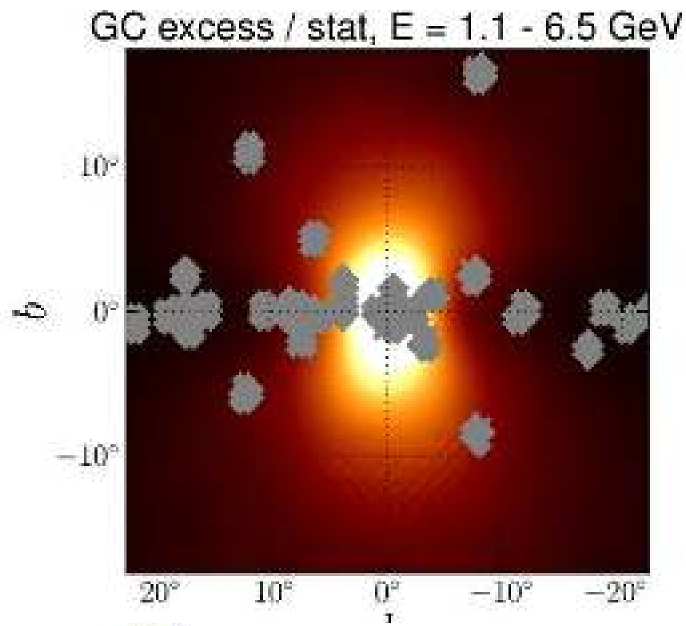
Astrophysical and collider implications of pseudo-Goldstone boson dark matter

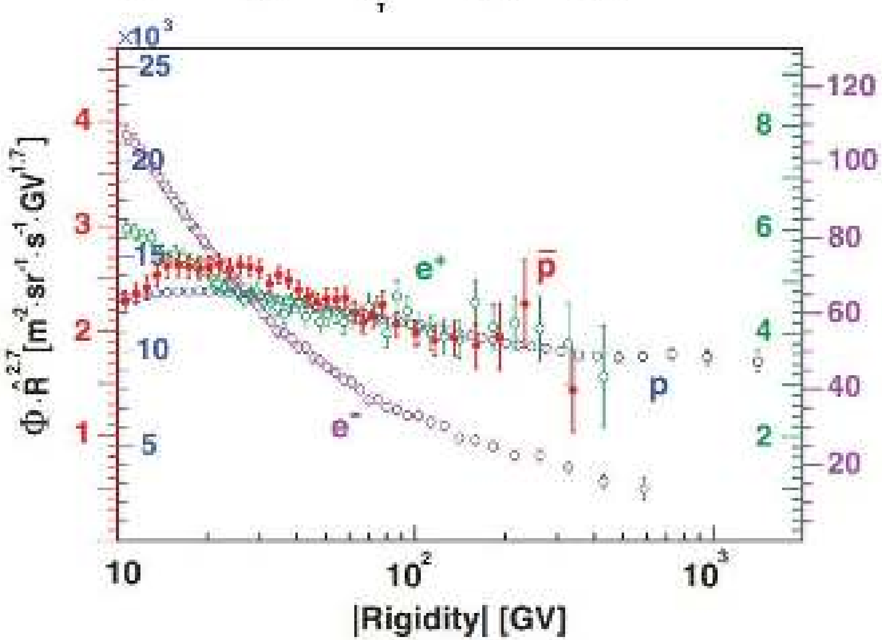
Jim Cline, McGill University

Inflation and the dark sector, Jyväskylä, 7 June 2019

Cosmic ray anomalies



Fermi-LAT observes excess ∼GeV γ-rays from the galactic center (1704.03910)

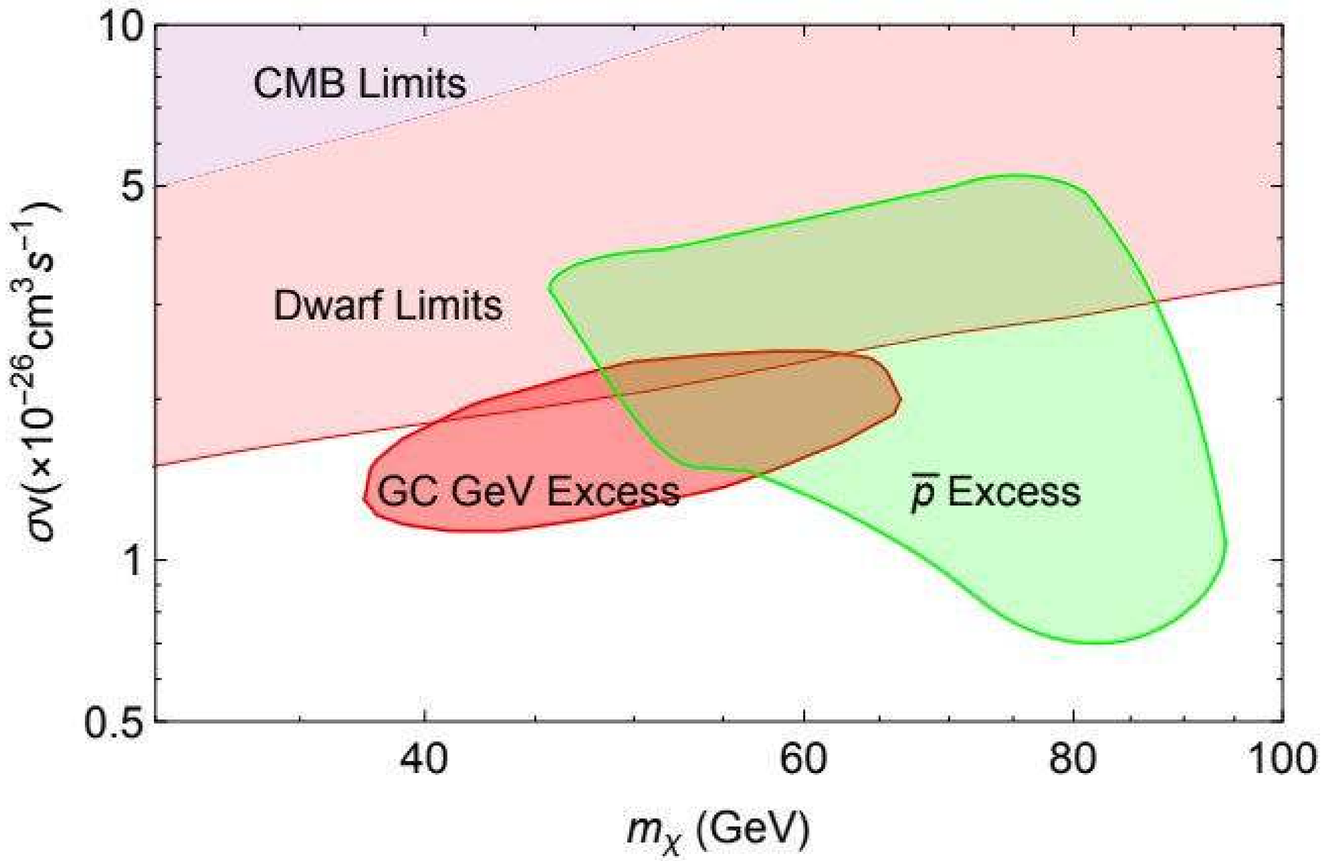


AMS detects antiprotons, determined by numerous theorists to exceed predicted flux (Phys.Rev.Lett. 2016)

Could they have a common dark matter origin?

DM annihilation to $b\bar{b}$

Cholis, Linden & Hooper find compatible parameters for both excesses from $\chi\chi \to b\bar{b}$ (1903.02549)



They also claim strong significance for the $\bar{p}$ excess, $4.7\,\sigma$.

Likelihood of other final states is less, $u\bar{u}$, $d\bar{d} \to 3.3\,\sigma$, $W^+W^- \to 3.6\,\sigma$.

The GC γ-ray excess and pulsars

Researchers vigorously debate DM versus millisecond pulsars (MSPs) as origin of the γ-ray excess.

Population of unresolved MSPs seemed a good astrophysical candidate.

pro-MSP:

Mirabal,1309.3428
Calore *et al.*, 1406.2706
O'Leary *et al.*, 504.02477
Bartels *et al.*, 1805.11097

anti-MSP:

Hooper *et al.*, 1305.0830
Cholis *et al.*, 1407.5625
Haggard *et al.*, 1701.02726

Statistics of γ-rays argued to favor MSPs over DM.

Bartels *et al.*, 1506.05104

Lee *et al.*, 1506.05124

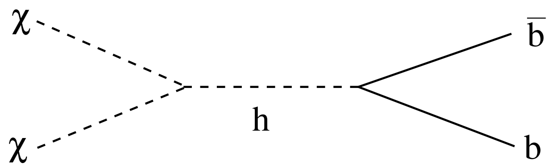
Recently Leane & Slatyer (1904.08430) dispute that claim, favoring DM. Encouragement to pursue DM explanations!

The Higgs portal

Scalar DM generically couples to Higgs,

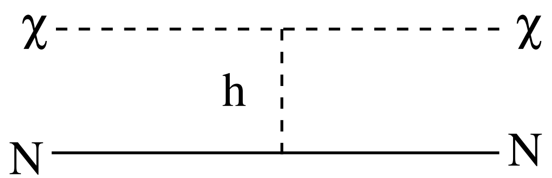
$$\tfrac{1}{4}\lambda_{hs}\chi^2 h^2 \to \tfrac{1}{2}\lambda_{hs} v\,\chi^2 h^2$$

A nice answer to the question "why $b\bar{b}$?" Higgs couples most strongly to b (assuming $m_\chi < m_t$).



$$\sigma v \sim \frac{\lambda_{hs}^2 m_b^2}{4\pi(4m_\chi^2 - m_h^2)^2}$$

There are strong constraints from direct detection,

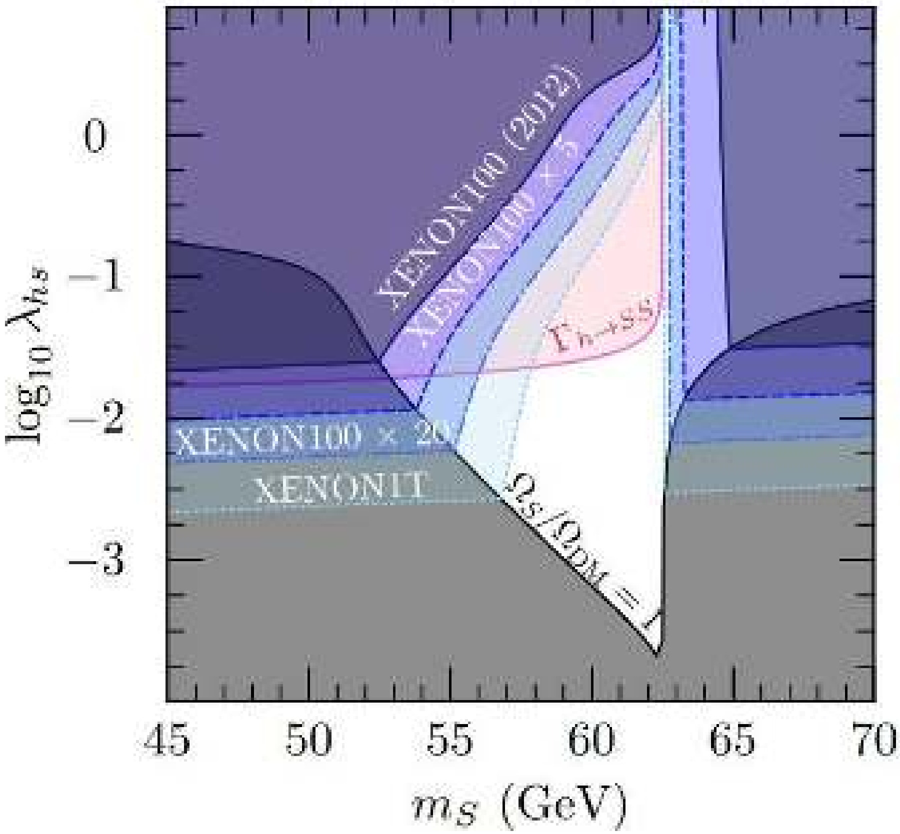


$$\sigma = \frac{\lambda_{hs}^2 f_N^2 m_n^4}{4\pi m_h^4 m_\chi^2}$$

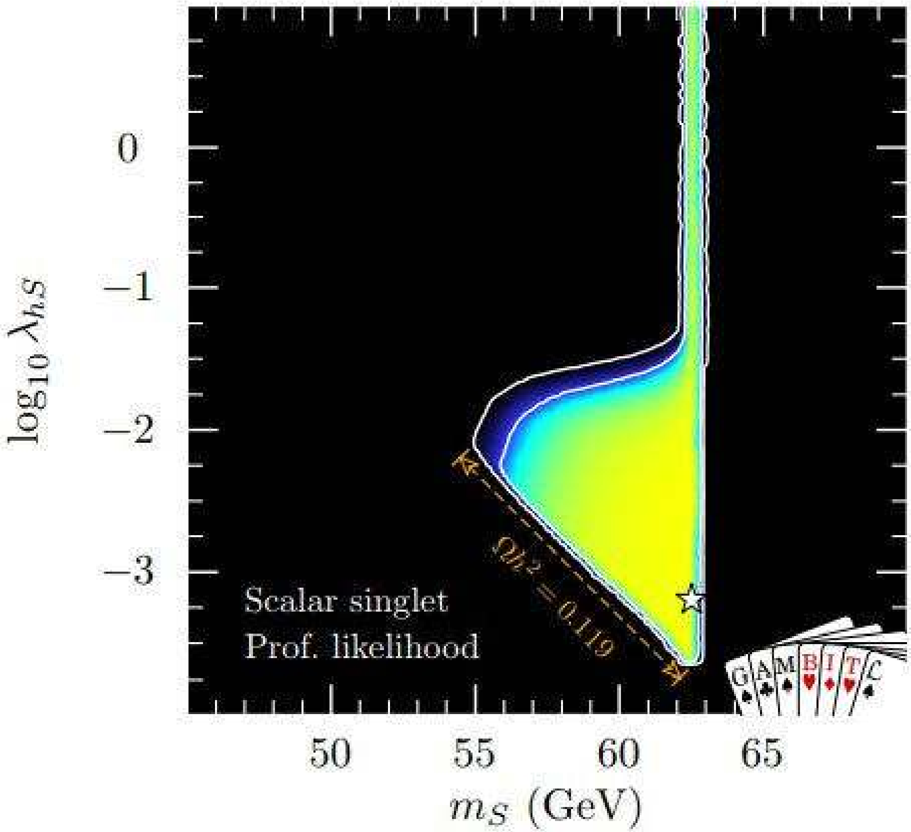
that can be evaded by being close to the Higgs resonance,

$$m_\chi \sim \frac{m_h}{2}$$

Singlet scalar DM global fits



JC, Kainulainen, Scott, Weniger 1306.4710



GAMBIT collaboration, 1705.07931

Region from 55 GeV to $m_h/2 = 62.5$ GeV is not ruled out.

But the indirect detection cross section is highly suppressed in this region!

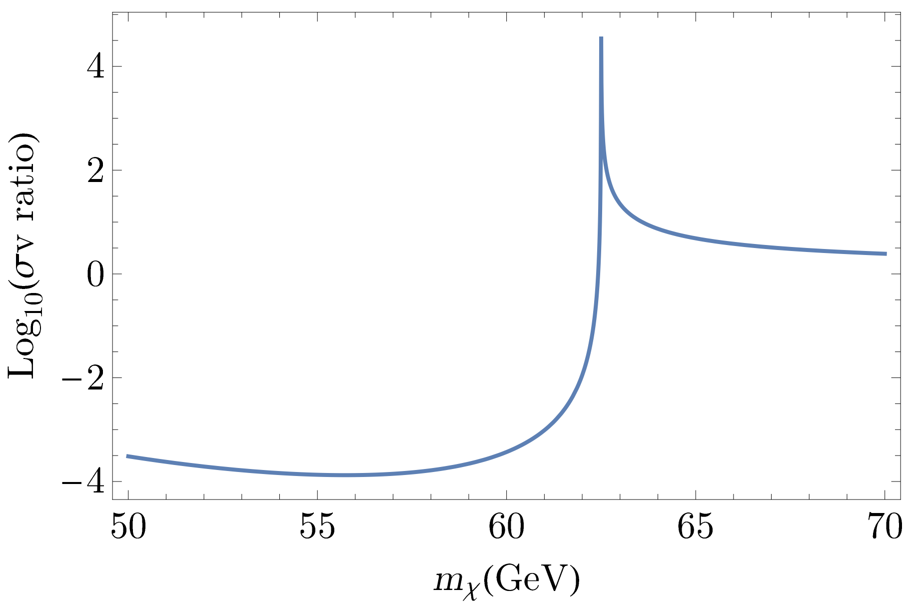
Suppression of σv in galaxy

Thermal average of σv for $\chi\chi \to b\bar{b}$ during freezeout of DM in early universe can probe resonance when $m_\chi < m_h/2$:

$$\langle \sigma v \rangle_{\rm f.o.} \sim N \int d^3p\, e^{-\beta E} \frac{\rm const.}{(4(m_\chi^2 + p^2) - m_h^2)^2 + (\Gamma_h m_h)^2}$$

Present-day annihilations in galaxy have $v \ll 1$,

$$\langle \sigma v \rangle_{\rm gal.} \sim \frac{\rm const.}{(4m_\chi^2 - m_h^2)^2 + (\Gamma_h m_h)^2}$$



The ratio $\langle \sigma v \rangle_{\rm gal.}/\langle \sigma v \rangle_{\rm f.o.}$ is highly suppressed for $m_\chi < m_h/2$.

We need it to be ~ 1 to explain the cosmic ray excesses.

Pseudo-Nambu-Goldstone Boson DM

JC & Takashi Toma, arxiv:1906.02175

pNGB DM can reconcile $m_\chi > m_h/2$ with direct detection constraints.

Introduce complex scalar singlet $S = (s + i\chi)/\sqrt{2}$ with softly- (and spontaneously) broken global U(1) symmetry:

$$V = \frac{\lambda_S}{2}\left(|S|^2 - \frac{v_s^2}{2}\right)^2 + \frac{m_\chi^2}{4}\left(S^2 + S^{*2}\right) + \lambda_{HS}|H|^2|S|^2$$

The pNGB gets mass m_χ, but its couplings to matter vanish as momentum transfer $\to 0$, no direct detection signal

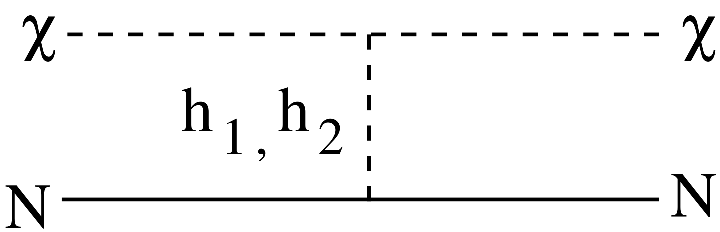
We can take $m_\chi > m_h/2$ to get large enough $\chi\chi \to b\bar{b}$ annihilation cross section

Suppression of direct detection signal

When S gets VEV, Higgs portal causes mixing between h and s,

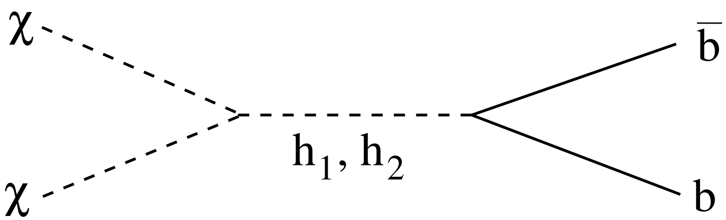
$$\begin{pmatrix} h \\ s \end{pmatrix} = \begin{pmatrix} c_\theta & s_\theta \\ -s_\theta & c_\theta \end{pmatrix} \begin{pmatrix} h_1 \\ h_2 \end{pmatrix}$$

The two diagrams interfere destructively, vanishing as $t \to 0$:



$$\frac{f_N}{2v_s} c_\theta s_\theta \left(\frac{m_{h_1}^2}{t - m_{h_1}^2} - \frac{m_{h_2}^2}{t - m_{h_2}^2} \right) (\bar{N} N)$$

Cancellation is ineffective in s-channel, leaving indirect signal,



$$\frac{y_b}{2v_s} c_\theta s_\theta \left(\frac{m_{h_1}^2}{s - m_{h_1}^2} - \frac{m_{h_2}^2}{s - m_{h_2}^2} \right) (\bar{b} b)$$

since $s \cong 4m_\chi^2$ is not small

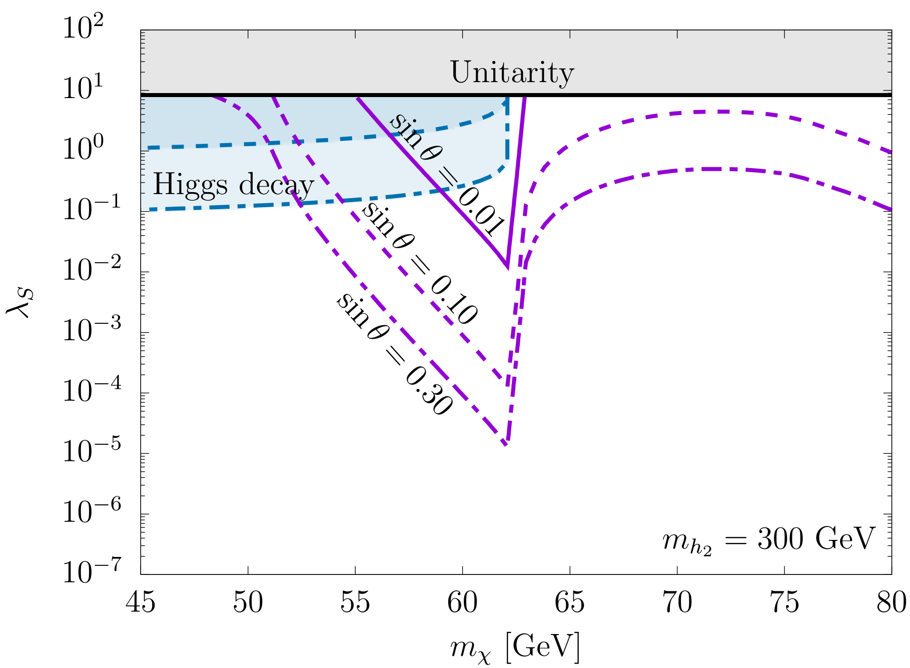
Searching parameter space

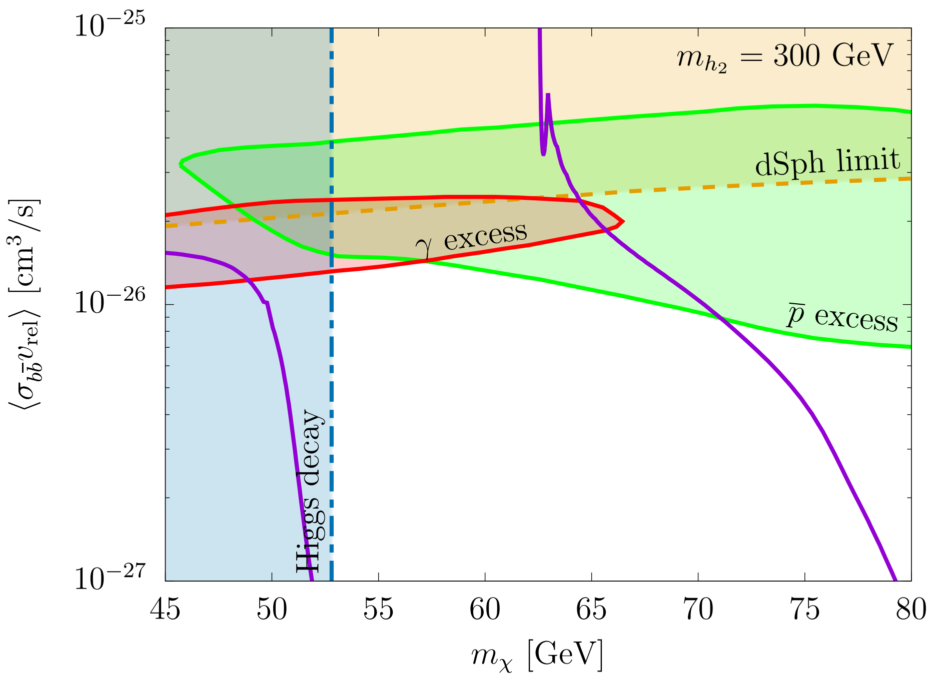
There are four independent parameters,

$$m_\chi, \quad \sin\theta, \quad m_{h_2}, \quad v_s \text{ (or } \lambda_s)$$

with $m_{h_1} = 125$ GeV the SM-like Higgs mass.

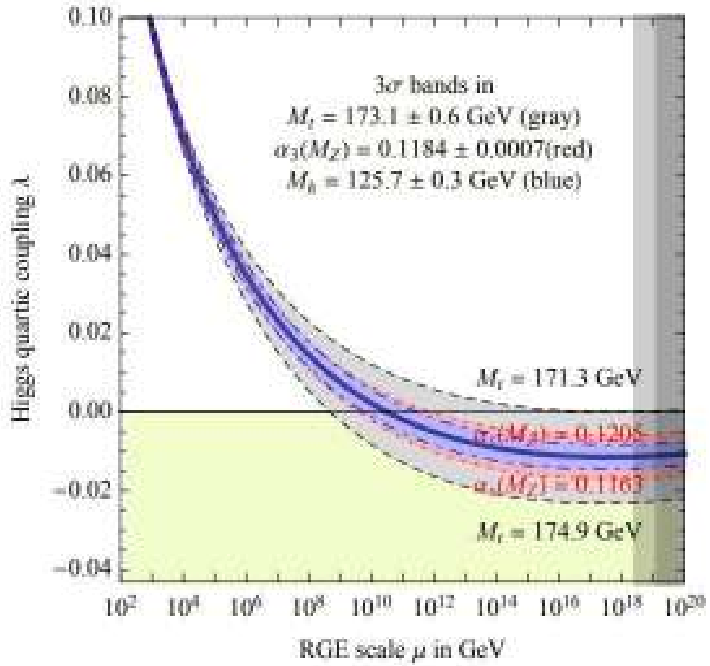
Relic abundance gives one constraint (MicrOmegas). For fixed m_{h_2} and $\sin\theta$, allowed regions are curves in m_χ-λ_s plane.



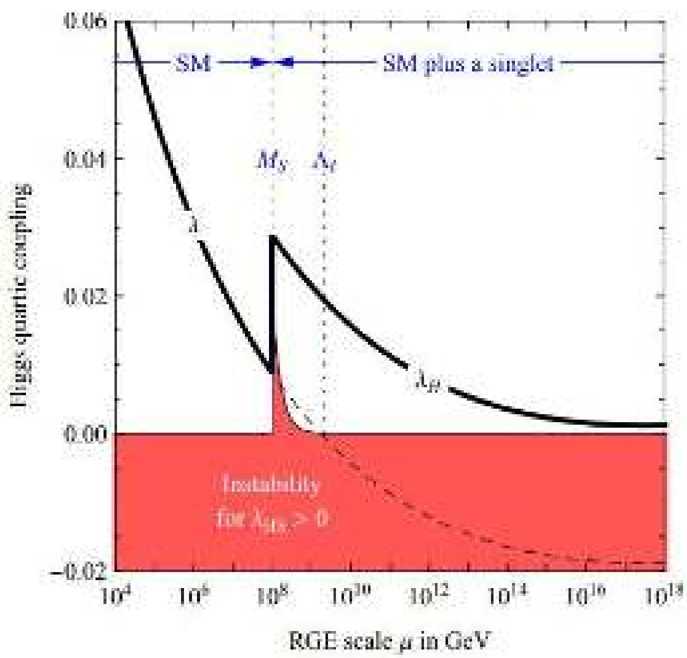


Galactic σv depends on combination $\sin^2\theta / v_s^2$; We explain cosmic ray excesses for $m_\chi = (64 - 67)$ GeV.

Higgs stability



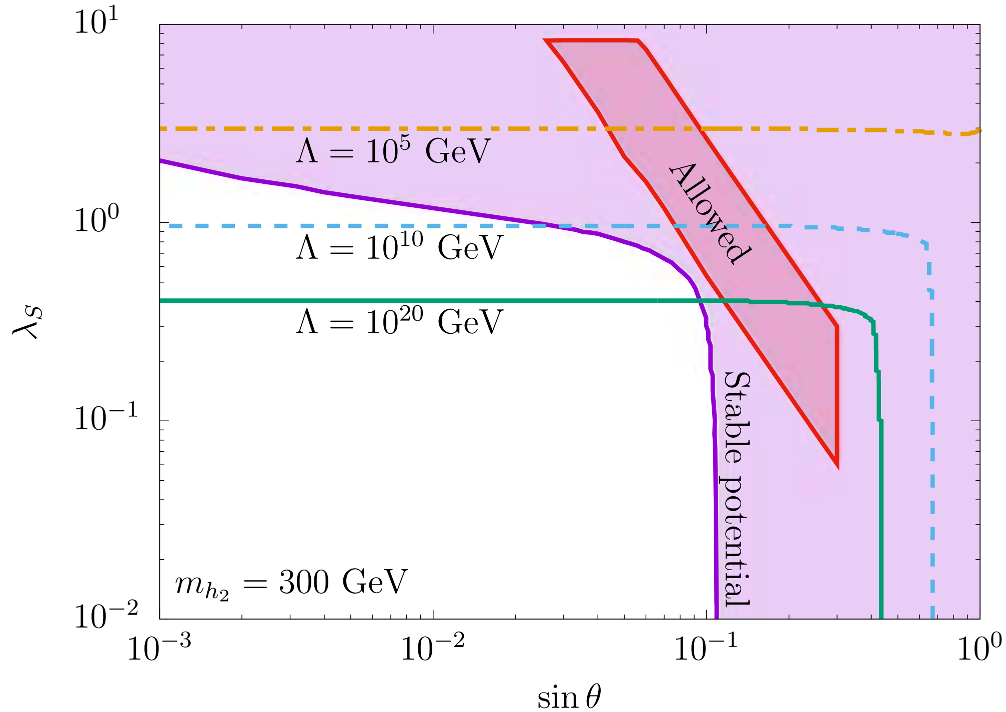
In the SM, the Higgs self-coupling $\lambda_H(\mu)$ becomes < 0 above scale $\mu \sim 10^{11}$ GeV (Degrassi *et al.* 1205.6497).



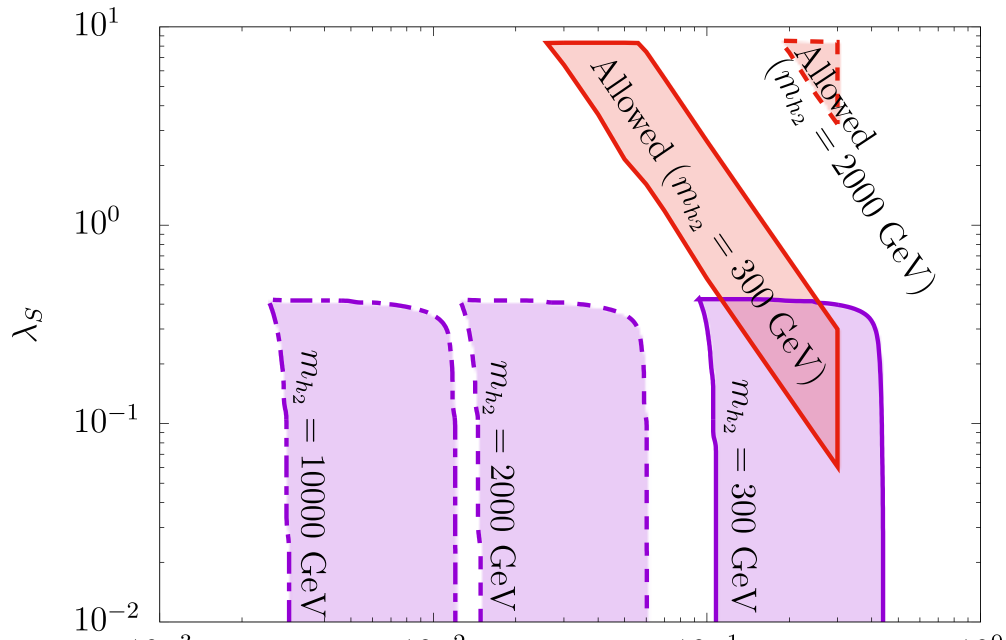
The portal coupling λ_{HS} can prevent this, through a threshold correction at scale $\mu = m_{h_2}$ (Elias-Miro *et al.* 1203.0237)

We find parameters that can do this + cosmic ray anomalies

Higgs stability + CR anomalies



For $m_{h_2} \sim 300$ GeV, we find overlap with CR-allowed region (red), Higgs stability (purple) and perturbativity of couplings (Λ = scale of Landau pole)



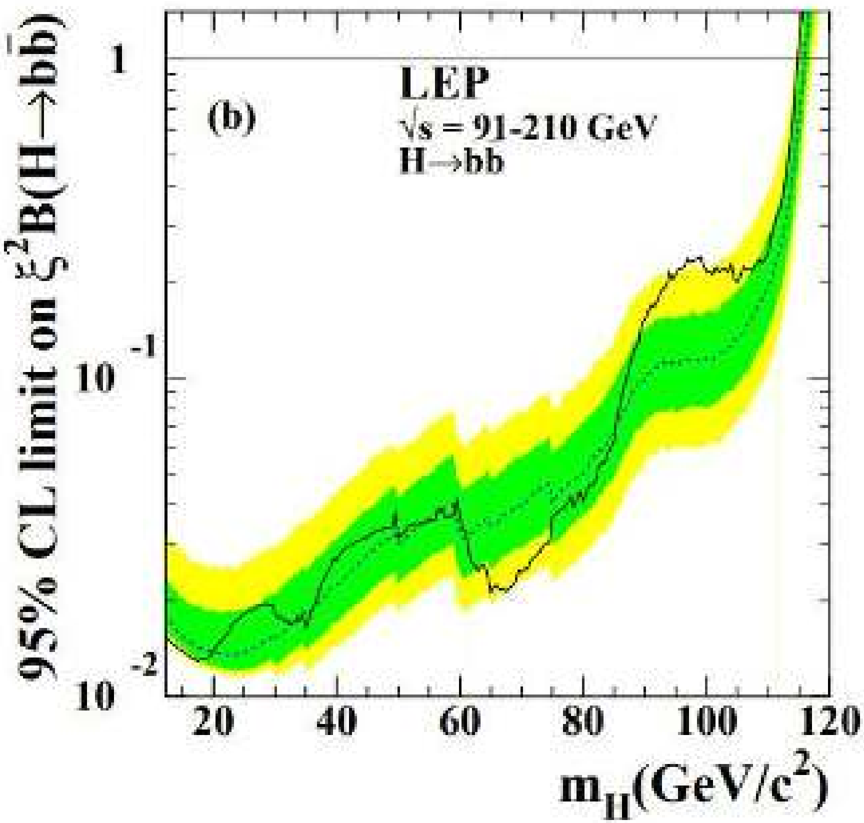
Overlap not present for higher m_{h_2}, and λ_H is not stabilized at lower m_{h_2}.

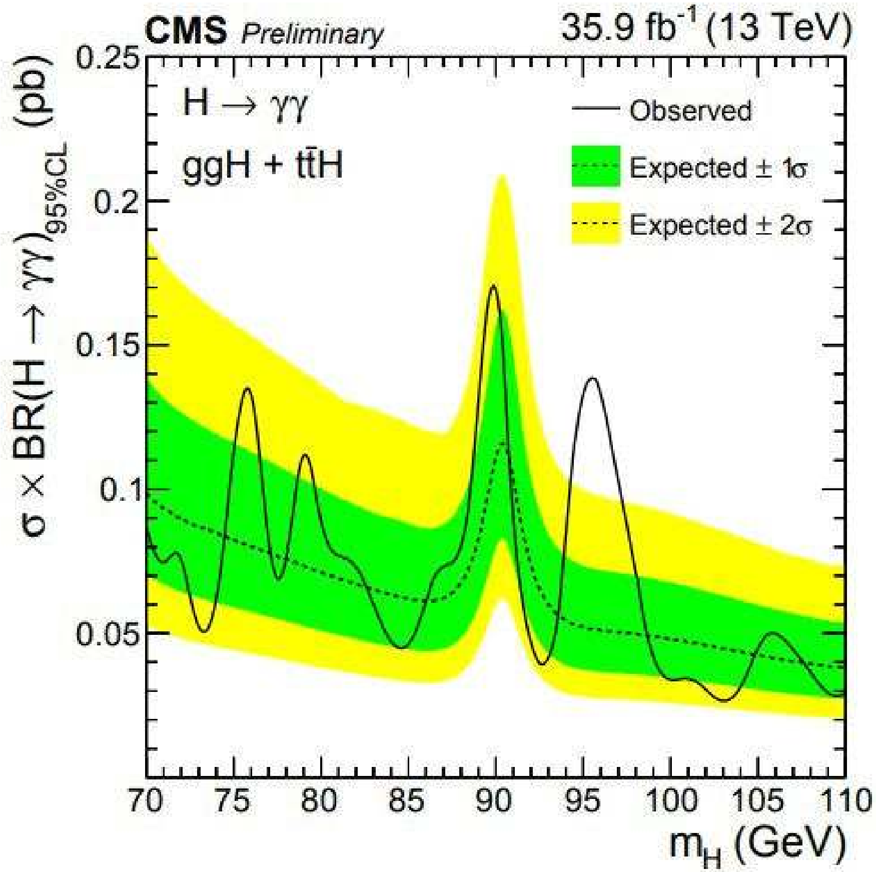
Tentative collider anomalies

If $m_{h_2} \sim 96$ GeV we can also explain unconfirmed excesses in collider experiments:

$$\text{LEP} \quad e^+e^- \to h_2 \to b\bar{b}, \quad 2.3\,\sigma \text{ excess}$$

$$\text{CMS} \quad g\,g \;\to\; h_2 \to \gamma\gamma, \quad 2.9\,\sigma \text{ excess}$$





Intriguing that they are at the same mass . . .

Strength of collider anomalies

It is instructive to compare to the signal of a 96 GeV SM Higgs:
(Fox & Weiner, 1710.07649; Biekötter *et al.*, 1905.03280)

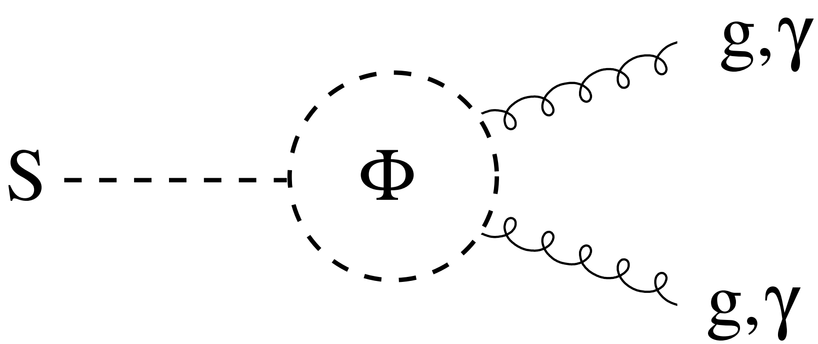
$$\frac{\sigma(e^+e^- \to h_2 \to Zb\bar{b})_{\rm LEP}}{\sigma(e^+e^- \to h \to Zb\bar{b})_{\rm SM}} = \mu_{\rm LEP} = 0.117 \pm 0.057$$

$$\frac{\sigma(gg \to h_2 \to \gamma\gamma)_{\rm CMS}}{\sigma(gg \to h \to \gamma\gamma)_{\rm SM}} = \mu_{\rm CMS} = 0.6 \pm 0.2$$

LEP anomaly can be explained by h_1-h_2 mixing alone, with

$$\sin\theta \cong \sqrt{\mu_{\rm LEP}} = 0.34$$

But this would predict too small $\mu_{\rm CMS} = \mu_{\rm LEP}$.



Need to couple singlet S to new colored/charged particles to enhance the diphoton signal

Models with charged/colored Φ

Since S carries global U(1), new particle Φ must be scalar to couple to S via $\Phi|^2|S|^2$.

Φ is pair-produced at LHC and must decay to quarks. We consider two possibilities, $\Phi \to qq$ and $\Phi \to qqqq$:

$$\begin{aligned} \mathcal{L} &\ni \lambda_{S\Phi}|S|^2|\Phi|^2 + \lambda_{H\Phi}|H|^2|\Phi|^2 \\ &+ \left(y_\Phi\, \Phi(\bar{q}_R q_R^c) \ \text{ or } \ \frac{1}{\Lambda^3}\Phi^*(\bar{q}_R q_R^c)^2 \right) + \text{H.c.} \end{aligned}$$

(Models with $\Phi \to 6q$ would tend to decay outside the detector.)

We take Φ to be in 3, $\bar{3}$ or 6 representation of SU(3)$_c$.

Possible charges are $^8/_3$, $^5/_3$, $^2/_3$, $-^1/_3$, $-^4/_3$ depending on quark flavors

Once charges of Φ are fixed, anomalous signal strengths depend only on θ, $m_\Phi/\sqrt{\lambda_{S\Phi}}$ and $\lambda_{H\phi}v/\lambda_{S\Phi}v_s$.

Higgs signal strengths

There is a third important observable: couplings of the SM Higgs get modified by the new physics.

Couplings to fermions and vector bosons:

$$\mathcal{L} \to c_\theta \frac{h}{v} \left(m_f \bar{f} f + 2m_W^2 W_\mu^+ W^{\mu-} + m_Z^2 Z_\mu Z^\mu \right)$$

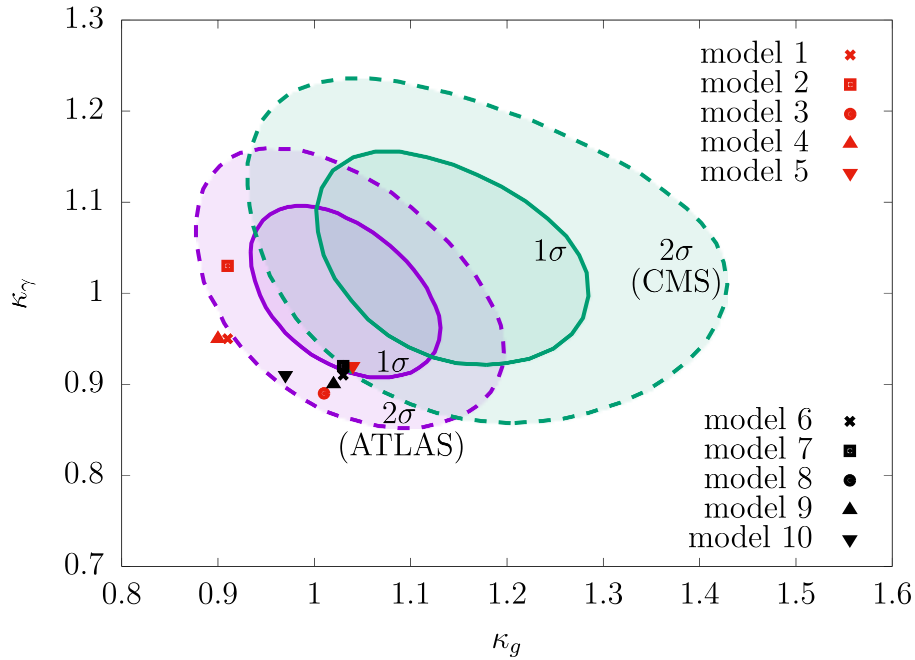
Couplings to photons and gluons:

$$\mathcal{L} \to \frac{\alpha}{8\pi v} h \Bigg(\left[R_\Phi(-s_\theta \eta_S + c_\theta \eta_H) + \tfrac{2}{3} c_\theta \right] G^a_{\mu\nu} G^{a\mu\nu} + \left[\frac{N_c}{3} q_\Phi^2 (-s_\theta \eta_S + c_\theta \eta_H) + b^\gamma_{\rm SM} c_\theta \right] F_{\mu\nu} F^{\mu\nu} \Bigg)$$

with $\eta_S = \lambda_{S\Phi} \frac{v v_s}{m_\Phi^2}$, $\eta_H = \lambda_{H\Phi} \frac{v^2}{m_\Phi^2}$, $b^\gamma_{\rm SM} = -6.5$, $R_\Phi = 1/6$ for triplet Φ ($5/6$ for sextet)

We fit to effective Higgs couplings κ_g, κ_γ, $\kappa_{W/Z}$ and signal strengths μ for $gg \to h \to \gamma\gamma$, $gg \to h \to ZZ \to 4\ell$.

Fits to Higgs couplings



Define $\kappa_x = \dfrac{\mathcal{M}(h\to xx)}{\mathcal{M}(h\to xx)_{SM}}$

Models $2-5$ give the best fits to κ_γ versus κ_g

observable	$gg\to\tilde h_1\to\gamma\gamma$	$gg\to h_1\to ZZ\to 4\ell$	κ_g	κ_γ	$\kappa_{Z,W}$
predicted	$\kappa_g^2\, c_{\gamma\gamma}$	$\kappa_g^2\, c_{ff}$	$\lvert\frac{3}{2}b_1^g\rvert$	$\lvert b_1^\gamma/b_{SM}^\gamma\rvert$	c_θ
model 1	0.87	0.82	0.91	0.95	0.92
model 2	1.02	0.83	0.91	1.03	0.93
model 3	0.91	1.00	1.01	0.89	0.94
model 4	0.87	0.82	0.90	0.95	0.92
model 5	1.03	1.06	1.04	0.92	0.93
model 6	0.99	1.04	1.03	0.91	0.94
model 7	1.03	1.03	1.03	0.92	0.92
model 8	1.02	1.04	1.03	0.92	0.93
model 9	0.95	1.02	1.02	0.90	0.94
model 10	0.88	0.94	0.97	0.91	0.94
CMS	1.15 ± 0.15 [84]	0.94 ± 0.10 [85]	$1.18^{+0.16}_{-0.14}$ [87]	1.07 ± 0.15 [87]	$\kappa_Z=1.00\pm0.11$ [87]
ATLAS	0.96 ± 0.14 [86]	$1.04^{+0.16}_{-0.15}$ [86]	$0.99^{+0.11}_{-0.10}$ [86]	1.05 ± 0.09 [86]	$\kappa_W=1.05\pm0.09$, $\kappa_Z=1.11\pm0.08$ [86]
combined	1.06 ± 0.10	0.99 ± 0.10	$1.09^{+0.10}_{-0.09}$	1.06 ± 0.09	1.05 ± 0.08

We compute χ^2 for κ_γ, κ_g, $\kappa_{W/Z}$, $\mu_{gg\to h\to\gamma\gamma}$, $\mu_{gg\to h\to ZZ\to 4\ell}$

Fits to all observables

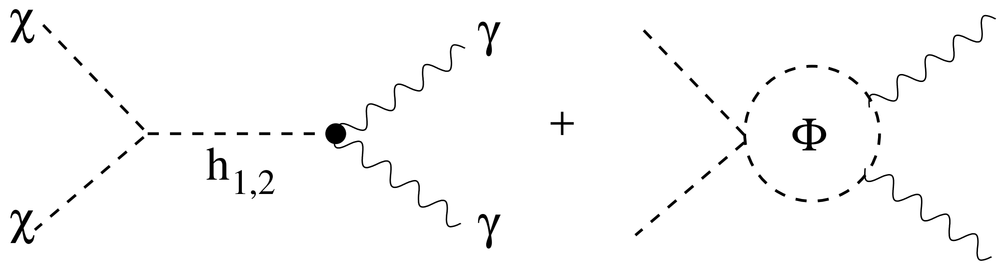
model	q_Φ	N_c	$\frac{m_\Phi}{\lvert\lambda_{S\Phi}\rvert^{1/2}}$	$\frac{\bar\mu_\Phi}{\lvert\lambda_{S\Phi}\rvert^{1/2}}$	s_θ	$\lambda_{S\Phi}$	$\lambda_{H\Phi}$	$\chi^2/\text{d.o.f.}$
1	$8/3$	6	943	836	0.39	1.9	3.3	3.6
2	$8/3$	3	601	778	0.36	1.4	1.6	2.2
3	$5/3$	6	700	741	0.34	3.4	3.4	2.1
4	$5/3$	3	417	838	0.39	3.0	3.0	3.7
5	$2/3$	6	588	795	0.37	4.8	5.9	1.4
6(∗)	$2/3$	3	284	765	0.35	3.4	3.6	1.5
7	$-1/3$	6	554	830	0.39	5.4	8.0	1.5
8(∗)	$-1/3$	3	256	810	0.38	4.1	5.6	1.4
9	$-4/3$	6	666	752	0.35	3.8	3.9	1.8
10(∗)	$-4/3$	3	333	737	0.34	2.4	3.0	2.5

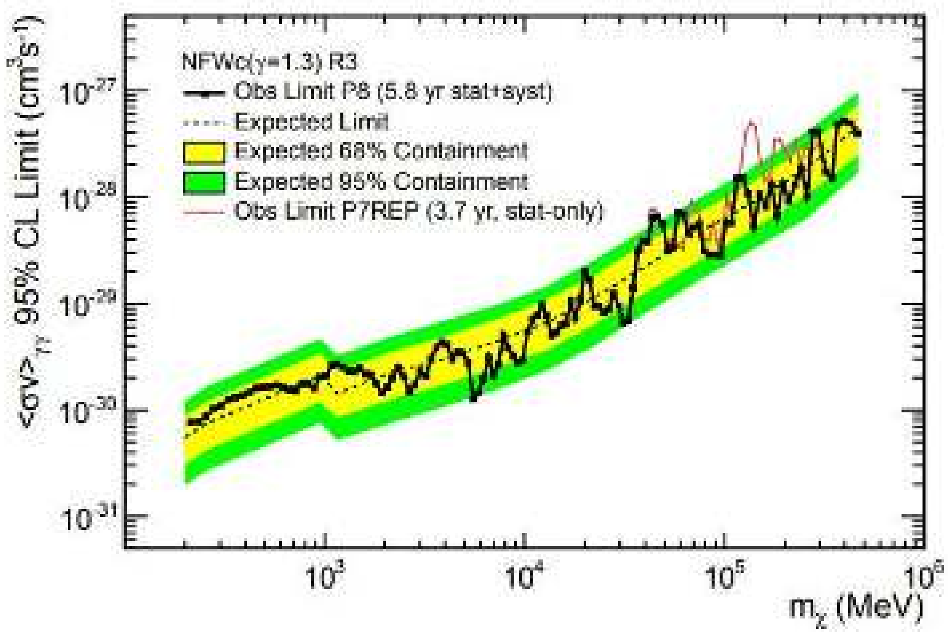
CMS constrains $m_\Phi > 720$ GeV (1.3 TeV) for triplet (sextet) $\Phi \to qqqq$.
$\lambda_{S\Phi} > (720/601)^2 = 1.4$ for model 2, least tuned scenario: 1-loop correction gives

$$\delta\lambda_{HS} \sim \frac{3\lambda_{H\Phi}\lambda_{S\Phi}}{16\pi^2} \sim 0.04, \quad \lambda_{HS} = 0.008 \sim \delta\lambda_{HS}/5$$

Fermi gamma-ray line prediction

We predict annihilation $\chi\chi \to \gamma\gamma$, dominated by Higgs exchange,





Fermi-LAT gets stringent constraints from line searches, depending on assumed DM profile:

$$\log_{10} \frac{\langle \sigma v \rangle_{\gamma\gamma}}{(10^{-29}\,\mathrm{cm}^3/\mathrm{s})} < 0.7 - 2.6$$

Our models predict $0.5 - 2$, close to current sensitivity of Fermi

Conclusions

pNGB DM is tightly constrained to explain GeV γ ray + $\bar{p}$ excesses: $m_\chi \in [64,\, 67]\,\mathrm{GeV}$.

Model is safe from direct detection constraints, somewhat below Fermi dwarf spheroidal limits

Can also stabilize Higgs + scalar potential up to Planck scale if second Higgs mass is $m_{h_2} \sim (200 - 600)\,\mathrm{GeV}$

Can accommodate tentative LEP & CMS anomalies if $m_{h_2} \cong 96\,\mathrm{GeV}$, adding new charged/colored scalar Φ with $m_\Phi \sim 720\,\mathrm{GeV}$

Extended model predicts up to 17% deviation in Higgs couplings, and observable $\chi\chi \to \gamma\gamma$ in the galaxy

Unfortunately, no two-step electroweak phase transition in this model