

SHINING HIGGS(es) ON DARK MATTER

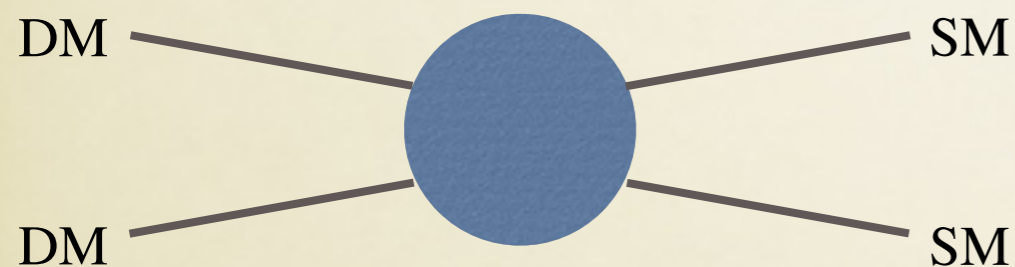
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INT
December 11, 2015

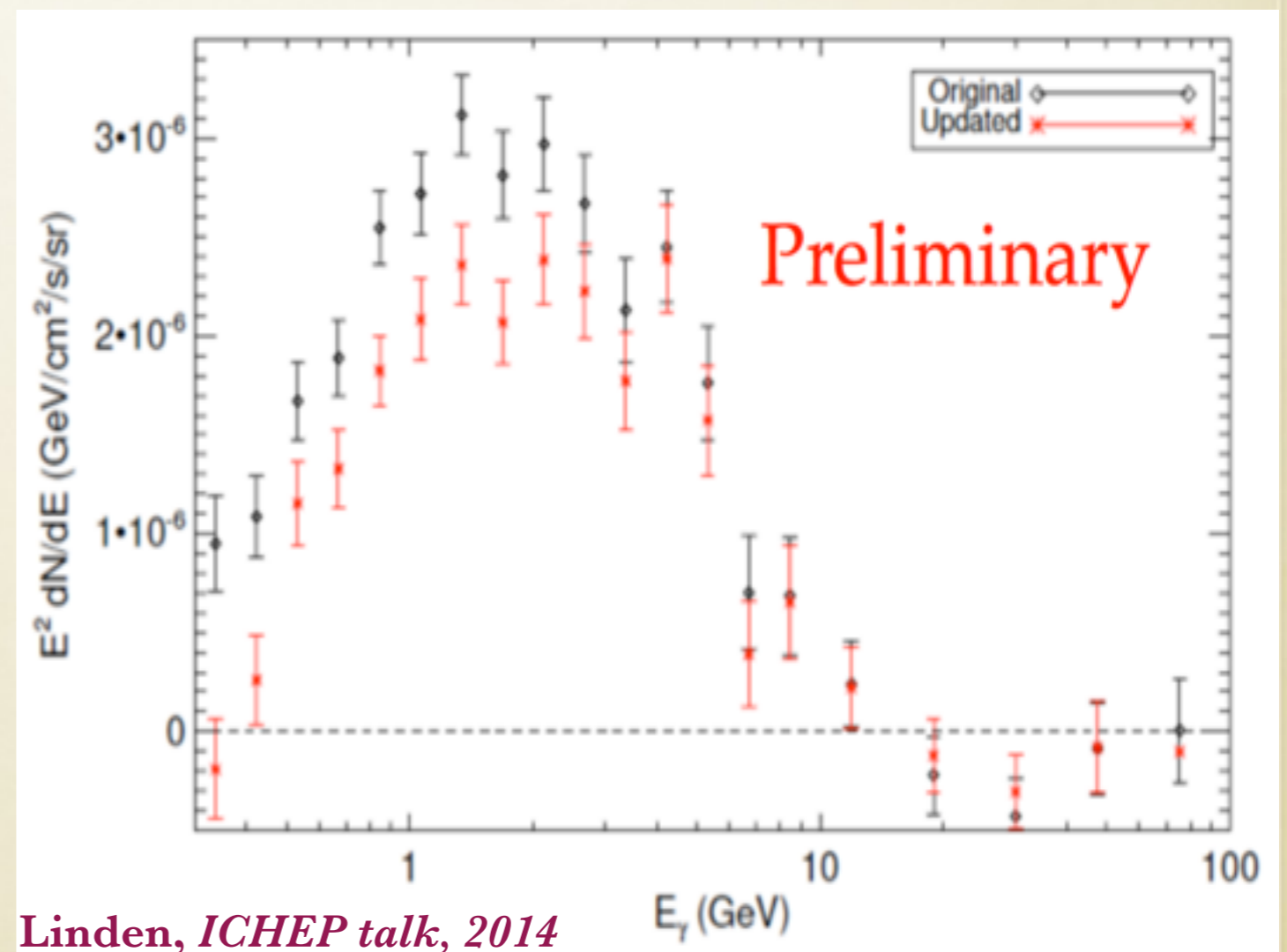
Gamma rays from the Galactic Center

- There is an excess of photons from the Galactic Center ($<5^\circ$)
- The excess extends to the Inner Galaxy ($\sim 10^\circ$ around GC)
- Spherically symmetric around Galactic Center
- Right annihilation cross section

Indirect detection:



Daylan, *et al*, [arxiv:1402.6703](https://arxiv.org/abs/1402.6703)
Abazajian, *et al*, [arxiv: 1402.4090](https://arxiv.org/abs/1402.4090)
Gordon, Macias, [arxiv:1306.5725](https://arxiv.org/abs/1306.5725)
Hooper, Linden, [arxiv:1110.0006](https://arxiv.org/abs/1110.0006)
...



Linden, *ICHEP talk, 2014*

What other people did

People usually focus on this effective operator:

Boehm, *et al*, [arxiv:1401.6458](#)

Alves, Profumo, Queiroz, Shepherd, [arxiv:1403.5027](#)

Berlin, Hooper, McDermott, [arxiv:1404.0022](#)

...

$$\mathcal{L}_{eff} = \frac{m_b}{\Lambda^3} \bar{\chi} i \gamma_5 \chi \bar{b} i \gamma_5 b$$



- Annihilation rate for γ -ray excess \Leftrightarrow relic abundance
- Direct detection cross section is spin dependent, velocity suppressed
- A spin-0 (scalar) mediator favors b-quarks

Realize:

$\bar{b} i \gamma^5 b = i (\bar{b}_L b_R - \bar{b}_R b_L)$ is not an $SU(2)$ singlet

Need to go beyond the effective theories!

- Fermionic DM coupled to a pseudoscalar: $\mathcal{L}_{\text{dark}} = y_{\chi} a_0 \bar{\chi} i \gamma^5 \chi$
- Pseudoscalar, a_0 , mixes with the two Higgs doublet model:

$$V = iB a_0 H_1^\dagger H_2 + \frac{1}{2} m_{a_0}^2 a_0^2 + \frac{\lambda_{a_0}}{4} a_0^4 + V_{2\text{HDM}}$$

- H_1 and H_2 are the two Higgs fields
- B and y_{χ} are real, and no CP violation in $V_{2\text{HDM}}$
- a_0 does not develop a vacuum expectation value

What is 2HDM?

Mass eigenstates + interactions

- 2 Higgs fields:

$$H_1 = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2}\phi_1^+ \\ v_1 + \rho_1 + i\eta_1 \end{pmatrix}, \quad H_2 = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2}\phi_2^+ \\ v_2 + \rho_2 + i\eta_2 \end{pmatrix}$$

8 degrees of freedom: 3 get eaten by $W, Z \rightarrow 5$ left

$$\tan \beta = \frac{v_1}{v_2}$$

$$H^\pm = \sin \beta \phi_1^\pm + \cos \beta \phi_2^\pm \quad \text{charged}$$

CP even

CP odd

$$H = \cos \alpha \rho_1 + \sin \alpha \rho_2$$

$$A = \cos \theta A_0 + \sin \theta a_0$$

$$h = -\sin \alpha \rho_1 + \cos \alpha \rho_2$$

$$a = -\sin \theta A_0 + \cos \theta a_0$$

- DM interactions:

$$\mathcal{L}_{\text{dark}} = y_\chi (\cos \theta a + \sin \theta A) \bar{\chi} i \gamma^5 \chi$$

Parameters of the model

- From the 2HDM:

$$\underline{m_h}, m_H, m_A, m_{H^\pm}, \alpha, \beta$$

we pick the observed Higgs to be h : $m_h = 125 \text{ GeV}$

- From the dark sector:

$$\underline{m_\chi}, \underline{y_\chi}, m_a, \theta$$

To fit the γ -ray excess we set: $m_\chi = 30 \text{ GeV}$

We also choose: $y_\chi = 0.5$

- Left: $m_H, m_A, m_{H^\pm}, \alpha, \beta, m_a, \theta$

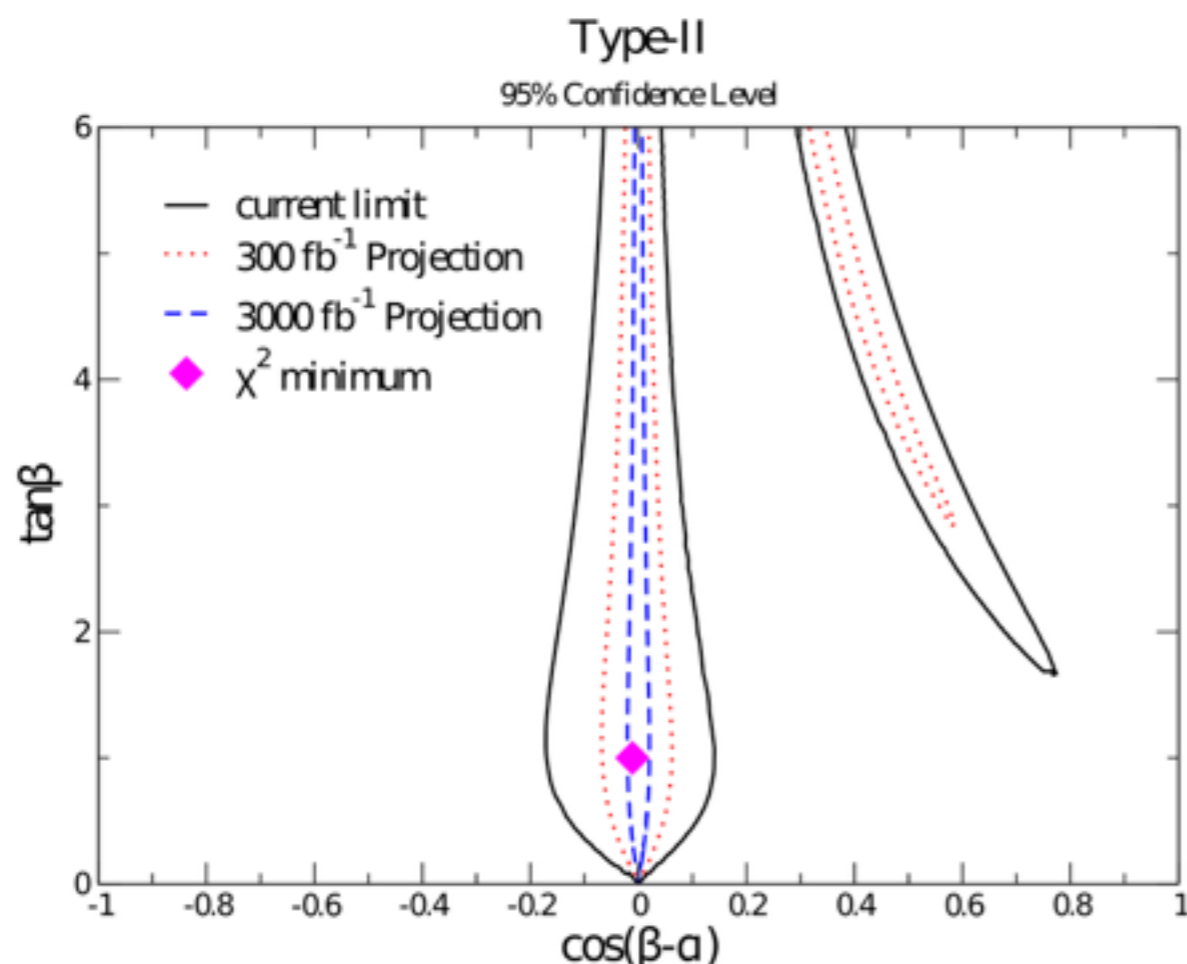
Pick reasonable values



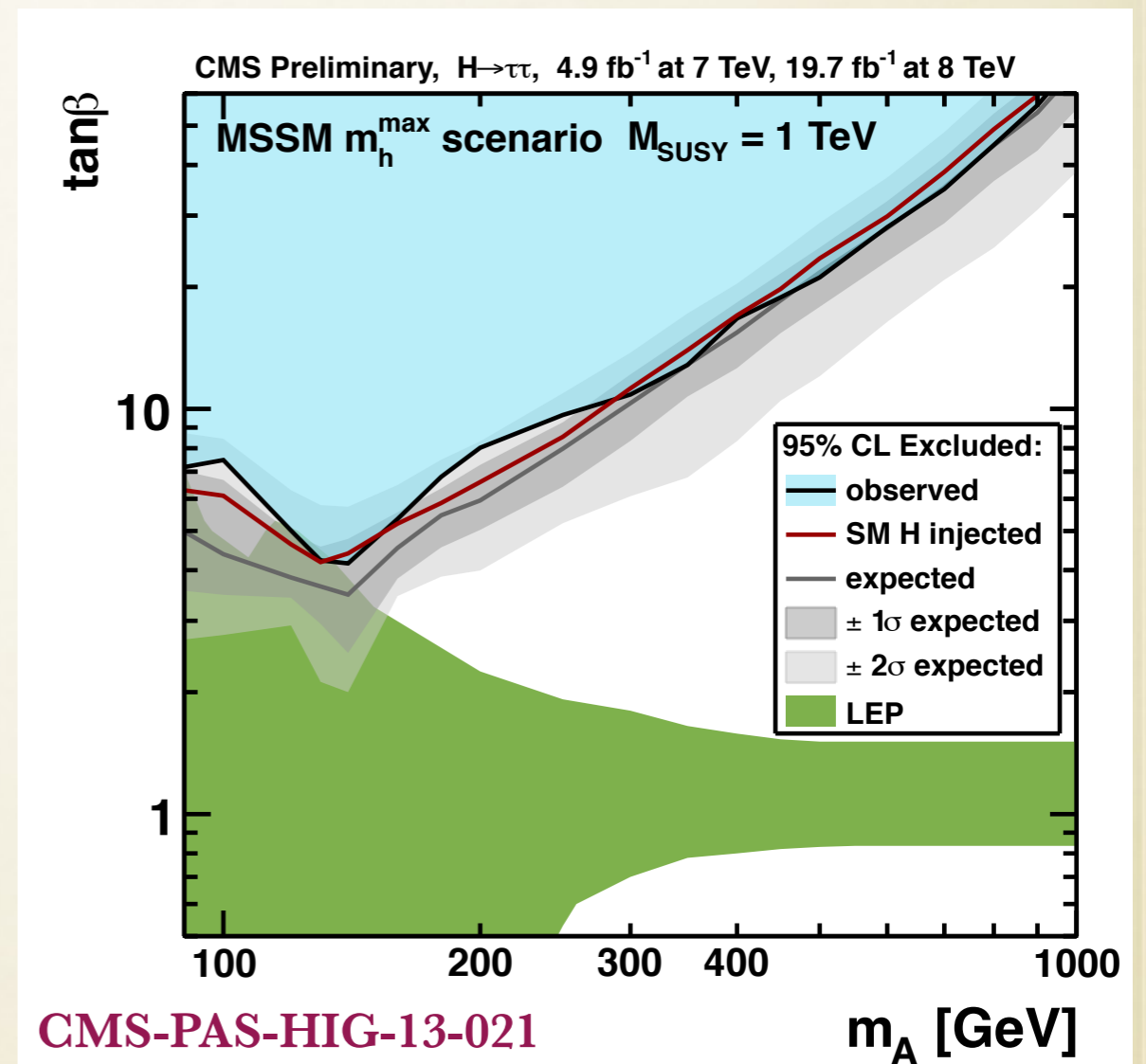
Heavy Higgs searches:

$$\tan \beta = 40$$

$$m_A = 800 \text{ GeV}$$



Chen, Dawson, *arxiv: 1305.1624*



125 GeV Higgs couplings:

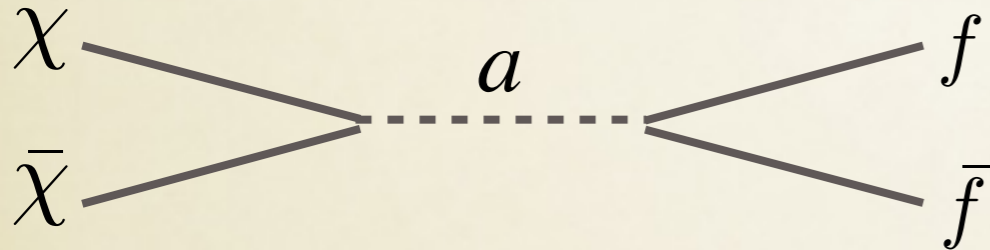
$$\beta - \alpha \simeq \pi/2$$

$$m_h \ll m_H \simeq m_{H^\pm} \simeq m_A$$

Region of Interest (relic abundance + γ -ray excess)

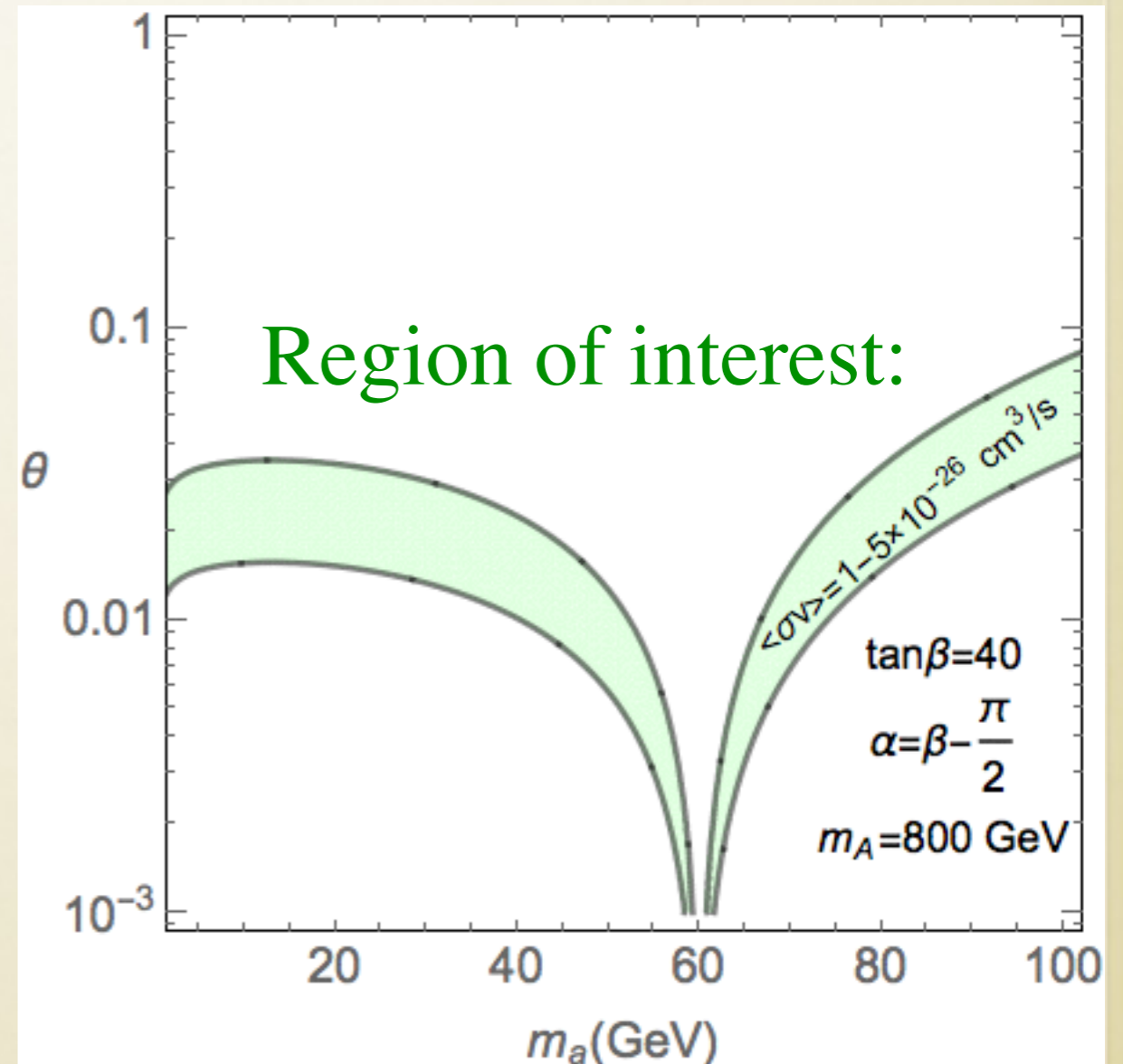
DM annihilation cross section:

$$\langle\sigma v_{\text{rel}}\rangle = \frac{y_\chi^2 m_\chi^2}{8\pi m_a^4} s_{2\theta}^2 \tan^2 \beta \left[\left(1 - \frac{4m_\chi^2}{m_a^2}\right)^2 + \frac{\Gamma_a^2}{m_a^2} \right]^{-1} \sum_{f=b,\tau,\dots} N_C \frac{m_f^2}{v^2} \sqrt{1 - \frac{m_f^2}{m_a^2}}$$



$$\langle\sigma v_{\text{rel}}\rangle \simeq 3 \times 10^{-26} \frac{\text{cm}^3}{\text{s}}$$

- fits the gamma-ray excess
- correct relic density



Direct Detection (spin independent)

$$\sigma_{\text{SI}} \simeq 2.2 \times 10^{-49} \text{ cm}^2 \left(\frac{m_A}{800 \text{ GeV}} \right)^4 \left(\frac{50 \text{ GeV}}{m_a} \right)^4 \left(\frac{m_\chi}{30 \text{ GeV}} \right)^2 \left(\frac{\theta}{0.1} \right)^4$$

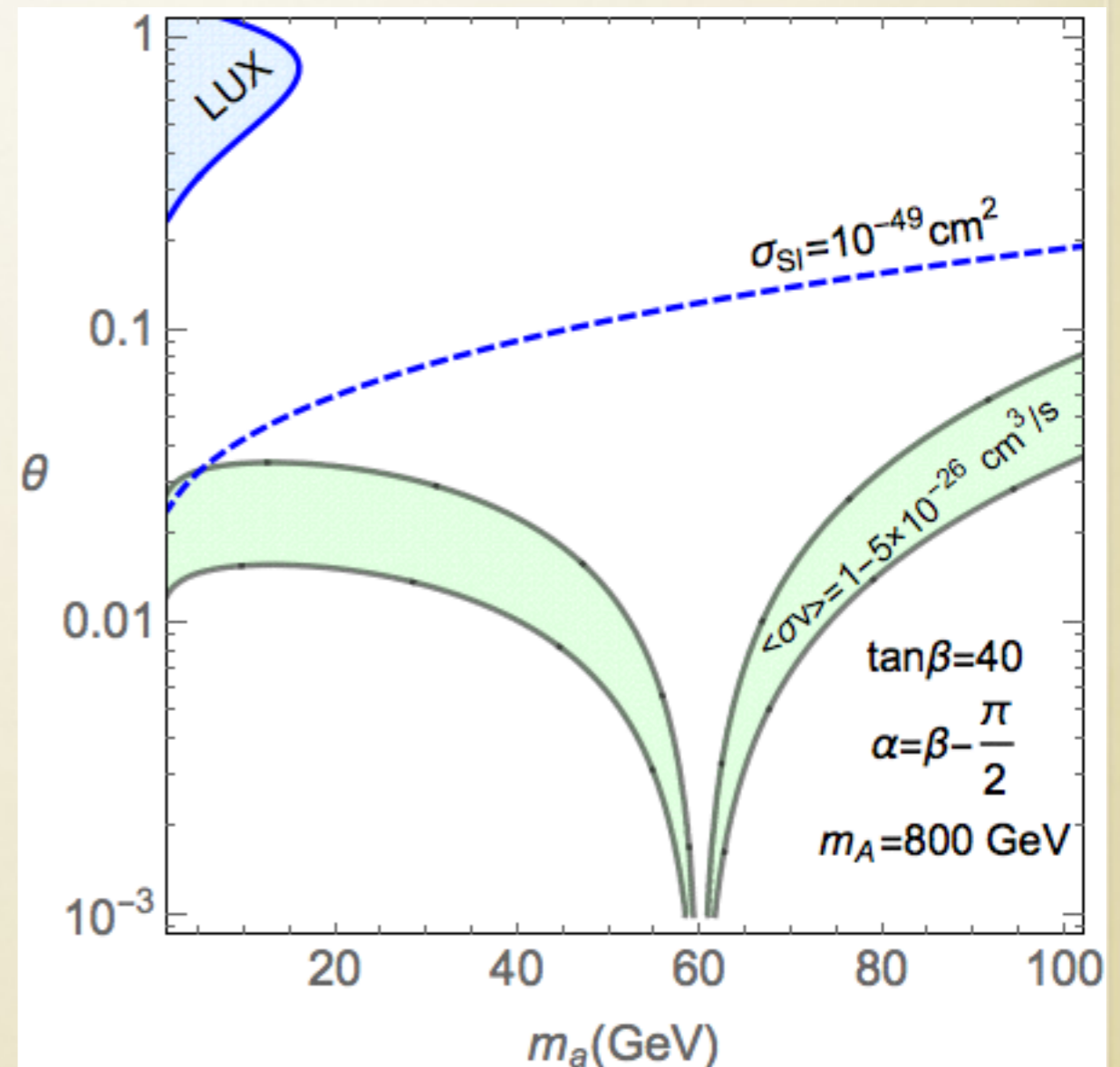
$$\times \left(\frac{y_\chi}{0.5} \right)^4 \left(\frac{\langle N | \sum_q m_q \bar{q}q | N \rangle}{330 \text{ MeV}} \right)^2$$

LUX limit for $m_\chi = 30 \text{ GeV}$:

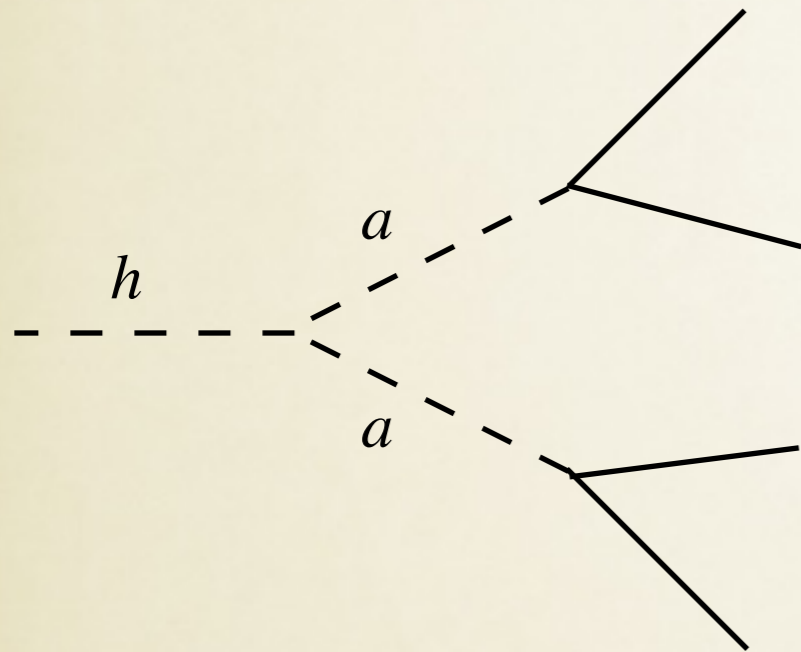
$$\sigma_{\text{SI}} < 8 \times 10^{-46} \text{ cm}^2$$

Above --- we have:

$$\sigma_{\text{SI}} > 10^{-49} \text{ cm}^2$$



Higgs decays: $h \rightarrow 4b$



$$V \supset \frac{1}{2v} (m_A^2 - m_a^2) \sin^2 2\theta h a a$$

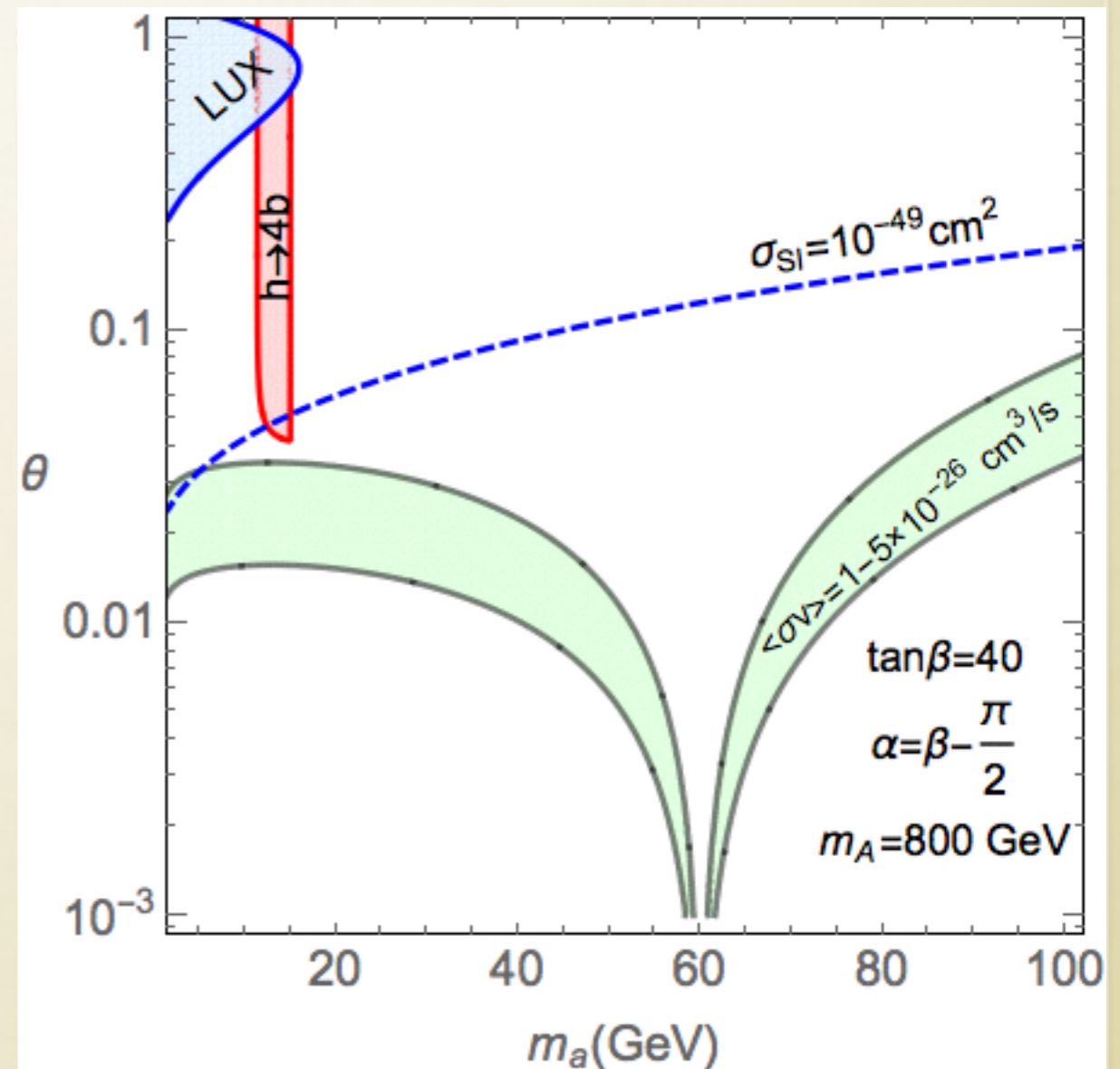
$m_\chi = 30 \text{ GeV} \Rightarrow 4b$ final state favored

- No $h \rightarrow 4b$ searches
- Use $h \rightarrow 2b$ from CMS:

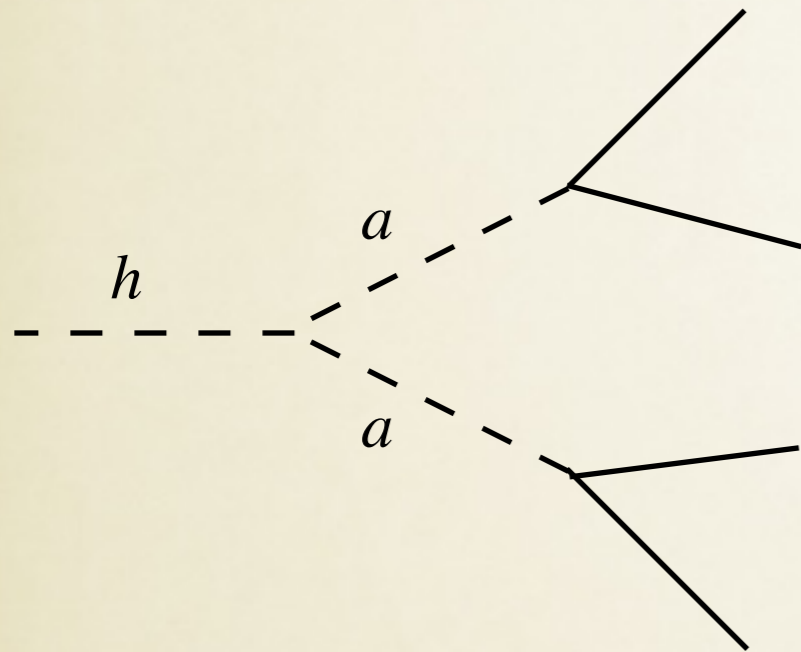
$$\text{Br}(h \rightarrow aa \rightarrow 4b) < 0.7$$

CMS, *arxiv:1310.3687*

Curtin, *et al*, *arxiv: 1312.4992*



Higgs decays: $h \rightarrow 2b2\mu$



$$V \supset \frac{1}{2v} (m_A^2 - m_a^2) \sin^2 2\theta h a a$$

$m_\chi = 30 \text{ GeV} \Rightarrow 4b$ final state favored

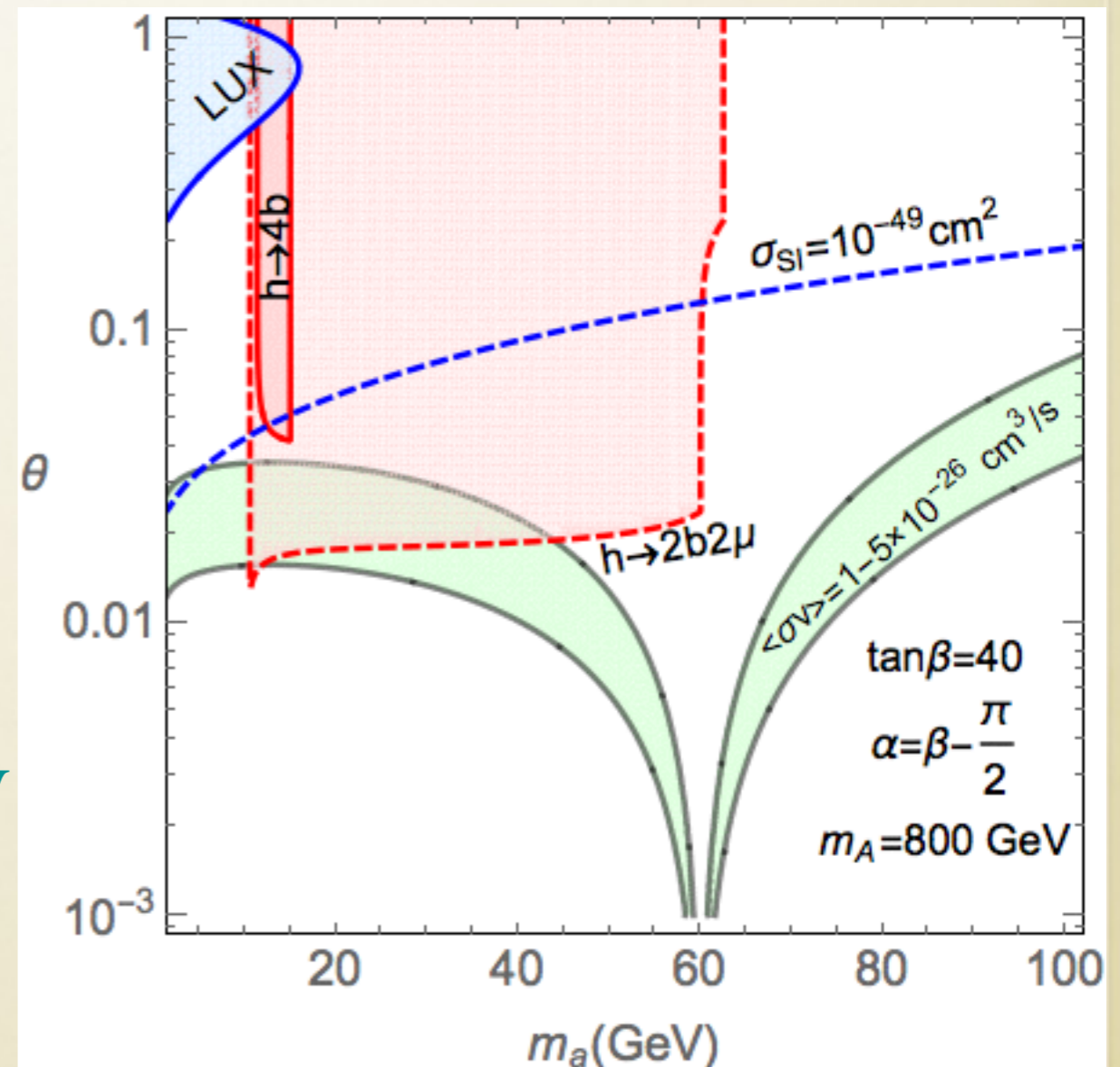
BUT: $2b2\mu$ final states is cleaner:

$$\text{Br}(h \rightarrow aa \rightarrow 2b2\mu) < 10^{-3} \text{ (} 10^{-4} \text{)}$$

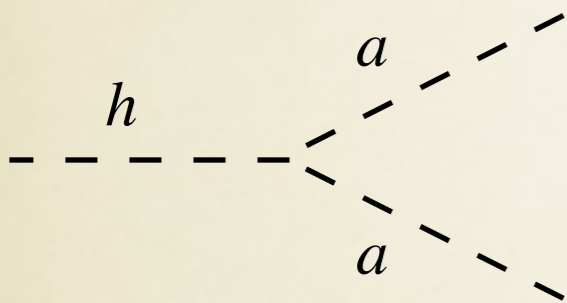
@14 TeV

CMS, *arxiv:1310.3687*

Curtin, *et al*, *arxiv: 1312.4992*



Higgs decays: $h \rightarrow aa$



$$V \supset \frac{1}{2v} (m_A^2 - m_a^2) \sin^2 2\theta h a a$$

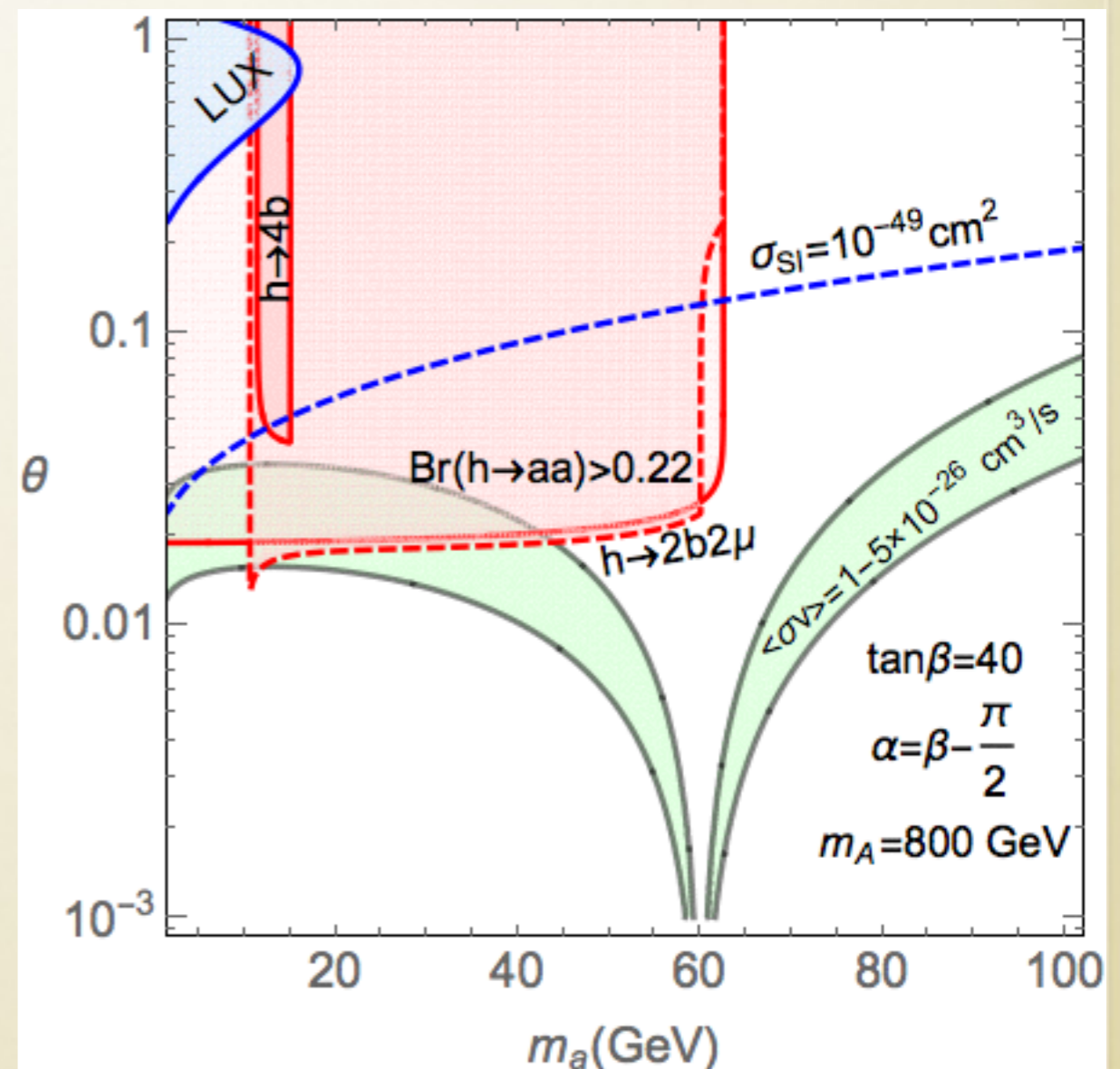
Higgs decay rate to aa :

$$\Gamma(h \rightarrow aa) = \frac{(m_A^2 - m_a^2)^2 \sin^4 2\theta}{32\pi m_h v^2} \sqrt{1 - \frac{4m_a^2}{m_h^2}}$$

$$\Gamma_h^{\text{SM}} = 4 \text{ MeV}$$

$$\text{Br}(h \rightarrow aa) < 0.22$$

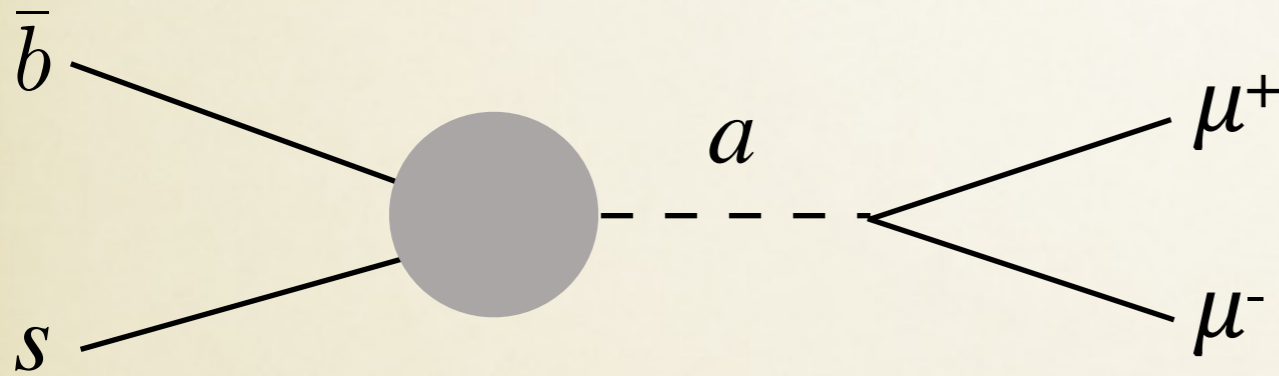
Giardano, et al, arxiv: 1303.3570



Rare decays: $B_s \rightarrow \mu^+ \mu^-$

Rare SM processes are good tests of New Physics!

$$\text{Br}(B_s \rightarrow \mu^+ \mu^-) \simeq \text{Br}(B_s \rightarrow \mu^+ \mu^-)_{\text{SM}} \left| 1 + \frac{m_b m_{B_s} t_\beta^2 s_\theta^2}{m_{B_s}^2 - m_a^2} f(m_t, m_W, m_{H^\pm}) \right|^2$$



CMS and LHCb combined:

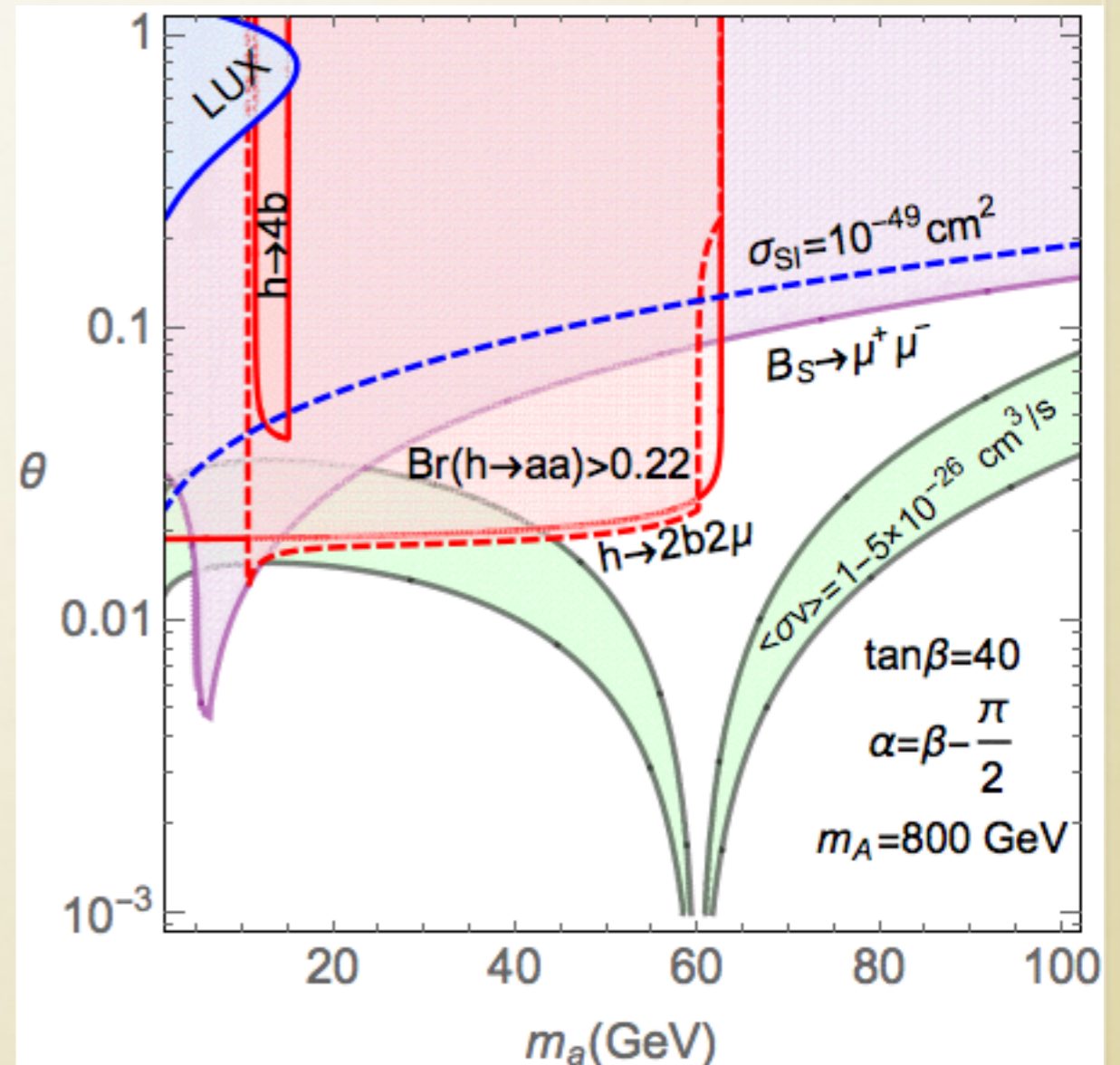
$$\text{Br}(B_s \rightarrow \mu^+ \mu^-) = (2.9 \pm 0.7) \times 10^{-9}$$

[CMS-PAS-BPH-13-007](#), [LHCb-CONF-2013-012](#)

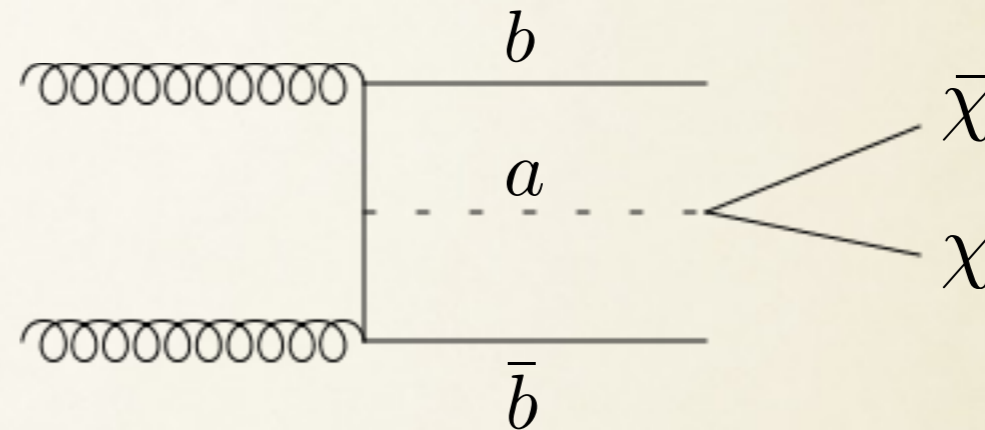
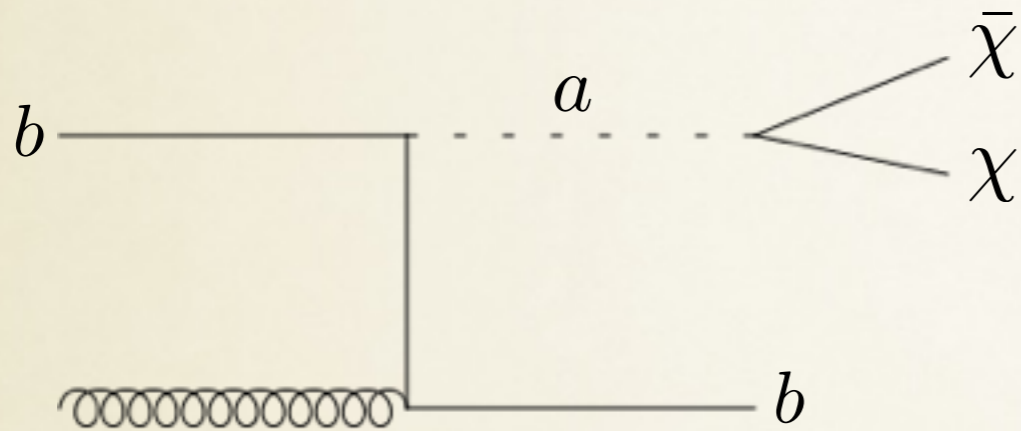
Compare to the SM expectation:

$$\text{Br}(B_s \rightarrow \mu^+ \mu^-)_{\text{SM}} = (3.65 \pm 0.23) \times 10^{-9}$$

[Bobeth, et al, arxiv:1311.0903](#)



Collider Searches: Monojets



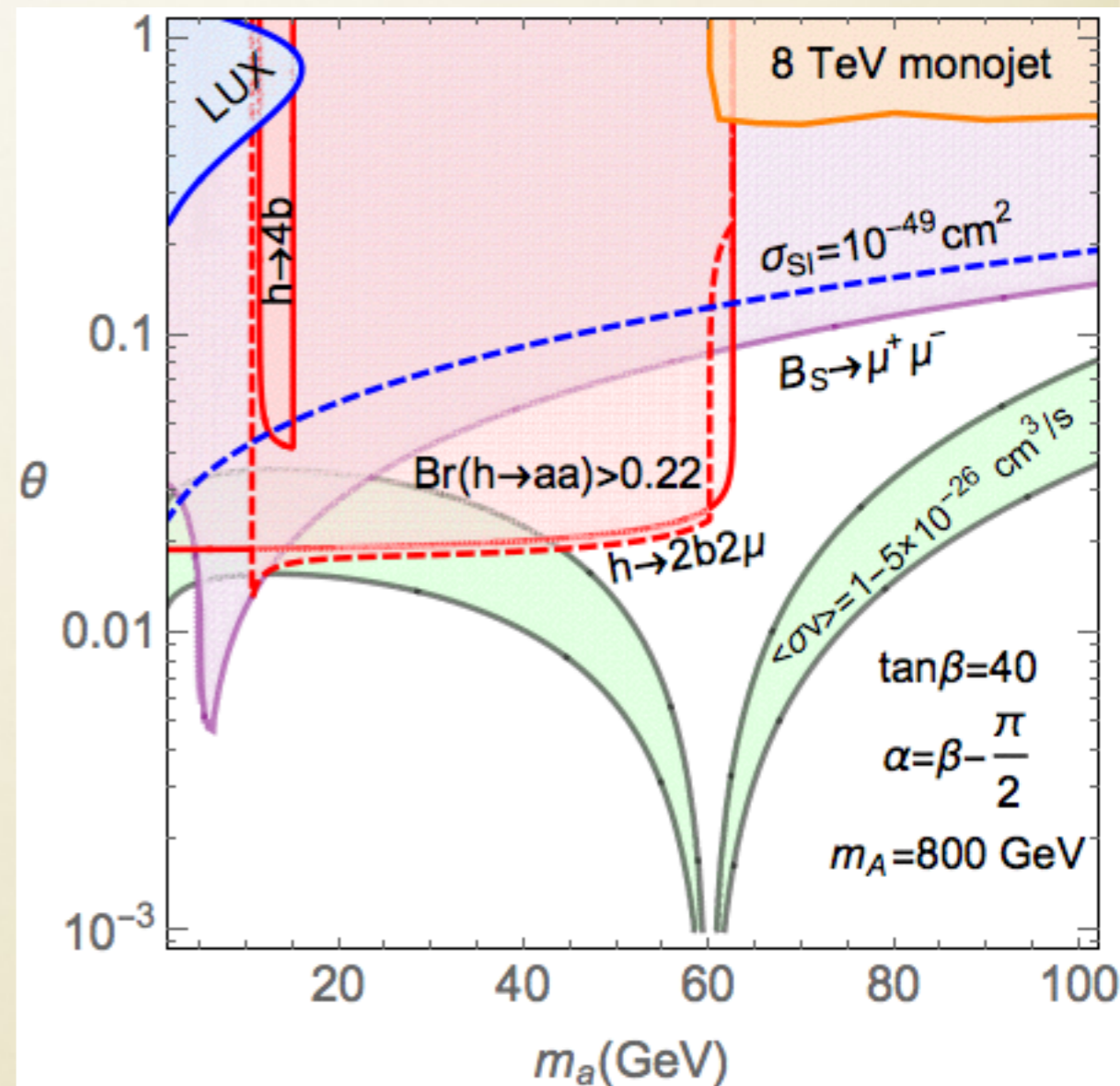
Lin, Kolb, Wang, *arxiv:1303.6638*

$pp \rightarrow (0, 1, 2) j + \text{missing energy}$

leading *jet* is *b*-tagged
missing energy > 350 GeV

good for $m_a > 2m_\chi$

No help from *top*-tagging:
top couplings are $\tan\beta$ suppressed!



Summary

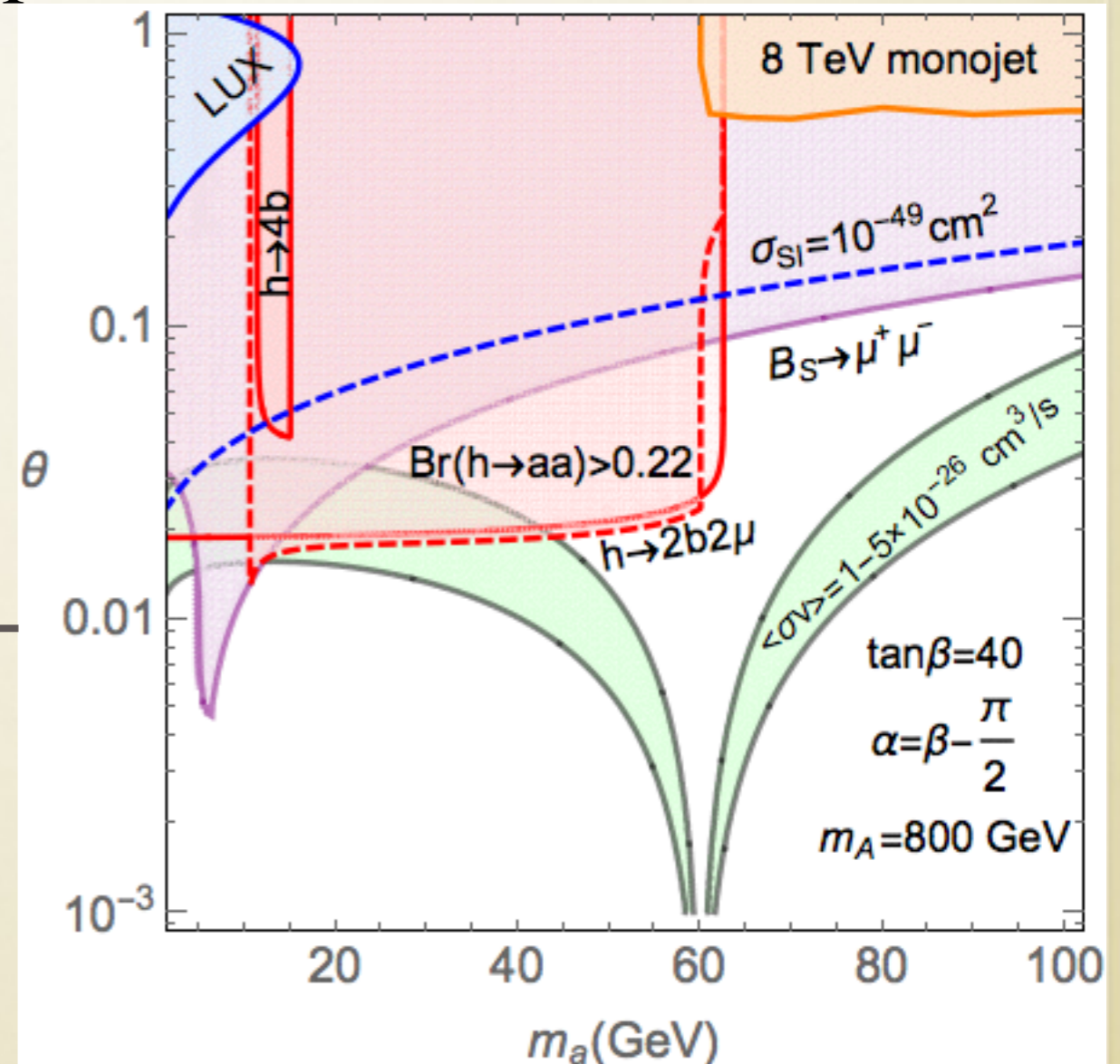
SI, McKeen, Nelson, *arXiv: 1404.3716*

- A consistent γ -ray excess from the Galactic Center
- Can be a signal from a 30 GeV dark matter
- We have a renormalizable model
- There are constraints on this model from different processes including Higgs decays

Outlook

One possible signature:

$$A \rightarrow ha \rightarrow 2b + inv$$



Fermion couplings

Mediator - DM coupling becomes:

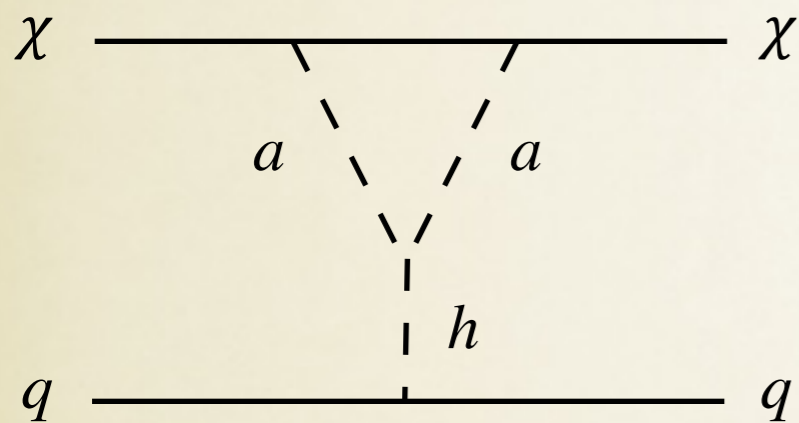
$$\mathcal{L}_{\text{dark}} = y_{\chi} (\cos \theta a + \sin \theta A) \bar{\chi} i \gamma^5 \chi$$

We work with a Type II 2HDM: H_1 couples to u and e , H_2 couples to d

	u	d	e
h	$\frac{\cos \alpha}{\sin \beta}$	$-\frac{\sin \alpha}{\cos \beta}$	$-\frac{\sin \alpha}{\cos \beta}$
H	$\frac{\sin \alpha}{\sin \beta}$	$\frac{\cos \alpha}{\cos \beta}$	$\frac{\cos \alpha}{\cos \beta}$
A	$\cot \beta \cos \theta$	$\tan \beta \cos \theta$	$\tan \beta \cos \theta$
a	$\cot \beta \sin \theta$	$-\tan \beta \sin \theta$	$-\tan \beta \sin \theta$

Table: Modified SM fermion couplings in units of the SM Higgs couplings

Direct Detection (spin independent)



$$\mathcal{L}_h = \frac{y_\chi^2 (m_A^2 - m_a^2) \sin^2 2\theta}{64\pi^2 m_h^2 m_a^2} G(x_\chi) \frac{m_\chi m_q}{v^2} \bar{\chi} \chi \bar{q} q$$

$$x_q = \frac{m_q^2}{m_a^2}$$



$$\mathcal{L}_{\text{box}} = \frac{m_q^2 y_\chi^2 \tan^2 \beta \sin^2 2\theta}{128\pi^2 m_a^2 (m_\chi^2 - m_q^2)} F(x_\chi, x_q) \frac{m_\chi m_q}{v^2} \bar{\chi} \chi \bar{q} q$$

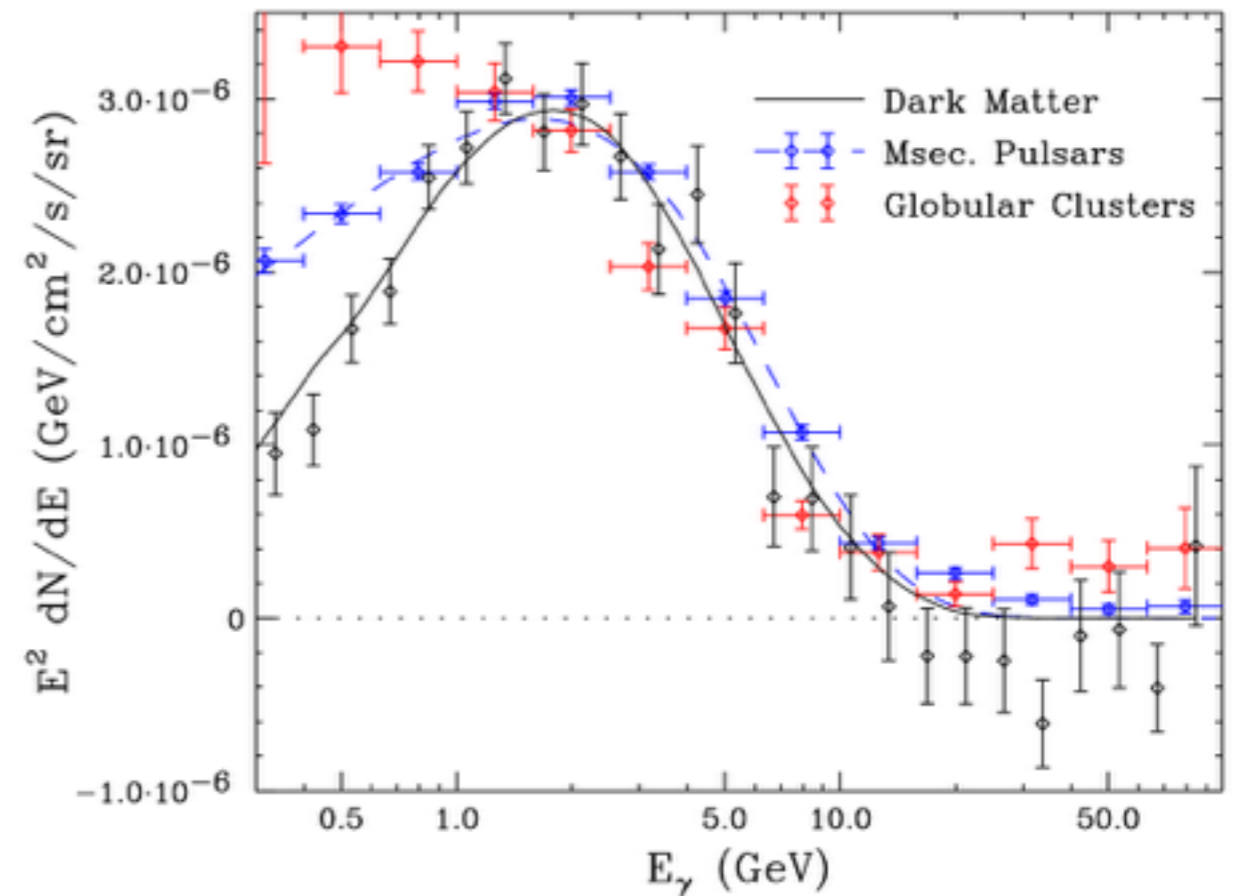
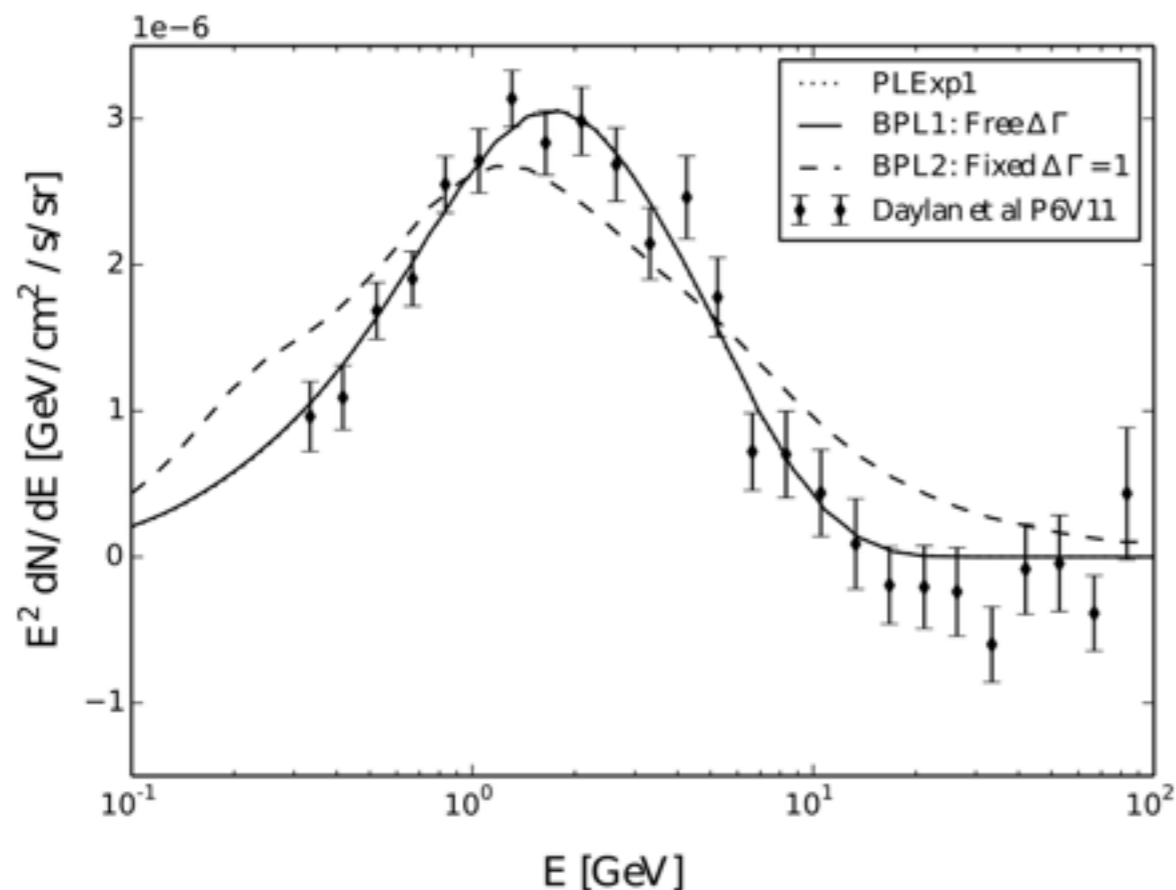
If: $\tan \beta \lesssim 100 \left(\frac{m_A}{800 \text{ GeV}} \right)$

Higgs exchange dominates over the box

Can we explain it without Dark Matter?

- Milisecond Pulsars?
 - ▶ Can account for 1-5%
 - ▶ Fermi would see extra point sources

Cholis, Hooper, Linden, *arxiv:1407.5625*



- Cosmic ray burst dominated by protons?
 - ▶ More disklike than spherical
 - ▶ Cosmic protons need to be injected with a δ -function like spectrum

Carlson, Profumo, *arxiv:1405.7685*