SHINING HIGGS(es) ON DARK MATTER

Seyda Ipek
University of Washington

PACIFIC 2014
Moorea, French Polynesia
September 17

Ipek, McKeen, Nelson, ***arXiv: 1404.3716 (to be published in PRD)***

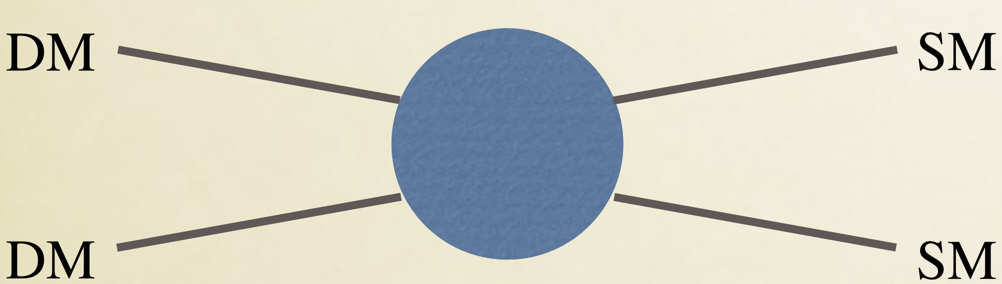
Teaser

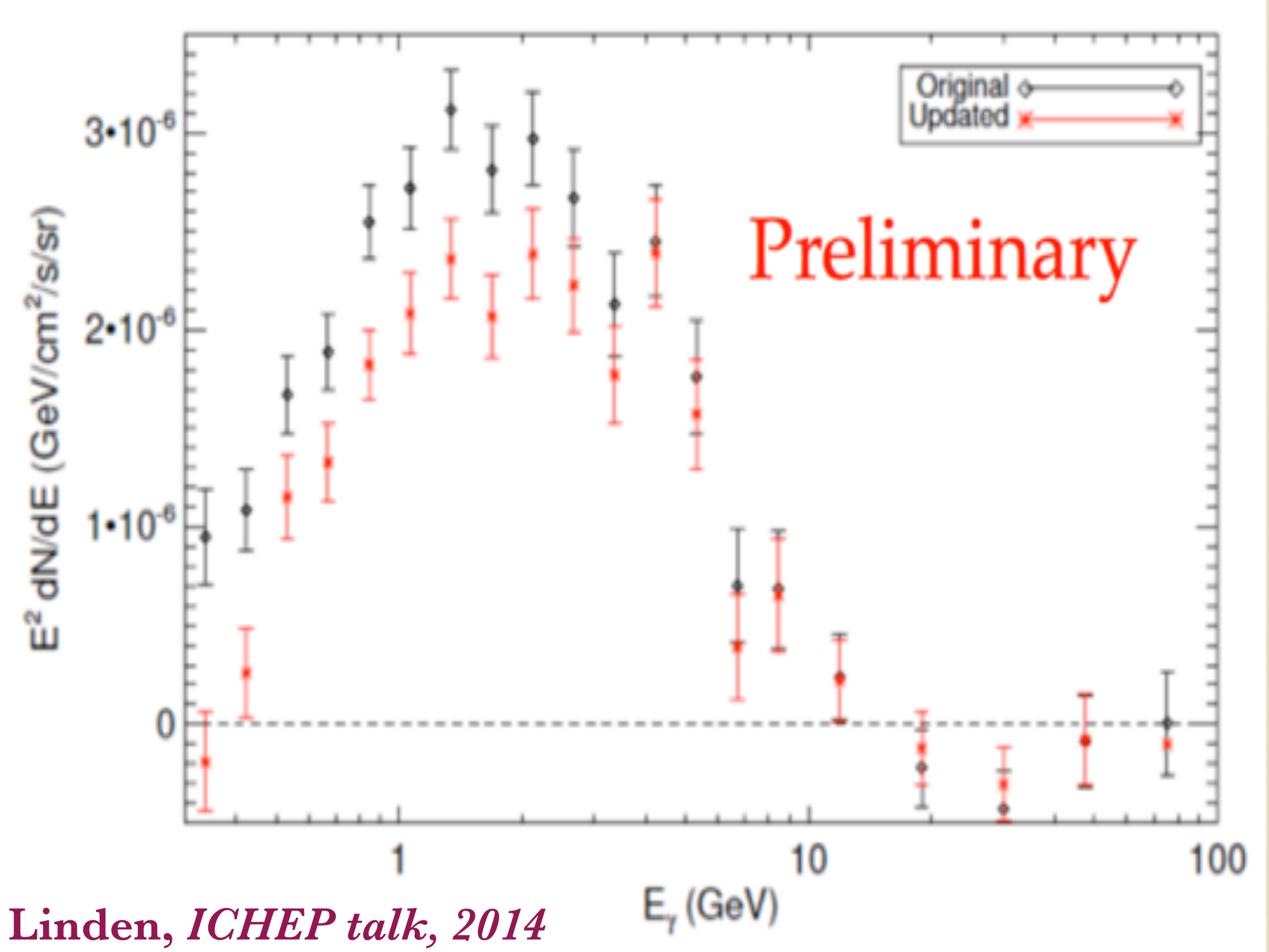
- There is dark matter
- There is an excess of gamma rays from the galactic center
- Could be an indirect signal of dark matter (DM)
- A renormalizable DM model: fermionic DM + a pseudoscalar mediator + two Higgs doublet model (2HDM)
- Explains the gamma ray excess + has rich phenomenology

Gamma rays from the Galactic Center

- There is an excess of photons from the Galactic Center ($<5^o$)
- The excess extends to the Inner Galaxy ($\sim10^o$ around GC)
- Spherically symmetric around Galactic Center
- Right annihilation cross section

Indirect detection:





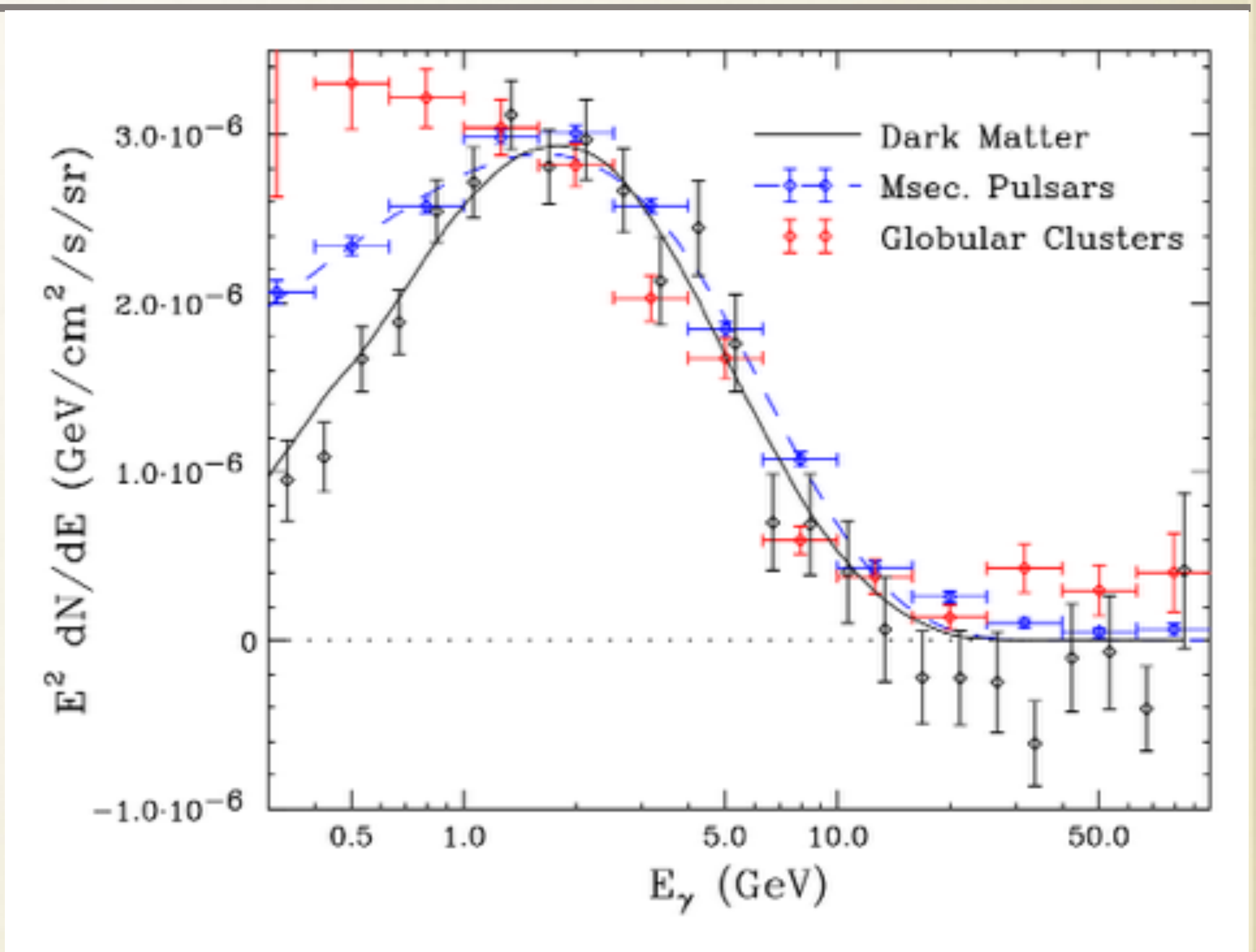
Linden, *ICHEP talk, 2014*

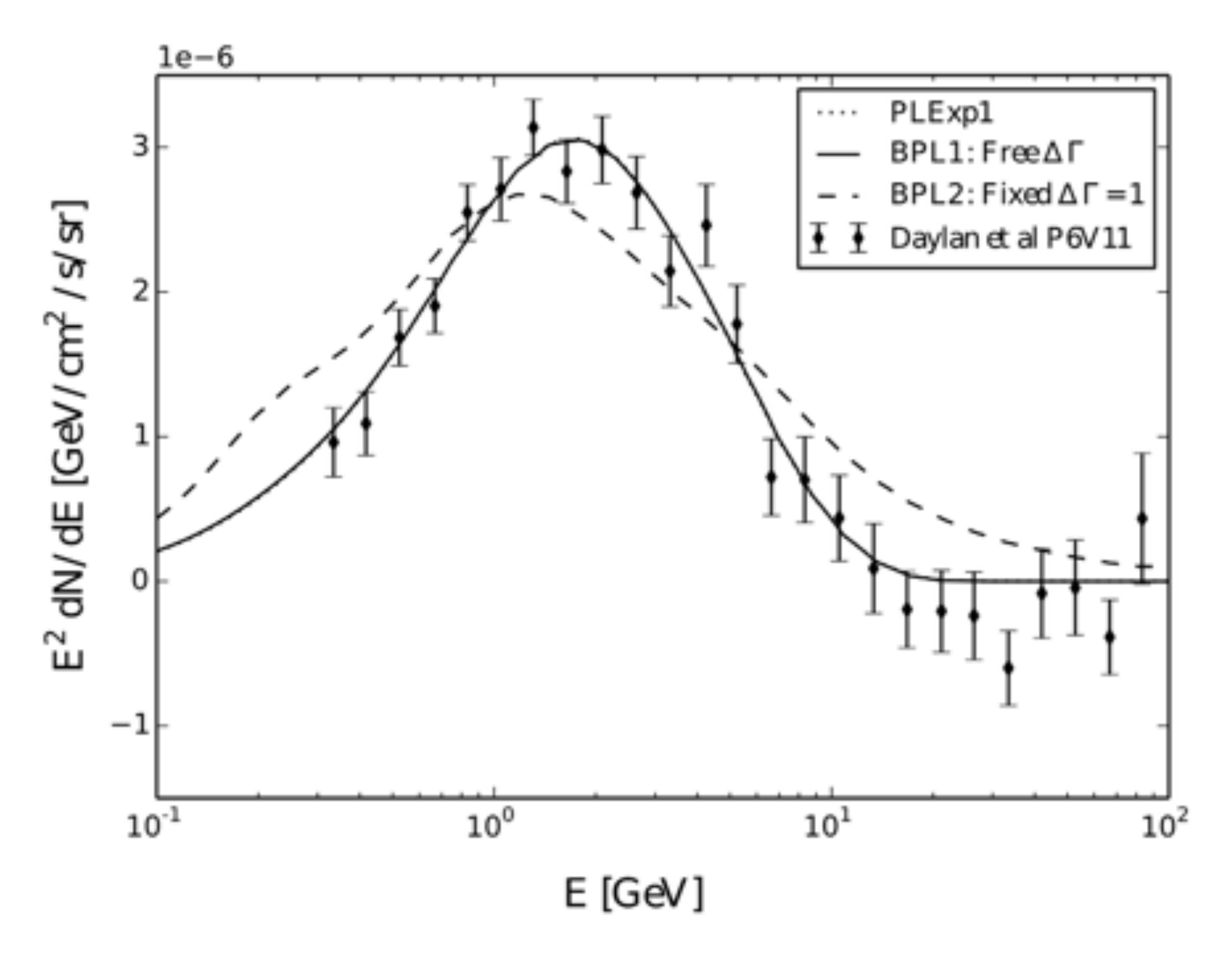
Daylan, ***et al, arxiv:1402.6703***
Abazaijan, ***et al, arxiv: 1402.4090***
Gordon, Macias, ***arxiv:1306.5725***
Hooper, Linden, ***arxiv:1110.0006***
…

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*

What other people did

People usually focus on this effective operator:

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

Boehm, *at al, arxiv:1401.6458*
Alves, Profumo, Queiroz, Shepherd, *arxiv:1403.5027*
Berlin, Hooper, McDermott, *arxiv:1404.0022*
…

- Annihilation rate for ɣ-ray excess coincides with what you expect for relic abundance
- Direct detection cross section is spin dependent, velocity suppressed.
- A spin-0 (scalar) mediator favors b-quarks

Realize:

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

Need to go beyond the effective theories!

Our Model

Ipek, McKeen, Nelson, *arXiv: 1404.3716*

- Fermionic DM coupled to a pseudoscalar: $\mathcal{L}_{\text{dark}} = y_\chi a_0 \bar{\chi} i \gamma^5 \chi$
- Pseduoscalar, a_0 , mixes with the 2HDM:

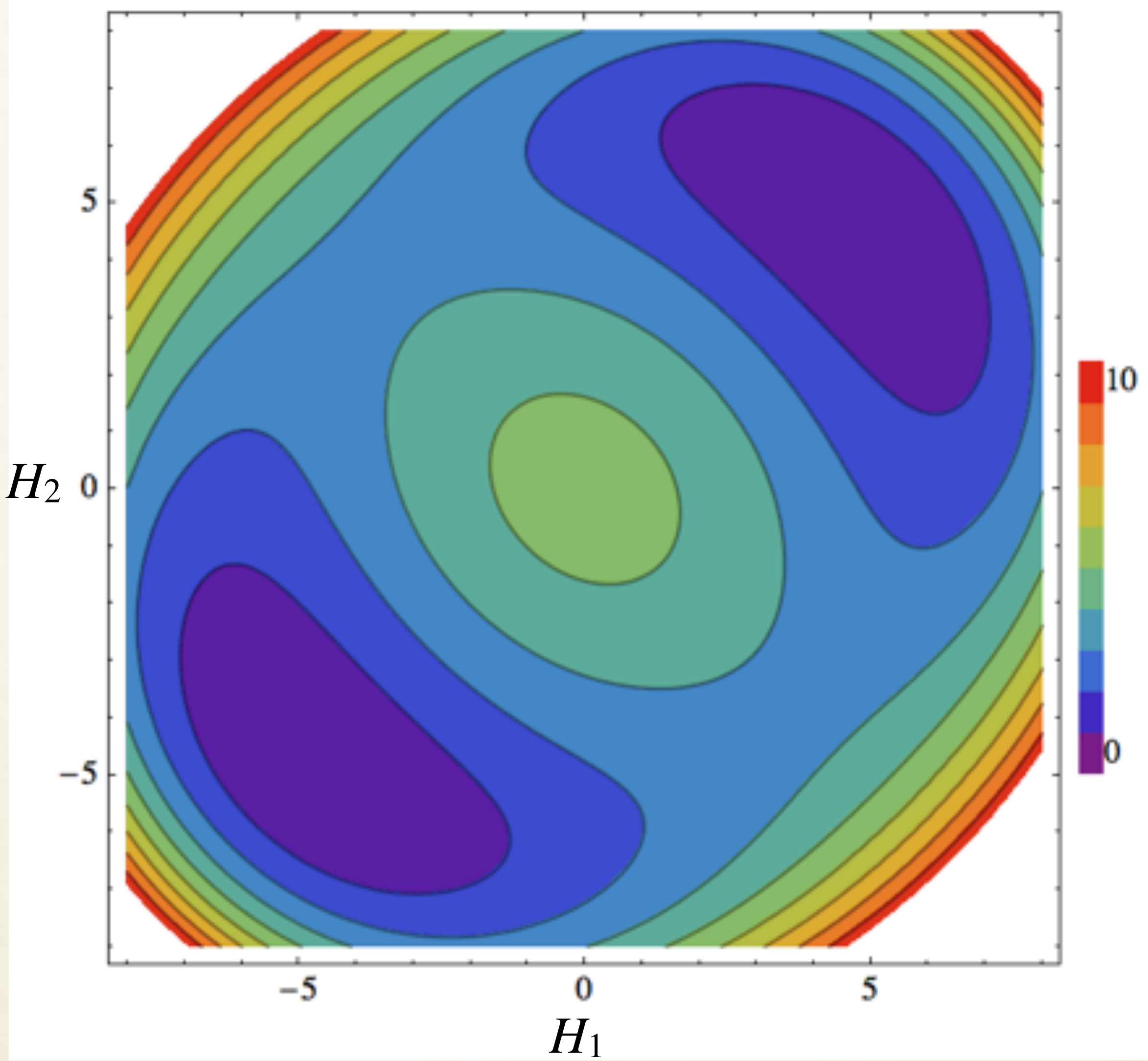
$$V = iBa_0 H_1^\dagger H_2 + \frac{1}{2} m_{a_0}^2 a_0^2 + \frac{\lambda_{a_0}}{4} a_0^4 + V_{\text{2HDM}}$$

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

What is in V_{2HDM}?

Two Higgs Doublet Model

$$V_{\rm 2HDM} = \lambda_1 \left(H_1^\dagger H_1 - \frac{v_1^2}{2} \right)^2 + \lambda_2 \left(H_2^\dagger H_2 - \frac{v_2^2}{2} \right)^2$$
$$+ \lambda_3 \left[\left(H_1^\dagger H_1 - \frac{v_1^2}{2} \right) + \left(H_2^\dagger H_2 - \frac{v_2^2}{2} \right) \right]^2$$
$$+ \lambda_4 \left[\left(H_1^\dagger H_1 \right) \left(H_2^\dagger H_2 \right) - \left(H_1^\dagger H_2 \right) \left(H_2^\dagger H_1 \right) \right]$$
$$+ \lambda_5 \left[{\rm Re} \left(H_1^\dagger H_2 \right) - \frac{v_1 v_2}{2} \right]^2 + \lambda_6 \left[{\rm Im} \left(H_1^\dagger H_2 \right) \right]^2$$



$V_{\rm 2HDM}$ is minimized at:

$$\langle H_i \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_i \end{pmatrix}$$

$$v = \sqrt{v_1^2 + v_2^2} = 246\,{\rm GeV}$$ ⟶ set by the *W* mass

Charged and *CP* even mass states

- Decompose the 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* → 5 left

- 2 charged Higgses:

$$H^\pm = \sin\beta\,\phi_1^\pm + \cos\beta\,\phi_2^\pm$$

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

- 2 CP even, neutral Higgses:

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

125 GeV Higgs →

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

CP odd mass states and mixing

CP odd eigenstate is NOT a mass eigenstate:

$$A_0 = \sin\beta\,\eta_1 - \cos\beta\,\eta_2$$

due to mixing between A_0 and a_0 : $V = iBa_0 H_1^\dagger H_2 + \frac{1}{2}m_{a_0}^2 a_0^2 + \frac{\lambda_{a_0}}{4} a_0^4 + V_{2\text{HDM}}$

- 2 CP odd, neutral scalars:

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

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

- Mixing term becomes:

$$iBa_0 H_1^\dagger H_2 \to -\frac{1}{2v}\left(m_A^2 - m_a^2\right)\sin^2(2\theta)\sin(\beta-\alpha)\, a^2 h$$

$$+\frac{1}{2v}\left(m_A^2 - m_a^2\right)\sin(4\theta)\, aAh \quad + \text{other}$$

Fermion couplings

Mediator - DM coupling becomes:

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

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

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

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

Parameters of the model

- From the 2HDM:

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

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

- From the dark sector:

$$m_\chi, y_\chi, m_a, \theta$$

$1\,\text{GeV} \simeq 10^{-57} M_\odot$

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

We also choose: $y_\chi = 0.5$

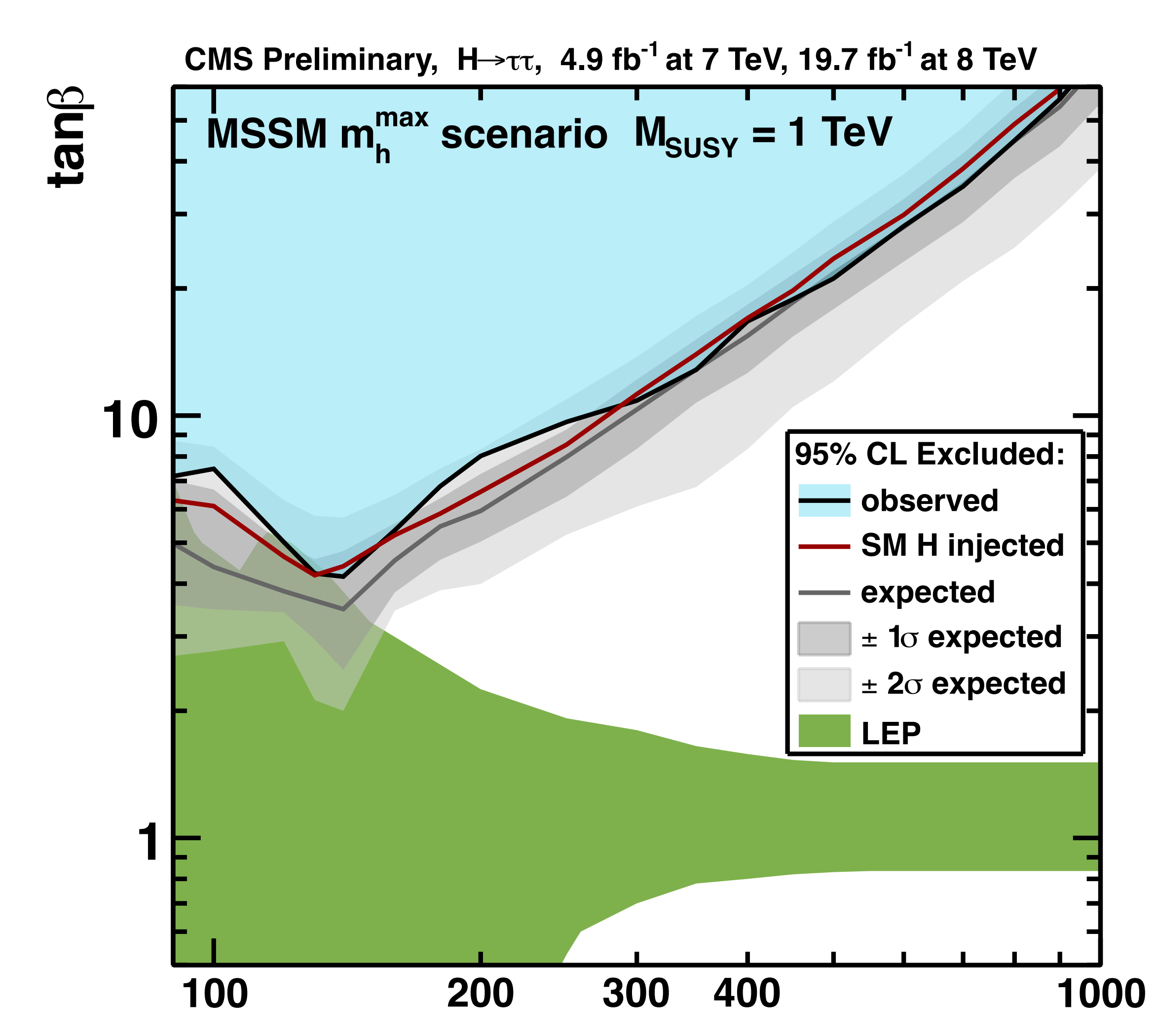
- Left: $m_H, m_A, m_{H^\pm}, \alpha, \beta, m_a, \theta$

Pick reasonable values

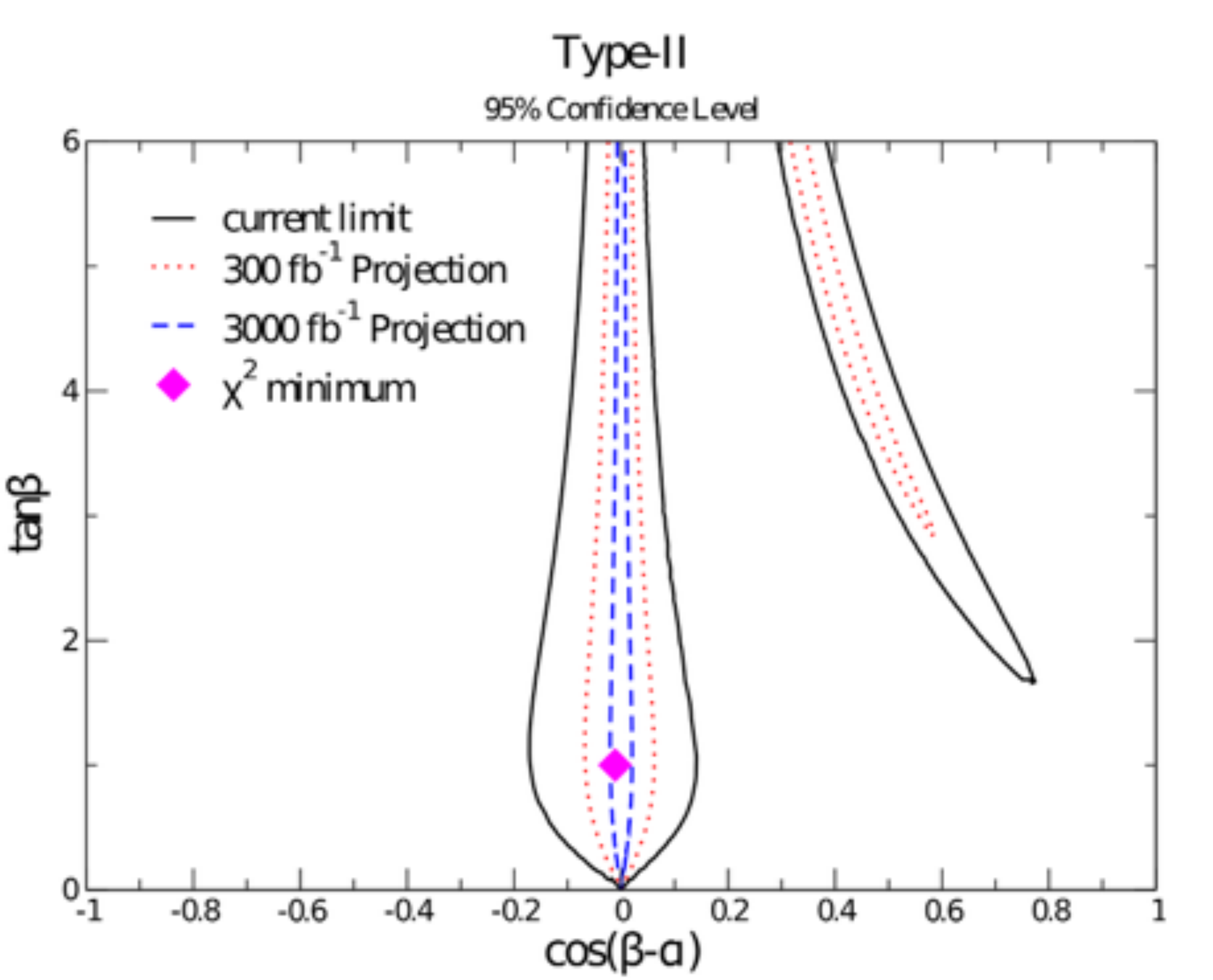
Heavy Higgs searches:

$$\tan\beta = 40$$

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



CMS-PAS-HIG-13-021



Chen, Dawson, *arxiv: 1305.1624*

125 GeV Higgs couplings:

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

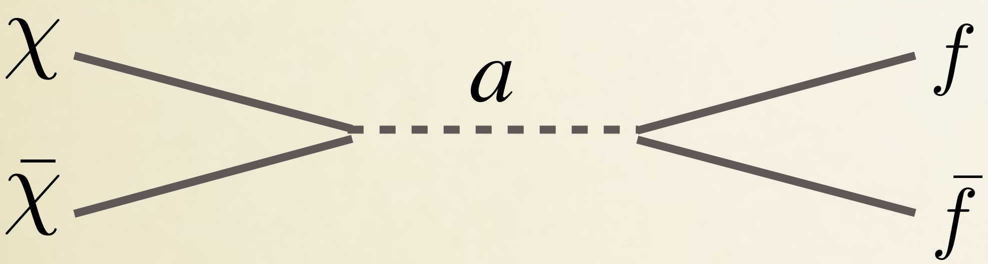
$$m_h \ll m_H \simeq m_{H^\pm} \simeq m_A$$

Constraining The m_a vs θ Space

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

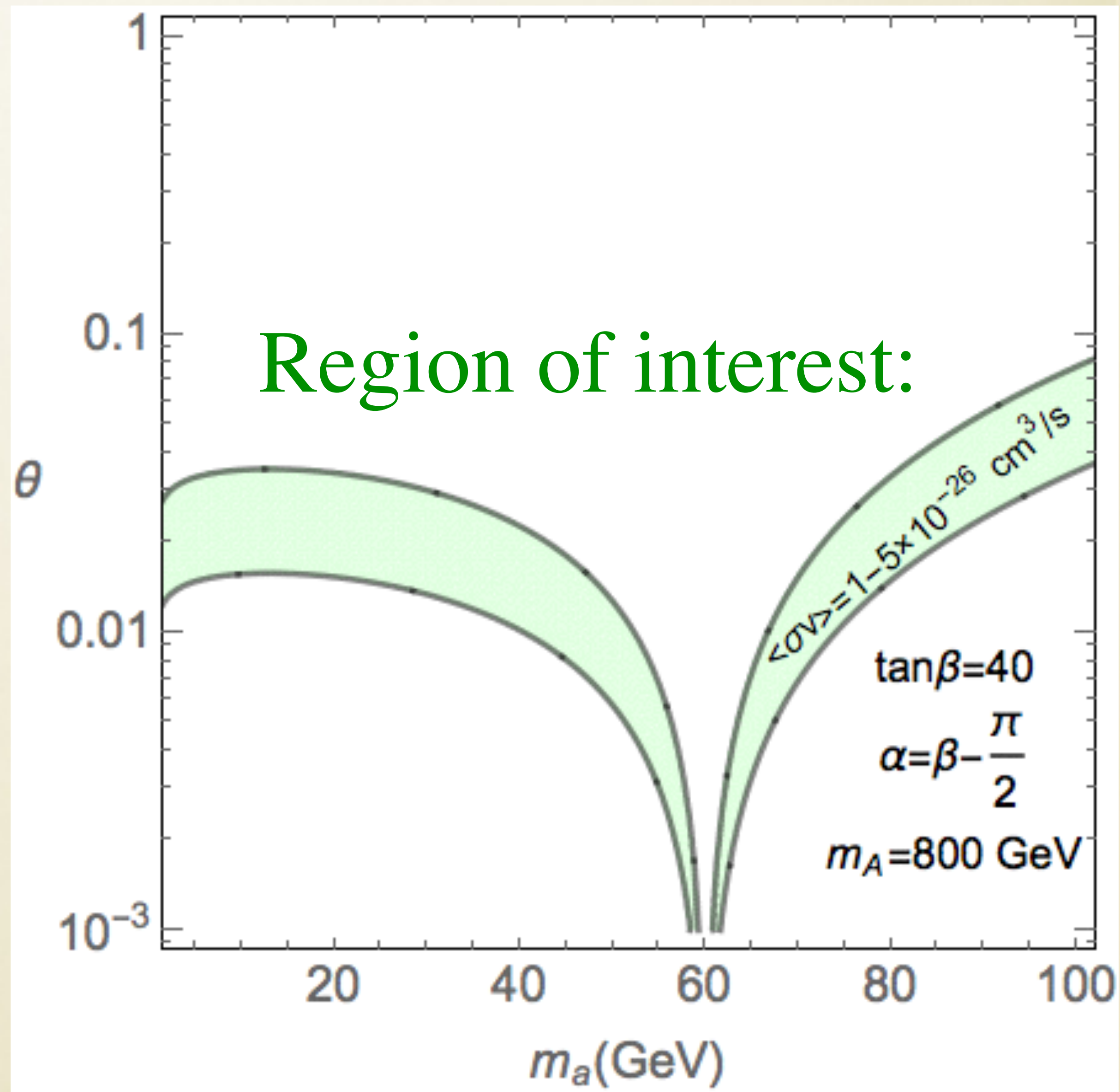
DM annihilation cross section:

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

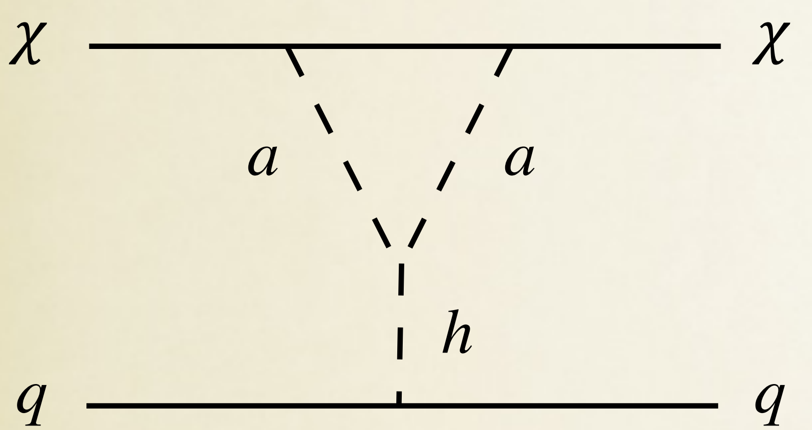


$$\langle \sigma v_{\rm rel} \rangle \simeq 3 \times 10^{-26} \, \frac{\rm cm^3}{\rm s}$$

- fits the gamma-ray excess
- correct relic density

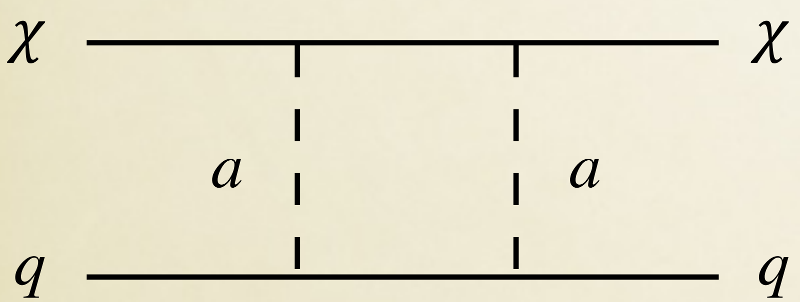


Direct Detection (spin independent)



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

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



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

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

Higgs exchange dominates over the box

Direct Detection (spin independent)

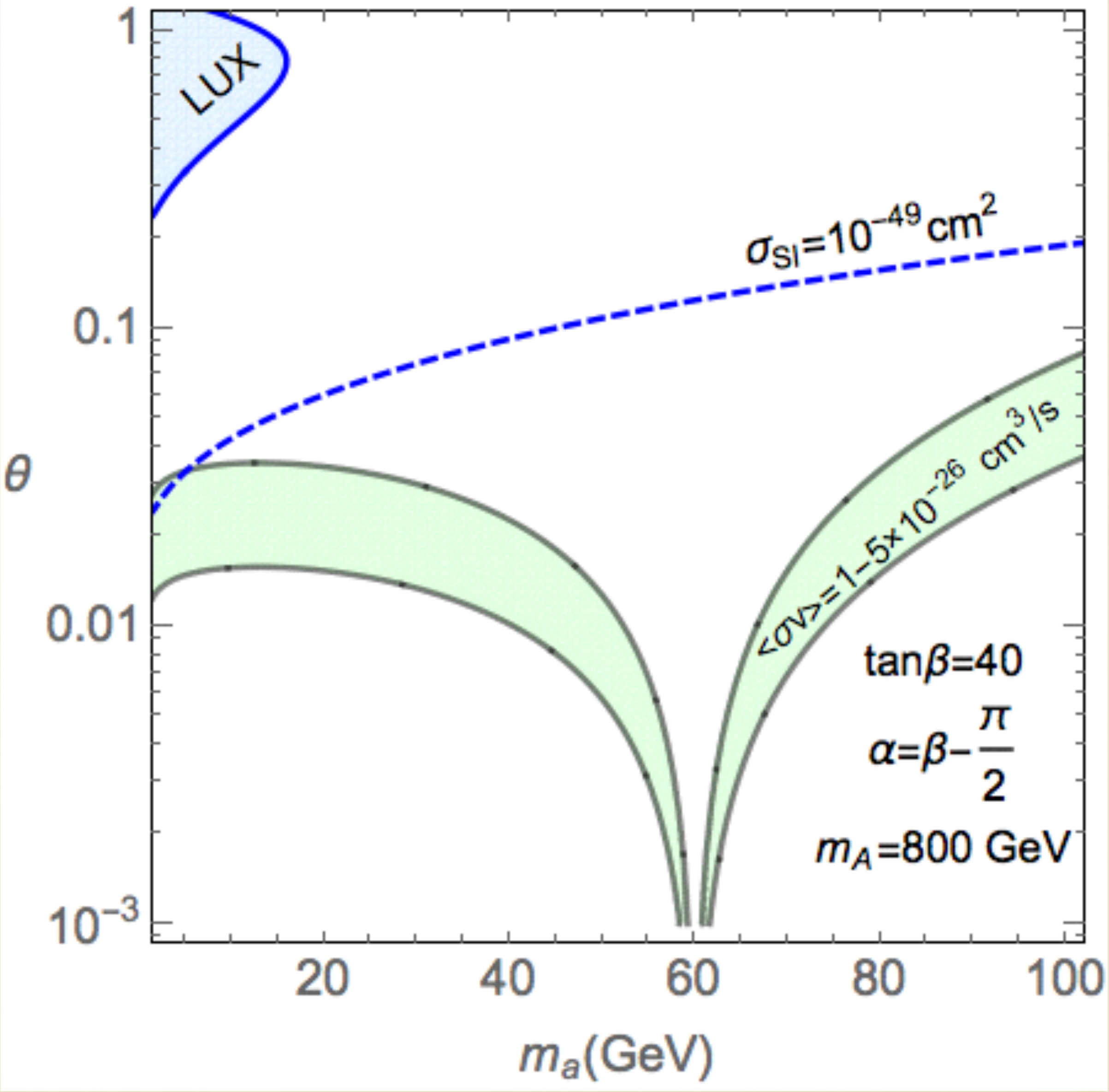
$$\sigma_{\rm SI} \simeq 2.2 \times 10^{-49}\ {\rm cm}^2 \left(\frac{m_A}{800\ {\rm GeV}}\right)^4 \left(\frac{50\ {\rm GeV}}{m_a}\right)^4 \left(\frac{m_\chi}{30\ {\rm GeV}}\right)^2 \left(\frac{\theta}{0.1}\right)^4 \times \left(\frac{y_\chi}{0.5}\right)^4 \left(\frac{\langle N|\sum_q m_q \bar{q}q|N\rangle}{330\ {\rm MeV}}\right)^2$$

LUX limit for $m_\chi = 30$ GeV:

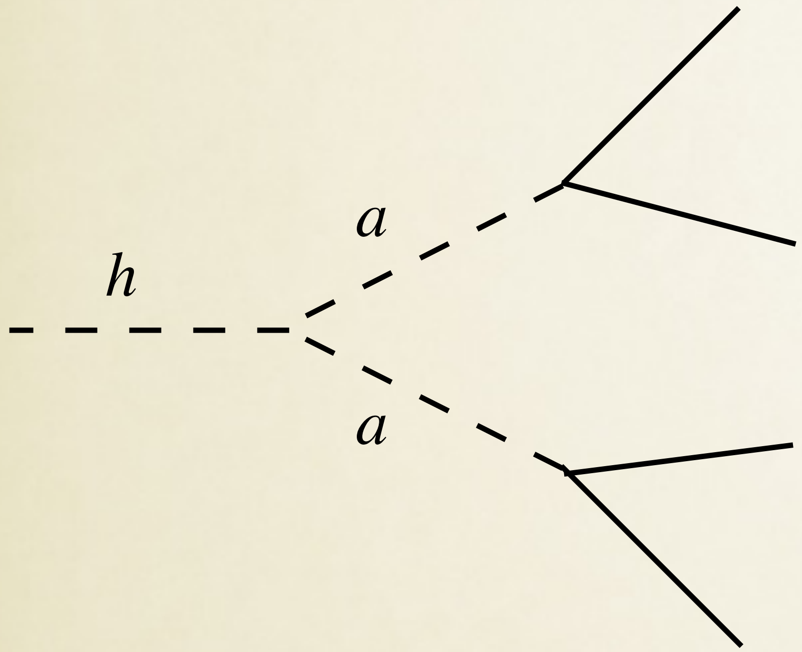
$$\sigma_{\rm SI} < 8\times 10^{-46}{\rm cm}^2$$

Above ---- we have:

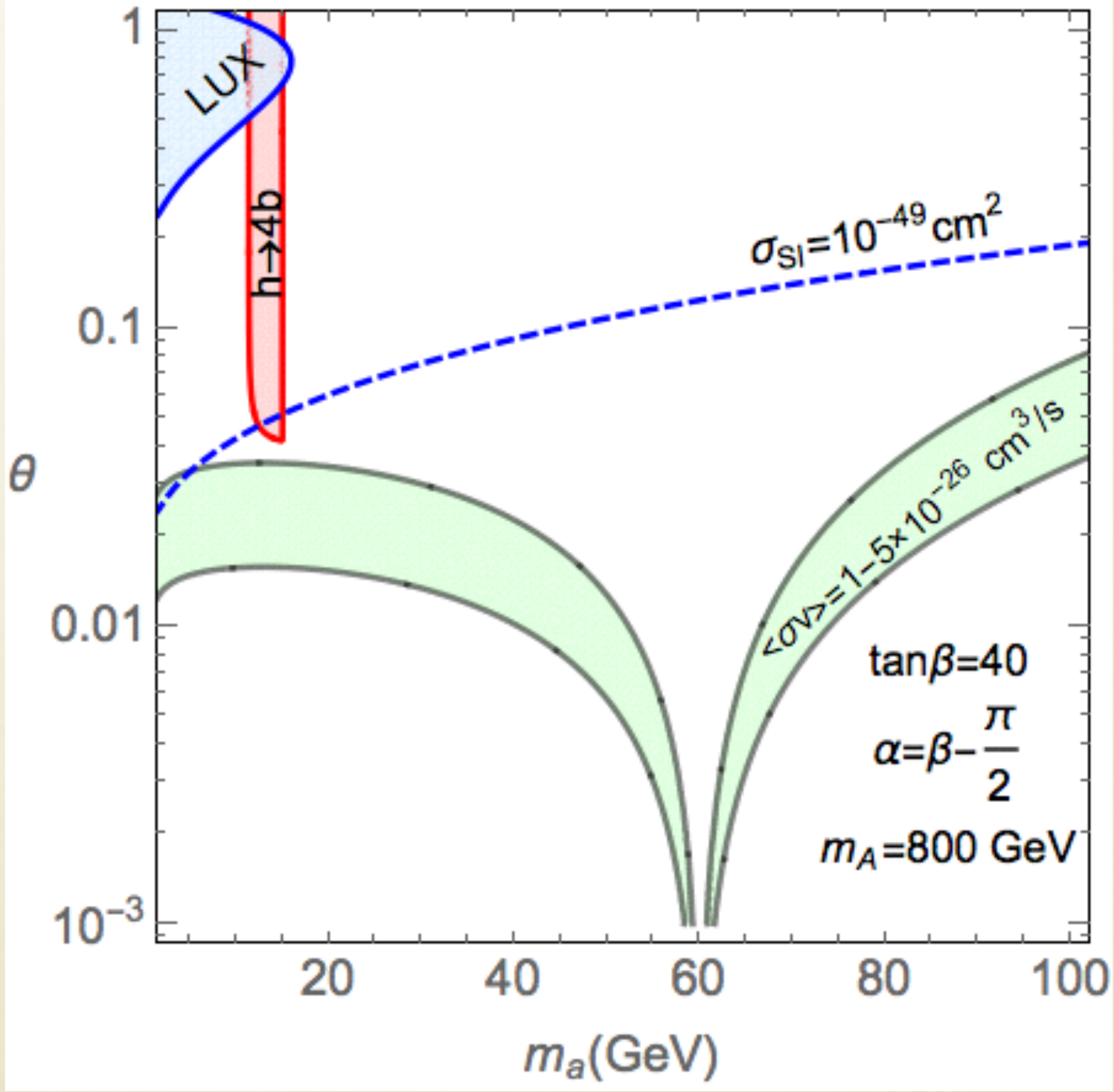
$$\sigma_{\rm SI} > 10^{-49}{\rm cm}^2$$



Higgs decays: $h \to 4b$



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



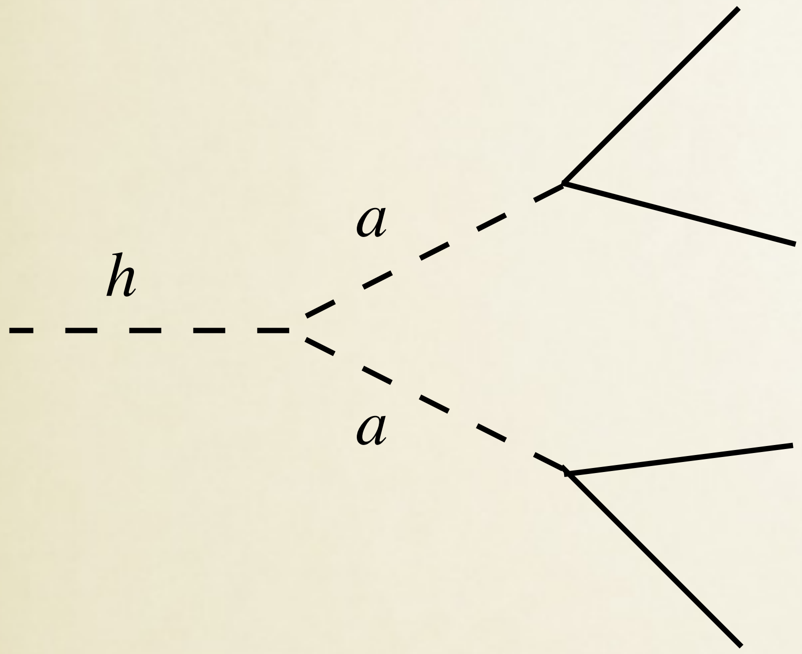
$m_\chi = 30$ GeV $\Rightarrow 4b$ final state favored

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

$$\mathrm{Br}(h \to aa \to 4b) < 0.7$$

CMS, *arxiv:1310.3687*
Curtin, *et al*, *arxiv: 1312.4992*

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

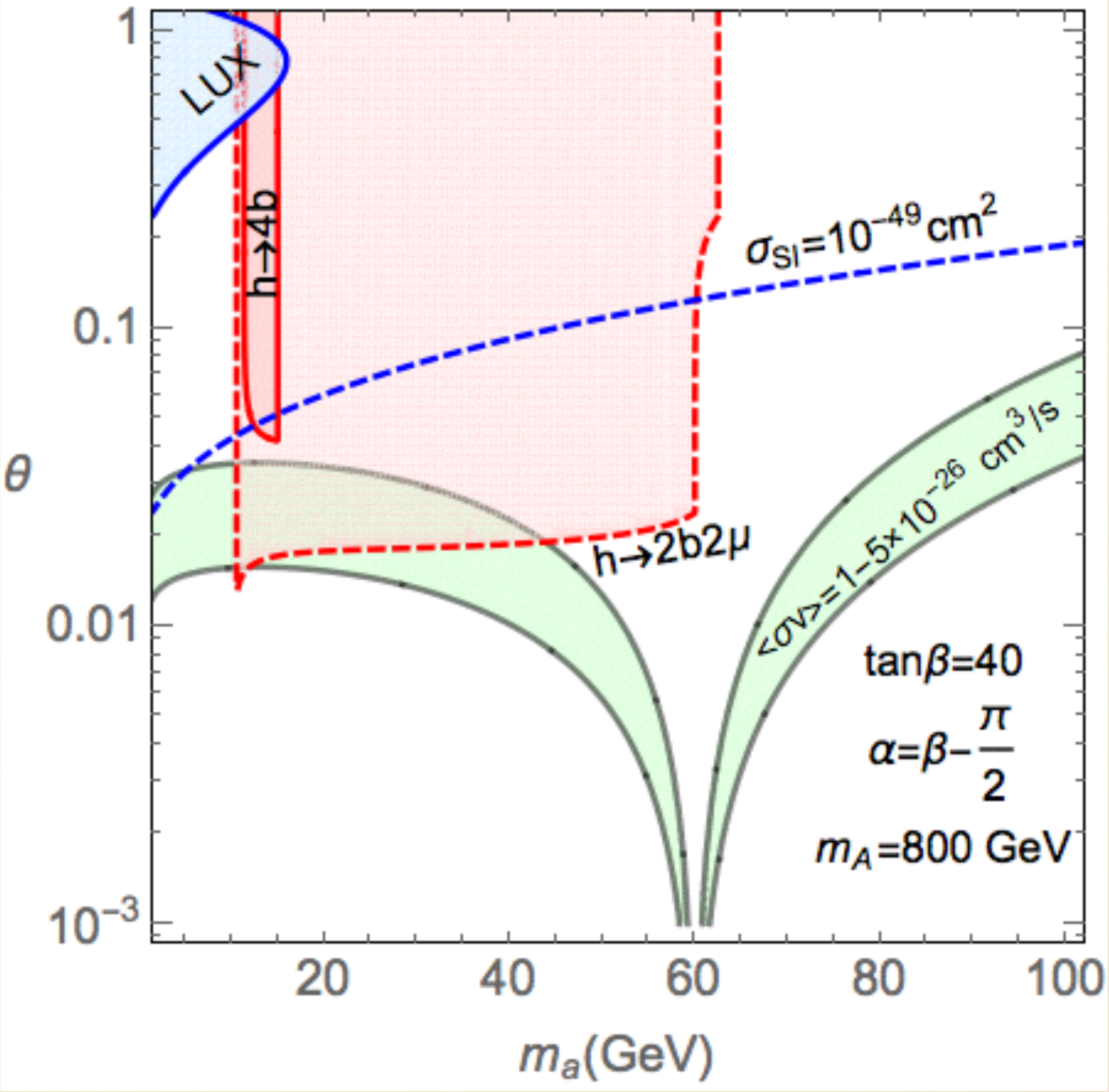


$$V \supset \frac{1}{2v}(m_A^2 - m_a^2)\sin^2 2\theta\, h\, a\, a$$

$m_\chi = 30$ GeV $\Rightarrow$ 4*b* final state favored

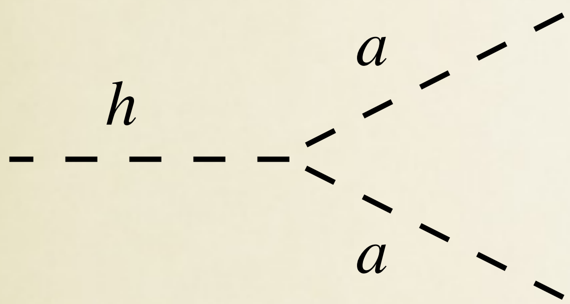
BUT: $2b2\mu$ final states is cleaner:

$Br(h \to aa \to 2b2\mu) < 10^{-3}$ (10^{-4}) @14 TeV



CMS, *arxiv:1310.3687*
Curtin, *et al*, *arxiv: 1312.4992*

Higgs decays: $h \to aa$



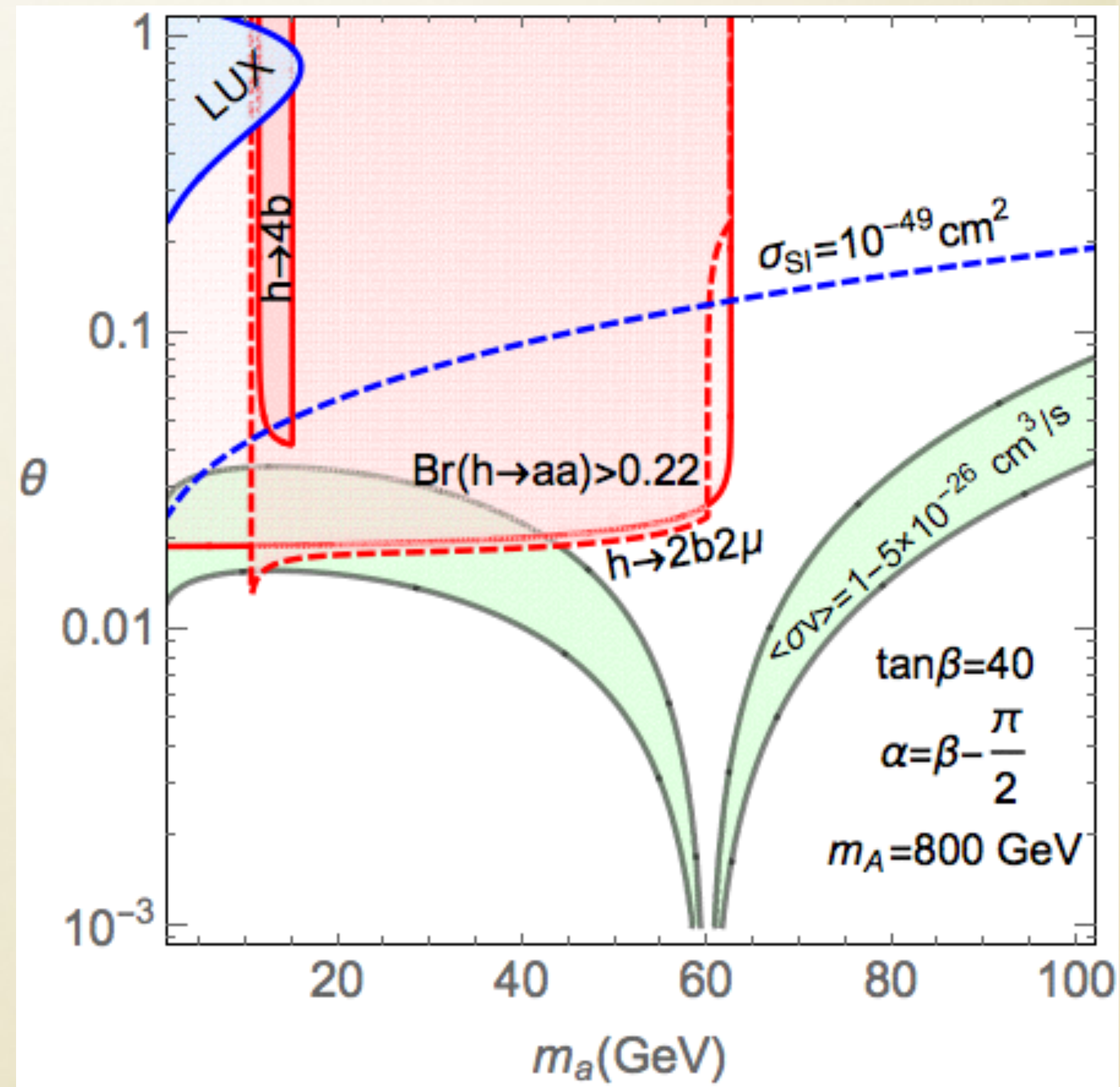
$$V \supset \frac{1}{2v}(m_A^2 - m_a^2)\sin^2 2\theta\, h\, a\, a$$

Higgs decay rate to *aa*:

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

$$\Gamma_h^{\rm SM} = 4\,\mathrm{MeV}$$

$$\mathrm{Br}(h \to aa) < 0.22$$

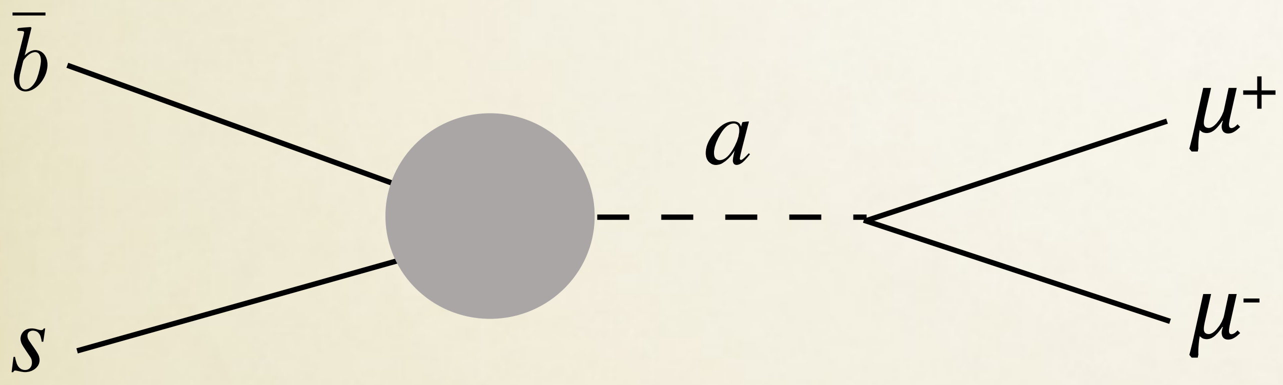


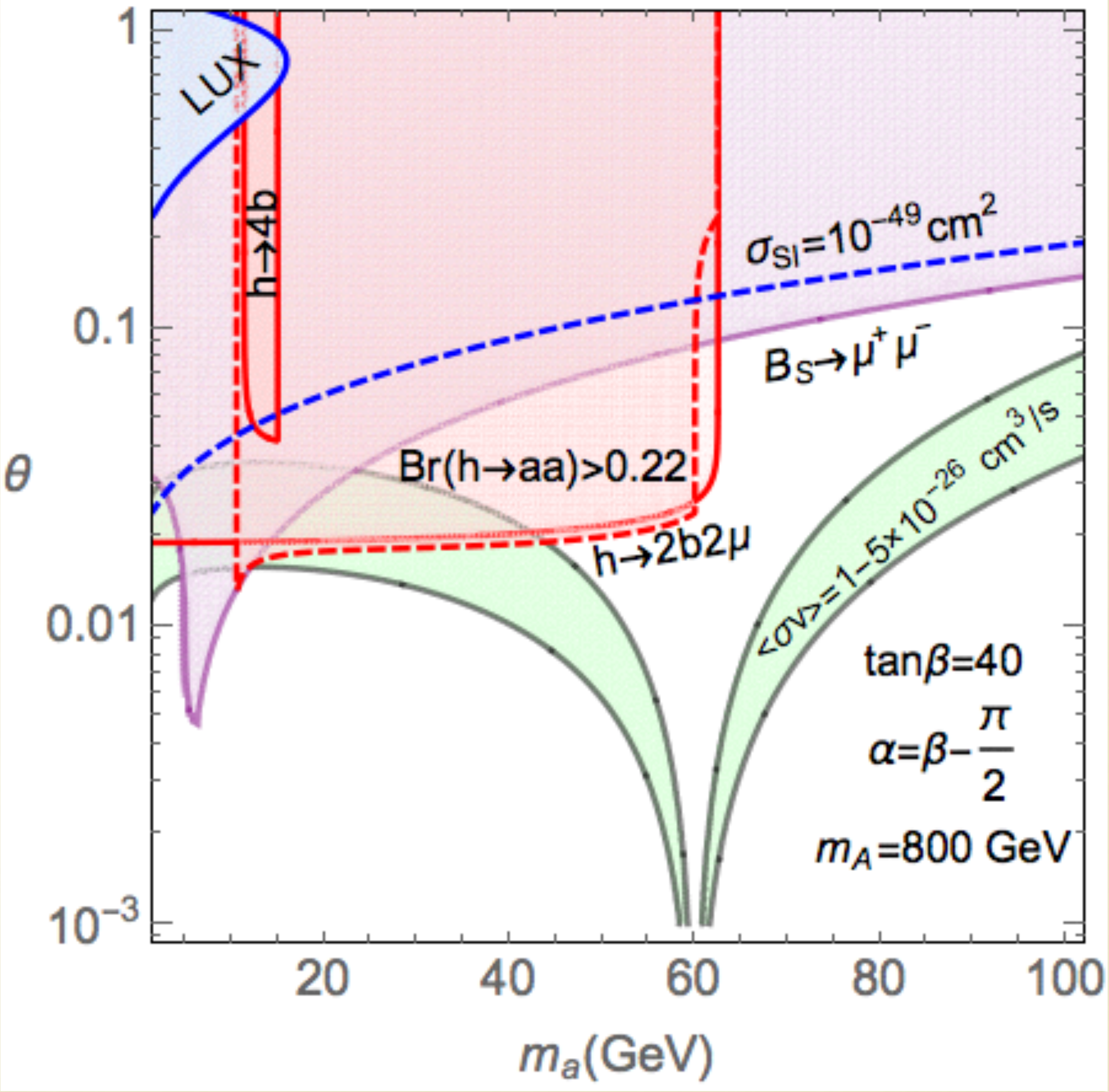
Giardiano, *et al*, *arxiv: 1303.3570*

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

Rare SM processes are good tests of New Physics!

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





CMS and LHCb combined:

$$\mathrm{Br}\left(B_s \to \mu^+\mu^-\right) = (2.9 \pm 0.7) \times 10^{-9}$$

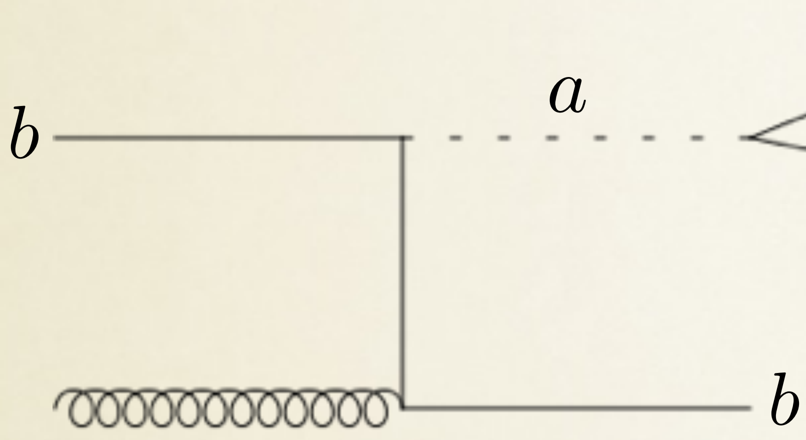
CMS-PAS-BPH-13-007 , LHCb-CONF-2013-012

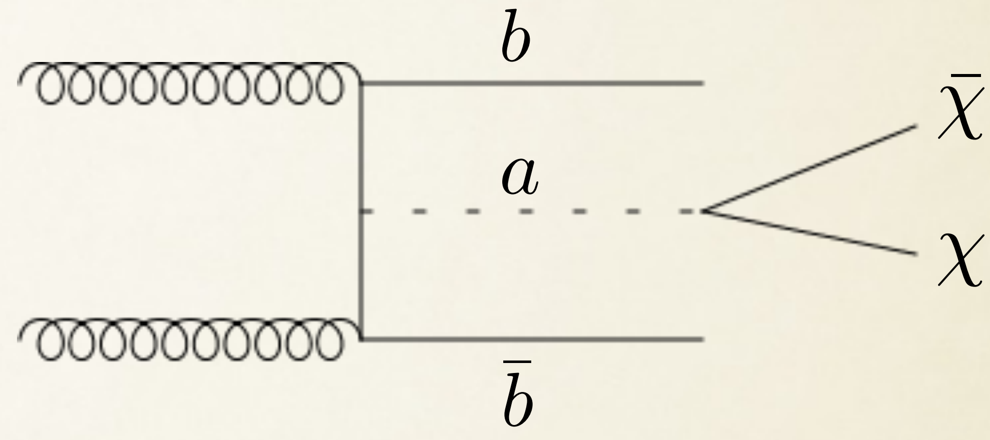
Compare to the SM expectation:

$$\mathrm{Br}\left(B_s \to \mu^+\mu^-\right)_{\mathrm{SM}} = (3.65 \pm 0.23) \times 10^{-9}$$

Bobeth, *et al, arxiv:1311.0903*

Collider Searches: Monojets





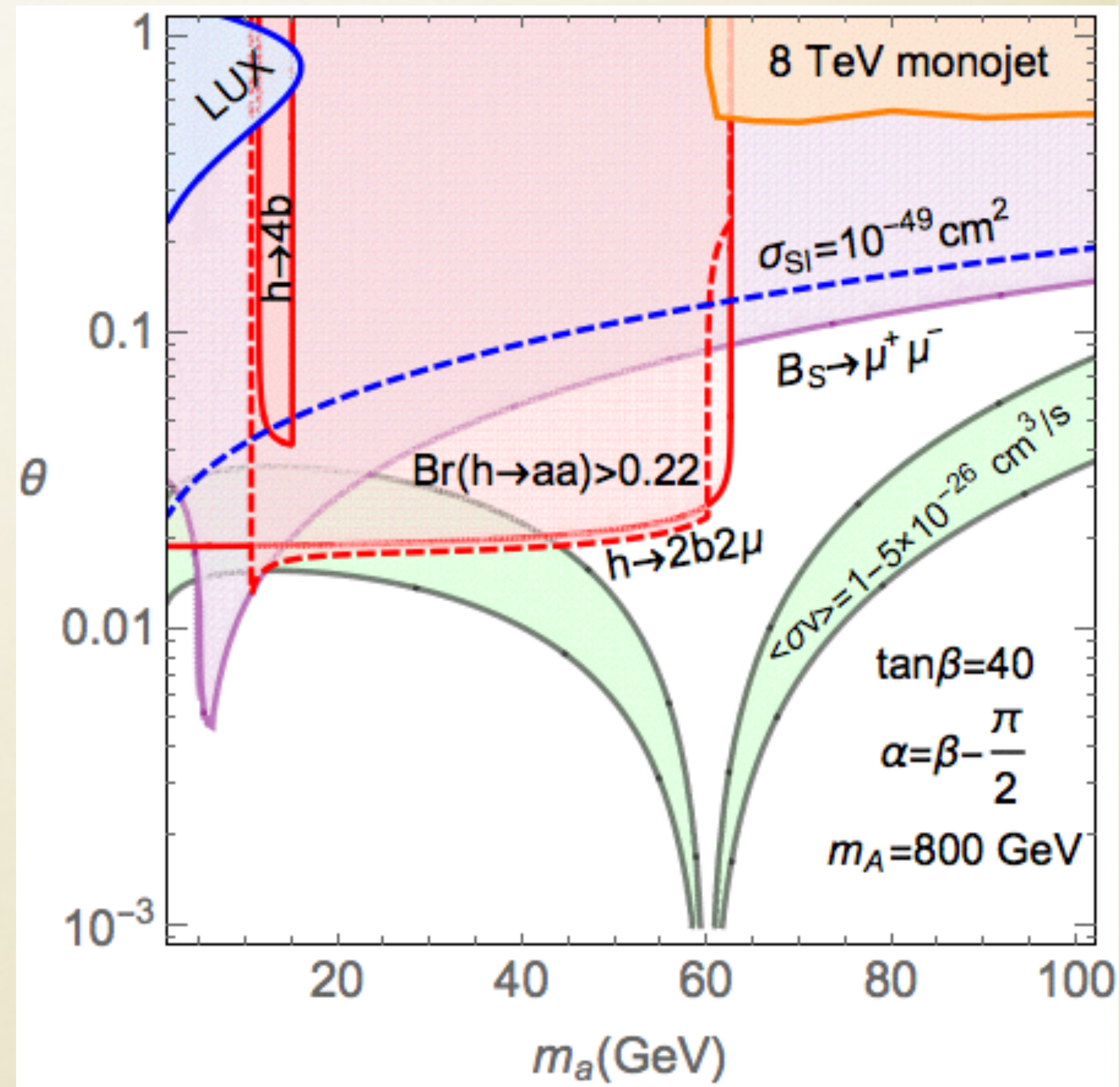
Lin, Kolb, Wang, *arxiv:1303.6638*

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

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

good for $m_a > 2m_\chi$

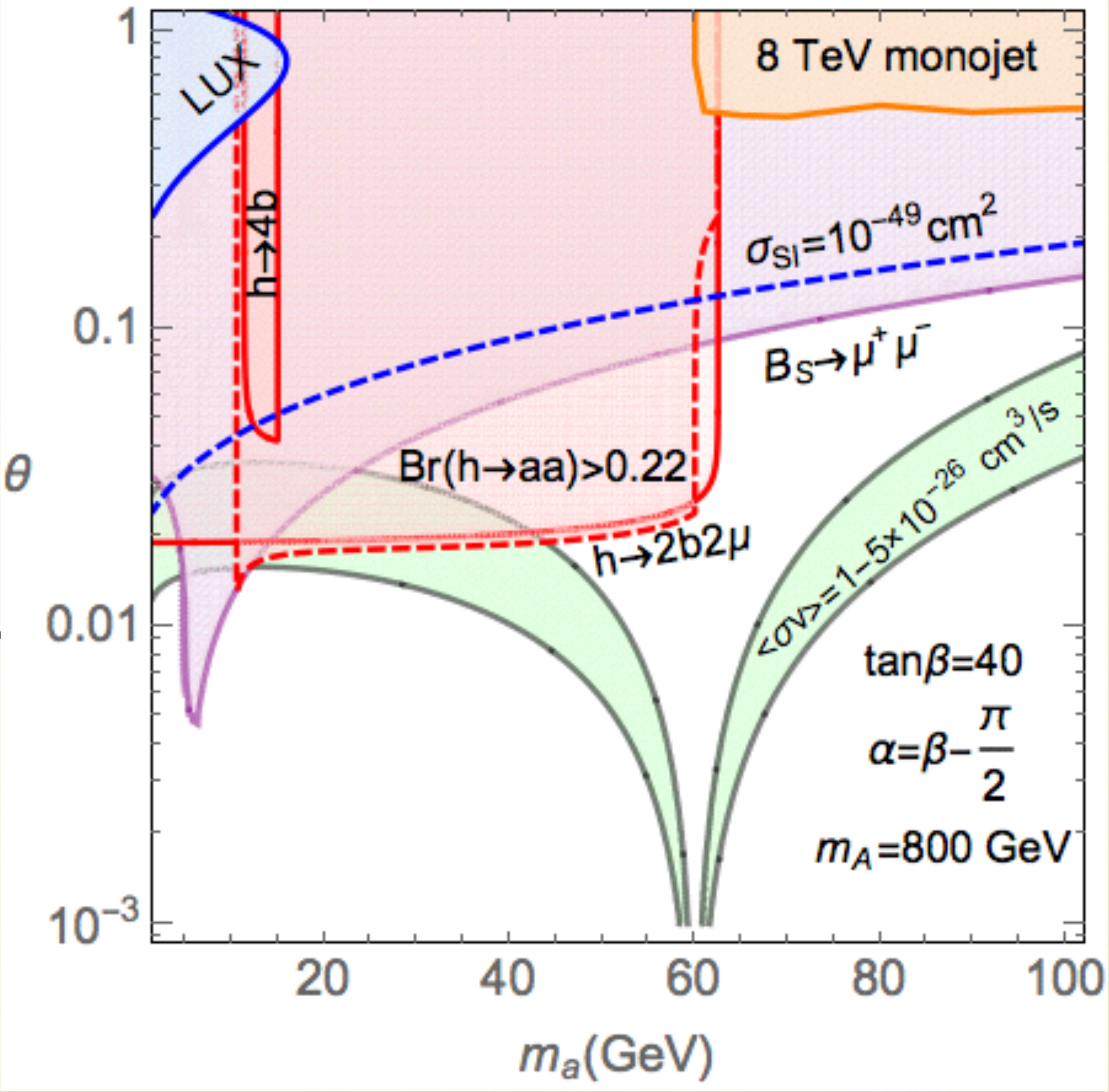
No help from *top*-tagging:
top couplings are tanβ suppressed!



Summary

Ipek, McKeen, Nelson, *arXiv: 1404.3716*

- A consistent ɣ-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

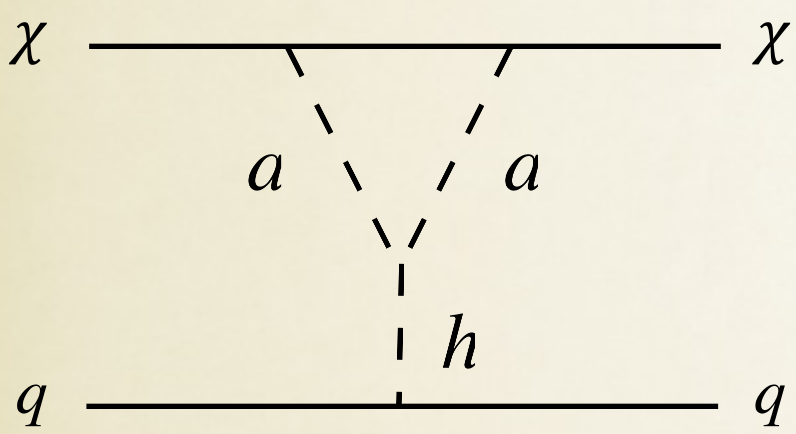


Outlook

One possible signature:

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

THANK YOU!



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

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