Impact of Dark Higgs on the LHC search for the singlet fermion DM

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COSMO 2017, Paris, France
Aug. 28-Sep.1, 2017

Questions about DM

- Electric Charge/Color neutral
- How many DM species are there ?
- Their masses and spins ?
- Are they absolutely stable or very long lived ?
- How do they interact with themselves and with the SM particles ?
- Where do their masses come from ? Another (Dark) Higgs mechanism ? Dynamical SB ?
- How to observe them ?

- Most studies on DM were driven by some anomalies: 511 keV gamma ray, PAMELA/ AMS02 positron excess, DAMA/CoGeNT, Fermi/LAT 135 GeV gamma ray, 3.5 keV Xray, Gamma ray excess from GC etc
- On the other hand, not so much attention given to DM stability/longevity in nonSUSY DM models
- Important to implement this properly in QFT which is supposed to a framework to describe DM properties (including its interactions)

- Note that extra particles (the so-called mediators, scalar, vector etc) are introduced to solve three puzzles in CDM paradigm in terms of DM self-interaction
- DR and its interaction with DM may help to relax the tension between H0 and σ_8
- Phenomenologically nice, but theoretically rather ad hoc
- Any good organizing principle ?

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- Phenomenologically nice, but theoretically rather ad hoc
- Any good organizing principle ?
- YES ! >> Dark Gauge Symmetry

Local Dark Gauge Sym

- Well tested principle in the SM
- Completely fix the dynamics of DM, SM
- Guarantees stability/longevity of DM
- Force mediators already present in a gauge invariant way (Only issue is the mass scales)
- Predictable amount of dark radiation

NB: The first 3 points are also true in the minimal DM scenarios (No new gauge sym, just SM gauge symmetries)

Basic assumptions

- DM, DR, Mediators : particles that can be described by conventional 4-dim QFT
- DM stability/longevity is due to unbroken dark gauge symmetry/accidental symmetry of dark gauge theory (similarly to the SM: electron stability / proton longevity)
- Very conservative approach to DM models

Contents

- Higgs portal singlet fermion/vector DM models :
  - EFT vs. renormalizable, gauge invariant, unitary models
  - GC gamma ray excess, Collider Signatures including the interference between the SM Higgs and dark Higgs
- Pseudoscalar portal DM models

Let us start with

Higgs portal (S,F,V) DM

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.

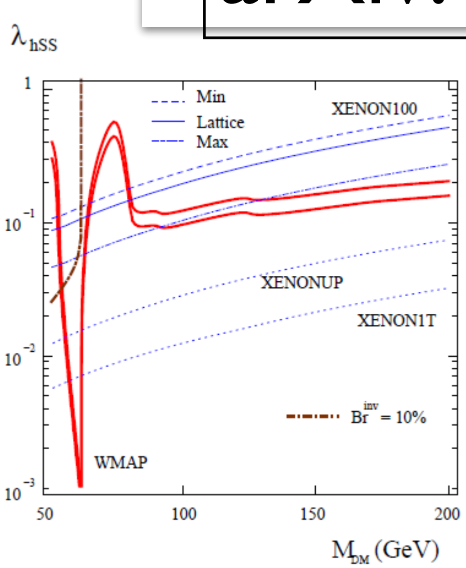

FIG. 1. Scalar Higgs-portal parameter space allowed by WMAP (between the solid red curves), XENON100 and $BR^{inv} = 10\%$ for $m_h = 125$ GeV. Shown also are the prospects for XENON upgrades.

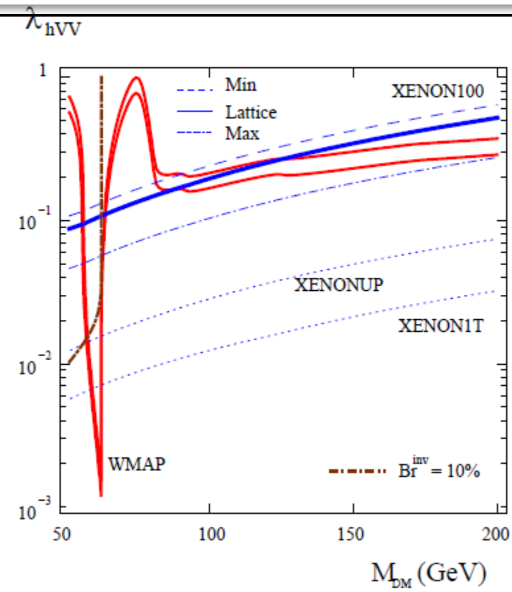

FIG. 2. Same as Fig. 1 for vector DM particles.

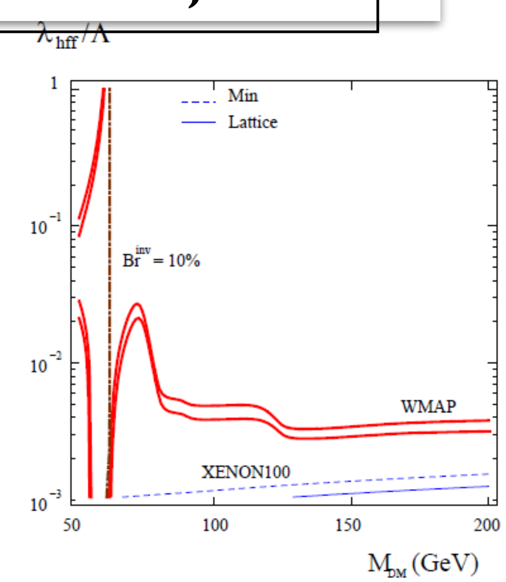

FIG. 3. Same as in Fig.1 for fermion DM; λ_{hff}/Λ is in GeV^{-1}.

Higgs portal DM models

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All invariant under ad hoc Z2 symmetry

- Scalar CDM : looks OK, renorm. .. BUT .....
- Fermion CDM : nonrenormalizable
- Vector CDM : looks OK, but it has a number of problems (in fact, it is not renormalizable)

Usual story within EFT

- Strong bounds from direct detection exp's put stringent bounds on the Higgs coupling to the dark matters
- So, the invisible Higgs decay is suppressed
- There is only one SM Higgs boson with the signal strengths equal to ONE if the invisible Higgs decay is ignored
- All these conclusions are not reproduced in the full theories (renormalizable) however

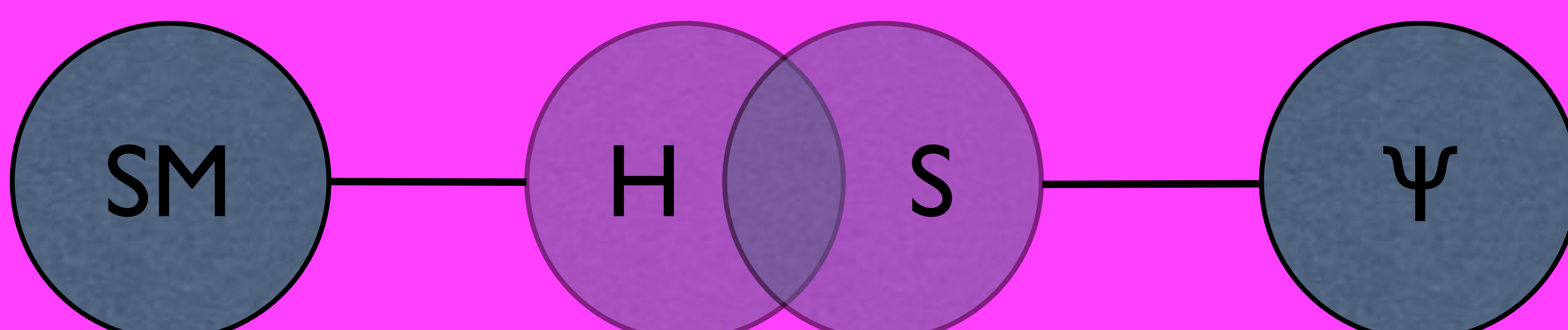
Singlet fermion CDM

Baek, Ko, Park, arXiv:1112.1847

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

mixing

invisible decay



Production and decay rates are suppressed relative to SM.

This simple model has not been studied properly !!

Ratiocination

- 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

Ratiocination

- Signal strength (reduction factor)

$$
\begin{aligned}
r_i &= \frac{\sigma_i \ \mathrm{Br}(H_i \to \mathrm{SM})}{\sigma_h \ \mathrm{Br}(h \to \mathrm{SM})} \\
r_1 &= \frac{\cos^4\alpha \ \Gamma^{\mathrm{SM}}_{H_1}}{\cos^2\alpha \ \Gamma^{\mathrm{SM}}_{H_1} + \sin^2\alpha \ \Gamma^{\mathrm{hid}}_{H_1}} \\
r_2 &= \frac{\sin^4\alpha \ \Gamma^{\mathrm{SM}}_{H_2}}{\sin^2\alpha \ \Gamma^{\mathrm{SM}}_{H_2} + \cos^2\alpha \ \Gamma^{\mathrm{hid}}_{H_2} + \Gamma_{H_2 \to H_1 H_1}}
\end{aligned}
$$

$0 < \alpha < \pi/2 \Rightarrow r_1(r_2) < 1$

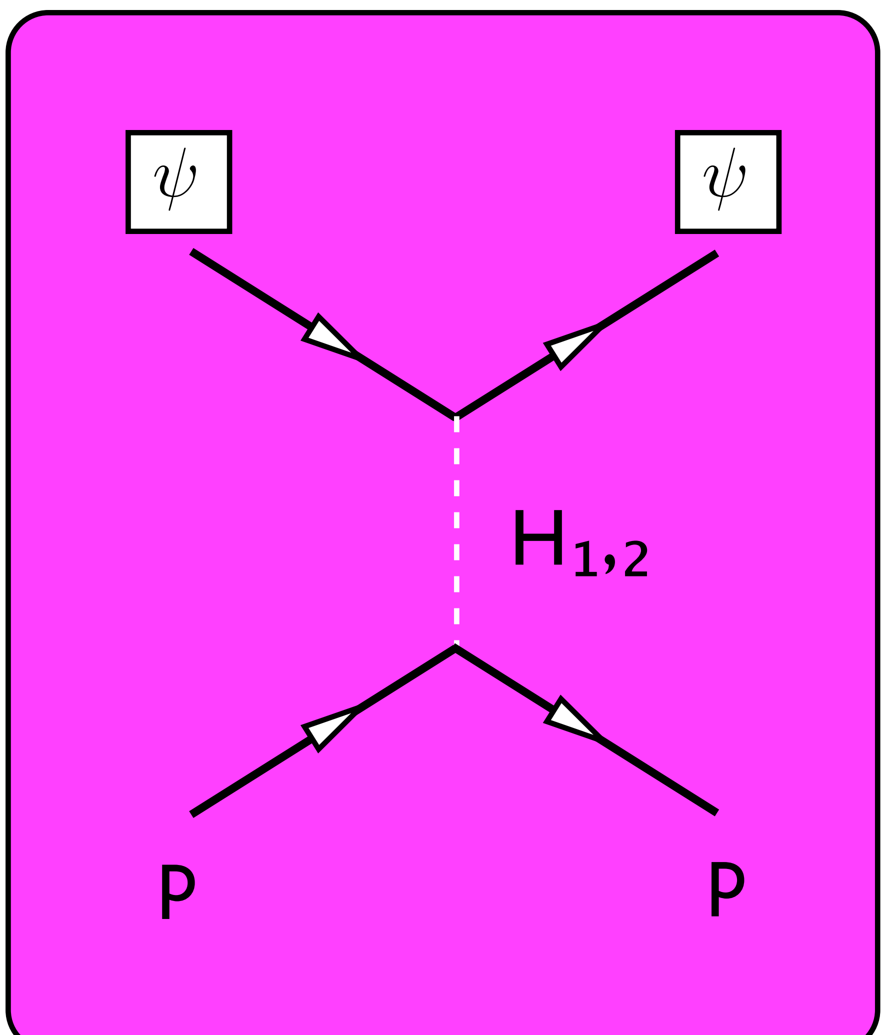
Invisible decay mode is not necessary!

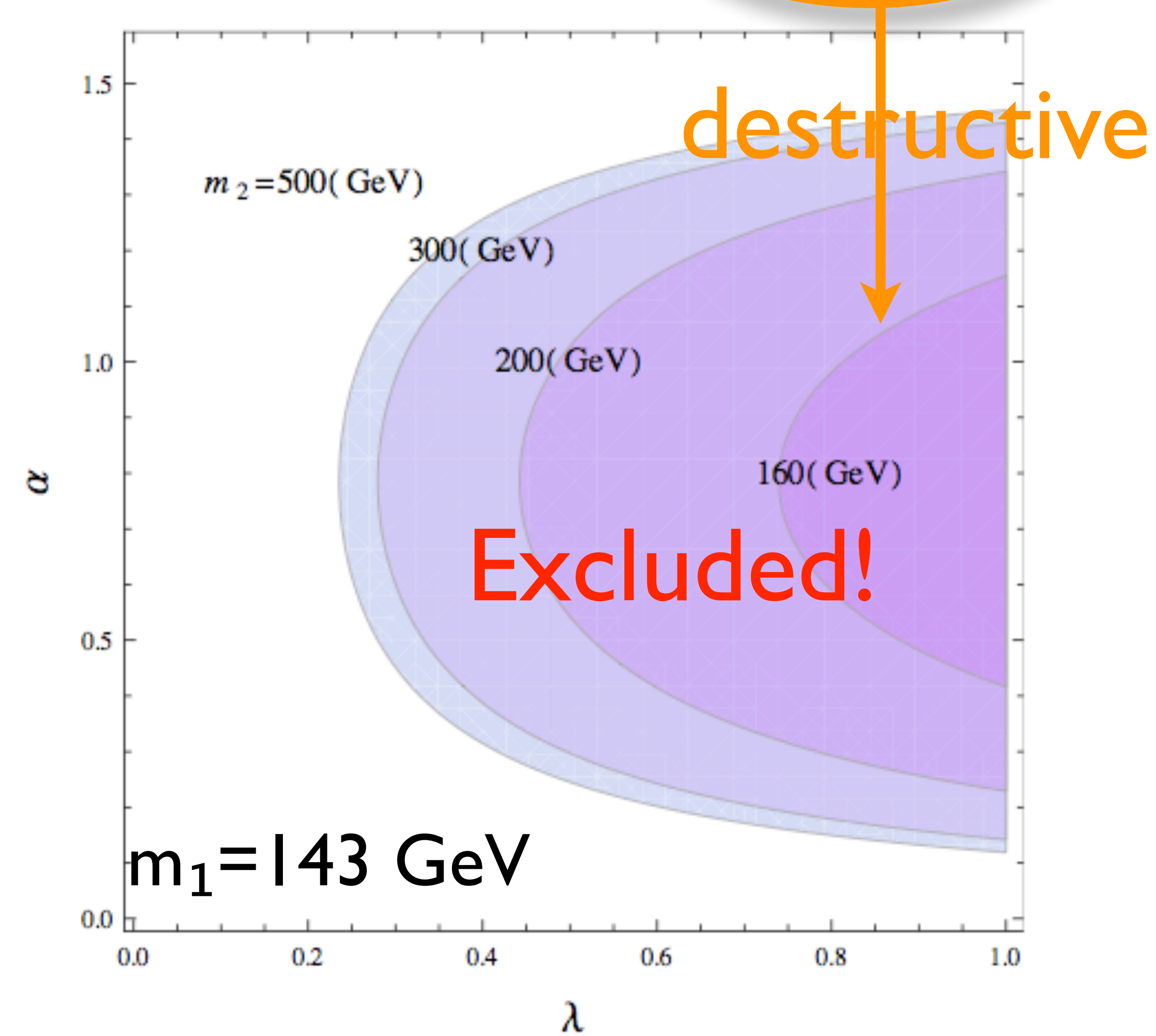
If r_i > 1 for any single channel,
this model will be excluded !!

Constraints

- Dark matter to nucleon cross section (constraint)

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





- We don't use the effective lagrangian approach (nonrenormalizable interactions), since we don't know the mass scale related with the CDM

$$\mathcal{L}_{\rm eff} = \overline{\psi} \left(m_0 + \frac{H^\dagger H}{\Lambda} \right) \psi. \quad \text{or} \quad \lambda h \overline{\psi} \psi$$

Breaks SM gauge sym

- Only one Higgs boson (alpha = 0)

- We cannot see the cancellation between two Higgs scalars in the direct detection cross section, if we used the above effective lagrangian

- The upper bound on DD cross section gives less stringent bound on the possible invisible Higgs decay

Low energy pheno.

- Universal suppression of collider SM signals

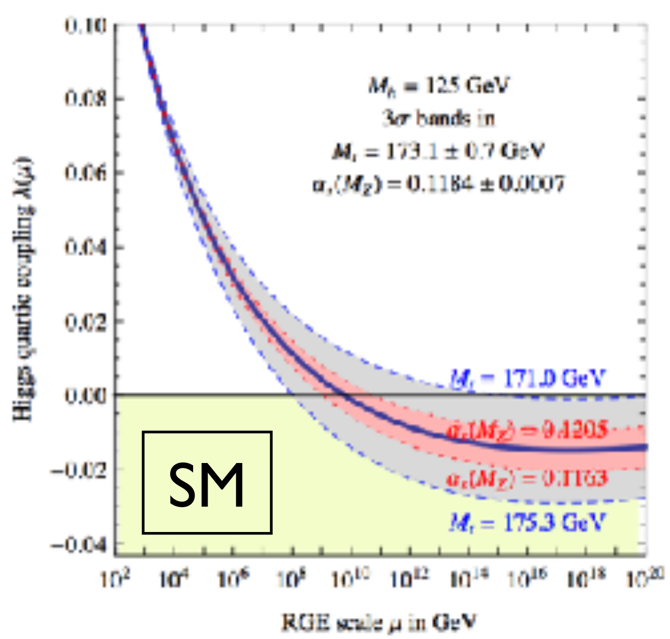
[See 1112.1847, Seungwon Baek, P. Ko & WIP]

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

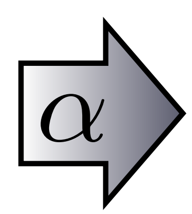
- Tree-level shift of $\lambda_{H,SM}$ (& loop correction)

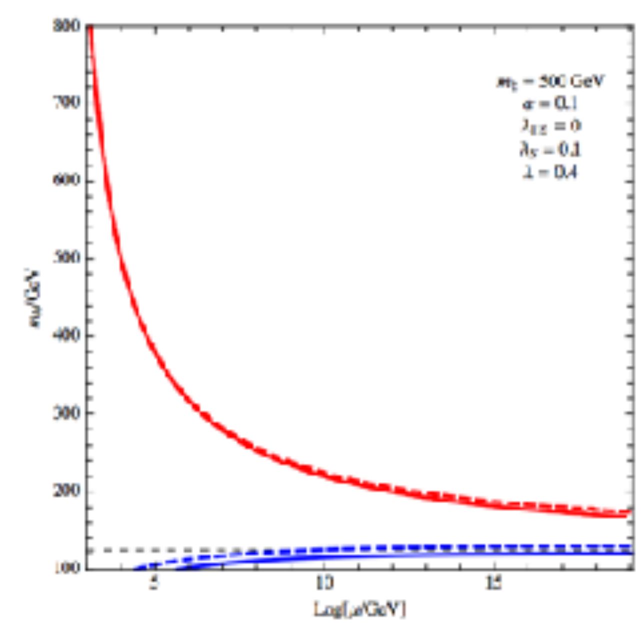
$$\lambda_{\Phi H} \Rightarrow \lambda_H = \left[1 + \left(\frac{m_\phi^2}{m_h^2} - 1\right)\sin^2\alpha\right]\lambda_H^{\rm SM}$$

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



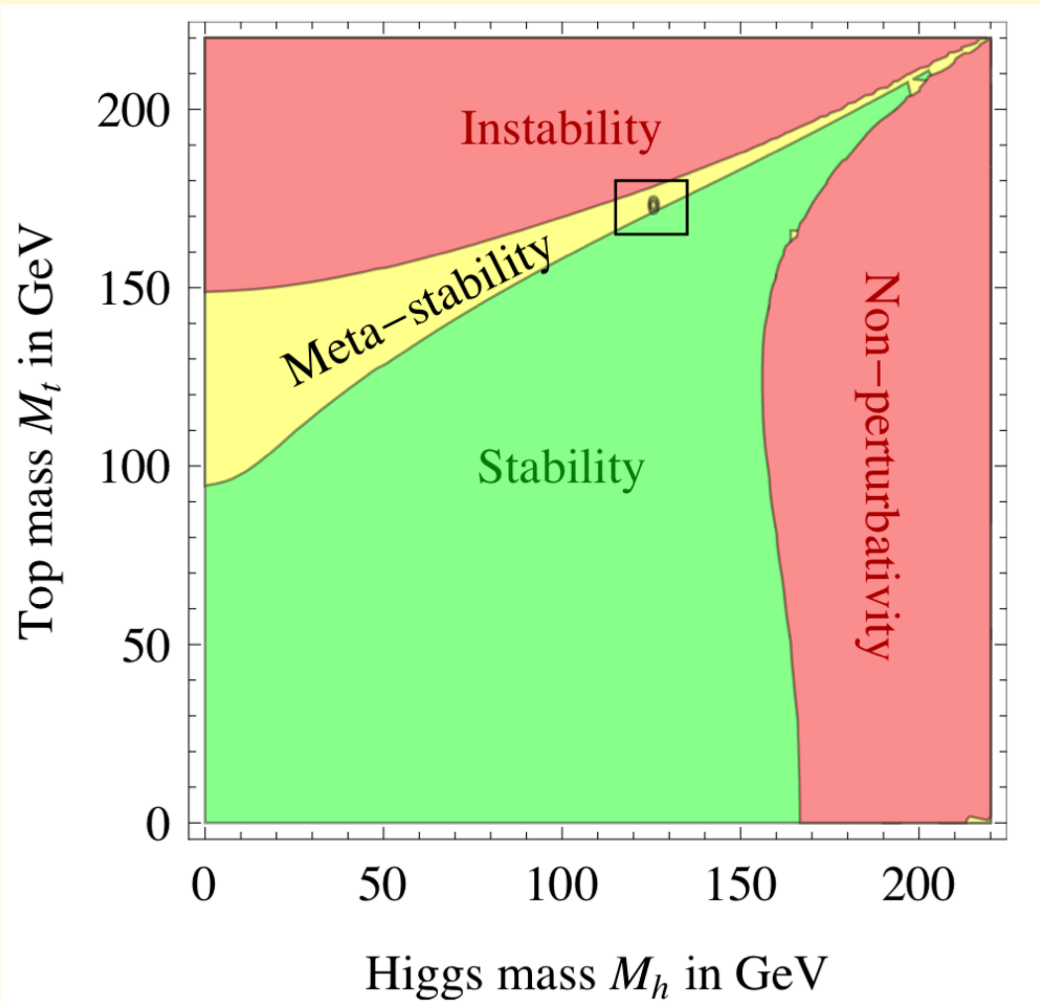
[G. Degrassi et al., 1205.6497]

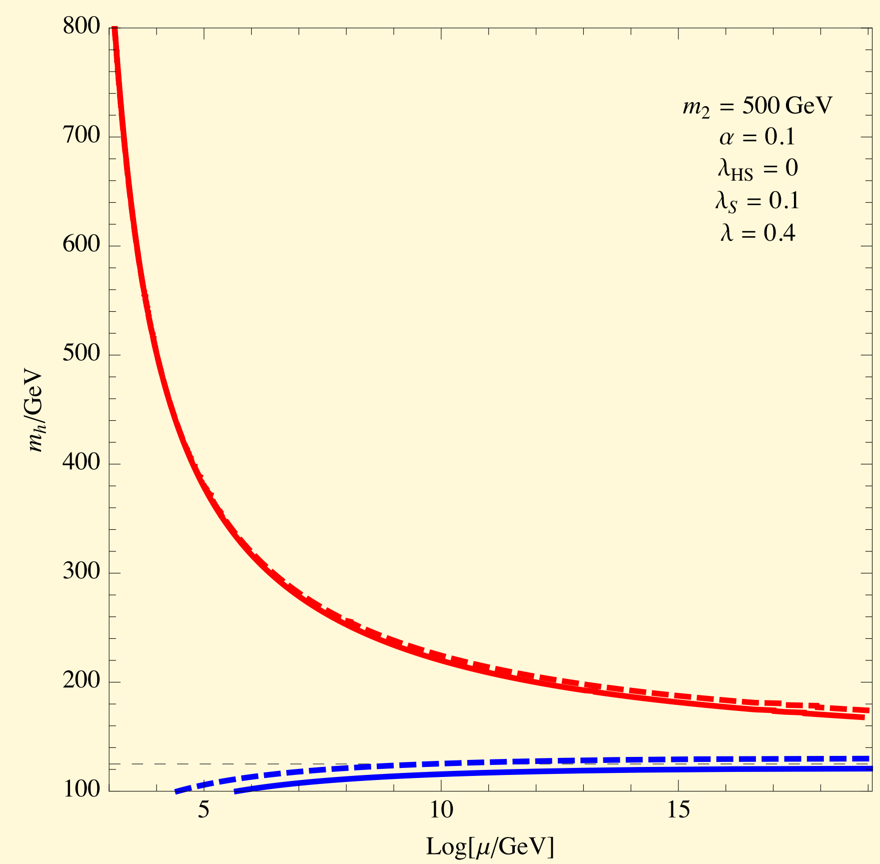




[S. Baek, P. Ko, WIP & E. Senaha, JHEP(2012)]

Vacuum Stability Improved by the singlet scalar S





A. Strumia, Moriond EW 2013

Baek, Ko, Park, Senaha (2012)

Similar for Higgs portal Vector DM

$$\mathcal{L} = -m_V^2 V_\mu V^\mu - \frac{\lambda_{VH}}{4} H^\dagger H V_\mu V^\mu - \frac{\lambda_V}{4} (V_\mu V^\mu)^2$$

- Although this model looks renormalizable, it is not really renormalizable, since there is no agency for vector boson mass generation
- Need to a new Higgs that gives mass to VDM
- A complete model should be something like this:

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

$$\langle 0|\phi_X|0\rangle = v_X + h_X(x)$$

$X_\mu \equiv V_\mu$ here

- There appear a new singlet scalar h_X from phi_X , which mixes with the SM Higgs boson through Higgs portal
- The effects must be similar to the singlet scalar in the fermion CDM model, and generically true in the DM with dark gauge sym
- Important to consider a minimal renormalizable and unitary model to discuss physics correctly [Baek, Ko, Park and Senaha, arXiv: 1212.2131 (JHEP)]
- Can accommodate GeV scale gamma ray excess from GC

New scalar improves EW vacuum stability

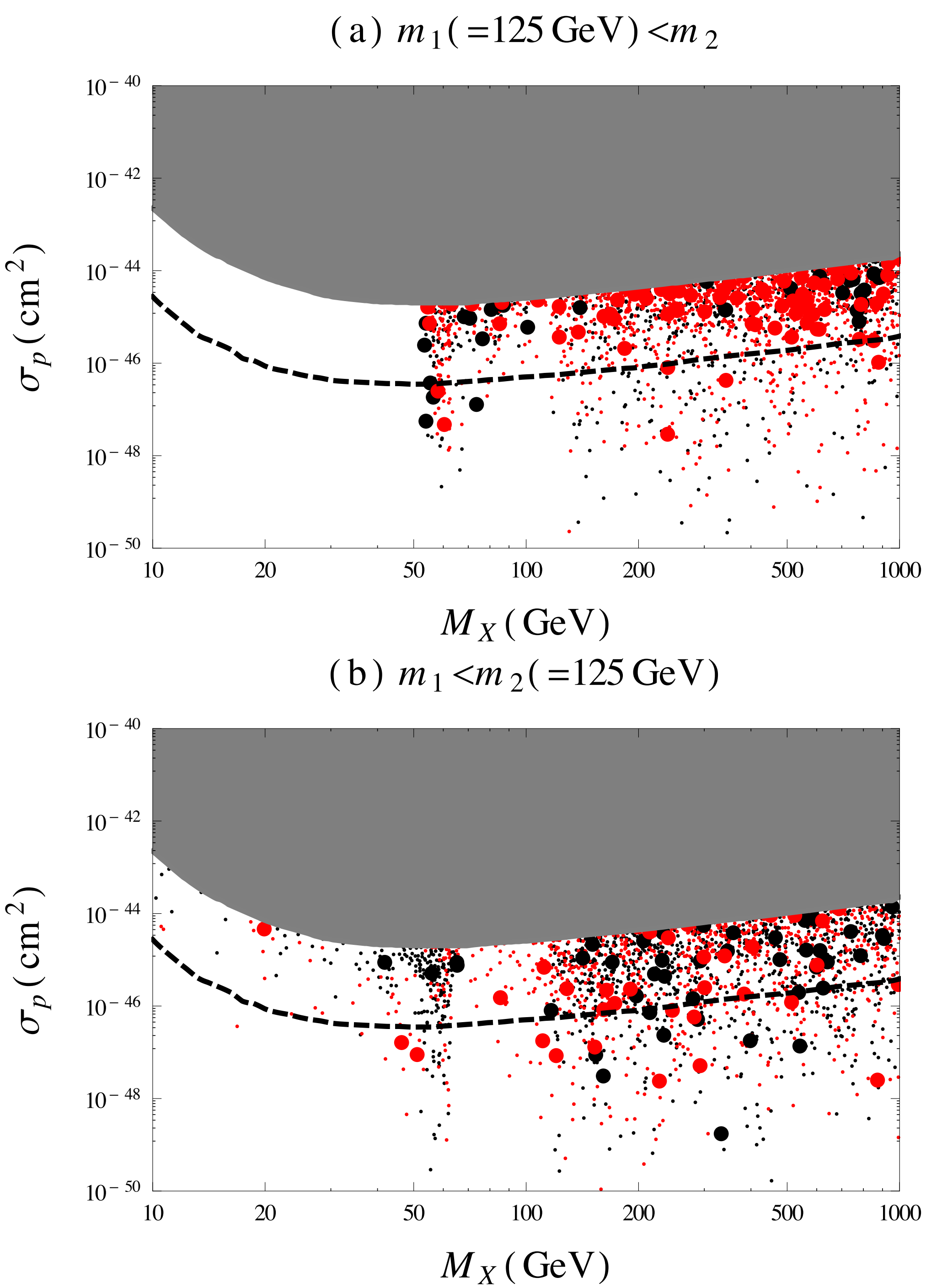


Figure 6. The scattered plot of σ_p as a function of M_X. The big (small) points (do not) satisfy the WMAP relic density constraint within 3 σ, while the red-(black-)colored points gives $r_1 > 0.7$($r_1 < 0.7$). The grey region is excluded by the XENON100 experiment. The dashed line denotes the sensitivity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

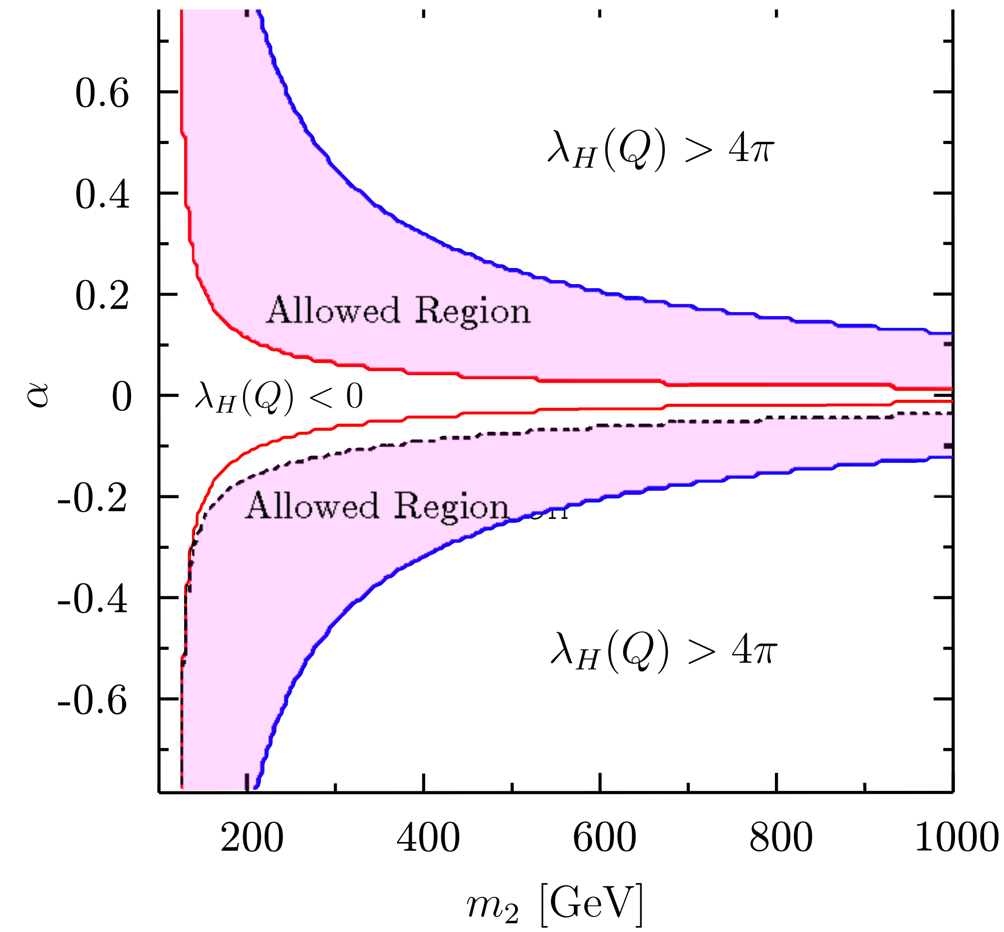


Figure 8. The vacuum stability and perturbativity constraints in the α-m_2 plane. We take $m_1 = 125$ GeV, $g_X = 0.05$, $M_X = m_2/2$ and $v_\Phi = M_X/(g_X Q_\Phi)$.

Higgs portal DM as examples

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

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All invariant under ad hoc Z2 symmetry

arXiv:1112.3299, … 1402.6287, etc.

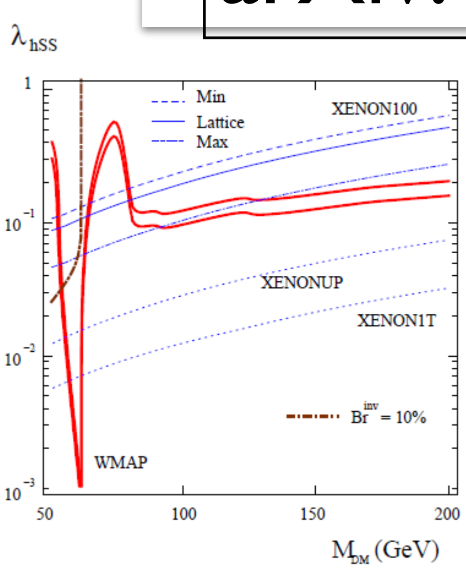


FIG. 1. Scalar Higgs-portal parameter space allowed by WMAP (between the solid red curves), XENON100 and $BR^{inv} = 10\%$ for $m_h = 125$ GeV. Shown also are the prospects for XENON upgrades.

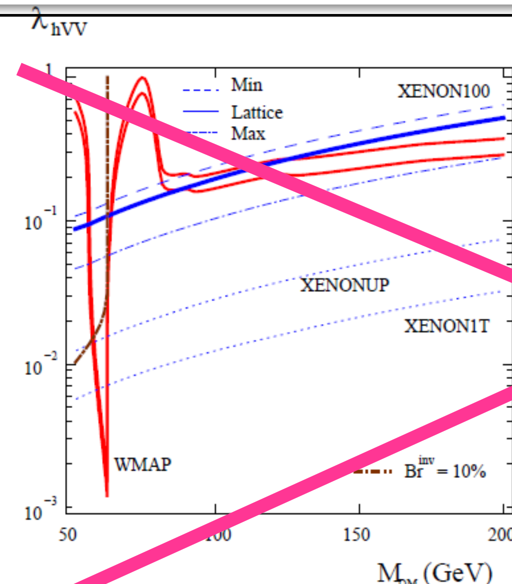
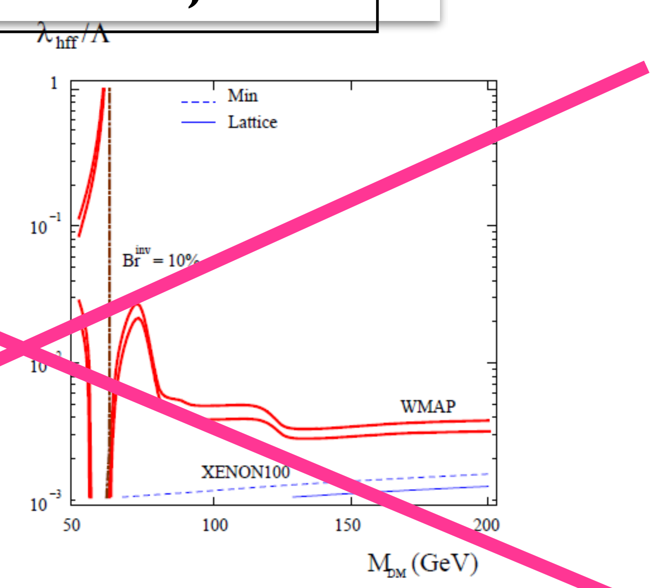


FIG. 2. Same as Fig. 1 for vector DM particles.



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All invariant under ad hoc Z2 symmetry

arXiv:1112.3299, … 1402.6287, etc.

λ_{hSS} λ_{hVV} λ_{hff}/Λ

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

M_{DM} (GeV)

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.

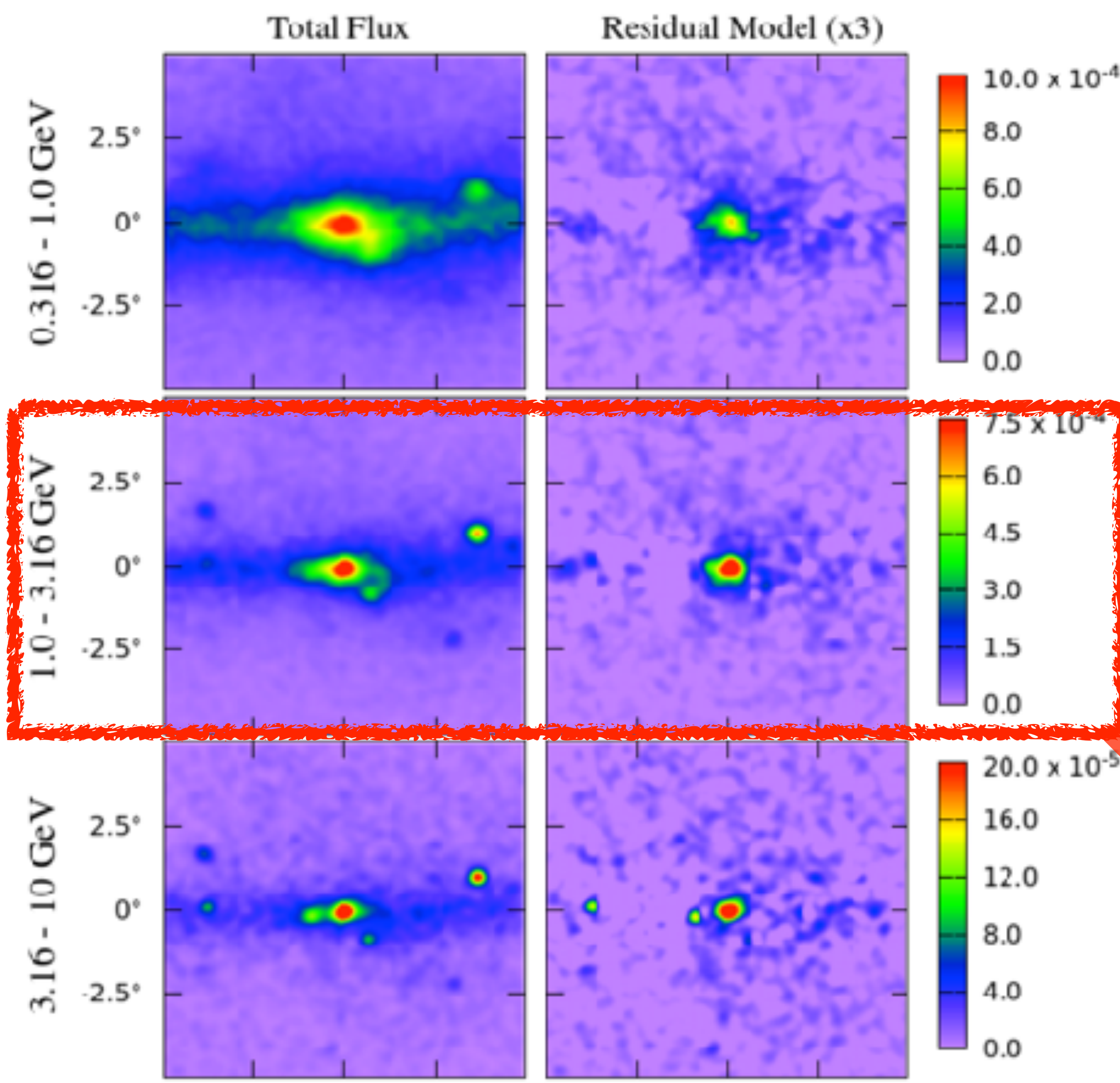
FIG. 3. Same as in Fig.1 for fermion DM; λ_{hff}/Λ is in GeV^{-1}.

Is this any useful in phenomenology ?

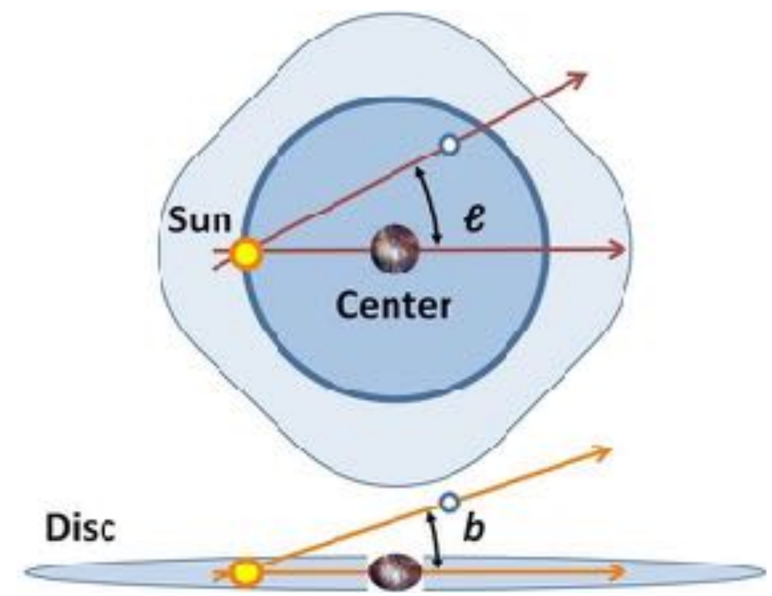
YES !

Fermi-LAT GC γ-ray excess

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



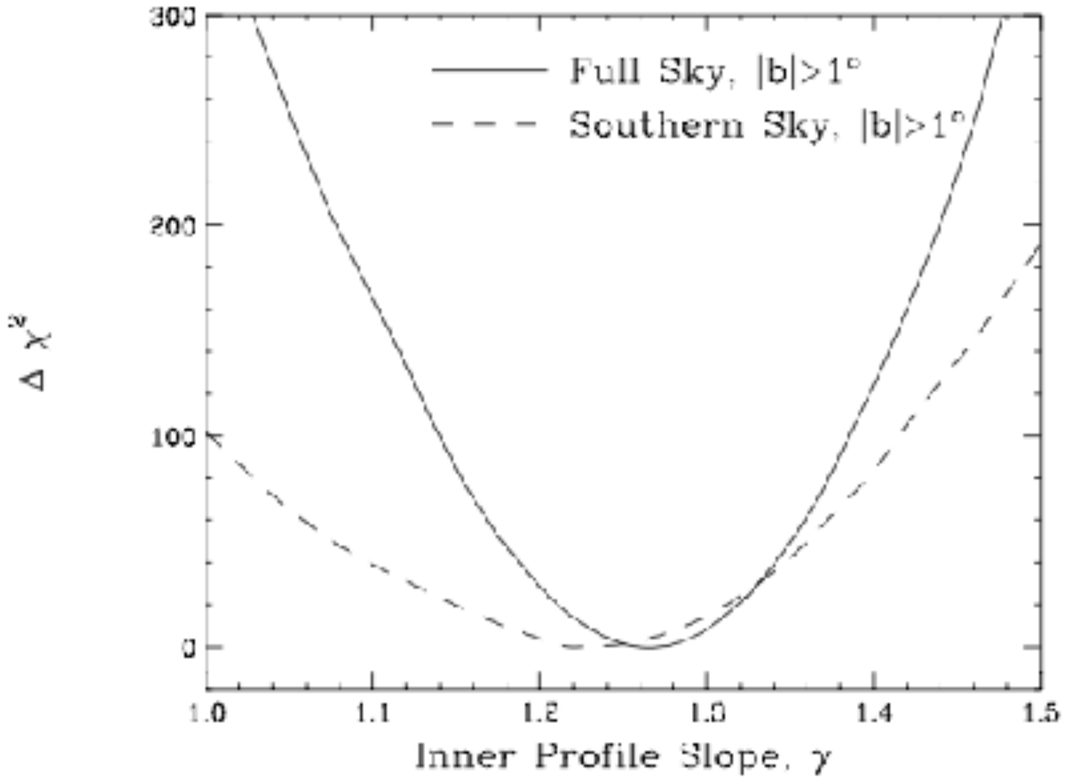
[1402.6703, T. Daylan et.al.]

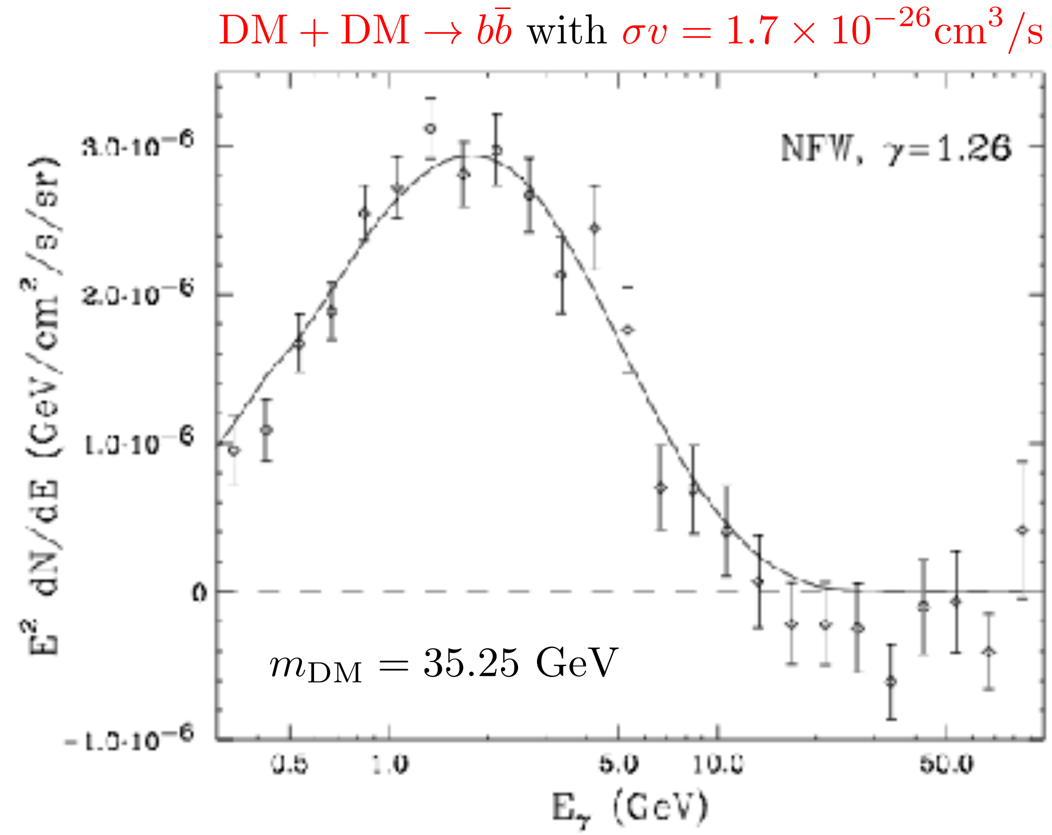


$$\mathrm{GC} : b \sim l \lesssim 0.1^\circ$$

extended
GeV scale excess!

- A DM interpretation





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

- Millisecond Pulars (astrophysical alternative)

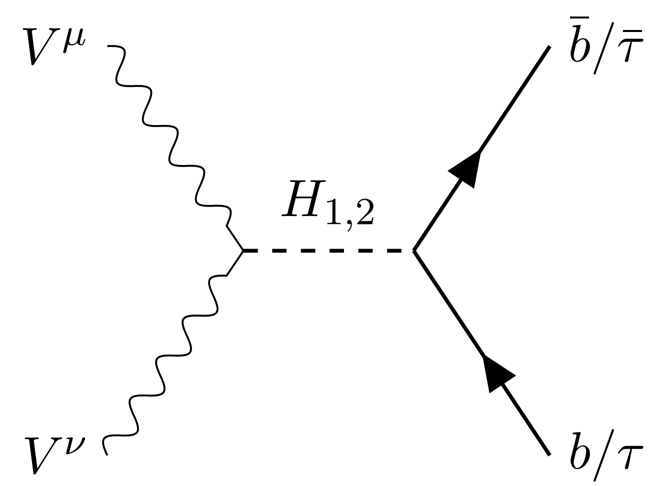
It may or may not be the main source, depending on

- 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 VDM

[1404.5257, P. Ko, WIP & Y. Tang] JCAP (2014)
(Also Celine Boehm et al. 1404.4977, PRD)



H2 : 125 GeV Higgs
H1 : absent in EFT

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

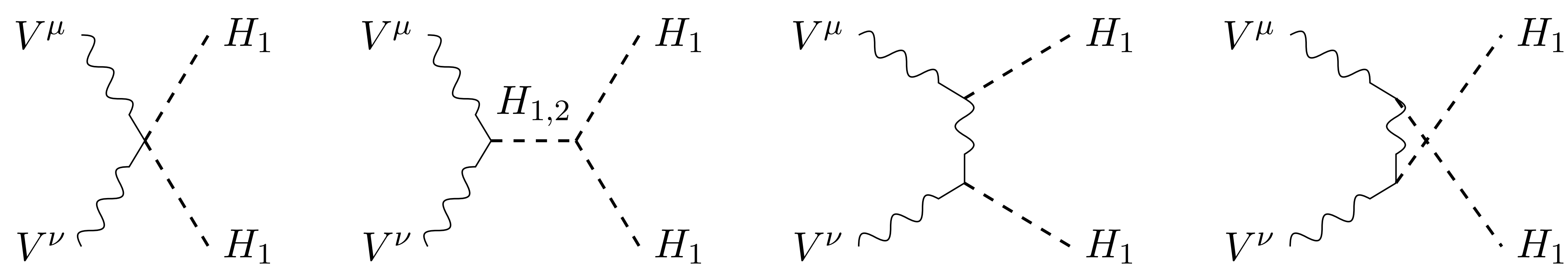


Figure 3. Dominant s/t-channel production of H_1s that decay dominantly to $b + \bar{b}$

Importance of VDM with Dark Higgs Boson

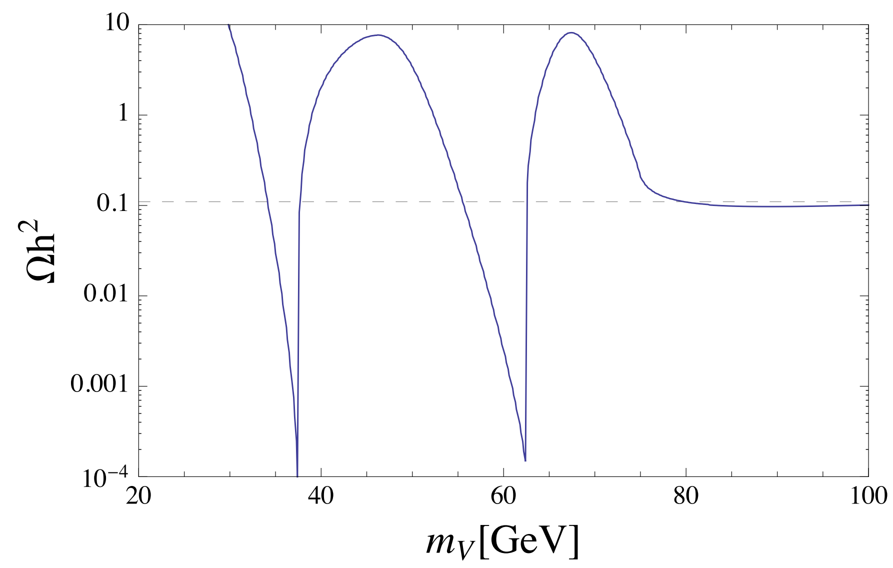


Figure 4. Relic density of dark matter as function of m_ψ for $m_h = 125$, $m_\phi = 75\,\mathrm{GeV}$, $g_X = 0.2$, and $\alpha = 0.1$.

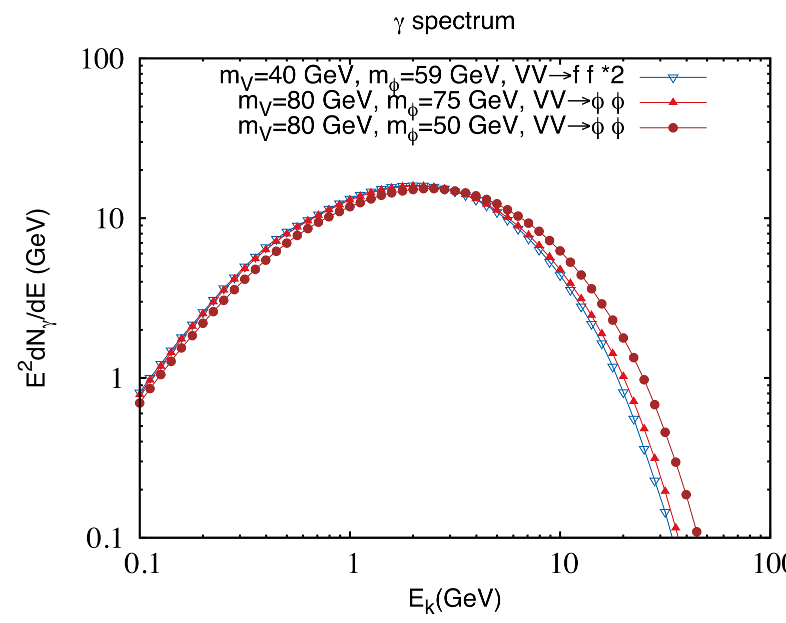
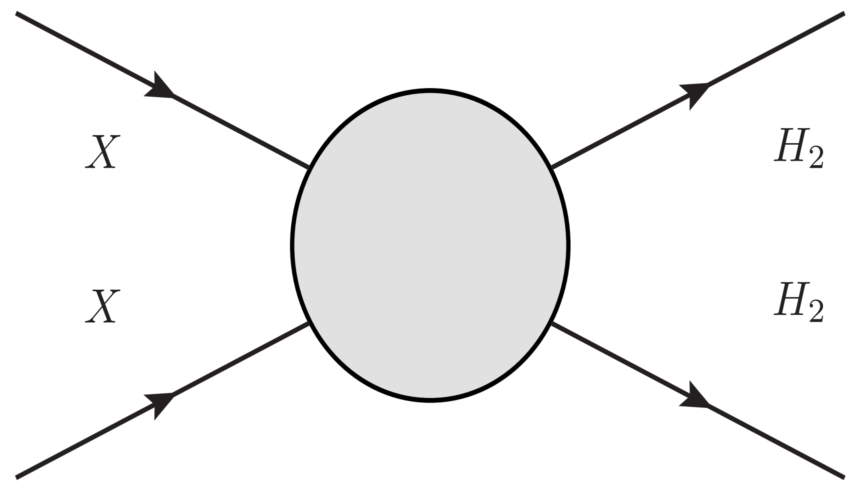


Figure 5. Illustration of γ spectra from different channels. The first two cases give almost the same spectra while in the third case γ is boosted so the spectrum is shifted to higher energy.

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

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



P.Ko, Yong Tang.
arXiv:1504.03908

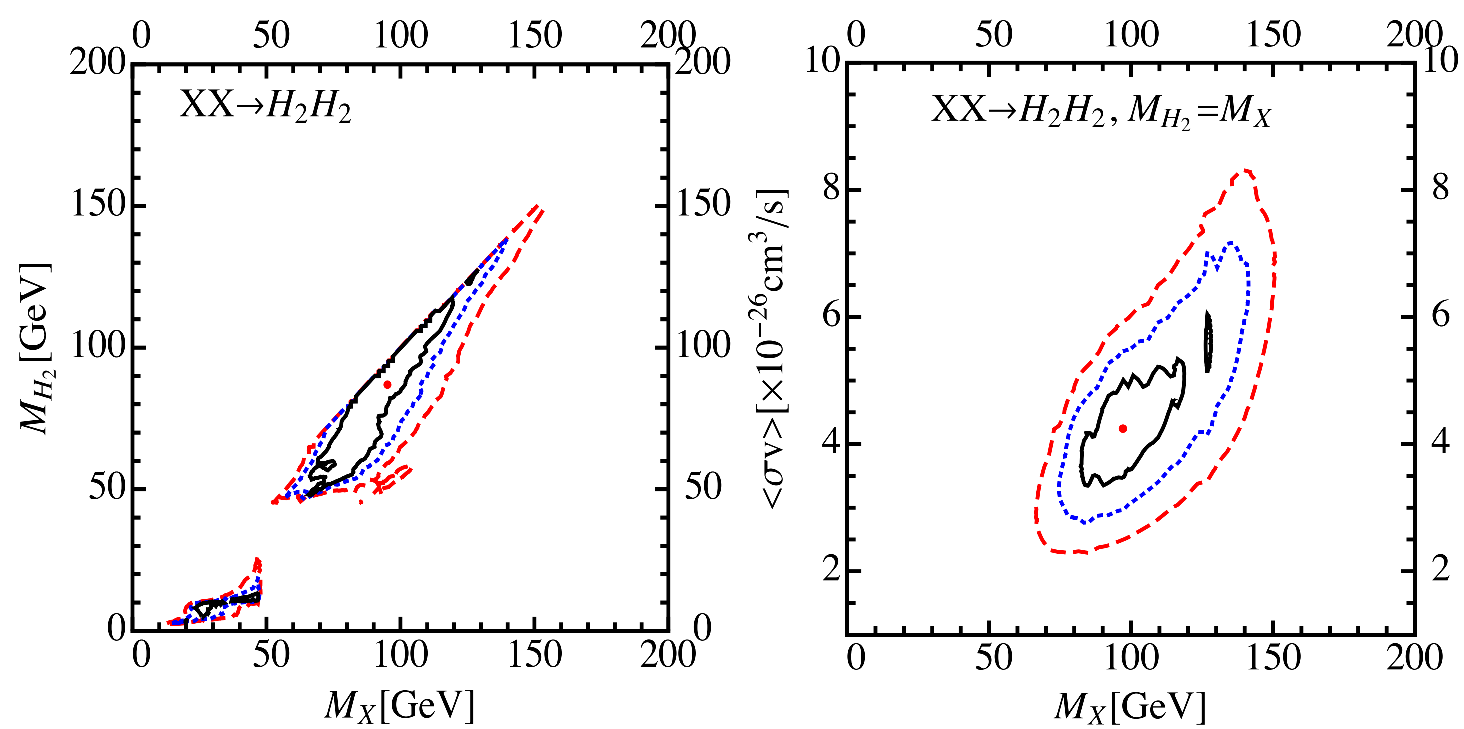


FIG. 3: The regions inside solid(black), dashed(blue) and long-dashed(red) contours correspond to 1σ, 2σ and 3σ, respectively. The red dots inside 1σ contours are the best-fit points. In the left panel, we vary freely M_X, M_{H_2} and $\langle\sigma v\rangle$. While in the right panel, we fix the mass of H_2, $M_{H_2} \simeq M_X$.

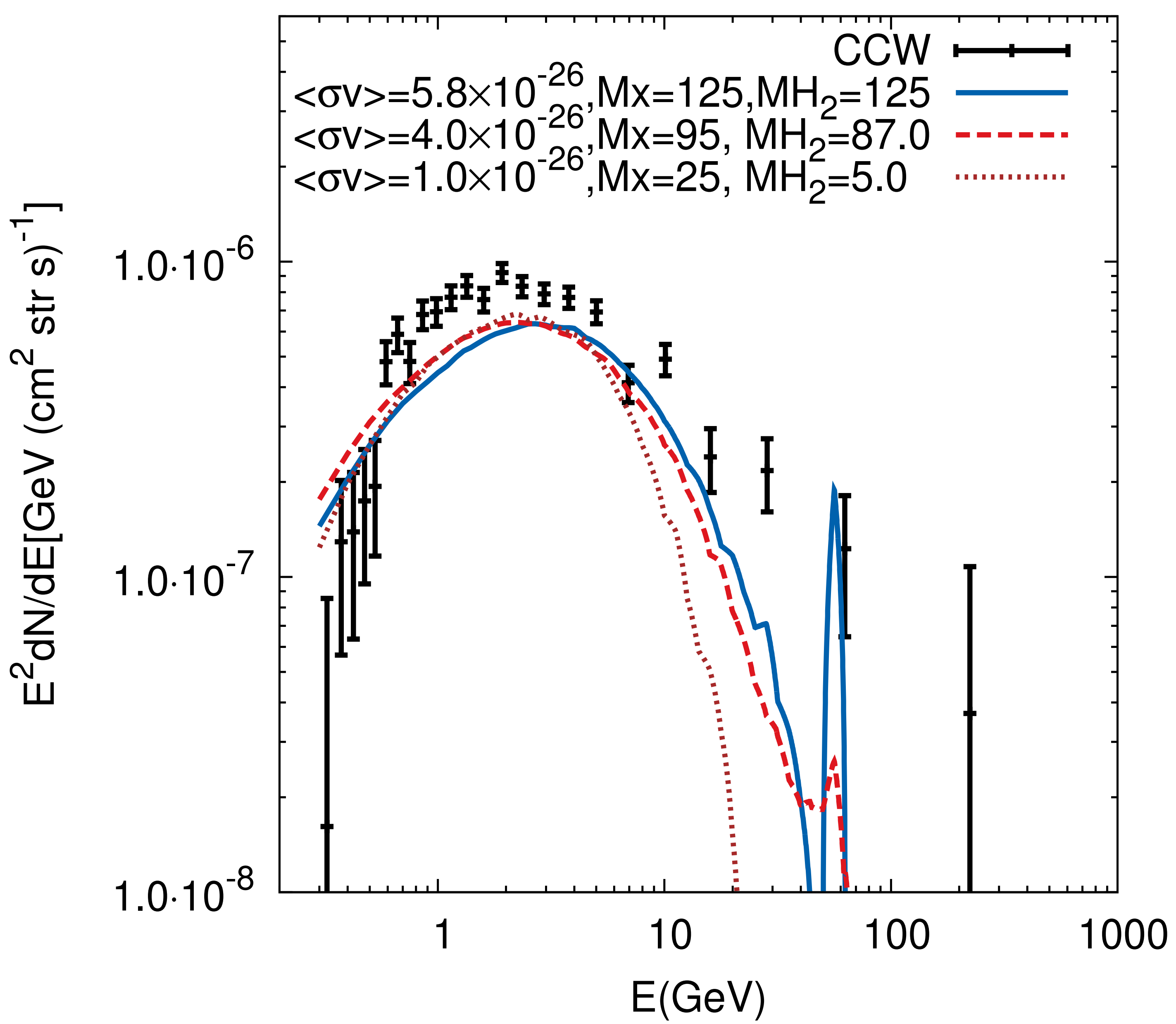


FIG. 2: Three illustrative cases for gamma-ray spectra in contrast with CCW data points [11]. All masses are in GeV unit and σv with cm^3/s. Line shape around $E \simeq M_{H_2}/2$ is due to decay modes, $H_2 \to \gamma\gamma, Z\gamma$.

This would have never been possible within the DM EFT

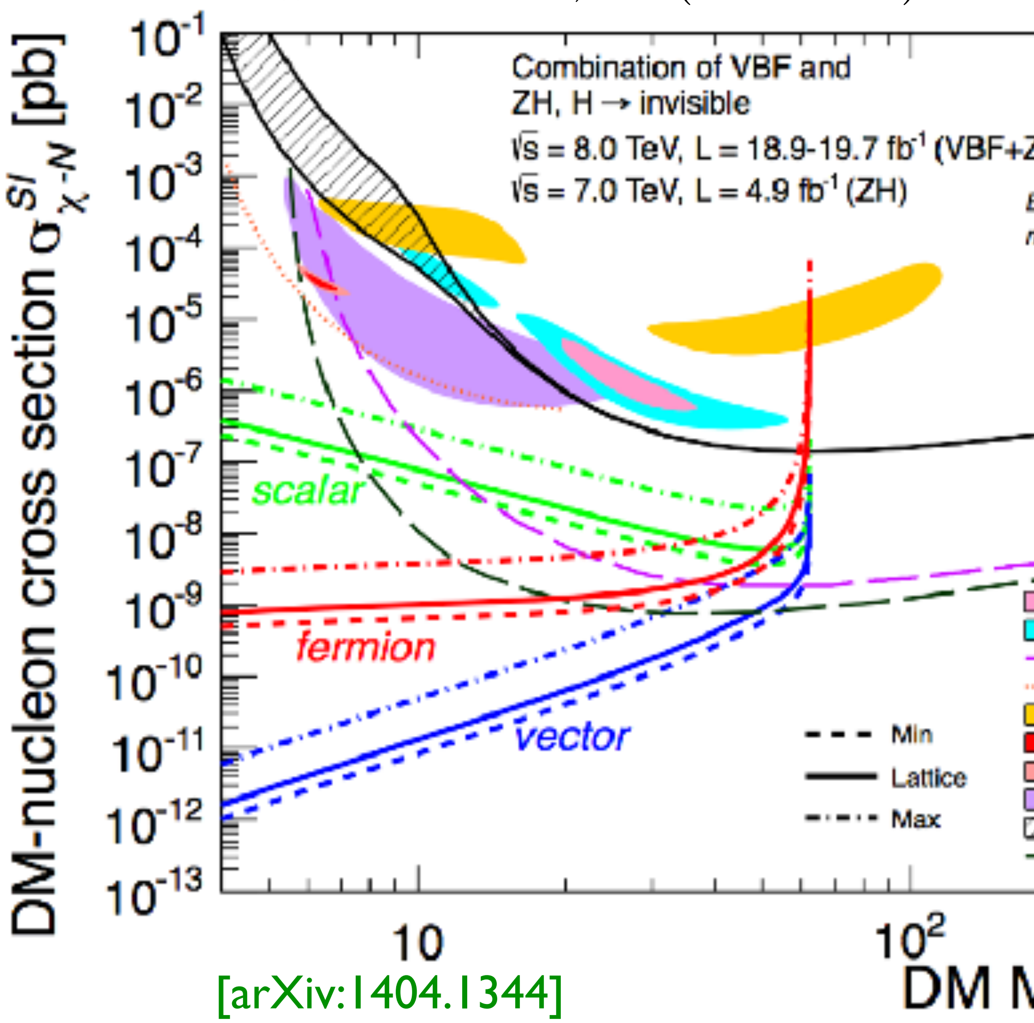
P.Ko, Yong Tang.
arXiv:1504.03908

Channels	Best-fit parameters	$\chi^2_{\text{min}}/\text{d.o.f.}$	p-value
$XX \to H_2H_2$ (with $M_{H_2} \neq M_X$)	$M_X \simeq 95.0\text{GeV}, M_{H_2} \simeq 86.7\text{GeV}$ $\langle\sigma v\rangle \simeq 4.0 \times 10^{-26}\text{cm}^3/\text{s}$	$22.0/21$	0.40
$XX \to H_2H_2$ (with $M_{H_2} = M_X$)	$M_X \simeq 97.1\text{GeV}$ $\langle\sigma v\rangle \simeq 4.2 \times 10^{-26}\text{cm}^3/\text{s}$	$22.5/22$	0.43
$XX \to H_1H_1$ (with $M_{H_1} = 125\text{GeV}$)	$M_X \simeq 125\text{GeV}$ $\langle\sigma v\rangle \simeq 5.5 \times 10^{-26}\text{cm}^3/\text{s}$	$24.8/22$	0.30
$XX \to b\bar{b}$	$M_X \simeq 49.4\text{GeV}$ $\langle\sigma v\rangle \simeq 1.75 \times 10^{-26}\text{cm}^3/\text{s}$	$24.4/22$	0.34

TABLE I: Summary table for the best fits with three different assumptions.

Collider Implications

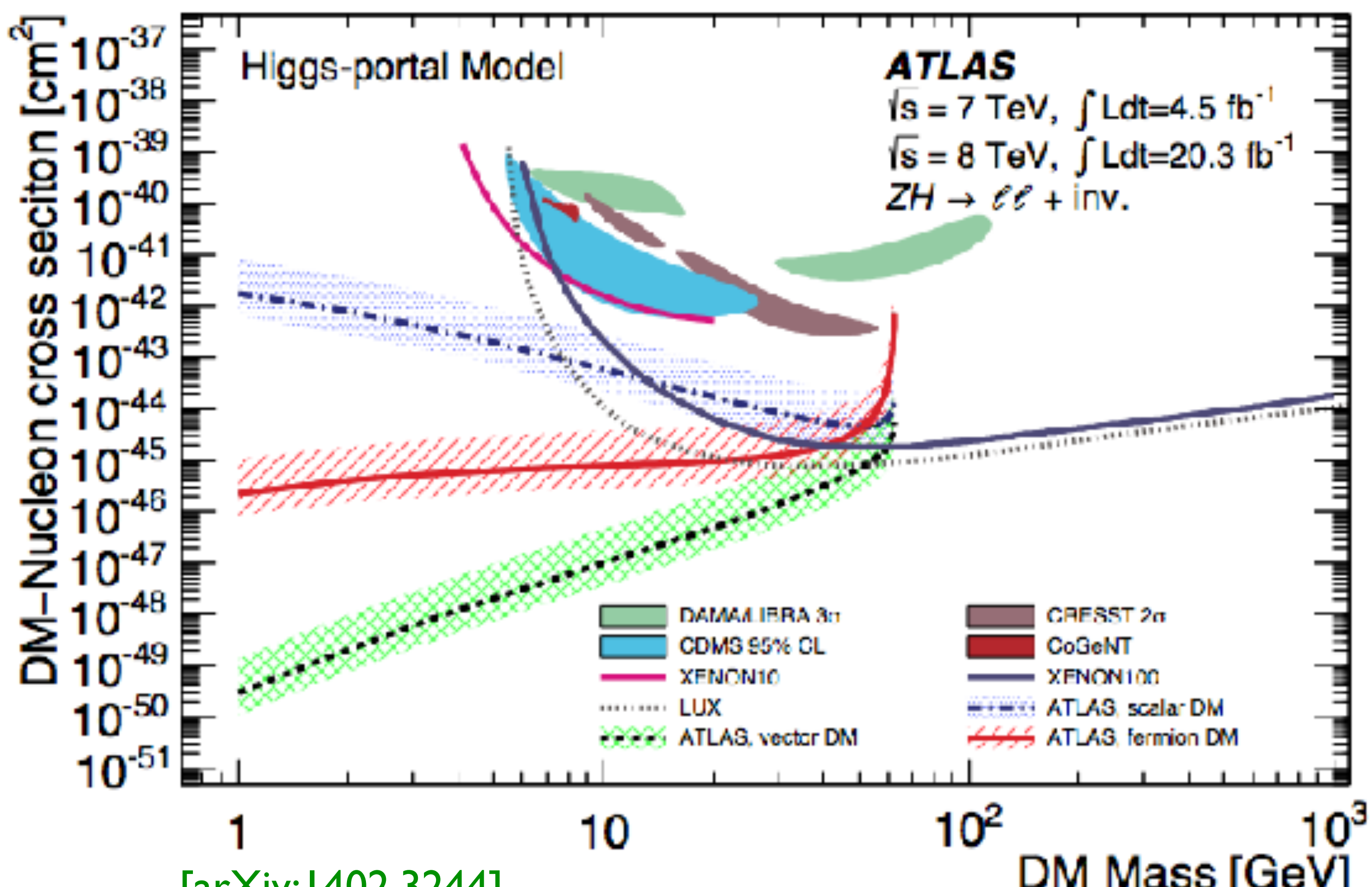
$m_h = 125\text{GeV},\ \text{Br}(H \to \text{inv}) < 0.51$ at 90% CL



[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

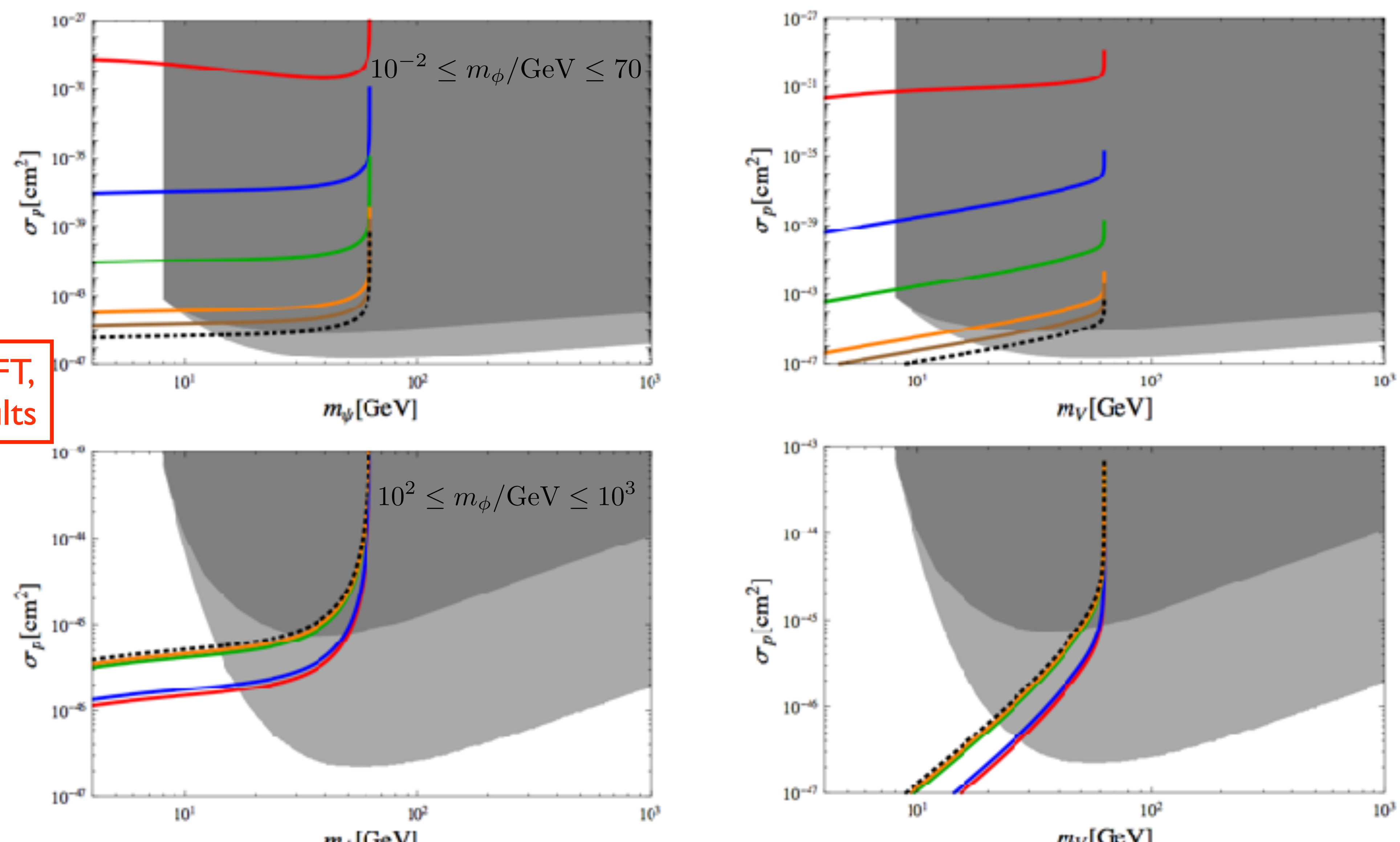
[arXiv: 1405.3530, S. Baek, P. Ko & WIPark, PRD]

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

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

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

Dashed curves:EFT, ATLAS,CMS results

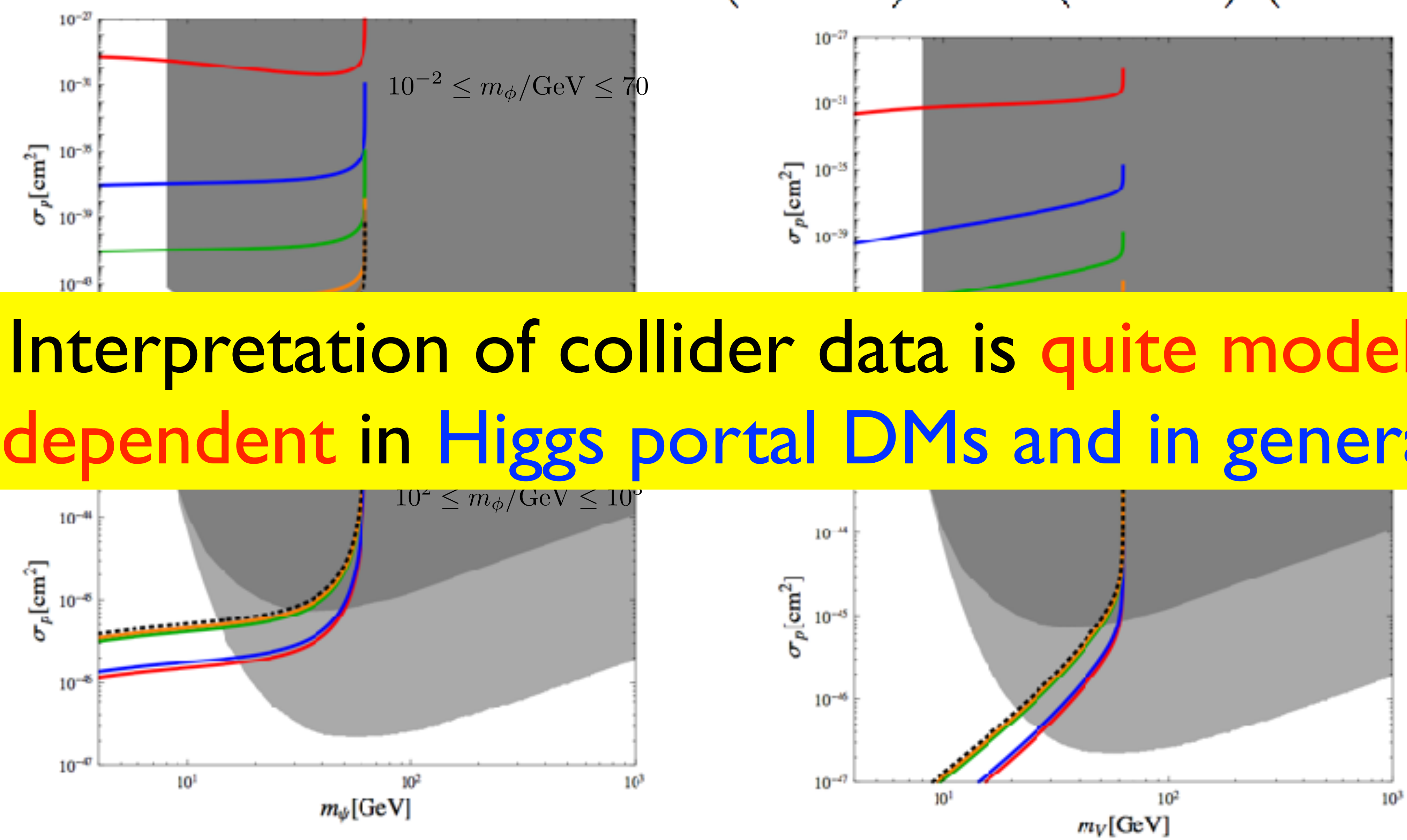


- However, in renormalizable unitary models of Higgs portals, 2 more relevant parameters

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

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

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



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

Invisible H decay into a pair of VDM

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

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

$$m_V \propto g_x Q_\Phi v_\Phi$$

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

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

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)

Why is it broken down in DM EFT ?

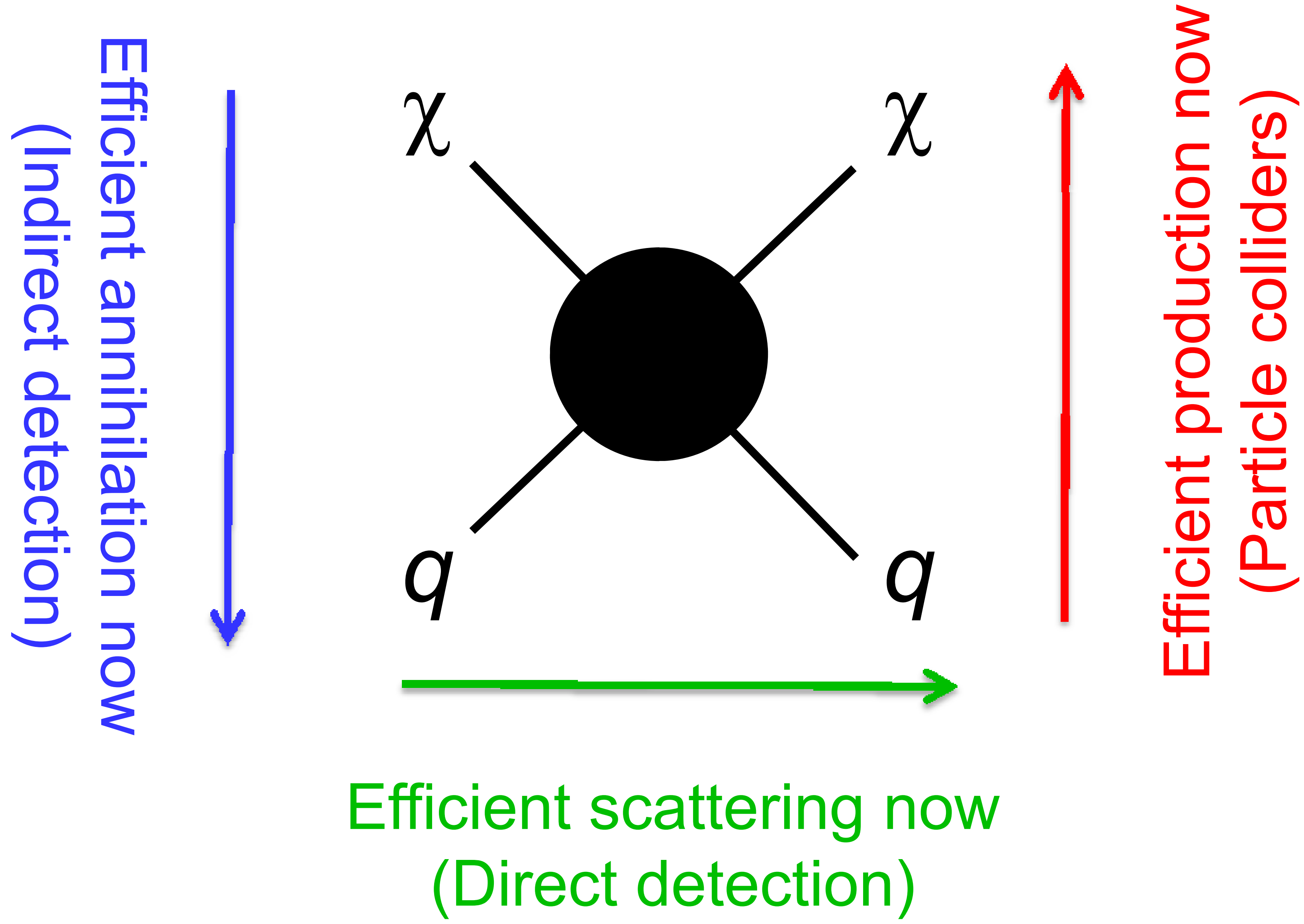
The most nontrivial example is the (scalar)x(scalar) operator for DM-N scattering

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

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

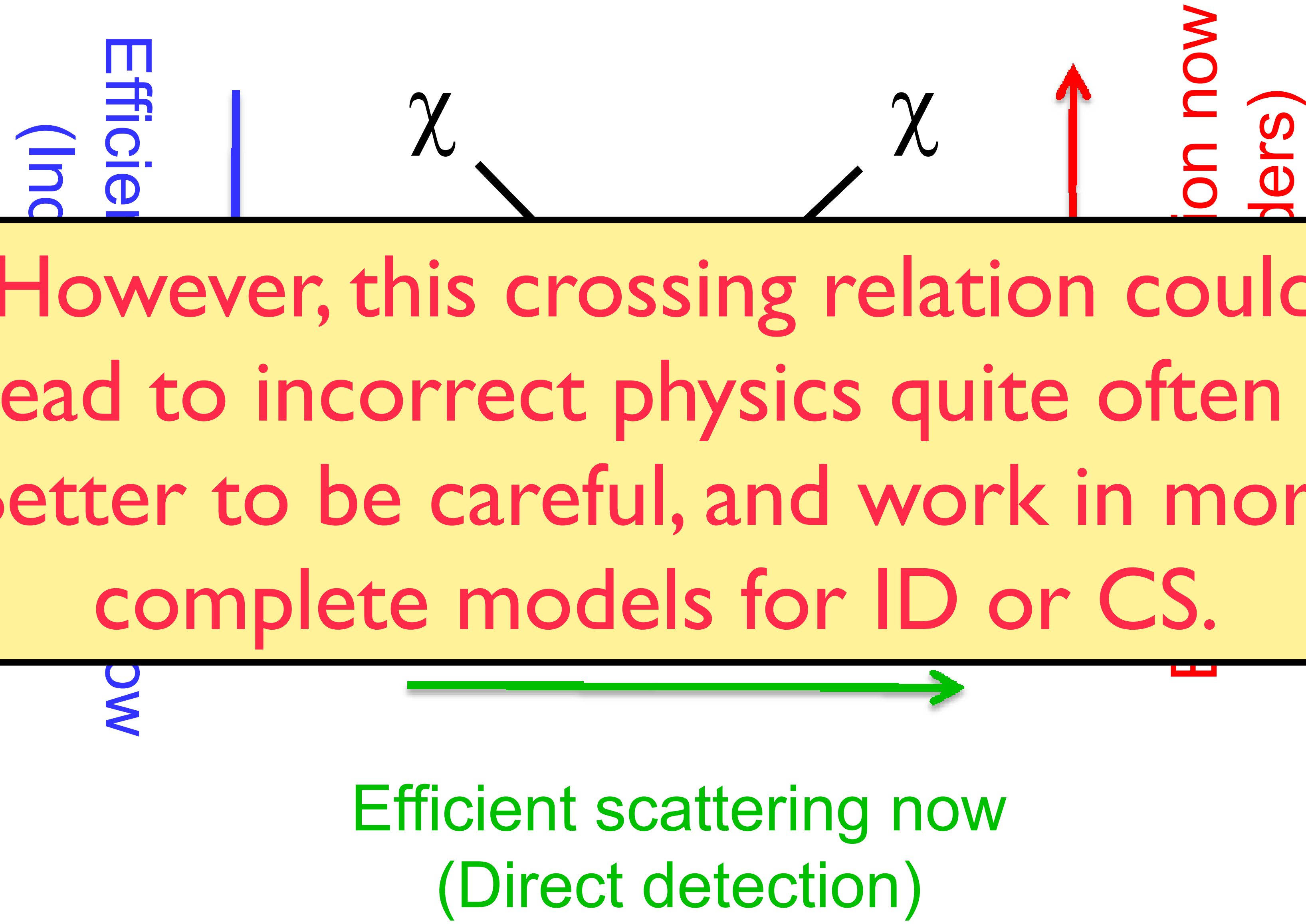
Crossing & WIMP detection

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.

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.

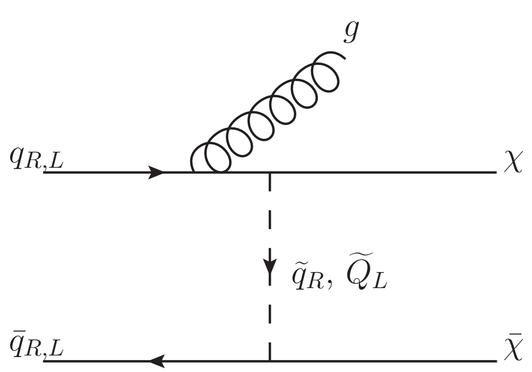
$$\frac{1}{\Lambda_i^2}\ \bar{q}\Gamma_i q\ \bar{\chi}\Gamma_i\chi \to \frac{g_q g_\chi}{m_\phi^2 - s}\ \bar{q}\Gamma_i q\ \bar{\chi}\Gamma_i\chi$$

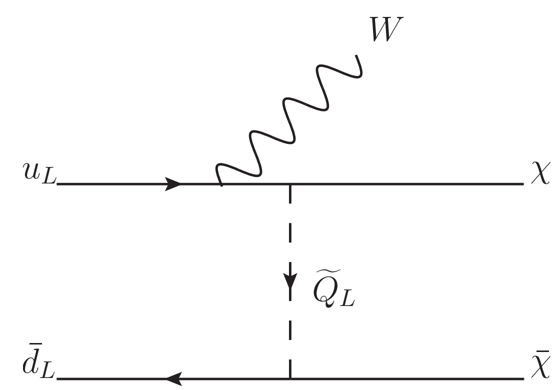
- Usually effective operator is replaced by a single propagator in simplified DM models
- This is not good enough, since we have to respect the full SM gauge symmetry (Bell et al for W+missing ET)
- In general we need two propagators, not one propagator, because there are two independent chiral fermions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

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

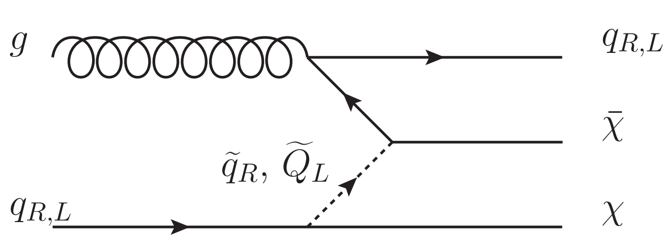
for t-channel mediator

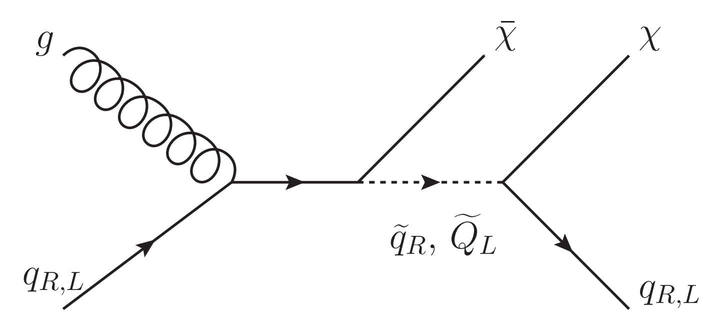
Our Model: a 'simplified model' of colored t-channel, spin-0, mediators which produce various mono-x + missing energy signatures (mono-Jet, mono-W, mono-Z, etc.):





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

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

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

Both break SM gauge

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

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

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

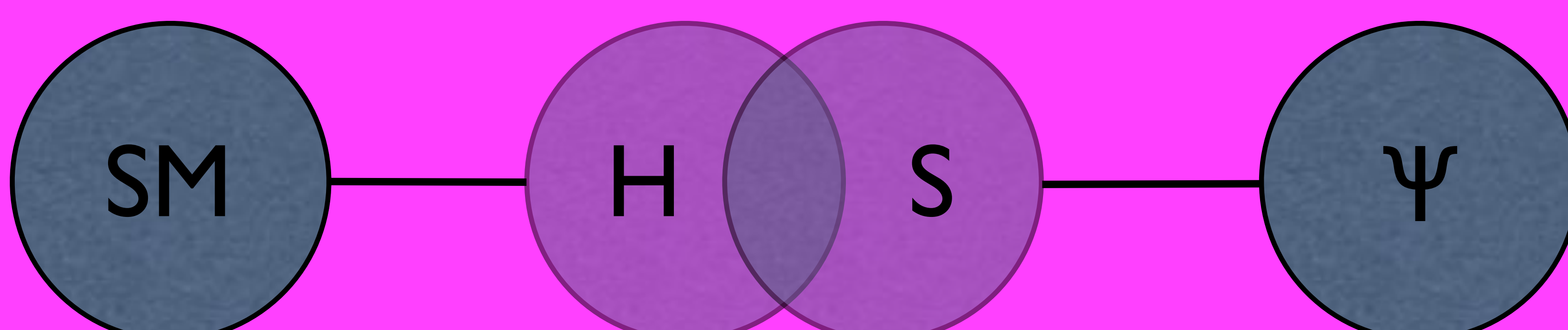
Singlet fermion CDM

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.

This simple model has not been studied properly !!

Full Theory Calculation

$$\chi(p) + q(k) \to \chi(p') + q(k')$$

$$\begin{aligned}
\mathcal{M} &= \overline{u(p')}u(p)\overline{u(q')}u(q)\ \frac{m_q}{v}\lambda_s \sin\alpha\cos\alpha\ \left[\frac{1}{t - m_{125}^2 + i m_{125}\Gamma_{125}} - \frac{1}{t - m_2^2 + i m_s \Gamma_2}\right] \\
&\to \overline{u(p')}u(p)\overline{u(q')}u(q)\ \frac{m_q}{2v}\lambda_s \sin 2\alpha \left[\frac{1}{m_{125}^2} - \frac{1}{m_2^2}\right] \\
&\to \overline{u(p')}u(p)\overline{u(q')}u(q)\ \frac{m_q}{2v}\lambda_s \sin 2\alpha \frac{1}{m_{125}^2} \equiv \frac{m_q}{\Lambda_{dd}^3}\overline{u(p')}u(p)\overline{u(q')}u(q)
\end{aligned}$$

$$\begin{aligned}
\Lambda_{dd}^3 &\equiv \frac{2 m_{125}^2 v}{\lambda_s \sin 2\alpha}\left(1 - \frac{m_{125}^2}{m_2^2}\right)^{-1} \\
\bar{\Lambda}_{dd}^3 &\equiv \frac{2 m_{125}^2 v}{\lambda_s \sin 2\alpha}
\end{aligned}$$

Monojet+missing ET

Can be obtained by crossing : s <>t

$$\frac{1}{\Lambda_{dd}^3} \rightarrow \frac{1}{\Lambda_{dd}^3}\left[\frac{m_{125}^2}{s-m_{125}^2+im_{125}\Gamma_{125}} - \frac{m_{125}^2}{s-m_2^2+im_2\Gamma_2}\right] \equiv \frac{1}{\Lambda_{col}^3(s)}$$

There is no single scale you can define for collider search for missing ET

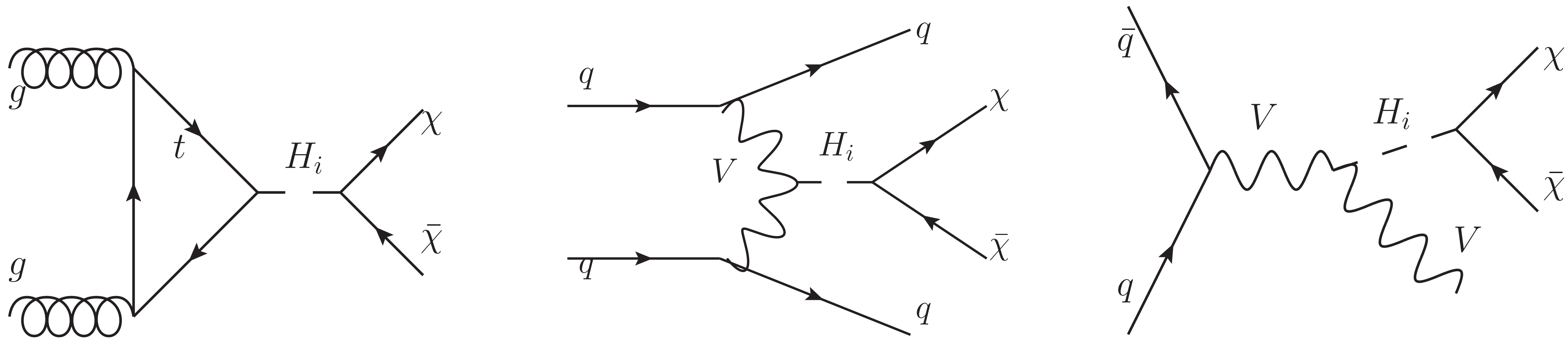


Figure 1: The dominant DM production processes at LHC.

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

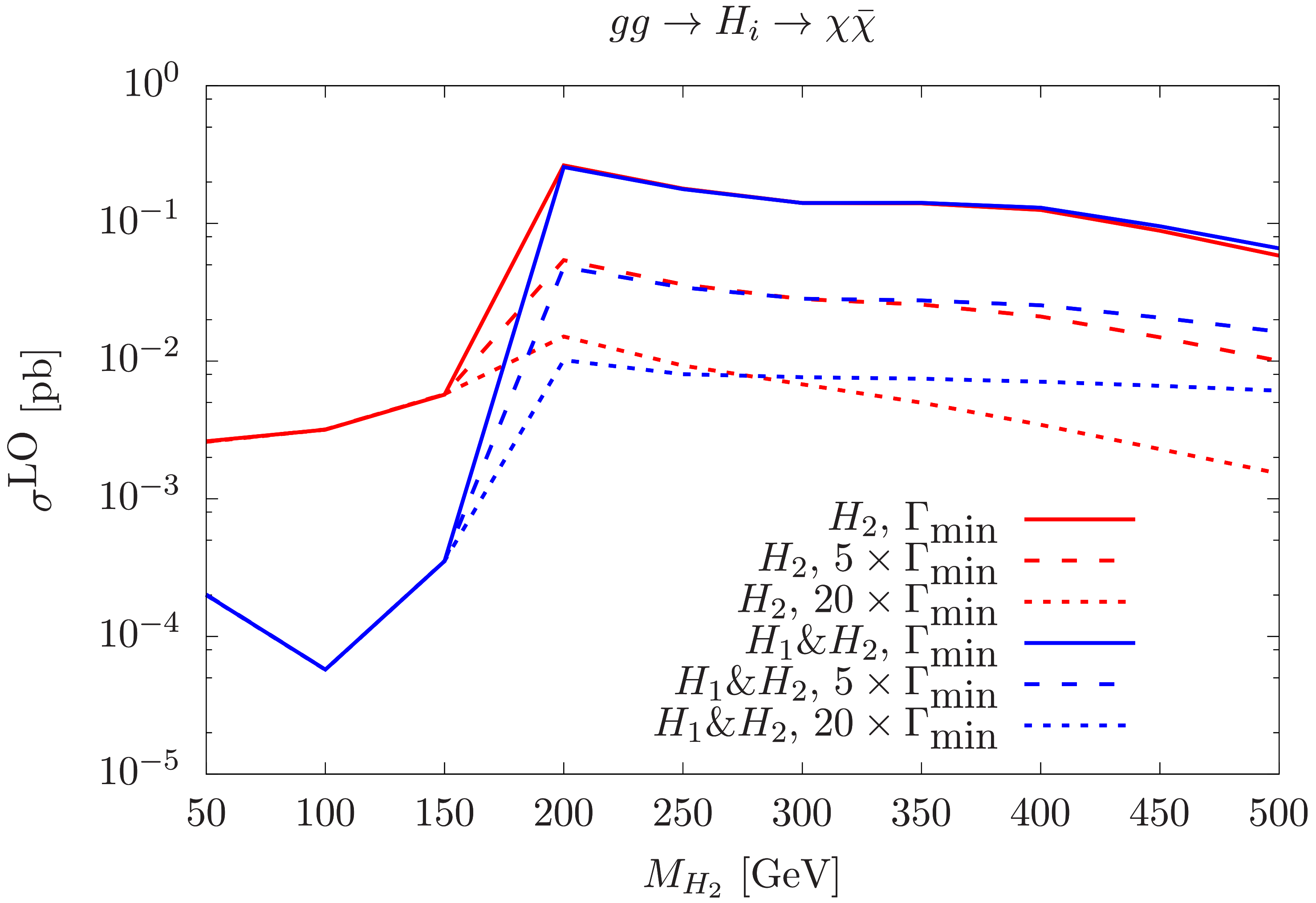


Figure 2: The LO cross section for gluon-gluon fusion process at 13 TeV LHC. The meanings of the different line types are explained in the text and the similar strategy will be used in all figures.

Parton level distributions

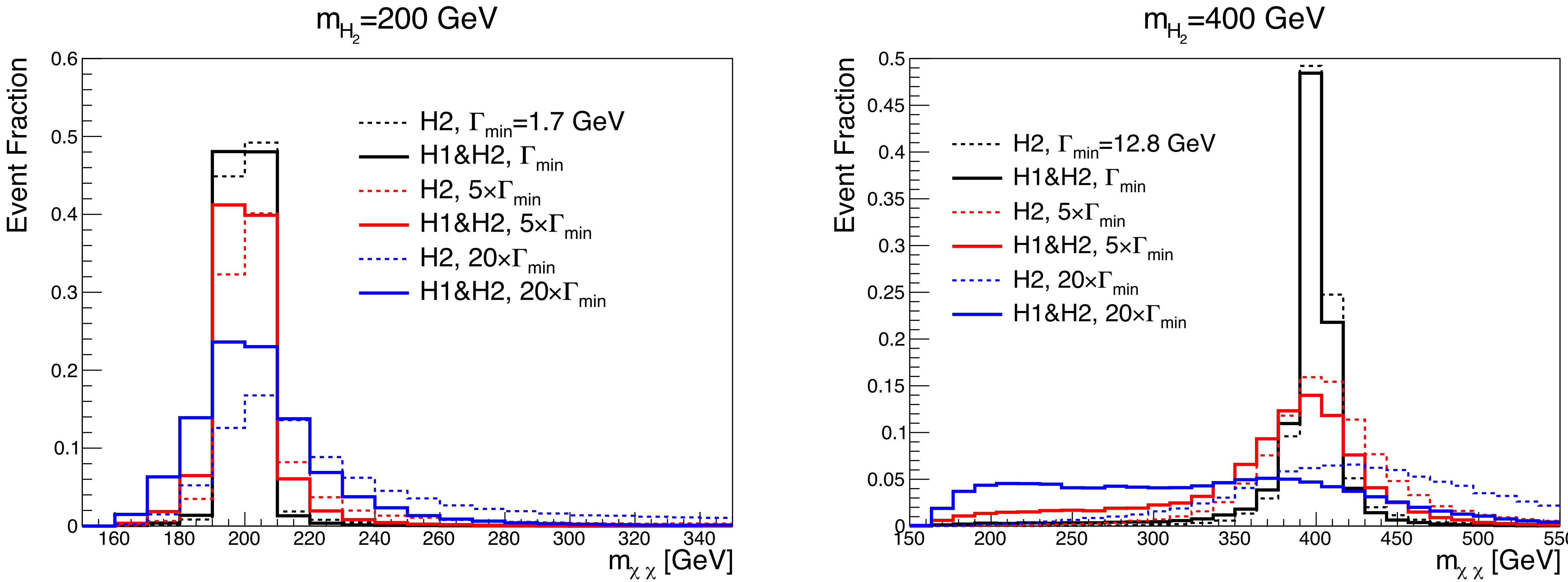


Figure 3: The parton level distributions of $m_{\chi\bar{\chi}}$ for gluon-gluon fusion process at 13 TeV LHC.

Exclusion limits with interference effects

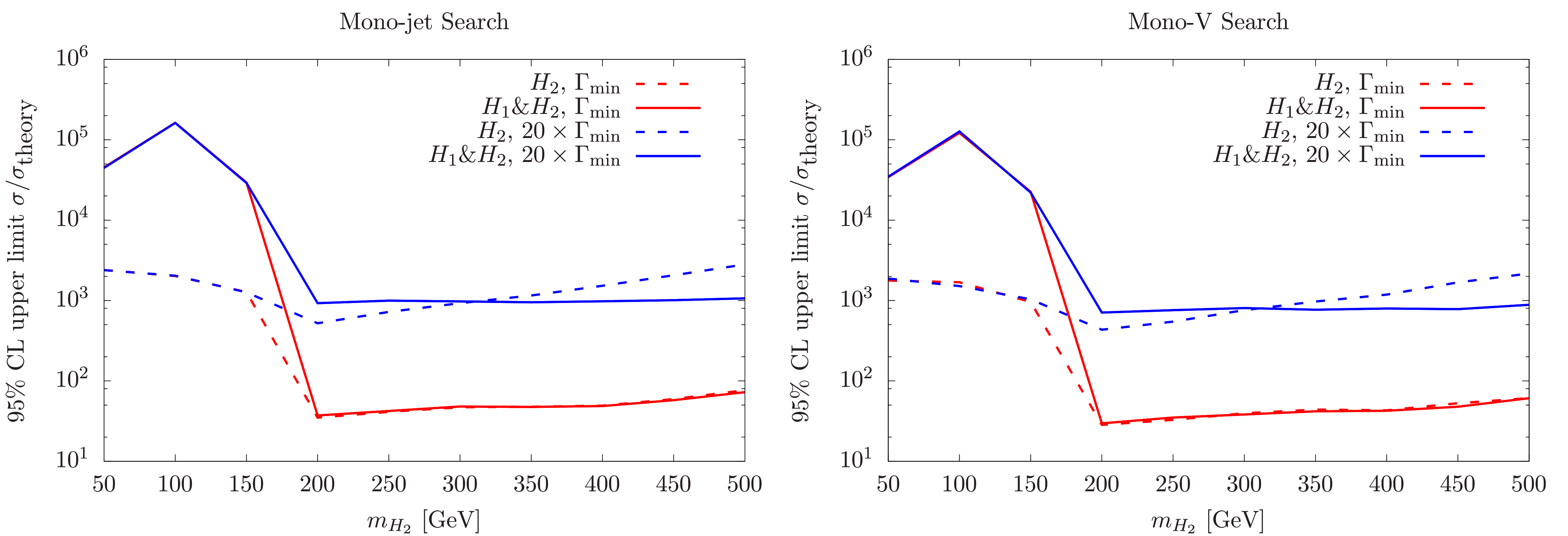
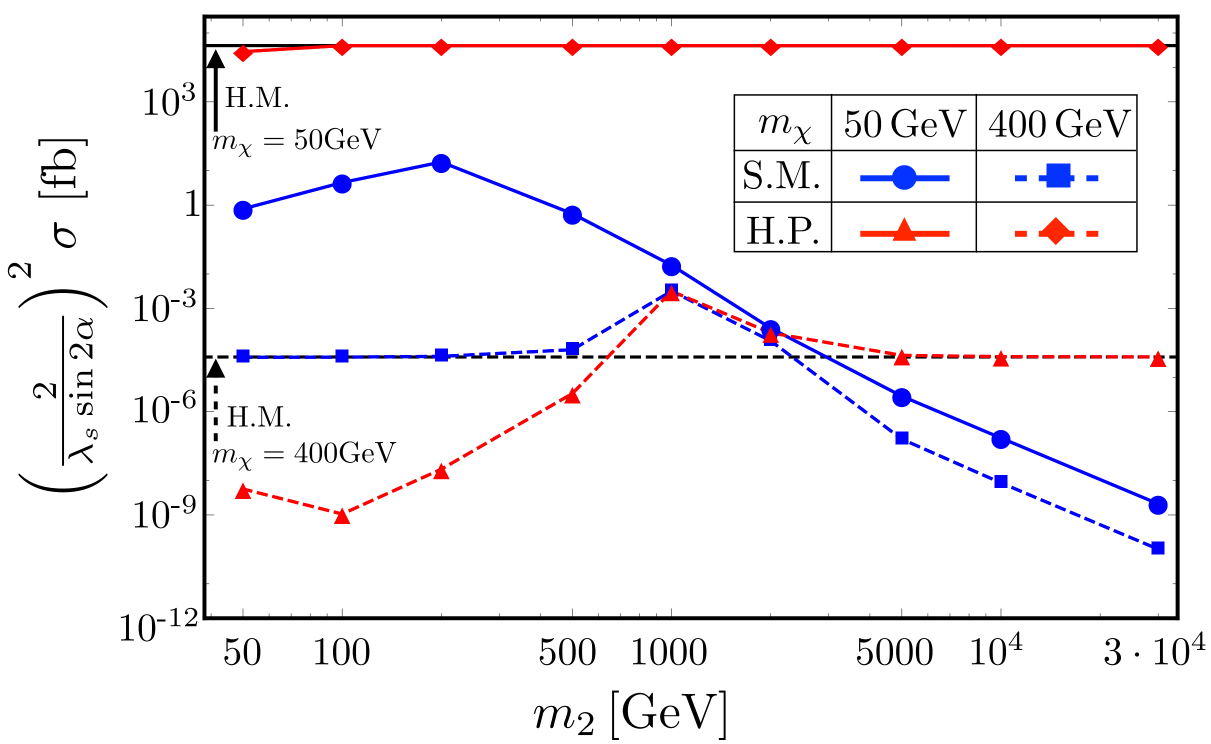


Figure 8: The CMS exclusion limits on our simplified models. Left: upper limit from mono-jet search. Right: upper limit from mono-V search.

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

- 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).



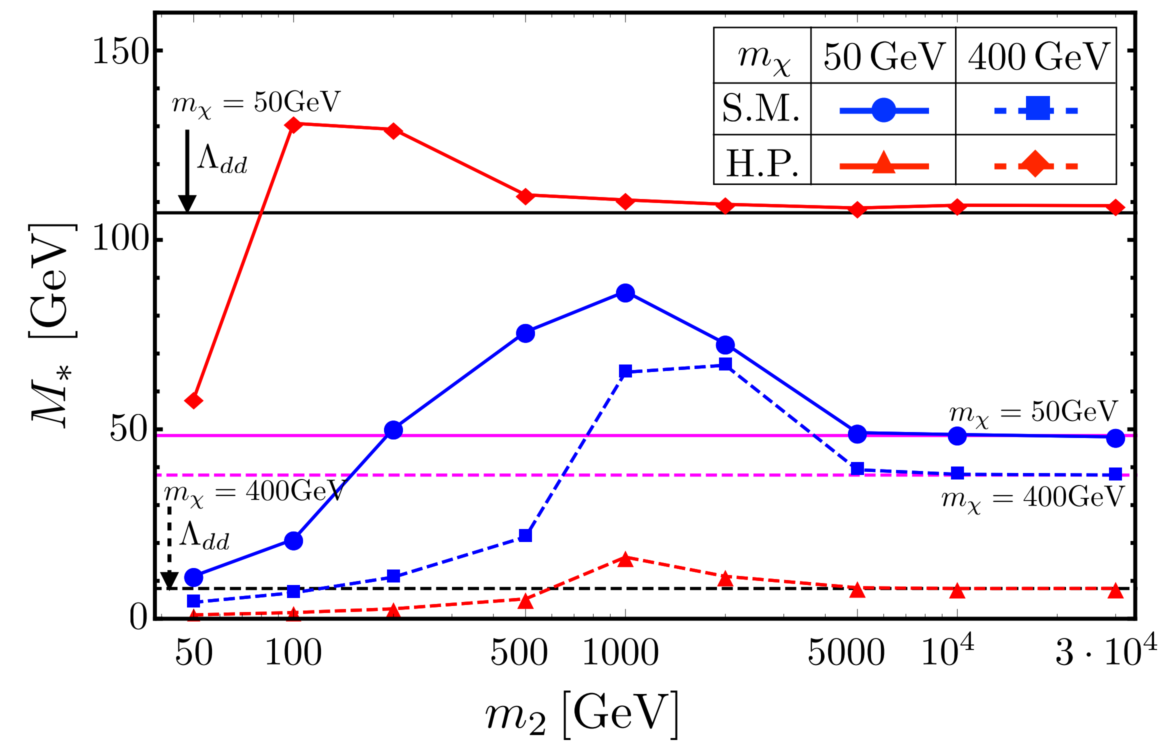


FIG. 1: We follow ATLAS 8TeV mono-jet+$\not{E}_T$ searches [2]. For (a) we simulated various models for the

tT + missing ET

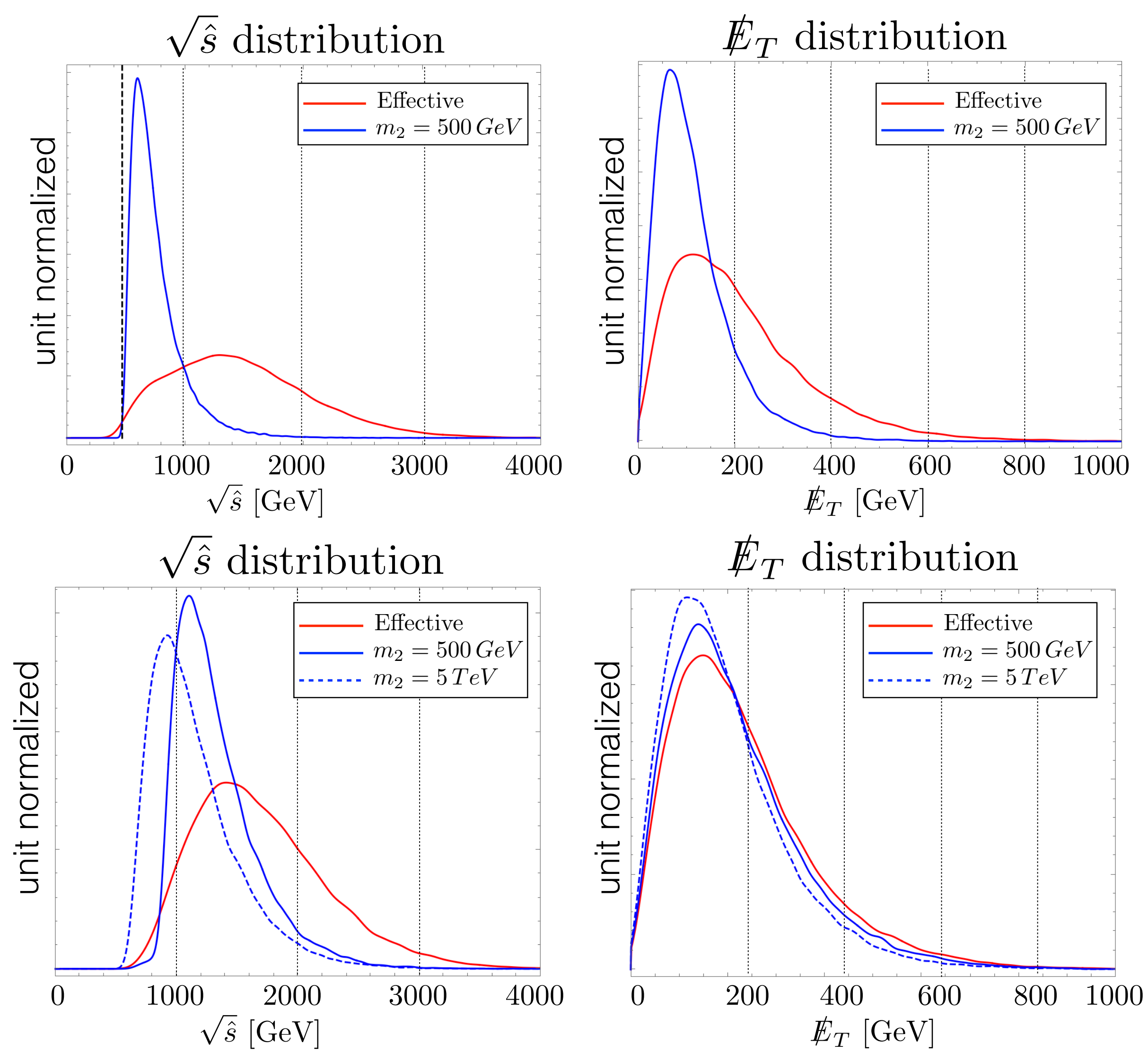


FIG. 2: Parton level distributions of various variables in a $(t\bar{t}\chi\bar{\chi})$ channel for a dark matter's mass $m_\chi = 10\,\text{GeV}$ (above) and $m_\chi = 100\,\text{GeV}$ (below) for LHC 8TeV. As we can see here, due to a higgs propagator, even when $m_2 \to \infty$ case, a missing transverse energy $\not{E}_T$ of a higgs portal model shall be different from an effective operator operator case.

- 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
$\mathcal{L}_{int} = -\left(\frac{m_q}{v_H}\cos\alpha\right) H\bar{q}q - \lambda_s \sin\alpha H\bar{\chi}\chi$
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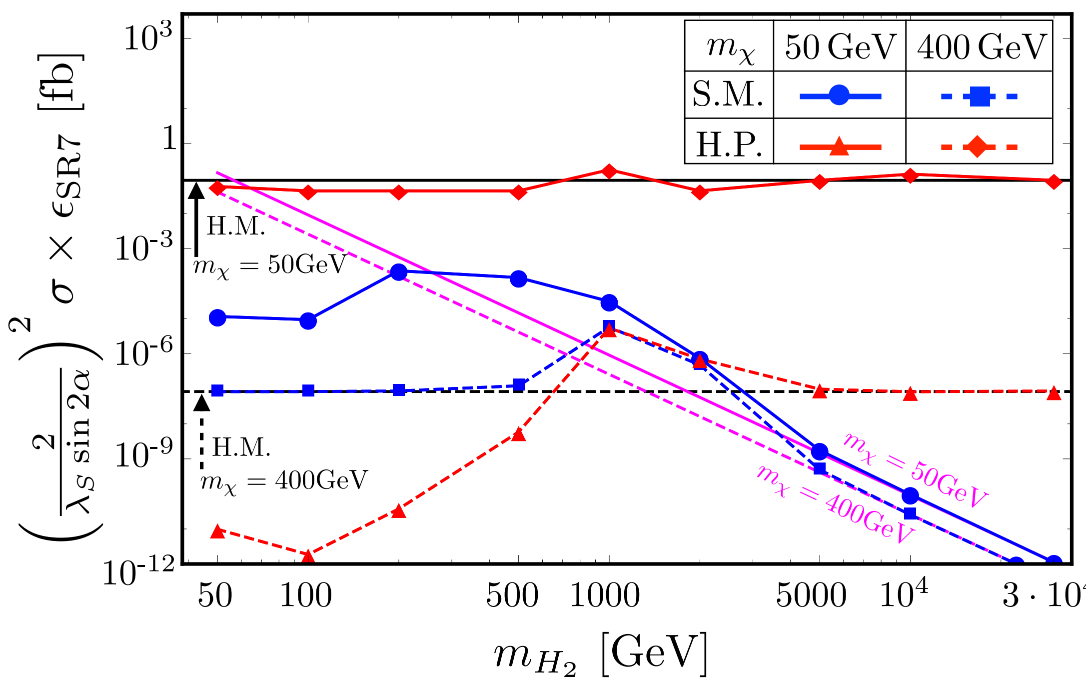

FIG. 2: Rescaled cross sections for the monojet+$\not{E}_T$ in the signal region SR7 ($\not{E}_T > 500\,\mathrm{GeV}$) at ATLAS [11]. Each line corresponds to the EFT approach (magenta), S.M. (blue), H.M. (black), and H.P. (red), respectively. The solid and dashed lines correspond to m_χ = 50 GeV and 400 GeV in each model, respectively.

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

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

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

- 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).

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

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

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

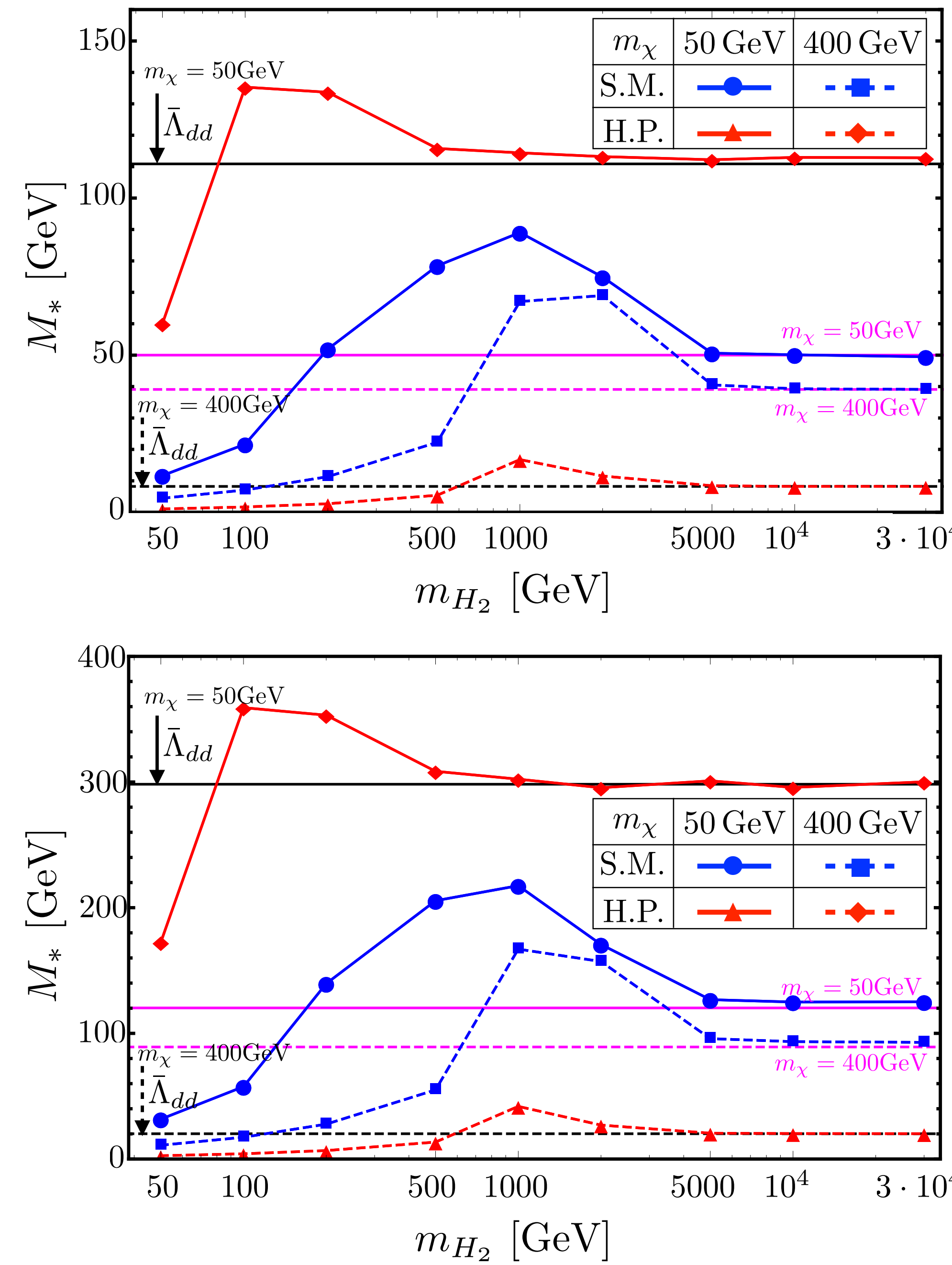

FIG. 3: The experimental bounds on M_* at 90% C.L. as a function of m_{H_2} (m_S in S.M. case) in the monojet+$\not{E}_T$ search (upper) and $t\bar{t} + \not{E}_T$ search (lower). Each line corresponds to the EFT approach (magenta), S.M. (blue), H.M. (black), and H.P. (red), respectively. The bound of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

A General Comment

assume: $2m_\chi \ll m_{125} \ll m_2 \ll \sqrt{s}$

$$\sigma(\sqrt{s}) = \int_0^1 d\tau \sum_{a,b} \frac{d\mathcal{L}_{ab}}{d\tau} \hat{\sigma}(\hat{s} \equiv \tau s)$$

$$= \left[\int_{4m_\chi^2/s}^{m_{125}^2/s} d\tau + \int_{m_{125}^2/s}^{m_2^2/s} d\tau + \int_{m_2^2/s}^{1} d\tau \right] \sum_{a,b} \frac{d\mathcal{L}_{ab}}{d\tau} \hat{\sigma}(\hat{s} \equiv \tau s)$$

For each integration region for tau,
we have to use different EFT

No single EFT applicable to the entire tau regions

Indirect Detection

$$
\begin{aligned}
|\frac{1}{\Lambda_{ann}^3}| &\simeq \frac{1}{\Lambda_{dd}^3}\left|\frac{m_{125}^2}{4m_\chi^2 - m_{125}^2 + i m_{125}\Gamma_{125}} - \frac{m_{125}^2}{4m_\chi^2 - m_2^2 + i m_2 \Gamma_2}\right| \\
&\to \frac{1}{\Lambda_{dd}^3}\left|\frac{m_{125}^2}{4m_\chi^2 - m_{125}^2 + i m_{125}\Gamma_{125}}\right| \neq \frac{1}{\Lambda_{dd}^3}
\end{aligned}
$$

- Again, no definite correlations between two scales in DD and ID
- Also one has to include other channels depending on the DM mass

Pseudoscalar Mediator with Higgs portal

S. Baek, P. Ko, Jinmian Li, arXiv:1701.04131
to appear in PRD

Pseudoscalar portal DM

(S. Baek, P. Ko, Jinmian Li, arXiv:1701.04131)

$$\frac{1}{\Lambda^2}\bar{f}f\bar{\chi}\gamma_5\chi$$

- Highly suppressed for SI/SD x-section
- DM pair annihilation in the S-wave

Its simplest UV completion:
(different from 2HDM portal)

$$\begin{aligned}\mathcal{L} = & \bar{\chi}(i\partial\cdot\gamma - m_\chi - ig_\chi a\gamma^5)\chi + \frac{1}{2}\partial_\mu a\partial^\mu a - \frac{1}{2}m_a^2 a^2 \\ & - (\mu_a a + \lambda_{Ha} a^2)\left(H^\dagger H - \frac{v_h^2}{2}\right) - \frac{\mu_a'}{3!}a^3 - \frac{\lambda_a}{4!}a^4 \\ & - \lambda_H\left(H^\dagger H - \frac{v_h^2}{2}\right)^2 \quad . \end{aligned} \tag{1}$$

see also Karim Ghorbani, arXiv:1408.4929 [hep-ph]

Interaction Lagrangians

$$\mathcal{L}_{\rm int} = -ig_\chi (H_0 \sin\alpha + A\cos\alpha)\ \bar\chi\gamma^5\chi - (H_0\cos\alpha - A\sin\alpha) \times \left[\sum_f \frac{m_f}{v_h}\bar f f - \frac{2m_W^2}{v_h} W_\mu^+ W^{-\mu} - \frac{m_Z^2}{v_h} Z_\mu Z^\mu\right] \quad (7)$$

For comparison, let us define 2 other cases

$$\mathcal{L}_{\rm int}^{\rm SS} = -g_\chi (H_1 \sin\alpha + H_2\cos\alpha)\ \bar\chi\chi - (H_1\cos\alpha - H_2\sin\alpha) \times \left[\sum_f \frac{m_f}{v_h}\bar f f - \frac{2m_W^2}{v_h} W_\mu^+ W^{-\mu} - \frac{m_Z^2}{v_h} Z_\mu Z^\mu\right] \quad (12)$$

(Higgs portal)

$$\mathcal{L}_{\rm int}^{\rm AA} = -ig_\chi (a \sin\alpha + A\cos\alpha)\ \bar\chi\gamma^5\chi - i(a\cos\alpha - A\sin\alpha)\sum_f \frac{m_f}{v_h}\bar f\gamma^5 f \quad (13)$$

(2HDM+a portal)

DM phenomenology

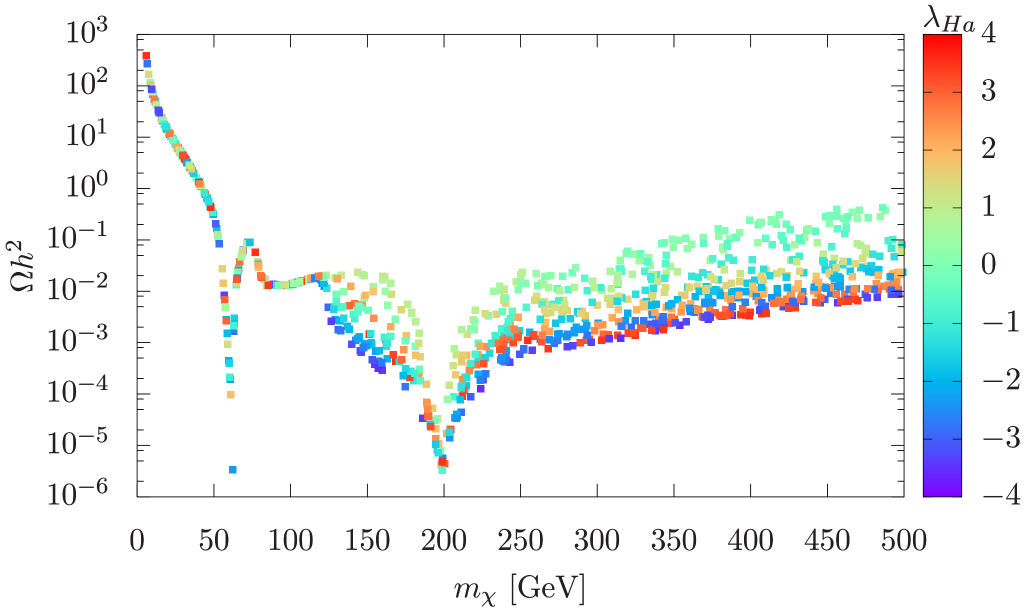

FIG. 1. Relic density with varying DM mass, for $m_A = 400$ GeV, $g_\chi = 1$ and $\alpha = 0.3$. Color code indicates the value of λ_{Ha}.

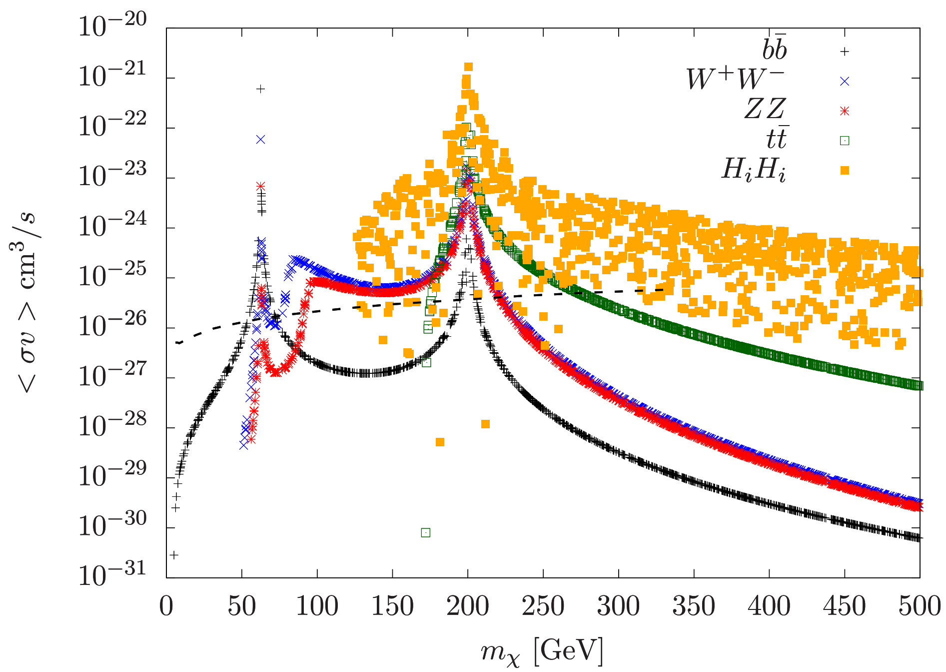

FIG. 2. The cross sections for different DM annihilation (at rest) channels. The dashed black curve correspond to the 95% CL exclusion limit on $b\bar{b}$ channel obtained from Milky Way Dwarf Spheroidal Galaxies with Six Years of Fermi-LAT Data [55].

Good scenario for DM phenomenology
in terms of (in)direct detection expt's

Collider Searches

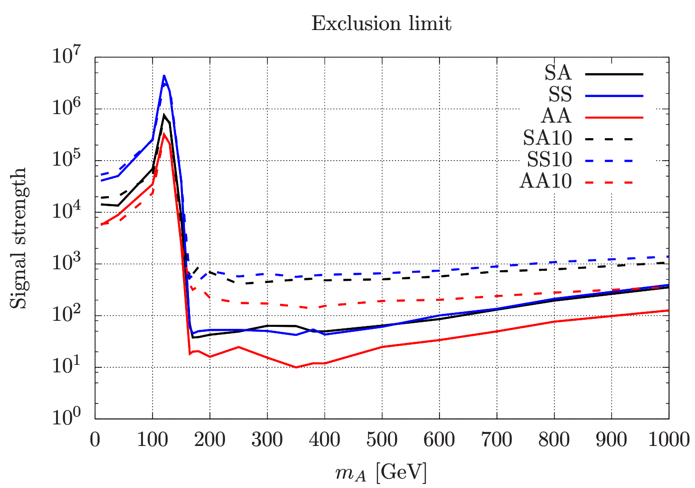

FIG. 5. The 95% CL exclusion limits from the ATLAS mono-jet search at 13 TeV with integrated luminosity of 3.2 fb^{-1} . The dashed curves correspond to models with ten times larger total width of A than $\Gamma_{\min}$ due to the opening of new decay channels.

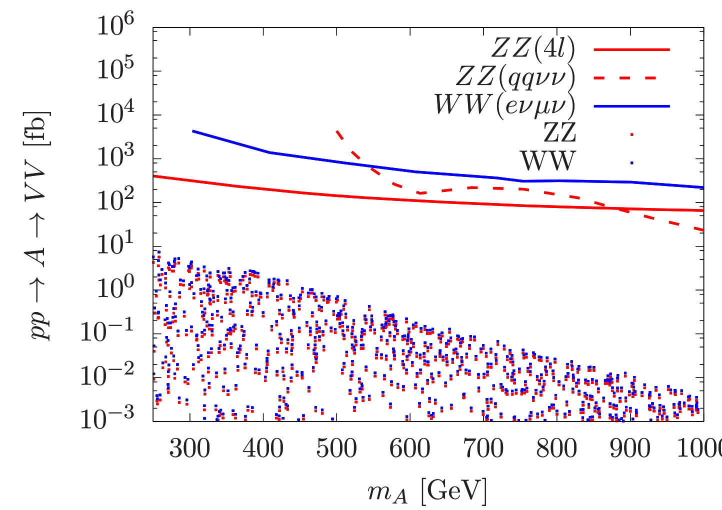

FIG. 6. Bounds correspond to the LHC searches for two vector boson resonance. The production cross sections of ZZ (WW) at 13 TeV in our model are shown by red (blue) points.

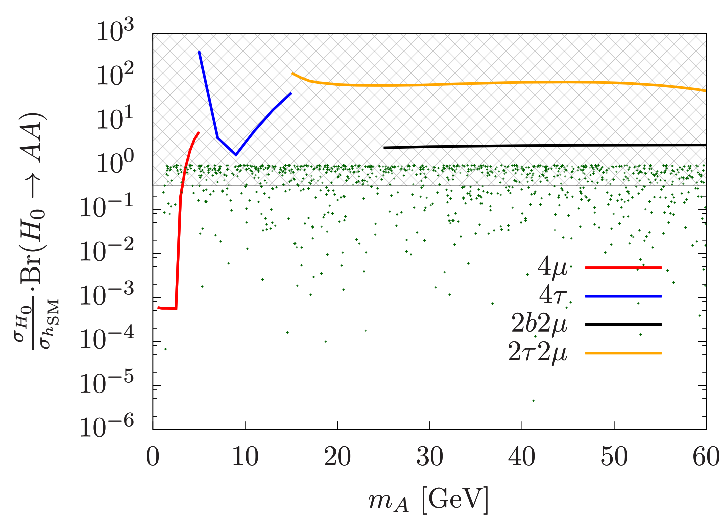

FIG. 7. Bounds correspond to the LHC searches for light boson pair from the SM Higgs decay. The shaded region is excluded by the Higgs precision measurement. Our models are shown by dark green points.

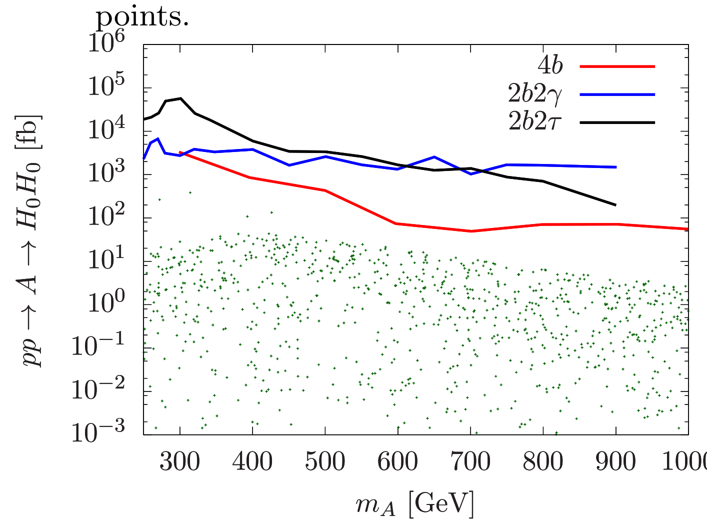

FIG. 8. Bounds correspond to the LHC di-Higgs searches in different final states. The production cross section of our models at 13 TeV are shown by dark green points.

Summary

- Renormalizable and unitary model (with some caveat) is important for DM phenomenology (EFT can fail completely)
- Imposing the full SM gauge symmetry is crucial for collider searches for DM
- Usually two propagators necessary for UV completion of the effective operators >> Important interference effects to be included in the data analysis

Conclusion

- Higgs can play portals to various dark sectors in a number of well motivated BSM models
- The full SM gauge invariance should be respected for DM searches @ high energy colliders
- UV completion of effective operators involve two independent mediators, except for W+missing ET
- In particular interference effects between the SM Higgs and dark Higgs could be important in certain cases

- Boosted Di-Higgs boson + missing ET signature can probe "Dark Sector"

- In many cases, there appear a "dark Higgs" (a singlet scalar) that mixes with the SM Higgs boson : it can also improve the Higgs inflation by Higgs-portal assistance
(arXiv:1405.1635 with Jinsu Kim, W.I.Park)

- Important to search for this singlet scalar at current/future colliders including the low mass region