EFT for Higgs to the invisibles

Connecting collider searches with Direct Detections

Pyungwon Ko (KIAS)

Roadmap of DM Models for Run3
CERN, May 13-17 (2024)

Higgs to the invisibles : EFT vs. UV completions

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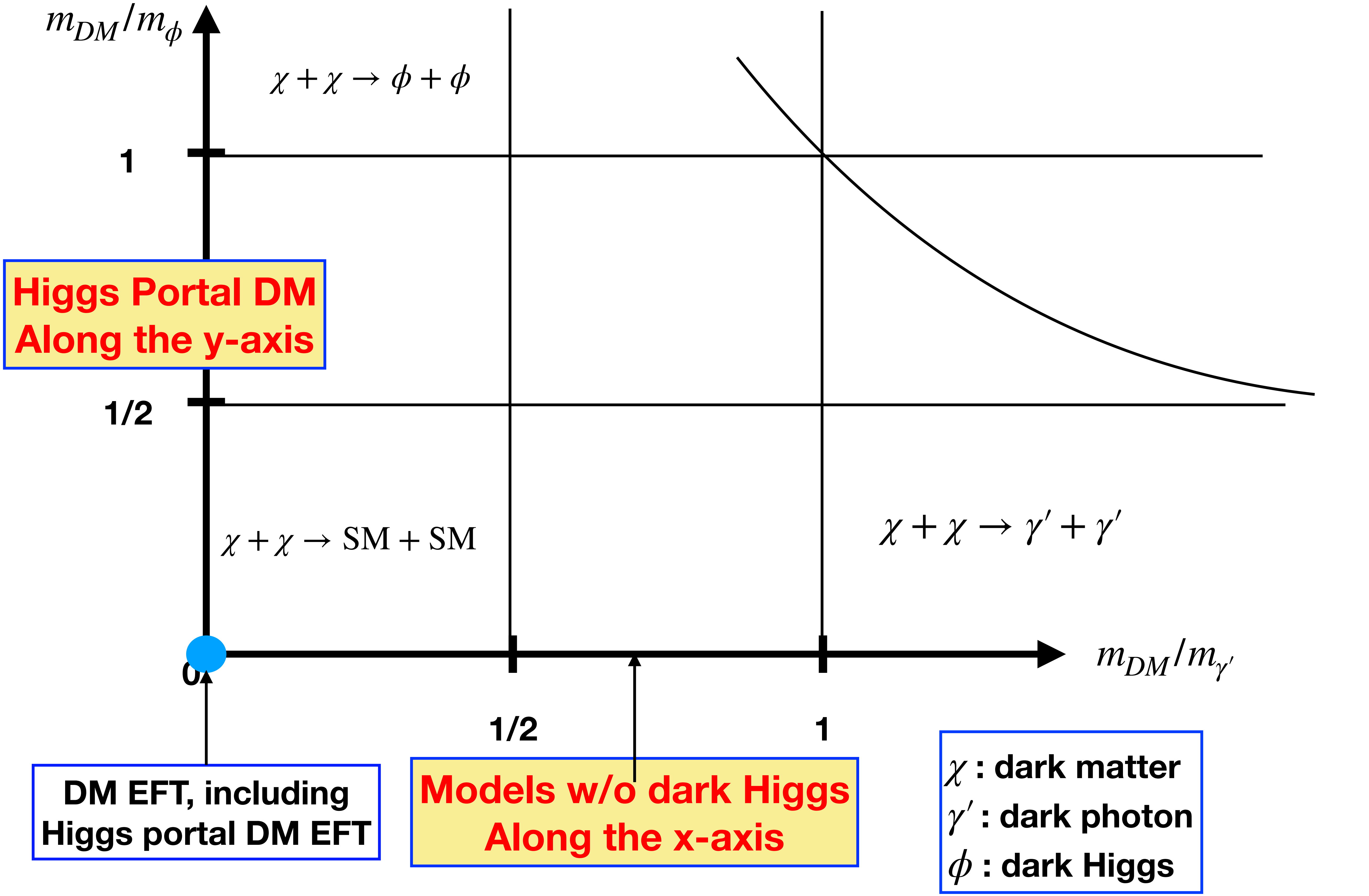
Contents

- Models for HP VDM and SFDM : EFT vs. UV completions
- Roles of Dark Higgs Boson in collider searches, indirect DM detections, direct detections, etc
- Higgs invisible decay width for VDM in the limit $m_V \to 0$
- (More on Interference between the SM and the dark Higgs)
- Conclusion & General Remarks

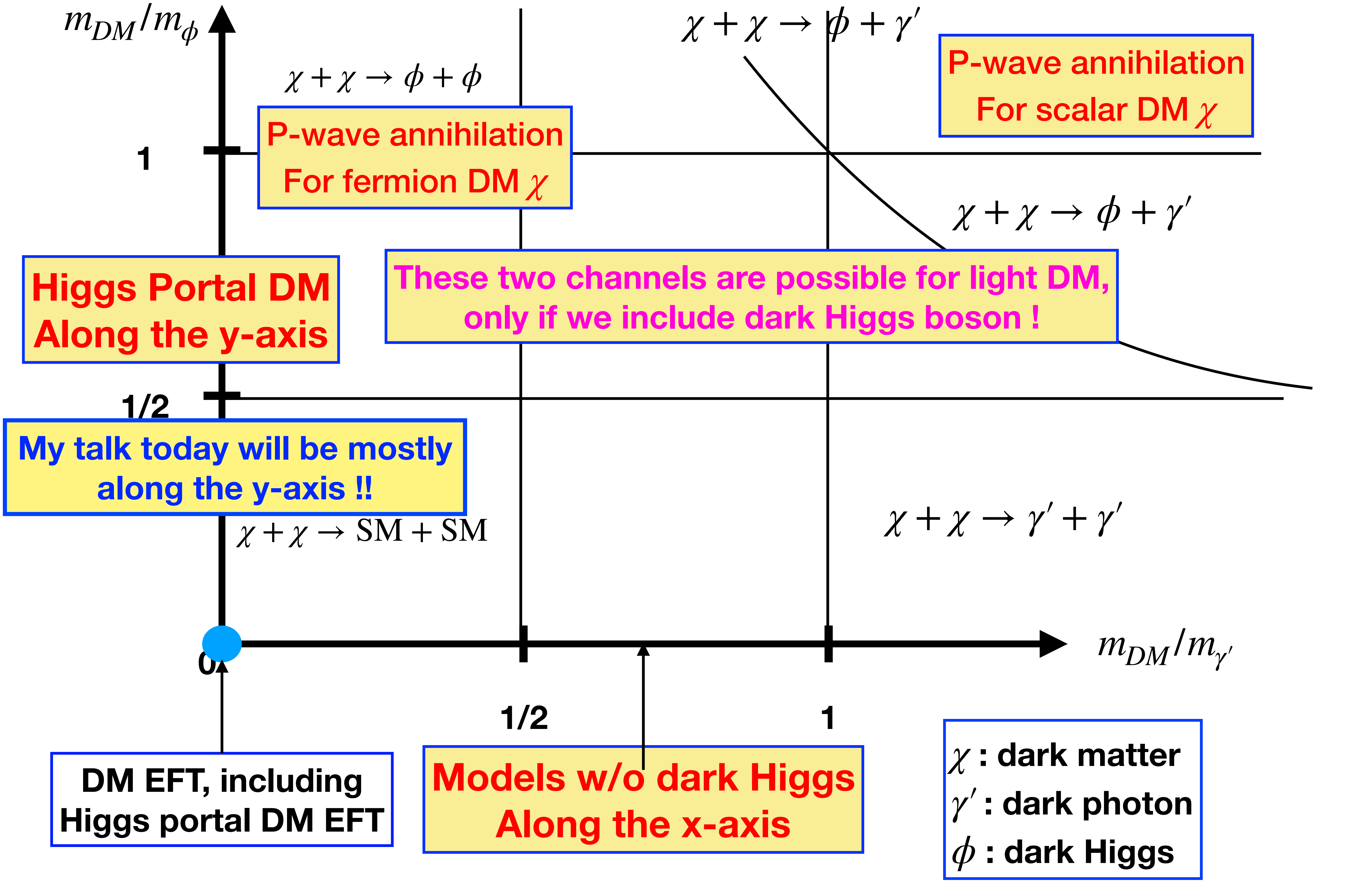
There could be some overlaps with dark Higgs boson talks.
Please excuse me !

Landscape of Dark Sector

Dark sector parameter space for a fixed m_{DM}



Dark sector parameter space for a fixed m_{DM}



Higgs portal DM:
EFT vs. UV Completions

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.

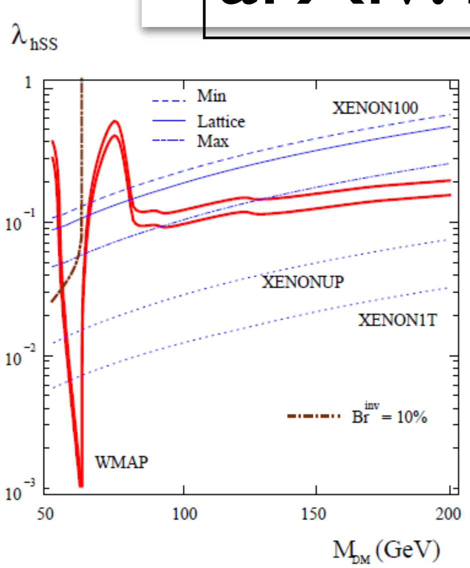


FIG. 1. Scalar Higgs-portal parameter space allowed by WMAP (between the solid red curves), XENON100 and $\mathrm{BR}^{\rm inv} = 10\%$ for $m_h = 125$ GeV. Shown also are the prospects for XENON upgrades.

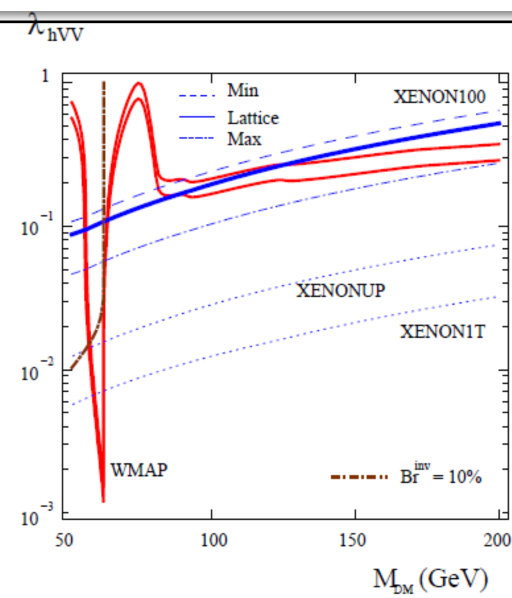


FIG. 2. Same as Fig. 1 for vector DM particles.

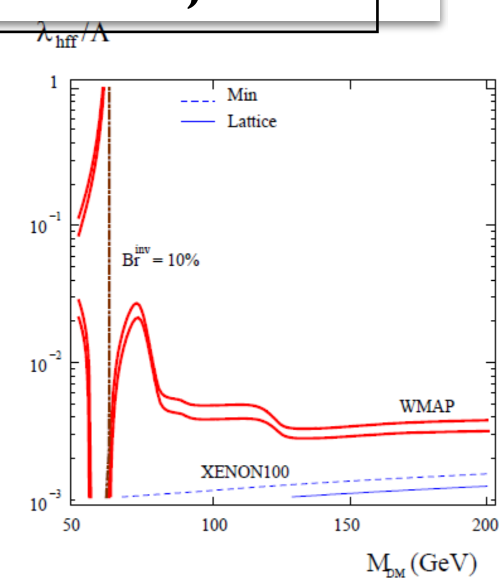


FIG. 3. Same as in Fig.1 for fermion DM; λ_{hff}/Λ is in GeV^{-1}.

Higgs portal DM as examples

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

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

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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; λ_{hff}/Λ is in GeV^{-1}.

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_ϕ , $\sin\alpha$) for DM physics**

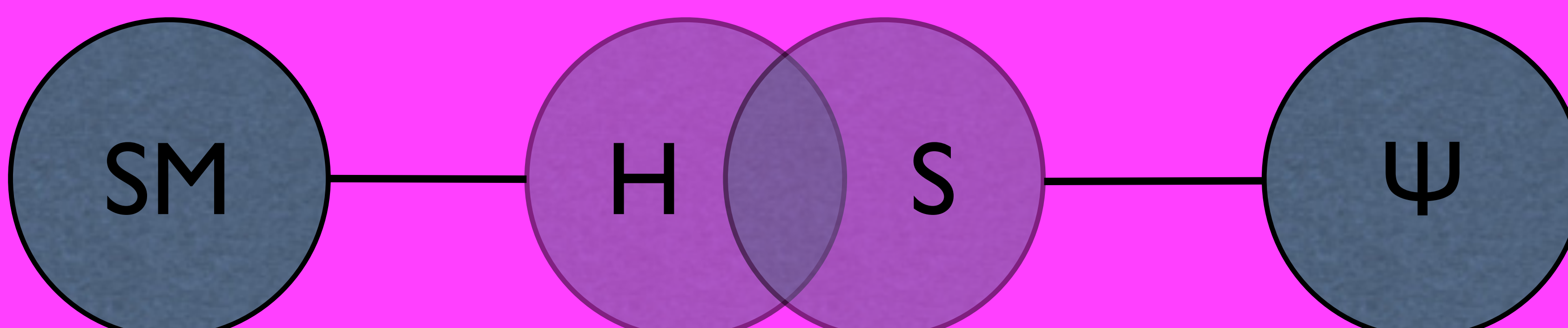
UV Completion for HP FDM

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

$$M^2_{\text{Higgs}} \equiv \begin{pmatrix} m^2_{hh} & m^2_{hs} \\ m^2_{hs} & m^2_{ss} \end{pmatrix} \equiv \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} m_1^2 & 0 \\ 0 & m_2^2 \end{pmatrix} \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix}$$

$$H_1 = h\cos\alpha - s\sin\alpha,$$

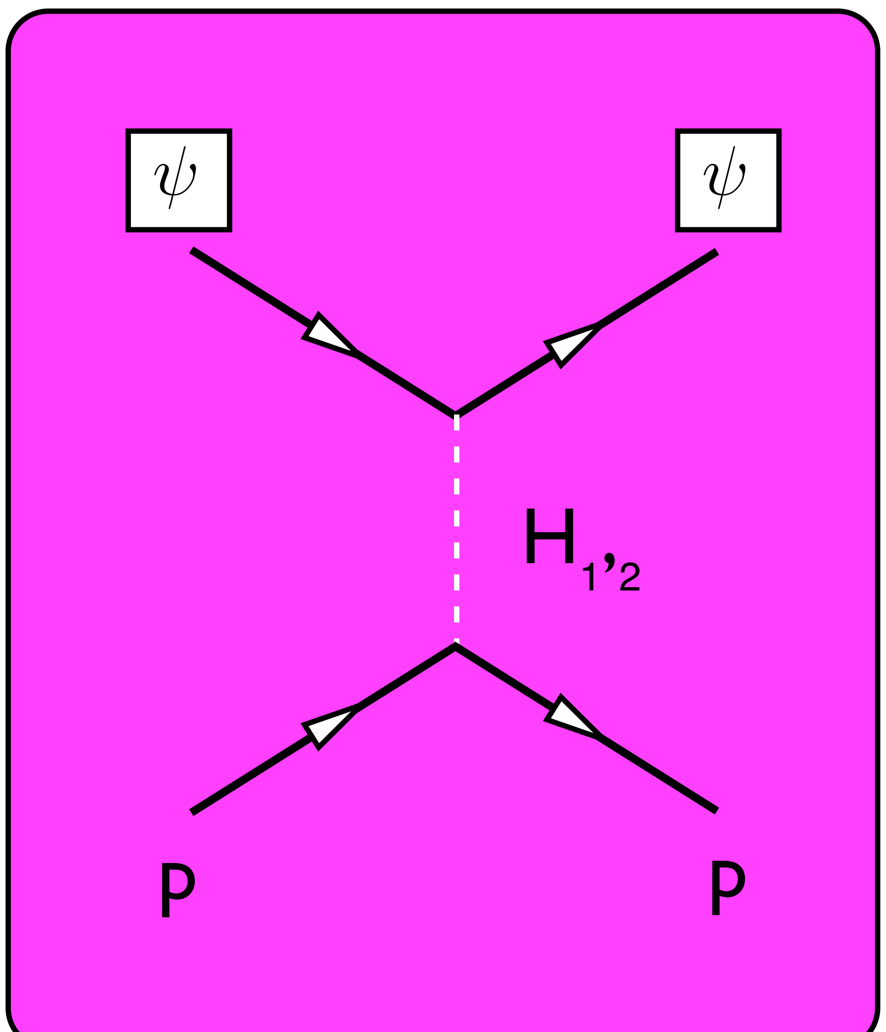
$$H_2 = h\sin\alpha + s\cos\alpha.$$

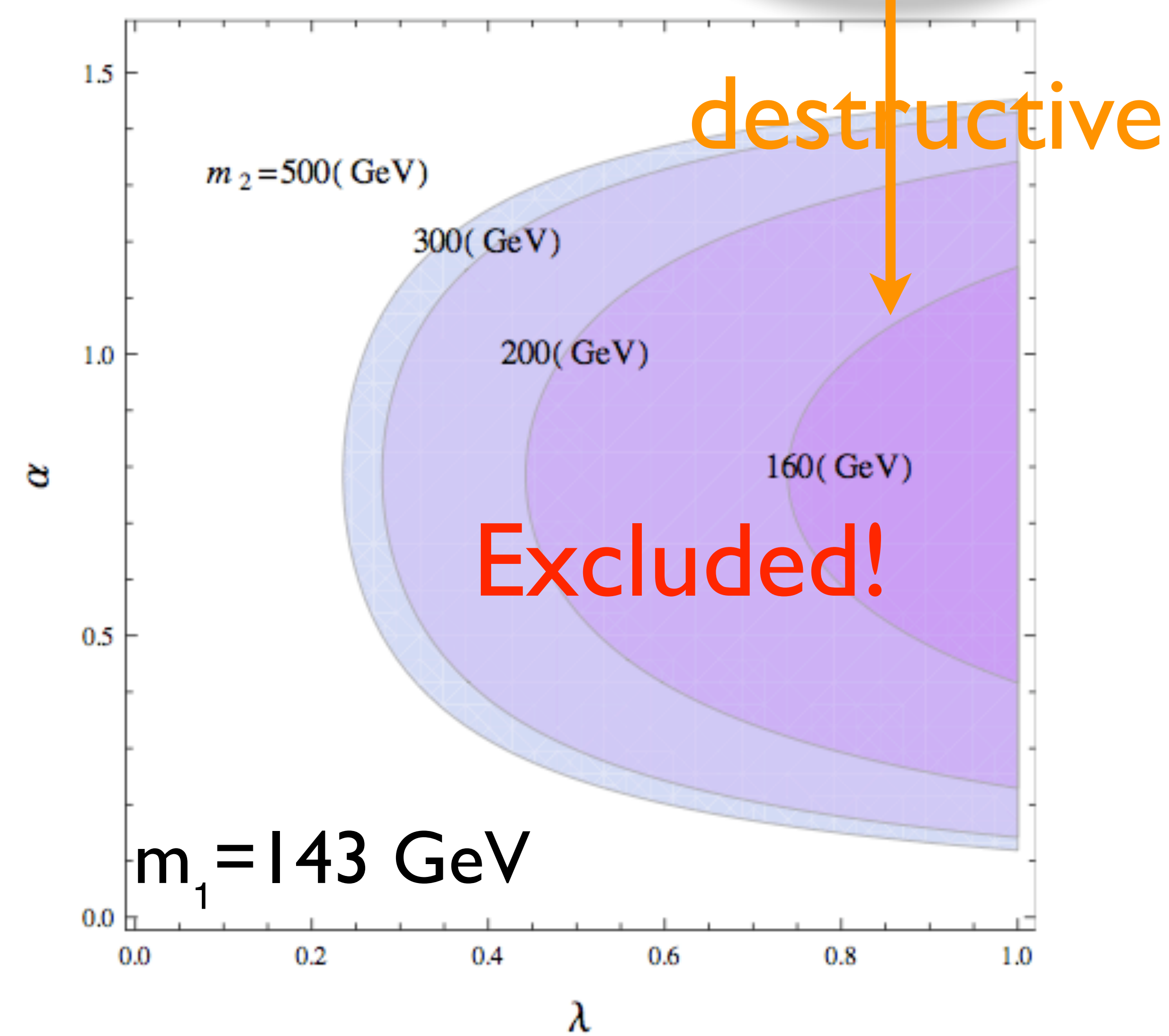
⇐ Mixing of Higgs and singlet

Constraints

- Dark matter to nucleon cross section (constraint)

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





Low energy pheno.

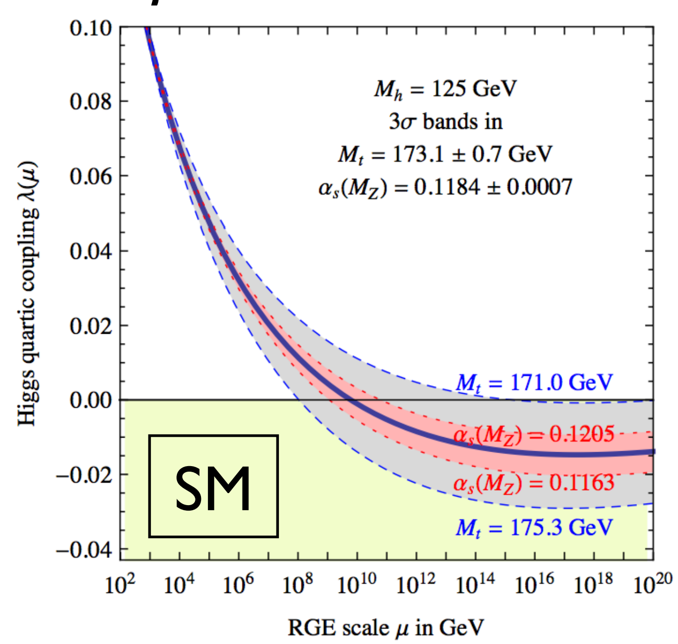
- Universal suppression of collider SM signals

[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)

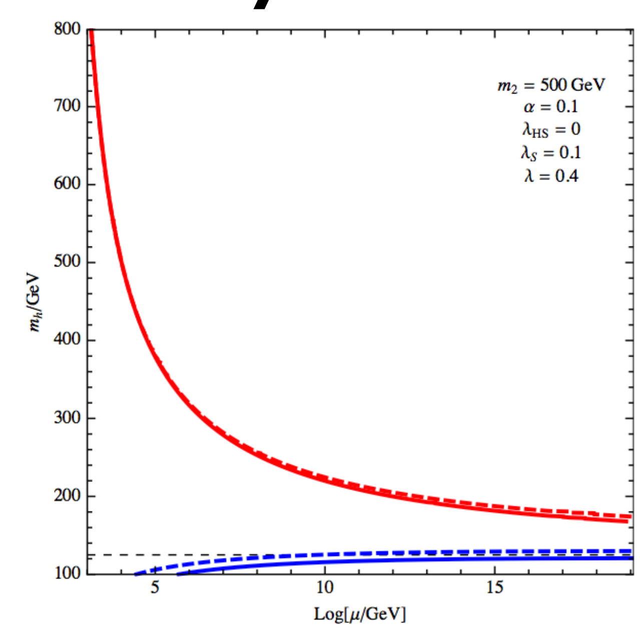
$$\lambda_{\Phi H} \Rightarrow \lambda_H = \left[1 + \left(\frac{m_\phi^2}{m_h^2} - 1\right)\sin^2\alpha\right]\lambda_H^{SM}$$

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



[G. Degrassi et al., 1205.6497]

α



[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

New scalar (Dark Higgs) improves EW vacuum stability

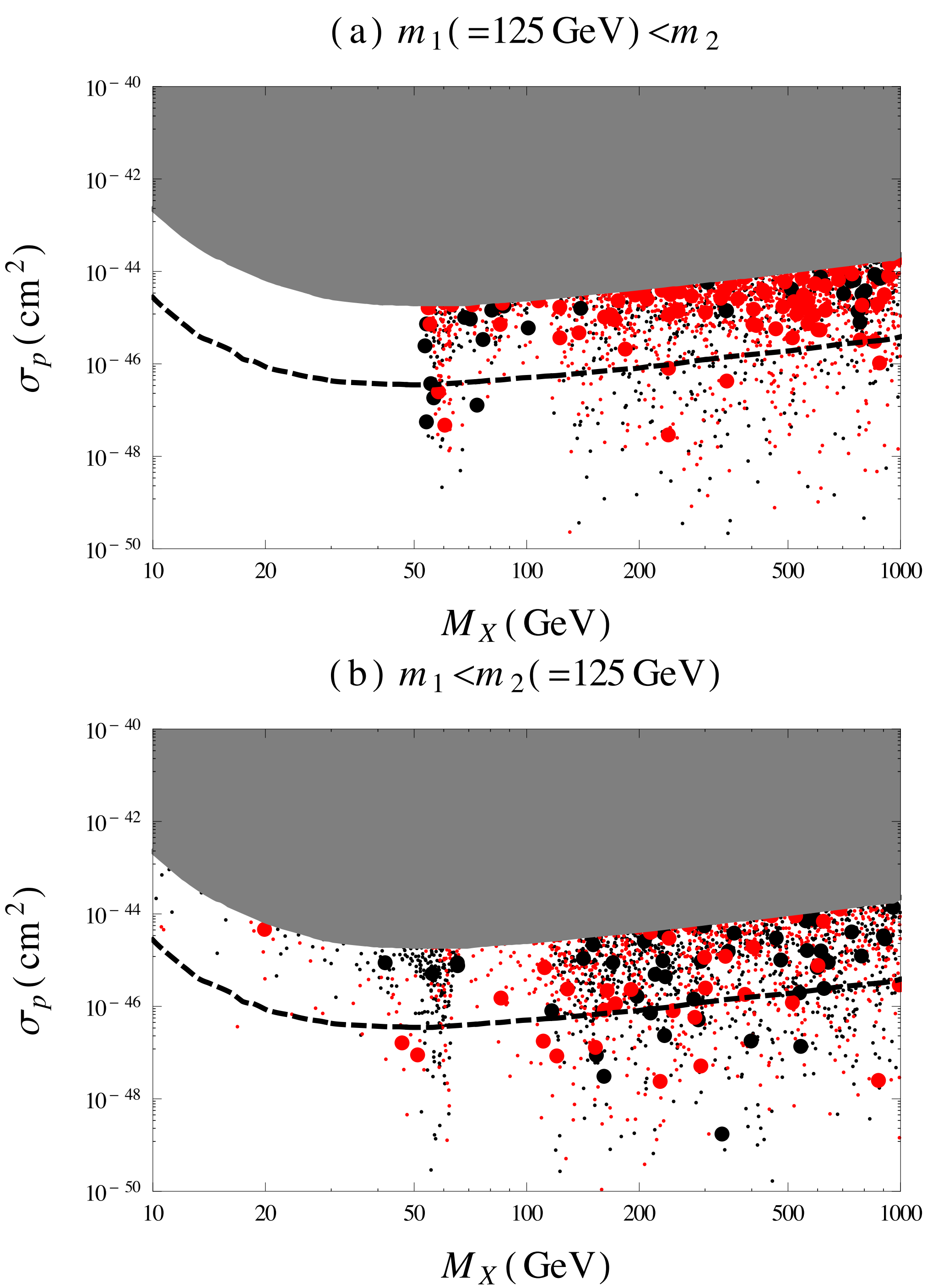


Figure 6. The scattered plot of σ_p as a function of M_X. The big (small) points (do not) satisfy the WMAP relic density constraint within 3 σ, while the red-(black-)colored points gives $r_1 > 0.7 (r_1 < 0.7)$. The grey region is excluded by the XENON100 experiment. The dashed line denotes the sensitivity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

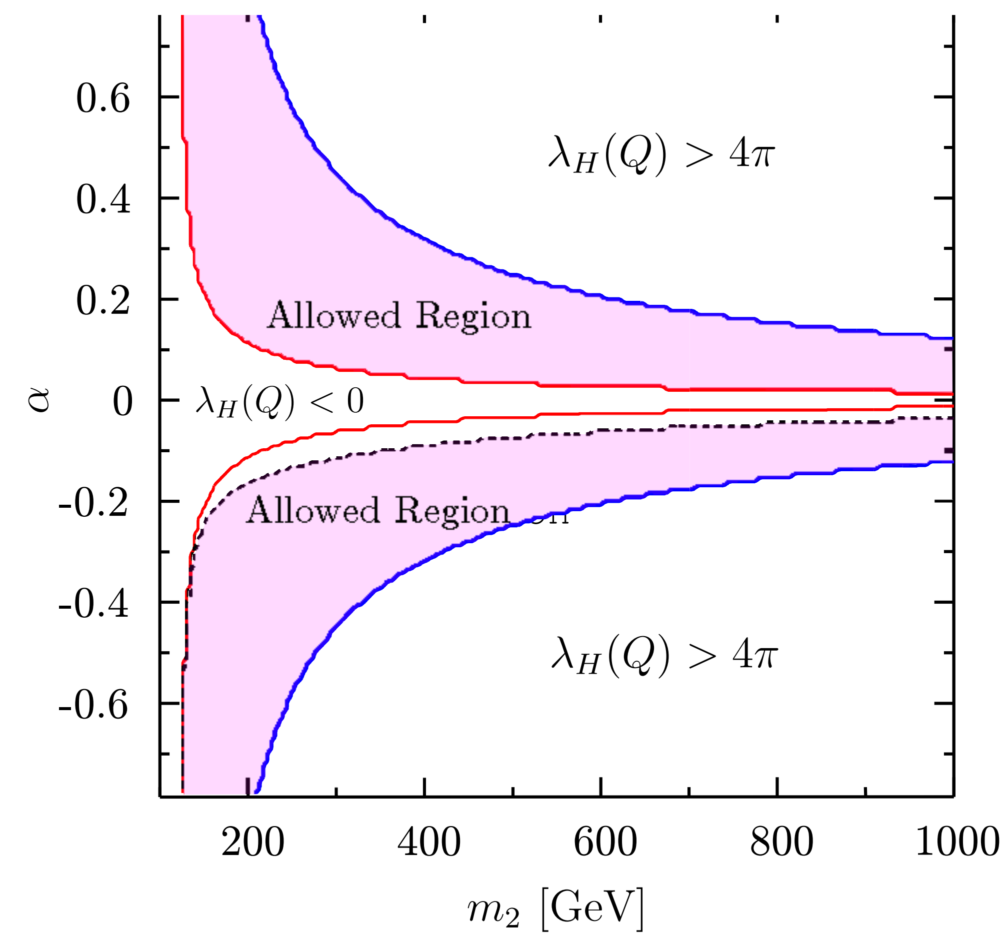


Figure 8. The vacuum stability and perturbativity constraints in the α-m_2 plane. We take $m_1 = 125$ GeV, $g_X = 0.05$, $M_X = m_2/2$ and $v_\Phi = M_X/(g_X Q_\Phi)$.

Interaction Lagrangians

Scalar DM

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

Singlet FDM

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

Vector DM

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

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

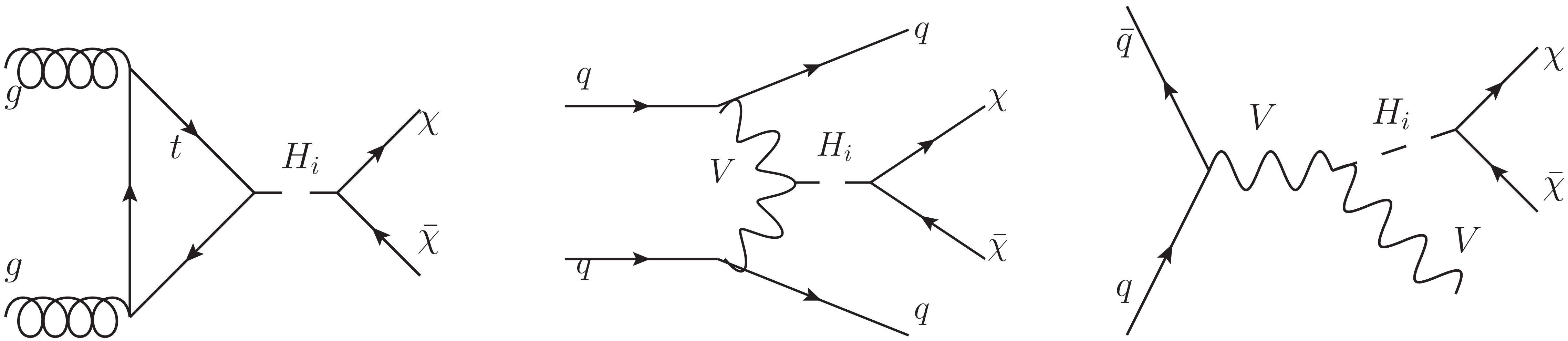


Figure 1: The dominant DM production processes at LHC.

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

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

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

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).

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

$$\text{H.P.} \underset{m_{H_2}^2 \gg \hat{s}}{\longrightarrow} \text{H.M.},$$

$$\text{S.M.} \underset{m_S^2 \gg \hat{s}}{\longrightarrow} \text{EFT},$$

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

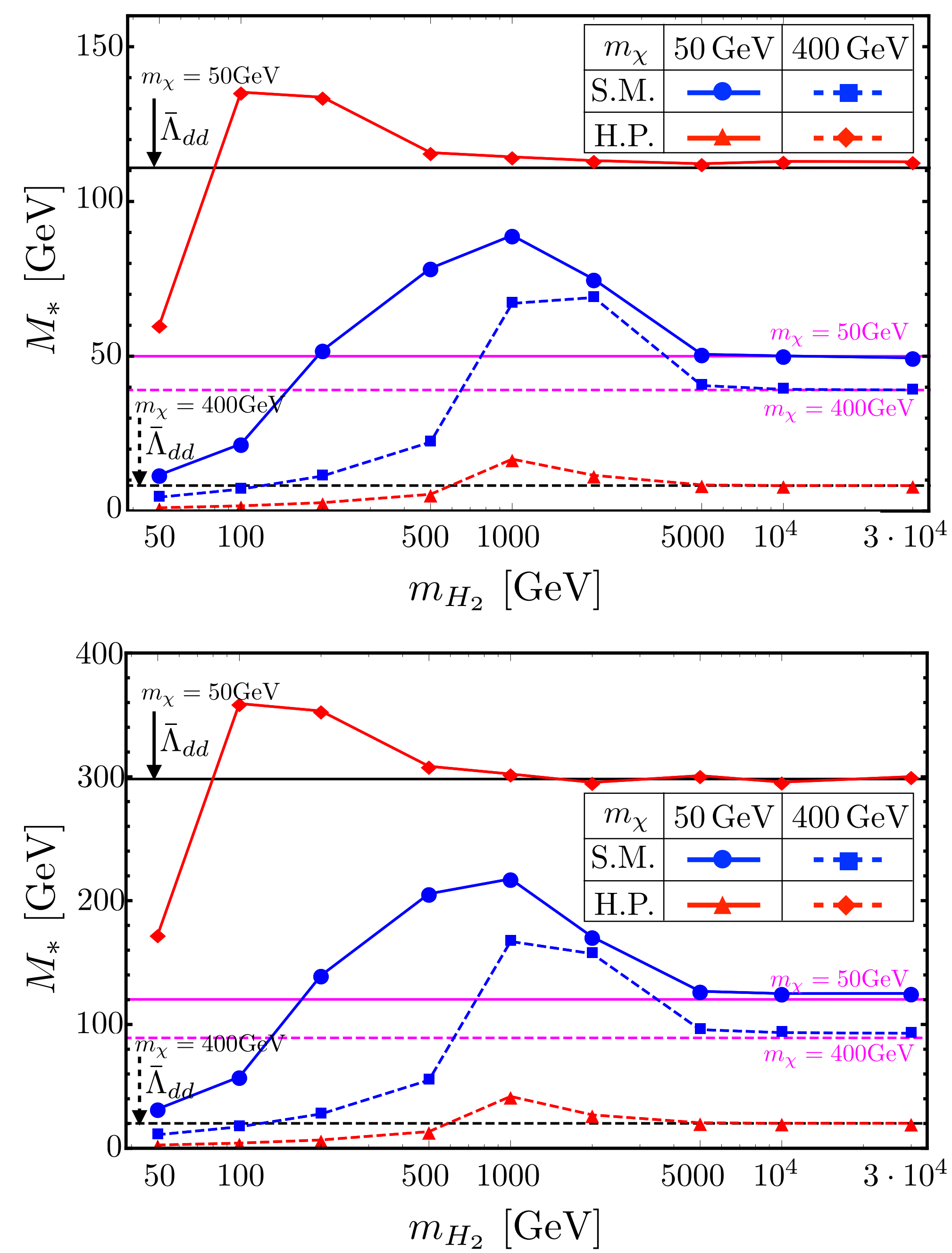


FIG. 3: The experimental bounds on M_* at 90% C.L. as a function of m_{H_2} (m_S in S.M. case) in the monojet+$\not{E}_T$ search (upper) and $t\bar{t} + \not{E}_T$ search (lower). Each line corresponds to the EFT approach (magenta), S.M. (blue), H.M. (black), and H.P. (red), respectively. The bound of 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.

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
  $\mathcal{L}_{int} = -$
- H.P.: Hi

$\frac{d\sigma_i}{dm_{\chi\chi}} \propto |\frac{}{m_{\chi\chi}^2 -}$

See Next Talk by Myeonghun Park !

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.

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

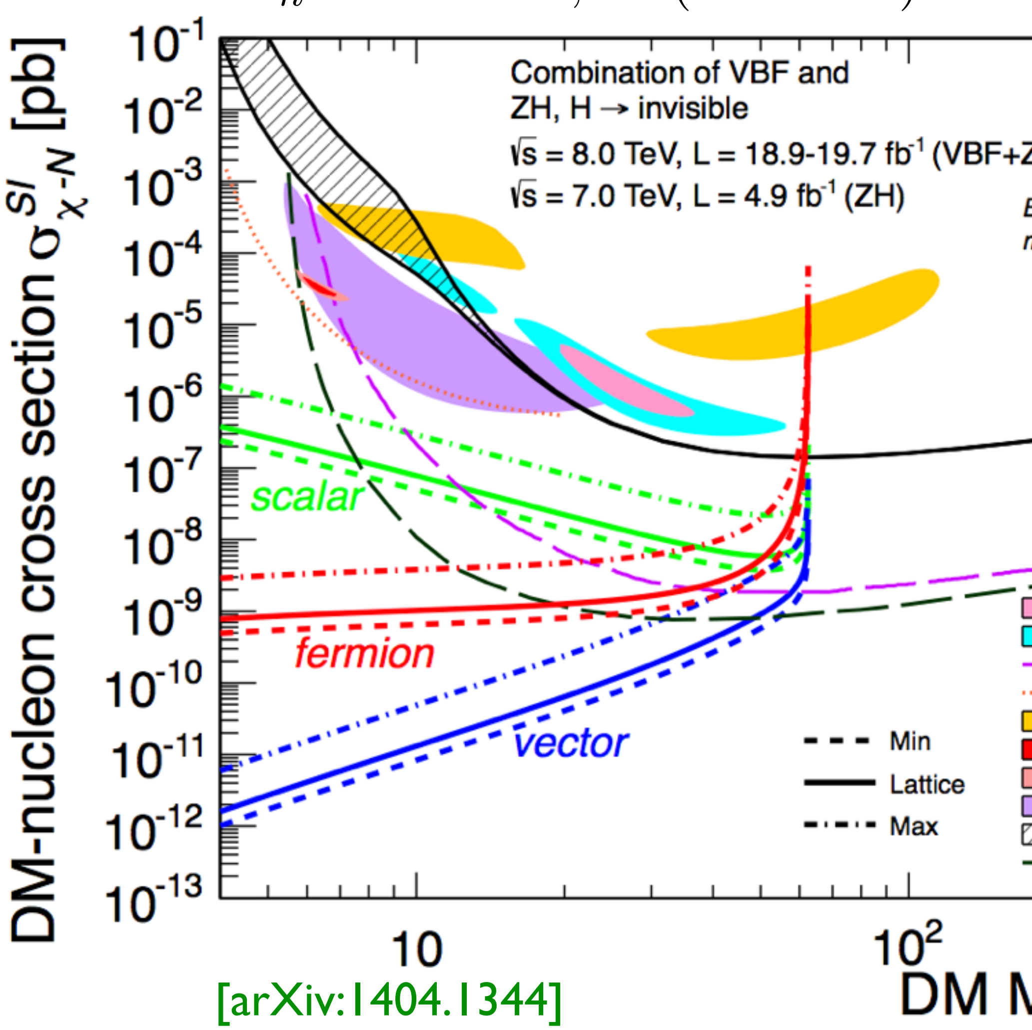
$$\text{S.M.} \xrightarrow[m_S^2 \gg \hat{s}]{} \text{EFT},$$

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

Higgs Invisible Br
vs. Direct Detection

Collider Implications

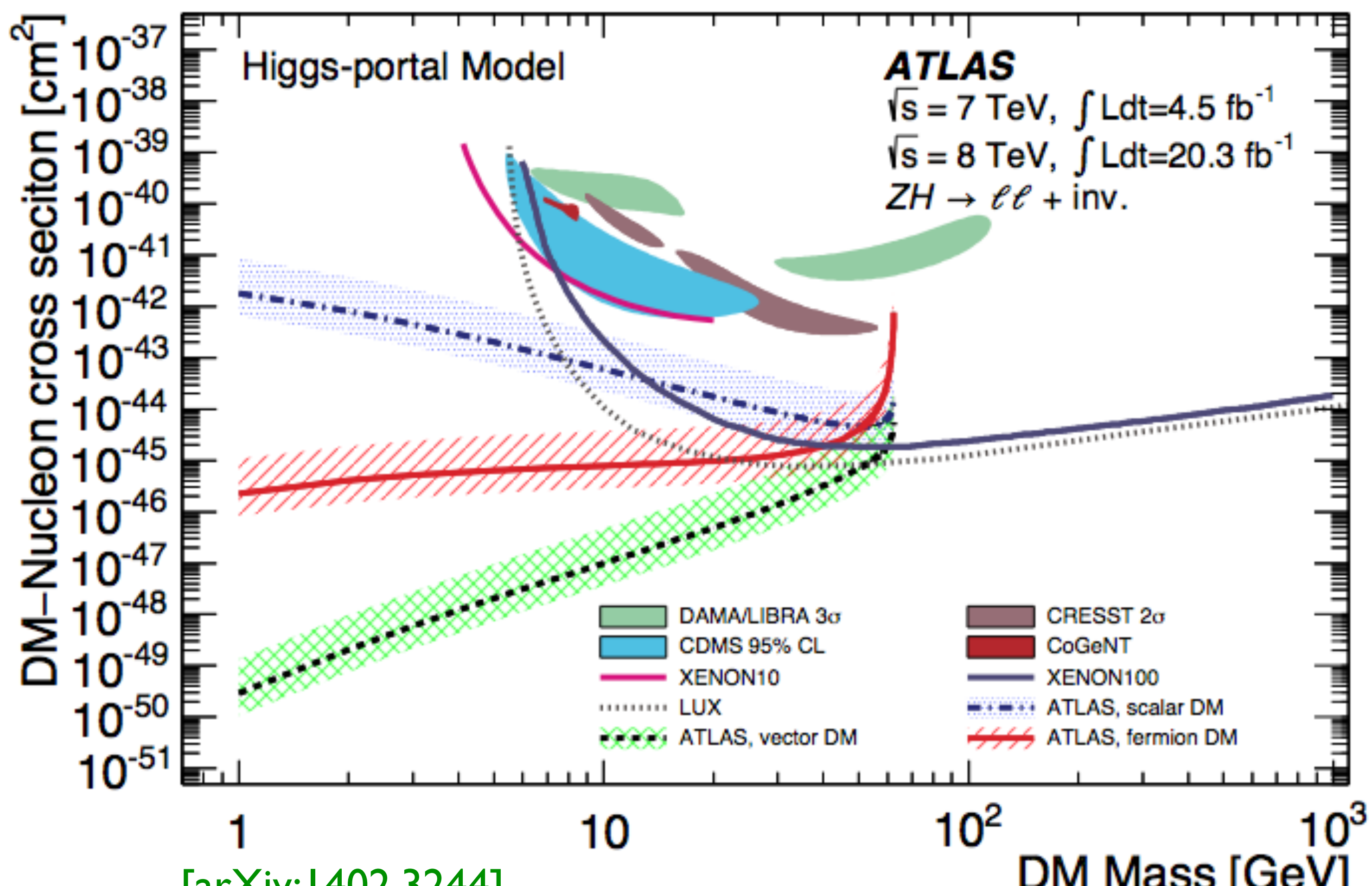
$m_h = 125\text{GeV},\ \text{Br}(H \to \text{inv}) < 0.51 \text{ at } 90\% \text{ CL}$



[arXiv:1404.1344]

Based on EFTs

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



[arXiv:1402.3244]

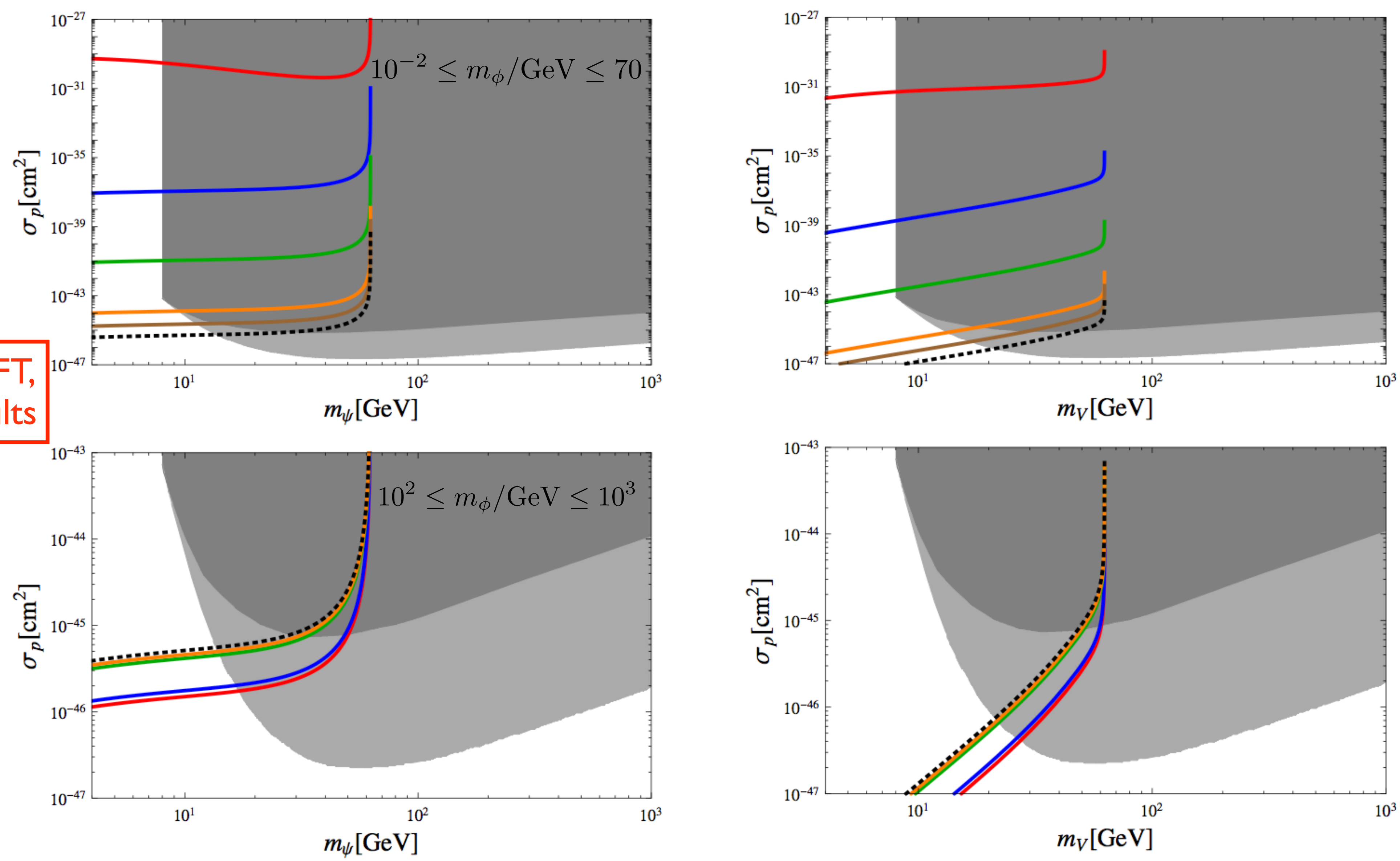
- However, in renormalizable unitary models of Higgs portals, 2 more relevant parameters !

[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

Slopes

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

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

when $\frac{4m_\psi^2 v^2}{m_2^2} \ll O(1)$

$$\mathcal{F} = \frac{1}{4m_\psi^2 v^2}\left[\sum_i \left(\frac{1}{m_i^2} - \frac{1}{4m_\psi^2 v^2 + m_i^2}\right) - \frac{2}{(m_2^2 - m_1^2)}\sum_i (-1)^{i-1} \ln\left(1 + \frac{4m_\psi^2 v^2}{m_i^2}\right)\right] \quad (13)$$

- $m_\psi = m_{\rm DM}$ dependence visible only when $\frac{4m_\psi^2 v^2}{m_2^2} \sim O(1)$
- This is why the slopes for $m_\phi = 10^{-2}$ GeV (red curves) are different from the slopes for the EFT cases

Slope changes for $m_\phi = 10^{-2}$ GeV

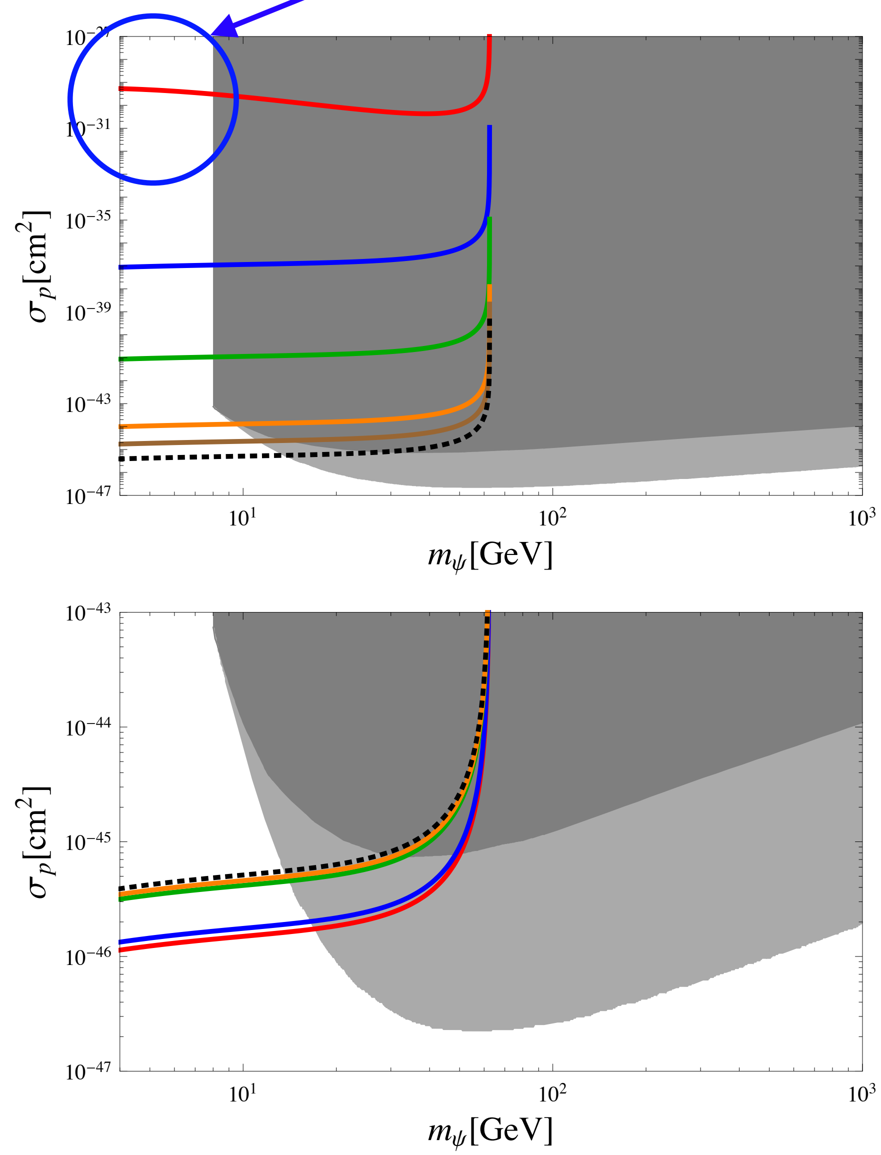


FIG. 1: σ_p^{SI} as a function of the mass of dark matter for SFDM for a mixing angle $\alpha = 0.2$. Upper panel: $m_2 = 10^{-2}, 1, 10, 50, 70\,\mathrm{GeV}$ for solid lines from top to bottom. Lower panel: $m_2 = 100, 200, 500, 1000\,\mathrm{GeV}$ for dashed lines from bottom to top. The balck dotted line is EFT prediction. Dark-gray and gray region are the exclusion regions of LUX [15] and projected XENON1T (gray) [16].

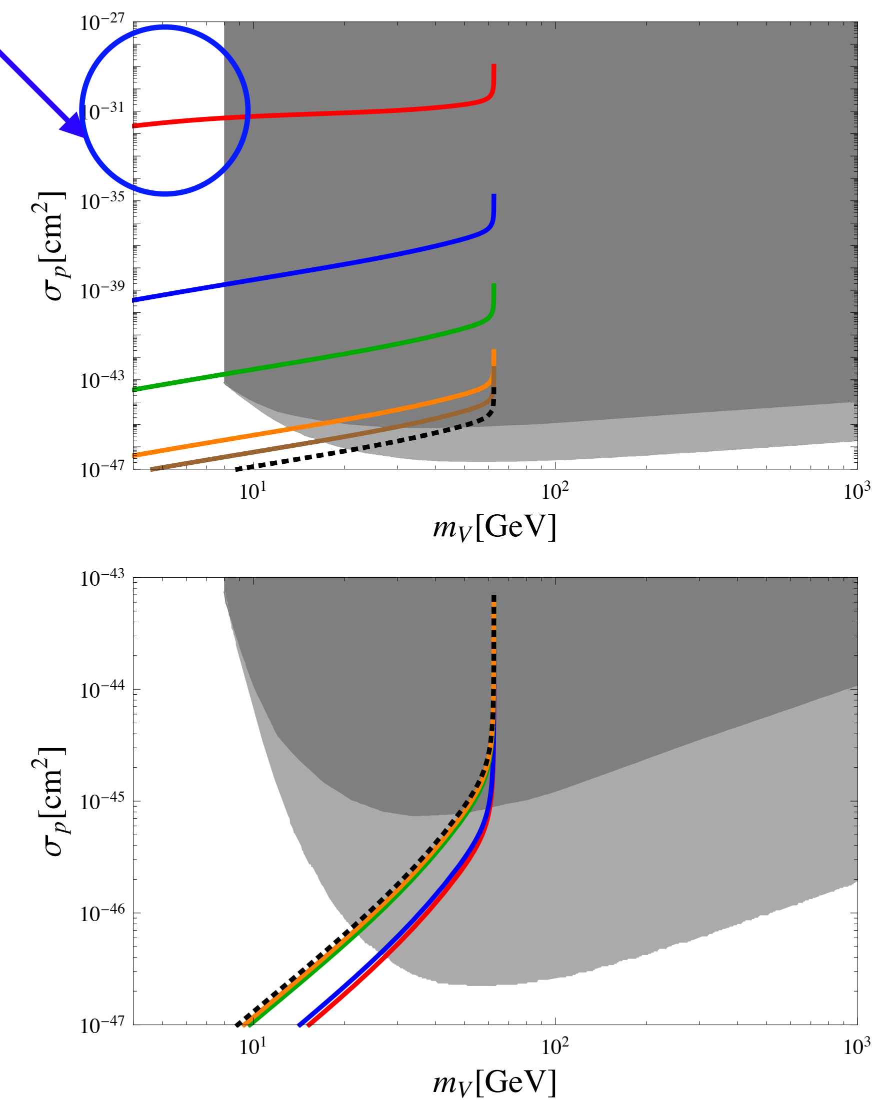


FIG. 2: σ_p^{SI} as a function of the mass of dark matter for SVDM for a mixing angle $\alpha = 0.2$. Same color and line scheme as Fig. 1.

Slope changes for very light $m_\phi = 10^{-2}$ GeV

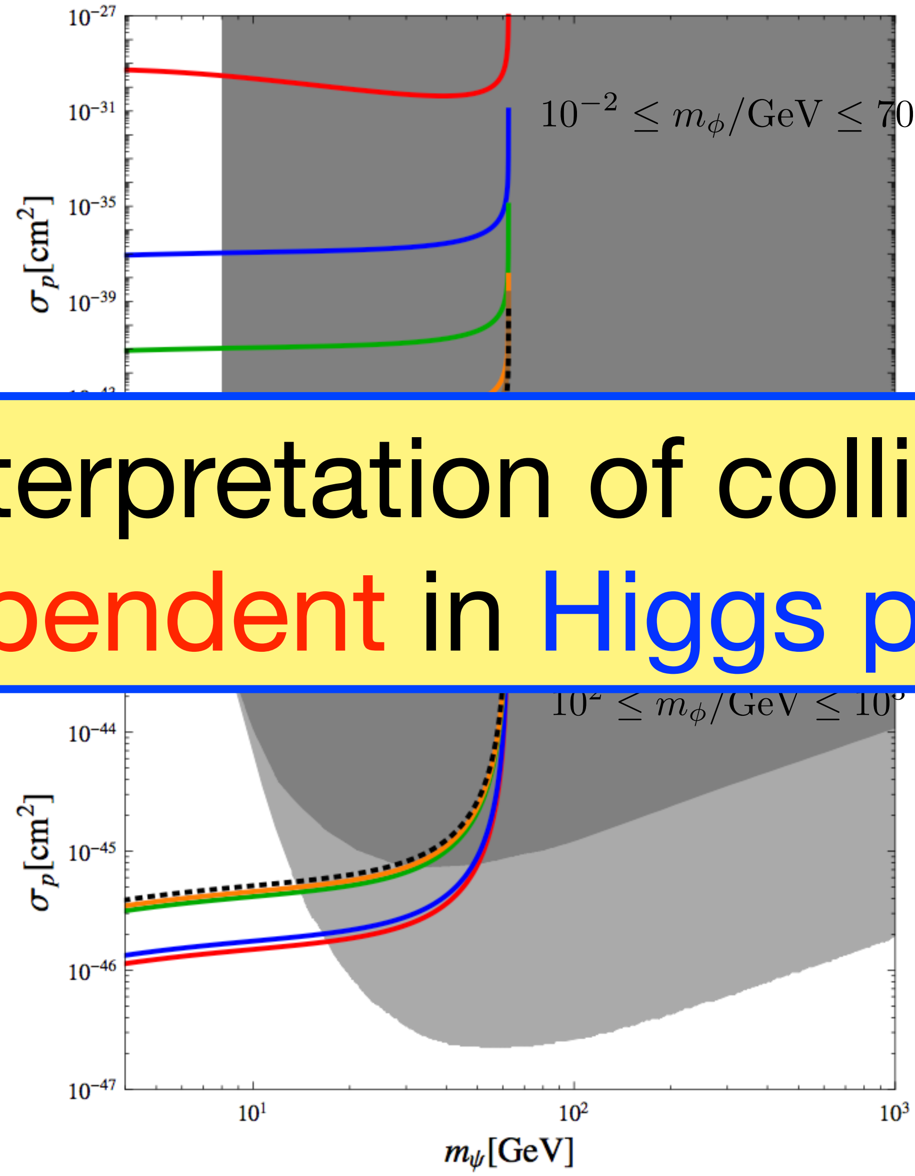
- However, in renormalizable unitary models of Higgs portals, 2 more relevant parameters

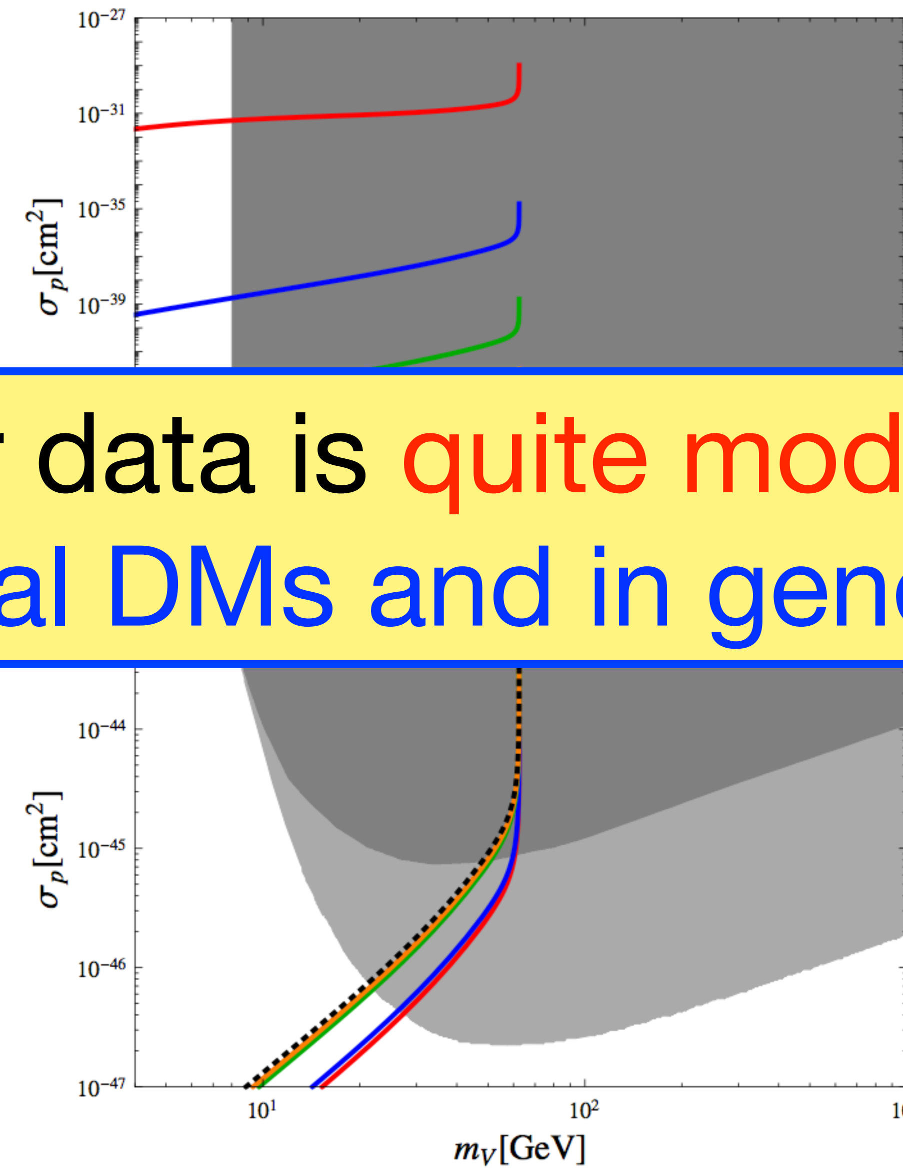
[arXiv: 1405.3530, S. Baek, P. Ko & WIPark, PRD]

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

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

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



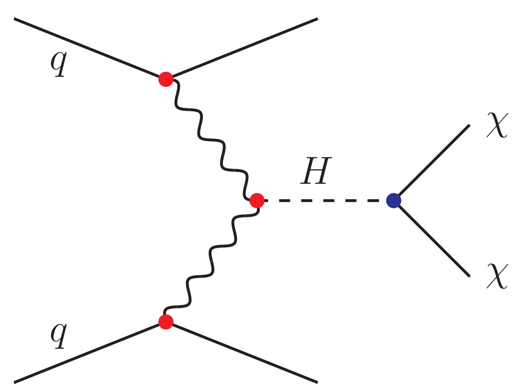


Interpretation of collider data is quite model-dependent in Higgs portal DMs and in general

Search for H→ Dark matter (invisible)

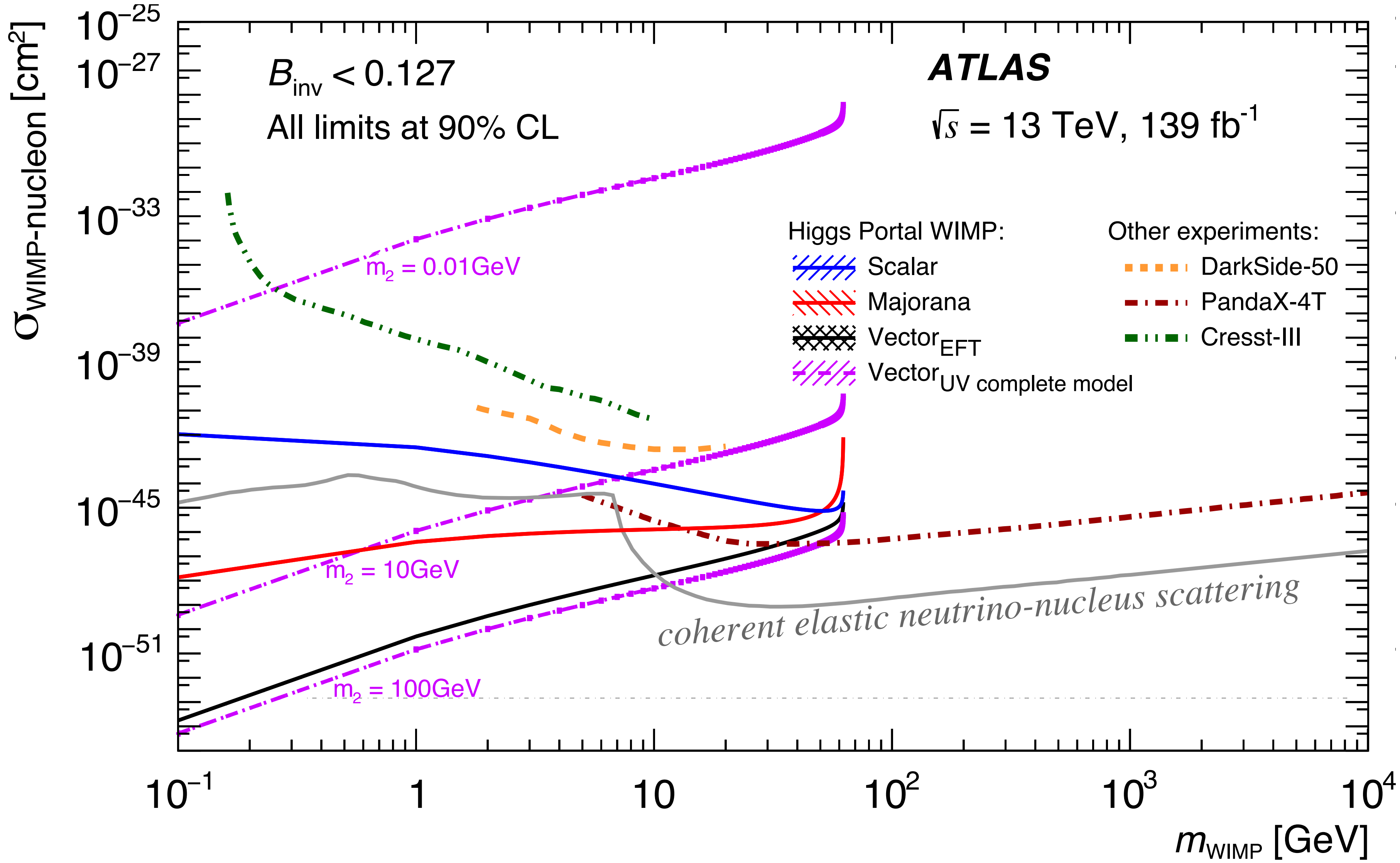
BR(H→invisible) < 14.5% (obs)   (10.3% exp.)
from search with VBF topology
(13% limit when combined with Higgs coupling measurements)

ATLAS Highlight talks
By G.Unal @ICHEP2022, and
By M. Cristinziani @ CORFU2022



Now implemented in the ATLAS results,
But only for VDM, and not for SFDM

arXiv:2202.07953



$\Gamma_{\rm inv}(H \to VV)$ for

$m_{\rm V} \to 0$?

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 $m_V \to 0$

See the addendum by S Baek, P Ko, WI Park (2021)

- $m_V = g_X Q_\Phi v_\Phi$ 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_Φ 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

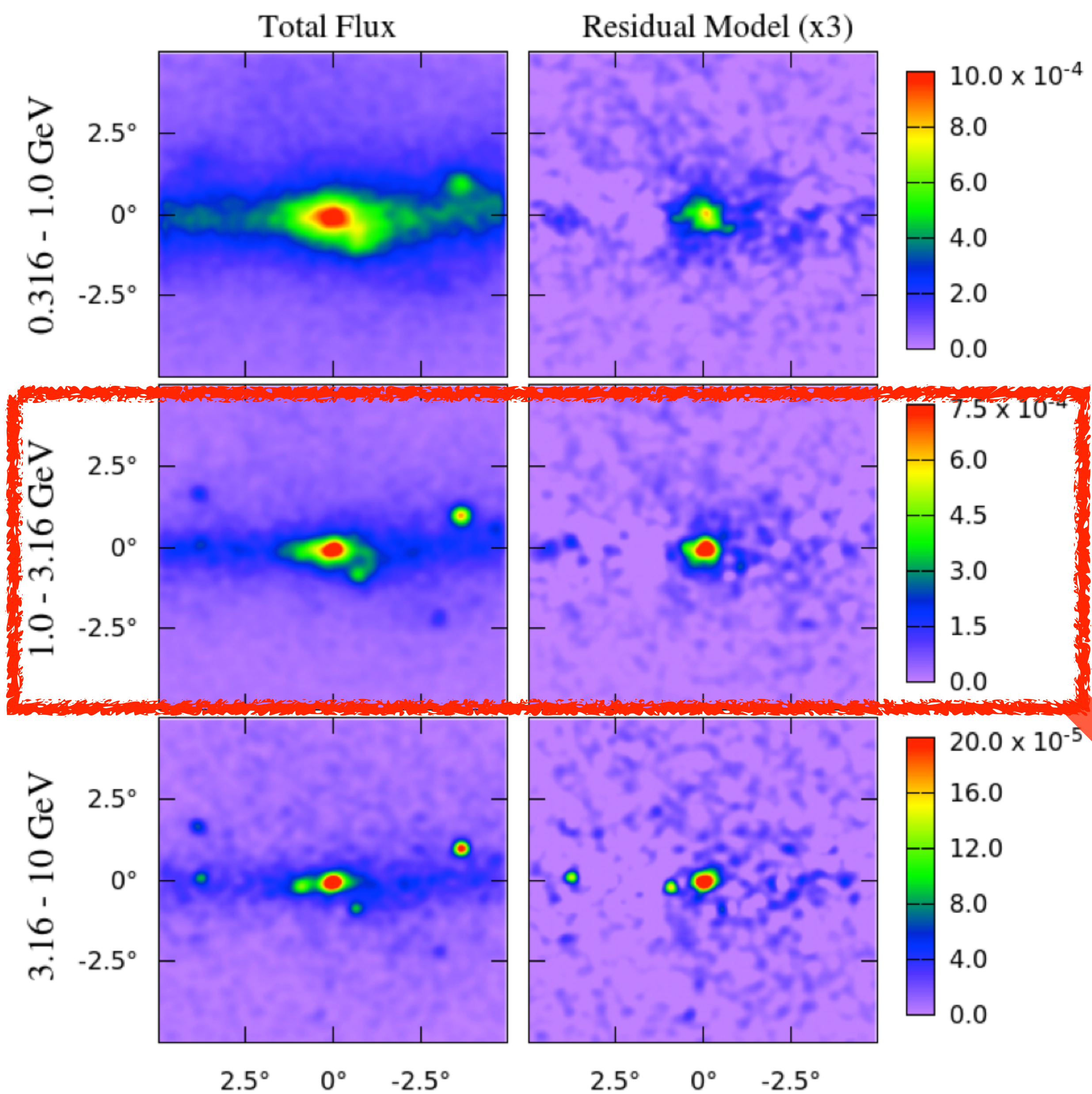
Also true in another UV completion proposed by DiFranzo, Fox, Tait (2015)

Roles of Dark Higgs

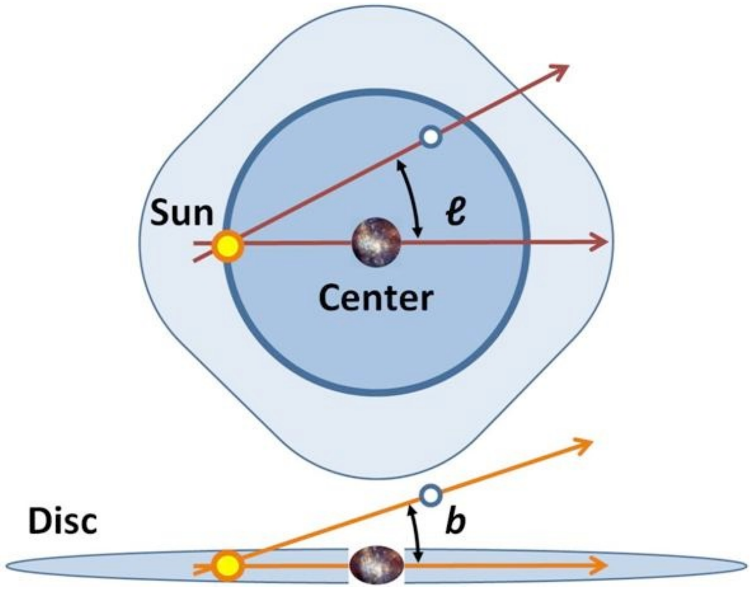
- Restore the full SM gauge invariance, both for spin-1 and spin-0 mediators
- Restore gauge invariance/unitarity in the presence of massive dark photon
- Many phenomenological implications and particle physics and cosmology (Higgs-portal assisted Higgs inflation)
- Interference with the SM Higgs boson can be important in DM collider searches in some cases

Fermi-LAT GC γ-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.]

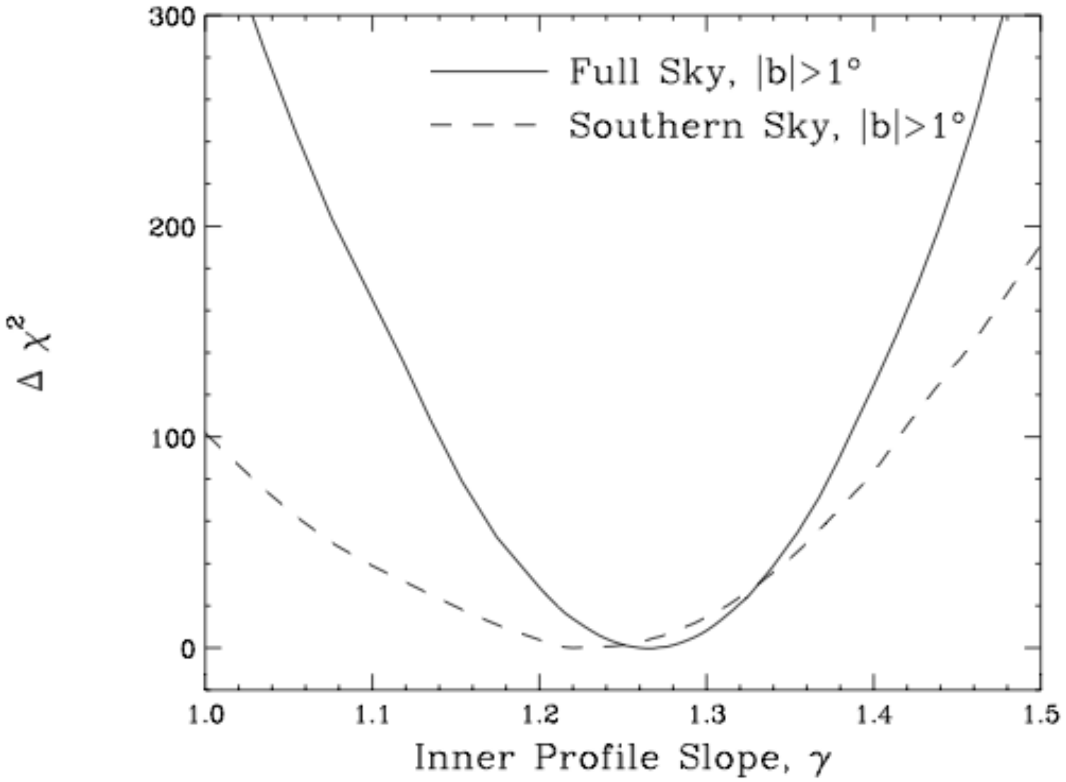


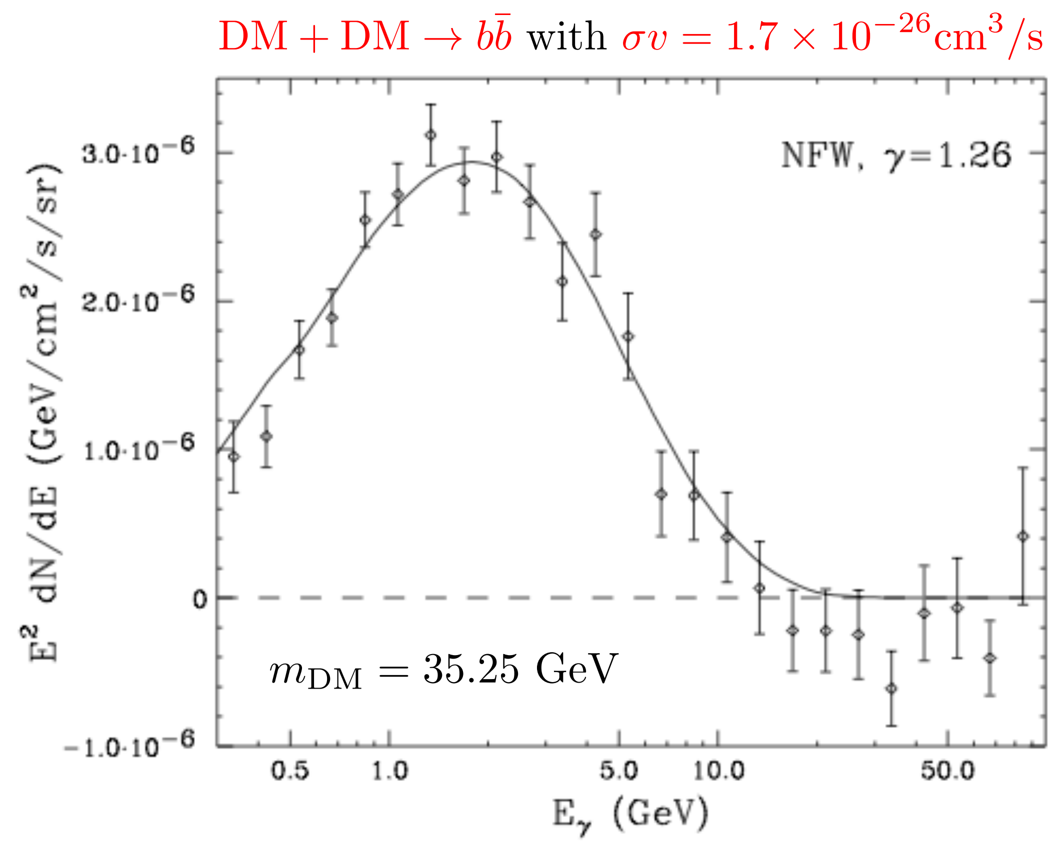
$$\mathrm{GC} : b \sim l \lesssim 0.1^\circ$$

extended

GeV scale excess!

• A DM interpretation





* 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

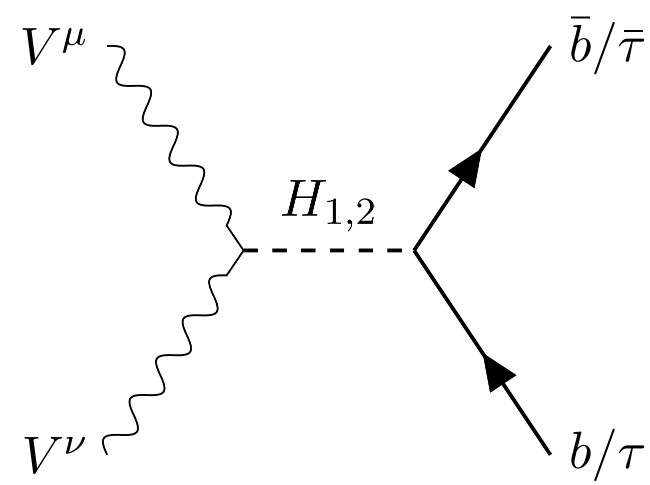


Figure 2. Dominant s channel $b+\bar{b}$ (and $\tau+\bar{\tau}$) production

H2 : 125 GeV Higgs
H1 : absent in EFT

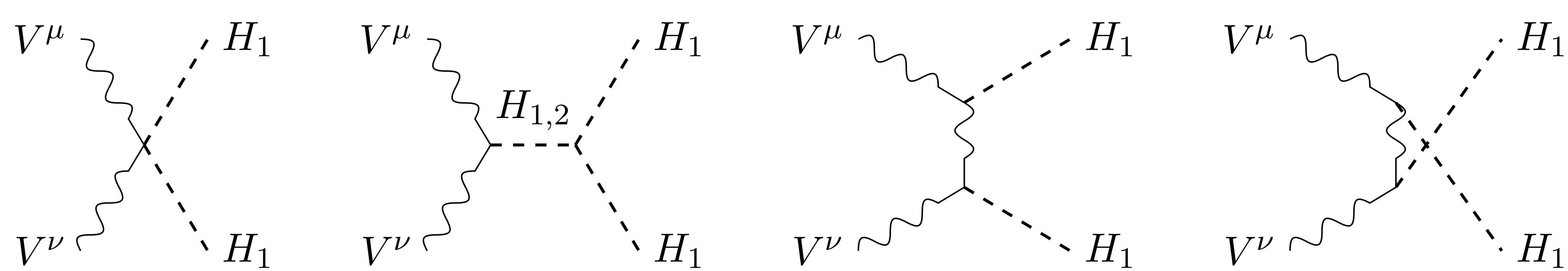


Figure 3. Dominant s/t-channel production of H_1s that decay dominantly to $b+\bar{b}$

Importance of HP VDM with Dark Higgs Boson

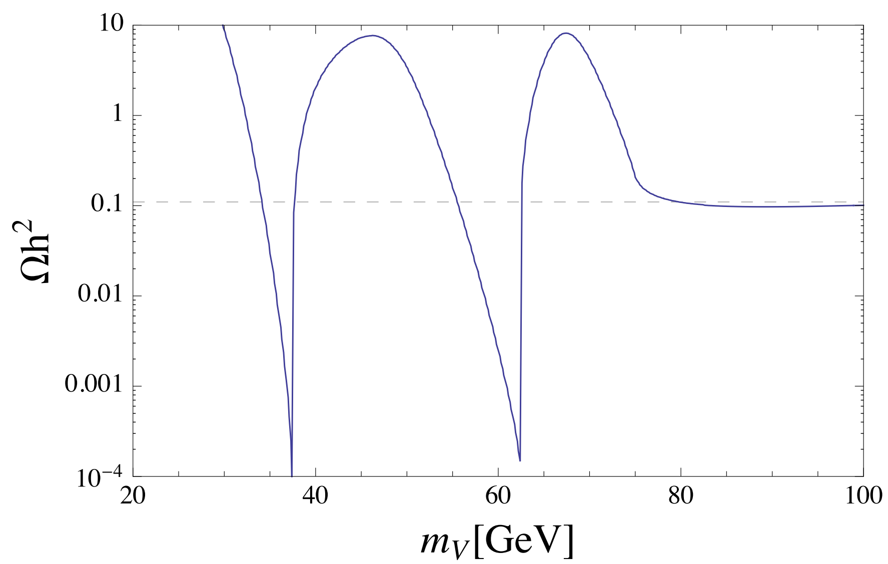


Figure 4. Relic density of dark matter as function of m_ψ for $m_h = 125$, $m_\phi = 75\,\mathrm{GeV}$, $g_X = 0.2$, and $\alpha = 0.1$.

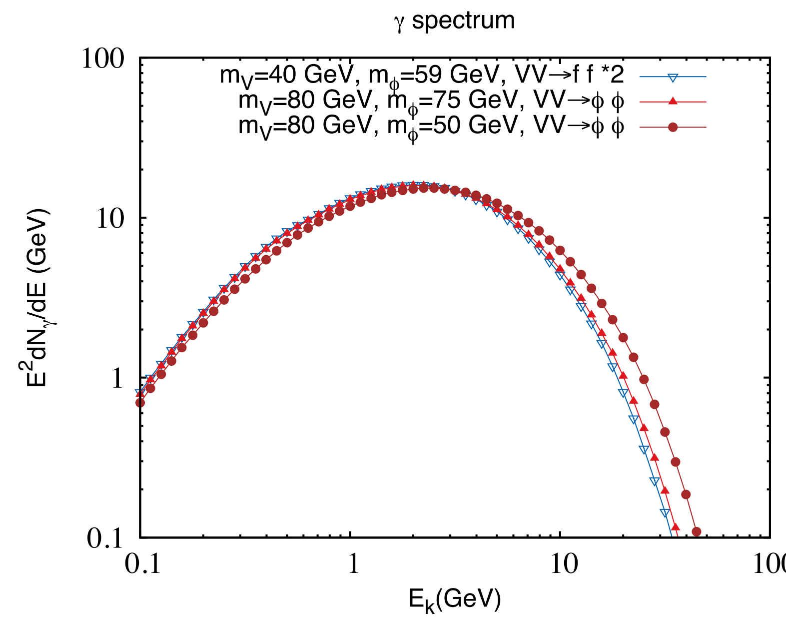


Figure 5. Illustration of γ spectra from different channels. The first two cases give almost the same spectra while in the third case γ is boosted so the spectrum is shifted to higher energy.

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

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

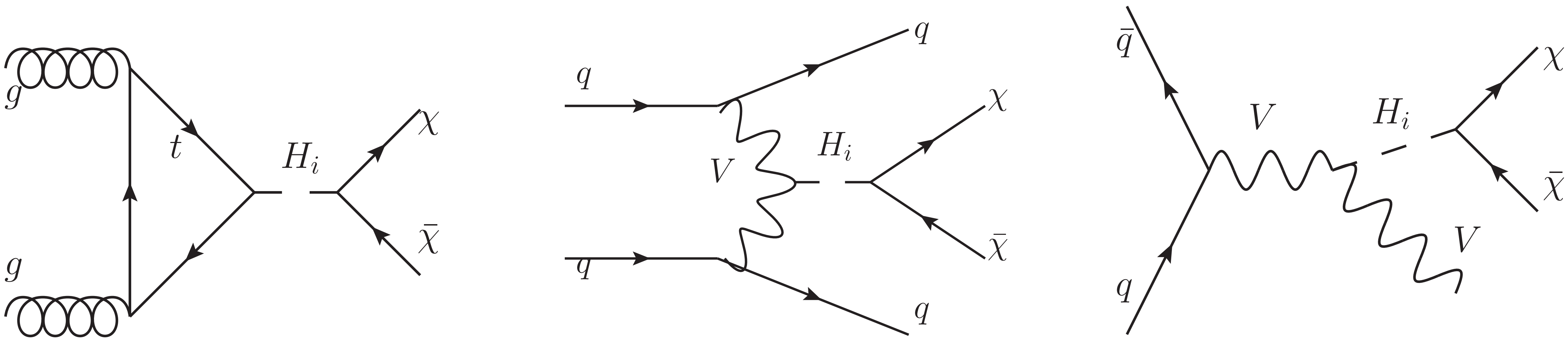


Figure 1: The dominant DM production processes at LHC.

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

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

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

DM EFT > Simplified Models > UV Compl's

- 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.

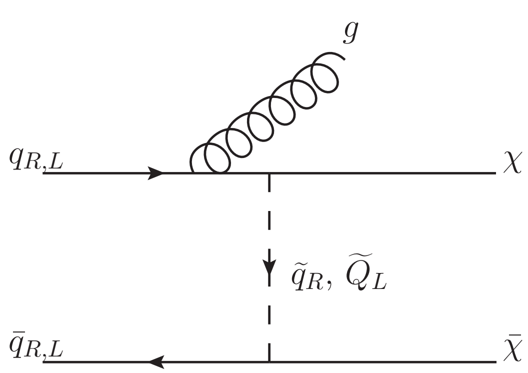
- Unlike the W boson case, more than one mediator should be included in general

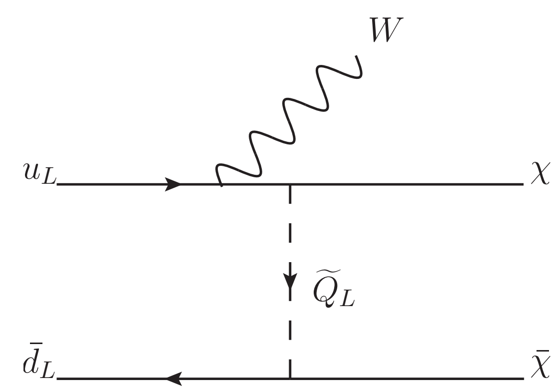
$$\frac{1}{\Lambda_i^2}\ \bar{q}\Gamma_i q\ \bar{\chi}\Gamma_i\chi \to \frac{g_q g_\chi}{m_\phi^2 - s}\ \bar{q}\Gamma_i q\ \bar{\chi}\Gamma_i\chi$$

- 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
  [Lesson from $e^+e^- \to W^+W^-$ at LEP2]
- In general we need two propagators, not one propagator, because there are two independent chiral fermions in 4-dim spacetime

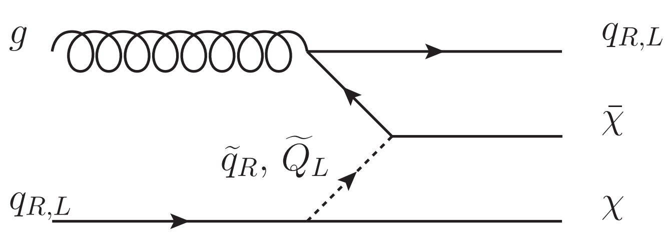
arXiv:1605.07058 (with A. Natale, M.Park, H. Yokoya) for t-channel mediator model

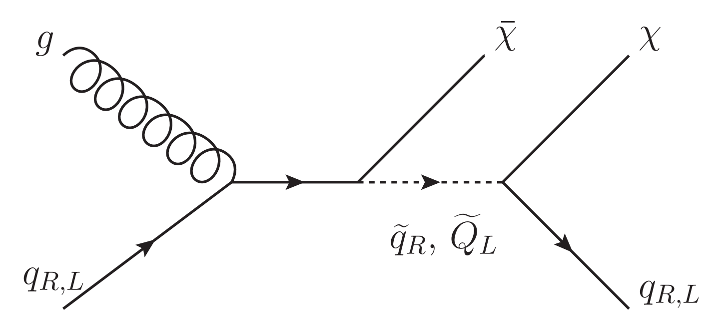
Our Model: a 'simplified model' of colored t-channel, spin-0, mediators which produce various mono-x + missing energy signatures (mono-Jet, mono-W, mono-Z, etc.):





W+missing ET : special



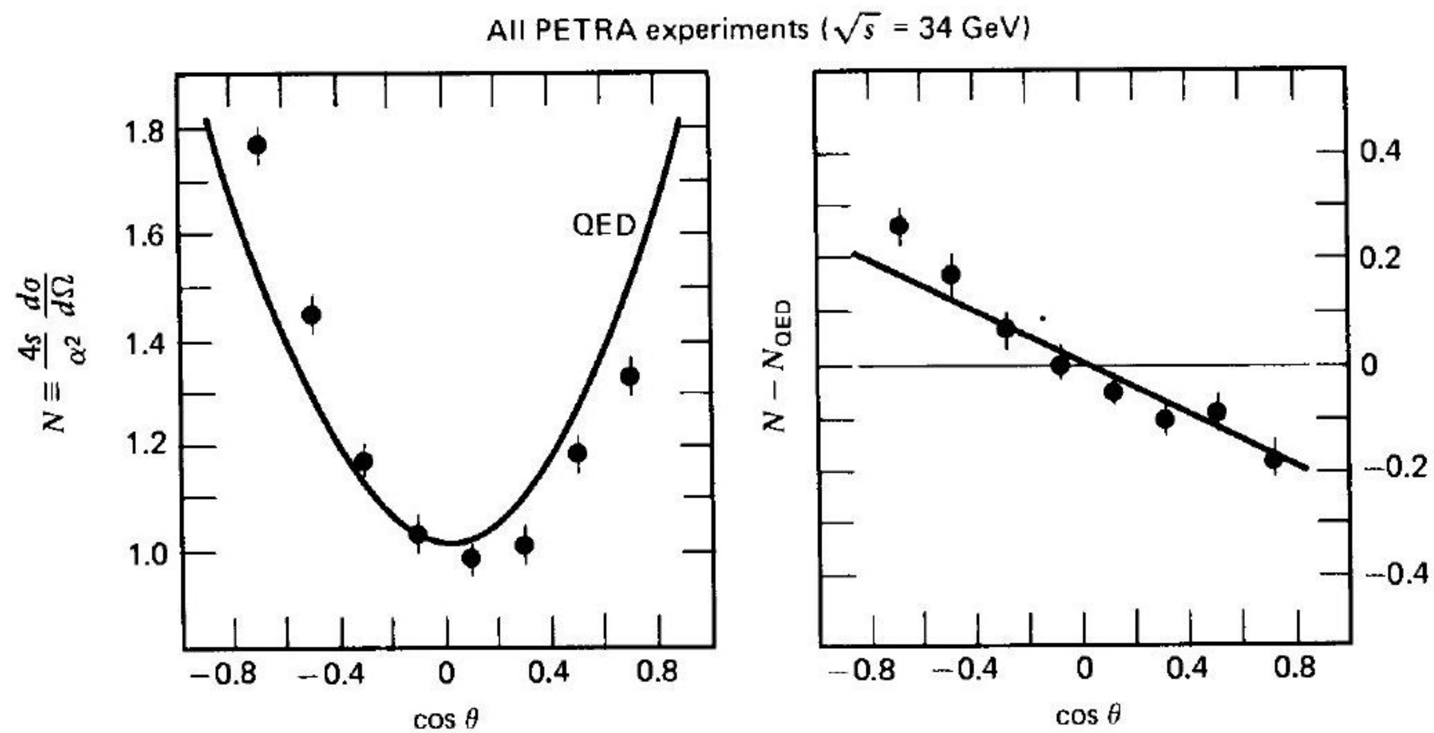


$$\frac{1}{\Lambda_i^2}\ \bar{q}\Gamma_i q\ \bar{\chi}\Gamma_i\chi \rightarrow \frac{g_q g_\chi}{m_\phi^2 - s}\ \bar{q}\Gamma_i q\ \bar{\chi}\Gamma_i\chi$$

- 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
- Come back to the s-channel scalar mediators

Lesson from EW physics

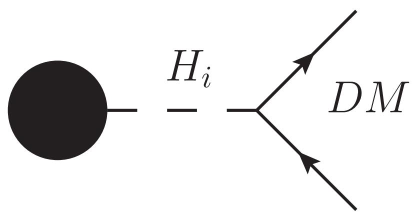
- The first evidence of asymmetry was found in angular distribution of muons from e^+e^- collisions at PETRA in the 80's ($\sqrt{s} \sim 30$ GeV , well below the Z^0 pole)



- Source of A_{FB} is a term linear in $\cos\theta$ from interference between γ or Z vector coupling and the axial vector Z coupling.

DM Production @ ILC

P Ko, H Yokoya, arXiv:1603.08802, JHEP



,

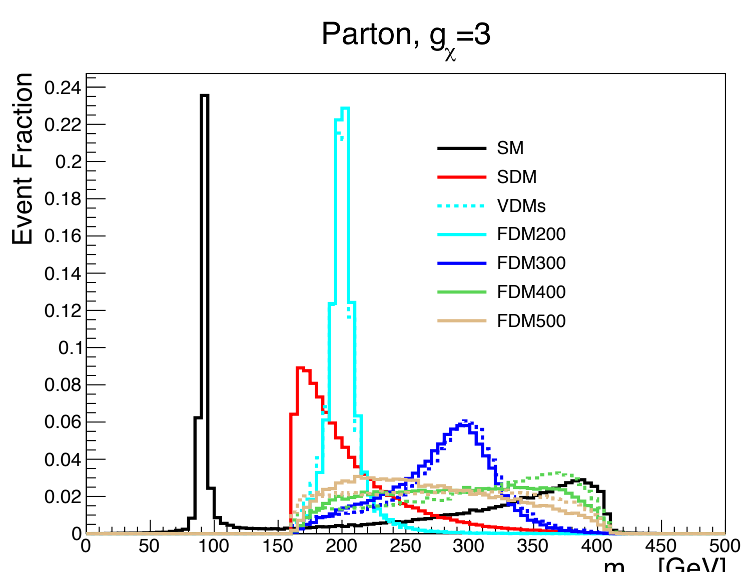
$$t \equiv m_{DD}^2$$

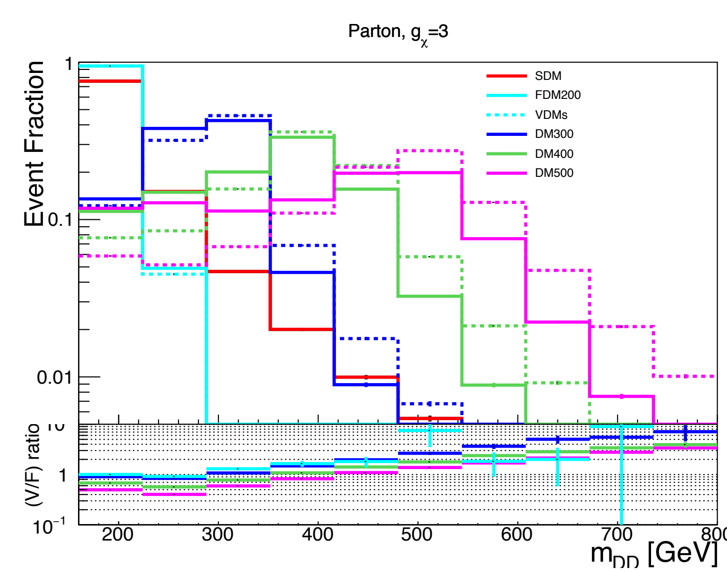
We consider $e^+e^- \to Z^* \to ZH_{i=1,2}$ followed by $H_i \to \bar{\chi}\chi$

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

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

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





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

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

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

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

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

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

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

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!

Interference effects

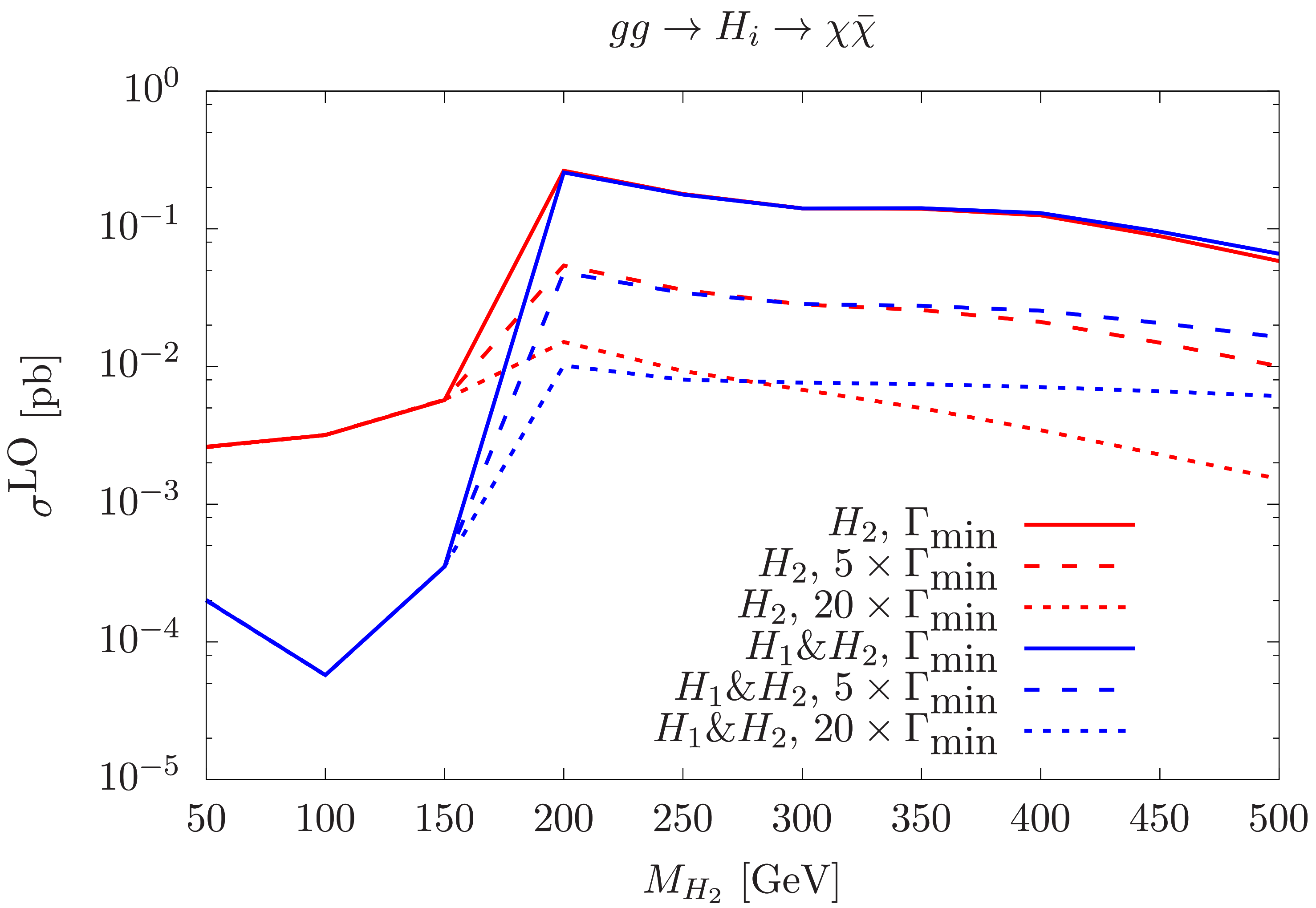


Figure 2: The LO cross section for gluon-gluon fusion process at 13 TeV LHC. The meanings of the different line types are explained in the text and the similar strategy will be used in all figures.

Parton level distributions

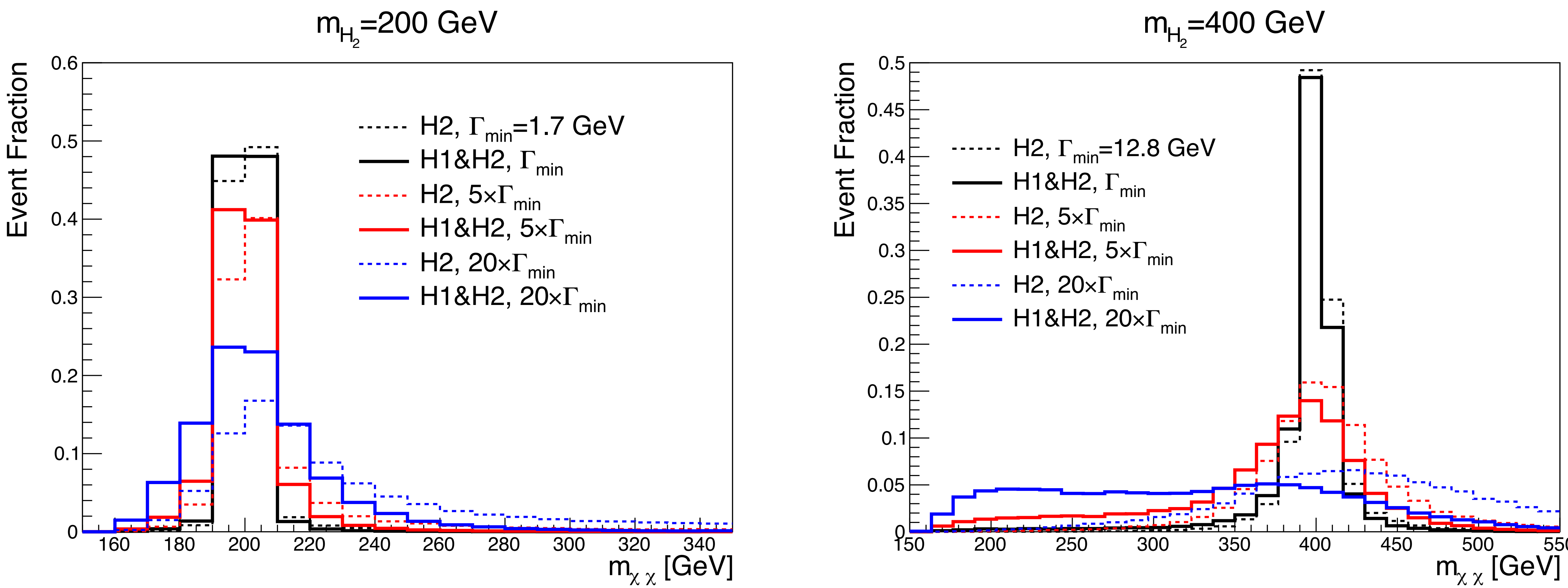


Figure 3: The parton level distributions of $m_{\chi\bar{\chi}}$ for gluon-gluon fusion process at 13 TeV LHC.

Exclusion limits with interference effects

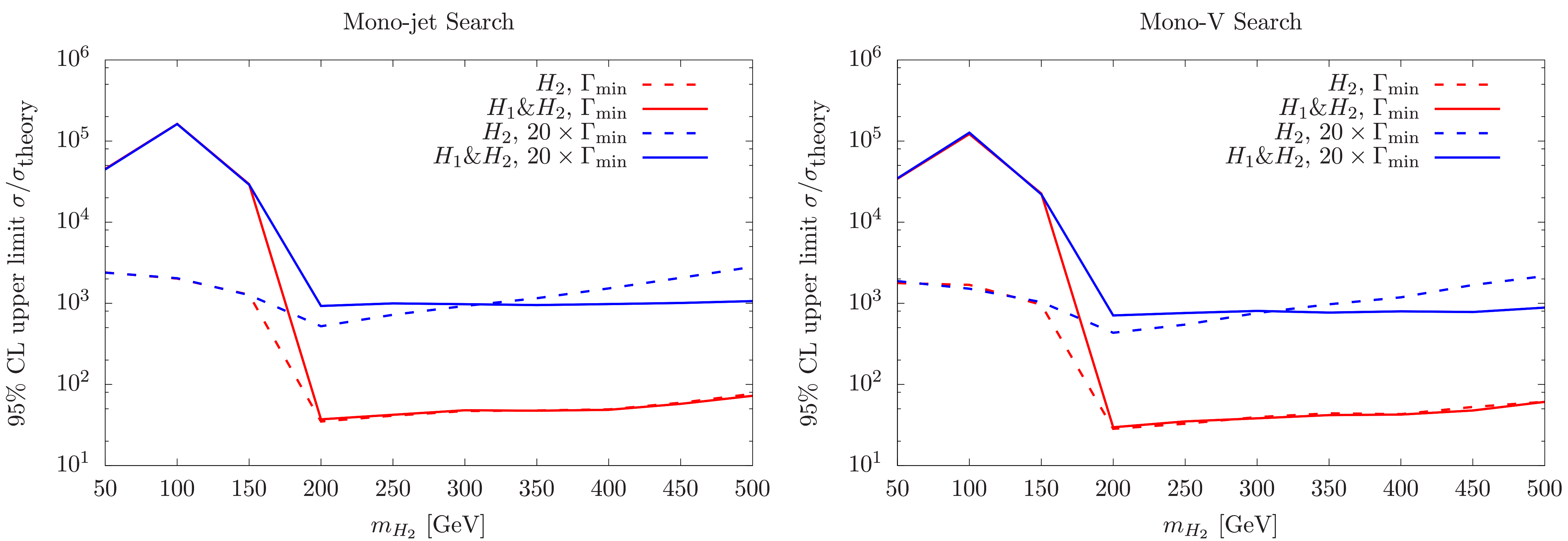


Figure 8: The CMS exclusion limits on our simplified models. Left: upper limit from mono-jet search. Right: upper limit from mono-V search.

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

Conclusion

- Phenomenology of HP VDM and SFDM 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 for DM collider searches]

- The dark Higgs ϕ can play crucial roles in interpreting the DM signatures at colliders, explaining the GC γ-ray excess ($VV \to \phi\phi$), improving vacuum stability up to Planck scale, modifying the Higgs inflation [ϕ should be actively searched for !]

General Remarks

- Gauge invariance is important for DM collider searches, not only for spin-1 but also for spin-1/2 SM fermions, because LH and RH fermions are different species
- Likewise, symmetries behind the DM stability or longevity are important too, but we don't have any ideas on them
- Simplified models often used are in a sense arbitrary truncations of underlying theories, not the same as EFTs. Lots of care needed when applied to real data analysis

References for more 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) : Next Talk by Myeonghun Park
- 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)