Pseudo-Goldstone Dark Matter

through the Higgs portal

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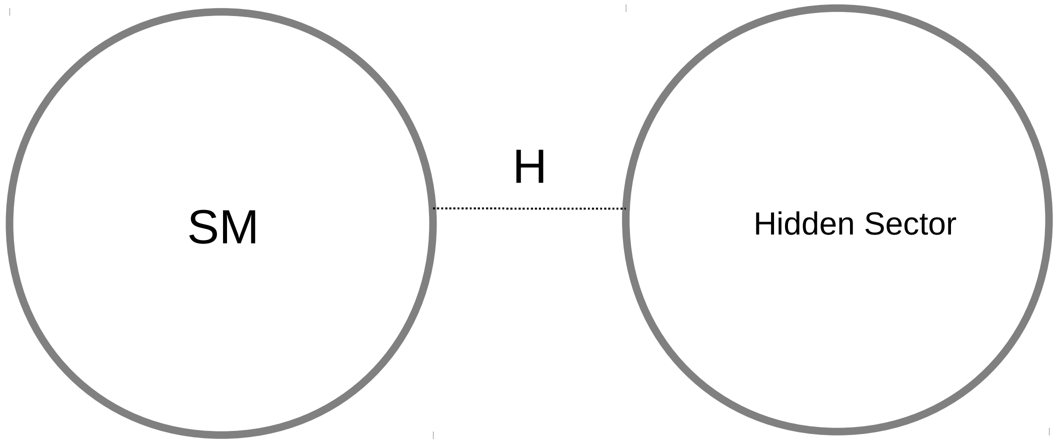
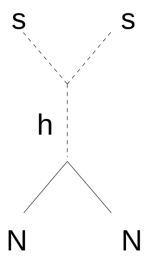
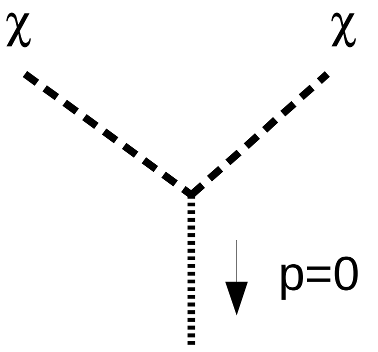




→ *strong constraints on a WIMP*

Main Goldstone feature:

derivative couplings $\partial\chi$ ...



$= \quad 0$

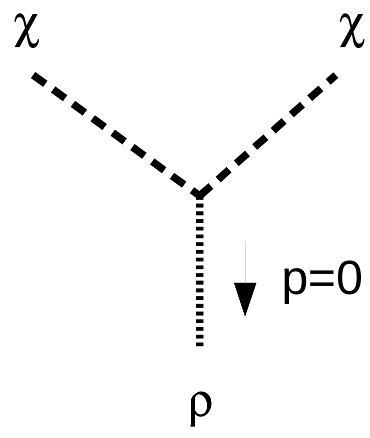
Perfect for χ – dark matter:

– no direct detection
– efficient annihilation (p≠0)

Massive ``Goldstone´´ case:

$$L = \partial_\mu S\, \partial^\mu S^* - m^2 SS^* + (\mu^2 S^2 + h.c.) - V(SS^*)$$

$S = \rho\, e^{i\chi}$ (χ = *pseudo-Goldstone boson with mass ~* μ)



$\sim \chi\, \rho\, (\Box + 4\,\mu^2)\, \chi = 0$ **(EOM)**

Still works! (*NB: only for an* S^2 *soft term)*

Pseudo-Goldstone dark matter

SM + a complex scalar *S*, require softly broken U(1) symmetry:

$$V = V_0 + V_{\rm soft} \ ,$$
$$V_0 = -\frac{\mu_H^2}{2}\,|H|^2 - \frac{\mu_S^2}{2}\,|S|^2 + \frac{\lambda_H}{2}|H|^4 + \lambda_{HS}|H|^2|S|^2 + \frac{\lambda_S}{2}|S|^4 \ ,$$
$$V_{\rm soft} = -\frac{\mu_S'^2}{4}\,S^2 + {\rm h.c.}$$

All parameters are real ⇨ <*S*> = real , ***S*** → ***S**** symmetry

Im *S* = Dark Matter

States:

$$S = \frac{1}{\sqrt{2}}(v_s + s + i\chi) \qquad H = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v+h \end{pmatrix}$$

CP-even mass eigenstates = ***h_1* , *h_2*** (mixtures of ***s*** and ***h***) :

$$O^T \mathcal{M}^2 O = \begin{pmatrix} m_{h_1}^2 & 0 \\ 0 & m_{h_2}^2 \end{pmatrix} \qquad O = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$$

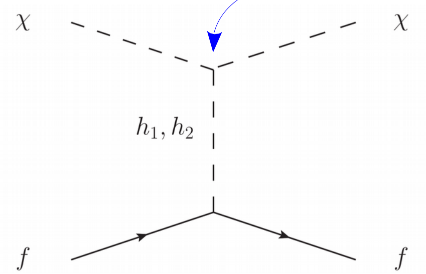
$$m_{h_1,h_2}^2 = \frac{1}{2}\left(\lambda_H v^2 + \lambda_S v_s^2 \mp \frac{\lambda_s v_s^2 - \lambda_H v^2}{\cos 2\theta}\right)$$

CP-odd mass eigenstate = dark matter χ :

$$m_\chi^2 = \mu'^2_S$$

Direct detection:

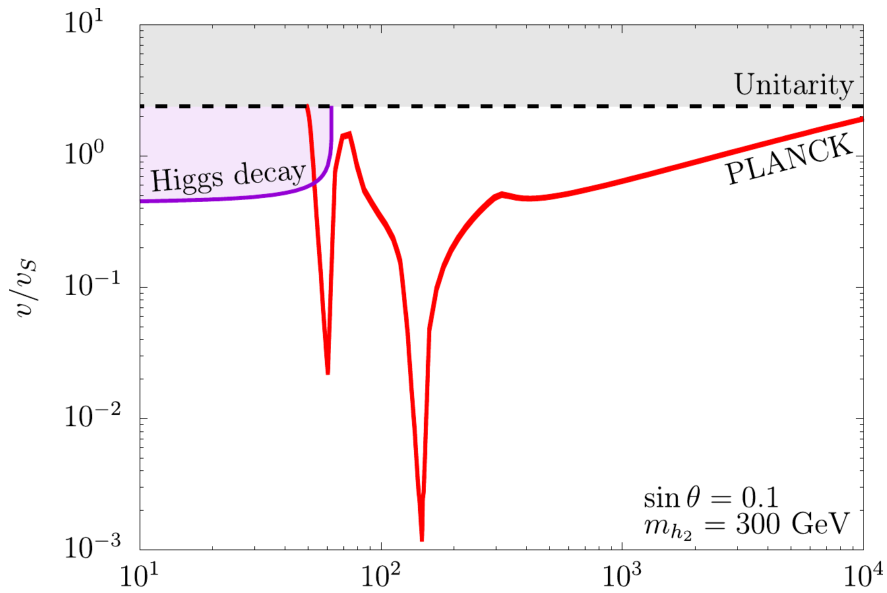
coupling$_i$ ~ m_i^2



Tree level:

$$\mathcal{A}_{dd}(t) \propto \sin\theta\cos\theta\left(\frac{m_2^2}{t-m_2^2}-\frac{m_1^2}{t-m_1^2}\right) \longrightarrow 0$$

Perfect cancellation for any parameter choice !



Direct detection = loop-suppressed

Annihilation = unsuppressed

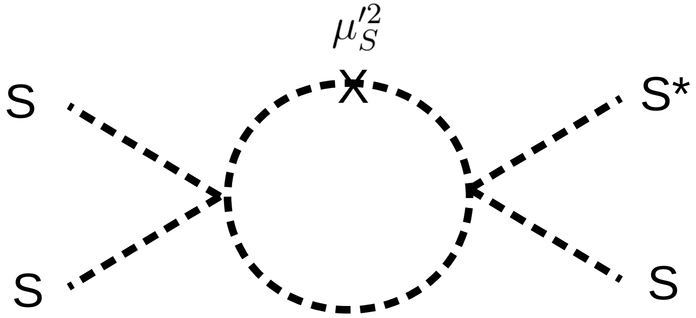
Excellent WIMP

(from 60 GeV to 10 TeV)

Loop corrections to the potential:

$$V_1 = \frac{\lambda'_{HS}}{2}|H|^2 S^2 + \frac{\lambda''_S}{4}|S|^2 S^2 + \frac{\lambda'_S}{4} S^4 + \text{h.c.}$$

$$\lambda'_{HS} = \frac{\lambda_{HS}\lambda_S}{32\pi^2}\ \ln\frac{\mu_S^2 + \mu_S'^2}{\mu_S^2 - \mu_S'^2}\ ,$$
$$\lambda''_S = \frac{\lambda_S^2}{8\pi^2}\ \ln\frac{\mu_S^2 + \mu_S'^2}{\mu_S^2 - \mu_S'^2}\ ,$$
$$\lambda'_S = \frac{\lambda_S^2}{64\pi^2}\ \left(\frac{\mu_S^2}{\mu_S'^2}\ln\frac{\mu_S^2 - \mu_S'^2}{\mu_S^2 + \mu_S'^2} + 2\right)$$



$\Rightarrow$ $\sigma \sim 10^{-49}\ \text{cm}^2$

Refined by Azevedo, Duch, Grzadkowski, Huang, Iglicki, Santos '18

Ishiwata, Toma '18

Couplings as spurions:

gauged U(1) + S + Φ :

$$\begin{cases} q_S = \text{even} \\ q_\Phi = \text{odd} \end{cases}$$

$$\Delta V \sim a\, S^2\, \Phi^n + b\, S^4\, \Phi^{2n} + \ldots$$

(no odd powers of S)

Here

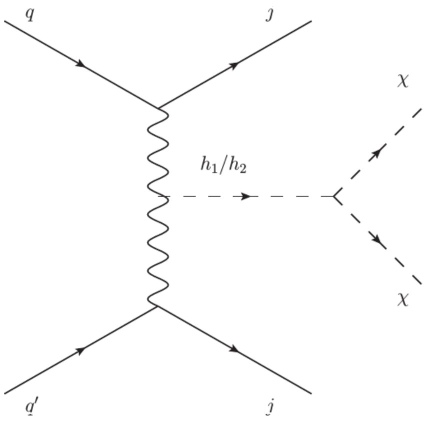
$$n \equiv -2\,\frac{q_S}{q_\Phi} \quad , \quad \epsilon \equiv \frac{\langle\Phi\rangle}{\Lambda}$$

$$\underbrace{\mu_S'^2 \sim \langle\Phi\rangle^2 \epsilon^{n-2}}_{\text{significant}} \quad , \quad \underbrace{\lambda'_{HS} \sim \lambda''_S \sim \epsilon^n \quad , \quad \lambda'_S \sim \epsilon^{2n}}_{\text{small}}$$

LHC search

Main signature: missing energy (via Higgs production)

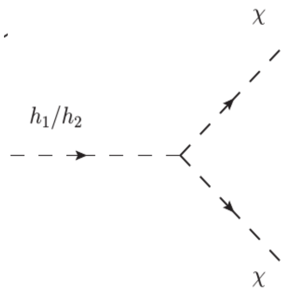
VBF:



BSM states: h_2, χ + (h_1)

The signal is significant only for **m_{h2}** or **$m_{h1} > 2\, m_{\chi}$**

invisible decay



Constraints:

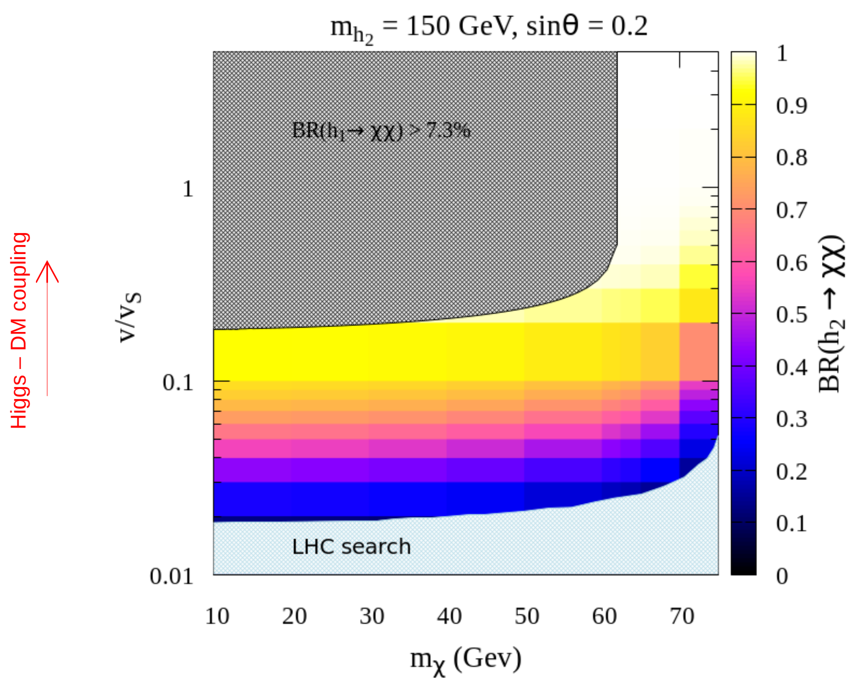
- h_1 Higgs signal strength $\mu = \cos^2\theta\,(1 - \mathrm{BR}_{\mathrm{inv}})$

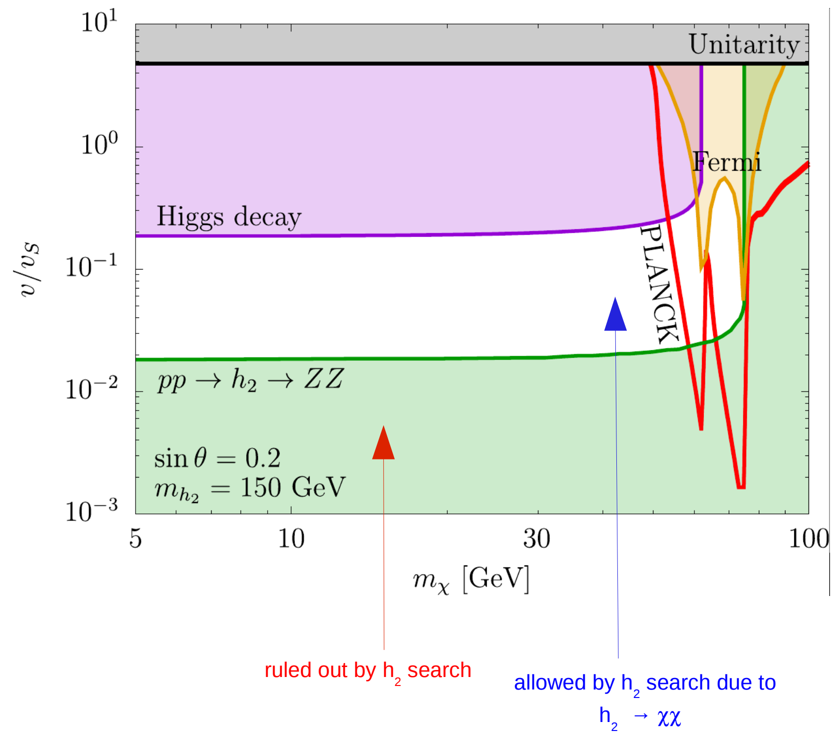
  → *θ - dependent bound on BR_{inv}*

- h_2 search

Example:

Use $\mu = 1.09^{+0.11}_{-0.10}$





– light h_2 allowed (e.g. ~ 150 GeV)

– h_2 invisible decay very efficient

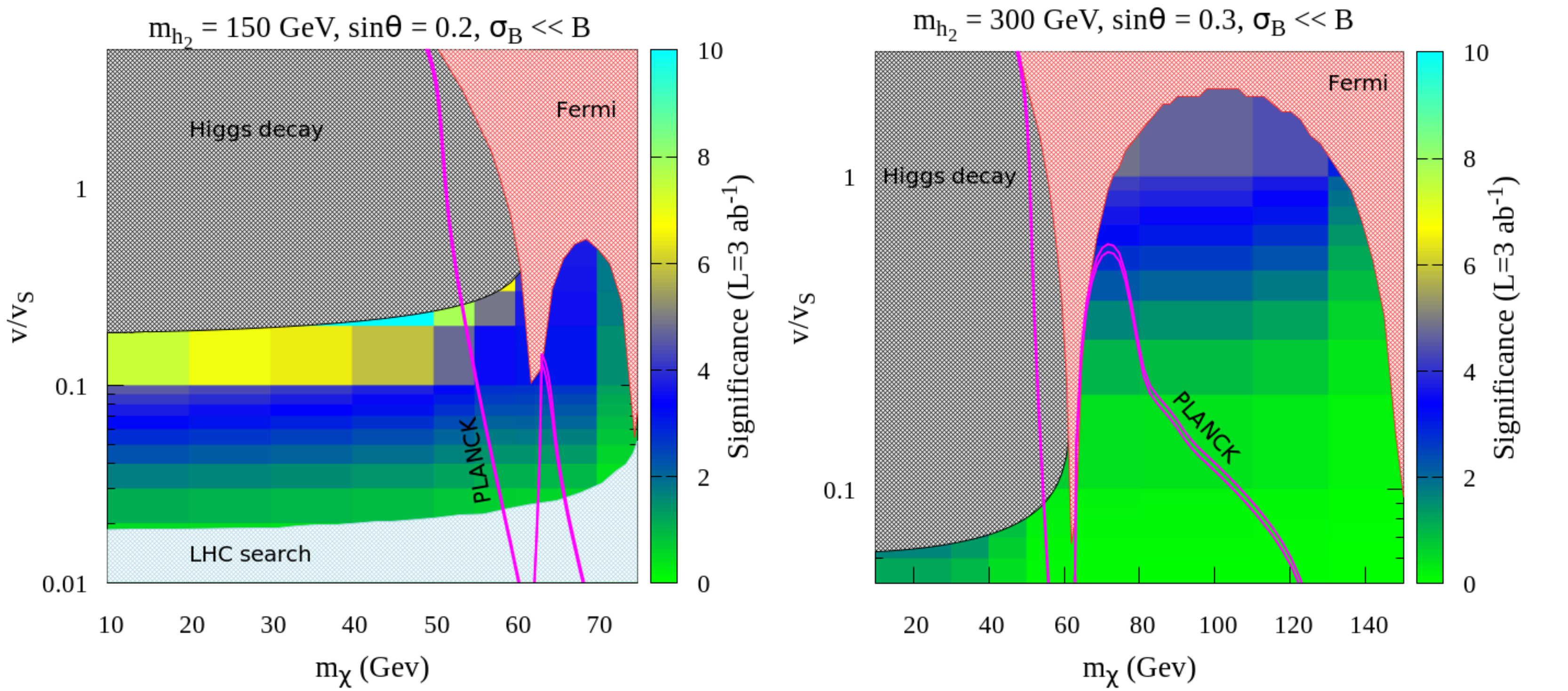
Signal selection (CMS, 13 TeV):

Observables	Requirements
Leading (trailing) jet	$p_T > 80(40)$ GeV, $\lvert\eta\rvert < 4.7$
$\not{E}_T$	> 250 GeV
$\Delta\phi(\vec{\not{E}}_T, \vec{p_T}^{\,\mathrm{jet}})$	> 0.5
$\lvert\Delta\phi_{jj}\rvert$	< 1.5
$\eta_{j1}.\eta_{j2}$	< 0
$\lvert\Delta\eta_{jj}\rvert$	> 4
$\lvert m_{jj}\rvert$	> 1300 GeV
Leptons	$N_{\mu,e} = 0$, $p_T > 10$ GeV, $\lvert\eta\rvert < 2.4(2.5)$
τ leptons	$N_{\tau_h} = 0$, $p_T > 10$ GeV, $\lvert\eta\rvert < 2.3$
Photons	$N_\gamma = 0$, $p_T > 15$ GeV, $\lvert\eta\rvert < 2.5$
b-jets	$N_b = 0$, $p_T > 20$ GeV, $\lvert\eta\rvert < 2.4$

Background: Z + jets, W + jets, ...

$$\mathcal{S} = \frac{S}{\sqrt{S + B + \sigma_B^2}}$$

Discovery potential at 3 ab^{-1}:



good prospects for non-thermal dark matter

Further studies:

– non–Abelian generalization Karamitros '19

– gravitational waves Kannike, Raidal '19

Conclusion

– very simple DM model: *SM + complex singlet*

– natural direct detection suppression: *pseudo–Goldstone nature*

– light DM < O(100) GeV can be probed at HL-LHC in *VBF +* $\not{E}_T$