Dark pion DM: WIMP vs. SIMP

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Portoroz 2019

- Only Higgs (~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)

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)

- Also, often 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 ?

- 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 ?
- 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

SM vs. DM Physics

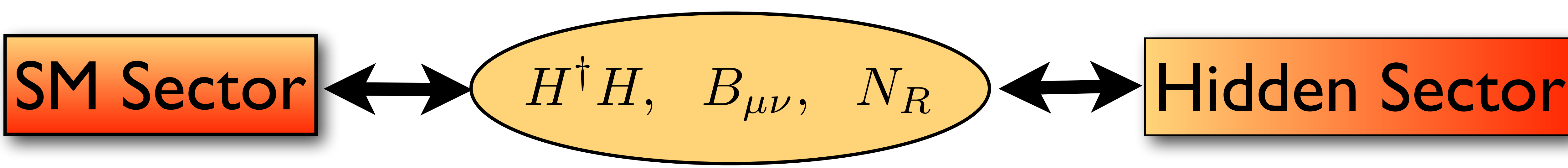
- Success of the Standard Model of Particle Physics lies in “local gauge symmetry” without imposing any internal global symmetries
- Electron stability : U(1)em gauge invariance, electric charge conservation
- Proton longevity : baryon # is an accidental sym of the SM
- No gauge singlets in the SM ;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

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

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



$N_R \leftrightarrow \widetilde{H} l_L$

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

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 in dark QCD scenario w/o and w/ Wess-Zumino-Witten term (WIMP vs. SIMP)

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-5,6 operators; proton is stable or very long lived) $\frac{1}{M_{\text{Planck}}} H^\dagger H \overline{q_h} \gamma_5 q_h$

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 >> 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

(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

Classical Scale Sym Model

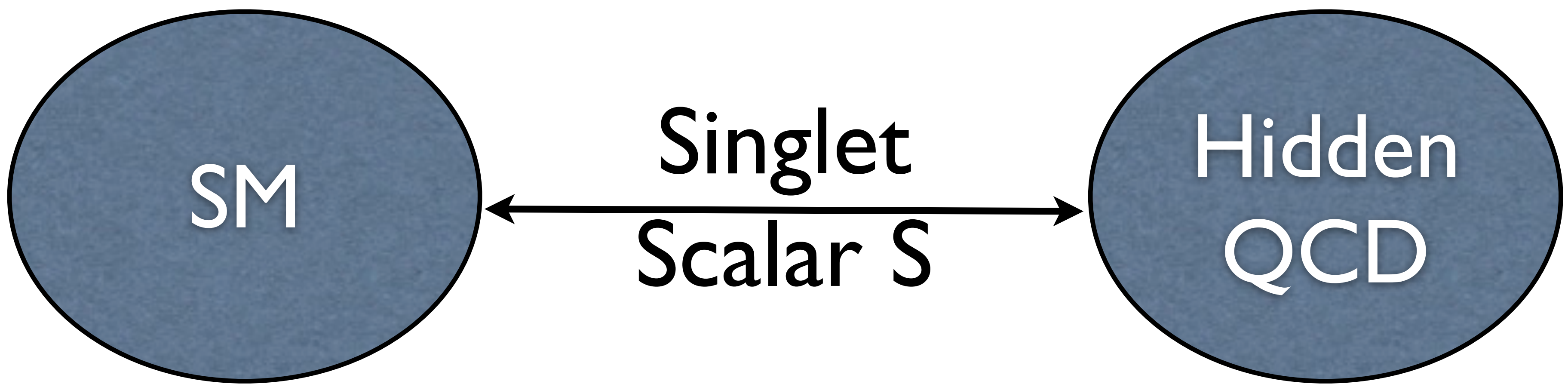
- Scale invariant extension of the SM + hQCD
- Mass scale is generated by nonperturbative strong dynamics in the hidden sector
- EWSB and CDM from hQCD sector

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

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

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

Hidden sector lagrangian with new strong interaction

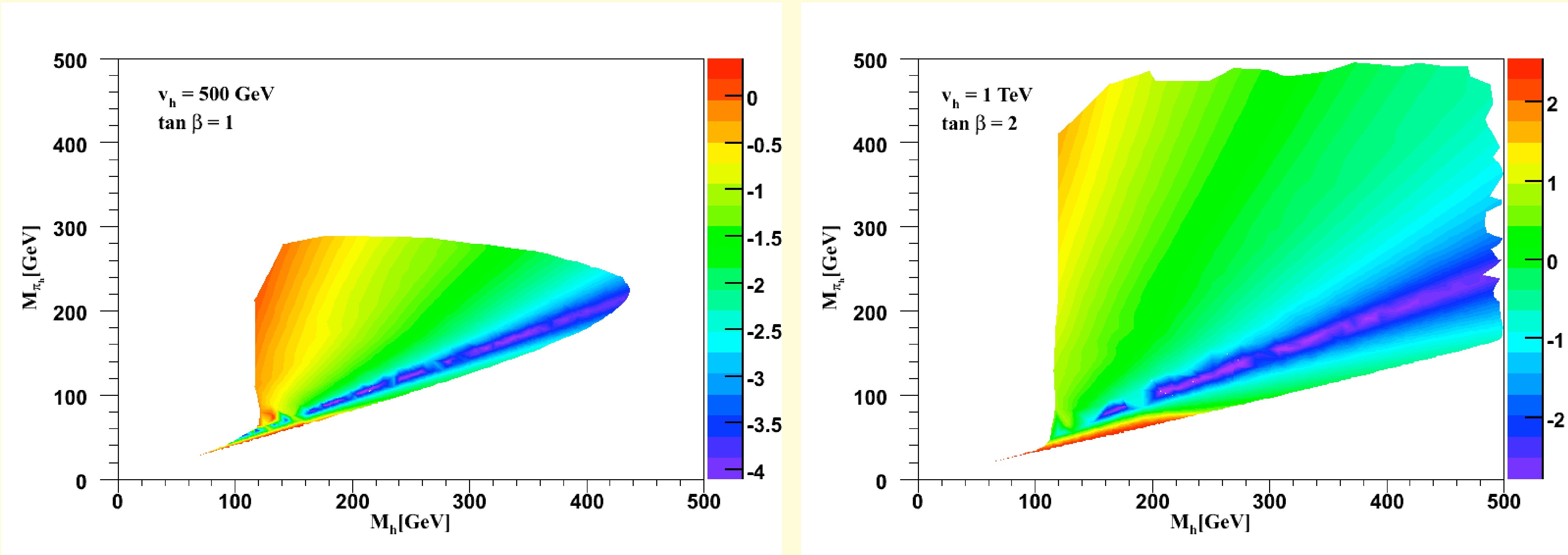
$$\mathcal{L}_{\rm hidden} = -\frac{1}{4}\mathcal{G}_{\mu\nu}\mathcal{G}^{\mu\nu} + \sum_{k=1}^{N_{HF}} \overline{\mathcal{Q}}_k (i\mathcal{D}\cdot\gamma - \lambda_k S)\mathcal{Q}_k$$

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

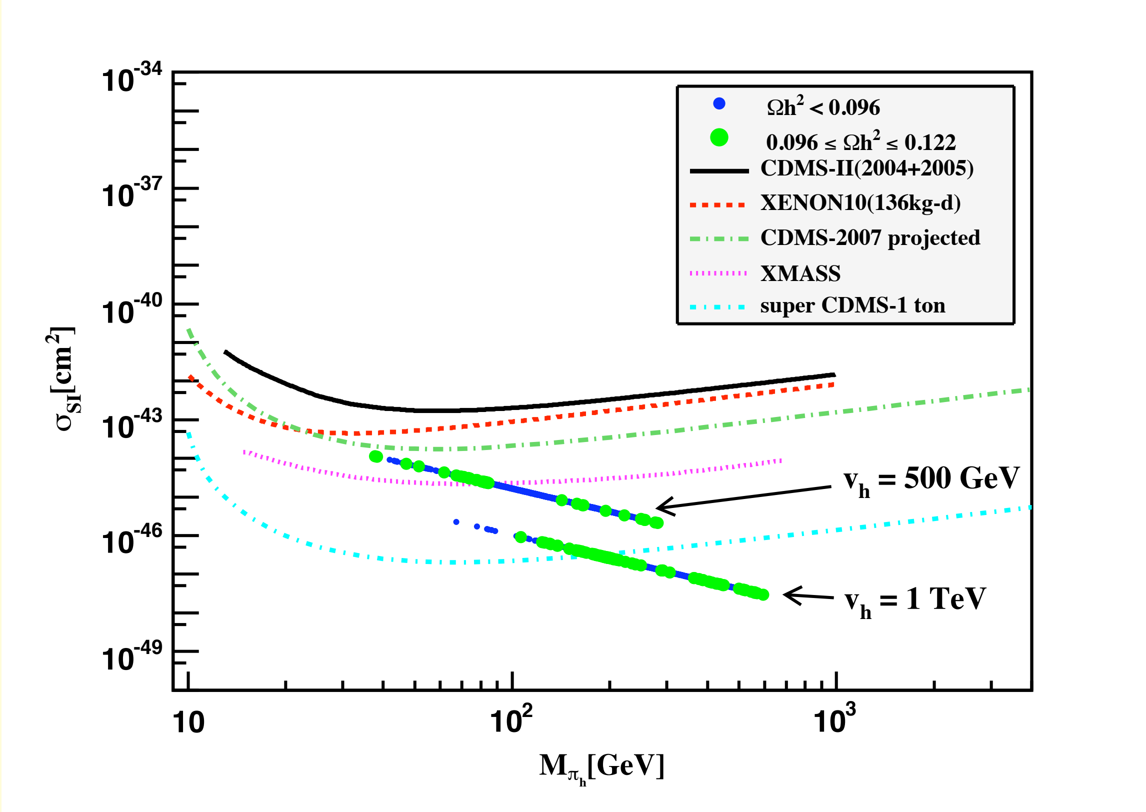


$\Omega_{\pi_h} h^2$ in the (m_{h_1}, m_{π_h}) plane for

(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 $\tan\beta = 2$.

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

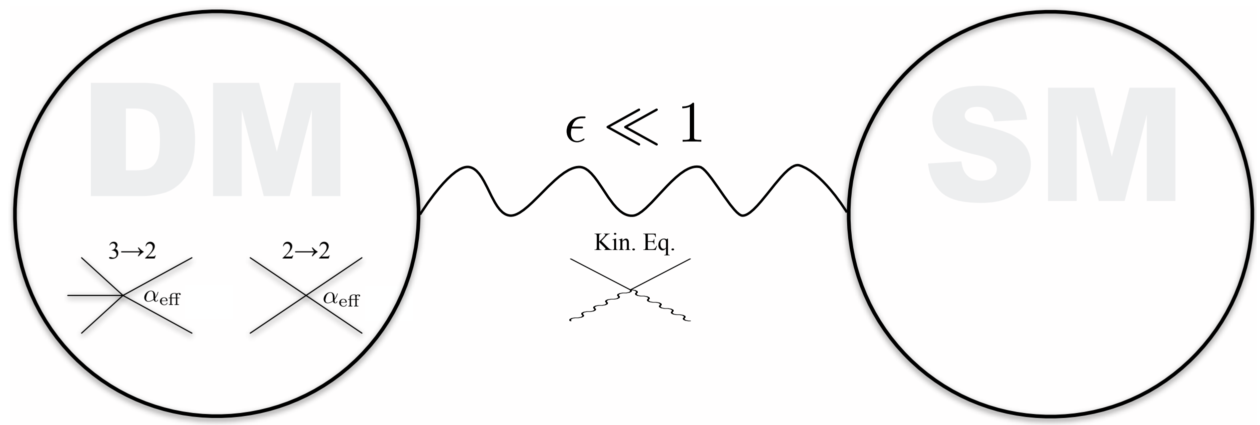


FIG. 1: A schematic description of the SIMP paradigm. The dark sector consists of DM which annihilates via a $3 \to 2$ process. Small couplings to the visible sector allow for thermalization of the two sectors, thereby allowing heat to flow from the dark sector to the visible one. DM self interactions 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 :

$$\Gamma_{3\to2} = n_{DM}^2 \langle \sigma v^2 \rangle_{3\to2} \sim H(T_F)$$

$$\langle \sigma v^2 \rangle_{3\to2} = \frac{\alpha_{\rm eff}^3}{m_{\rm DM}^5}$$

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

2->2 Self scattering :

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

with a~O(1)

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

Dark QCD + WZW

- Dark flavor symmetry $G=SU(N_f)_L \times SU(N_f)_R$ is SSB into diagonal $H=SU(N_f)_V$ by dark QCD condensation

- Effective Lagrangian for NG bosons (dark pions) contain 5-point self interaction : WZW term for $\pi_5(G/H) = Z$ ($N_f > 2$)

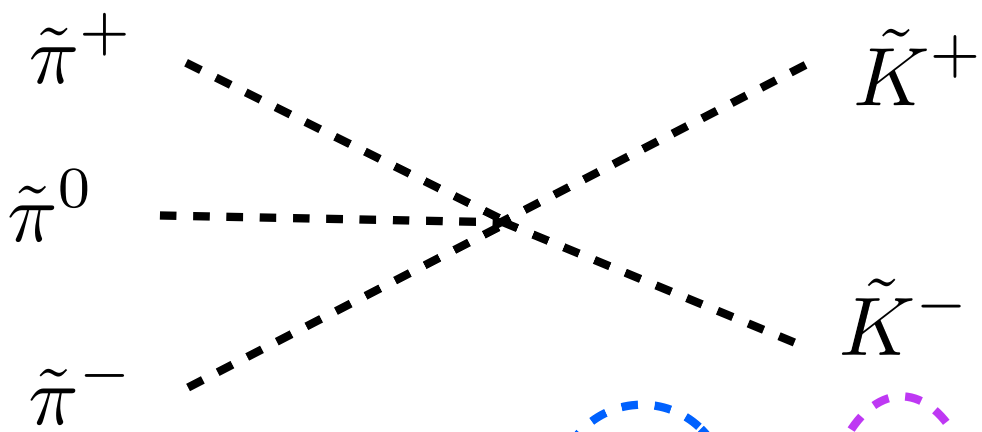
$$\Gamma_{\mathrm{WZ}} = C \int_{M^5} d^5x \ \mathrm{Tr}(\alpha^5) \qquad \text{with} \quad \alpha = dUU^\dagger .$$

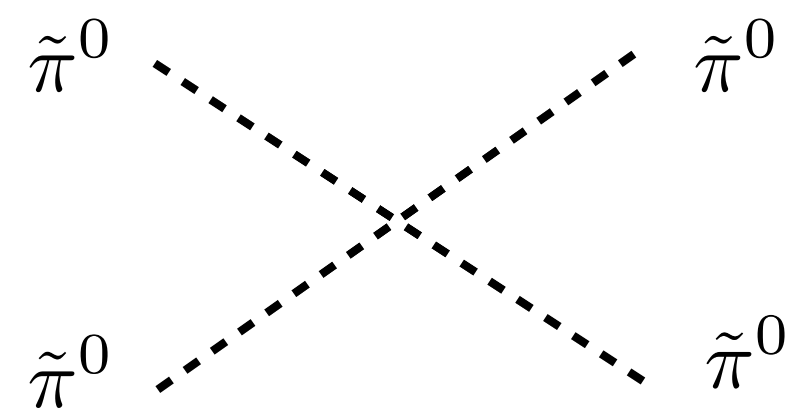
$$U = e^{2i\pi/F}$$

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

in the absence of external gauge fields

SIMP Dark Mesons





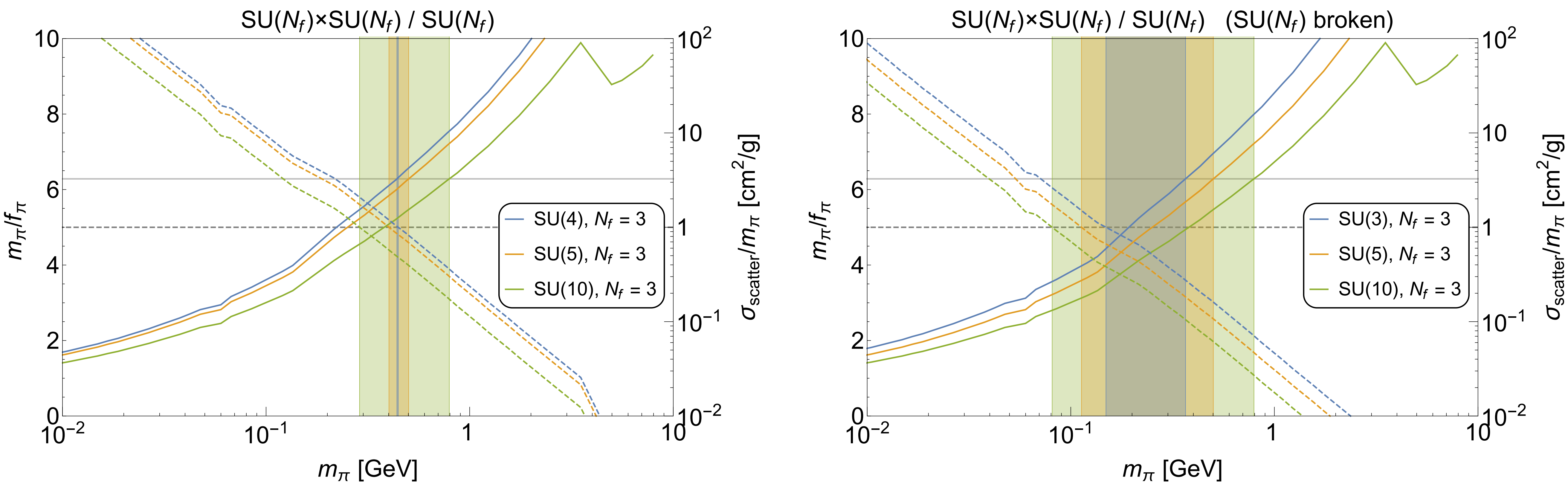
~const ~const

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

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

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

SIMP Parameter Space



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

- DM self scattering : $\sigma_{\rm self}/m_{\rm DM} < 1\,{\rm cm}^2/{\rm g}$

Large Nc > 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 pionscan help. Work in progress.)

Digression on ChPT + VM

- We consider G_{global} SSB into H_{global} : non Linear sigma model on G_{global}/H_{global} is equivalent to linear sigma model on G_{global} X H_{local}

- Vector meson ~ 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 $\xi_L^\dagger(x) = \xi_R(x) = \exp[i\pi(x)/f_\pi]$:

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

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

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

Vector meson as hidden local gauge boson

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

$$V_\mu = \frac{1}{\sqrt{2}} \begin{pmatrix} \frac{1}{\sqrt{2}}\rho^0_\mu + \frac{1}{\sqrt{6}}\omega_{8\mu} + \frac{1}{\sqrt{3}}\omega_{0\mu} & \rho^+_\mu K^{*+}_\mu & \\ \rho^-_\mu & -\frac{1}{\sqrt{2}}\rho^0_\mu + \frac{1}{\sqrt{6}}\omega_{8\mu} + \frac{1}{\sqrt{3}}\omega_{0\mu} & K^{*0}_\mu \\ K^{*-}_\mu & \overline{K^{*0}_\mu} & -\frac{2}{\sqrt{6}}\omega_{8\mu} + \frac{1}{\sqrt{3}}\omega_{0\mu} \end{pmatrix} \tag{7}$$

Ch Lagrangian (pi,V)

The chiral Lagrangian for pions and vector mesons is given by

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

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

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

Another useful quantities

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

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

WZW (gauged)

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

WZW with vector mesons

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

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

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

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

SIMP + VDM

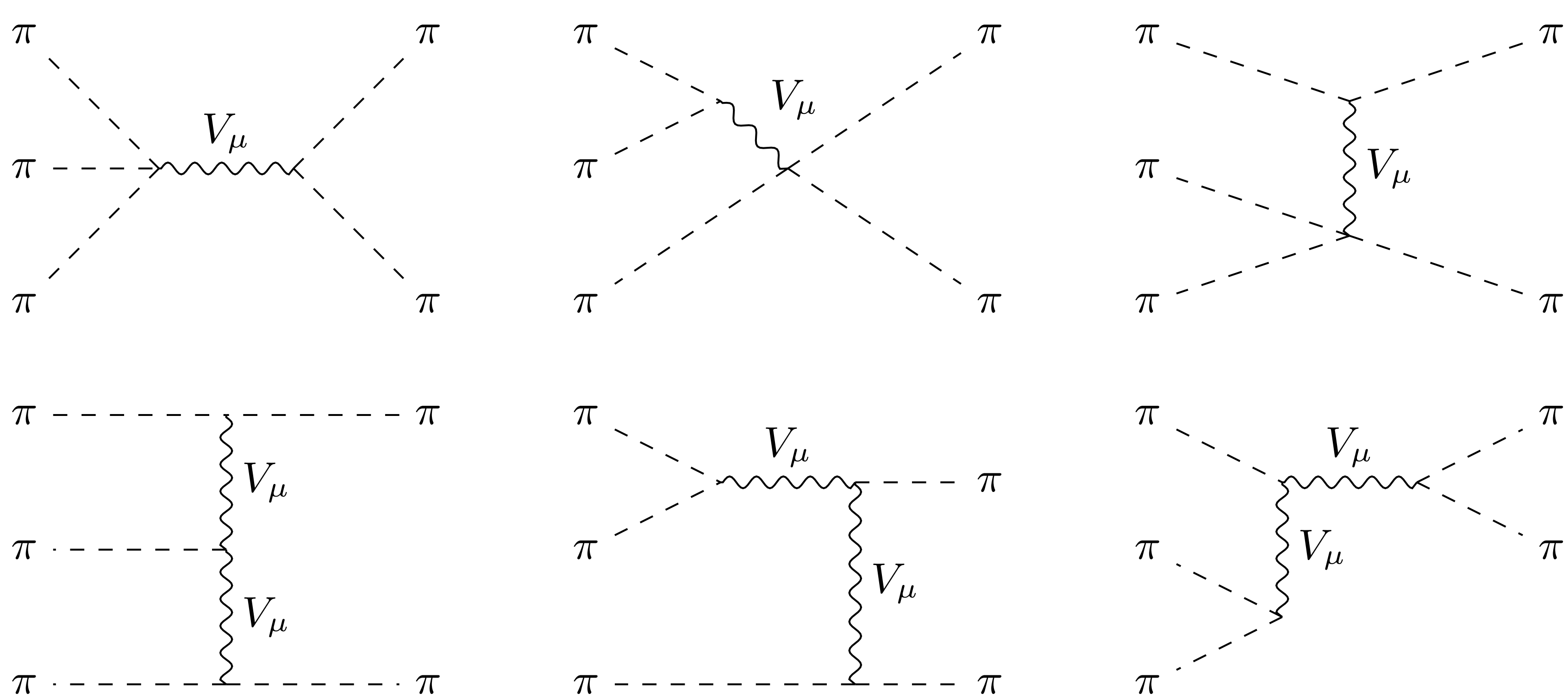


FIG. 1: Feynman diagrams contributing to $3 \to 2$ processes for the dark pions with the vector meson interactions.

SIMP + VM

New diagrams involveng dark vector mesons

$$\pi^+\pi^-\pi^0 \to \omega \to K^+K^-(K^0\overline{K^0})$$

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

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

Results

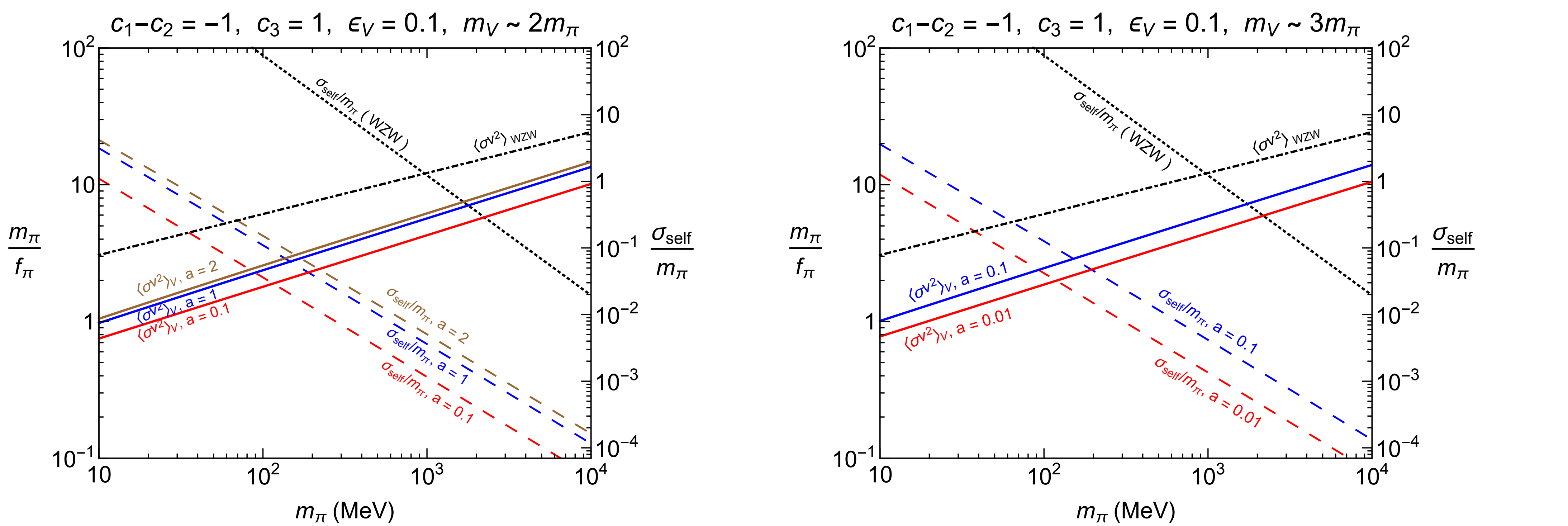


FIG. 2: Contours of relic density ($\Omega h^2 \approx 0.119$) for m_π and m_π/f_π and self-scattering cross section per DM mass in cm^2/g as a function of m_π. The case without and with vector mesons are shown in black lines and colored lines respectively. We have imposed the relic density condition 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

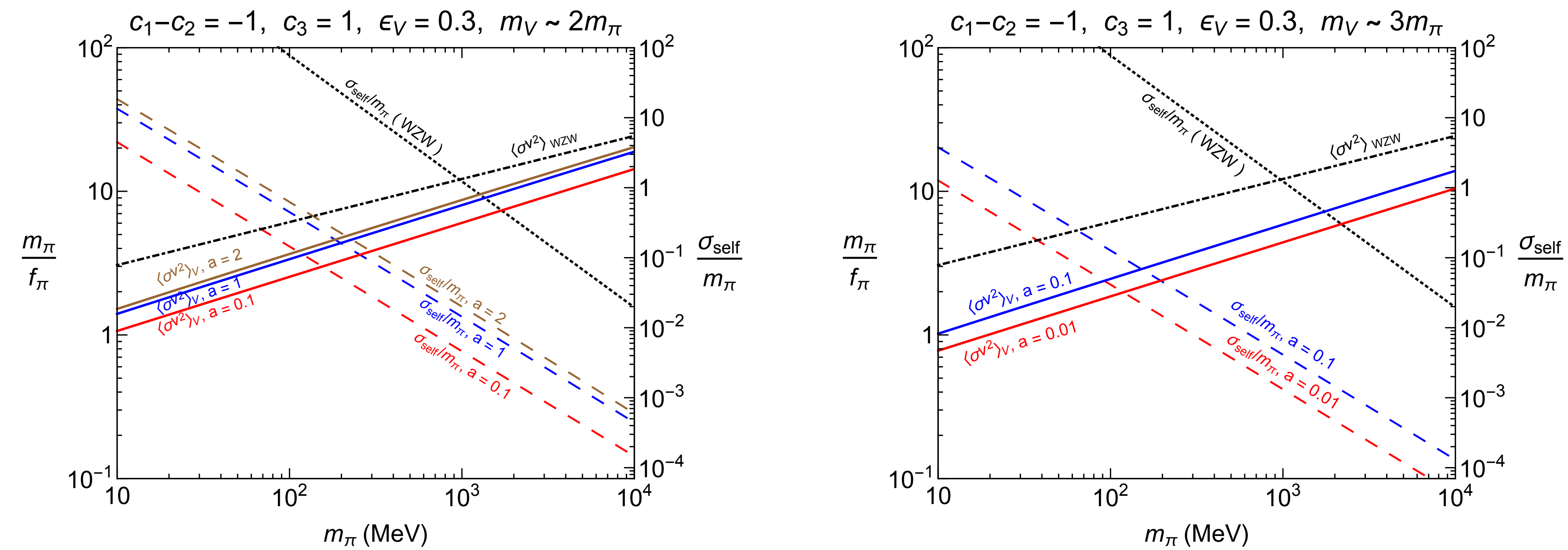


FIG. 3: Similar contours of relic density for m_π and m_π/f_π and self-scattering cross section per DM mass as in Fig. 2. Vector meson masses are taken off the resonance with $\epsilon_V = 0.3$, and $c_1 - c_2 = -1$ and $c_3 = 1$ are chosen.

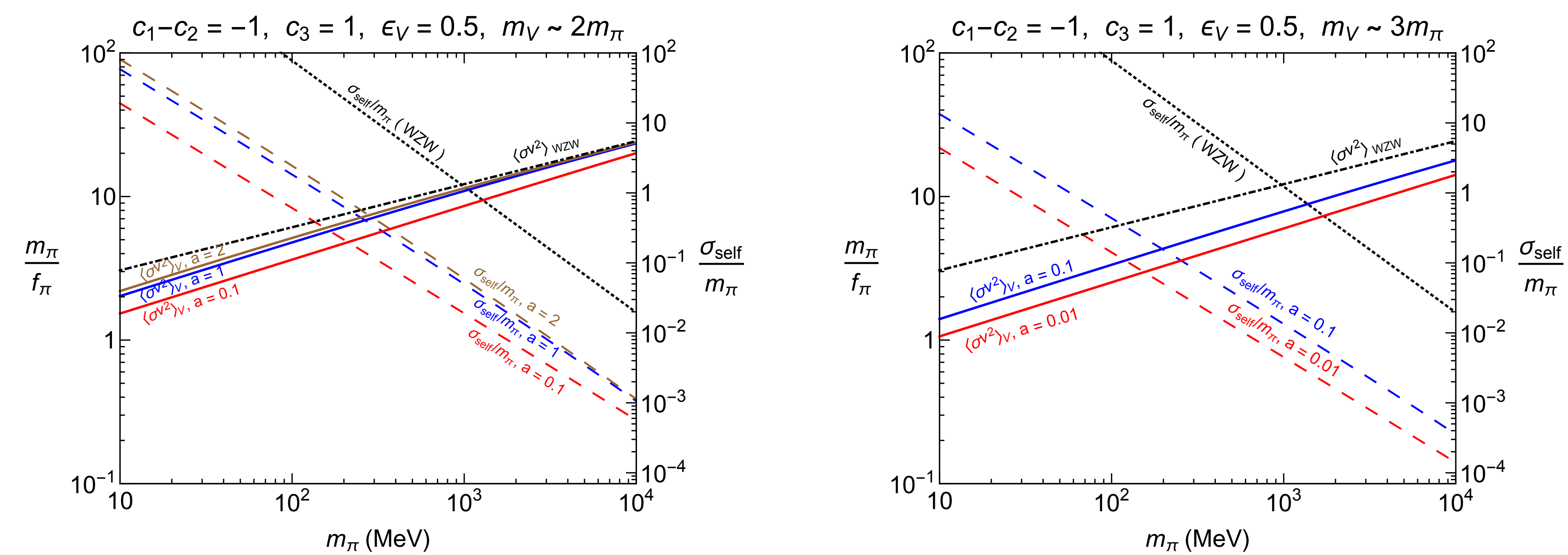


FIG. 4: Similar contours of relic density for m_π and m_π/f_π and self-scattering cross section per DM mass as in Fig. 2. Vector meson masses are taken off the resonance with $\epsilon_V = 0.5$, and $c_1 - c_2 = -1$ and $c_3 = 1$ are chosen.

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->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)