Dark Matter and 2HDMs

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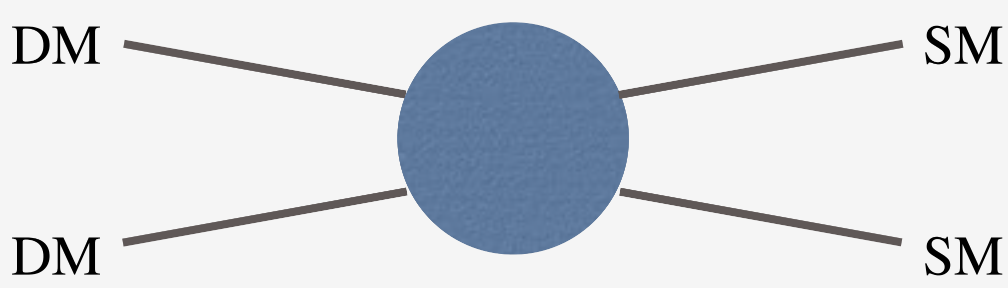
December 15, 2016

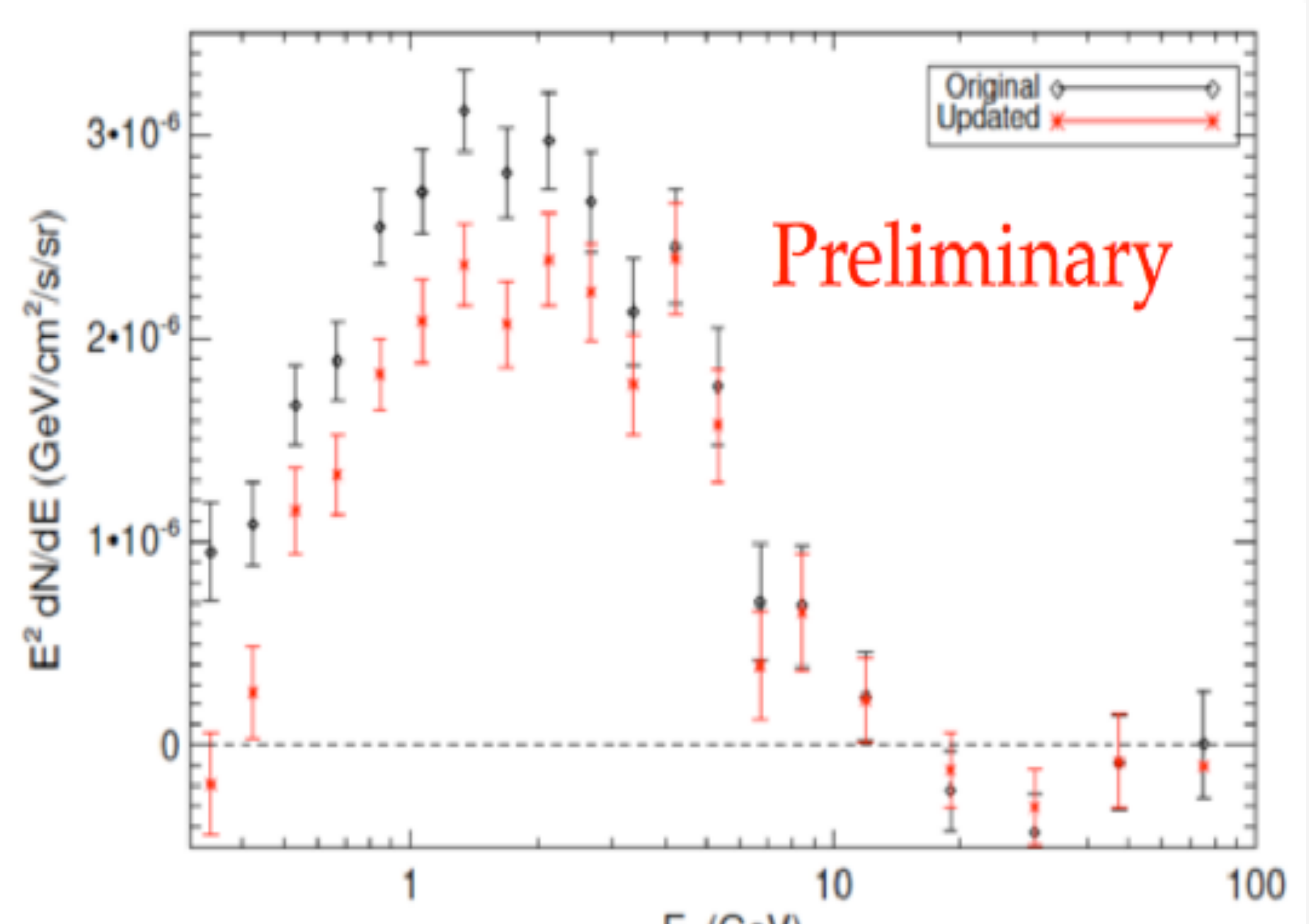
SI, McKeen, Nelson, ***arXiv: 1404.3716, PRD90 (2014) no.7, 076005***

Galactic Center Excess

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

Indirect detection:





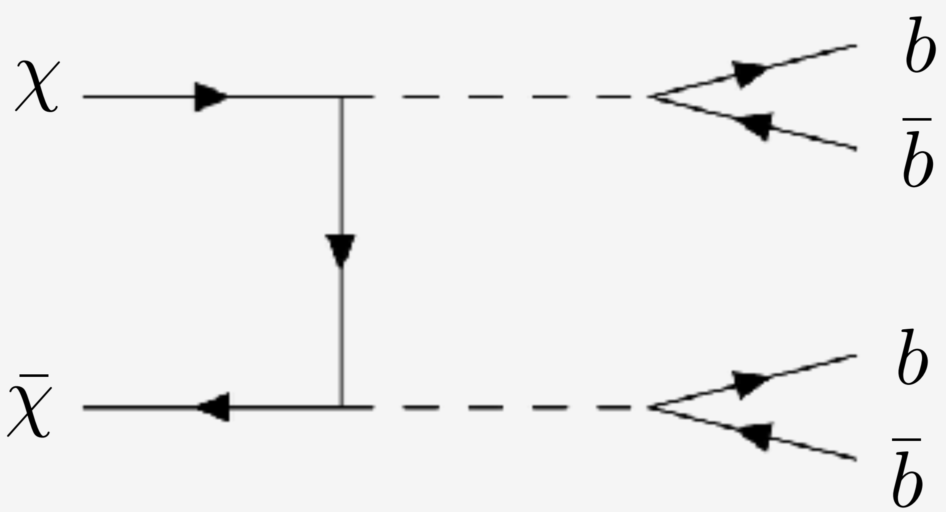
Linden, ICHEP talk, 2014

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

DM interpretation

GC excess is fit nicely with 30 GeV DM with pseudoscalar, s-channel annihilations to b quarks

BUT DM can be ~ 100 GeV if



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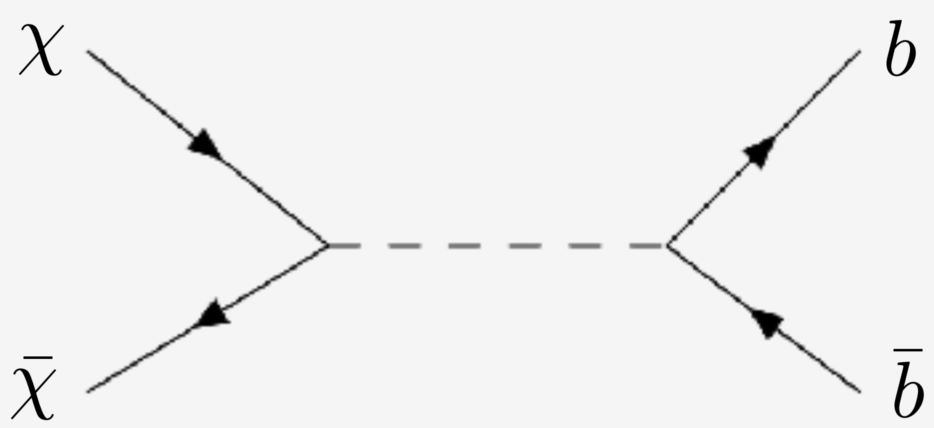


Tim Tait, *et al*, arXiv:1404.6528v3

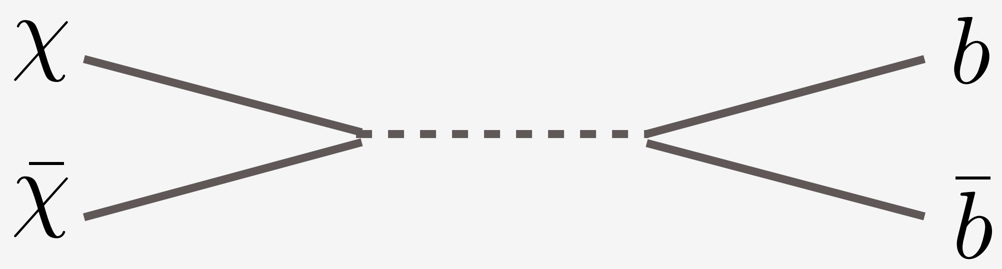
interesting and different phenomenology!

Pseudoscalar portal

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 <u>not</u> an *SU(2)* singlet

Need to go beyond the effective theories!

UV Completion

SI, McKeen, Nelson, *arXiv: 1404.3716*

- Fermionic DM coupled to a pseudoscalar:

$$\mathcal{L}_{\rm dark} = y_\chi a_0 \bar{\chi} i \gamma^5 \chi$$

- Pseduoscalar, a_0, mixes with the 2HDM:

$$V = (iBa_0 H_1^\dagger H_2 + \text{h.c.}) + \frac{1}{2} m_{a_0}^2 a_0^2 + \frac{\lambda_{a_0}}{4} a_0^4 + V_{\rm 2HDM}$$

the portal term

usual 2HDM potential

y_χ : real

↓

no scalar coupling to DM

B : real + no CP violation in 2HDM

↓

no scalar coupling to SM

Charged and CP-even Higges: the usuals

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

- 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 scalars mix

CP-odd eigenstate of the 2HDM:

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

A_0 and a_0 mixes due to the portal term:

$$V_{\rm port} = B a_0 A_0 \left[v + \sin(\beta-\alpha)\,h + \cos(\beta-\alpha)\,H\right]$$

CP-odd mass eigenstates:

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

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

with the mixing angle: $\tan 2\theta = \dfrac{B\,v}{m_{A_0}^2 - m_{a_0}^2}$

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

From the 2HDM: $m_h, m_H, m_A, m_{H^\pm}, \alpha, \beta$

Let's pick: $m_h = 125\,\mathrm{GeV}$

From the dark sector: $m_\chi, y_\chi, m_a, \theta$

(To fit the ɣ-ray excess we set) $m_\chi = 30\,\mathrm{GeV}$ quite interesting for Higgs physics!

We also choose: $y_\chi = 0.5$

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

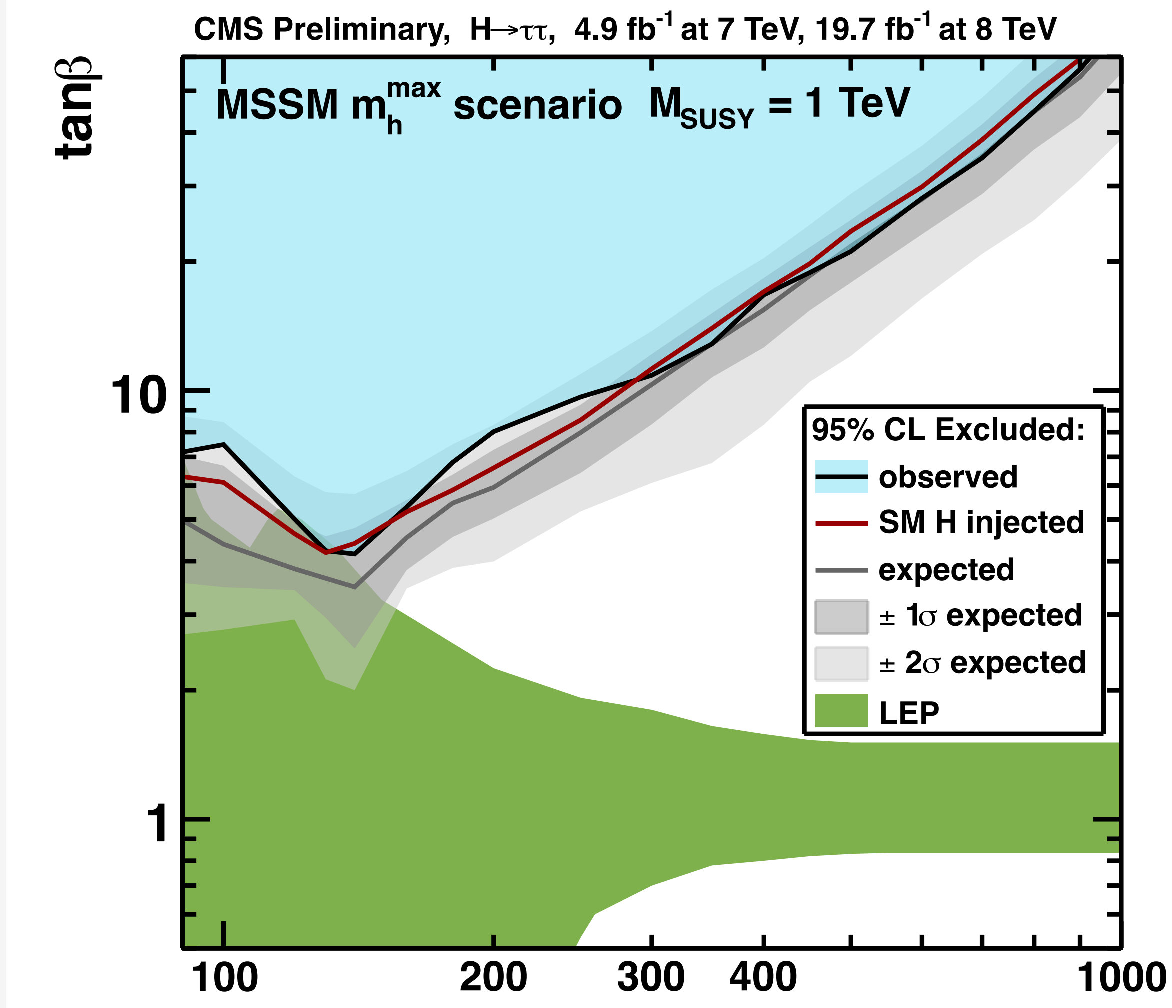
take degenerate

Parameters

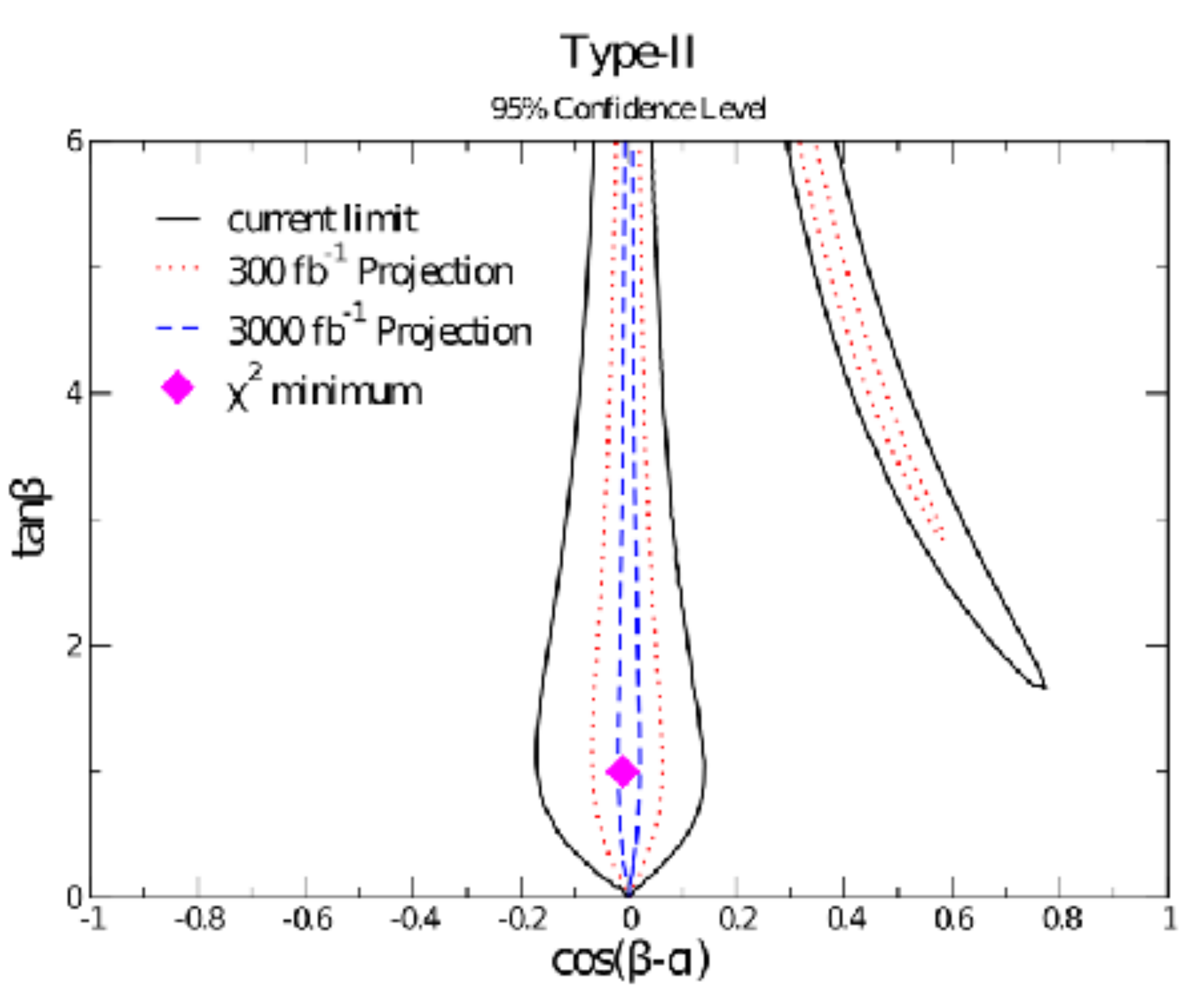
Heavy Higgs searches:

$$\tan\beta = 40$$

$$m_{A,H,H^\pm} = 800 \text{ GeV}$$



CMS-PAS-HIG-13-021



Chen, Dawson, *arxiv: 1305.1624*

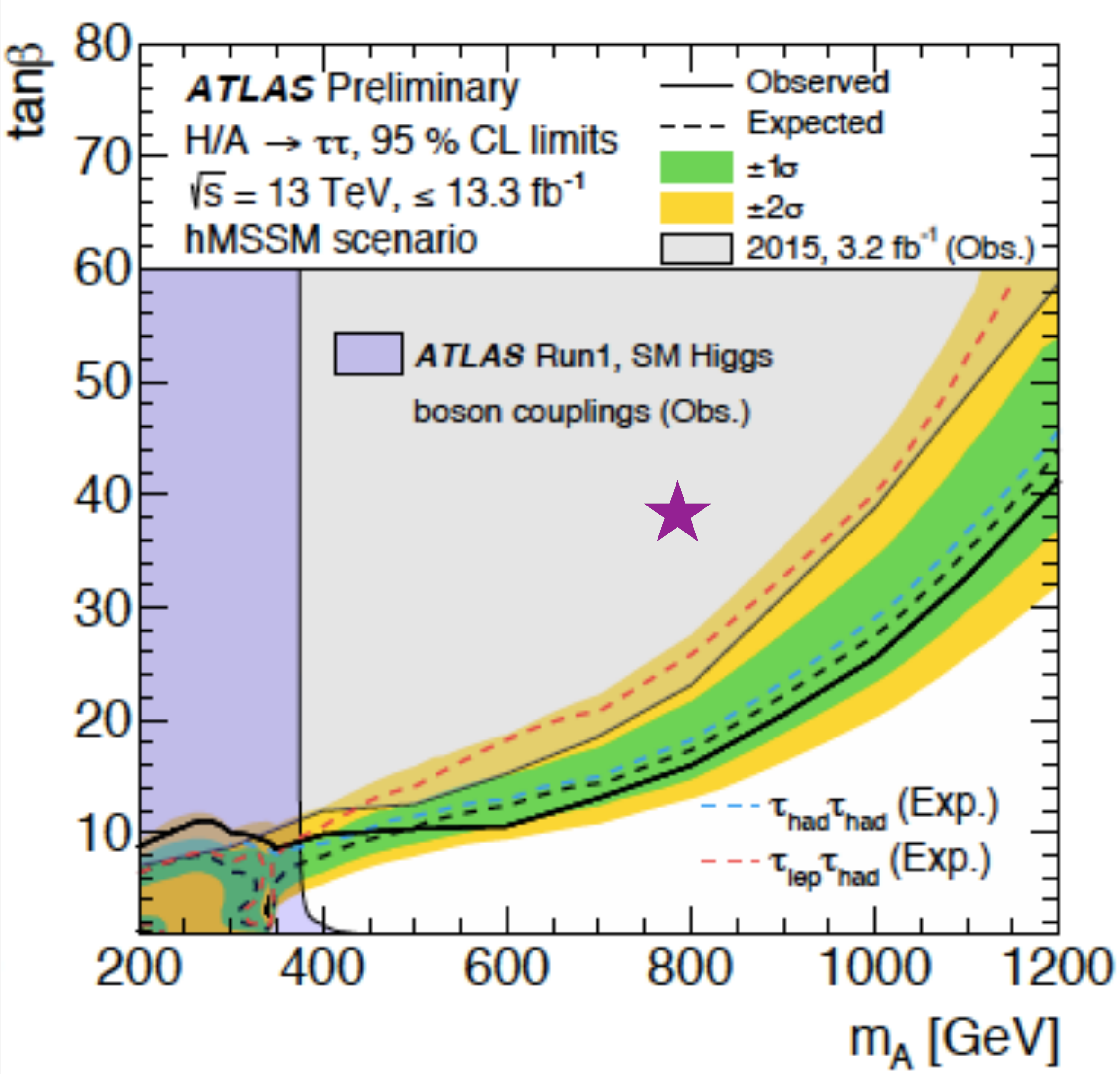
125 GeV Higgs couplings:

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

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

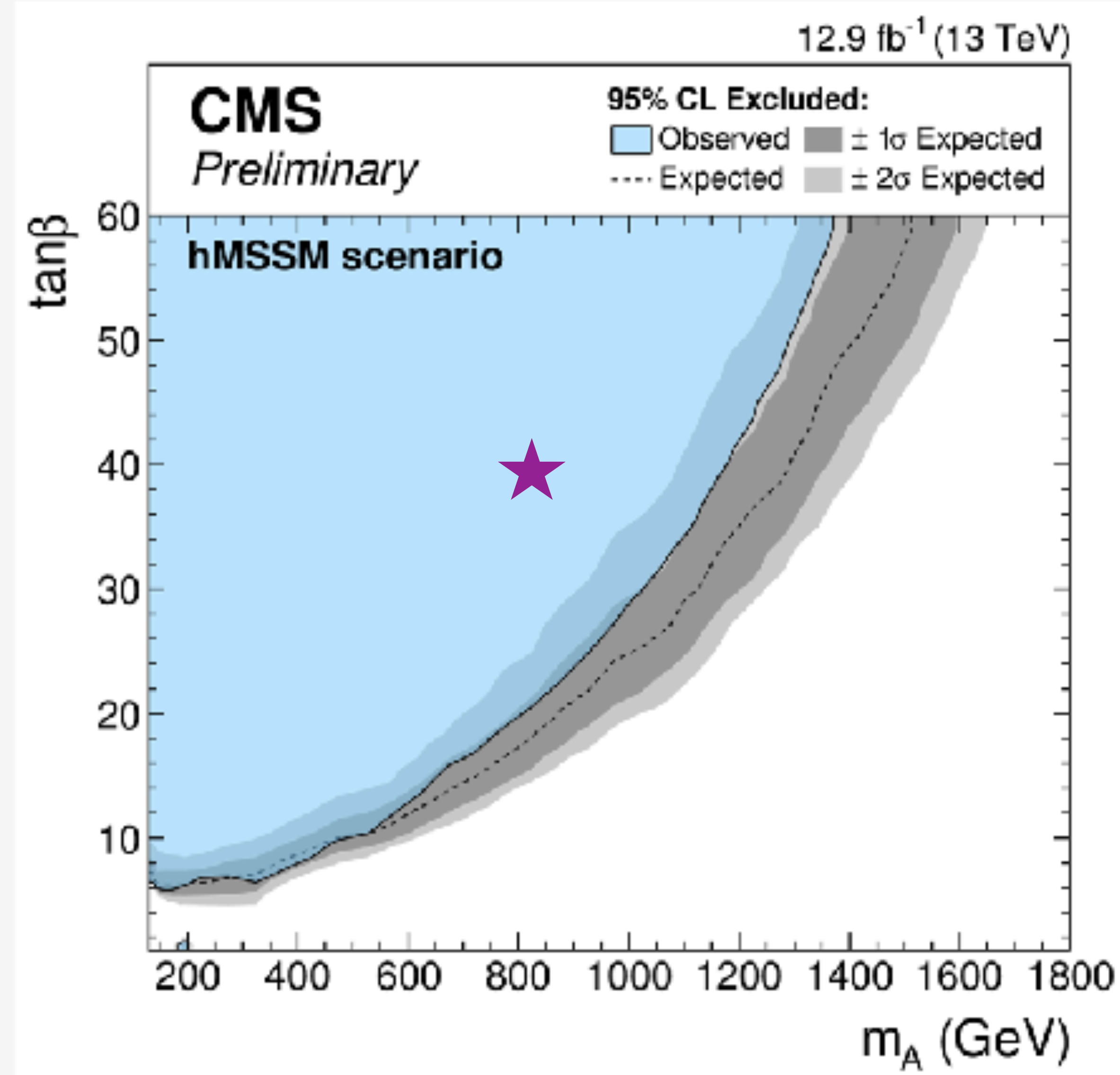
New results should be included

ATLAS-CONF-2016-085



(d) hMSSM scenario

CMS-PAS-HIG-16-037



(b) hMSSM

$$\tan\beta = 40$$

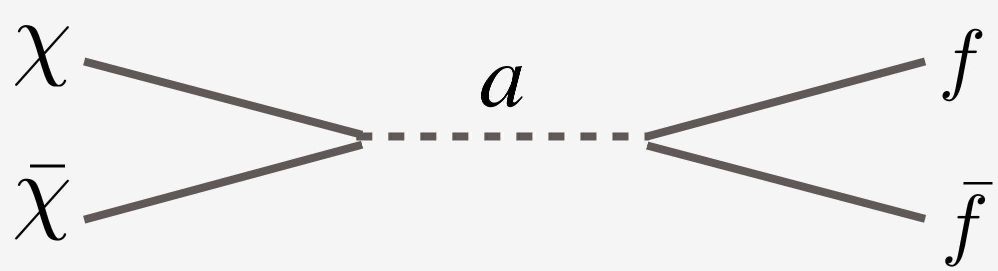
$$m_{A,H,H^{\pm}} = 800 \text{ GeV}$$

a bit excluded — didn't have time to change

Relic Abundance

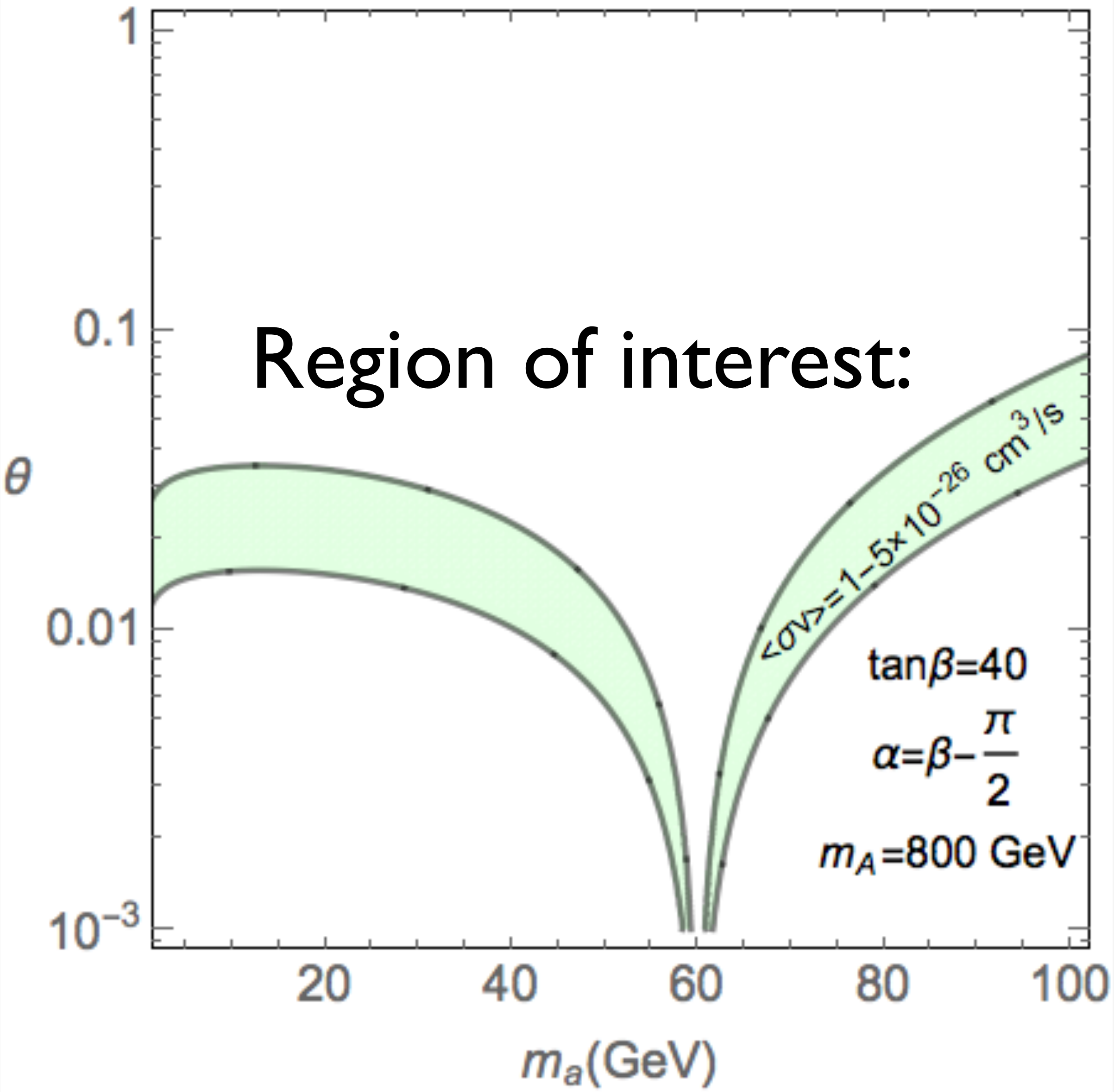
$$\langle \sigma v_{\rm rel}\rangle = \frac{y_\chi^2}{8\pi}\frac{m_\chi^2}{m_a^4} s_{2\theta}^2 \tan^2\beta \left[\left(1-\frac{4m_\chi^2}{m_a^2}\right)^2 + \frac{\Gamma_a^2}{m_a^2}\right]^{-1} \sum_{f=b,\tau,\ldots} N_C \frac{m_f^2}{v^2}\sqrt{1-\frac{m_f^2}{m_a^2}}$$

DM annihilation x-section

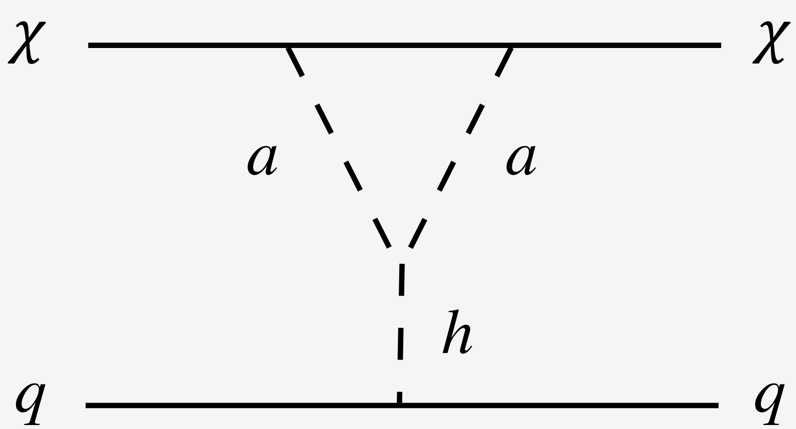


$$\langle \sigma v_{\rm rel}\rangle \simeq 3\times 10^{-26}\ \frac{\rm cm^3}{\rm s}$$

correct relic abundance

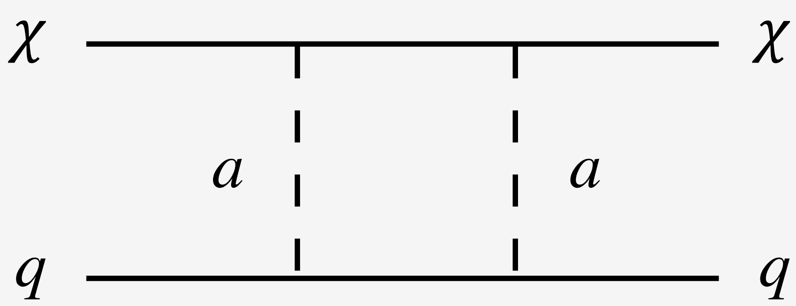


Direct detection (spin indep.)



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

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



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

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

Higgs exchange dominates over the box

Direct detection (spin indep.)

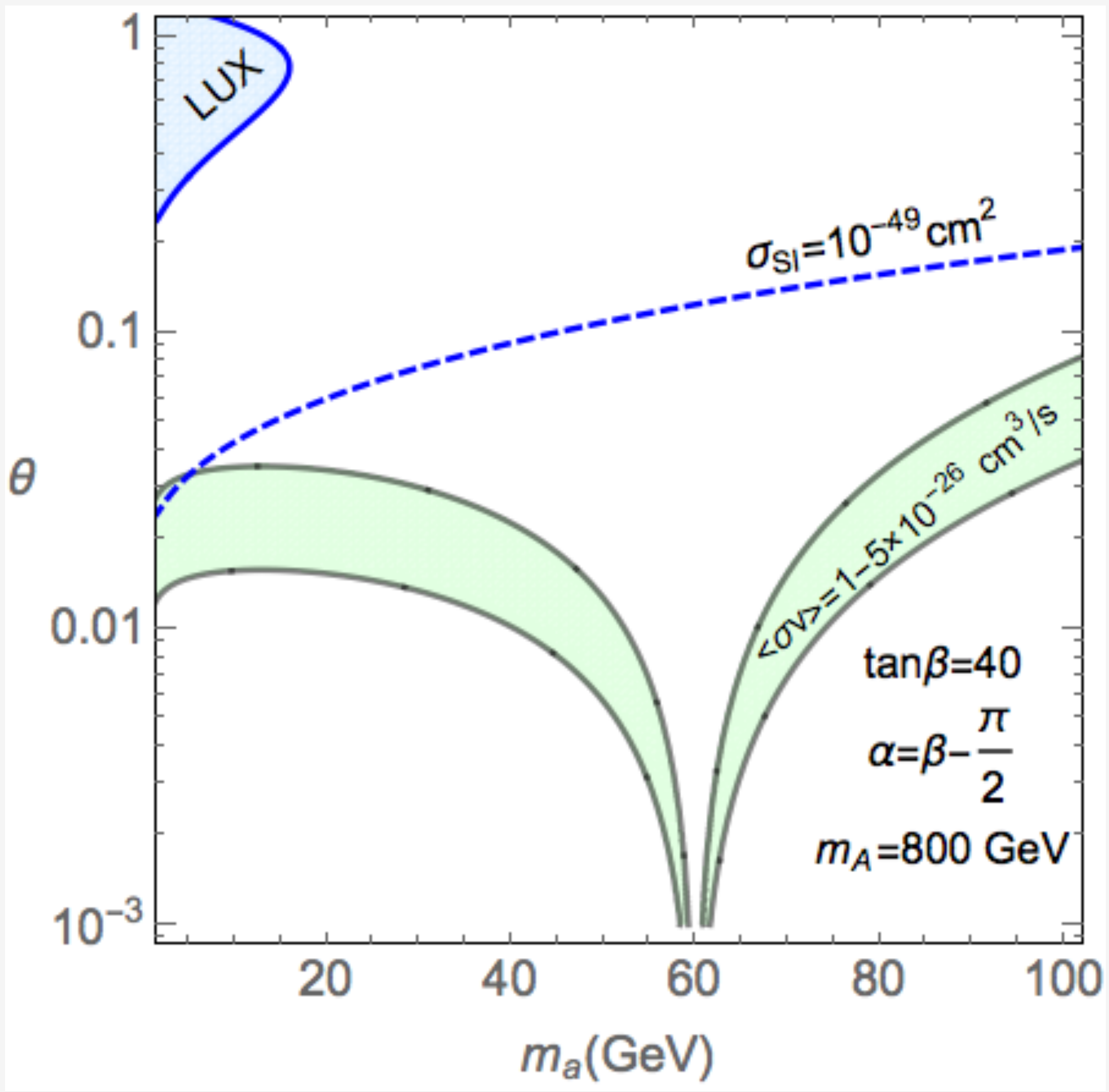
$$\sigma_{\rm SI} \simeq 2.2 \times 10^{-49}\ {\rm cm}^2 \left(\frac{m_A}{800\ {\rm GeV}}\right)^4 \left(\frac{50\ {\rm GeV}}{m_a}\right)^4 \left(\frac{m_\chi}{30\ {\rm GeV}}\right)^2 \left(\frac{\theta}{0.1}\right)^4 \times \left(\frac{y_\chi}{0.5}\right)^4 \left(\frac{\langle N|\sum_q m_q \bar{q} q|N\rangle}{330\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

LUX limit for m_χ = 30 GeV:

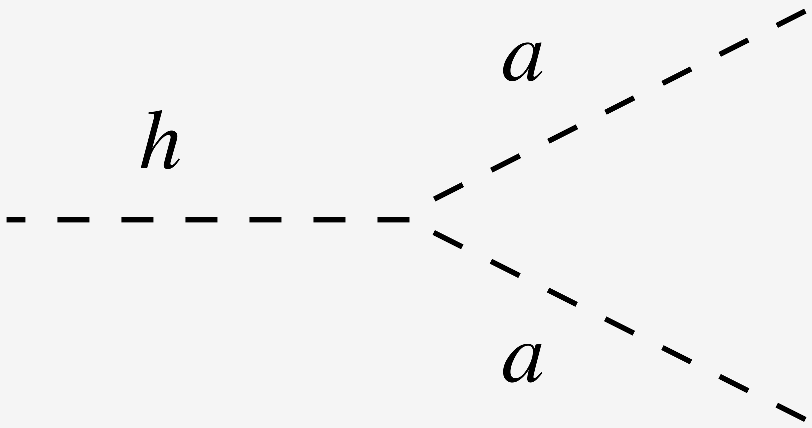
$$\sigma_{\rm SI} < 8\times 10^{-46}{\rm cm}^2$$

Above - - - - we have:

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



Higgs decays: $m_a < m_h/2$



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

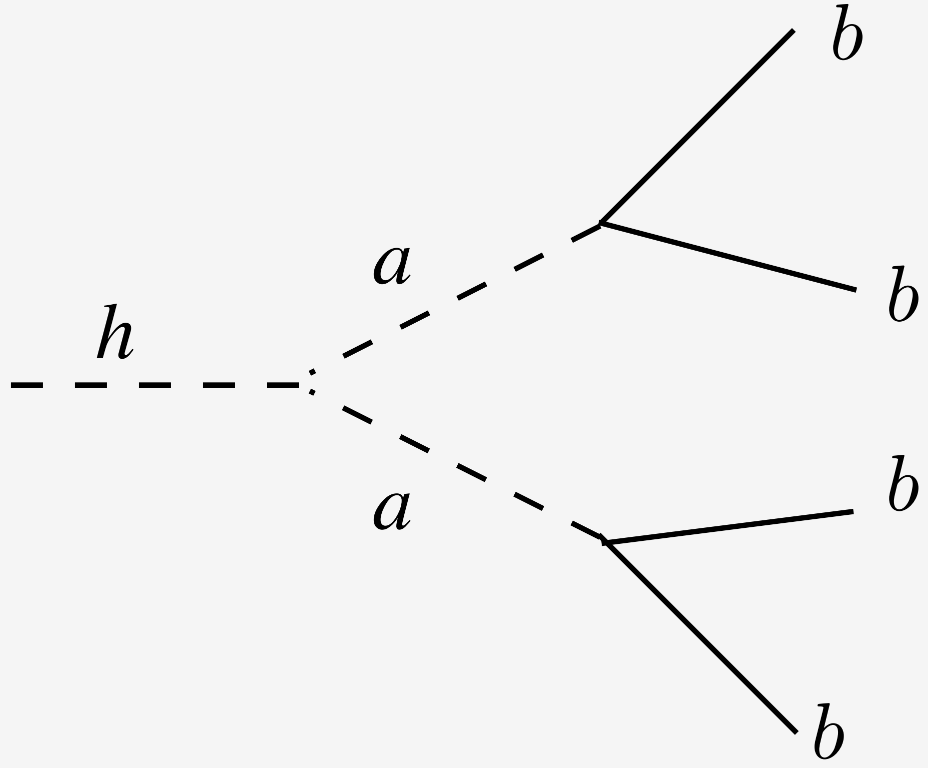
$$\Gamma(h \to aa) = \frac{(m_A^2 - m_a^2)^2 \sin^4 2\theta}{32\pi\, m_h\, v^2}\sqrt{1 - \frac{4m_a^2}{m_h^2}}$$

$$\simeq 840\ \mathrm{MeV}\left(\frac{m_A}{800\ \mathrm{GeV}}\right)^4\left(\frac{\theta}{0.1}\right)^4$$

Remember: SM Higgs width is ~ 4 MeV

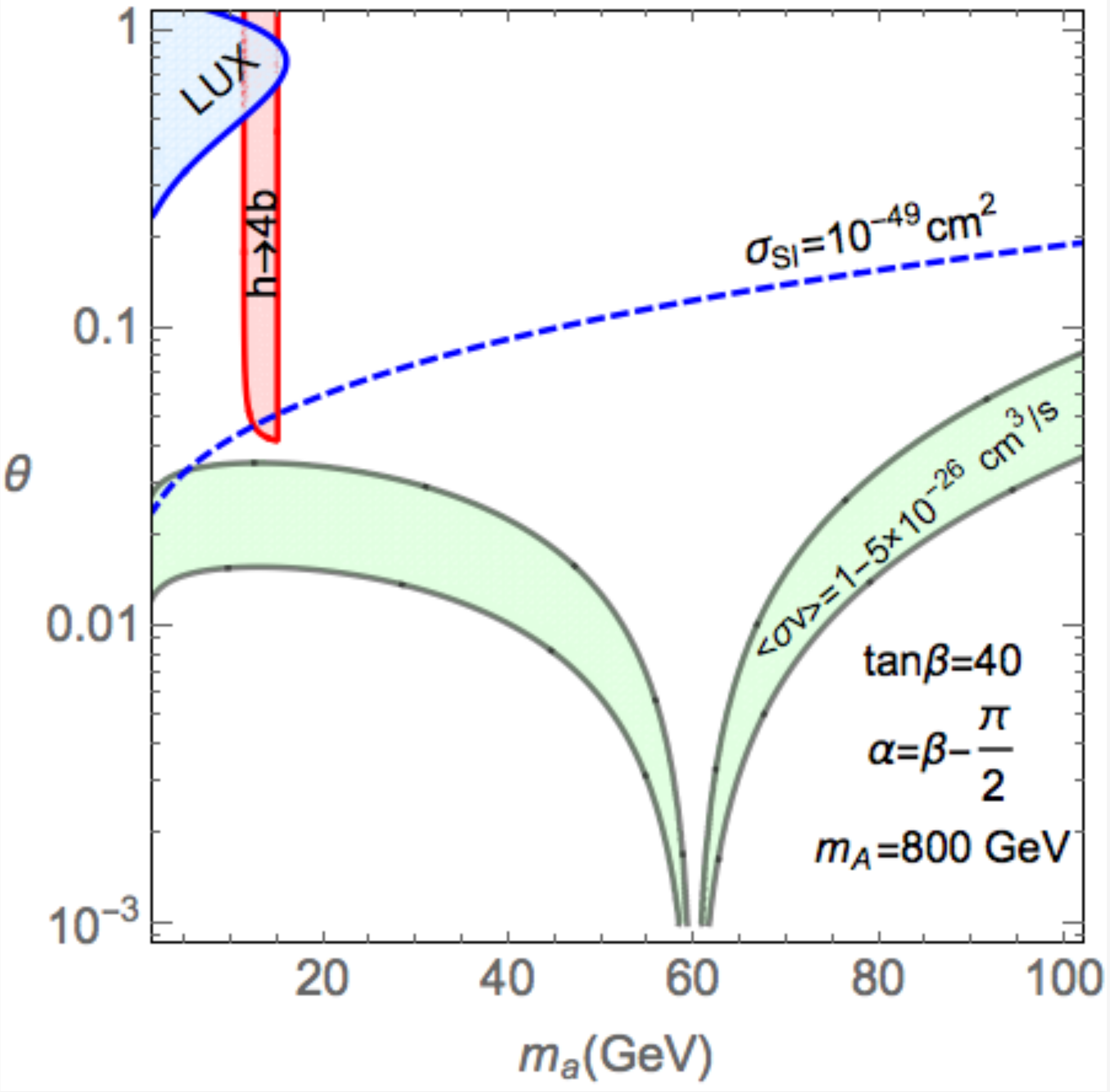
Higgs decays: $h \to 4b$

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



Since $m_a < m_h/2 \simeq 2m_\chi$

$4b$ final state is favored



No dedicated search

Use W/Z + (h → 2b) channel

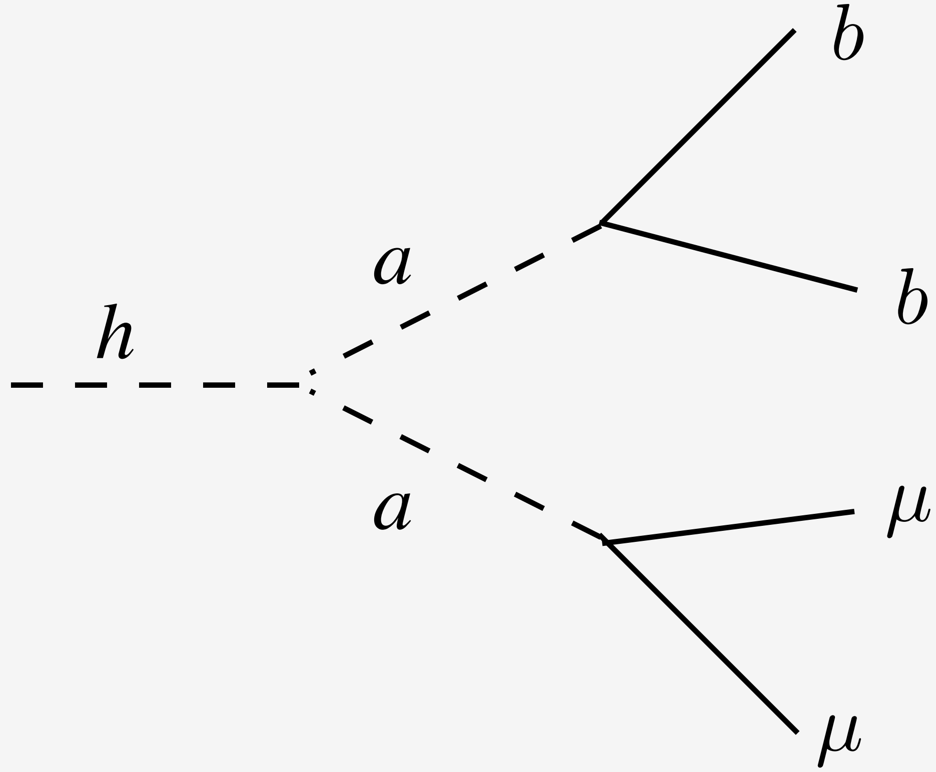
$$\mathrm{Br}(h \to aa \to 4b) < 0.7$$

for

$$2m_b < m_a < 15 \text{ GeV}$$

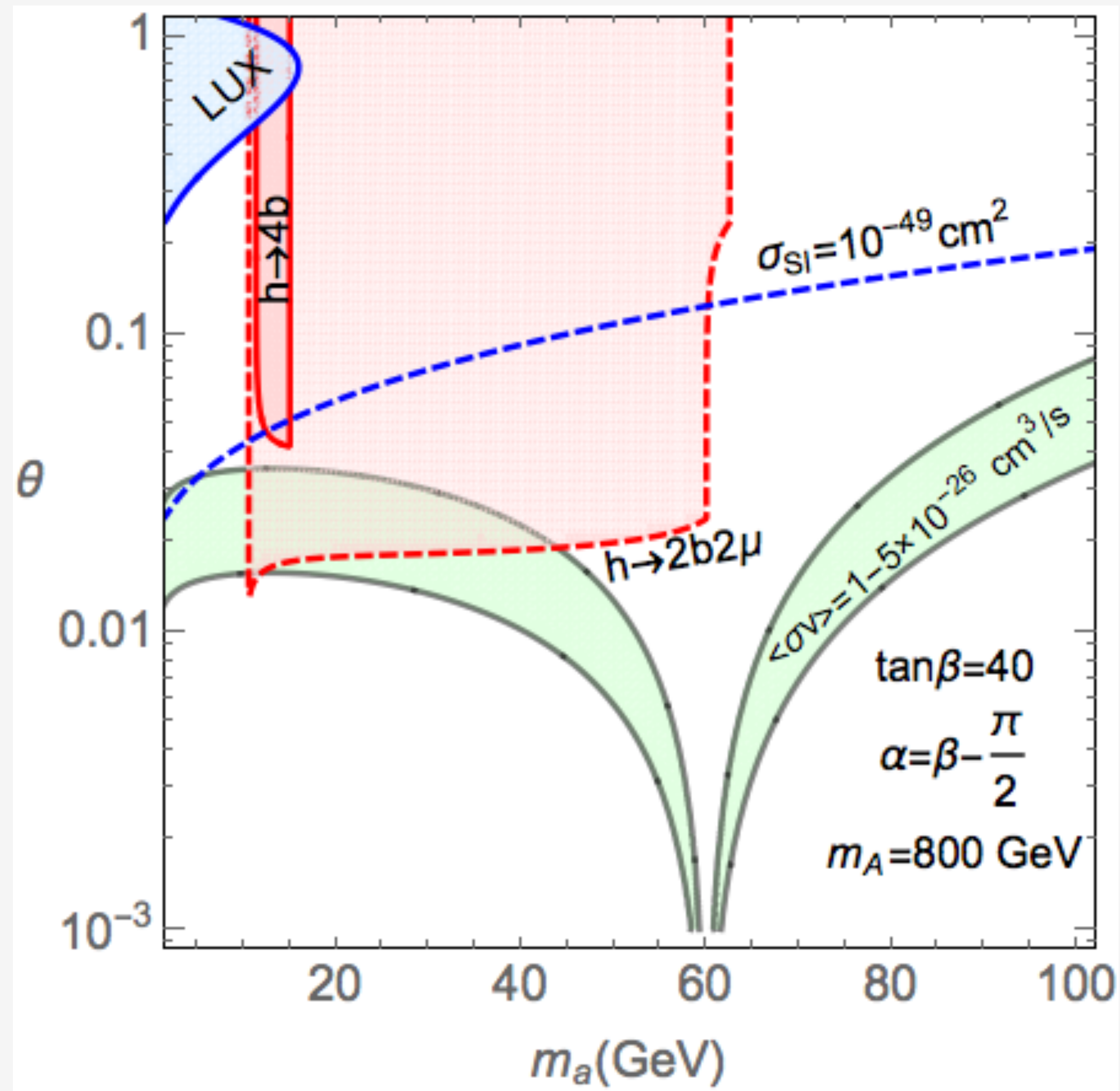
Higgs decays: h → 2b2μ

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

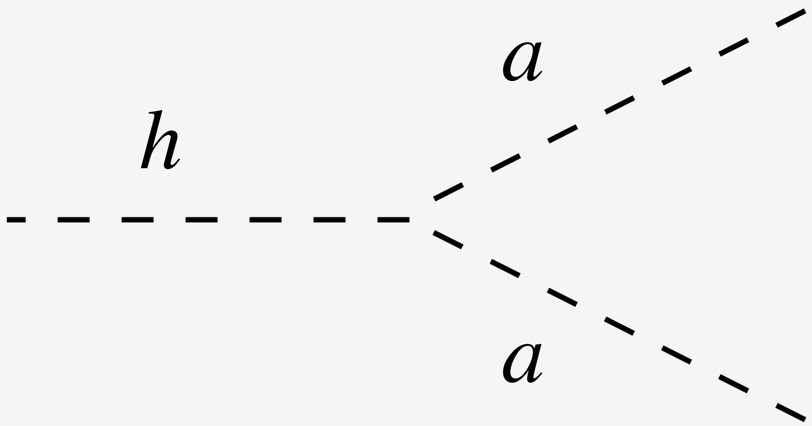


4b is favored, but 2b2$\boldsymbol{\mu}$ is cleaner

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



Invisible Higgs decays



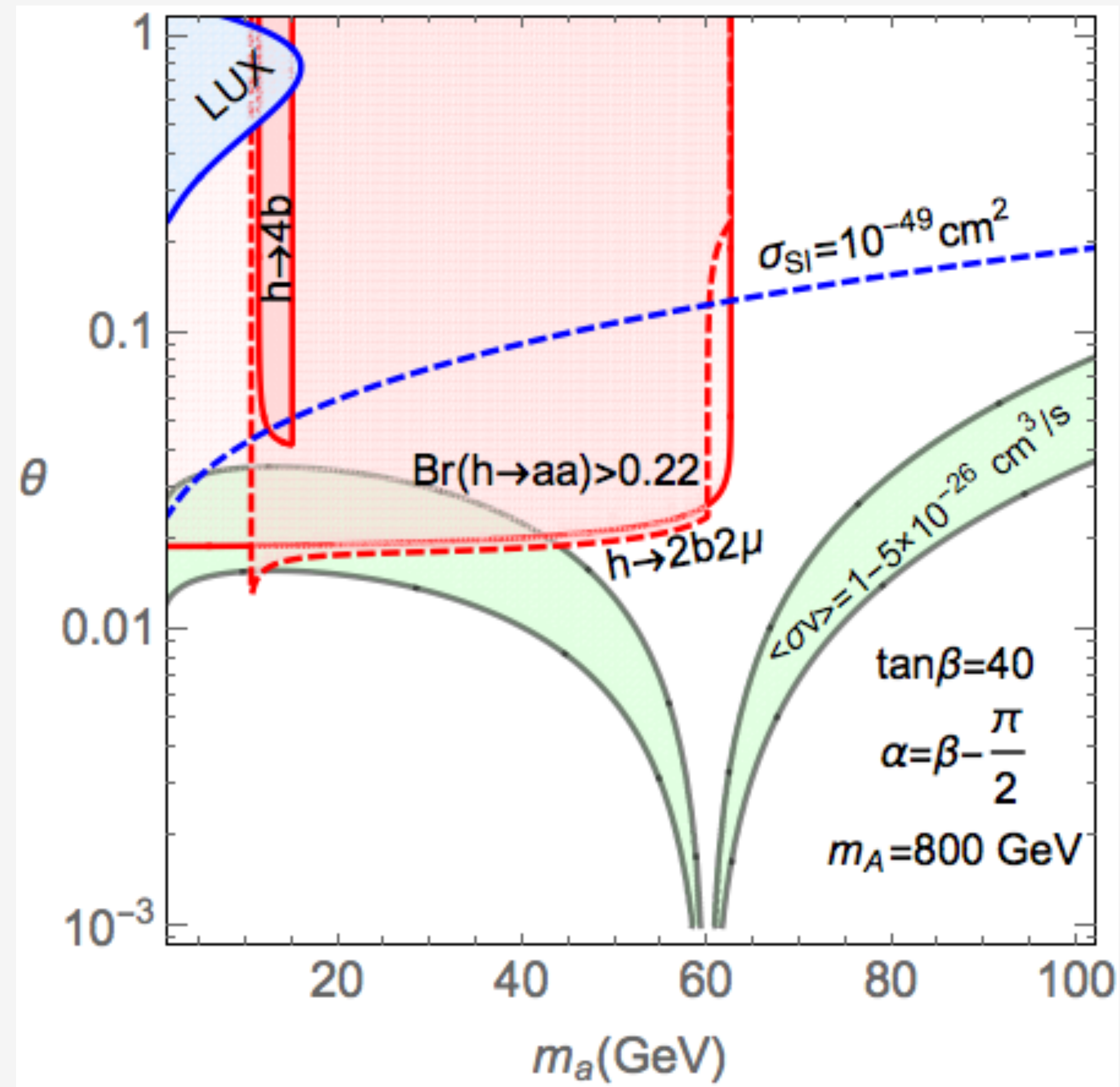
$$V \supset \frac{1}{2v}(m_A^2 - m_a^2)\sin^2 2\theta\, h\, a\, a$$

Higgs decay rate to *aa*:

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

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

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

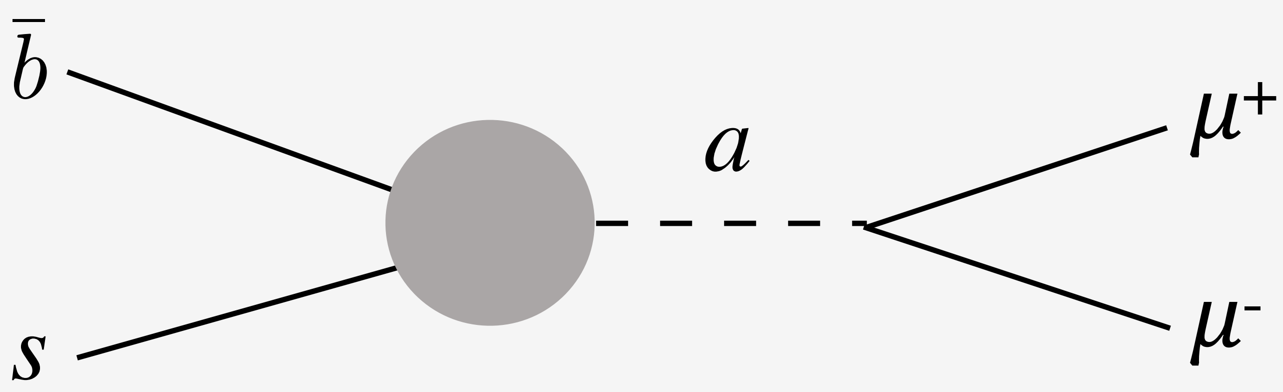


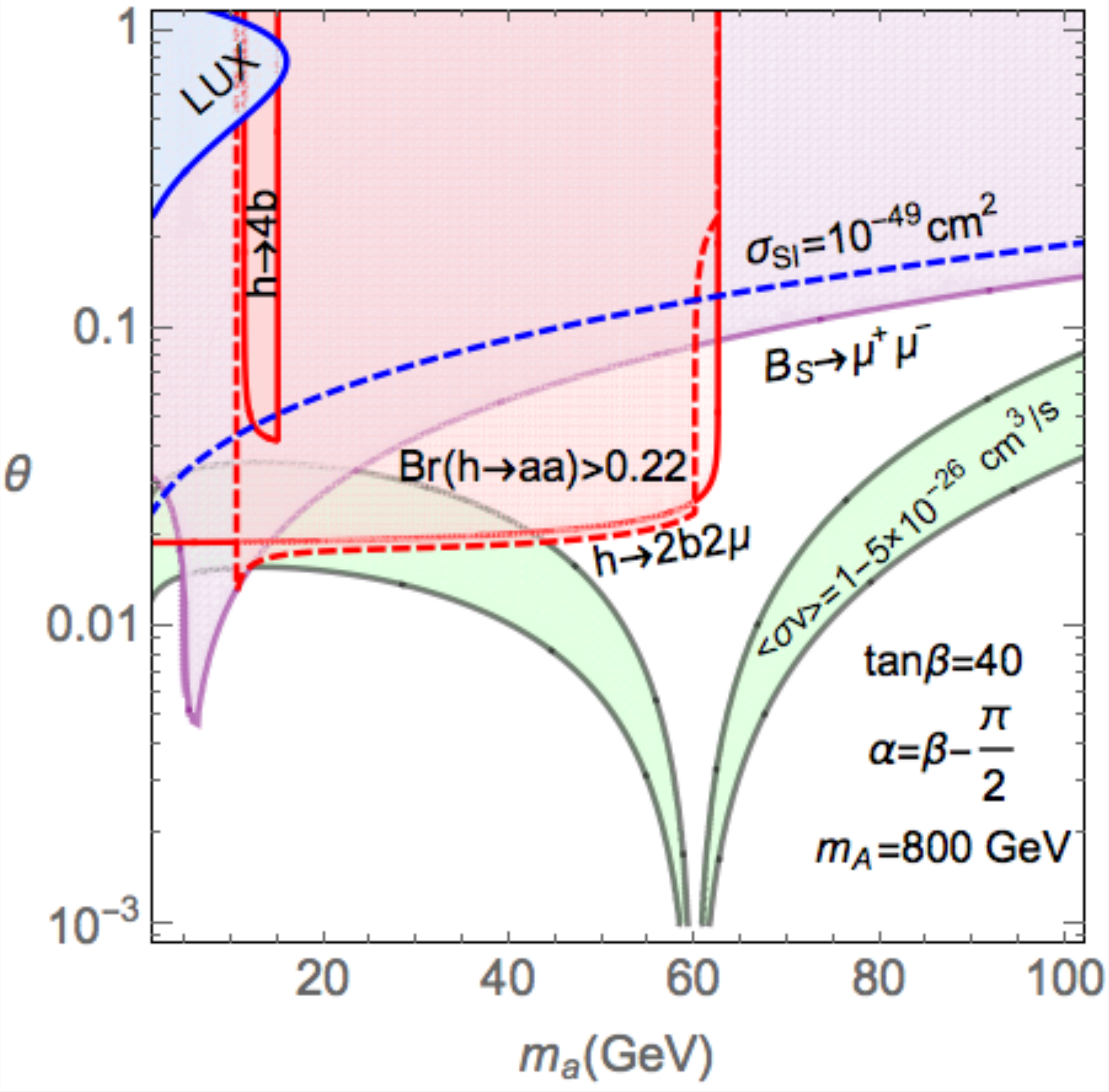
Giardiano, *et al, arxiv: 1303.3570*

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:

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

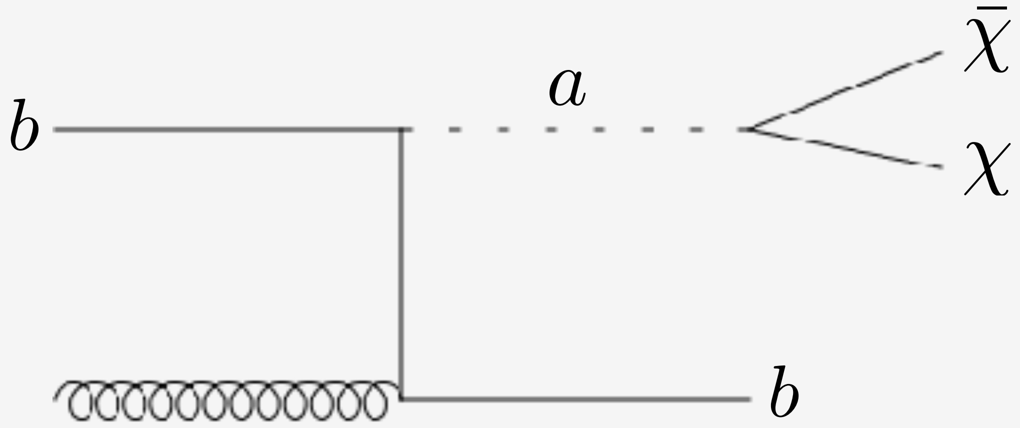
CMS-PAS-BPH-13-007 , LHCb-CONF-2013-012

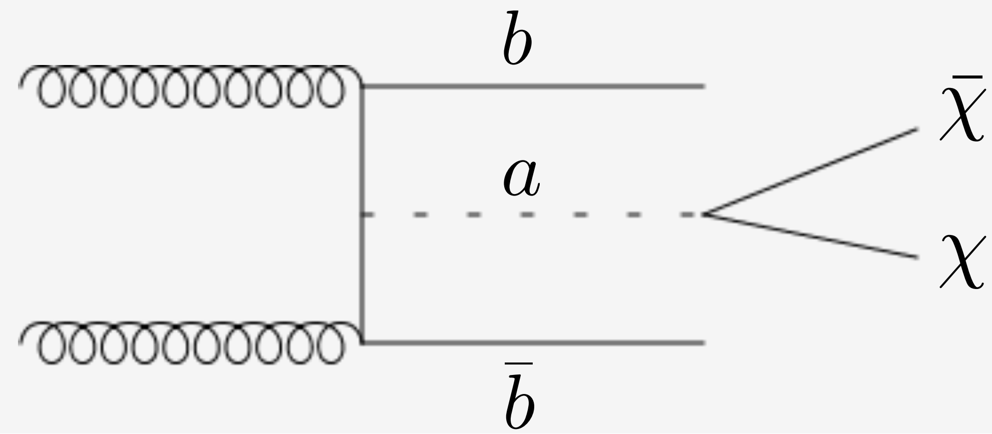
Compare to the SM expectation:

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

Bobeth, *et al*, *arxiv:1311.0903*

(Mono)jets?



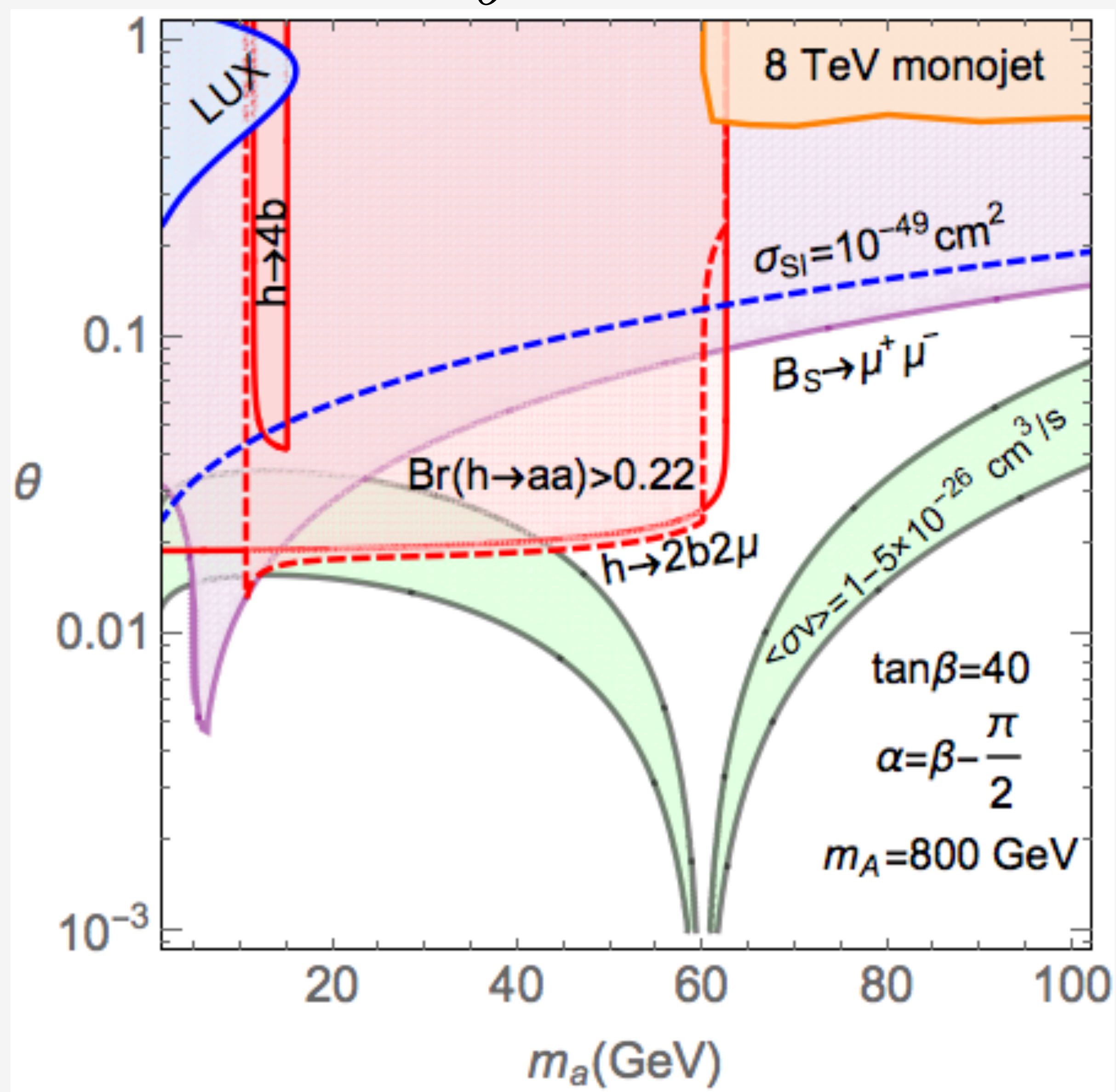


$pp \to (0, 1, 2)\ j$ + missing energy

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

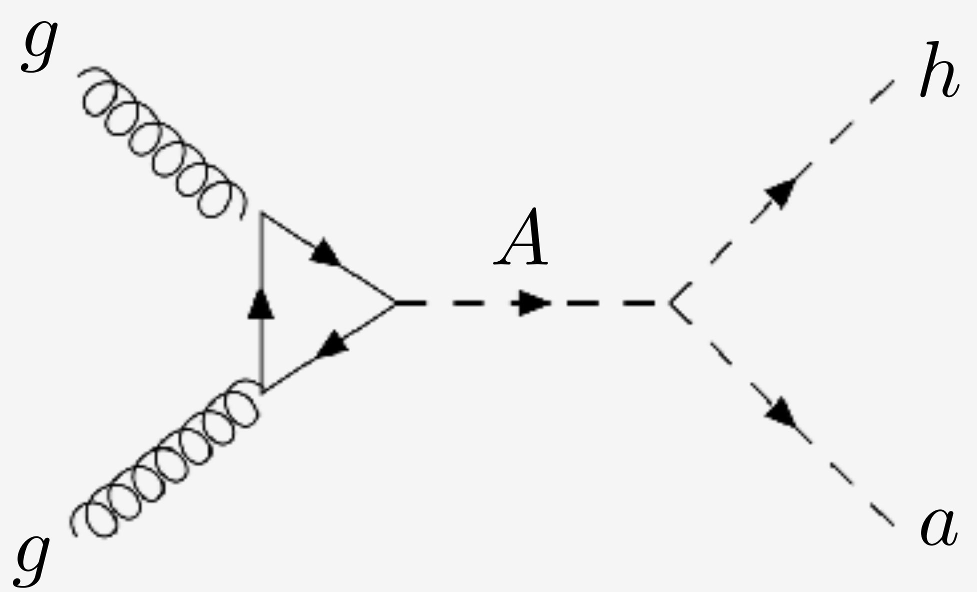
good for $m_a > 2m_\chi$

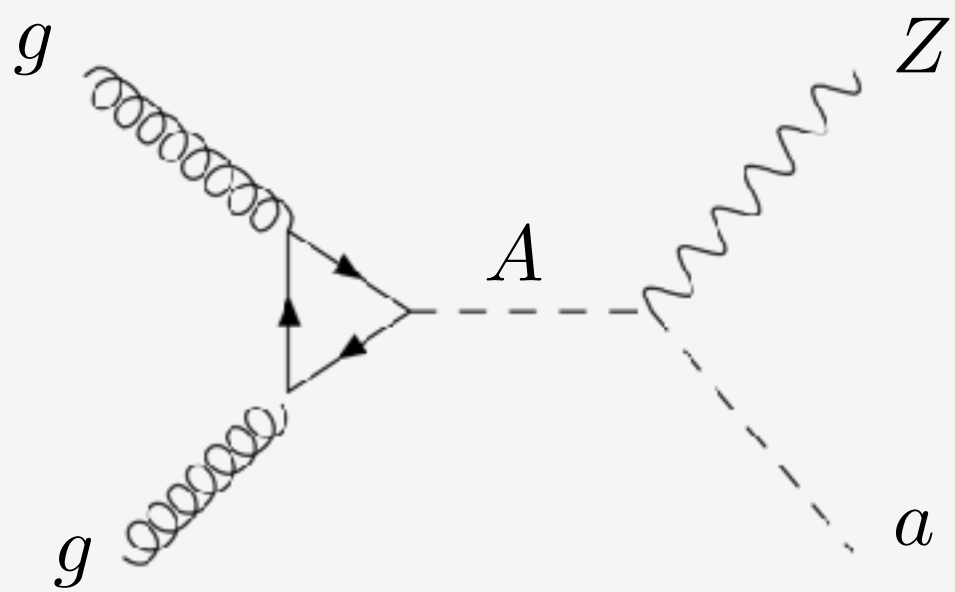
No help from *top*-tagging:
top couplings are $\tan\beta$ suppressed!

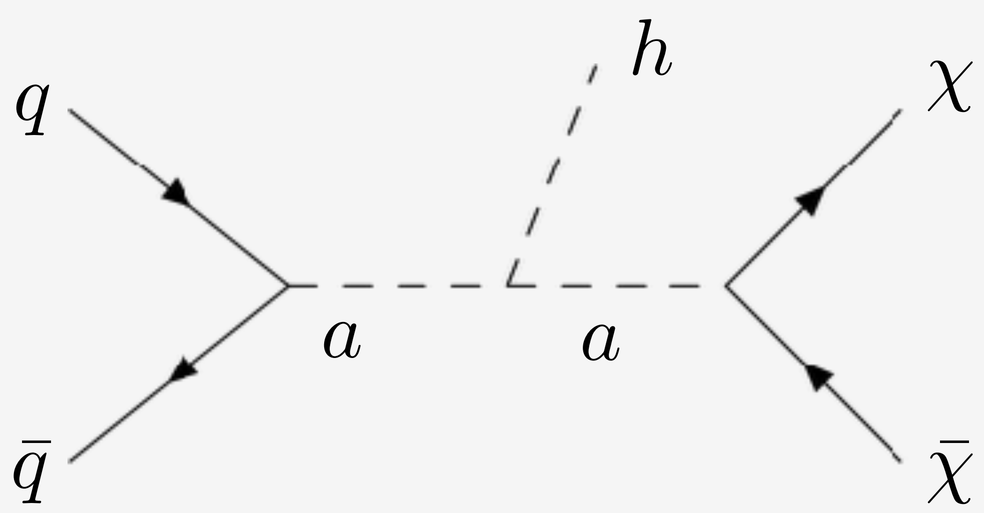


Lin, Kolb, Wang, *arxiv:1303.6638*

MonoHiggs and MonoZ







what else?