

Dark pion DM: WIMP vs. SIMP

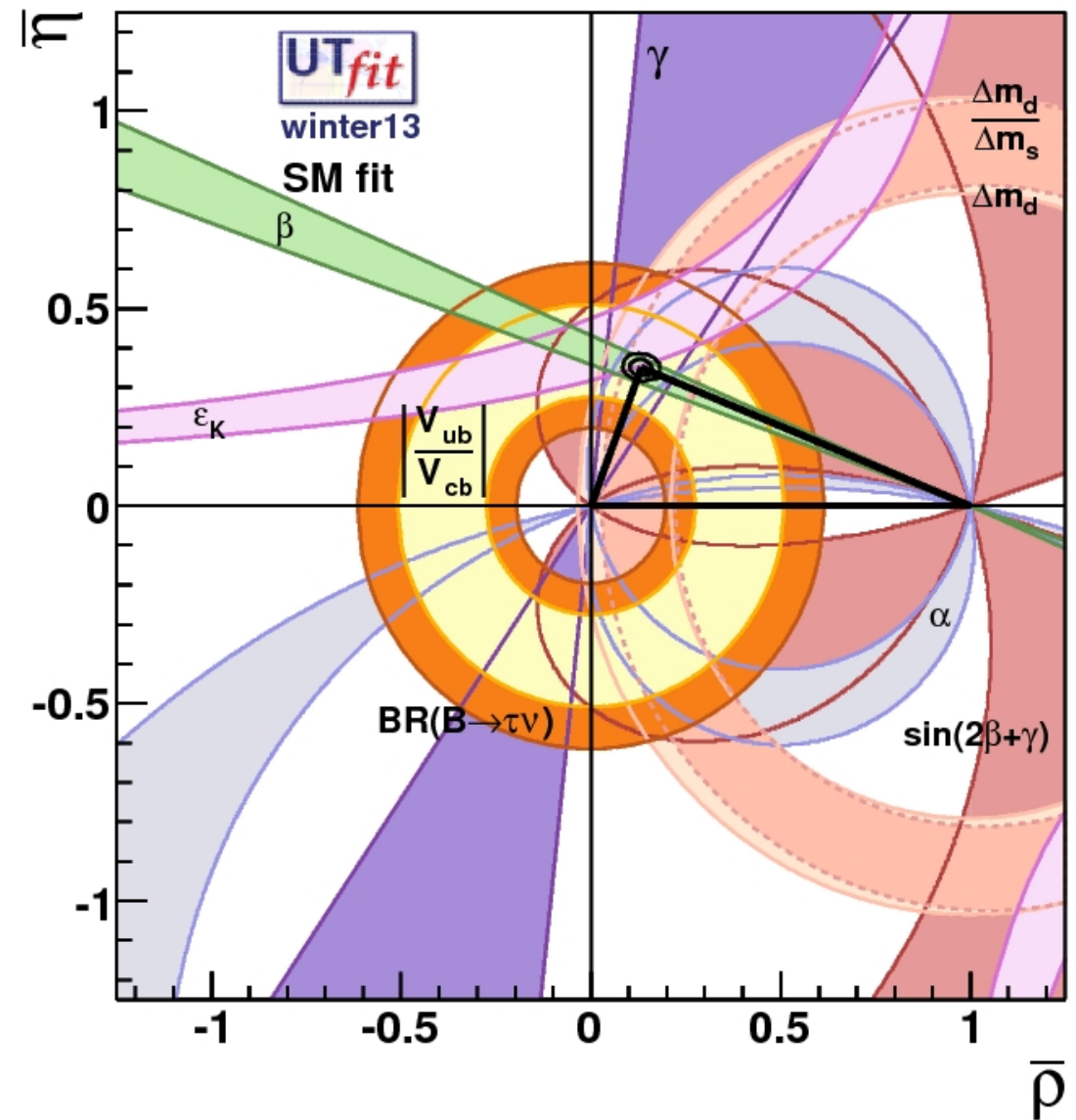
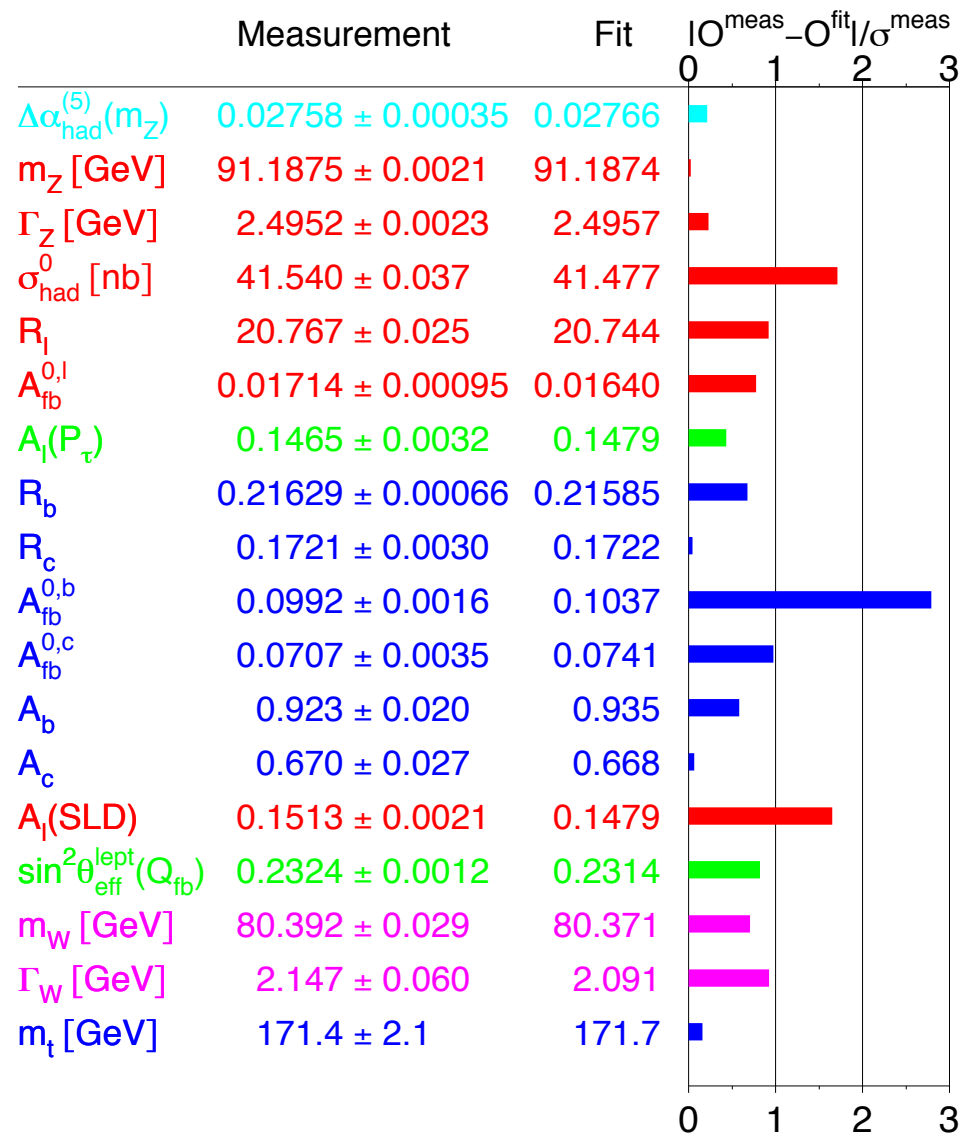
Pyungwon Ko (KIAS)

Strong DM 2019, ESI
Aug. 5-16 (2019)

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

EWPT & CKM



Almost Perfect !

SM Lagrangian

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

Based on local gauge principle

- Only Higgs (\sim SM) and Nothing Else So Far at the LHC
- Nature is described by Local Gauge Theories
- All the observed particles carry some gauge charges (no gauge singlets observed so far)

Motivations for BSM

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

Leptogenesis

Starobinsky

?

Higgs Inflation

Many candidates

Can we attack these problems ?

Maybe it is right time to
think about what LHC and
Planck data tell us about
New Physics@EW scale

Origin of EWSB ?

- LHC discovered a scalar \sim 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)

- Also, often extra particles (the so-called mediators, scalar, vector etc) are introduced to solve three puzzles in Λ CDM paradigm in terms of DM self-interaction
- DR and its interaction with DM may help to relax the tension between H_0 and σ_8
- Phenomenologically nice, but theoretically rather ad hoc
- Any good organizing principle ?

- Note that extra particles (the so-called mediators, scalar, vector etc) are introduced to solve three puzzles in Λ CDM paradigm in terms of DM self-interaction
- DR and its interaction with DM may help to relax the tension between H_0 and σ_8
- Phenomenologically nice, but theoretically rather ad hoc
- Any good organizing principle ?
- YES ! >> Dark Gauge Symmetry

Local Dark Gauge Sym

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

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

SM vs. DM Physics

- Success of the Standard Model of Particle Physics lies in “local gauge symmetry” without imposing any internal global symmetries
- Electron stability : $U(1)_{\text{em}}$ gauge invariance, electric charge conservation
- Proton longevity : baryon # is an accidental sym of the SM
- No gauge singlets in the SM ; all the SM fermions chiral

- Dark sector with (excited) dark matter, dark radiation and force mediators might have the same structure as the SM
- “Dark gauge theories without any ad hoc 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)

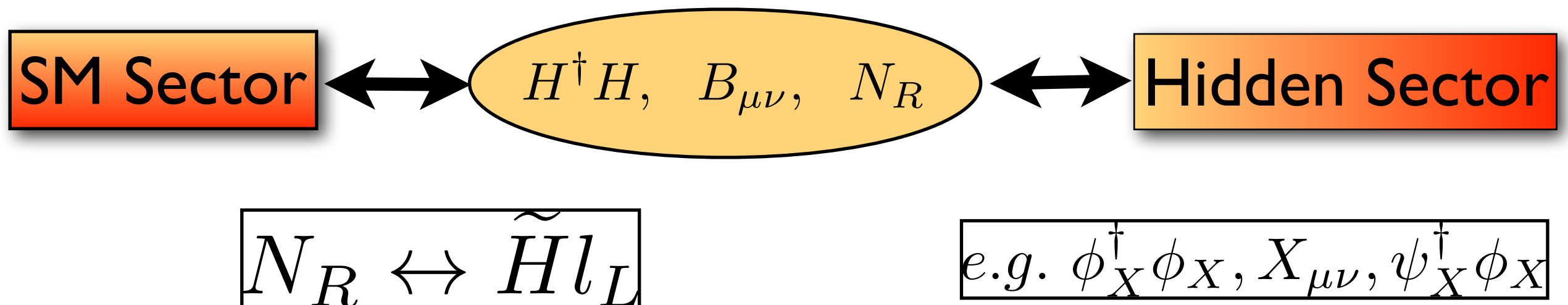
Basic assumptions

- 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

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



Why Dark Gauge 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

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 Z_2 symmetry come from ?
- Is it Global or Local ?

Fate of CDM with Z_2 sym

- Global Z_2 cannot save DM from decay with long enough lifetime

Consider Z_2 breaking operators such as

$$\frac{1}{M_{\text{Planck}}} SO_{\text{SM}}$$

keeping dim-4 SM
operators only

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

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

The lifetime is too short for ~ 100 GeV DM

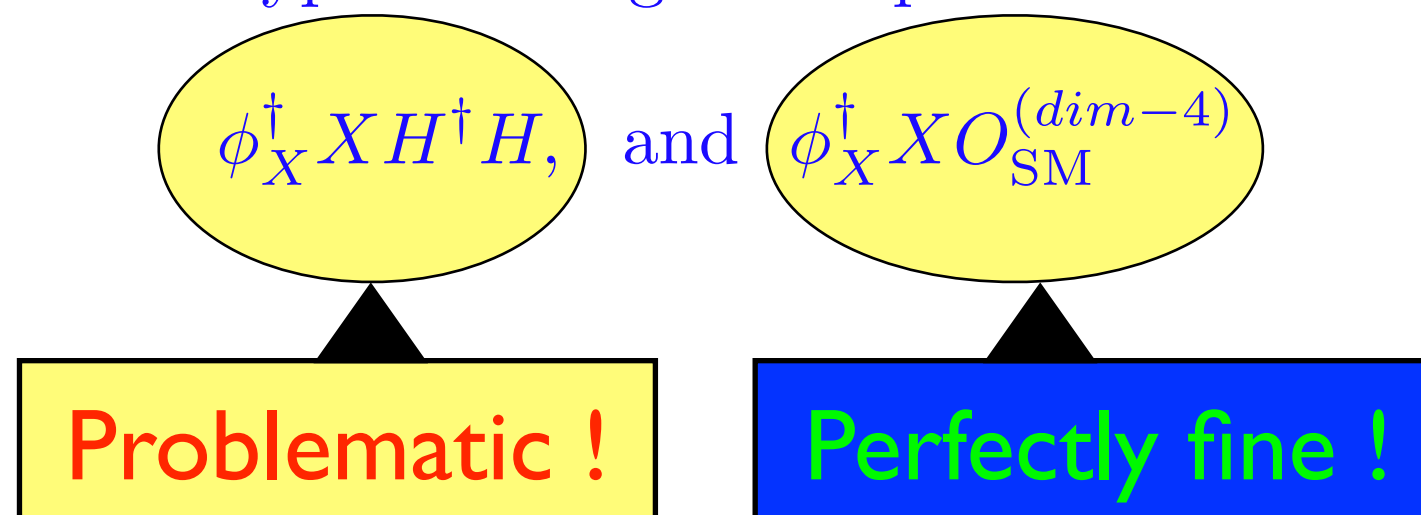
Fate of CDM with Z_2 sym

- 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:



- 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 $U(1)_H$
- Talk by T. Matsui on Z_2 fermion DM (Tue)

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

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

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

Unbroken Local Z2 symmetry
Gauge models for excited DM

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

The heavier state decays into the lighter state

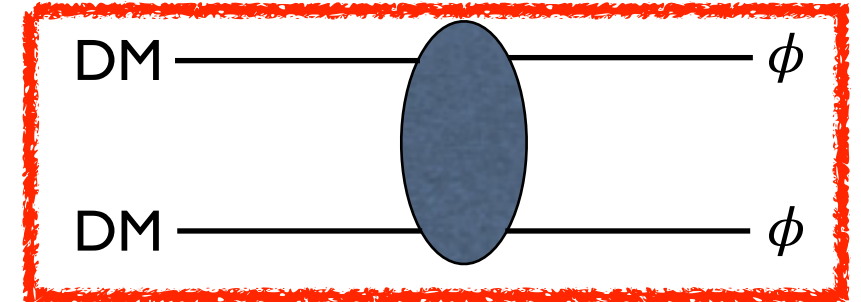
The local Z2 model is not that simple as the usual Z2 scalar DM model (also for the fermion CDM)

- Some DM models with Higgs portal

- Vector DM with Z2

[I404.5257, P. Ko, VIP & Y. Tang]

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

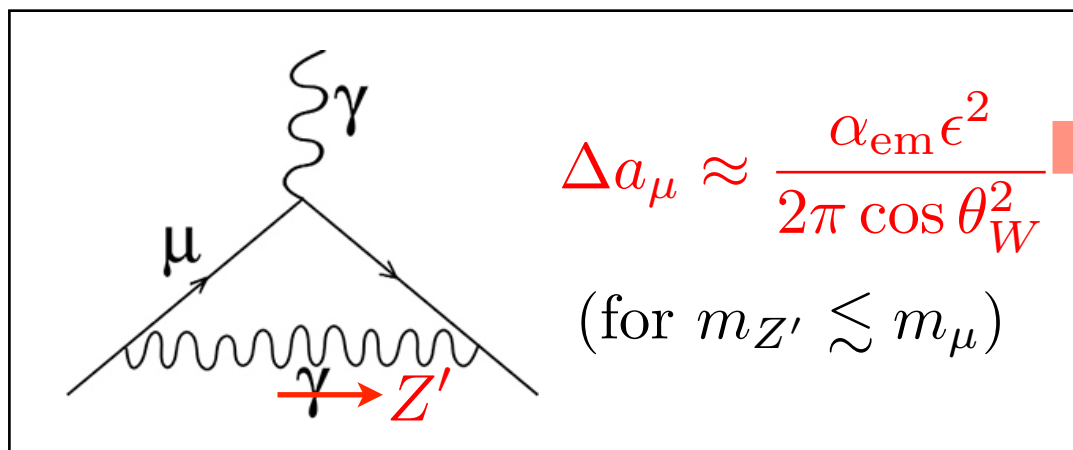


- Scalar DM with local Z2

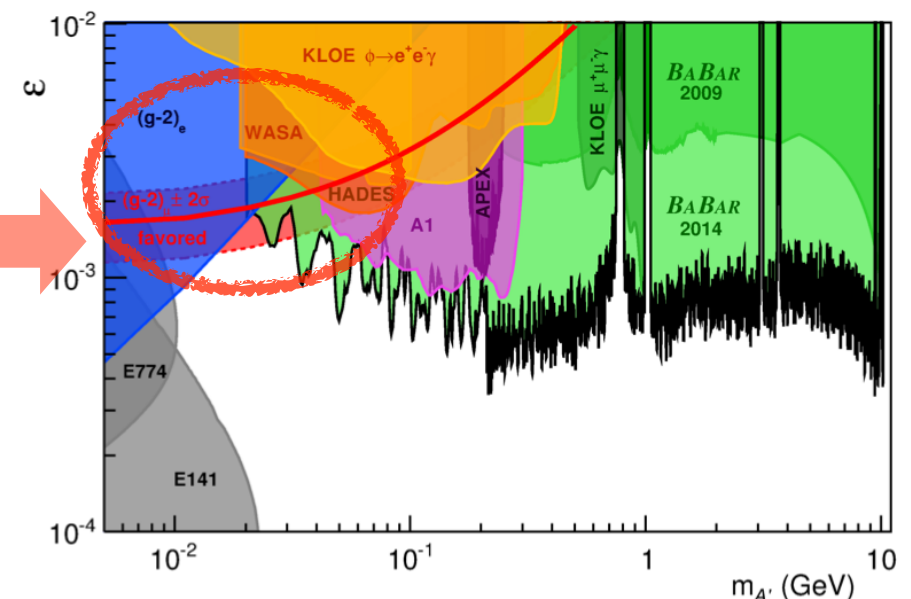
[I407.6588, Seungwon Baek, P. Ko & VIP]

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

- 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'



$$\Delta a_\mu \approx \frac{\alpha_{\text{em}}\epsilon^2}{2\pi \cos\theta_W^2} \quad (\text{for } m_{Z'} \lesssim m_\mu)$$



[I406.2980, BaBar collaboration]

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)
- Today I will mainly talk about dark pion DM

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, CMB and LSS, etc.

Contents

- Hidden (Dark) QCD scenario
- WIMP scenario with the S-H portal
- SIMP scenario in dark QCD
- SIMP + dark resonances (vector, scalar, etc.)

Hidden (Dark) QCD Scenario

hQCD (Dark QCD): WIMP & SIMP

- Strassler + Zurek (2006) : hQCD + $U(1)'$, new collider signatures but no discussion on DM from hQCD. hep-ph/0604261. PLB (2007)
- B. Patt and F. Wilczek, hep-ph/0605188. “Higgs portal”
- Hur, Ko, Jung, Lee (2007): EWSB and CDM from h-QCD, arXiv:0709.1218 [hep-ph], PLB (2011)
- Hur, Ko (2007) : scale inv. extension of SM+hQCD. All the mass scales (including DM mass) from hQCD, written in 2007, arXiv:1103.2571 [hep-ph] PRL(2011)
- Proceedings: Int.J.Mod.Phys. A23 (2008) 3348-3351, AIP Conf.Proc. 1178 (2009) 37-43, arXiv:1012.0103 (ICHEP), etc
- Many works on scale sym. models or dark QCD models during the past years (apology for not citing all of them)
- Hochberg et al. : SIMP in Dark QCD (2014, 2015)
- Hatanaka, Jung, Ko : AdS/QCD approach, arXiv:1606.02969, JHEP (2016)

Hidden Sector

- Any NP @ TeV scale is strongly constrained by EWPT and CKMology
- Hidden sector made of SM singlets, and less constrained, and could make CDM
- Hidden gauge sym can stabilize CDM
- Generic in many BSM's including SUSY models
- Can address “QM generation of all the mass scales from strong dynamics in the hidden sector” (orthogonal to the Coleman-Weinberg) : Hur and Ko, PRL (2011) and earlier paper and proceedings

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,
ignoring dim-5 operators; proton is stable
or very long lived)

$$\frac{1}{M_{\text{Planck}}} H^\dagger H \bar{q}_h \gamma_5 q_h$$

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 \gg 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

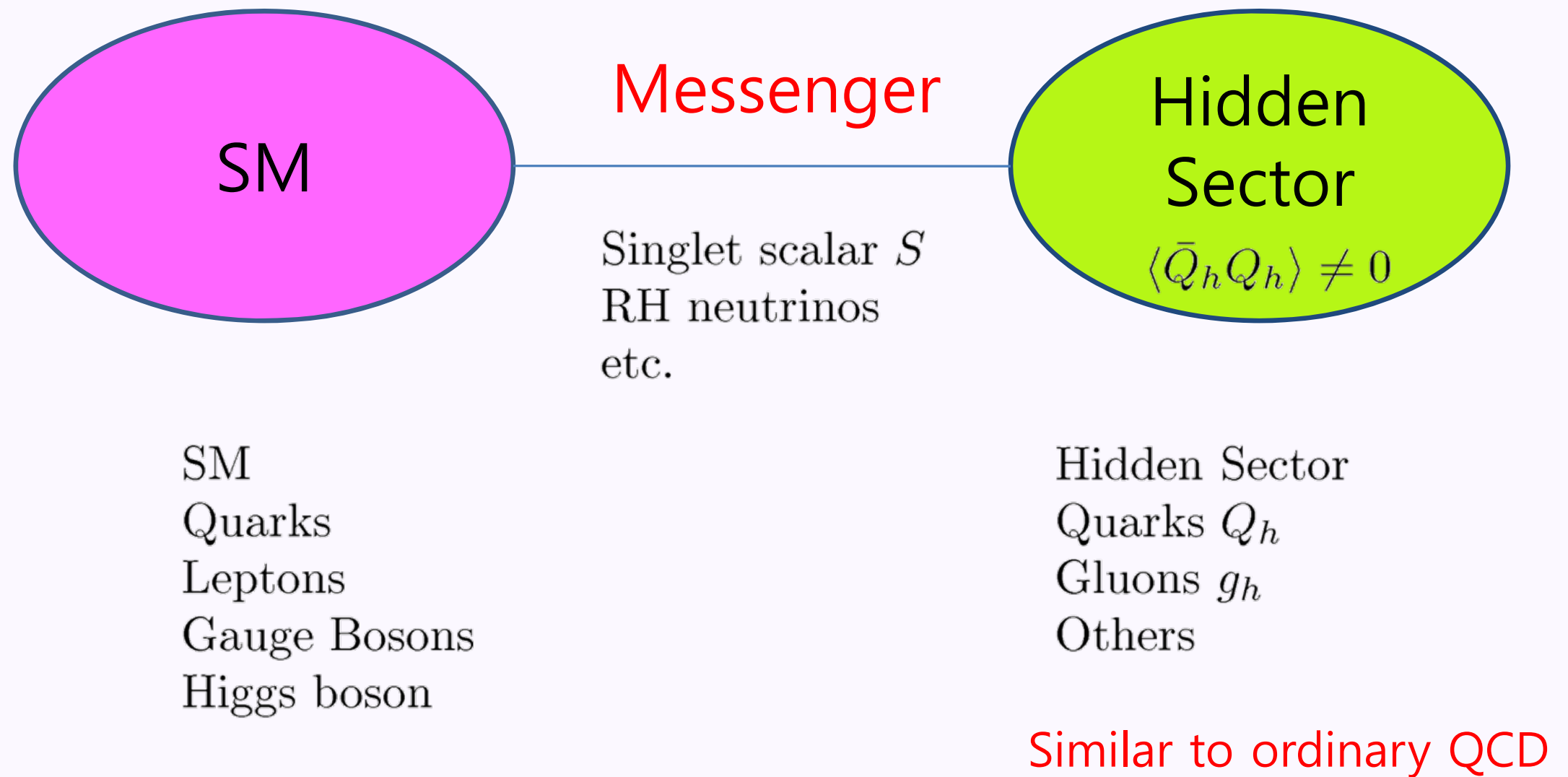
WIMP scenario with the Higgs-Singlet portal

- Hur, Jung, Ko, Lee, arXiv:0709.1218
- Hur, Ko, 1103.2571, PRL (2011)
- Hatanaka, Jung, Ko, 1606.02969, JHEP (2016)

And proceedings:

- Int. J. Mod. Phys. A23 (2008) 3348-3351
- AIP Conf. Proc. 1178 (2009) 37-43
- ICHEP 2010 Proceeding, hep-ph/1012.0103

Basic Picture



Key Observation

- If we switch off gauge interactions of the SM, then we find
- Higgs sector \sim 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

$$V(H_1, H_2) = -\mu_1^2(H_1^\dagger H_1) + \frac{\lambda_1}{2}(H_1^\dagger H_1)^2 - \mu_2^2(H_2^\dagger H_2) + \frac{\lambda_2}{2}(H_2^\dagger H_2)^2 + \lambda_3(H_1^\dagger H_1)(H_2^\dagger H_2) + \frac{av_2^3}{2}\sigma_h$$

● Stability : $\lambda_{1,2} > 0$ and $\lambda_1 + \lambda_2 + 2\lambda_3 > 0$

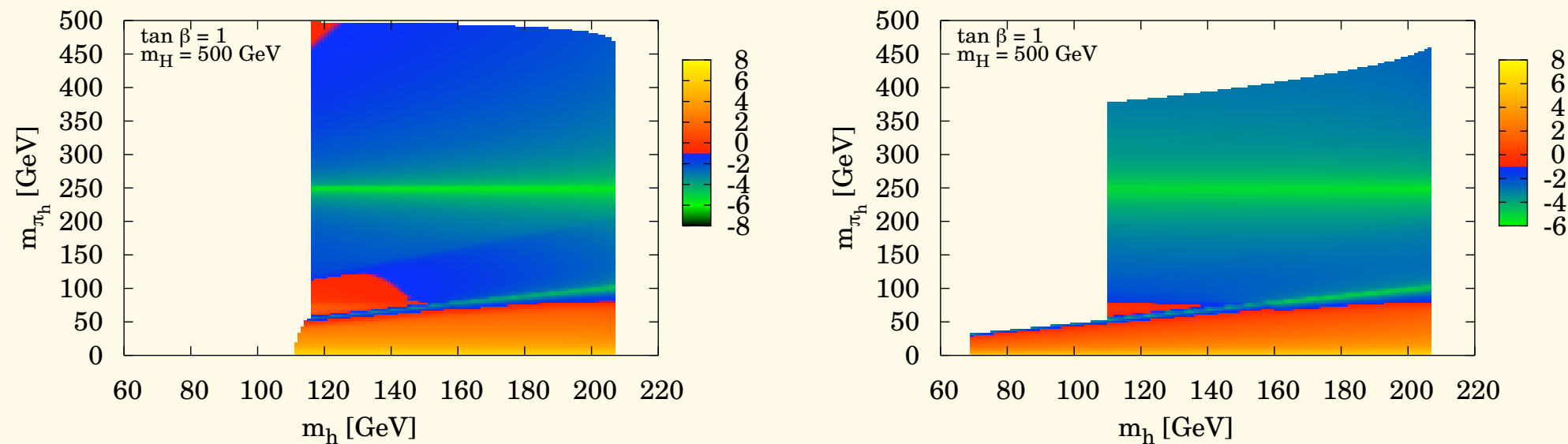
● Consider the following phase:

Not present in the two-Higgs Doublet model

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

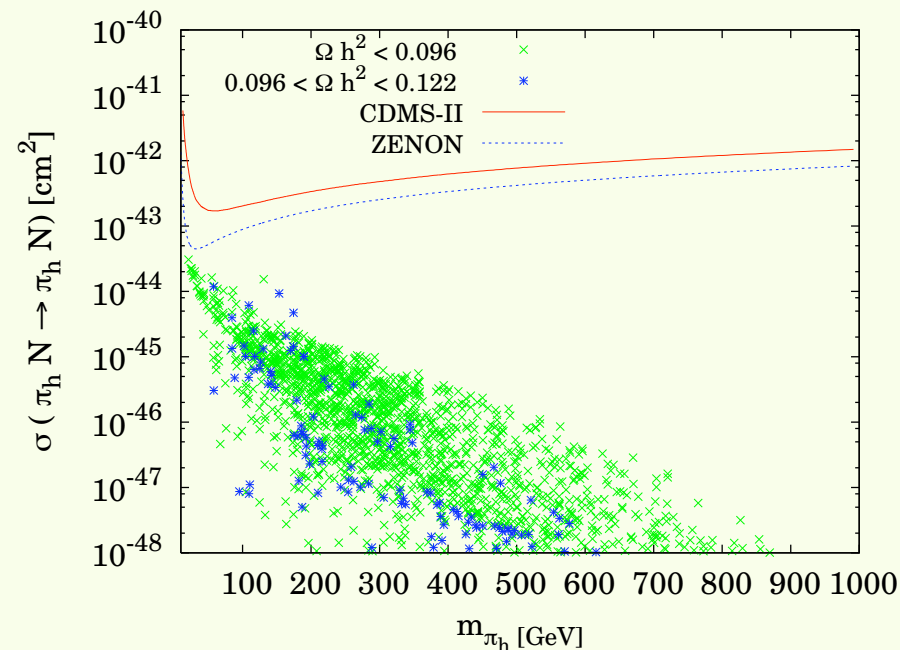
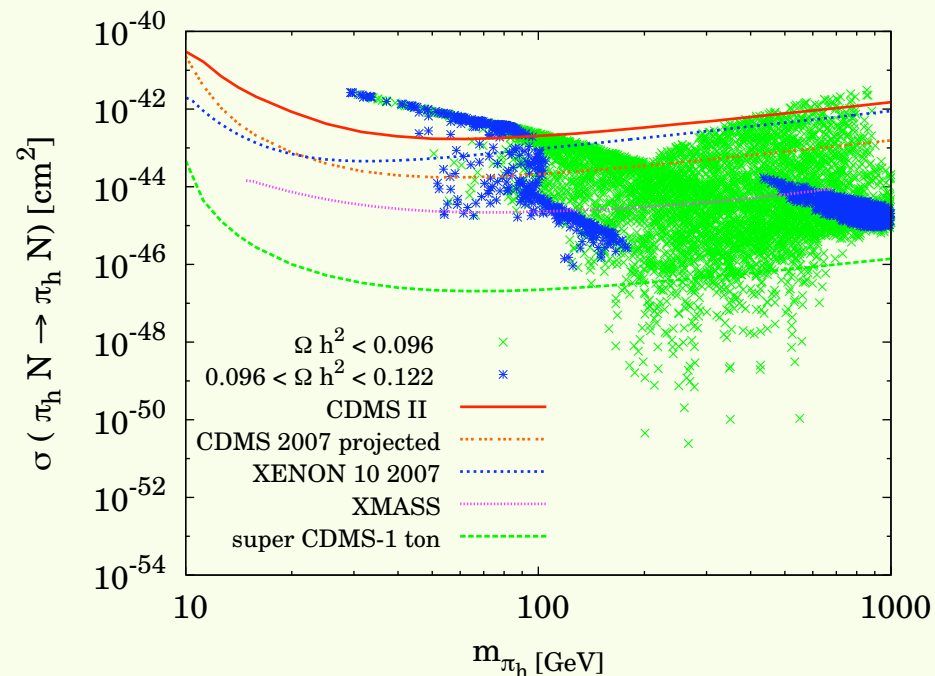
● Correct EWSB : $\lambda_1(\lambda_2 + a/2) \equiv \lambda_1\lambda'_2 > \lambda_3^2$

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



- $\sigma_{SI}(\pi_h p \rightarrow \pi_h p)$ 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 also 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

Classical Scale Sym Model

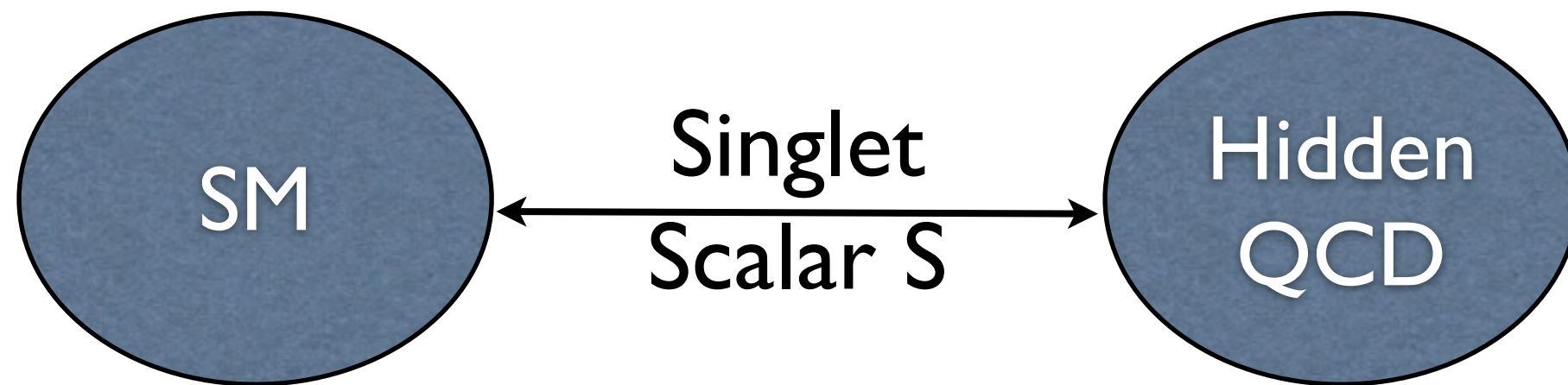
- Scale invariant extension of the SM + hQCD
- Mass scale is generated by nonperturbative strong dynamics in the hidden sector
- EWSB and CDM from hQCD sector

All the masses (including CDM mass)
from hidden sector strong dynamics

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

Model I (Scalar Messenger)



- 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

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

Model considered by Meissner and Nicolai, hep-th/0612165

Hidden sector lagrangian with new strong interaction

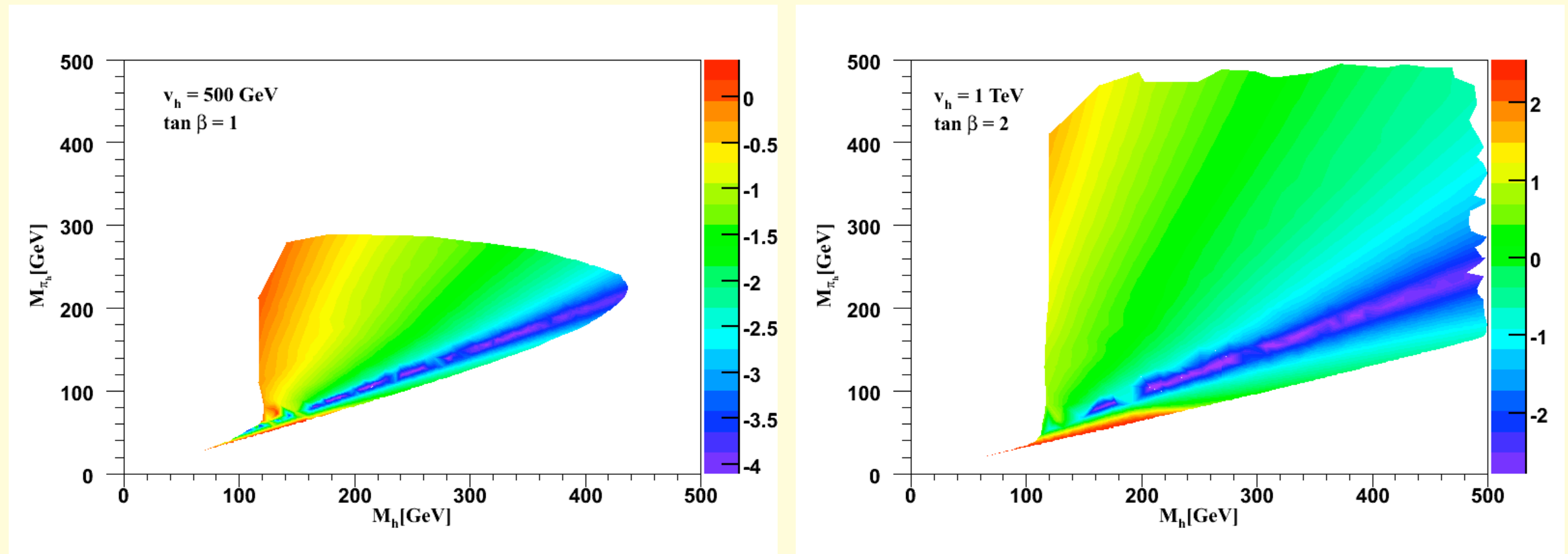
$$\mathcal{L}_{\text{hidden}} = -\frac{1}{4} \mathcal{G}_{\mu\nu} \mathcal{G}^{\mu\nu} + \sum_{k=1}^{N_{HF}} \bar{\mathcal{Q}}_k (i \mathcal{D} \cdot \gamma - \lambda_k S) \mathcal{Q}_k$$

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

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

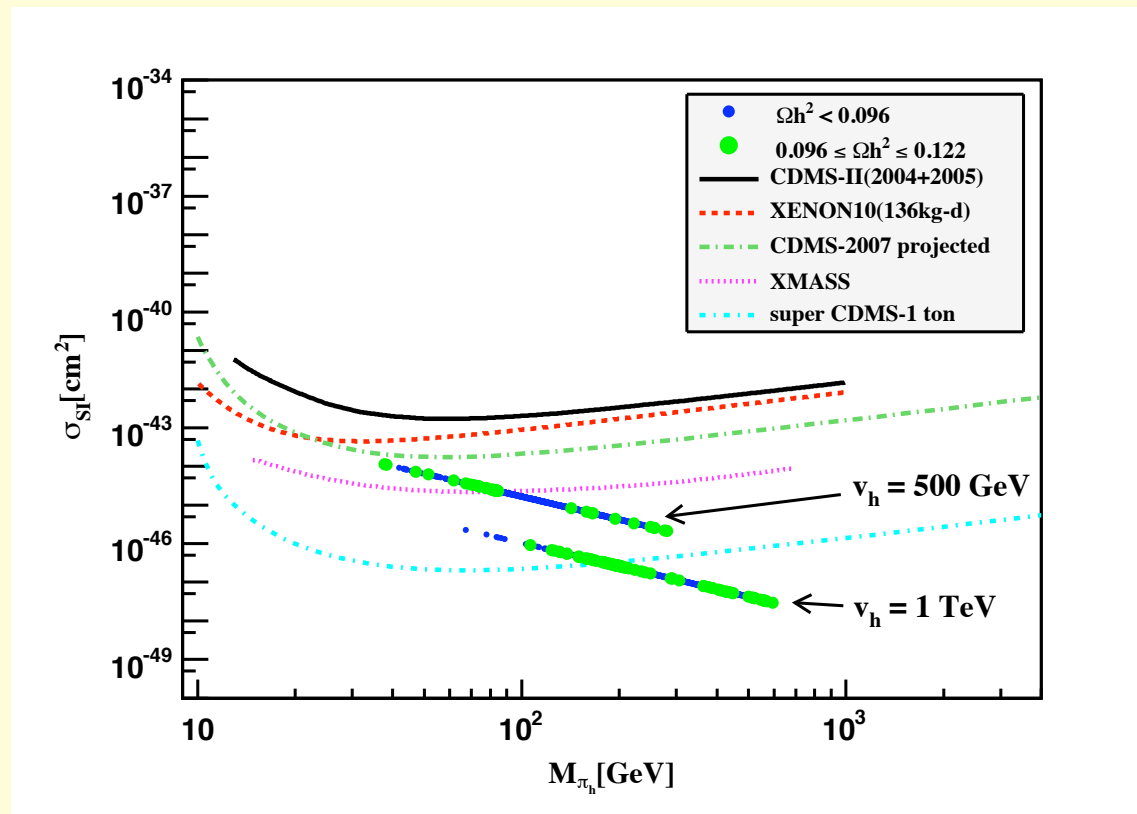
$$\begin{aligned}
 \mathcal{L}_{\text{full}} &= \mathcal{L}_{\text{hidden}}^{\text{eff}} + \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{mixing}} \\
 \mathcal{L}_{\text{hidden}}^{\text{eff}} &= \frac{v_h^2}{4} \text{Tr}[\partial_\mu \Sigma_h \partial^\mu \Sigma_h^\dagger] + \frac{v_h^2}{2} \text{Tr}[\lambda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

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



$\sigma_{SI}(\pi_h p \rightarrow \pi_h p)$ 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 $\tan \beta = 2$.

Comparison with the previous models

- Dark gauge symmetry is unbroken (DM could be absolutely stable if they appeared in the asymptotic states), but confining like QCD (No long range dark force, DM becomes composite)
- 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

- Additional singlet scalar improves the vacuum stability up to Planck scale
- Can modify Higgs inflation scenario (Higgs-portal assisted Higgs inflation [arXiv:1405.1635, JCAP (2017) with Jinsu Kim, WIPark])
- The 2nd scalar could be very very elusive
- Can we find the 2nd scalar at LHC ?
- We will see if this class of DM can survive the LHC Higgs data in the coming years

SIMP scenario + dark resonances

**arXiv:1801.07726, PRD (2018)
Soo-Min Choi, Hyunmin Lee (CAU)
and Alexander Natale (KIAS)**

SIMP Scenario in Dark QCD

SIMP paradigm

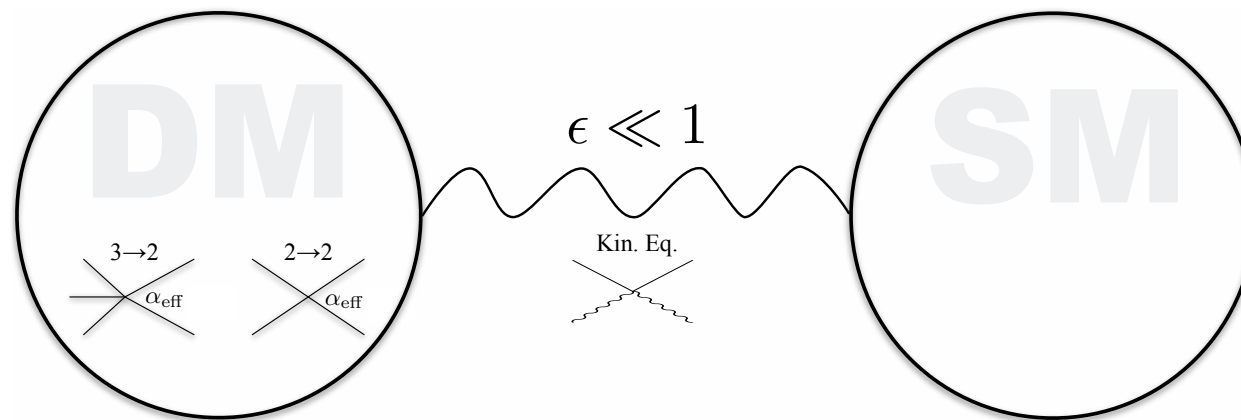


FIG. 1: A schematic description of the SIMP paradigm. The dark sector consists of DM which annihilates via a $3 \rightarrow 2$ process. Small couplings to the visible sector allow for thermalization of the two sectors, thereby allowing heat to flow from the dark sector to the visible one. DM self interactions are naturally predicted to explain small scale structure anomalies while the couplings to the visible sector predict measurable consequences.

**Hochberg, Kuflik, Tolansky, Wacker, arXiv:1402.5143
Phys. Rev. Lett. 113, 171301 (2014)**

SIMP Conditions

Freeze-out :

$$\Gamma_{3 \rightarrow 2} = n_{DM}^2 \langle \sigma v^2 \rangle_{3 \rightarrow 2} \sim H(T_F)$$
$$\langle \sigma v^2 \rangle_{3 \rightarrow 2} = \frac{\alpha_{\text{eff}}^3}{m_{DM}^5}$$

$$\alpha_{\text{eff}} = 1 - 30 \rightarrow m_{DM} \sim 10\text{MeV} - 1\text{GeV}$$

2->2 Self scattering :

$$\frac{\sigma_{\text{scatter}}}{m_{DM}} = \frac{a^2 \alpha_{\text{eff}}^2}{m_{DM}^3}$$

with $a \sim O(1)$

$$\frac{\sigma_{\text{scatter}}}{m_{DM}} \lesssim 1 \text{ cm}^2/\text{g}$$

Dark QCD + WZW

- Dark flavor symmetry $G = \text{SU}(N_f)_L \times \text{SU}(N_f)_R$ is SSB into diagonal $H = \text{SU}(N_f)_V$ by dark QCD condensation
- Effective Lagrangian for NG bosons (dark pions) contain 5-point self interaction : WZW term for π^5 ($G/H = Z$ ($N_f > 2$))

$$\Gamma_{\text{WZ}} = C \int_{M^5} d^5x \text{Tr}(\alpha^5) \quad \text{with} \quad \alpha = dUU^\dagger.$$

$$U = e^{2i\pi/F}$$

$$C = -i \frac{N_c}{240\pi^2}$$

in the absence of external gauge fields

SIMP Dark Mesons

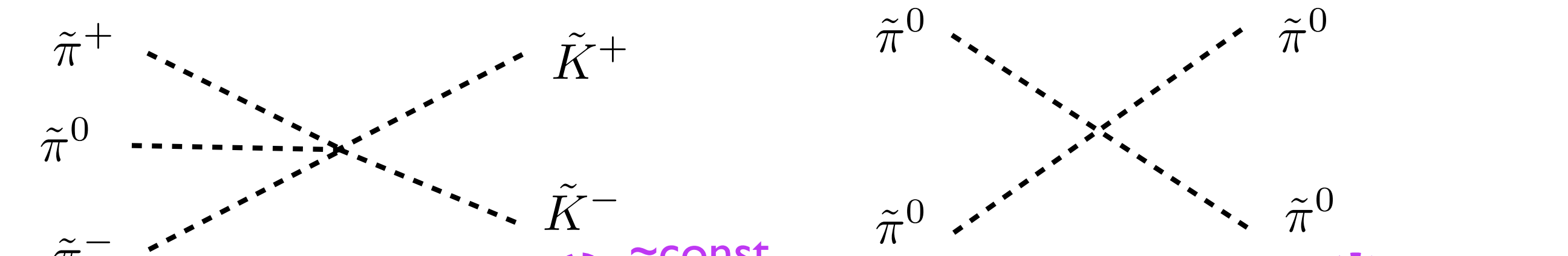


Diagram 1 (Left): 3-to-2 interaction. Incoming particles: $\tilde{\pi}^+$, $\tilde{\pi}^0$, $\tilde{\pi}^-$. Outgoing particles: \tilde{K}^+ , \tilde{K}^- . Dashed lines represent the interaction.

Diagram 2 (Right): Self-interaction. Incoming particles: $\tilde{\pi}^0$, $\tilde{\pi}^0$. Outgoing particles: $\tilde{\pi}^0$, $\tilde{\pi}^0$. Dashed lines represent the interaction.

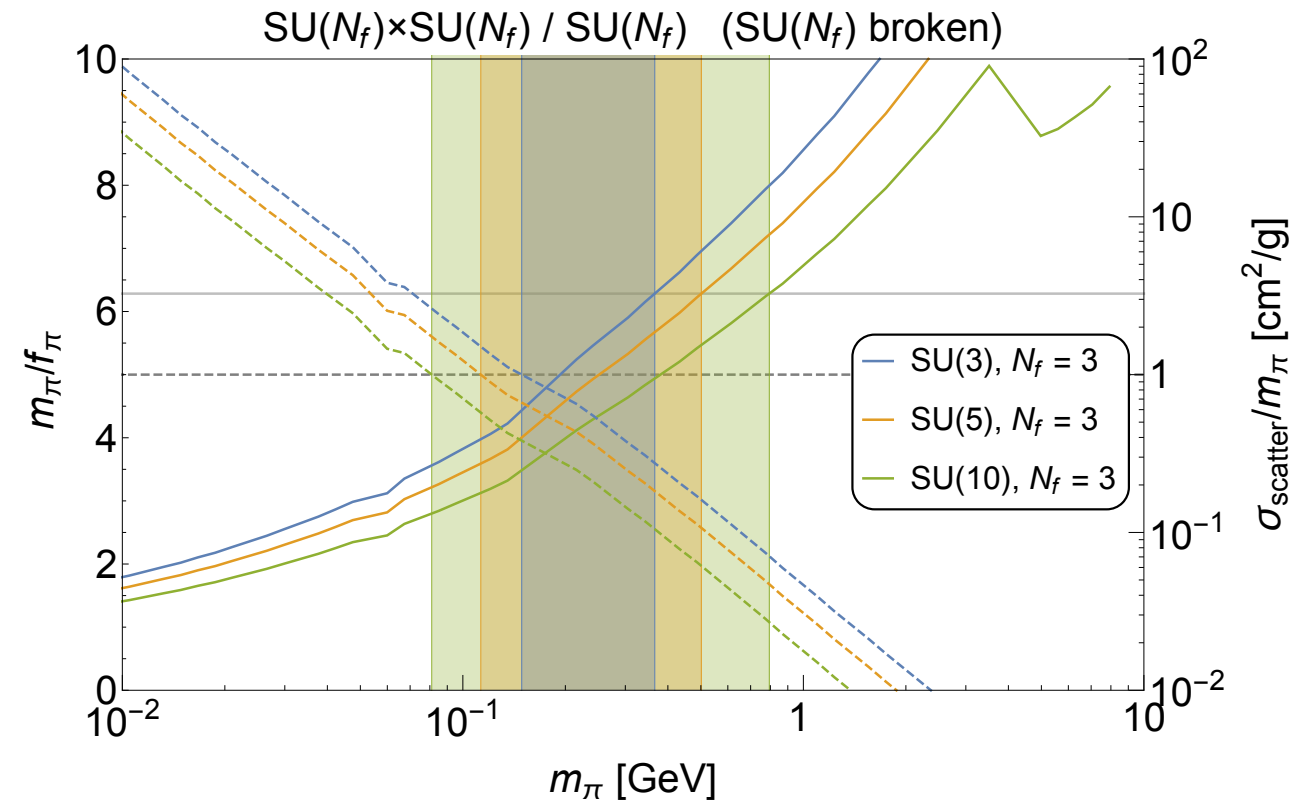
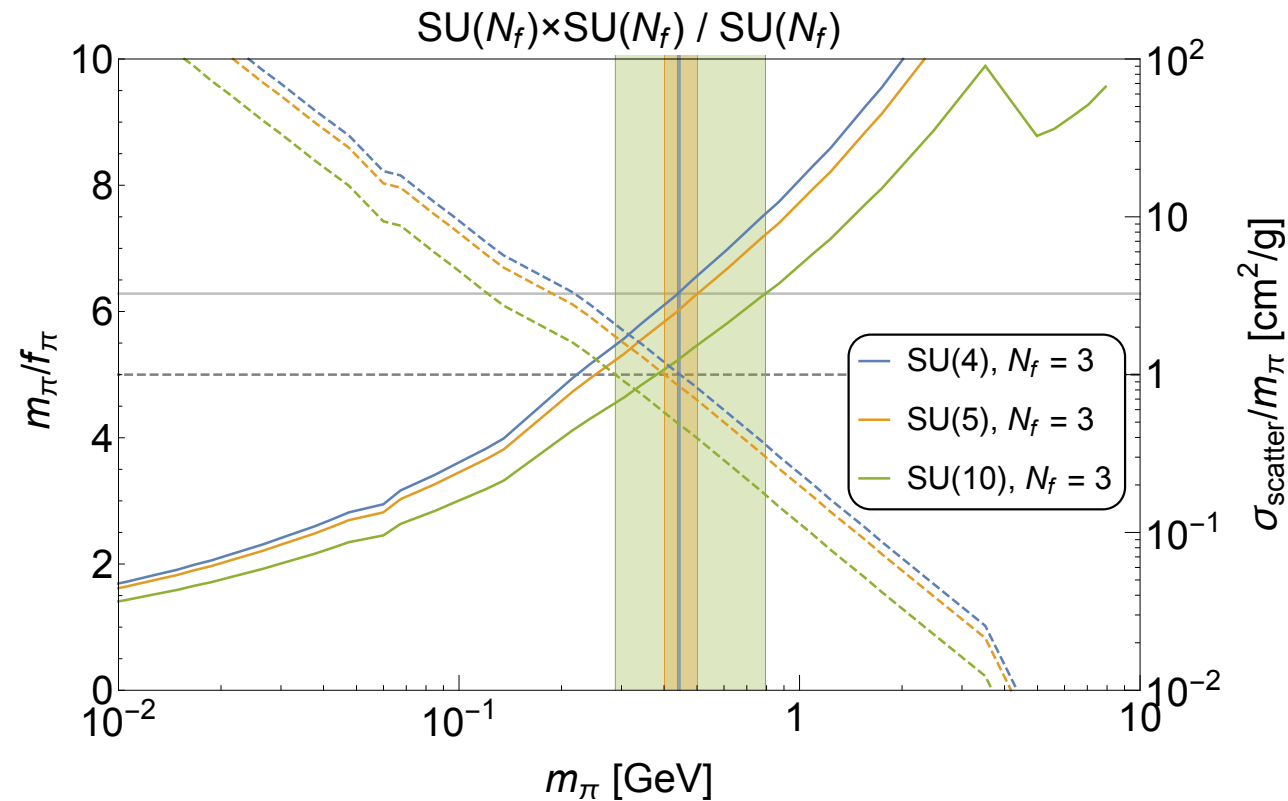
$$\langle \sigma v^2 \rangle_{3 \rightarrow 2} = \frac{5\sqrt{5}N_c^2 m_\pi^5}{2\pi^5 F^{10}} \frac{t^2}{N_\pi^3} \left(\frac{T_F}{m_\pi} \right)^2, \quad \sigma_{\text{self}} = \frac{m_\pi^2}{32\pi F^4} \frac{a^2}{N_\pi^2}$$

Annotations: $\sim \text{const}$ is written in purple next to the t^2 term in the first equation and the a^2 term in the second equation. The terms N_c^2 and N_π^3 in the first equation, and N_π^2 in the second equation, are circled in blue and purple dashed lines respectively.

G_c	G_f/H	N_π	t^2	$N_f^2 a^2$
$\text{SU}(N_c)$	$\frac{\text{SU}(N_f) \times \text{SU}(N_f)}{\text{SU}(N_f)}$ ($N_f \geq 3$)	$N_f^2 - 1$	$\frac{4}{3}N_f(N_f^2 - 1)(N_f^2 - 4)$	$8(N_f - 1)(N_f + 1)(3N_f^4 - 2N_f^2 + 6)$
$\text{SO}(N_c)$	$\text{SU}(N_f)/\text{SO}(N_f)$ ($N_f \geq 3$)	$\frac{1}{2}(N_f + 2)(N_f - 1)$	$\frac{1}{12}N_f(N_f^2 - 1)(N_f^2 - 4)$	$(N_f - 1)(N_f + 2)(3N_f^4 + 7N_f^3 - 2N_f^2 - 12N_f + 24)$
$\text{Sp}(N_c)$	$\text{SU}(2N_f)/\text{Sp}(2N_f)$ ($N_f \geq 2$)	$(2N_f + 1)(N_f - 1)$	$\frac{2}{3}N_f(N_f^2 - 1)(4N_f^2 - 1)$	$4(N_f - 1)(2N_f + 1)(6N_f^4 - 7N_f^3 - N_f^2 + 3N_f + 3)$

[Hochberg, Kuflik, Murayama, Volansky, Wacker, 1411.3727, PRL (2015)]

SIMP Parameter Space




Hochberg, Kuflik, Murayama, Volansky, Wacker, 1411.3727, PRL

- DM self scattering : $\sigma_{\text{self}}/m_{\text{DM}} < 1 \text{ cm}^2/\text{g}$ **Large $N_c > 3$**

- Validity of ChPT : $m_\pi/f_\pi < 2\pi$

More serious in NNLO ChPT
Sannino et al, 1507.01590

Issues in the SIMP w/ hQCD

- Dark flavor sym is not good enough to stabilize dark pion (We have to assume dim-5 operator is highly suppressed)
- Dark baryons can make additional contribution to DM of the universe (It could produce additional diagrams for SIMP)
- Validity region of ChPT : need to include resonances (dark rho meson, dark sigma meson, etc.  this talk)
- How to achieve Kinetic equilibrium with the SM ? (Dark sigma meson or adding singlet scalar S may help. Or lifting the mass degeneracy of dark pions can help. Work in progress.)

Digression on ChPT + VM

- We consider G_{global} SSB into H_{global} : non Linear sigma model on $G_{\text{global}}/H_{\text{global}}$ is equivalent to linear sigma model on $G_{\text{global}} \times H_{\text{local}}$
- Vector meson \sim gauge field for H_{local}
 - **CCWZ (1969)**
 - **Bando, Kugo, Yamawaki, Phys. Rept. 164, 217 (1988)**

The Lagrangian \mathcal{L}_A can be cast into the following form in terms of a new exponential field $U(x)$ defined as $\Sigma(x) \equiv \xi_L^\dagger(x)\xi_R(x) = \exp[2i\pi(x)/f_\pi]$ with $\xi_L^\dagger(x) = \xi_R(x) = \exp[i\pi(x)/f_\pi]$:

$$\Sigma(x) \rightarrow L\Sigma(x)R^\dagger$$

Note that the π field is normalized in such a way that

$$\pi(x) = \frac{1}{\sqrt{2}} \begin{pmatrix} \frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta_8 + \frac{1}{\sqrt{3}}\eta_0 & \pi^+ K^+ & \\ \pi^- & -\frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta_8 + \frac{1}{\sqrt{3}}\eta_0 & K^0 \\ K^- & \frac{K^0}{\sqrt{6}} & -\frac{2}{\sqrt{6}}\eta_8 + \frac{1}{\sqrt{3}}\eta_0 \end{pmatrix} \quad (6)$$

Vector meson as hidden local gauge boson

$$\begin{aligned}
 \xi_L(x) &\rightarrow U(x)\xi_L(x)L^\dagger \\
 \xi_R(x) &\rightarrow U(x)\xi_R(x)R^\dagger \\
 gV_\mu(x) &\rightarrow U(x) [\partial_\mu - igV_\mu(x)] U^\dagger(x) \\
 D_\mu \xi_L &= (\partial_\mu - igV_\mu)\xi_L(x) + i\xi_L(x)l_\mu \\
 D_\mu \xi_R &= (\partial_\mu - igV_\mu)\xi_R(x) + i\xi_R(x)l_\mu
 \end{aligned}$$

$$V_\mu = \frac{1}{\sqrt{2}} \begin{pmatrix} \frac{1}{\sqrt{2}}\rho_\mu^0 + \frac{1}{\sqrt{6}}\omega_{8\mu} + \frac{1}{\sqrt{3}}\omega_{0\mu} & \rho_\mu^+ K_\mu^{*+} & K_\mu^{*0} \\ \rho_\mu^- & -\frac{1}{\sqrt{2}}\rho_\mu^0 + \frac{1}{\sqrt{6}}\omega_{8\mu} + \frac{1}{\sqrt{3}}\omega_{0\mu} & -\frac{2}{\sqrt{6}}\omega_{8\mu} + \frac{1}{\sqrt{3}}\omega_{0\mu} \\ K_\mu^{*-} & \frac{K_\mu^{*0}}{K_\mu^{*0}} & \end{pmatrix} \quad (7)$$

Ch Lagrangian (pi,V)

The chiral Lagrangian for pions and vector mesons is given by

$$\begin{aligned}
 \mathcal{L} &= \mathcal{L}_A + \mathcal{L}_m + \mathcal{L}_B + \mathcal{L}_{\text{kin}}(V) + \Gamma^{\text{anom}}(\xi_L, \xi_R, V, l, r) \\
 \mathcal{L}_A &= -\frac{f_\pi^2}{4} \text{Tr} \left[(D_\mu \xi_L) \xi_L^\dagger - (D_\mu \xi_R) \xi_R^\dagger \right]^2 \\
 \mathcal{L}_m &= -\frac{f_\pi^2}{2} \text{Tr} \left[\mu (\Sigma + \Sigma^\dagger) \right] \\
 \mathcal{L}_B &= -a \frac{f_\pi^2}{4} \text{Tr} \left[(D_\mu \xi_L) \xi_L^\dagger + (D_\mu \xi_R) \xi_R^\dagger \right]^2 \\
 \mathcal{L}_{\text{kin}} &= -\frac{1}{2} \text{Tr} [F_{\mu\nu} F^{\mu\nu}] \\
 F_{\mu\nu} &= \partial_\mu V_\nu - \partial_\nu V_\mu - ig[V_\mu, V_\nu]
 \end{aligned}$$

$ \begin{aligned} \mathcal{L}_B &= m_V^2 \text{Tr} V_\mu V^\mu - 2ig_{V\pi\pi} \text{Tr} (V_\mu [\partial^\mu \pi, \pi]) + \dots \\ m_V^2 &= ag^2 f_\pi^2 \\ g_{V\pi\pi} &= \frac{1}{2} ag \end{aligned} $
--

**a~2 and g~6
in real QCD.
In Dark QCD,
we consider
they are free**

Another useful quantities

$$\begin{aligned}\xi(x) &\rightarrow L\xi(x)U^\dagger(x) = U(x)\xi(x)R^\dagger \\ \mathcal{A}_\mu(x) &\equiv \frac{i}{2} \left[\xi^\dagger \partial_\mu \xi - \xi \partial_\mu \xi^\dagger \right] \\ &\rightarrow U(x) \mathcal{A}_\mu(x) U^\dagger(x) \\ \mathcal{V}_\mu(x) &\equiv \frac{i}{2} \left[\xi^\dagger \partial_\mu \xi + \xi \partial_\mu \xi^\dagger \right] \\ &\rightarrow U(x) \mathcal{V}_\mu(x) U^\dagger(x) + U(x) \partial_\mu U^\dagger(x) \\ V_\mu(x) &\rightarrow U(x) V_\mu(x) U^\dagger(x) + U(x) \partial_\mu U^\dagger(x)\end{aligned}$$

**Here 'V' is the vector meson associated with
hidden local gauge symmetry**

WZW (gauged)

$$\begin{aligned}\Gamma_{LR}(U, l_\mu, r_\mu) = & C \int_{M^5} d^5x \operatorname{Tr}(\alpha^5) \\ & + 5C \int_{M^4} d^4x \operatorname{Tr} \{ i(l\alpha^3 + r\beta^3) - [(dl\,l + l\,dl)\alpha + (dr\,r + r\,dr)\beta] + (dl\,dU\,rU^{-1} - dr\,dU^{-1}\,lU) \\ & + (rU^{-1}\,lU\beta^2 - lU\,rU^{-1}\alpha^2) + \tfrac{1}{2}[(l\alpha)^2 - (r\beta)^2] + i[l^3\alpha + r^3\beta] \\ & + i[(dr\,r + r\,dr)U^{-1}\,lU - (dl\,l + l\,dl)U\,rU^{-1}] + i[lU\,rU^{-1}\,l\alpha + rU^{-1}\,lU\,r\beta] . \\ & + [r^3U^{-1}\,lU - l^3U\,rU^{-1} + \tfrac{1}{2}(U\,rU^{-1}\,l)^2] \} ,\end{aligned}$$

WZW with vector mesons

$$\begin{aligned}
 \hat{\alpha}_L &= D\xi_L \cdot \xi_L^\dagger = \alpha_L - igV + i\hat{l} \\
 \hat{\alpha}_R &= D\xi_R \cdot \xi_R^\dagger = \alpha_L - igV + i\hat{r} \\
 \alpha_L &= d\xi_L \cdot \xi_L^\dagger, \\
 \alpha_R &= d\xi_R \cdot \xi_R^\dagger \\
 \hat{l} &= \xi_L \cdot \xi_L^\dagger, \\
 \hat{r} &= \xi_R \cdot \xi_R^\dagger \\
 F_V &= dV - igV^2 \\
 \hat{F}_L &= \xi_L \cdot F_L \cdot \xi_L^\dagger = \xi_L(dl - il^2)\xi_L^\dagger \\
 \hat{F}_R &= \xi_R \cdot F_R \cdot \xi_R^\dagger = \xi_R(dr - ir^2)\xi_R^\dagger
 \end{aligned}$$

$$\Gamma^{\text{anom}} = \Gamma_{\text{WZW}} + \sum_{i=1}^4 c_i \mathcal{L}_i$$

$$\begin{aligned}
 \mathcal{L}_1 &= \text{TR} [\hat{\alpha}_L^3 \hat{\alpha}_R - \hat{\alpha}_R^3 \hat{\alpha}_L] - (\xi_L = \xi_R = 1, V = 0, l, r) \\
 \mathcal{L}_2 &= \text{TR} [\hat{\alpha}_L \hat{\alpha}_R \hat{\alpha}_L \hat{\alpha}_R] - (\xi_L = \xi_R = 1, V = 0, l, r) \\
 \mathcal{L}_3 &= i\text{Tr} [F_V (\hat{\alpha}_L \hat{\alpha}_R - \hat{\alpha}_R \hat{\alpha}_L)] - (\xi_L = \xi_R = 1, V = 0, l, r) \\
 \mathcal{L}_4 &= i\text{Tr} [\hat{F}_L \hat{\alpha}_L \hat{\alpha}_R - \hat{F}_R \hat{\alpha}_R \hat{\alpha}_L] - (\xi_L = \xi_R = 1, V = 0, l, r)
 \end{aligned}$$

- Fujiwara, Kugo, Yamawaki et al., Prog. Theo. Phys. 73, 926 (1985)
- P.Ko, PRD44, 139 (1991) 139 for a useful compact summary

SIMP + VDM

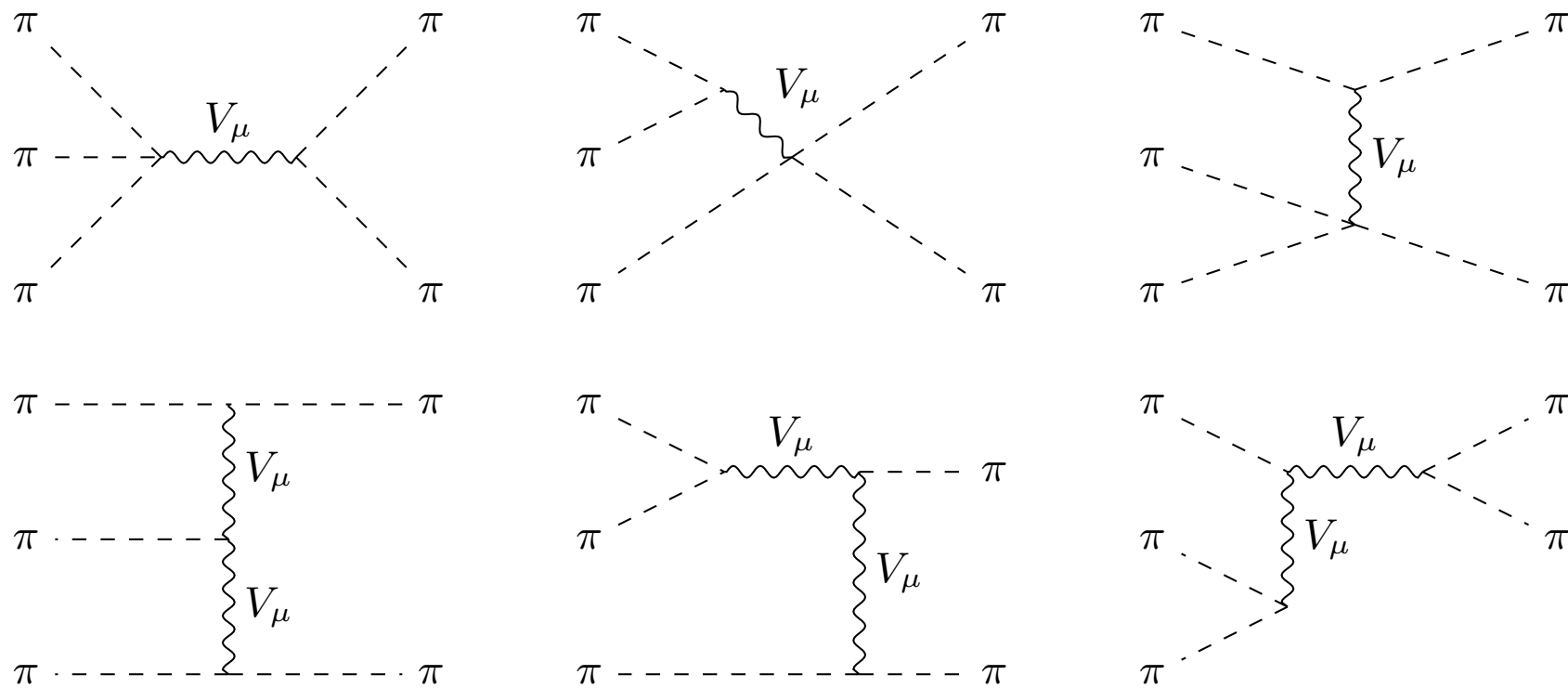


FIG. 1: Feynman diagrams contributing to $3 \rightarrow 2$ processes for the dark pions with the vector meson interactions.

SIMP + VM

New diagrams involveng dark vector mesons

$$\pi^+ \pi^- \pi^0 \rightarrow \omega \rightarrow K^+ K^- (K^0 \bar{K}^0)$$

$$\gamma = \frac{m_V \Gamma}{9m_\pi^2}, \text{ and } \epsilon = \frac{m_V^2 - 9m_\pi^2}{9m_\pi^2} \text{ (for 3 pi resonance case)}$$

**We choose a small epsilon [say, 0.1 (near resonance)]
and a small gamma (NWA)**

Results

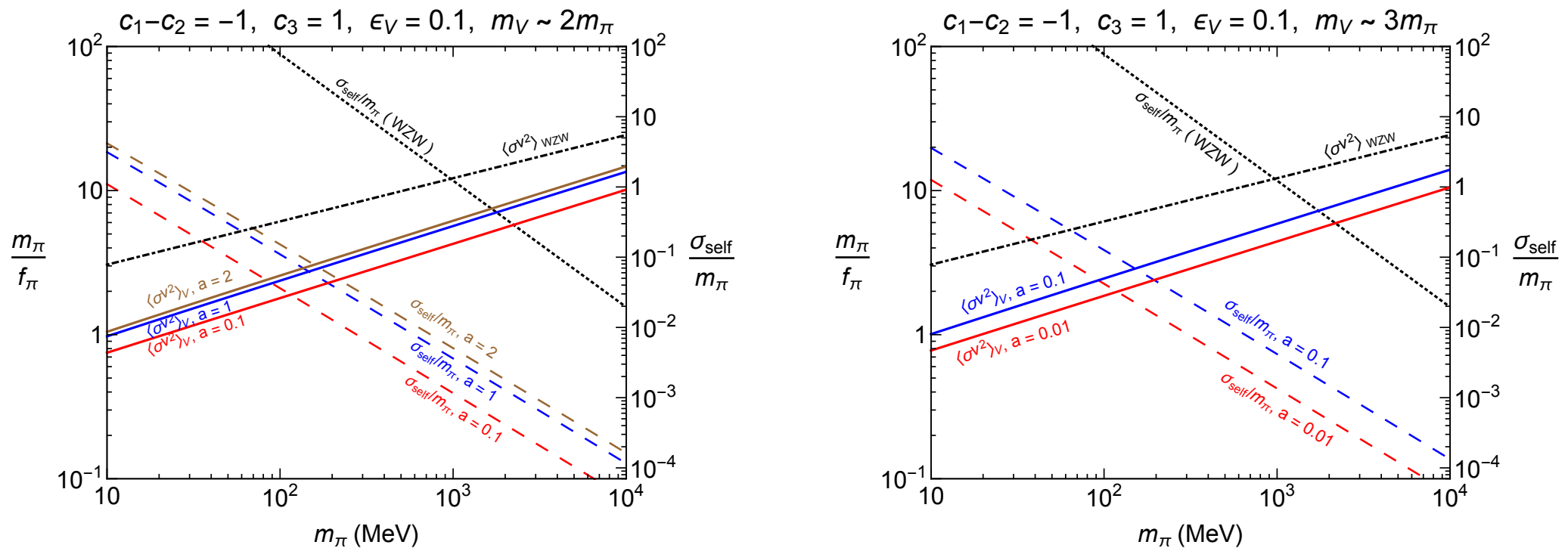


FIG. 2: Contours of relic density ($\Omega h^2 \approx 0.119$) for m_π and m_π/f_π and self-scattering cross section per DM mass in cm^2/g as a function of m_π . The case without and with vector mesons are shown in black lines and colored lines respectively. We have imposed the relic density condition for obtaining the contours of self-scattering cross section. Vector meson masses are taken near the resonances with $m_V = 2(3)m_\pi\sqrt{1 + \epsilon_V}$ on left(right) plots. In both plots, $c_1 - c_2 = -1$ and $\epsilon_V = 0.1$ are taken.

- The allowed parameter space is in a better shape now, especially for 2 pi resonance case

Masses of V and Pi

- In QCD, the origin of vector meson and pion masses are not exactly the same.

$$\begin{array}{lcl} m_V^2 & \sim & \Lambda^2 \\ m_\pi^2 & \sim & m_q \Lambda \end{array}$$

- We can tune the QCD scale and the current quark mass independently, thus varying masses of dark vector mesons and dark pions independently

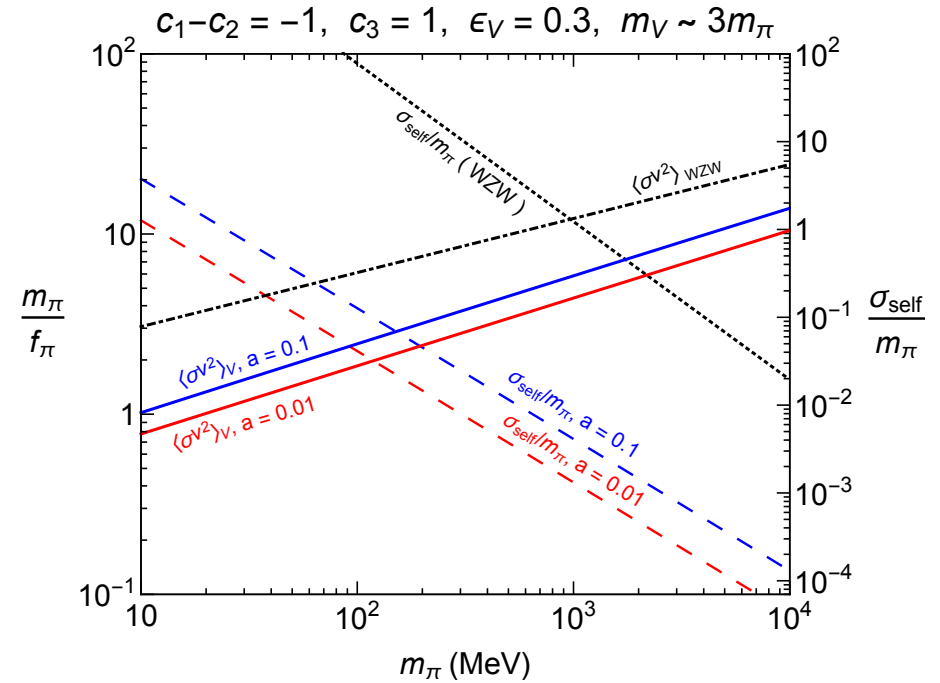
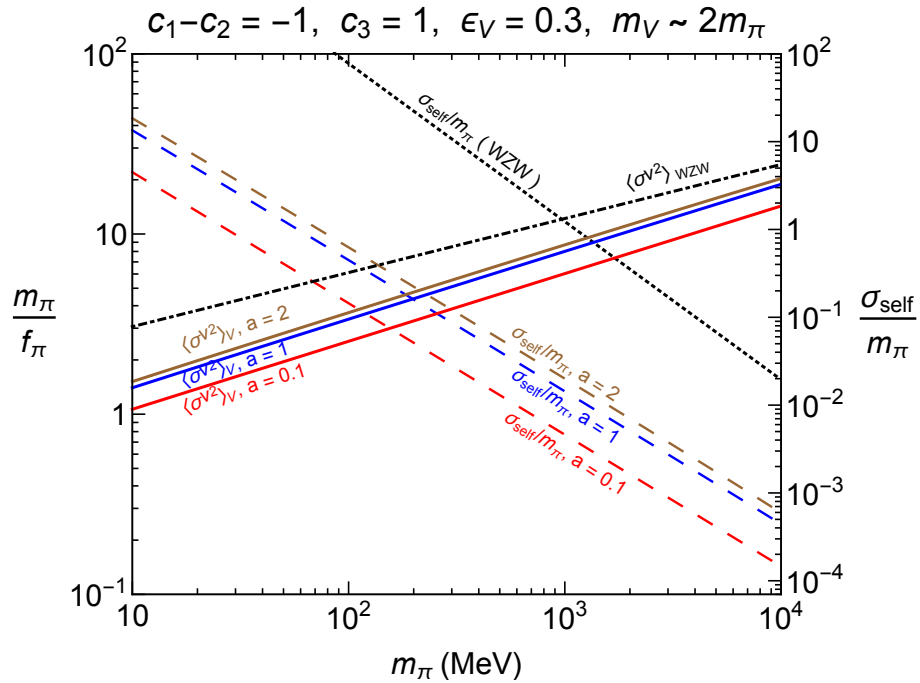


FIG. 3: Similar contours of relic density for m_π and m_π/f_π and self-scattering cross section per DM mass as in Fig. 2. Vector meson masses are taken off the resonance with $\epsilon_V = 0.3$, and $c_1 - c_2 = -1$ and $c_3 = 1$ are chosen.

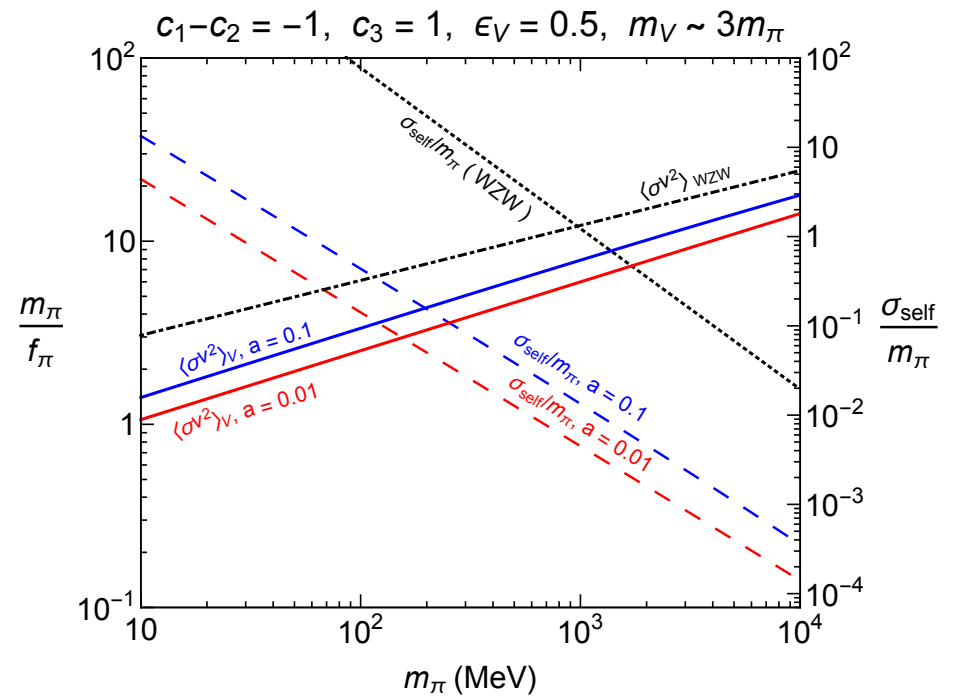
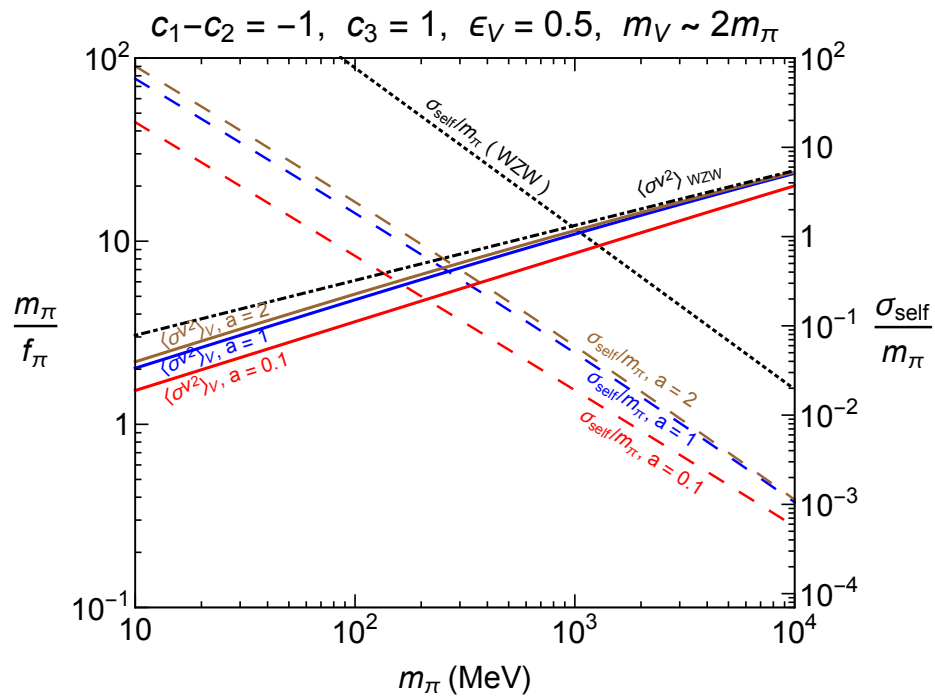


FIG. 4: Similar contours of relic density for m_π and m_π/f_π and self-scattering cross section per DM mass as in Fig. 2. Vector meson masses are taken off the resonance with $\epsilon_V = 0.5$, and $c_1 - c_2 = -1$ and $c_3 = 1$ are chosen.

Conclusion

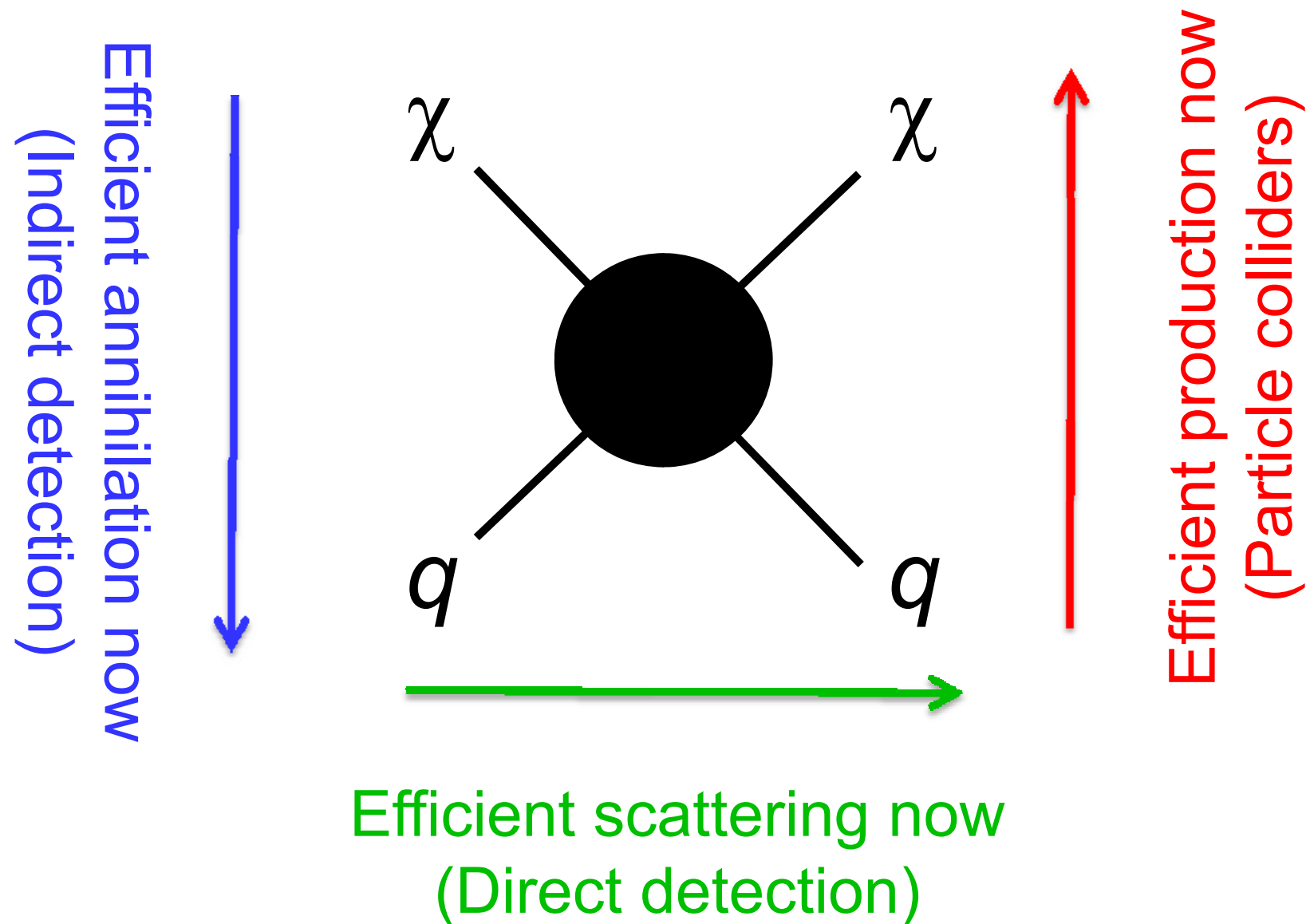
- Hidden (dark) QCD models make an interesting possibility to study the origin of EWSB, (C)DM
- WIMP scenario is still viable, and will be tested to some extent by precise measurements of the Higgs signal strength and by discovery of the singlet scalar, which is however a formidable task unless we are very lucky
- SIMP scenario using $3 \rightarrow 2$ scattering via WZW term is interesting, but there are a few issues which ask for further study (dark resonance could play an important role for thermal relic and kinetic contact with the SM sector)

BACKUP

Digress on importance
of gauge invariance, unitarity
and renormalizability

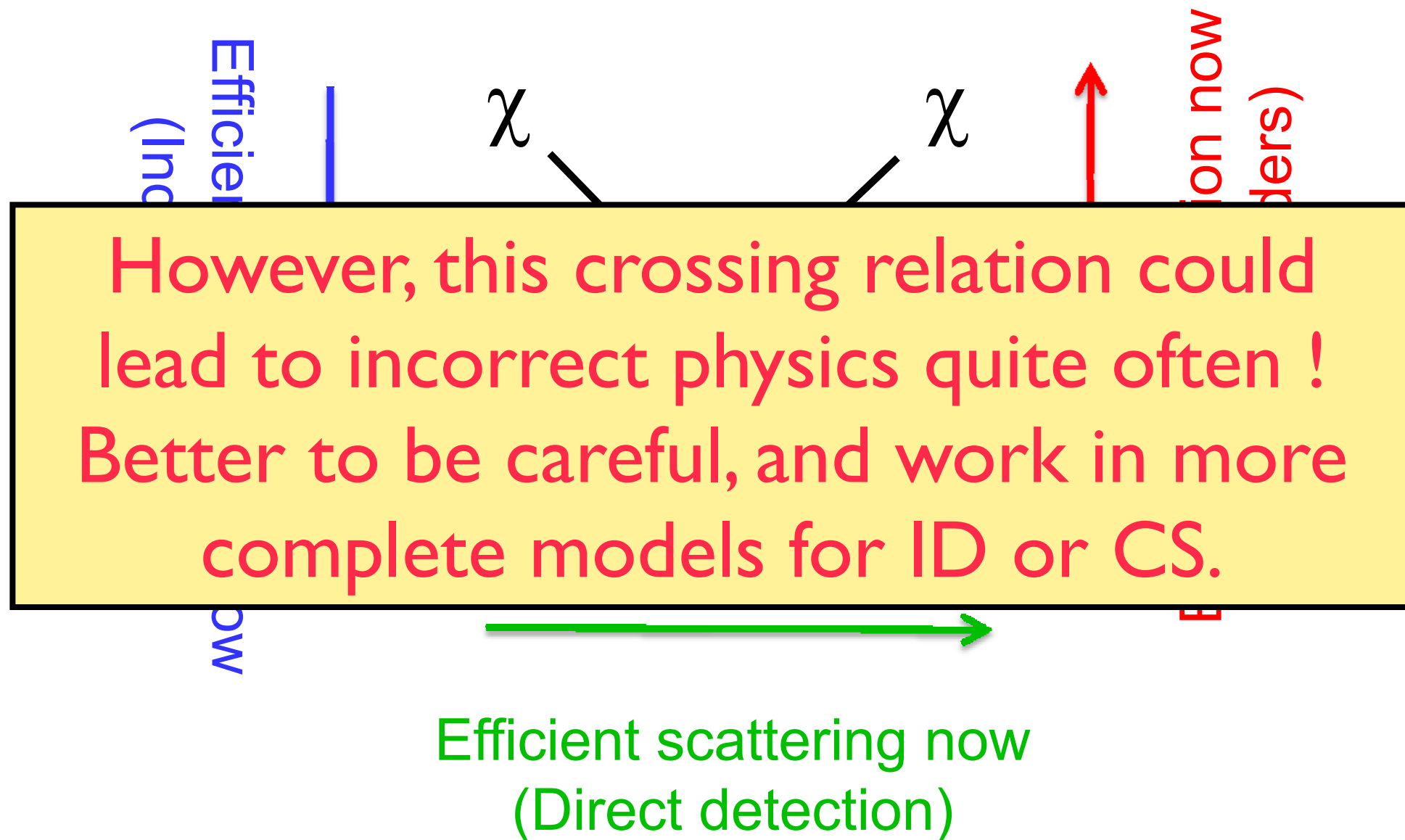
Crossing & WIMP detection

Correct relic density \rightarrow Efficient annihilation then



Crossing & WIMP detection

Correct relic density \rightarrow Efficient annihilation then



Higgs portal DM as examples

All invariant
under ad hoc
Z2 symmetry

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

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

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

arXiv:1112.3299, ... 1402.6287, etc.

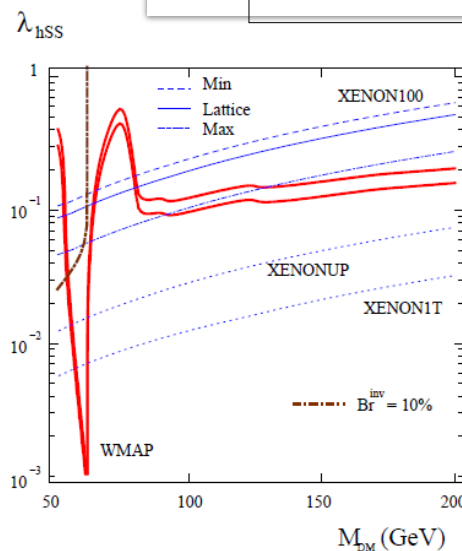


FIG. 1. Scalar Higgs-portal parameter space allowed by WMAP (between the solid red curves), XENON100 and $\text{Br}^{\text{inv}} = 10\%$ for $m_h = 125$ GeV. Shown also are the prospects for XENON upgrades.

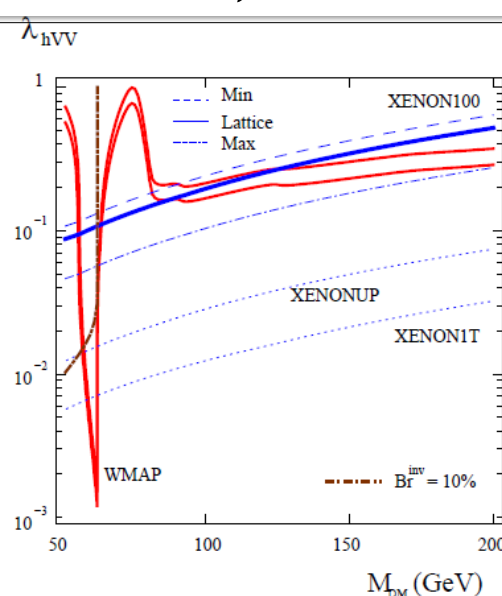


FIG. 2. Same as Fig. 1 for vector DM particles.

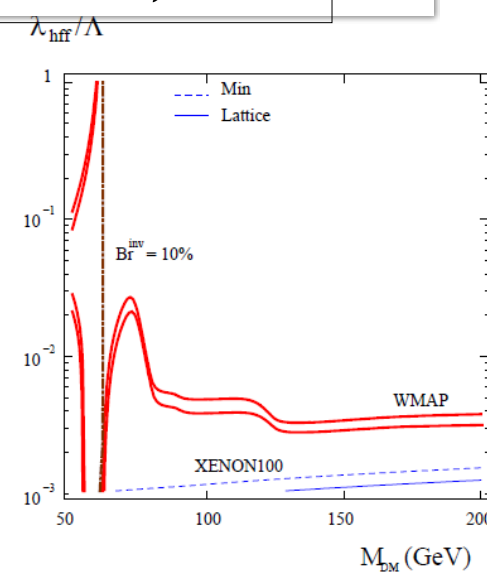


FIG. 3. Same as in Fig.1 for fermion DM; λ_{hff}/Λ is in GeV^{-1} .

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

Usual story within EFT

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

Case of 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:

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

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

$$X_\mu \equiv V_\mu \text{ here}$$

- There appear a new singlet scalar h_X from ϕ_X , which mixes with the SM Higgs boson through Higgs portal
- The effects must be similar to the singlet scalar in the fermion CDM model, 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

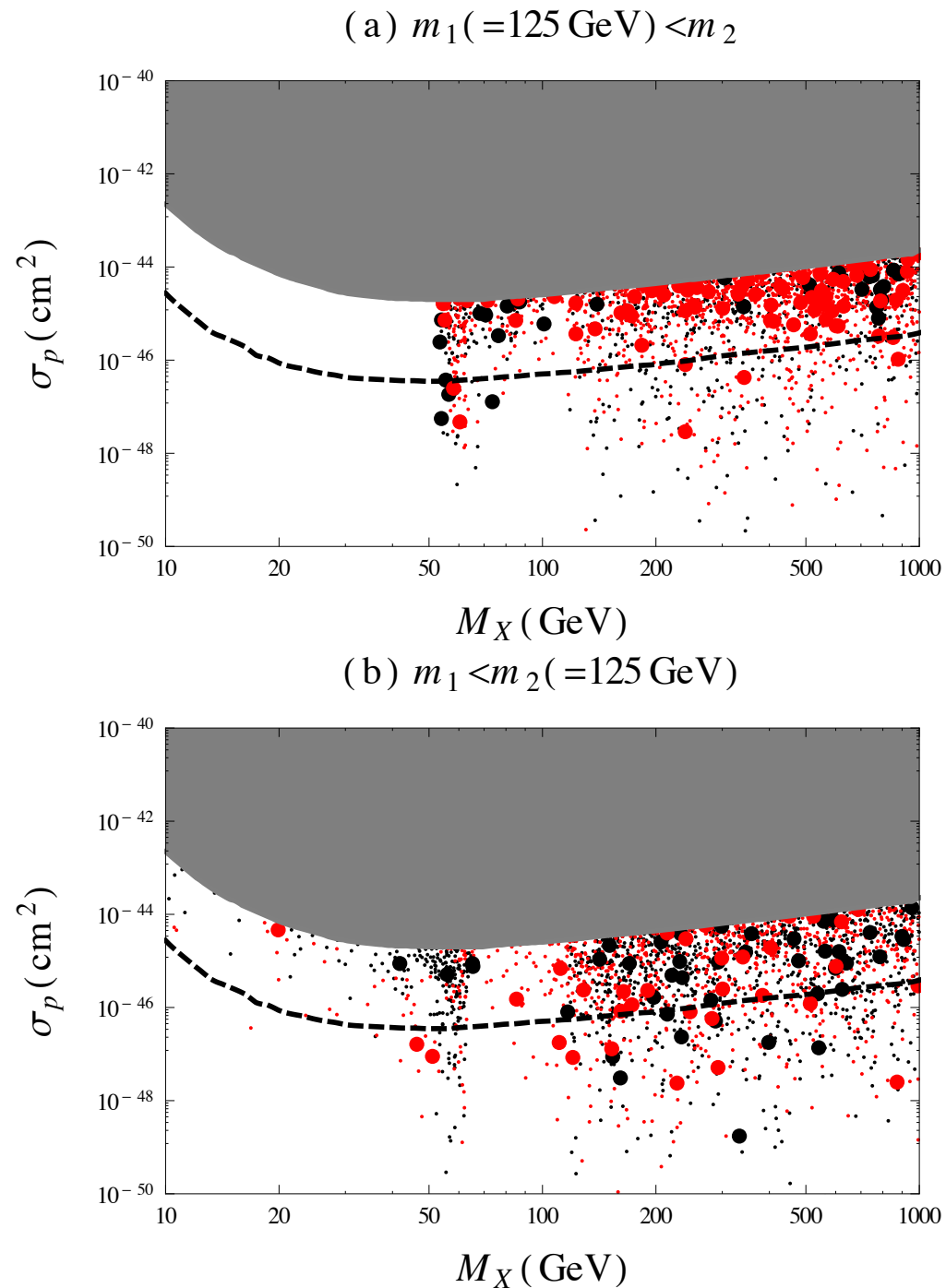


Figure 6. The scattered plot of σ_p as a function of M_X . The big (small) points (do not) satisfy the WMAP relic density constraint within 3σ , while the red-(black-)colored points gives $r_1 > 0.7$ ($r_1 < 0.7$). The grey region is excluded by the XENON100 experiment. The dashed line denotes the sensitivity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

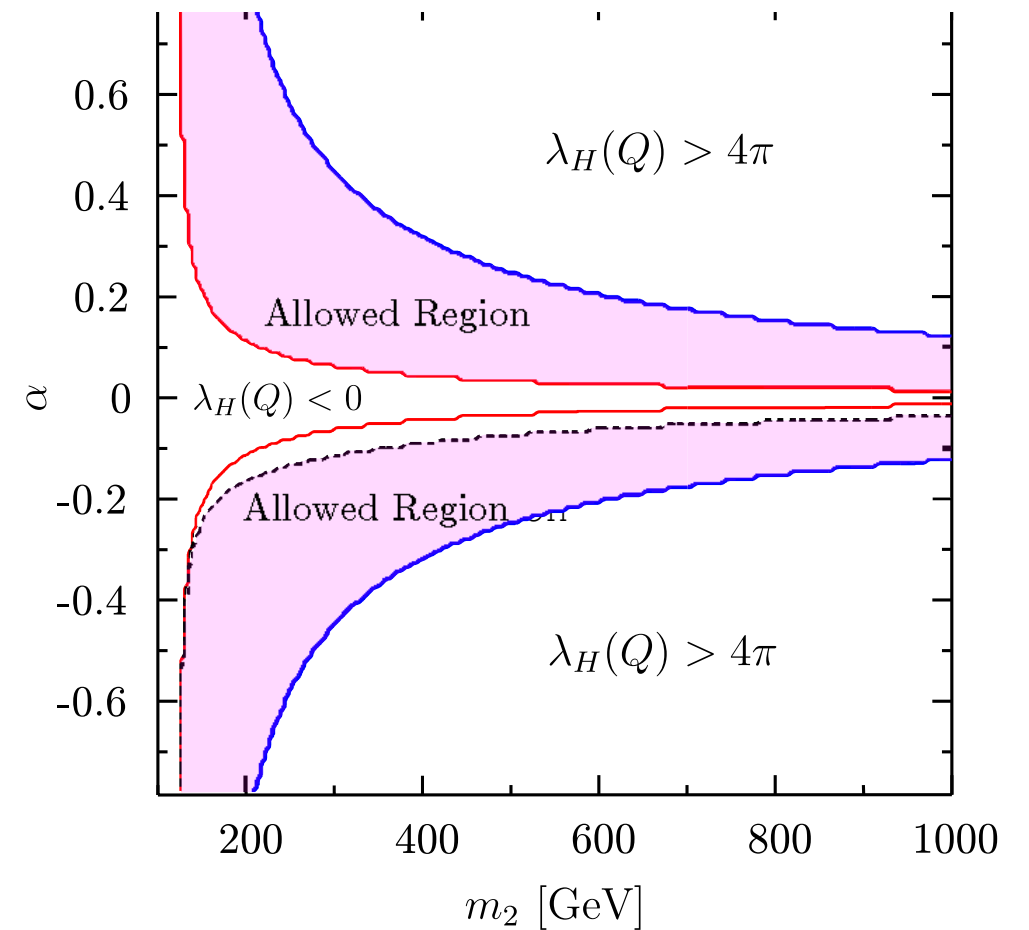


Figure 8. The vacuum stability and perturbativity constraints in the α - m_2 plane. We take $m_1 = 125 \text{ GeV}$, $g_X = 0.05$, $M_X = m_2/2$ and $v_\Phi = M_X/(g_X Q_\Phi)$.

Higgs portal DM as examples

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under ad hoc
Z2 symmetry

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arXiv:1112.3299, ... 1402.6287, etc.

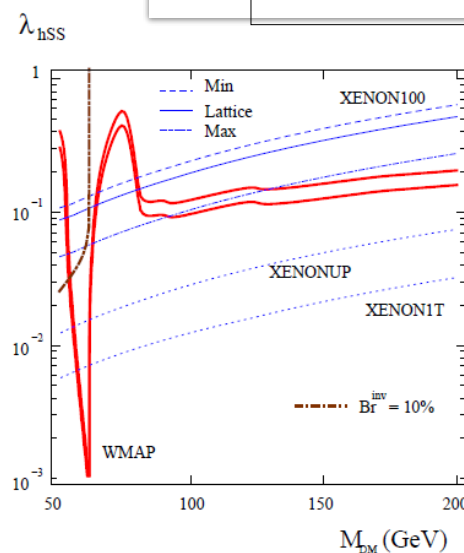


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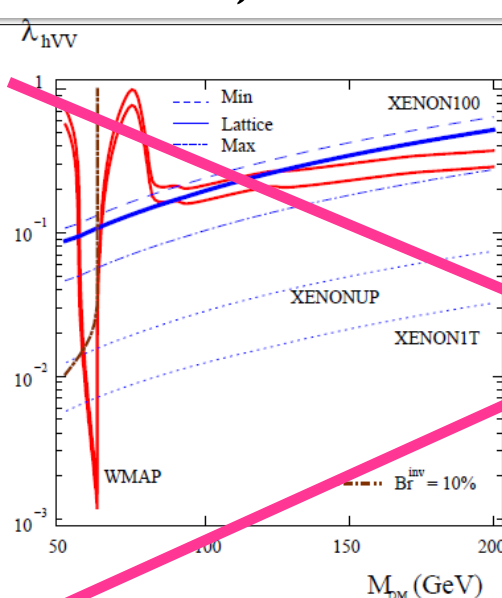


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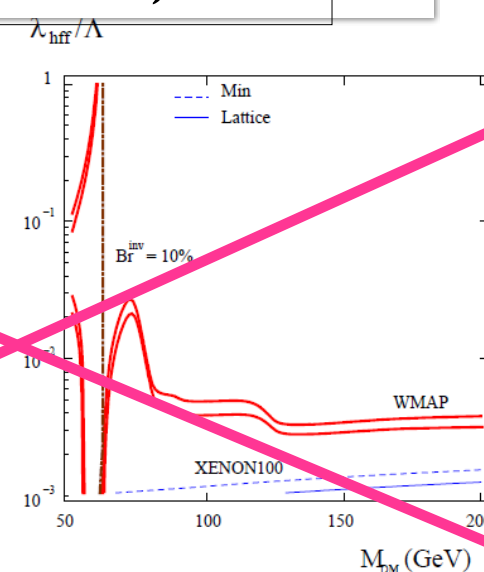
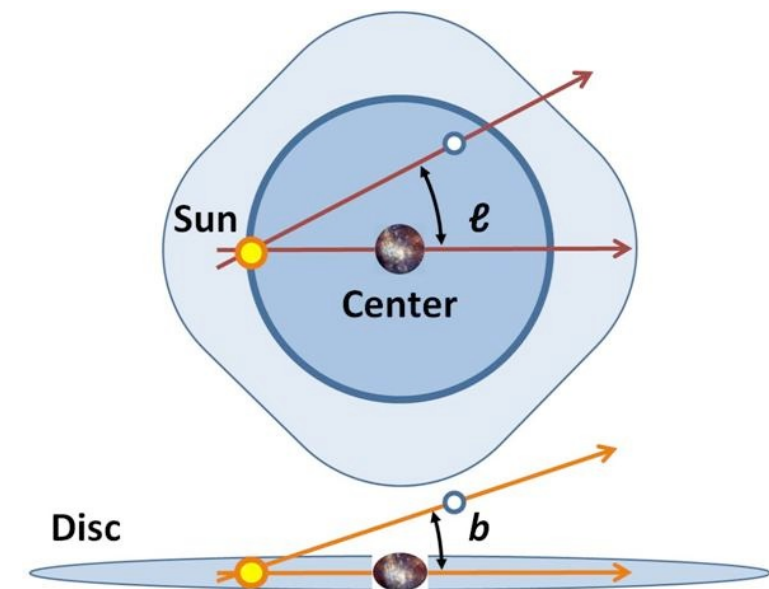
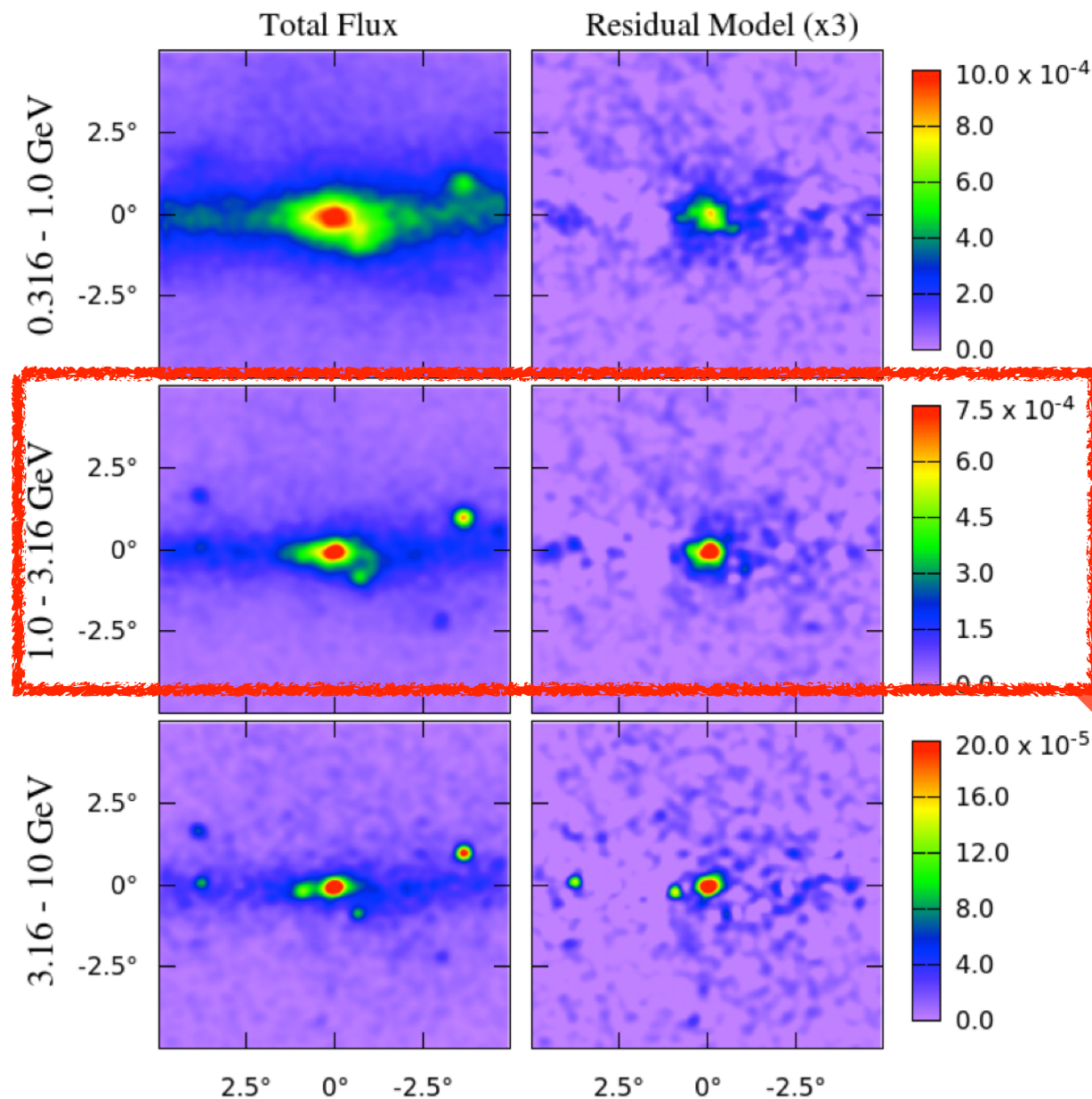


FIG. 3. Same as in Fig.1 for fermion DM; λ_{hff}/Λ is in GeV^{-1} .

Example: Fermi-LAT γ -ray excess

- Gamma-ray excess in the direction of GC



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

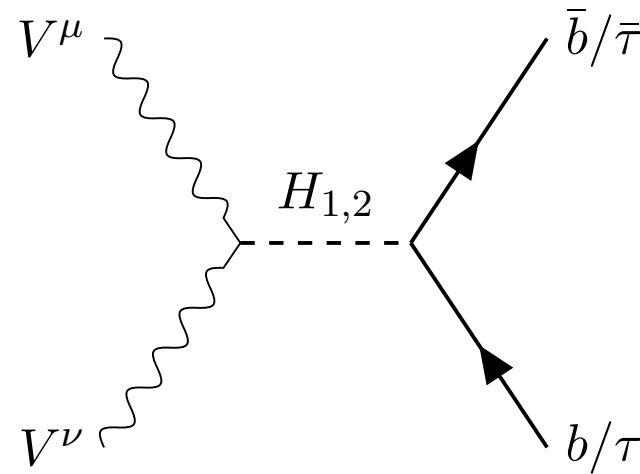
extended
GeV scale excess!

[1402.6703, T. Daylan et.al.]

(Talk by Dan Hooper)

GC gamma ray in VDM

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



H_2 : 125 GeV Higgs
 H_1 : present in VDM
with dark gauge sym

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

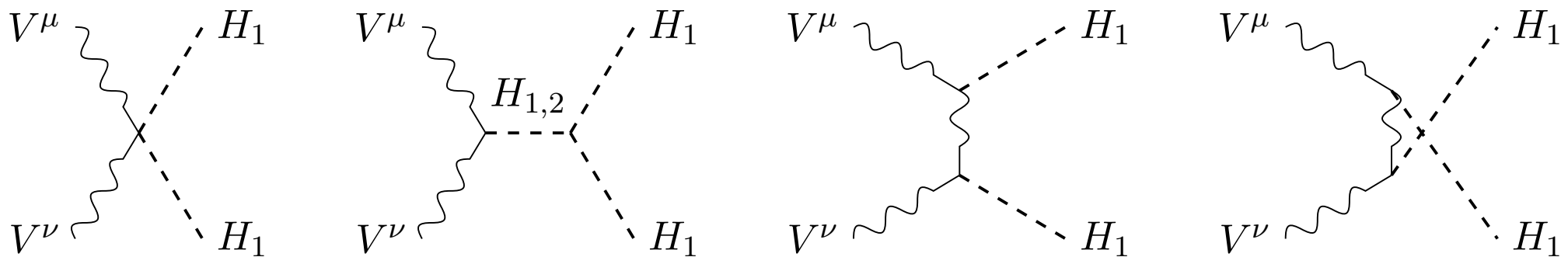
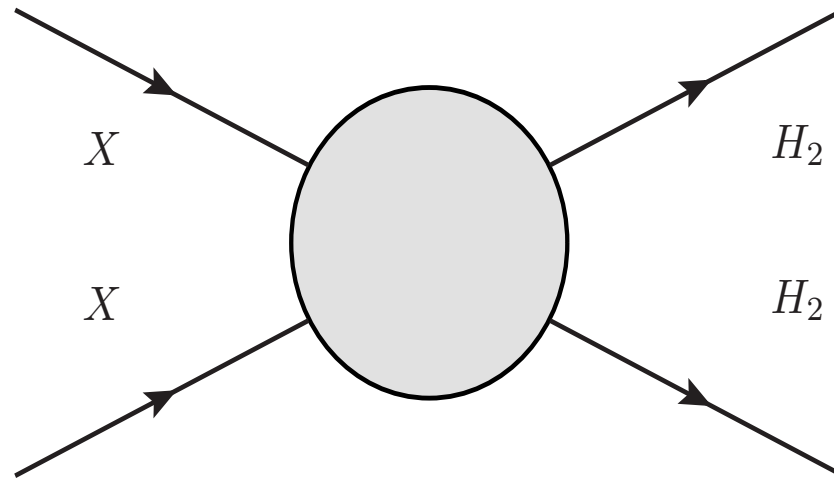


Figure 3. Dominant s/t -channel production of H_1 s that decay dominantly to $b + \bar{b}$



P.Ko, Yong Tang.
arXiv:1504.03908

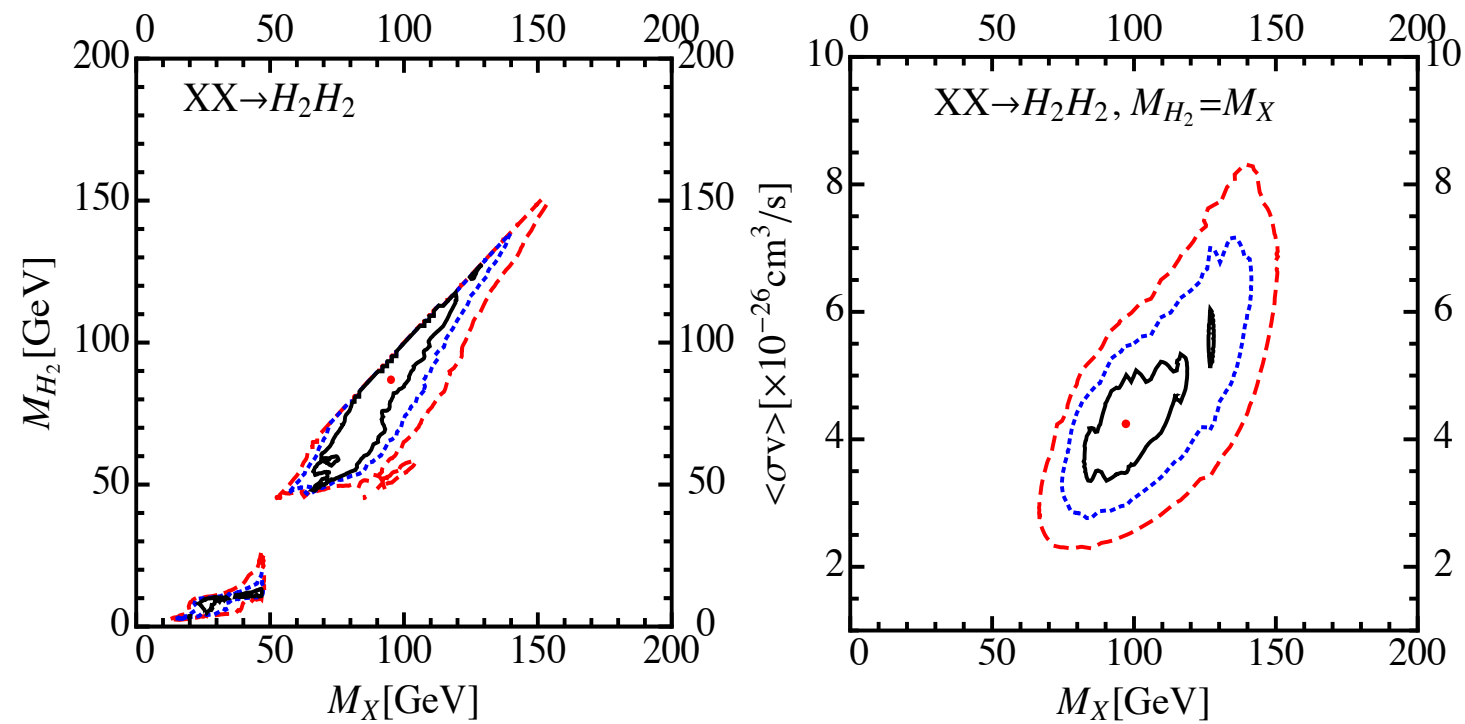


FIG. 3: The regions inside solid(black), dashed(blue) and long-dashed(red) contours correspond to 1σ , 2σ and 3σ , respectively. The red dots inside 1σ contours are the best-fit points. In the left panel, we vary freely M_X , M_{H_2} and $\langle\sigma v\rangle$. While in the right panel, we fix the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

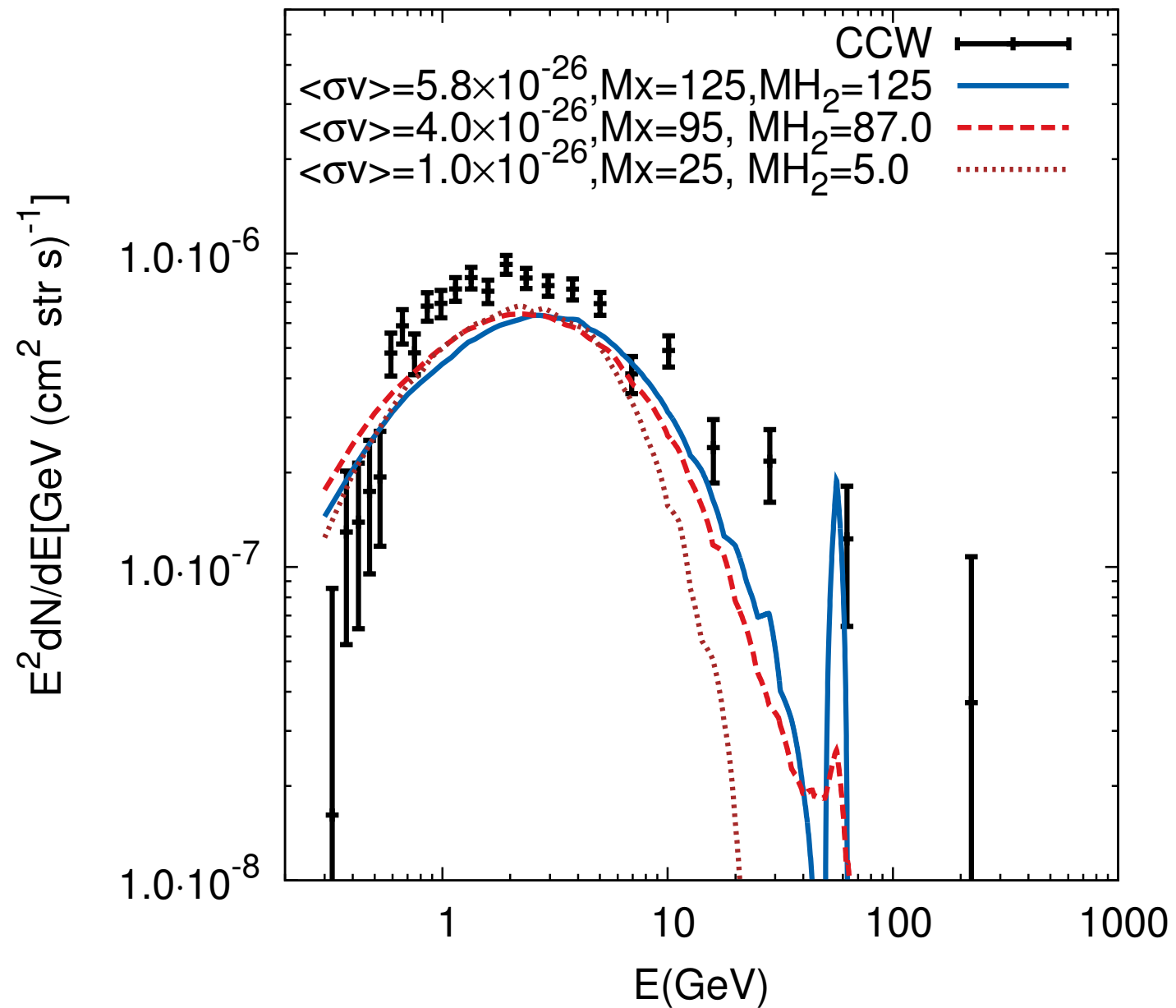


FIG. 2: Three illustrative cases for gamma-ray spectra in contrast with CCW data points [11]. All masses are in GeV unit and σv with cm^3/s . Line shape around $E \simeq M_{H_2}/2$ is due to decay modes, $H_2 \rightarrow \gamma\gamma, Z\gamma$.

Thanks to C. Weniger
for the covariant matrix

This explanation is possible only in DM models with dark gauge symmetry

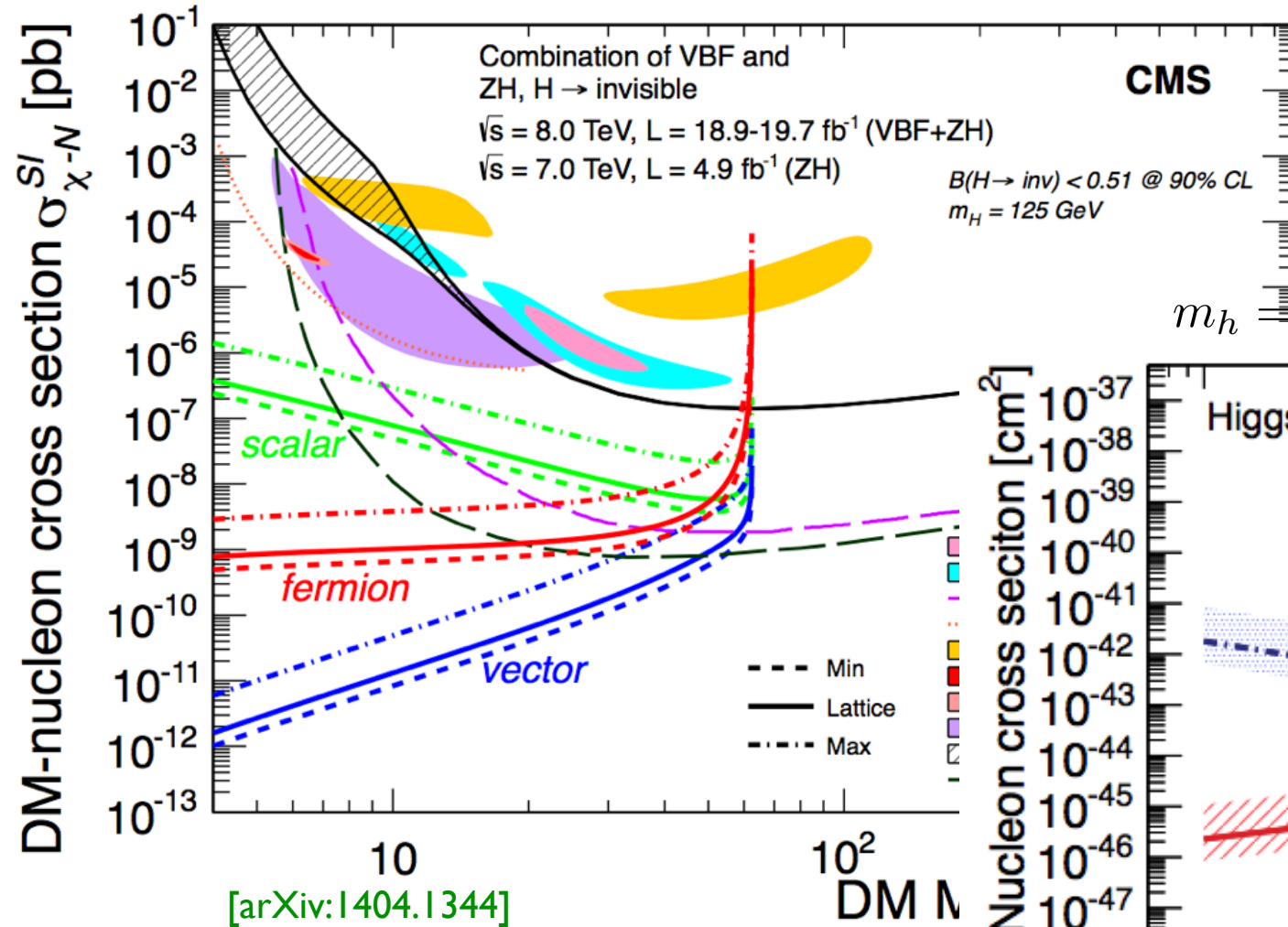
P.Ko, Yong Tang.
arXiv:1504.03908

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

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

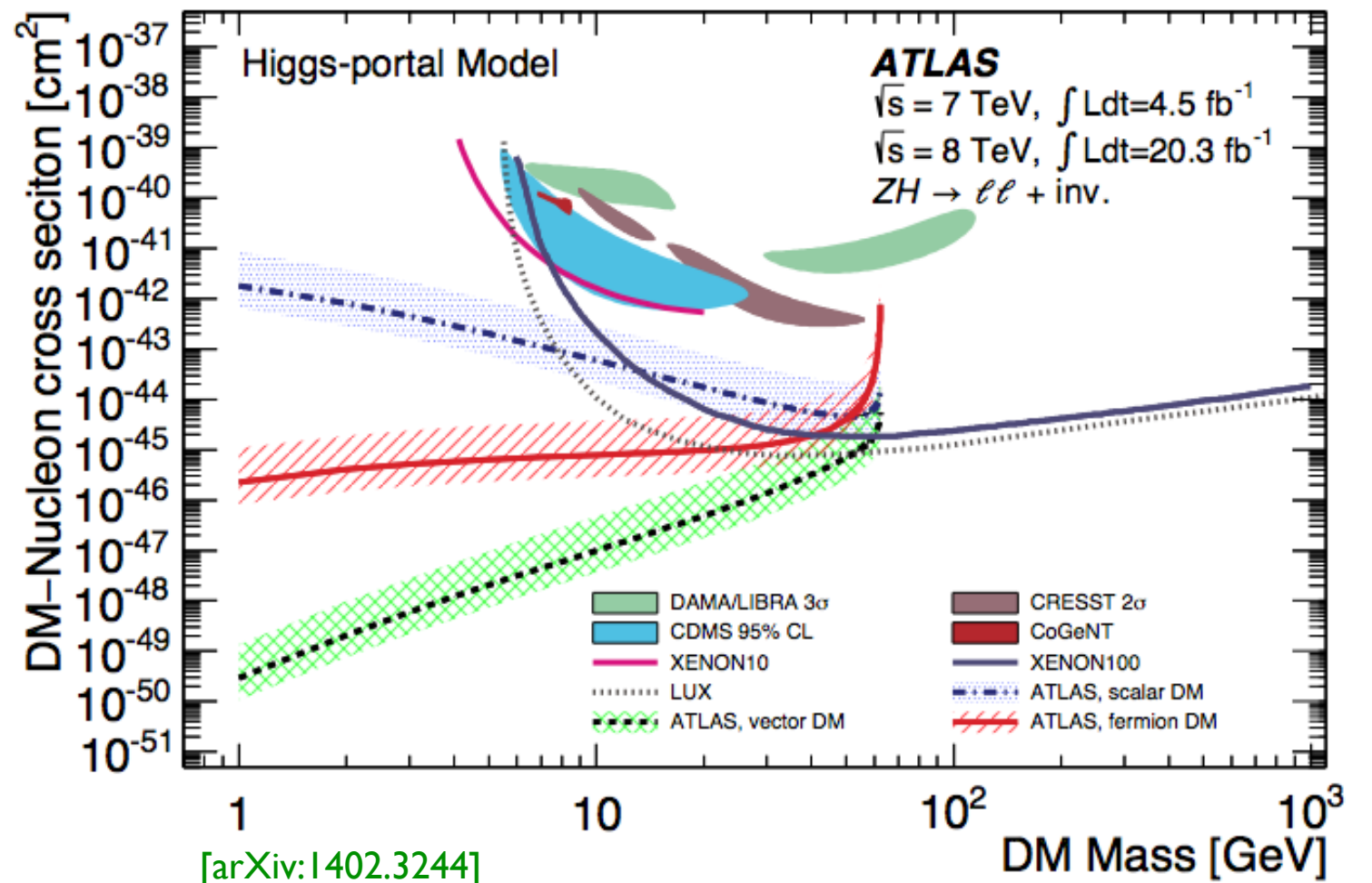
Collider Implications

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



Based on EFTs

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



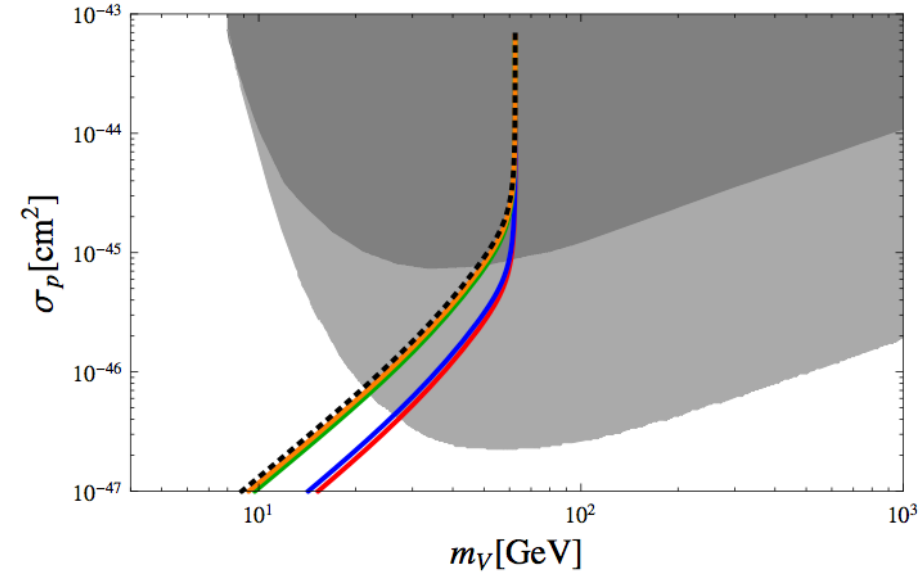
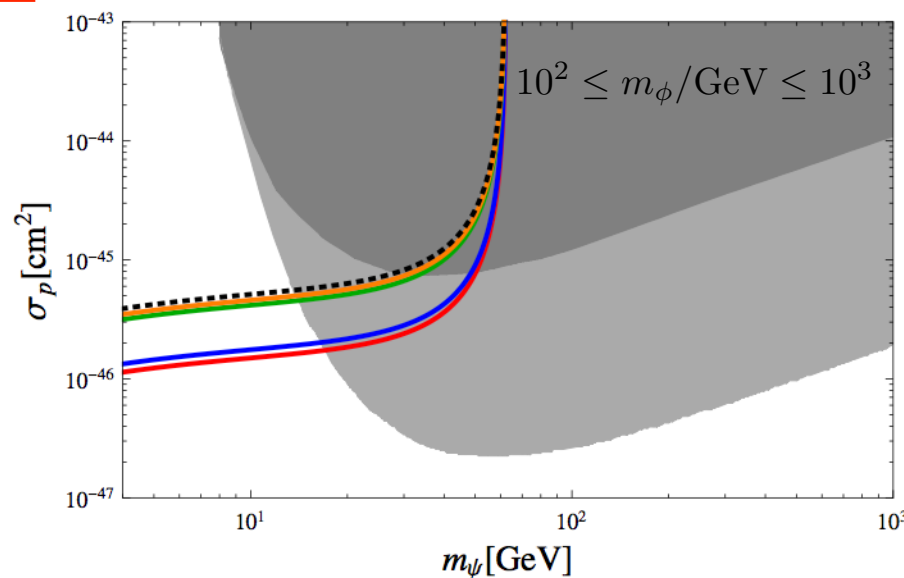
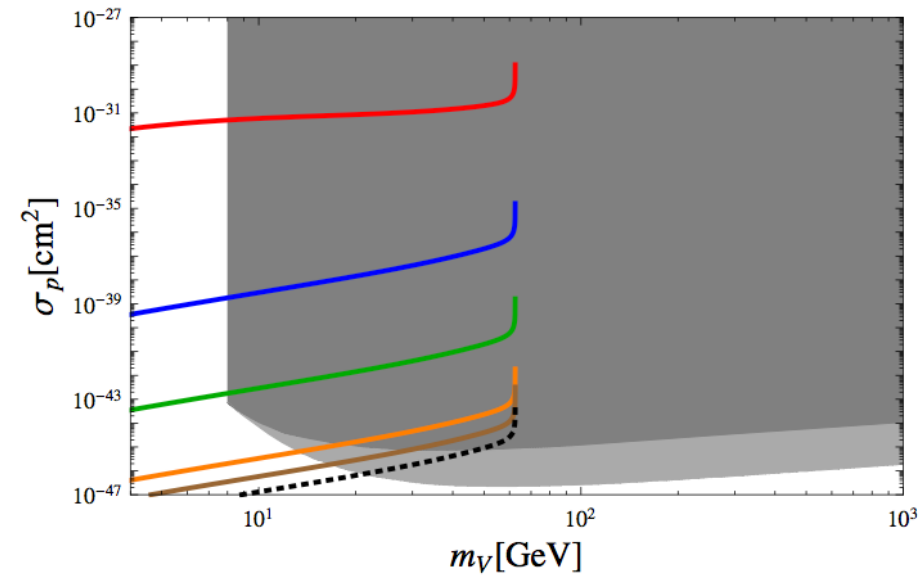
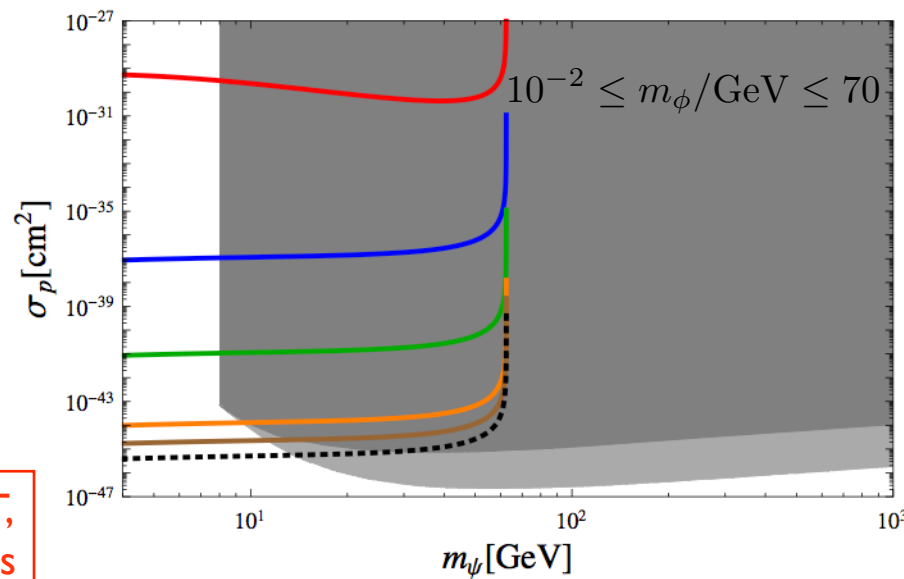
- However, in renormalizable unitary models of Higgs portals, **2 more relevant parameters**

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

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

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

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



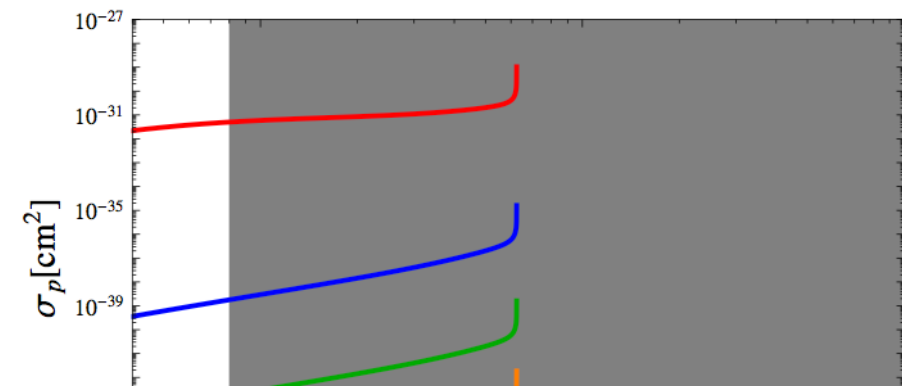
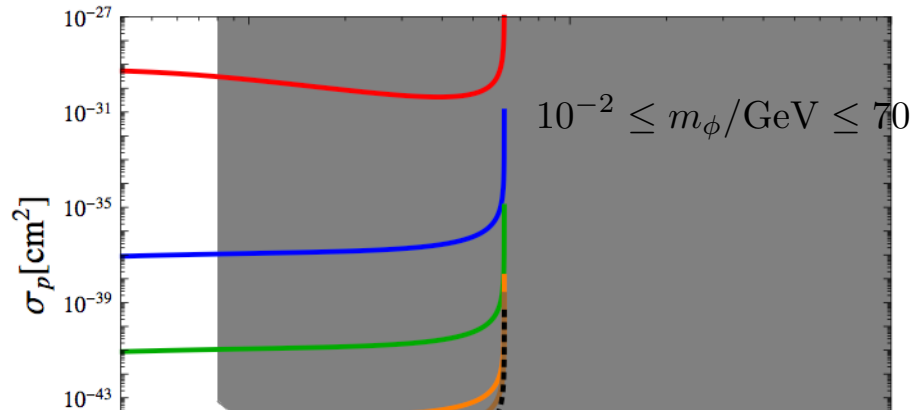
Dashed curves: EFT,
ATLAS, CMS results

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

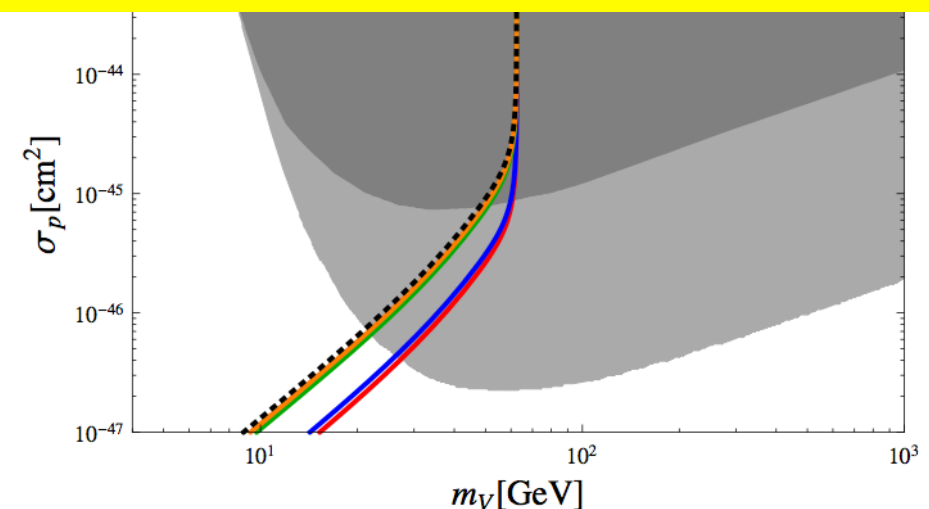
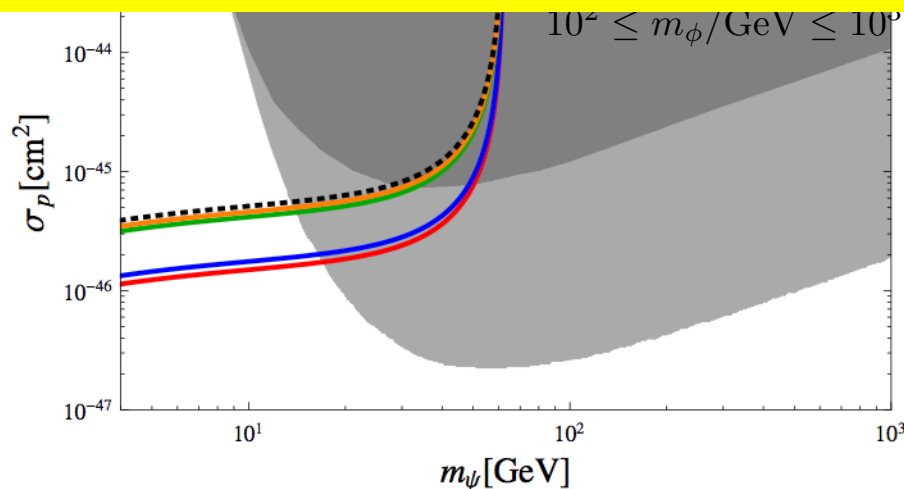
$$\mathcal{L}_{\text{SFDM}} = \bar{\psi}(i\partial - m_\psi - \lambda_\psi S) - \mu_{HS} S H^\dagger H - \frac{\lambda_{HS}}{2} S^2 H^\dagger H \\ + \frac{1}{2} \partial_\mu S \partial^\mu S - \frac{1}{2} m_S^2 S^2 - \mu'_S S - \frac{\mu'_S}{3} S^3 - \frac{\lambda_S}{4} S^4.$$

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

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



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



Invisible H decay into a pair of VDM

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

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

VS.

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

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

NB: it is infinite in the effective VDM model

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

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

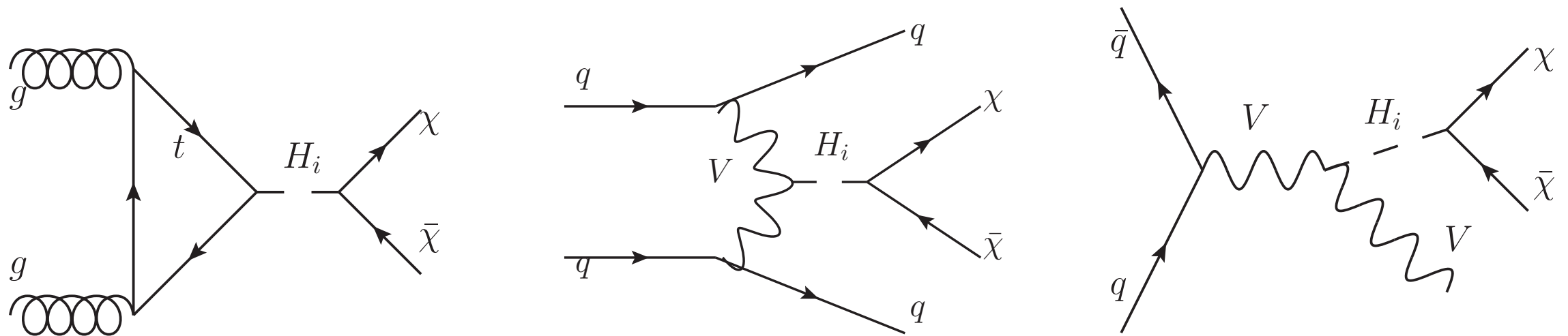


Figure 1: The dominant DM production processes at LHC.

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

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

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

Interference effects

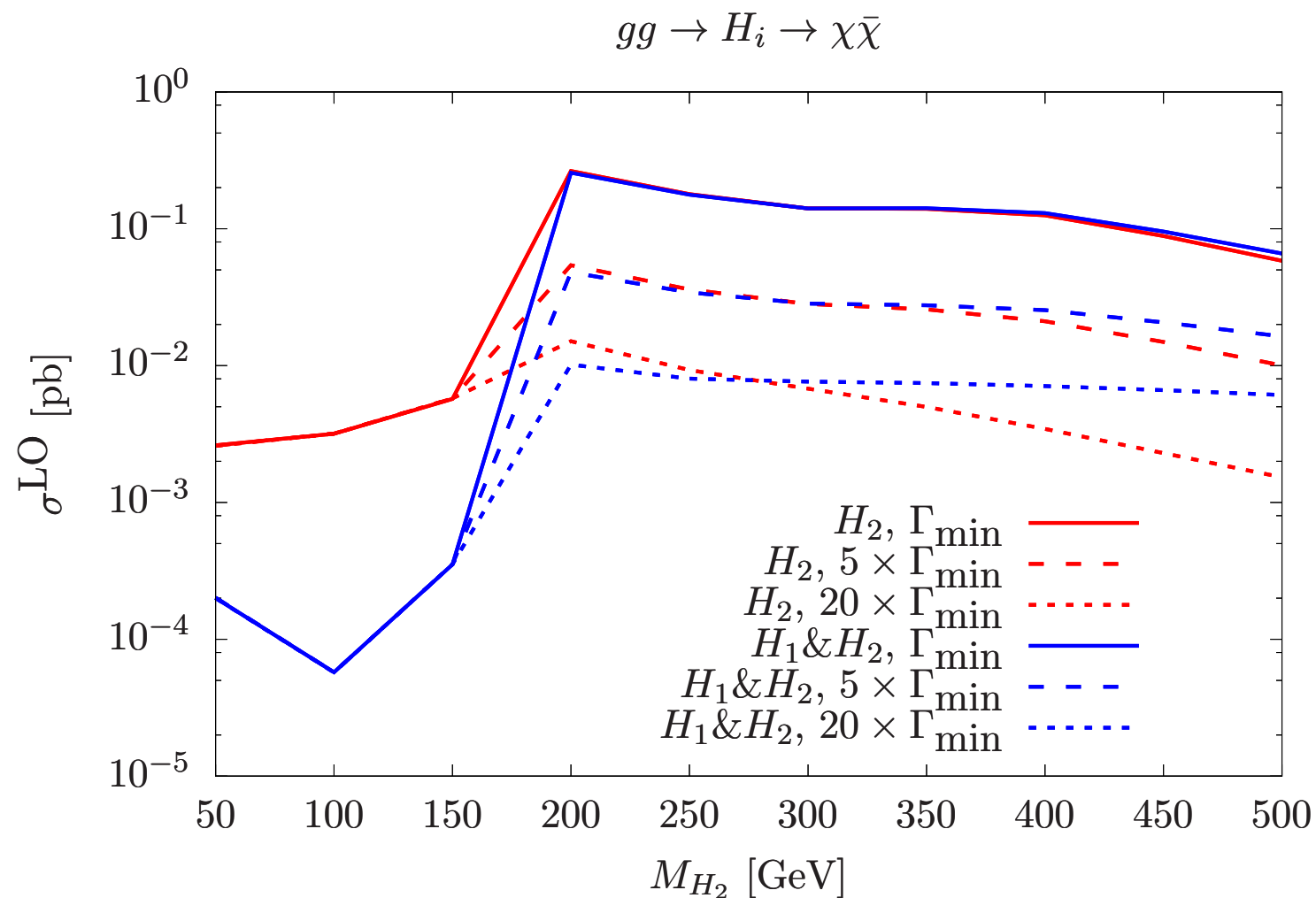


Figure 2: The LO cross section for gluon-gluon fusion process at 13 TeV LHC. The meanings of the different line types are explained in the text and the similar strategy will be used in all figures.

- EFT : Effective operator $\mathcal{L}_{int} = \frac{m_q}{\Lambda_{dd}^3} \bar{q}q\bar{\chi}\chi$
- S.M.: Simple scalar mediator S of

$$\mathcal{L}_{int} = \left(\frac{m_q}{v_H} \sin \alpha \right) S \bar{q}q - \lambda_s \cos \alpha S \bar{\chi}\chi$$
- H.M.: A case where a Higgs is a mediator

$$\mathcal{L}_{int} = - \left(\frac{m_q}{v_H} \cos \alpha \right) H \bar{q}q - \lambda_s \sin \alpha H \bar{\chi}\chi$$
- H.P.: Higgs portal model as in eq. (2).

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

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

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

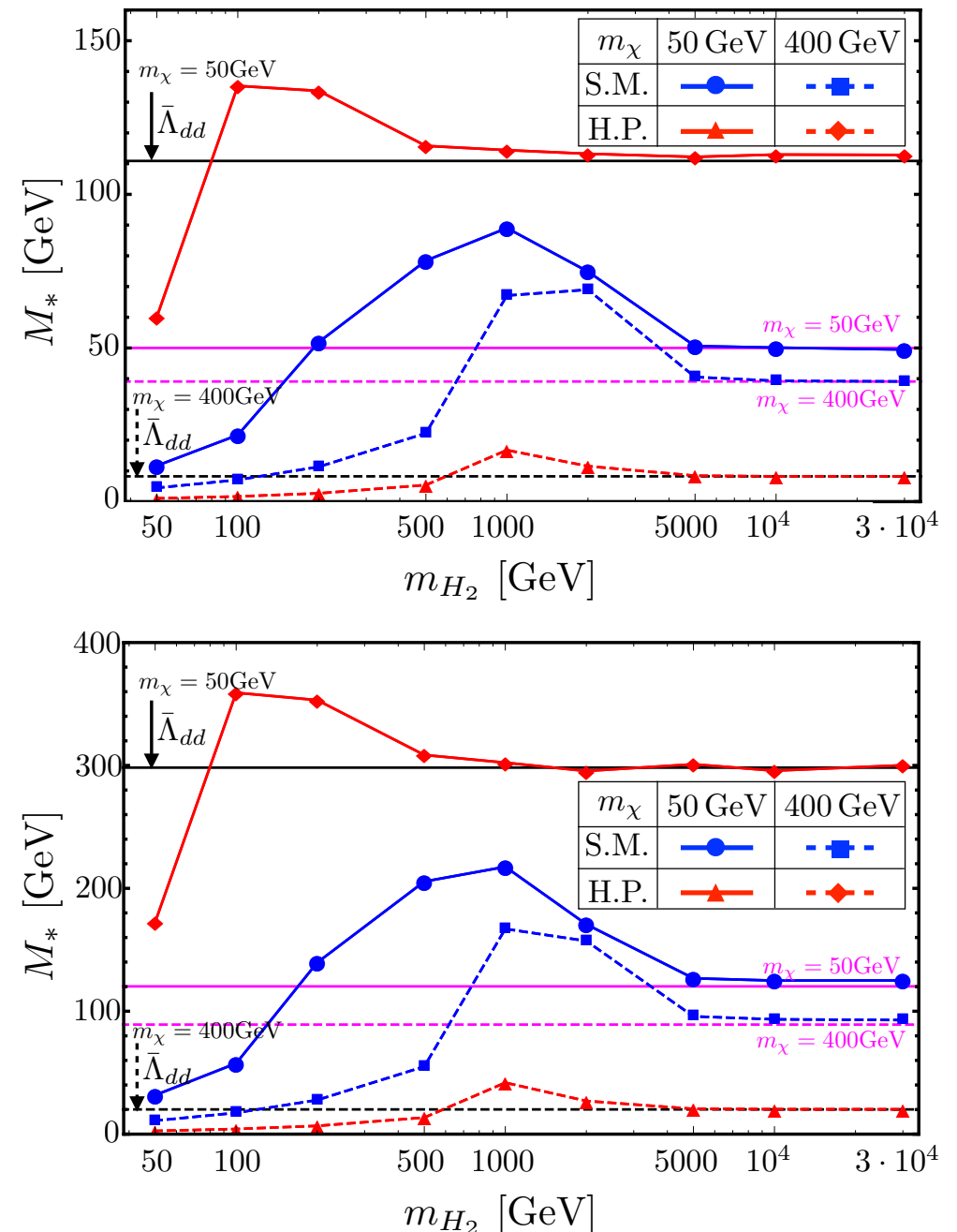


FIG. 3: The experimental bounds on M_* at 90% C.L. as a function of m_{H_2} (m_S in S.M. case) in the monojet+ \cancel{E}_T search (upper) and $t\bar{t}$ + \cancel{E}_T search (lower). Each line corresponds to the EFT approach (magenta), S.M. (blue), H.M. (black), and H.P. (red), respectively. The bound of S.M., H.M., and H.P., are expressed in terms of the effective mass M_* through the Eq.(16)-(20). The solid and dashed lines correspond to $m_\chi = 50$ GeV and 400 GeV in each model, respectively.