Higgs implications for DM

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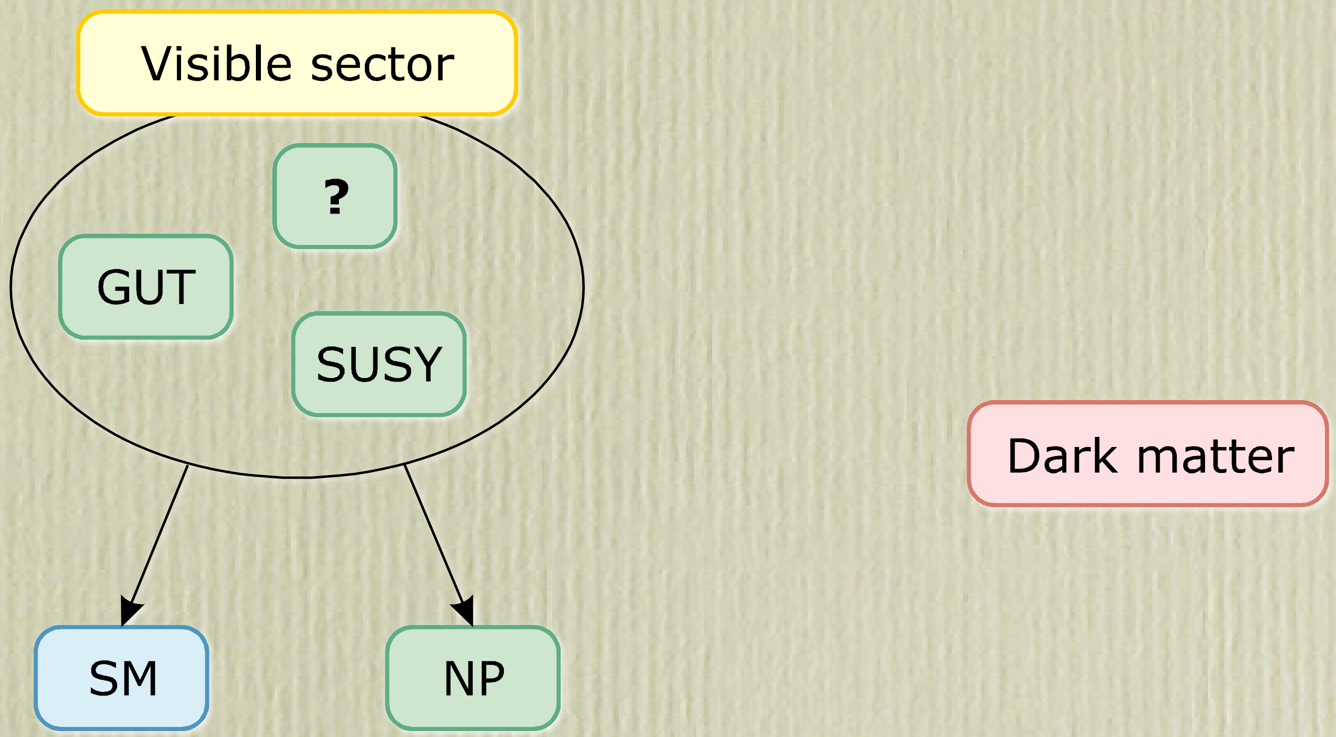
How to probe low-energy particle content?

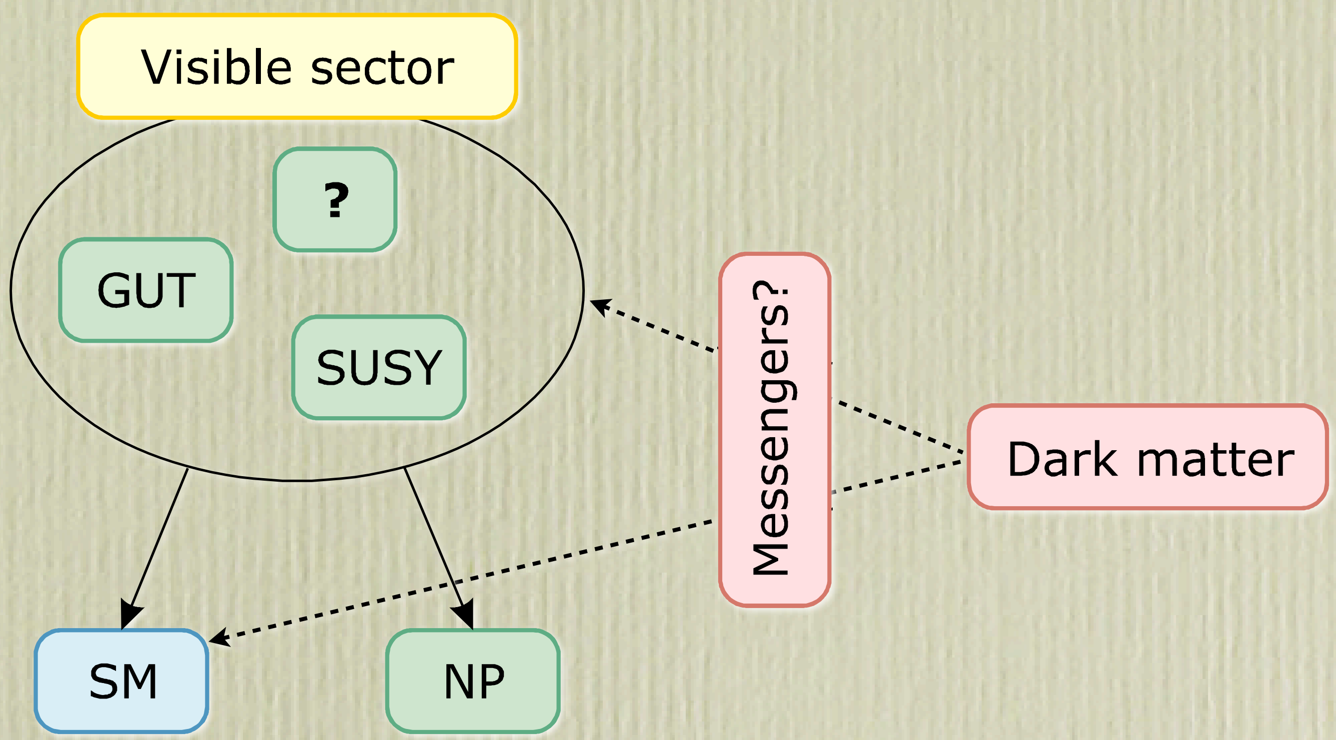


Heavy NP can be projected onto effective gauge-invariant operators built in terms of SM fields.

Buchmuller & Wyler, Nucl.Phys. B268 (1986) 621
Grzadkowski et al., arXiv:1008.4884

$$\mathcal{L}_{SM} + \frac{c_\nu}{\Lambda}(HL)^2 + \frac{c_i}{\Lambda^2} Q_i + \ldots$$

How to probe low-energy particle content?



X = dark matter state connected to the SM, or a light messenger.

J. F. K. & C. Smith, 1111.6402

$$\mathcal{L}_{SM} + \frac{c_\nu}{\Lambda}(HL)^2 + \frac{c_i}{\Lambda^2} Q_i + \ldots \quad + \sum_{d \geq 3} \frac{c_i}{\tilde{\Lambda}^{d-4}} Q'_i + \ldots$$

How to probe low-energy particle content?

Assumptions about the dark state X :

- Long-lived ⇒ Escapes as missing energy.
- Weakly coupled ⇒ Does not affect SM processes.

⇒ Main impact is then to open new decay and production channels.

What a light Higgs could tell?

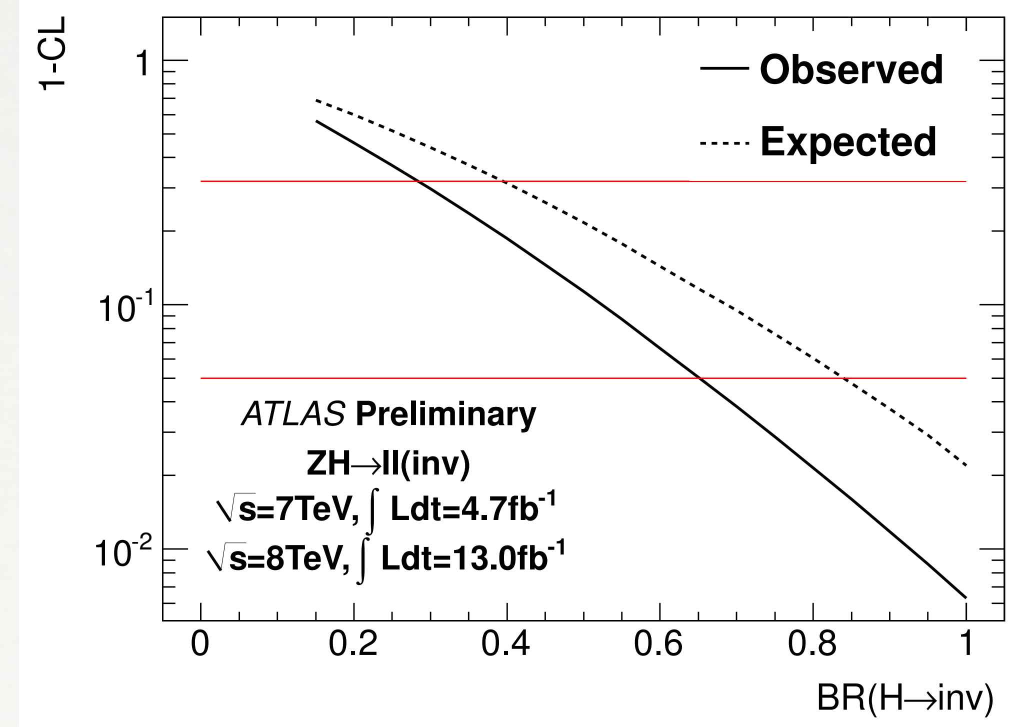
J. F. K. & C. Smith, 1201.4814
Greljo, Julio, J.F.K., Smith & Zupan, 1309.3561

What a light Higgs could tell?

- In SM BR(h→inv) ~ 0.1%
- Testing invisible Higgs decays directly is notoriously difficult
- Assuming SM ZH production rate: BR(h→inv) < 0.58

CMS, 1404.1344

ATLAS-CONF-2013-011, 1402.3244



see also talk by R. Wang

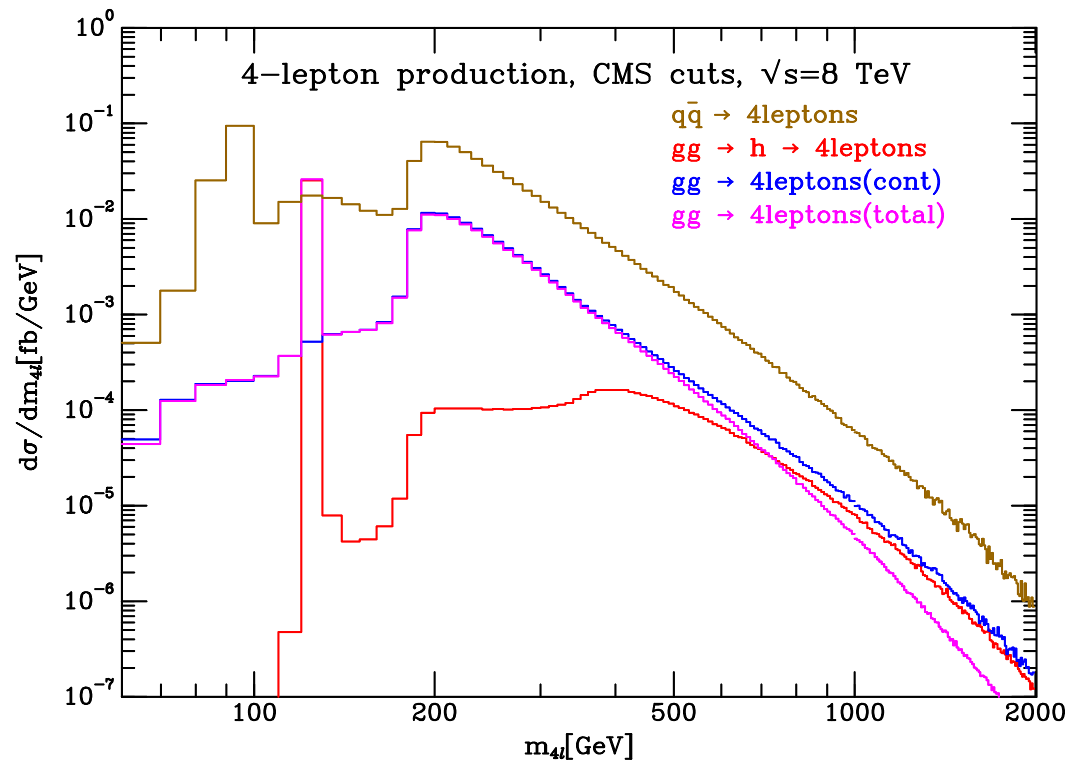
What a light Higgs could tell?

- Total width of light SM Higgs boson difficult to measure at LHC ($\Gamma(h)_{SM} \sim 4 \times 10^{-3}$ GeV)
- Using off-shell interference effects in the ZZ^* channel $\Gamma(h)/\Gamma(h)_{SM} < 5.4$

CMS, 1405.3455

- Can be translated to BR(h→inv) < 0.84

Campbell, Ellis & Williams, 1311.3589

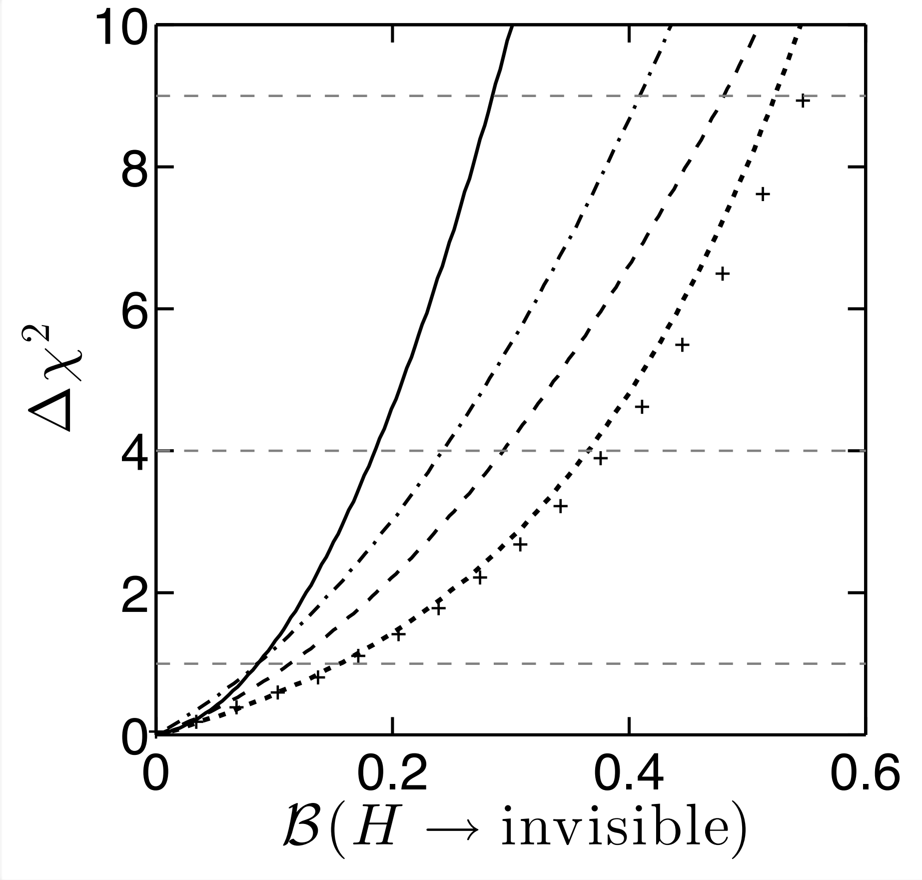


What a light Higgs could tell?

- Indirect constraints on BR(h→inv) < 0.2 - 0.4 from global fits to Higgs signal yields

- subject to assumptions on NP effects in h→VV, h→ff.

Belanger et al., 1306.2941



Crosses: varying $\varkappa_U$, $\varkappa_D$, $\varkappa_V$, $\Delta\varkappa_g$ and $\Delta\varkappa_\gamma$.
Dotted: varying $\varkappa_U$, $\varkappa_D$ and $\varkappa_V$ for $\Delta\varkappa_g = \Delta\varkappa_\gamma = 0$.
Dashed: varying $\Delta\varkappa_g$ and $\Delta\varkappa_\gamma$ for $\varkappa_U = \varkappa_D = \varkappa_V = 1$.
Dot-dashed: varying $\varkappa_U$, $\varkappa_D$ and $\varkappa_V \leq 1$ for $\Delta\varkappa_g = \Delta\varkappa_\gamma = 0$.

$\varkappa_X = g_X/g_X^{SM}$

What a light Higgs could tell?

- A light Higgs is very narrow in the SM:

$$\frac{\Gamma_h^{SM}}{M_h} \approx 3 \times 10^{-5} \quad \text{(comparable to } \Gamma_{J/\psi}/M_{J/\psi}\text{)}$$

What a light Higgs could tell?

- A light Higgs is very narrow in the SM:

$$\frac{1}{5} \times \frac{\Gamma_h^{SM}}{M_h} \gtrsim \frac{\Gamma_h^{dark}}{M_h} \sim \frac{1}{8\pi}\left(\frac{M_h^2}{\Lambda_d^2}\right)^{d-4} \quad \Rightarrow \Lambda_5 \gtrsim 10 \text{ TeV} \ , \ \Lambda_6 \gtrsim 1.1 \text{ TeV}$$

(assuming 2-body kinematics)

possible to probe relatively high NP scales

$$\mathcal{L} \ni \frac{1}{\Lambda_d^{(d-4)}}[\mathcal{Q}_h \times \mathcal{Q}_{dark}]^{(d)}$$

What a light Higgs could tell?

- A light Higgs is very narrow in the SM
- Lorentz scalar - can couple to most operator structures

$$H^\dagger H \to \frac{1}{2}(v^2 + 2vh + h^2)$$

$$H^\dagger \overleftrightarrow{D}_\mu H \to \frac{ig}{2c_W}(v+h)^2 Z_\mu$$

$$\bar{u}HQ \to \frac{1}{\sqrt{2}}(v+h)\bar{u}_R u_L$$

...

$$HL \to \frac{1}{\sqrt{2}}(v+h)\nu$$

when $H \to \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v+h \end{pmatrix}$

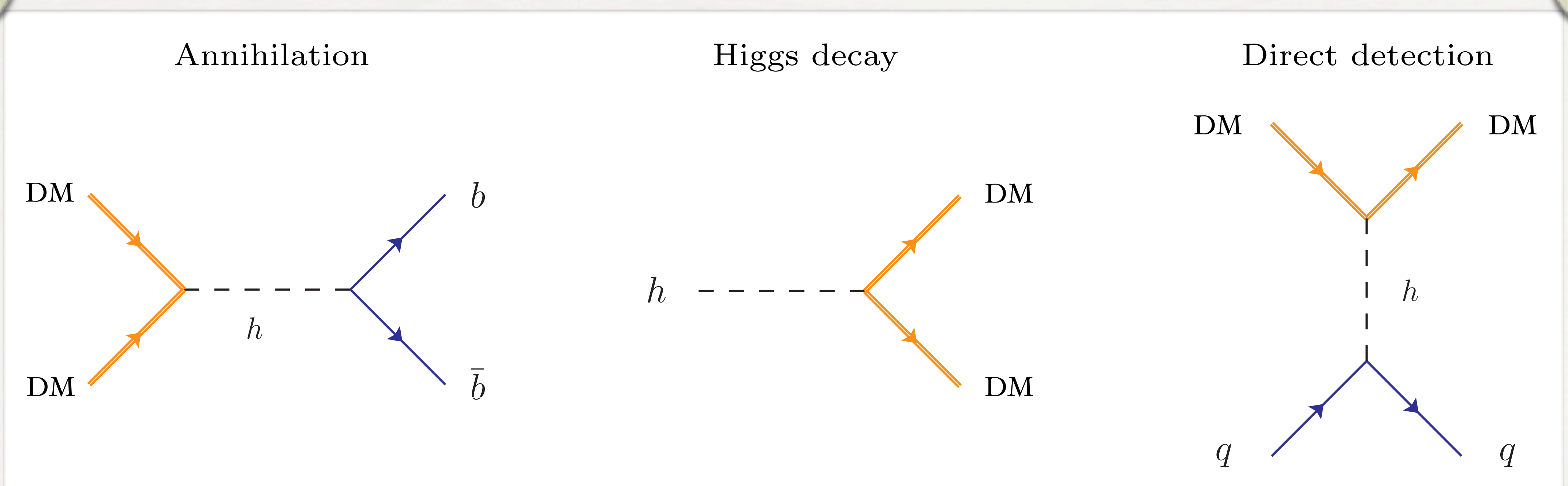
Higgs portals to DM

- Higgs boson could act as mediator of DM-SM interactions

Silveira & Zee, Phys. Lett. B161 (1985) 136
Shrock & Suzuki, Phys. Lett. B110 (1982) 250

$$\mathcal{Q}_{H-\mathrm{DM}} \sim H^\dagger H \times \mathcal{Q}_{\mathrm{DM}}$$

- Subject to several nontrivial constraints



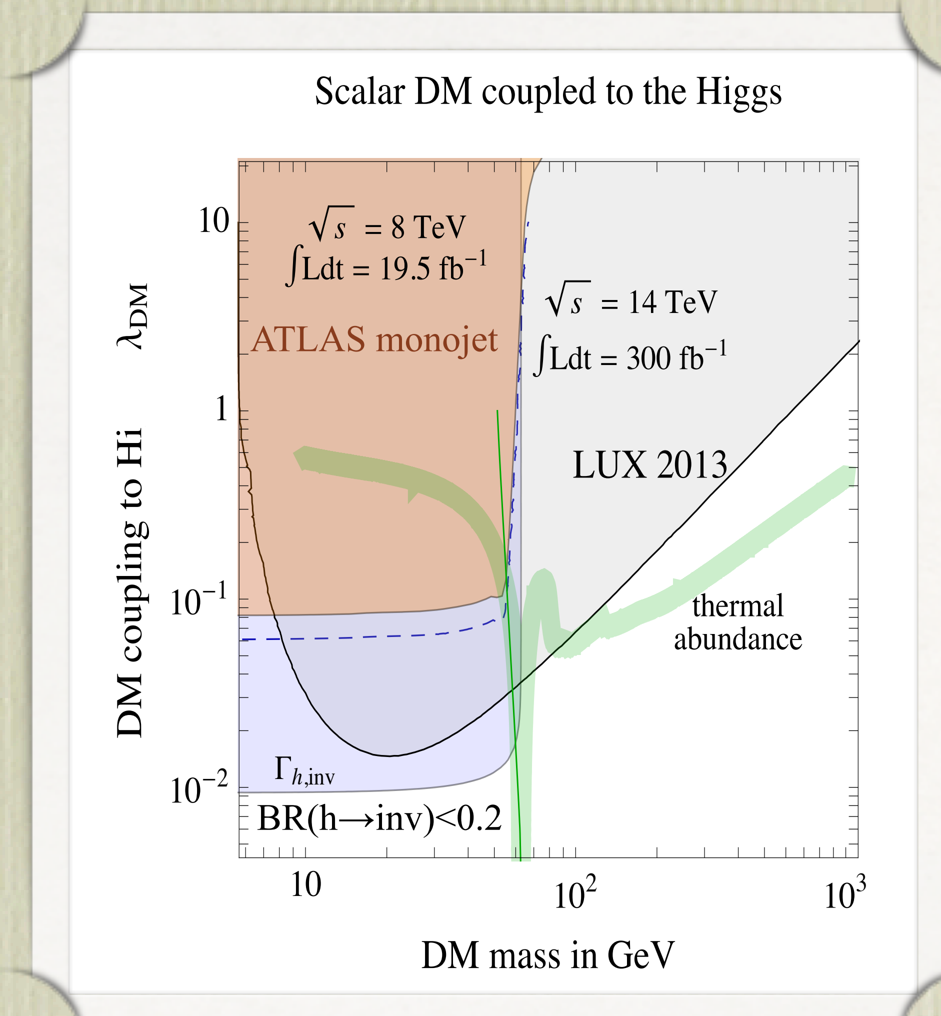
Higgs portals to DM

Example: renormalizable portal to scalar DM

$$\mathcal{H}^0_{eff} = \lambda' H^\dagger H \times \phi^\dagger \phi$$

- Ω_{DM} requires $\lambda' \gtrsim 0.1$
- for $m_{DM} < m_h/2$, BR(h→inv) imposes $\lambda' < y_b \sim 0.02$
- for larger m_{DM} accessible via direct detection

see also Lebedev et al. 1111.4482, Mambrini 1106.4819, Djouadi et al. 1112.3299, 1205.3169, Lopez-Honorez, Schwetz & Zupan, 1203.2064, Cline et al., 1306.4710, ...



De Simone, Giudice & Strumia, 1402.6287

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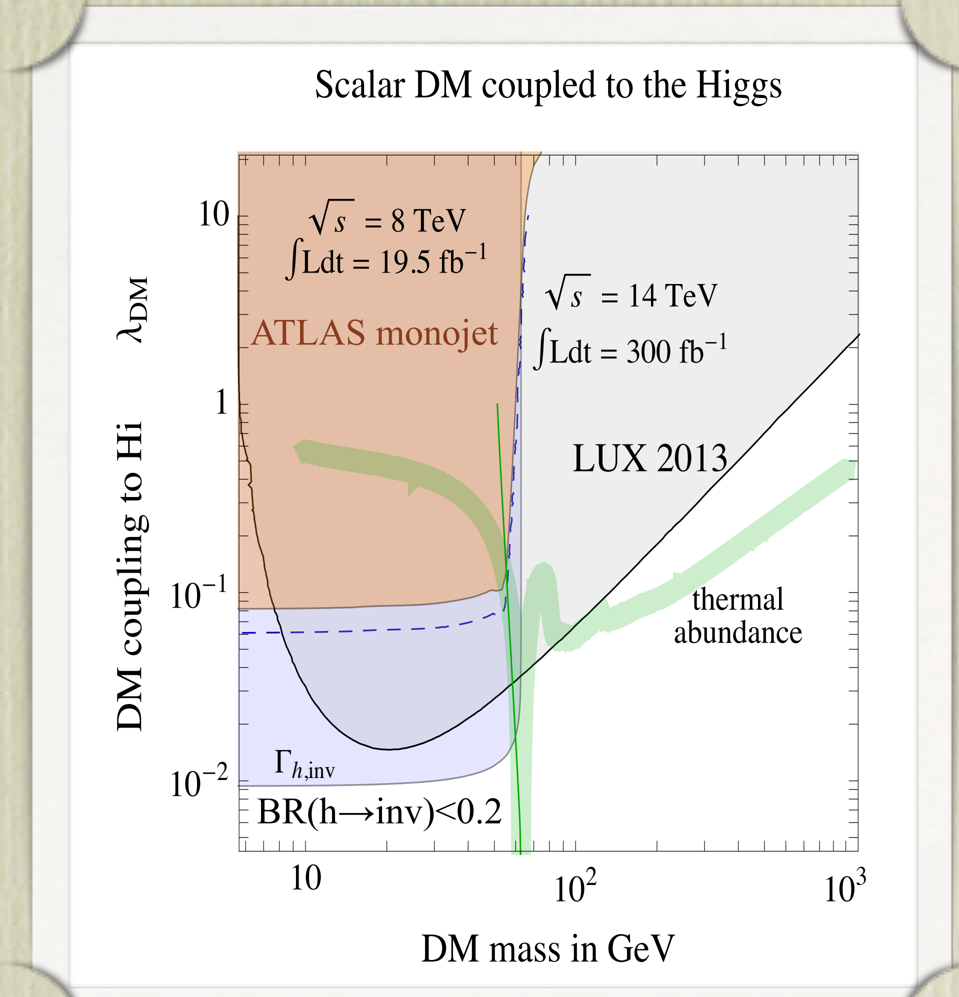

De Simone, Giudice & Strumia, 1402.6287

All lowest dimensional HP operators excluded (for $m_{DM} < m_h/2$)

Saving Higgs portals to light DM

Can light DM which couples predominantly to the Higgs be reconciled with its tiny width (and other exp. constraints)?

Beyond minimal Higgs portal

Scaling of thermal x-section & constraints with HP operator dimension (n)

$$\mathcal{H}_{\rm eff} \sim \sum_n \frac{1}{\Lambda^n} \mathcal{Q}^{(n)}_{H-{\rm DM}}$$

$$\langle \sigma_{\rm ann.} v \rangle \sim \frac{y_f^2}{32\pi} \left(\frac{m_h}{\Lambda}\right)^{2n} \left(\frac{m_{\rm DM}}{m_h}\right)^k G_F$$ (controls relic abundance)

$$\mathcal{B}(h \to {\rm invisible}) \sim 10^3 \left(\frac{m_h}{\Lambda}\right)^{2n}$$ (assuming 2-body h decays)

$$\frac{\langle \sigma_{\rm dir} \rangle}{\langle \sigma_{\rm dir} \rangle_{\rm excl.}} \sim 10^2 \left(\frac{m_h}{\Lambda}\right)^{2n} \left(\frac{m_{\rm DM}}{m_h}\right)^m \beta^{2m'}$$ (XENON100 bound)

$\beta \sim 10^{-3}$ (DM velocity)

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Presently for light DM Higgs constraints stronger than direct DM detection for any operator dimension

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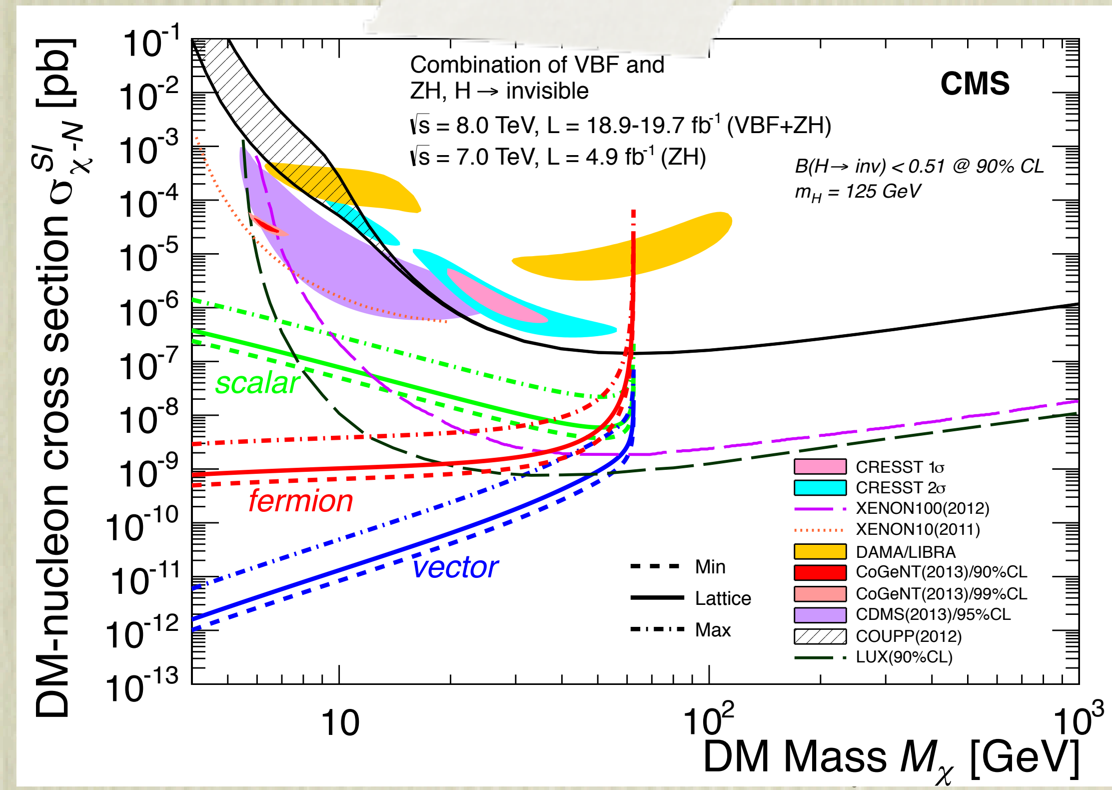

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$$\mathcal{H}_{\text{eff}} \sim \sum_n \frac{1}{\Lambda^n} \mathcal{Q}^{(n)}_{H-\text{DM}}$$

$$\langle \sigma_{\text{ann.}} v \rangle \sim \frac{y_f^2}{32\pi} \left(\frac{m_h}{\Lambda} \right)^{2n} \left(\frac{m_{\text{DM}}}{m_h} \right)^k G_F$$

(controls relic abundance)

$$\mathcal{B}(h \to \text{invisible}) \sim 10^3 \left(\frac{m_h}{\Lambda} \right)^{2n}$$

(assuming 2-body h decays)

$$\left(\frac{\mathcal{B}_h^{\text{invis.}}}{\langle \sigma_{\text{ann.}} v \rangle} \right)_n \sim \left(\frac{m_h}{m_{\text{DM}}} \right)^{k-k_{\min}} \left(\frac{\mathcal{B}_h^{\text{invis.}}}{\langle \sigma_{\text{ann.}} v \rangle} \right)_{n_{\min}}$$

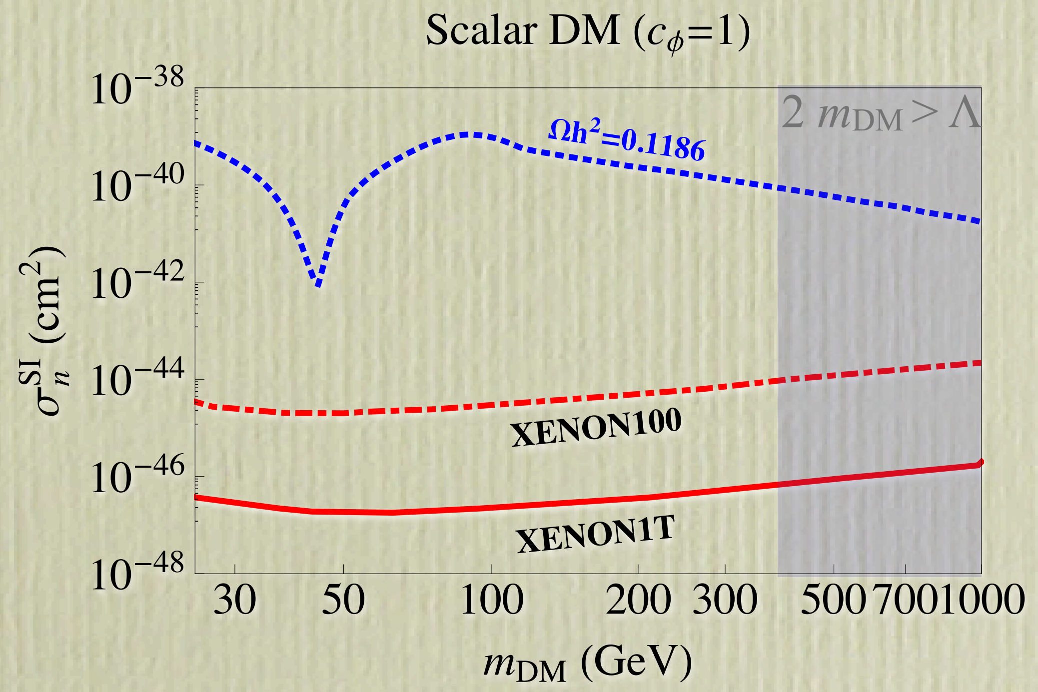
$k \geq k_{\min}$ for $n > n_{\min}$

Higgs constraints can only become stronger for higher dimensional HP operators

Beyond minimal Higgs portal

Circumvent Higgs bound via multi-body decay modes

1. couple to Higgs current: $H^\dagger \overleftrightarrow{D}_\mu H \to \frac{ig}{2c_W}(v+h)^2 Z_\mu$ ("Z portal")



Example:

$$\mathcal{H}^0_{\rm eff} = \frac{c_\phi}{\Lambda^2} H^\dagger \overleftrightarrow{D}_\mu H \times \phi^\dagger \overleftrightarrow{\partial}^\mu \phi$$

All possibilities excluded by direct detection experiments

Beyond minimal Higgs portal

Circumvent Higgs bound via multi-body decay modes

2. fermionic bilinears

$$\Gamma^S = H^\dagger \bar{D} Q, \;\; H^\dagger \bar{E} L, \;\; H^{*\dagger} \bar{U} Q, \qquad \Gamma^T_{\mu\nu} = H^\dagger \bar{D} \sigma_{\mu\nu} Q, \;\; H^\dagger \bar{E} \sigma_{\mu\nu} L, \;\; H^{*\dagger} \bar{U} \sigma_{\mu\nu} Q$$

- need to specify flavor structure of DM-SM couplings
- generically severe FCNC constraints

Simplest possibility: assume MFV

$\Rightarrow \;\; \mathcal{B}(h \to \mathrm{DM} + \mathrm{DM} + b\bar{b}) \sim \mathcal{O}(10^{-7})$ (for thermal relic DM, m_{DM}~20GeV)

Beyond minimal Higgs portal

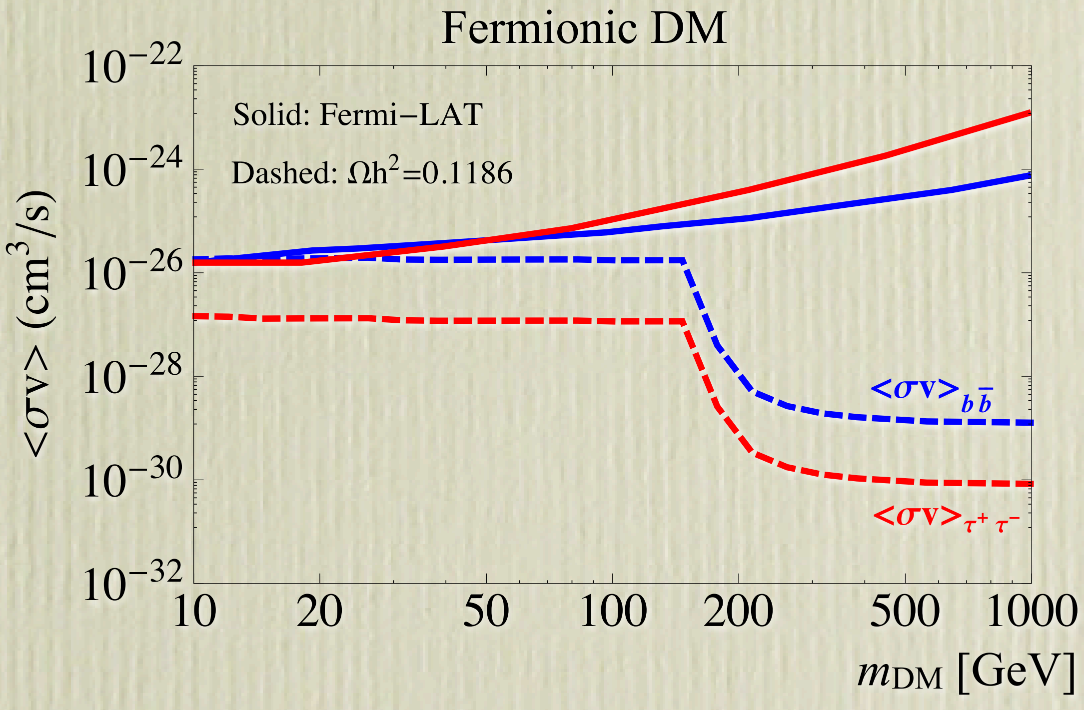
Circumvent Higgs bound via multi-body decay modes

2. fermionic bilinears

- severe direct detection bounds (can be avoided for leptophilic DM)
- indirect constraints still relevant

Example:

$$\mathcal{H}_{\text{eff}}^{1/2} = \frac{\sqrt{2} m_f}{v \Lambda^3} \Gamma_f^S \times i \bar{\psi} \gamma_5 \psi$$



Beyond minimal Higgs portal

Circumvent Higgs bound via multi-body decay modes

3. neutrino portals: $\mathcal{Q}_{H-\mathrm{DM}} \sim L^i L^j H^k H^l \epsilon_{ik}\epsilon_{jl} \times \mathcal{Q}_{\mathrm{DM}}$

In general severe neutrino mass constraints - can be avoided via:

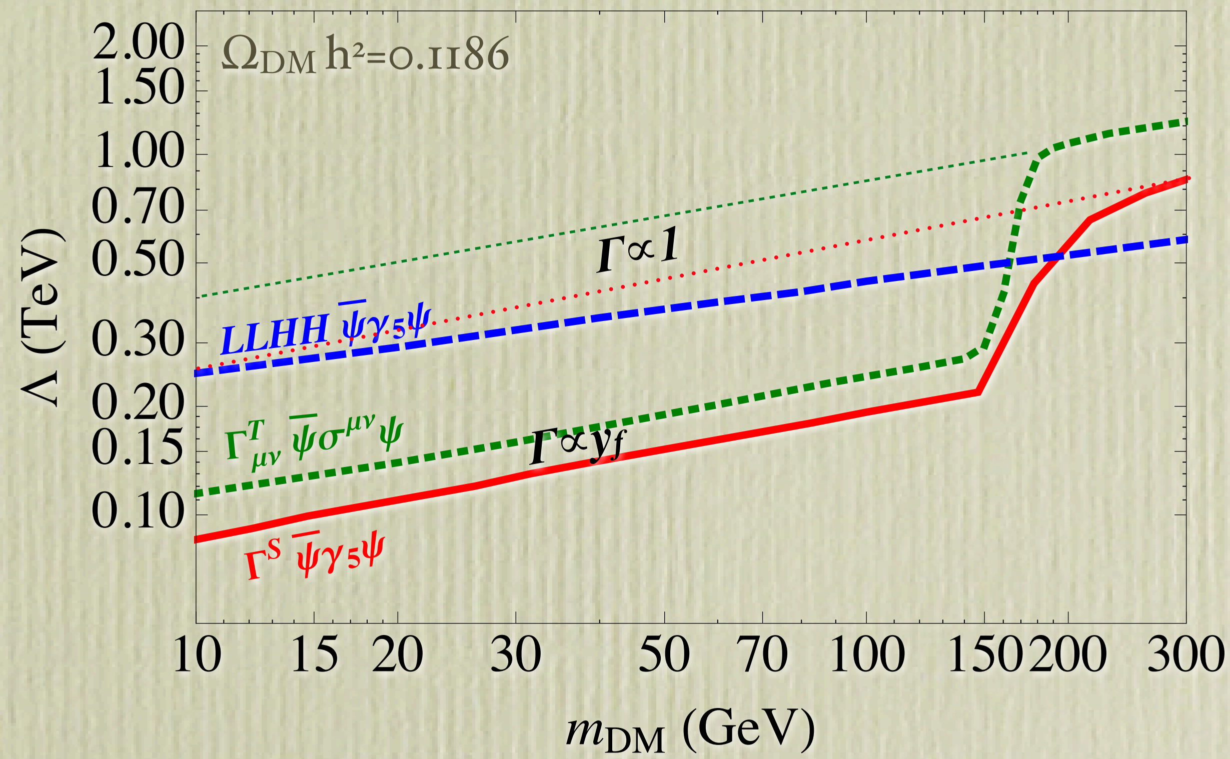
- parity invariance (purely pseudoscalar DM coupling, $\bar{\psi}\gamma_5\psi$)
- lepton number conservation (DM charged under it, $\bar{\psi}^C\psi$)

DM-nucleon x-sections severely suppressed - no direct constraints

$\Rightarrow \quad \mathcal{B}(h \to \mathrm{DM} + \mathrm{DM} + \bar{\nu}\bar{\nu}) \simeq 10^{-7}$ (for thermal relic DM, m_{DM}~20GeV)

Beyond minimal Higgs portal

Generic implication of viable extended Higgs portals?



Correct relic abundance requires low Λ - O(few 100 GeV)

⇒ new particles with weak scale masses beside DM with possibly non-trivial flavor interactions!

Example I: THDM II + DM

THDM II + DM

- Simplest realization of extended HP using fermionic bilinears

- Extended scalar sector + 2 x Z_2

He et al., 0811.0658
Bai et al., 1212.5604
...

$$H_1 \sim (1,2,1/2)\ , \quad H_2 \sim (1,2,1/2)\ , \quad S \sim (1,1,0)$$

(generates m_d,m_e), (generates m_u) (DM)

- After EWSB $\begin{pmatrix} H \\ h \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} h_1 \\ h_2 \end{pmatrix}$ $\tan\beta \equiv v_2/v_1$

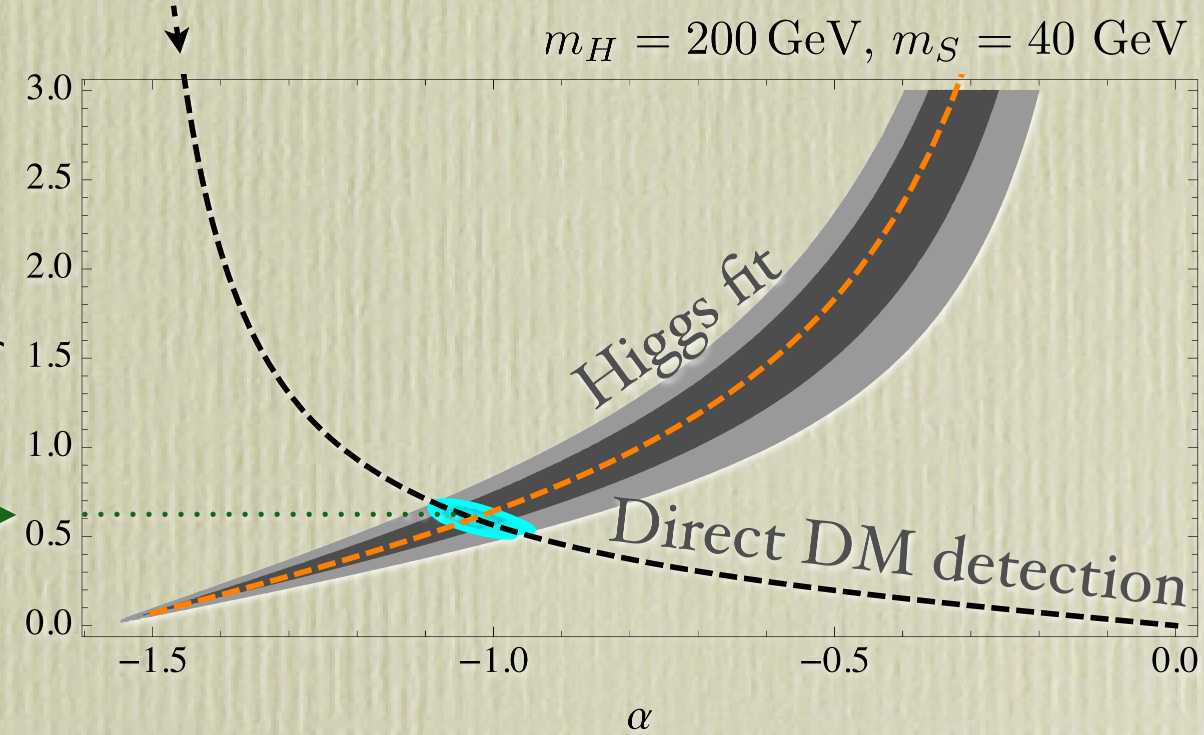
  - α, β completely determine *h*, *H* couplings to SM gauge bosons, fermions

THDM II + DM

Vanishing $\Gamma(h \to SS)$ and σ_p^{SI}.

Cancellation among

$\bar{u}\tilde{H}_2 Q S^2 \quad \bar{d} H_1 Q S^2$



h couplings to gauge bosons SM like: $\beta - \alpha = \pi/2$

Perturbativity of the HSS coupling requires: $m_H \lesssim 450\ \text{GeV}$

LHC monojet searches

Englert et al., 1111.1719

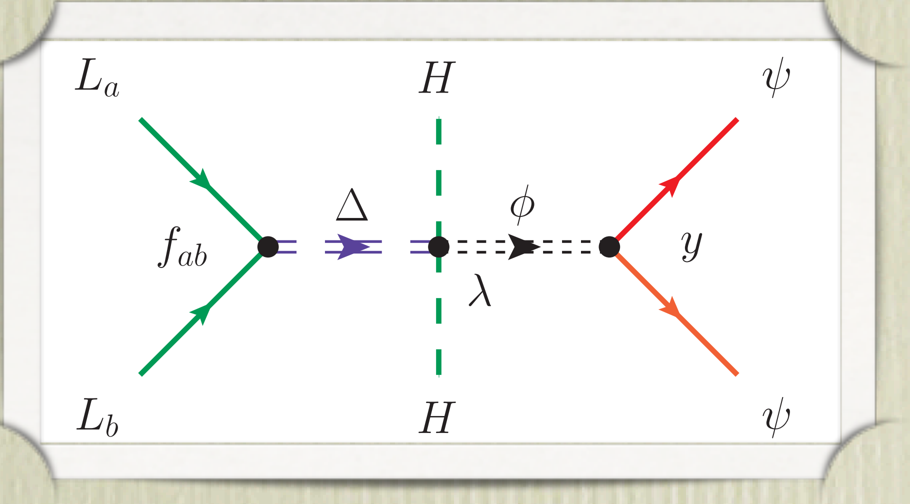
$$\frac{\sigma_{gg\to Hj} \times \mathcal{B}(H \to \text{inv.})}{\sigma^{SM}_{gg\to hj}\big|_{m_h=m_H}} \simeq 3$$

Example II: Neutrino portal

Neutrino portal

- Toy model for generating $L^i L^j H^k H^l \epsilon_{ik}\epsilon_{jl} \times \bar{\psi}^C \psi$
- Fermion DM + 2 scalars (all charged under LN)

$\psi \sim (1,1,0)$, $\phi \sim (1,1,0)$,
(DM)
$\Delta \sim (1,3,1)$



- Need to suppress leading HP operator by hand

Neutrino portal

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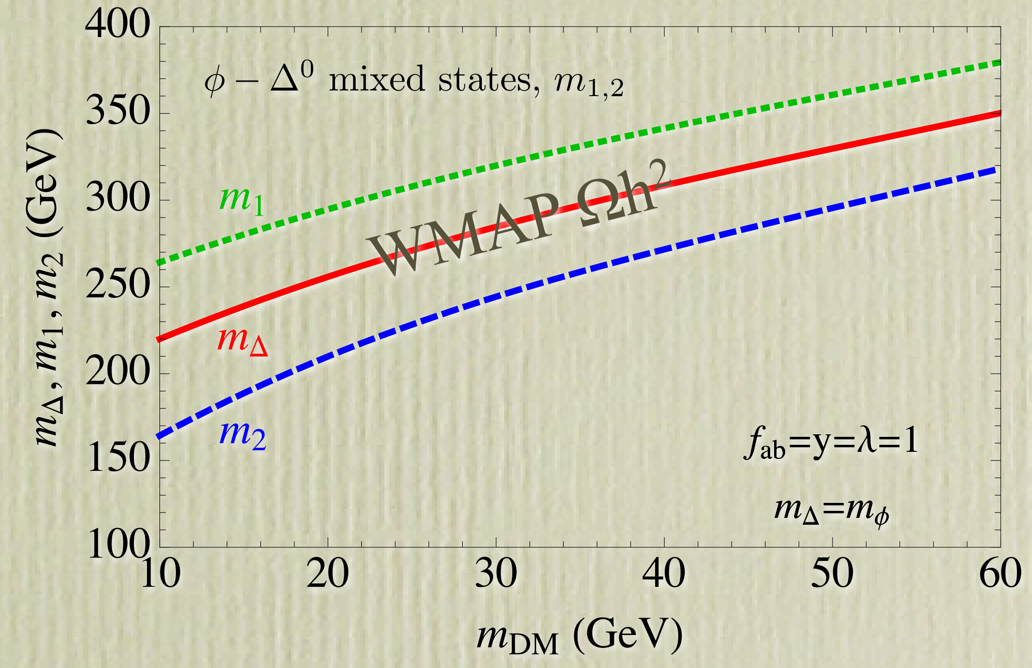

- Severe LFV constraints on off-diagonal f_{ab}
- Direct LHC searches for Δ assume f_{aa}=konst.: $m_\Delta > 403$ GeV, CMS, 1207.2666

  can be relaxed to $m_\Delta > 204$ GeV if $f_{\tau\tau} >> f_{ee}, f_{\mu\mu}$

Example III: Singlet scalars

Singlet scalars

- Example where DM not lightest NP particle

$$\phi \sim (1,1,0)\,, \quad S \sim (1,1,0)\,.$$

(Z_2 odd DM)

Barger et al., 0811.0393
Arina et al., 1004.3953
Piazza & Pospelov, 1003.2313
...

- Higgs - singlet mixing via $\mu_2 H^\dagger H \phi$

$$h_1 = h\cos\alpha + \phi\sin\alpha\,,$$

$$h_2 = -h\sin\alpha + \phi\cos\alpha\,,$$

- Interesting when $m_{h_1}/2 > m_S > m_{h_2}$ with $m_{h_1} = 125\,\text{GeV}$

Singlet scalars

- h_2 couplings SM-like (reduced by $|\sin\alpha|$)
- $|\sin\alpha| < 0.1 - 0.2$ from LEP for $m_{h_2} \sim$ few 10GeV
- Ω_{DM} set by DM annihilation $SS \to h_2 h_2$
- Satisfies Higgs constraints for comparable SSh_1 and SSh_2 couplings
- Interesting LHC(b) phenomenology
    - $h_1 \to h_2\, h_2 \to 4b$ (possibly displaced) with Br ~ 0.2

see also Halyo et al., 1308.6213

Conclusions

- If light and long-lived "dark" particles exists:
  - Small width of a light Higgs offers unique window also well beyond minimal portals.
  - Worth to search also for deviations in missing energy modes, $h \to \not{E}$, $h \to \not{E} + (\gamma, Z)$, $h \to \not{E}$ + (fermions) .
  - Beyond threshold, can exploit mono-Higgs production

Petrov & Shepherd, 1311.1511
Carpenter et al., 1312.2592
Berlin, Lin & Wang, 1402.7074

Conclusions

- Could this state be the (thermal relic) dark matter constituent?
  - Couplings through minimal portals disfavored for light DM
  - Significant higher dim. HP interactions allowed only if not inducing h→DM DM
  - Light DM necessarily implies presence of additional new particles with masses below few 100GeV