

Collider Search for Higgs portal DM

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Only Higgs (\sim SM) and Nothing
Else So Far at the LHC &
Local Gauge Principle Works !

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 ?

Why Higgs-DM special ?

- $|H|^2$: dim-2 gauge invariant operator
- Origin of many problems (hierarchy prob., DM instability without extra symmetry...)
- Dark gauge symmetry can guarantee DM stability/longevity
- Dark Higgs ϕ would break dark gauge sym spontaneously
- $|H|^2 |\phi|^2$: dim-4 gauge inv operator

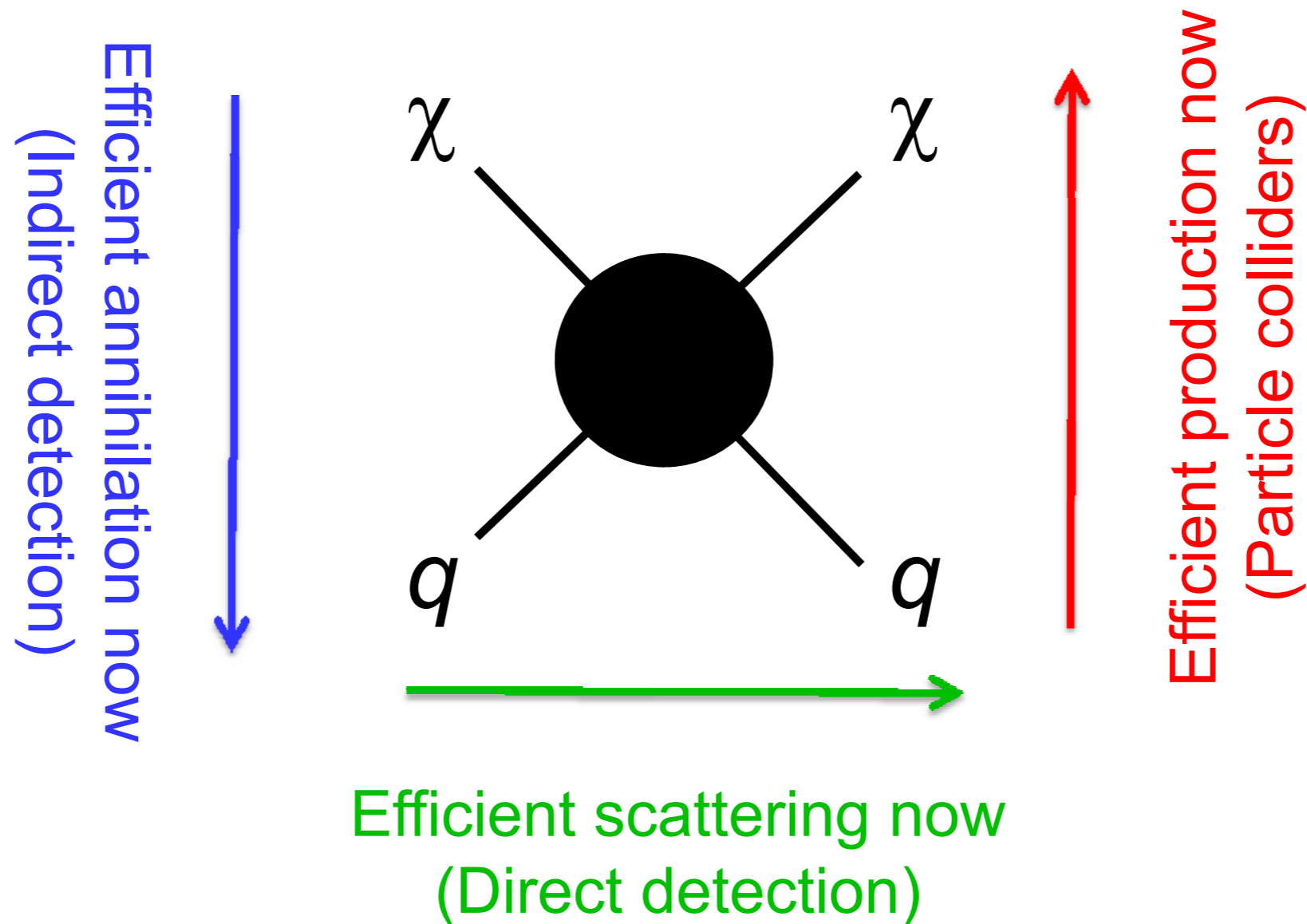
Based on the works

(with S.Baek, Jinmian Li, Alex Natale, W.I.Park, E.Senaha, Yong Tang, Hiroshi Yokoya in various combinations)

- Singlet fermion dark matter (1112.1847 JHEP)
- Higgs portal vector dark matter (1212.2131 JHEP)
- Vacuum structure and stability issues (1209.4163 JHEP)
- Higgs-portal assisted Higgs inflation, Higgs portal VDM for gamma ray excess from GC (1404.5257 JCAP; 1407.5492 JCAP ; 1407.6588, PLB in review)
- Invisible Higgs decay vs. DD (1405.3530 PRD)
- Search for Higgs portal DM at ILC (1603.04737 JHEP)
- Simplified models with the full SM gauge sym (1605.07058, JHEP in review)
- Interference effects of two scalar mediators..... (1610.03997 to appear in PLB)

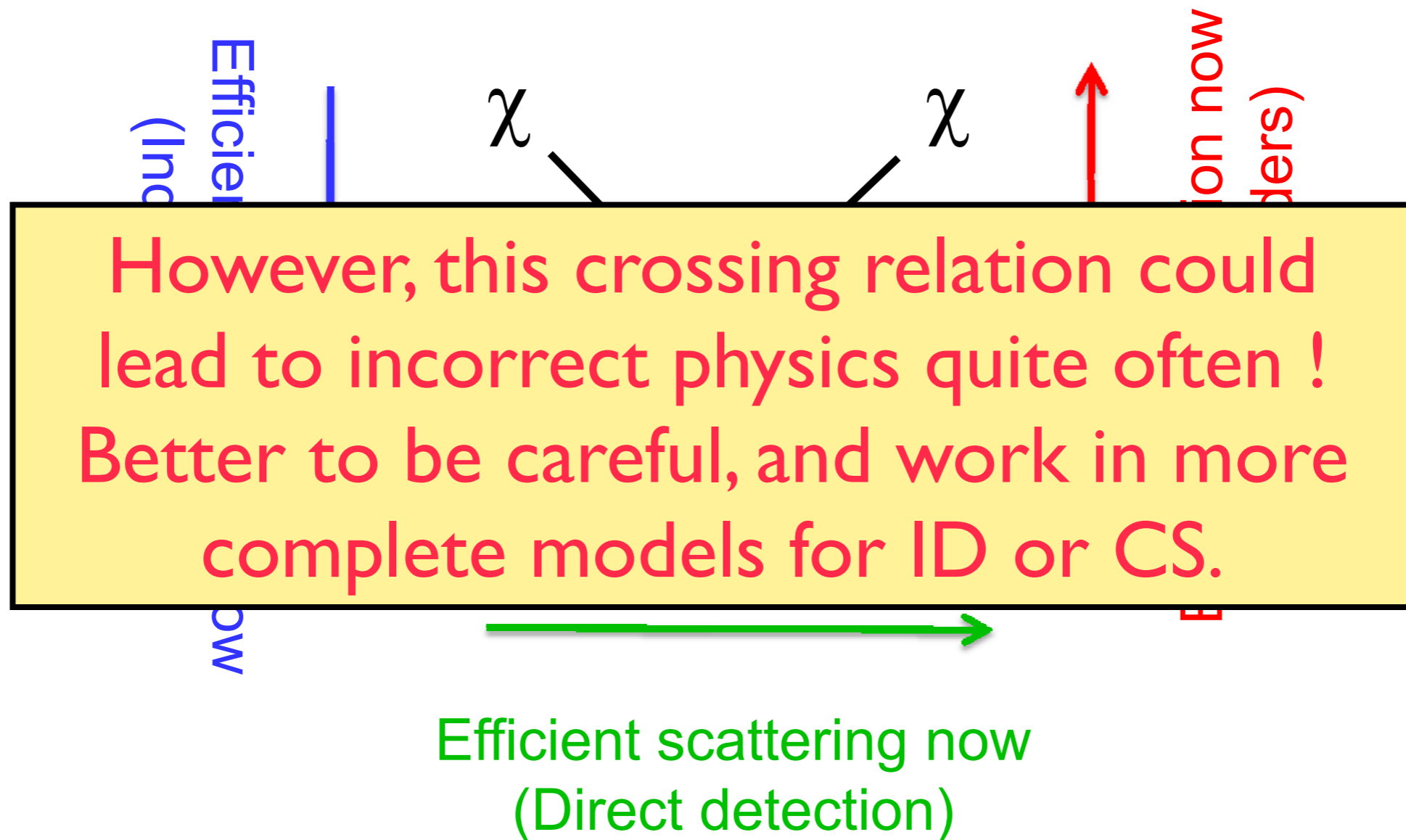
Crossing & WIMP detection

Correct relic density \rightarrow Efficient annihilation then



Crossing & WIMP detection

Correct relic density \rightarrow Efficient annihilation then



From Paolo Gondolo's talk

Effective operators: LHC & direct detection

Name	Operator	Coefficient
D1	$\bar{\chi}\chi\bar{q}q$	m_q/M_*^3
D2	$\bar{\chi}\gamma^5\chi\bar{q}q$	im_q/M_*^3
D3	$\bar{\chi}\chi\bar{q}\gamma^5q$	im_q/M_*^3
D4	$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5q$	m_q/M_*^3
D5	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D6	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D7	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5q$	$1/M_*^2$
D8	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5q$	$1/M_*^2$
D9	$\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$	$1/M_*^2$
D10	$\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi\bar{q}\sigma_{\alpha\beta}q$	i/M_*^2
D11	$\bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^3$
D12	$\bar{\chi}\gamma^5\chi G_{\mu\nu}G^{\mu\nu}$	$i\alpha_s/4M_*^3$
D13	$\bar{\chi}\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^3$
D14	$\bar{\chi}\gamma^5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\alpha_s/4M_*^3$

Name	Operator	Coefficient
C1	$\chi^\dagger\chi\bar{q}q$	m_q/M_*^2
C2	$\chi^\dagger\chi\bar{q}\gamma^5q$	im_q/M_*^2
C3	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu q$	$1/M_*^2$
C4	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu\gamma^5q$	$1/M_*^2$
C5	$\chi^\dagger\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^2$
C6	$\chi^\dagger\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^2$
R1	$\chi^2\bar{q}q$	$m_q/2M_*^2$
R2	$\chi^2\bar{q}\gamma^5q$	$im_q/2M_*^2$
R3	$\chi^2 G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/8M_*^2$
R4	$\chi^2 G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/8M_*^2$

Table of effective operators relevant for the collider/direct detection connection

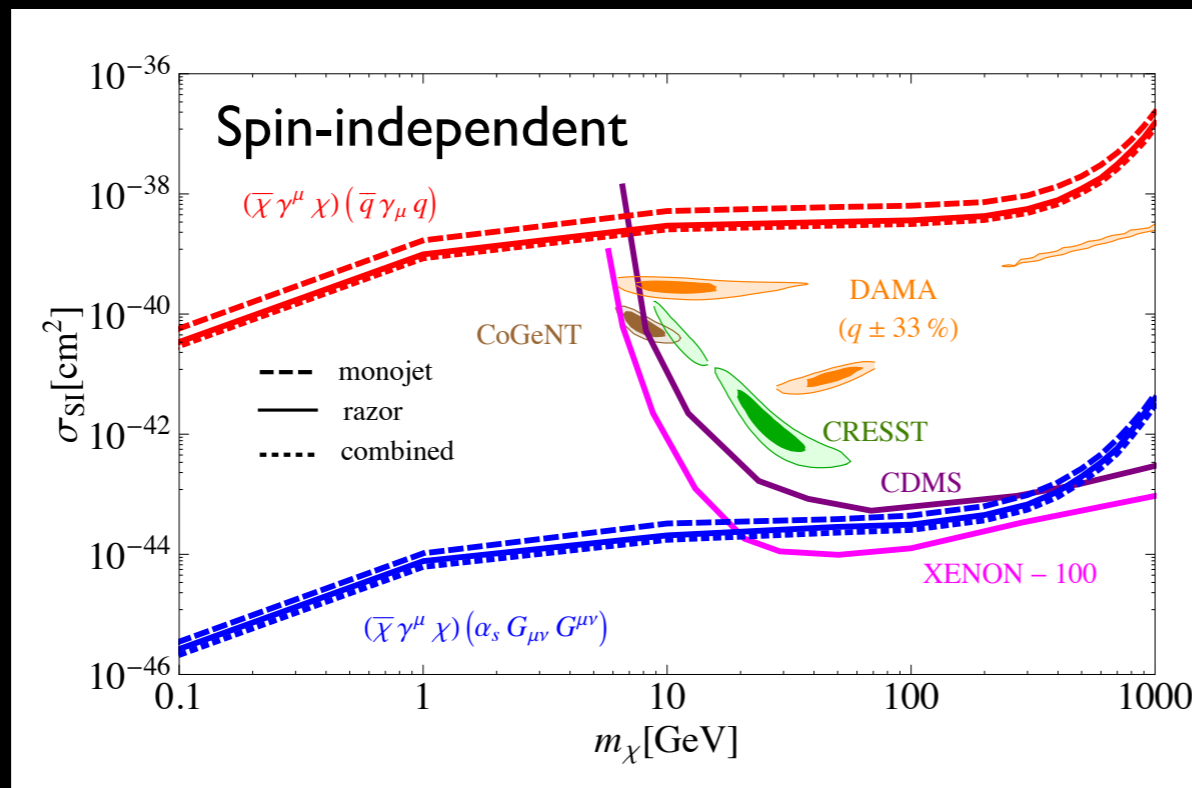
Goodman, Ibe, Rajaraman, Shepherd, Tait, Yu 2010

From Paolo Gondolo's talk

Effective operators: LHC & direct detection

LHC limits on WIMP-quark and WIMP-gluon interactions are competitive with direct searches

Beltran et al, Agrawal et al., Goodman et al., Bai et al., 2010; Goodman et al., Rajaraman et al. Fox et al., 2011; Cheung et al., Fitzpatrick et al., March-Russel et al., Fox et al., 2012.....



Fox, Harnik, Primulando, Yu 2012

These bounds do not apply to SUSY, etc.

Complete theories contain sums of operators (interference) and not-so-heavy mediators (Higgs)

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.

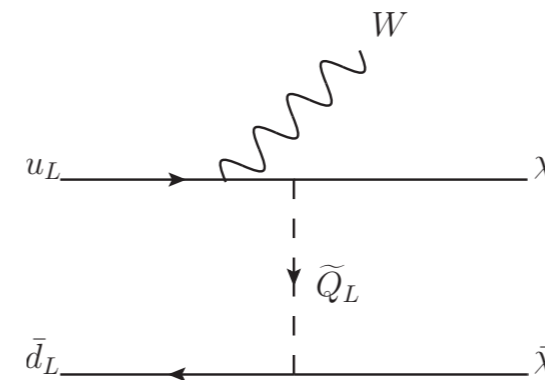
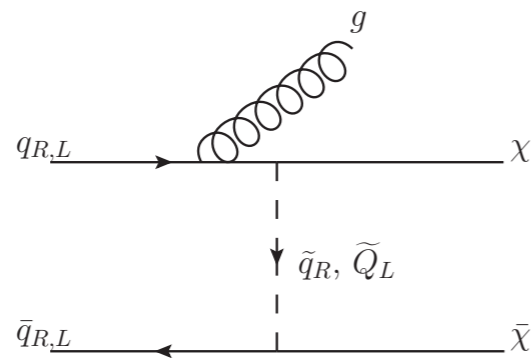
$$\frac{1}{\Lambda_i^2} \bar{q} \Gamma_i q \bar{\chi} \Gamma_i \chi \rightarrow \frac{g_q g_\chi}{m_\phi^2 - s} \bar{q} \Gamma_i q \bar{\chi} \Gamma_i \chi$$

- 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
- In general we need two propagators, not one propagator, because there are two chiral fermions in 4-dim spacetime

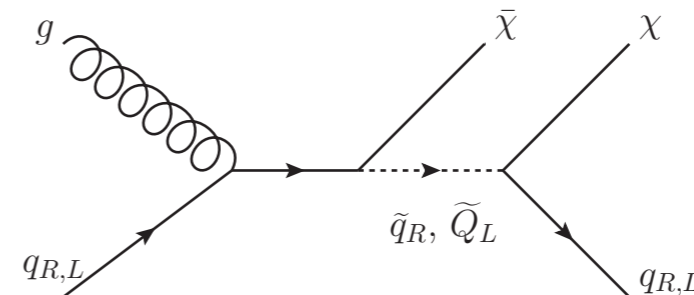
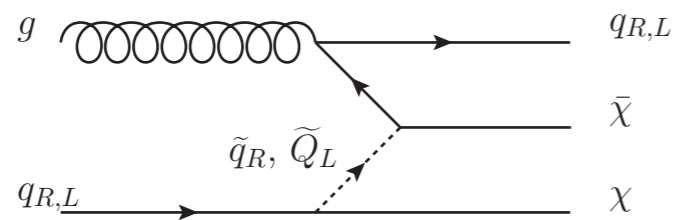
arXiv:1605.07058 (with A. Natale, M. Park, H. Yokoya)

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 singatures
- 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

DD vs. Monojet : Why complementarity breaks down in EFT ?

with S. Baek, Myeonghun Park,
W.I.Park, Chaehyun Yu

arXiv:1506.06556

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

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

OK

$$h \bar{\chi} \chi,$$

$$s \bar{q} q$$

Not OK

Both break SM gauge invariance !

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

Need the mixing between s and h

Higgs portal DM as examples

All invariant
under ad hoc
Z2 symmetry

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

$$\mathcal{L}_{\text{fermion}} = \bar{\psi} [i\gamma \cdot \partial - m_\psi] \psi - \frac{\lambda_{H\psi}}{\Lambda} H^\dagger H \bar{\psi} \psi$$

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

arXiv:1112.3299, 1205.3169, 1402.6287, to name a few

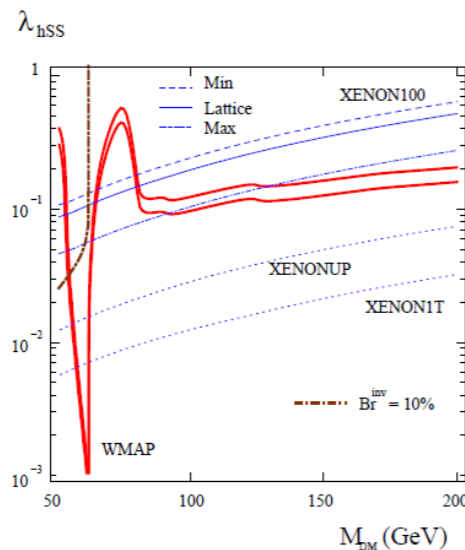


FIG. 1. Scalar Higgs-portal parameter space allowed by WMAP (between the solid red curves), XENON100 and $\text{BR}^{\text{inv}} = 10\%$ for $m_h = 125$ GeV. Shown also are the prospects for XENON upgrades.

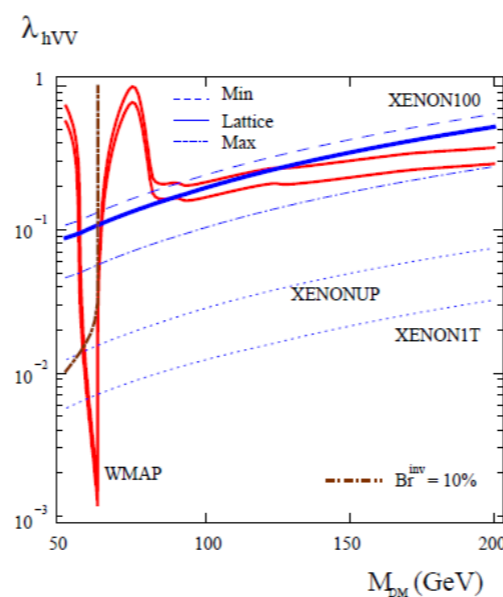


FIG. 2. Same as Fig. 1 for vector DM particles.

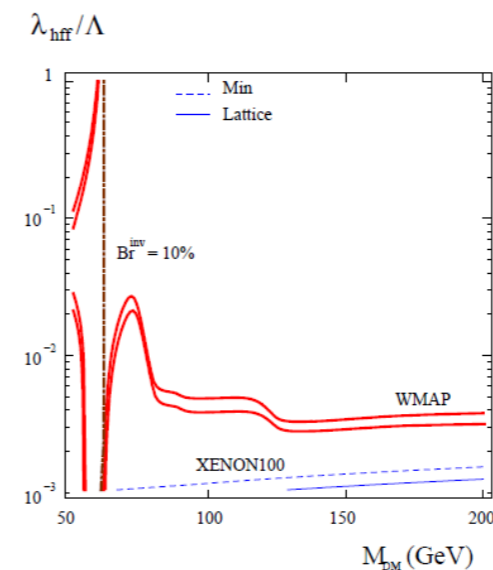


FIG. 3. Same as in Fig.1 for fermion DM; λ_{hff}/Λ is in GeV^{-1} .

Higgs portal DM as examples

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

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- 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

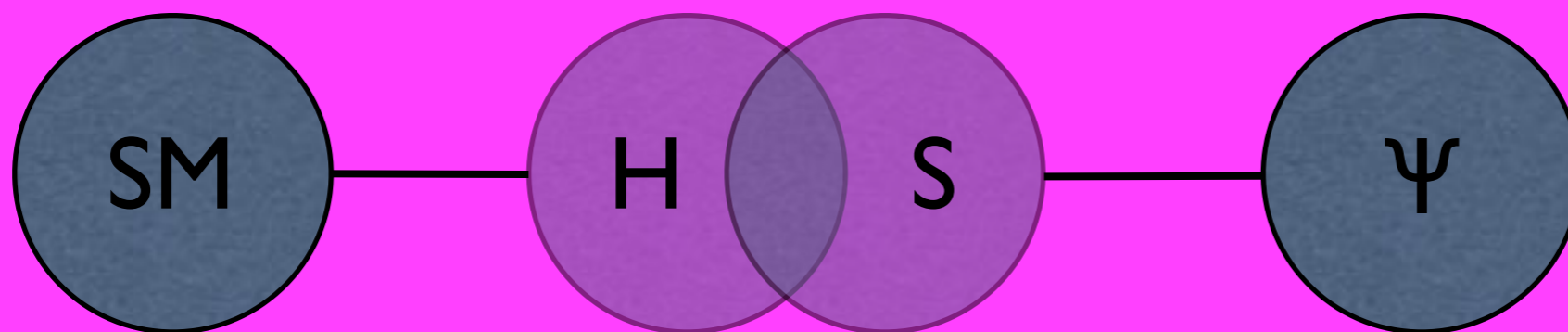
Singlet fermion CDM

Baek, Ko, Park, arXiv:1112.1847

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

→ 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

$$\mu_H^2 = \lambda_H v_H^2 + \mu_{HS} v_S + \frac{1}{2} \lambda_{HS} v_S^2,$$

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

at vacuum

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

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

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



Mixing of Higgs and singlet

Ratiocination

- Signal strength (reduction factor)

$$r_i = \frac{\sigma_i \text{Br}(H_i \rightarrow \text{SM})}{\sigma_h \text{Br}(h \rightarrow \text{SM})}$$

$$r_1 = \frac{\cos^4 \alpha \Gamma_{H_1}^{\text{SM}}}{\cos^2 \alpha \Gamma_{H_1}^{\text{SM}} + \sin^2 \alpha \Gamma_{H_1}^{\text{hid}}}$$

$$r_2 = \frac{\sin^4 \alpha \Gamma_{H_2}^{\text{SM}}}{\sin^2 \alpha \Gamma_{H_2}^{\text{SM}} + \cos^2 \alpha \Gamma_{H_2}^{\text{hid}} + \Gamma_{ll_2 \rightarrow ll_1 ll_1}}$$

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

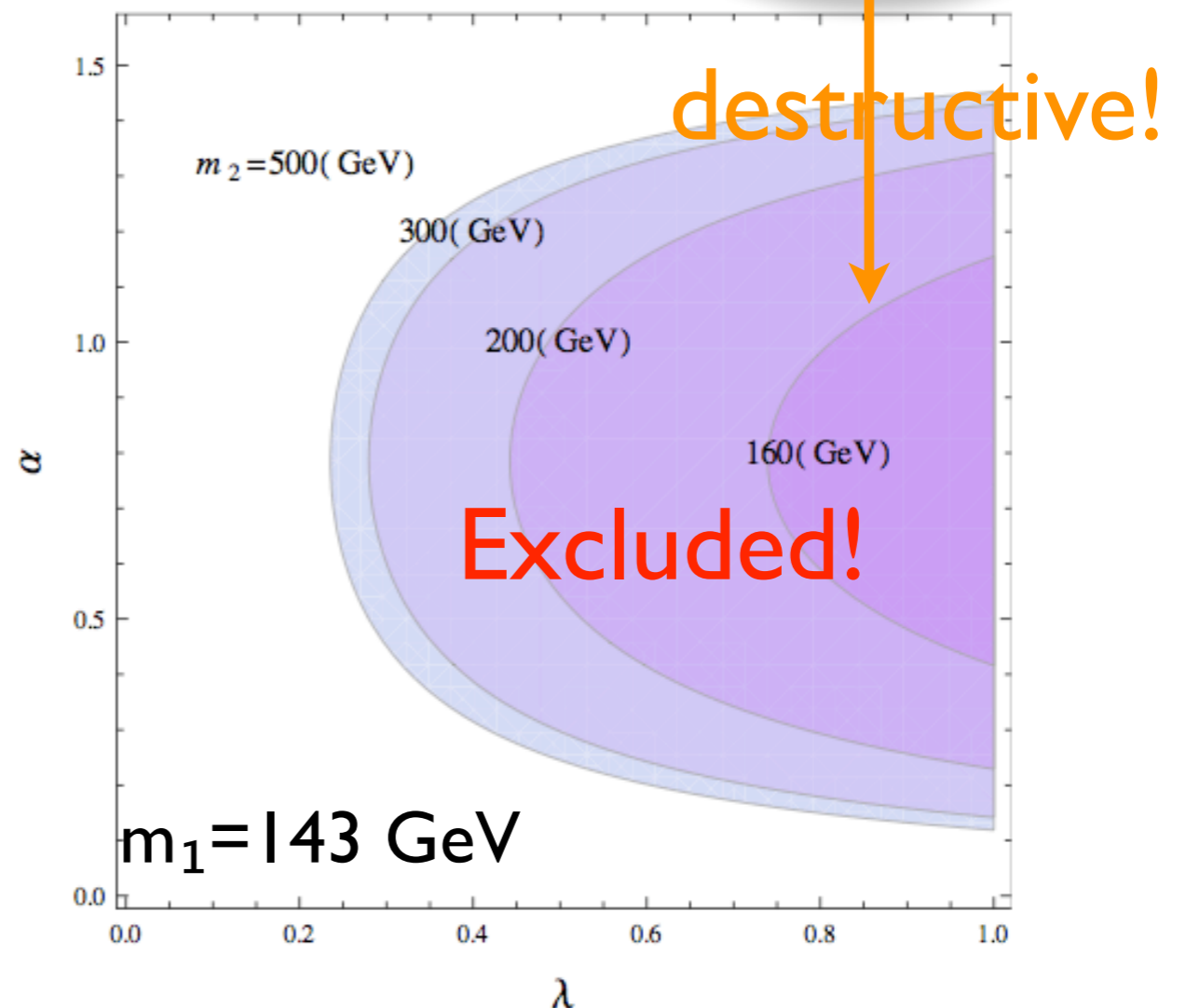
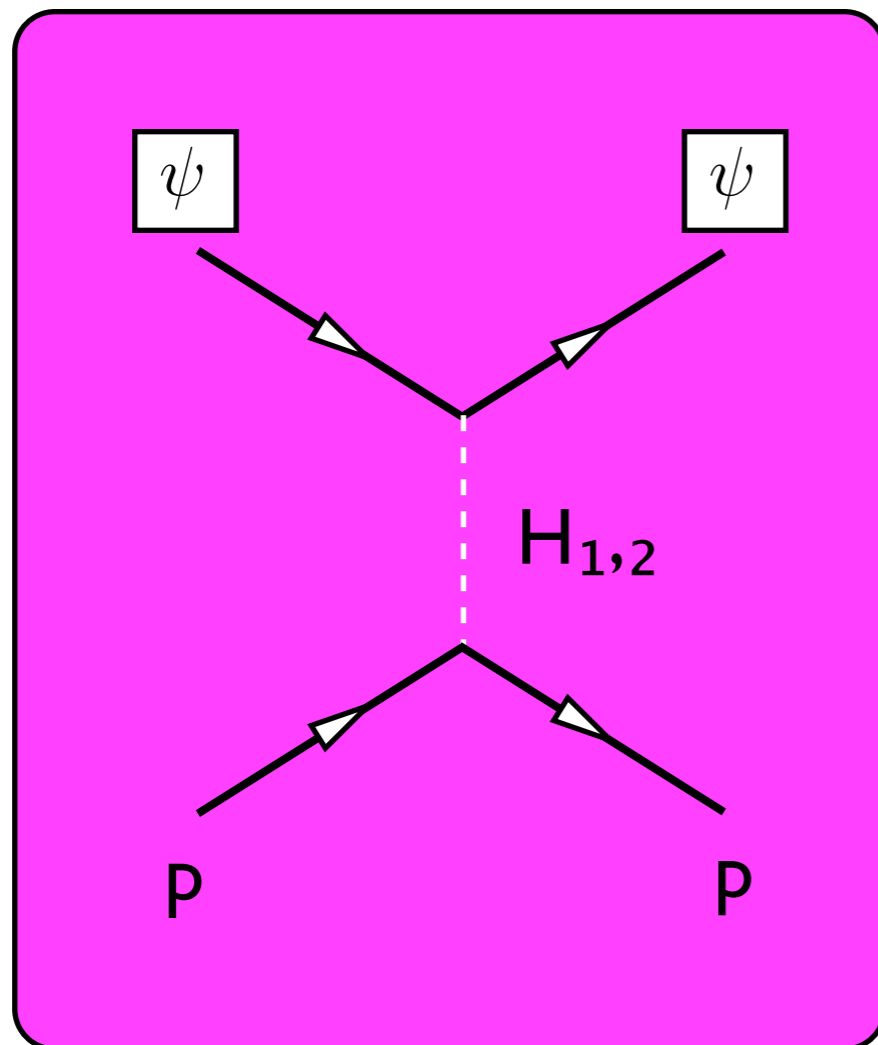
Invisible decay mode is not necessary!

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

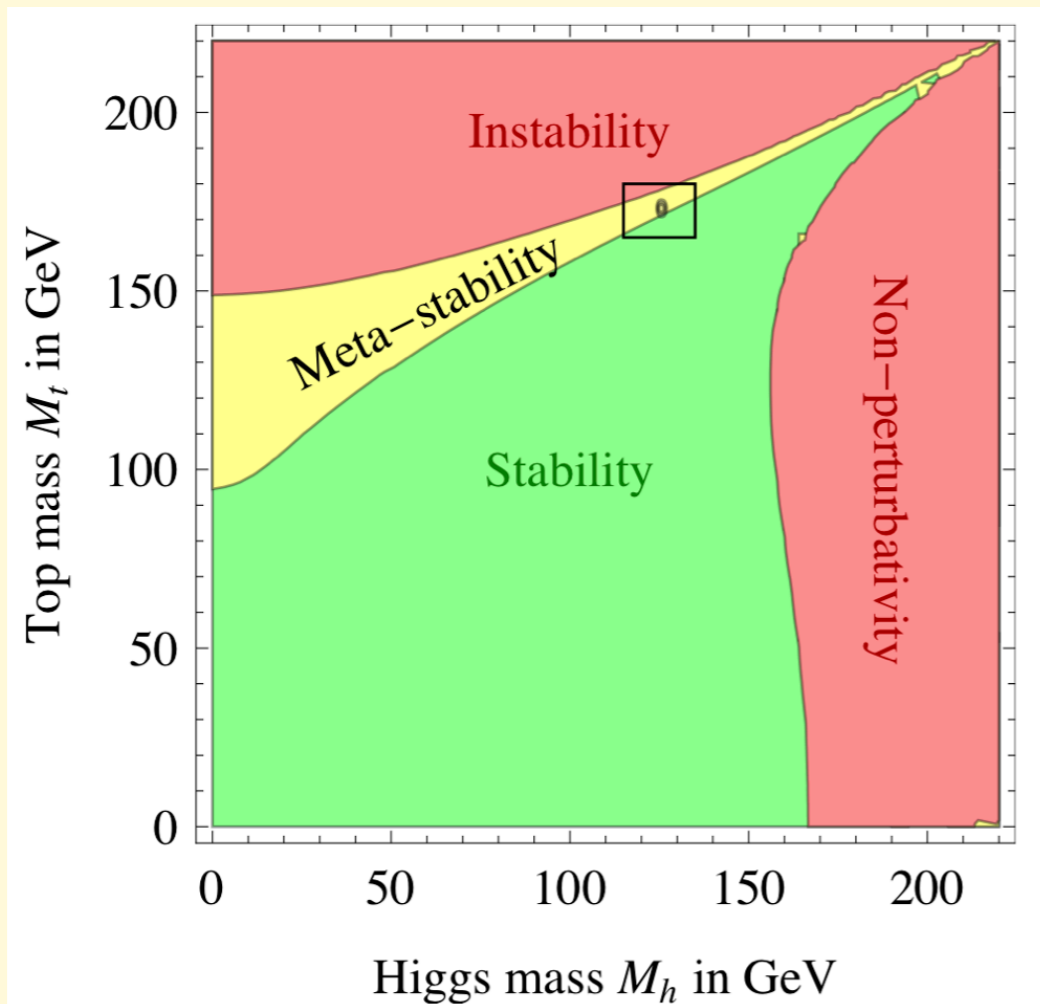
Constraints

- Dark matter to nucleon cross section (constraint)

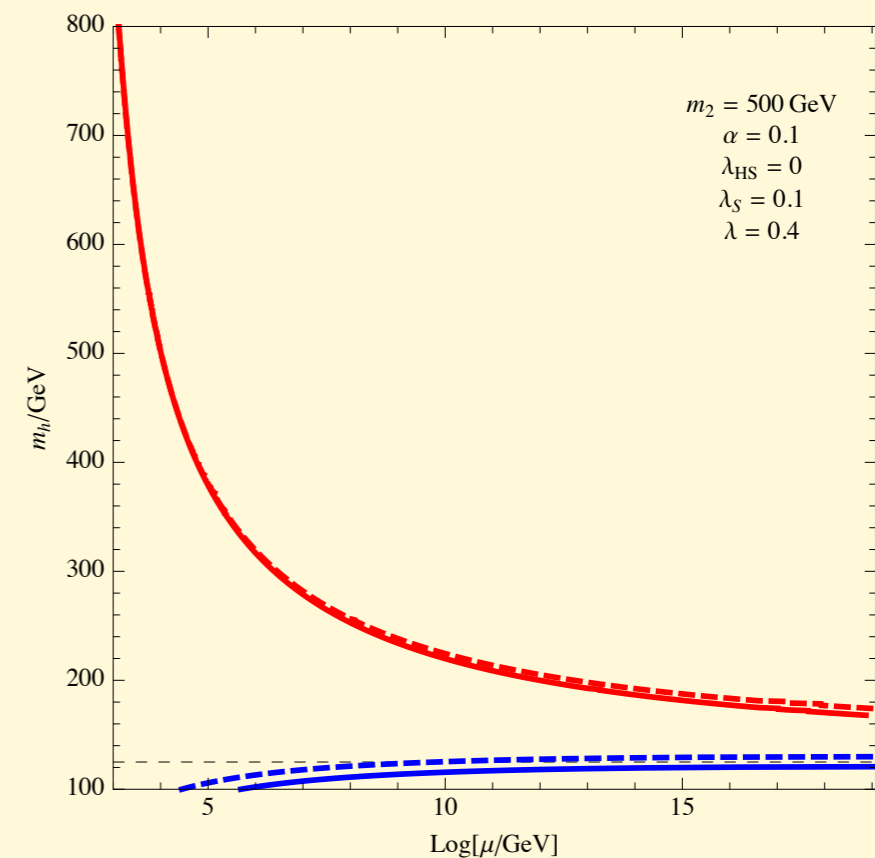
$$\sigma_p \approx \frac{1}{\pi} \mu^2 \lambda_p^2 \simeq 2.7 \times 10^{-2} \frac{m_p^2}{\pi} \left| \left(\frac{m_p}{v} \right) \lambda \sin \alpha \cos \alpha \left(\frac{1}{m_1^2} - \frac{1}{m_2^2} \right) \right|^2$$



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
- Stueckelberg mechanism ?? (work in progress)
- A complete model should be something like this:

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

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

- There appear a new singlet scalar h_X from ϕ_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
- Important to consider a minimal renormalizable model to discuss physics correctly
- Baek, Ko, Park and Senaha, arXiv:1212.2131 (JHEP)

New scalar improves EW vacuum stability

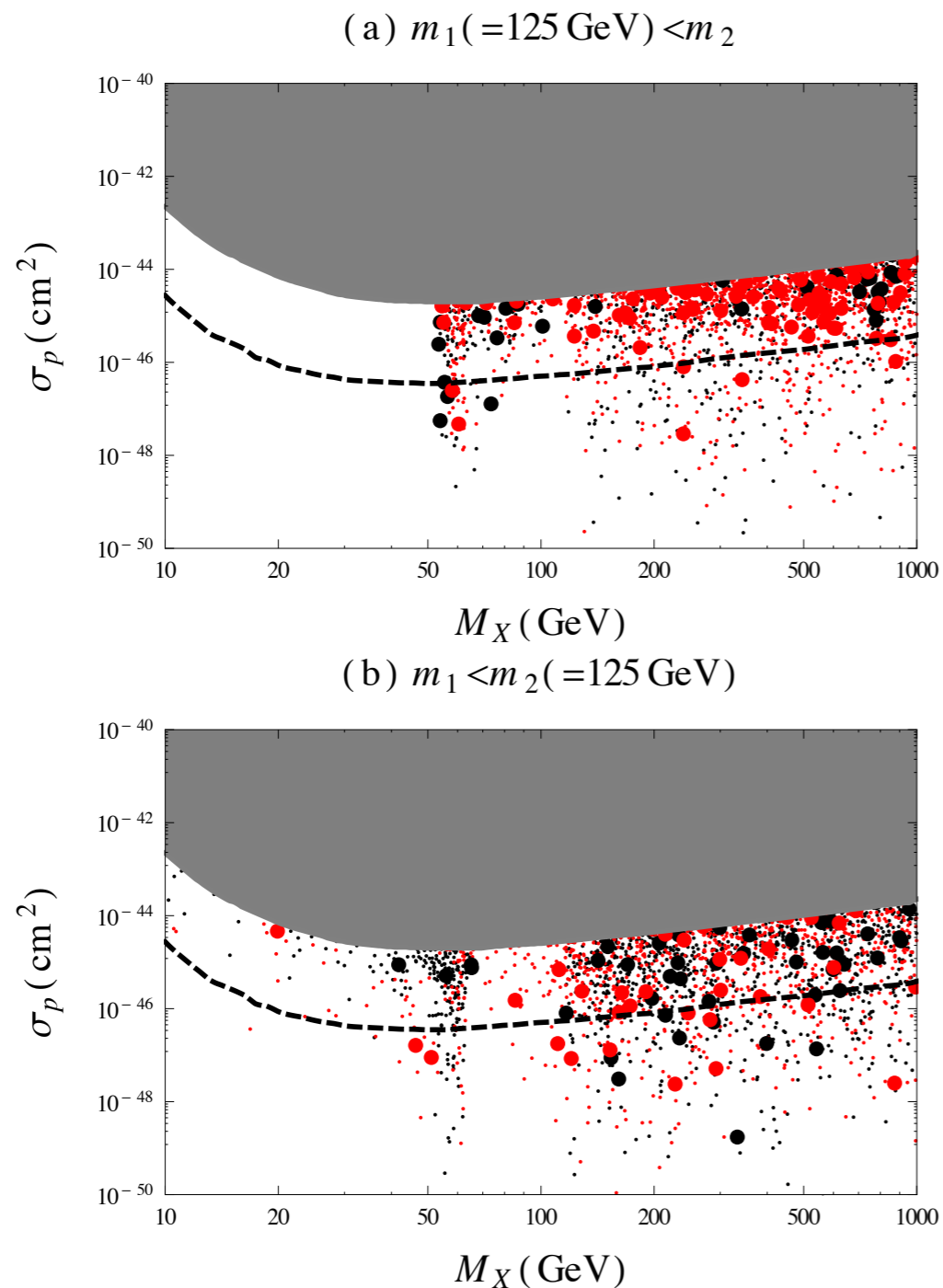


Figure 6. The scattered plot of σ_p as a function of M_X . The big (small) points (do not) satisfy the WMAP relic density constraint within 3σ , while the red-(black-)colored points gives $r_1 > 0.7$ ($r_1 < 0.7$). The grey region is excluded by the XENON100 experiment. The dashed line denotes the sensitivity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

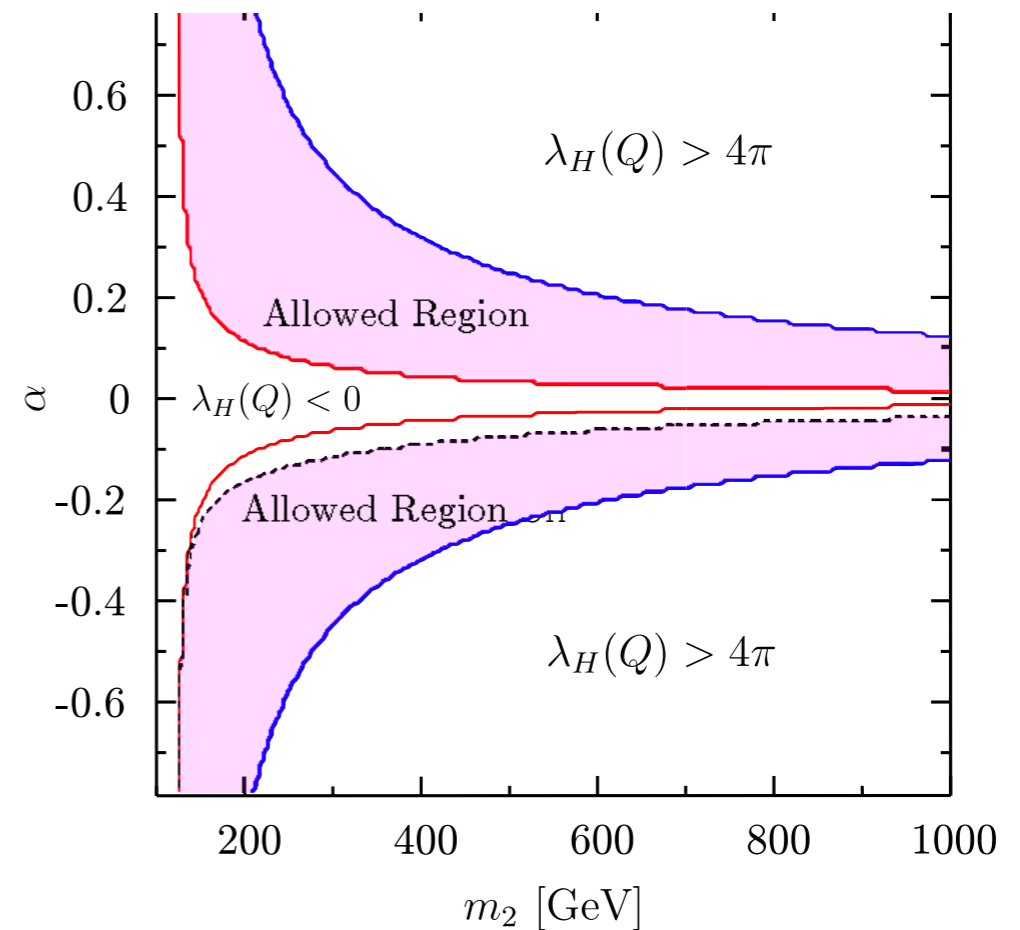


Figure 8. The vacuum stability and perturbativity constraints in the α - m_2 plane. We take $m_1 = 125 \text{ GeV}$, $g_X = 0.05$, $M_X = m_2/2$ and $v_\Phi = M_X/(g_X Q_\Phi)$.

Comparison with the EFT approach

- SFDM scenario is ruled out in the EFT
- We may lose information in DM pheno.

arXiv:1112.3299, 1205.3169, 1402.6287, to name a few

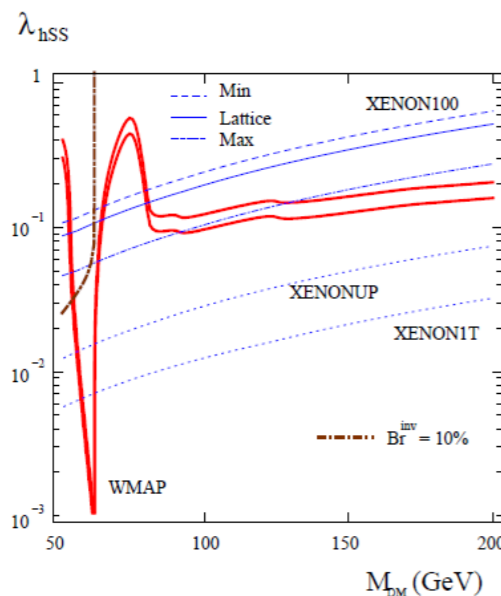


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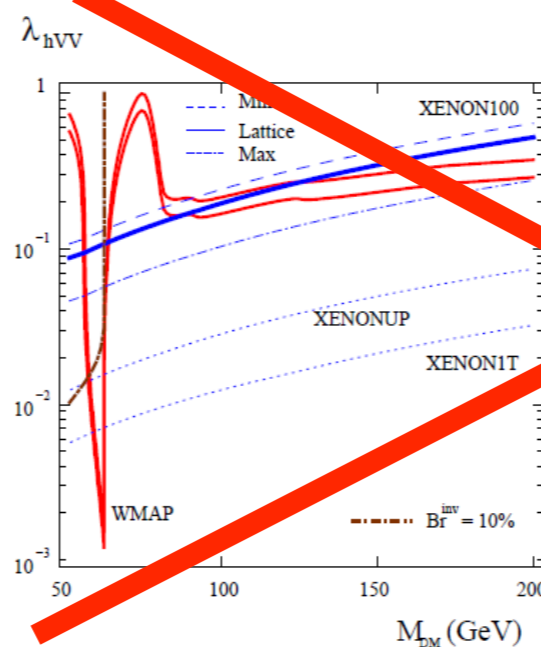


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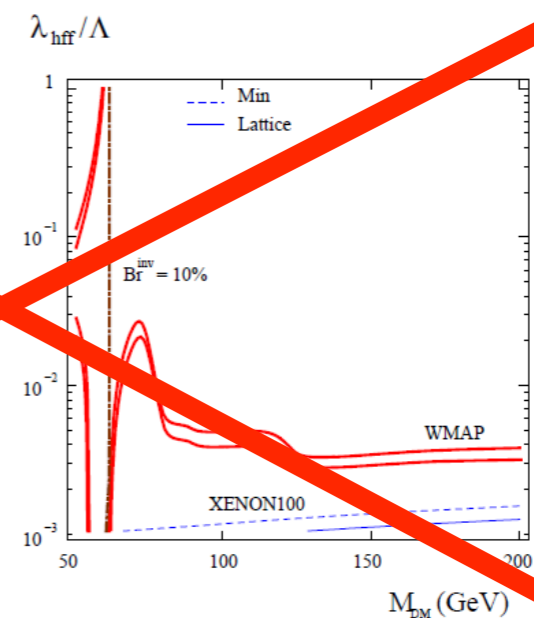


FIG. 3. Same as in Fig.1 for fermion DM; λ_{hff}/Λ is in GeV^{-1} .

With renormalizable lagrangian,
we get different results !

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

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

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

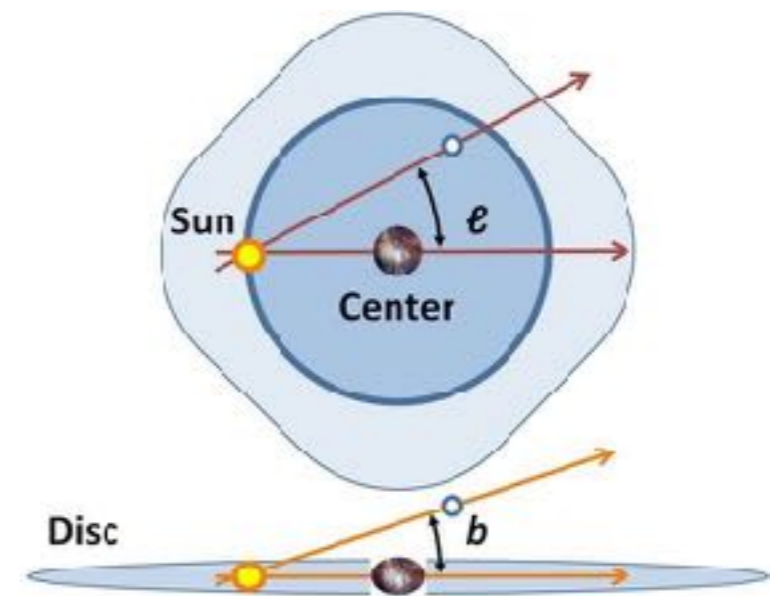
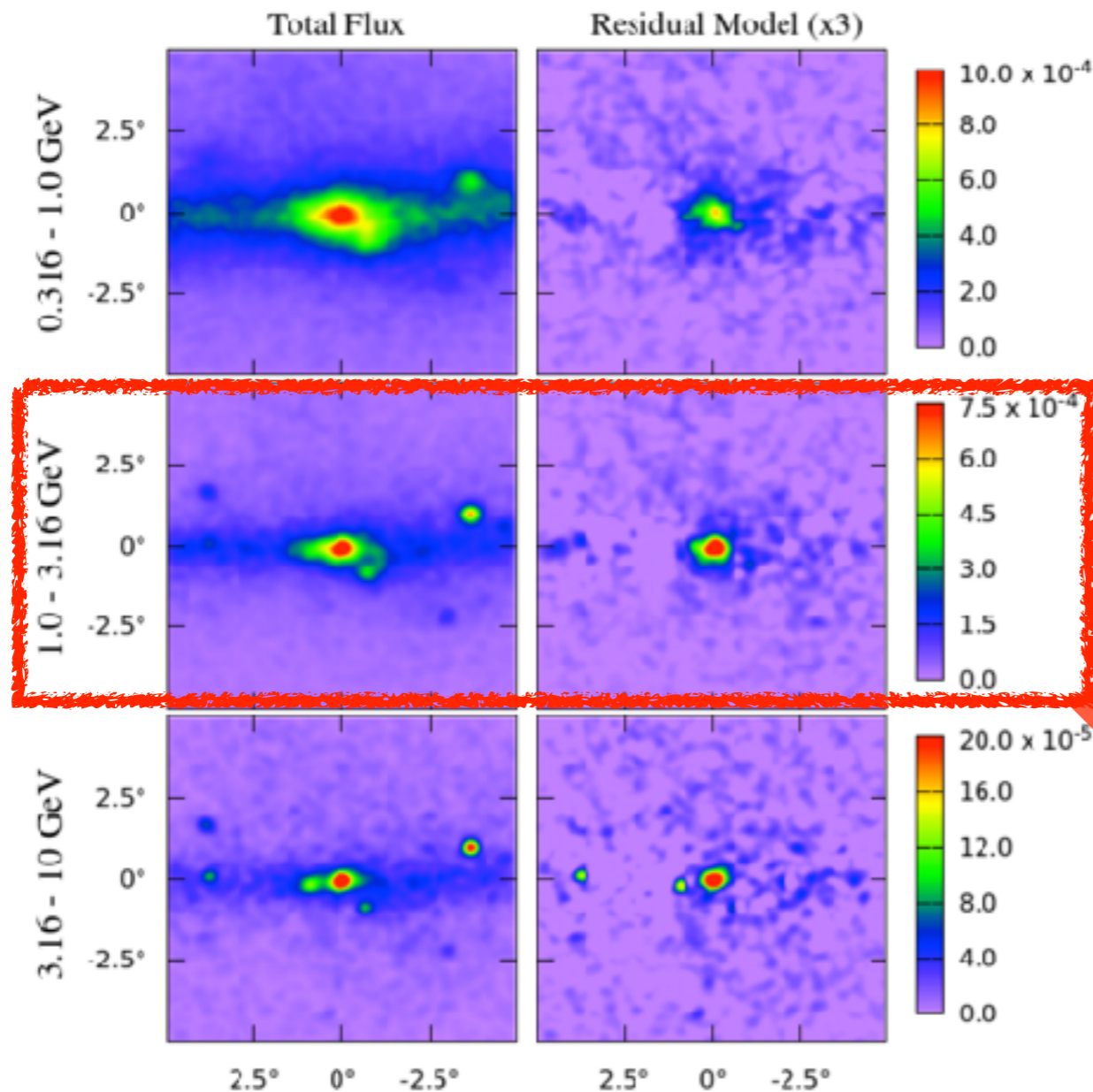
Is this any useful in
phenomenology ?

Is this any useful in
phenomenology ?

YES !

Fermi-LAT γ -ray excess

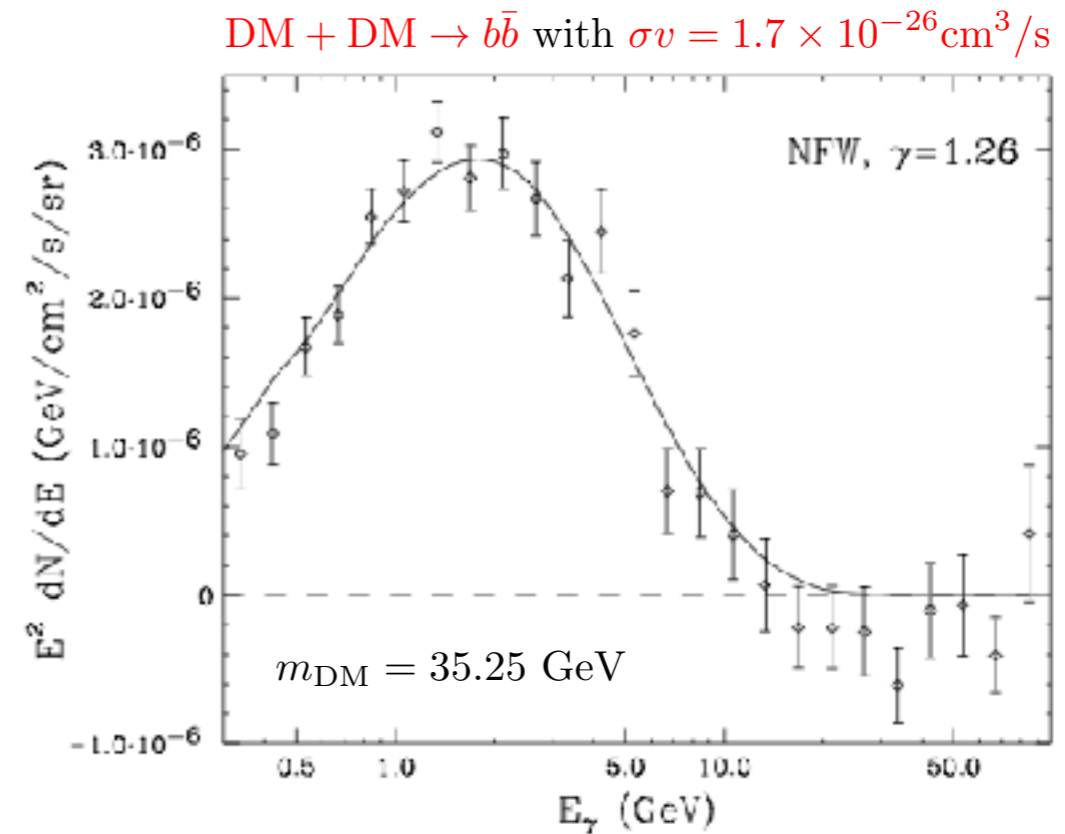
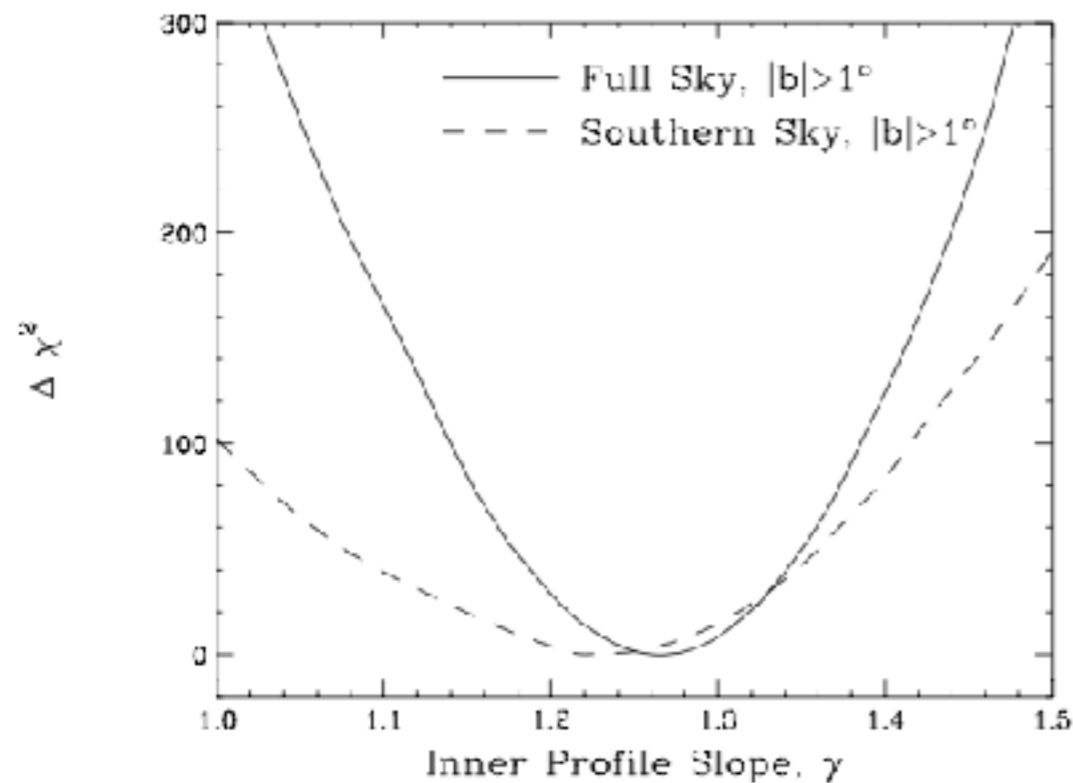
- Gamma-ray excess in the direction of GC



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

extended
GeV scale excess!

● A DM interpretation



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

● Millisecond Pulsars (astrophysical alternative)

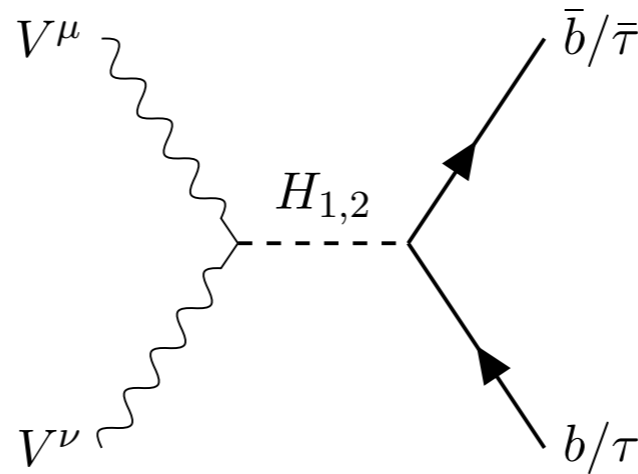
It may or may not be the main source, depending on

- 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

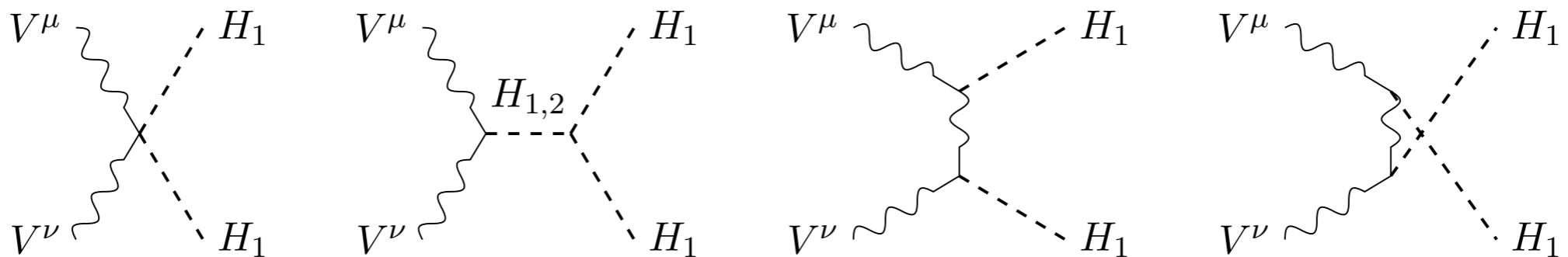


Figure 3. Dominant s/t -channel production of H_1 s that decay dominantly to $b + \bar{b}$

Importance of VDM with Dark Higgs Boson

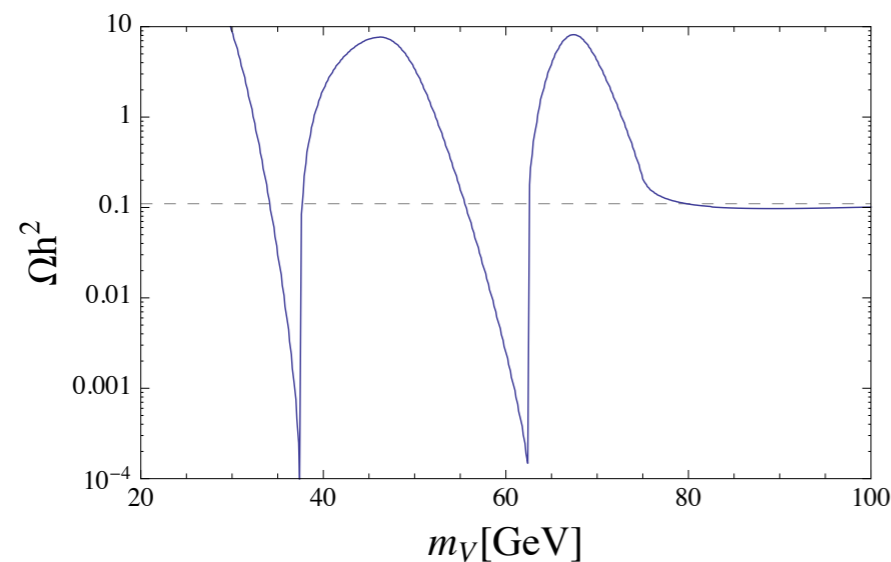


Figure 4. Relic density of dark matter as function of m_ψ for $m_h = 125$, $m_\phi = 75$ GeV, $g_X = 0.2$, and $\alpha = 0.1$.

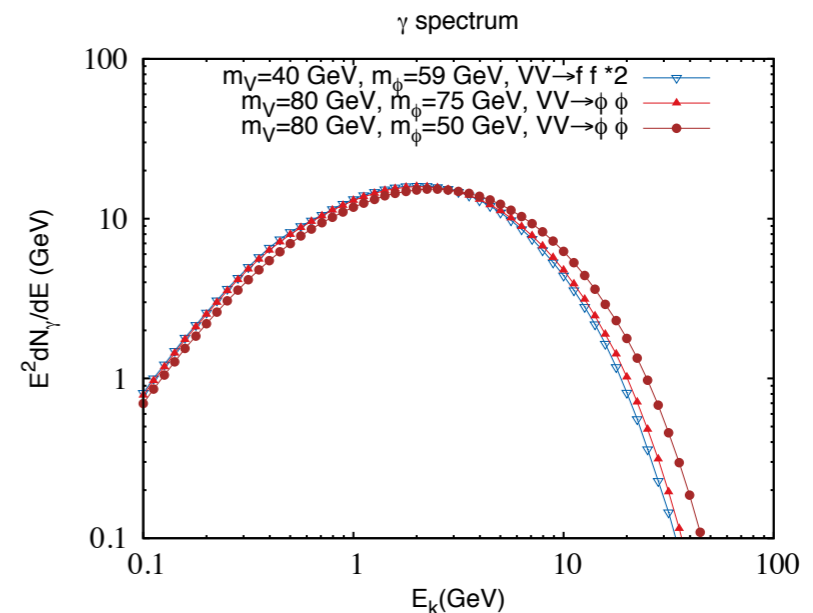
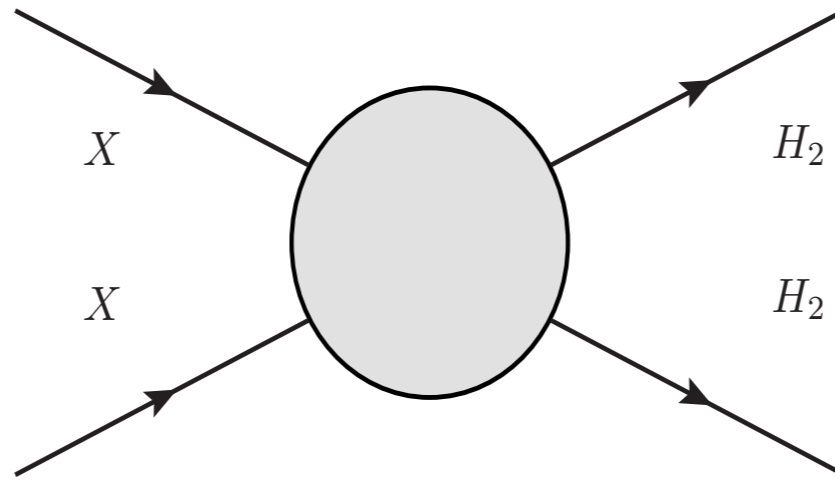


Figure 5. Illustration of γ spectra from different channels. The first two cases give almost the same spectra while in the third case γ is boosted so the spectrum is shifted to higher energy.

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

And there would be no second scalar in EFT



P.Ko, Yong Tang.
arXiv:1504.03908

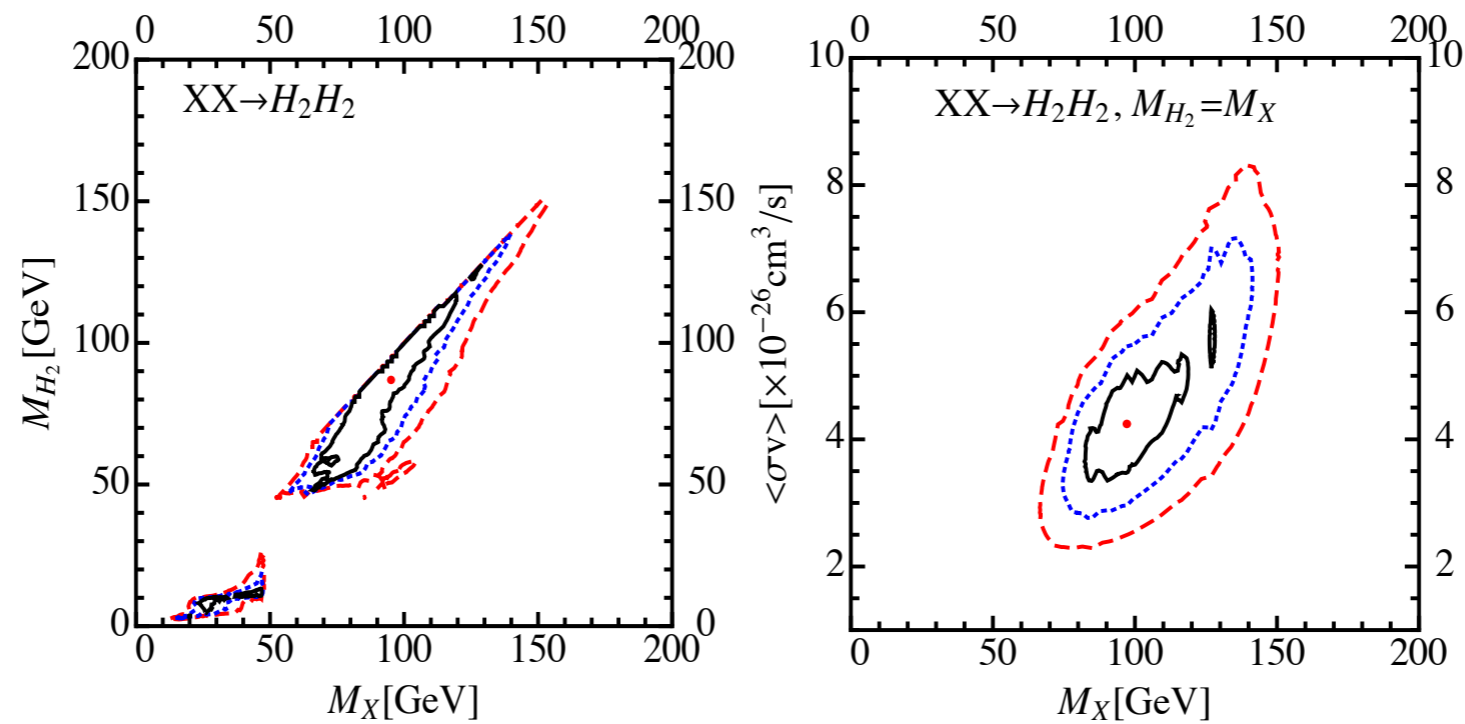


FIG. 3: The regions inside solid(black), dashed(blue) and long-dashed(red) contours correspond to 1σ , 2σ and 3σ , respectively. The red dots inside 1σ contours are the best-fit points. In the left panel, we vary freely M_X , M_{H_2} and $\langle\sigma v\rangle$. While in the right panel, we fix the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

This would have never been possible within the DM EFT

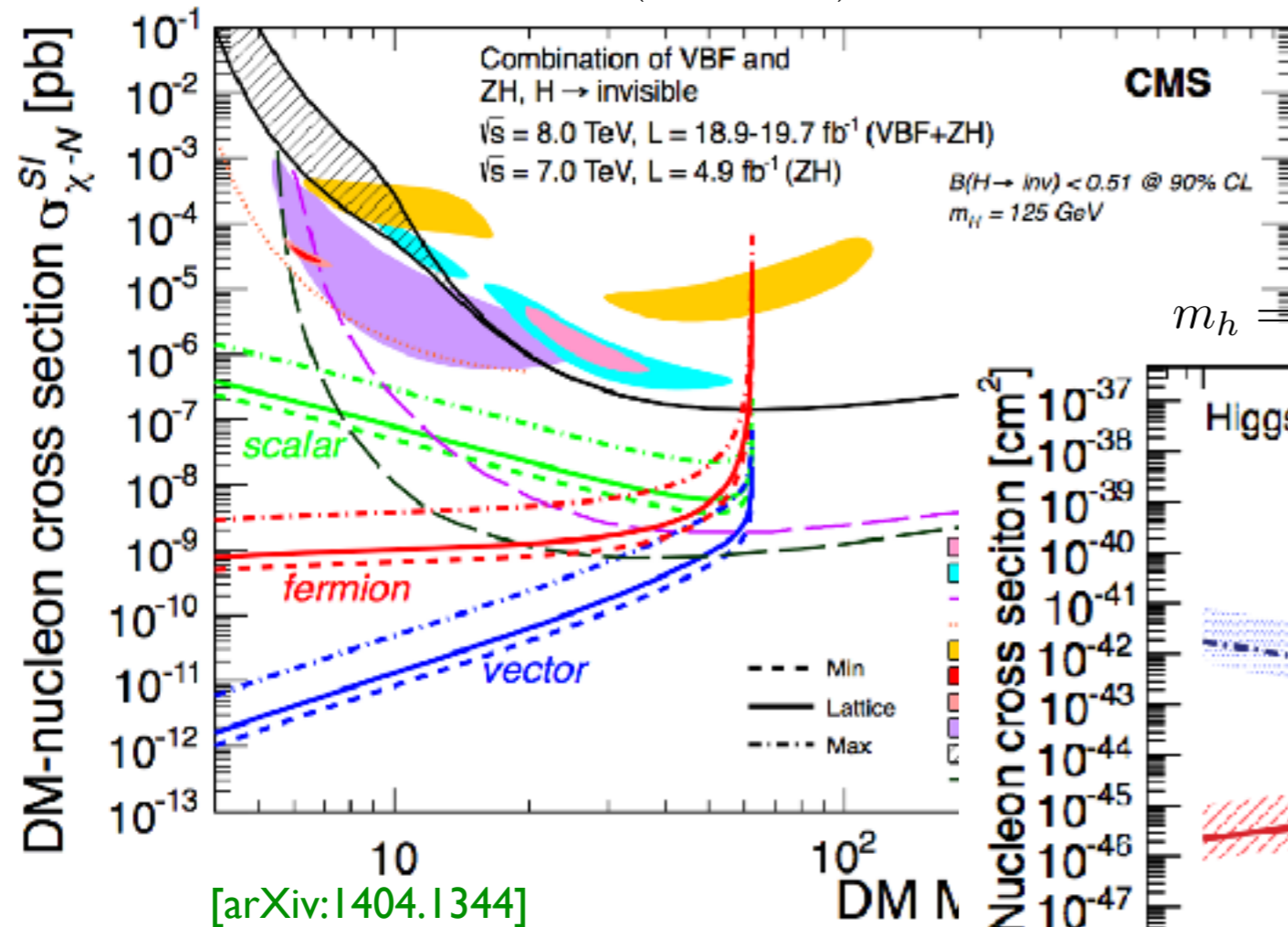
P.Ko, Yong Tang.
arXiv:1504.03908

Channels	Best-fit parameters	$\chi^2_{\min}/\text{d.o.f.}$	p -value
$XX \rightarrow H_2 H_2$ (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
$XX \rightarrow H_2 H_2$ (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
$XX \rightarrow H_1 H_1$ (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
$XX \rightarrow b\bar{b}$	$M_X \simeq 49.4\text{GeV}$ $\langle\sigma v\rangle \simeq 1.75 \times 10^{-26}\text{cm}^3/\text{s}$	24.4/22	0.34

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

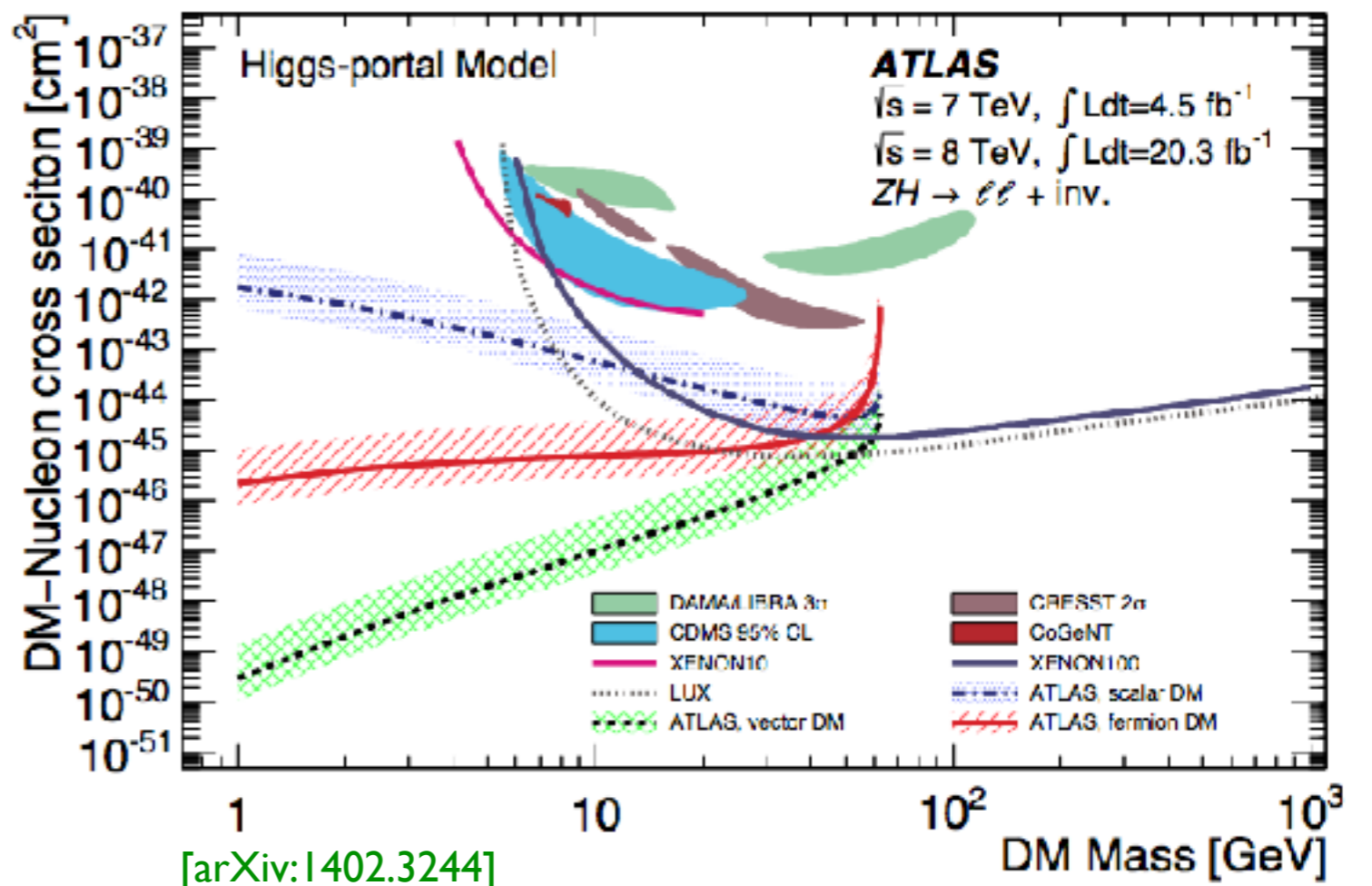
Collider Implications

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



Based on EFTs

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



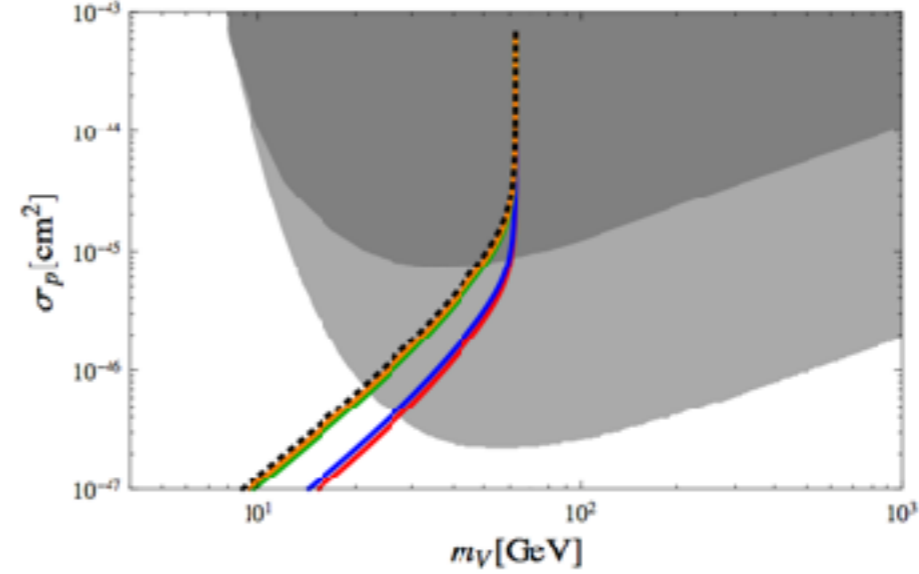
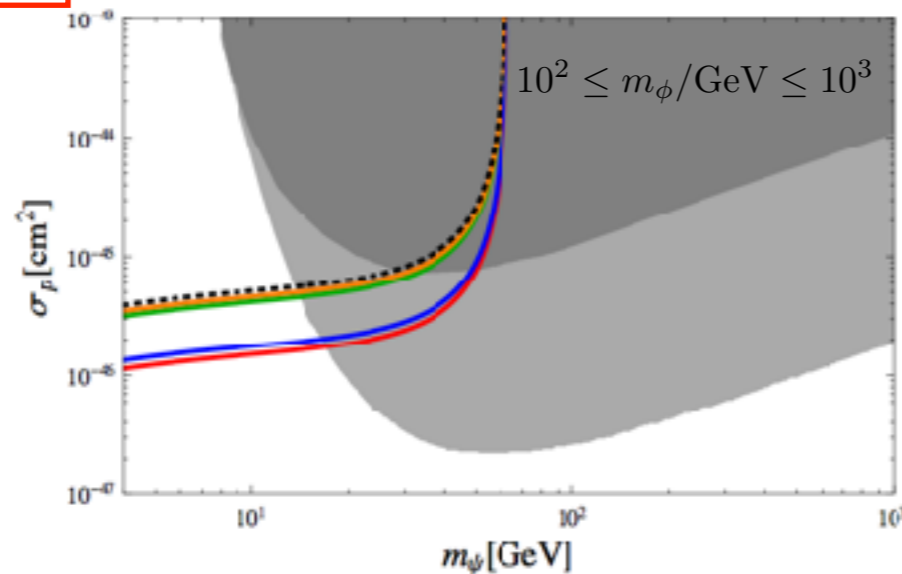
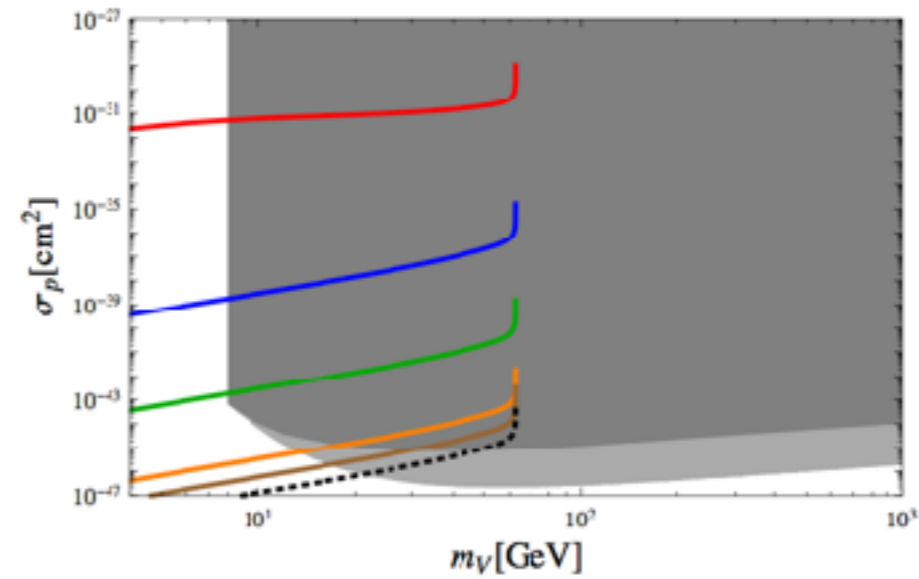
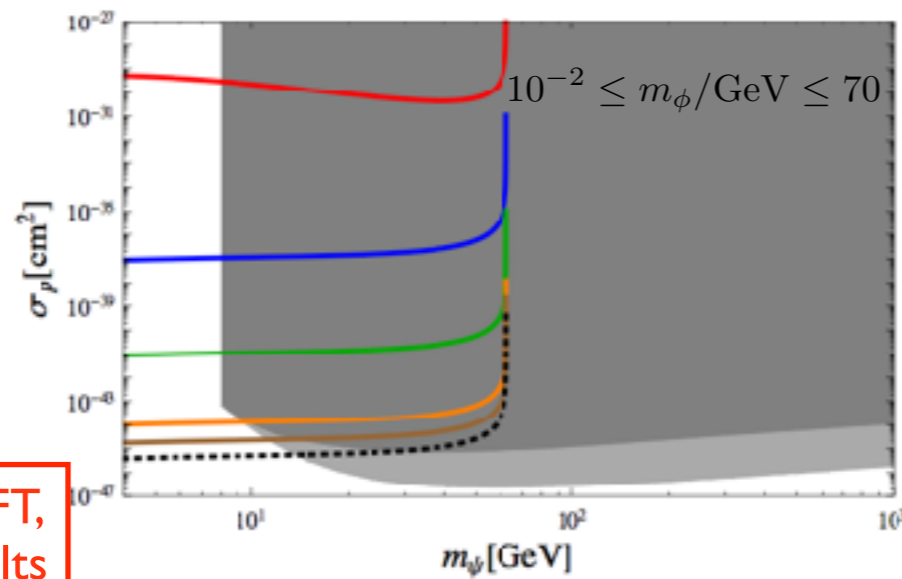
- However, in renormalizable unitary models of Higgs portals, **2 more relevant parameters**

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

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

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

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



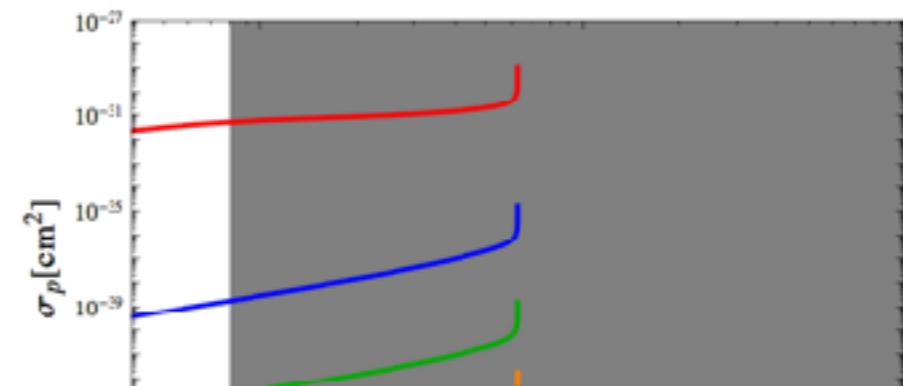
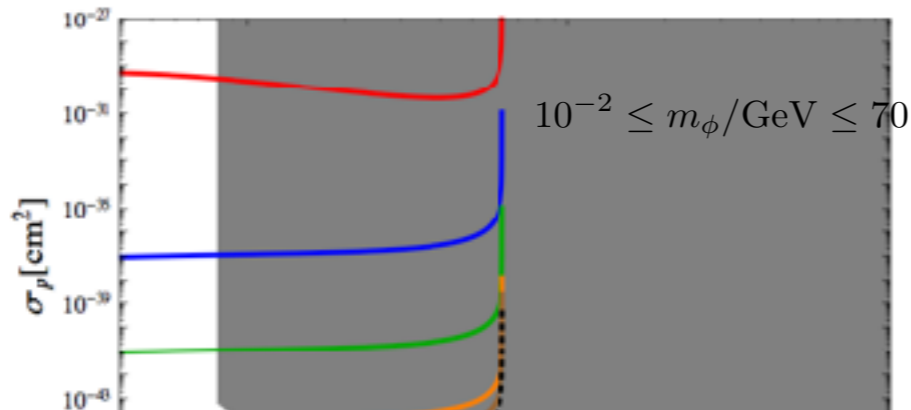
Dashed curves: EFT, ATLAS, CMS results

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

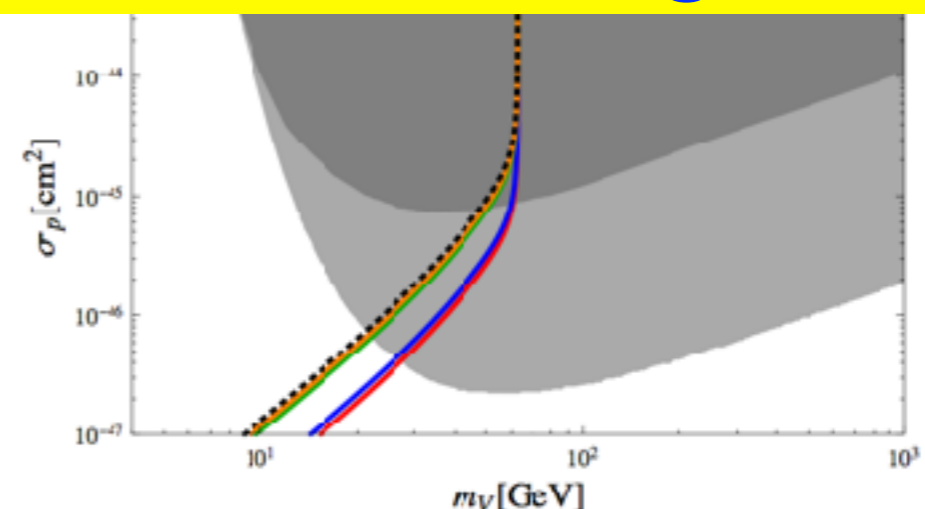
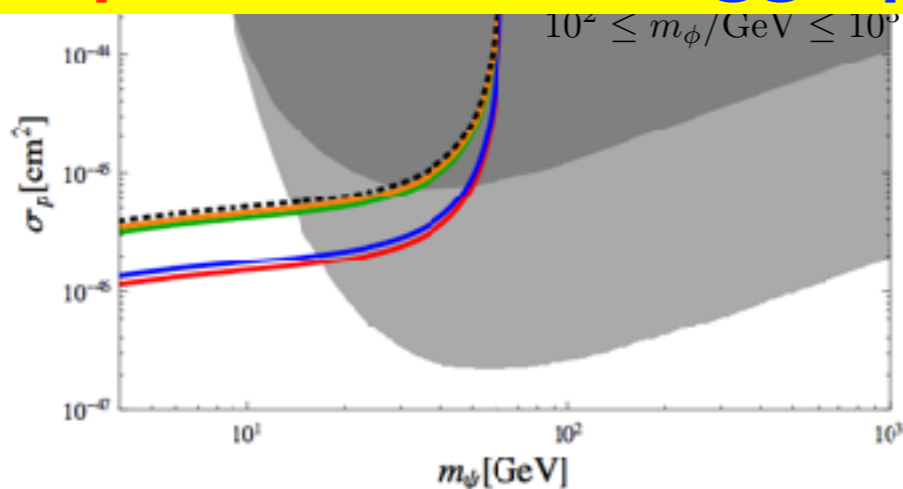
$$\mathcal{L}_{\text{SFDM}} = \bar{\psi}(i\partial - m_\psi - \lambda_\psi S) - \mu_{HS} S H^\dagger H - \frac{\lambda_{HS}}{2} S^2 H^\dagger H \\ + \frac{1}{2} \partial_\mu S \partial^\mu S - \frac{1}{2} m_S^2 S^2 - \mu'_S S - \frac{\mu'_S}{3} S^3 - \frac{\lambda_S}{4} S^4.$$

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

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



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]

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

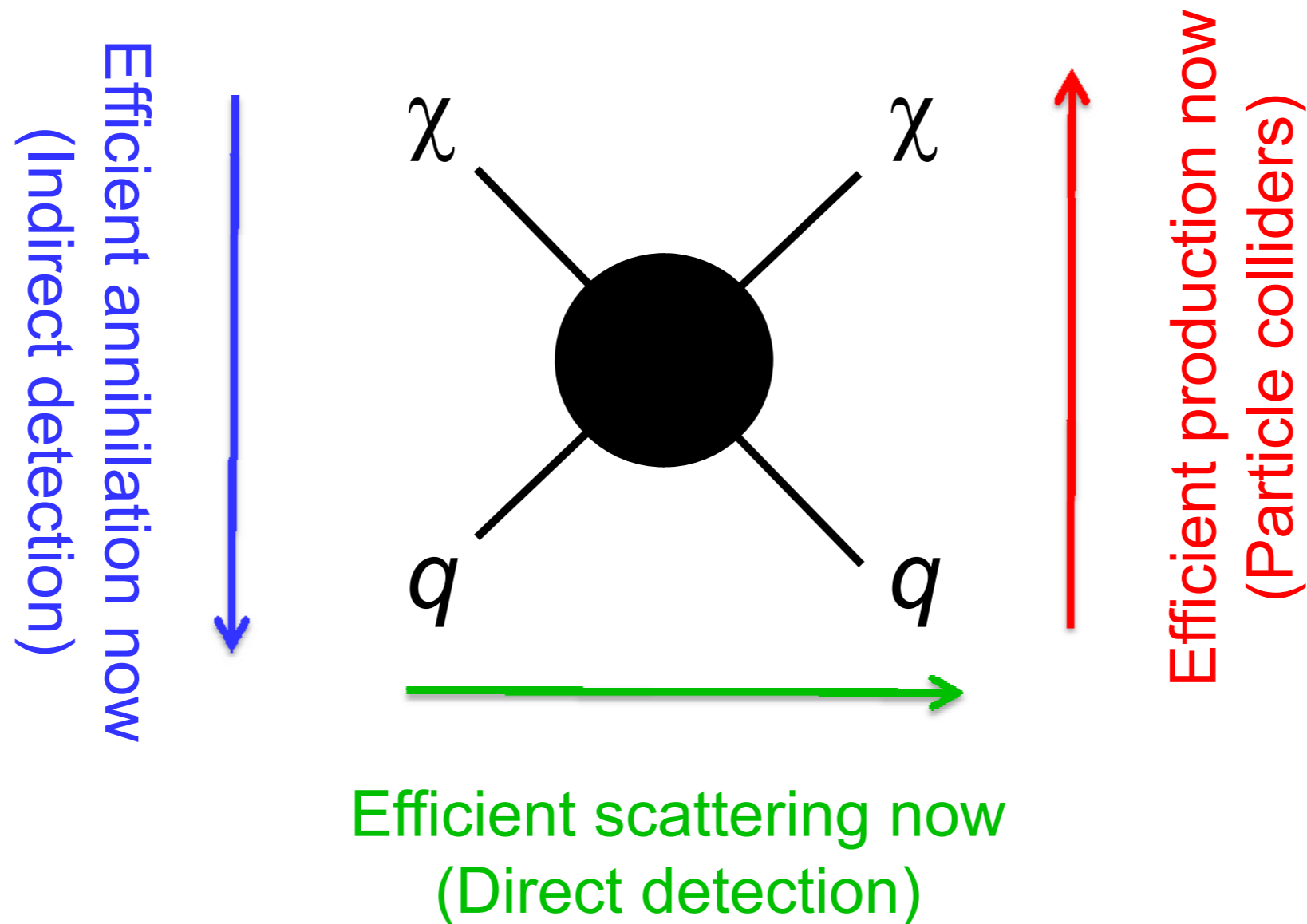
VS.

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

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

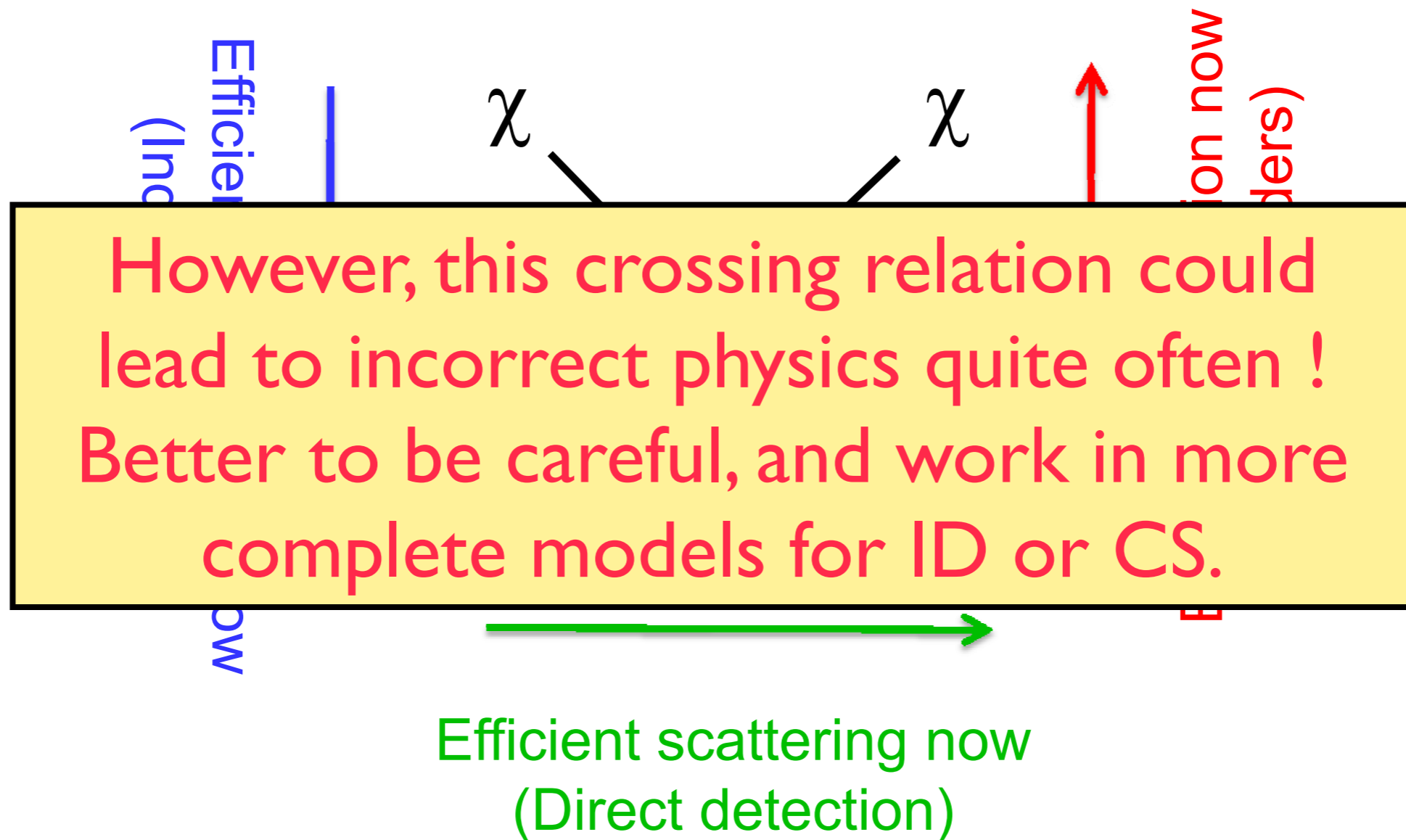
Crossing & WIMP detection

Correct relic density \rightarrow Efficient annihilation then



Crossing & WIMP detection

Correct relic density \rightarrow Efficient annihilation then



DD vs. Monojet : Why complementarity breaks down in EFT ?

Work in preparation with
S. Baek, Myeonghun Park,
W.I.Park, Chaehyun Yu

Now arXiv:1506.06556

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

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

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

Both break SM gauge invariance

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

Need the mixing between s and h

Full Theory Calculation

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

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

$$\Lambda_{dd}^3 \equiv \frac{2m_{125}^2 v}{\lambda_s \sin 2\alpha} \left(1 - \frac{m_{125}^2}{m_2^2} \right)^{-1}$$

$$\bar{\Lambda}_{dd}^3 \equiv \frac{2m_{125}^2 v}{\lambda_s \sin 2\alpha}$$

Monojet+missing ET

Can be obtained by crossing : $s \leftrightarrow t$

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

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

- 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).

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

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

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

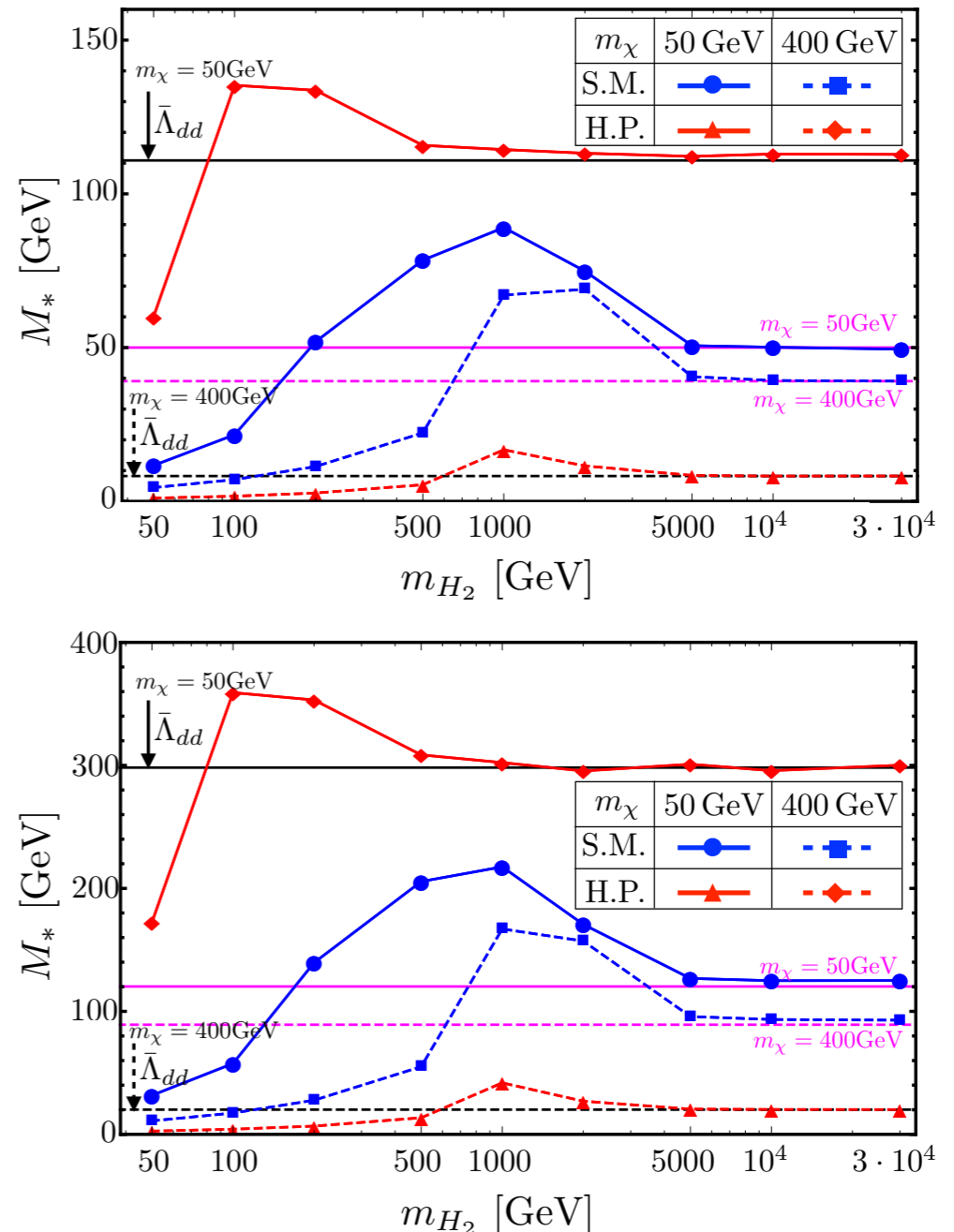


FIG. 3: The experimental bounds on M_* at 90% C.L. as a function of m_{H_2} (m_S in S.M. case) in the monojet+ \cancel{E}_T search (upper) and $t\bar{t}$ + \cancel{E}_T search (lower). Each line corresponds to the EFT approach (magenta), S.M. (blue), H.M. (black), and H.P. (red), respectively. The bound 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: $2m_\chi \ll m_{125} \ll m_2 \ll \sqrt{s}$

$$\begin{aligned}\sigma(\sqrt{s}) &= \int_0^1 d\tau \sum_{a,b} \frac{d\mathcal{L}_{ab}}{d\tau} \hat{\sigma}(\hat{s} \equiv \tau s) \\ &= \left[\int_{4m_\chi^2/s}^{m_{125}^2/s} d\tau + \int_{m_{125}^2/s}^{m_2^2/s} d\tau + \int_{m_2^2/s}^1 d\tau \right] \sum_{a,b} \frac{d\mathcal{L}_{ab}}{d\tau} \hat{\sigma}(\hat{s} \equiv \tau s)\end{aligned}$$

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

No single EFT applicable to the entire tau regions

Indirect Detection

$$\begin{aligned} \left| \frac{1}{\Lambda_{ann}^3} \right| &\simeq \frac{1}{\Lambda_{dd}^3} \left| \frac{m_{125}^2}{4m_\chi^2 - m_{125}^2 + im_{125}\Gamma_{125}} - \frac{m_{125}^2}{4m_\chi^2 - m_2^2 + im_2\Gamma_2} \right| \\ &\rightarrow \frac{1}{\Lambda_{dd}^3} \left| \frac{m_{125}^2}{4m_\chi^2 - m_{125}^2 + im_{125}\Gamma_{125}} \right| \neq \frac{1}{\Lambda_{dd}^3} \end{aligned}$$

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

Interference between 2 scalar mediators

1610.03997 with Jinmian Li

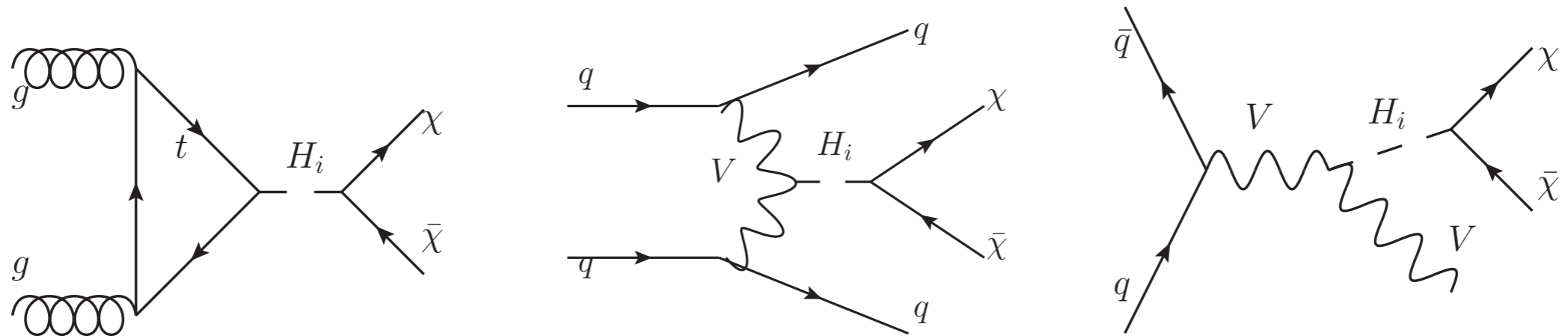


Figure 1: The dominant DM production processes at LHC.

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

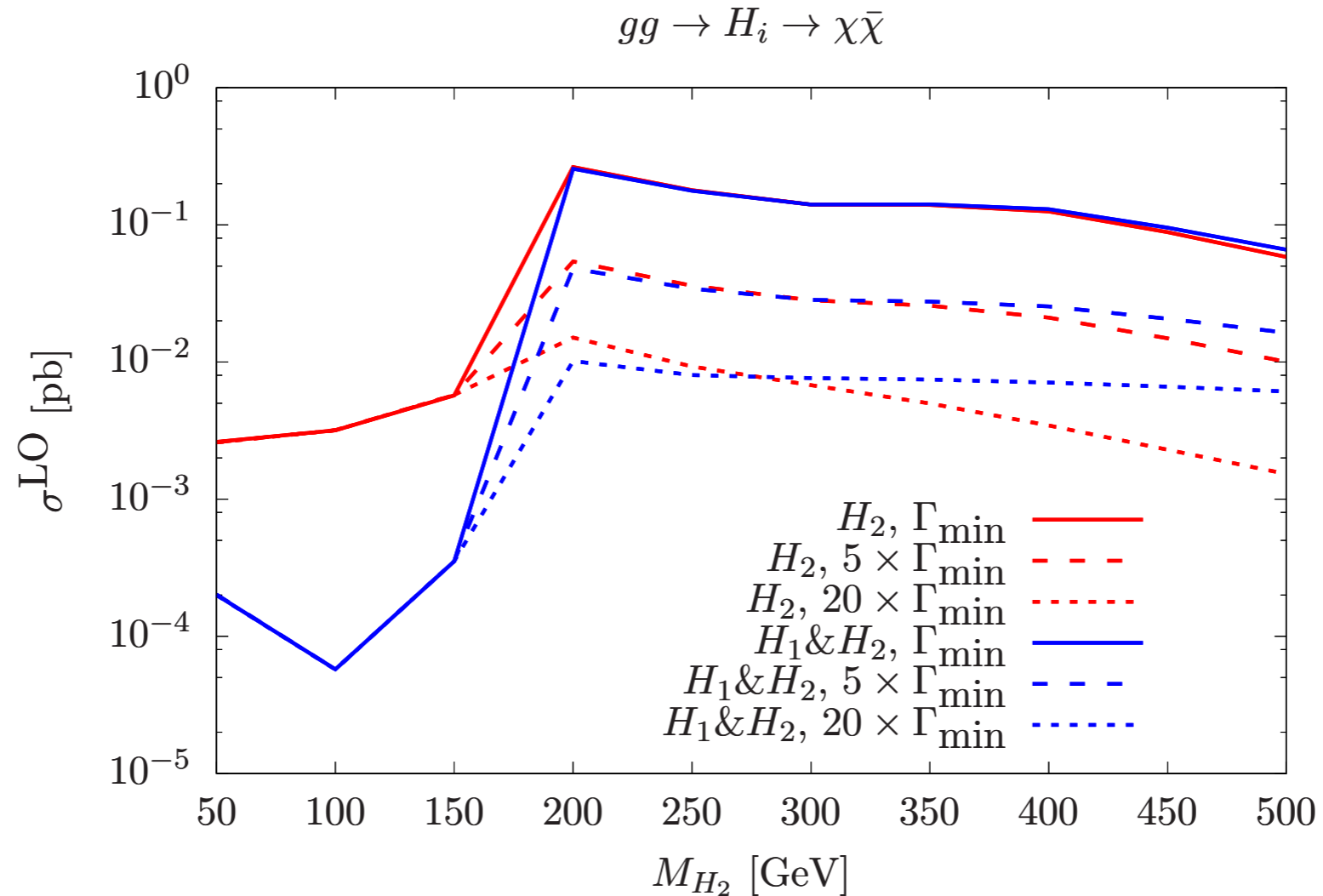


Figure 2: The LO cross section for gluon-gluon fusion process at 13 TeV LHC. The meanings of the different line types are explained in the text and the similar strategy will be used in all figures.

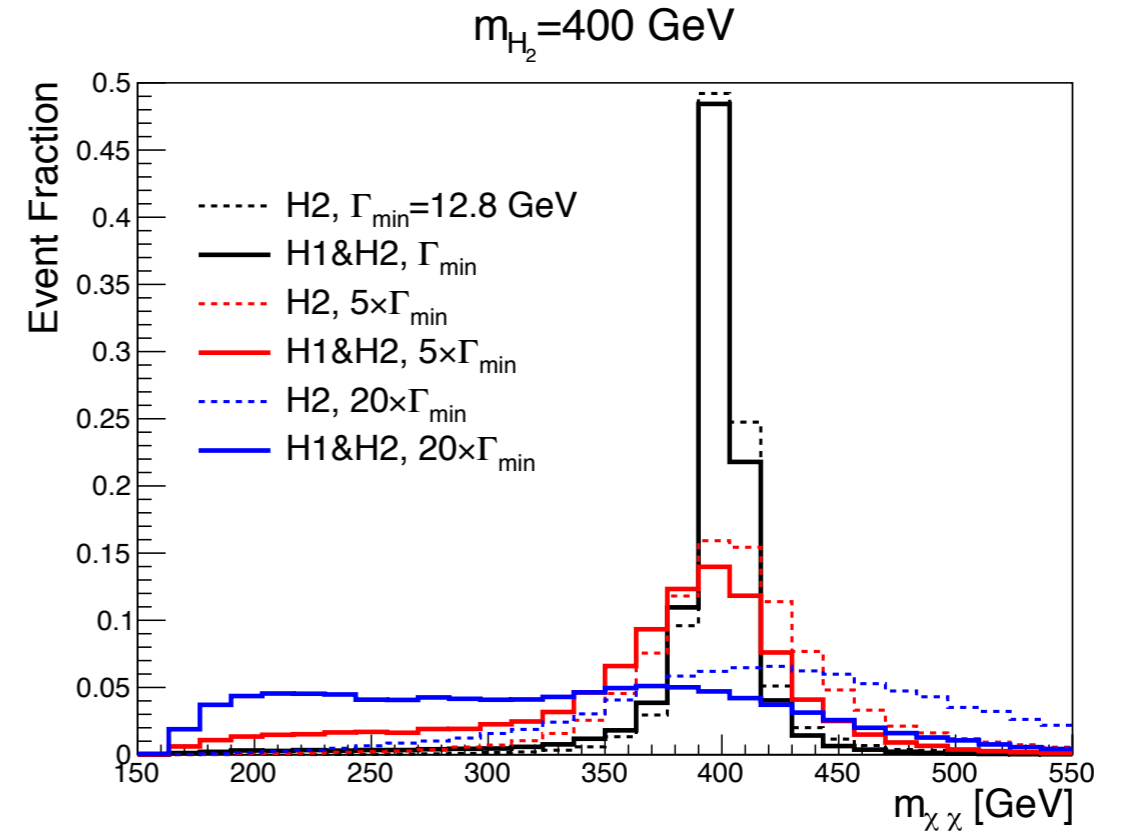
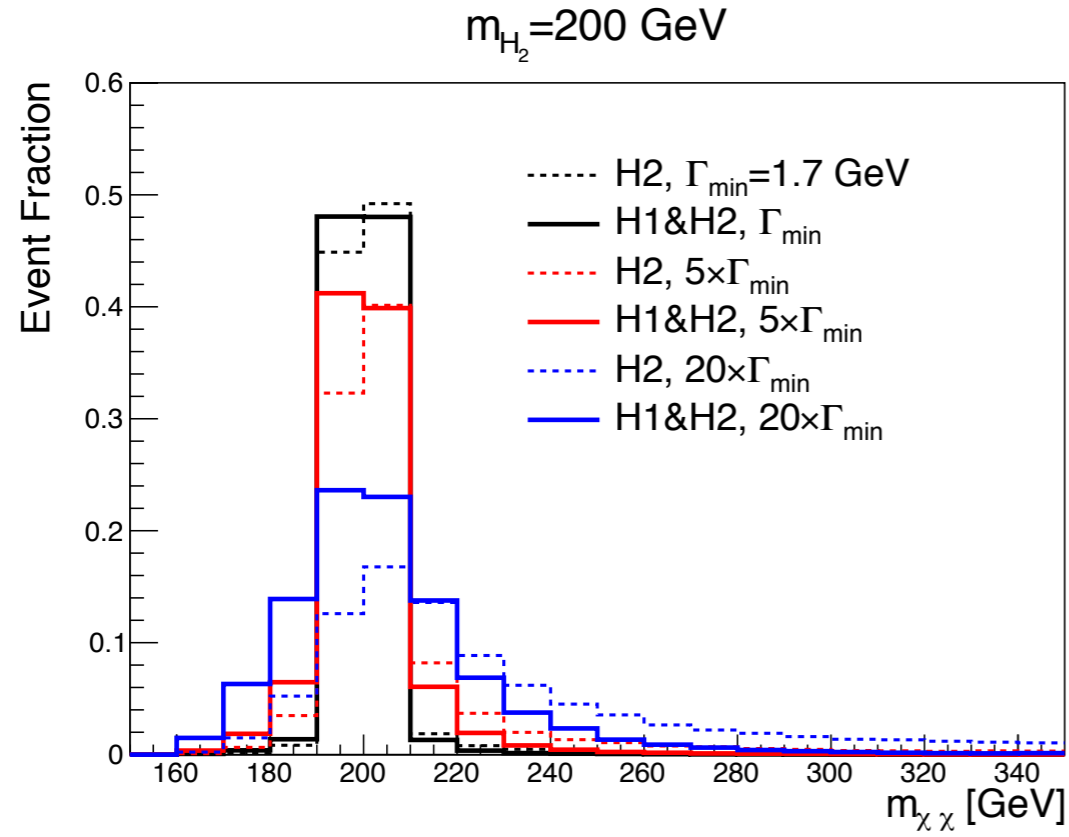


Figure 3: The parton level distributions of $m_{\chi\bar{\chi}}$ for gluon-gluon fusion process at 13 TeV LHC.

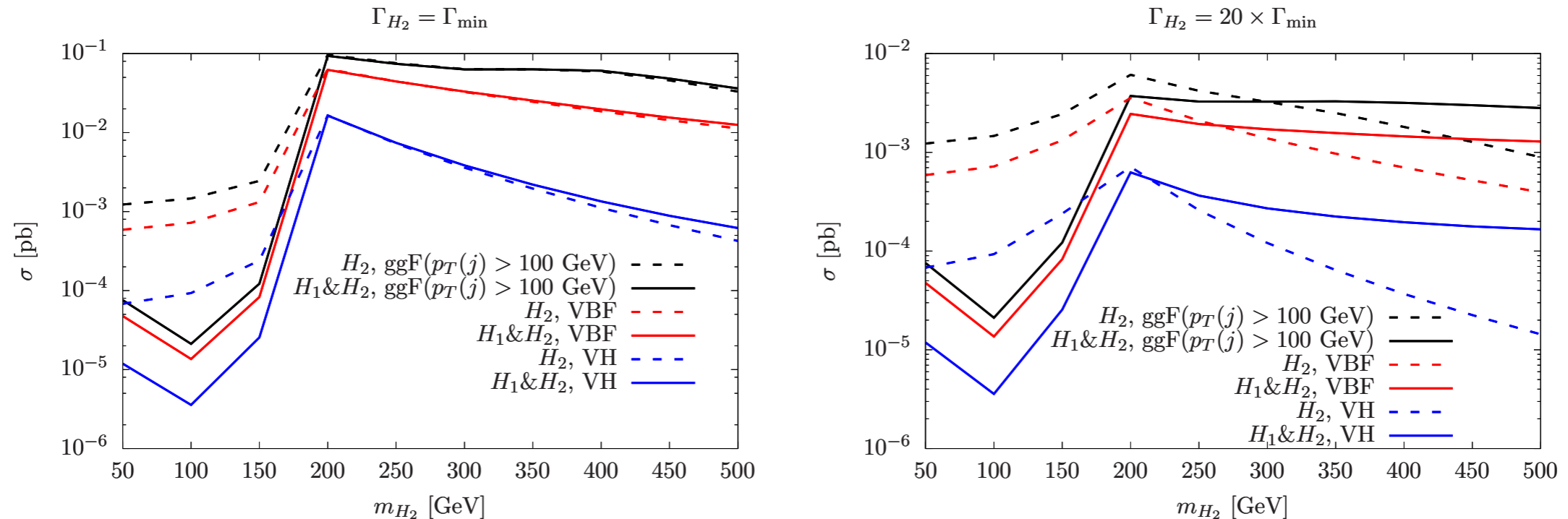


Figure 6: The production cross sections for ggF (black), VBF (red) and VH (blue) processes at 13 TeV LHC. Left panel: The decay width of H_2 is Γ_{\min} . Right panel: A relatively large decay width of H_2 is chosen, $20 \times \Gamma_{\min}$. The difference between the solid and the dashed lines with the same color show the importance of the interference effects from two scalar boson propagators.

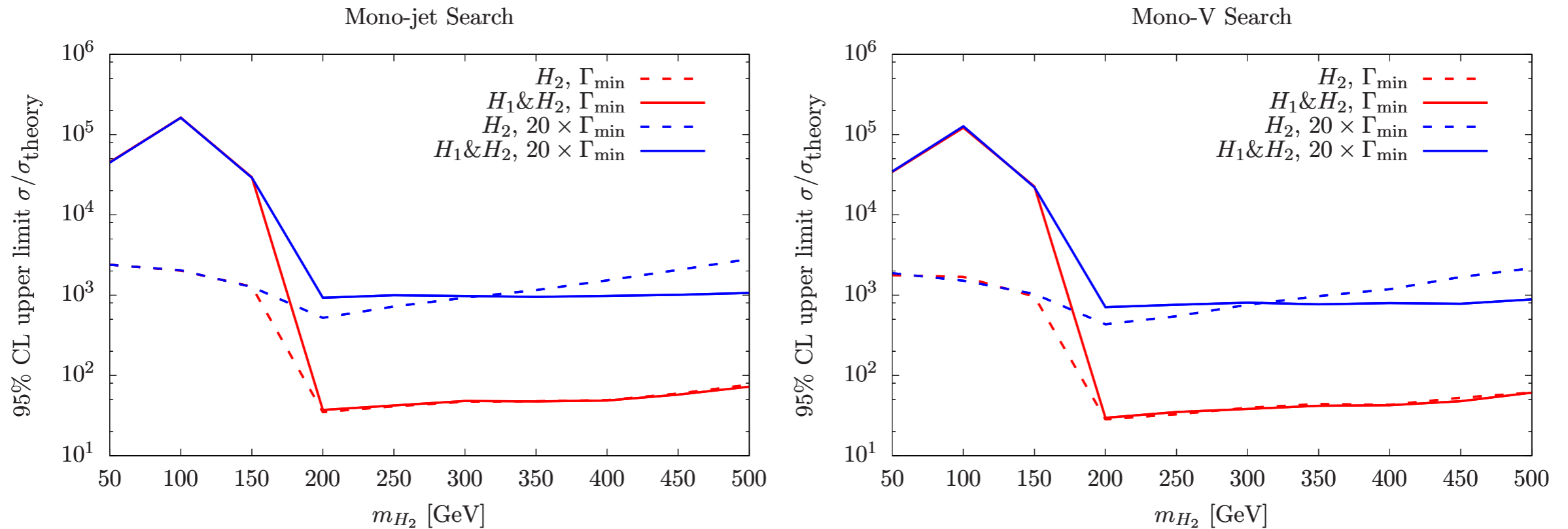


Figure 8: The CMS exclusion limits on our simplified models. Left: upper limit from mono-jet search. Right: upper limit from mono-V search.

Underlying Points

- EFT + Complementarity : No good at high energy collider
- SM gauge invariance (full SM gauge symmetry), Renormalizability and unitarity
- Dark (gauge) symmetry equally important, although it is usually ignored (this part is also completely unknown to us as of now)
- See arXiv:1605.07058 (with A. Natale, M.Park, H.Yokoya) for t-channel mediator

- Higgs portal DM : simple viable DM models (natural if one assumes dark gauge sym)
- UV completion of (scalar)x(scalar) effective op : two Higgs propagators with negative relative sign
- EFT: not reliable for collider searches for DM, and one has to consider UV completions
- Full SM gauge symmetry, unitarity and renormalizability are important when constructing UV completions
- Search for Higgs portal DM at ILC, FCC-ee, LHC and FCC-hh, SPPC being studied