$U(1)_H$ extensions of 2HDM's

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After the Higgs boson discovery, we are deeply depressed

- What would be the next ?
- Let me experiment with new ideas (not on SUSY, RS, (partially) composite Higgs boson, etc..), while waiting for exciting news from various experiments/observations
- Personal favorite : (chiral) gauge principle, (local) scale invariance for gravity (Weyl quadratic gravity) in particle physics and cosmology
- Note that both gauge principle and general covariance extremely well tested in many different circumstances

Contents

- Ingredients of the extremely successful SM
- Examples of importance of gauge sym in DM physics
- Motivations for $U(1)_H$ extensions of 2HDM
- Type-I 2HDM (including Inert 2HDM), Type-II 2HDM
- New chiral gauge sym requires more Higgs doublets
- Side remark on Classical scale invariance (CSI)
- Conclusion

Ingredients of the extremely successful SM

SM Lagrangian

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

Based on local gauge principle

- Only Higgs (~SM) and Nothing Else so far at the LHC (No SUSY, KK, etc..)
- Our perception for the fine tuning problem is to be modified (revised) ???
- Nature is surely described by Local Gauge Theories and QFT works
- All the observed particles carry some gauge charges (no gauge singlets observed so far)
- And no higher dim representations for matter fields (gauge fields~adj)

Phenomonological Motivations for BSM

- Neutrino masses and mixings
- Baryogenesis — Leptogenesis & many other ways
- Inflation (inflaton) — Starobinsky ? Higgs Inflations
- Nonbaryonic DM — Many candidates for CDM
- Origin of EWSB and Cosmological Const ?

Can we attack these problems ?

Ingredients of the SM

- Success of the Standard Model of Particle Physics lies in Poincare sym + “local gauge symmetry” without imposing any internal global symmetries
- electron stability : U(1)em gauge invariance, electric charge conservation
- proton longevity : baryon # is an accidental sym; proton composite
- No gauge singlets in the SM ; all the SM fermions chiral
- Only fundamental rep’s

Ingredients of the SM

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  invarianc
  conserva
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P, C invariance of low energy QED, QCD : accidental sym of the SM

SM vs. DM models

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- proton longevity : baryon # is an accidental sym; proton composite
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- Dark sector with (excited) dark matter, dark radiation and force mediators might have the same structure as the SM
- “Chiral dark gauge theories without any global sym”
- Origin of DM stability/ longevity from dark gauge sym, and not from dark global symmetries, as in the SM
- Just like the SM (conservative)

In QFT

- DM could be absolutely stable due to unbroken local gauge symmetry (DM with local Z_2, Z_3 etc.) or topology (hidden sector monopole + vector DM + dark radiation)
- Longevity of DM could be due to some accidental symmetries (hidden sector pions and baryons)
- In any case, DM models with local dark gauge symmetry ~ the success of the SM

Examples of importance of gauge symmetry in DM physics

WIMP with ad hoc Z2 sym

- Global sym. is not enough since

$$-\mathcal{L}_{\rm int} = \begin{cases} \lambda \frac{\phi}{M_{\rm P}} F_{\mu\nu} F \mu\nu & \text{for boson} \\ \lambda \frac{1}{M_{\rm P}} \bar{\psi} \gamma^\mu D_\mu \ell_{Li} H^\dagger & \text{for fermion} \end{cases}$$

Observation requires [M.Ackermann et al. (LAT Collaboration), PRD 86, 022002 (2012)]

$$\tau_{\rm DM} \gtrsim 10^{26-30} {\rm sec} \Rightarrow \begin{cases} m_\phi \lesssim \mathcal{O}(10){\rm keV} \\ m_\psi \lesssim \mathcal{O}(1){\rm GeV} \end{cases}$$

$\Rightarrow$ WIMP is unlikely to be stable

- SM is guided by gauge principle

It looks natural and may need to consider a gauge symmetry in dark sector, too.

Why Dark Symmetry ?

- Is DM absolutely stable or very long lived ?
- If DM is absolutely stable, one can assume it carries a new conserved dark charge, associated with unbroken dark gauge sym
- DM can be long lived (lower bound on DM lifetime is much weaker than that on proton lifetime) if dark sym is spontaneously broken

Higgs is harmful to weak scale DM stability

Z_2 sym Scalar DM

$$\mathcal{L} = \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{1}{2} m_S^2 S^2 - \frac{\lambda_S}{4!} S^4 - \frac{\lambda_{SH}}{2} S^2 H^\dagger H.$$

- Very popular alternative to SUSY LSP
- Simplest in terms of the # of new dof's
- But, where does this Z2 symmetry come from ?
- Is it Global or Local ?

Fate of CDM with Z2 sym

- Global Z2 cannot save EW scale DM from decay with long enough lifetime

Consider Z_2 breaking operators such as

$$\frac{1}{M_{\rm Planck}} S O_{\rm SM}$$

keeping dim-4 SM operators only

The lifetime of the Z_2 symmetric scalar CDM S is roughly given by

$$\Gamma(S) \sim \frac{m_S^3}{M_{\rm Planck}^2} \sim \left(\frac{m_S}{100{\rm GeV}}\right)^3 10^{-37} GeV$$

The lifetime is too short for ~100 GeV DM

Fate of CDM with Z2 sym

Spontaneously broken local U(1)X can do the job to some extent, but there is still a problem

Let us assume a local $U(1)_X$ is spontaneously broken by $\langle \phi_X \rangle \neq 0$ with

$$Q_X(\phi_X) = Q_X(X) = 1$$

Then, there are two types of dangerous operators:

$\phi_X^\dagger X H^\dagger H,$ and $\phi_X^\dagger X O_{\rm SM}^{(dim-4)}$

Problematic !

Perfectly fine !

- These arguments will apply to DM models based on ad hoc symmetries (Z_2,Z_3 etc.)
- One way out is to implement Z_2 symmetry as local U(1) symmetry (arXiv:1407.6588 with Seungwon Baek and Wan-Il Park);
- See a paper by Ko and Tang on local Z_3 scalar DM, and another by Ko, Omura and Yu on inert 2HDM with local $U(1)_H$
- DM phenomenology richer and DM stability/ longevity on much solider ground

$Q_X(\phi) = 2, \quad Q_X(X) = 1$

arXiv:1407.6588 w/ WIPark and SBaek

$$\mathcal{L} = \mathcal{L}_{\rm SM} + -\frac{1}{4} X_{\mu\nu} X^{\mu\nu} - \frac{1}{2}\epsilon X_{\mu\nu} B^{\mu\nu} + D_\mu \phi_X^\dagger D^\mu \phi_X - \frac{\lambda_X}{4}\left(\phi_X^\dagger \phi_X - v_\phi^2\right)^2 + D_\mu X^\dagger D^\mu X - m_X^2 X^\dagger X$$
$$- \frac{\lambda_X}{4}\left(X^\dagger X\right)^2 - \left(\mu X^2 \phi^\dagger + H.c.\right) - \frac{\lambda_{XH}}{4} X^\dagger X H^\dagger H - \frac{\lambda_{\phi_X H}}{4} \phi_X^\dagger \phi_X H^\dagger H - \frac{\lambda_{XH}}{4} X^\dagger X \phi_X^\dagger \phi_X$$

The lagrangian is invariant under $X \to -X$ even after $U(1)_X$ symmetry breaking.

Unbroken Local Z2 symmetry

Gauge models for excited DM

$X_R \to X_I \gamma_h^*$ followed by $\gamma_h^* \to \gamma \to e^+ e^-$ etc.

The heavier state decays into the lighter state

The local Z2 model is not that simple as the usual Z2 scalar DM model (also for the fermion CDM)

Model Lagrangian

$$q_X(X,\phi) = (1,2)$$

[1407.6588, Seungwon Baek, P. Ko & WIP]

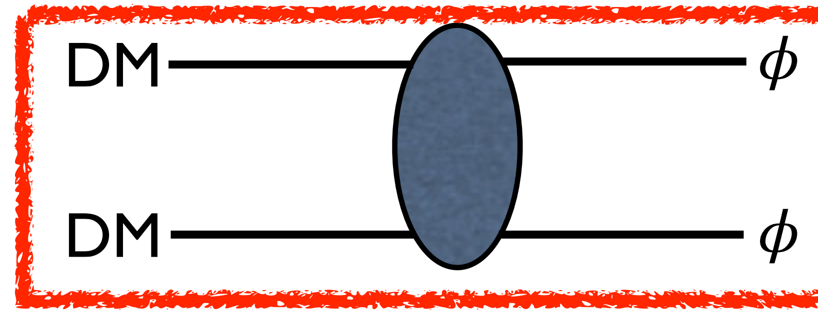
$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{4}\hat{X}_{\mu\nu}\hat{X}^{\mu\nu} - \frac{1}{2}\sin\epsilon\hat{X}_{\mu\nu}\hat{B}^{\mu\nu} + D_\mu\phi D^\mu\phi + D_\mu X^\dagger D^\mu X - m_X^2 X^\dagger X + m_\phi^2\phi^\dagger\phi$$
$$-\lambda_\phi\left(\phi^\dagger\phi\right)^2 - \lambda_X\left(X^\dagger X\right)^2 - \lambda_{\phi X}X^\dagger X\phi^\dagger\phi - \lambda_{\phi H}\phi^\dagger\phi H^\dagger H - \lambda_{HX}X^\dagger X H^\dagger H - \mu\left(X^2\phi^\dagger + H.c.\right).$$

- X : scalar DM (XI and XR, excited DM)
- phi : Dark Higgs
- X_mu : Dark photon
- 3 more fields than Z2 scalar DM model
- Z2 Fermion DM can be worked out too

- Some DM models with Higgs portal

  - Vector DM with Z2 [1404.5257, P. Ko, WIP & Y. Tang]

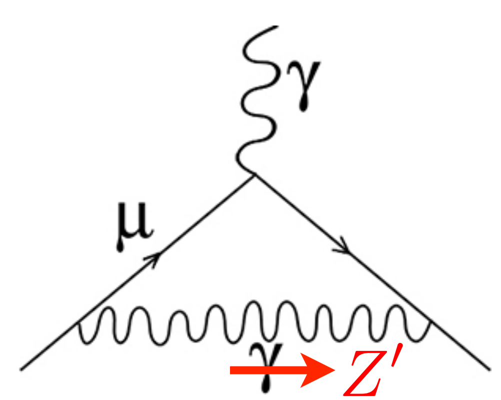
$$\mathcal{L}_{VDM} = -\frac{1}{4}X_{\mu\nu}X^{\mu\nu} + (D_\mu\Phi)^\dagger(D^\mu\Phi) - \lambda_\Phi\left(\Phi^\dagger\Phi - \frac{v_\Phi^2}{2}\right)^2 -\lambda_{\Phi H}\left(\Phi^\dagger\Phi - \frac{v_\Phi^2}{2}\right)\left(H^\dagger H - \frac{v_H^2}{2}\right),$$



  - Scalar DM with local Z2 [1407.6588, Seungwon Baek, P. Ko & WIP]

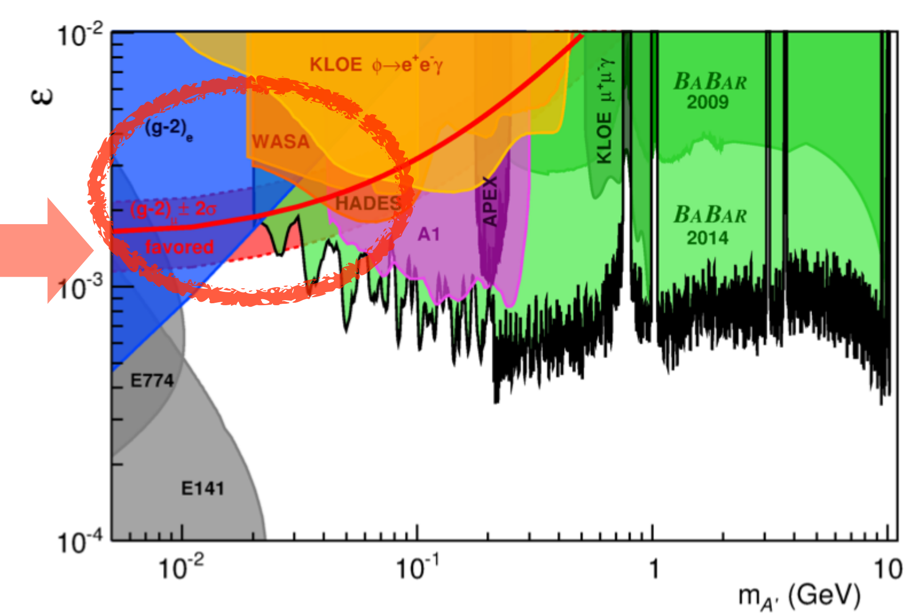
$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{4}\hat{X}_{\mu\nu}\hat{X}^{\mu\nu} - \frac{1}{2}\sin\epsilon\hat{X}_{\mu\nu}\hat{B}^{\mu\nu} + D_\mu\phi D^\mu\phi + D_\mu X^\dagger D^\mu X - m_X^2 X^\dagger X + m_\phi^2\phi^\dagger\phi -\lambda_\phi\left(\phi^\dagger\phi\right)^2 - \lambda_X\left(X^\dagger X\right)^2 - \lambda_{\phi X}X^\dagger X\phi^\dagger\phi - \lambda_{\phi H}\phi^\dagger\phi H^\dagger H - \lambda_{HX}X^\dagger X H^\dagger H - \mu\left(X^2\phi^\dagger + H.c.\right)$$

- muon (g-2) as well as GeV scale gamma-ray excess explained
- natural realization of excited state of DM
- free from direct detection constraint even for a light Z’



$$\Delta a_\mu \approx \frac{\alpha_{\rm em}\epsilon^2}{2\pi\cos\theta_W^2}$$

$$(\text{for } m_{Z'} \lesssim m_\mu)$$



[1406.2980, BaBar collaboration]

Talk by T. Matsui

- Local Z_2 Fermion DM (similiar to the local Z_2 scalar DM)
- Dark Higgs can play a very important role in DM phenomenology (relic density, indirect detection signatures, etc.), whereas it was largely ignored in most earlier literature

Gauge symmetries for (Stable) Vector Dark Matter

- Phenomenological models : Lebedev, Lee, Mambrini (2012) VDM + Higgs portal (EFT); Farzan and Akbarieh (2012), Baek, Ko, Park, Senaha (2012), Duch, Grzadkowski, McGarrie (2015), renormalizable models for VDM

- Completely broken dark gauge symmetries : Hambye (2009) dark SU(2); Gross, Lebedev, Mambrini (2015) completely broken SU(2), SU(3) [VDM decays because of dim>=5 op's]

- Dark gauge sym with unbroken subgroups : Baek, Ko, Park (2013) SO(3) broken to SO(2)~U(1), hidden sector (or dark monopole) + stable VDM ; Ko and Tang (2016), SU(3) broken to SU(2), stable VDM + Non-Abelian DR

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

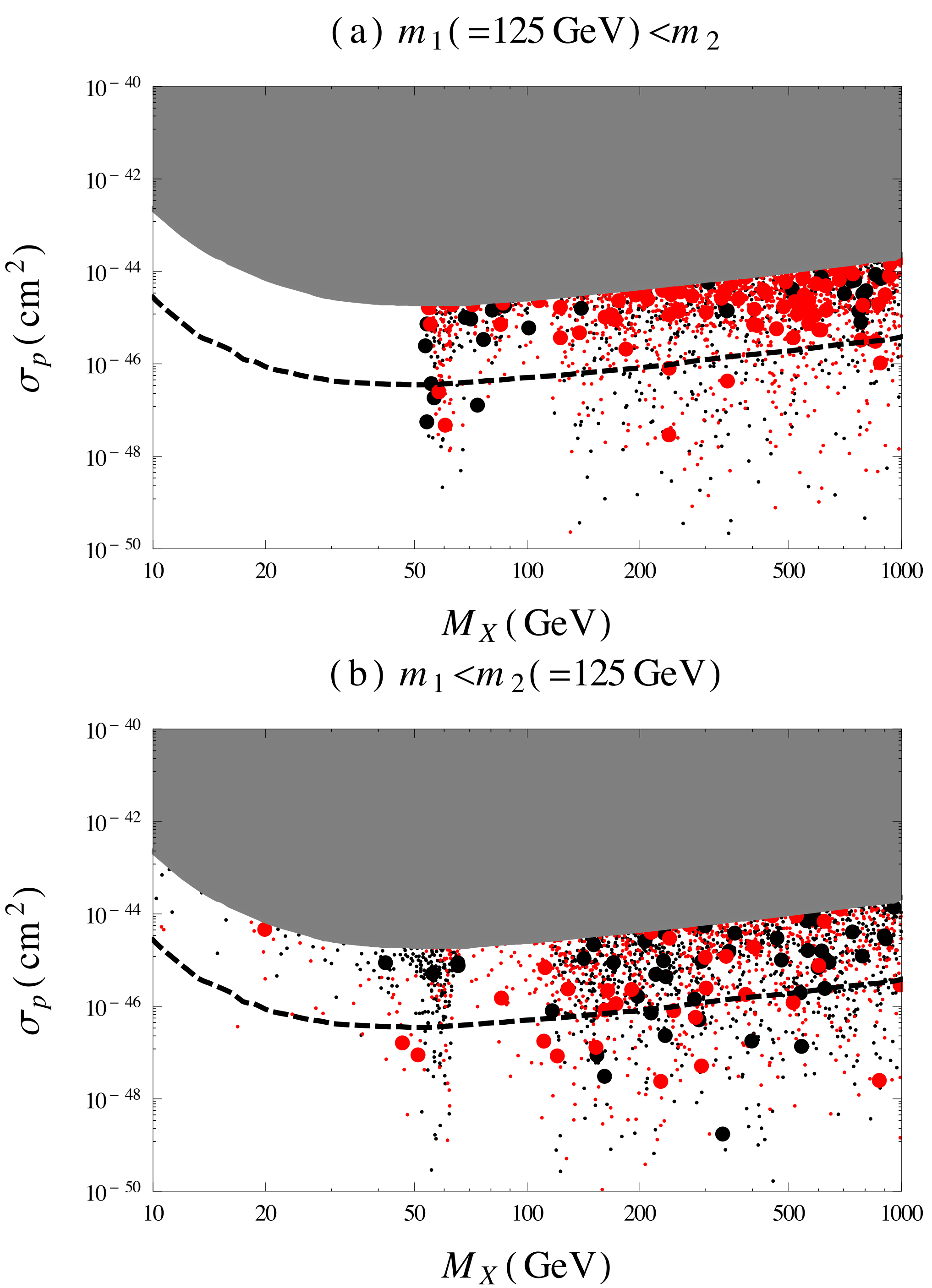


Figure 6. The scattered plot of σ_p as a function of M_X. The big (small) points (do not) satisfy the WMAP relic density constraint within 3 σ, while the red-(black-)colored points gives $r_1 > 0.7 (r_1 < 0.7)$. The grey region is excluded by the XENON100 experiment. The dashed line denotes the sensitivity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

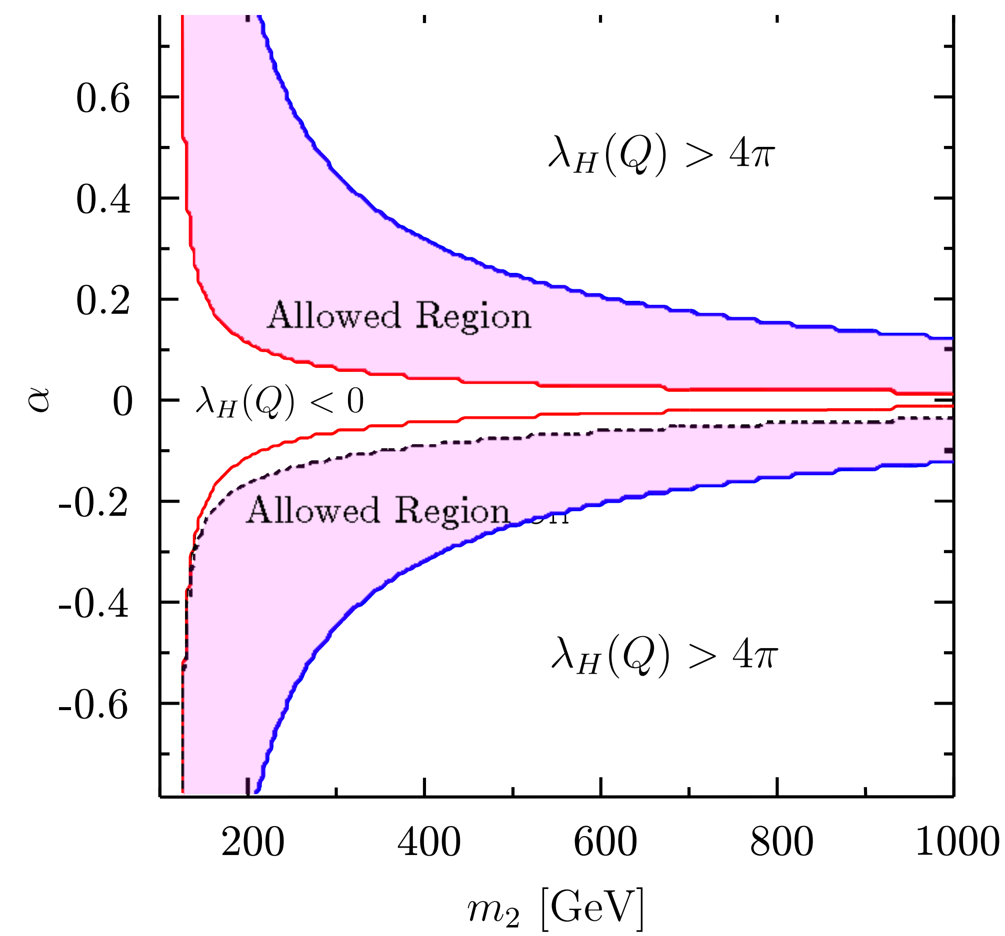


Figure 8. The vacuum stability and perturbativity constraints in the α-m_2 plane. We take $m_1 = 125$ GeV, $g_X = 0.05$, $M_X = m_2/2$ and $v_\Phi = M_X/(g_X Q_\Phi)$.

Higgs portal (EFT) no good

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

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

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

All invariant under ad hoc Z2 symmetry

arXiv:1112.3299, … 1402.6287, etc.

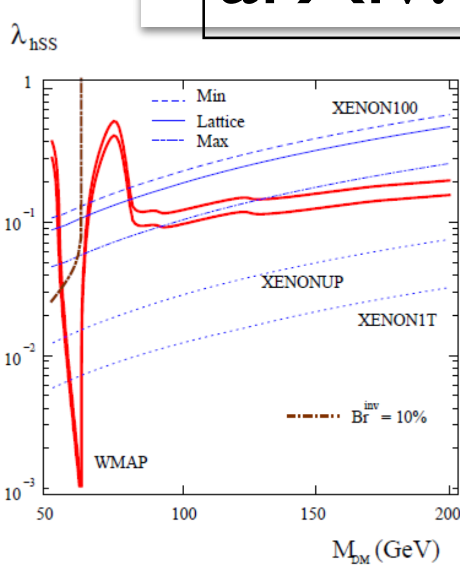


FIG. 1. Scalar Higgs-portal parameter space allowed by WMAP (between the solid red curves), XENON100 and $BR^{\rm inv} = 10\%$ for $m_h = 125$ GeV. Shown also are the prospects for XENON upgrades.

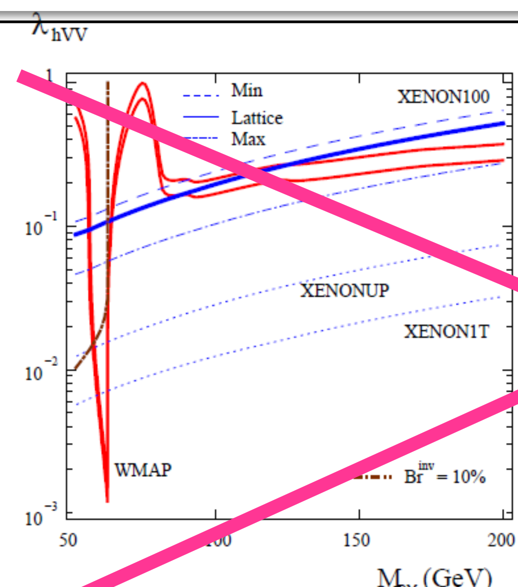


FIG. 2. Same as Fig. 1 for vector DM particles.

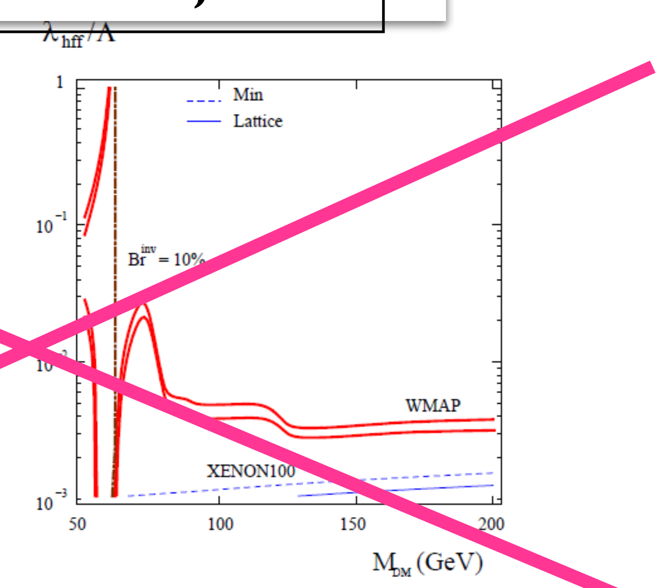


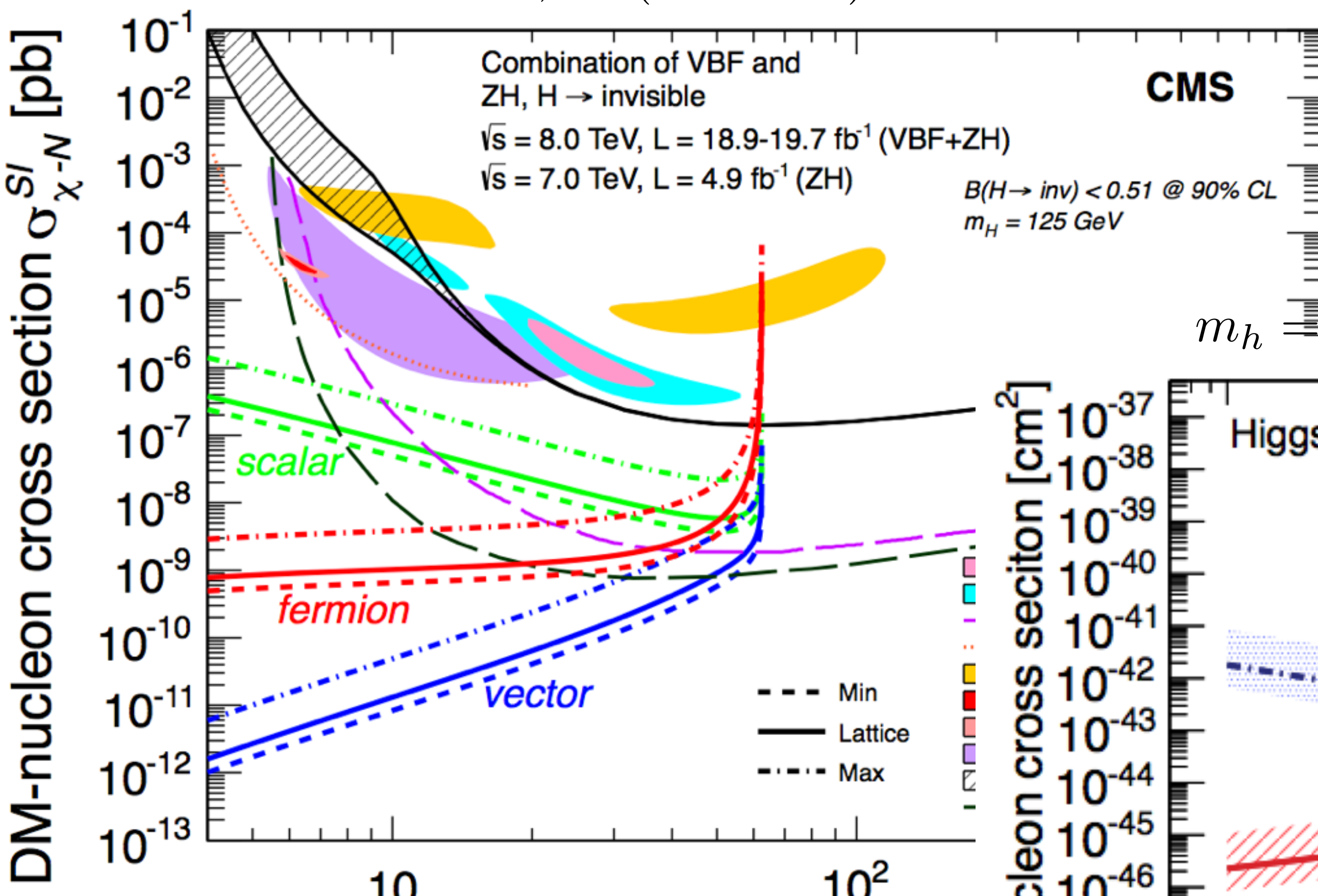
FIG. 3. Same as in Fig.1 for fermion DM; λ_{hff}/Λ is in GeV^{-1}.

Is this any useful and/or important in phenomenology ?

YES !

Collider Implications

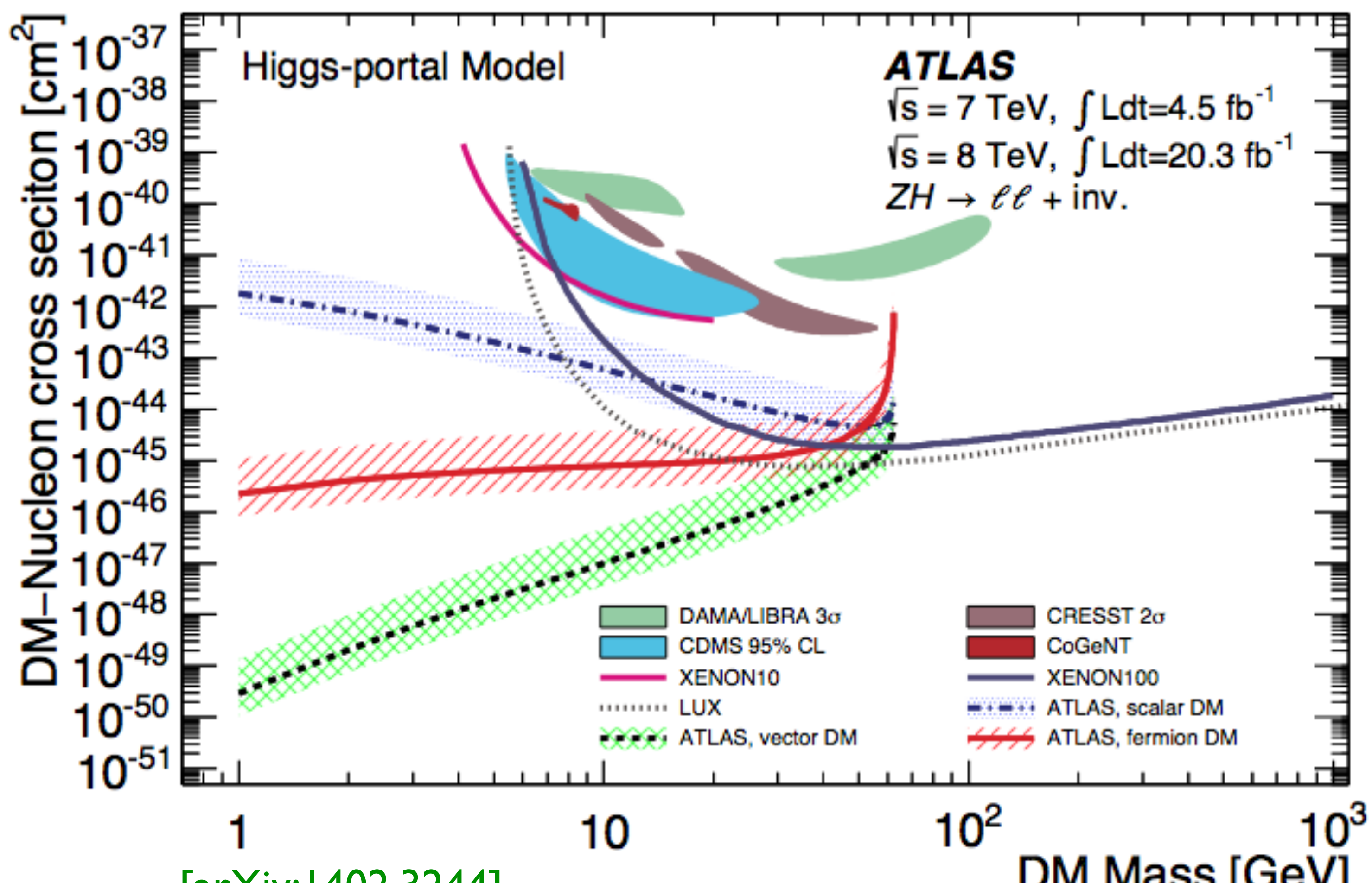
$m_h = 125\text{GeV},\ \text{Br}(H \to \text{inv}) < 0.51 \text{ at } 90\% \text{ CL}$



[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,

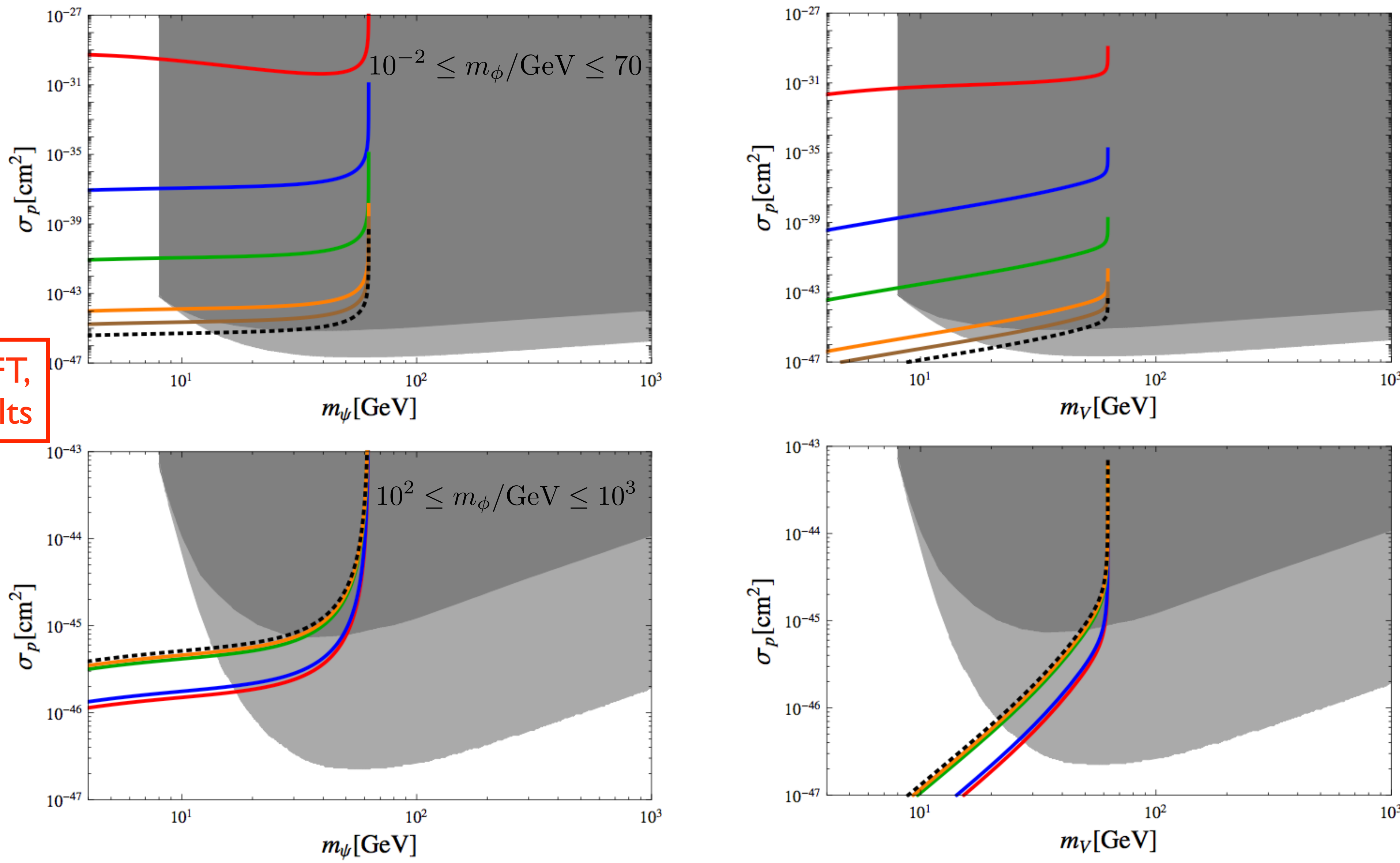
2 more relevant parameters

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

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

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

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



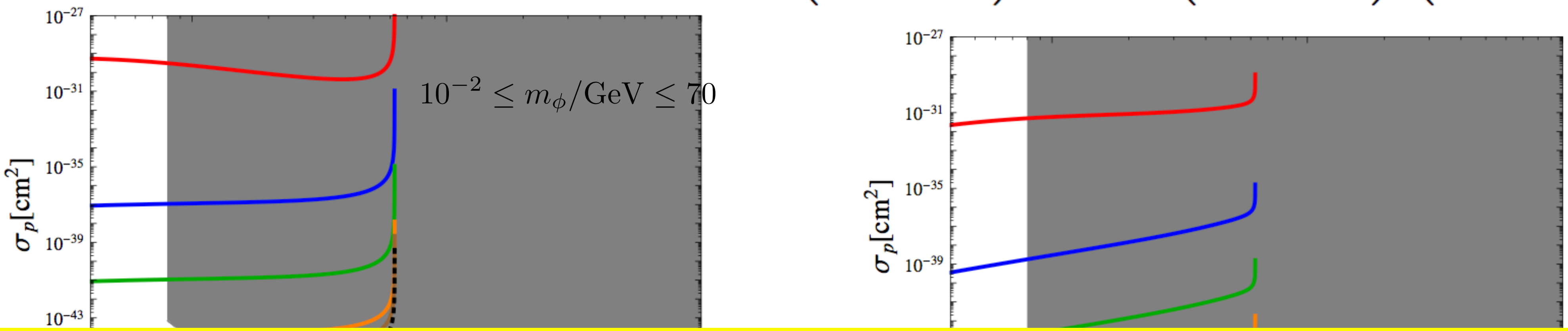
Dashed curves:EFT, ATLAS,CMS results

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

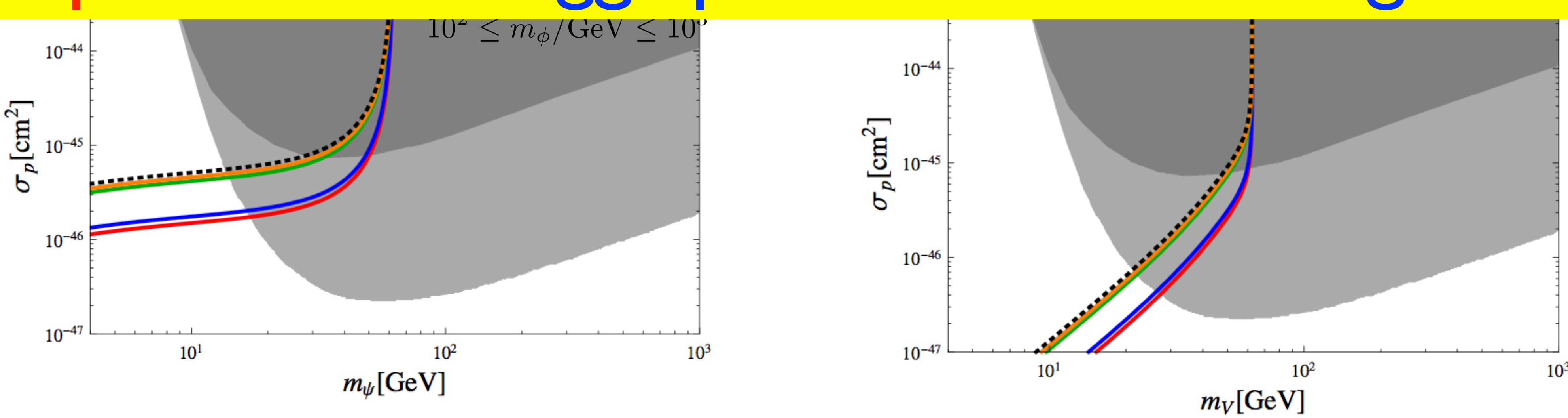
$$\mathcal{L}_{\rm SFDM} = \overline{\psi}\left(i\partial - m_\psi - \lambda_\psi S\right) - \mu_{HS} S H^\dagger H - \frac{\lambda_{HS}}{2} S^2 H^\dagger H + \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{1}{2} m_S^2 S^2 - \mu_S^3 S - \frac{\mu_S'}{3} S^3 - \frac{\lambda_S}{4} S^4 .$$

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

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



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]

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

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

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

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

Hidden Sector Monopole, Stable VDM and Dark Radiation

$SU(2)_h \rightarrow U(1)_h$

+

Higgs portal

[S. Baek, P. Ko & WIP, arXiv:1311.1035]

The Model

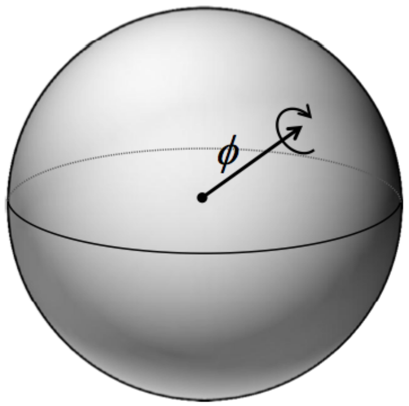
- Lagrangian

$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{4}V^a_{\mu\nu}V^{a\mu\nu} + \frac{1}{2}D_\mu\vec{\phi}\cdot D^\mu\vec{\phi} - \frac{\lambda_\phi}{4}\left(\vec{\phi}\cdot\vec{\phi} - v_\phi^2\right)^2 - \frac{\lambda_{\phi H}}{2}\vec{\phi}\cdot\vec{\phi}H^\dagger H$$

't Hooft-Polyakov monopole — Higgs portal

- Symmetry breaking

$$\phi^T = (0, 0, v_\phi) \Rightarrow SU(2) \to U(1)$$



- Particle spectra $\left(V^\pm \equiv \frac{1}{\sqrt{2}}(V_1 \mp iV_2),\ \gamma' \equiv V_3,\ H_1,\ H_2\right)$
  - VDM: $m_V = g_X v_\phi$
  - Monopole: $m_M = m_V/\alpha_X$
  - Higgses: $m_{1,2} = \frac{1}{2}\left[m_{hh}^2 + m_{\phi\phi}^2 \mp \sqrt{\left(m_{hh}^2 - m_{\phi\phi}^2\right)^2 + 4m_{\phi h}^4}\right]$

Stable due to topology and U(1)

Main Results

- h-Monopole is stable due to topological conservation
- h-VDM is stable due to the unbroken U(1) subgroup, even if we consider higher dim nonrenormalizable operators
- Massless h-photon contributes to the dark radiation at the level of 0.08-0.11
- Higgs portal plays an important role

Residual Non-Abelian DM&DR

P.Ko&YT, 1609.02307

- Consider *SU(N)* Yang-Mills gauge fields and a Dark Higgs field Φ

$$\mathcal{L} = -\frac{1}{4} F^a_{\mu\nu} F^{a\mu\nu} + (D_\mu \Phi)^\dagger (D^\mu \Phi) - \lambda_\phi \left(|\Phi|^2 - v_\phi^2/2 \right)^2 ,$$

- Take *SU(3)* as an example,

$$A^a_\mu t^a = \frac{1}{2} \begin{pmatrix} A^3_\mu + \frac{1}{\sqrt{3}} A^8_\mu & A^1_\mu - i A^2_\mu & A^4_\mu - i A^5_\mu \\ A^1_\mu + i A^2_\mu & -A^3_\mu + \frac{1}{\sqrt{3}} A^8_\mu & A^6_\mu - i A^7_\mu \\ A^4_\mu + i A^5_\mu & A^6_\mu + i A^7_\mu & -\frac{2}{\sqrt{3}} A^8_\mu \end{pmatrix} .$$

- *SU(3)* → *SU(2)*

$$\langle \Phi \rangle = \begin{pmatrix} 0 & 0 & \frac{v_\phi}{\sqrt{2}} \end{pmatrix}^T , \Phi = \begin{pmatrix} 0 & 0 & \frac{v_\phi + \phi(x)}{\sqrt{2}} \end{pmatrix}^T ,$$

The massive gauge bosons $A^{4,\cdots,8}$ as dark matter obtain masses,

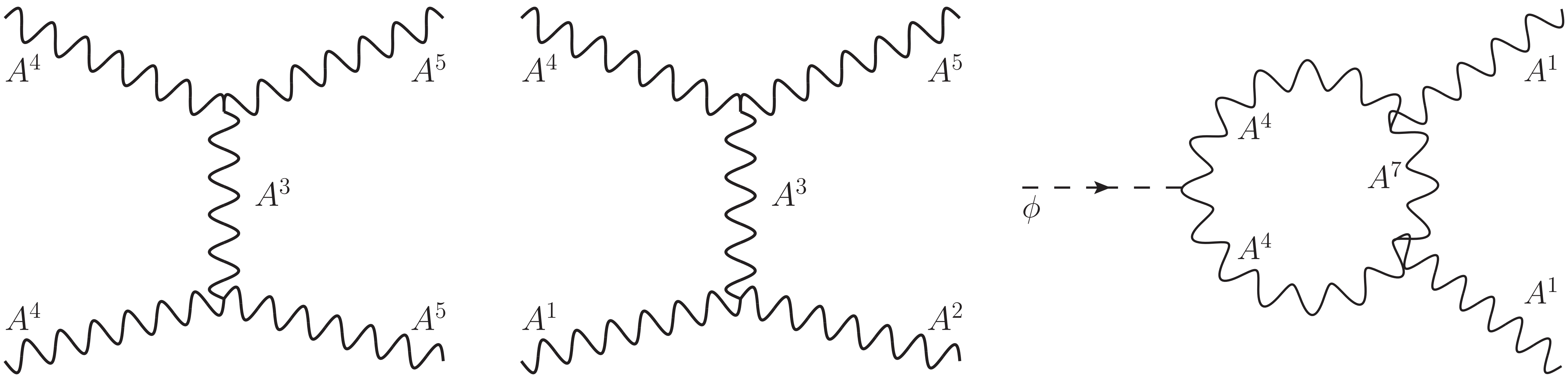
$$m_{A^{4,5,6,7}} = \frac{1}{2} g v_\phi , \; m_{A^8} = \frac{1}{\sqrt{3}} g v_\phi ,$$

and massless gauge bosons $A^{1,2,3}_\mu$. The physical scalar ϕ can couple to $A^{4,\cdots,8}_\mu$ at tree level and to $A^{1,2,3}$ at loop level.

Phenomenology

- Scattering and decay processes

P.Ko&**YT**, 1609.02307



- Constraints

$$\delta N_{\rm eff} = \frac{8}{7}\left[(N-1)^2 - 1\right] \times 0.055,$$

$$g^2 \lesssim \frac{T_\gamma}{T_A}\left(\frac{m_A}{M_P}\right)^{1/2} \sim 10^{-7},$$

$$\frac{m_A}{T_{\rm reh}} \sim \ln\left[\frac{\Omega_b M_P g^4}{\Omega_X m_p \eta}\right] \sim \mathcal{O}(30).$$

- ***N<6 if thermal***
- ***small coupling,***
- ***non-thermal production,***
- ***low reheating temperature***

Schmaltz et al(2015) EW charged DM

Matter Power Spectrum

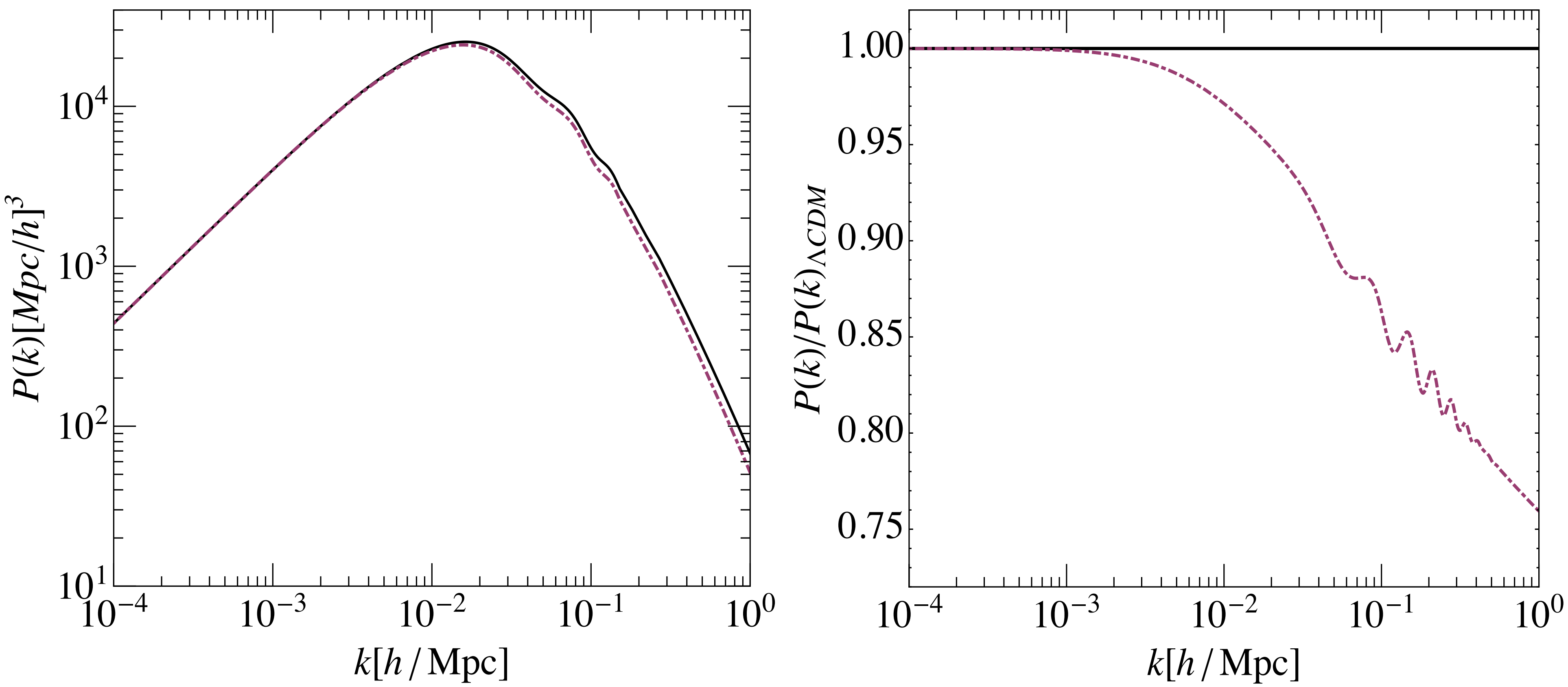


FIG. 3. Matter power spectrum $P(k)$ (left) and ratio (right) with $m_\chi \simeq 10\text{TeV}$ and $g_X^2 \simeq 10^{-7}$, in comparison with ΛCDM. The black solid lines are for ΛCDM and the purple dot-dashed lines for interacting DM-DR case, with input parameters in Eq. 21. We can easily see that $P(k)$ is suppressed for modes that enter horizon at radiation-dominant era. Those little wiggles are due to the well-known baryon acoustic oscillation.

Cosmological Data Crucial

- If we ignored the cosmological data, we could simply assume this non Abelian VDM is thermalized by a Higgs portal coupling with a larger gauge coupling without any conflict with collider data or (in)direct DM detection experiments

- Sometimes cosmologycal data could impose more crucial constraint on the DM models than (in)direct DM detections or colliders

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)
- P. Ko, Gang Li, and Jinmian Li, arXiv:1807.06697, PRD (2018)

Why is it broken down in DM EFT ?

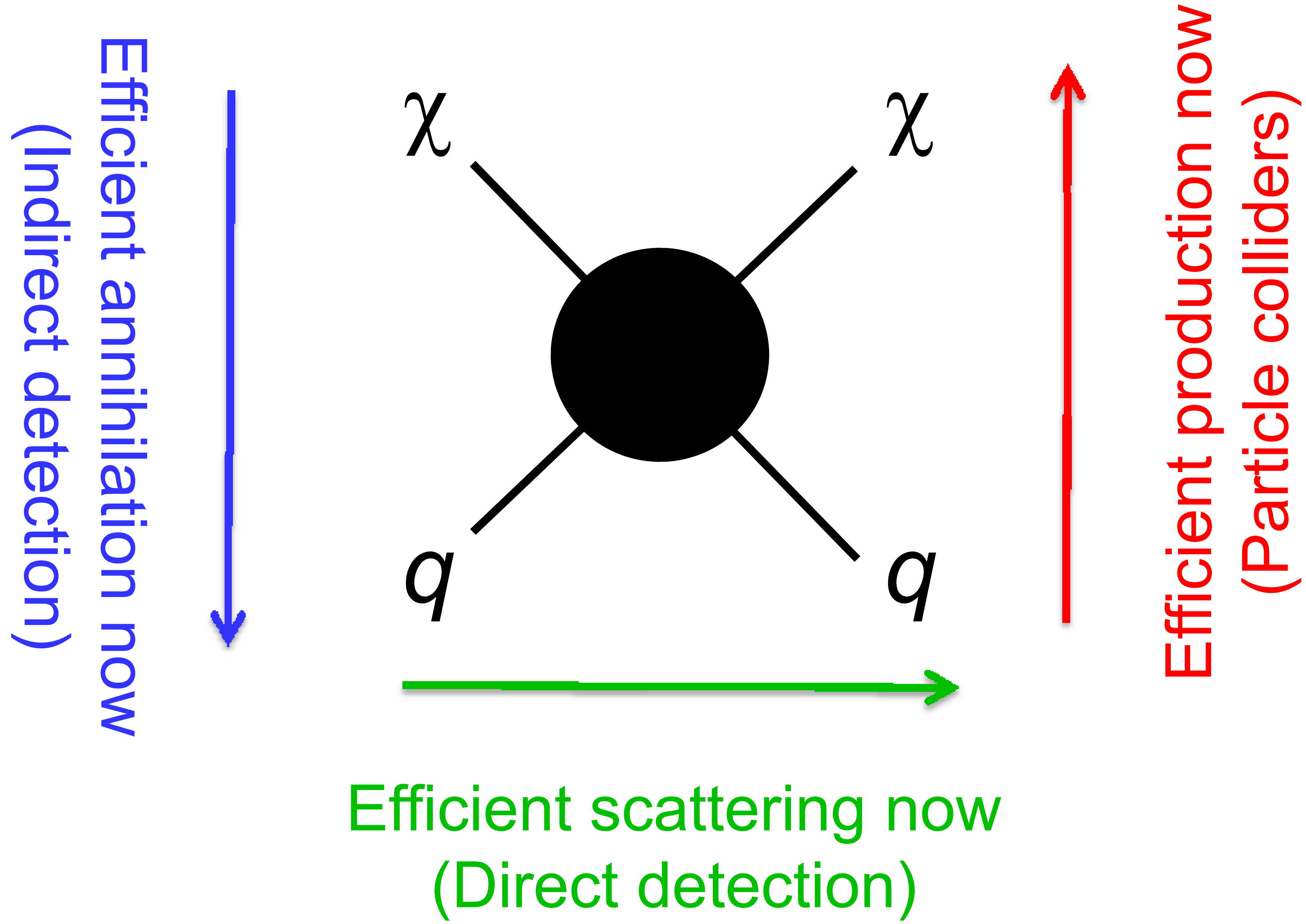
The most nontrivial example is the (scalar)x(scalar) operator for DM-N scattering

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

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

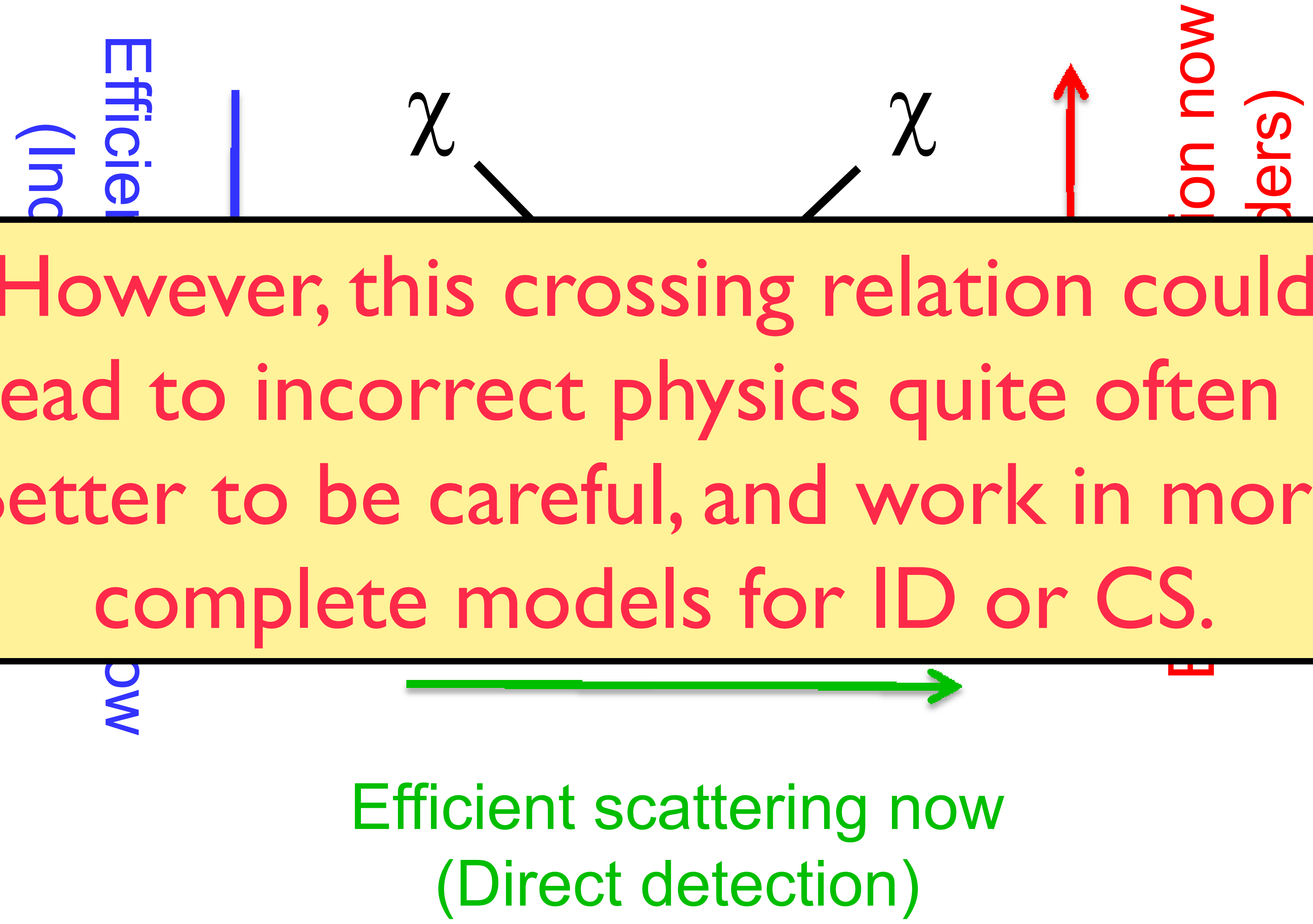
Crossing & WIMP detection

Correct relic density → Efficient annihilation then



Crossing & WIMP detection

Correct relic density → Efficient annihilation then



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

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.

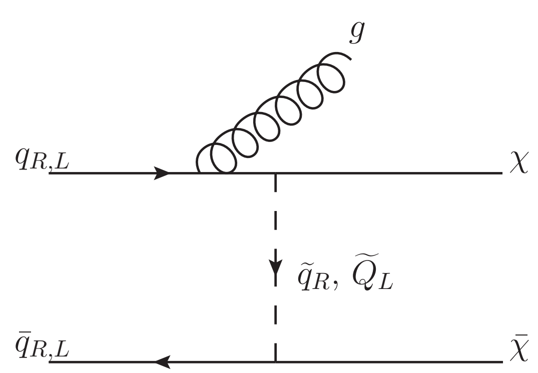
$$\frac{1}{\Lambda_i^2}\ \bar{q}\Gamma_i q\ \bar{\chi}\Gamma_i\chi \rightarrow \frac{g_q g_\chi}{m_\phi^2 - s}\ \bar{q}\Gamma_i q\ \bar{\chi}\Gamma_i\chi$$

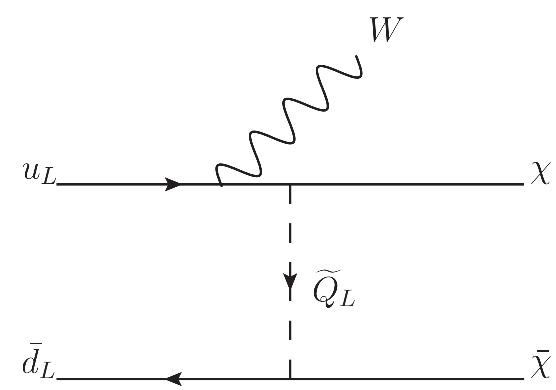
- Usually effective operator is replaced by a single propagator in simplified DM models
- This is not good enough, since we have to respect the full SM gauge symmetry (Bell et al for W+missing ET)
- In general we need two propagators, not one propagator, because there are two independent chiral fermions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

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

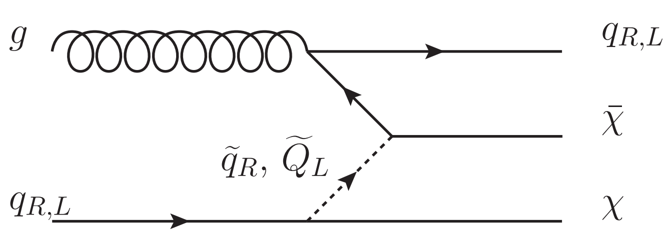
for t-channel mediator

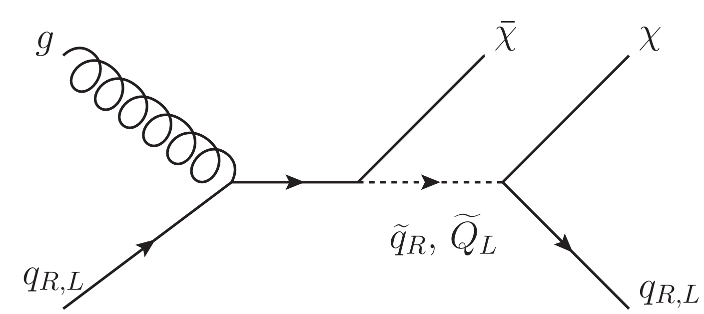
Our Model: a 'simplified model' of colored t-channel, spin-0, mediators which produce various mono-x + missing energy signatures (mono-Jet, mono-W, mono-Z, etc.):





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

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

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

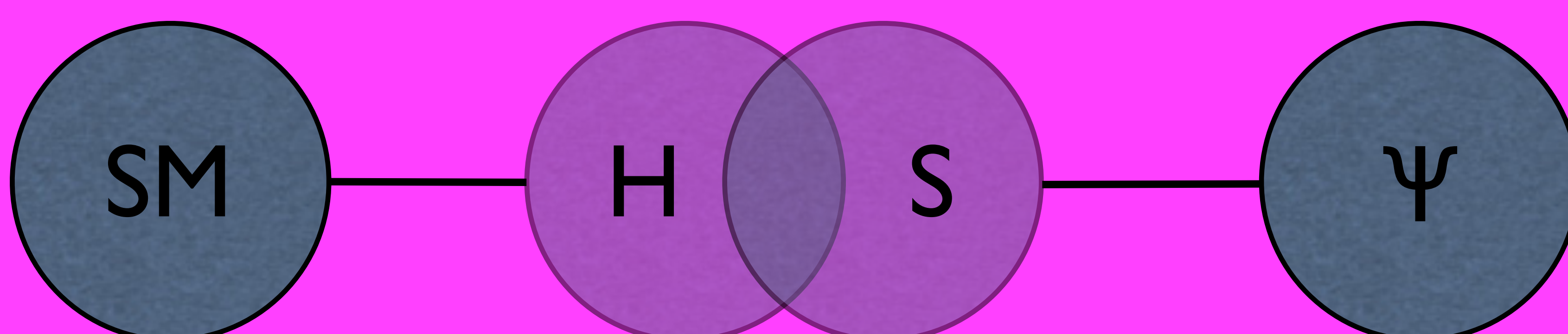
Singlet fermion CDM

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

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

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

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

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

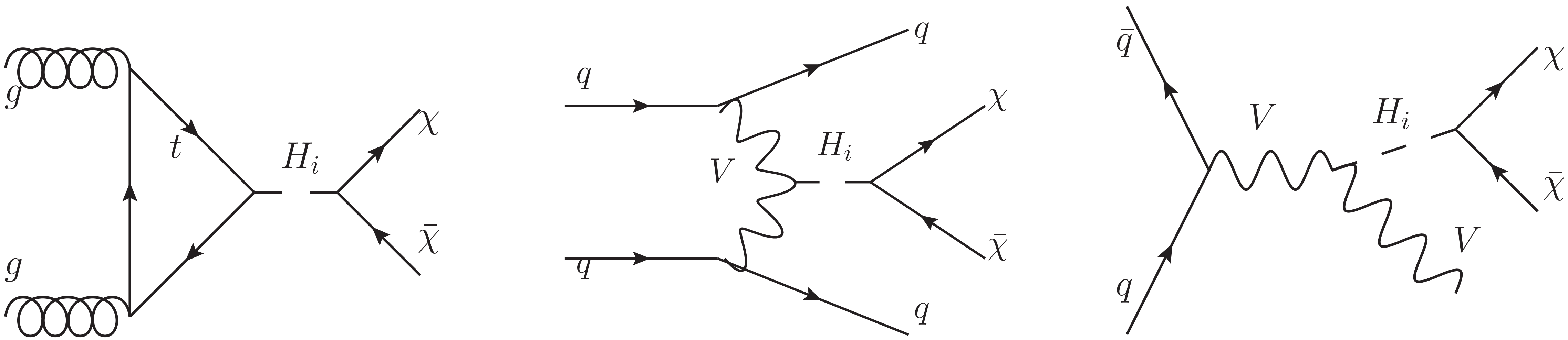


Figure 1: The dominant DM production processes at LHC.

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

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

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

Interference effects

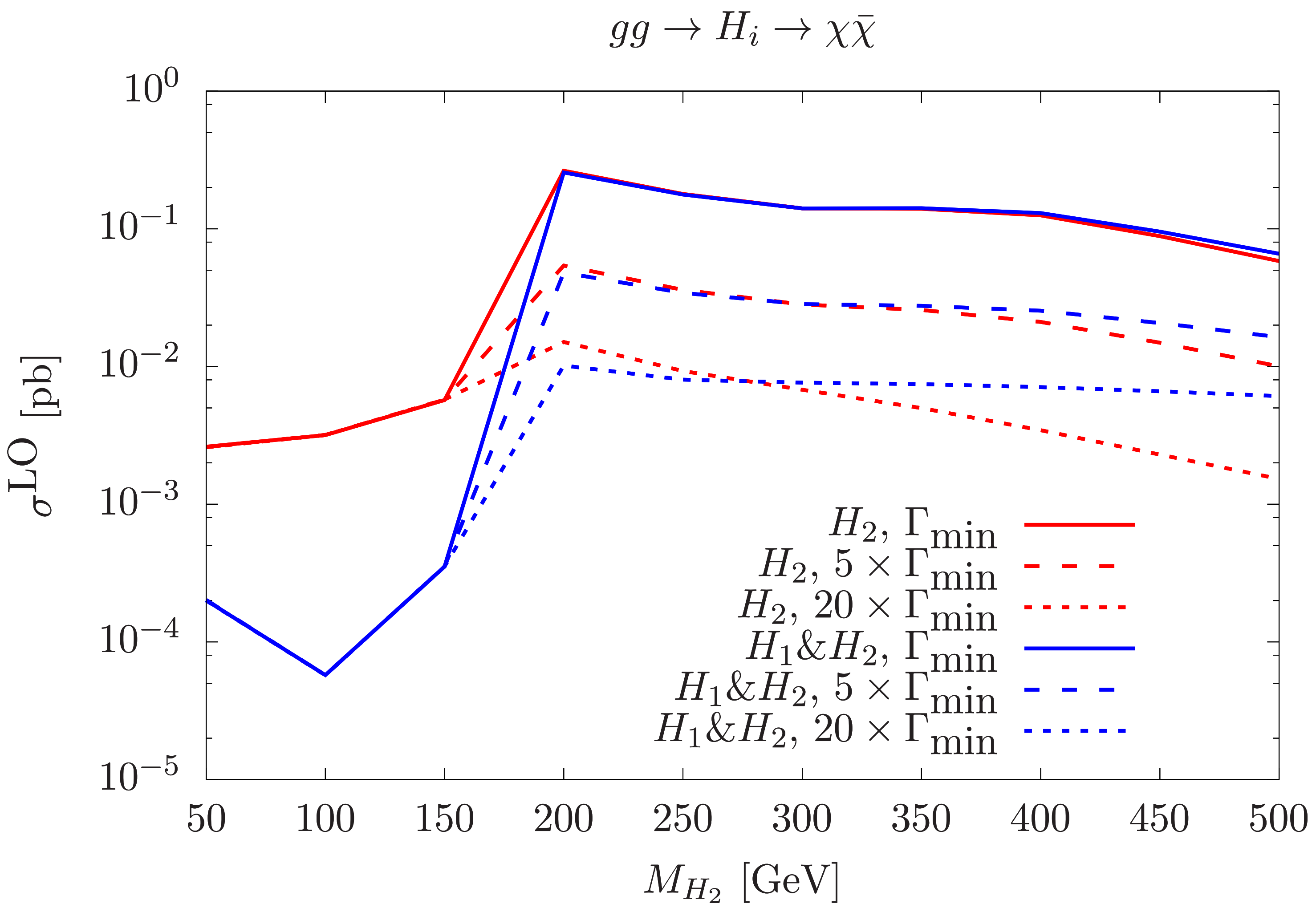


Figure 2: The LO cross section for gluon-gluon fusion process at 13 TeV LHC. The meanings of the different line types are explained in the text and the similar strategy will be used in all figures.

Exclusion limits with interference effects

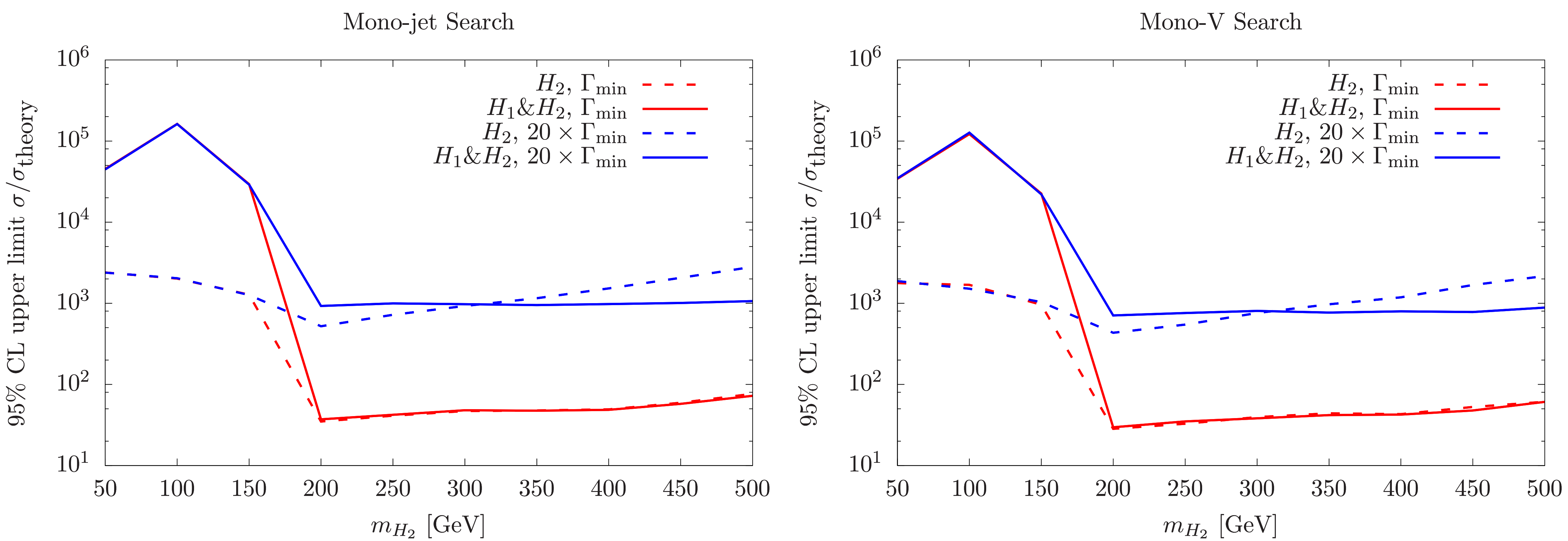


Figure 8: The CMS exclusion limits on our simplified models. Left: upper limit from mono-jet search. Right: upper limit from mono-V search.

- 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).

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

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

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

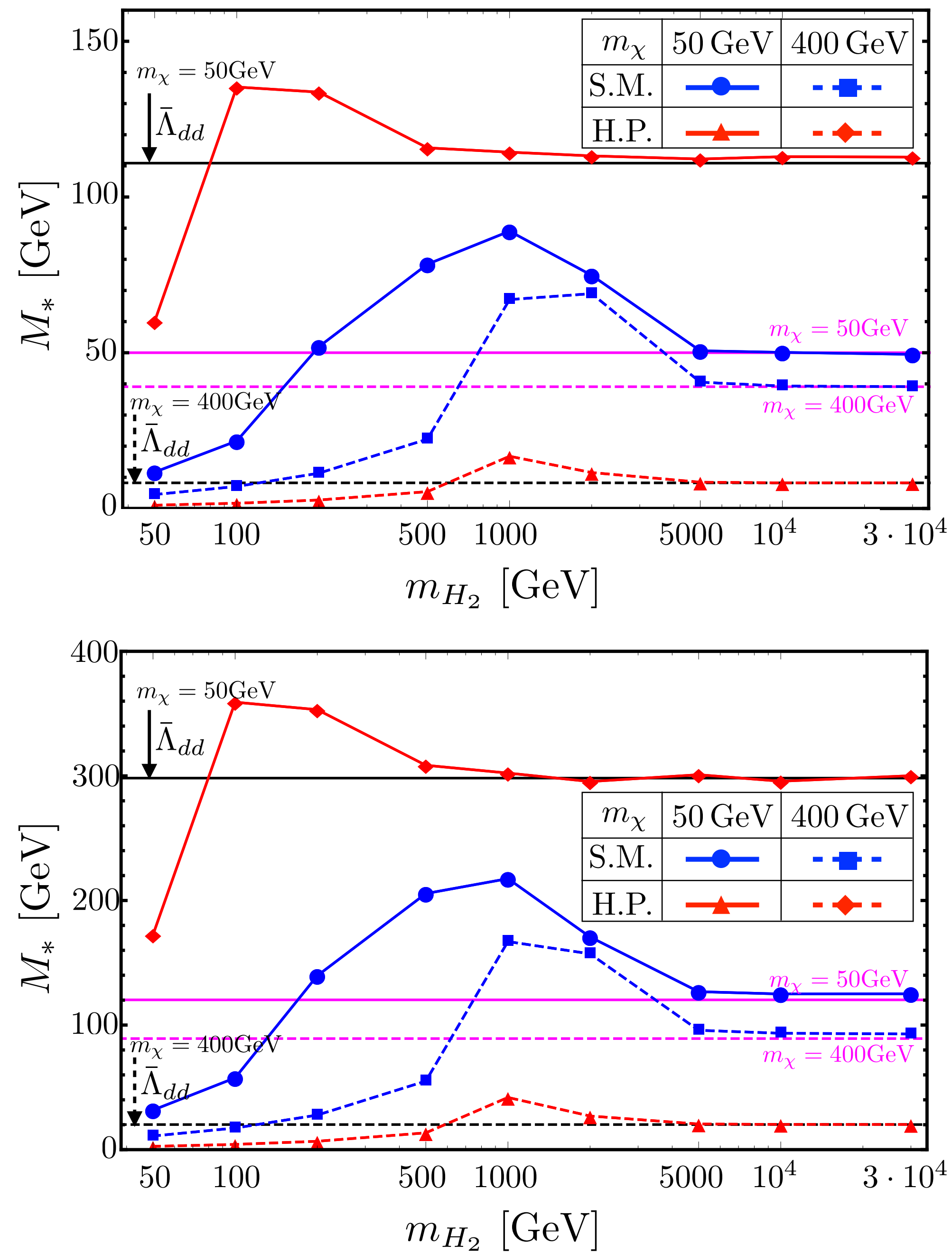


FIG. 3: The experimental bounds on M_* at 90% C.L. as a function of m_{H_2} (m_S in S.M. case) in the monojet+$\not{E}_T$ search (upper) and $t\bar{t} + \not{E}_T$ search (lower). Each line corresponds to the EFT approach (magenta), S.M. (blue), H.M. (black), and H.P. (red), respectively. The bound of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

Higgs Strahlung

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

arXiv:1603.04737
w/ H. Yokoya

Differential cross section

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Unitarity violated !

Asymtotic behavior in the full theory

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

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

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

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

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

Asym (EFT)

For pseudo Goldstone boson DM, the form factors are different and so are high energy behaviors

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

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

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

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

Unitarity violated !

Motivations for U(1)H extensions of 2HDM

Two Higgs doublet model

- Many high-energy models predict extra Higgs doublets.
  - SUSY, GUT, flavor symmetric models, etc.

- Two Higgs doublet model could be an effective theory of a high-energy t heory.

- Two (or multi) Higgs doublet model itself is interesting.
  - Higgs physics (heavy Higgs, pseudoscalar, charged Higgs physics)
  - dark matter physics (one of Higgs scalar or extra fermions could be CDM.) Ma,PRD73;Barbieri,Hall,Rychkov,PRD74♪
  - baryon asymmetry of the Universe Shu,Zhang,PRL111♪
  - neutrino mass generation Kanemura,Matsui,Sugiyama,PLB727♪
  - can resolve experimental anomalies (top A_{FB} at Tevatron, $B \to D(*)\tau\nu$ at BA BAR) Ko,Omura,Yu,EPJC73;JHEP1303♪

Motivations

- Generic 2HDM suffer from neutral Higgs mediated FCNC
- Glashow-Weinberg criterion :
- Impose Z_2 symmetry under which both H_1 and H_2 are charged differently; the SM fermions are also charged appropriately to allow realistic Yukawa interactions (Type-I, II, X, Y)
- This Z_2 symmetry is softly broken by dim-2 operator

Natural Flavor Conservation
(Glashow and Weinberg, 1977)

- Fermions of the same electric charge get their masses from the same Higgs doublet [Glashow and Weinberg, PRD (1977)]
- The usual way to achieve this is to impose a discrete Z_2 sym under which two Higgs doublets H_1 and H_2 are charged differently
- This Z_2 is softly broken to avoid the domain wall problem and massless Goldstone boson

However

- The discrete Z_2 seems to be rather ad hoc, and its origin and the reason for its soft breaking are not clear
- We implement the discrete Z_2 into a continuous local U(1) Higgs flavor sym under which H_1 and H_2 are charged differently [Ko, Omura, Yu PLB (2012)]
- This simple idea opens a new window for the multi-Higgs doublet models, which was not considered before

2HDMs with U(1) Higgs gauge symmetry

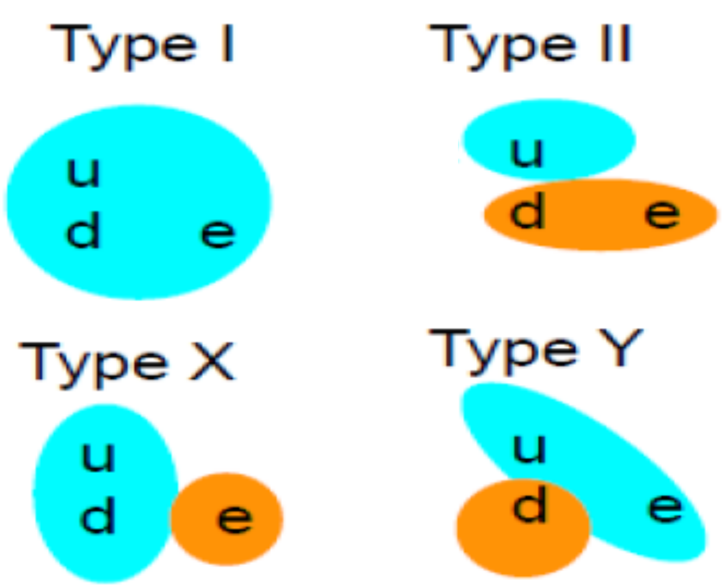
Based on works with
Yuji Omura and Chaehyun Yu
arXiv:1204.4588 (PLB)
arXiv:1309.7156 (JHEP)
arXiv:1405.2138 (JHEP), etc..

2HDM with Z_2 symmetry (2HDMwZ_2)

- One of the simplest models to extend the SM Higgs sector.
- In general, flavor changing neutral currents (FCNCs) appear.
- A simple way to avoid the FCNC problem is to assign ad hoc Z_2 symmetry.

Z_2 : Chiral

Type	H_1	H_2	U_R	D_R	E_R	N_R	Q_L, L
I	+	−	+	+	+	+	+
II	+	−	+	−	−	+	+
X	+	−	+	+	−	−	+
Y	+	−	+	−	+	−	+



Fermions of same electric charges get their masses from one Higgs VEV.

$$\mathcal{L} = \bar{L}_i (y^E_{1ij} H_1 + \cancel{y^E_{2ij} H_2}) E_{Rj} + \text{H.c.}$$

or vice versa

NO FCNC at tree level.

Generic problems of 2HDM

• It is well known that discrete symmetry could generate a domain wall pr oblem when it is spontaneously broken.

• Usually the Z_2 symmetry is assumed to be broken softly by a dim-2 oper ator, $H_1^\dagger H_2$ term.

The softly broken Z_2 symmetric 2HDM potential

$$V = m_1^2 H_1^\dagger H_1 + m_2^2 H_2^\dagger H_2 - (m_{12}^2 H_1^\dagger H_2 + h.c.) + \frac{1}{2}\lambda_1 (H_1^\dagger H_1)^2 + \frac{1}{2}\lambda_2 (H_2^\dagger H_2)^2 + \lambda_3 (H_1^\dagger H_1)(H_2^\dagger H_2) + \lambda_4 (H_1^\dagger H_2)(H_2^\dagger H_1) + \frac{1}{2}\lambda_5 [(H_1^\dagger H_2)^2 + h.c.]$$

• the origin of the softly breaking term?

Z_2 symmetry in 2HDM can be replaced by new $U(1)_H$ symmetry associated with Higgs flavors.

Setup of 2HDM with U(1)H

Type I

Only one Higgs couples with fermion

$$V_y = y^U_{ij}\overline{Q_{Li}}\widetilde{H_1}U_{Rj} + y^D_{ij}\overline{Q_{Li}}H_1 D_{Rj} + y^E_{ij}\overline{L_i}H_1 E_{Rj} + y^N_{ij}\overline{L_i}\widetilde{H_1}N_{Rj}.$$

Anomaly free U(1)H with RH neutrino

U_R	D_R	Q_L	L	E_R	N_R	H_1	Type
u	d	$\frac{(u+d)}{2}$	$\frac{-3(u+d)}{2}$	$-(2u+d)$	$-(u+2d)$	$\frac{(u-d)}{2}$	

Setup of 2HDM with $U(1)_H$

Type I

Only one Higgs couples with fermion

$$V_y = y_{ij}^U \overline{Q_{Li}} \widetilde{H}_1 U_{Rj} + y_{ij}^D \overline{Q_{Li}} H_1 D_{Rj} + y_{ij}^E \overline{L_i} H_1 E_{Rj} + y_{ij}^N \overline{L_i} \widetilde{H}_1 N_{Rj}.$$

Anomaly free U(1)H with RH neutrino

H-Z-ZH coupling

U_R	D_R	Q_L	L	E_R	N_R	H_1	Type
u	d	$\frac{(u+d)}{2}$	$\frac{-3(u+d)}{2}$	$-(2u+d)$	$-(u+2d)$	$\frac{(u-d)}{2}$	
0	0	0	0	0	0	0	$h_2 \neq 0$
$1/3$	$1/3$	$1/3$	-1	-1	-1	0	$U(1)_{B-L}$
1	-1	0	0	-1	1	1	$U(1)_R$
$2/3$	$-1/3$	$1/6$	$-1/2$	-1	0	$1/2$	$U(1)_Y$

Drell-Yan

Anomaly free U(1)H with extra chiral fermion

$U(1)_B$, $U(1)_L$, and so on.

Setup of 2HDM with U(1)$_H$

Type II

two Higgs couples with fermion

$$V_y = y^U_{ij}\overline{Q_{Li}}\widetilde{H_1}U_{Rj} + y^D_{ij}\overline{Q_{Li}}H_2 D_{Rj} + y^E_{ij}\overline{L_i}H_2 E_{Rj} + y^N_{ij}\overline{L_i}\widetilde{H_1}N_{Rj}.$$

U_R	D_R	Q_L	L	E_R	N_R	H_1	H_2
$+1$	0	0	0	0	$+1$	0	1

Require extra chiral fermions. (q_L, q_R)

Extra fermion may cause FCNC.

Suppress FCNC ⟷ Decouple with SM (Yukawa int.) ⟷ Stable charged (colored) particle

$\lambda_i \overline{Q^i_L}\widetilde{H_1}q_R$

$\lambda_i \to 0$

"safe" mixing required

Type II   one way for anomaly free

"E₆" Model (leptophobic)   by Rosner, London, etc.

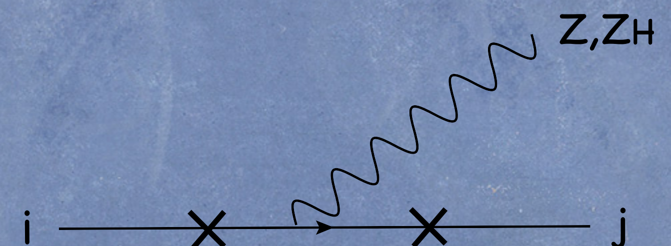
U_R	D_R	Q_L	L	E_R	N_R	H_1	H_2
$2/3$	$-1/3$	$-1/3$	0	0	1	1	0

Extra fields for anomaly free

	$SU(3)$	$SU(2)$	$U(1)_Y$	$U(1)_H$
q_{Li}	3	1	$-1/3$	$2/3$
q_{Ri}	3	1	$-1/3$	$-1/3$
l_{Li}	1	2	$-1/2$	0
l_{Ri}	1	2	$-1/2$	-1
n_{Li}	1	1	0	-1

tree-level mixing

$$V_m = Y_{ij}^{q}\overline{Q_{Li}}H_2 q_{Rj} + Y_{ij}^{E}\overline{l_{Li}}H_2 E_{Rj} + Y_{ij}^{N}\overline{l_{Li}}\widetilde{H_1} N_{Rj} + \ldots$$



J.L. Rosner, hep-ph/9607207 (PLB)

Table 1: Assignment of quantum numbers to left-handed members of the **27**-plet of E_6.

(SO(10), SU(5))	Q_η	State	Q	I_{3L}	I_{3R}	Y_L	Y_R	Q'
$(\mathbf{16}, \mathbf{5}^*)$	1	d^c	1/3	0	1/2	0	−1/3	1/3
		e^-	−1	−1/2	0	−1/3	−2/3	0
		ν_e	0	1/2	0	−1/3	−2/3	0
$(\mathbf{16}, \mathbf{10})$	−2	u	2/3	1/2	0	1/3	0	−1/3
		d	−1/3	1/2	0	1/3	0	−1/3
		u^c	−2/3	0	−1/2	0	−1/3	−2/3
		e^+	1	0	1/2	2/3	1/3	0
$(\mathbf{16}, \mathbf{1})$	−5	N_e^c	0	0	−1/2	2/3	1/3	−1
$(\mathbf{10}, \mathbf{5}^*)$	1	h^c	1/3	0	0	0	2/3	1/3
		E^-	−1	−1/2	−1/2	−1/3	1/3	0
		ν_E	0	1/2	−1/2	−1/3	1/3	0
$(\mathbf{10}, \mathbf{5})$	4	h	−1/3	0	0	−2/3	0	2/3
		E^+	1	1/2	1/2	−1/3	1/3	1
		ν_E^c	0	−1/2	1/2	−1/3	1/3	1
$(\mathbf{1}, \mathbf{1})$	−5	n	0	0	0	2/3	−2/3	−1

$$Q' = (Q_\eta + Y_W)/5 = I_{3R} - Y_L + (1/2)Y_R$$

$$A_{FB} = \frac{3}{4} \frac{[Q(u)^2 - Q(u^c)^2][Q(f)^2 - Q(f^c)^2]}{[Q(u)^2 + Q(u^c)^2][Q(f)^2 + Q(f^c)^2]}$$

Table 2: Branching ratios for a Z' coupling to the charge Q' into various members of a single family in the **27**-plet of E_6.

State f	Squared charge	Branching ratio	Branching ratio/3 (%)	$A_{FB}(u\bar{u} \to Z' \to f\bar{f})$
d	$(1+1)/3$	$1/12$	2.8	0
u	$(1+4)/3$	$5/24$	6.9	0.27
N_e^c	1	$1/8$	4.2	0.45
h	$(4+1)/3$	$5/24$	6.9	-0.27
E	$0+1$	$1/8$	4.2	0.45
ν_E	$0+1$	$1/8$	4.2	0.45
n	1	$1/8$	4.2	-0.45
Total	8	1	33.3	

Inert Doublet Model (IDMwZ$_2$)

• a 2HDM ~ one of the simplest extension

• One of Higgs doublets does not develop VEV and exact Z$_2$ symmetry is imposed.

• The new Higgs doublet does not participate in the EW symmetry breaking.

• Under the Z$_2$ symmetry, SM particles are even, but the new Higgs doublet is odd.

We don't have to impose extra dark gauge sym to ensure DM longevity. The SM gauge sym just does the job.

• Viable DM candidate

$$H_1 = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(H + iA) \end{pmatrix}, \quad H_2 = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v + h + iG^0) \end{pmatrix}$$

DM candidates (H, A)

SM-like Higgs (h)

Inert Doublet Model (IDMwZ$_2$)

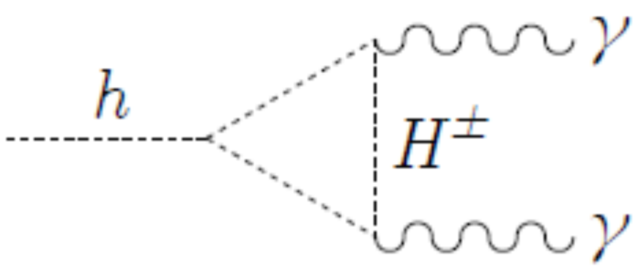
- CP-conserving potential

forbidden by the Z_2 symmetry

$$V = \mu_1 (H_1^\dagger H_1) + \mu_2 (H_2^\dagger H_2) - \mu_{12} (H_1^\dagger H_2 + \mathrm{h.c.}) + \frac{\lambda_1}{2} (H_1^\dagger H_1)^2 + \frac{\lambda_2}{2} (H_2^\dagger H_2)^2$$
$$+ \lambda_3 (H_1^\dagger H_1)(H_2^\dagger H_2) + \lambda_4 | H_1^\dagger H_2 |^2 + \frac{\lambda_5}{2} \{ (H_1^\dagger H_2)^2 + h.c. \}.$$

- Type-I Yukawa interactions ~ only H_2 couples to the SM fermions.

- The h decay to two photons receives additional contribution through charg ed Higgs loop.



- H,A,H$^\pm$ ~ do not couple to SM fermions at tree level.

Inert Double Model (IDMwU(1)$_H$)

- We replace the Z_2 symmetry by U(1) gauge symmetry.
- A SM-singlet Φ has to be added.
- Without Φ, Z_H boson becomes massless.

$$V = (m_1^2 + \tilde{\lambda}_1 |\Phi|^2)(H_1^\dagger H_1) + (m_2^2 + \tilde{\lambda}_2 |\Phi|^2)(H_2^\dagger H_2) - (m_{12}^2 H_1^\dagger H_2 + \text{h.c.})$$
$$+ \frac{\lambda_1}{2}(H_1^\dagger H_1)^2 + \frac{\lambda_2}{2}(H_2^\dagger H_2)^2 + \lambda_3 (H_1^\dagger H_1)(H_2^\dagger H_2) + \lambda_4 |H_1^\dagger H_2|^2$$
$$+ \frac{\lambda_5}{2}\{(H_1^\dagger H_2)^2 + h.c.\} + m_\Phi^2 |\Phi|^2 + \lambda_\Phi |\Phi|^4$$

- Φ breaks the U(1)$_H$ symmetry while H_2 breaks the EW symmetry.
- The remnant symmetry of U(1)$_H$ is the origin of the exact Z_2 symmetry.

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$$+ \frac{\lambda_1}{2}(H_1^\dagger H_1)^2 + \frac{\lambda_2}{2}(H_2^\dagger H_2)^2 + \lambda_3 (H_1^\dagger H_1)(H_2^\dagger H_2) + \lambda_4 |H_1^\dagger H_2|^2$$

$$+ \frac{\lambda_5}{2}\{(H_1^\dagger H_2)^2 + h.c.\} + m_\Phi^2 |\Phi|^2 + \lambda_\Phi |\Phi|^4$$

forbidden by the U(1)$_H$ symmetry ($q_{H_2}=0, q_{H_1} \neq 0$)

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$$+ \frac{\lambda_5}{2}\{(H_1^\dagger H_2)^2 + h.c.\} + m_\Phi^2 |\Phi|^2 + \lambda_\Phi |\Phi|^4$$

forbidden by the U(1)$_H$ symmetry ($q_{H_2}=0, q_{H_1}\neq 0$)

- Φ breaks the U(1)$_H$ symmetry while H_2 breaks the EW symmetry.
- The remnant symmetry of U(1)$_H$ is the origin of the exact Z_2 symmetry.

Inert Double Model (IDMwU(1)$_H$)

- IDM + SM-singlet .

forbidden
by the Z_2 symmetry

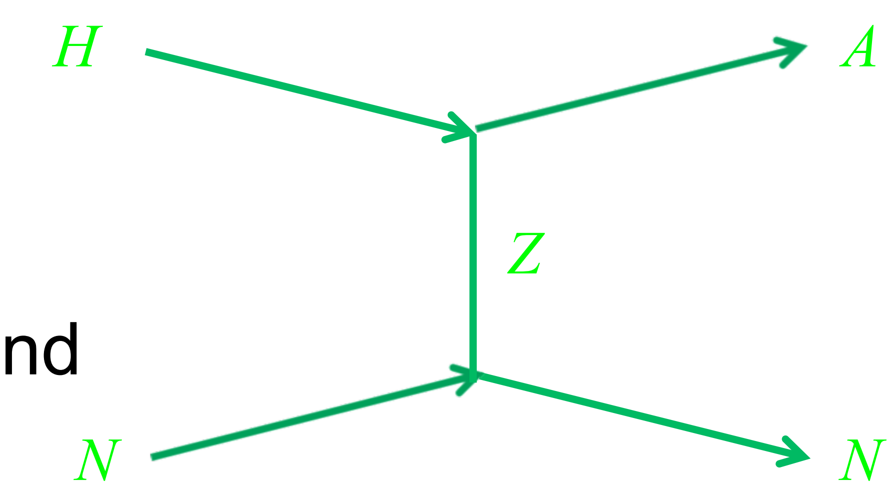
$$V = (m_1^2 + \tilde{\lambda}_1 |\Phi|^2)(H_1^\dagger H_1) + (m_2^2 + \tilde{\lambda}_2 |\Phi|^2)(H_2^\dagger H_2) - (m_{12}^2 H_1^\dagger H_2 + \mathrm{h.c.})$$
$$+ \frac{\lambda_1}{2}(H_1^\dagger H_1)^2 + \frac{\lambda_2}{2}(H_2^\dagger H_2)^2 + \lambda_3 (H_1^\dagger H_1)(H_2^\dagger H_2) + \lambda_4 |H_1^\dagger H_2|^2$$
$$+ \frac{\lambda_5}{2}\{(H_1^\dagger H_2)^2 + h.c.\} + m_\Phi^2 |\Phi|^2 + \lambda_\Phi |\Phi|^4$$

forbidden by the U(1)$_H$ symmetry (q_{H_2}=0,q_{H_1}≠0)

- Without λ_5, H and A are degenerate.

$$m_A = \sqrt{m_H^2 - \lambda_5 v^2}$$

- Direct searches for DM at XENON100 and LUX exclude this degenerate case.



Inert Double Model (IDMwU(1)$_H$)

- IDM + SM-singlet [illegible].

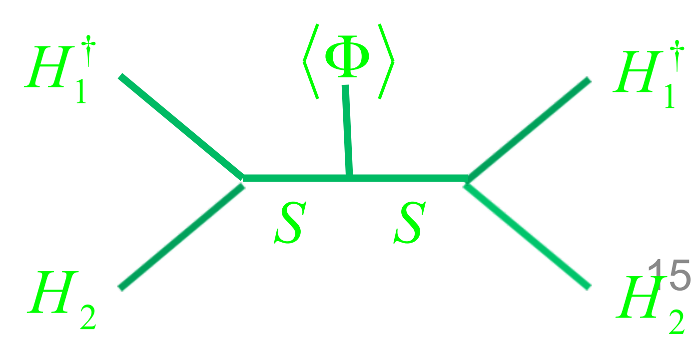
forbidden
by the Z_2 symmetry

$$V = (m_1^2 + \tilde{\lambda}_1 |\Phi|^2)(H_1^\dagger H_1) + (m_2^2 + \tilde{\lambda}_2 |\Phi|^2)(H_2^\dagger H_2) - (m_{12}^2 H_1^\dagger H_2 + \mathrm{h.c.})$$
$$+ \frac{\lambda_1}{2}(H_1^\dagger H_1)^2 + \frac{\lambda_2}{2}(H_2^\dagger H_2)^2 + \lambda_3 (H_1^\dagger H_1)(H_2^\dagger H_2) + \lambda_4 |H_1^\dagger H_2|^2$$
$$+ \{c_l \left(\frac{\Phi}{\Lambda}\right)^l (H_1^\dagger H_2)^2 + h.c.\} + m_\Phi^2 |\Phi|^2 + \lambda_\Phi |\Phi|^4$$

- The λ_5 term can effectively be generated by a higher-dimensional operator.
- It could be realized by introducing a singlet S charged under U(1)$_H$ with $q_S = q_{H_1}$.

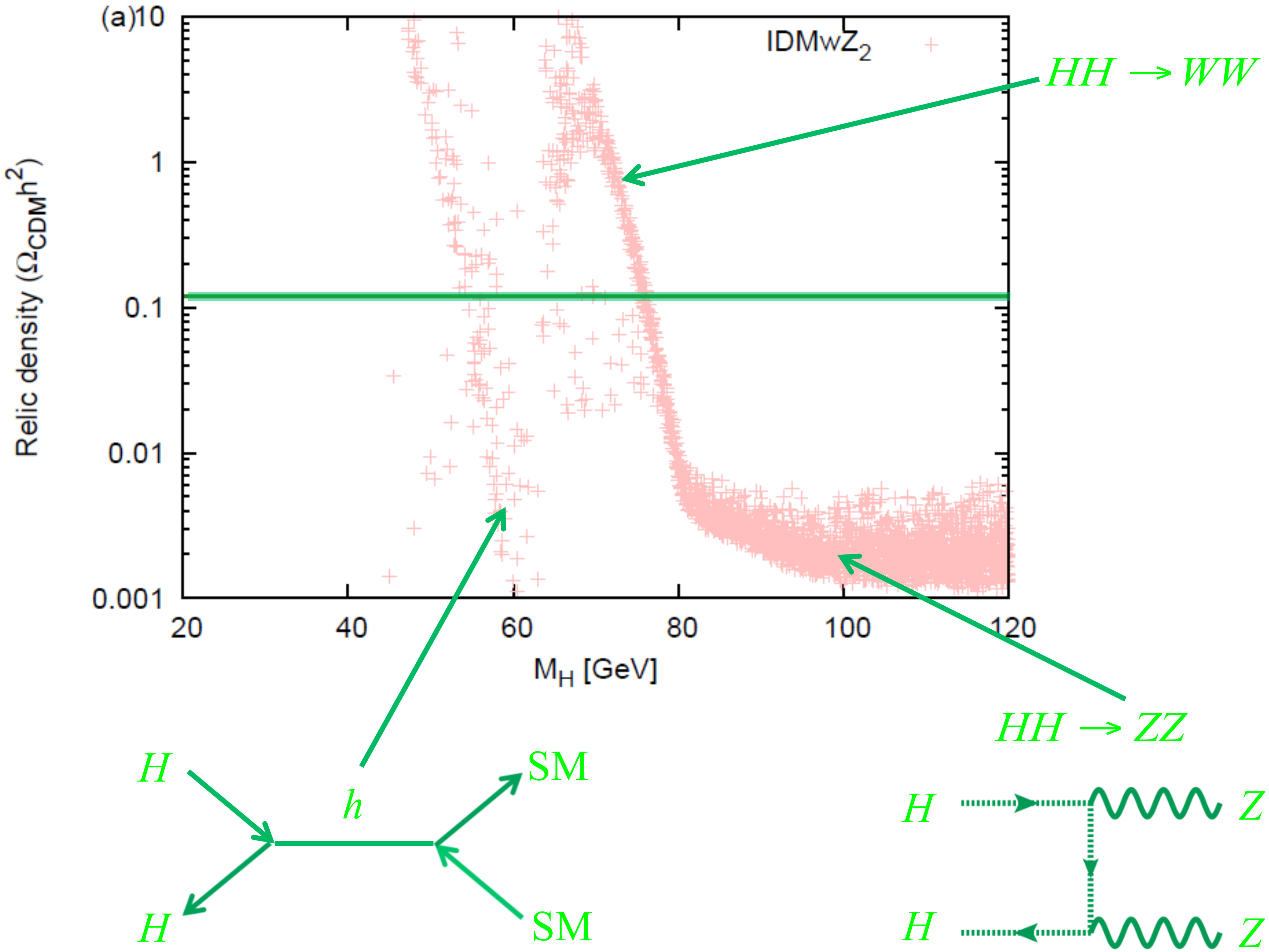
$$V_\Phi(|\Phi|^2, |S|^2) + V_H(H_i, H_i^\dagger) + \lambda_S(\Phi) S^2 + \lambda_H(S) H_1^\dagger H_2 + h.c..$$

$$\lambda_H = \lambda_H^0 S \qquad \lambda_5 \sim \frac{(\lambda_H^0)^2}{2} \frac{\Delta m^2}{m_{Re(S)}^2 m_{Im(S)}^2},$$



Relic density (low mass)

$$\Omega_{\mathrm{CDM}} h^2 = 0.1199 \pm 0.0027$$



+ IDMwZ$_2$

LUX bound is satisfied.

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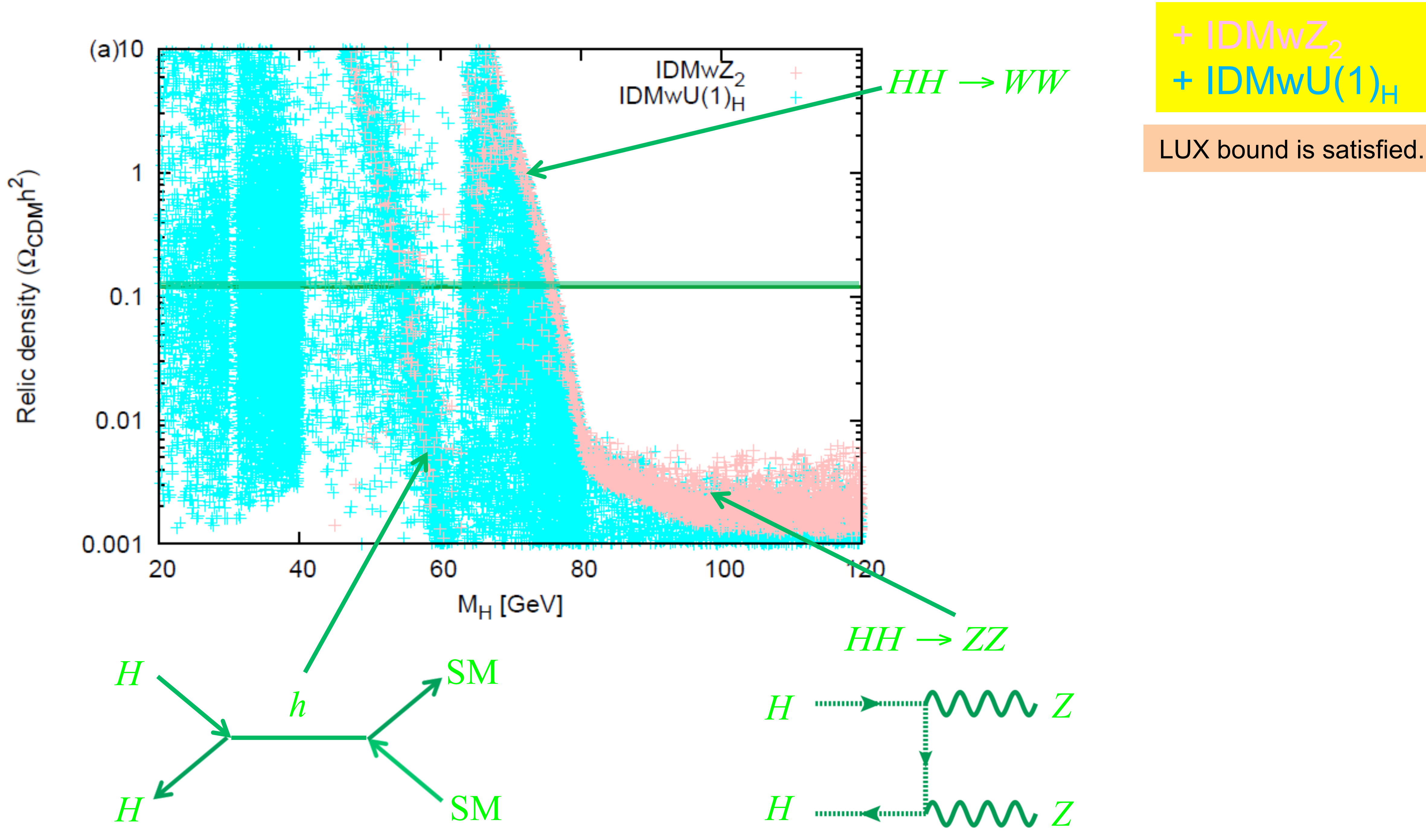


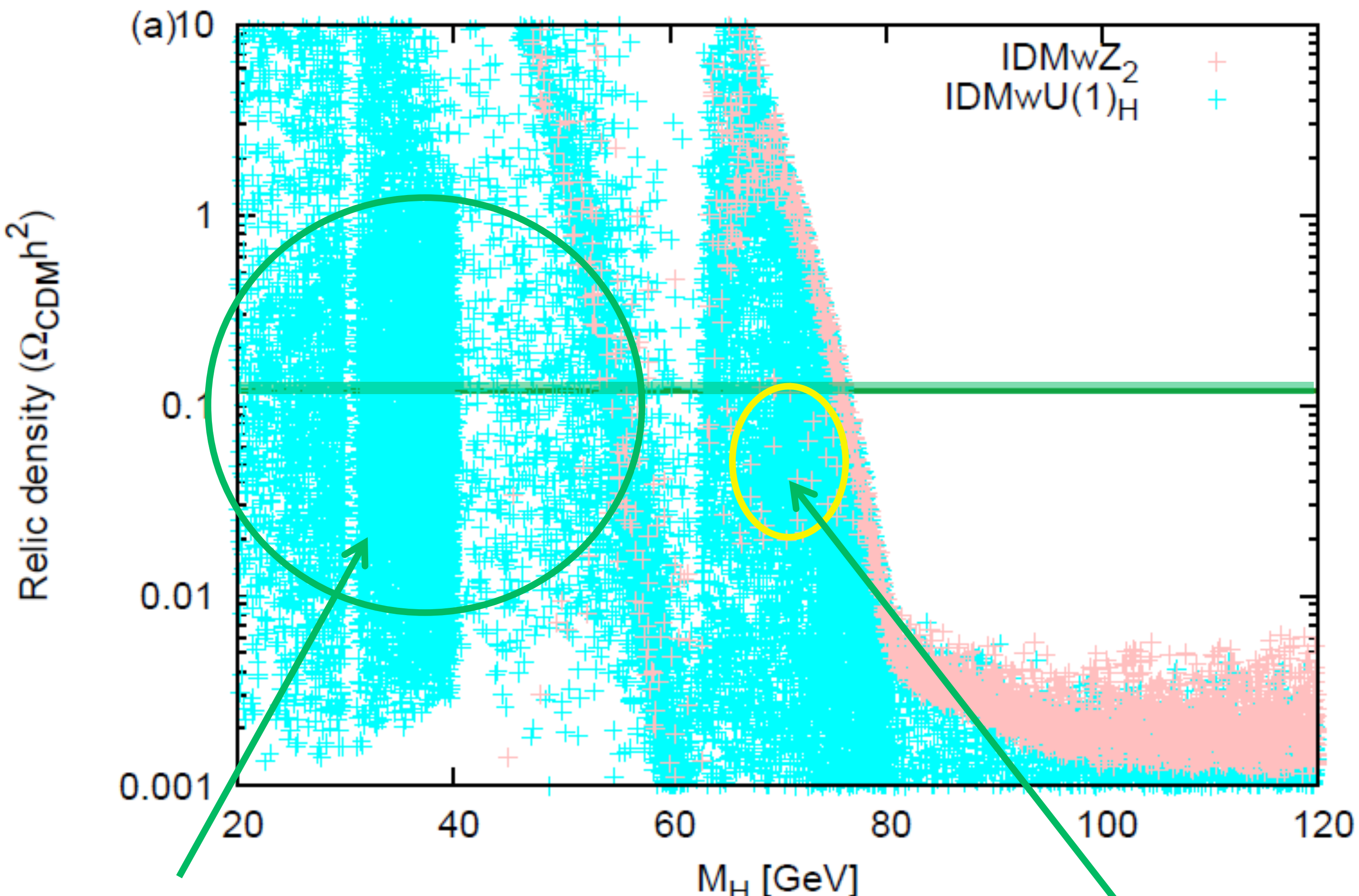
LUX bound is satisfied.

Relic density (low mass)

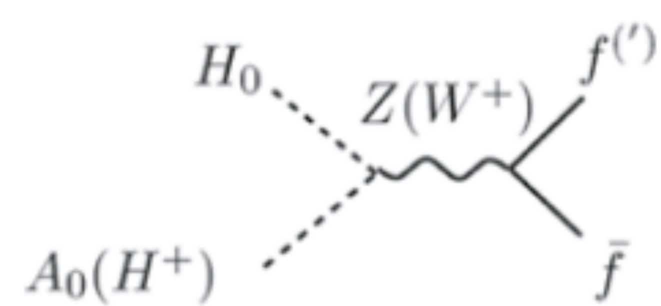
$$\Omega_{\mathrm{CDM}} h^2 = 0.1199 \pm 0.0027$$

+ $IDMwZ_2$
+ $IDMwU(1)_H$

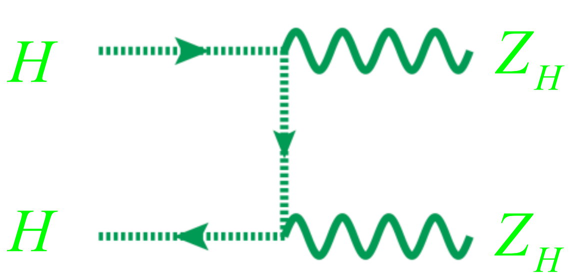
LUX bound is satisfied.



Co-annihilation



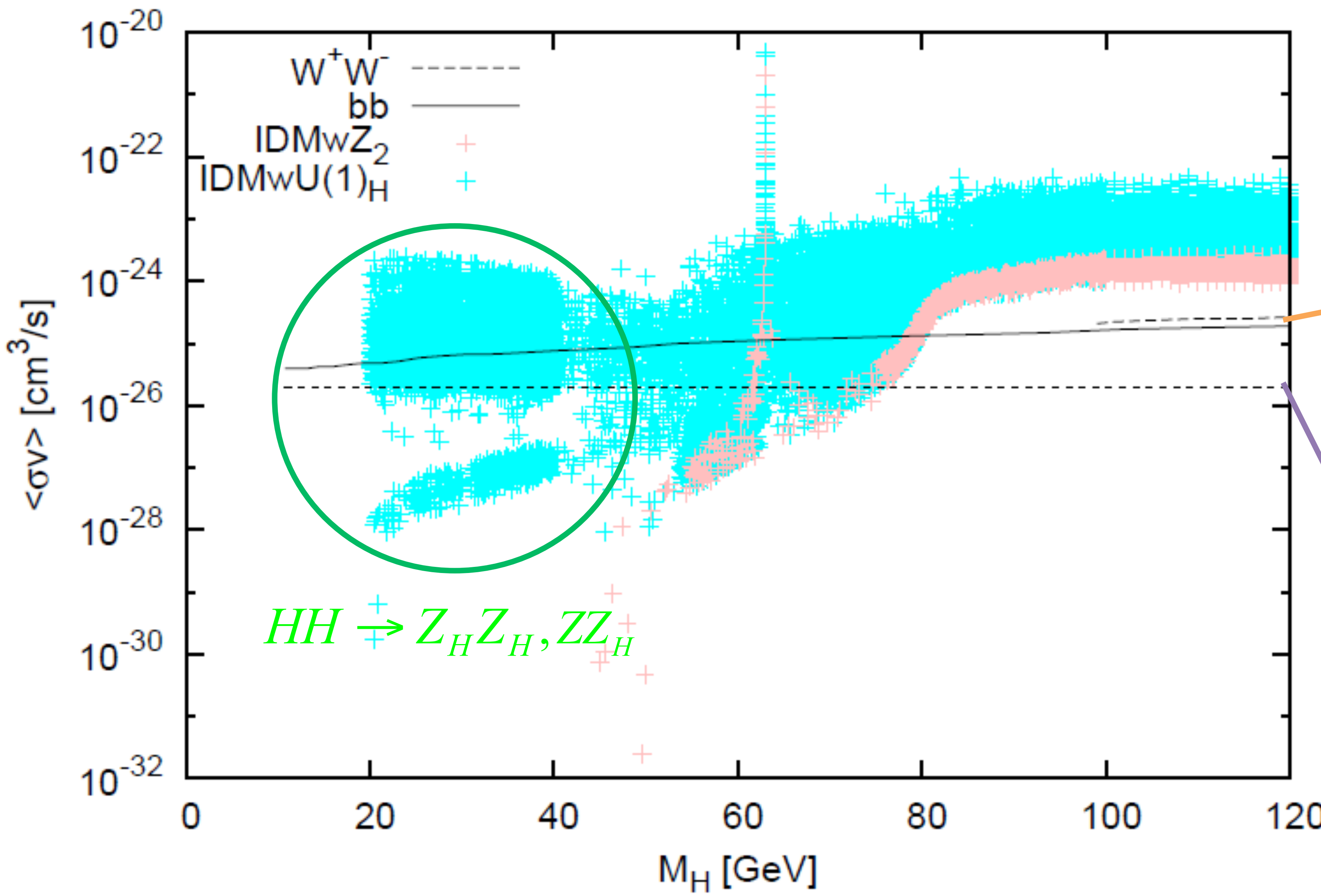
$HH \to Z_H Z_H, ZZ_H$



$HA, HH^{\pm} \to \mathrm{SM}+\mathrm{SM}^{(\prime)}$

$H^+H^- \to A + Z_H, Z + Z_H, \ldots$

Indirect searches (low mass)



+ IDMwZ$_2$
+ IDMwU(1)$_H$

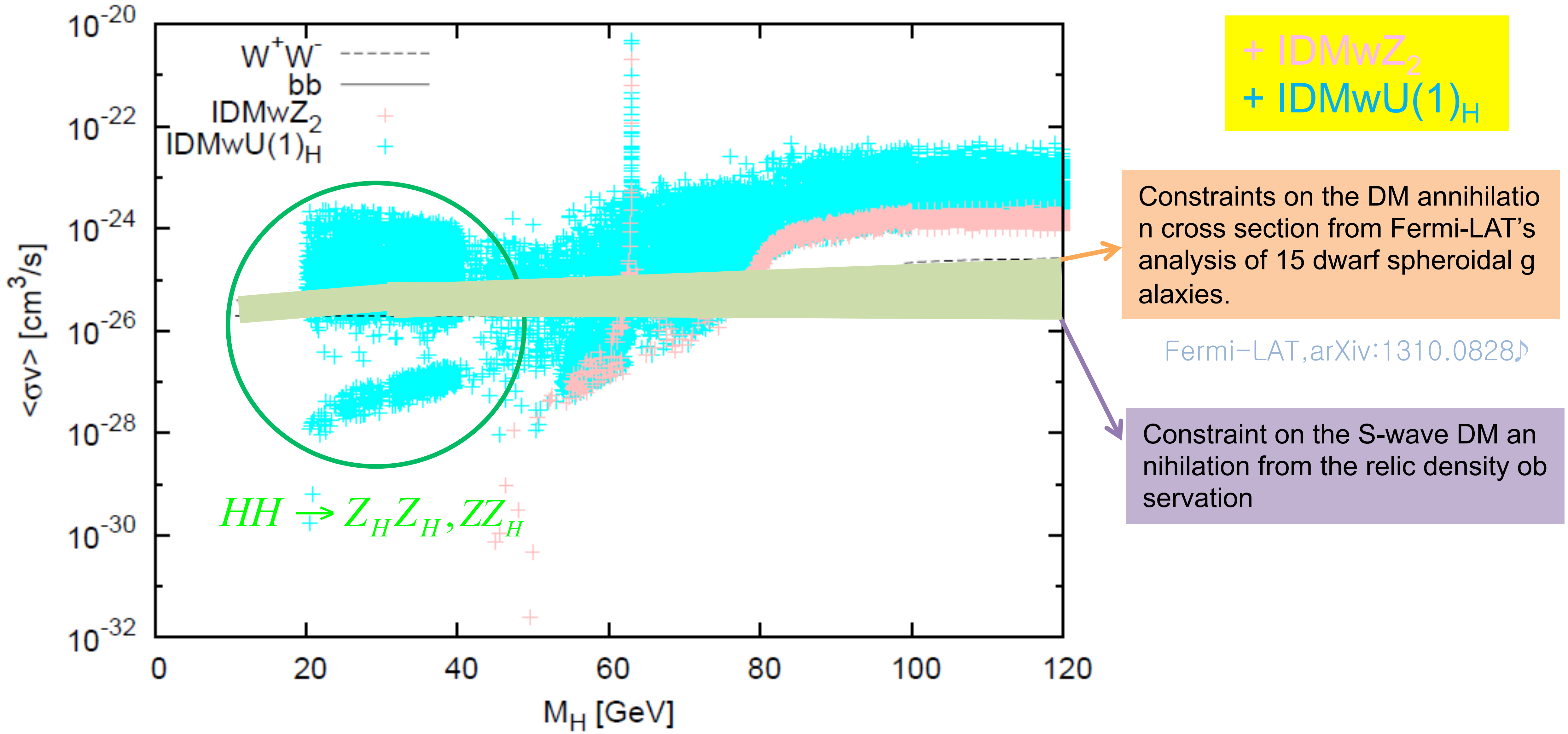
Constraints on the DM annihilation cross section from Fermi-LAT's analysis of 15 dwarf spheroidal galaxies.

Fermi-LAT,arXiv:1310.0828

Constraint on the S-wave DM annihilation from the relic density observation

- All points satisfy constraints from the relic density observation and LUX experiments.

Indirect searches (low mass)



- But, indirect DM signals depend on the decay patterns of produced particles from annihilation or decay of DMs.

Gamma ray flux from DM annihilation

• Dwarf spheroidal galaxies are excellent targets to search for annihilatin g DM signatures because of DM-dominant nature without astrophysical b ackgrounds like hot gas.

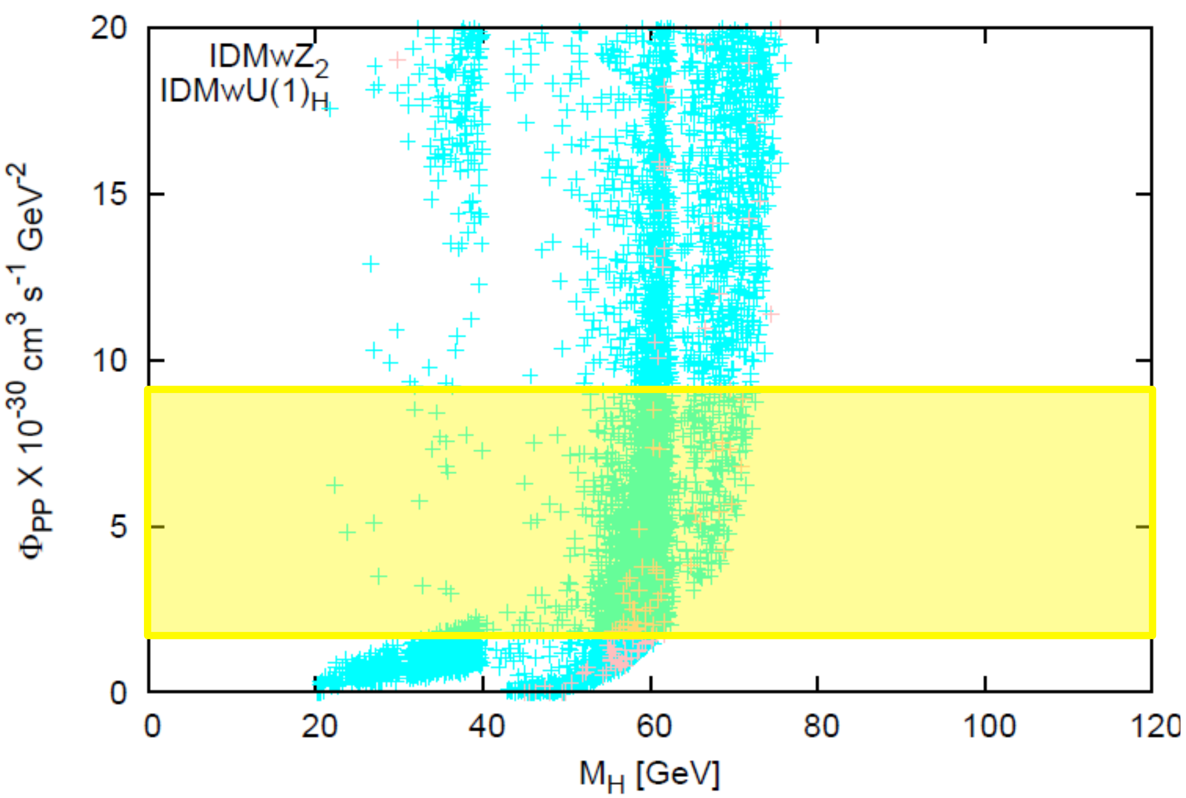
$$\phi_s(\Delta\Omega) = \underbrace{\frac{1}{4\pi}\frac{\langle\sigma v\rangle}{2m_{\rm DM}^2}\int_{E_{\rm min}}^{E_{\rm max}}\frac{{\rm d}N_\gamma}{{\rm d}E_\gamma}{\rm d}E_\gamma}_{\Phi_{\rm PP}} \cdot \underbrace{\int_{\Delta\Omega}\left\{\int_{\rm l.o.s.}\rho^2(r){\rm d}l\right\}{\rm d}\Omega'}_{\text{J-factor}} .$$

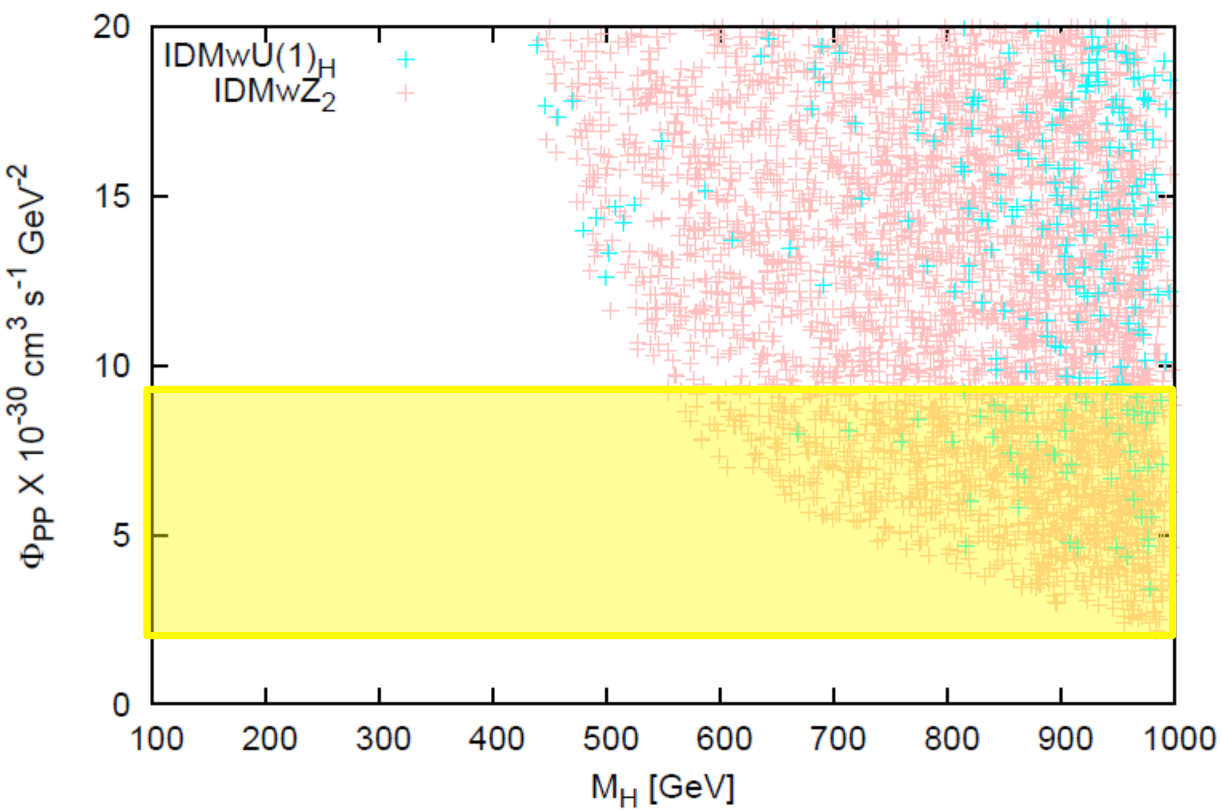
The final γ-ray spectrum.

contains information about the distribution of DM.

A 95% upper bound is $\Phi_{\rm PP} = 5.0^{+4.3}_{-4.5}\times 10^{-30}\,{\rm cm^3 s^{-1} GeV^{-2}}$

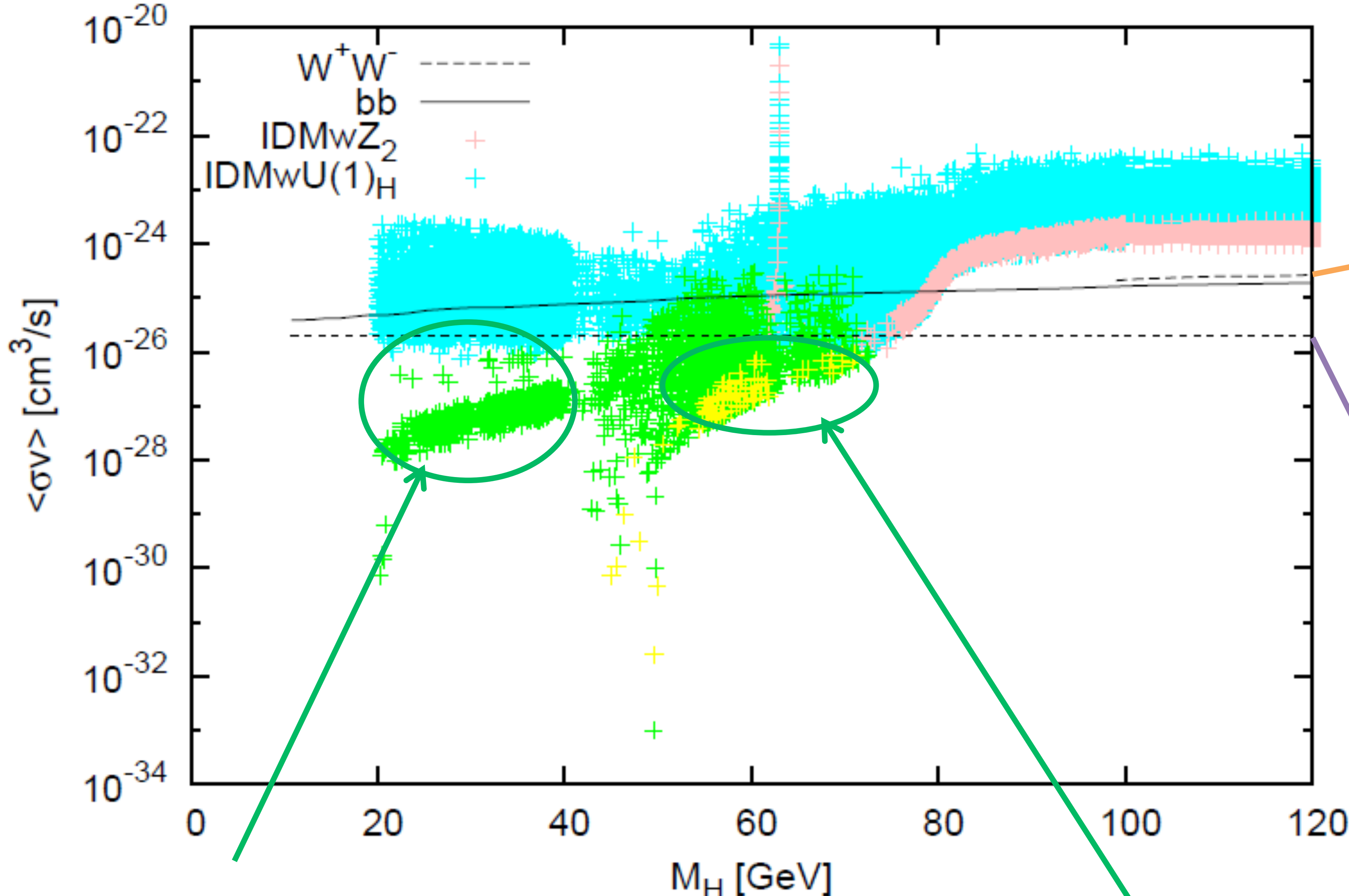
Geringer-Sameth,Koushiappas, PRL107♪





Indirect searches (low mass)

$+$ IDMwZ_2
$+$ IDMw$U(1)_H$



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$m_H \sim m_{Z_H}$

Co-annihilation

Relic density (high mass)

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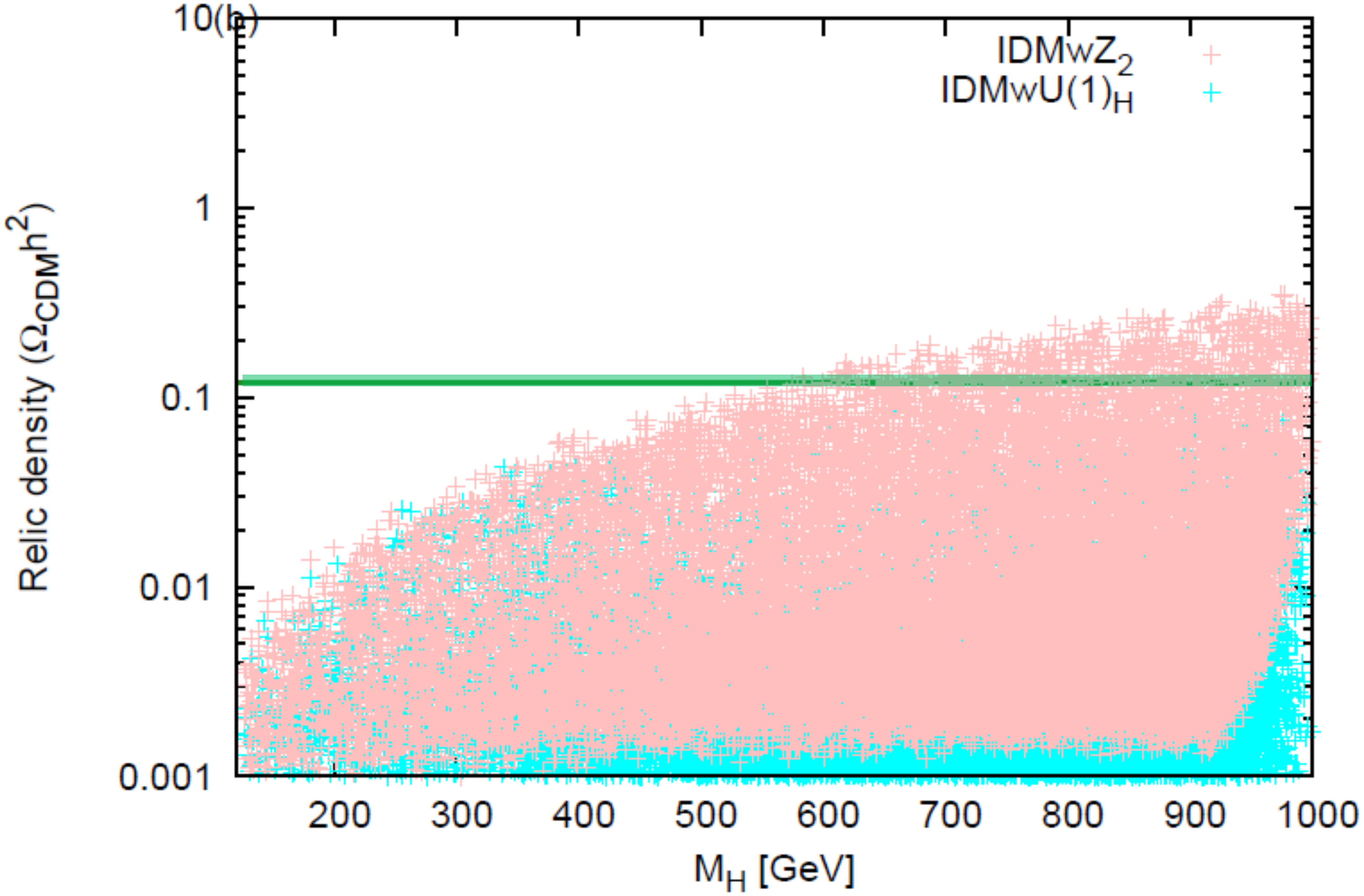
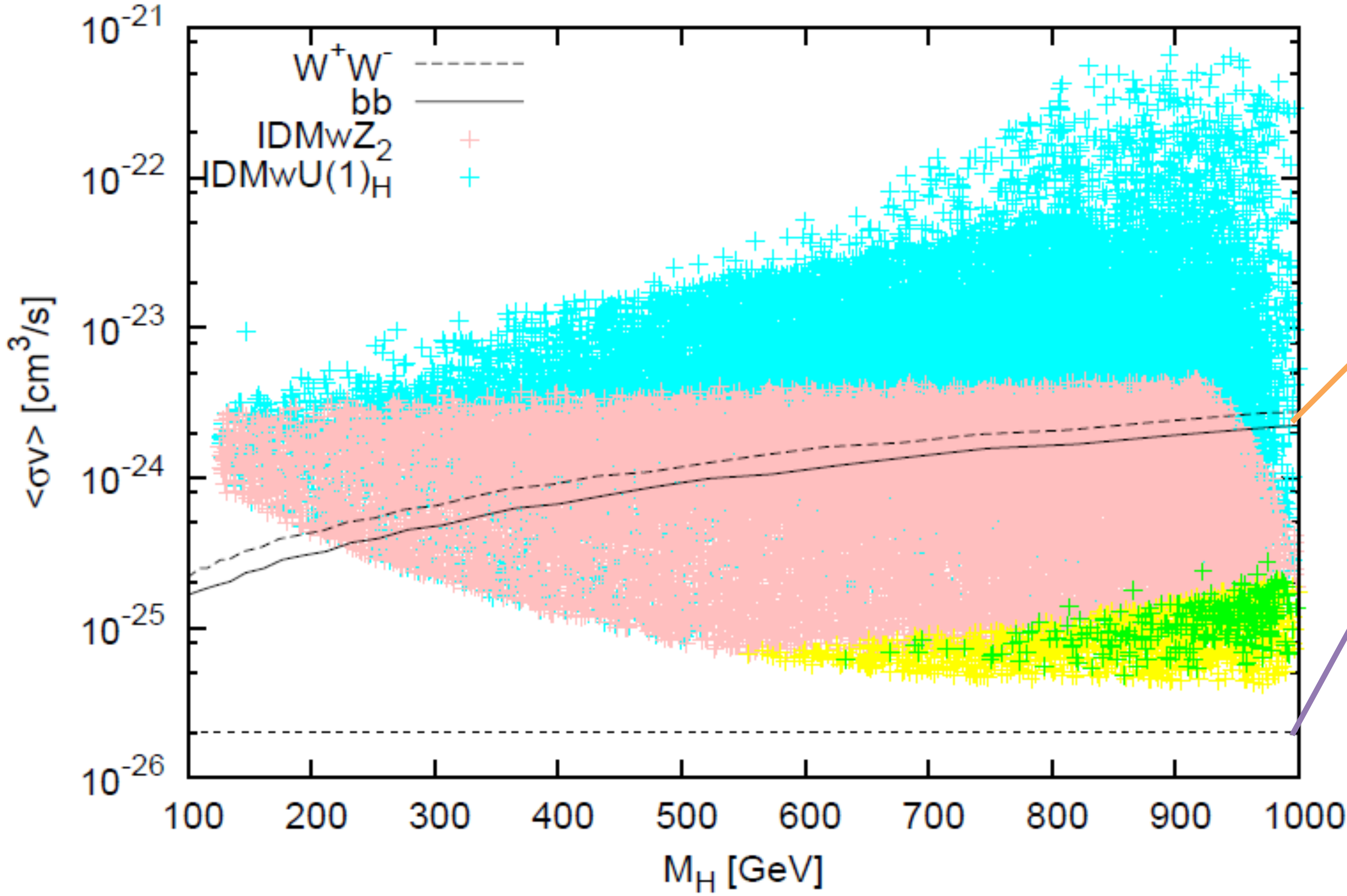


+ $IDMwZ_2$
+ $IDMwU(1)_H$

Indirect searches (high mass)



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Fermi-LAT,arXiv:1310.0828♪

Constraint on the S-wave DM annihilation from the relic density observation

Gamma flux from GC

- DM with mass 30-40 GeV with pair annihilating into Z_H Z_H should be able to accommodate the gamma ray excess from the galactic center (work in progress)
- This DM mass range is impossible within the usual IDM
- Becomes possible in IDM with local U(1)H because of new channels involving Z_H s

New chiral gauge symmetry requires more Higgs doublets

New chiral gauge sym

- If we introduce a new chiral gauge symmetry, we have to introduce more Higgs doublets in order that we can write down realistic Yukawa matrices for the SM fermions

- Interference between gauge boson and additional Higgs boson contributions can be important (especially for the 3rd generation fermions)

- Examples in the top FBA, B physics anomalies, etc..

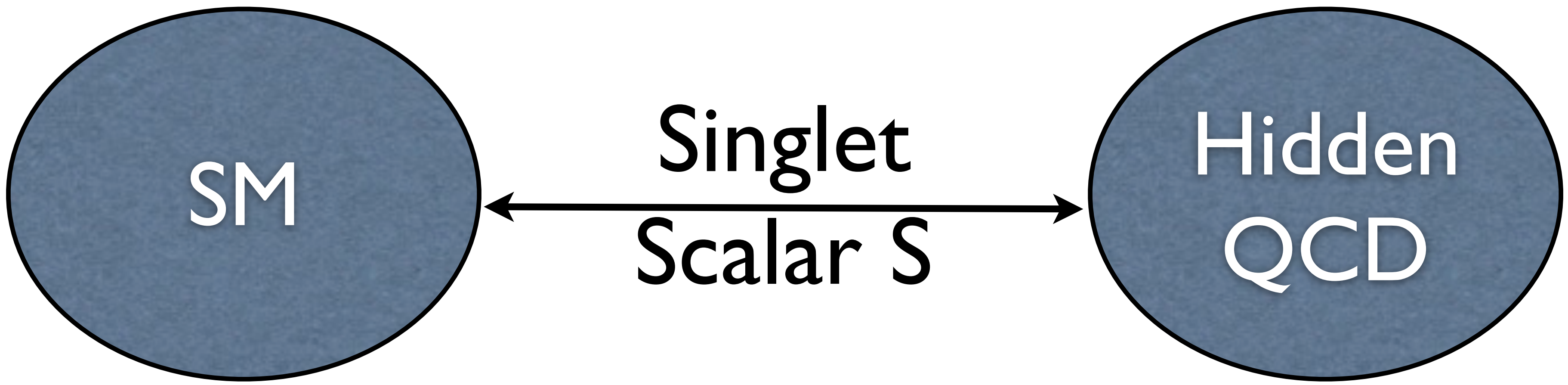
- If additional charged/neutral Higgs bosons are discovered, that may indicate the existence of a new chiral gauge symmetry, and not of weak scale SUSY

CSI (classical scale inv)

- Chiral fermion get massive by spontaneous gauge symmetry breaking (as in the SM)
- Gauge fields get massive by Higgs mechanism or by confinement (one of the millenium problems)
- No such principle for scalar fields (related with fine tuning problem of Higgs mass) $m^2 = m_0^2 + \alpha\Lambda^2$
- Probably CSI may be the only way to understand the origin of scalar fields in a dynamical manner
- CSI broken radiatively or by new strong dynamics

Model I (Scalar Messenger)

Hur, Ko, PRL (2011)



- SM - Messenger - Hidden Sector QCD
- Assume classically scale invariant lagrangian --> No mass scale in the beginning
- Chiral Symmetry Breaking in the hQCD generates a mass scale, which is injected to the SM by "S"

Scale invariant extension of the SM with strongly interacting hidden sector

Modified SM with classical scale symmetry

$$\begin{aligned}\mathcal{L}_{\rm SM} &= \mathcal{L}_{\rm kin} - \frac{\lambda_H}{4}\,(H^\dagger H)^2 - \frac{\lambda_{SH}}{2}\,S^2\,H^\dagger H - \frac{\lambda_S}{4}\,S^4 \\ &+ \Big(\overline{Q}^i H Y_{ij}^D D^j + \overline{Q}^i \tilde{H} Y_{ij}^U U^j + \overline{L}^i H Y_{ij}^E E^j \\ &+ \overline{L}^i \tilde{H} Y_{ij}^N N^j + S N^{iT} C Y_{ij}^M N^j + h.c.\Big)\end{aligned}$$

Hidden sector lagrangian with new strong interaction

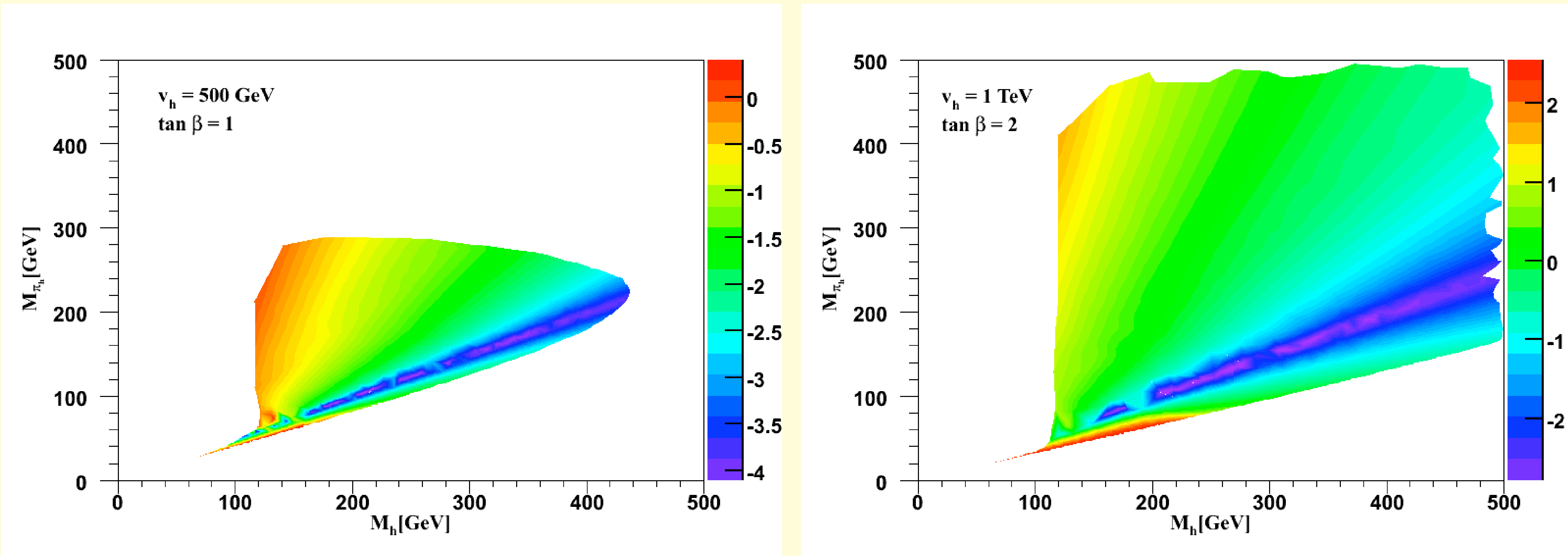
$$\mathcal{L}_{\rm hidden} = -\frac{1}{4}\mathcal{G}_{\mu\nu}\mathcal{G}^{\mu\nu} + \sum_{k=1}^{N_{HF}} \overline{\mathcal{Q}}_k (i\mathcal{D}\cdot\gamma - \lambda_k S)\mathcal{Q}_k$$

3 neutral scalars : h, S and hidden sigma meson
Assume h-sigma is heavy enough for simplicity

Effective lagrangian far below $\Lambda_{h,\chi} \approx 4\pi\Lambda_h$

$$
\begin{aligned}
\mathcal{L}_{\rm full} &= \mathcal{L}^{\rm eff}_{\rm hidden} + \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm mixing} \\
\mathcal{L}^{\rm eff}_{\rm hidden} &= \frac{v_h^2}{4}{\rm Tr}[\partial_\mu \Sigma_h \partial^\mu \Sigma_h^\dagger] + \frac{v_h^2}{2}{\rm Tr}[\lambda S \mu_h (\Sigma_h + \Sigma_h^\dagger)] \\
\mathcal{L}_{\rm SM} &= -\frac{\lambda_1}{2}(H_1^\dagger H_1)^2 - \frac{\lambda_{1S}}{2} H_1^\dagger H_1 S^2 - \frac{\lambda_S}{8} S^4 \\
\mathcal{L}_{\rm mixing} &= -v_h^2 \Lambda_h^2 \left[\kappa_H \frac{H_1^\dagger H_1}{\Lambda_h^2} + \kappa_S \frac{S^2}{\Lambda_h^2} + \kappa_S' \frac{S}{\Lambda_h} \right. \\
&+ \left. O(\frac{S H_1^\dagger H_1}{\Lambda_h^3}, \frac{S^3}{\Lambda_h^3}) \right] \\
&\approx -v_h^2 \left[\kappa_H H_1^\dagger H_1 + \kappa_S S^2 + \Lambda_h \kappa_S' S \right]
\end{aligned}
$$

Relic density

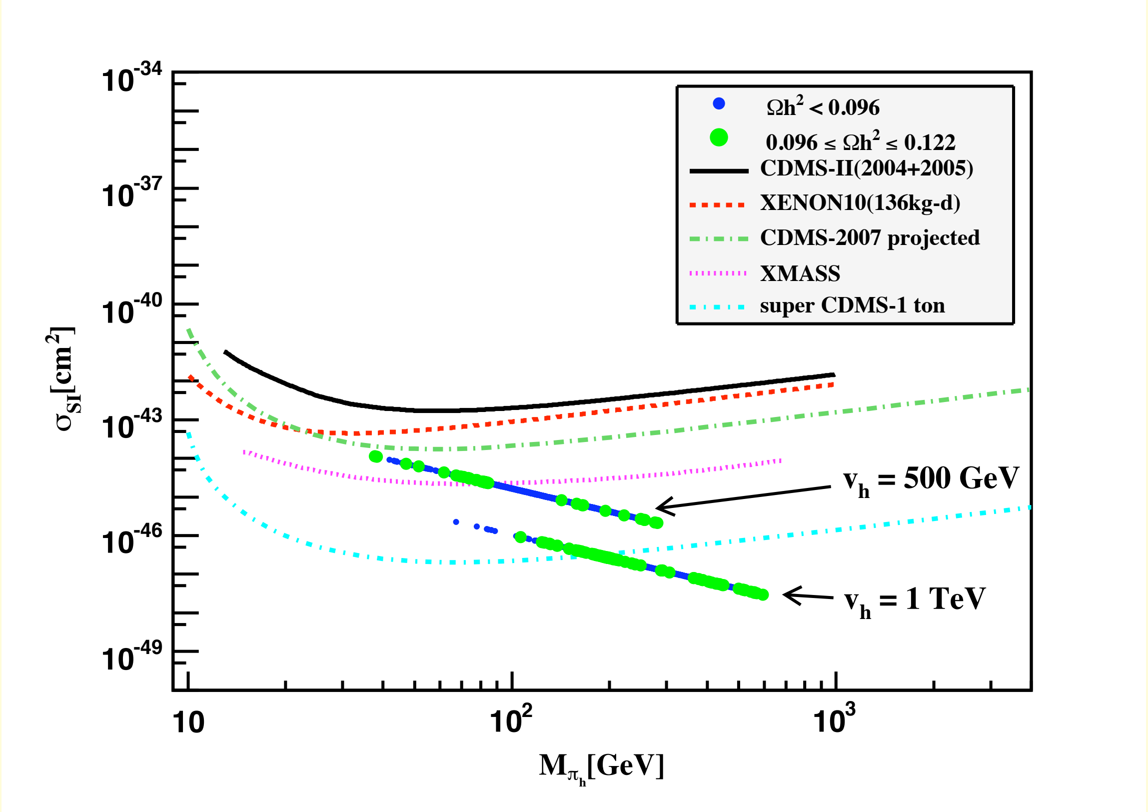


$\Omega_{\pi_h} h^2$ in the (m_{h_1}, m_{π_h}) plane for

(a) $v_h = 500$ GeV and $\tan\beta = 1$,

(b) $v_h = 1$ TeV and $\tan\beta = 2$.

Direct Detection Rate



$\sigma_{SI}(\pi_h p \to \pi_h p)$ as functions of m_{π_h}.
the upper one: $v_h = 500$ GeV and $\tan\beta = 1$,

the lower one: $v_h = 1$ TeV and $\tan\beta = 2$.

Conclusions

- Local gauge symmetries play a key role in the unsurpassed successful SM
- It may play the same role in DM physics ; many evidences that they really do
- $U(1)_H$ extensions of 2HDM (and multi Higgs doublet models) can be interesting possibilities to consider ; Inert 2HDM with $U(1)_H$ is a good example ; Top FBA and B anomalies
- A lot of possibilities for new ways to look at Physics of Higgs, Flavor, DM, Neutrinos (one can consider CSI as well)