Role of dark Higgs boson in particle physics and cosmology

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CERN-EPFL-Korea Theory Institute for
“New Physics at the Intensity Frontier”
Feb. 20 - Mar. 3 (2017)

- The main theme of this meeting is the "New physics at the intensity frontier"

- light DM, light mediators, etc.

- Dark photon is very common in literature

- In this talk, I talk on theoretical motivations for dark Higgs boson (as well as dark photon or dark gauge boson), focusing on the role of (light) dark Higgs boson in DM phenomenology in PPC

Contents

Based on works with Seungwon Baek, Jinsu Kim, Jinmian Li, Myeonghun Park, Wan-Il Park, Eibun Senaha, Yong Tang, Chaehyun Yu

- DM EFT vs. UV completions : appearance of dark Higgs boson
- GC gamma ray excess
- Its role in Higgs inflation
- Dark Higgs search at colliders

Examples such as AMS02 positron excess, ICECUBE high energy neutrino flux, etc. are not discussed here

Key Ideas

- Stability/Longevity of Dark Matter (DM)
- Local Dark Gauge Symmetry
- Thermal DM through Singlet Portals (especially Higgs Portal)
- Connections between Higgs, DM and Higgs Inflation, especially the role of "Dark Higgs"
- Improved vacuum stability, Self Interacting DM, GC gamma ray excess, Higgs inflation, (750 GeV Diphoton excess), etc.

SM Chapter is being closed

- SM has been tested at quantum level
  - EWPT favors light Higgs boson
  - CKM paradigm is working very well so far
  - LHC found a SM-Higgs like boson around 125 GeV
- No smoking gun for new physics at LHC so far

SM Lagrangian

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

Based on local gauge principle

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

Local Gauge Principle Works !

Motivations for BSM

- Neutrino masses and mixings
- Baryogenesis
- Inflation (inflaton)
- Nonbaryonic DM
- Origin of EWSB and Cosmological Const ?

Leptogenesis

Starobinsky ? Higgs Inflations

Many candidates

Can we attack these problems ?

Origin of EWSB ?

- LHC discovered a scalar ~ SM Higgs boson
- This answers the origin of EWSB within the SM in terms of the Higgs VEV, v
- Still we can ask the origin of the scale "v"
- Can we understand its origin by some strong dynamics similar to QCD or TC ?

Origin of Mass

- Massive SM particles get their masses from Higgs mechanism or confinement in QCD
- How about DM particles ? Where do their masses come from ?
- SM Higgs ? SUSY Breaking ? Extra Dim ?
- Can we generate all the masses as in proton mass from dim transmutation in QCD ? (proton mass in massless QCD)

Questions about DM

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

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

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

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- Any good organizing principle ?
- YES ! >> Dark Gauge Symmetry

Local Dark Gauge Sym

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

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

Basic assumptions

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

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)
- I will talk about each scenario one by one, and focusing on the roles of (light) dark Higgs boson

Principles for DM Physics

- Local Dark Gauge Symmetry for DM

  - can make DM absolutely stable or long lived
  - all the known particles feel gauge force

- Renormalizability with some caveat

  - does not miss physics which EFT can not catch.

- Singlet portals

  - allows communication of DS to SM (thermalization, detectability, ...)

Hidden Sector

- Any NP @ TeV scale is strongly constrained by EWPT and CKMology
- Hidden sector made of SM singlets, and less constrained, and could be CDM
- Generic in many BSM's including SUSY models
- E8 X E8' , SO(32) : natural setting for SM X Hidden Sector

Hidden Sector

- Hidden sector gauge symmetry can stabilize hidden DM
- There could be some contributions to the dark radiation (dark photon or sterile neutrinos)
- Consistent with GUT in a broader sense
- Can address "QM generation of all the mass scales from strong dynamics in the hidden sector" (alternative to the Coleman-Weinberg) : Hur and Ko, PRL (2011) and earlier paper and proceedings

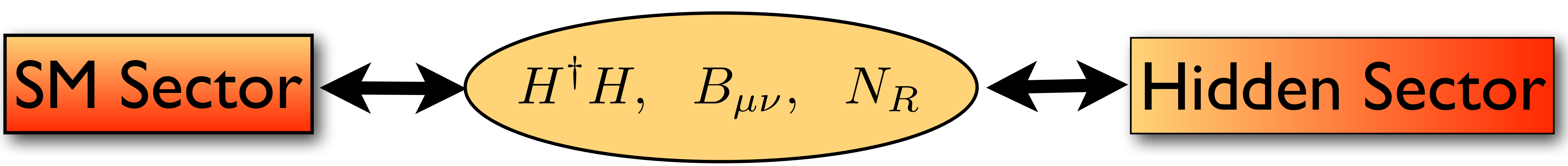
How to specify hidden sector ?

- Gauge group (G_h) : Abelian or Nonabelian
- Strength of gauge coupling : strong or weak
- Matter contents : singlet, fundamental or higher dim representations of G_h
- All of these can be freely chosen at the moment : Any predictions possible ?
- But there are some generic testable features in Higgs phenomenology and dark radiation

Singlet Portal

Baek, Ko, Park, arXiv:1303.4280, JHEP

- If there is a hidden sector and DM is thermal, then we need a portal to it
- There are only three unique gauge singlets in the SM + RH neutrinos



$$N_R \leftrightarrow \widetilde{H} l_L$$

$$e.g. \ \phi_X^\dagger \phi_X, X_{\mu\nu}, \psi_X^\dagger \phi_X$$

Higgs signal strength/Dark radiation/DM

in preparation with Baek and W.I. Park

Models	Unbroken U(1)X	Local Z2	Unbroken SU(N)	Unbroken SU(N) (confining)
Scalar DM	1 0.08 complex scalar	<1 ~0 real scalar	1 ~0.08*# complex scalar	1 ~0 composite hadrons
Fermion DM	<1 0.08 Dirac fermion	<1 ~0 Majorana	<1 ~0.08*# Dirac fermion	<1 ~0 composite hadrons

: The number of massless gauge bosons

Generic Aspects

- Two types of force mediators :
  - Higgs-Dark Higgs portals (Higgs-singlet mixing)
  - Kinetic portal to dark photon for U(1) dark gauge sym (absent for non-Abelian dark gauge sym@renor. level)
  - Naturally there due to underlying dark gauge symmetry
- RH neutrino portal if it is a gauge singlet (not in the presence of U(1) B-L gauge sym)
- These (especially Higgs portal which has been often neglected) can thermalize CDM efficiently

General Comments

- Many studies on DM physics using EFT
- However we don't know the mass scales of DM and the force mediator, and also dark sym
- Sometimes one can get misleading results
- Better to work in a minimal renormalizable and anomaly-free models
- Explicit examples : singlet fermion Higgs portal DM, vector DM, Z2 scalar CDM

Why renormalizable models ?
&
Limitation of EFT for DM

Higgs portal DM as examples

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

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

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

All invariant under ad hoc Z2 symmetry

arXiv:1112.3299, … 1402.6287, etc.

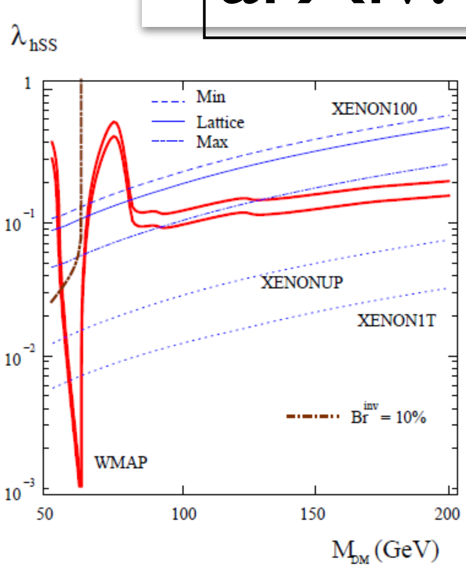


FIG. 1. Scalar Higgs-portal parameter space allowed by WMAP (between the solid red curves), XENON100 and $BR^{inv} = 10\%$ for $m_h = 125$ GeV. Shown also are the prospects for XENON upgrades.

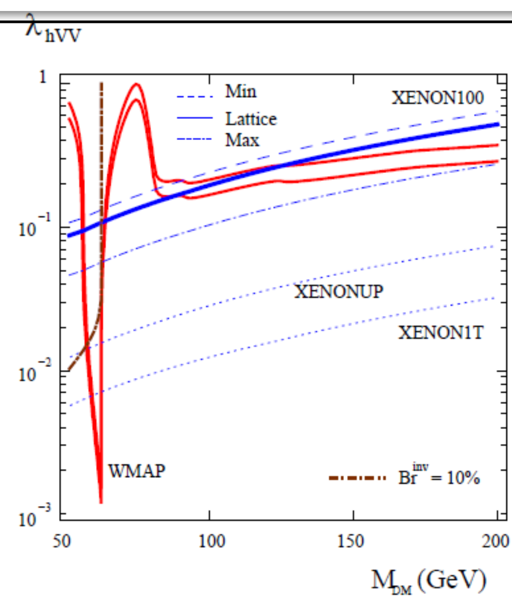


FIG. 2. Same as Fig. 1 for vector DM particles.

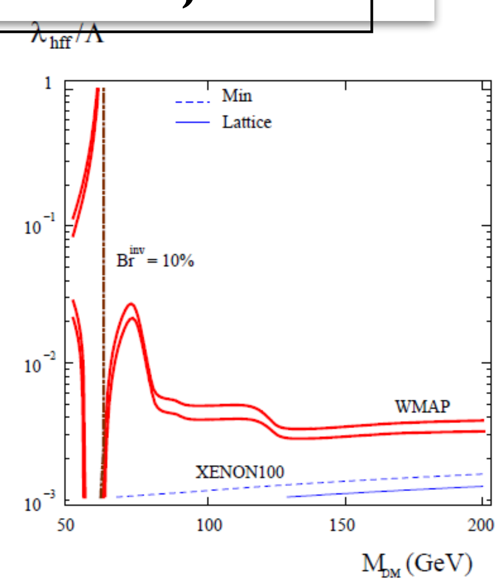


FIG. 3. Same as in Fig.1 for fermion DM; λ_{hff}/Λ is in GeV^{-1}.

Higgs portal DM as examples

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All invariant under ad hoc Z2 symmetry

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

Usual story within EFT

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

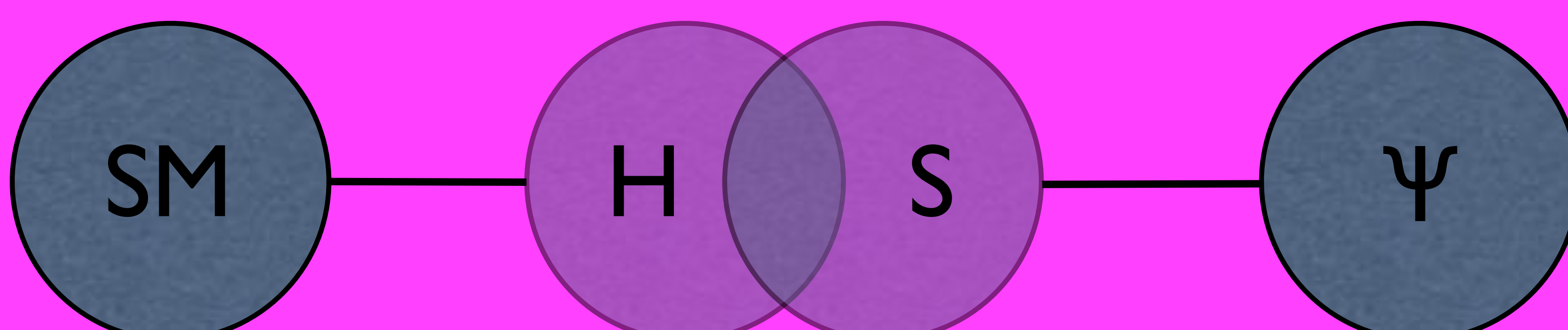
Singlet fermion CDM

Baek, Ko, Park, arXiv:1112.1847

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

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

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

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

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

Mixing of Higgs and singlet

Ratiocination

- Signal strength (reduction factor)

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

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

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

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

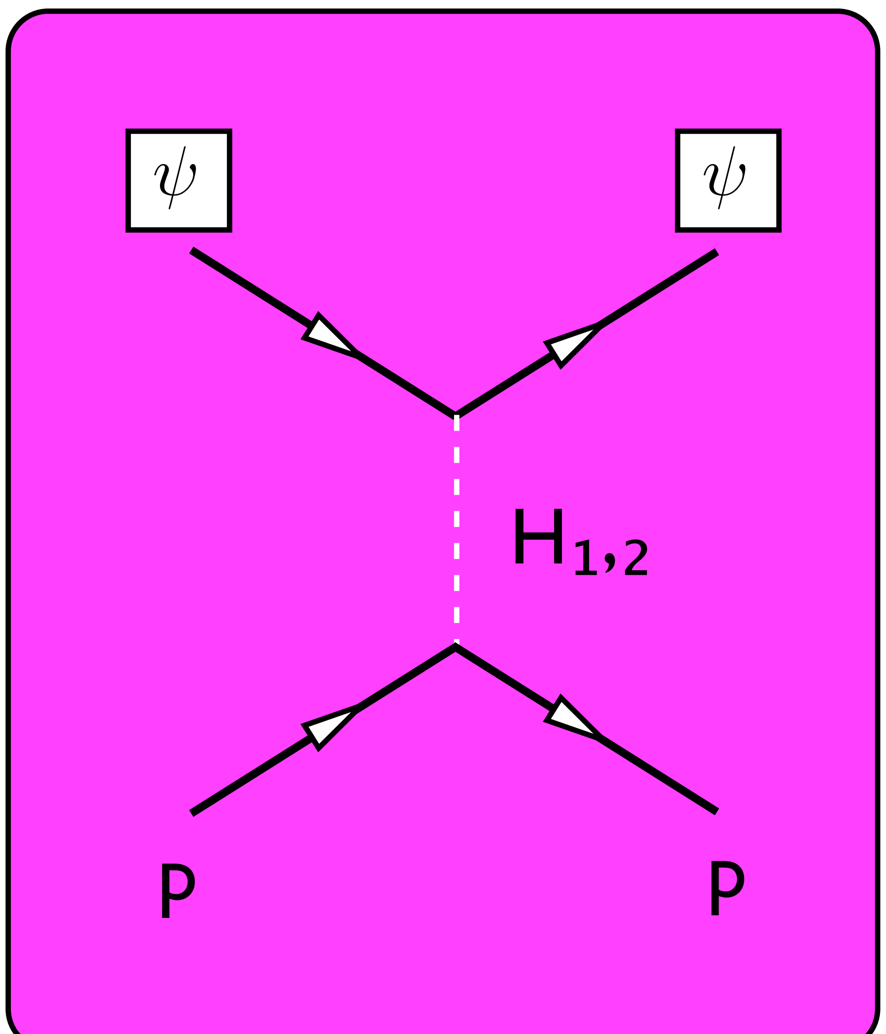
Invisible decay mode is not necessary!

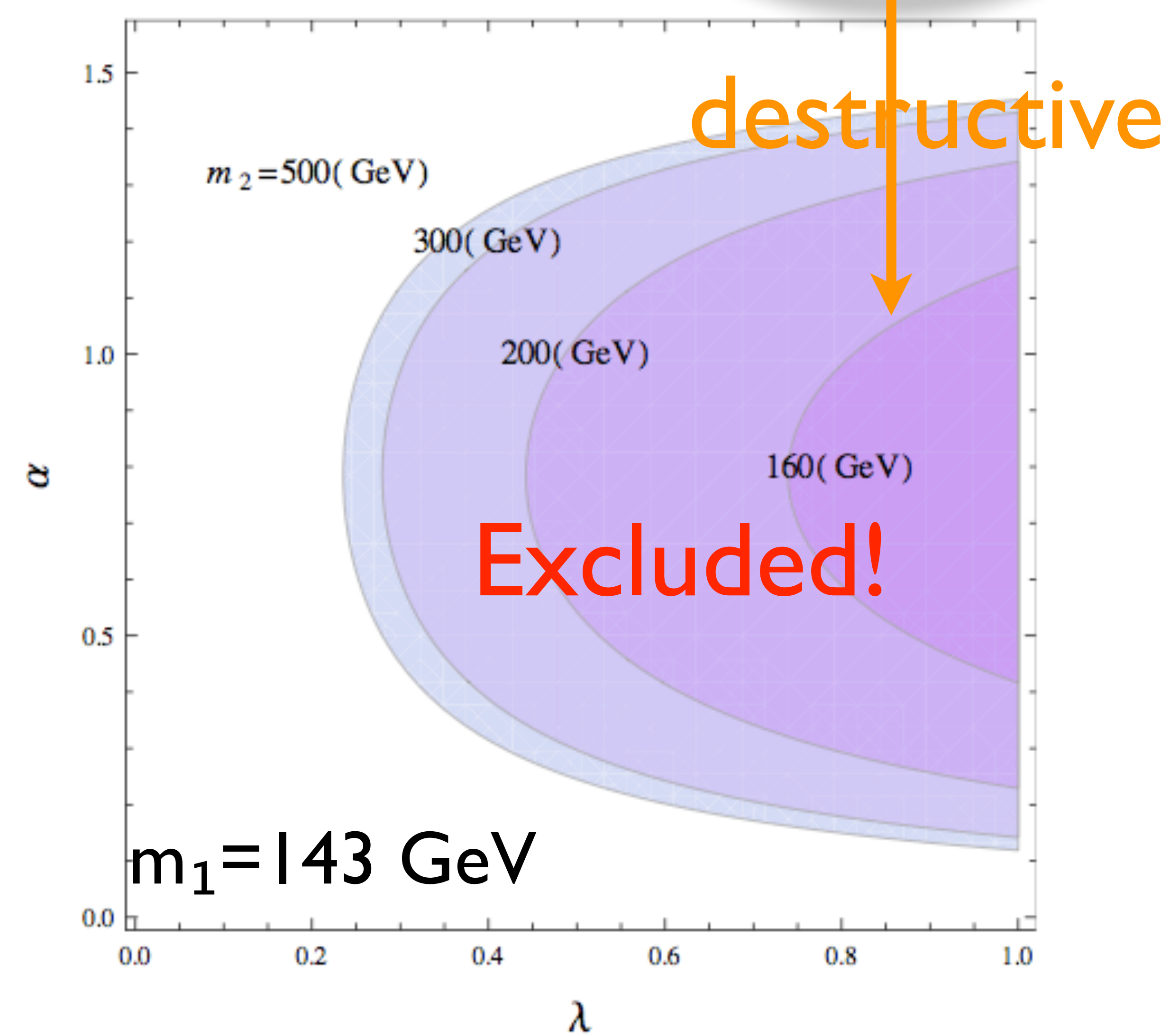
If r_i > 1 for any single channel,
this model will be excluded !!

Constraints

- Dark matter to nucleon cross section (constraint)

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





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

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

Breaks SM gauge sym

- Only one Higgs boson (alpha = 0)

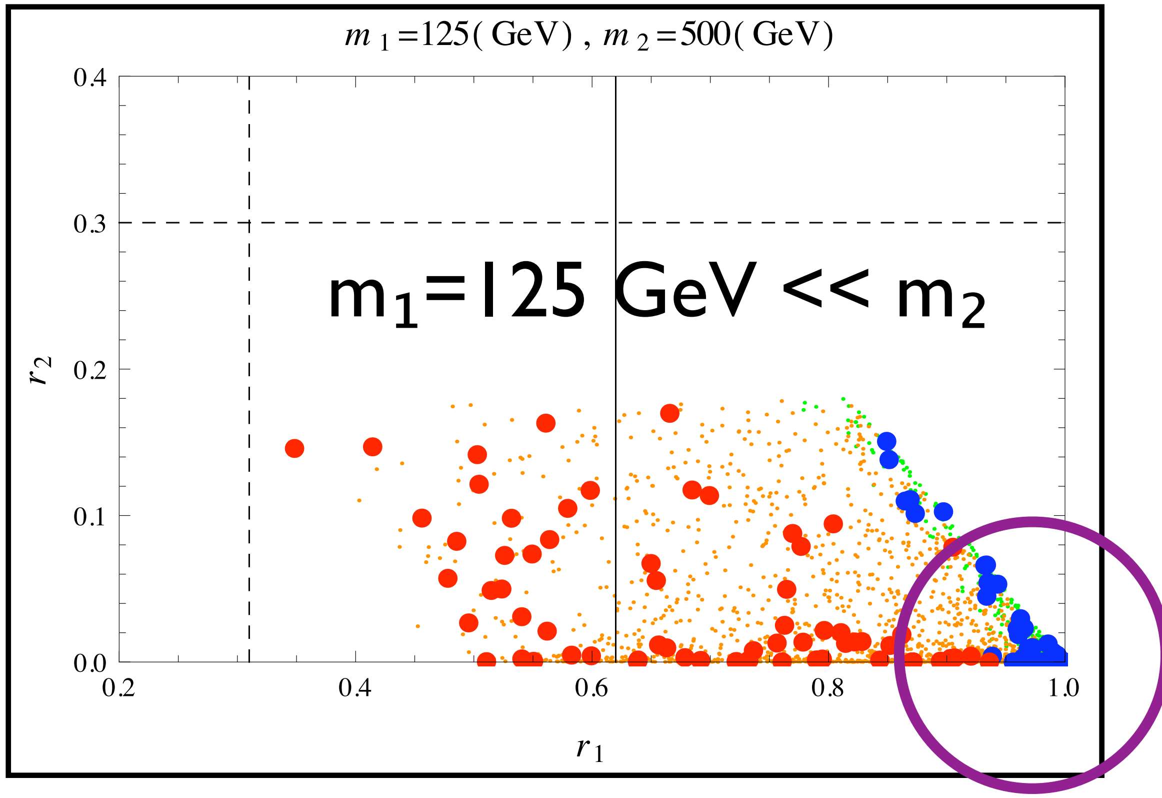
- We cannot see the cancellation between two Higgs scalars in the direct detection cross section, if we used the above effective lagrangian

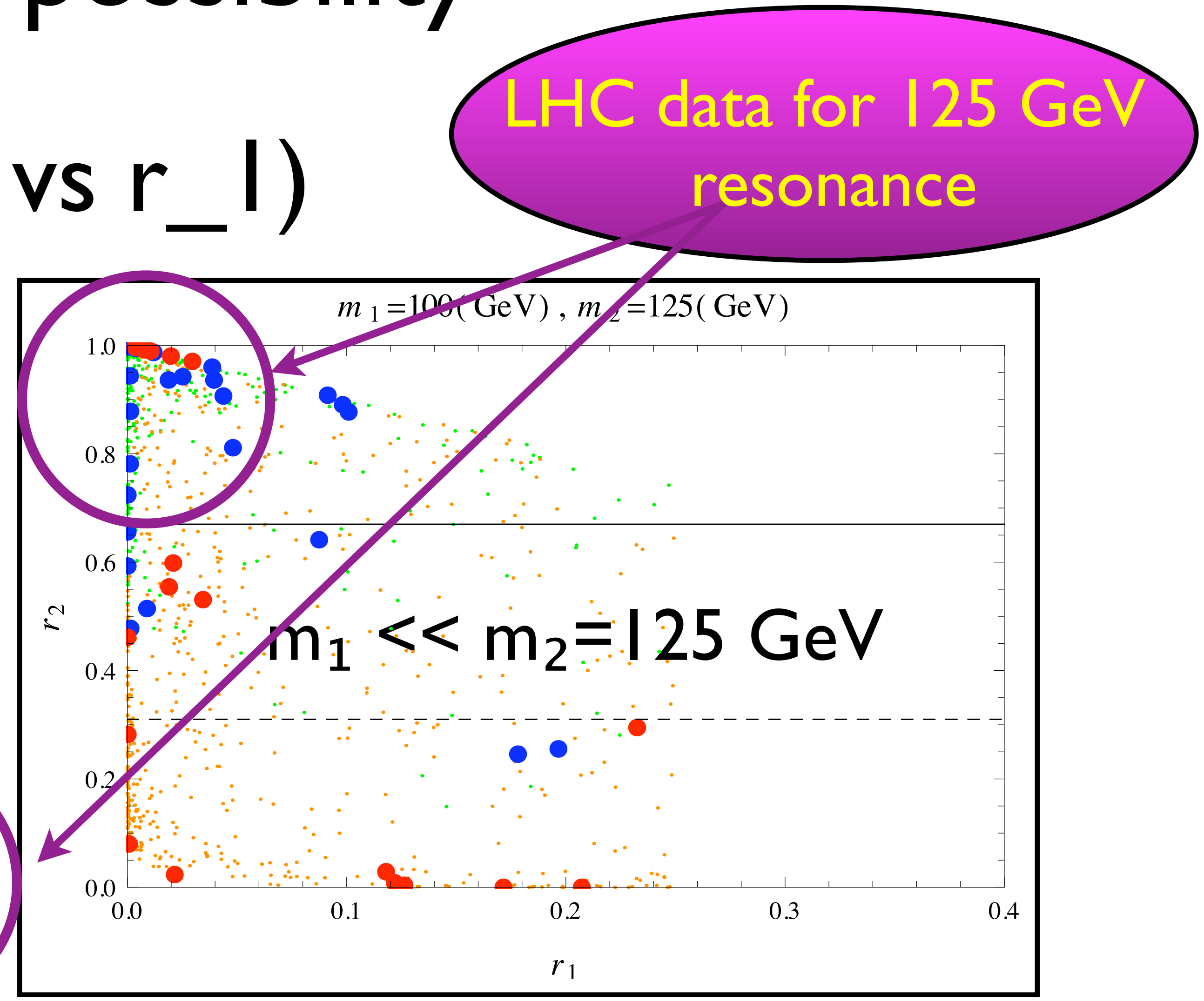
- The upper bound on DD cross section gives less stringent bound on the possible invisible Higgs decay

Discovery possibility

- Signal strength (r_2 vs r_1)

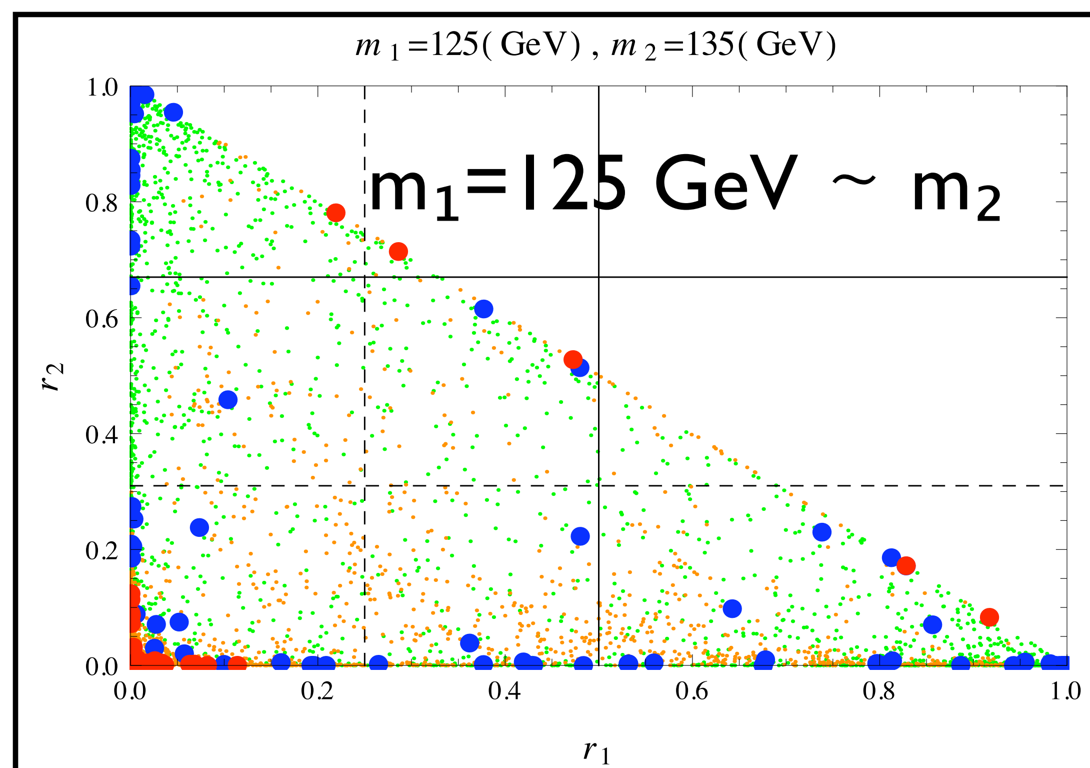
LHC data for 125 GeV resonance





: L= 5 fb⁻¹ for 3σ Sig.

: L=10 fb⁻¹ for 3σ Sig.



- (green): Ω(x),σ_p(x)
- (orange): Ω(x),σ_p(o)
- (blue): Ω(o),σ_p(x)
- (red): Ω(o),σ_p(o)

Low energy pheno.

- Universal suppression of collider SM signals

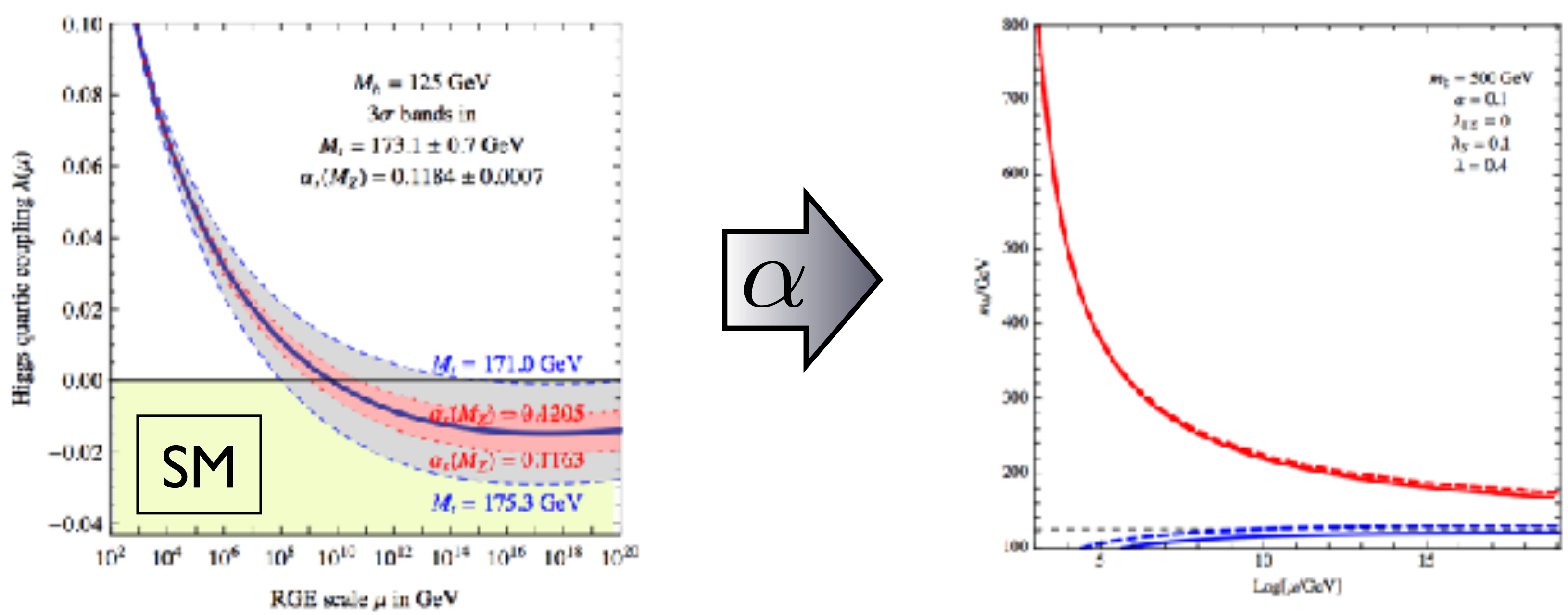
[See 1112.1847, Seungwon Baek, P. Ko & WIP]

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

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

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

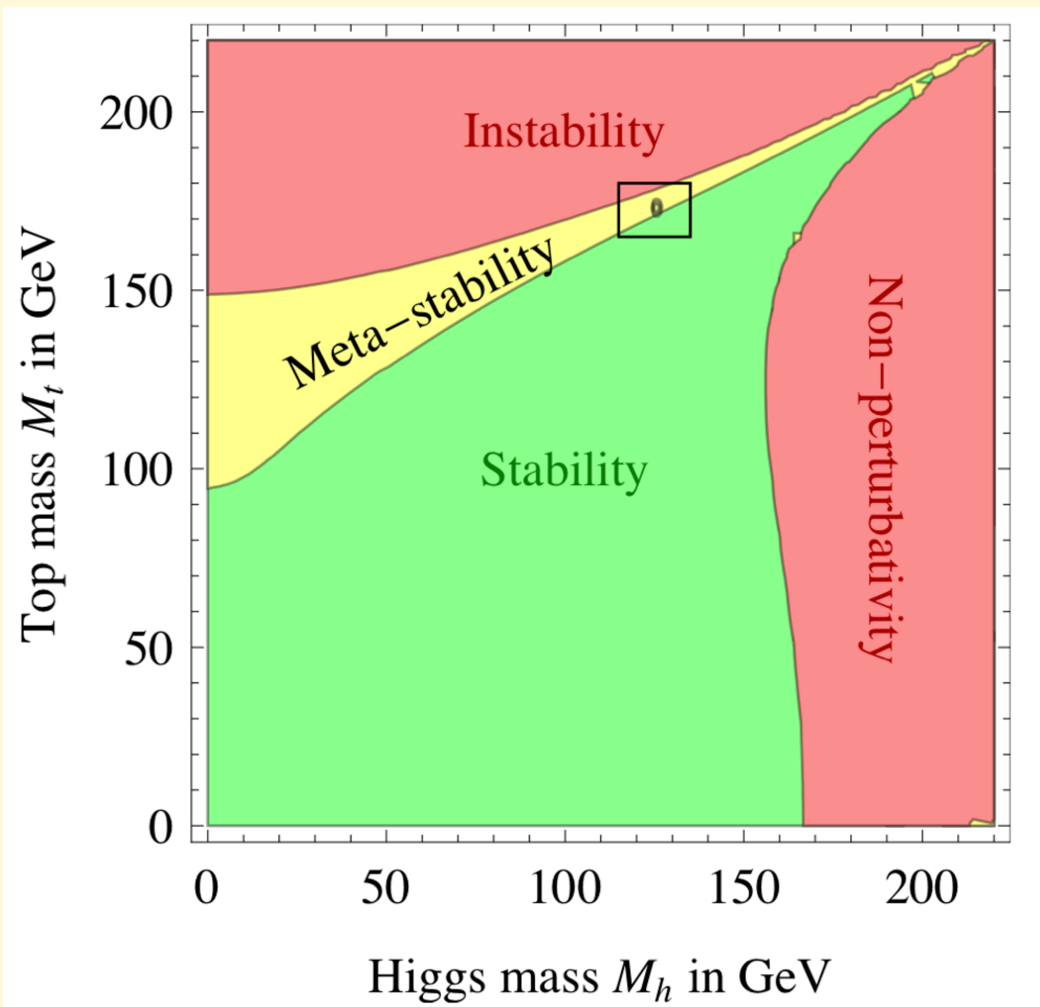
If "$m_\phi > m_h$", vacuum instability can be cured.

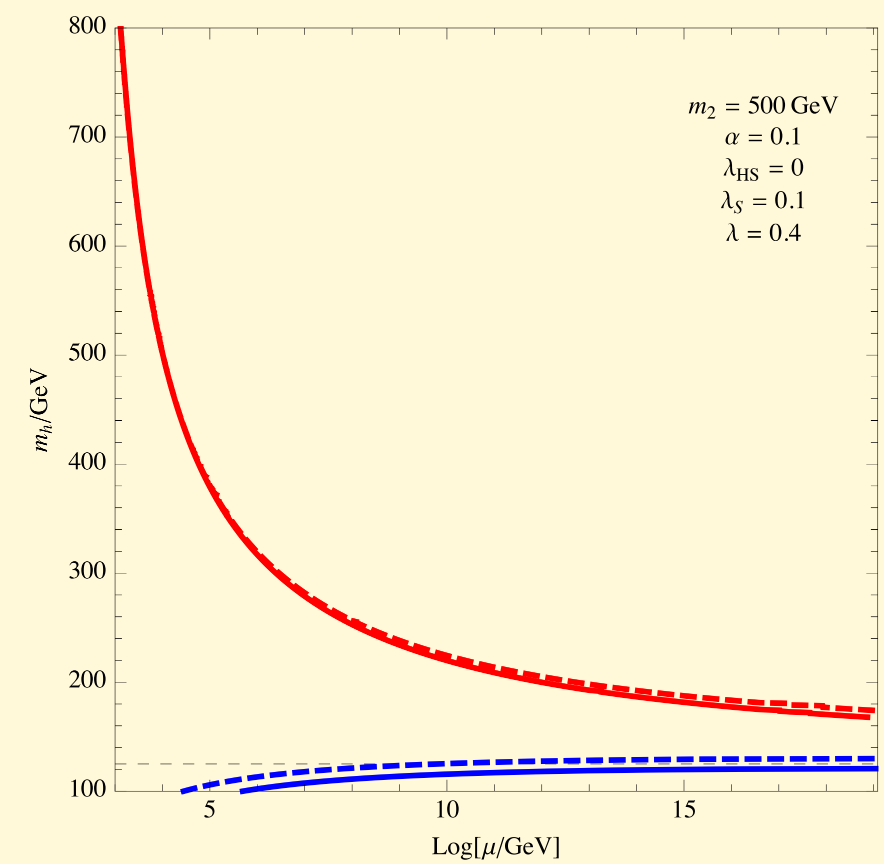


[G. Degrassi et al., 1205.6497]

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

Vacuum Stability Improved by the singlet scalar S





A. Strumia, Moriond EW 2013

Baek, Ko, Park, Senaha (2012)

Similar for Higgs portal Vector DM

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

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

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

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

$X_\mu \equiv V_\mu$ here

- There appear a new singlet scalar h_X from phi_X , which mixes with the SM Higgs boson through Higgs portal

- The effects must be similar to the singlet scalar in the fermion CDM model, and generically true in the DM with dark gauge sym

- Important to consider a minimal renormalizable and unitary model to discuss physics correctly [Baek, Ko, Park and Senaha, arXiv: 1212.2131 (JHEP)]

- Can accommodate GeV scale gamma ray excess from GC

New scalar improves EW vacuum stability

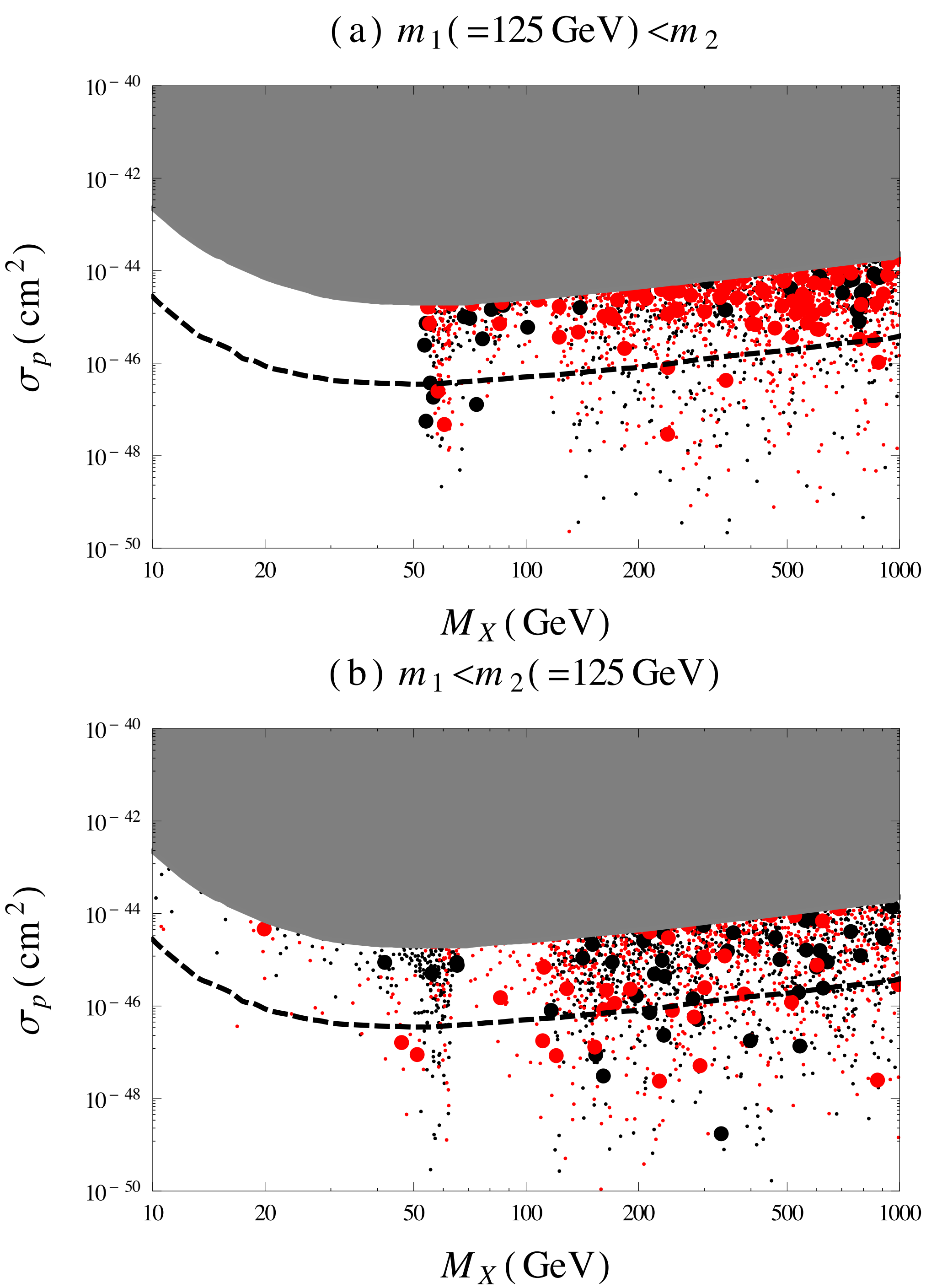


Figure 6. The scattered plot of σ_p as a function of M_X. The big (small) points (do not) satisfy the WMAP relic density constraint within 3 σ, while the red-(black-)colored points gives $r_1 > 0.7 (r_1 < 0.7)$. The grey region is excluded by the XENON100 experiment. The dashed line denotes the sensitivity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

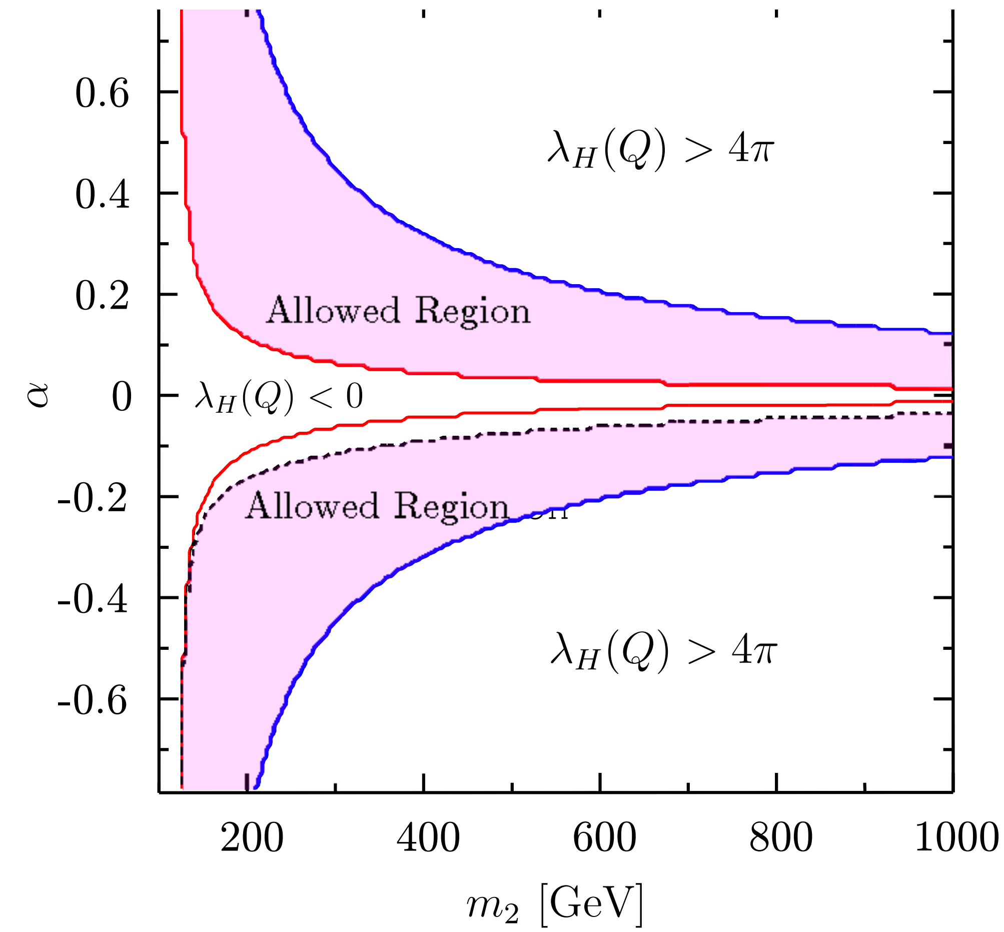


Figure 8. The vacuum stability and perturbativity constraints in the α-m_2 plane. We take $m_1 = 125$ GeV, $g_X = 0.05$, $M_X = m_2/2$ and $v_\Phi = M_X/(g_X Q_\Phi)$.

Higgs portal DM as examples

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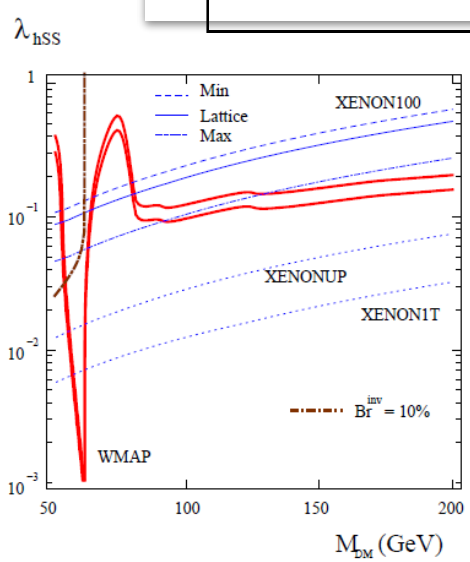
All invariant under ad hoc Z2 symmetry

arXiv:1112.3299, … 1402.6287, etc.



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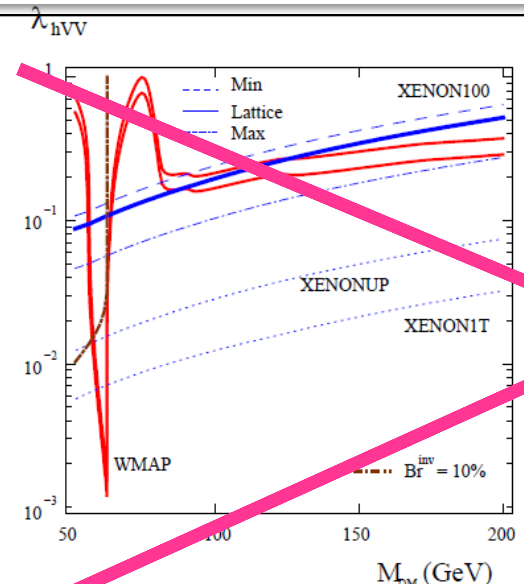


FIG. 2. Same as Fig. 1 for vector DM particles.

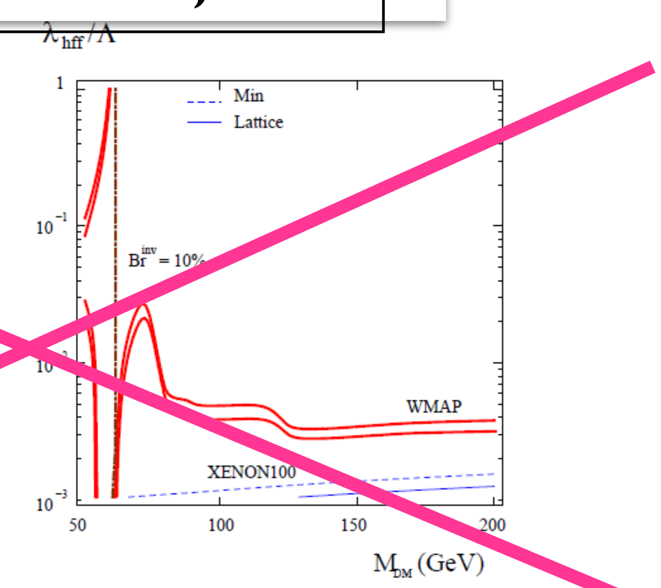


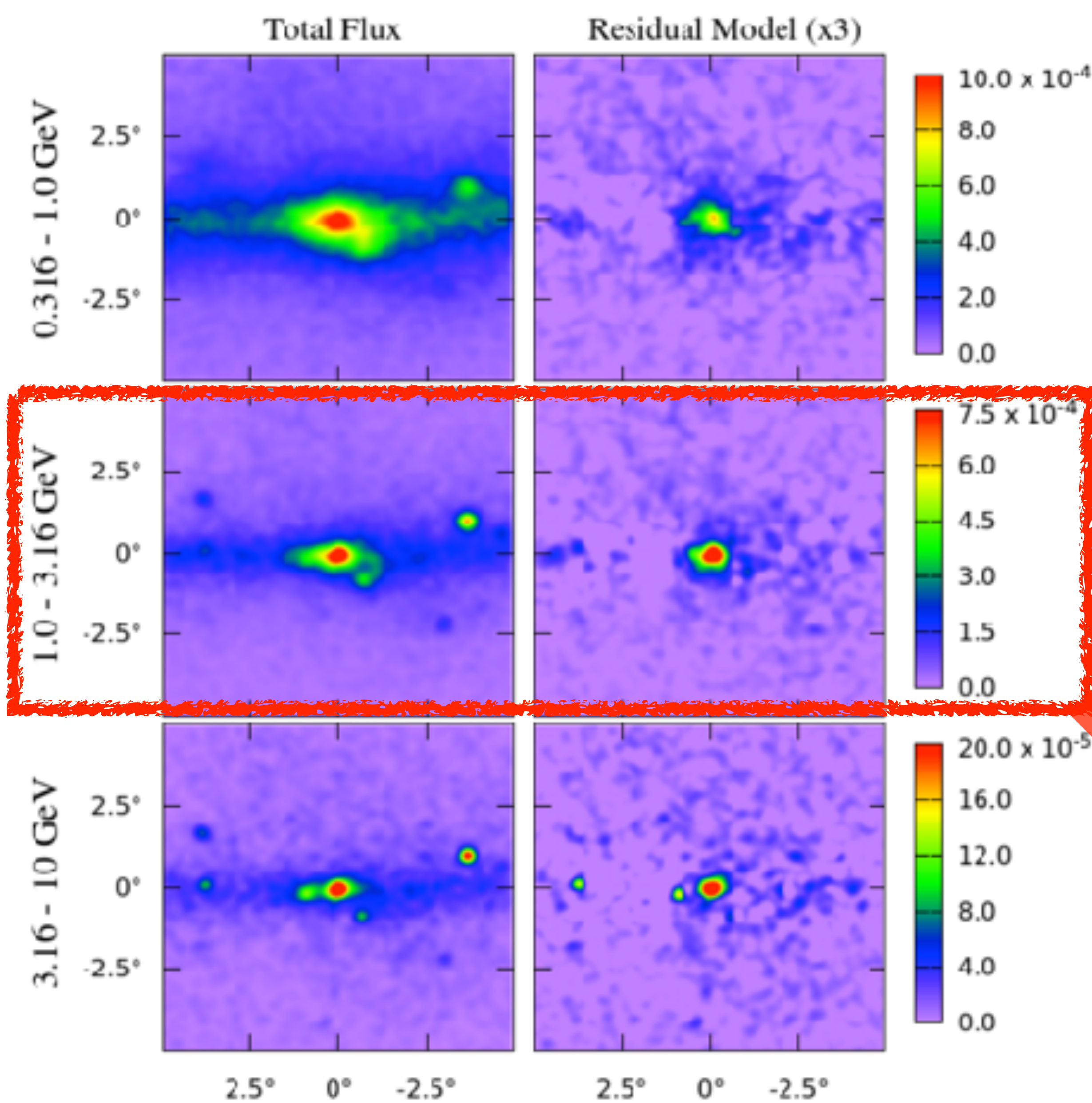
FIG. 3. Same as in Fig.1 for fermion DM; λ_{hff}/Λ is in GeV^{-1}.

Is this any useful in phenomenology ?

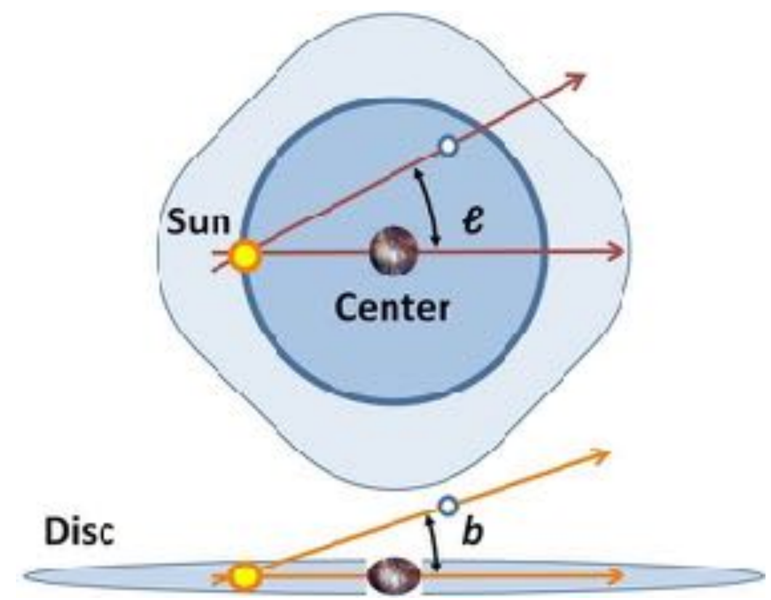
YES !

Fermi-LAT γ-ray excess

- Gamma-ray excess in the direction of GC



[1402.6703, T. Daylan et.al.]

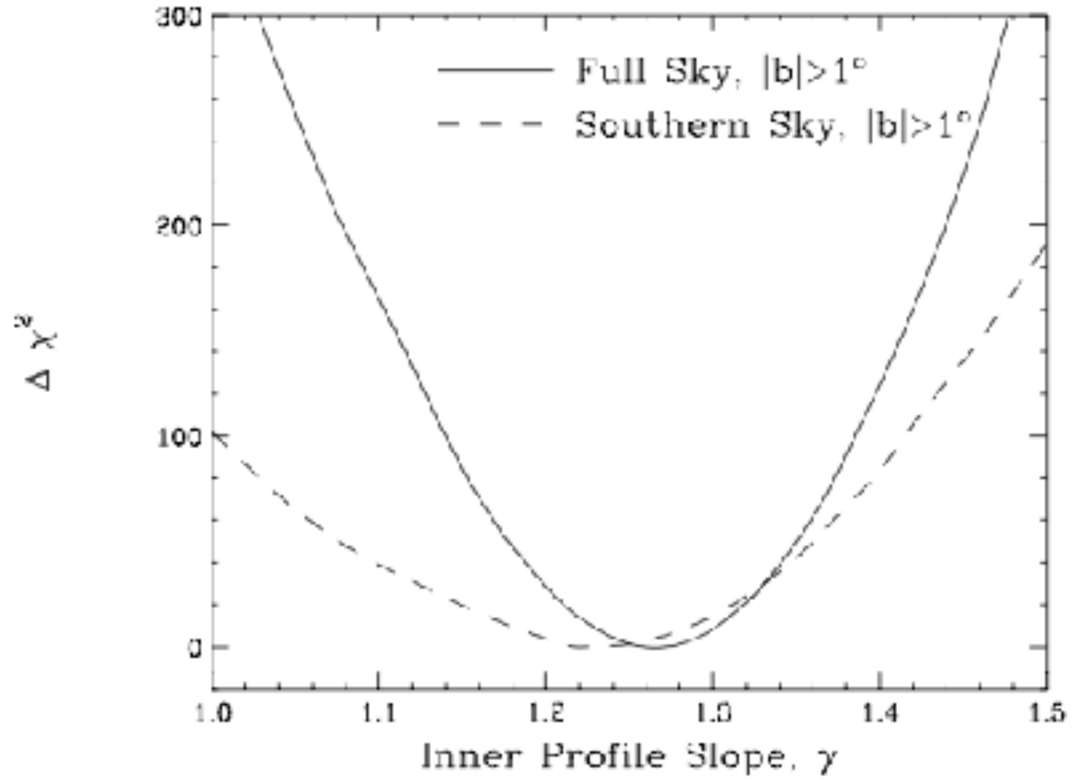


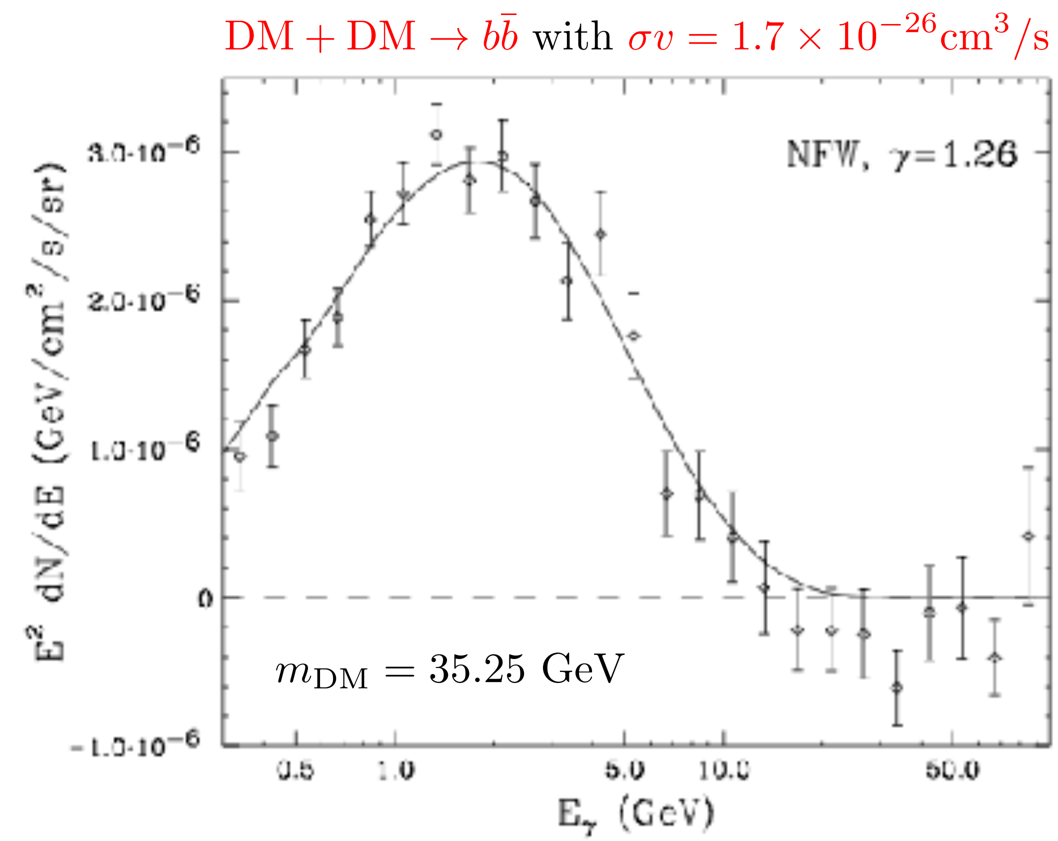
$$\mathrm{GC} : b \sim l \lesssim 0.1^\circ$$

extended

GeV scale excess!

• A DM interpretation





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

• Millisecond Pulars (astrophysical alternative)

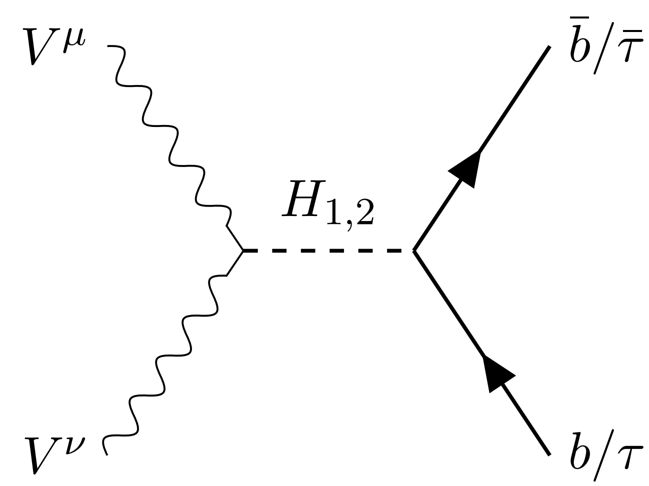
It may or may not be the main source, depending on

- 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

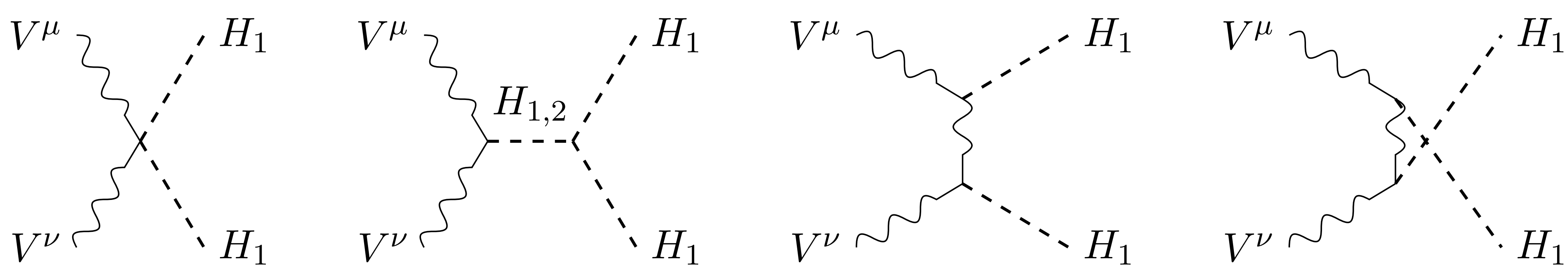


Figure 3. Dominant s/t-channel production of H_1s that decay dominantly to $b + \bar{b}$

Importance of VDM with Dark Higgs Boson

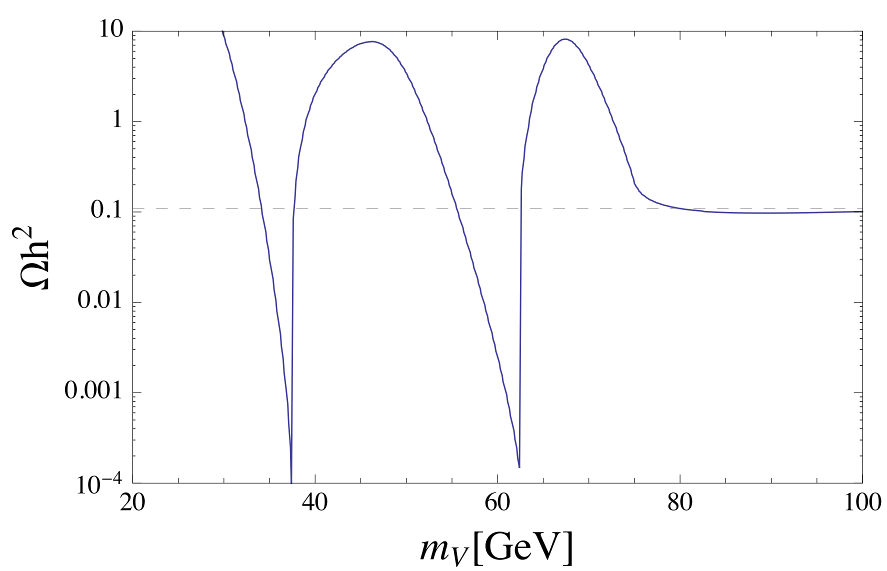


Figure 4. Relic density of dark matter as function of m_ψ for $m_h = 125$, $m_\phi = 75\,\text{GeV}$, $g_X = 0.2$, and $\alpha = 0.1$.

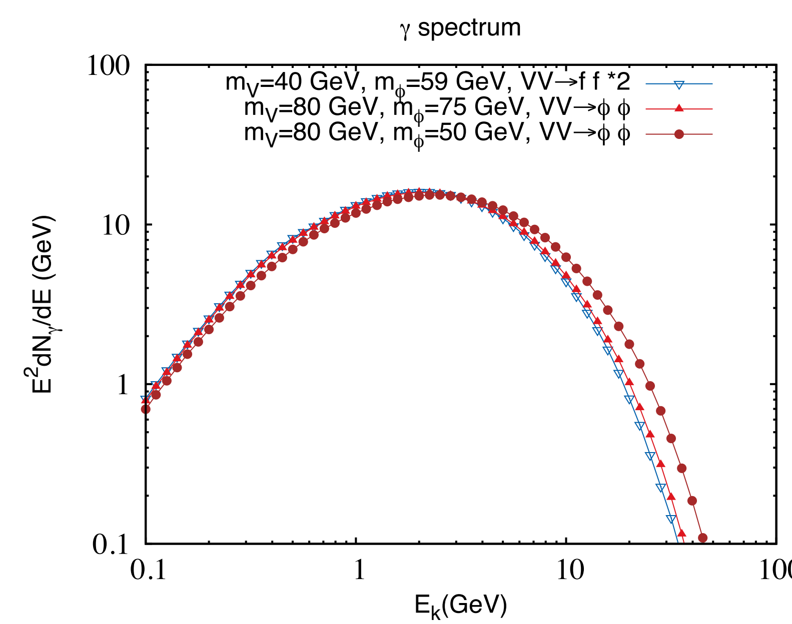
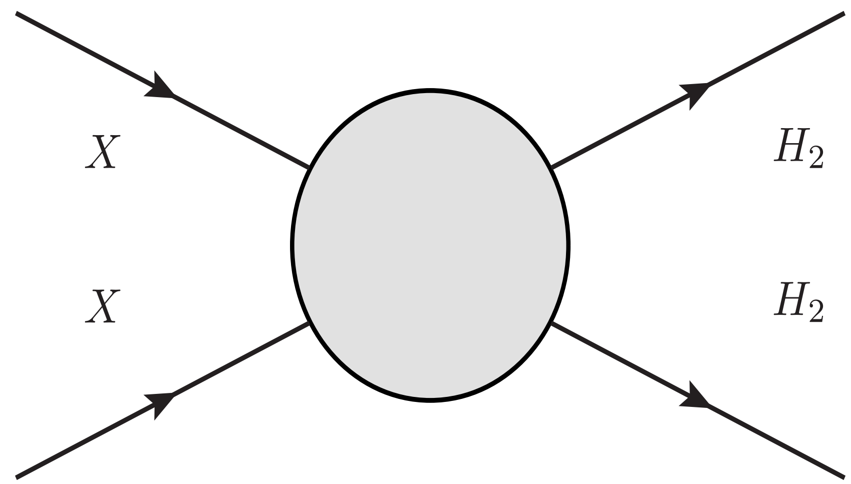


Figure 5. Illustration of γ spectra from different channels. The first two cases give almost the same spectra while in the third case γ is boosted so the spectrum is shifted to higher energy.

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

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



P.Ko, Yong Tang.
arXiv:1504.03908

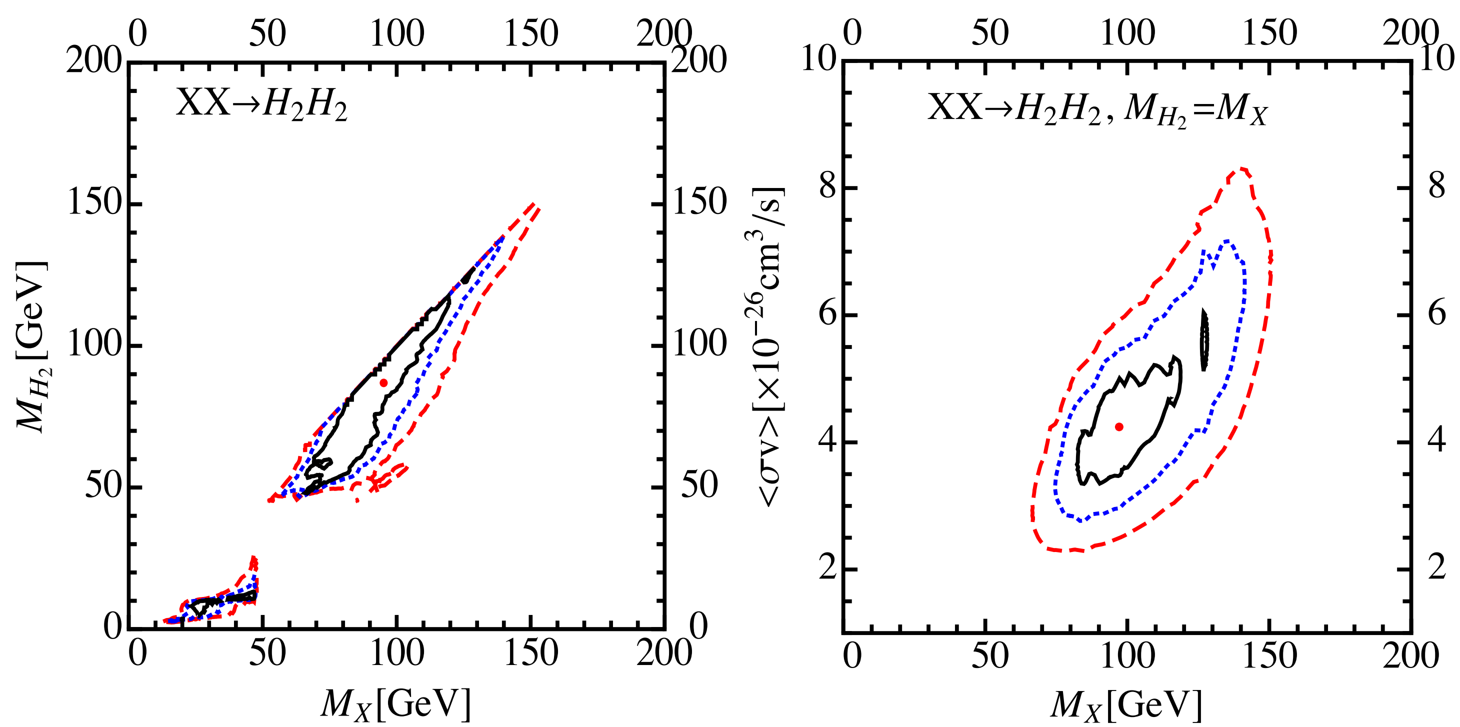


FIG. 3: The regions inside solid(black), dashed(blue) and long-dashed(red) contours correspond to 1σ, 2σ and 3σ, respectively. The red dots inside 1σ contours are the best-fit points. In the left panel, we vary freely M_X, M_{H_2} and $\langle\sigma v\rangle$. While in the right panel, we fix the mass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

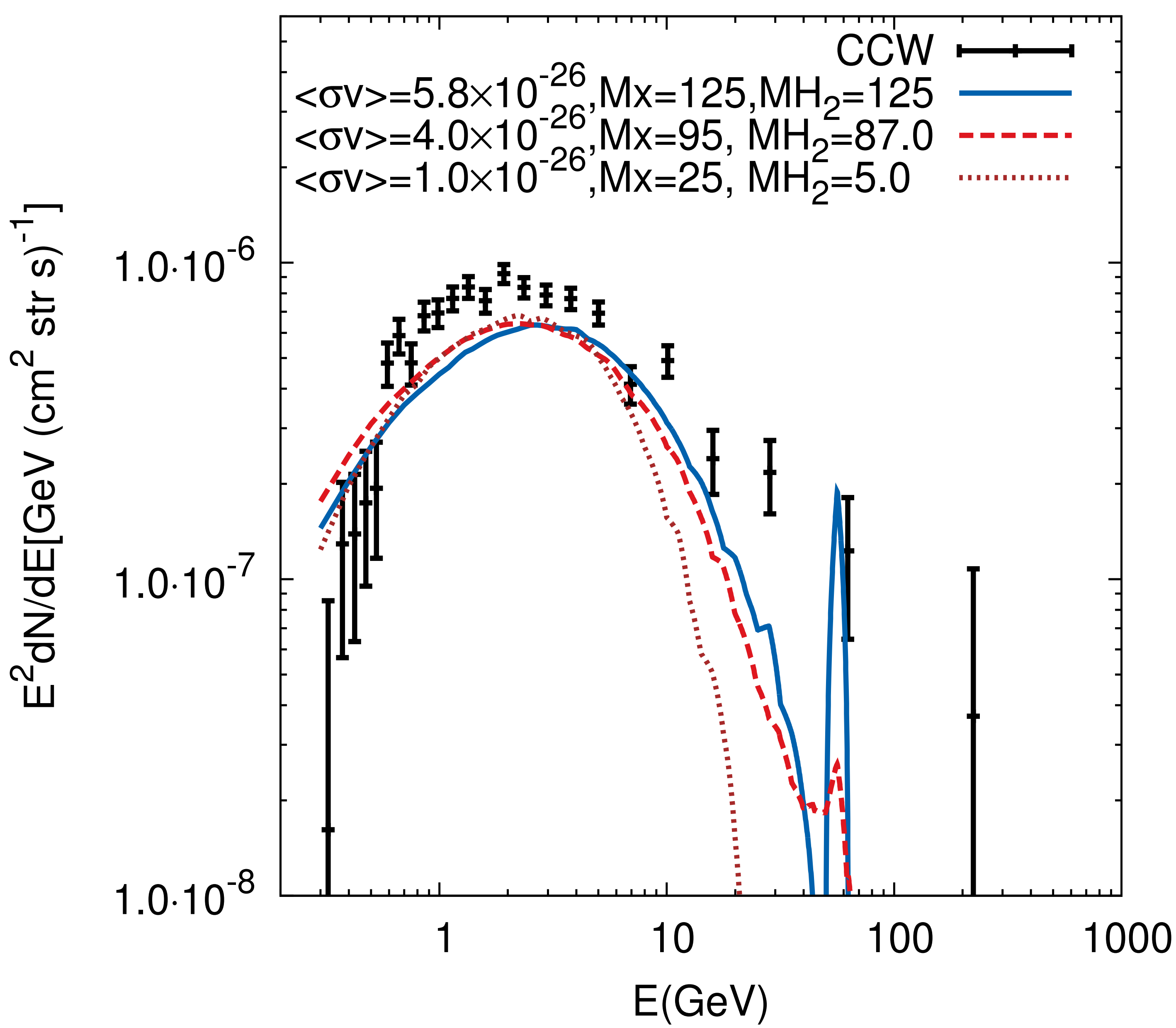


FIG. 2: Three illustrative cases for gamma-ray spectra in contrast with CCW data points [11]. All masses are in GeV unit and σv with cm^3/s. Line shape around $E \simeq M_{H_2}/2$ is due to decay modes, $H_2 \to \gamma\gamma, Z\gamma$.

This would have never been possible within the DM EFT

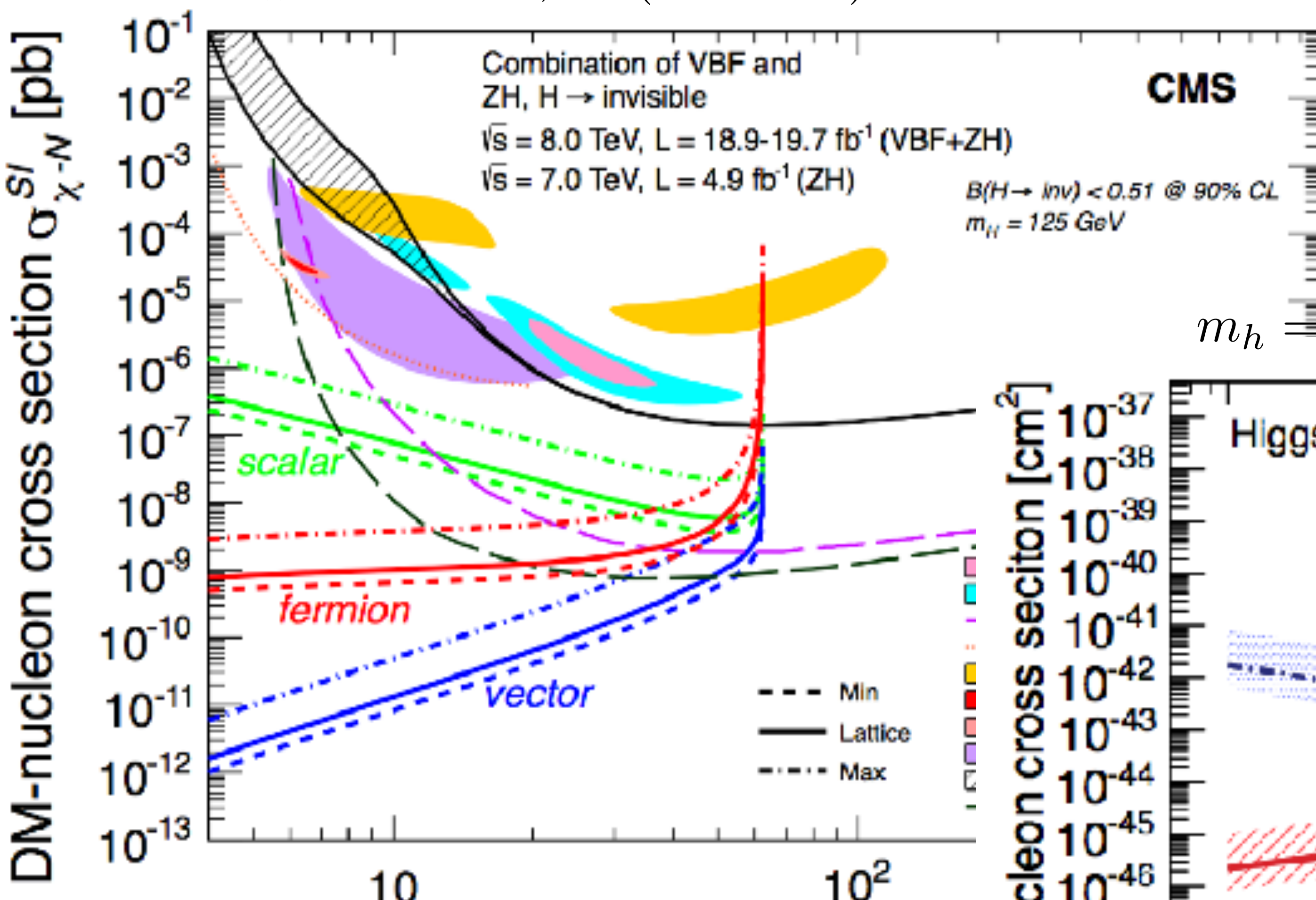
P.Ko, Yong Tang.
arXiv:1504.03908

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

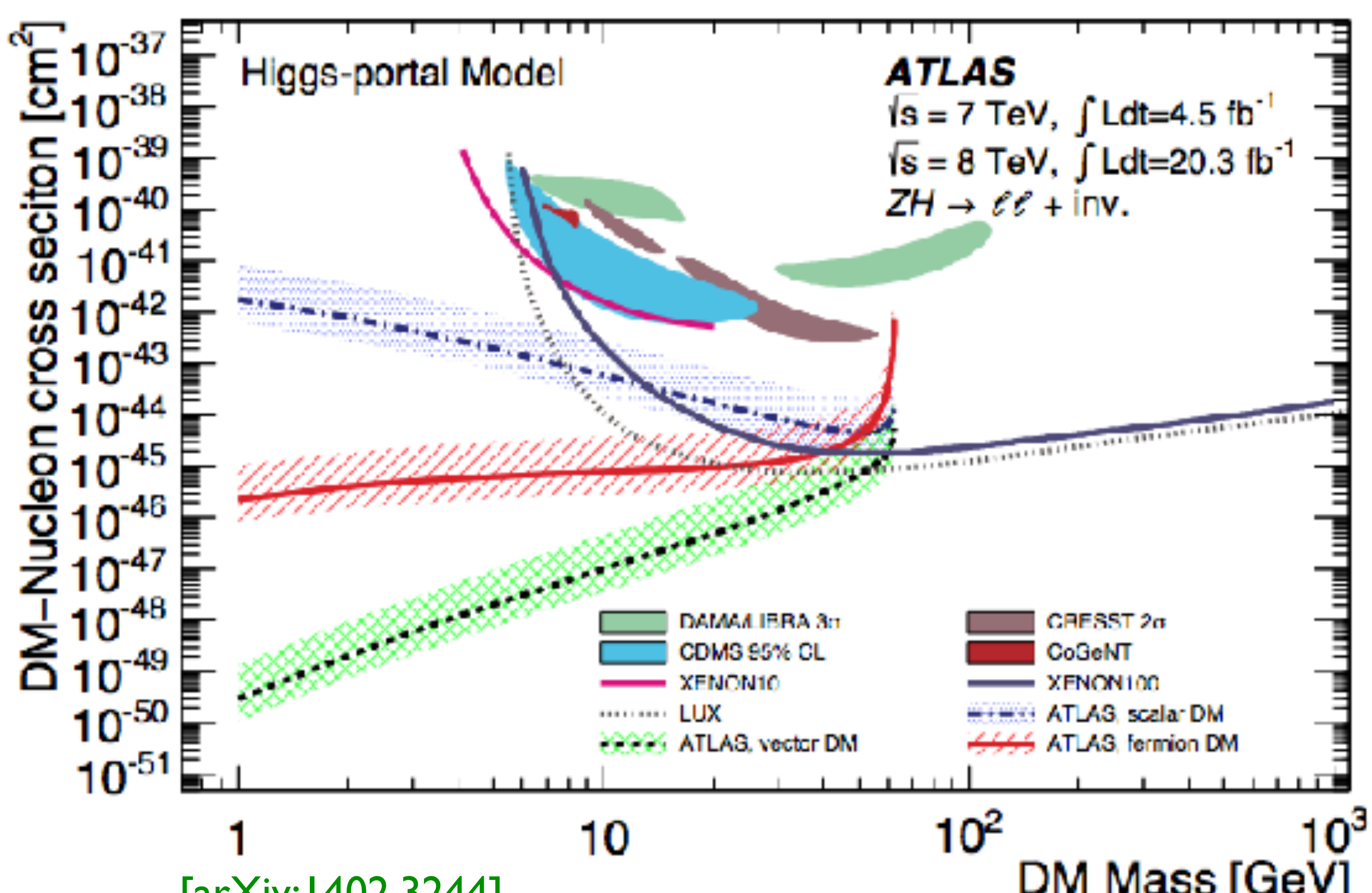
$m_h = 125\text{GeV},\ \text{Br}(H \to \text{inv}) < 0.51 \text{ at } 90\% \text{ CL}$



[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]

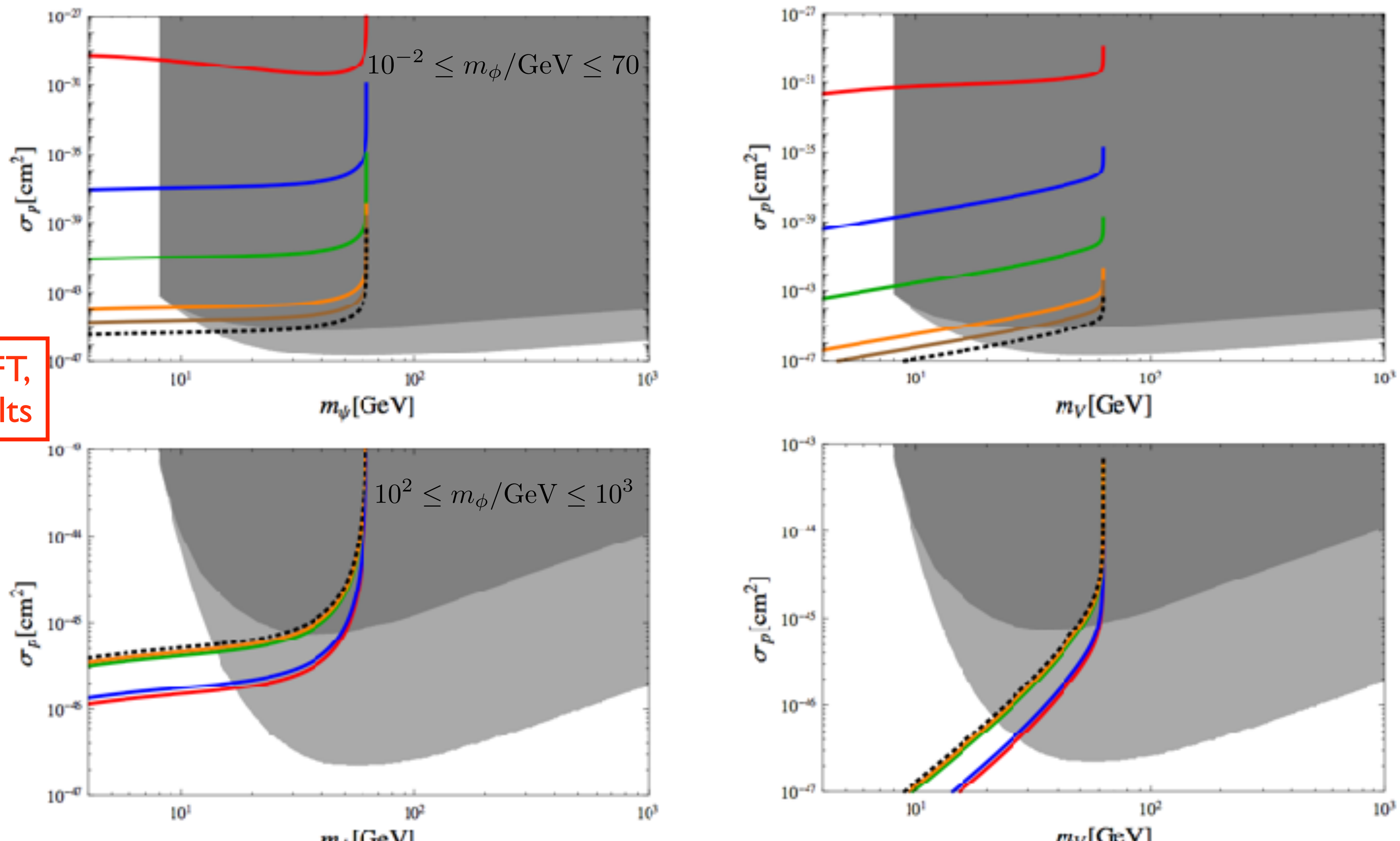
- However, in renormalizable unitary models of Higgs portals, 2 more relevant parameters

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

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

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

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



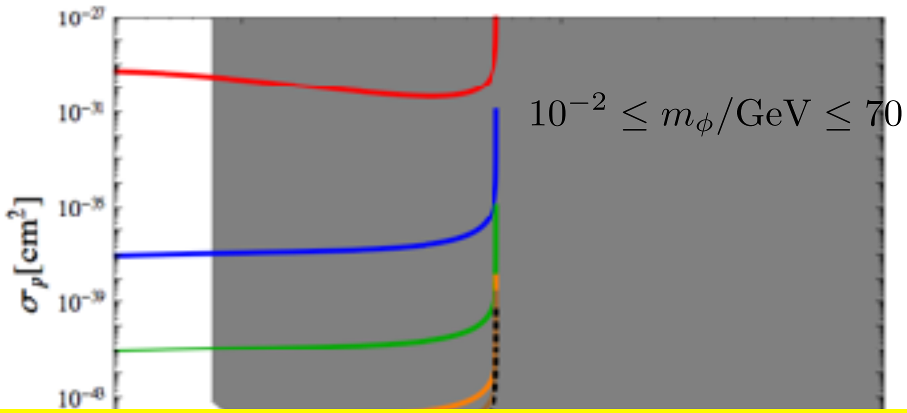
Dashed curves:EFT, ATLAS,CMS results

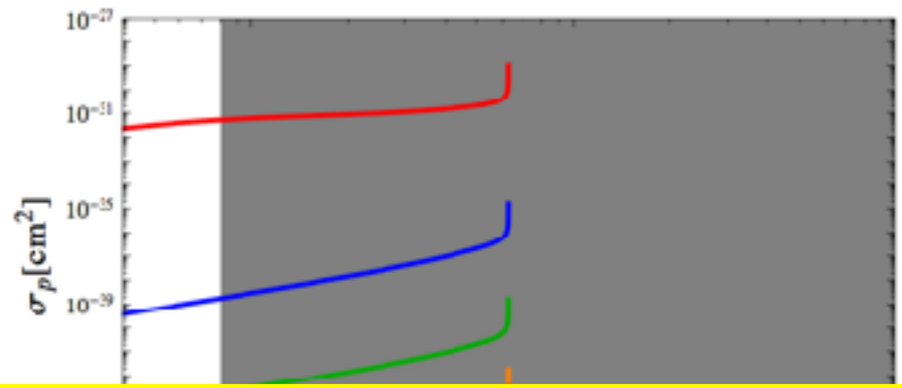
- However, in renormalizable unitary models of Higgs portals, 2 more relevant parameters

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

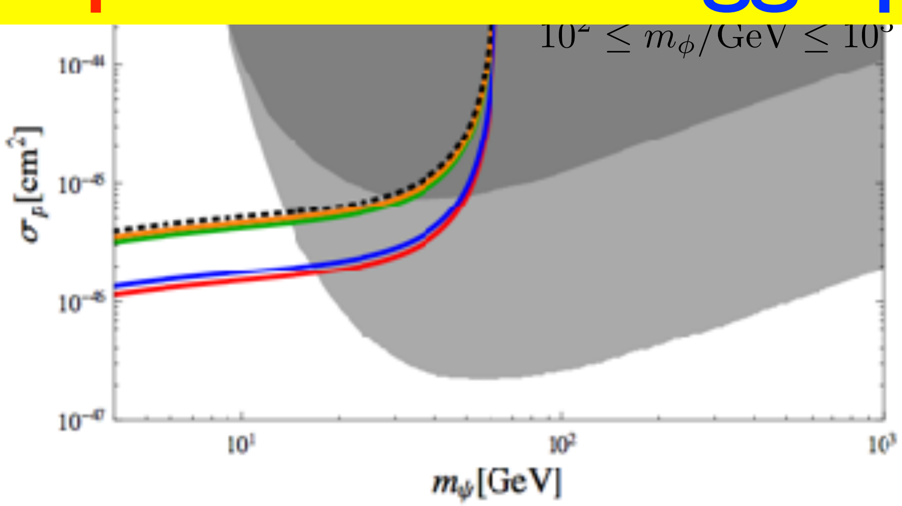
$$\mathcal{L}_{\rm VDM} = -\frac{1}{4} V_{\mu\nu} V^{\mu\nu} + D_\mu \Phi^\dagger D^\mu \Phi - \lambda_\Phi \left(\Phi^\dagger \Phi - \frac{v_\Phi^2}{2}\right)^2 - \lambda_{\Phi H}\left(\Phi^\dagger \Phi - \frac{v_\Phi^2}{2}\right)\left(H^\dagger H - \frac{v_H^2}{2}\right)$$

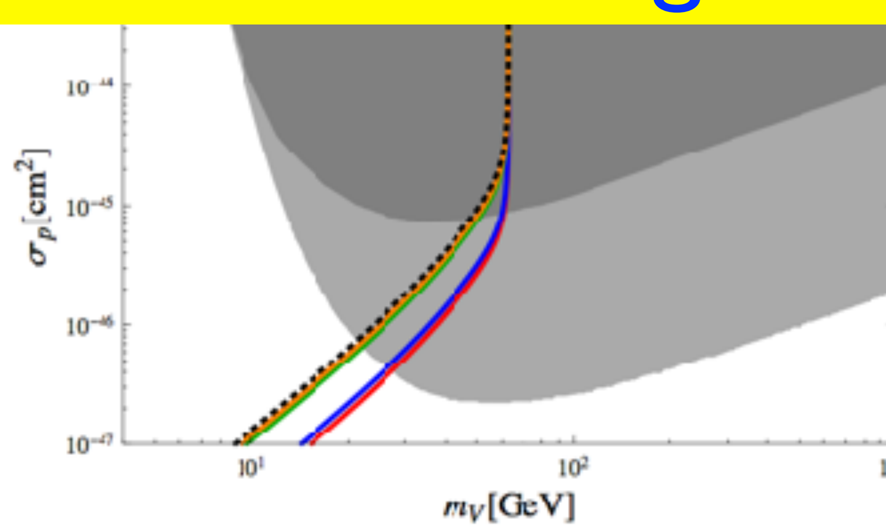
$$\sigma_p^{\rm SI} = (\sigma_p^{\rm SI})_{\rm EFT}\; c_\alpha^4 m_h^4 \mathcal{F}(m_{\rm DM}, \{m_i\}, v) \simeq (\sigma_p^{\rm SI})_{\rm EFT}\; c_\alpha^4 \left(1 - \frac{m_h^2}{m_2^2}\right)^2$$





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.

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

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

General Remarks

- Sometimes we need new fields beyond the SM ones and the CDM, in order to make DM models realistic and theoretically consistent
- If there are light fields in addition to the CDM, the usual Eff. Lag. with SM+CDM would not work
- Better to work with minimal renormalizable models
- See papers by Ko, Omura, Yu on the top FB asym with leptophobic Z' coupling to the RH up-type quarks only : new Higgs doublets coupled to Z' are mandatory in order to make a realistic model

Stable DM w/ unbroken dark gauge sym

DM is stable/long lived because...

- Symmetries

  - (ad hoc) Z_2 symmetry
  - R-parity
  - Topology (from a broken sym.)

- Very small mass and weak coupling

  e.g: QCD-axion ($m_a \sim \Lambda_{QCD}^2/f_a$; $f_a \sim 10^{9\text{-}12}$ GeV)

$$\Rightarrow \quad \Gamma_a \sim \mathcal{O}(10^{-5}) \frac{m_a^3}{f_a^2} \ll H_0 \sim 10^{-42} \mathrm{GeV}$$

But for WIMP ...

- 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 can be harmful to weak scale DM stability

Z2 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 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

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

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 all the CDM models based on ad hoc Z_2 symmetry
- 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

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

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

$$X_R \to X_I\gamma_h^* \quad \text{followed by} \quad \gamma_h^* \to \gamma \to e^+e^- \qquad \text{etc.}$$

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]

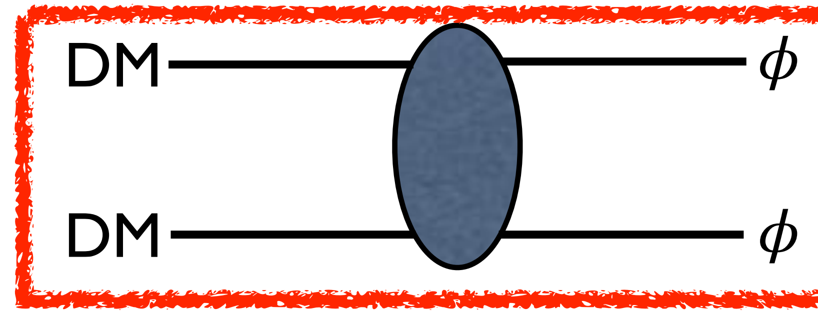
$$\begin{aligned}\mathcal{L} &= \mathcal{L}_{\rm SM} - \frac{1}{4}\hat{X}_{\mu\nu}\hat{X}^{\mu\nu} - \frac{1}{2}\sin\epsilon\hat{X}_{\mu\nu}\hat{B}^{\mu\nu} + D_\mu\phi D^\mu\phi + D_\mu X^\dagger D^\mu X - m_X^2 X^\dagger X + m_\phi^2\phi^\dagger\phi \\ &-\lambda_\phi\left(\phi^\dagger\phi\right)^2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

- 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]

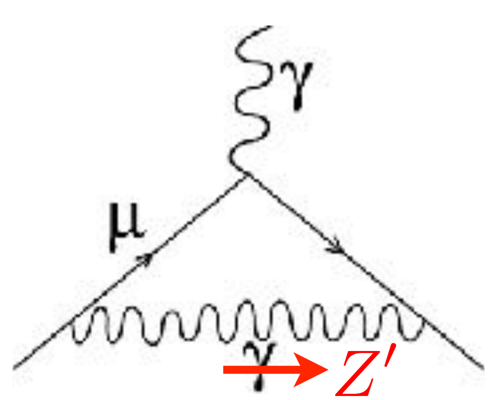
$$\mathcal{L}_{VDM} = -\frac{1}{4}X_{\mu\nu}X^{\mu\nu} + (D_\mu\Phi)^\dagger(D^\mu\Phi) - \lambda_\Phi\left(\Phi^\dagger\Phi - \frac{v_\Phi^2}{2}\right)^2$$
$$-\lambda_{\Phi H}\left(\Phi^\dagger\Phi - \frac{v_\Phi^2}{2}\right)\left(H^\dagger H - \frac{v_H^2}{2}\right),$$



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

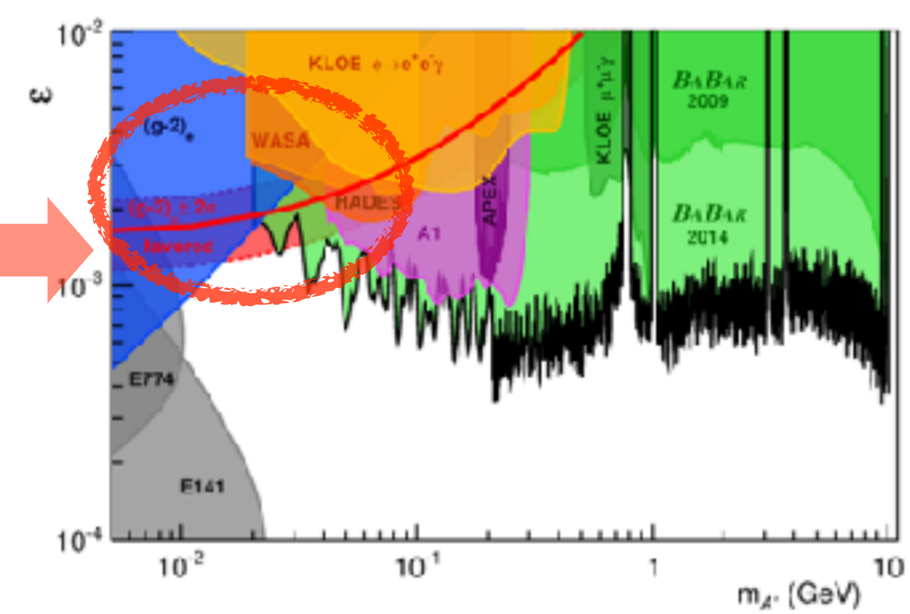
$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{4}\hat{X}_{\mu\nu}\hat{X}^{\mu\nu} - \frac{1}{2}\sin\epsilon\hat{X}_{\mu\nu}\hat{B}^{\mu\nu} + D_\mu\phi D^\mu\phi + D_\mu X^\dagger D^\mu X - m_X^2 X^\dagger X + m_\phi^2\phi^\dagger\phi$$
$$-\lambda_\phi\left(\phi^\dagger\phi\right)^2 - \lambda_X\left(X^\dagger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

- 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'



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

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



[1406.2980, BaBar collaboration]

Gamma ray from GC

$$\frac{m_h}{2} < m_I \lesssim 80\,\text{GeV}\,, \quad \frac{m_I - m_\phi}{m_I} \ll \mathcal{O}(0.1)$$

- Possible to satisfy thermal relic density, (in)direct detection constraints
- For light Z' with small kinetic mixing, muon g-2 can be accommodated
- Similar to the excited DM models by Weiner et al, etc. except for dark Higgs field

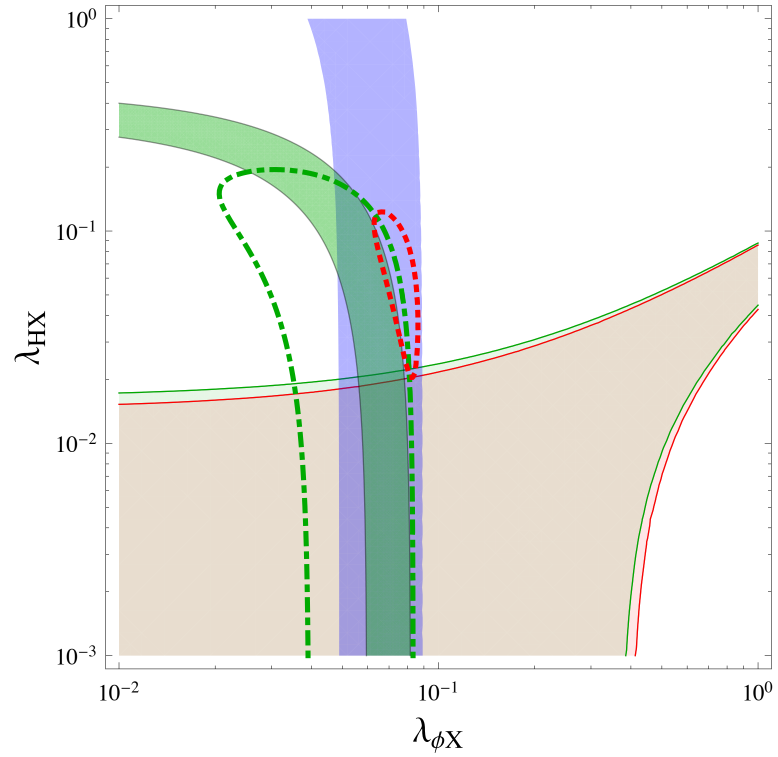


FIG. 3: Parameter space for $m_I = 80$, $m_\phi = 75\,\text{GeV}$ with $\alpha = 0.1$, $v_\phi = 100\,\text{GeV}$, satisfying constraints from LUX direct search experiment (Green region between thin green lines: $\mu = 5\,\text{GeV}$. Red region between thin red lines: $\mu = 7\,\text{GeV}$), $\langle\sigma v_{\rm rel}\rangle_{\rm tot}/\langle\sigma v_{\rm rel}\rangle_{26} = 1$ (Dot-dashed green line: $\mu = 5\,\text{GeV}$. Dotted red line: $\mu = 7\,\text{GeV}$), and $1/3 \leq \langle\sigma v_{\rm rel}\rangle_{\phi\phi}/\langle\sigma v_{\rm rel}\rangle_{26} \leq 1$ (Blue region). In the dark green region, $\langle\sigma v_{\rm rel}\rangle_{Z'Z'}/\langle\sigma v_{\rm rel}\rangle_{26} \leq 0.1$, so the contribution of Z'-decay to GeV scale excess of γ-ray may be safely ignored.

Local Z3 Scalar DM

P.Ko, YTang, arXiv:1402.6449

Again an extra U(1)X gauge symmetry is introduced, with scalar DM X and dark higgs with charges 1 and 3, respectively.

$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{4}\tilde{X}_{\mu\nu}\tilde{X}^{\mu\nu} - \frac{1}{2}\sin\epsilon\tilde{X}_{\mu\nu}\tilde{B}^{\mu\nu} + D_\mu\phi_X^\dagger D^\mu\phi_X + D_\mu X^\dagger D^\mu X - V$$

$$V = -\mu_H^2 H^\dagger H + \lambda_H \left(H^\dagger H\right)^2 - \mu_\phi^2\phi_X^\dagger\phi_X + \lambda_\phi\left(\phi_X^\dagger\phi_X\right)^2 + \mu_X^2 X^\dagger X + \lambda_X\left(X^\dagger X\right)^2 + \lambda_{\phi H}\phi_X^\dagger\phi_X H^\dagger H + \lambda_{\phi X}X^\dagger X\phi_X^\dagger\phi_X + \lambda_{HX}X^\dagger X H^\dagger H + \left(\lambda_3 X^3\phi_X^\dagger + H.c.\right)$$

$$X \to e^{\mathrm{i}\frac{2\pi}{3}} X$$

Z3 symmetry $X^\dagger \to e^{-\mathrm{i}\frac{2\pi}{3}} X^\dagger$

$$X^3 + X^{\dagger 3}$$

Comparison with global Z3

$$V_{\text{eff}} \simeq -\mu_H^2 H^\dagger H + \lambda_H \left(H^\dagger H\right)^2 + \mu_X^2 X^\dagger X + \lambda_X \left(X^\dagger X\right)^2 + \lambda_{HX} X^\dagger X H^\dagger H + \mu_3 X^3$$
$$+ \text{higher order terms} + H.c,$$

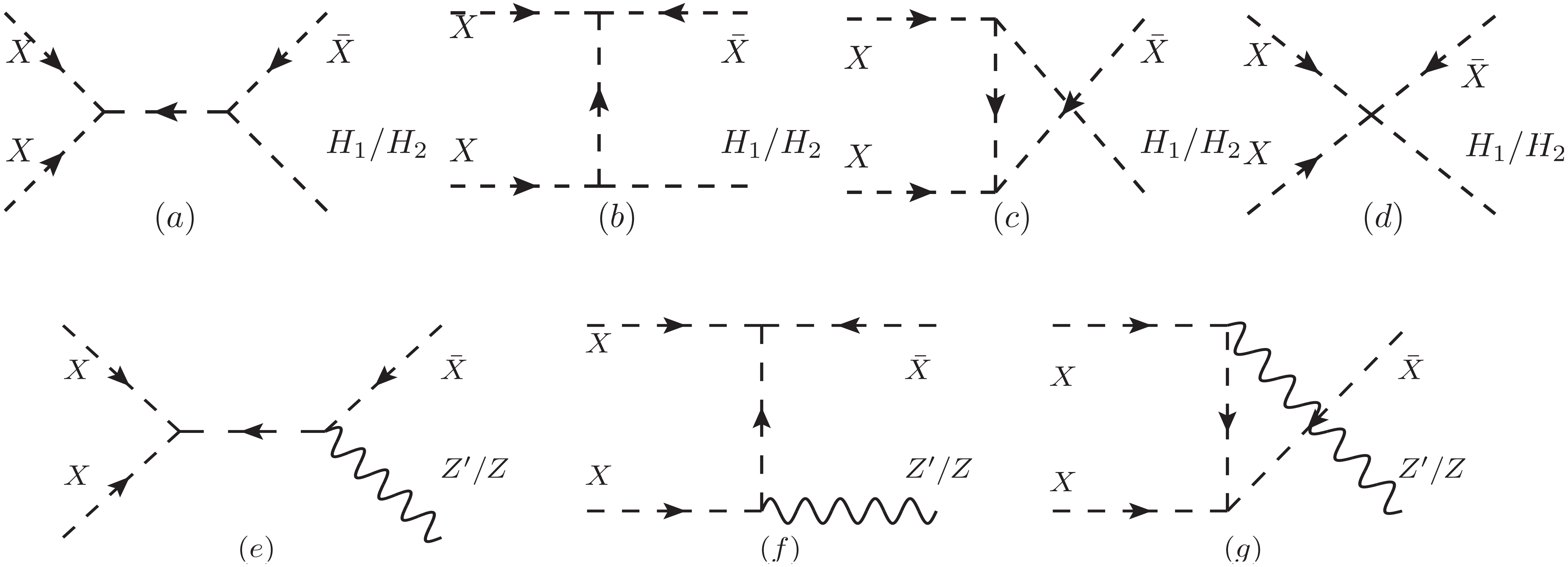
- However global symmetry can be broken by gravity induced nonrenormalizable op's:

$$\frac{1}{\Lambda} X F_{\mu\nu} F^{\mu\nu}$$

Global Z3 "X" will decay immediately and can not be a DM

- Also particle spectra different : Z' and H_2
- DM & H phenomenology change a lot

Semi-annihilation

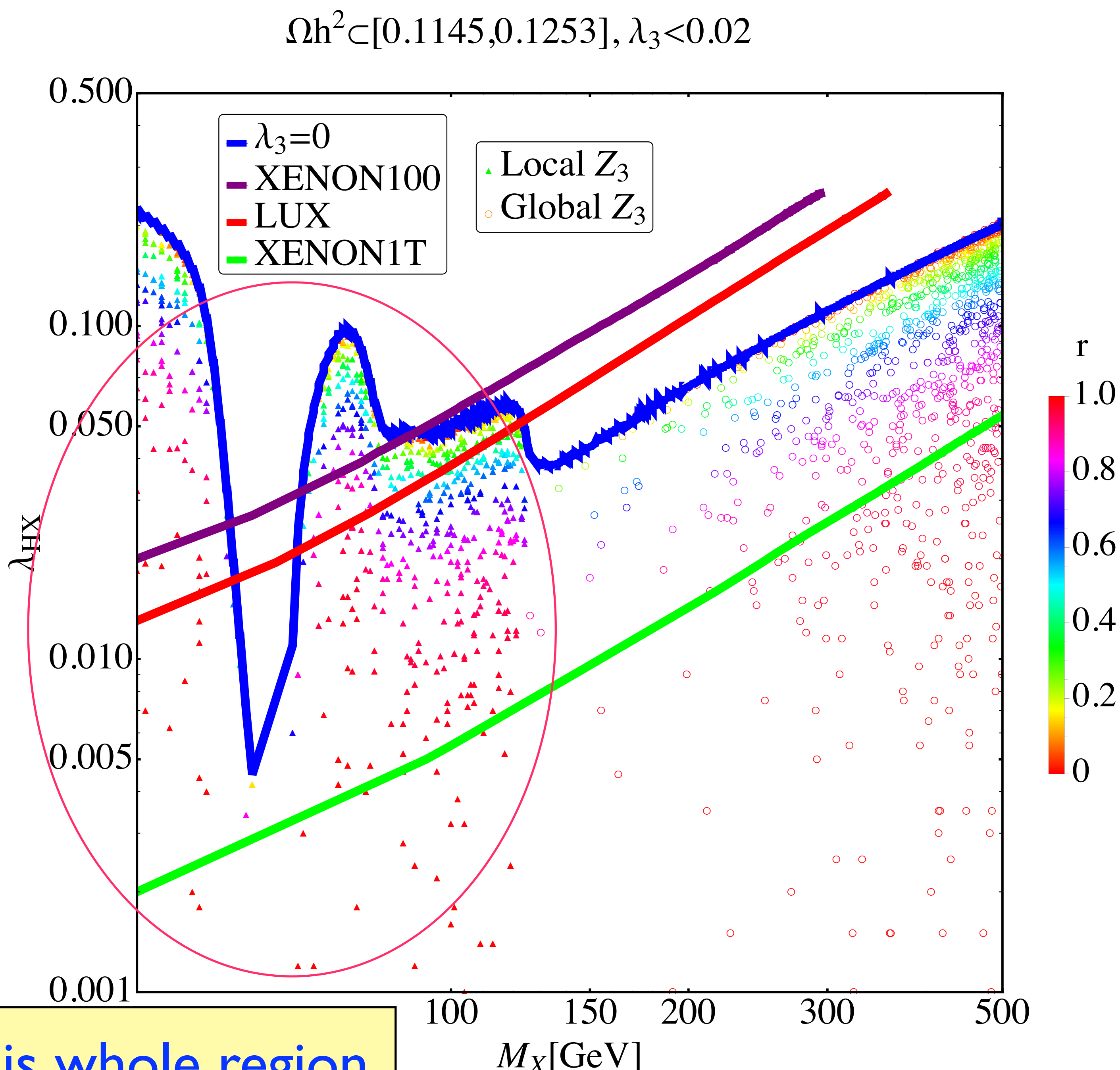


$$\frac{dn_X}{dt} = -v\sigma^{XX^* \to YY}\left(n_X^2 - n_{X\,\mathrm{eq}}^2\right) - \frac{1}{2}v\sigma^{XX \to X^*Y}\left(n_X^2 - n_X n_{X\,\mathrm{eq}}\right) - 3Hn_X,$$

$$r \equiv \frac{1}{2}\frac{v\sigma^{XX \to X^*Y}}{v\sigma^{XX^* \to YY} + \frac{1}{2}v\sigma^{XX \to X^*Y}}.$$

micrOMEGAs

Relic density and Direct Search



This whole region is allowed in local Z3 case

- Blue band marks the upper bound,
- All points are allowed in our local Z3 model, 1402.6449
- only circles are allowed in global Z3 model,1211.1014

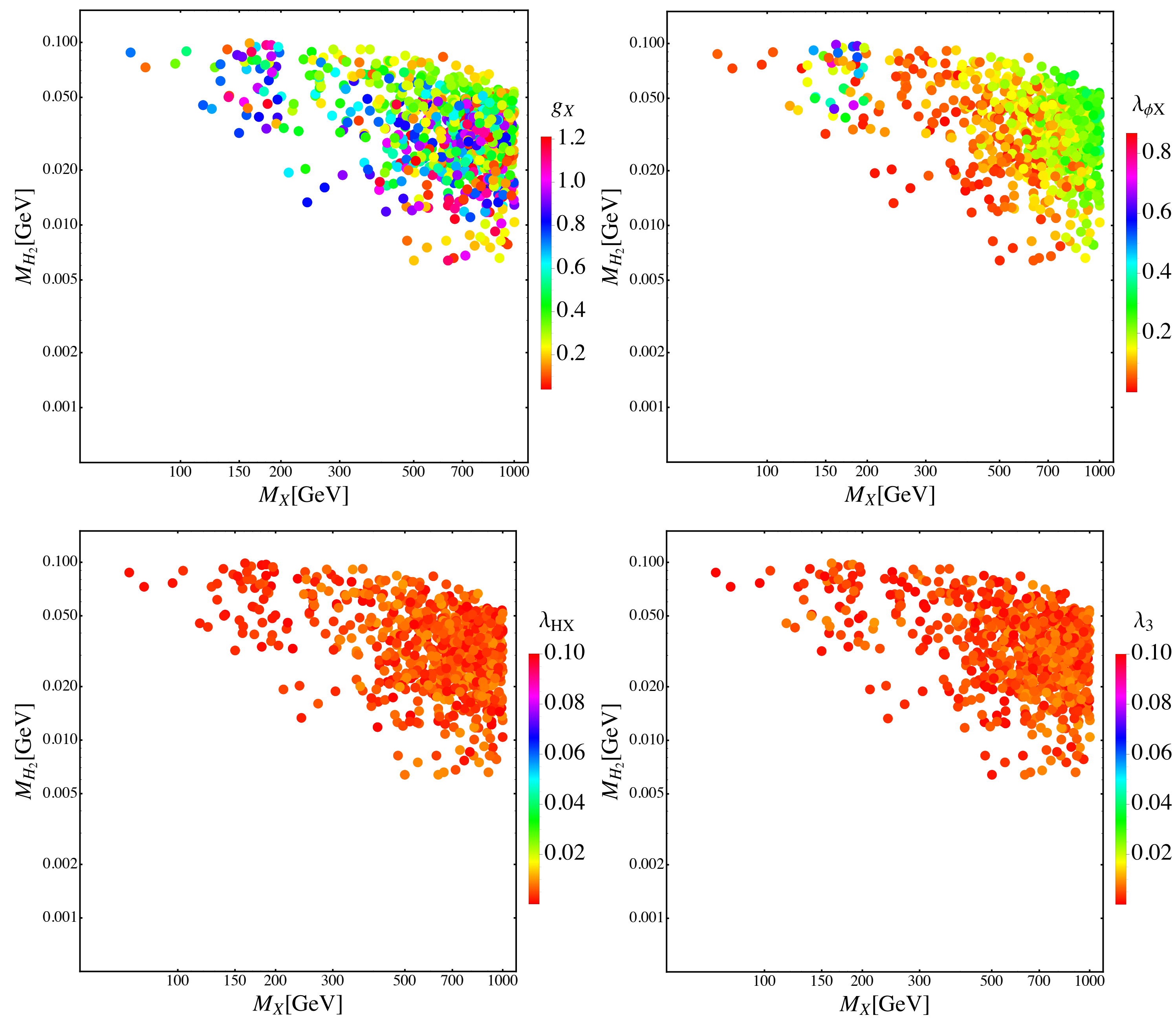
Global Z3
(Belanger, Pukhov et al)

- SM + X
- DD & Thermal relic >> mX > 120 GeV
- Vacuum stability >> DD cross section within Xenon1T experiment
- No light mediators

Local Z3
(Ko, Yong Tang)

- SM + X , phi , Z'
- Additional Annihilation Channels open
- DD constraints relaxed
- Light mX allowed
- Light mediator phi : strong self interactions of X's

Dark matter self-interactions



Such a light dark Higgs could be studied at SHiP, but would be difficult to produce.

Comparison with EFT

$$U(1)_X \text{ sym}: \quad X^\dagger X H^\dagger H, \ \frac{1}{\Lambda^2}\left(X^\dagger D_\mu X\right)\left(H^\dagger D^\mu H\right), \ \frac{1}{\Lambda^2}\left(X^\dagger D_\mu X\right)\left(\overline{f}\gamma^\mu f\right), \ etc. \quad (4.3)$$

$$Z_3 \text{ sym}: \quad \frac{1}{\Lambda} X^3 H^\dagger H, \quad \frac{1}{\Lambda^2} X^3 \overline{f} f, \ etc. \quad (4.4)$$

$$\left(\text{or } \frac{1}{\Lambda^3} X^3 \overline{f_L} H f_R, \text{if we imposed the full SM gauge symmetry}\right) \quad (4.5)$$

- There is no Z', H2 in the EFT, and so indirect detection or thermal relic density cal.s can be completely different
- Complementarity breaks down : (4.3) cannot capture semi-annihilation described by (4.4)

Gamma ray excess from the GC

(P. Ko, Yong Tang, 1407.5492, JCAP)

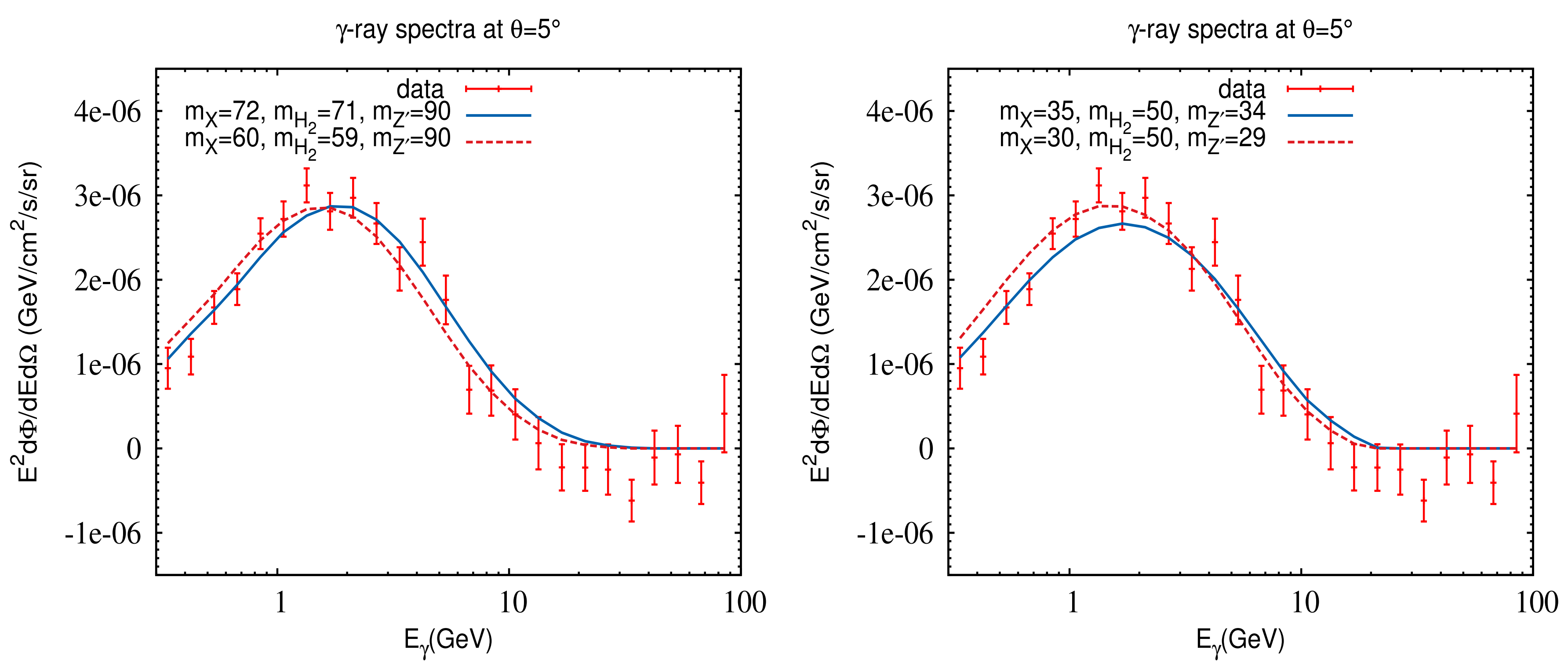


FIG. 4: γ-ray spectra from dark matter (semi-)annihilation with H_2(left) and Z'(right) as final states. In each case, mass of H_2 or Z' is chosen to be close to m_X to avoid large lorentz boost. Masses are in GeV unit. Data points at $\theta = 5$ degree are extracted from [1].

Possible only in local Z3
not in global Z3 or DM EFT

Other possible phenomenology

- Another possibility was to use this model for 511 keV gamma ray and PAMELA/AMS02 positron excess (strong tension with CMB constraints, however)
- 3.55 keV Xray using endo(exo)thermic scattering : for future work
- In any case, the local Z_2 model has new fields with interesting important own roles, and can modify phenomenology a lot

Main points

- Local Dark Gauge Symmetry can guarantee the DM stability (or longevity, see later discussion)
- Minimal models have new fields other than DM (Dark Higgs and Dark Gauge Bosons) for theoretical consistency
- Can solve many puzzles in CDM by large self-interactions, and also muon g-2, and also calculable amount of Dark Radiation

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

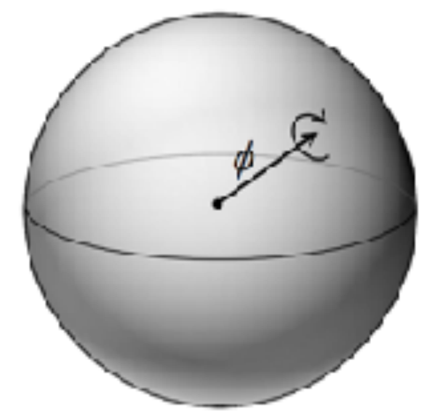
- Lagrangian

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

't Hooft-Polyakov monopole — Higgs portal

- Symmetry breaking

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



- Particle spectra $\left(V^\pm \equiv \frac{1}{\sqrt{2}} (V_1 \mp i V_2),\ \gamma' \equiv V_3,\ H_1,\ H_2 \right)$
  - VDM: $m_V = g_X v_\phi$
  - Monopole: $m_M = m_V / \alpha_X$
  - Higgses: $$m_{1,2} = \frac{1}{2} \left[m_{hh}^2 + m_{\phi\phi}^2 \mp \sqrt{\left(m_{hh}^2 - m_{\phi\phi}^2 \right)^2 + 4 m_{\phi h}^4} \right]$$

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

EWSB and CDM from Strongly Interacting Hidden Sector

All the masses (including CDM mass) from hidden sector strong dynamics, and CDM long lived by accidental sym

Hur, Jung, Ko, Lee : 0709.1218, PLB (2011)
Hur, Ko : arXiv:1103.2517,PRL (2011)
Proceedings for workshops/conferences during 2007-2011 (DSU,ICFP,ICHEP etc.)

Origin of Mass

- Massive SM particles get their masses from Higgs mechanism or confinement in QCD
- What is the origin of Higgs VEV ?
- How about DM particles ? Where do their masses come from ?
- SM Higgs ? SUSY Breaking ? Extra Dim ?
- Can we generate all the masses as in proton mass from dim transmutation in QCD ? (proton mass in massless QCD)

- There are basically three different approaches on the origin of masses
- Standard Higgs mechanism with fundamental scalars (SM, MSSM etc.)
- Dynamical Symmetry Breaking : Technicolor, BCS (Hur and Ko; Kubo and Lindner et al)
- Radiative Symmetry Breaking : Coleman-Weinberg mechanism (Recently renewed interests in this approach : Meissner & Nicolai; Foot and Volkas; Okada & Iso et al; Lindner et al; and many more)
- NB : If we consider extra dim, more options

Main Motivations

- Understanding DM Stability or Longevity ?
- Origin of Mass (including DM, RHN) ?
- Assume the standard seesaw for neutrino masses and mixings, and leptogenesis for baryon number asymmetry of the universe
- Assume minimal inflation models : Higgs(+singlet scalar) inflation (Starobinsky inflation)

Nicety of QCD

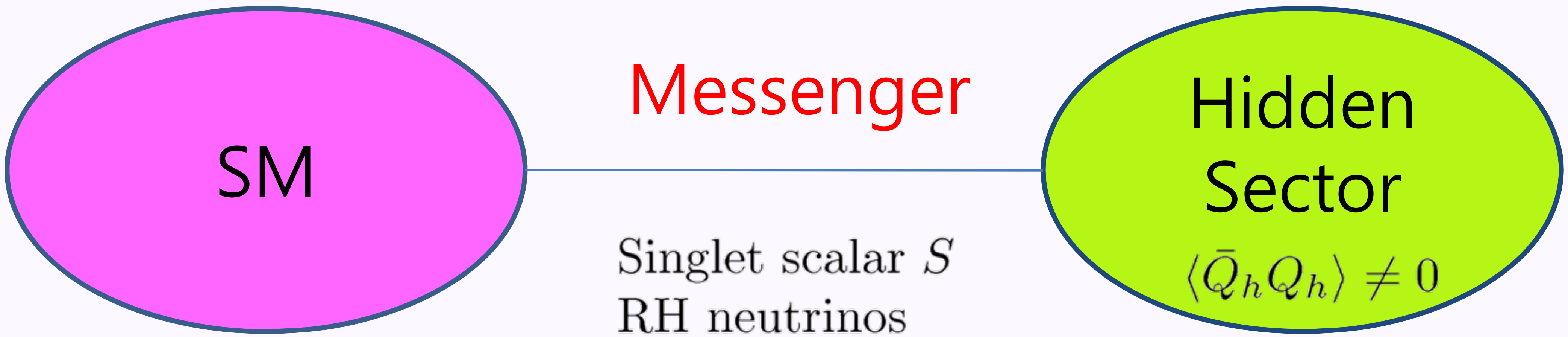
- Renormalizable
- Asymptotic freedom : no Landau pole
- QM dim transmutation :
- Light hadron masses from QM dynamics
- Flavor & Baryon # conservations : accidental symmetries of QCD (pion is stable if we switch off EW interaction; proton is stable or very long lived)

h-pion & h-baryon DMs

- In most WIMP DM models, DM is stable due to some ad hoc Z_2 symmetry
- If the hidden sector gauge symmetry is confining like ordinary QCD, the lightest mesons and the baryons could be stable or long-lived >> Good CDM candidates
- If chiral sym breaking in the hidden sector, light h-pions can be described by chiral Lagrangian in the low energy limit

(arXiv:0709.1218 with T.Hur, D.W.Jung and J.Y.Lee)

Basic Picture



Singlet scalar S
RH neutrinos
etc.

SM
Quarks
Leptons
Gauge Bosons
Higgs boson

Hidden Sector
Quarks Q_h
Gluons g_h
Others

Similar to ordinary QCD

Key Observation

- If we switch off gauge interactions of the SM, then we find
- Higgs sector ~ Gell-Mann-Levy's linear sigma model which is the EFT for QCD describing dynamics of pion, sigma and nucleons
- One Higgs doublet in 2HDM could be replaced by the GML linear sigma model for hidden sector QCD

- Potential for H_1 and H_2

$$V(H_1, H_2) = -\mu_1^2(H_1^\dagger H_1) + \frac{\lambda_1}{2}(H_1^\dagger H_1)^2 - \mu_2^2(H_2^\dagger H_2) + \frac{\lambda_2}{2}(H_2^\dagger H_2)^2 + \lambda_3(H_1^\dagger H_1)(H_2^\dagger H_2) + \frac{a v_2^3}{2}\sigma_h$$

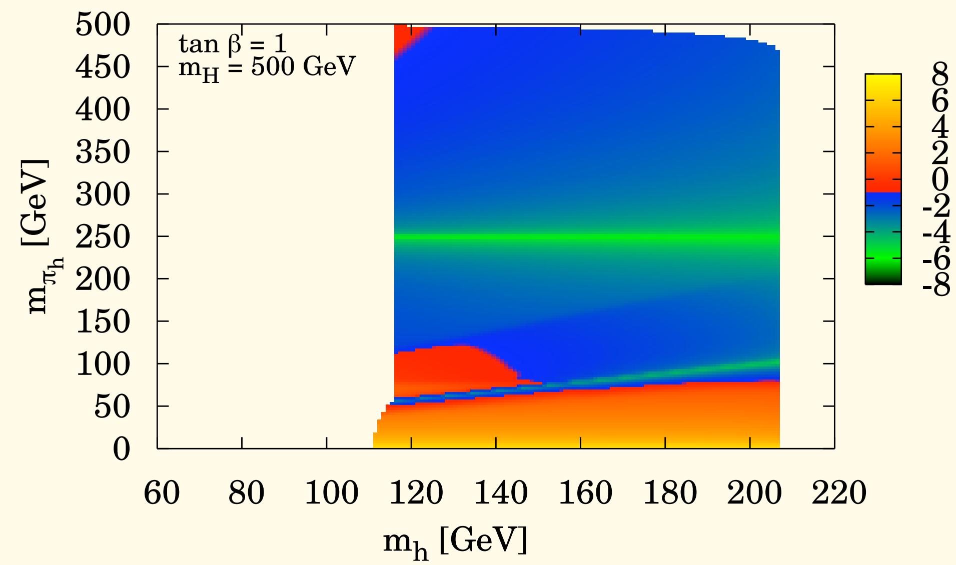
Not present in the two-Higgs Doublet model

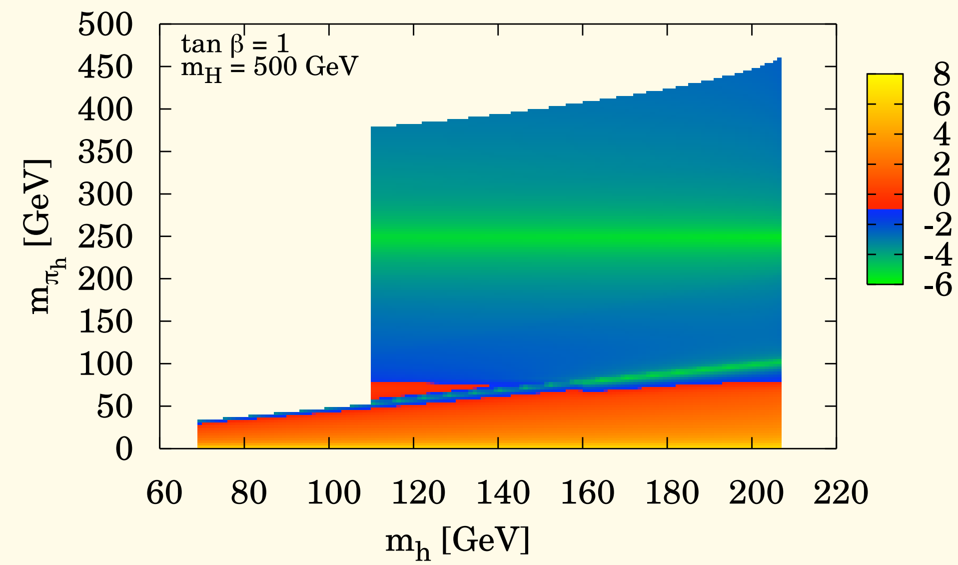
- Stability : $\lambda_{1,2} > 0$ and $\lambda_1 + \lambda_2 + 2\lambda_3 > 0$
- Consider the following phase:

$$H_1 = \begin{pmatrix} 0 \\ \frac{v_1 + h_{\rm SM}}{\sqrt{2}} \end{pmatrix}, \qquad H_2 = \begin{pmatrix} \pi_h^+ \\ \frac{v_2 + \sigma_h + i\pi_h^0}{\sqrt{2}} \end{pmatrix}$$

- Correct EWSB : $\lambda_1(\lambda_2 + a/2) \equiv \lambda_1 \lambda_2' > \lambda_3^2$

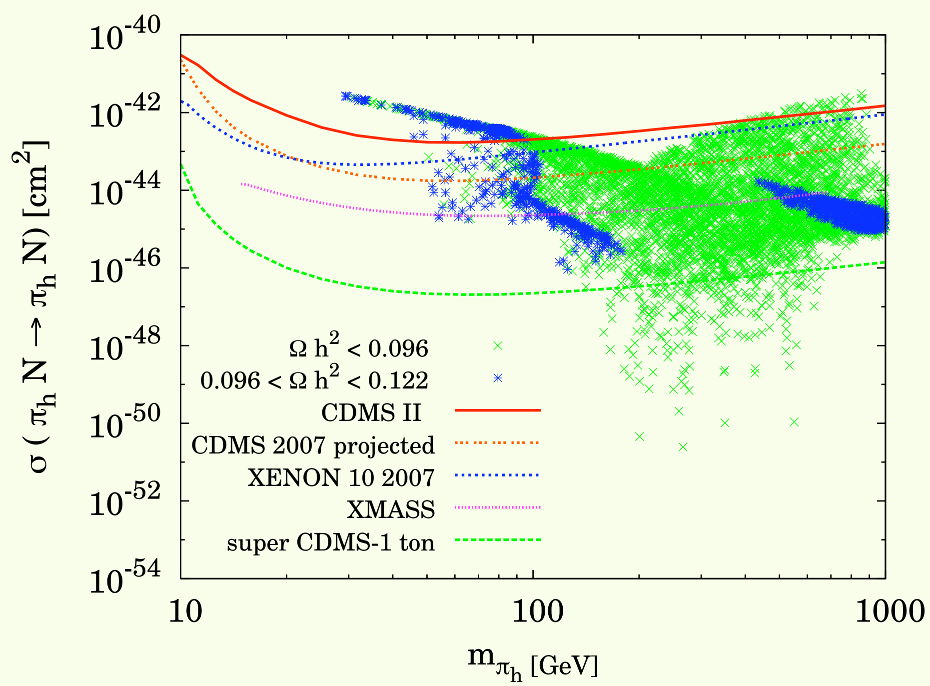
Relic Density

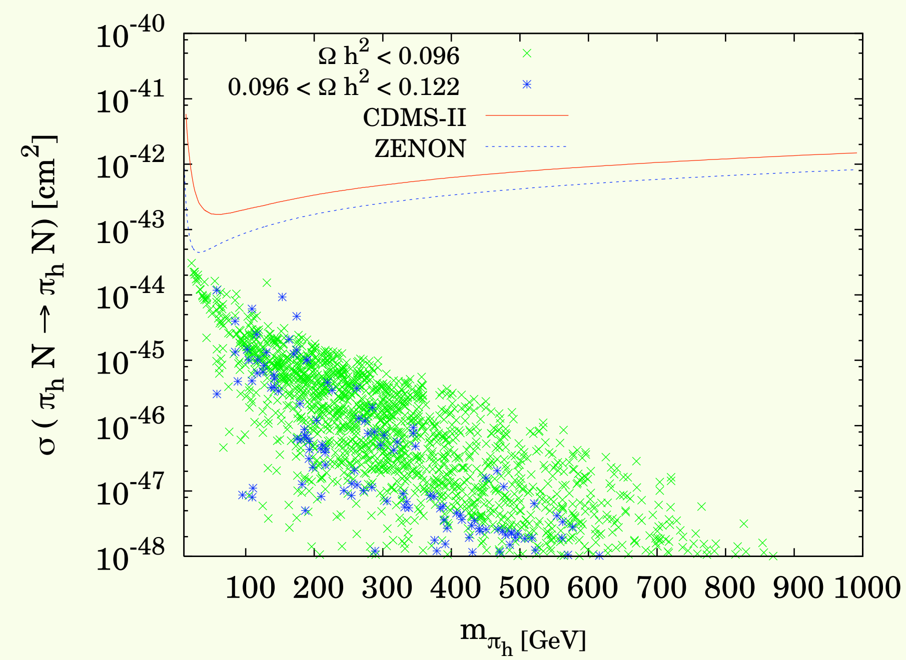




- $\Omega_{\pi_h} h^2$ in the (m_{h_1}, m_{π_h}) plane for $\tan\beta = 1$ and $m_H = 500$ GeV
- Labels are in the $\log_{10}$
- Can easily accommodate the relic density in our model

Direct detection rate

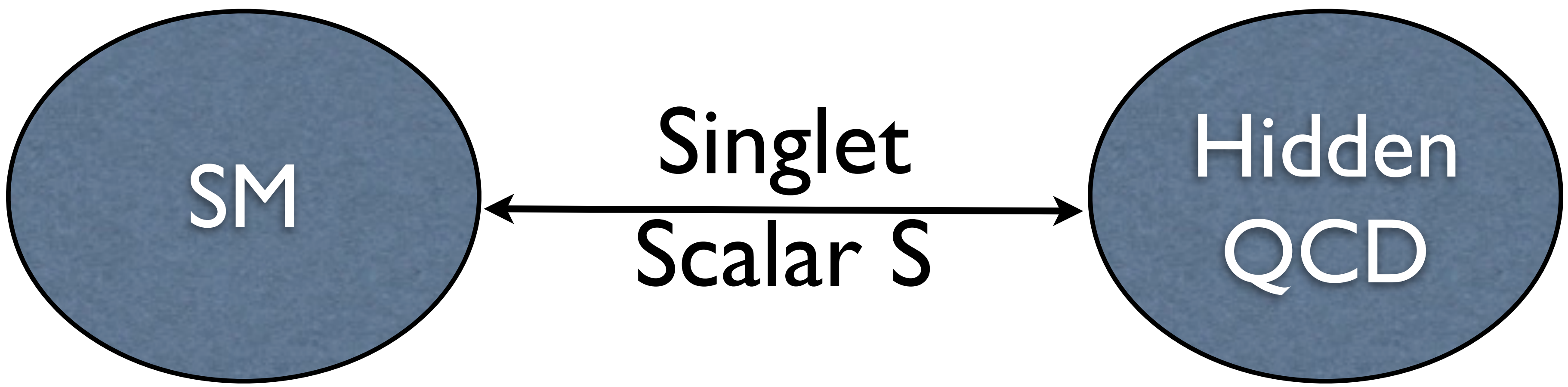




- $\sigma_{SI}(\pi_h p \to \pi_h p)$ as functions of m_{π_h} for $\tan\beta = 1$ and $\tan\beta = 5$.
- σ_{SI} for $\tan\beta = 1$ is very interesting, partly excluded by the CDMS-II and XENON 10, and als can be probed by future experiments, such as XMASS and super CDMS
- $\tan\beta = 5$ case can be probed to some extent at Super CDMS

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”

Appraisal of Scale Invariance

- May be the only way to understand the origin of mass dynamically (including spontaneous sym breaking)
- Without it, we can always write scalar mass terms for any scalar fields, and Dirac mass terms for Dirac fermions, the origin of which is completely unknown
- Probably only way to control higher dimensional op's suppressed by Planck scale

Scale invariant extension of the SM with strongly interacting hidden sector

Modified SM with classical scale symmetry

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

Hidden sector lagrangian with new strong interaction

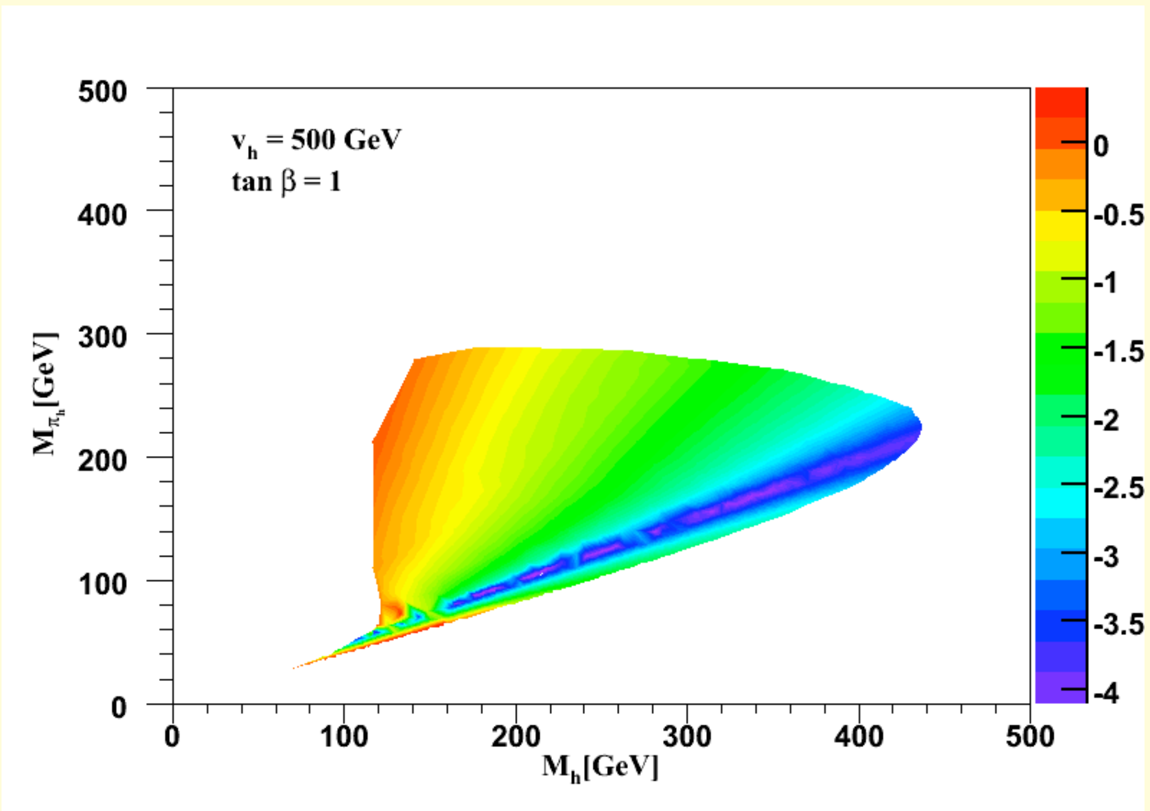
$$\mathcal{L}_{\rm hidden} = -\frac{1}{4}\mathcal{G}_{\mu\nu}\mathcal{G}^{\mu\nu} + \sum_{k=1}^{N_{HF}} \overline{\mathcal{Q}}_k (i\mathcal{D}\cdot\gamma - \lambda_k S)\mathcal{Q}_k$$

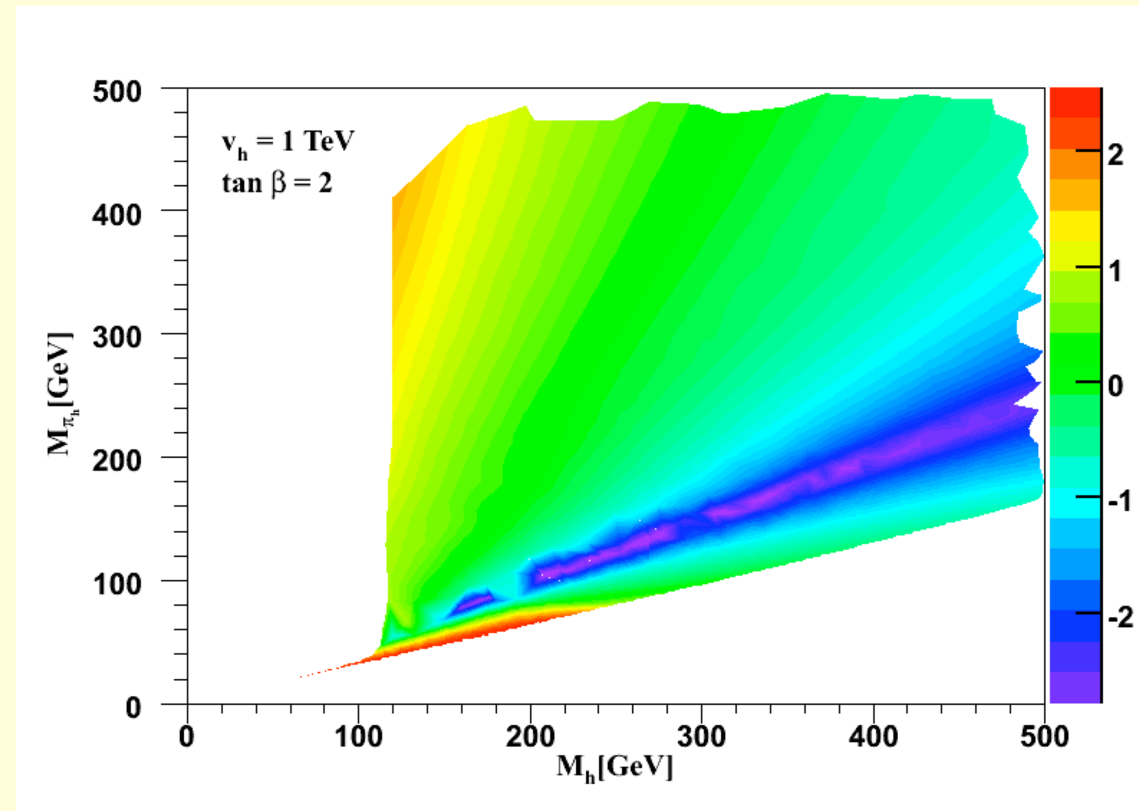
3 neutral scalars : h, S and hidden sigma meson
Assume h-sigma is heavy enough for simplicity

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



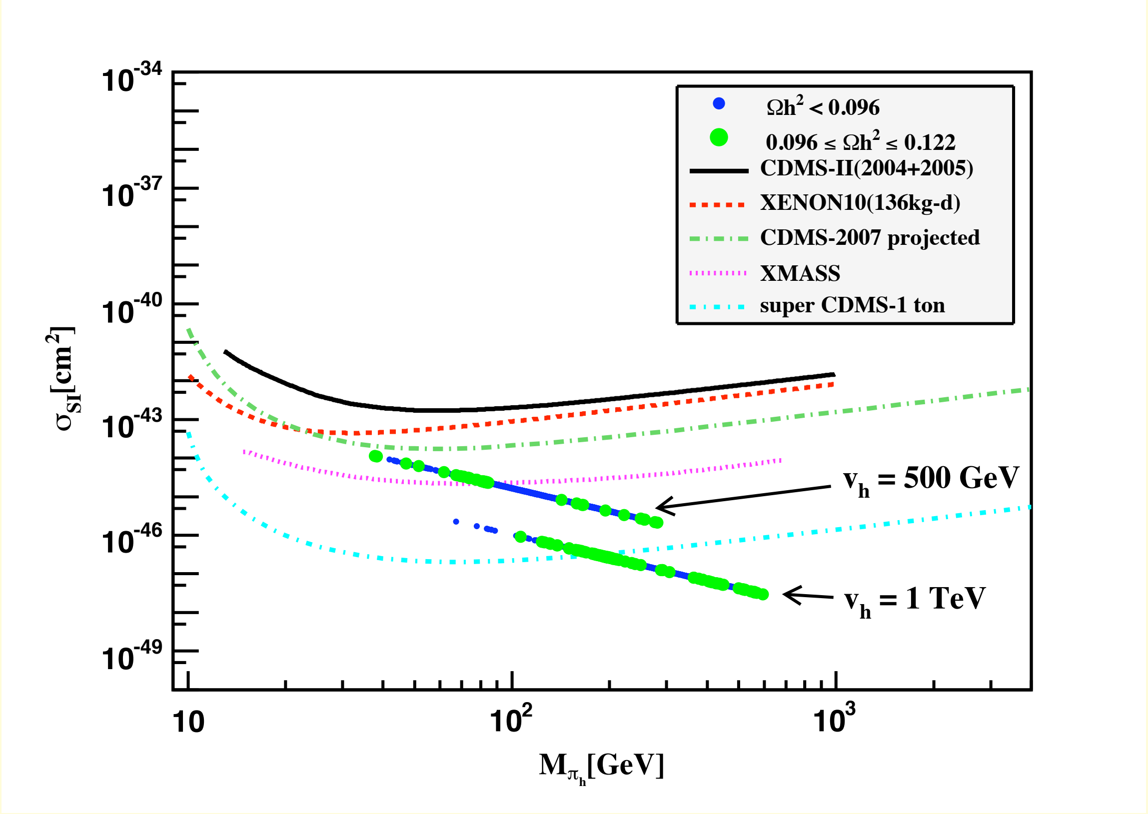


$\Omega_{\pi_h} h^2$ in the (m_{h_1}, m_{π_h}) plane for

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

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

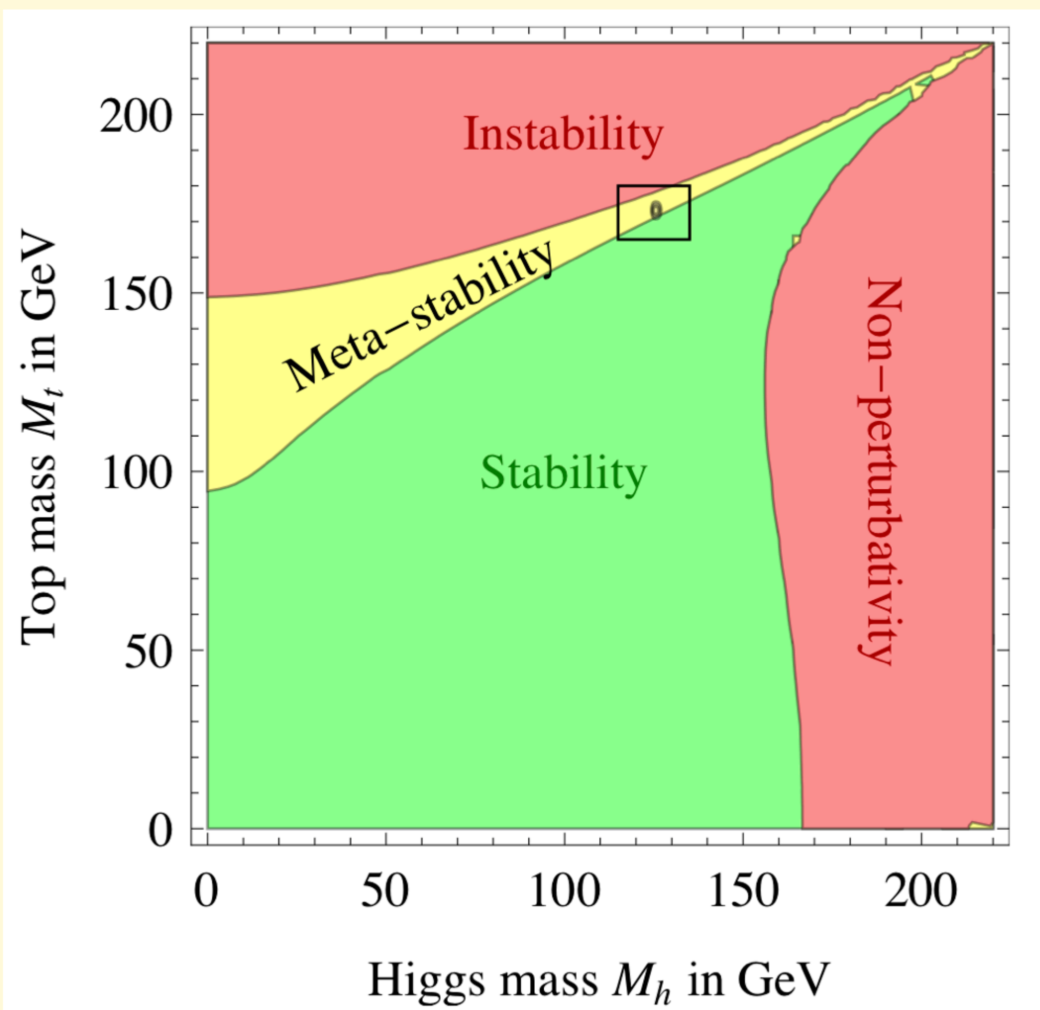
Direct Detection Rate

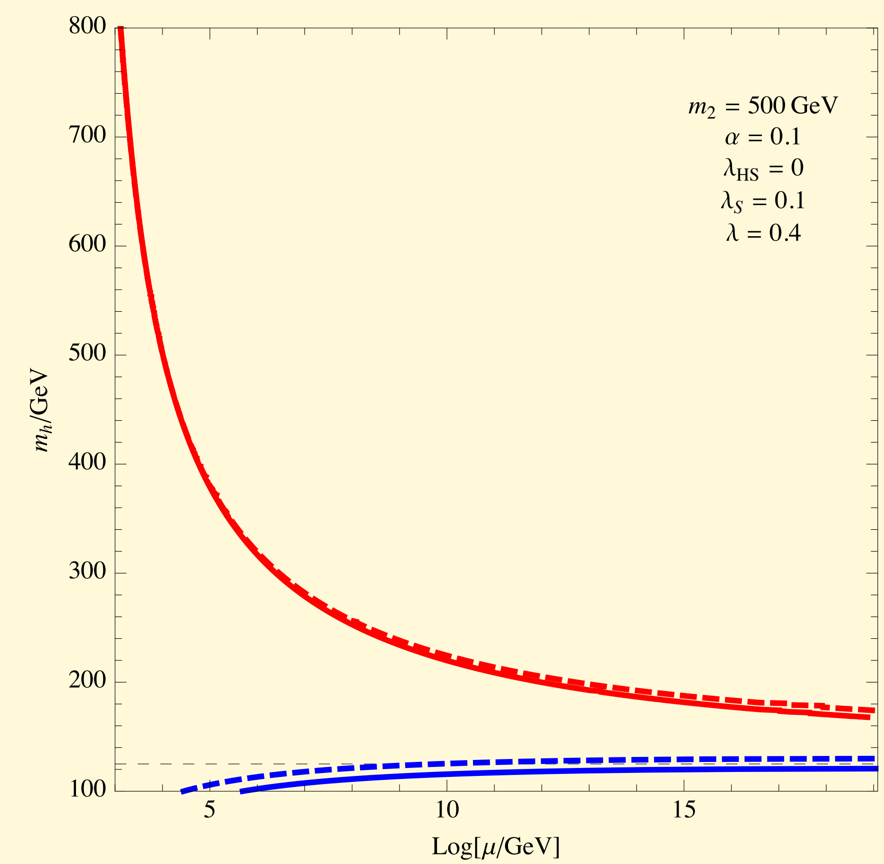


$\sigma_{SI}(\pi_h p \to \pi_h p)$ as functions of m_{π_h}.
the upper one: $v_h = 500$ GeV and $\tan\beta = 1$,

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

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

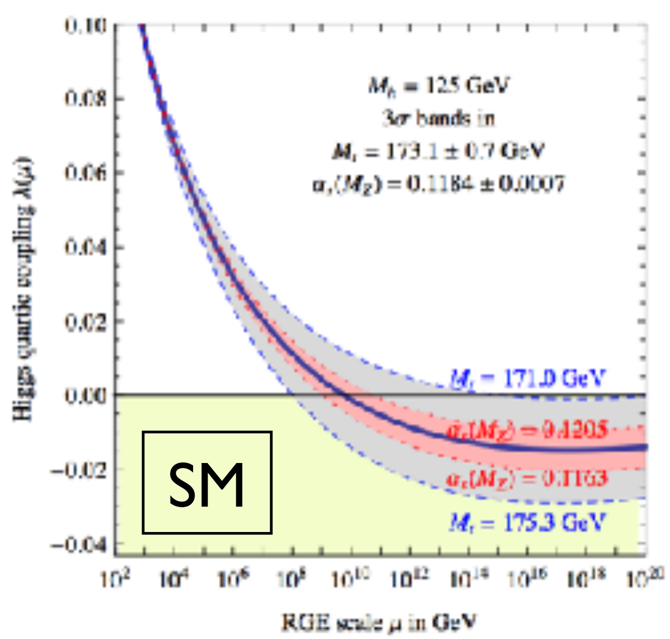
[See 1112.1847, Seungwon Baek, P. Ko & WIP]

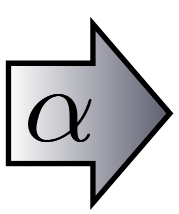
- If "m_h > 2 m_ϕ", non-SM Higgs decay!

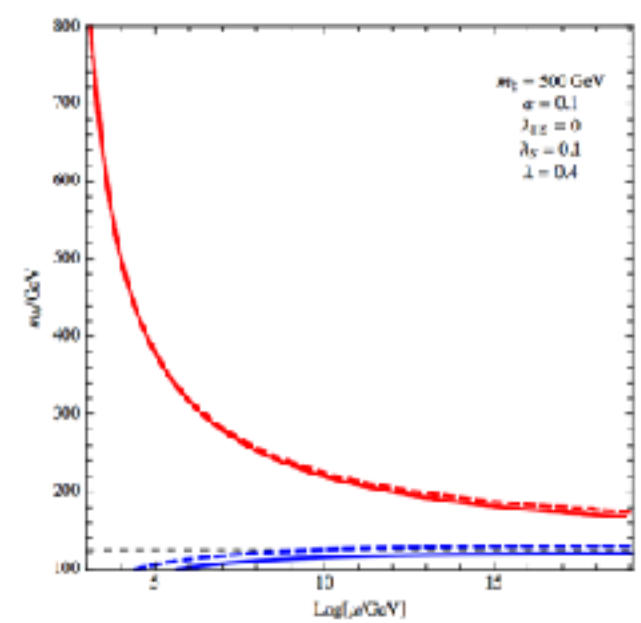
- Tree-level shift of $\lambda_{H,SM}$ (& loop correction)

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

➡ If "m_ϕ> m_h", vacuum instability can be cured.







[G. Degrassi et al., 1205.6497]

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

Comparison w/ other model

- Dark gauge symmetry is unbroken (DM is absolutely stable), but confining like QCD (No long range dark force and no Dark Radiation)
- DM : composite hidden hadrons (mesons and baryons)
- All masses including CDM masses from dynamical sym breaking in the hidden sector
- Singlet scalar is necessary to connect the hidden sector and the visible sector
- Higgs Signal strengths : universally reduced from one

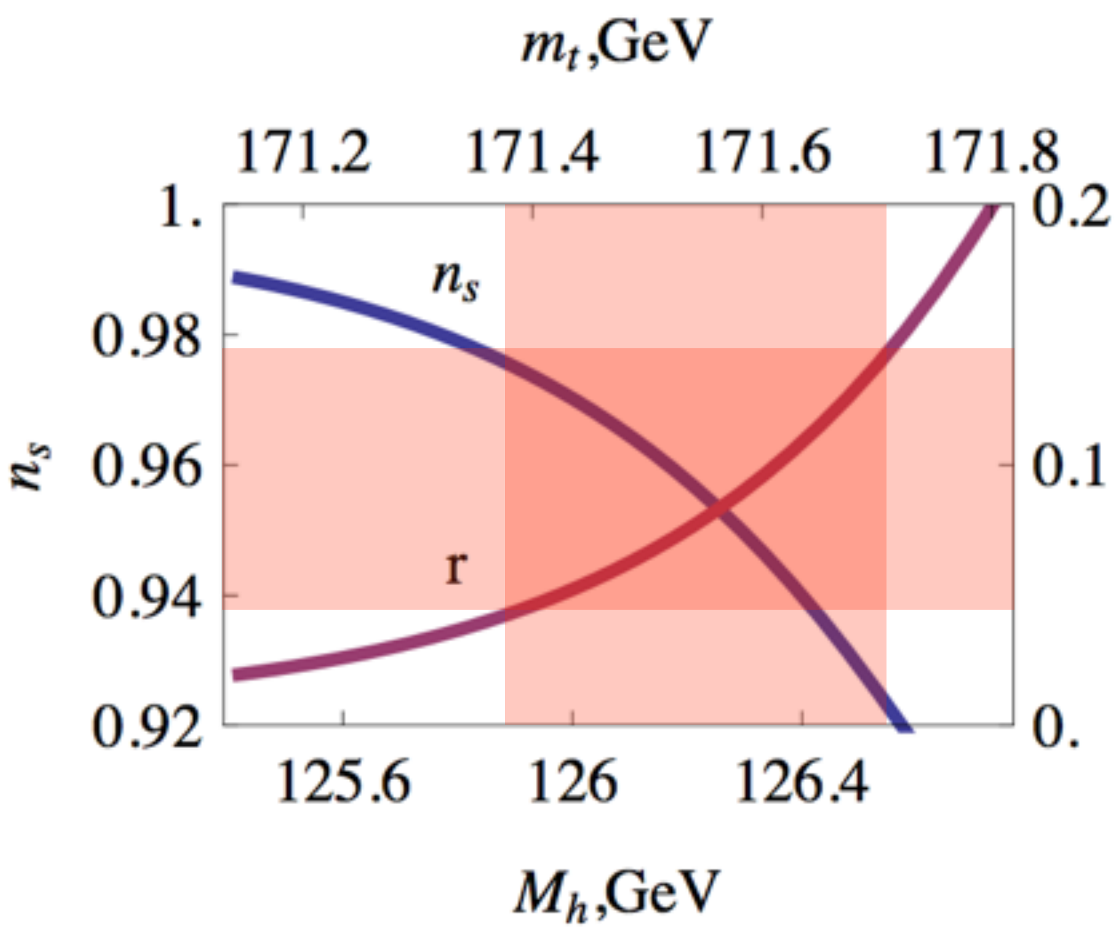
- Similar to the massless QCD with the physical proton mass without finetuning problem
- Similar to the BCS mechanism for SC, or Technicolor idea
- Eventually we would wish to understand the origin of DM and RH neutrino masses, and this model is one possible example
- Could consider SUSY version of it

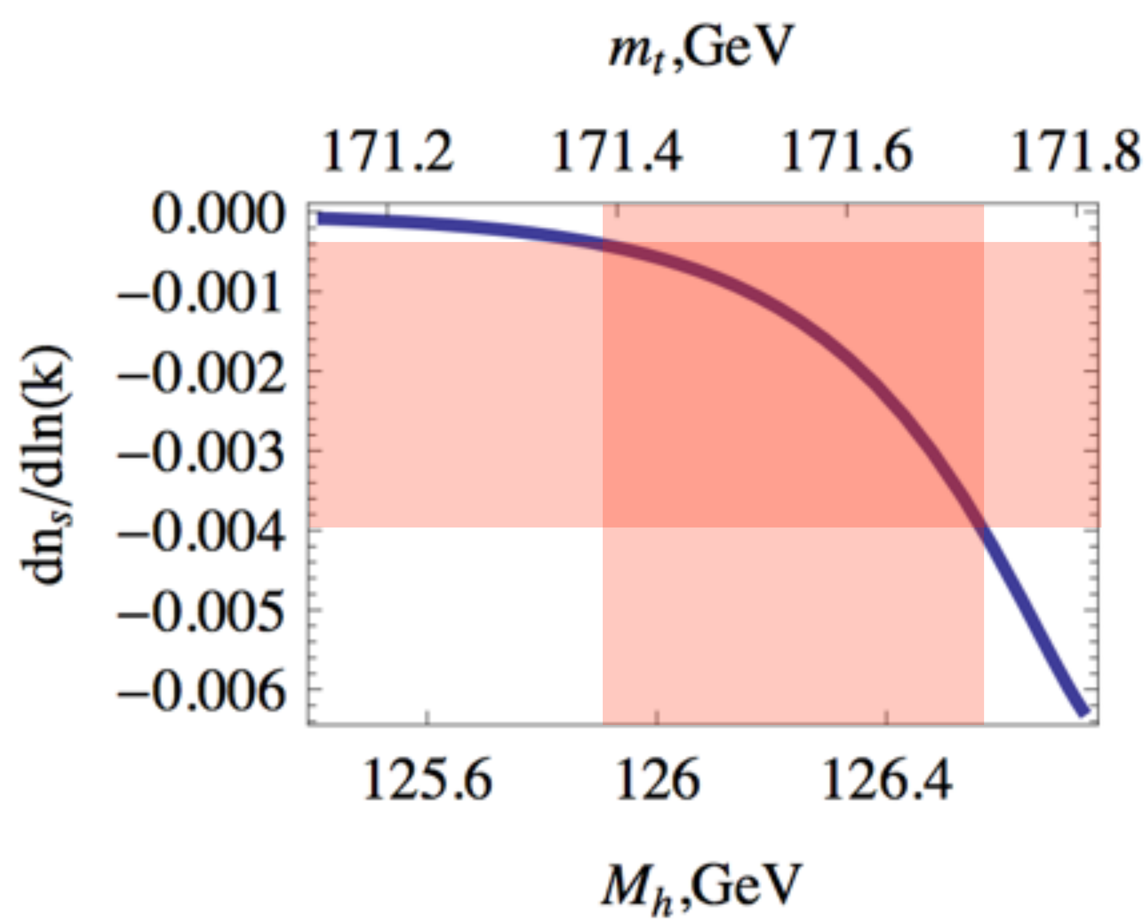
Impact of dark higgs -Cosmo.

(Higgs-portal assisted Higgs inflation)

- Jinsu Kim, P. Ko, WIPark, arXiv: 1405.1635, , JCAP (2017)

- Prediction of SM Higgs inflation



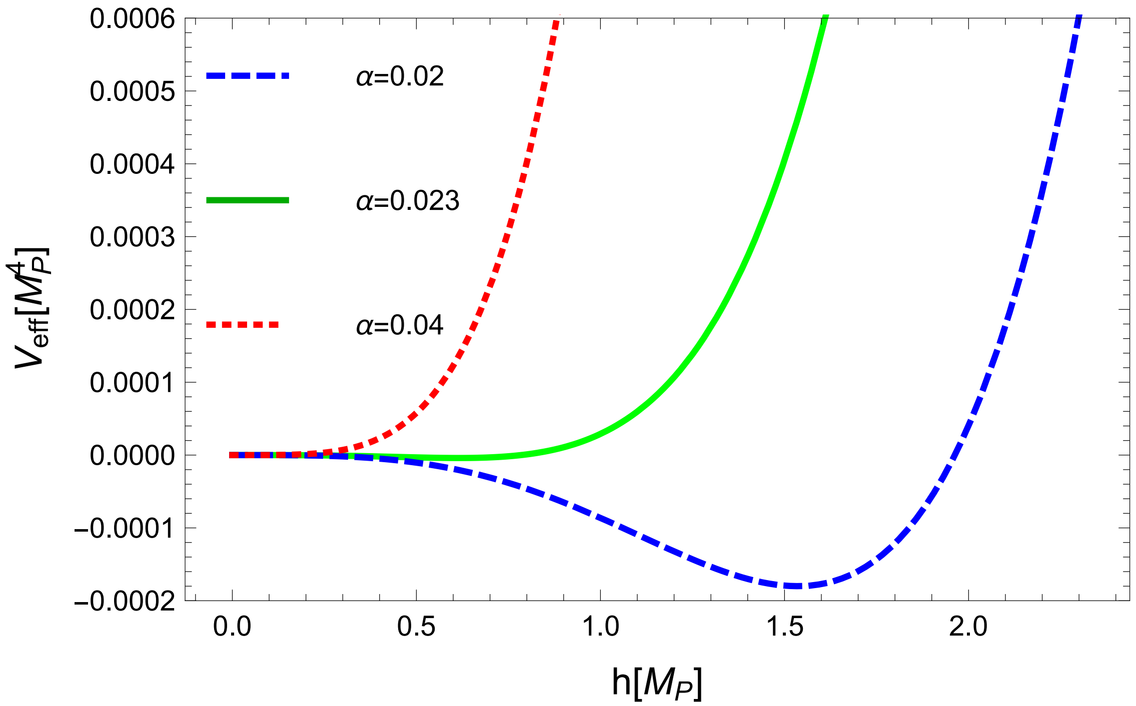


$$\frac{dn_s}{d\ln k} \sim 10^{-3}$$

- Y. Hamada, H. Kawai, K.Y. Oda, S.C.Park, arXiv:1403.5043
- F. Bezrukov, M. Shaposhnikov, arXiv:1403.6078

Higgs portal interaction with Dark Higgs can change the whole story

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



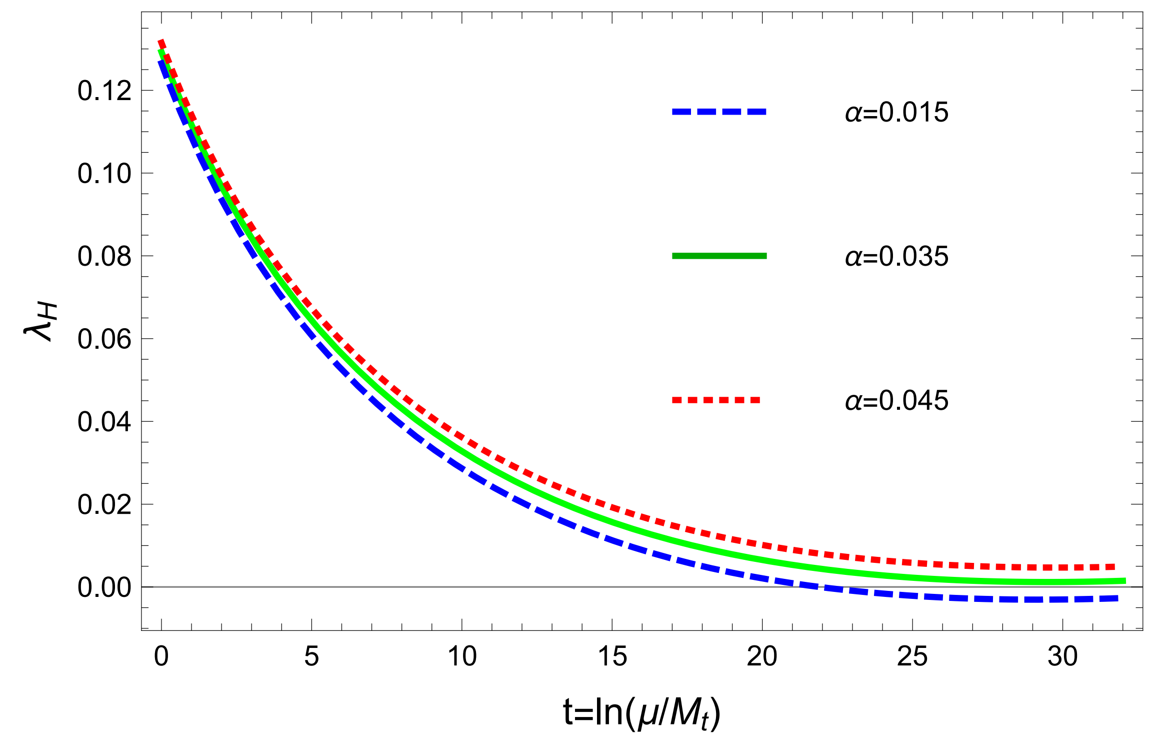


Figure 3. Jordan-frame Higgs potential $V_{\rm eff}$ (left panel) and the running of λ_H (right panel) in SFDM for $\xi_h = 440$, $\xi_s = 0$, $m_s = 600\,\text{GeV}$, $\lambda_{SH} = 0.1$, $\lambda_S = 0.2$, and $\lambda_\psi = 0.3$ chosen at M_t scale.

α	m_s	λ_{SH}	λ_S	λ_ψ	ξ_h	N_e	$10^9 P_S$	n_s	r	α_s
0.036	500	0.1	0.2	0.3	433	57.3	2.2	0.9758	0.0926	−0.0003
0.03885	500	0.1	0.1	0.1	396	57.3	2.2	0.9775	0.0878	−0.0003

Table 1. Cosmological observables in SFDM. Two parameter sets which result in a sizeable value of the tensor-to-scalar ratio r are presented. Here the pivot scale $k_* = 0.05\,\text{Mpc}^{-1}$ is chosen. For the upper (lower) case, we obtained $x \approx 0.25$ (0.26) and $y \approx 0.11$ (0.11), where x and y are defined as eq. (3.15).

Predictions

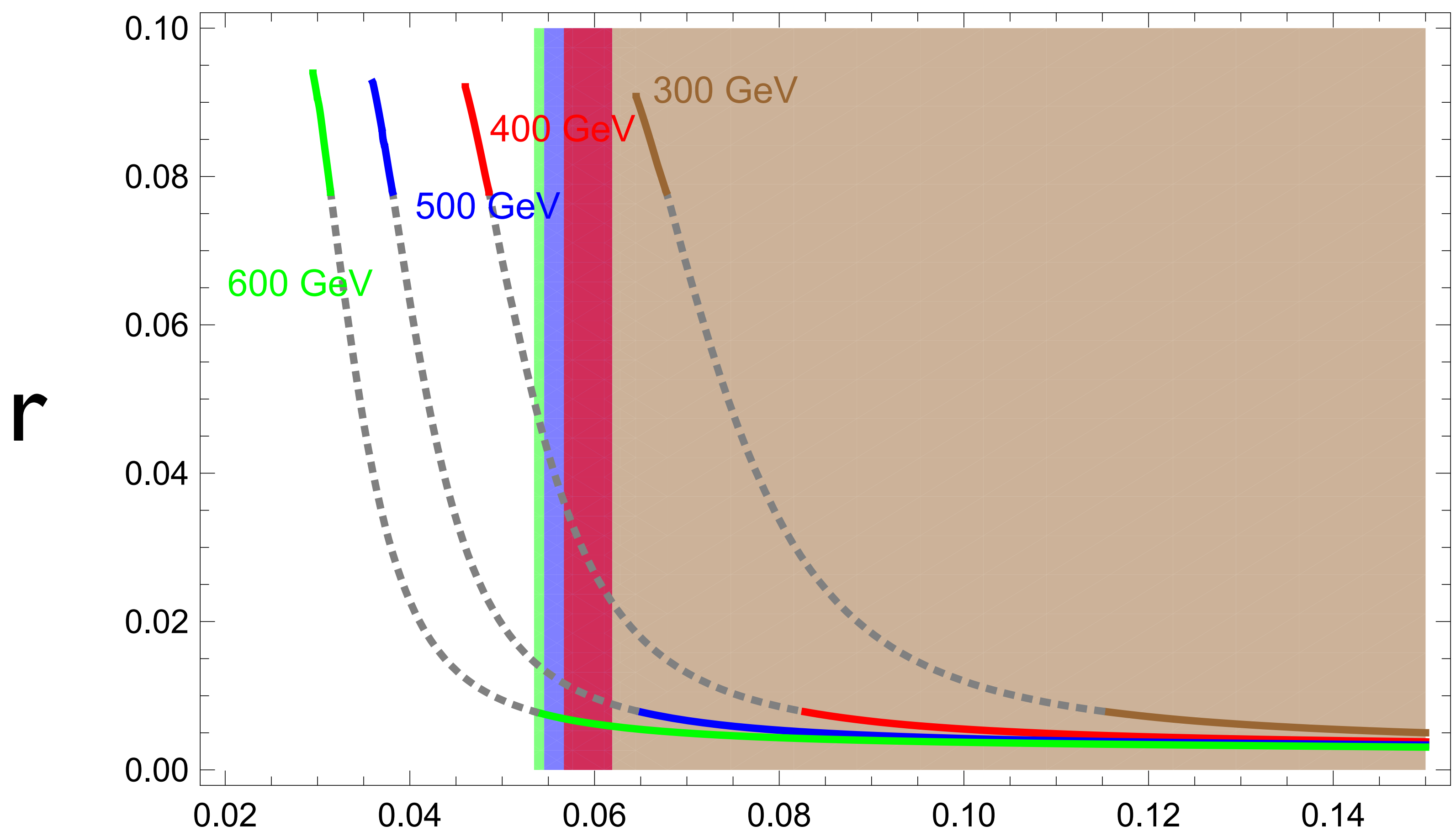


Figure 6. Tensor-to-scalar ratio as a function of the mixing angle α for $m_s = 300\,\text{GeV}$, $400\,\text{GeV}$, $500\,\text{GeV}$ and $600\,\text{GeV}$, with the constraints discussed in the main text. The stringent upper bounds for a given m_s comes from the DM physics. The values of the other parameters are the same as in figure 4. Color-shaded regions (following the scheme of colored lines) are the excluded regions from the latest LUX experiment, corresponding to different dark Higgs masses.

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

- S. Baek, P. Ko, M. Park, WIPark, C. Yu, arXiv:1506.06556 Phys. Lett. B756 (2016)289
- P. Ko and Jinmian Li, arXiv:1610.03997, PLB (2017)

Why is it broken down in DM EFT ?

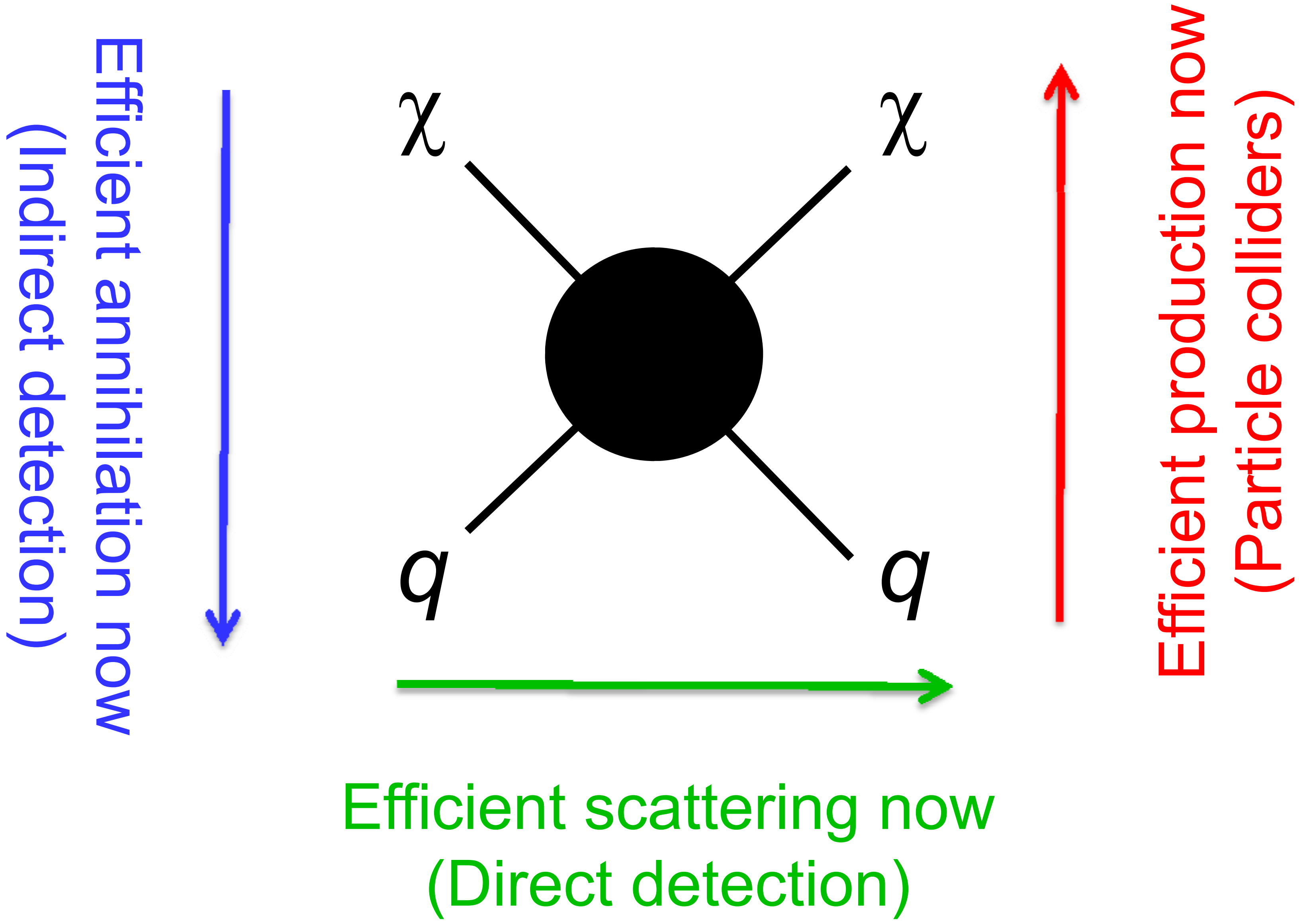
The most nontrivial example is the (scalar)x(scalar) operator for DM-N scattering

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

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

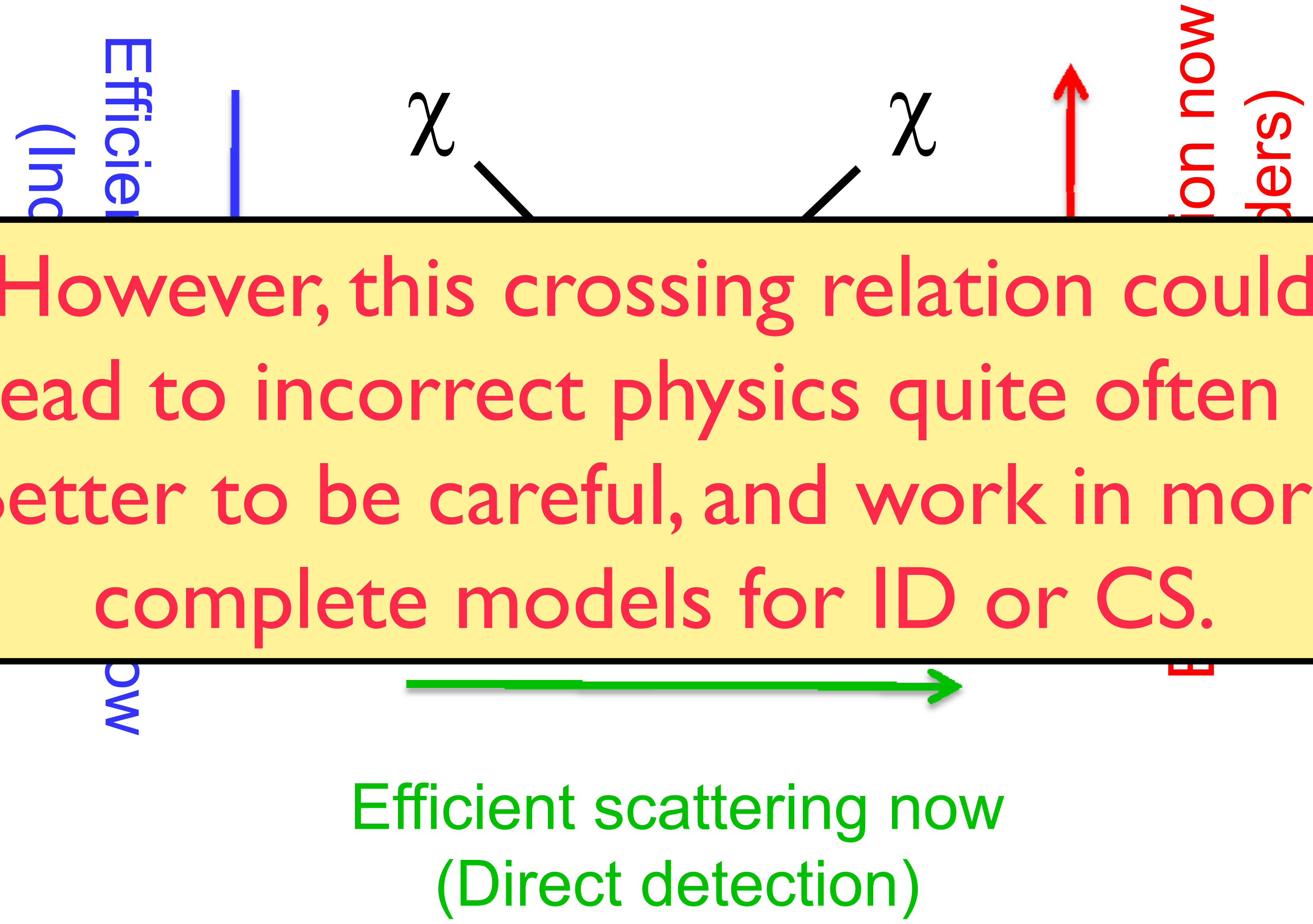
Crossing & WIMP detection

Correct relic density → Efficient annihilation then



Crossing & WIMP detection

Correct relic density → Efficient annihilation then



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

From Paolo Gondolo's talk

Effective operators: LHC & direct detection

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

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

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

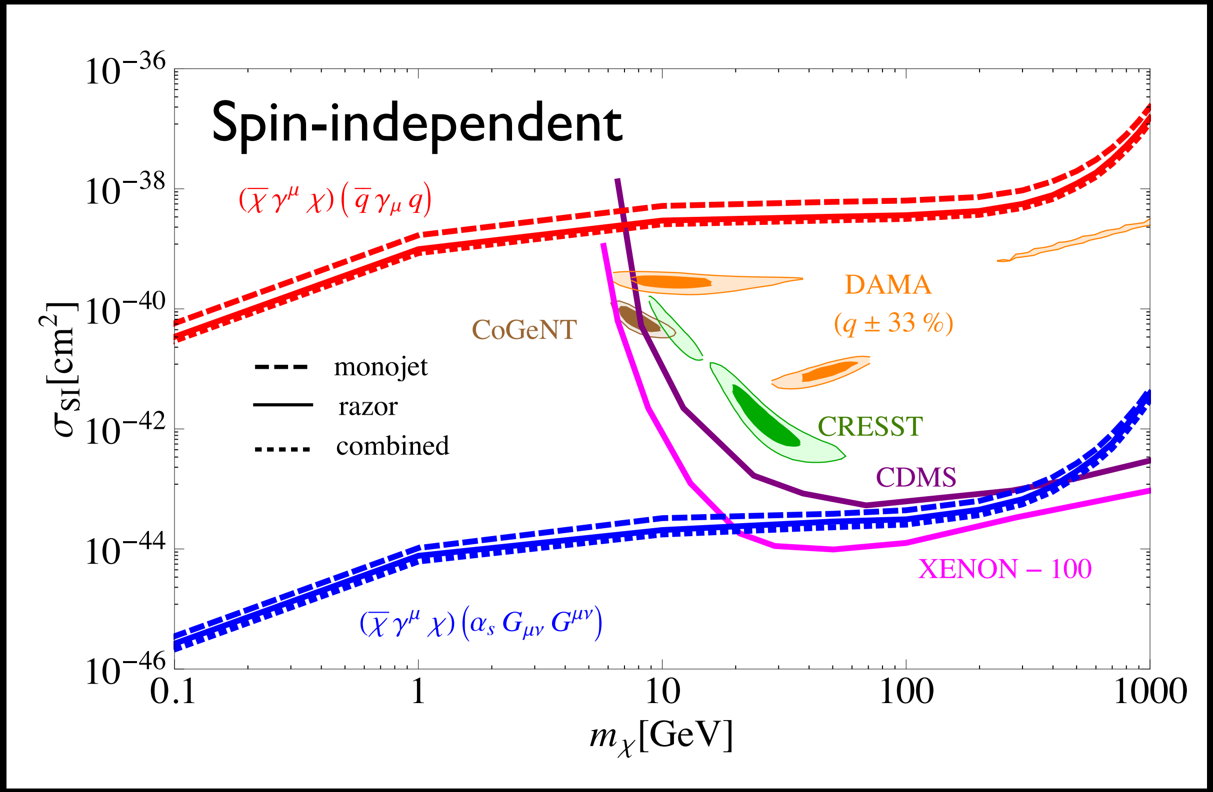
Goodman, Ibe, Rajaraman, Shepherd, Tait, Yu 2010

From Paolo Gondolo's talk

Effective operators: LHC & direct detection

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

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



Fox, Harnik, Primulando, Yu 2012

These bounds do not apply to SUSY, etc.

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

Limitation and Proposal

- EFT is good for direct detection, but not for indirect or collider searches as well as thermal relic density calculations in general
- Issues : Violation of Unitarity and SM gauge invariance, Identifying the relevant dynamical fields at energy scale we are interested in, Symmetry stabilizing DM etc.

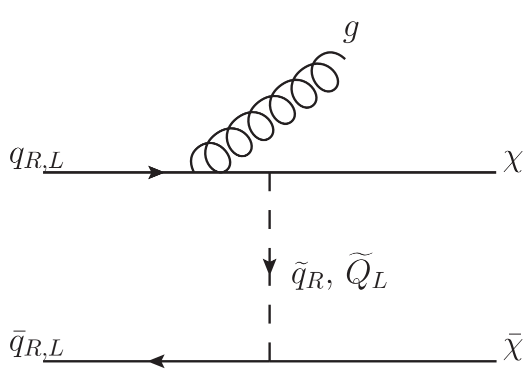
$$\frac{1}{\Lambda_i^2}\ \bar{q}\Gamma_i q\ \bar{\chi}\Gamma_i\chi \rightarrow \frac{g_q g_\chi}{m_\phi^2 - s}\ \bar{q}\Gamma_i q\ \bar{\chi}\Gamma_i\chi$$

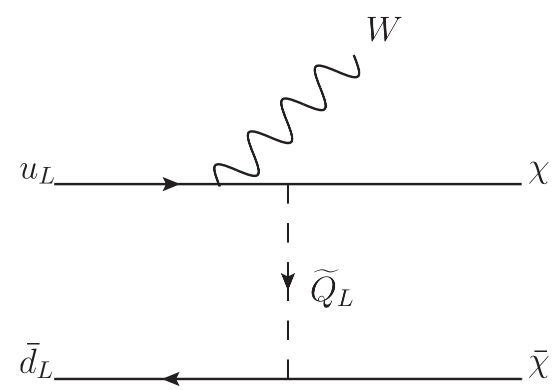
- Usually effective operator is replaced by a single propagator in simplified DM models
- This is not good enough, since we have to respect the full SM gauge symmetry (Bell et al for W+missing ET)
- In general we need two propagators, not one propagator, because there are two independent chiral fermions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

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

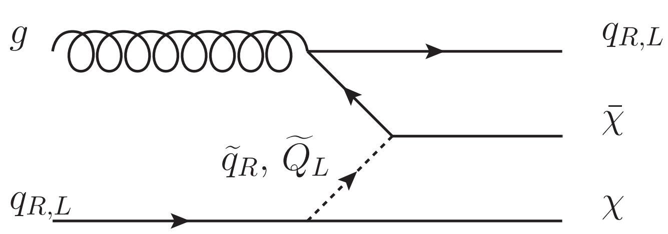
for t-channel mediator

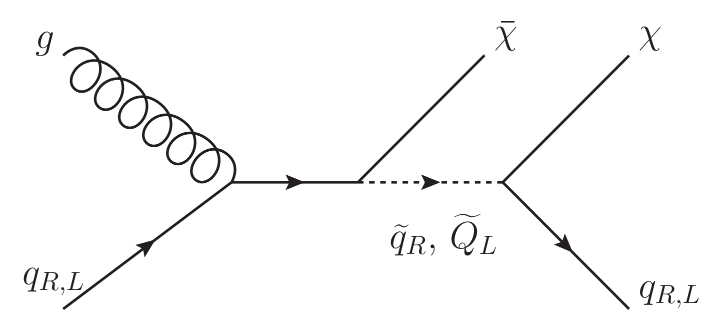
Our Model: a 'simplified model' of colored t-channel, spin-0, mediators which produce various mono-x + missing energy signatures (mono-Jet, mono-W, mono-Z, etc.):





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 singatures
- The same is also true for (scalar)x(scalar) operator, and lots of confusion on this operator in literature
- Therefore let me concentrate on this case in detail in this talk

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

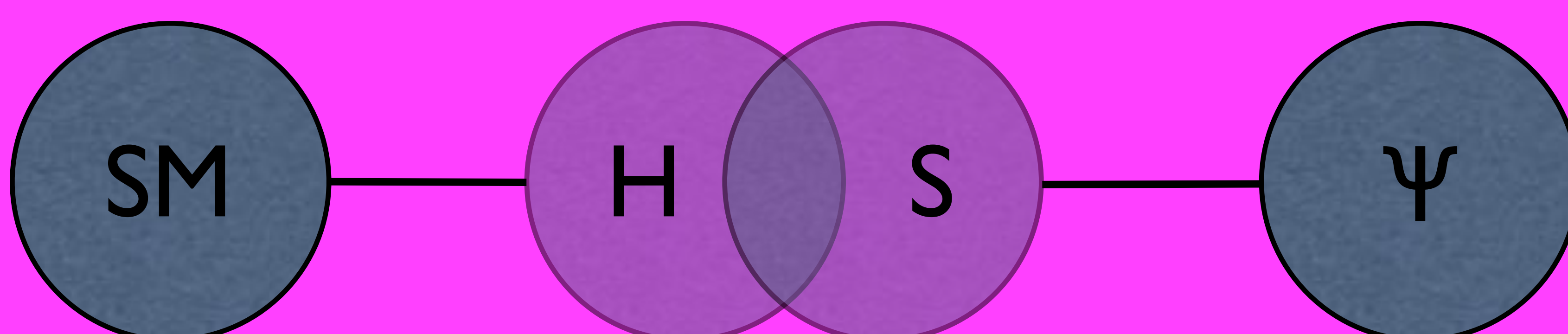
Singlet fermion CDM

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

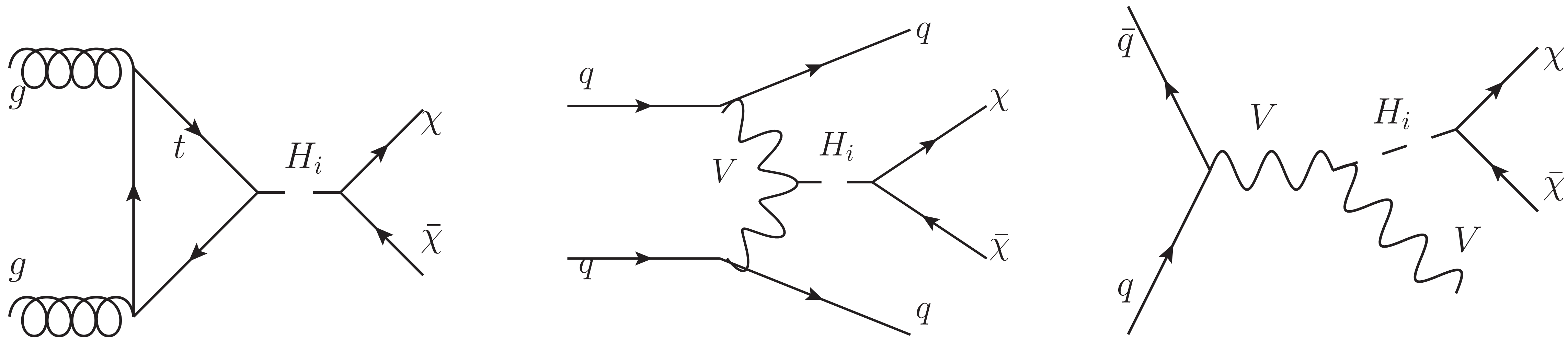


Figure 1: The dominant DM production processes at LHC.

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

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

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

Interference effects

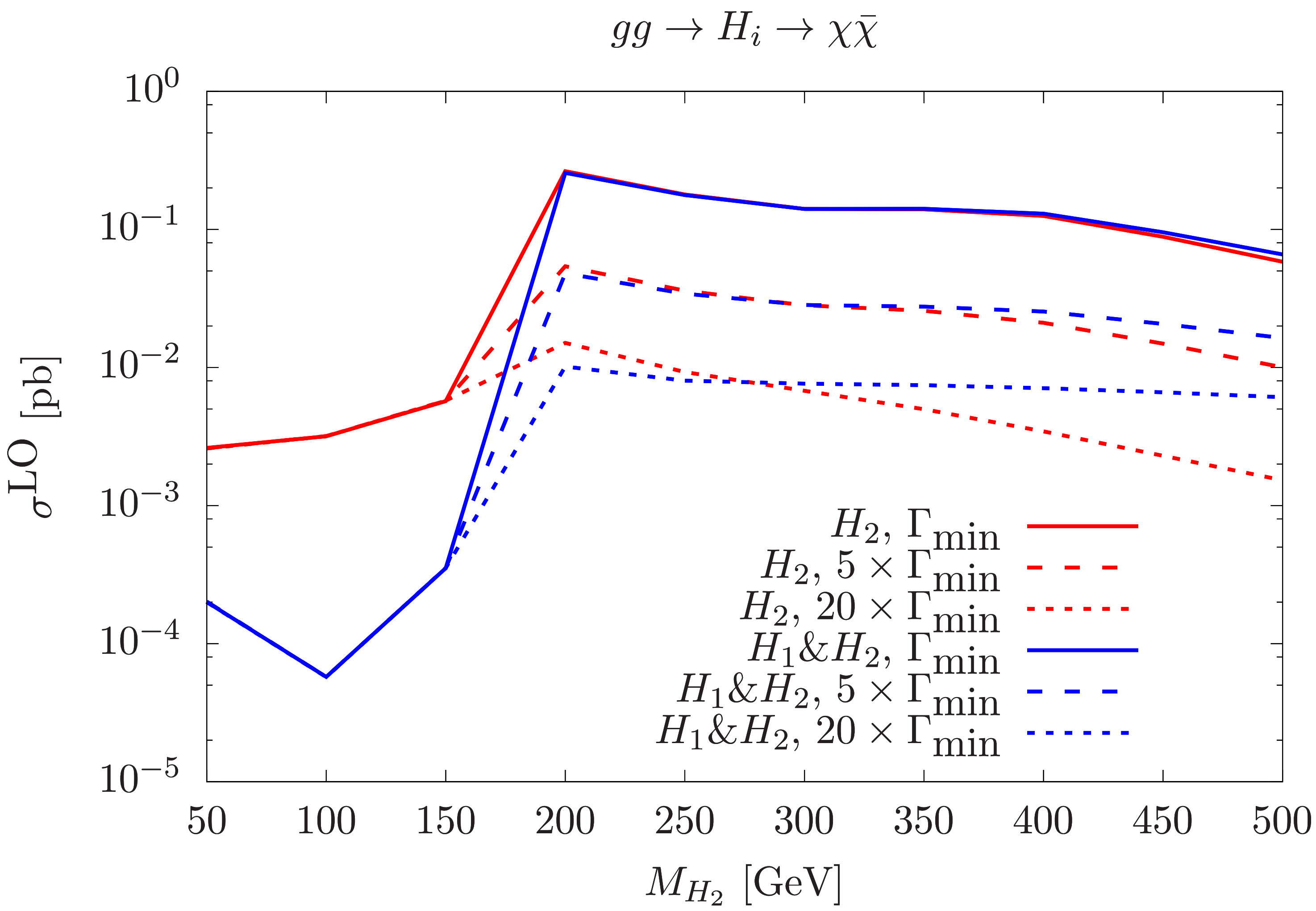


Figure 2: The LO cross section for gluon-gluon fusion process at 13 TeV LHC. The meanings of the different line types are explained in the text and the similar strategy will be used in all figures.

Parton level distrib.

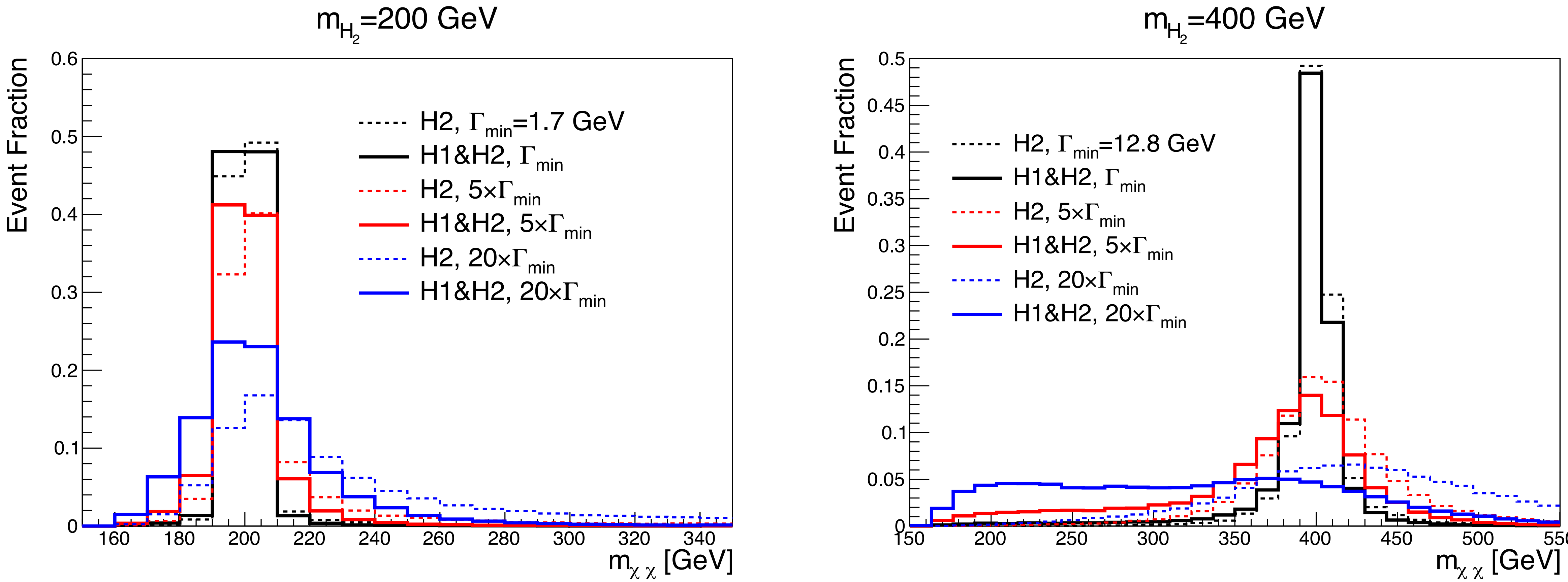


Figure 3: The parton level distributions of $m_{\chi\bar{\chi}}$ for gluon-gluon fusion process at 13 TeV LHC.

Exclusion limits with interference effects

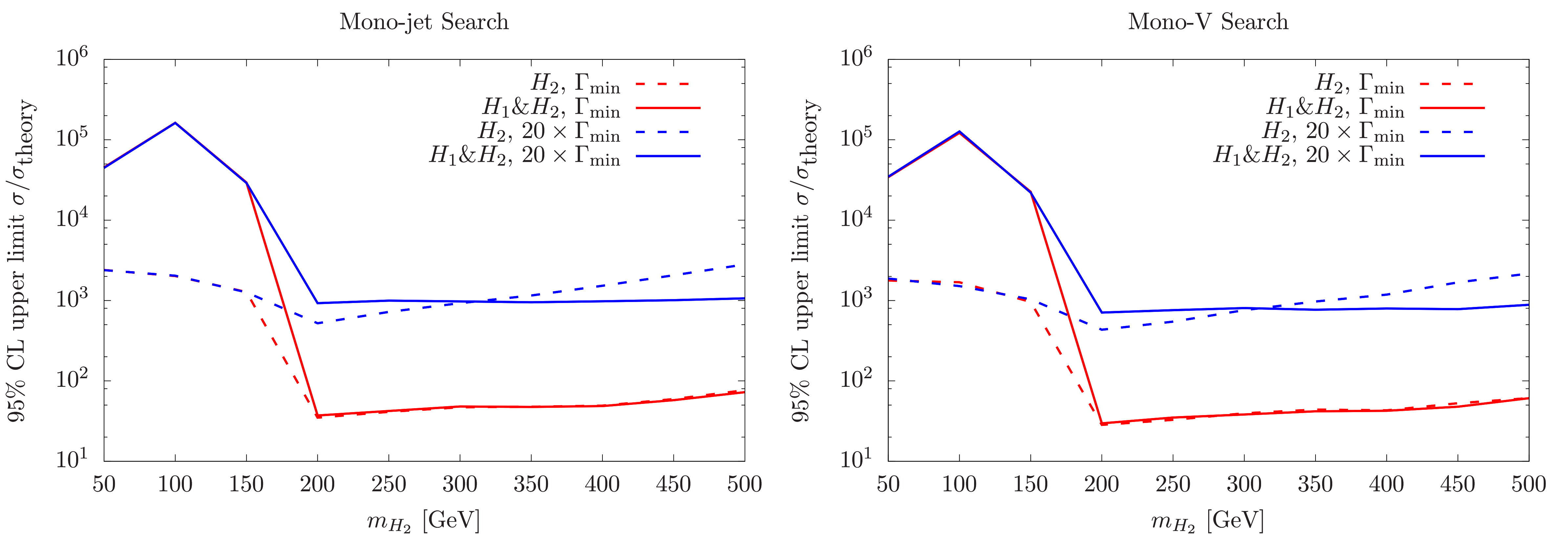


Figure 8: The CMS exclusion limits on our simplified models. Left: upper limit from mono-jet search. Right: upper limit from mono-V search.

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

- EFT : Effective operator $\mathcal{L}_{int} = \frac{m_q}{\Lambda_{dd}^3}\bar{q}q\bar{\chi}\chi$
- S.M.: Simple scalar mediator S of
  $\mathcal{L}_{int} = \left(\frac{m_q}{v_H}\sin\alpha\right) S\bar{q}q - \lambda_s \cos\alpha S\bar{\chi}\chi$
- H.M.: A case where a Higgs is a mediator
  $\mathcal{L}_{int} = -\left(\frac{m_q}{v_H}\cos\alpha\right) H\bar{q}q - \lambda_s \sin\alpha H\bar{\chi}\chi$
- H.P.: Higgs portal model as in eq. (2).

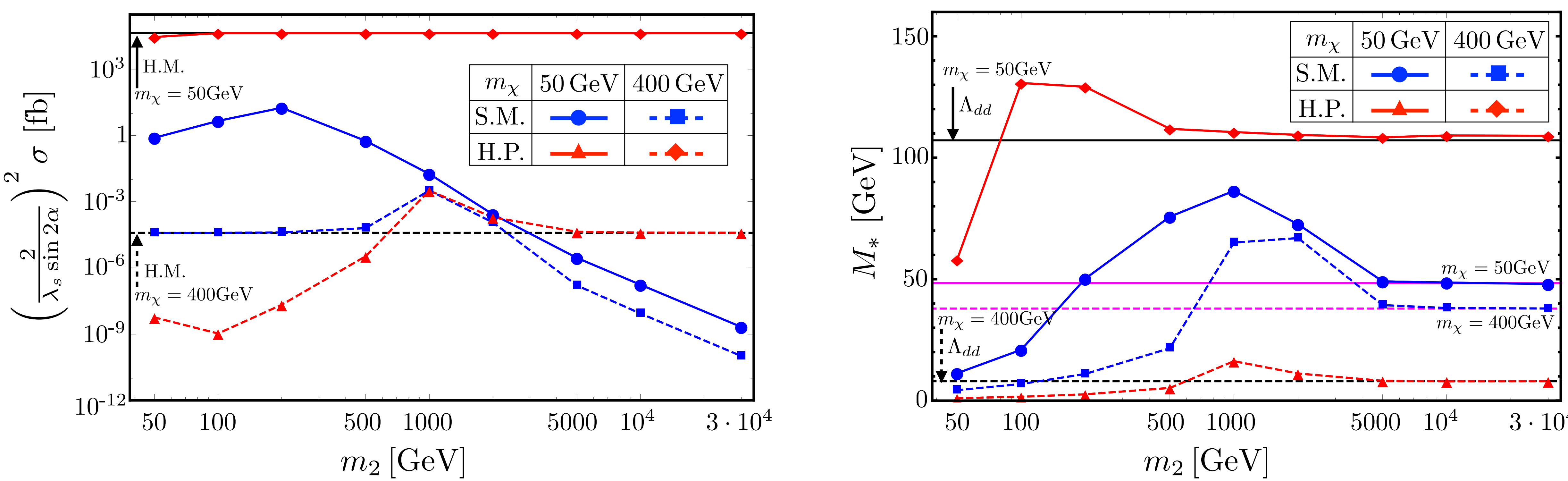


FIG. 1: We follow ATLAS 8TeV mono-jet+$\not{E}_T$ searches [2]. For (a) we simulated various models for the

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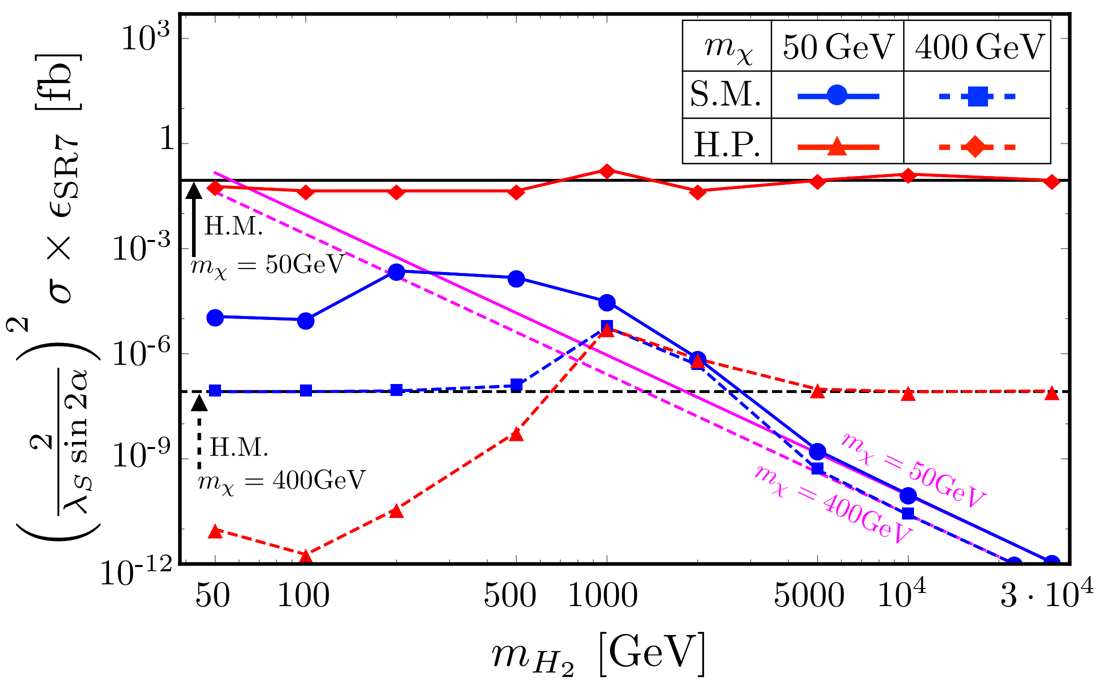

FIG. 2: Rescaled cross sections for the monojet+$\not{E}_T$ in the signal region SR7 ($\not{E}_T > 500\,\text{GeV}$) at ATLAS [11]. Each line corresponds to the EFT approach (magenta), S.M. (blue), H.M. (black), and H.P. (red), respectively. The solid and dashed lines correspond to $m_\chi = 50$ GeV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

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

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

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

- EFT : Effective operator $\mathcal{L}_{int} = \frac{m_q}{\Lambda_{dd}^3}\bar{q}q\bar{\chi}\chi$
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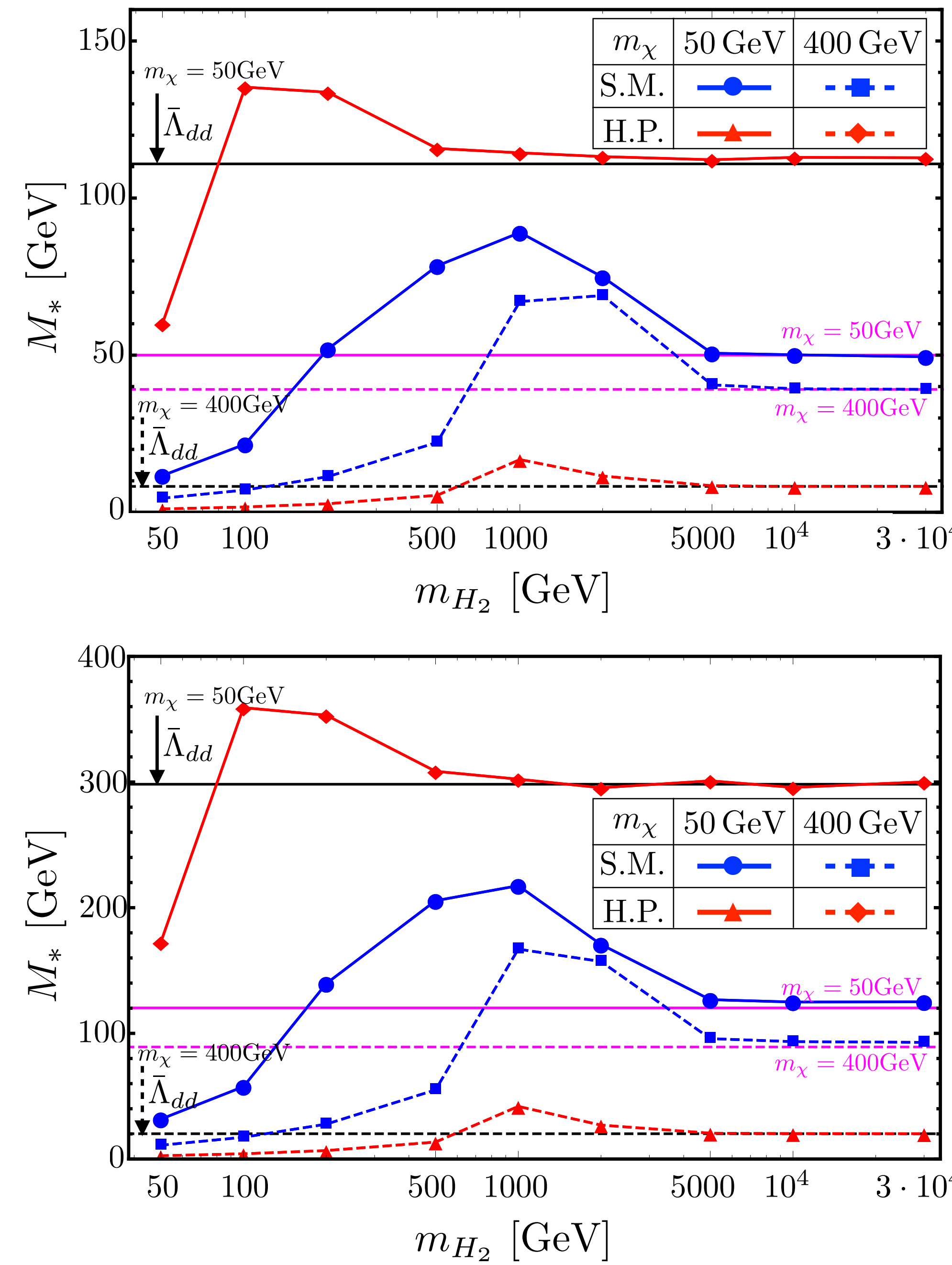

FIG. 3: The experimental bounds on M_* at 90% C.L. as a function of m_{H_2} (m_S in S.M. case) in the monojet+$\not{E}_T$ search (upper) and $t\bar{t} + \not{E}_T$ search (lower). Each line corresponds to the EFT approach (magenta), S.M. (blue), H.M. (black), and H.P. (red), respectively. The bound of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

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

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

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

Conclusion

- Renormalizable and unitary model (with some caveat) is important for DM phenomenology (EFT can fail completely)
- Hidden sector DM with Dark Gauge Sym is well motivated, can guarantee DM stability/ longevity, solves some puzzles in CDM paradigm, open a new window in DM models including DM-DR interaction
- Especially a wider region of DM mass is allowed due to new open channels

- DM Dynamics dictated by local gauge symmetry
- Non Standard Higgs decays into a pair of DM, light dark Higgs bosons, or dark gauge bosons, etc.
- Additional singlet-like scalar "S" (Dark Higgs) : generic, can play important roles in DM phenomenology, improves EW vac stability, helps Higgs inflation with larger tensor/scalar ratio (also strong 1st order ph tr. in the dark sector, GW, etc. ?) >> Should be actively searched for
- Searches @ LHC & other future colliders

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