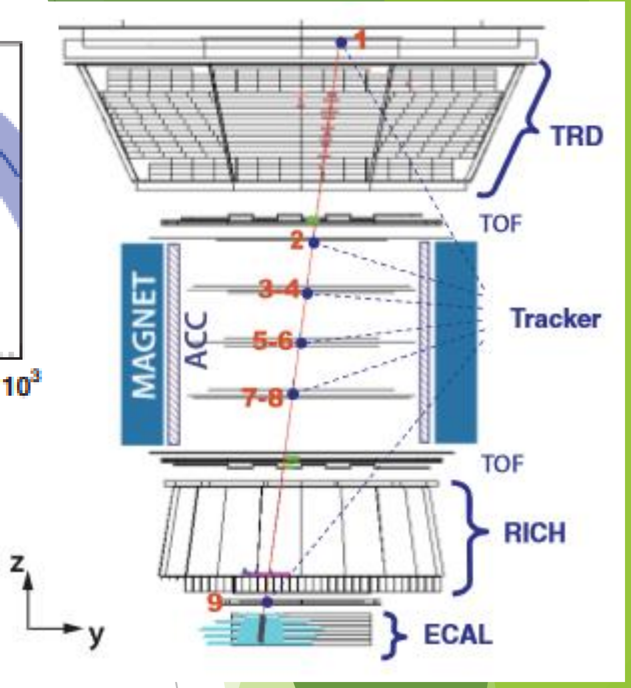
Outline

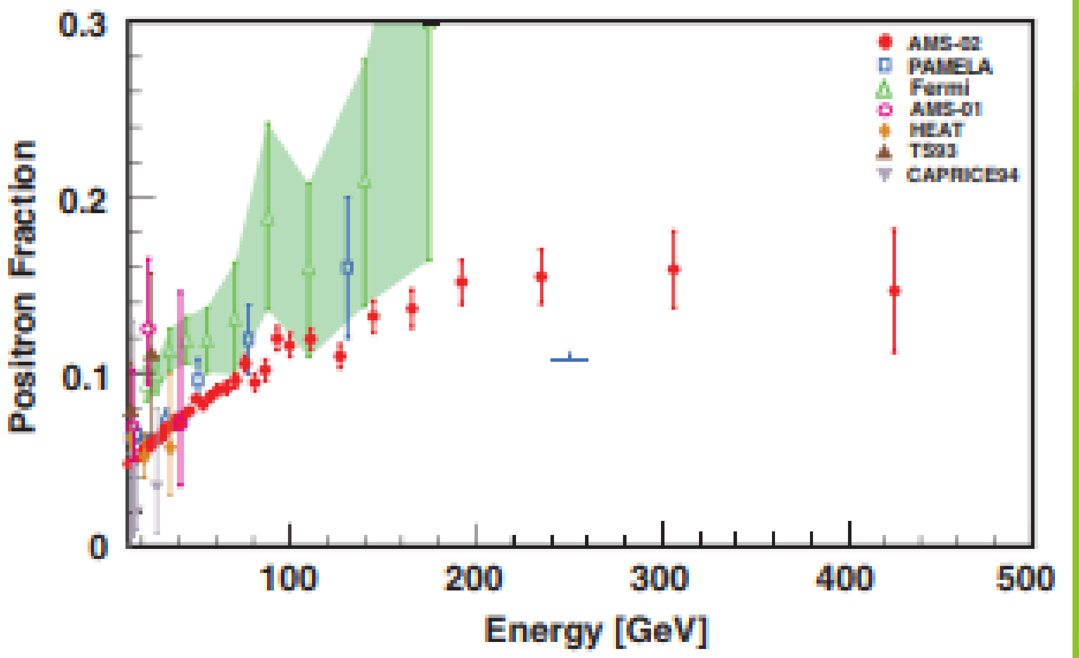
- AMS-02 Results
- Two-Higgs doublet model:-Lepton Specific configuration
- Fermionic DM Model in 2HDM Framework
- Constraining the Model
- Calculation of Positron Fraction from DM+DM annihilation
- Conclusion

AMS-02 Results

- The Alpha Magnetic Spectrometer is a general purpose detector on-board the International Space Station.
- Positron fraction in primary cosmic rays in the energy range from 0.5 to 500 GeV based on 10.9 million positron and electron events collected over a duration of 30 months.
- The positron fraction is steadily increasing from 10 to ~250 GeV, where after it reaches a plateau followed by an apparent decreasing trend.
- The corresponding measurements for anti-proton flux do not however exhibit significant peak.







Ref:- Phys. Rev. Lett. 113, 121101 (2014)

Dark Matter Model

Two Higgs Doublet Model

$$\Phi_l = \begin{pmatrix} c_\beta G^+ - s_\beta H^+ \\ \frac{1}{\sqrt{2}}(v_l + c_\alpha H - s_\alpha h + i c_\beta G - i s_\beta A) \end{pmatrix}$$

$$\Phi_q = \begin{pmatrix} s_\beta G^+ + c_\beta H^+ \\ \frac{1}{\sqrt{2}}(v_q + s_\alpha H + c_\alpha h + i s_\beta G + i c_\beta A) \end{pmatrix}$$

- Here, h is the SM like Higgs boson discovered at the LHC and H is the extra scalar (non-SM)

$$v = \sqrt{v_q^2 + v_l^2} = 246 \text{ GeV}$$

- α is the mixing angle of two scalars.
- β is defined as $tan\ \beta = \frac{v_q}{v_l}$.

$$\begin{aligned} V(\Phi_1, \Phi_2) &= m_1^2 \Phi_1^\dagger \Phi_1 + m_2^2 \Phi_2^\dagger \Phi_2 + (m_{12}^2 \Phi_1^\dagger \Phi_2 + h.c.) \\ &+ \frac{1}{2}\lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \frac{1}{2}\lambda_2 (\Phi_2^\dagger \Phi_2)^2 \\ &+ \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) \\ &+ \frac{1}{2}\lambda_5 [(\Phi_1^\dagger \Phi_2)^2 + h.c.] \end{aligned}$$

$$g_{WWh} = 2i\frac{M_W^2}{v}\sin(\beta - \alpha) g^{\mu\nu}, \quad g_{WWH} = 2i\frac{M_W^2}{v}\cos(\beta - \alpha) g^{\mu\nu}$$

$$g_{ZZh} = 2i\frac{M_Z^2}{v}\sin(\beta - \alpha) g^{\mu\nu}, \quad g_{ZZH} = 2i\frac{M_Z^2}{v}\cos(\beta - \alpha) g^{\mu\nu}$$

Lepton Specific Configuration

Doublet	Type I	Type II	Lepton Specific
Φ_1	--	d, l	l
Φ_2	u, d, l	u	u, d

$$\mathcal{L}_{Yukawa} = -y_{ij}^{l1}\bar{e}_{Ri}\Phi_l^{\dagger}L_{Lj} - y_{ij}^{d2}\bar{d}_{Ri}\Phi_q^{\dagger}Q_{Lj} - y_{ij}^{u2}\bar{u}_{Ri}\Phi_q^{\dagger}Q_{Lj}$$

Ref:-Heather E. Logan, Phys. Rev. D 83, 035022 (2011)

$$g_{qqh} = -i\frac{m_q}{v}\frac{\cos\alpha}{\sin\beta}, \quad g_{qqH} = -i\frac{m_q}{v}\frac{\sin\alpha}{\sin\beta}$$

$$g_{llh} = -i\frac{m_l}{v}\frac{-\sin\alpha}{\cos\beta}, \quad g_{llH} = -i\frac{m_l}{v}\frac{\cos\alpha}{\cos\beta}$$

Dark Matter Candidate

- The Standard Model is extended by a fermion, which is the dark matter, and a second Higgs doublet.
- Out of the two physical scalar states we identify h as the SM like Higgs and H as the non-SM Higgs.
- The Lagrangian for such a case can be written as,

$$\mathcal{L} = \mathcal{L}_{THDM} + \mathcal{L}_{\chi} + \mathcal{L}_{int}$$

- Where $\mathcal{L}_{\chi} = \bar{\chi}(i\gamma^{\mu}\partial_{\mu} - m_0)\chi$ is the DM Lagrangian.
- $\mathcal{L}_{int} = -\frac{g_1}{\Lambda}(\Phi_1^{\dagger}\Phi_1)\bar{\chi}\chi - \frac{g_2}{\Lambda}(\Phi_2^{\dagger}\Phi_2)\bar{\chi}\chi$ is the interaction Lagrangian.

- The DM couplings to the two scalars are given by

$$g_{\bar{\chi}\chi h} = \frac{v}{\Lambda}(-g_1 \sin\alpha\cos\beta + g_2\cos\alpha\sin\beta)$$

$$g_{\bar{\chi}\chi H} = \frac{v}{\Lambda}(g_1 \cos\alpha\cos\beta + g_2\sin\alpha\sin\beta)$$

Back

- The mass of the dark matter is thus

$$m_\chi = m_0 + \frac{v^2}{2\Lambda}(g_1\cos^2\beta + g_2\sin^2\beta)$$

- The cross-section for this model is given by

$$\sigma v = (s - 4m_\chi^2)\left[A\frac{1}{(s-m_h^2)+m_h^2\Gamma_h^2} + B\frac{1}{(s-m_H^2)+m_H^2\Gamma_H^2} + C\frac{2(s-m_h^2)(s-m_H^2)+2m_h m_H\Gamma_h\Gamma_H}{[(s-m_h^2)+m_h^2\Gamma_h^2][(s-m_H^2)+m_H^2\Gamma_H^2]}\right]$$

Ref:-A. Dutta Banik, D. Majumdar, Eur. Phys. J. C (2015), 75:364.

- A, B and C in the Lepton Specific 2HDM are given as:-

$$A = \mathrm{g}_{\bar{\chi}\chi h}^2 \frac{G_F}{4\pi\sqrt{2}} \left[\frac{c_\alpha^2}{s_\beta^2} N_c m_{q_i}^2 \gamma_{q_i}^3 + \frac{s_\alpha^2}{c_\beta^2} m_{l_i}^2 \gamma_{l_i}^3 + \frac{1}{2} s_{\beta-\alpha}^2 s(1 - x_W + \frac{3}{4} x_W^2) \gamma_W + \frac{1}{4} s_{\beta-\alpha}^2 s(1 - x_Z + \frac{3}{4} x_Z^2) \gamma_Z \right]$$

$$x_i = \frac{4m_i^2}{s}$$

$$\gamma_i = \sqrt{1 - \frac{4m_i^2}{s}}$$

$$B = \mathrm{g}_{\bar{\chi}\chi H}^2 \frac{G_F}{4\pi\sqrt{2}} \left[\frac{s_\alpha^2}{s_\beta^2} N_c m_{q_i}^2 \gamma_{q_i}^3 + \frac{c_\alpha^2}{c_\beta^2} m_{l_i}^2 \gamma_{l_i}^3 + \frac{1}{2} c_{\beta-\alpha}^2 s(1 - x_W + \frac{3}{4} x_W^2) \gamma_W + \frac{1}{4} c_{\beta-\alpha}^2 s(1 - x_Z + \frac{3}{4} x_Z^2) \gamma_Z \right]$$

$$C = \mathrm{g}_{\bar{\chi}\chi h} \mathrm{g}_{\bar{\chi}\chi H} \frac{G_F}{4\pi\sqrt{2}} \left[\frac{s_\alpha c_\alpha}{s_\beta^2} N_c m_{q_i}^2 \gamma_{q_i}^3 - \frac{s_\alpha c_\alpha}{c_\beta^2} m_{l_i}^2 \gamma_{l_i}^3 + \frac{1}{2} s_{\beta-\alpha} c_{\beta-\alpha} s(1 - x_W + \frac{3}{4} x_W^2) \gamma_W + \frac{1}{4} s_{\beta-\alpha} c_{\beta-\alpha} s(1 - x_Z + \frac{3}{4} x_Z^2) \gamma_Z \right]$$

Constraining the Model

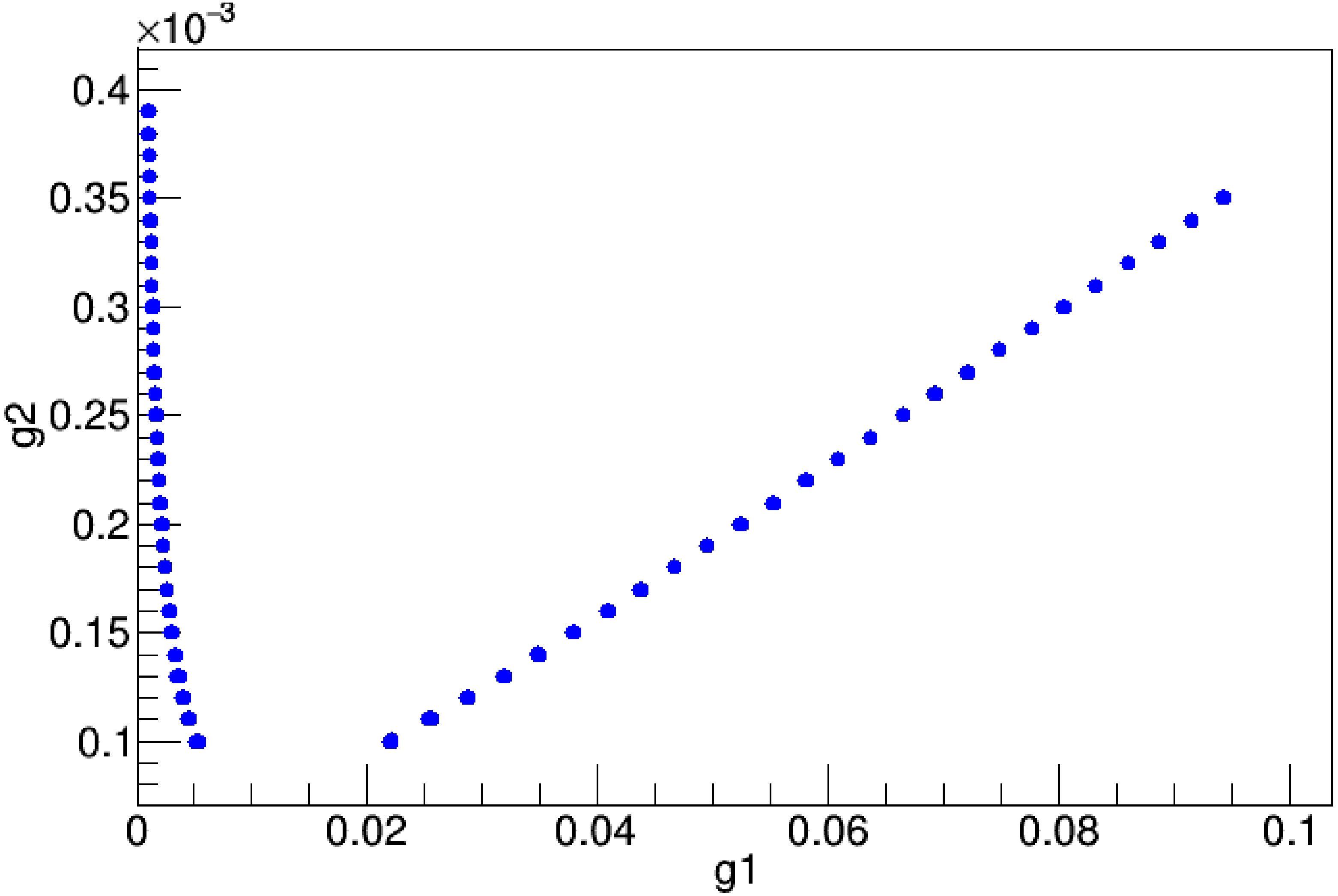
- The model contains many free parameters in the form of the mixing angle α, the ratio of the two vevs tanβ and the dark matter coupling strengths to the two doublets (g_i/Λ).
- The relic density is given as $\Omega_{DM}h^2 = \frac{1.07\times10^9 x_F}{\sqrt{g_*}M_{Pl}<\sigma v>}$ and the value is 0.1199±0.0027.

$$< \sigma v > = \frac{1}{8m_\chi^4 T_F K_2^2(m_\chi/T_F)} \times \int_{4m_\chi^2}^{\infty} ds\sigma(s)(s - 4m_\chi^2)\sqrt{s}K_1(\sqrt{s}/T_F)$$

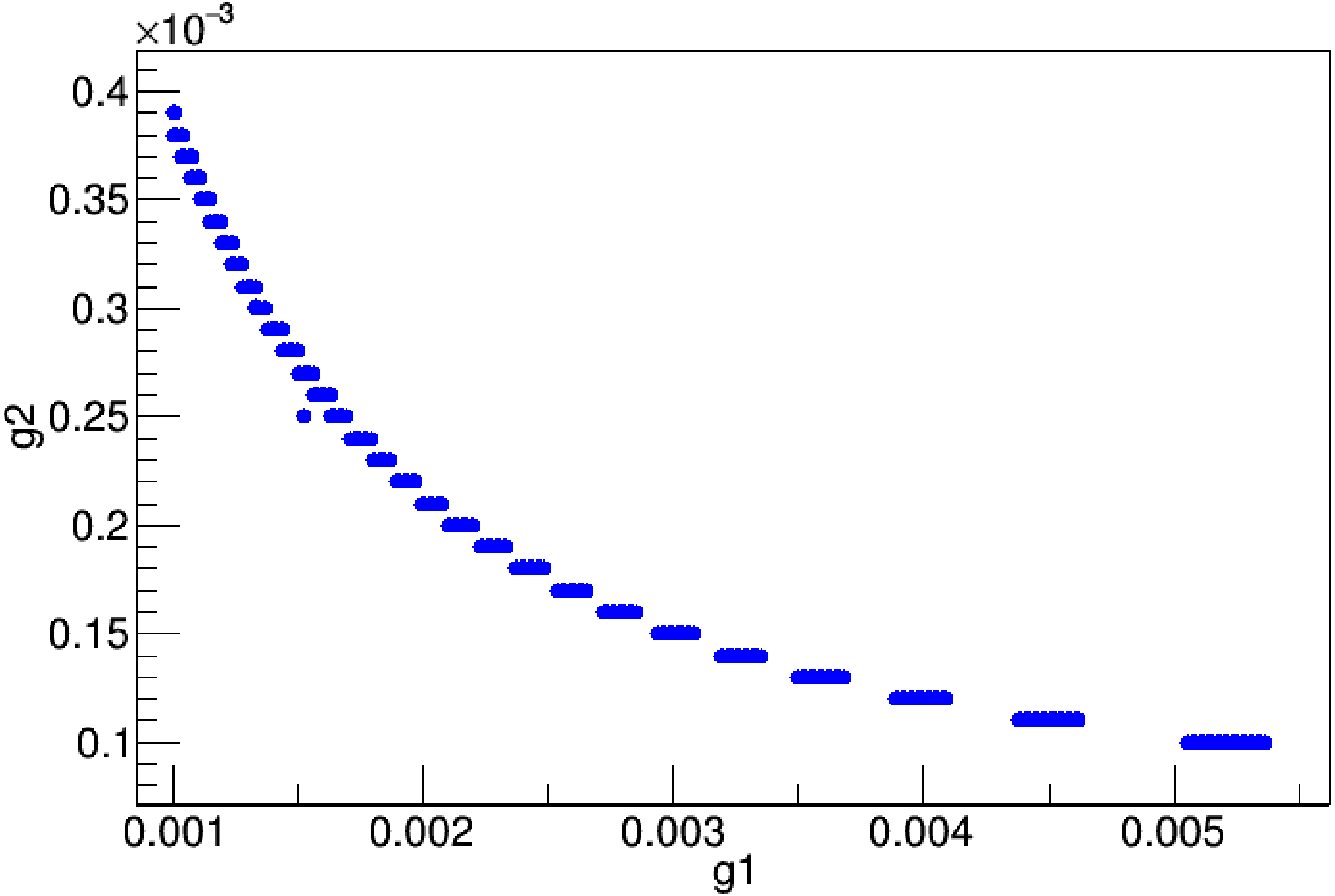
- The spin-independent direct detection cross-section is given by

$$\sigma_{SI} \simeq \frac{m_r^2}{\pi}\left(\frac{g_{\bar{\chi}\chi h}g_{NNh}}{m_h^2} + \frac{g_{\bar{\chi}\chi H}g_{NNH}}{m_H^2}\right)^2$$

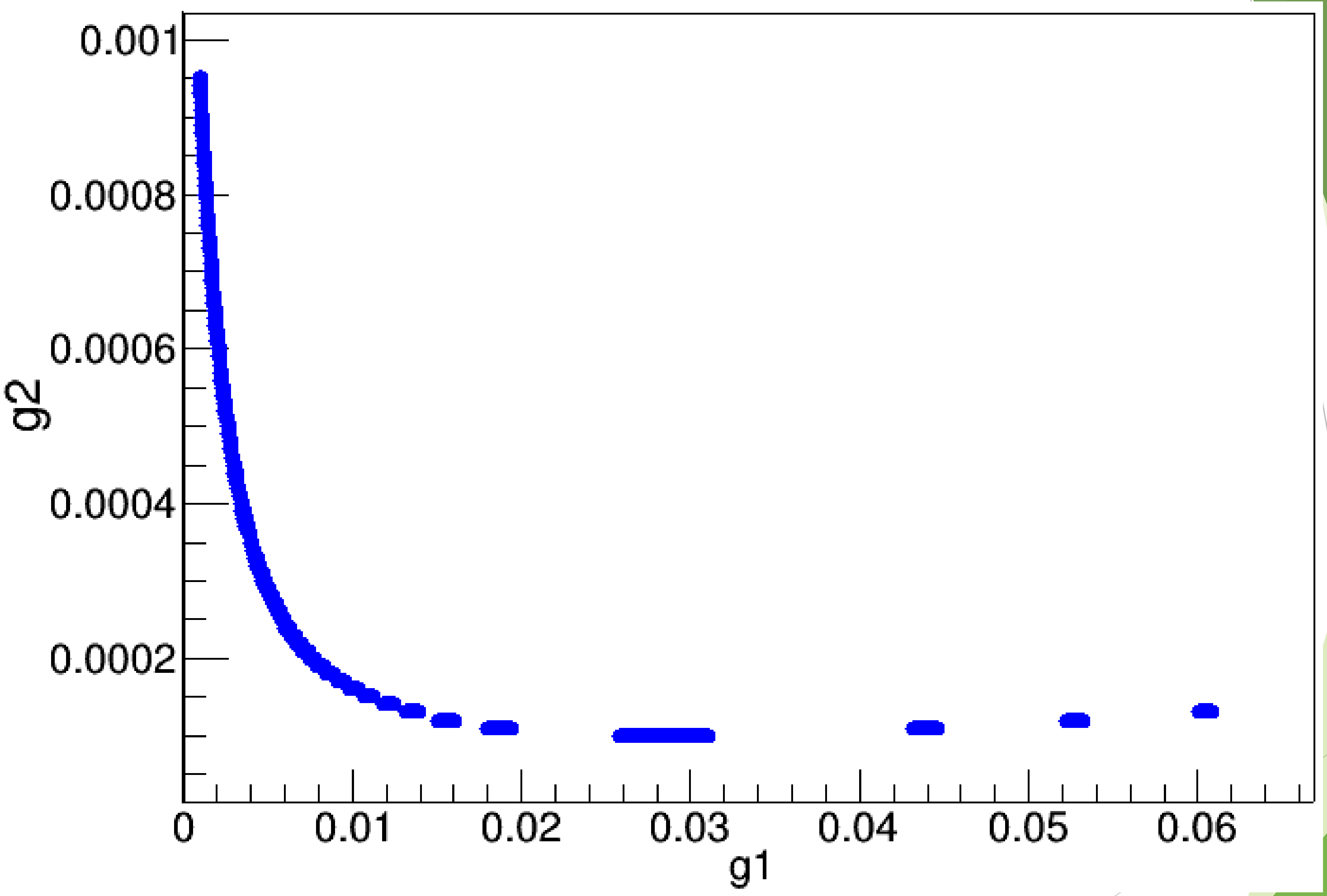
Constraints from Relic Density and Direct Detection



tanβ=8.62, $g_i=(g_i^*v/\Lambda)$



×10⁻³
0.4
0.35
0.3
0.25
0.2
0.15
0.1
g2
0.001
0.002
0.003
0.004
0.005
g1



tanβ=18.03

Constraints contd…

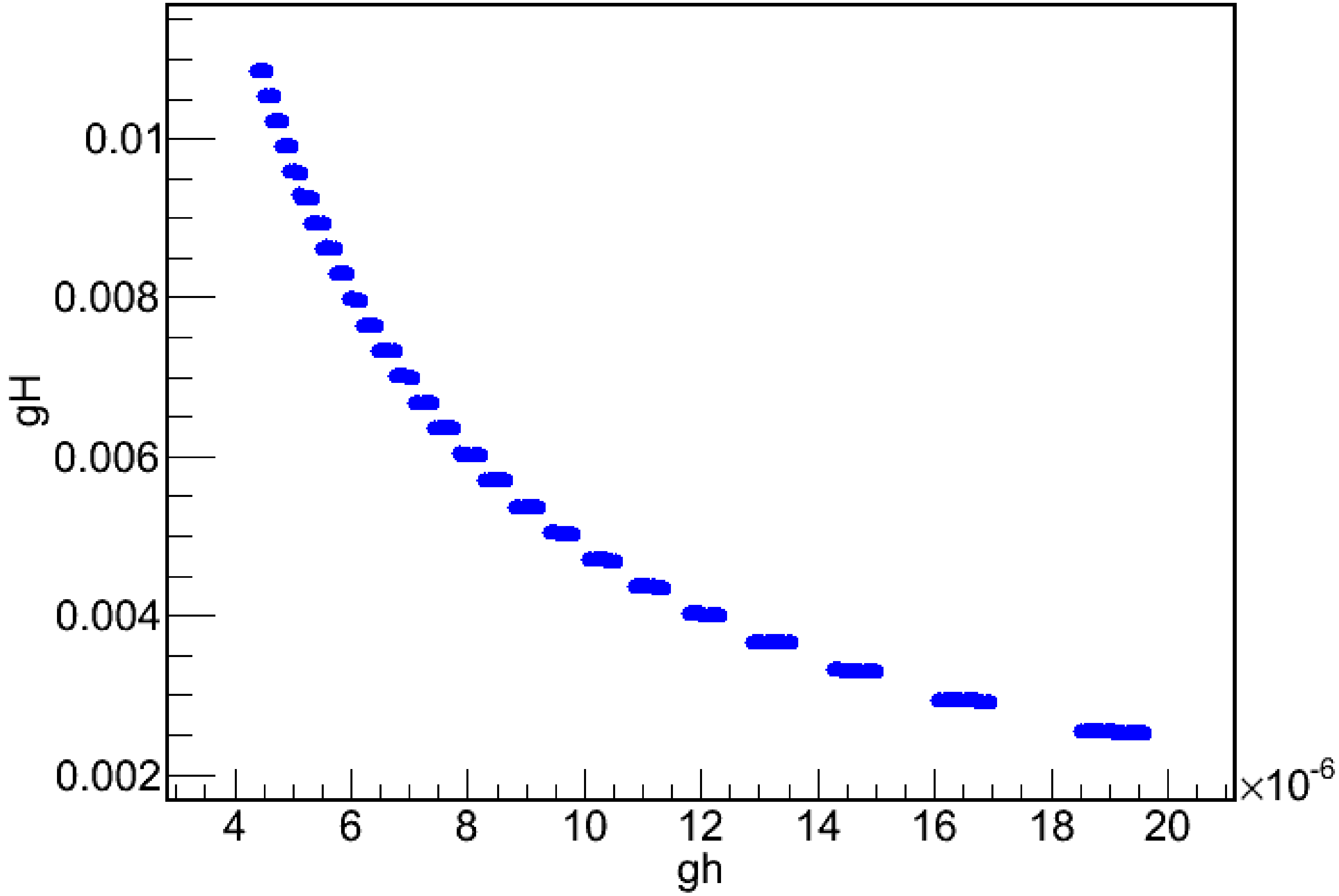
- The parameter space has also been constrained from LHC signal strength values.

$$R_{LS} = \frac{\sigma^{LS}_{h,H}}{\sigma^{SM}} \frac{BR^{LS}}{BR^{SM}}$$

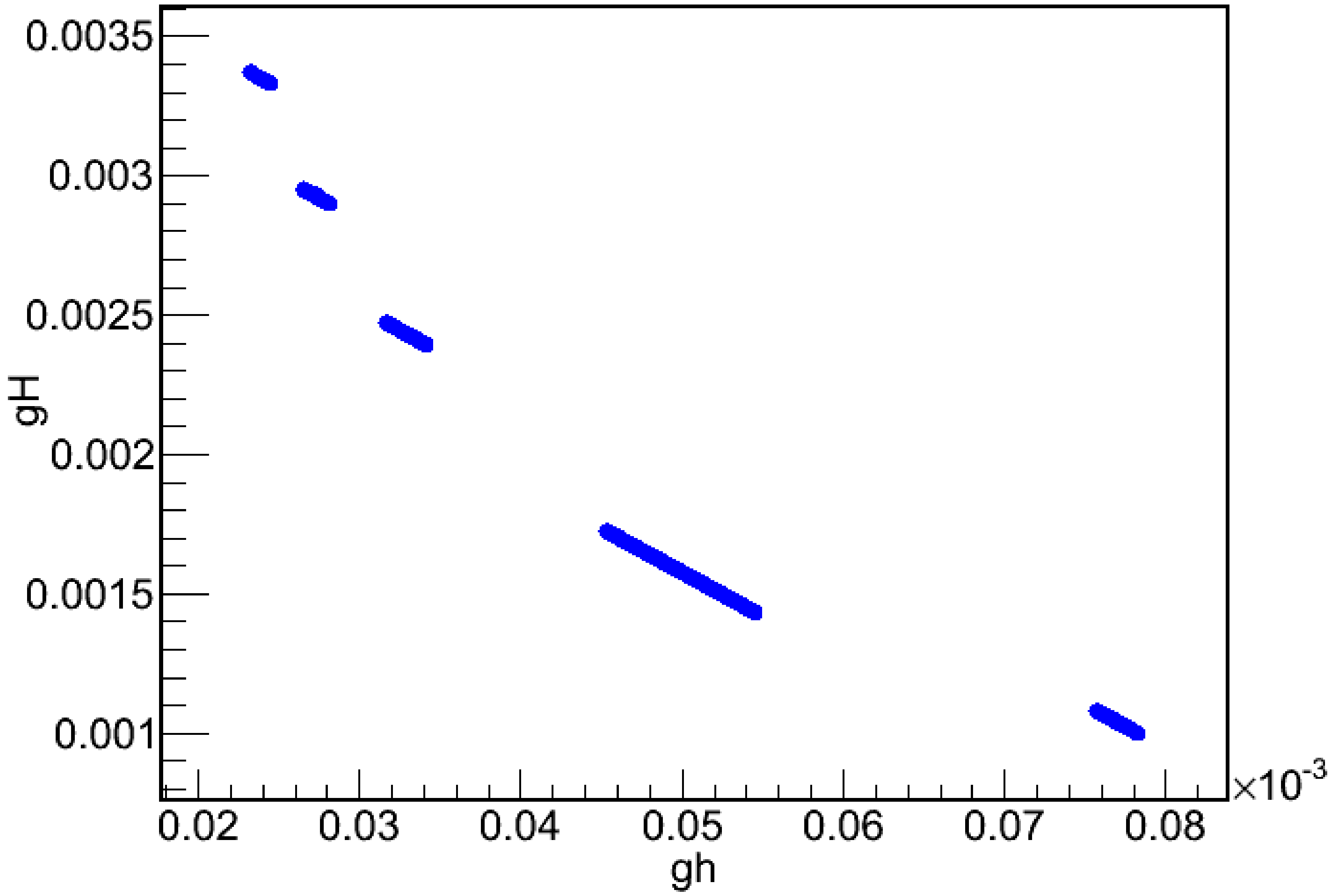
- We have used the mean signal strength of the ATLAS and CMS experiments for the light scalar.
- For the heavier scalar we have used taken R^{H}_{LS}<0.2.

Final parameter space

Link



tanβ=8.62


0.0035
0.003
0.0025
0.002
0.0015
0.001
gH
$\times10^{-3}$
0.02
0.03
0.04
0.05
0.06
0.07
0.08
gh

tanβ=18.03

Calculation of Positron Fraction

- The background flux of positrons and electrons can be written as

$$\frac{d\Phi^{e^-}_{bkg}}{dE} = \frac{0.16E^{-1.1}}{1+11E^{0.9}+3.2E^{2.15}} + \frac{0.70E^{0.7}}{1+110E^{1.5}+660E^{2.9}+580E^{4.2}}$$

$$\frac{d\Phi^{e^+}_{bkg}}{dE} = \frac{4.5E^{0.7}}{1+650E^{2.3}+1500E^{4.2}}$$

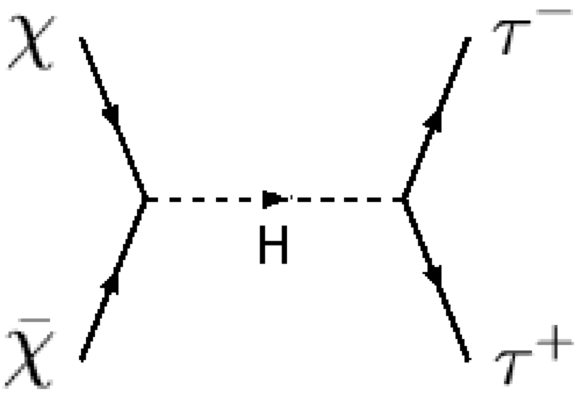
Ref:-M. Cirelli, et. al., Nucl. Phys. B800 (2008) 204–220
E. A. Baltz and J. Edsjo, Phys. Rev. D59 (1998) 023511

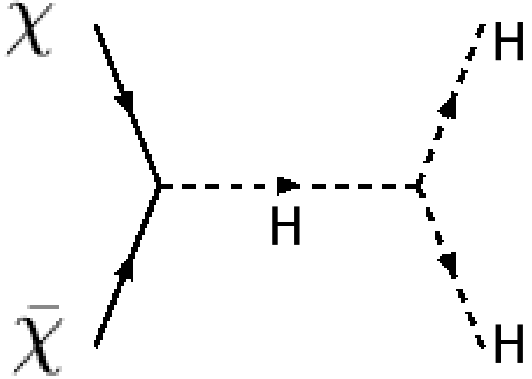
- The positron fraction is defined as

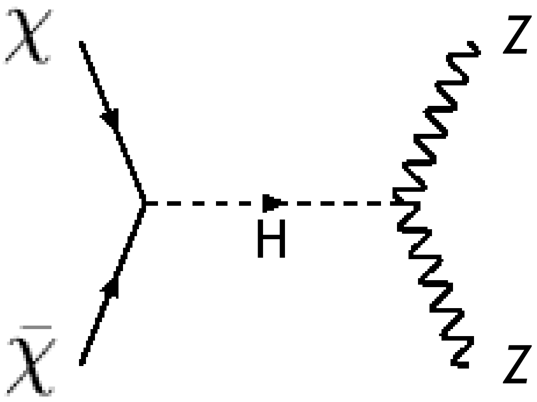
$$f_{e^+} = \frac{\Phi^{e^+}_{sig} + \Phi^{e^+}_{bkg}}{2\Phi^{e^+}_{sig} + \Phi^{e^+}_{bkg} + \Phi^{e^-}_{bkg}}$$

Yang Bai, et. al., Phys. Rev. D 97, 115012 (2018)

Processes Considered







Flux was calculated using the [*PPPC 4 DM ID*](#) code.

Sommerfeld Enhancement

- Due to the fact that velocity of dark matter at present is non-relativistic and $v_{rel} \approx 10^{-3}$, the annihilation cross-sections are enhanced. Due to this annihilation signals are boosted.
- The effective enhancement factor arising due to the above reason is given as

$$S_{eff} = \frac{(\sigma v_{rel})_0 \bar{S}_{now}}{3 \times 10^{-26} cm^3/s}$$

- Where $\bar{S}_{now}$ is defined by the following integral

$$\bar{S}_{now} \simeq \frac{x_{now}^{3/2}}{2\sqrt{\pi} N} \int_0^{v_{max}} S v_{rel}^2 e^{-x_{now} v_{rel}^2/4} dv_{rel}$$

$$S \simeq \frac{\pi^2 \alpha_\chi m_\phi}{6 m_\chi v^2}$$

Ref:-Jonathan L. Feng, et. al., Phys. Rev. D 82, 083525 (2010)

Conclusion

Link

- The peak of positron fraction calculated by our model was giving a value of ~0.1, while the AMS-02 data reports the same as ~0.15.

- The total background flux calculated from the model shown before does not match well with that from the data in AMS Collaboration, M. Aguilar et al., Phys. Rev. Lett. 113 (2014) 121101, especially in the low energy side.

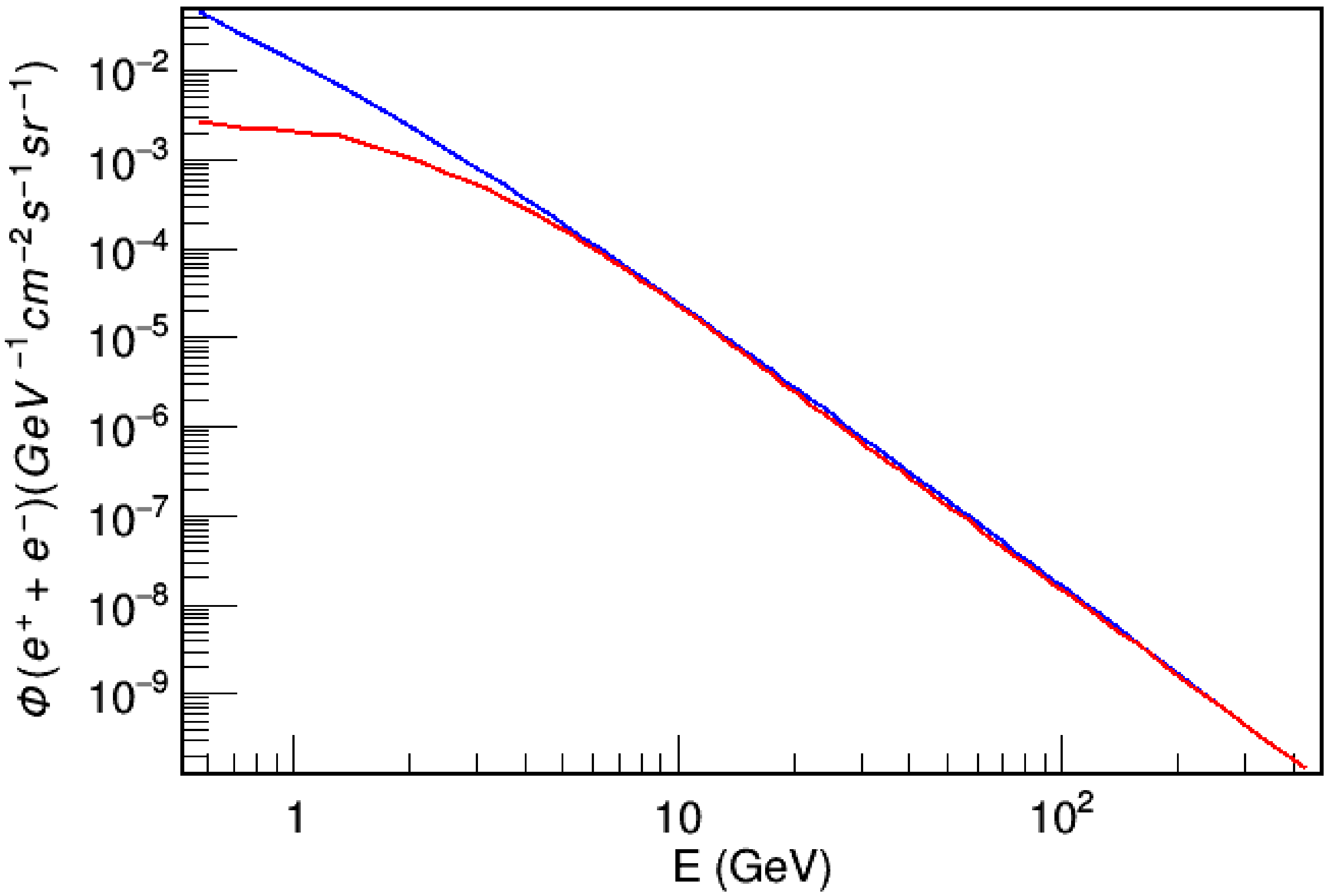
- The overall signal is also boosted by other factors arising due to dark matter clumping and fluctuations and uncertainties in the density profile of dark matter.

Acknowledgement

- I acknowledge the contribution of Prof. Satyajit Saha, Applied Nuclear Physics Division and Prof. Debasish Majumdar, Astroparticle Physics and Cosmology Division, Saha Institute of Nuclear Physics, Kolkata.

- I would also like to acknowledge the contribution of Dr. Amit Dutta Banik, Department of Physics, Indian Institute of Technology Guwahati, Guwahati.

Thank You



10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
$\Phi(e^+ + e^-)(GeV^{-1}cm^{-2}s^{-1}sr^{-1})$
1
10
10^2
E (GeV)

Back