Higgs and DM

Pyungwon Ko (KIAS)

DM@LHC Workshop, Amsterdam
March 30-April 1(2016)

Contents

- Higgs is harmful to DM stability : dark gauge symmetry + singlet portal
- Higgs portal DM : EFT vs. UV completions
- Simplified DM model with full SM gauge symmetry

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 phi would break dark gauge sym spontaneously
- |H|^2 |phi|^2 : dim-4 gauge inv operator

Higgs is harmful to DM

- DM : color/electric charge neutral
- If DM is a SM singlet with EW scale mass , it will decay immediately because of Higgs field if couplings ~ O(1)
- S: scalar DM, chi : fermion DM (singlet)

$$\dim \leq 4 \qquad SH^\dagger H, \quad \bar{l}_L \tilde{H} \chi,$$

$$\dim = 5 \qquad \frac{1}{M_{Planck}} S F_{\mu\nu} F^{\mu\nu}, \ldots\ldots$$

introduce Z2

Local dark gauge sym

- Better to assign new (approximately) conserved quantum #' (dark charge) and gauge it
- DM-DM, DM-SM interactions are all fixed by local gauge symmetry, and all the particles feel some kind of gauge interactions, exactly like in the SM
- Two different kind of force mediators : dark photon (or dark gauge boson) and dark Higgs boson
- Natural playground for self-interacting DM, light mediators, etc.

Some works along this line

(with S.Baek, Suyong Choi, P. Gondolo, T. Hur, D.W.Jung, Sunghoon Jung, J.Y.Lee, W.I.Park, E.Senaha, Yong Tang in various combinations)

- Strongly interacting hidden sector, h-pion DM (0709.1218 PLB, 1103.2571 PRL)
- 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)
- Recent works

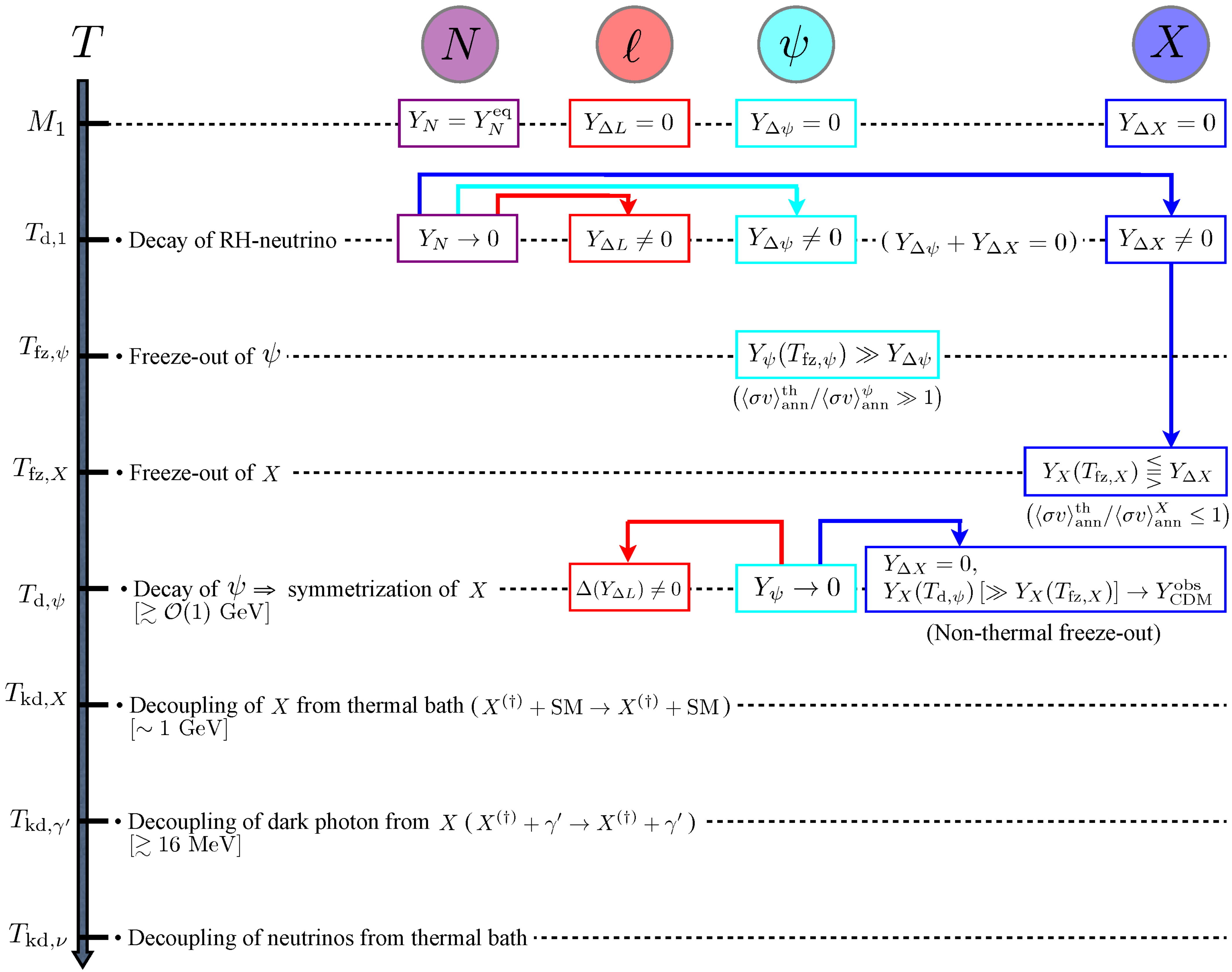
Singlet portal extension of SM with dark gauge sym

arXiv:1303.4280 [hep-ph]S. Baek, P. Ko and Wan-Il Park

$$
\begin{aligned}
\mathcal{L}_X &= \left|\left(\partial_\mu + i g_X q_X \hat{B}'_\mu\right) X\right|^2 - \frac{1}{4}\hat{B}'_{\mu\nu}\hat{B}'^{\mu\nu} - m_X^2 X^\dagger X - \frac{1}{4}\lambda_X \left(X^\dagger X\right)^2, \\
\mathcal{L}_\psi &= i\bar{\psi}\gamma^\mu \left(\partial_\mu + i g_X q_X \hat{B}'_\mu\right)\psi - m_\psi \bar{\psi}\psi, \\
\mathcal{L}_{\rm kin-mix} &= -\frac{1}{2}\sin\epsilon \hat{B}'_{\mu\nu}\hat{B}^{\mu\nu}, \\
\mathcal{L}_{\rm H-portal} &= -\frac{1}{2}\lambda_{HX} X^\dagger X H^\dagger H, \\
-\mathcal{L}_{\rm RHN-portal} &= \frac{1}{2} M_i \overline{N_{Ri}^C} N_{Ri} + \left[Y_\nu^{ij}\overline{N_{Ri}}\ell_{Lj}H^\dagger + \lambda^i \overline{N_{Ri}}\psi X^\dagger + {\rm H.c.}\right].
\end{aligned}
$$

Physics Issues

- Small and large scale structure
- Vacuum stability of Higgs potential
- CDM relic density and direct/indirect DM searches
- Dark radiation
- Leptogenesis
- Higgs inflation in case of a large non-minimal gravitational couplings



T
N
ℓ
ψ
X
M_1
$Y_N = Y_N^{\rm eq}$
$Y_{\Delta L} = 0$
$Y_{\Delta\psi} = 0$
$Y_{\Delta X} = 0$
$T_{\rm d,1}$
• Decay of RH-neutrino
$Y_N \to 0$
$Y_{\Delta L} \neq 0$
$Y_{\Delta\psi} \neq 0$
$(Y_{\Delta\psi} + Y_{\Delta X} = 0)$
$Y_{\Delta X} \neq 0$
$T_{{\rm fz},\psi}$
• Freeze-out of ψ
$Y_\psi(T_{{\rm fz},\psi}) \gg Y_{\Delta\psi}$
$(\langle\sigma v\rangle^{\rm th}_{\rm ann}/\langle\sigma v\rangle^{\psi}_{\rm ann} \gg 1)$
$T_{{\rm fz},X}$
• Freeze-out of X
$Y_X(T_{{\rm fz},X}) \lesseqqgtr Y_{\Delta X}$
$(\langle\sigma v\rangle^{\rm th}_{\rm ann}/\langle\sigma v\rangle^{X}_{\rm ann} \leq 1)$
$T_{{\rm d},\psi}$
• Decay of $\psi \Rightarrow$ symmetrization of X
$[\gtrsim \mathcal{O}(1)$ GeV$]$
$\Delta(Y_{\Delta L}) \neq 0$
$Y_\psi \to 0$
$Y_{\Delta X} = 0,$
$Y_X(T_{{\rm d},\psi})\, [\gg Y_X(T_{{\rm fz},X})] \to Y^{\rm obs}_{\rm CDM}$
(Non-thermal freeze-out)
$T_{{\rm kd},X}$
• Decoupling of X from thermal bath $(X^{(\dagger)} + {\rm SM} \to X^{(\dagger)} + {\rm SM})$
$[\sim 1$ GeV$]$
$T_{{\rm kd},\gamma'}$
• Decoupling of dark photon from X $(X^{(\dagger)} + \gamma' \to X^{(\dagger)} + \gamma')$
$[\gtrsim 16$ MeV$]$
$T_{{\rm kd},\nu}$
• Decoupling of neutrinos from thermal bath

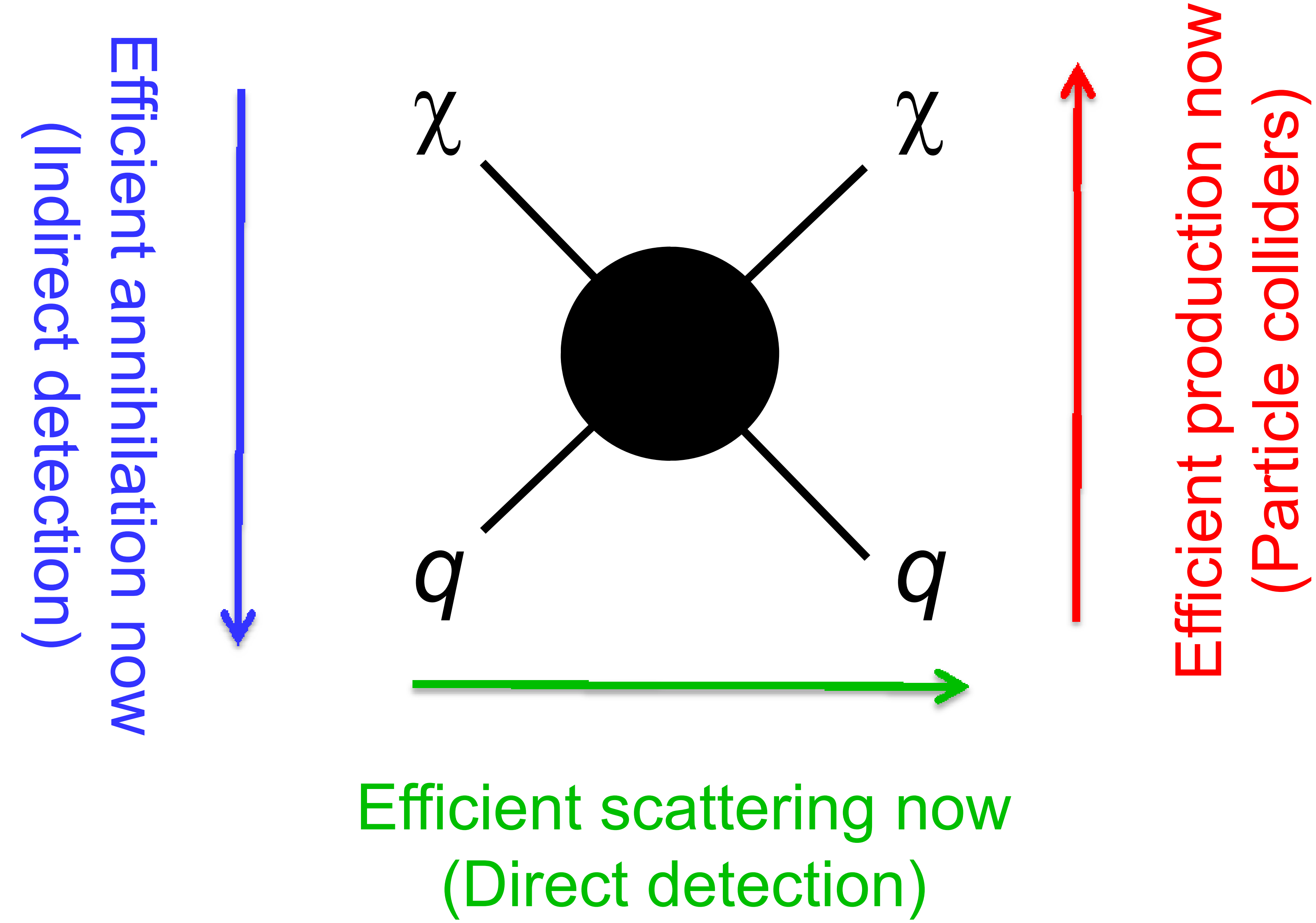
DD vs. Monojet : Why complementarity breaks down in EFT ?

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

arXiv:1506.06556
Phys. Lett. B756 (2016)289

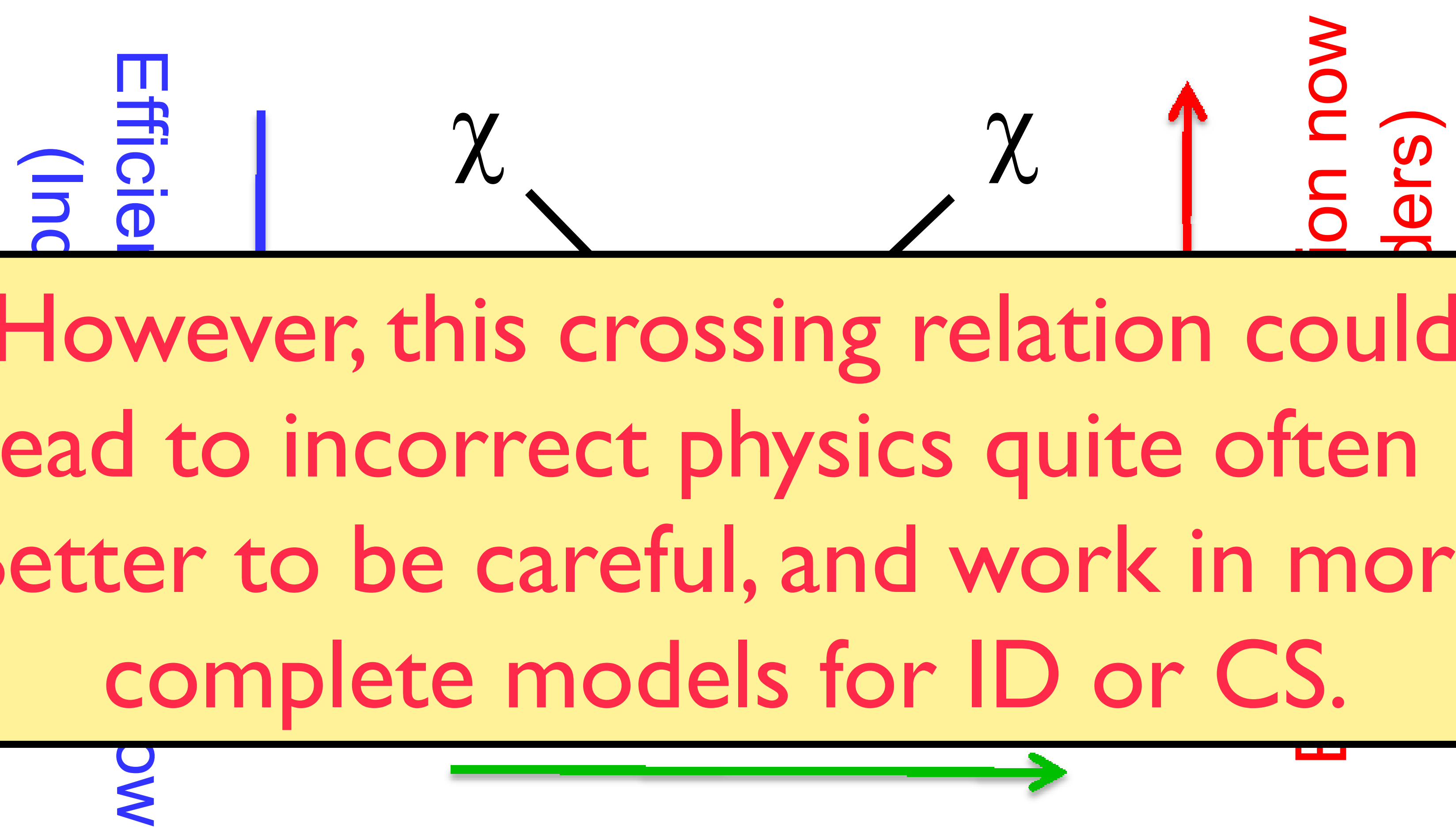
Crossing & WIMP detection

Correct relic density → Efficient annihilation then



Crossing & WIMP detection

Correct relic density → Efficient annihilation then



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

Efficient scattering now
(Direct detection)

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

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

$\boxed{\text{OK}}$

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

$\boxed{\text{Not OK}}$

$\boxed{\text{Both break SM gauge invariance !}}$

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

$\boxed{\text{Need the mixing between s and h}}$

Higgs portal DM as examples

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

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

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

All invariant under ad hoc Z2 symmetry

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

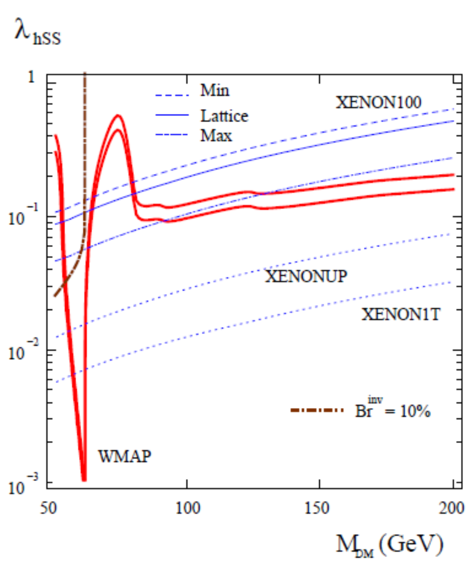


FIG. 1. Scalar Higgs-portal parameter space allowed by WMAP (between the solid red curves), XENON100 and $BR^{inv} = 10\%$ for $m_h = 125$ GeV. Shown also are the prospects for XENON upgrades.

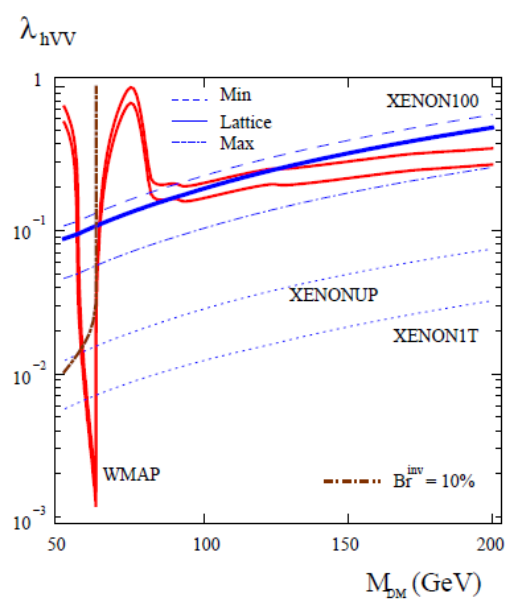


FIG. 2. Same as Fig. 1 for vector DM particles.

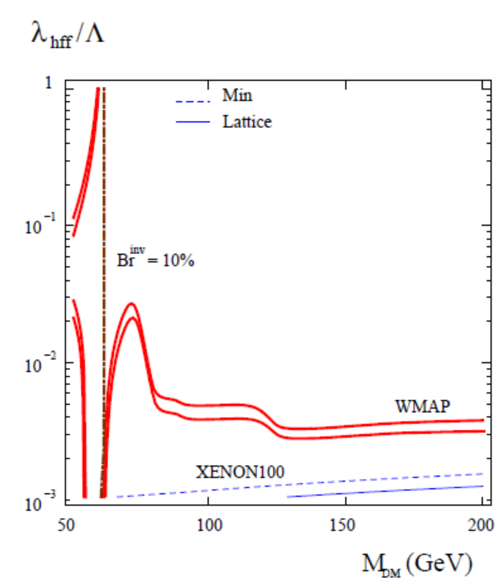


FIG. 3. Same as in Fig.1 for fermion DM; λ_{hff}/Λ is in GeV^{-1}.

Higgs portal DM as examples

All invariant under ad hoc Z2 symmetry

$$
\begin{aligned}
\mathcal{L}_{\rm scalar} &= \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{1}{2} m_S^2 S^2 - \frac{\lambda_{HS}}{2} H^\dagger H S^2 - \frac{\lambda_S}{4} S^4 \\
\mathcal{L}_{\rm fermion} &= \overline{\psi}\left[i \gamma \cdot \partial - m_\psi \right] \psi - \frac{\lambda_{H\psi}}{\Lambda} H^\dagger H \, \overline{\psi}\psi \\
\mathcal{L}_{\rm vector} &= -\frac{1}{4} V_{\mu\nu} V^{\mu\nu} + \frac{1}{2} m_V^2 V_\mu V^\mu + \frac{1}{4} \lambda_V (V_\mu V^\mu)^2 + \frac{1}{2} \lambda_{HV} H^\dagger H V_\mu V^\mu .
\end{aligned}
$$

- 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

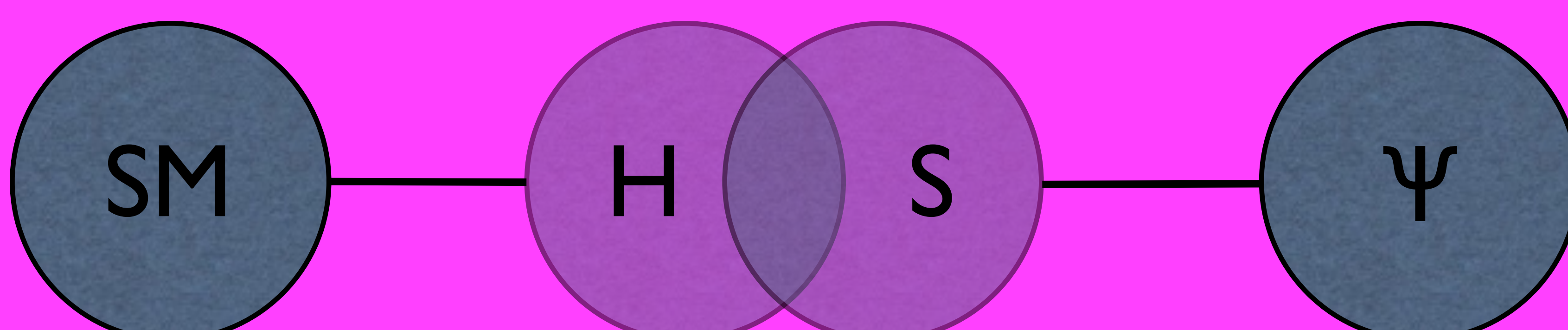
Singlet fermion CDM

Baek, Ko, Park, arXiv:1112.1847

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

mixing

invisible decay



Production and decay rates are suppressed relative to SM.

This simple model has not been studied properly !!

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

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

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

Mixing of Higgs and singlet

Ratiocination

- Signal strength (reduction factor)

$$r_i = \frac{\sigma_i \, \mathrm{Br}(H_i \to \mathrm{SM})}{\sigma_h \, \mathrm{Br}(h \to \mathrm{SM})}$$

$$r_1 = \frac{\cos^4\alpha \, \Gamma^{\mathrm{SM}}_{H_1}}{\cos^2\alpha \, \Gamma^{\mathrm{SM}}_{H_1} + \sin^2\alpha \, \Gamma^{\mathrm{hid}}_{H_1}}$$

$$r_2 = \frac{\sin^4\alpha \, \Gamma^{\mathrm{SM}}_{H_2}}{\sin^2\alpha \, \Gamma^{\mathrm{SM}}_{H_2} + \cos^2\alpha \, \Gamma^{\mathrm{hid}}_{H_2} + \Gamma_{H_2 \to H_1 H_1}}$$

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

Invisible decay mode is not necessary!

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

Constraints

EW precision observables

Peskin & Takeuchi, Phys.Rev.Lett.65,964(1990)

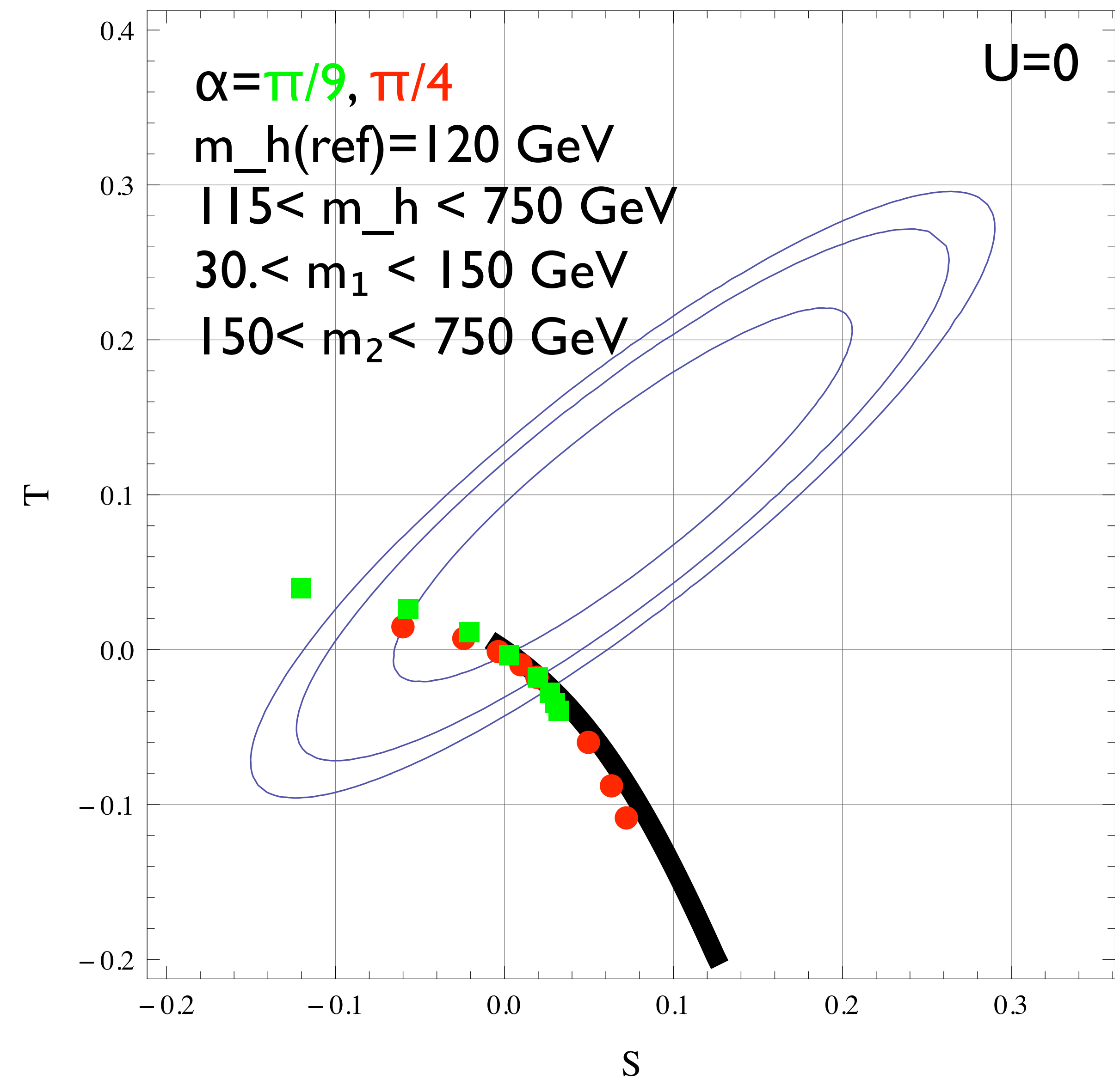
$$\alpha_{\rm em} S = 4 s_W^2 c_W^2 \left[\frac{\Pi_{ZZ}(M_Z^2) - \Pi_{ZZ}(0)}{M_Z^2} \right]$$

$$\alpha_{\rm em} T = \frac{\Pi_{WW}(0)}{M_W^2} - \frac{\Pi_{ZZ}(0)}{M_Z^2}$$

$$\alpha_{\rm em} U = 4 s_W^2 \left[\frac{\Pi_{WW}(M_W^2) - \Pi_{WW}(0)}{M_W^2} \right]$$

$$S = \cos^2\alpha \; S(m_1) + \sin^2\alpha \; S(m_2)$$

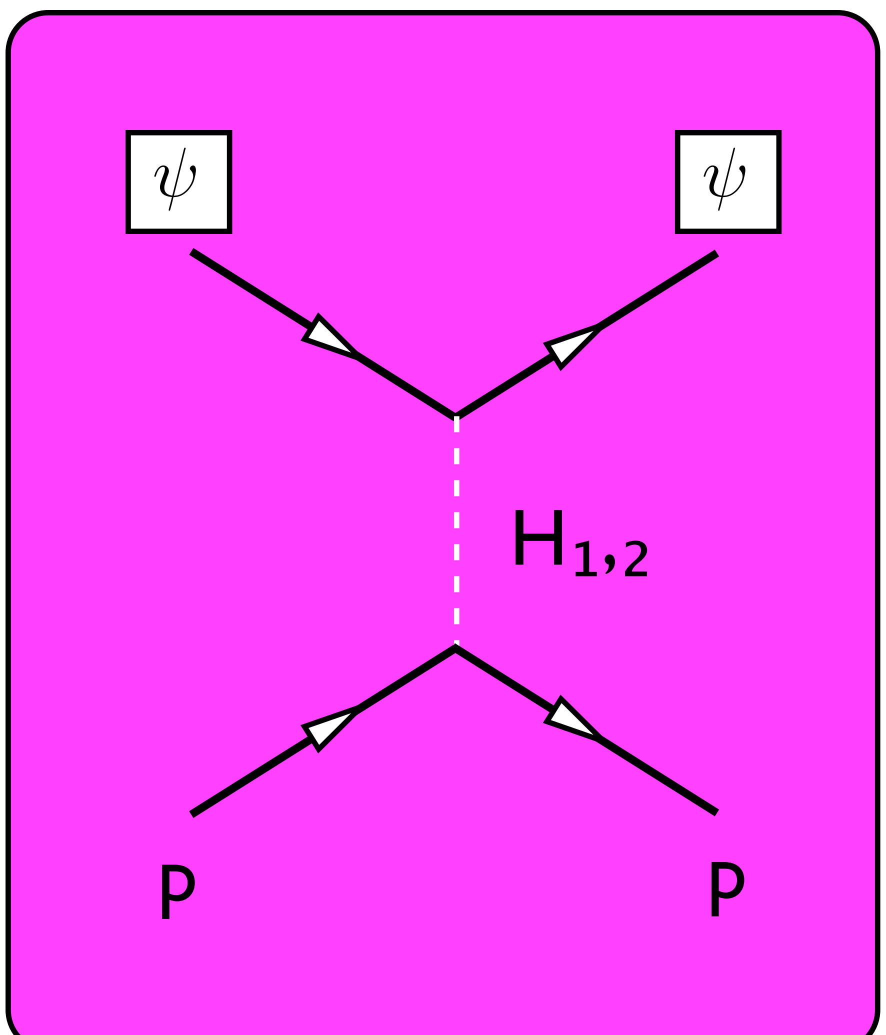
Same for T and U

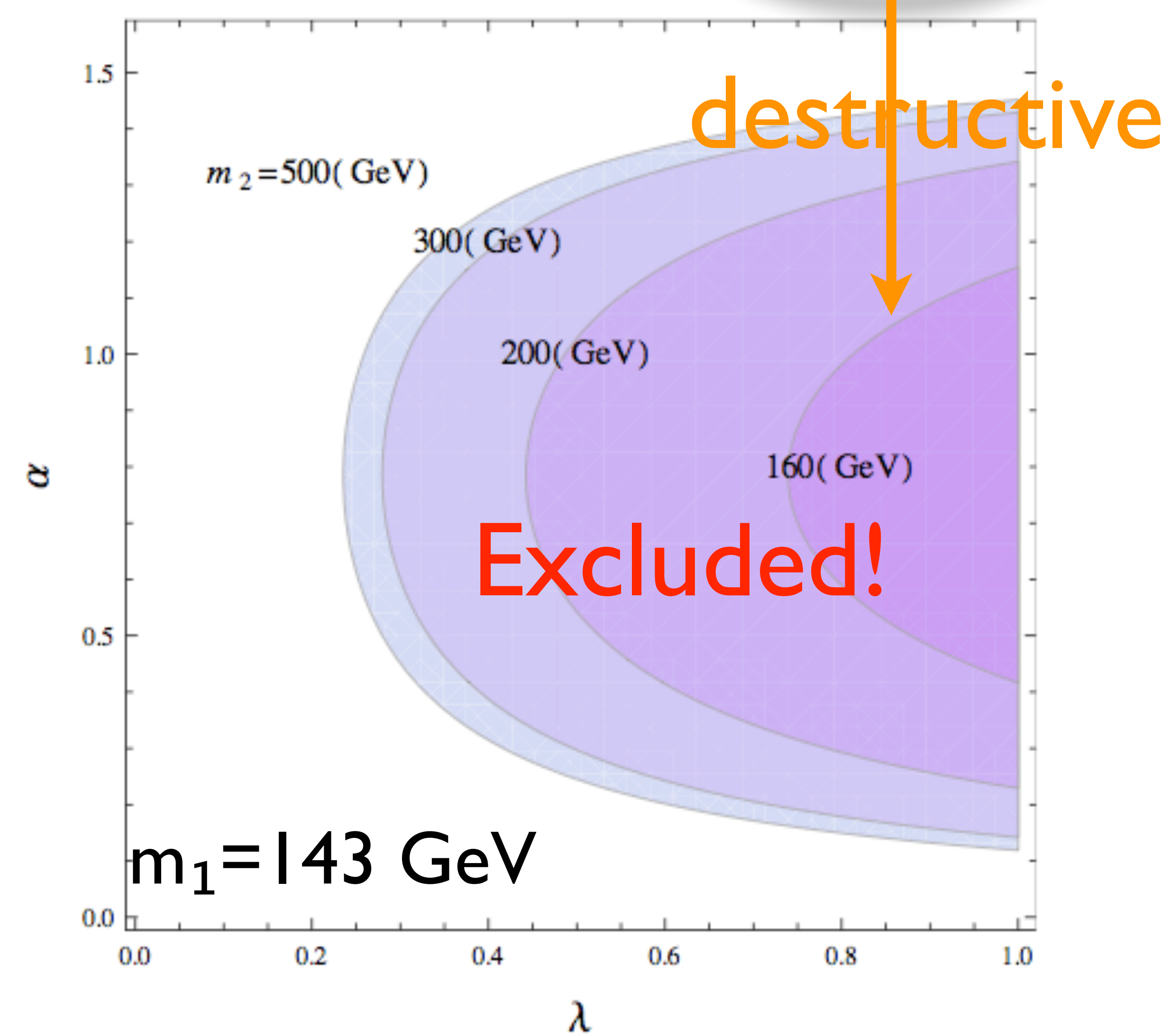


Constraints

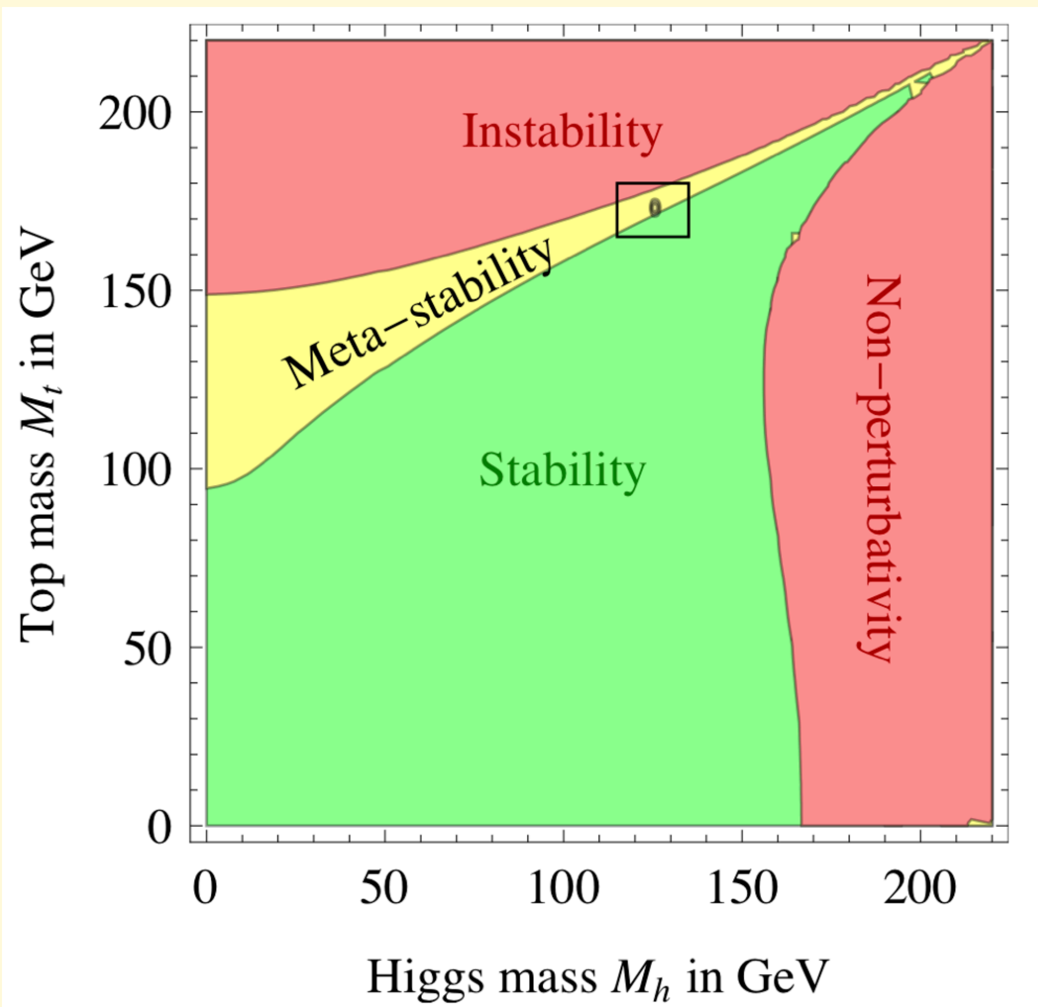
- Dark matter to nucleon cross section (constraint)

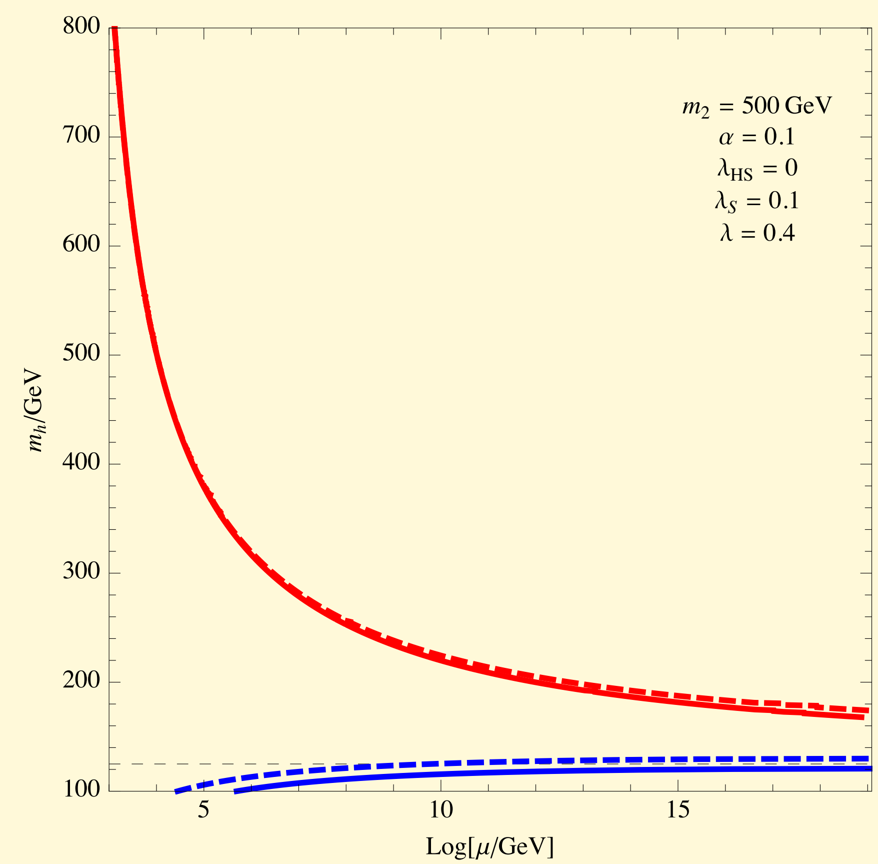
$$\sigma_p \approx \frac{1}{\pi}\mu^2\lambda_p^2 \simeq 2.7\times 10^{-2}\frac{m_p^2}{\pi}\left|\left(\frac{m_p}{v}\right)\lambda\sin\alpha\cos\alpha\left(\frac{1}{m_1^2}-\frac{1}{m_2^2}\right)\right|^2$$





Vacuum Stability Improved by the singlet scalar S





A. Strumia, Moriond EW 2013

Baek, Ko, Park, Senaha (2012)

Low energy pheno.

- Universal suppression of collider SM signals

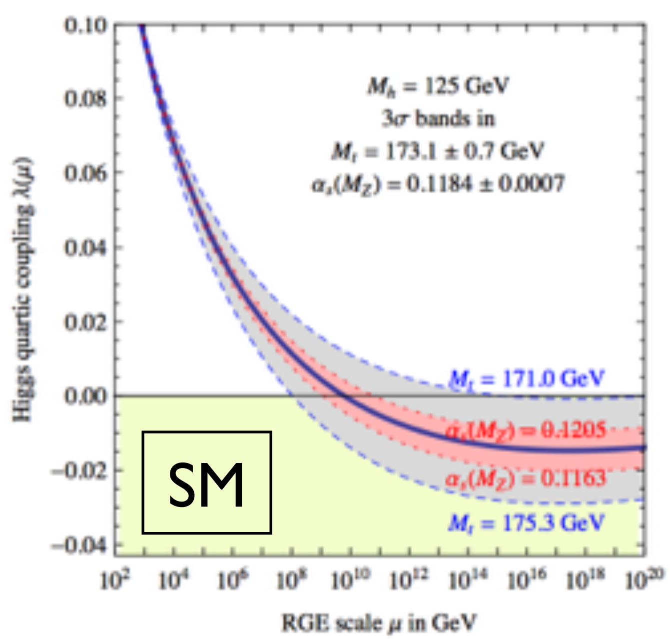
[See 1112.1847, Seungwon Baek, P. Ko & WIP]

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

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

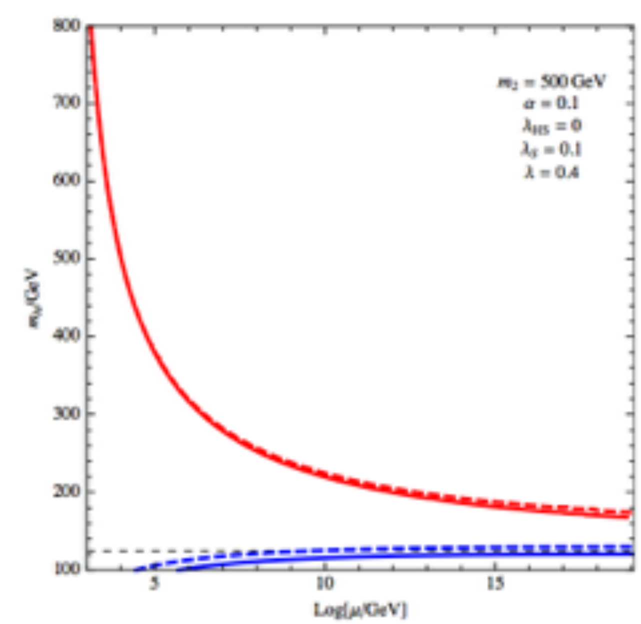
$$\lambda_{\Phi H} \Rightarrow \lambda_H = \left[1 + \left(\frac{m_\phi^2}{m_h^2} - 1\right)\sin^2\alpha\right]\lambda_H^{SM}$$

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)]

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 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
- 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

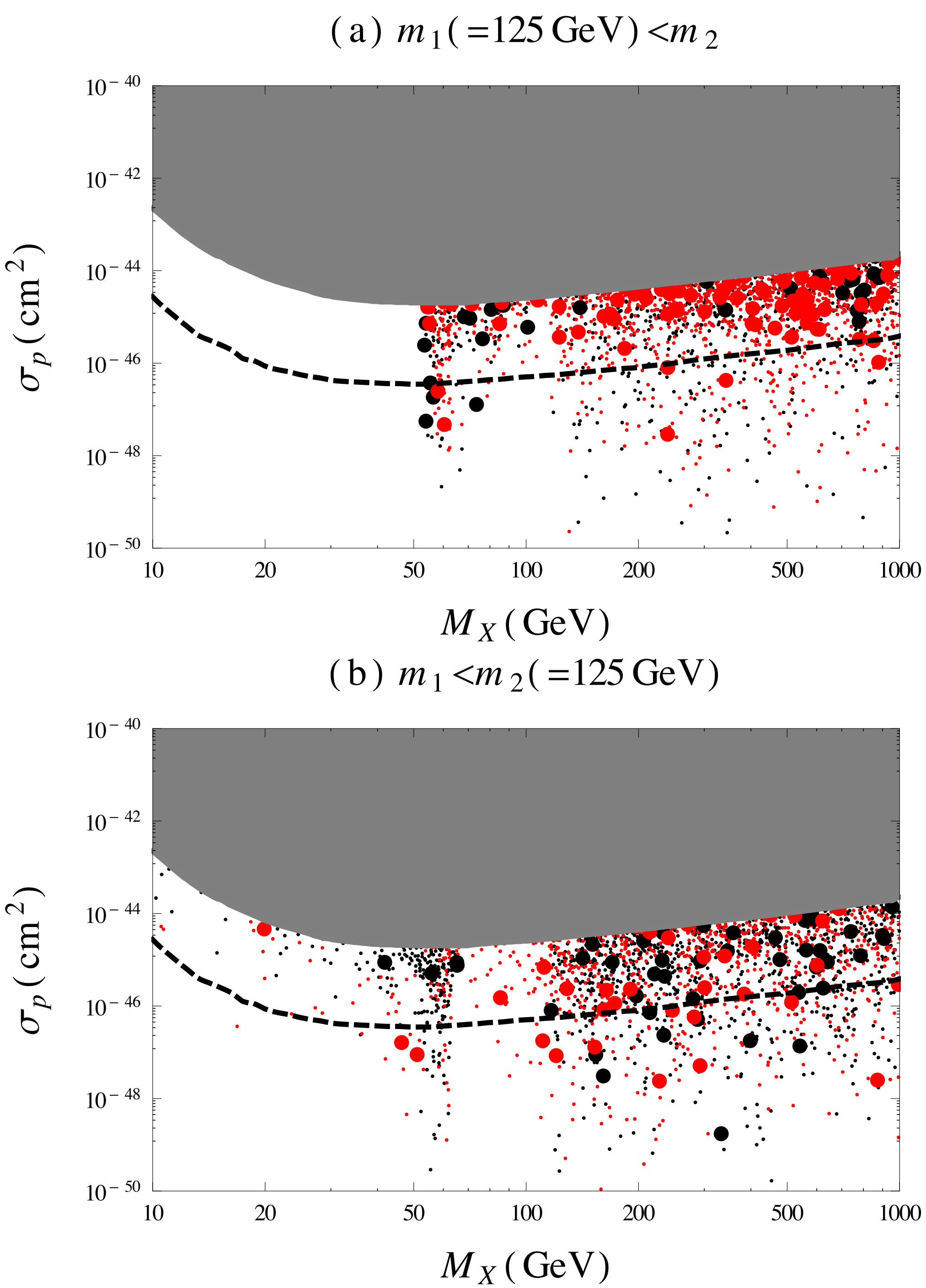


Figure 6. The scattered plot of σ_p as a function of M_X. The big (small) points (do not) satisfy the WMAP relic density constraint within 3 σ, while the red-(black-)colored points gives $r_1 > 0.7 (r_1 < 0.7)$. The grey region is excluded by the XENON100 experiment. The dashed line denotes the sensitivity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

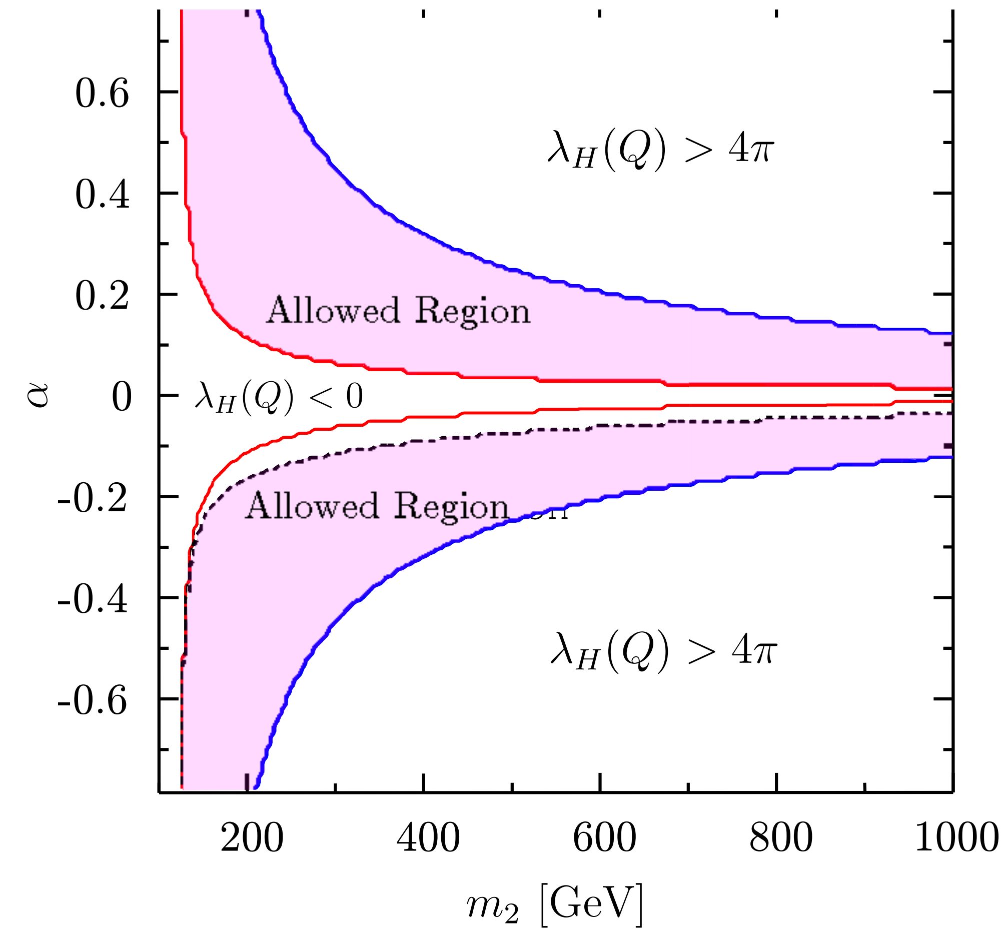


Figure 8. The vacuum stability and perturbativity constraints in the α-m_2 plane. We take $m_1 = 125$ GeV, $g_X = 0.05$, $M_X = m_2/2$ and $v_\Phi = M_X/(g_X Q_\Phi)$.

Comparison with the EFT approach

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

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

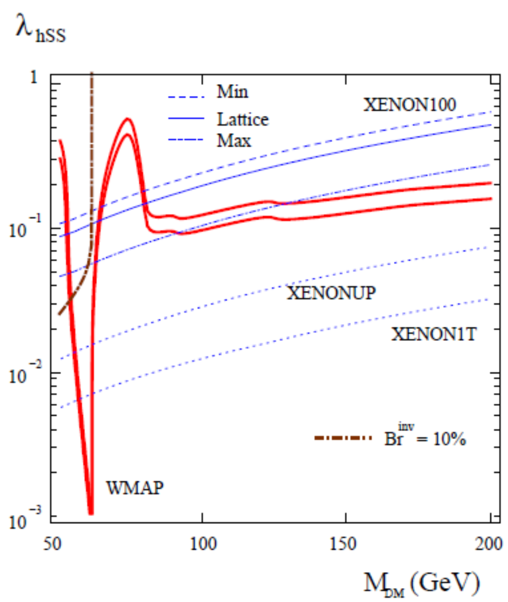


FIG. 1. Scalar Higgs-portal parameter space allowed by WMAP (between the solid red curves), XENON100 and BR^{inv} = 10% for m_h = 125 GeV. Shown also are the prospects for XENON upgrades.

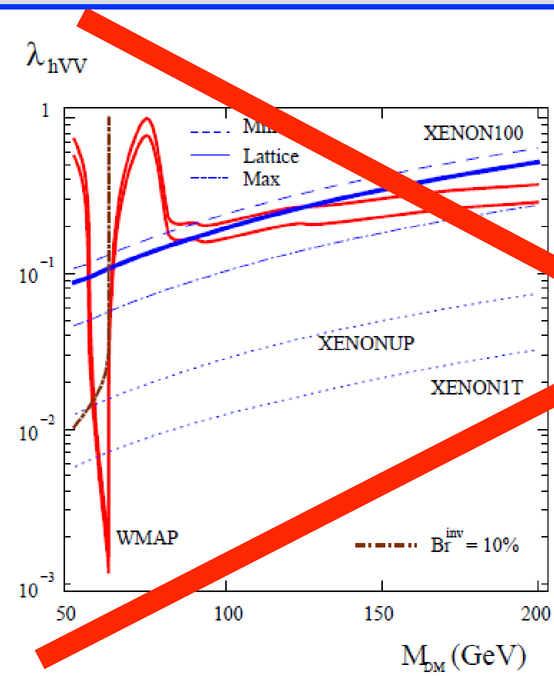


FIG. 2. Same as Fig. 1 for vector DM particles.

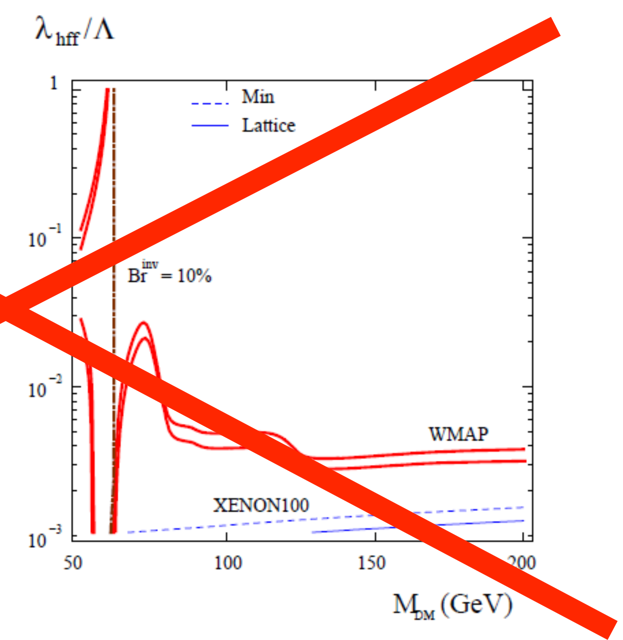


FIG. 3. Same as in Fig.1 for fermion DM; λ_{hff}/Λ is in GeV^{-1}.

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

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

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

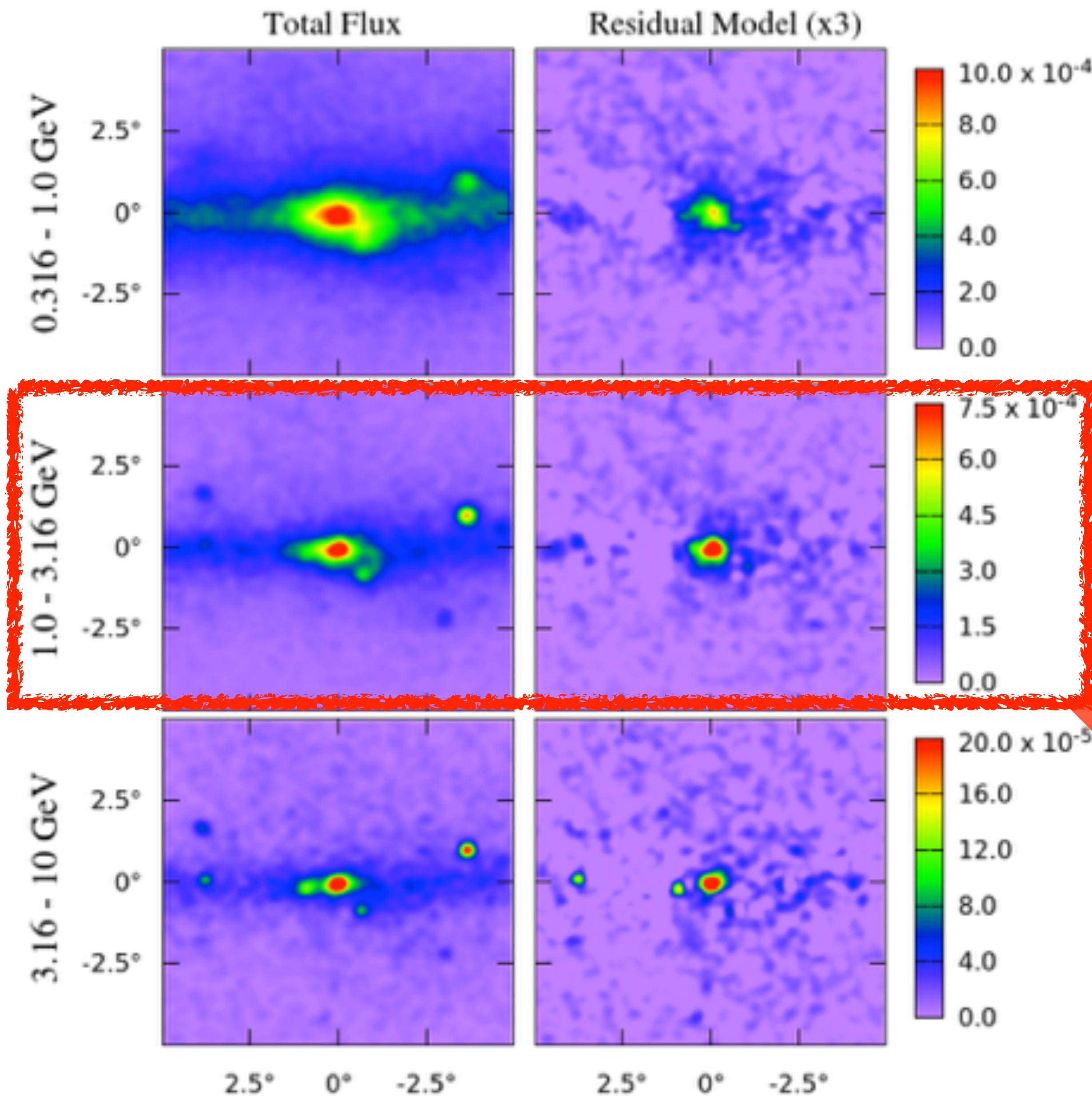
Is this any useful in phenomenology ?

Is this any useful in phenomenology ?

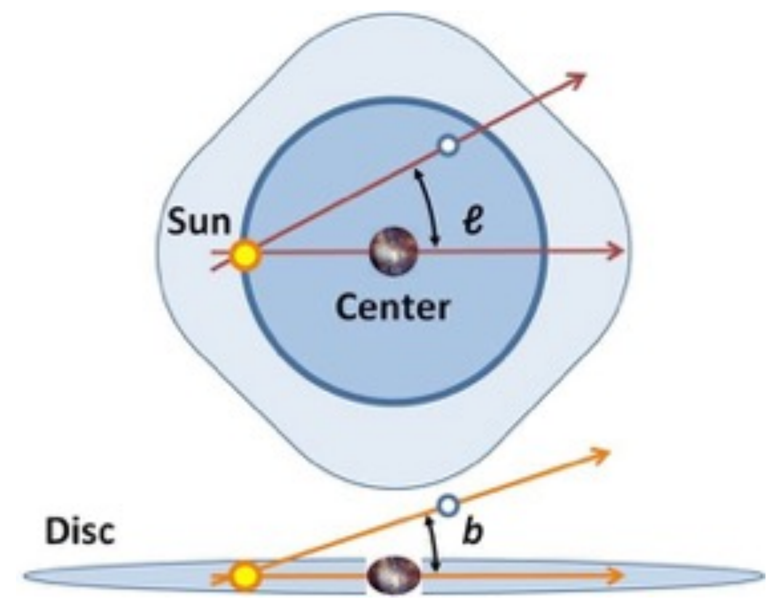
YES !

Fermi-LAT γ-ray excess

- Gamma-ray excess in the direction of GC



[1402.6703, T. Daylan et.al.]

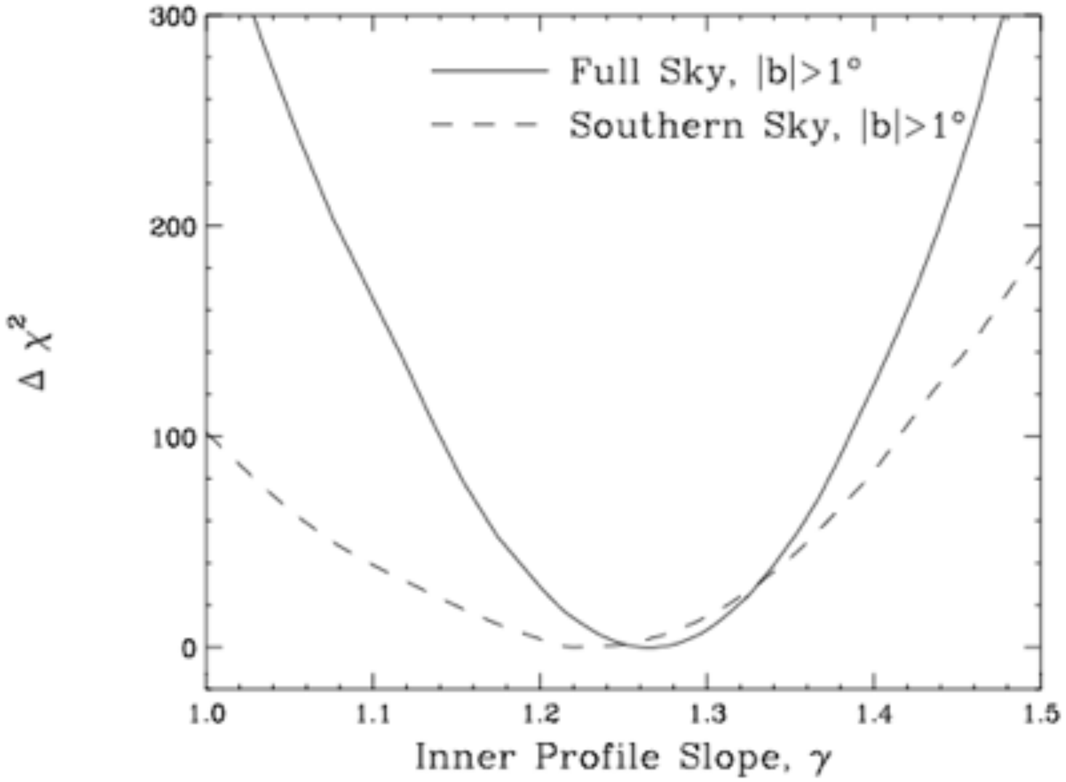


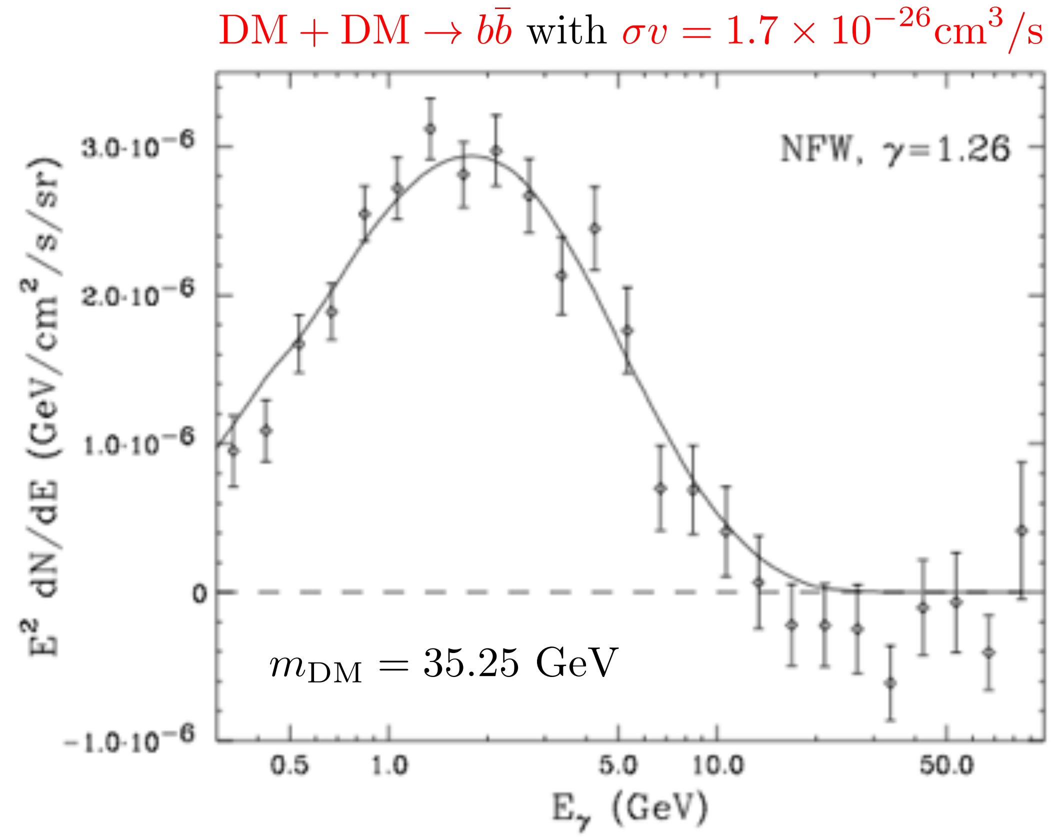
$$\mathrm{GC} : b \sim l \lesssim 0.1^\circ$$

extended

GeV scale excess!

• A DM interpretation





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

• Millisecond Pulars (astrophysical alternative)

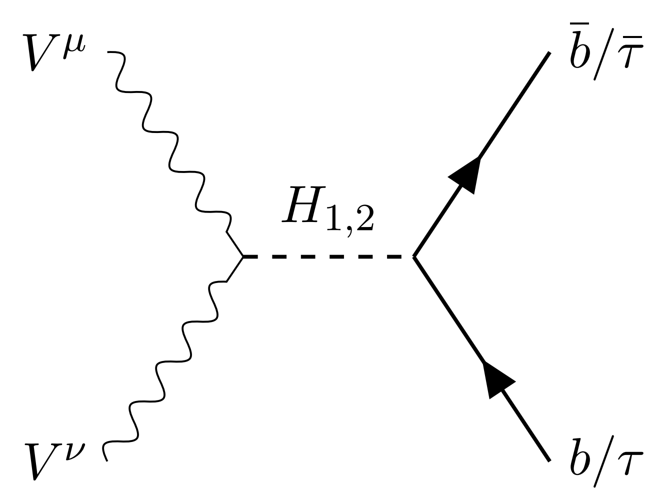
It may or may not be the main source, depending on

- 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

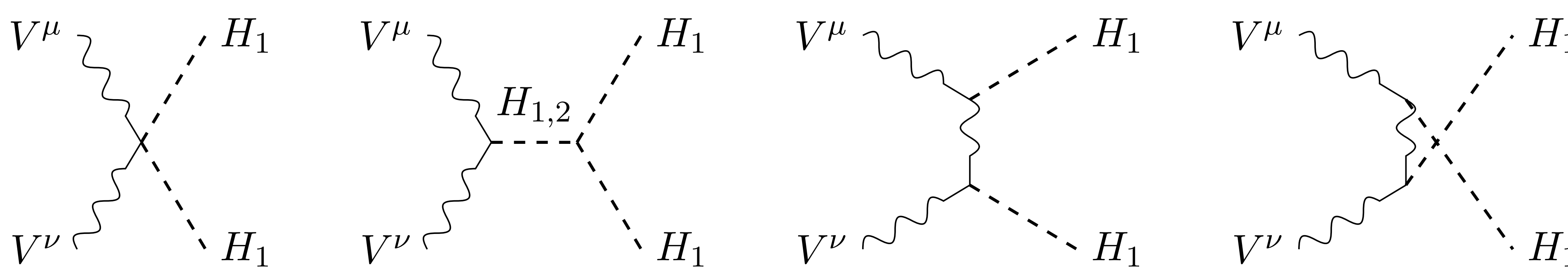


Figure 3. Dominant s/t-channel production of H_1s that decay dominantly to $b + \bar{b}$

Importance of VDM with Dark Higgs Boson

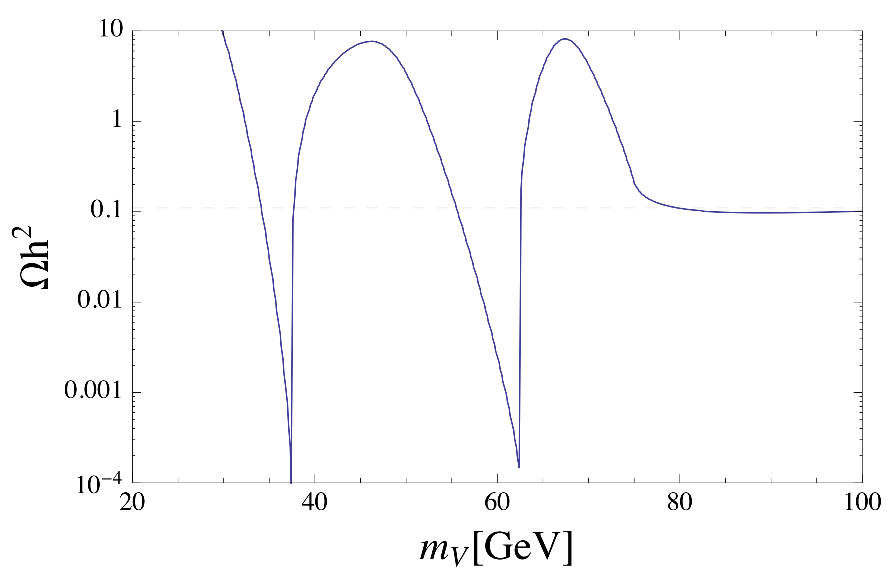


Figure 4. Relic density of dark matter as function of m_ψ for $m_h = 125$, $m_\phi = 75\,\mathrm{GeV}$, $g_X = 0.2$, and $\alpha = 0.1$.

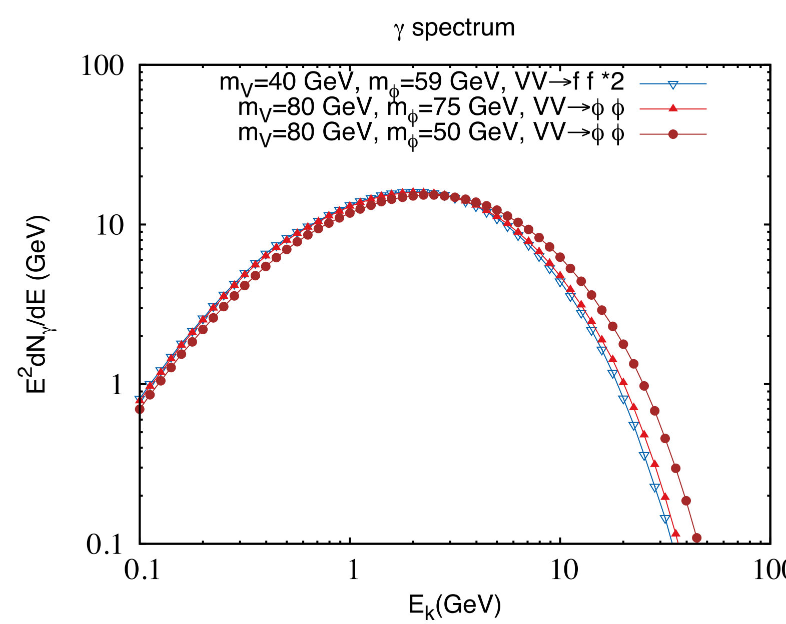
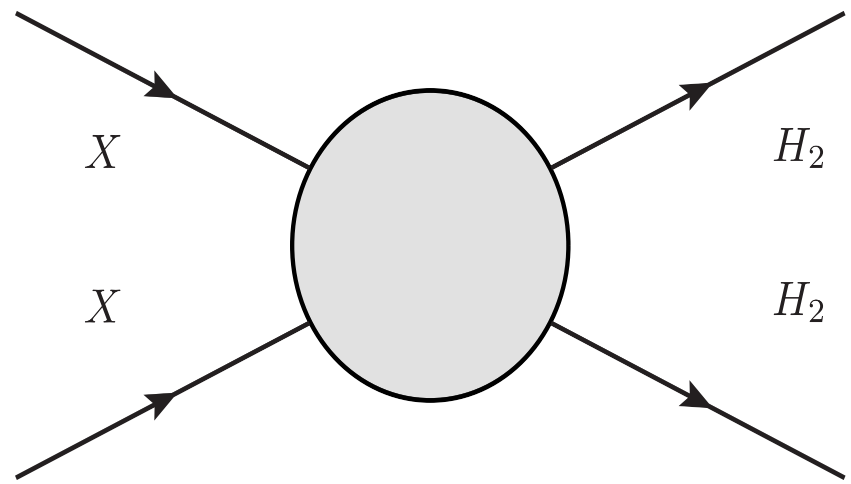


Figure 5. Illustration of γ spectra from different channels. The first two cases give almost the same spectra while in the third case γ is boosted so the spectrum is shifted to higher energy.

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

And there would be no second scalar in EFT



P.Ko, Yong Tang.
arXiv:1504.03908

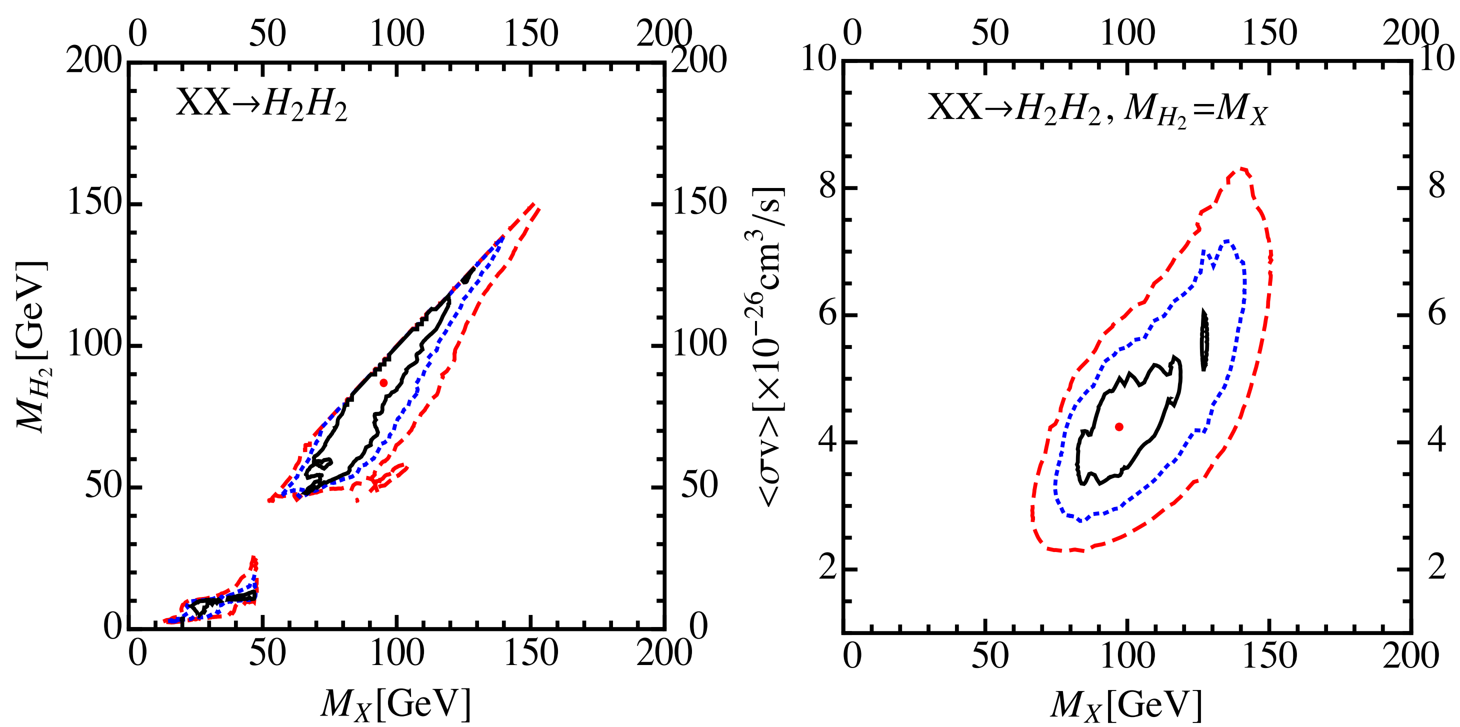


FIG. 3: The regions inside solid(black), dashed(blue) and long-dashed(red) contours correspond to 1σ, 2σ and 3σ, respectively. The red dots inside 1σ contours are the best-fit points. In the left panel, we vary freely M_X, M_{H_2} and $\langle\sigma v\rangle$. While in the right panel, we fix the mass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

This would have never been possible within the DM EFT

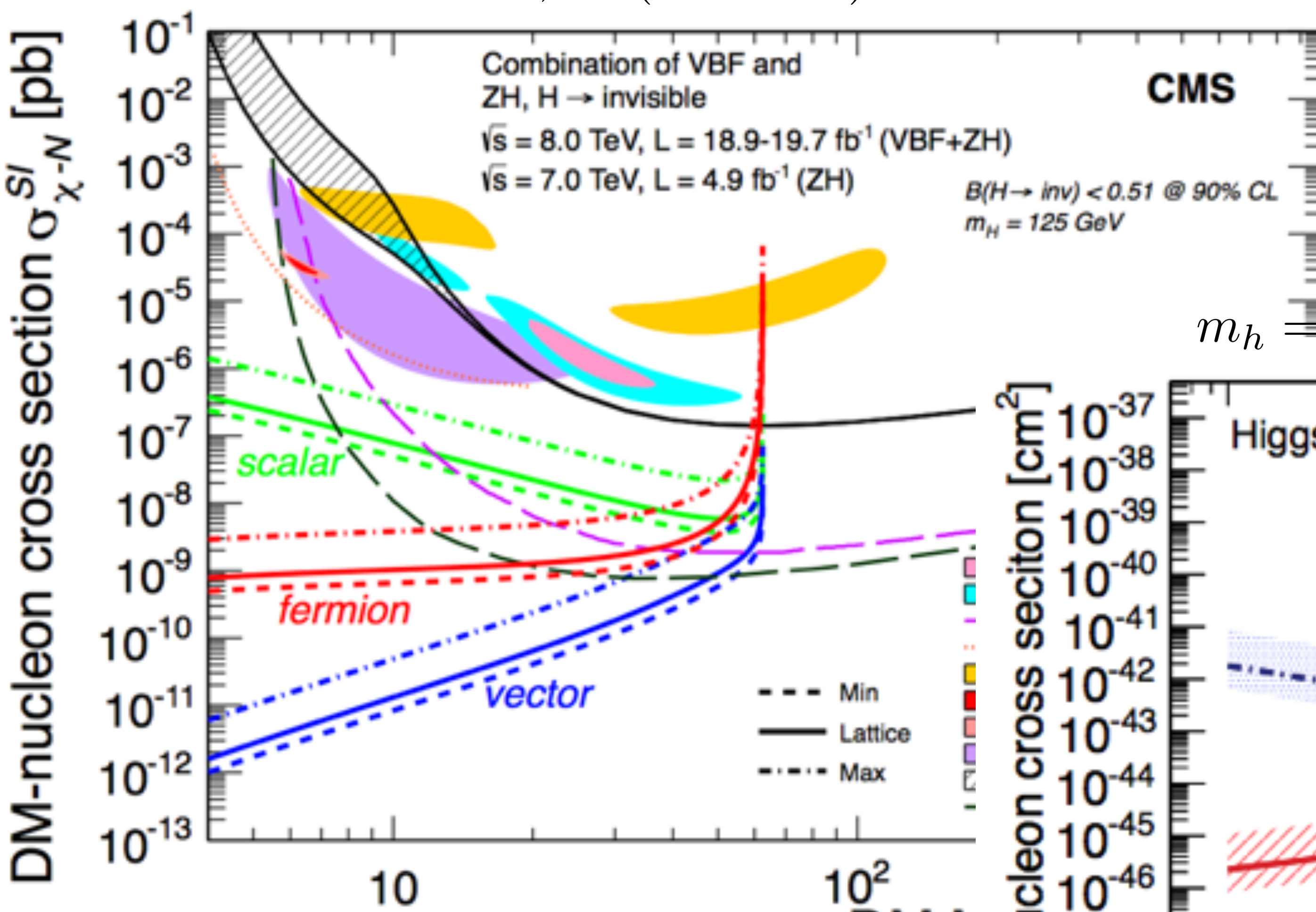
P.Ko, Yong Tang.
arXiv:1504.03908

Channels	Best-fit parameters	$\chi^2_{\rm min}/\text{d.o.f.}$	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

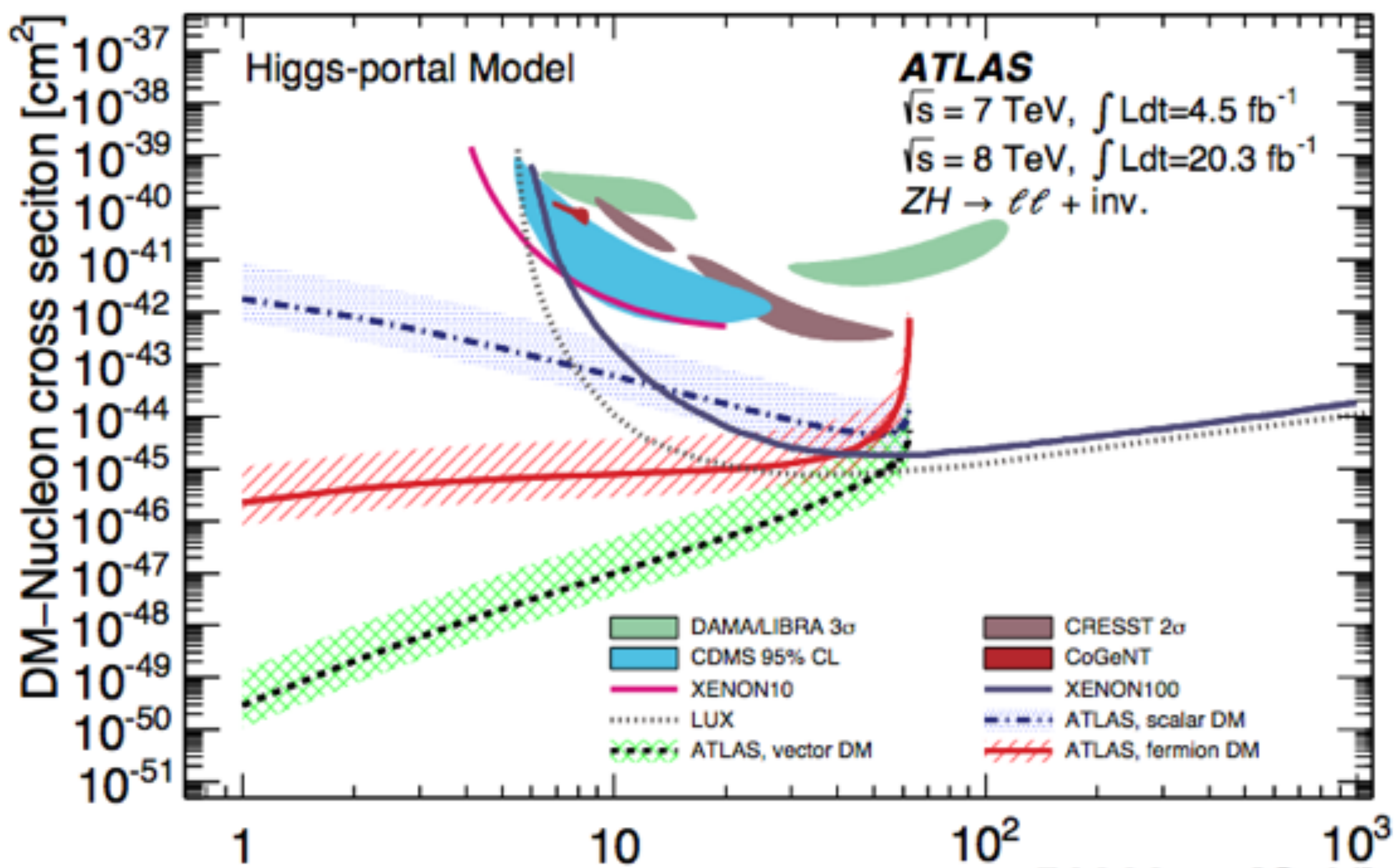
$m_h = 125\text{GeV},\ \text{Br}(H \to \text{inv}) < 0.51 \text{ at } 90\% \text{ CL}$



[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]

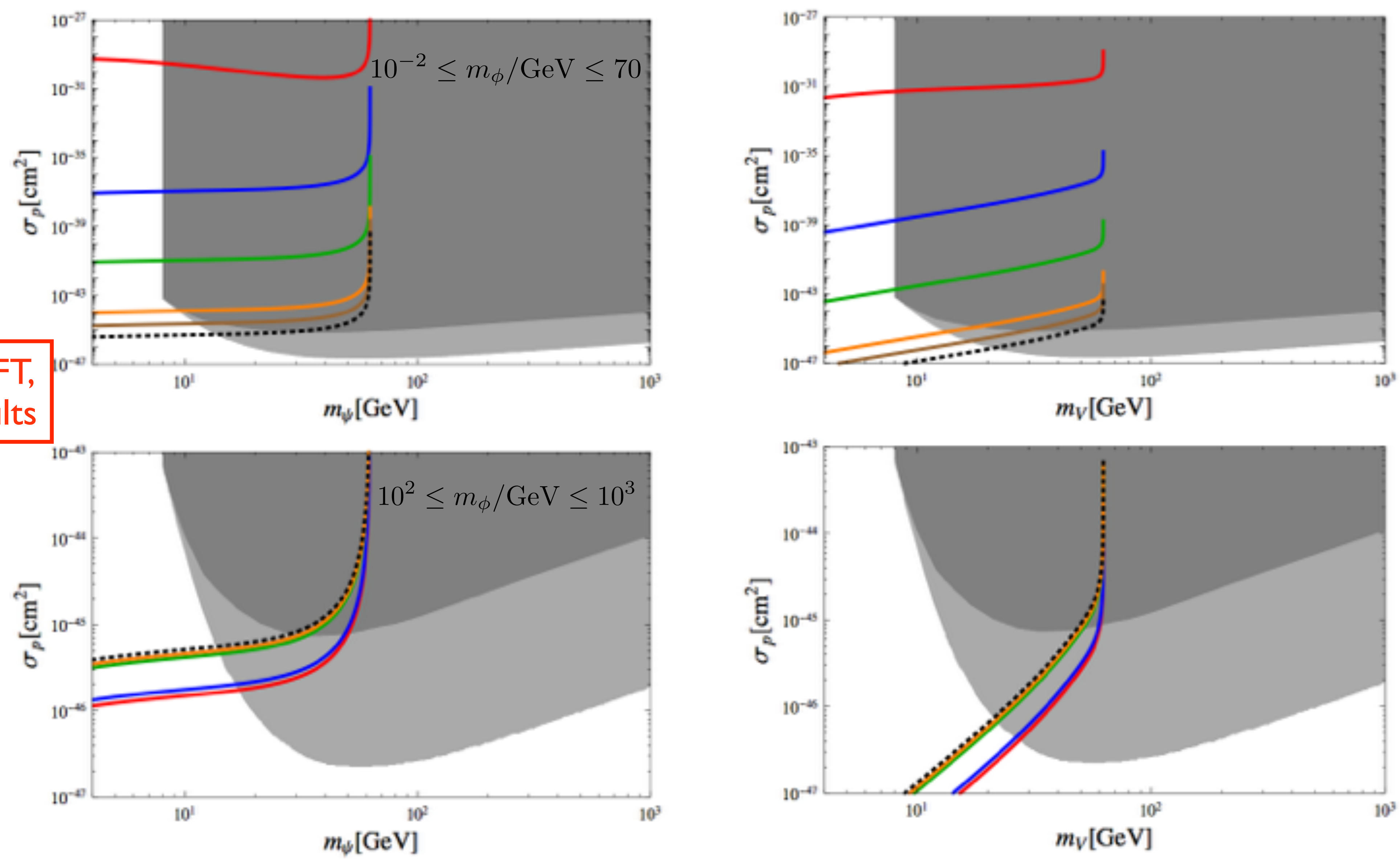
- However, in renormalizable unitary models of Higgs portals, 2 more relevant parameters

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

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

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

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



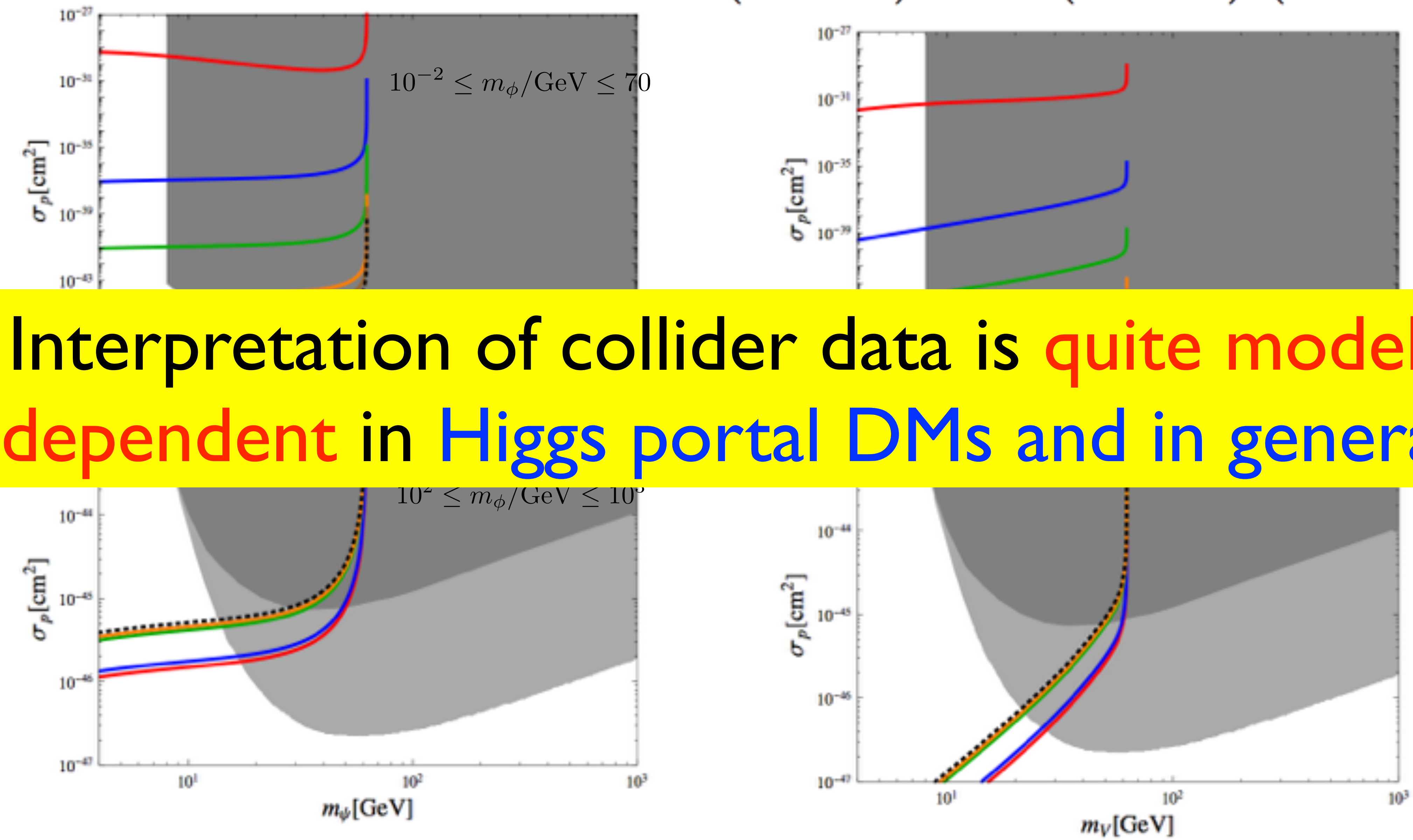
Dashed curves:EFT, ATLAS,CMS results

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

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

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

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



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]

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

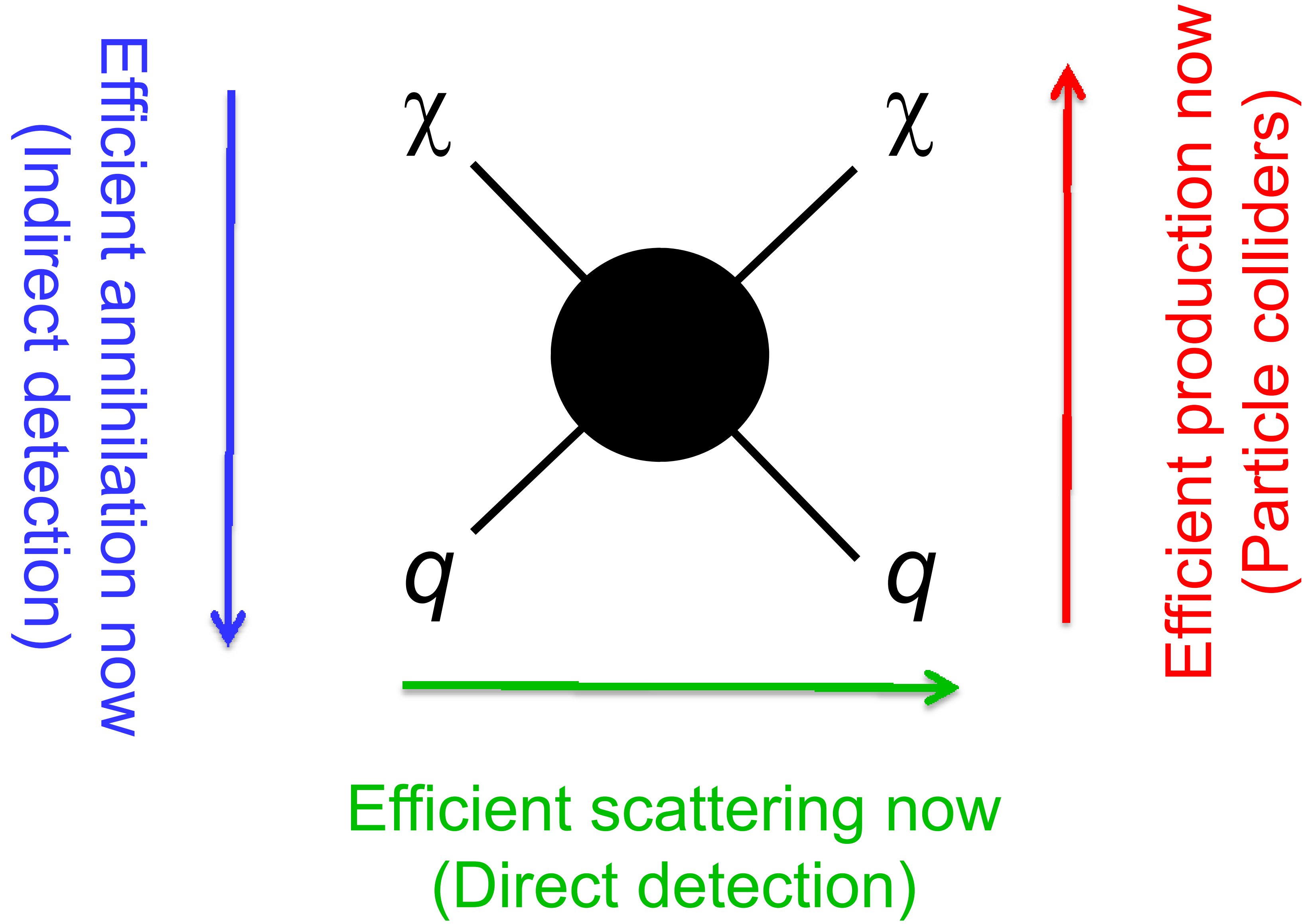
VS.

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

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

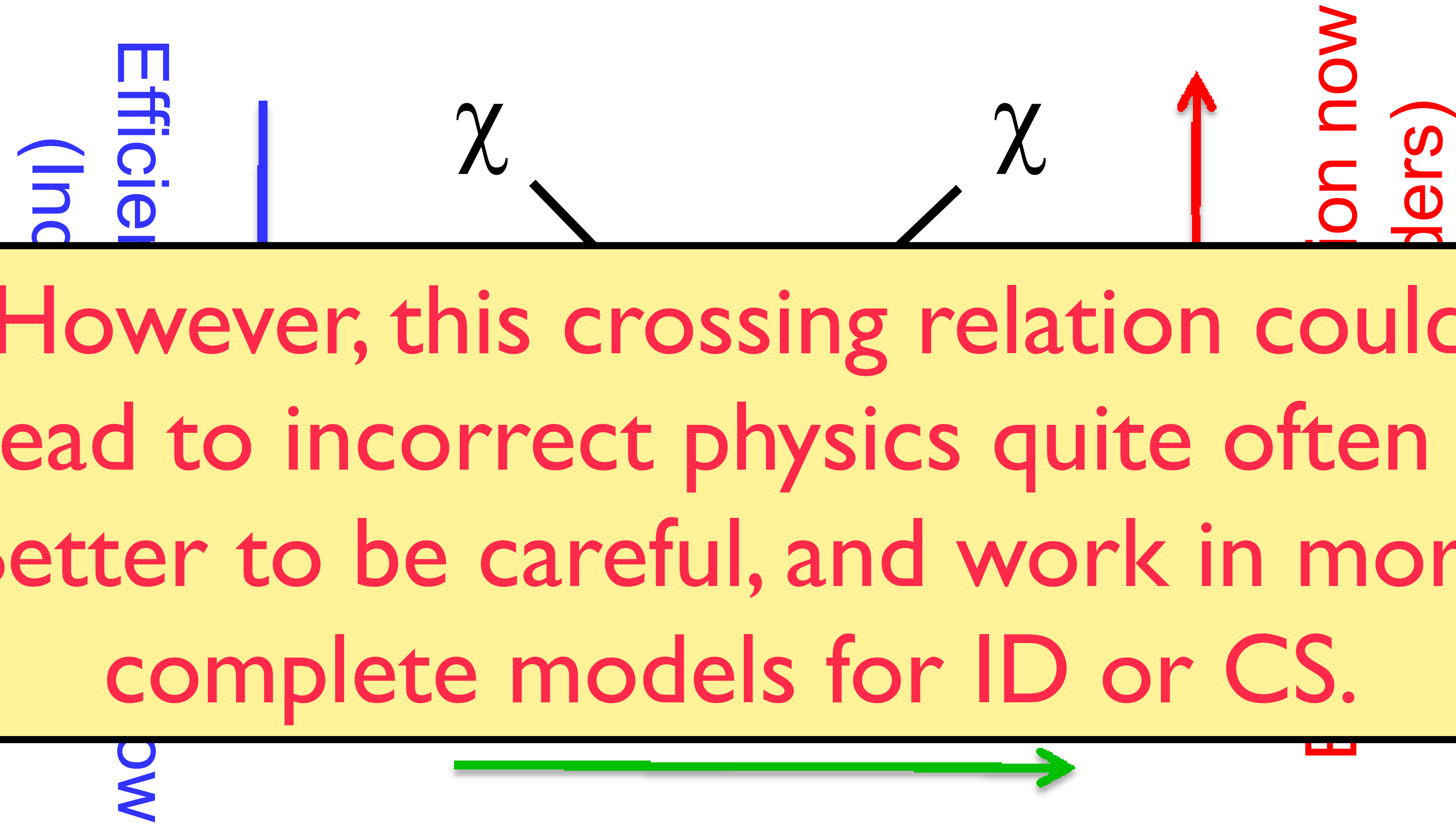
Crossing & WIMP detection

Correct relic density → Efficient annihilation then



Crossing & WIMP detection

Correct relic density → Efficient annihilation then



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

Efficient scattering now
(Direct detection)

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

arXiv:1506.06556
Phys. Lett. B756 (2016)289

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

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

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

Both break SM gauge invariance

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

Need the mixing between s and h

Full Theory Calculation

$$\boxed{\chi(p) + q(k) \to \chi(p') + q(k')}$$

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

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

Monojet+missing ET

Can be obtained by crossing : s <>t

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

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

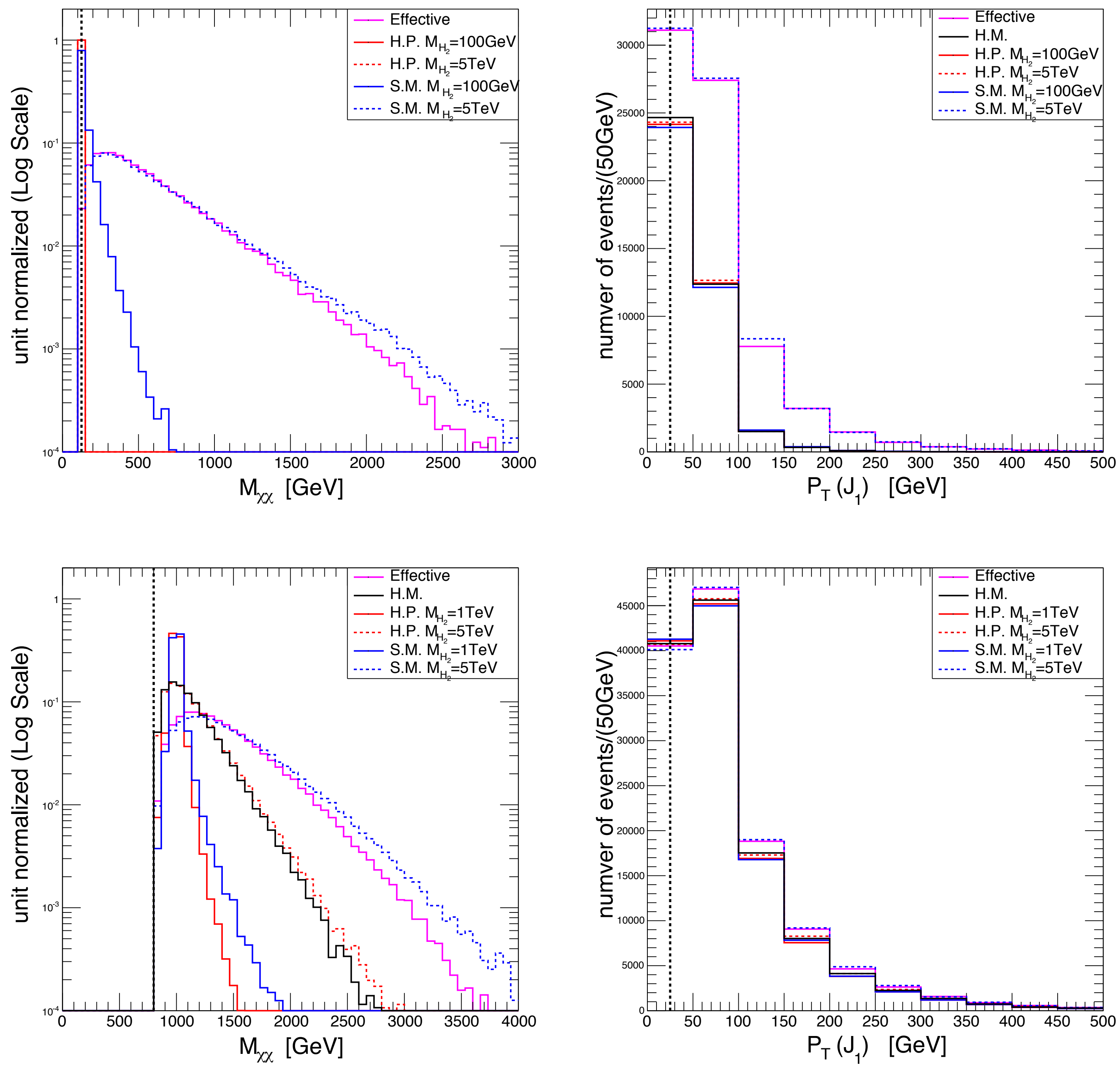


FIG. 1: In ATLAS 8TeV mono-jet+$\not{E}_T$ search [6] we plot $M_{\chi\chi}$ and the P_T of a hardest jet in a reconstruction level (after a detector simulation). Upper panels are with $m_\chi = 50\,\text{GeV}$ and lower panels are of $m_\chi = 400\,\text{GeV}$.

- 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).

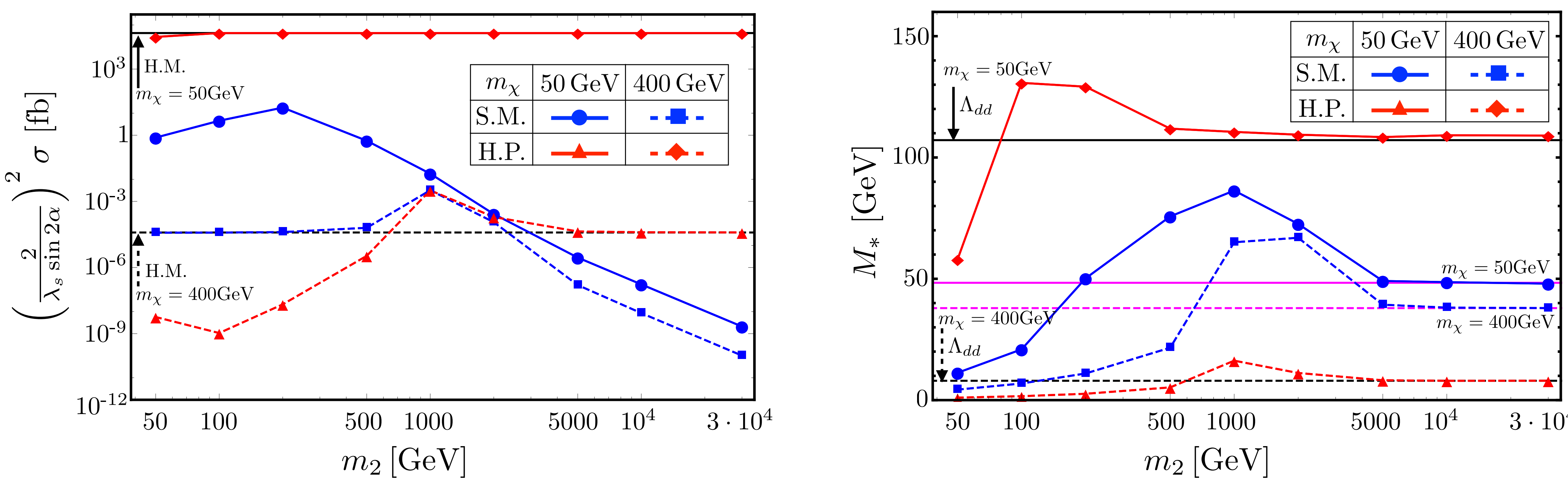


FIG. 1: We follow ATLAS 8TeV mono-jet+$\not{E}_T$ searches [2]. For (a) we simulated various models for the

tT + missing ET

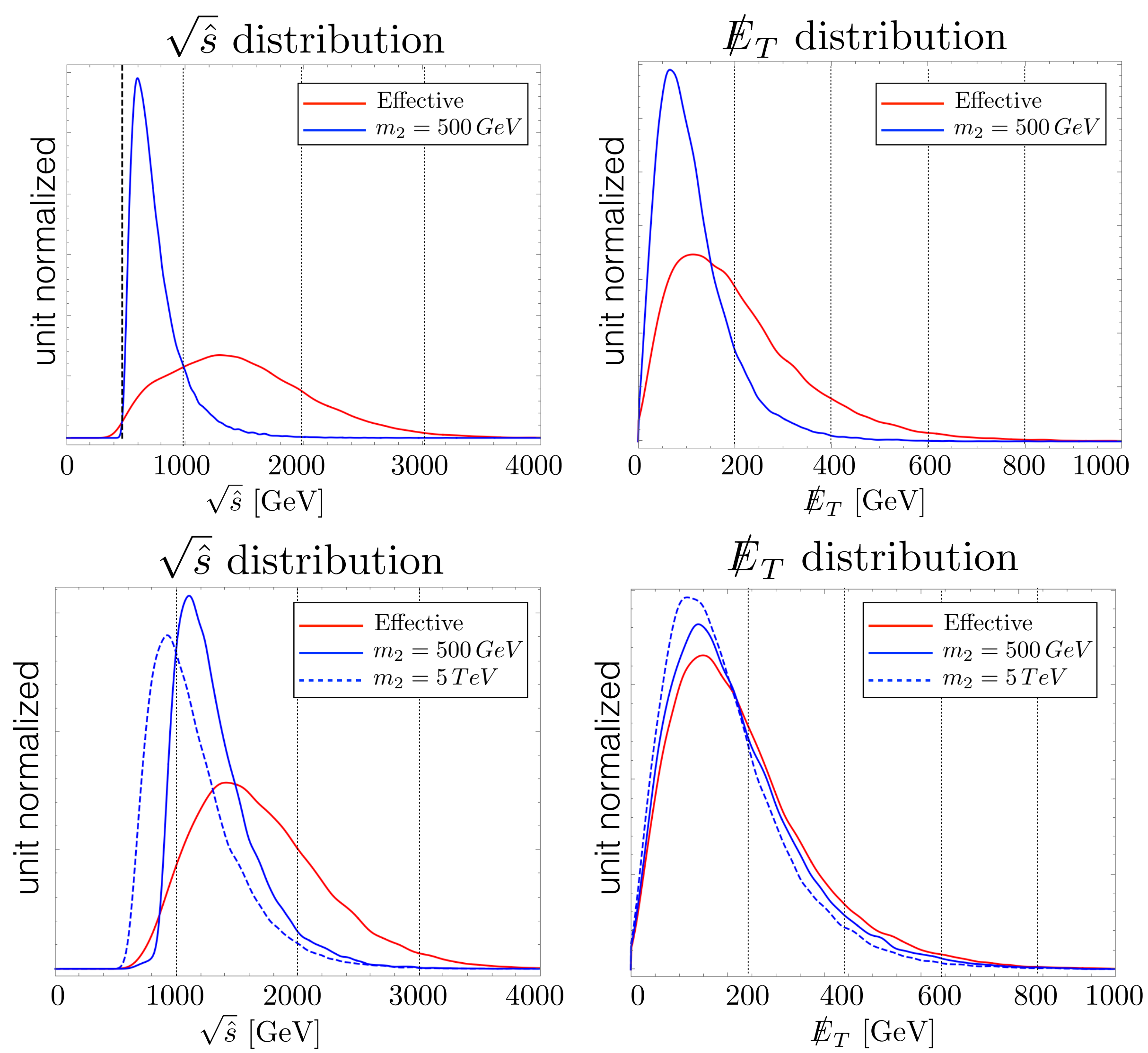


FIG. 2: Parton level distributions of various variables in a $(t\bar{t}\chi\bar{\chi})$ channel for a dark matter's mass $m_\chi = 10\,\text{GeV}$ (above) and $m_\chi = 100\,\text{GeV}$ (below) for LHC 8TeV. As we can see here, due to a higgs propagator, even when $m_2 \to \infty$ case, a missing transverse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

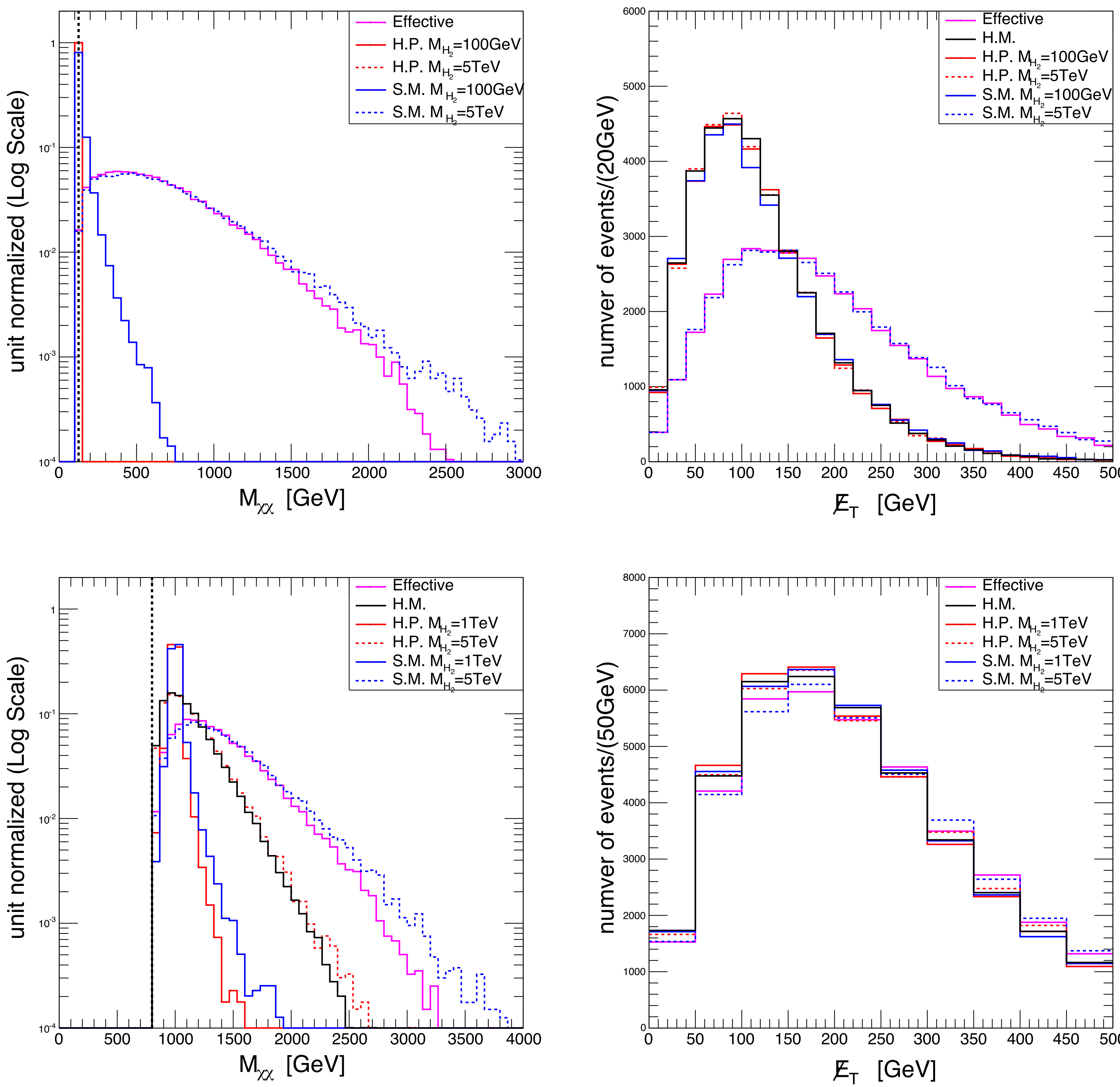


FIG. 4: With CMS 8TeV $t\bar{t} + \not{E}_T$ search [6], we plot $M_{\chi\chi}$ and the $\not{E}_T$ in a reconstruction level. Upper panels are with $M_\chi = 50\,\text{GeV}$ and lower panels are of $M_\chi = 400\,\text{GeV}$.

- 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).

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

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

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

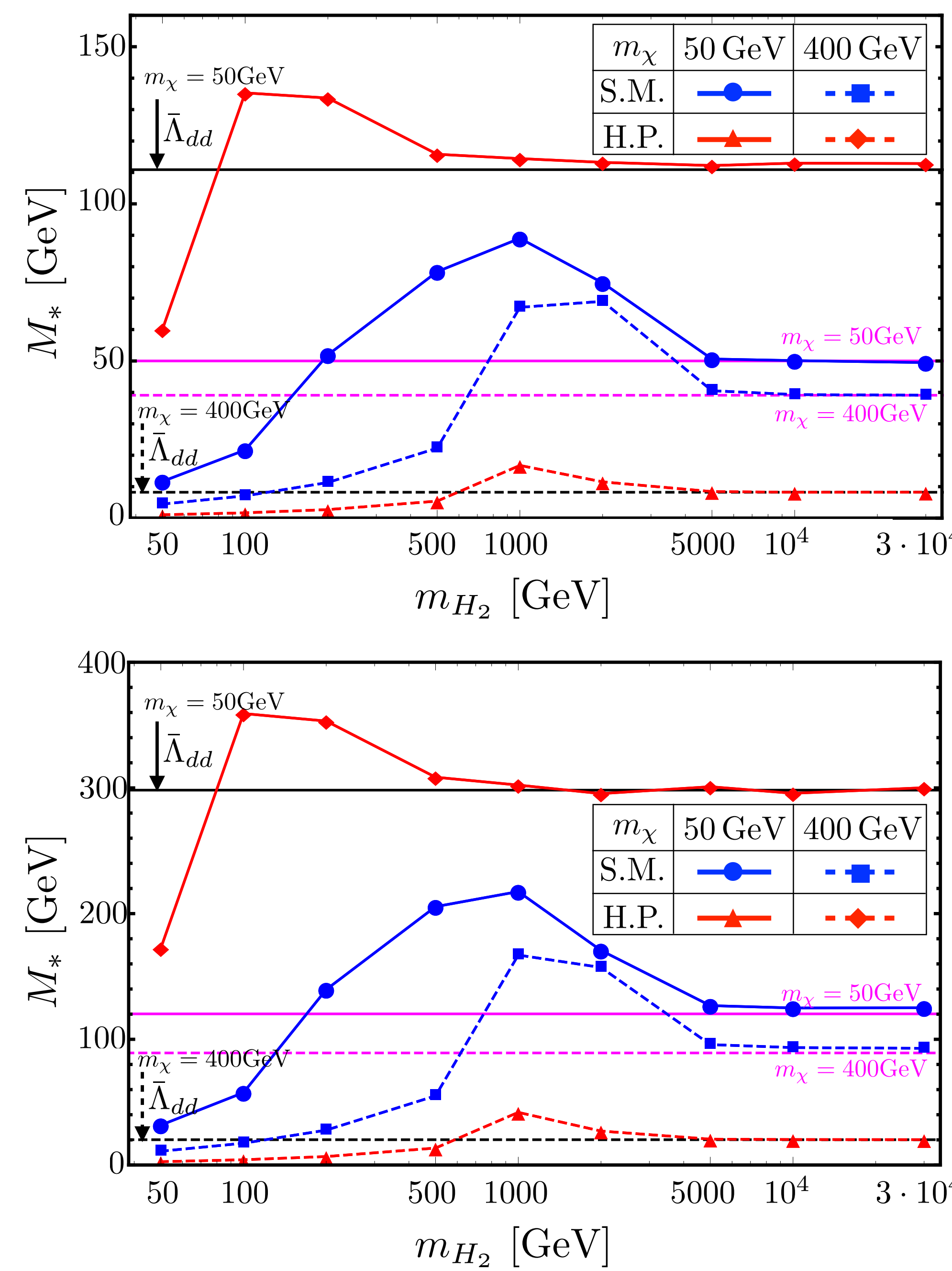


FIG. 3: The experimental bounds on M_* at 90% C.L. as a function of m_{H_2} (m_S in S.M. case) in the monojet+$\not{E}_T$ search (upper) and $t\bar{t} + \not{E}_T$ search (lower). Each line corresponds to the EFT approach (magenta), S.M. (blue), H.M. (black), and H.P. (red), respectively. The bound of 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: $2m_\chi \ll m_{125} \ll m_2 \ll \sqrt{s}$

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

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

No single EFT applicable to the entire tau regions

Indirect Detection

$$
\begin{aligned}
|\frac{1}{\Lambda^3_{ann}}| &\simeq \frac{1}{\Lambda^3_{dd}}\left|\frac{m^2_{125}}{4m^2_\chi - m^2_{125} + i m_{125}\Gamma_{125}} - \frac{m^2_{125}}{4m^2_\chi - m^2_2 + i m_2\Gamma_2}\right| \\
&\to \frac{1}{\Lambda^3_{dd}}\left|\frac{m^2_{125}}{4m^2_\chi - m^2_{125} + i m_{125}\Gamma_{125}}\right| \neq \frac{1}{\Lambda^3_{dd}}
\end{aligned}
$$

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

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)
- We are working on simplified models with all these conditions (coming soon)

Higgs portal DM at ILC (/s=500GeV)

with Hiroshi Yokoya (QUC,KIAS)
arXiv:1603.04737

Higgs Strahlung

$$e^{+}(p_1) + e^{-}(p_2) \to h^{*}(q) + Z(p_Z) \to S(k_1) + S(k_2) + Z(p_Z)$$

Differential cross section

$$\boxed{\frac{d\sigma_{SD}}{dt} = \frac{1}{2\pi}\sigma_{h^* Z}(s,t) \cdot F_S(t)}$$

$$\lambda_F = y_F \sin\alpha\cos\alpha.$$

$$\mu_V = \lambda_V m_D = 2m_D^2/v_\phi \cdot \sin\alpha\cos\alpha$$

$$F_S(t) = C_S \frac{\beta_D}{8\pi}\left|\frac{2\lambda_{HS} v}{t - m_h^2 + i m_h \Gamma_h}\right|^2$$

$$F_F(t) = C_F \lambda_F^2 \cdot \frac{\beta_D^3}{8\pi} \cdot 2t \cdot \left|\frac{1}{t - m_1^2 + i m_1 \Gamma_1} - \frac{1}{t - m_2^2 + i m_2 \Gamma_2}\right|^2$$

$$F_V(t) = C_V \frac{\beta_D}{8\pi} \cdot \frac{\mu_V^2 t^2}{4 m_D^4}\left(1 - \frac{4m_D^2}{t} + \frac{12 m_D^4}{t^2}\right) \cdot \left|\frac{1}{t - m_1^2 + i m_1 \Gamma_1} - \frac{1}{t - m_2^2 + i m_2 \Gamma_2}\right|^2$$

General Comments

- One can calculate the collider signatures at high energy scale, since the amplitudes were obtained in renormalizable and unitary models for singlet fermion DM and VDM
- There are two scalar propagators for SFDM and VDM, because of the SM gauge sym, unitarity and renormalizability
- EFT results can be obtained only if H2 is much heavier than the ILC CM energy

Asymtotic behavior in the full theory

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

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

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

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

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

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

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

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

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

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

Unitarity violated !

Recoil mass distribution

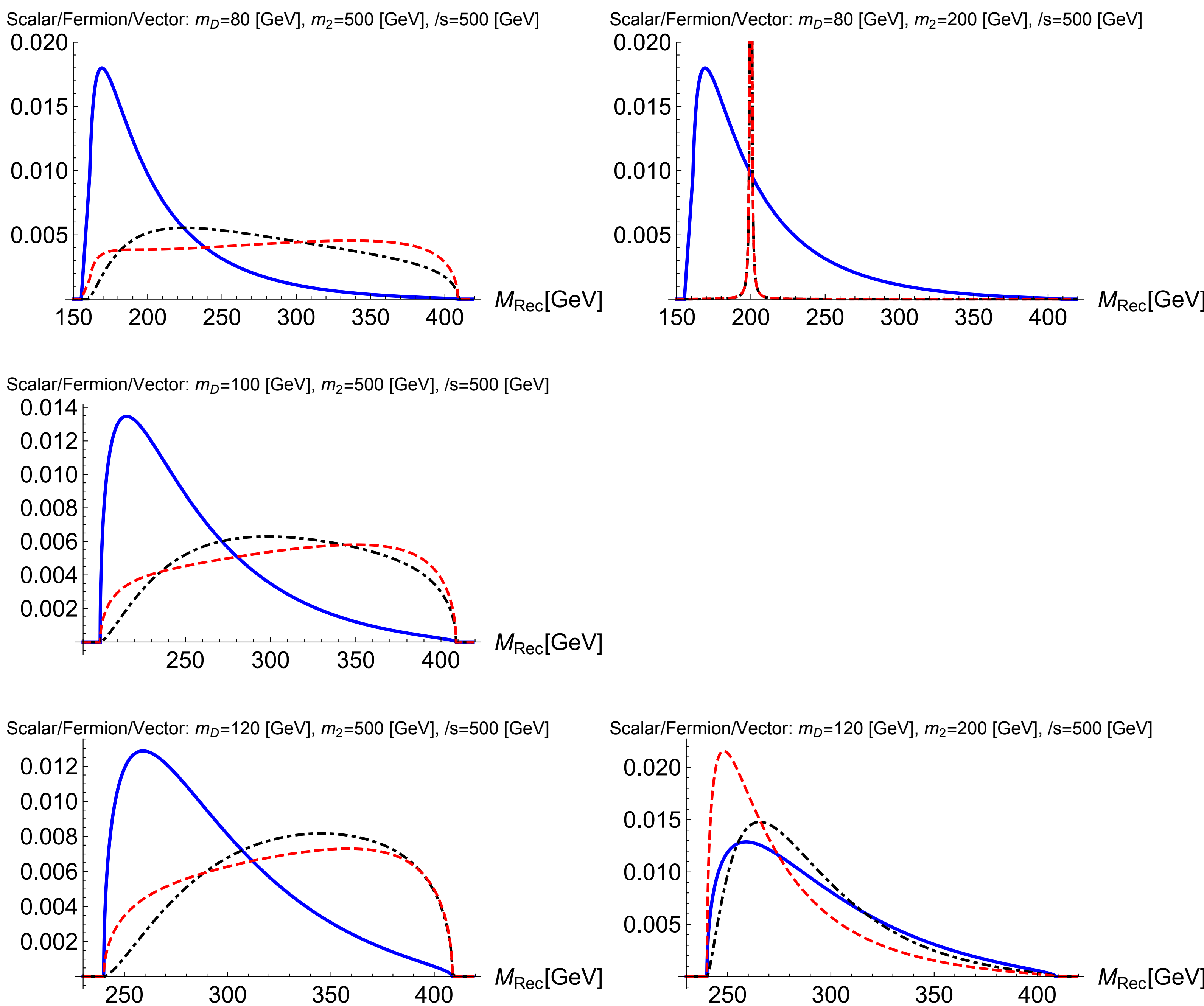


Figure 1: Normalized Distribution of the Recoil mass. Blue: Scalar DM, Black: Fermion DM, Red: Vector DM.

H2 mass dependence

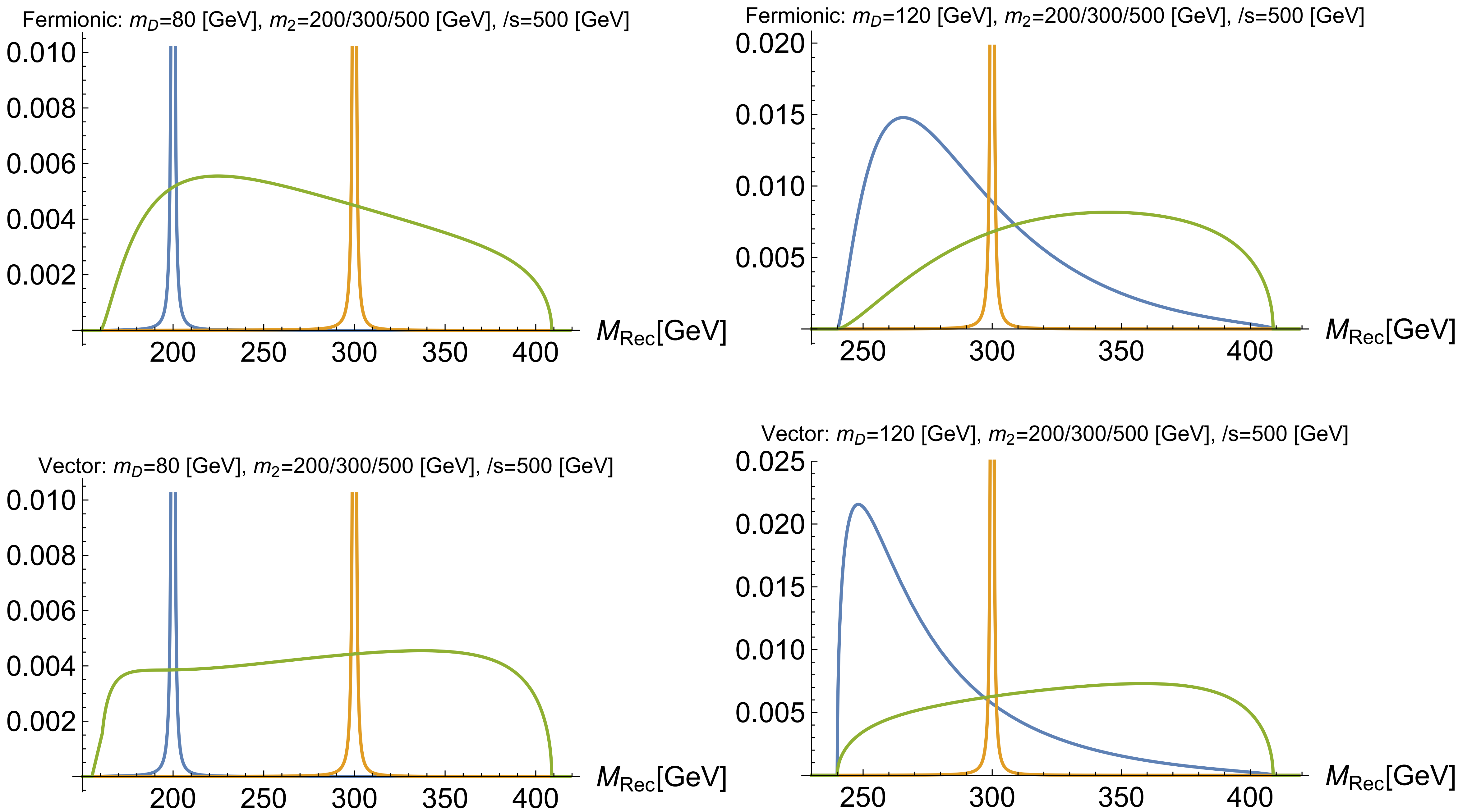


Figure 2: Normalized Distribution of the Recoil mass. Blue: $m_{H_2} = 200$ GeV, Orange: 300 GeV, Green: 500 GeV.

Total cross sections

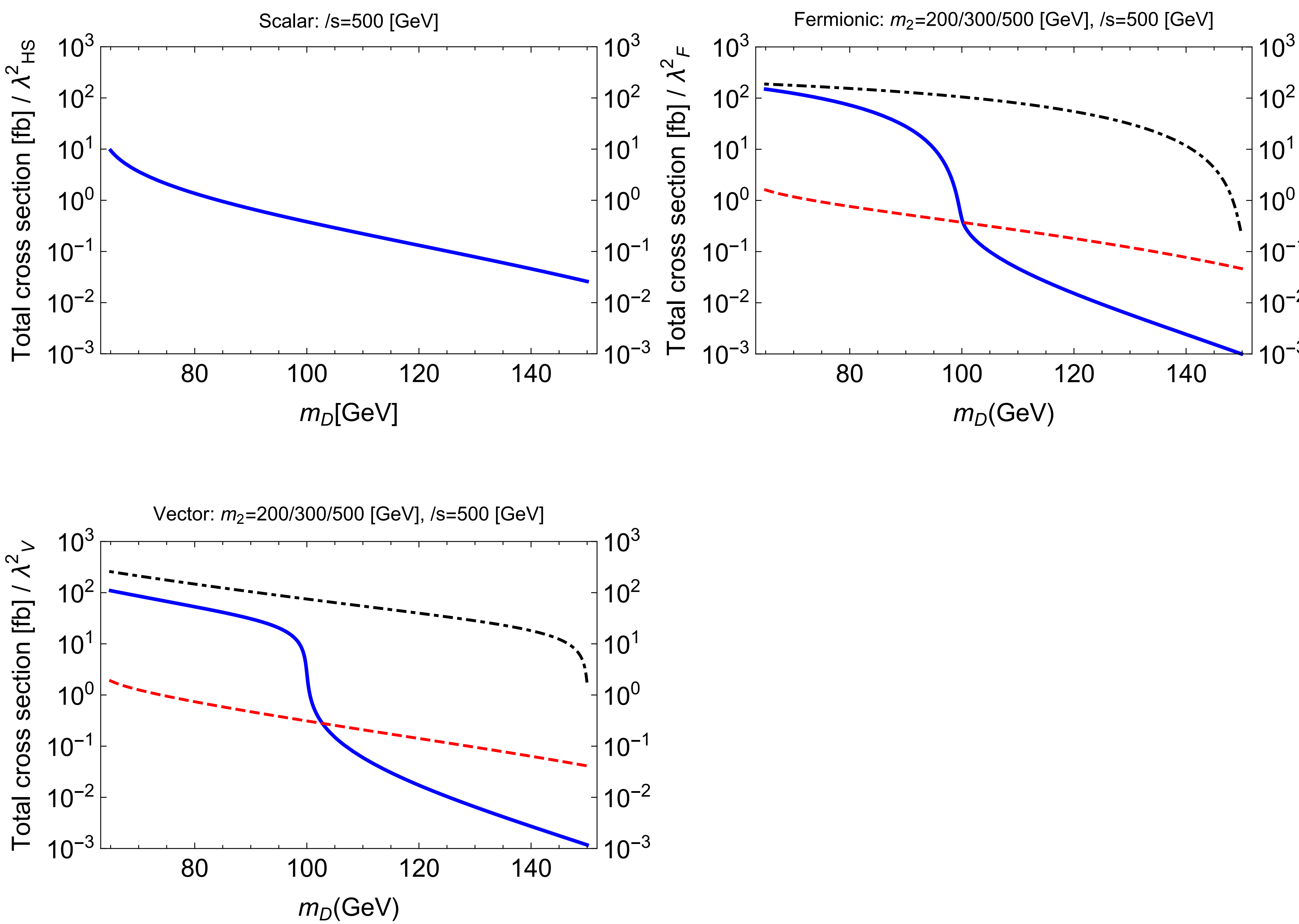


Figure 3: Total Cross sections for $e^+e^- \to ZDD$ at $\sqrt{s} = 500$ GeV. λ_{HS}, λ_F, λ_V are set to unity, and $m_{H_2} = 200$ (Blue), 300 (Black), 500 GeV (Red) are taken for Fermion and Vector DM models.

Parameter Constraints

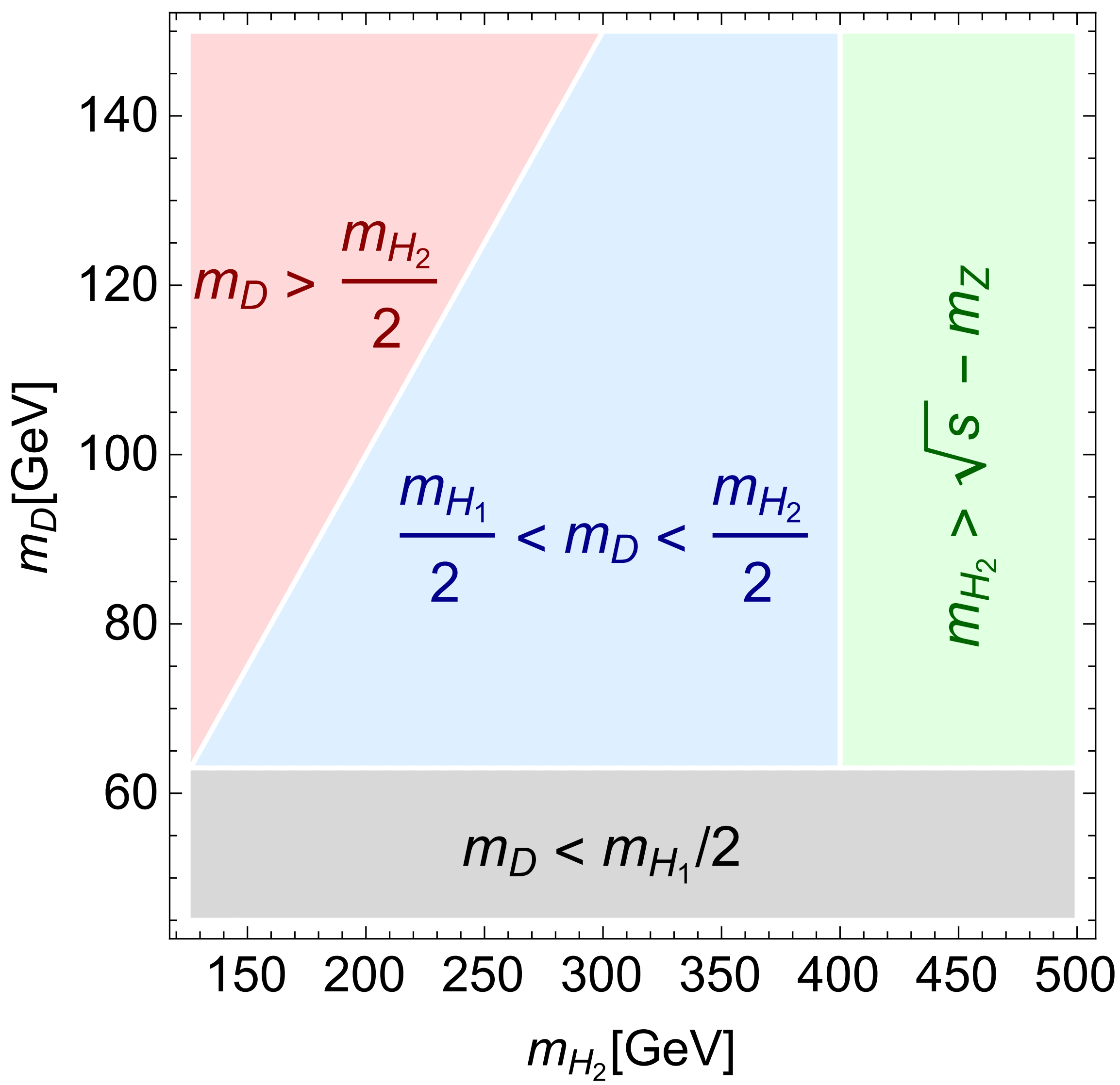


Figure 4:

Event selections

$$e^+e^- \to ZDD \to (jj \text{ or } \ell^+\ell^-) + \not{E}_T$$

$$p_T^Z \geq 100 \text{ GeV},$$

$$\left|\eta^Z\right| \leq 1.,$$
$$m_{H_2} \leq M_{\rm rec} \leq m_{H_2} + 50 \ [\text{GeV}]$$

$$S = \frac{\sigma_{ZDD}\mathcal{B}(Z \to jj)\epsilon_S \mathcal{L}}{\sqrt{\sigma_{\rm BG}\mathcal{B}(Z \to jj)\epsilon_B \mathcal{L}}} \quad > 5$$

Discovery potential

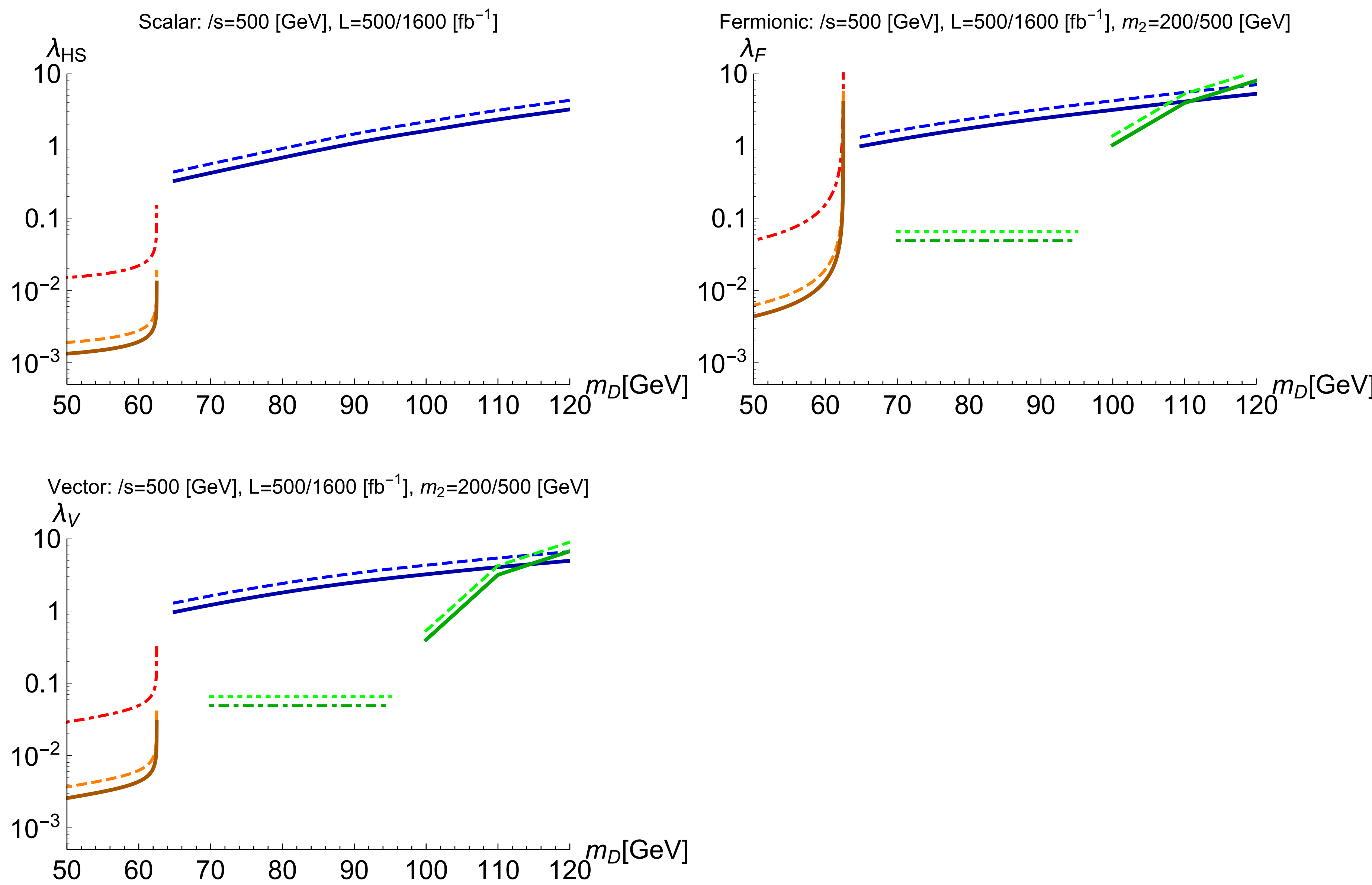


Figure 5: Contour plots for the discovery potential at 95% C.L. in $e^+e^- \to Z(\to jj)DD$ searches at the ILC with $\sqrt{s} = 500$ GeV and $\mathcal{L} = 500,\ 1600$ [fb^{-1}]. Red contour is the limit by the invisible Higgs decay search at the LHC, and orange contours are the expected limits at the ILC. Blue and green contours are the expected limit by the $Z + \not{E}_T$ searches at the ILC. For the fermion and vector DM models, blue (green) contours are for $m_{H_2} = 500$ GeV (200 GeV).

Take-Home Messages

- Lorentz/Poincare symmetry
- Local gauge symmetry (G_{SM} X G_{Dark} ?)
- Unitarity (and renormalizability) is important for collider study, especially for hadron colliders (because the parton level CM energy is not fixed)
- UV compete Lagrangian > low E EFT for direct detection

Simplified DM model with full SM gauge sym

- Fermions in 4-dim : chiral
- Mono X + missing ET : X=W, Z, g, gamma,.. probe different chiral structure, namely different aspects (parts) of dark sector
- We can not control the chiral structures of the initial states at hadron colliders
- Ko, Natale, Park, Yokoya in preparation

Conclusion

- Higgs portal DM : simple viable DM models (natural if one assumes dark gauge sym)
- EFT: not reliable for collider searches for DM, and one has to consider UV completions
- Full SM gauge symmetry, renormalizability, and unitarity are important for constructing UV completions and for collider study
- Search for Higgs portal DM at ILC, FCC-ee, LHC and FCC-hh, SPPC being studied

Backup I

SM Lagrangian

$$\mathcal{L}_{MSM} = -\frac{1}{2g_s^2}\mathrm{Tr}G_{\mu\nu}G^{\mu\nu} - \frac{1}{2g^2}\mathrm{Tr}W_{\mu\nu}W^{\mu\nu}$$
$$-\frac{1}{4g'^2}B_{\mu\nu}B^{\mu\nu} + i\frac{\theta}{16\pi^2}\mathrm{Tr}G_{\mu\nu}\tilde{G}^{\mu\nu} + M_{Pl}^2 R$$
$$+|D_\mu H|^2 + \bar{Q}_i i\not{D} Q_i + \bar{U}_i i\not{D} U_i + \bar{D}_i i\not{D} D_i$$
$$+\bar{L}_i i\not{D} L_i + \bar{E}_i i\not{D} E_i - \frac{\lambda}{2}\left(H^\dagger H - \frac{v^2}{2}\right)^2$$
$$-\left(h_u^{ij} Q_i U_j \tilde{H} + h_d^{ij} Q_i D_j H + h_l^{ij} L_i E_j H + c.c.\right) .(1)$$

Based on local gauge principle

Only Higgs (~SM) and Nothing Else So Far at the LHC &

Local Gauge Principle Works !

Building Blocks of SM

- Lorentz/Poincare Symmetry
- Local Gauge Symmetry : Gauge Group + Matter Representations from Experiments
- Higgs mechanism for masses of weak gauge bosons and SM chiral fermions
- These principles lead to unsurpassed success of the SM in particle physics

Lessons from SM

- Specify local gauge sym, matter contents and their representations under local gauge group
- Write down all the operators upto dim-4
- Check anomaly cancellation
- Consider accidental global symmetries
- Look for nonrenormalizable operators that break/conserve the accidental symmetries of the model

- If there are spin-1 particles, extra care should be paid : need an agency which provides mass to the spin-1 object
- Check if you can write Yukawa couplings to the observed fermion
- One may have to introduce additional Higgs doublets with new gauge interaction if you consider new chiral gauge symmetry (Ko, Omura, Yu on chiral U(1)' model for top FB asymmetry)
- Impose various constraints and study phenomenology

(3,2,1) or SU(3)cXU(1)em ?

- Well below the EW sym breaking scale, it may be fine to impose SU(3)c X U(1)em
- At EW scale, better to impose (3,2,1) which gives better description in general after all
- Majorana neutrino mass is a good example
- For example, in the Higgs + dilaton (radion) system, and you get different results
- Singlet mixing with SM Higgs