# Comments on HP VDM : EFT vs. UV completions

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**DM@LHC WG**
**Nov 30 (2021)**

# Contents

- Models for HP VDM and SFDM : EFT vs. UV completions
- Higgs invisible decay width for VDM in the limit $m_V \to 0$
- Roles of Dark Higgs Boson in collider searches, indirect DM detections, direct detections, etc..
- Conclusion

# Higgs portal DM models

$$\mathcal{L}_{\rm scalar} = \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{1}{2} m_S^2 S^2 - \frac{\lambda_{HS}}{2} H^\dagger H S^2 - \frac{\lambda_S}{4} S^4$$

$$\mathcal{L}_{\rm fermion} = \overline{\psi}\left[i\gamma\cdot\partial - m_\psi\right]\psi - \frac{\lambda_{H\psi}}{\Lambda} H^\dagger H\,\overline{\psi}\psi$$

$$\mathcal{L}_{\rm vector} = -\frac{1}{4} V_{\mu\nu} V^{\mu\nu} + \frac{1}{2} m_V^2 V_\mu V^\mu + \frac{1}{4}\lambda_V (V_\mu V^\mu)^2 + \frac{1}{2}\lambda_{HV} H^\dagger H V_\mu V^\mu .$$

**All invariant under ad hoc Z2 symmetry**

arXiv:1112.3299, … 1402.6287, etc.

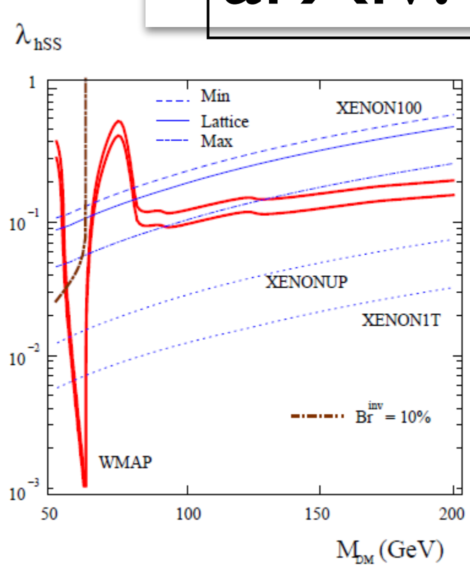



FIG. 1. Scalar Higgs-portal parameter space allowed by WMAP (between the solid red curves), XENON100 and $BR^{inv} = 10\%$ for $m_h = 125$ GeV. Shown also are the prospects for XENON upgrades.

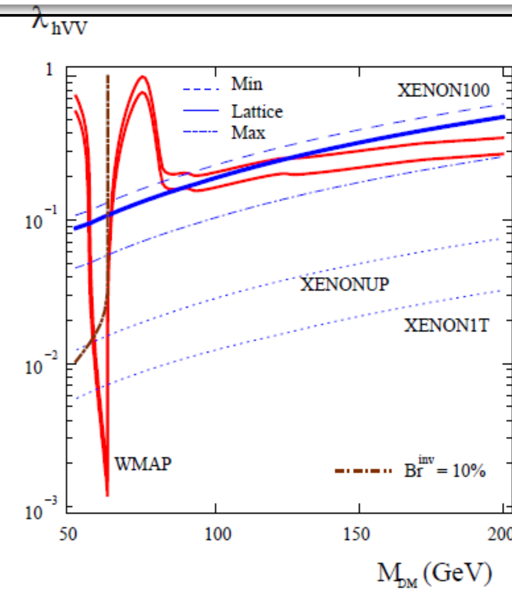



FIG. 2. Same as Fig. 1 for vector DM particles.

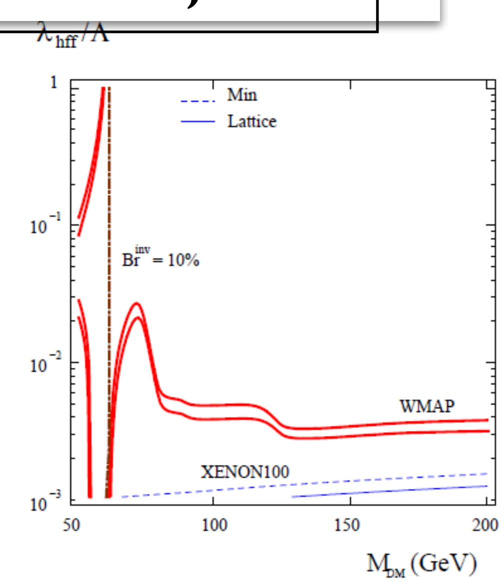



FIG. 3. Same as in Fig.1 for fermion DM; $\lambda_{hff}/\Lambda$ is in $\rm GeV^{-1}$.

# Higgs portal DM as examples

$$\mathcal{L}_{\rm scalar} = \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{1}{2} m_S^2 S^2 - \frac{\lambda_{HS}}{2} H^\dagger H S^2 - \frac{\lambda_S}{4} S^4$$

$$\mathcal{L}_{\rm fermion} = \overline{\psi}\left[ i\gamma\cdot\partial - m_\psi \right]\psi - \frac{\lambda_{H\psi}}{\Lambda} H^\dagger H \, \overline{\psi}\psi$$

$$\mathcal{L}_{\rm vector} = -\frac{1}{4} V_{\mu\nu} V^{\mu\nu} + \frac{1}{2} m_V^2 V_\mu V^\mu + \frac{1}{4}\lambda_V (V_\mu V^\mu)^2 + \frac{1}{2}\lambda_{HV} H^\dagger H V_\mu V^\mu .$$

All invariant under ad hoc Z2 symmetry

arXiv:1112.3299, … 1402.6287, etc.

**We need to include dark Higgs or singlet scalar to get renormalizable/unitary models for Higgs portal singlet fermion or vector DM**

**[NB: UV Completions : Not unique]**

$m_h = 125$ GeV. Shown also are the prospects for XENON upgrades.

FIG. 2. Same as Fig. 1 for vector DM particles.

FIG. 3. Same as in Fig.1 for fermion DM; $\lambda_{hff}/\Lambda$ is in GeV

**Talk by P. Fox for another UV completion**

# Models for HP SFDM & VDM

**UV Completion of HP Singlet Fermion DM (SFDM)**

$$\begin{aligned}\mathcal{L} \;=\;& \mathcal{L}_{\rm SM} - \mu_{HS} S H^\dagger H - \frac{\lambda_{HS}}{2} S^2 H^\dagger H \\ & + \frac{1}{2}(\partial_\mu S \partial^\mu S - m_S^2 S^2) - \mu_S^3 S - \frac{\mu_S'}{3} S^3 - \frac{\lambda_S}{4} S^4 \\ & + \overline{\psi}(i \not\partial - m_{\psi_0})\psi - \lambda S \overline{\psi}\psi\end{aligned}$$

**UV Completion of HP VDM**

$$\begin{aligned}\mathcal{L}_{VDM} =& -\frac{1}{4} X_{\mu\nu} X^{\mu\nu} + (D_\mu \Phi)^\dagger (D^\mu \Phi) - \frac{\lambda_\Phi}{4}\left(\Phi^\dagger \Phi - \frac{v_\Phi^2}{2}\right)^2 \\ & -\lambda_{H\Phi}\left(H^\dagger H - \frac{v_H^2}{2}\right)\left(\Phi^\dagger \Phi - \frac{v_\Phi^2}{2}\right) ,\end{aligned}$$

- **The simplest UV completions in terms of # of new d.o.f.**
- **At least, 2 more parameters, ( $m_\phi$ , $\sin\alpha$ ) for DM physics**

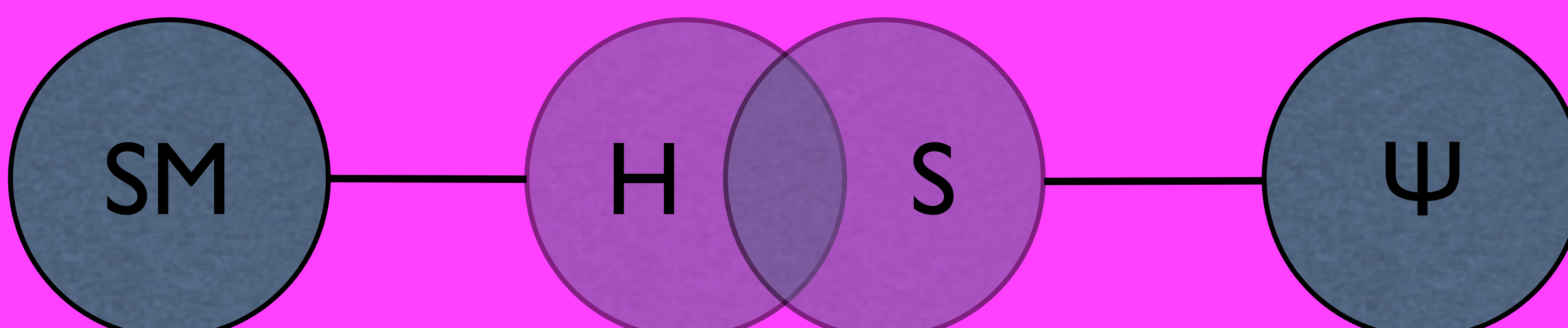
# UV Completion for HP FDM

Baek, Ko, Park, arXiv:1112.1847

$$\begin{aligned}\mathcal{L} &= \mathcal{L}_{\rm SM} - \mu_{HS} S H^\dagger H - \frac{\lambda_{HS}}{2} S^2 H^\dagger H \\ &+ \frac{1}{2}(\partial_\mu S \partial^\mu S - m_S^2 S^2) - \mu_S^3 S - \frac{\mu'_S}{3} S^3 - \frac{\lambda_S}{4} S^4 \\ &+ \overline{\psi}(i \not{\partial} - m_{\psi_0})\psi - \lambda S \overline{\psi}\psi\end{aligned}$$

mixing

invisible decay




Production and decay rates are suppressed relative to SM.

# Higgs-Singlet Mixing

- Mixing and Eigenstates of Higgs-like bosons

$$\mu_H^2 = \lambda_H v_H^2 + \mu_{HS} v_S + \frac{1}{2}\lambda_{HS} v_S^2,$$
$$m_S^2 = -\frac{\mu_S^3}{v_S} - \mu_S' v_S - \lambda_S v_S^2 - \frac{\mu_{HS} v_H^2}{2 v_S} - \frac{1}{2}\lambda_{HS} v_H^2,$$

at vacuum

$$M_{\rm Higgs}^2 \equiv \begin{pmatrix} m_{hh}^2 & m_{hs}^2 \\ m_{hs}^2 & m_{ss}^2 \end{pmatrix} \equiv \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} m_1^2 & 0 \\ 0 & m_2^2 \end{pmatrix} \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix}$$

$$H_1 = h\cos\alpha - s\sin\alpha,$$
$$H_2 = h\sin\alpha + s\cos\alpha.$$

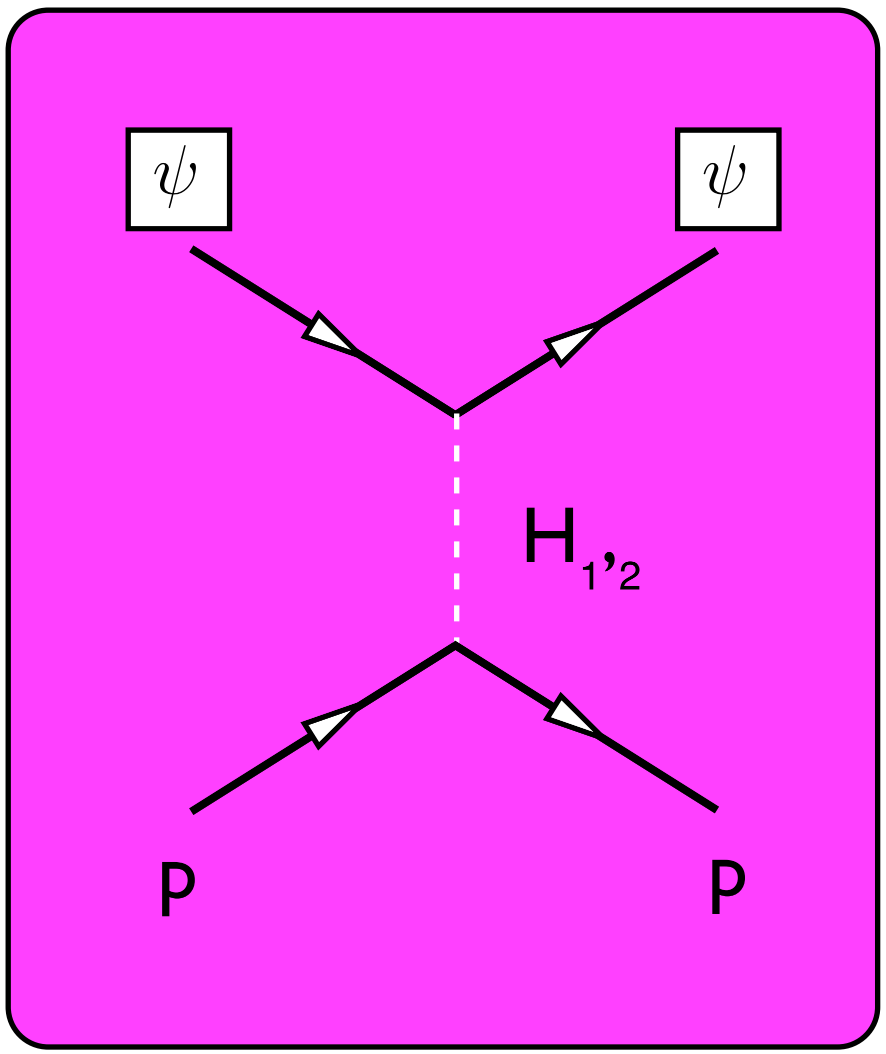
⇐ Mixing of Higgs and singlet

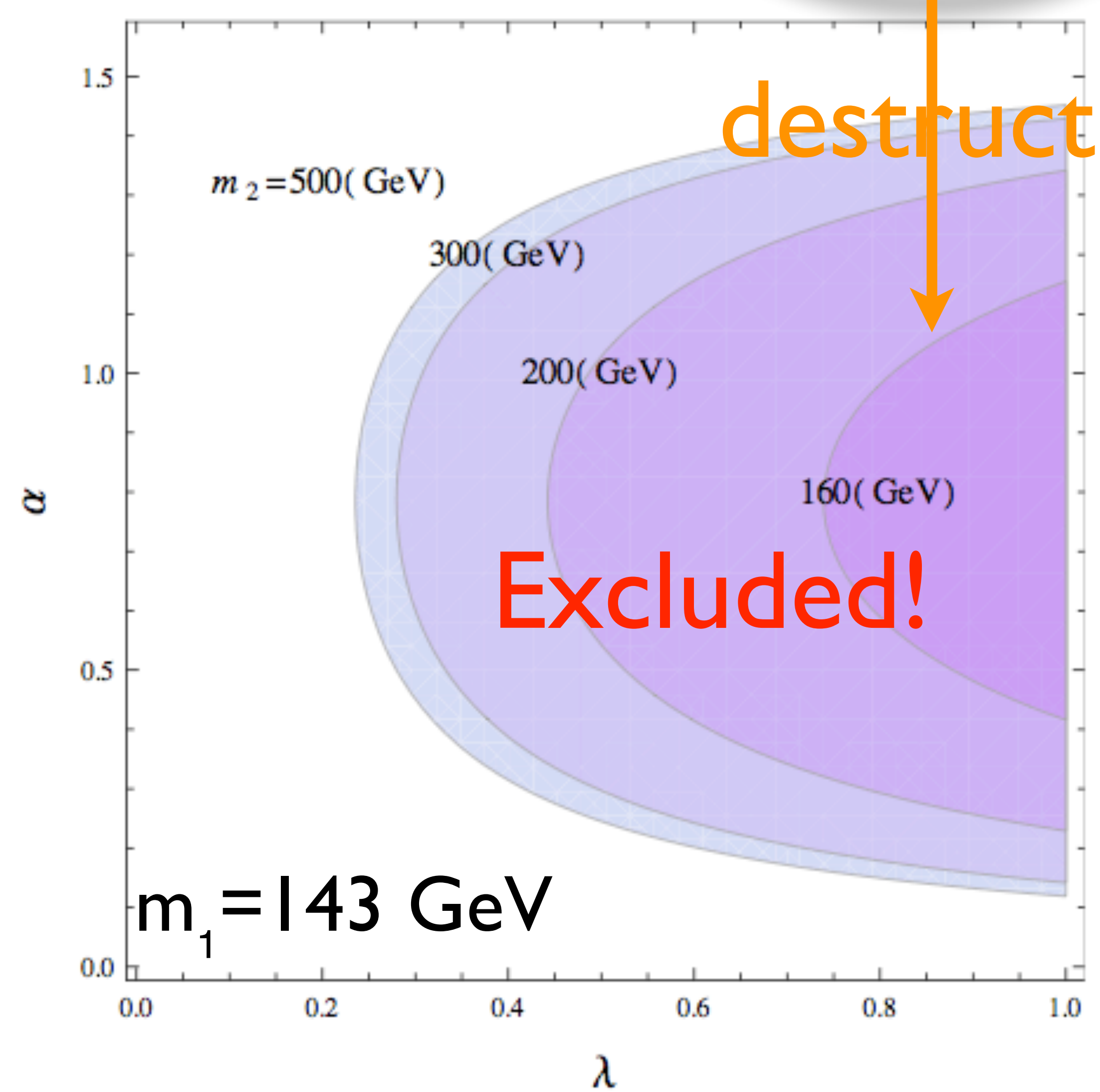
# Constraints

- Dark matter to nucleon cross section (constraint)

$$\sigma_p \approx \frac{1}{\pi}\mu^2\lambda_p^2 \simeq 2.7\times 10^{-2}\frac{m_p^2}{\pi}\left|\left(\frac{m_p}{v}\right)\lambda\sin\alpha\cos\alpha\left(\frac{1}{m_1^2}-\frac{1}{m_2^2}\right)\right|^2$$

destructive!



# Low energy pheno.

- Universal suppression of collider SM signals

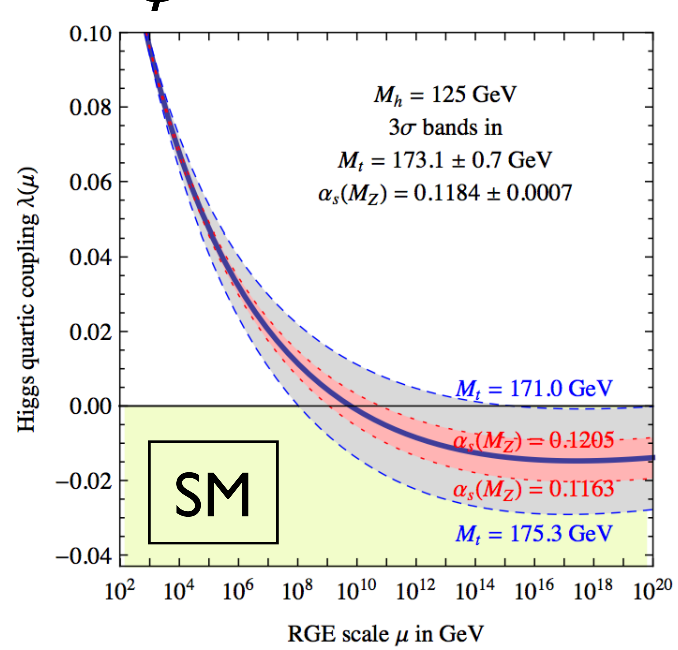
[See 1112.1847, Seungwon Baek, P. Ko & WIP]

- If "$m_h > 2\, m_\phi$", non-SM Higgs decay!

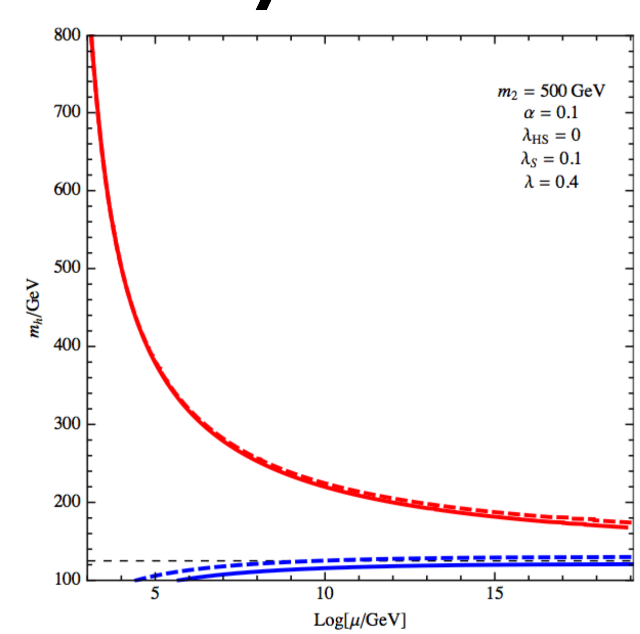
- Tree-level shift of $\lambda_{H,SM}$ (& loop correction)

$$\lambda_{\Phi H} \Rightarrow \lambda_H = \left[1 + \left(\frac{m_\phi^2}{m_h^2} - 1\right)\sin^2\alpha\right]\lambda_H^{SM}$$

If "$m_\phi > m_h$", vacuum instability can be cured.




[G. Degrassi et al., 1205.6497]




[S. Baek, P. Ko, WIP & E. Senaha, JHEP(2012)]

# UV Completion of HP VDM

[ S Baek, P Ko, WI Park, E Senaha, arXiv:1212.2131 (JHEP) ]

$$\mathcal{L}_{VDM} = -\frac{1}{4} X_{\mu\nu} X^{\mu\nu} + (D_\mu \Phi)^\dagger (D^\mu \Phi) - \frac{\lambda_\Phi}{4} \left( \Phi^\dagger \Phi - \frac{v_\Phi^2}{2} \right)^2 - \lambda_{H\Phi} \left( H^\dagger H - \frac{v_H^2}{2} \right) \left( \Phi^\dagger \Phi - \frac{v_\Phi^2}{2} \right) ,$$

$X_\mu \equiv V_\mu$ here

$$\Phi(x) = (v_\phi + \phi(x))/\sqrt{2}$$

- There appear a new singlet scalar (dark Higgs) $\phi(x)$ from $\Phi(x)$ , which mixes with the SM Higgs boson through Higgs portal interaction ($\lambda_{H\Phi}$ term)

- The effects must be similar to the singlet scalar in the fermion CDM model, and generically true in the DM with dark gauge symmetry

- Can accommodate GeV scale gamma ray excess from GC with $VV \to \phi\phi$

- Can modify the Higgs inflation : No tight correlation with top mass

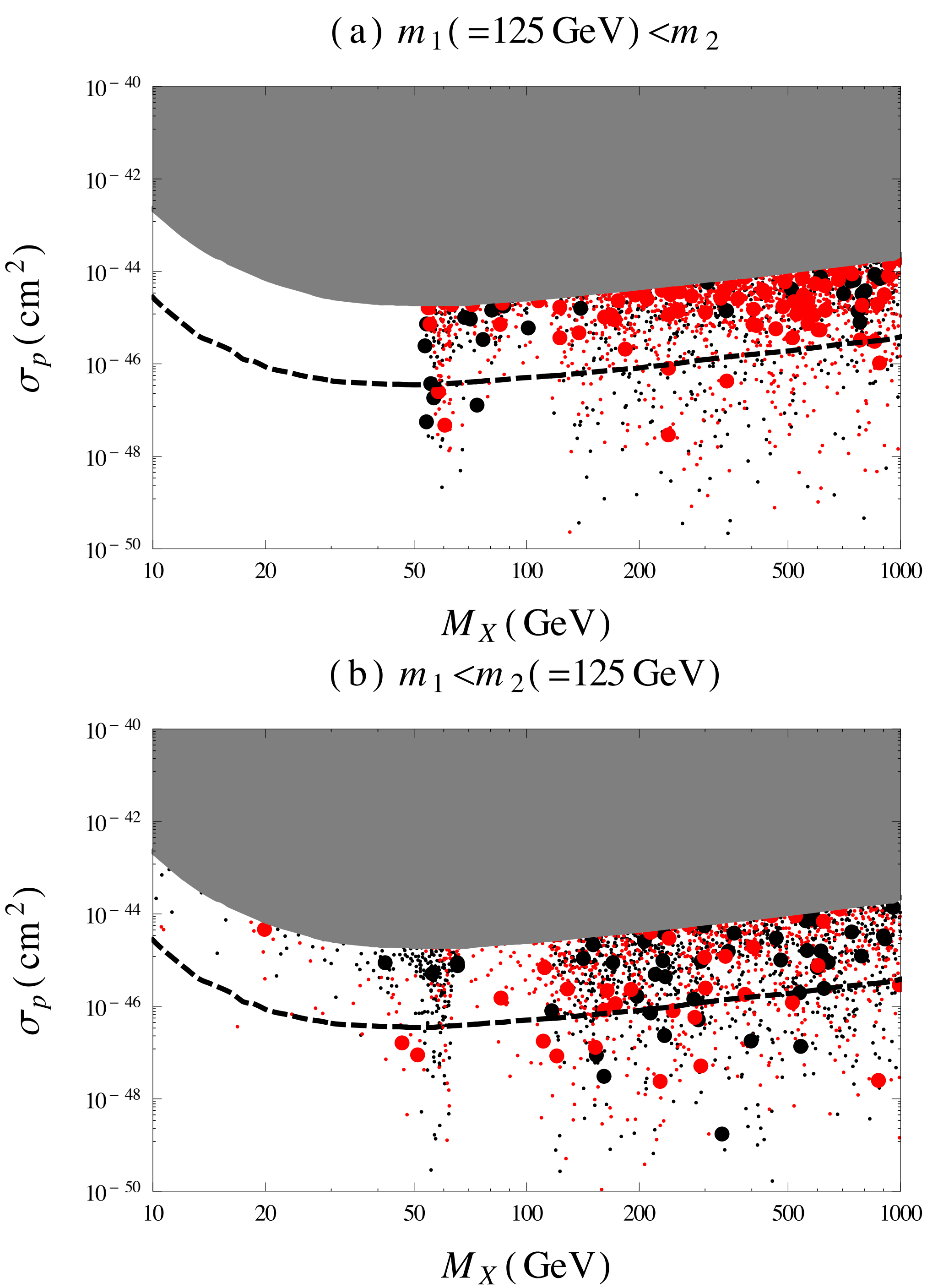



**Figure 6**. The scattered plot of $\sigma_p$ as a function of $M_X$. The big (small) points (do not) satisfy the WMAP relic density constraint within 3 $\sigma$, while the red-(black-)colored points gives $r_1 > 0.7 (r_1 < 0.7)$. The grey region is excluded by the XENON100 experiment. The dashed line denotes the sensitivity of the next XENON experiment, XENON1T.

New scalar (Dark Higgs) improves EW vacuum stability

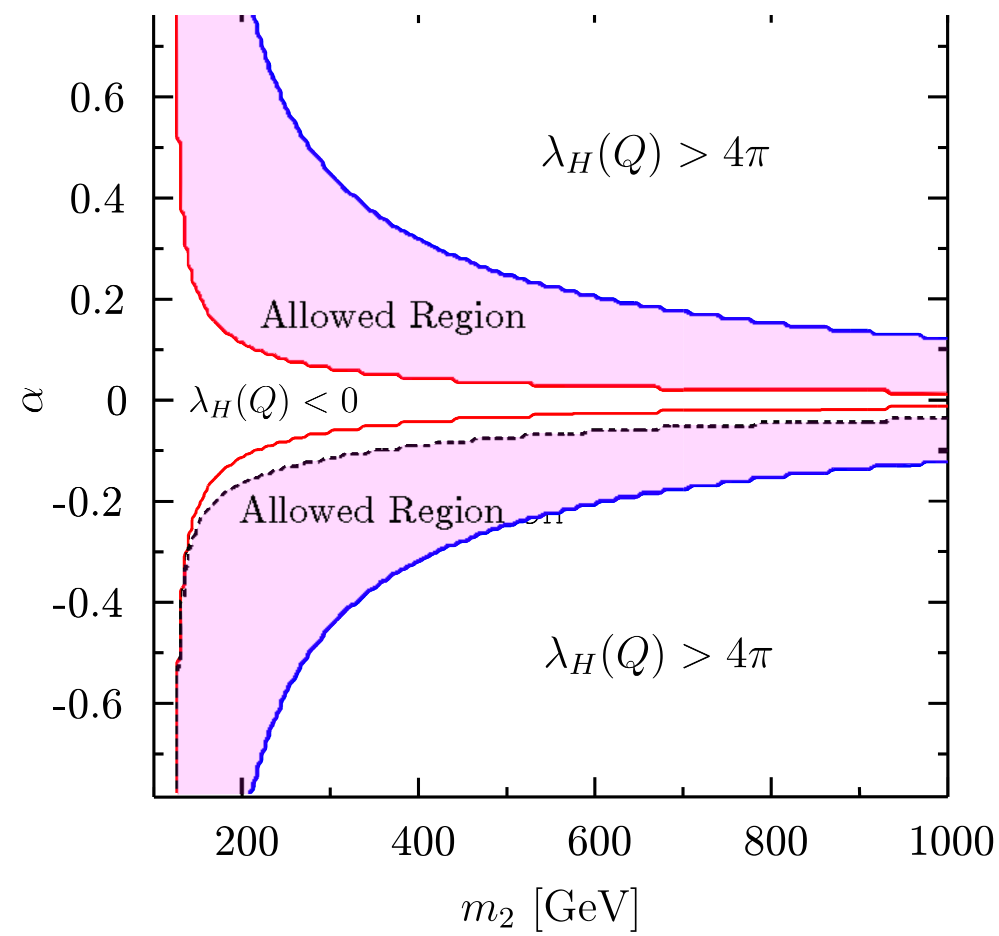



**Figure 8**. The vacuum stability and perturbativity constraints in the $\alpha$-$m_2$ plane. We take $m_1 = 125$ GeV, $g_X = 0.05$, $M_X = m_2/2$ and $v_\Phi = M_X/(g_X Q_\Phi)$.

# Interaction Lagrangians

Scalar DM

$$\mathcal{L}_{\rm SDM}^{\rm int} = -h \left( \frac{2m_W^2}{v_h} W_\mu^+ W^{-\mu} + \frac{m_Z^2}{v_h} Z_\mu Z^\mu \right) - \lambda_{HS} v_h \; h S^2 .$$

Singlet FDM

$$\mathcal{L}_{\rm FDM}^{\rm int} = -\left(H_1 \cos\alpha + H_2 \sin\alpha\right) \left( \sum_f \frac{m_f}{v_h} \bar{f} f - \frac{2m_W^2}{v_h} W_\mu^+ W^{-\mu} - \frac{m_Z^2}{v_h} Z_\mu Z^\mu \right) + g_\chi \left(H_1 \sin\alpha - H_2 \cos\alpha\right) \; \bar{\chi}\chi \; .$$

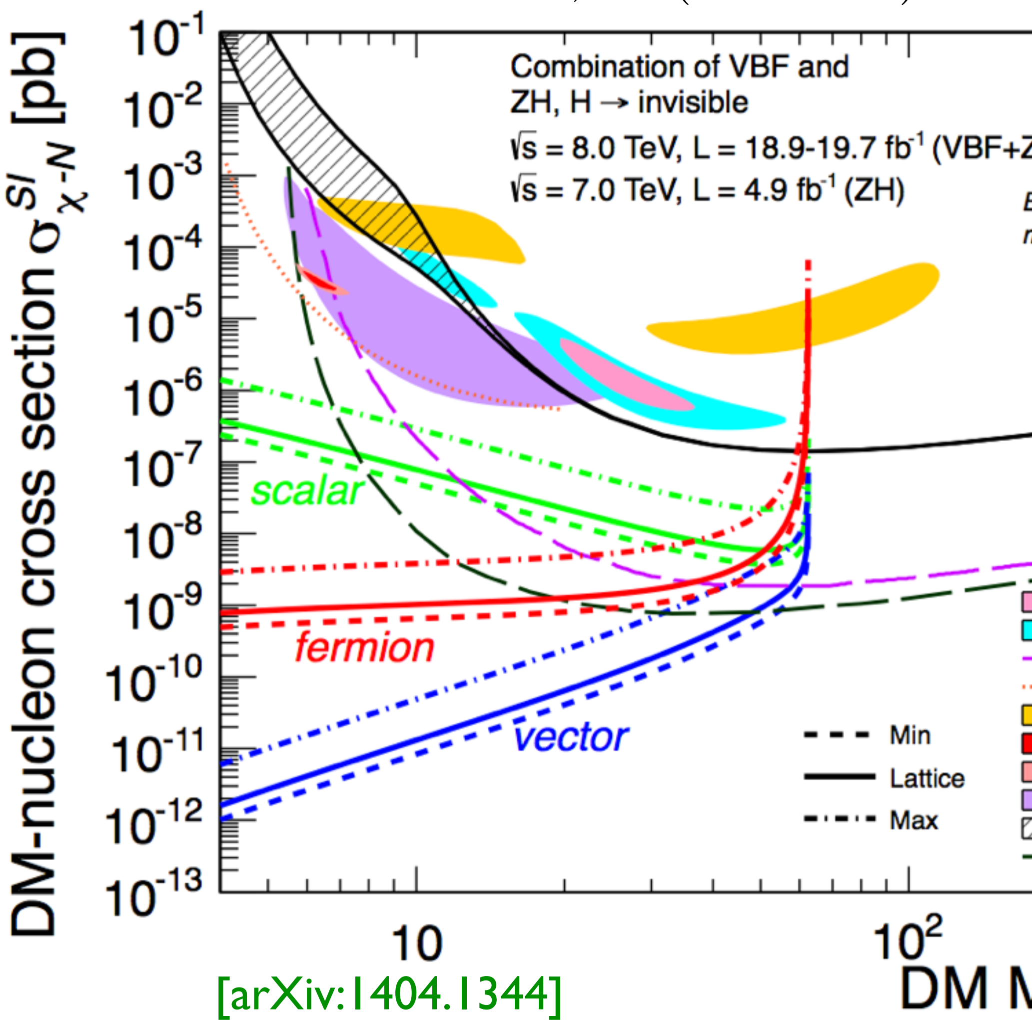
Vector DM

$$\mathcal{L}_{\rm VDM}^{\rm int} = -\left(H_1 \cos\alpha + H_2 \sin\alpha\right) \left( \sum_f \frac{m_f}{v_h} \bar{f} f - \frac{2m_W^2}{v_h} W_\mu^+ W^{-\mu} - \frac{m_Z^2}{v_h} Z_\mu Z^\mu \right) - \frac{1}{2} g_V m_V \left(H_1 \sin\alpha - H_2 \cos\alpha\right) \; V_\mu V^\mu \; .$$

NB: One can not ignore 125 GeV Higgs Boson or singlet scalar by hand : Not Well defined EFT, Breaks gauge invariance, etc.

# Collider Implications

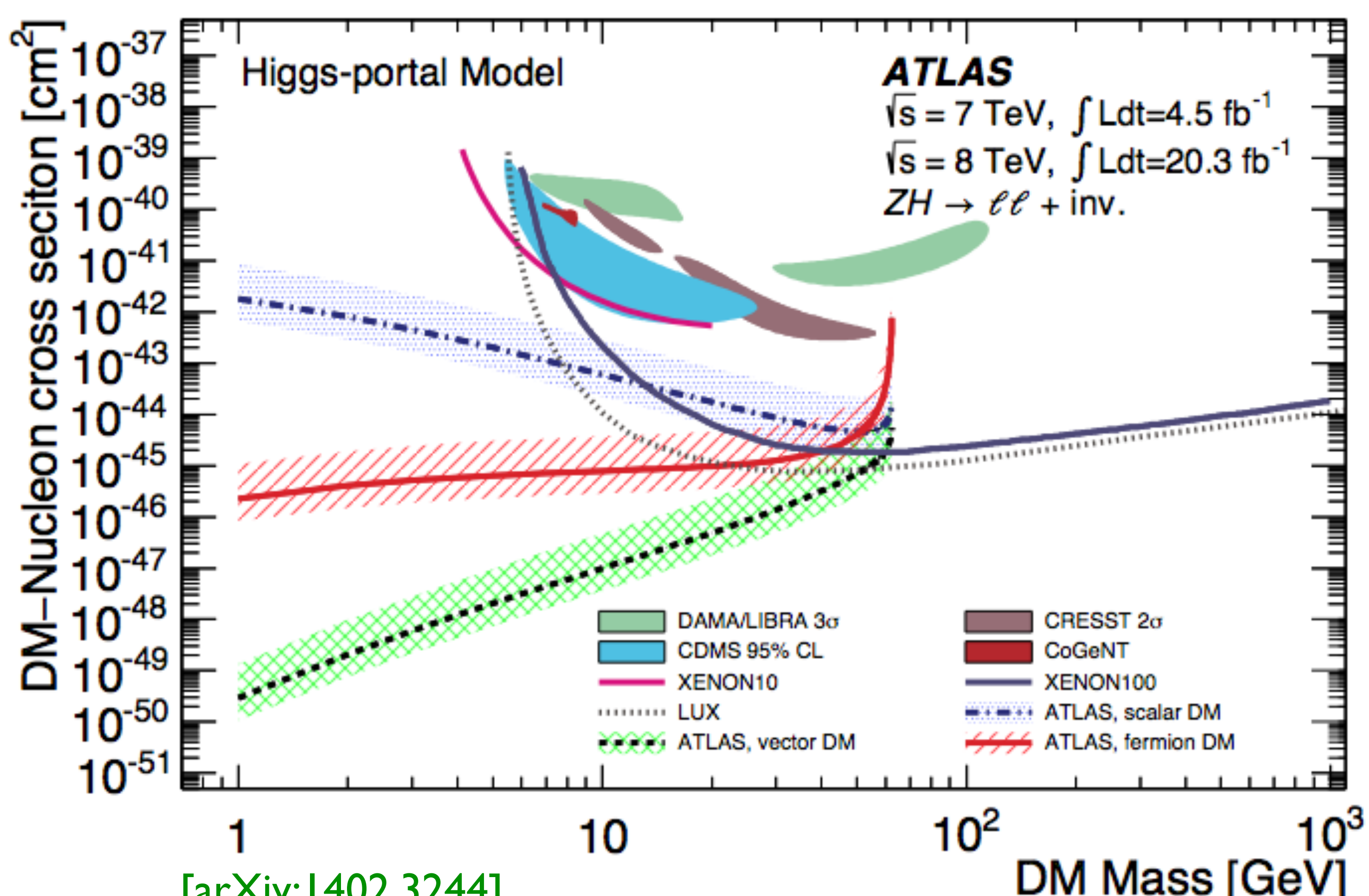
$m_h = 125\text{GeV},\ \text{Br}(H \to \text{inv}) < 0.51$ at 90% CL




[arXiv:1404.1344]

Based on EFTs

$m_h = 125.5\text{GeV},\ \text{Br}(H \to \text{inv}) < 0.52$ at 90% CL




[arXiv:1402.3244]

- However, in renormalizable unitary models of Higgs portals, 2 more relevant parameters !

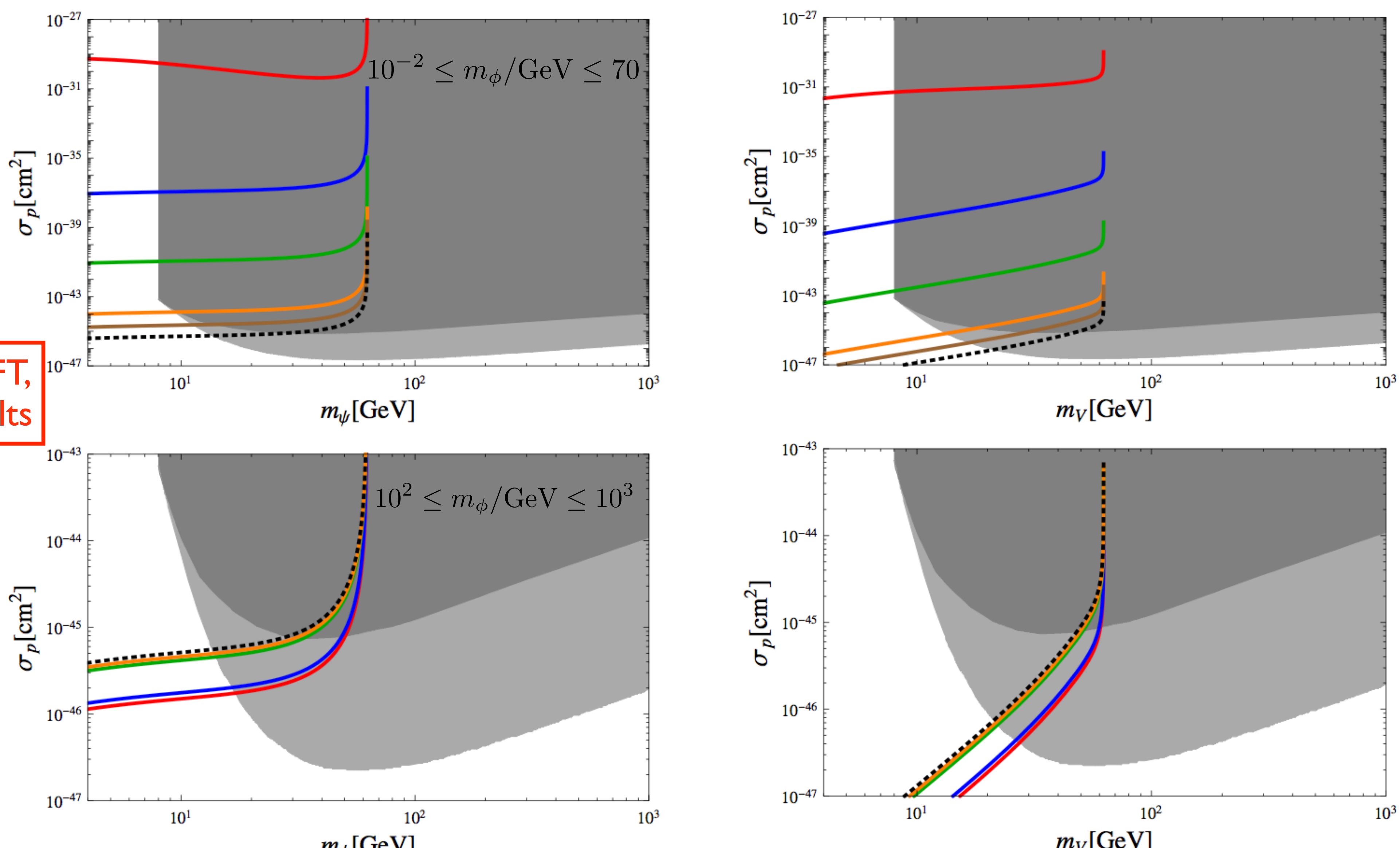
[arXiv: 1405.3530, S. Baek, P. Ko & WIPark, PRD]

$$\mathcal{L}_{\rm SFDM} = \overline{\psi}\left(i\partial\!\!\!/ - m_\psi - \lambda_\psi S\right) - \mu_{HS} S H^\dagger H - \frac{\lambda_{HS}}{2} S^2 H^\dagger H + \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{1}{2} m_S^2 S^2 - \mu_S^3 S - \frac{\mu_S'}{3} S^3 - \frac{\lambda_S}{4} S^4 .$$

$$\mathcal{L}_{\rm VDM} = -\frac{1}{4} V_{\mu\nu} V^{\mu\nu} + D_\mu \Phi^\dagger D^\mu \Phi - \lambda_\Phi \left(\Phi^\dagger\Phi - \frac{v_\Phi^2}{2}\right)^2 - \lambda_{\Phi H}\left(\Phi^\dagger\Phi - \frac{v_\Phi^2}{2}\right)\left(H^\dagger H - \frac{v_H^2}{2}\right)$$

$$\sigma_p^{\rm SI} = (\sigma_p^{\rm SI})_{\rm EFT}\, c_\alpha^4 m_h^4 \mathcal{F}(m_{\rm DM}, \{m_i\}, v) \simeq (\sigma_p^{\rm SI})_{\rm EFT}\, c_\alpha^4 \left(1 - \frac{m_h^2}{m_2^2}\right)^2$$

Dashed curves:EFT, ATLAS,CMS results



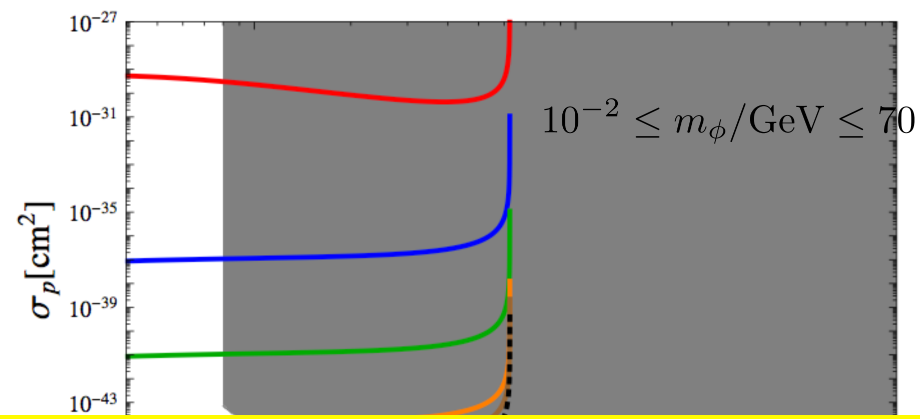
- However, in renormalizable unitary models of Higgs portals, 2 more relevant parameters

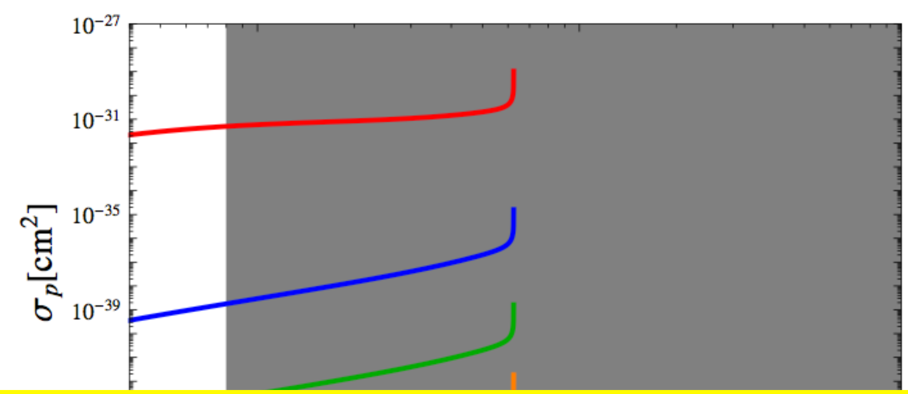
$$\mathcal{L}_{\rm SFDM} = \overline{\psi}\left(i\partial\!\!\!/ - m_\psi - \lambda_\psi S\right) - \mu_{HS} S H^\dagger H - \frac{\lambda_{HS}}{2} S^2 H^\dagger H + \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{1}{2} m_S^2 S^2 - \mu_S^3 S - \frac{\mu_S'}{3} S^3 - \frac{\lambda_S}{4} S^4.$$

[arXiv: 1405.3530, S. Baek, P. Ko & WIPark, PRD]

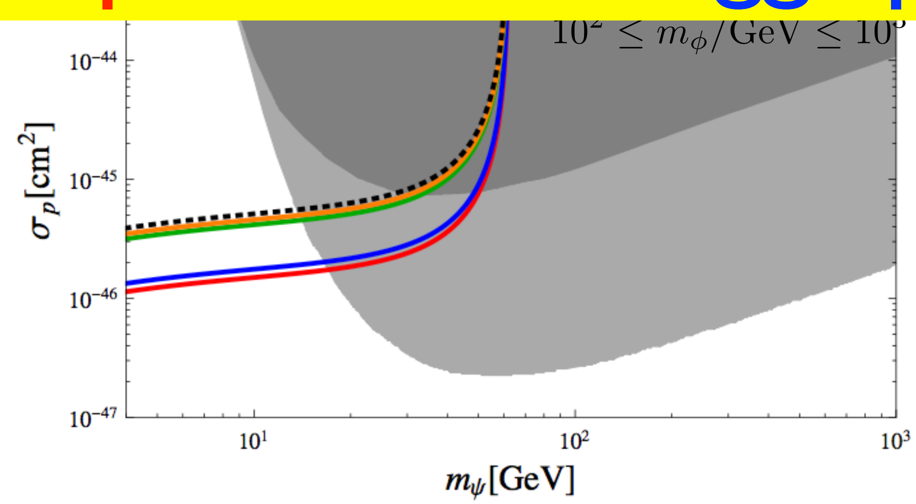
$$\sigma_p^{\rm SI} = (\sigma_p^{\rm SI})_{\rm EFT}\, c_\alpha^4 m_h^4 \mathcal{F}(m_{\rm DM}, \{m_i\}, v) \simeq (\sigma_p^{\rm SI})_{\rm EFT}\, c_\alpha^4 \left(1 - \frac{m_h^2}{m_2^2}\right)^2$$

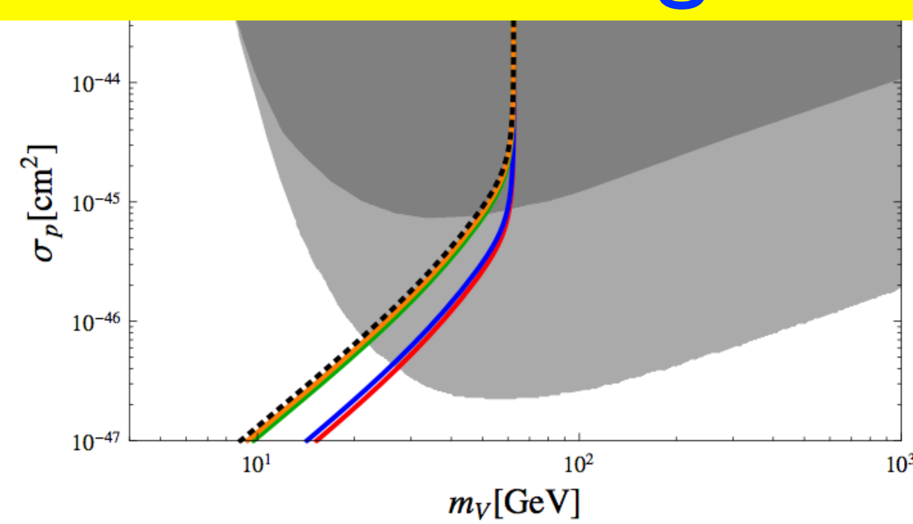
$$\mathcal{L}_{\rm VDM} = -\frac{1}{4} V_{\mu\nu} V^{\mu\nu} + D_\mu \Phi^\dagger D^\mu \Phi - \lambda_\Phi \left(\Phi^\dagger \Phi - \frac{v_\Phi^2}{2}\right)^2 - \lambda_{\Phi H}\left(\Phi^\dagger \Phi - \frac{v_\Phi^2}{2}\right)\left(H^\dagger H - \frac{v_H^2}{2}\right)$$




Interpretation of collider data is quite model-dependent in Higgs portal DMs and in general



S. Baek, P. Ko, M. Park, WIPark, C.Yu, arXiv:1506.06556, PLB (2016)

- EFT : Effective operator $\mathcal{L}_{int} = \frac{m_q}{\Lambda_{dd}^3}\bar{q}q\bar{\chi}\chi$
- S.M.: Simple scalar mediator $S$ of
  $\mathcal{L}_{int} = \left(\frac{m_q}{v_H}\sin\alpha\right) S\bar{q}q - \lambda_s \cos\alpha S\bar{\chi}\chi$
- H.M.: A case where a Higgs is a mediator
  $\mathcal{L}_{int} = -\left(\frac{m_q}{v_H}\cos\alpha\right) H\bar{q}q - \lambda_s \sin\alpha H\bar{\chi}\chi$
- H.P.: Higgs portal model as in eq. (2).

$$\frac{d\sigma_i}{dm_{\chi\chi}} \propto \left|\frac{\sin 2\alpha\ g_\chi}{m_{\chi\chi}^2 - m_{H_1}^2 + i m_{H_1}\Gamma_{H_1}} - \frac{\sin 2\alpha\ g_\chi}{m_{\chi\chi}^2 - m_{H_2}^2 + i m_{H_2}\Gamma_{H_2}}\right|^2$$

$$\text{H.P.} \xrightarrow[m_{H_2}^2 \gg \hat{s}]{} \text{H.M.},$$

$$\text{S.M.} \xrightarrow[m_S^2 \gg \hat{s}]{} \text{EFT},$$

$$\text{H.M.} \neq \text{EFT}\,.$$

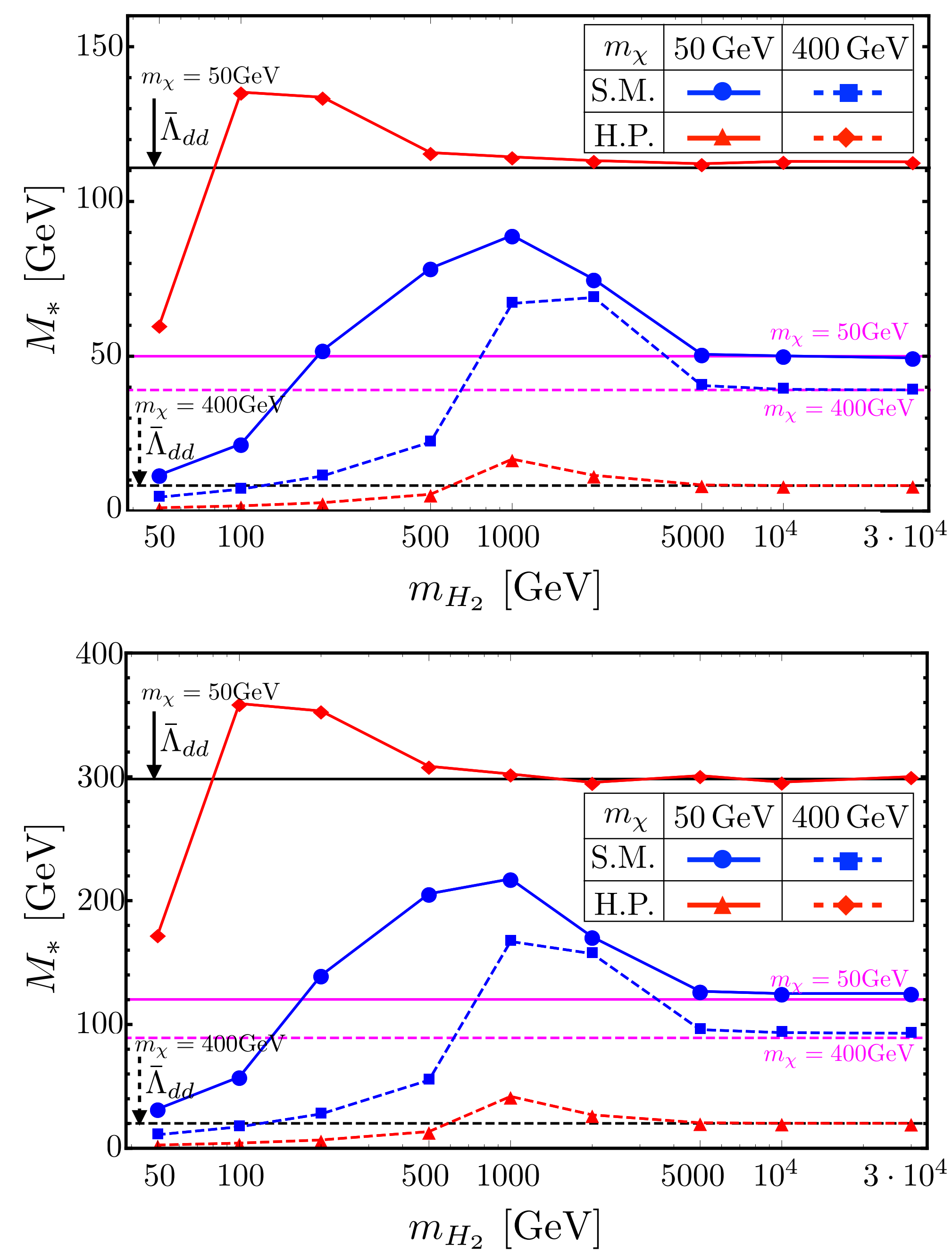



FIG. 3: The experimental bounds on $M_*$ at 90% C.L. as a function of $m_{H_2}$ ($m_S$ in S.M. case) in the monojet+$\not{E}_T$ search (upper) and $t\bar{t} + \not{E}_T$ search (lower). Each line corresponds to the EFT approach (magenta), S.M. (blue), H.M. (black), and H.P. (red), respectively. The bound of S.M., H.M., and H.P., are expressed in terms of the effective mass $M_*$ through the Eq.(16)-(20). The solid and dashed lines correspond to $m_\chi = 50$ GeV and 400 GeV in each model, respectively.

# Invisible H decay into a pair of VDM

[arXiv: 1405.3530, S. Baek, P. Ko & WI Park, PRD]

$$(\Gamma_h^{\rm inv})_{\rm EFT} = \frac{\lambda_{VH}^2}{128\pi} \frac{v_H^2 m_h^3}{m_V^4} \times \left(1 - \frac{4m_V^2}{m_h^2} + 12\frac{m_V^4}{m_h^4}\right)\left(1 - \frac{4m_V^2}{m_h^2}\right)^{1/2} \quad (23)$$

VS.

$$\Gamma_i^{\rm inv} = \frac{g_X^2}{32\pi} \frac{m_i^3}{m_V^2} \left(1 - \frac{4m_V^2}{m_i^2} + 12\frac{m_V^4}{m_i^4}\right)\left(1 - \frac{4m_V^2}{m_i^2}\right)^{1/2} \sin^2\alpha \quad (22)$$

Invisible H decay width : finite for small mV in unitary/renormalizable model

# Two Limits for $m_V \to 0$

**Also see the addendum (under review now)**
**by S Baek, P Ko, WI Park**

- $m_V = g_X Q_\Phi v_\Phi$ in the UV completion with dark Higgs boson

- Case I : $g_X \to 0$ with finite $v_\Phi \neq 0$

$$\frac{g_X^2 Q_\Phi^2}{m_V^2} = \frac{g_X^2 Q_\Phi^2}{g_X^2 Q_\Phi^2 v_\Phi^2} = \frac{1}{v_\Phi^2} = \text{finite}.$$

$$\left(\Gamma_h^{\rm inv}\right)_{\rm UV} = \frac{1}{32\pi} \frac{m_h^3}{v_\Phi^2} \sin^2\alpha = \Gamma(h \to a_\Phi a_\Phi)$$

with $a_\Phi$ being the NG boson for spontaneously broken global $U(1)_X$

- Case II : $v_\Phi \to 0$ with finite $g_X \neq 0$

$$\alpha \xrightarrow{v_\Phi \to 0^+} \frac{2\lambda_{H\Phi} v_\Phi}{\lambda_H v_H}$$

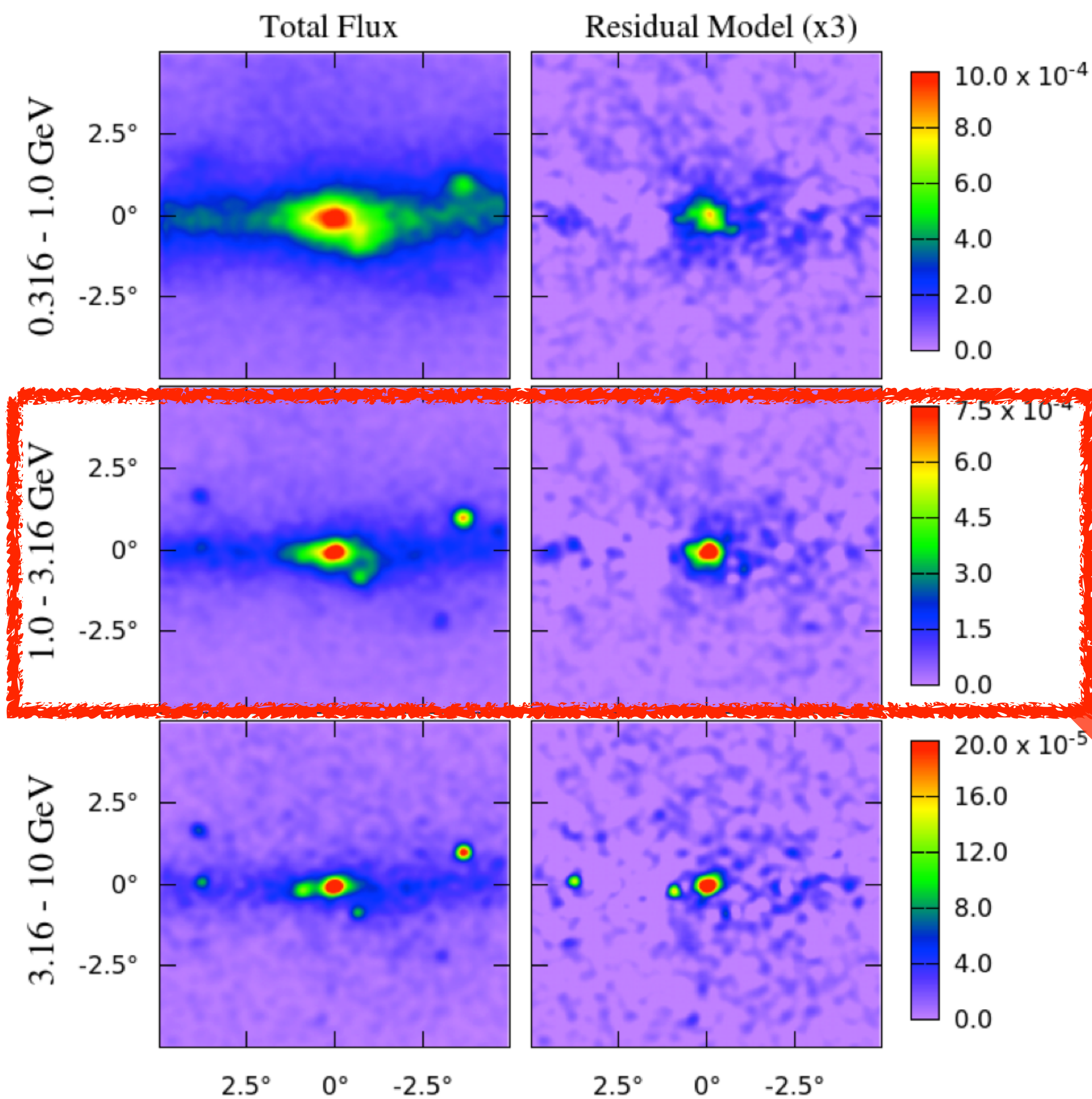
$$\frac{g_X^2 Q_\Phi^2}{m_V^2} \sin^2\alpha \xrightarrow{v_\Phi \to 0^+} \frac{4\lambda_{H\Phi}^2}{\lambda_H^2 v_H^2} = \frac{2\lambda_{H\Phi}^2}{\lambda_H m_h^2} = \text{finite},$$

$$\left(\Gamma_h^{\rm inv}\right)_{\rm UV} \xrightarrow{v_\Phi \to 0^+} \frac{1}{16\pi} \frac{\lambda_{H\Phi}^2 m_h}{\lambda_H}$$

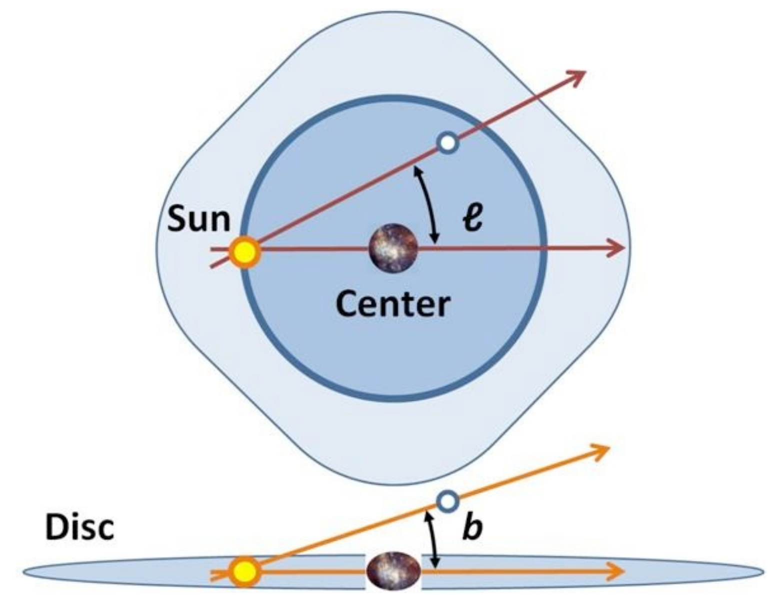
**Therefore $\Gamma(h \to VV)$ is finite when $m_V \to 0$ in the UV completions**

# Fermi-LAT GC $\gamma$-ray

see arXiv:1612.05687 for a recent overview by
C.Karwin, S. Murgia, T. Tait, T.A.Porter, P. Tanedo




[1402.6703, T. Daylan et.al.]

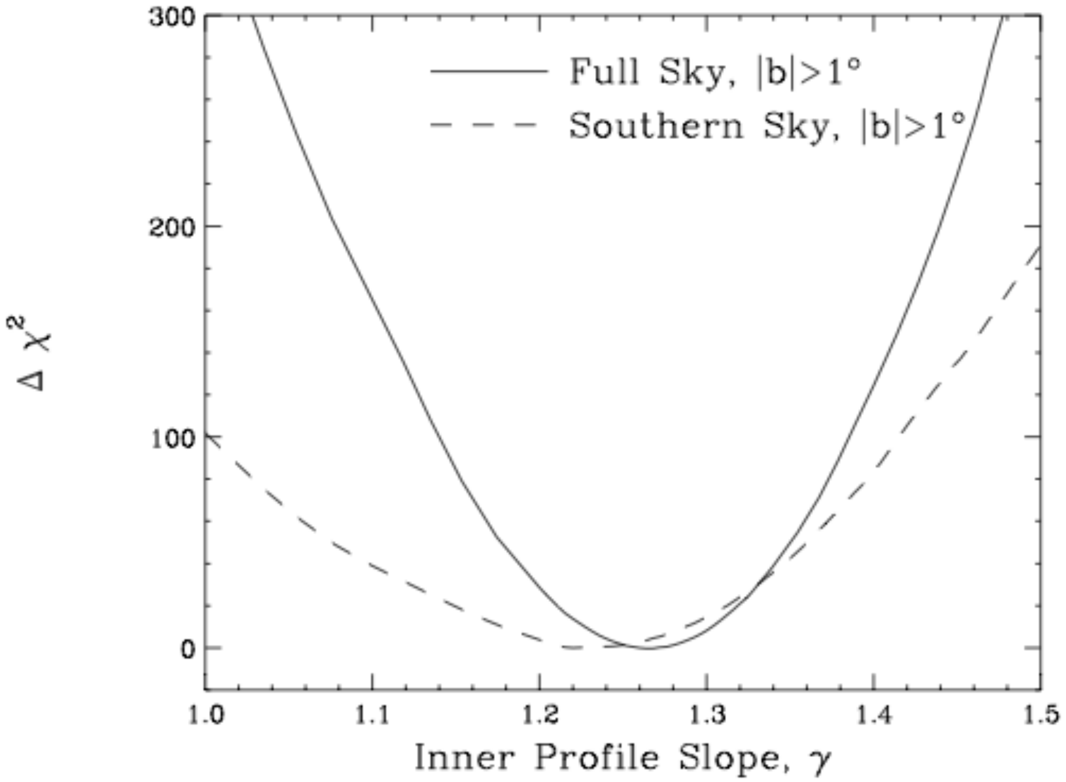



$$\mathrm{GC}: b \sim l \lesssim 0.1^\circ$$

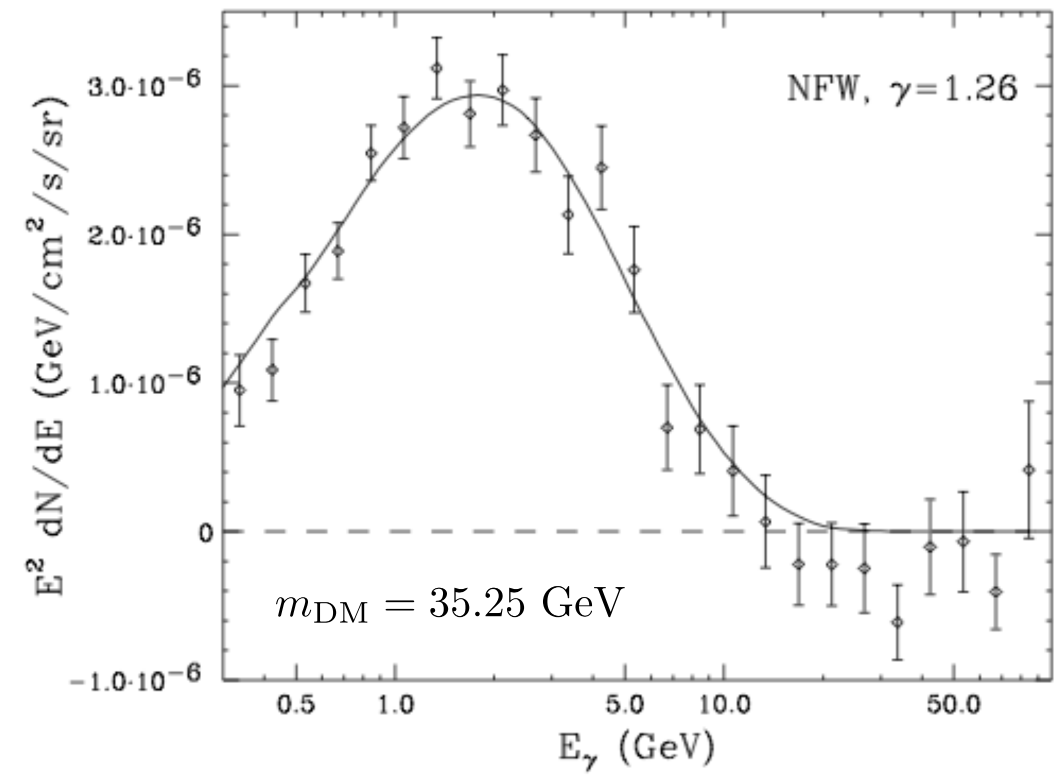
extended

GeV scale excess!

- A DM interpretation




$\mathrm{DM} + \mathrm{DM} \rightarrow b\bar{b}$ with $\sigma v = 1.7 \times 10^{-26}\mathrm{cm}^3/\mathrm{s}$




* See "1402.6703, T. Daylan et.al." for other possible channels

- Millisecond Pulars (astrophysical alternative)

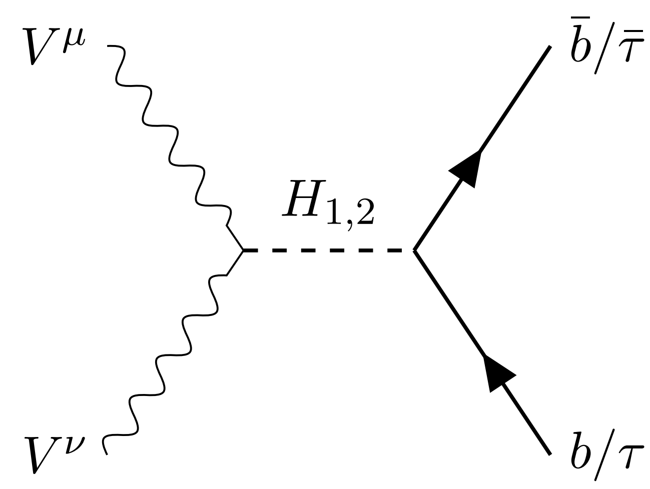
It may or may not be the main source, depending on

- luminosity func.
- bulge population
- distribution of bulge population

* See "1404.2318, Q. Yuan & B. Zhang" and "1407.5625, I. Cholis, D. Hooper & T. Linden"

# GC gamma ray in HP VDM

P. Ko, WI Park, Y. Tang. arXiv:1404.5257, JCAP




H2 : 125 GeV Higgs
H1 : absent in EFT

**Figure 2**. Dominant $s$ channel $b + \bar{b}$ (and $\tau + \bar{\tau}$) production

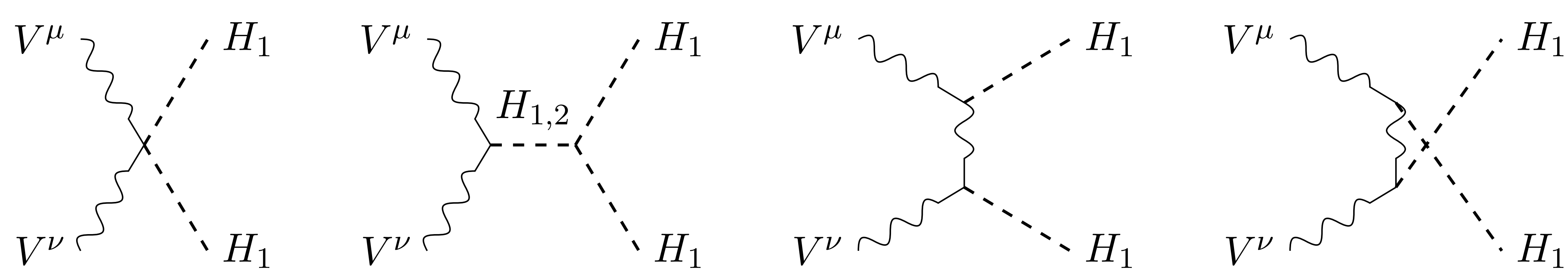



**Figure 3**. Dominant $s/t$-channel production of $H_1$s that decay dominantly to $b + \bar{b}$

# Importance of HP VDM with Dark Higgs Boson

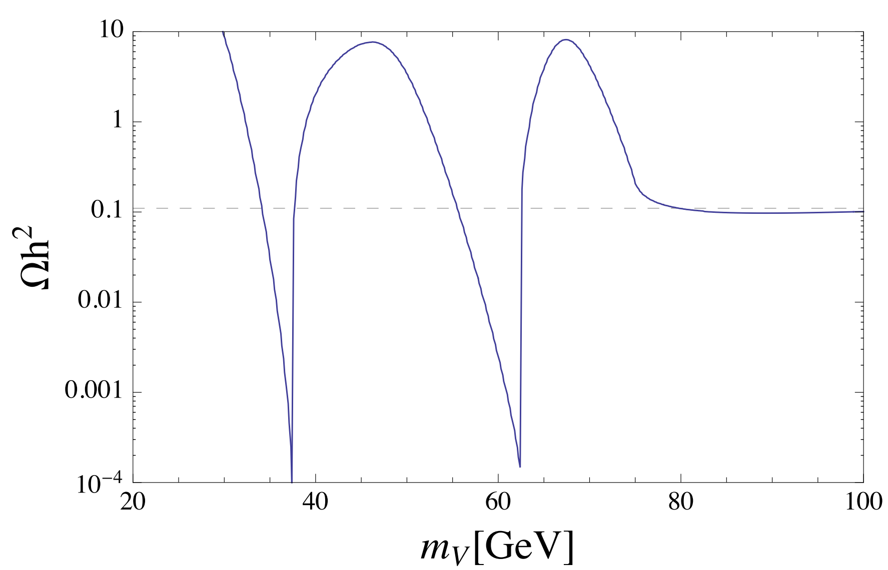



**Figure 4**. Relic density of dark matter as function of $m_\psi$ for $m_h = 125$, $m_\phi = 75\,\text{GeV}$, $g_X = 0.2$, and $\alpha = 0.1$.

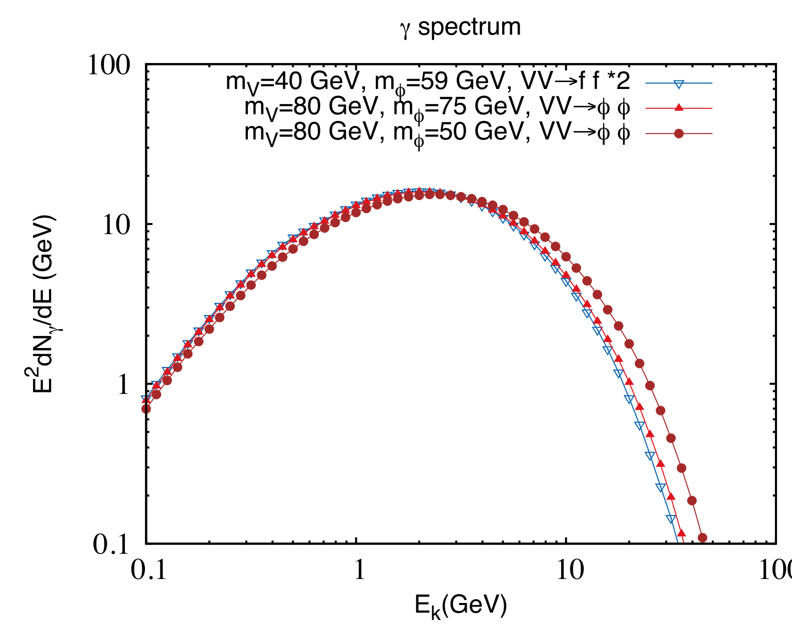


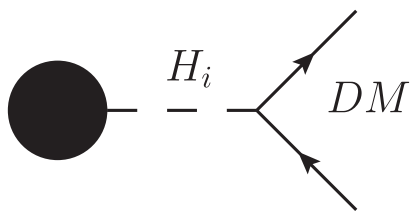

**Figure 5**. Illustration of $\gamma$ spectra from different channels. The first two cases give almost the same spectra while in the third case $\gamma$ is boosted so the spectrum is shifted to higher energy.

This mass range of VDM would have been impossible in the VDM model (EFT)

And No 2nd neutral scalar (Dark Higgs) in EFT

# DM Production @ ILC

**P Ko, H Yokoya, arXiv:1603.08802, JHEP**



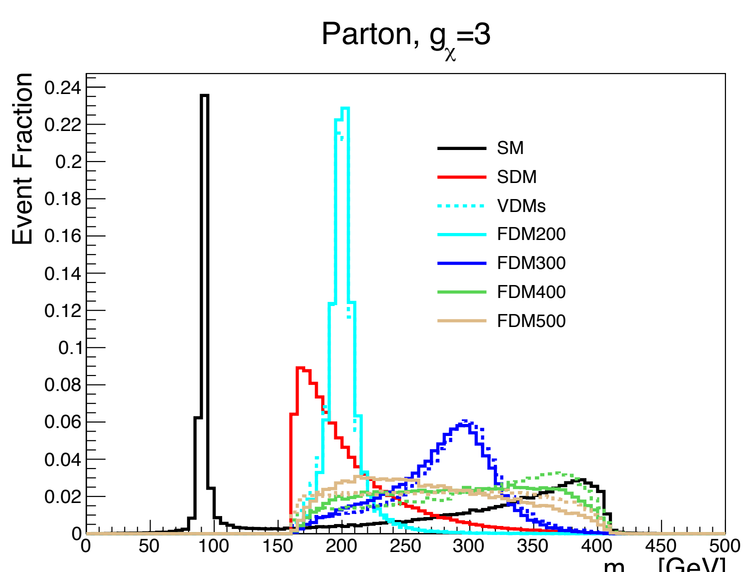

,  $t \equiv m_{DD}^2$

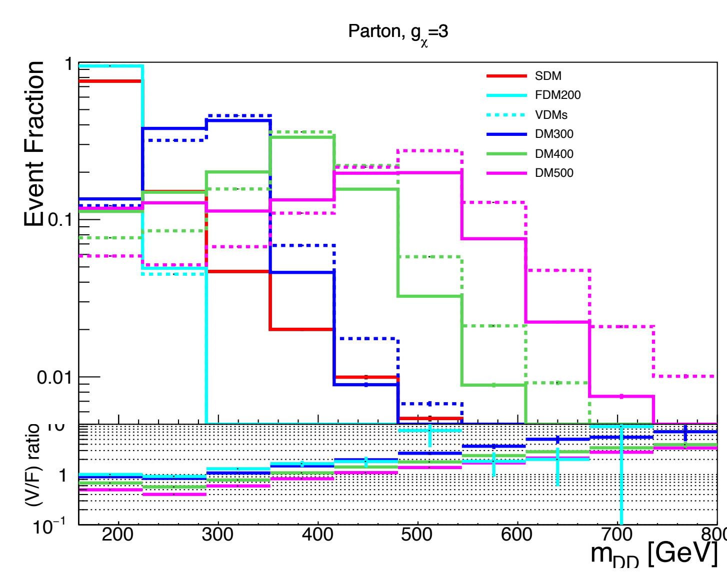
**We consider $e^+e^- \to Z^* \to ZH_{i=1,2}$ followed by $H_i \to \bar{\chi}\chi$**

$$\frac{d\sigma_{\rm SDM}}{dt} \propto \sigma^{h^*}_{\rm SDM} \times |\frac{1}{t - m_h^2 + i m_h \Gamma_h}|^2,$$

$$\frac{d\sigma_{\rm FDM}}{dt} \propto \sigma^{h^*}_{\rm FDM} \times |\frac{1}{t - m_{H_1}^2 + i m_{H_1}\Gamma_{H_1}} - \frac{1}{t - m_{H_2}^2 + i m_{H_2}\Gamma_{H_2}}|^2 \cdot \left(2t - 8m_\chi^2\right),$$

$$\frac{d\sigma_{\rm VDM}}{dt} \propto \sigma^{h^*}_{\rm VDM} \times |\frac{1}{t - m_{H_1}^2 + i m_{H_1}\Gamma_{H_1}} - \frac{1}{t - m_{H_2}^2 + i m_{H_2}\Gamma_{H_2}}|^2 \cdot \left(2 + \frac{(t - 2m_D^2)^2}{4m_V^4}\right).$$




Fix DM mass = 80 GeV, sin(alpha) = 0.3, and vary H2 mass (200,300,400,500) GeV

# Asymptotic behavior in the full theory ($t \equiv m_{\chi\chi}^2$)

$$\text{ScalarDM}: \quad G(t) \sim \frac{1}{(t-m_H^2)^2 + m_H^2\Gamma_H^2} \tag{5.7}$$

$$\text{SFDM}: \quad G(t) \sim \left| \frac{1}{t-m_1^2+im_1\Gamma_1} - \frac{1}{t-m_2^2+im_2\Gamma_2} \right|^2 \left(t-4m_\chi^2\right) \tag{5.8}$$

$$\to \left|\frac{1}{t^2}\right|^2 \times t \sim \frac{1}{t^3} \ (\text{as } t \to \infty) \tag{5.9}$$

$$\text{VDM}: \quad G(t) \sim \left| \frac{1}{t-m_1^2+im_1\Gamma_1} - \frac{1}{t-m_2^2+im_2\Gamma_2} \right|^2 \left[2 + \frac{(t-2m_V^2)^2}{4m_V^4}\right] \tag{5.10}$$

$$\to \left|\frac{1}{t^2}\right|^2 \times t^2 \sim \frac{1}{t^2} \ (\text{as } t \to \infty) \tag{5.11}$$

# Asymptotic behavior w/o the 2nd Higgs (EFT)

$$\text{SFDM}: \quad G(t) \sim \frac{1}{(t-m_H^2)^2 + m_H^2\Gamma_H^2} \left(t-4m_\chi^2\right)$$

$$\to \frac{1}{t} \ (\text{as } t \to \infty)$$

$$\text{VDM}: \quad G(t) \sim \frac{1}{(t-m_H^2)^2 + m_H^2\Gamma_H^2} \left[2 + \frac{(t-2m_V^2)^2}{4m_V^4}\right]$$

$$\to \text{constant} \ (\text{as } t \to \infty)$$

Unitarity is violated in EFT!

# Conclusion

- Phenomenology of HP VDM and Singlet FDM presented within EFT vs. UV completed models
- EFT approach has a number of drawbacks : non-renormalizable, unitarity violation at high energy colliders, and it applies only if $m_{DM}, m_{\rm SM} \ll m_\phi$ [We don't know mass scales of dark particles]
- In particular, one has $\Gamma_{\rm EFT}(H_{125} \to VV) \to \infty$ , as $m_V \to 0$ , whereas it is finite in UV completed models [Importance of gauge invariance, unitarity and renormalizability]
- The dark Higgs $\phi$ can play crucial roles in interpreting the DM signatures at colliders, explaining the GC $\gamma$-ray excess ($VV \to \phi\phi$), improving vacuum stability up to Planck scale, modifying the Higgs inflation [$\phi$ should be actively searched for !]

# Some More References for details

- arXiv:1405.3530 w/ S.Baek, W.I.Park, (Higgs inv. decay vs. Direct detection)
- arXiv:1506.06556 w/ S.Baek, M.Park, W.I.Park, C. Yu (ATLAS and CMS analysis @ 8 TeV)
- arXiv:1603.08802 w/H. Yokoya (ILC@500GeV)
- arXiv:1610.03997 w/ J.Li, (interference of the SM Higgs)
- arXiv:1701.04131 w/ S.Baek, J.Li, (pseudoscalar mediator)
- arXiv:1705.02149 w/T.Kamon, J.Li (mass and spin @ ILC@500GeV)
- arXiv:1712.05123 w/B.Dutta, T.Kamon, J.Li, (mass and spin @100TeV pp)
- arXiv:1807.06697 w/G.Li, J.Li (Impact of 125 GeV Higgs boson)

# Backup Slides

# DM searches @ colliders : Beyond the EFT and simplified DM models

- S. Baek, P. Ko, M. Park, WIPark, C.Yu, arXiv:1506.06556, PLB (2016)
- P. Ko and Hiroshi Yokoya, arXiv:1603.04737, JHEP (2016)
- P. Ko, A. Natale, M. Park, H. Yokoya, arXiv:1605.07058, JHEP(2017)
- P. Ko and Jinmian Li, arXiv:1610.03997, PLB (2017)
- T. Kamon, P. Ko, Jinmian Li, arXiv:1705.02149, EPJC (2017)
- B. Dutta, T. Kamon, P. Ko, Jinmian Li, arXiv:1712.05123, EPJC (2018)
- P. Ko, Gang Li, Jinmian Li, arXiv:1807.06697, PRD (2018)

# Why is it broken down in DM EFT ?

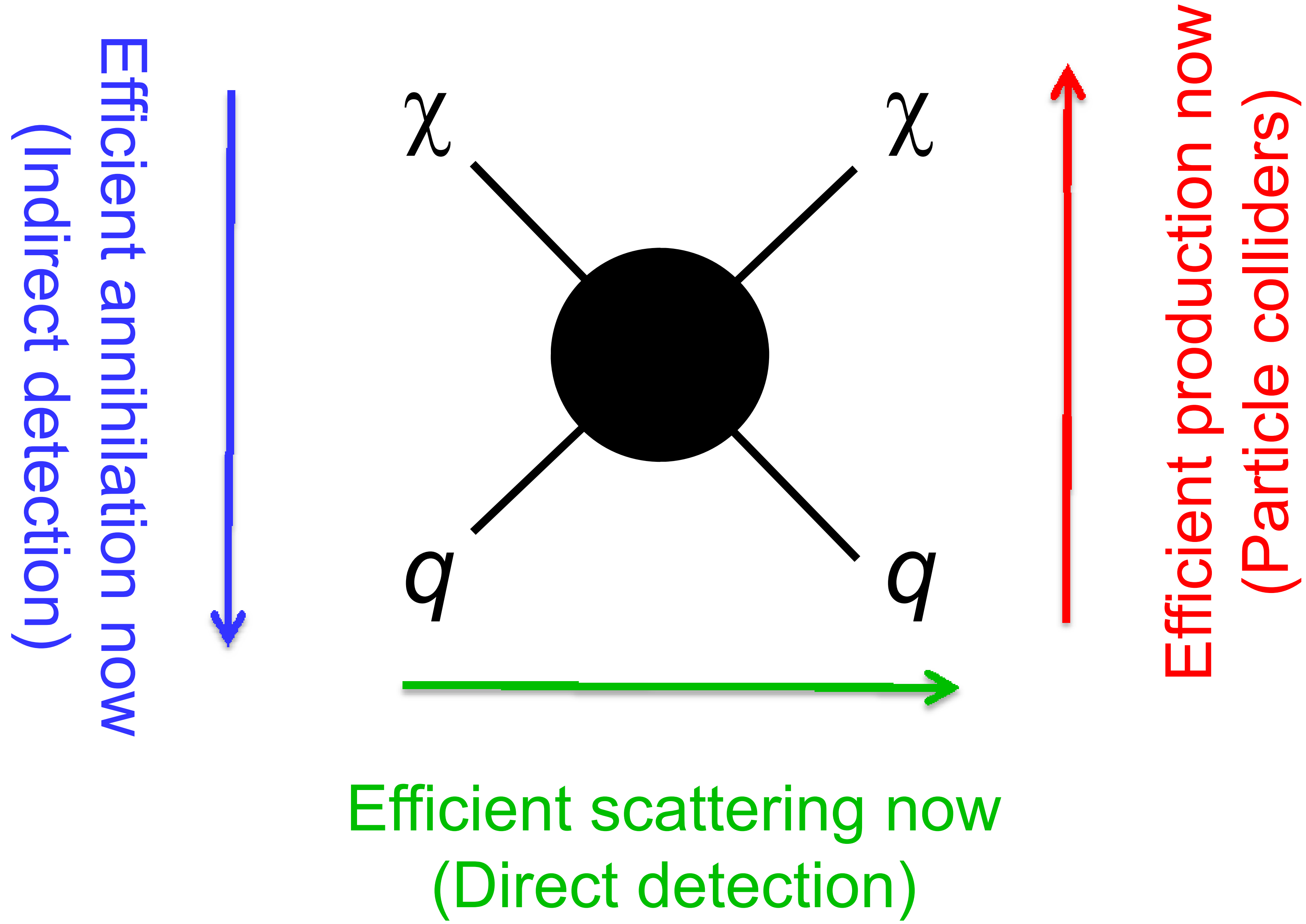
The most nontrivial example is the (scalar)x(scalar) operator for DM-N scattering

$$\mathcal{L}_{SS} \equiv \frac{1}{\Lambda_{dd}^2}\bar{q}q\bar{\chi}\chi \quad \text{or} \quad \frac{m_q}{\Lambda_{dd}^3}\bar{q}q\bar{\chi}\chi$$

This operator clearly violates the SM gauge symmetry, and we have to fix this problem

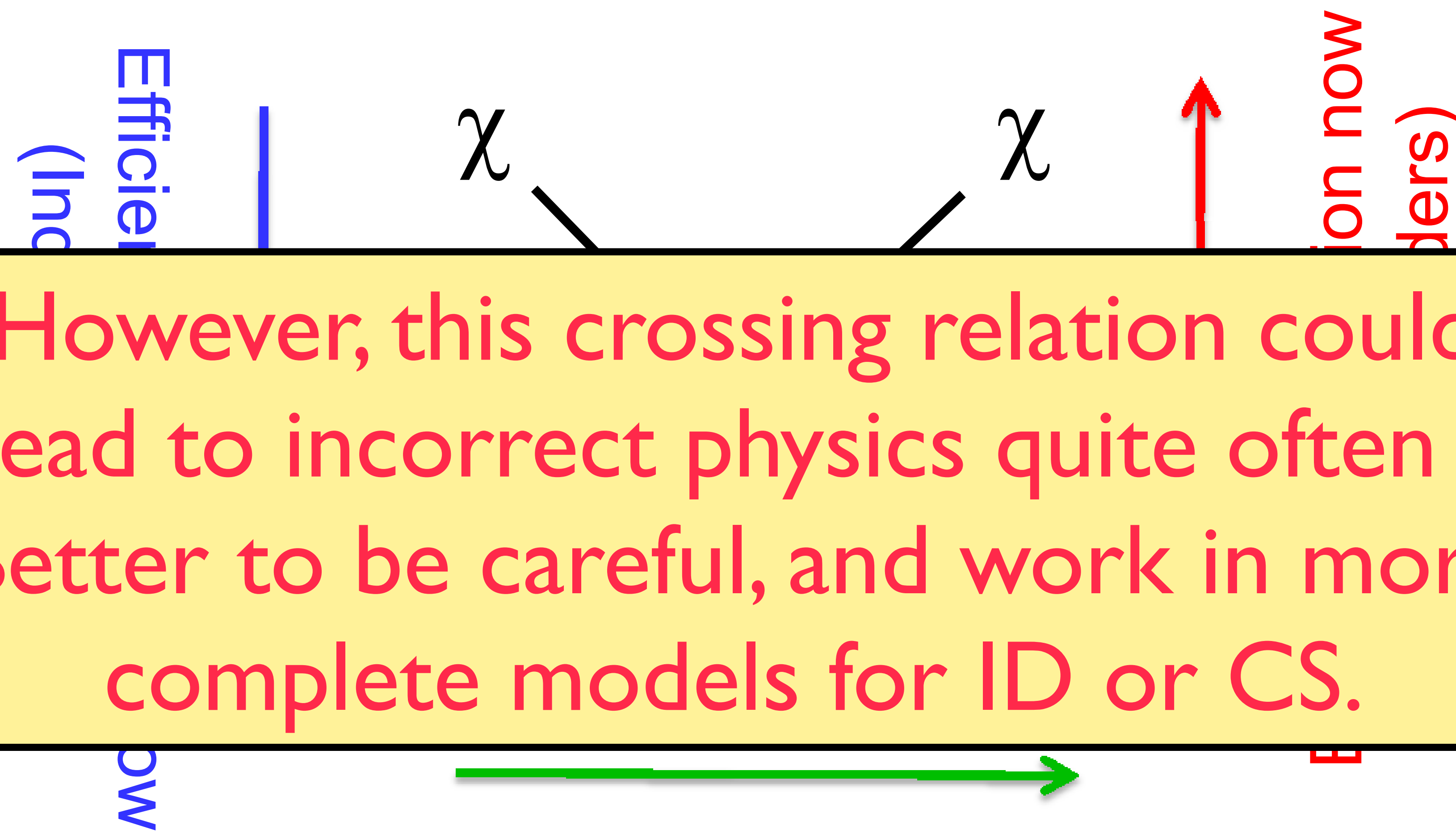
# Crossing & WIMP detection

Correct relic density → Efficient annihilation then



# Crossing & WIMP detection

Correct relic density → Efficient annihilation then




**However, this crossing relation could lead to incorrect physics quite often ! Better to be careful, and work in more complete models for ID or CS.**

Efficient scattering now
(Direct detection)

# Limitation and Proposal

- EFT is good for direct detection, but not for indirect or collider searches as well as thermal relic density calculations in general
- Issues : Violation of Unitarity and SM gauge invariance, Identifying the relevant dynamical fields at energy scale we are interested in, Symmetry stabilizing DM etc.

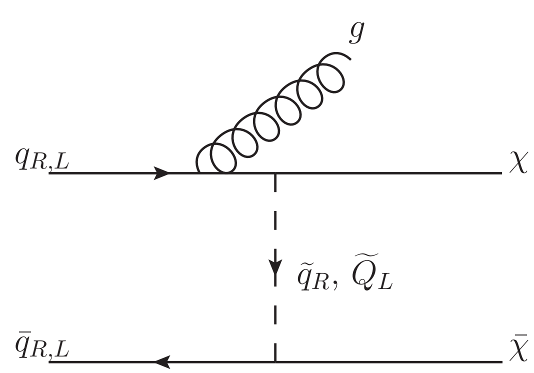
$$\frac{1}{\Lambda_i^2}\ \bar{q}\Gamma_i q\ \bar{\chi}\Gamma_i\chi \to \frac{g_q g_\chi}{m_\phi^2 - s}\ \bar{q}\Gamma_i q\ \bar{\chi}\Gamma_i\chi$$

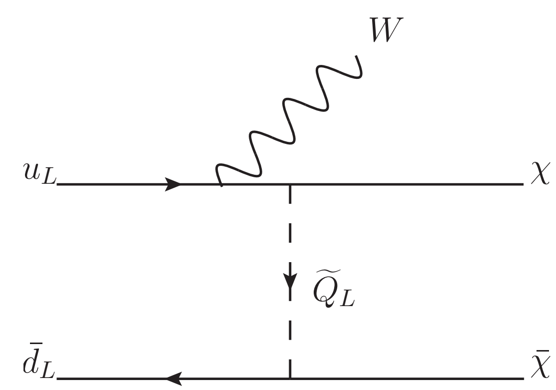
- Usually effective operator is replaced by a single propagator in simplified DM models
- This is not good enough, since we have to respect the full SM gauge symmetry (Bell et al for W+missing ET)
- In general we need two propagators, not one propagator, because there are two independent chiral fermions in 4-dim spacetime

**arXiv:1605.07058 (with A. Natale, M.Park, H. Yokoya)**

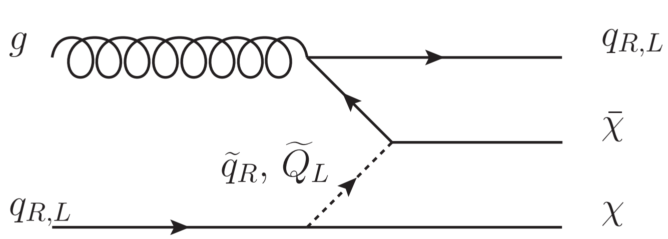
**for t-channel mediator**

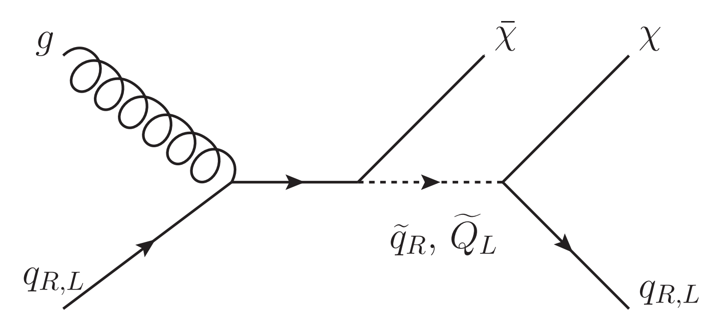
Our Model: a 'simplified model' of colored $t$-channel, spin-0, mediators which produce various mono-$x$ + missing energy signatures (mono-Jet, mono-W, mono-Z, etc.):




W+missing ET : special



$$\frac{1}{\Lambda_i^2}\ \bar{q}\Gamma_i q\ \bar{\chi}\Gamma_i\chi \rightarrow \frac{g_q g_\chi}{m_\phi^2 - s}\ \bar{q}\Gamma_i q\ \bar{\chi}\Gamma_i\chi$$

- This is good only for W+missing ET, and not for other signatures

- The same is also true for (scalar)x(scalar) operator, and lots of confusion on this operator in literature

- Therefore let me concentrate on this case in detail in this talk

$$\overline{Q}_L H d_R \quad \text{or} \quad \overline{Q}_L \widetilde{H} u_R, \qquad \text{OK}$$

$$h\bar{\chi}\chi, \qquad\qquad s\bar{q}q$$

Both break SM gauge invariance

$$\mathcal{L} = \frac{1}{2} m_S^2 S^2 - \lambda_{s\chi} s\bar{\chi}\chi - \lambda_{sq} s\bar{q}q$$

$$\mathcal{L} = -\lambda_{h\chi} h\bar{\chi}\chi - \lambda_{hq} h\bar{q}q$$

Therefore these Lagragians often used in the literature are not good enough

$$s\bar{\chi}\chi \times h\bar{q}q \to \frac{1}{m_s^2} \bar{\chi}\chi\bar{q}q$$

Need the mixing between s and h

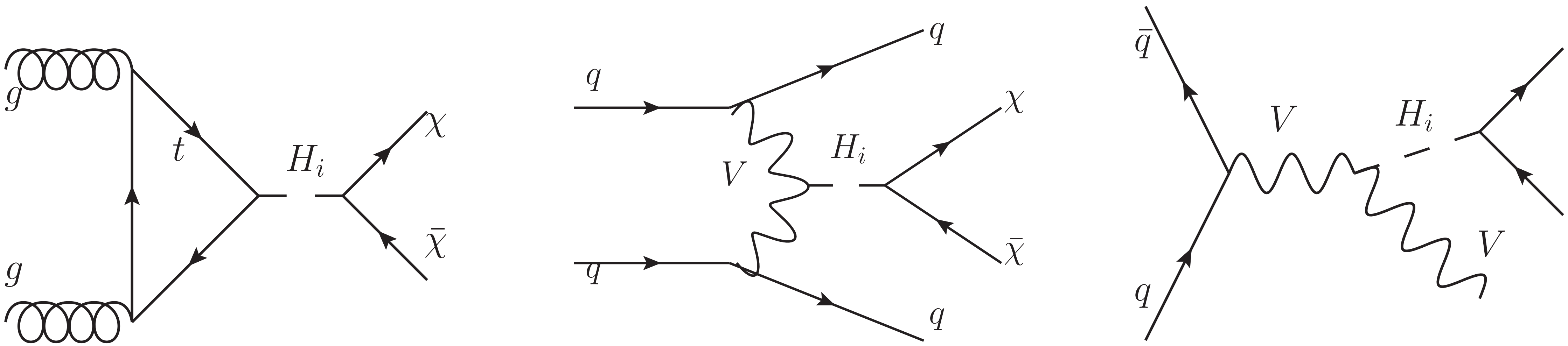



**Figure 1**: The dominant DM production processes at LHC.

Interference between 2 scalar bosons could be important in certain parameter regions

$$\frac{d\sigma_i}{dm_{\chi\chi}} \propto \left| \frac{\sin 2\alpha \; g_\chi}{m_{\chi\chi}^2 - m_{H_1}^2 + i m_{H_1}\Gamma_{H_1}} - \frac{\sin 2\alpha \; g_\chi}{m_{\chi\chi}^2 - m_{H_2}^2 + i m_{H_2}\Gamma_{H_2}} \right|^2$$

$$\boxed{\sin\alpha = 0.2, g_\chi = 1, m_\chi = 80\text{GeV}}$$

# Interference effects

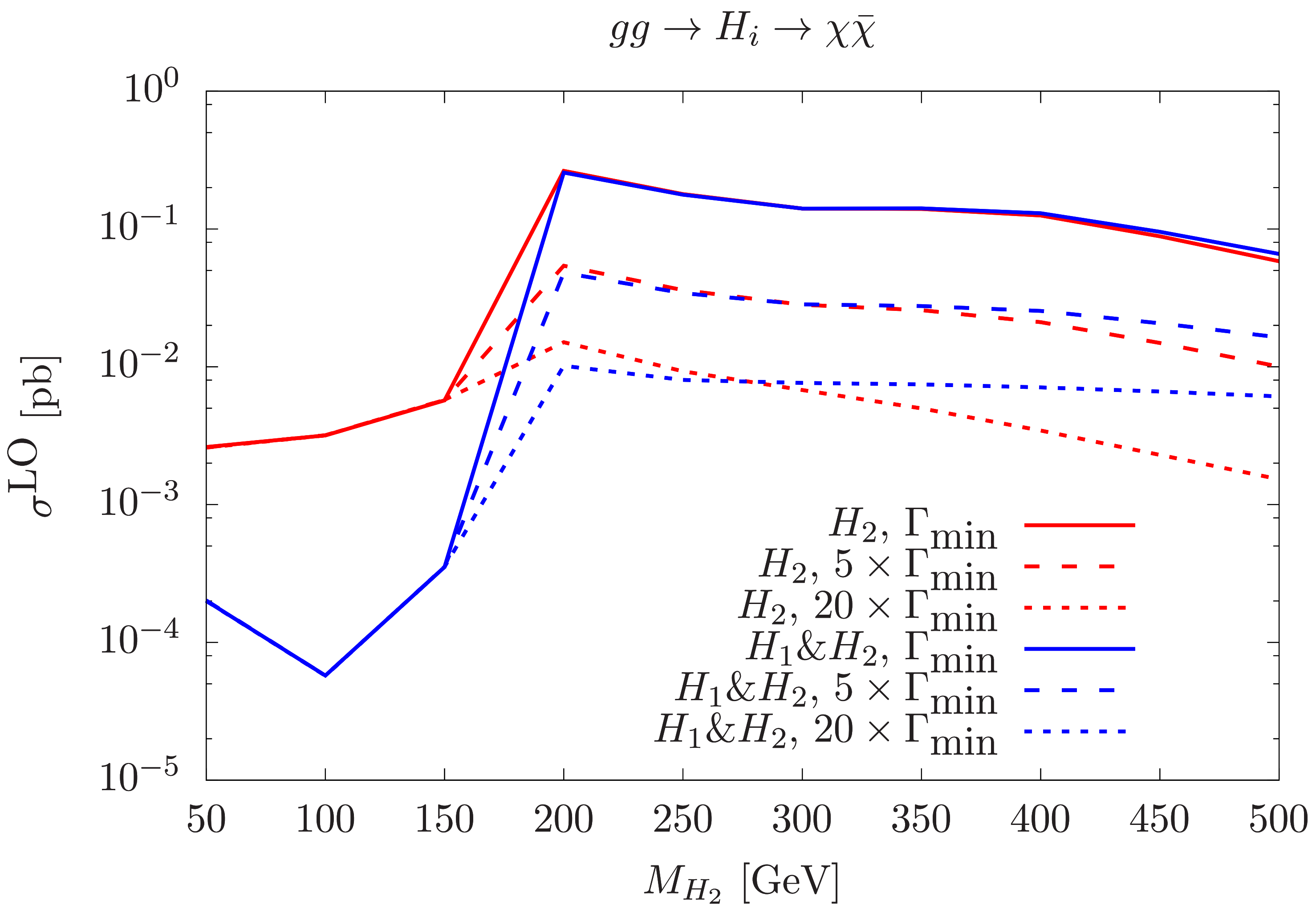



**Figure 2**: The LO cross section for gluon-gluon fusion process at 13 TeV LHC. The meanings of the different line types are explained in the text and the similar strategy will be used in all figures.

# Parton level distributions

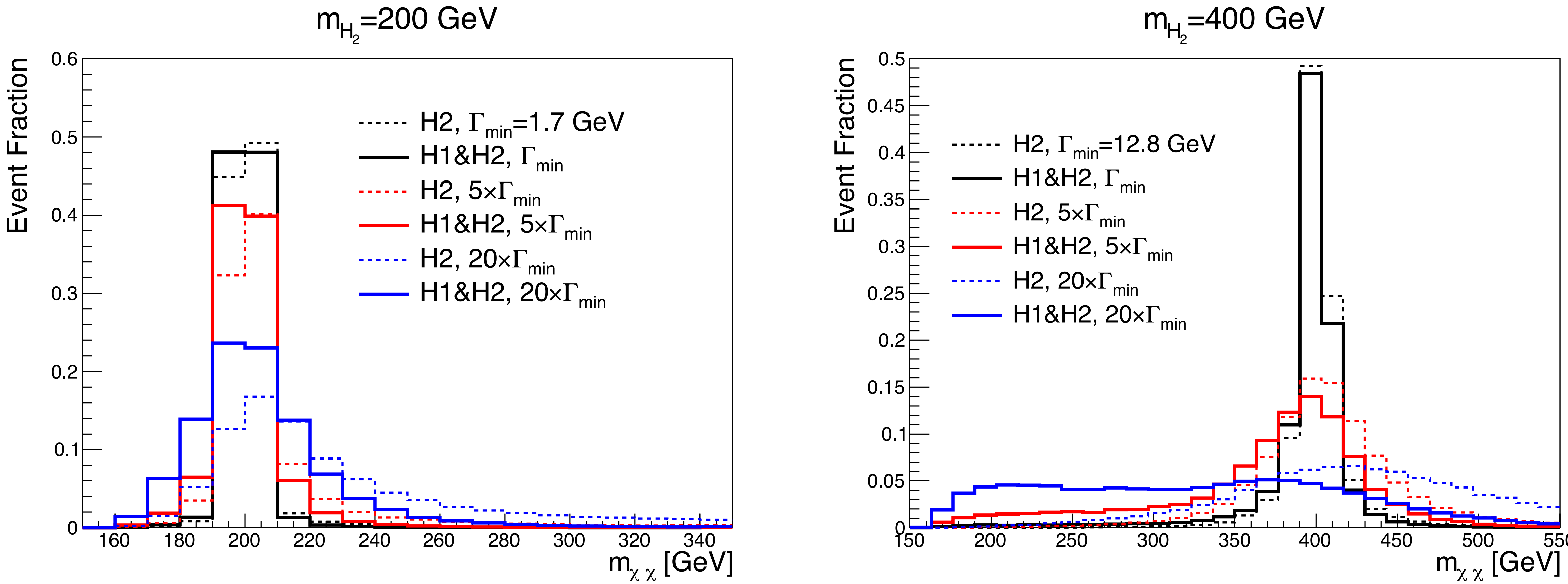



**Figure 3**: The parton level distributions of $m_{\chi\bar{\chi}}$ for gluon-gluon fusion process at 13 TeV LHC.

# Exclusion limits with interference effects

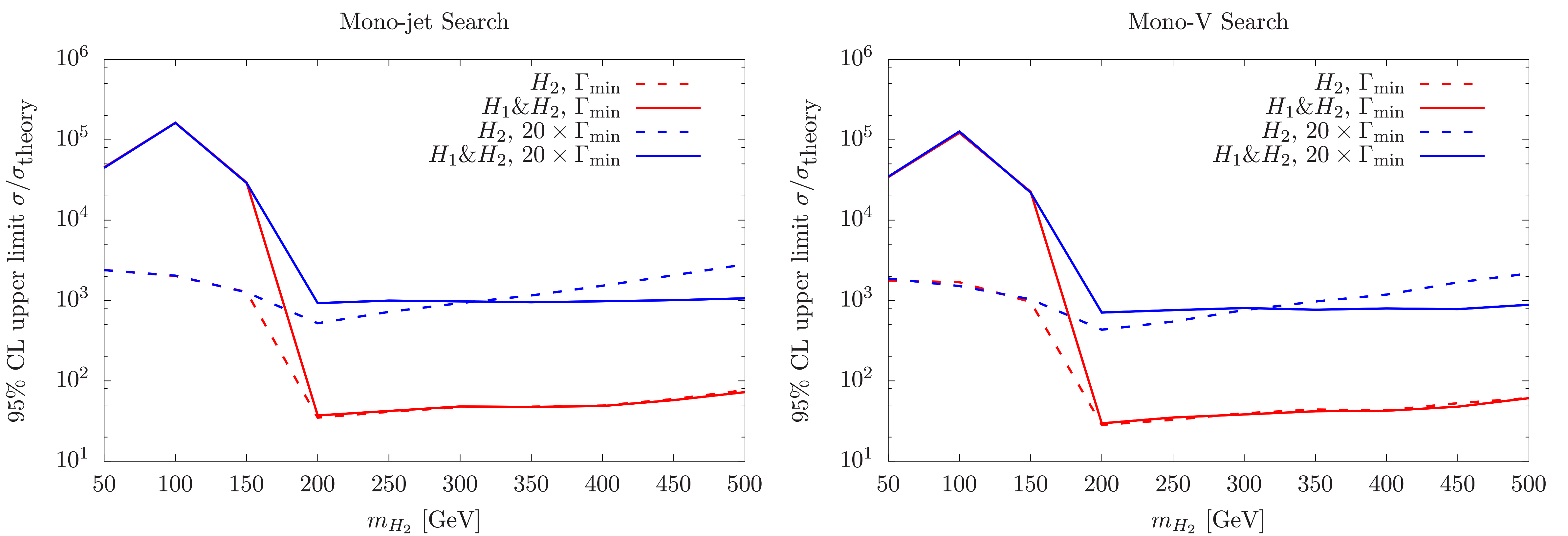



**Figure 8**: The CMS exclusion limits on our simplified models. Left: upper limit from mono-jet search. Right: upper limit from mono-V search.

- P. Ko and Jinmian Li, 1610.03997, PLB (2017)
- S. Baek, P. Ko and Jinmian Li, 1701.04131