Inelastic DM models with dark Higgs boson

Pyungwon Ko (KIAS)

Talk @ CAU BSM workshop
Feb. 1-3 (2021)

Contents

KNOWNS

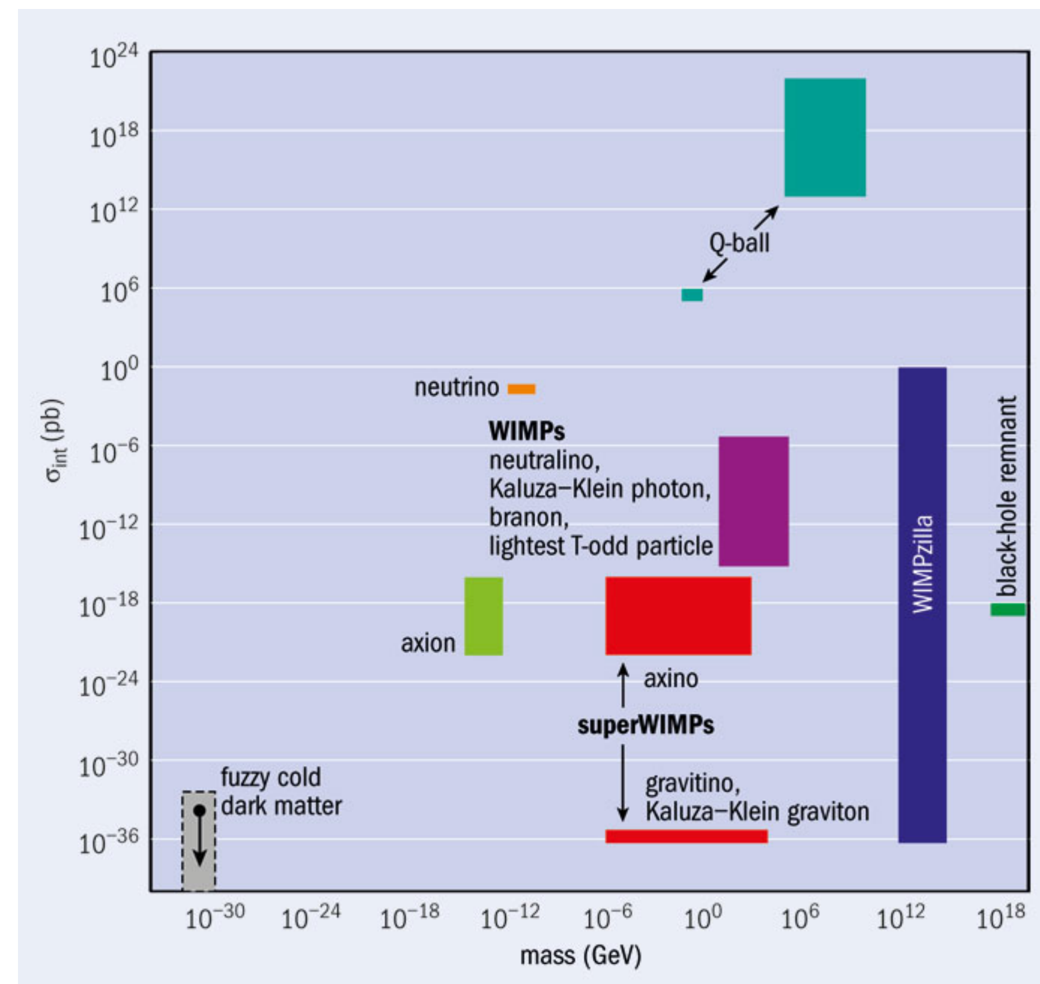
- Feels Gravity > Currently evidences come only thru this
- (Color) Charge neutral
- Its lifetime >> Age of Universe
- $\rho(\simeq m) \gg \ p(\simeq 0)$ (Nonrel.)
- $\Omega_{\rm DM} \sim 5 \ \Omega_{\rm Baryon}$
- $\rho_{\rm local} \sim 0.3 {\rm GeV/cm}^3$
- It forms a halo, not a disk

UNKNOWNS

- Mass, Spin ?
- How many species ?
- Any internal quantum #'s ?
- Any internal structures ?
- Interactions w/ SM particles ?
- DM self int. ? ($\sigma_{\chi\chi}/m_\chi \lesssim 1 g/cm^2$)
- Almost nothing known about particle physics nature of DM

DM models in the market : Mass & Couplings ?

- WIMP, SIMP, ELDERS,…
- Axion (axino), gravitino, sterile ν
- PBH (Primordial Blackhole)
- Fuzzy DM (Scalar Field DM)
- Topological objects
- Some DM models also solve another particle physics problems (🏌🐦🐦 ??)
- More than Baskin Robbins 31…



Portals to DM

- Higgs portal : $H^\dagger HS,\ H^\dagger HS^2,\ H^\dagger H\phi^\dagger\phi$
- U(1) Vector portal : $\epsilon B_{\mu\nu}X^{\mu\nu}$
- Neutrino portal : $\overline{N_R}(\widetilde{H}\,l_L + \phi^\dagger\psi)$
- (Dark) Axion portal (HSLee et al)
- So on & on & on …
- <u>Eventually “Portal” is what we observe in the experiments</u>

ϕ : Dark Scalars

X_μ : Dark photon

ψ : Dark fermion
~ Sterile ν

Portals to DM

- Higgs portal : $H^\dagger HS,\ H^\dagger HS^2,\ H^\dagger H\phi^\dagger\phi$
- U(1) Vector porta
- Neutrino portal : $\overline{N_R}(\widetilde{H} l_L +$
- (Dark) Axion portal (HSLee
- So on, & on & on , …
- Eventually "Portal" is what we observe in experiments

Singlet Portals to Dark sector w/ local dark gauge sym
(Baek, Park, Ko, arXiv:1303.4280 [hep-ph])

DM stability is guaranteed by
Local gauge symmetry
OR
DM longevity is gauranteed by
Accidental global sym

Search for WIMP

- Direct Detections ; Indirect Detections (Current Universe, Early Universe) ; Collider Searches

- Quantum Force and search for the 5th force

- DM EFT/Simplified model : Not good for collider searches $\longrightarrow$ Dark Higgs is important for unitarity, gauge invariance, renormalizability (including anomaly free)

- Theoretical consistency important for DM model buildings and phenomenology study

Dark Gauge Symmetry

Z2 real scalar DM

- Simplest DM model with Z2 symmetry : $S \to -S$

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

- Global Z2 could be broken by gravity effects (higher dim operators)
- e.g. consider Z2 breaking dim-5 op : $\frac{1}{M_{\text{Planck}}} S O_{\text{SM}}^{(4)}$
- Lifetime of EW scale mass “S” is too short to be a DM
- Similarly for singlet fermion DM

Fate of CDM with Z2 sym

(Baek,Ko,Park,arXiv:1303.4280)

Consider Z_2 breaking operators such as

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

keeping dim-4 SM operators only

3 3

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

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

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

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:

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

Problematic !

Perfectly fine !

Higgs is not good for DM stability/longevity

Have to choose dark Higgs charge judiciously
Unless you can be patient with excessive fine tuning

- These arguments will apply to DM models based on ad hoc symmetries (Z_2,Z_3 etc.)

- One way out is to implement Z_2 symmetry as local U(1) symmetry (arXiv:1407.6588 with Seungwon Baek and Wan-Il Park);

- See a paper by Ko and Tang on local Z_3 scalar DM, and another by Ko, Omura and Yu on inert 2HDM with local $U(1)_H$

- DM phenomenology richer and DM stability/ longevity on much solider ground arXiv:1407.6588 w/ WIPark and SBaek

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

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

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

Unbroken Local Z2 symmetry

Gauge models for excited DM

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

The heavier state decays into the lighter state

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

Local dark gauge symmetry

- Better to use local gauge symmetry for DM stability
  (Baek,Ko,Park,arXiv:1303.4280)

- 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, massless photon
- 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)

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 focus on the roles of (light) dark Higgs boson

Role of Dark Higgs

HP DM @ LHC

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

2 more relevant parameters in UV completions

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

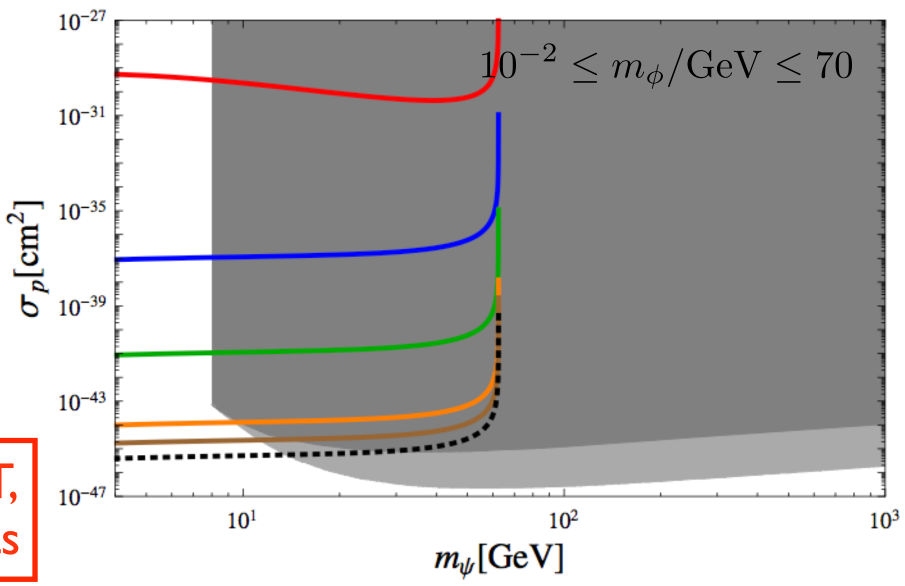
$$\mathcal{L}_{\rm fermion} = \overline{\psi}\left[i\gamma \cdot \partial - m_\psi \right] \psi - \frac{\lambda_{H\psi}}{\Lambda} H^\dagger H \, \overline{\psi}\psi$$

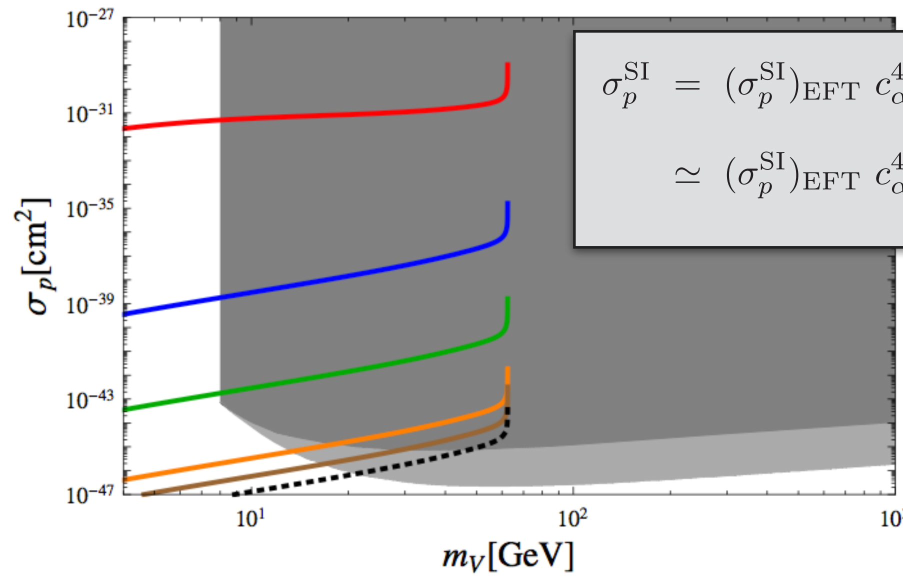
$$\mathcal{L}_{\rm vector} = -\frac{1}{4} V_{\mu\nu} V^{\mu\nu} + \frac{1}{2} m_V^2 V_\mu V^\mu + \frac{1}{4}\lambda_V (V_\mu V^\mu)^2 + \frac{1}{2}\lambda_{HV} H^\dagger H V_\mu V^\mu .$$

EFT

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

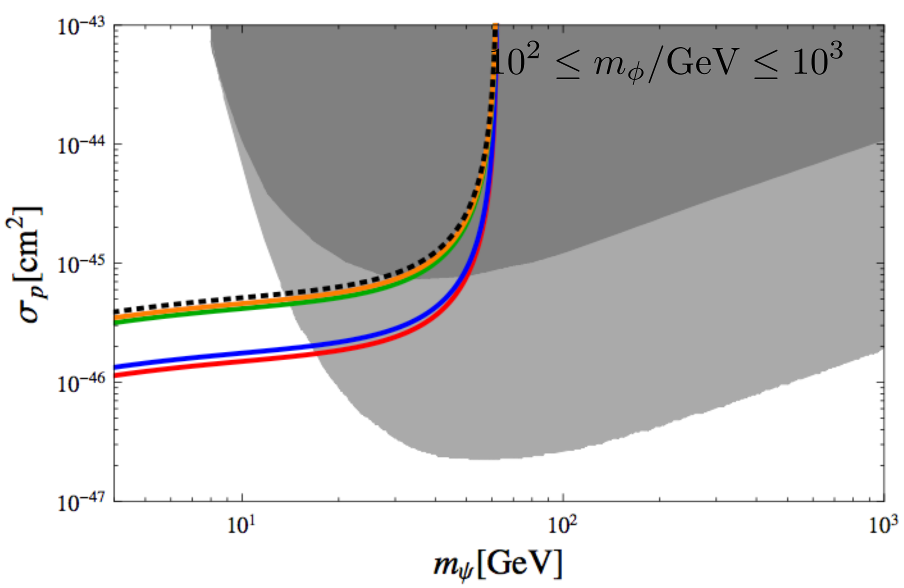
$$\mathcal{L}_{\rm VDM} = -\frac{1}{4} V_{\mu\nu} V^{\mu\nu} + D_\mu \Phi^\dagger D^\mu \Phi - \lambda_\Phi \left(\Phi^\dagger \Phi - \frac{v_\Phi^2}{2} \right)^2 - \lambda_{\Phi H} \left(\Phi^\dagger \Phi - \frac{v_\Phi^2}{2} \right) \left(H^\dagger H - \frac{v_H^2}{2} \right)$$

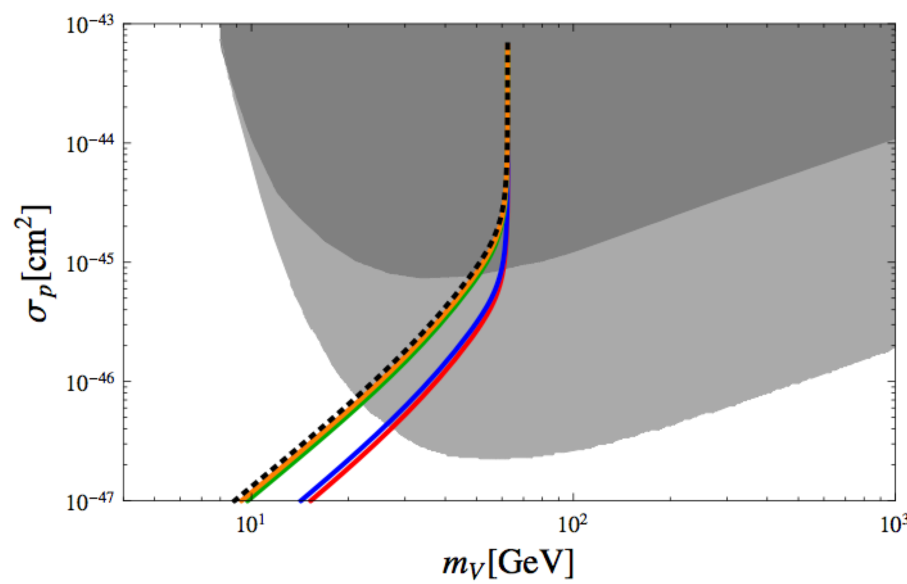




$$\sigma_p^{\rm SI} = (\sigma_p^{\rm SI})_{\rm EFT} \, c_\alpha^4 m_h^4 \mathcal{F}(m_{\rm DM}, \{m_i\}, v) \simeq (\sigma_p^{\rm SI})_{\rm EFT} \, c_\alpha^4 \left(1 - \frac{m_h^2}{m_2^2} \right)^2$$

Dashed curves:EFT, ATLAS,CMS results





Invisible H decay into a pair of VDM

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

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

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

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

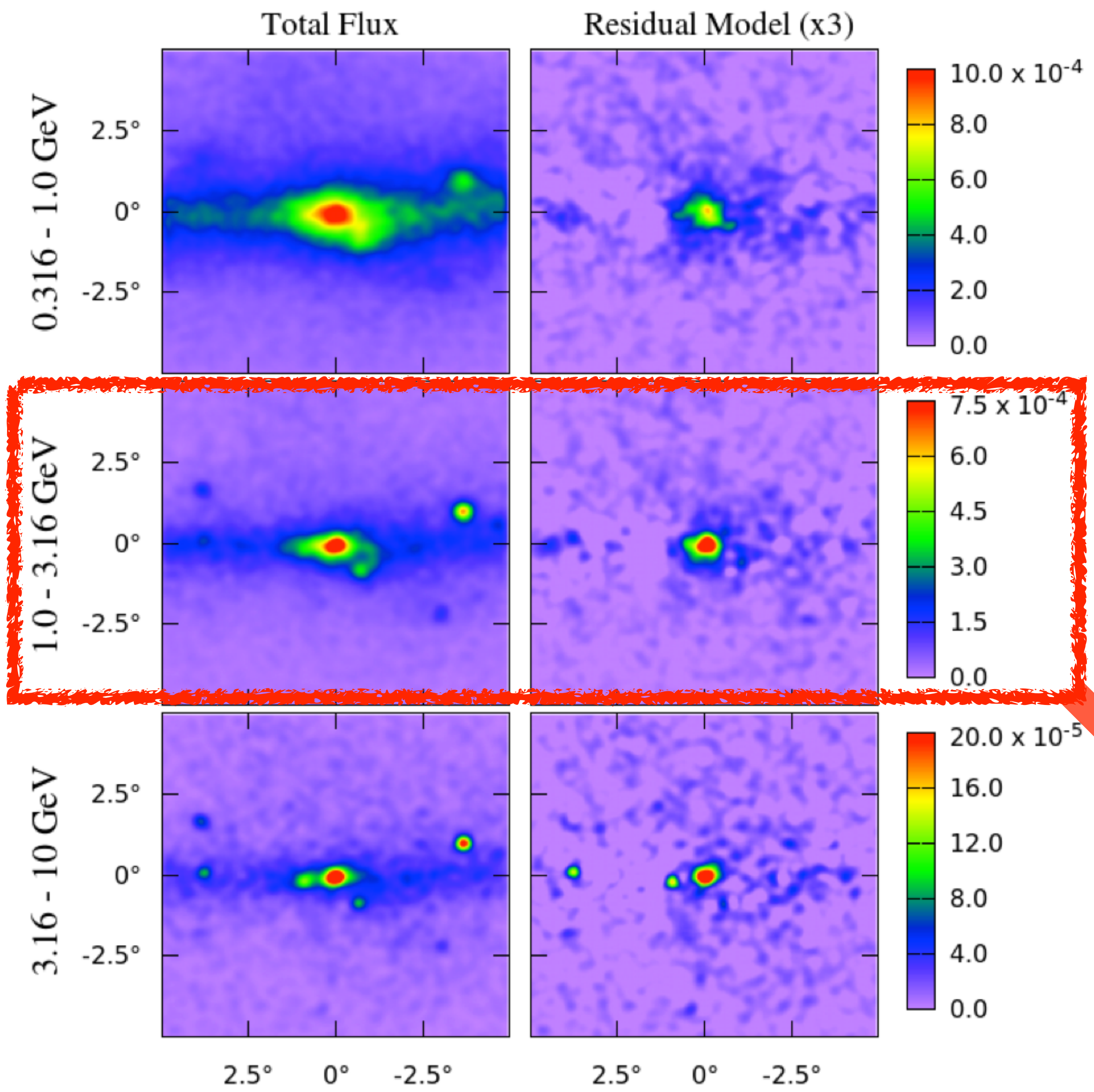
VS.

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

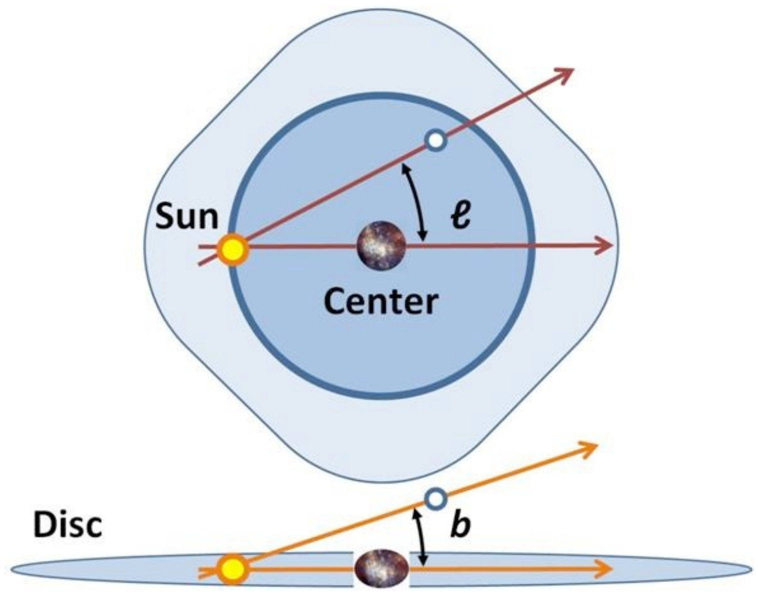
Invisible H decay width : finite for $m_V \to 0$
in unitary/renormalizable model
NB: it is infinite in the effective VDM model

Fermi-LAT γ-ray excess

- Gamma-ray excess in the direction of GC



[1402.6703, T. Daylan et.al.]

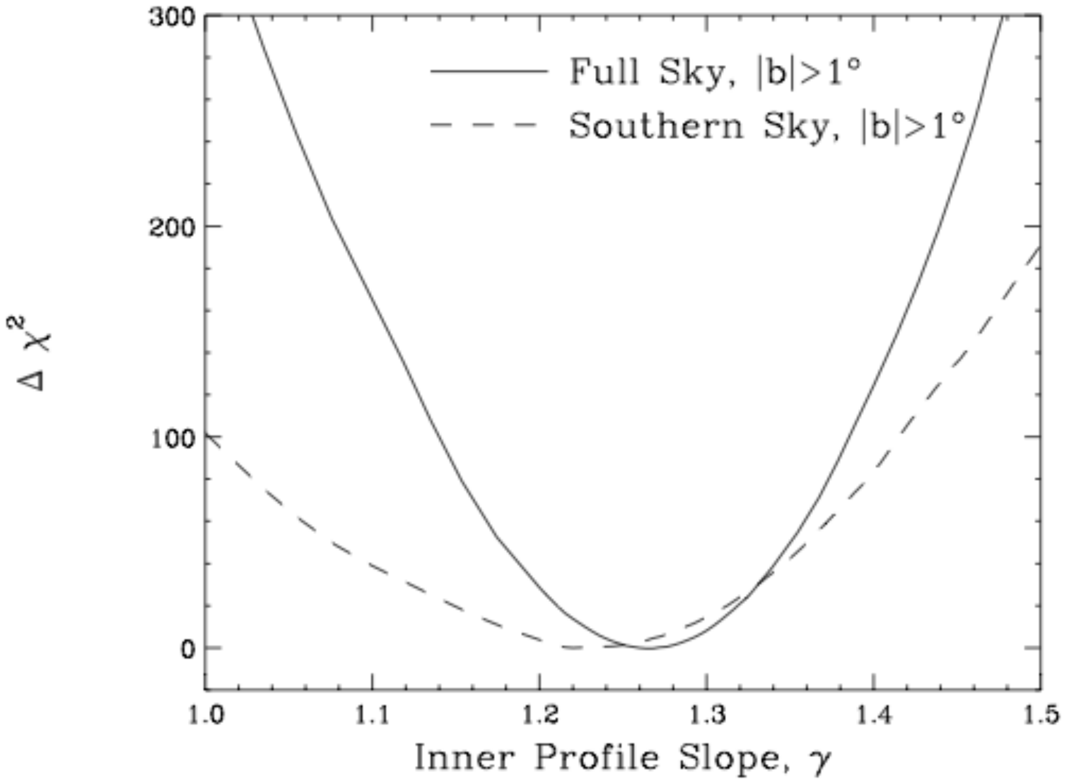


$$\text{GC} : b \sim l \lesssim 0.1^\circ$$

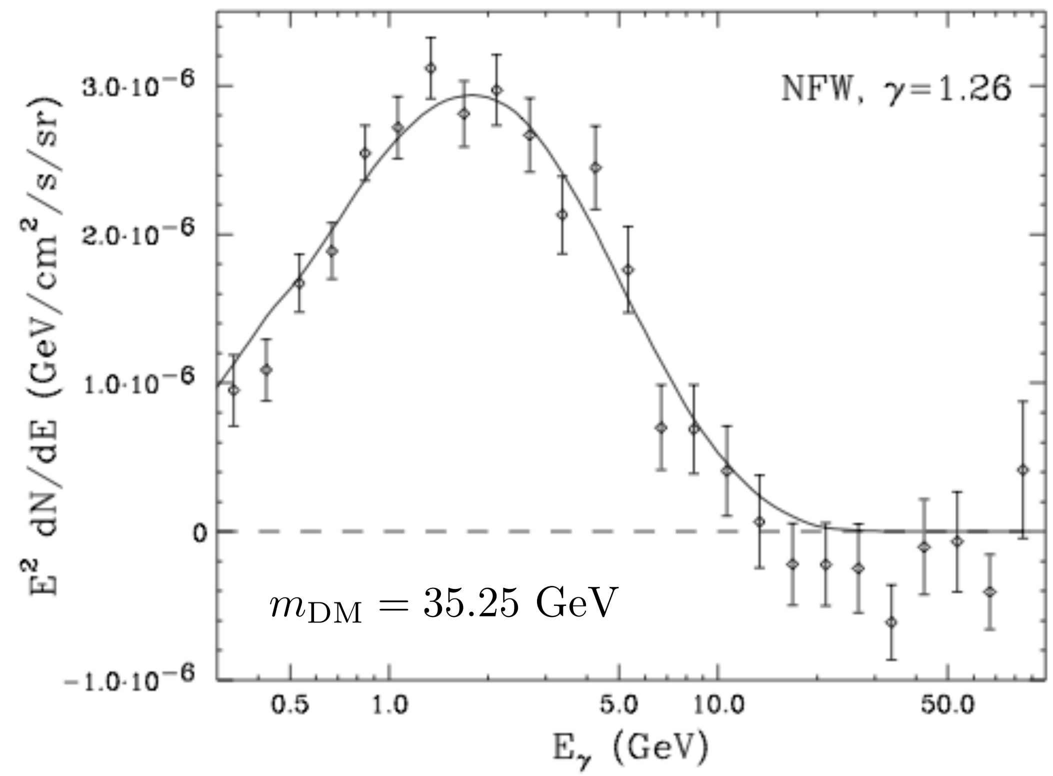
extended

GeV scale excess!

• A DM interpretation



$\mathrm{DM} + \mathrm{DM} \to b\bar{b}$ with $\sigma v = 1.7 \times 10^{-26} \mathrm{cm}^3/\mathrm{s}$



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

• Millisecond Pulars (astrophysical alternative)

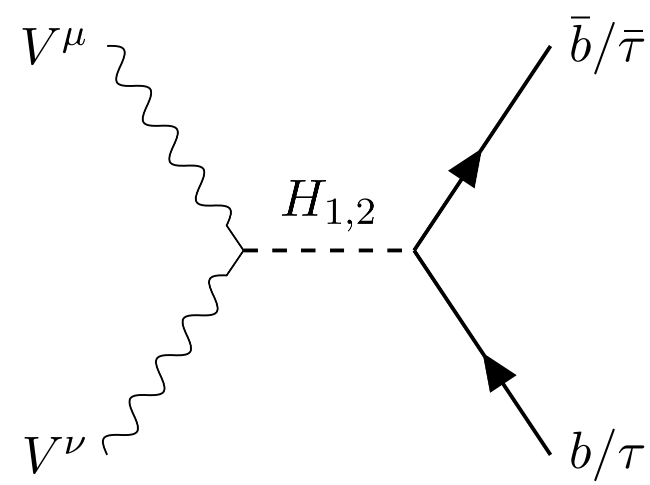
It may or may not be the main source, depending on

- 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]
To appear in JCAP (2014)



H2 : 125 GeV Higgs
H1 : absent in EFT

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

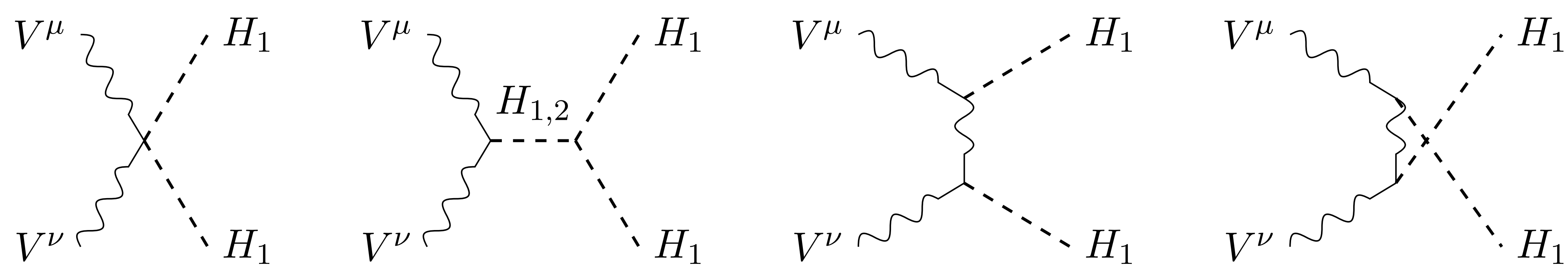


Figure 3. Dominant s/t-channel production of H_1s that decay dominantly to $b + \bar{b}$

Importance of VDM with Dark Higgs Boson

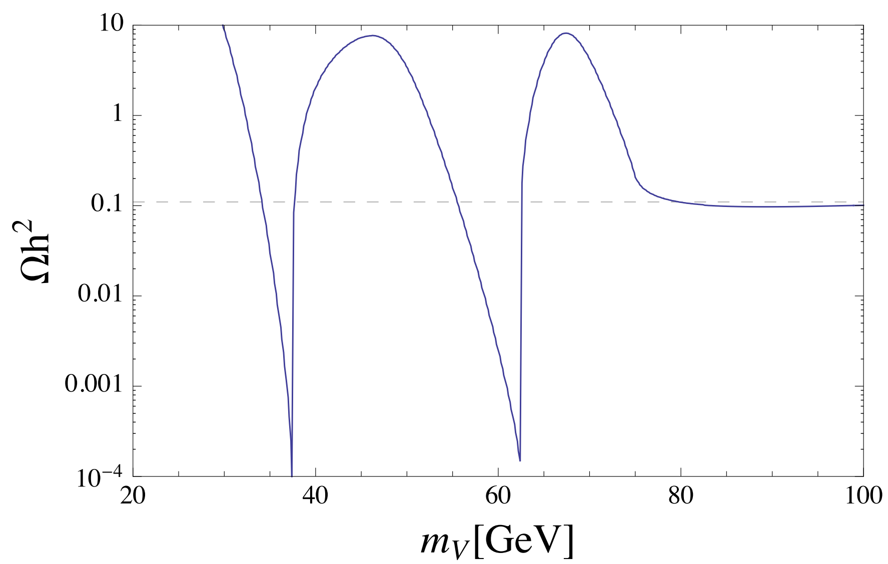


Figure 4. Relic density of dark matter as function of m_ψ for $m_h = 125$, $m_\phi = 75\,\mathrm{GeV}$, $g_X = 0.2$, and $\alpha = 0.1$.

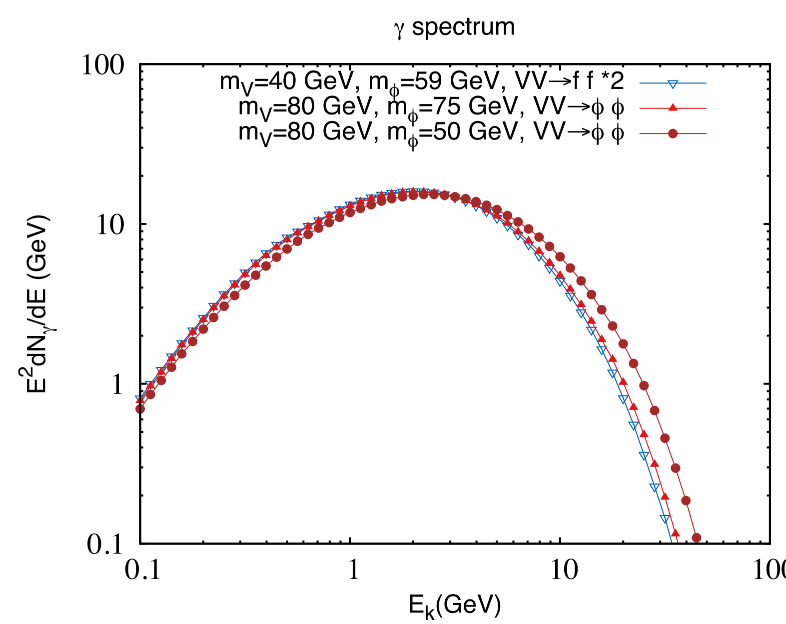


Figure 5. Illustration of γ spectra from different channels. The first two cases give almost the same spectra while in the third case γ is boosted so the spectrum is shifted to higher energy.

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

Baek, Ko, MHPark,WIPark, CHYu
arXiv:1506.06556 [hep-ph]

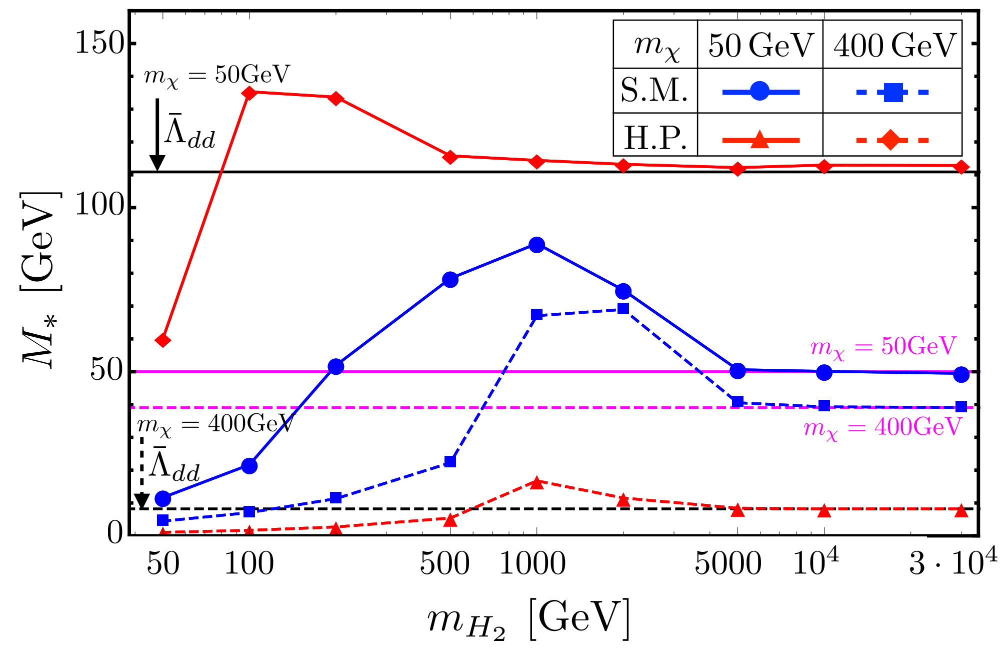
- EFT : Effective operator $\mathcal{L}_{int} = \frac{m_q}{\Lambda_{dd}^3}\bar{q}q\bar{\chi}\chi$
- S.M.: Simple scalar mediator S of
  $\mathcal{L}_{int} = \left(\frac{m_q}{v_H}\sin\alpha\right) S\bar{q}q - \lambda_s \cos\alpha S\bar{\chi}\chi$
- H.M.: A case where a Higgs is a mediator
  $\mathcal{L}_{int}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

$$\mathcal{L}_{\rm int} = -(H_1\cos\alpha + H_2\sin\alpha)\left[\sum_f \frac{m_f}{v_H}\bar{f}f - \frac{2m_W^2}{v_H}W_\mu^+W^{-\mu} - \frac{m_Z^2}{v_H}Z_\mu Z^\mu\right] + \lambda(H_1\sin\alpha - H_2\cos\alpha)\bar{\chi}\chi$$

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

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

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



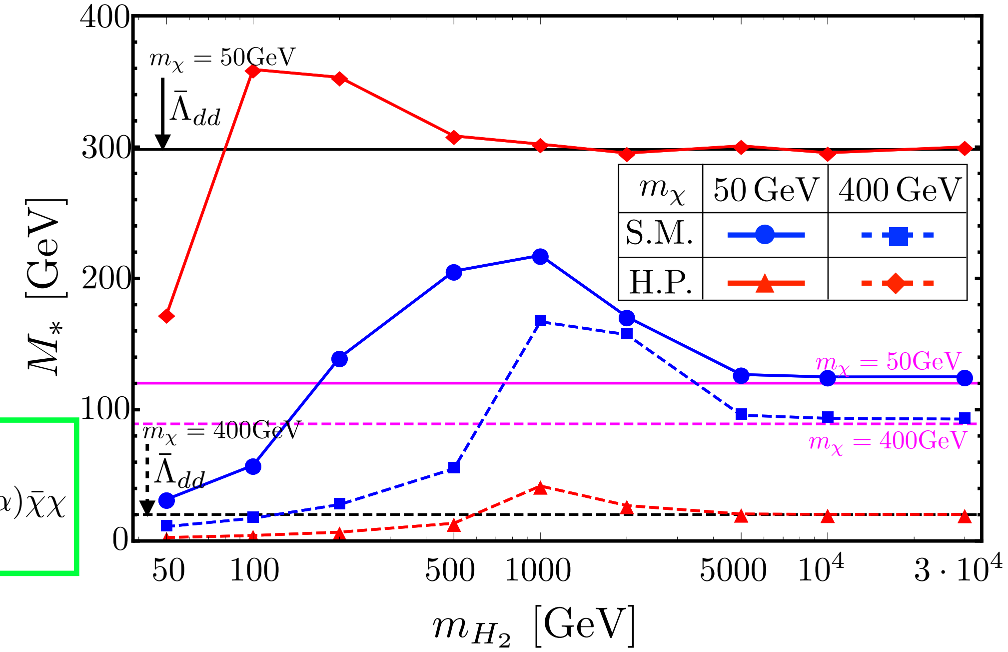


FIG. 3: The experimental bounds on M_* at 90% C.L. as a function of m_{H_2} (m_S in S.M. case) in the monojet+$\not{E}_T$ search (upper) and $t\bar{t} + \not{E}_T$ search (lower). Each line corresponds to the EFT approach (magenta), S.M. (blue), H.M. (black), and H.P. (red), respectively. The bound of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

Higgs Strahlung

With Hirosh Yokoya (2017)

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

Differential cross section

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

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

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

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

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

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

General Comments

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

Asymtotic behavior in the full theory

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

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

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

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

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

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

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

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

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

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

Unitarity violated !

Inelastic DM for XENON1T excess

Motivations for XDM

- In the usual real scalar DM with Z_2 symmetry, DM stability is not guaranteed in the presence of high dim op's induced by gravity effects

- Better to have local gauge symmetry for absolutely stable DM (Baek,Ko,Park,arXiv:1303.4280)

- Then XDM appears quite naturally $U(1) \to Z_2$ for both scalar and fermion DM cases

- XDM : elementary or composite (dark mesons/baryons/atom…)

- NB : complex scalar DM for $U(1) \to Z_3$ [Ko, Tang, hep-ph:1402.6449, JCAP ; hep-ph:1407.5492, JCAP]

Motivations for XDM

- XDM : phenomenologically interesting possibility, used for interpretation of DAMA, 511 keV γ-ray & PAMELA e^+ excesses, and XENON1T excess, muon (g-2), etc
- Constraints from DD and Colliders are different
- Co-annihilation could be important for relic density calculations
- Usually the mass difference btw XDM & DM is put in by hand, by dim-2 for scalar and dim-3 for fermions DM cases, and dark photon is introduced
- However such theories are mathematically inconsistent and unitarity will be violated in some channels, when (X)DM couples to dark photon

Usual Approaches

For example, Harigaya, Nagai, Suzuki, arXiv:2006.11938

$$V(\phi) = m^2|\phi|^2 + \Delta^2\left(\phi^2 + \phi^{*2}\right), \qquad (1)$$

This term is problematic : Current is not conserved

$$\mathcal{L} = g_D A'^{\mu}\left(\chi_1\partial_\mu\chi_2 - \chi_2\partial_\mu\chi_1\right) + \epsilon e A'_\mu J^\mu_{\mathrm{EM}},$$

Similarly for the fermion DM case

$\Delta\ \overline{\psi^C}\psi$: **breaks U(1) explicitly**

Without dark Higgs

P.Ko, T.Matsui, Yi-Lei Tang, arXiv:1910.04311, Appendix A

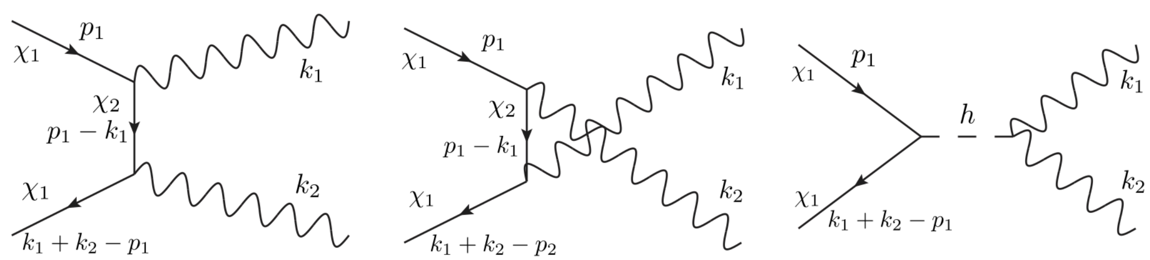


Figure 9: $\chi_1\chi_1 \to \gamma'\gamma'$ diagrams. Compared with the Higgsless soft-breaking model, the third diagram arises in our model

- Only the first two diagrams if the mass gap is given by hand
- The third diagram if the mass gap is generated by dark Higgs mechanism
- Without the last diagram, the amplitude violates unitarity at large $E_{\gamma'}$

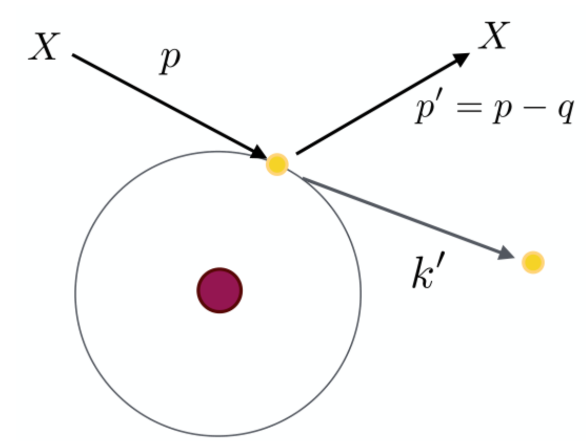
XENON1T Excess

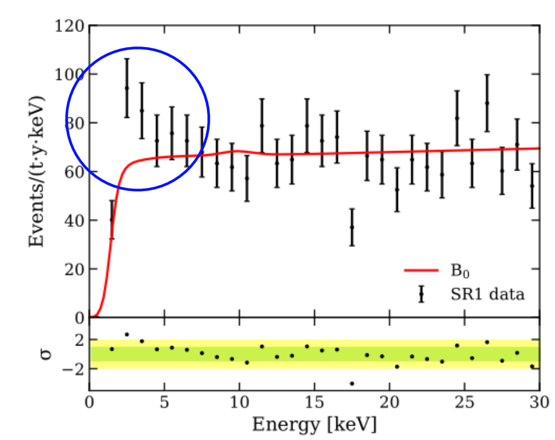
(Scalar XDM, Fermion XDM)

XENON1T Excess

- Excess between 1-7 keV
  - Expectated : 232 ± 15 , Observed : 285
  - Deviation ~ 3.5 σ
- Tritium contamination
  - Long half lifetime (12.3 years)
  - Abundant in atmosphere and cosmogenically produced in Xenon
- Solar axion
  - Produced in the Sun
  - Favored over bkgd @ 3.5 σ
- Neutrino magnetic dipole moment
  - Favored @ 3.2 σ

Electron recoil



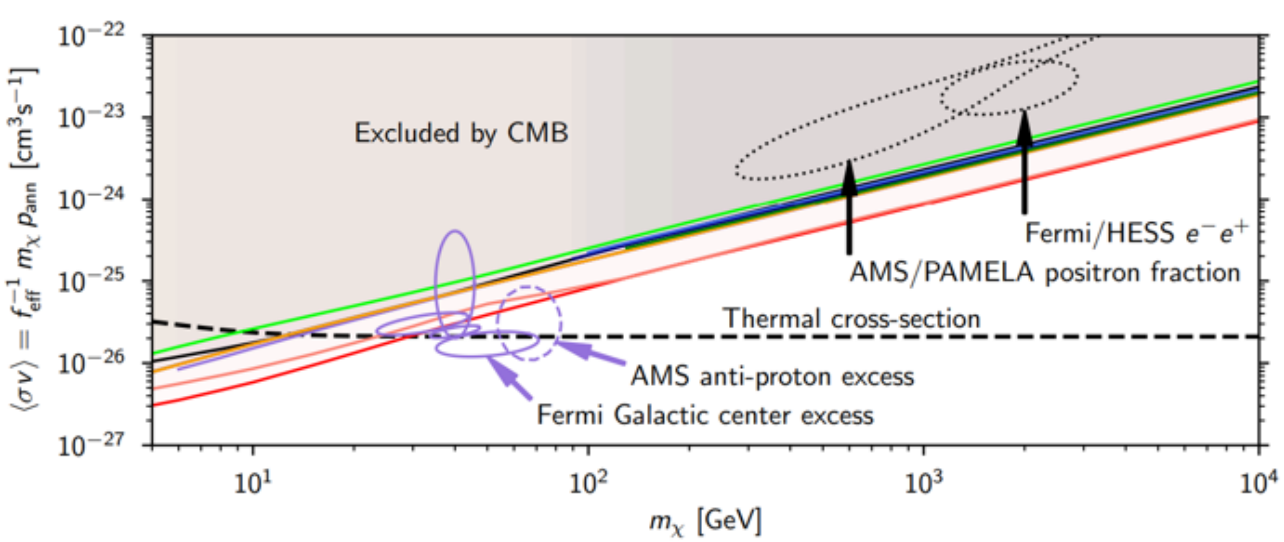


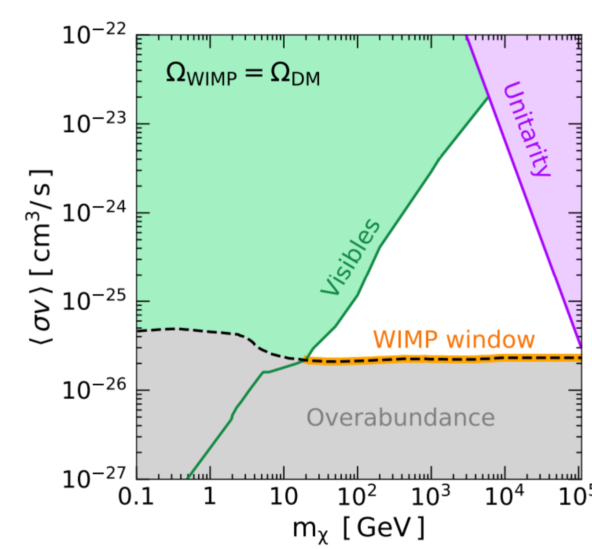
DD/CMB Constraints

- To evade stringent bounds from direct detection expt's : sub GeV DM

- CMB bound excludes thermal DM freeze-out determined by S-wave annihilation : DM annihiliation should be mainly in P-wave $\langle \sigma v \rangle \sim a + bv^2$

Planck 2018
R.K.Leane 35 al, PRD2018





Exothermic DM

- Inelastic exothermic scattering of XDM
- $XDM + e_{\text{atomic}} \to DM + e_{\text{free}}$ by dark photon exchange + kinetic mixing
- Excess is determined by $E_R \sim \delta = m_{XDM} - m_{DM}$
- Most works are based on effective/toy models where δ is put in by hand, or ignored dark Higgs
- dim-2 op for scalar DM and dim-3 op for fermion DM : soft and explicit breaking of local gauge symmetry), and include massive dark photon as well → theoretically inconsistent !

Z_2 DM models with dark Higgs

- We solve this inconsistency and unitarity issue with Krauss-Wilczek mechanism
- By introducing a dark Higgs, we have many advantages:
  - Dark photon gets massive
  - Mass gap δ is generated by dark Higgs mechanism
  - We can have DM pair annihilation in P-wave involving dark Higgs in the final states, unlike in other works

Usual Approaches

For example, Harigaya, Nagai, Suzuki, arXiv:2006.11938

$$V(\phi) = m^2|\phi|^2 + \Delta^2\left(\phi^2 + \phi^{*2}\right), \qquad (1)$$

This term is problematic

$$\mathcal{L} = g_D A'^{\mu}\left(\chi_1\partial_\mu\chi_2 - \chi_2\partial_\mu\chi_1\right) + \epsilon e A'_\mu J^\mu_{\mathrm{EM}},$$

Similarly for the fermion DM case

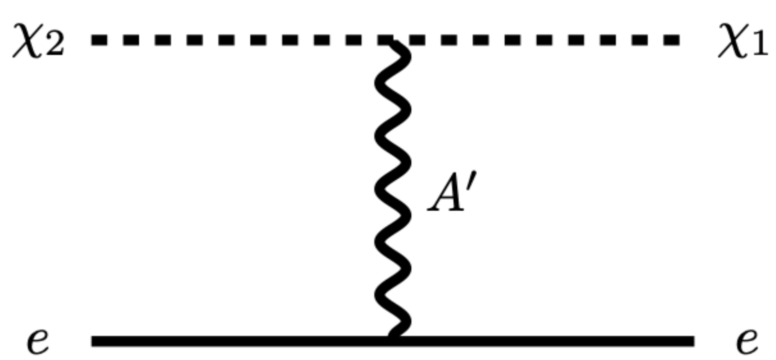


FIG. 1. Inelastic scattering of the heavier DM particle χ_2 off the electron e into the lighter particle χ_1, mediated by the dark photon A'.

- The model is not mathematically consistent, since there is no conserved current a dark photon can couple to in the massless limit
- The second term with Δ^2 breaks $U(1)_X$ explicitly, although softly

Relic Density from

$$XX^{\dagger} \to Z'^{*} \to f\bar{f}$$

(P-wave annihilation)

For example, Harigaya, Nagai, Suzuki, arXiv:2006.11938

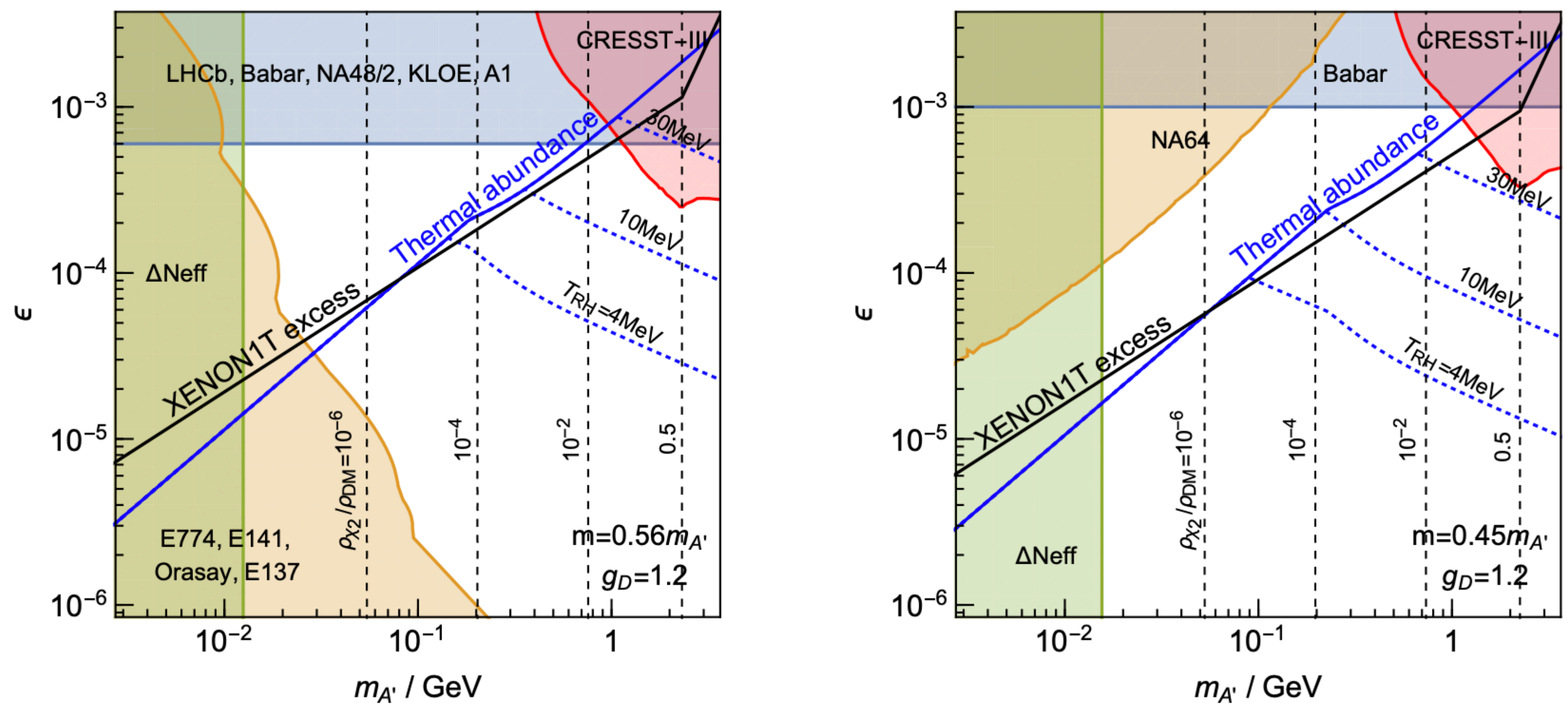


FIG. 4. The required value of ϵ to explain the observed excess of events at XENON1T in terms of the dark photon mass $m_{A'}$ (black solid lines). The left and right panels correspond to the cases of $m > m_{A'}/2$ and $m < m_{A'}/2$ respectively. We assume $g_D = 1.2$ in both cases. The blue lines denote the required value of ϵ to obtain the observed DM abundance by the thermal freeze-out process, discussed in Sec. IV. The solid lines correspond to the case without any entropy production. The dashed lines assume freeze-out during a matter dominated era and the subsequent reheating at $T_{\rm RH}$, which suppresses the DM abundance by a factor of $(T_{\rm RH}/T_{\rm FO})^3$. The black dashed lines denote the mass density of χ_2 normalized by the total DM density. The shaded regions show the constraints from dark radiation and various searches for the dark photon A' which are discussed in Sec. V.

- Only scalar DM can be in P-wave annihilation w/o dark Higgs
- Fermion DM impossible unless dark Higgs is included

Scalar XDM (X_R & X_I)

Field	ϕ	X	χ
U(1) charge	2	1	1

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

$$X = \frac{1}{\sqrt{2}}(X_R + iX_I),$$

$$H = \begin{pmatrix} 0 \\ \frac{1}{\sqrt{2}}(v_H + h_H) \end{pmatrix}, \quad \phi = \frac{1}{\sqrt{2}}(v_\phi + h_\phi),$$

$$\mathcal{L} \supset \epsilon g_X s_W Z^\mu(X_R\partial_\mu X_I - X_I\partial_\mu X_R) - \frac{g_Z}{2}Z_\mu\overline{\nu}_L\gamma^\mu\nu_L.$$

$$\mathcal{L} \supset g_X Z'^\mu(X_R\partial_\mu X_I - X_I\partial_\mu X_R) - \epsilon\, e c_W Z'_\mu\overline{e}\gamma^\mu e,$$

$U(1) \to Z_2$ by $v_\phi \neq 0 : X \to -X$

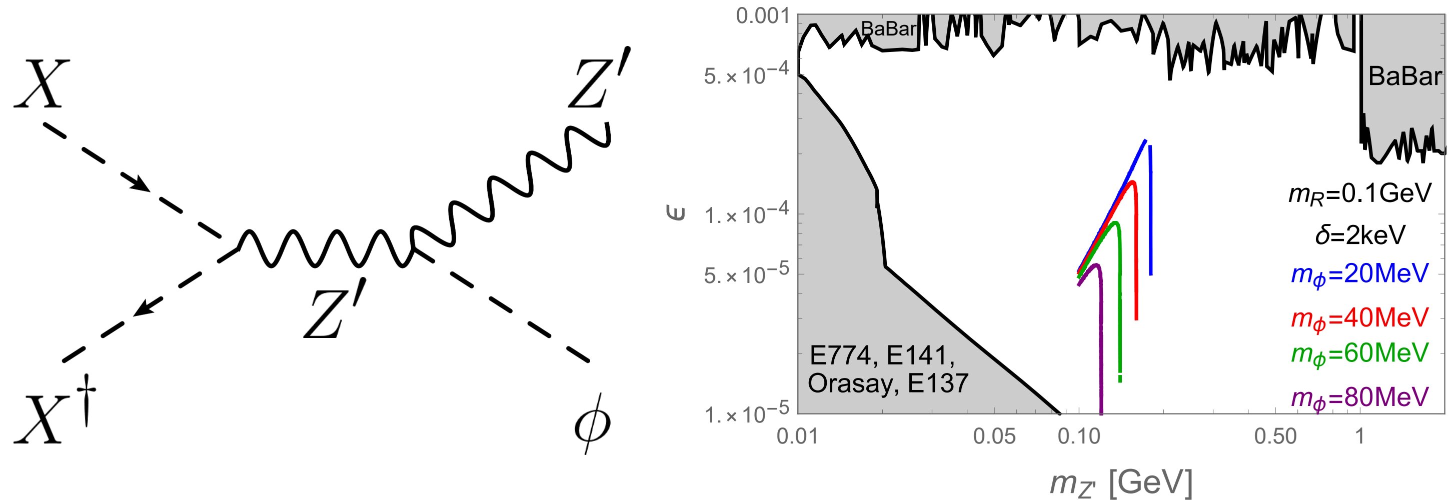


FIG. 1: (*left*) Feynman diagrams relevant for thermal relic density of DM: $XX^\dagger \to Z'\phi$ and (*right*) the region in the $(m_{Z'}, \epsilon)$ plane that is allowed for the XENON1T electron recoil excess and the correct thermal relic density for scalar DM case for $\delta = 2$ keV : (a) $m_{\rm DM} = 0.1$ GeV. Different colors represents $m_\phi = 20, 40, 60, 80$ MeV. The gray areas are excluded by various experiments, from BaBar [61], E774 [62], E141 [63], Orasay [64], and E137 [65], assuming $Z' \to X_R X_I$ is kinematically forbidden.

P-wave annihilation x-sections

Scalar DM : $XX^\dagger \to Z'^* \to Z'\phi$

$$\sigma v \simeq \frac{g_X^4 v^2}{384\pi\, m_X^4 (4m_X^2 - m_{Z'}^2)^2} \left(16 m_X^4 + m_{Z'}^4 + m_\phi^4 + 40 m_X^2 m_{Z'}^2 - 8 m_X^2 m_\phi^2 - 2 m_{Z'}^2 m_\phi^2\right)$$
$$\times \left[\left\{4m_X^2 - (m_{Z'} + m_\phi)^2\right\} \left\{4m_X^2 - (m_{Z'} - m_\phi)^2\right\} \right]^{1/2} + \mathcal{O}(v^4), \qquad (10)$$

Fermion XDM (χ_R & χ_I)

$$\mathcal{L} = -\frac{1}{4}\hat{X}^{\mu\nu}\hat{X}_{\mu\nu} - \frac{1}{2}\sin\epsilon\hat{X}_{\mu\nu}B^{\mu\nu} + \overline{\chi}\left(i\not{D} - m_\chi\right)\chi + D_\mu\phi^\dagger D^\mu\phi$$
$$- \mu^2\phi^\dagger\phi - \lambda_\phi|\phi|^4 - \frac{1}{\sqrt{2}}\left(y\phi^\dagger\overline{\chi^C}\chi + \text{h.c.}\right) - \lambda_{\phi H}\phi^\dagger\phi H^\dagger H$$

$$\chi = \frac{1}{\sqrt{2}}(\chi_R + i\chi_I),$$
$$\chi^c = \frac{1}{\sqrt{2}}(\chi_R - i\chi_I),$$
$$\chi_R^c = \chi_R, \quad \chi_I^c = \chi_I,$$

$$\mathcal{L} = \frac{1}{2}\sum_{i=R,I}\overline{\chi_i}\left(i\not{\partial} - m_i\right)\chi_i - i\frac{g_X}{2}(Z'_\mu + \epsilon s_W Z_\mu)\left(\overline{\chi_R}\gamma^\mu\chi_I - \overline{\chi_I}\gamma^\mu\chi_R\right)$$
$$- \frac{1}{2}yh_\phi\left(\overline{\chi_R}\chi_R - \overline{\chi_I}\chi_I\right),$$

$U(1) \rightarrow Z_2$ by $v_\phi \neq 0 : \chi \rightarrow -\chi$

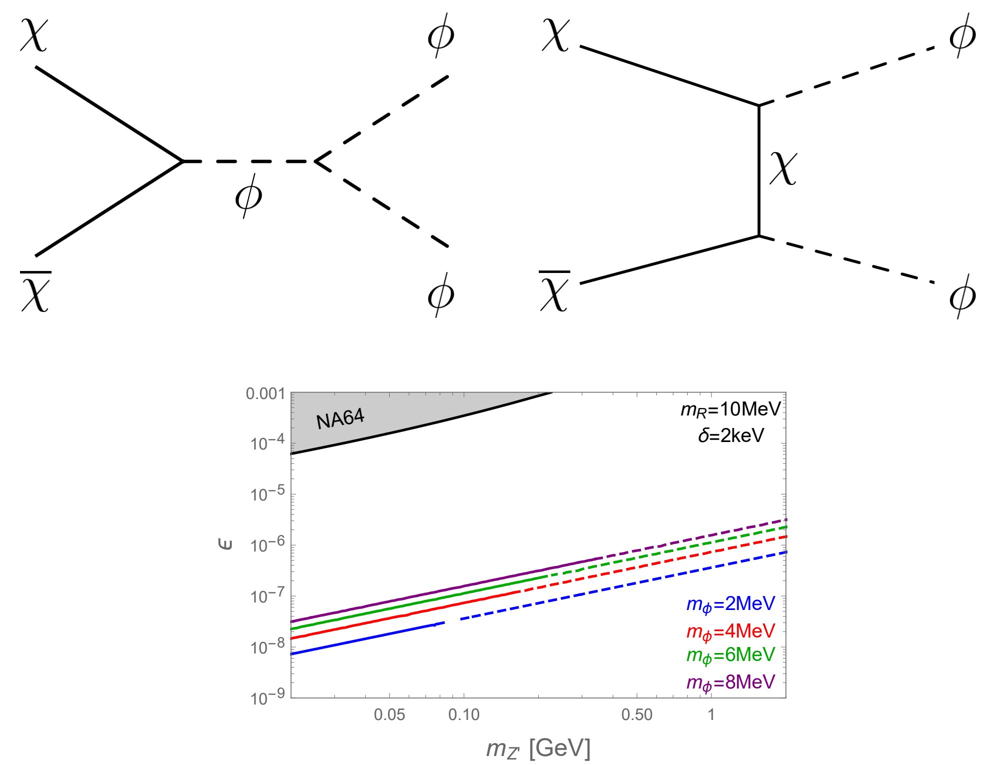


FIG. 2: (*top*) Feyman diagrams for $\chi\bar{\chi} \to \phi\phi$. (*bottom*) the region in the $(m_{Z'}, \epsilon)$ plane that is allowed for the XENON1T electron recoil excess and the correct thermal relic density for fermion DM case for $\delta = 2$ keV and the fermion DM mass to be $m_R = 10$ MeV. Different colors represents $m_\phi = 2, 4, 6, 8$ MeV. The gray areas are excluded by various experiments, assuming $Z' \to \chi_R \chi_I$ is kinematically allowed, and the experimental constraint is weaker in the ϵ we are interested in, compared with the scalar DM case in Fig. 1 (right). We also show the current experimental bounds by NA64 [66].

P-wave annihilation x-sections

Scalar DM : $XX^\dagger \to Z'^* \to Z'\phi$

$$\sigma v \simeq \frac{g_X^4 v^2}{384\pi\, m_X^4 (4m_X^2 - m_{Z'}^2)^2} \left(16m_X^4 + m_{Z'}^4 + m_\phi^4 + 40m_X^2 m_{Z'}^2 - 8m_X^2 m_\phi^2 - 2m_{Z'}^2 m_\phi^2\right)$$
$$\times \left[\left\{4m_X^2 - (m_{Z'} + m_\phi)^2\right\} \left\{4m_X^2 - (m_{Z'} - m_\phi)^2\right\} \right]^{1/2} + \mathcal{O}(v^4), \qquad (10)$$

Fermion DM : $\chi\bar{\chi} \to \phi\phi$

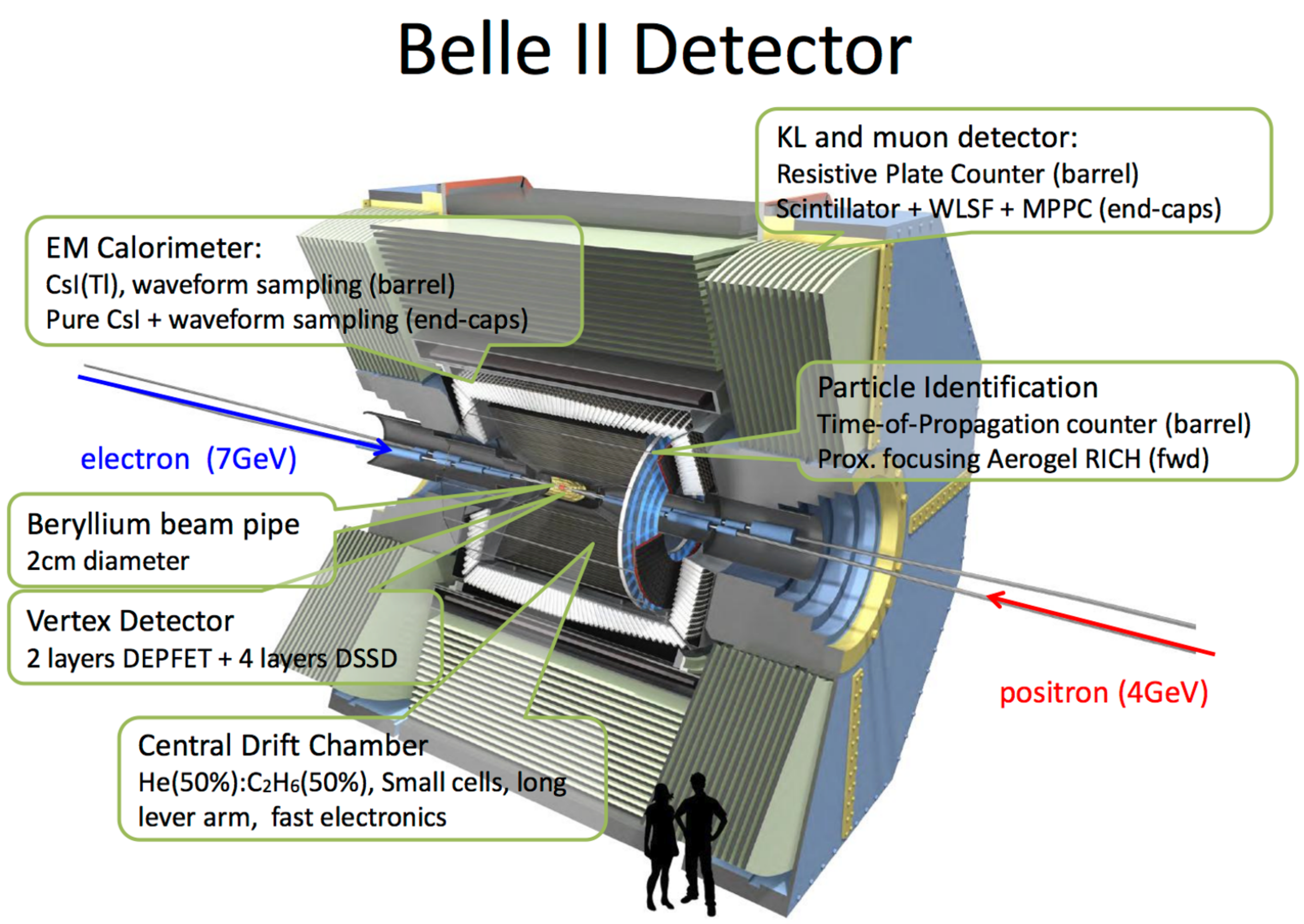
$$\sigma v = \frac{y^2 v^2 \sqrt{m_\chi^2 - m_\phi^2}}{96\pi m_\chi} \left[\frac{27\lambda_\phi^2 v_\phi^2}{(4m_\chi^2 - m_\phi^2)^2} + \frac{4y^2 m_\chi^2 (9m_\chi^4 - 8m_\chi^2 m_\phi^2 + 2m_\phi^4)}{(2m_\chi^2 - m_\phi^2)^4} \right] + \mathcal{O}(v^4), \qquad (28)$$

Crucial to include "dark Higgs" to have DM pair annihilation in P-wave

Determination of (M,spin) @ Belle2

Work in preparation with
DongWoo Kang, Chih-Ting Lu

Search for long-lived particles in inelastic DM models at Belle II



The tracking resolution of electron/muon momenta in the drift chamber detector is given by

$$\sigma_{p_{l^\pm}}/p_{l^\pm} = 0.0011 p_{l^\pm}[GeV] \oplus 0.0025/\beta$$

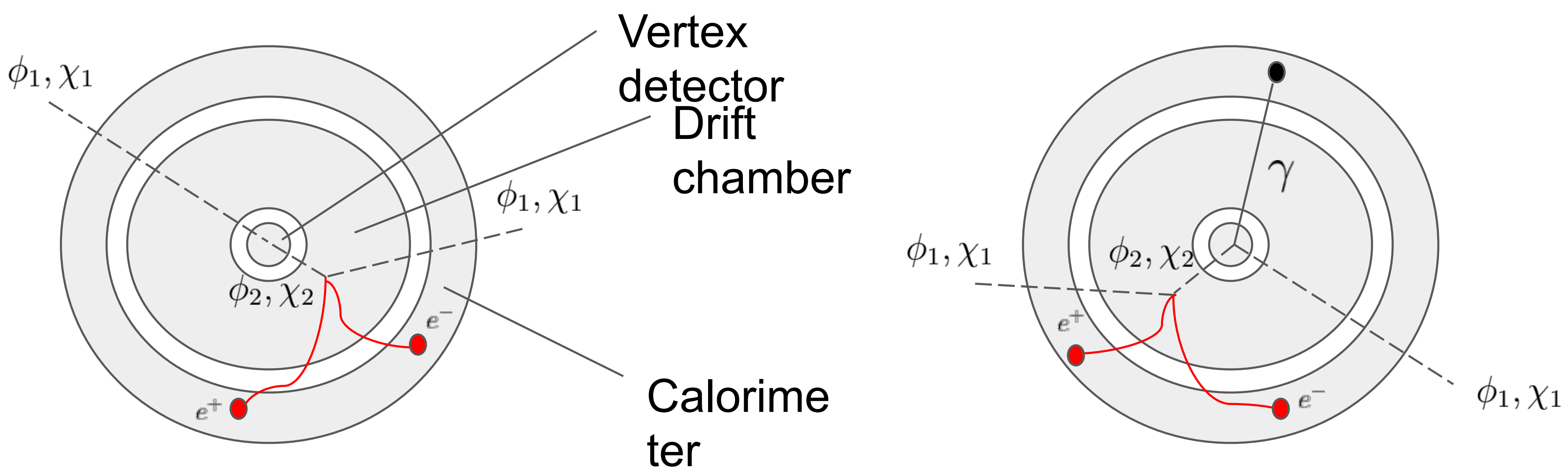
The resolution of photon momenta in the calorimeter

$$\sigma_{E_\gamma}/E_\gamma = 2\%$$

The resolution for the displaced vertex of lepton pair

$$\sigma_{r_{DV}} = 26\mu m$$

Displaced signature examples in Belle II detector (xy-plane)



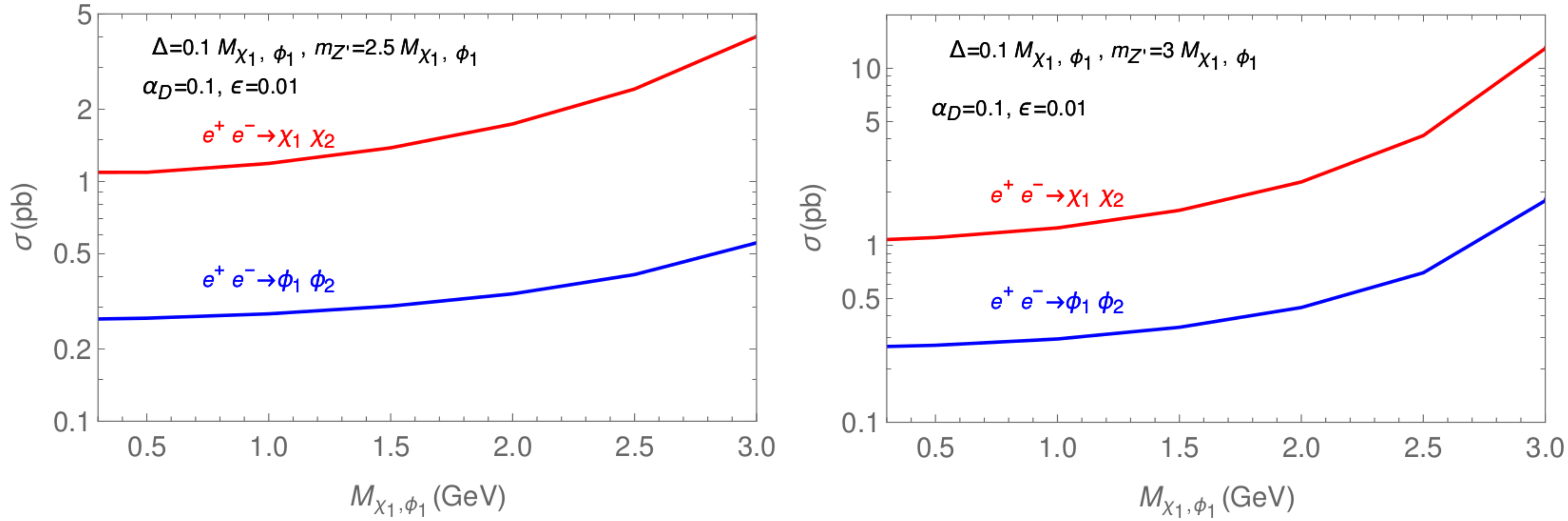
$$e^+e^- \to \phi_1\phi_2 \to \phi_1\phi_1 e^+e^-$$
$$e^+e^- \to \chi_1\chi_2 \to \chi_1\chi_1 e^+e^-$$

$$e^+e^- \to \phi_1\phi_2\gamma \to \phi_1\phi_1 e^+e^-\gamma$$
$$e^+e^- \to \chi_1\chi_2\gamma \to \chi_1\chi_1 e^+e^-\gamma$$

Any difference for fermion and scalar boson pair productions @ colliders ?

1. The cross sections for fermion and scalar boson pair productions are scaled by $\beta^{1/2}$ and $\beta^{3/2}$ respectively, where β is the velocity of the final state particle in the center-of-mass frame.

2. Hence, one can expect the production of the scalar pair is suppressed by an extra factor of β compared with the fermionic case.



If ϕ_2, χ_2 are long-lived, can we determine their spins at colliders ?

In the center of mass (CM) frame, the normalized differential cross section can be written as

$$\frac{1}{\sigma}\frac{d\sigma}{dcos\theta} = \frac{3}{4}(1 - cos^2\theta)$$

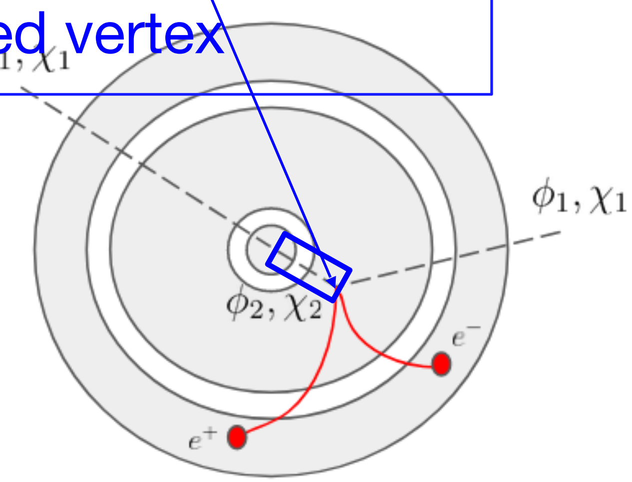
for the scalar case $(e^+e^- \rightarrow \phi_2\phi_1)$

$$\frac{1}{\sigma}\frac{d\sigma}{dcos\theta} = \frac{(1 - \frac{(M_{\chi 2}^2 - M_{\chi 1}^2)^2}{s^2} + \frac{4M_{\chi 1}M_{\chi 2}}{s})\xi + \xi^{3/2}cos^2\theta}{2(1 - \frac{(M_{\chi 2}^2 - M_{\chi 1}^2)^2}{s^2} + \frac{4M_{\chi 1}M_{\chi 2}}{s})\xi + \frac{2}{3}\xi^{3/2}}$$

for the fermion case $(e^+e^- \rightarrow \chi_2\chi_1)$

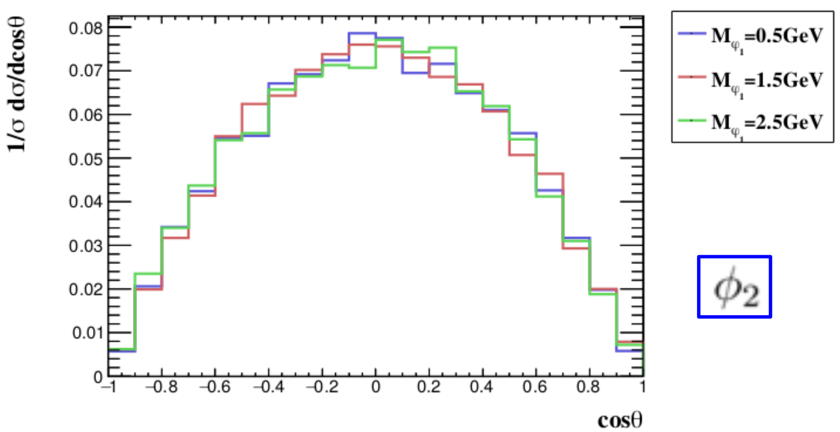
where $\xi = \sqrt{1 - \frac{2(M_{\chi 2}^2 + M_{\chi 1}^2)}{s} + \frac{(M_{\chi 2}^2 - M_{\chi 1}^2)^2}{s^2}}$

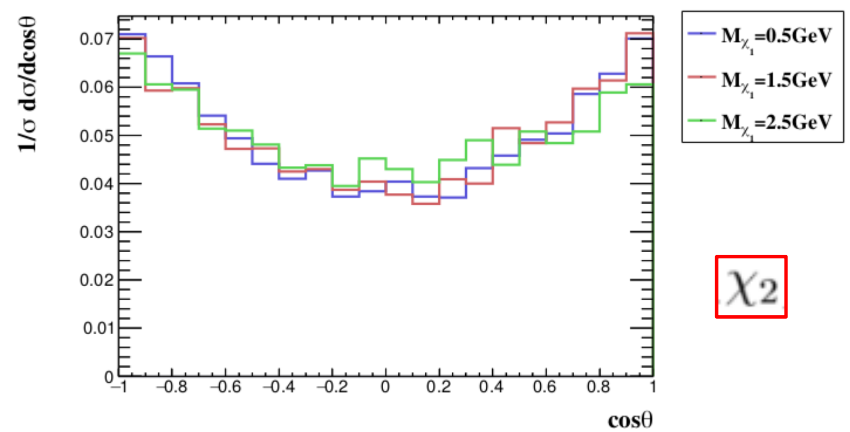
We need to know the direction of the displaced vertex



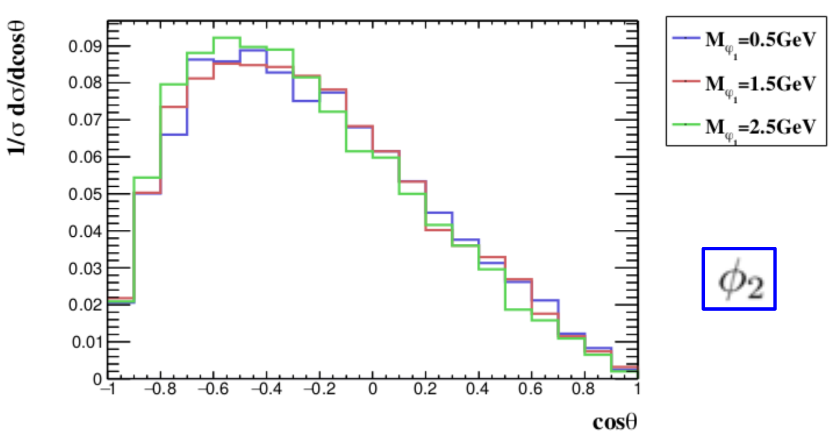
Note θ is the direction of ϕ_2 , χ_2 relative to the beam direction.

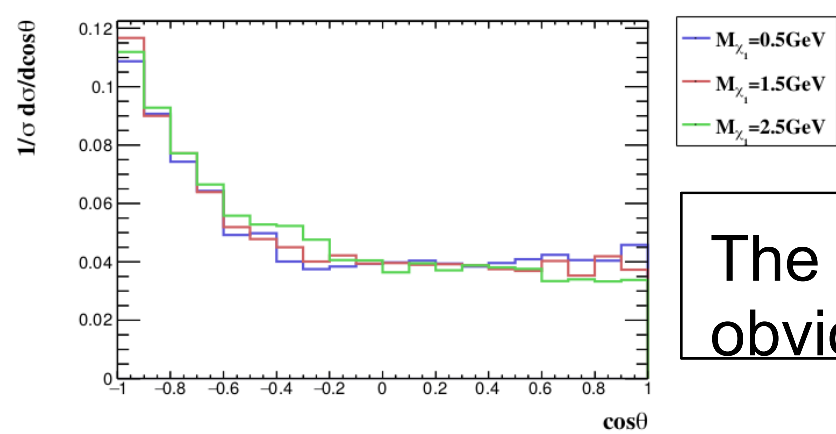
If ϕ_2, χ_2 are long-lived, can we determine their spins at colliders ?





Fix $\alpha_D = 0.1$, $\epsilon = 0.01$, $\Delta = 0.1 M_{\phi_1,\chi_1}$, and $m_{Z'} = 3.0 M_{\phi_1,\chi_1}$





χ_2

The differences are still obvious in the LAB frame!

If the excited DM is long-lived, can we determine its mass at colliders ?

In the center of mass (CM) frame for the process $e^+e^- \to \chi_1\chi_2 \to \chi_1\chi_1 e^+e^-$

There are 8 unknown values from four-momentum of two dark matters in the final states.

However, we have 7 constraints for this process :

1. four-momentum conservation (4)
2. two dark matters with the same mass (1)
3. because of the charge neutrality of the excited DM, a three-momentum vector is proportional to the displaced vertex (2) : $\overrightarrow{p_{\chi_2}} = |\overrightarrow{p_{\chi_2}}|\,\hat{r}_{DV}$

Therefore, we cannot get the unique solution for 8 unknown values. We need to find other ways to determine the mass of DM and mass splitting !

If the excited DM is long-lived, can we determine its mass at colliders ?

In the center of mass (CM) frame for the process $e^+e^- \rightarrow \chi_1\chi_2 \rightarrow \chi_1\chi_1 e^+e^-$

We can first write down the following equation with the help of four-momentum conservation,

$$m_{\chi_2}^2 - m_{\chi_1}^2 - 2E(1+\alpha)E_{V'} + E_{V'}^2 - |\overrightarrow{p_{V'}}|^2 + 2\sqrt{(E(1+\alpha))^2 - m_{\chi_2}^2}(\hat{r_{DV}} \cdot \overrightarrow{p_{V'}}) = 0$$

where $\hat{r_{DV}}$ is the direction of displaced vertex, E is half of the center of mass energy,

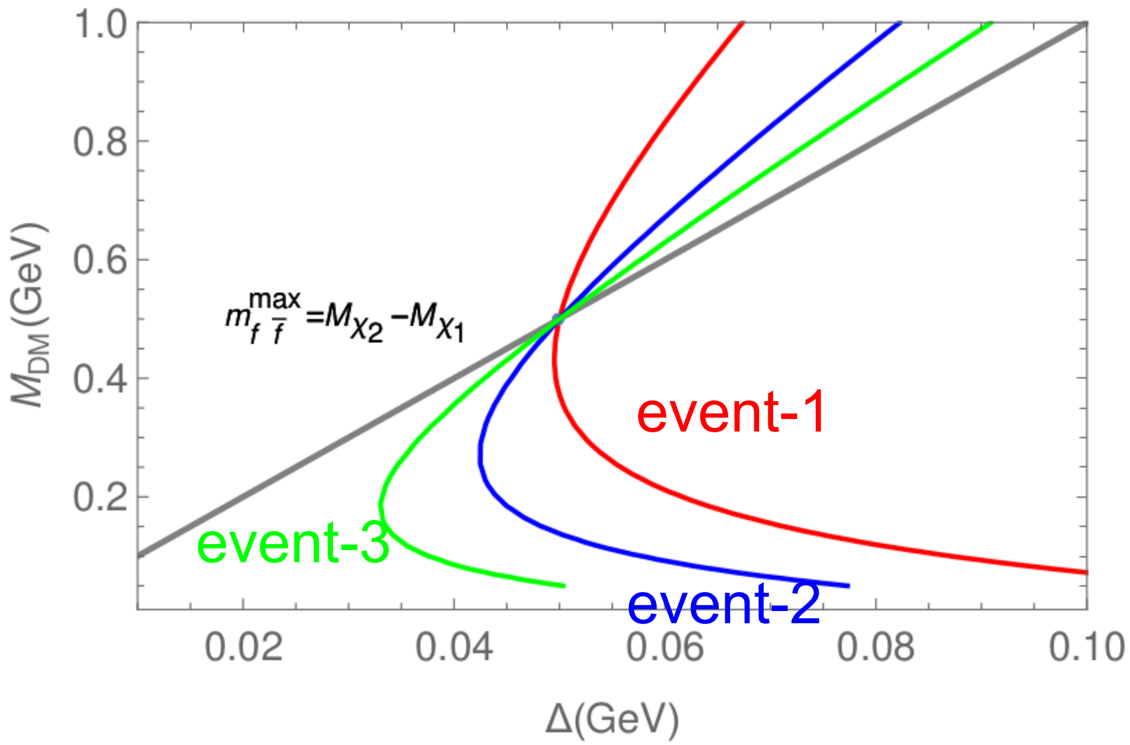
$E_{V'}$, $\overrightarrow{p_{V'}}$ are the visible energy and three-momentum in the final states, and

$$\alpha = \frac{m_{\chi_2}^2 - m_{\chi_1}^2}{4E^2}$$

For each event, we can receive a relation between the mass of DM and mass splitting.

If the excited DM is long-lived, can we determine its mass at colliders ?

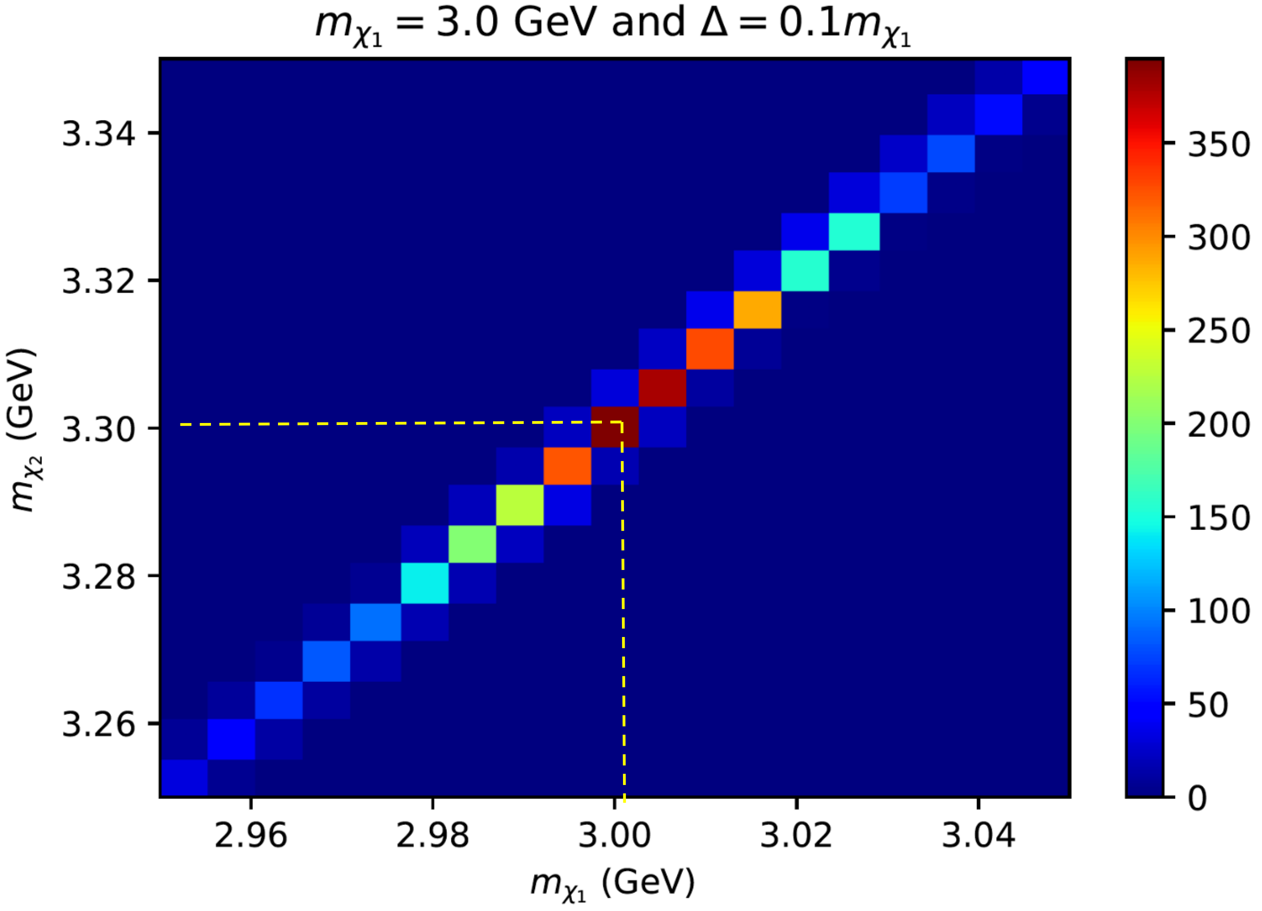
The crossing point from these events and kinematic endpoint measurement $m_{f\bar{f}}^{max}$ can help us to determine the mass of DM and mass splitting. This method is based on "Kinematic focus point" from arXiv:1906.0282 (Kim,Matchev,Shyamsundar).



$(\Delta, M_D) = (0.05, 0.5)$ GeV

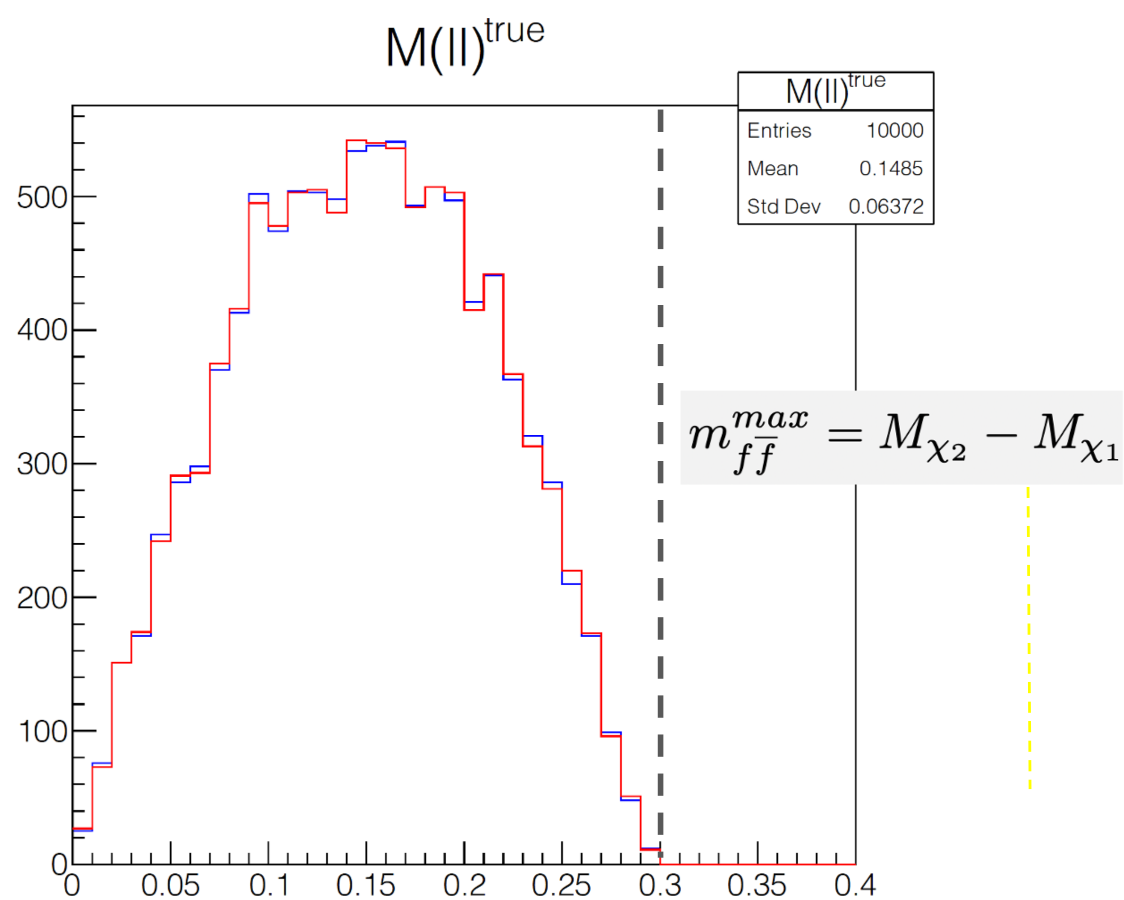
If the excited DM is long-lived, can we determine its mass at colliders ?

Assume we can have 100 signal events at the Belle II, then we will get 4950 solutions from each two events !

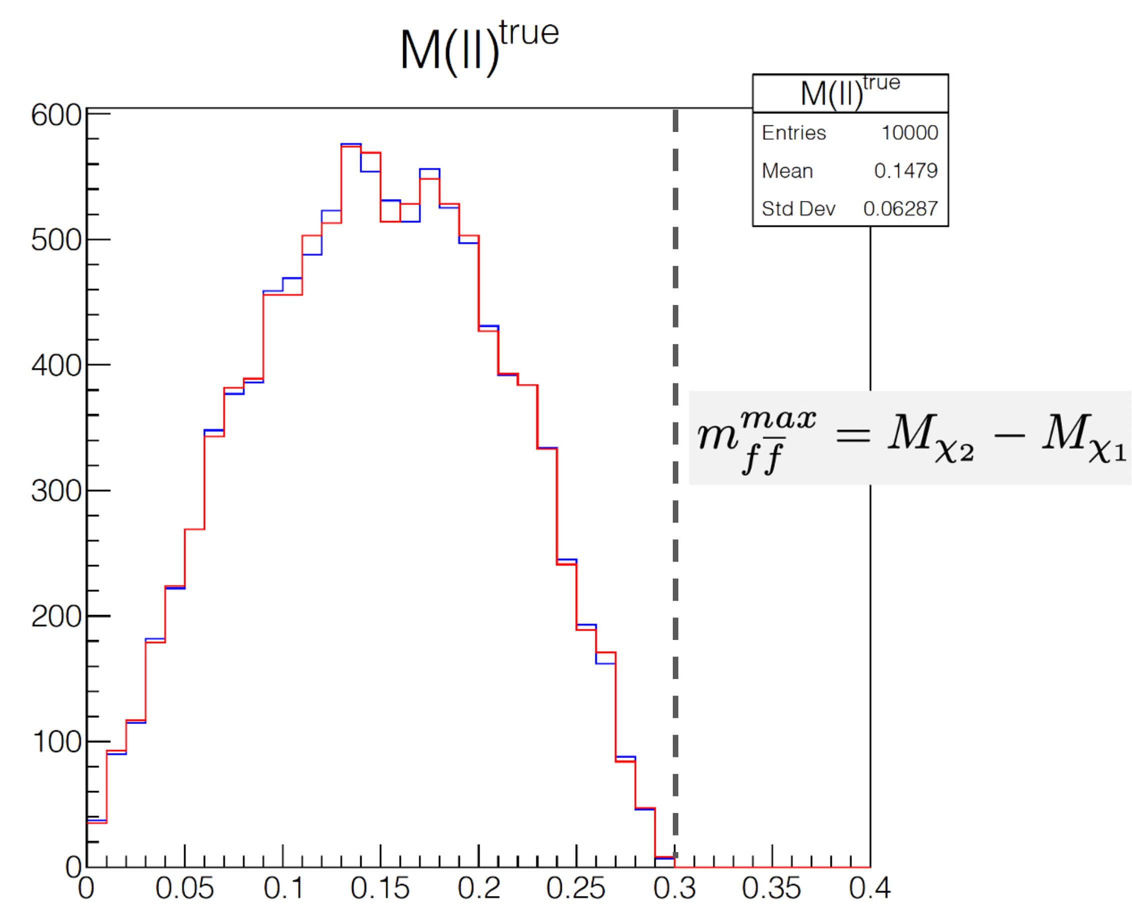


If the excited DM is long-lived, can we determine its mass at colliders ?

$$e^+e^- \to \chi_1\chi_2 \to \chi_1\chi_1 e^+e^-$$



$$e^+e^- \to \chi_1\chi_2\gamma \to \chi_1\chi_1 e^+e^-\gamma$$



Summary

- Local Z_2 scalar/fermion DM : theoretically well defined & mathematically consistent models for XDM

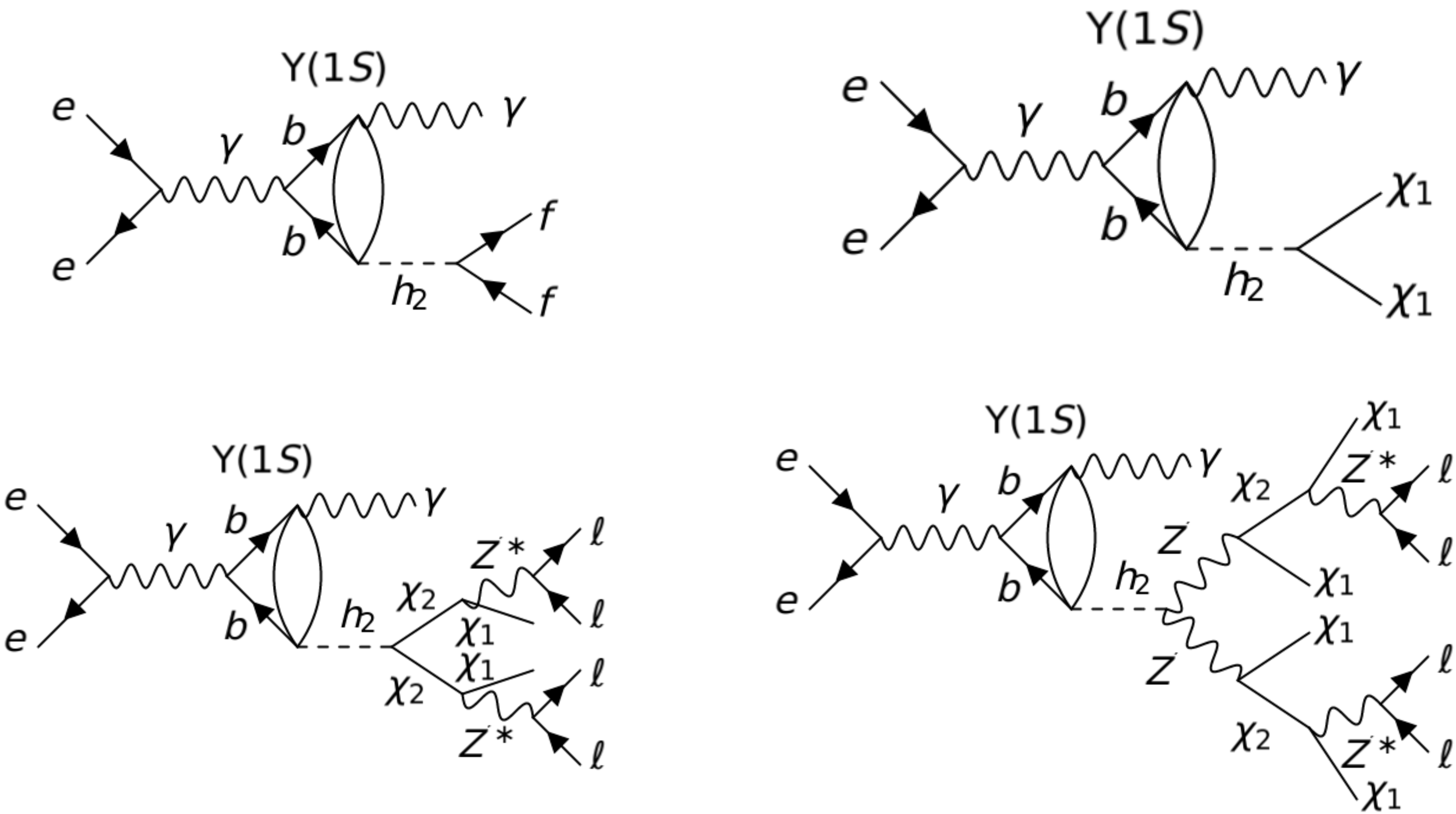
- Can explain a number of phenomena including the recent XENON1T data

- One can discriminate the spin of (X)DM at Belle II from the polar angle distributions of the decaying points

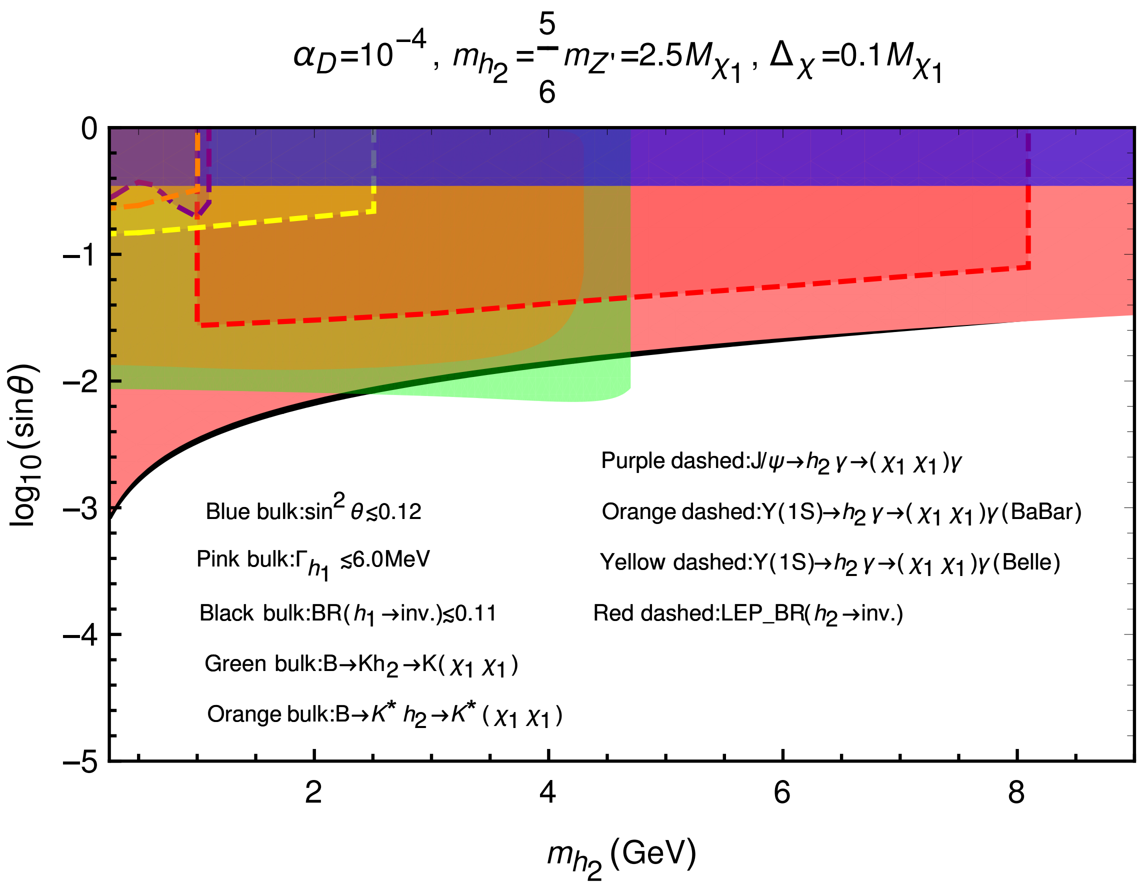
- DM mass and the Δm can be determined with the focus point method

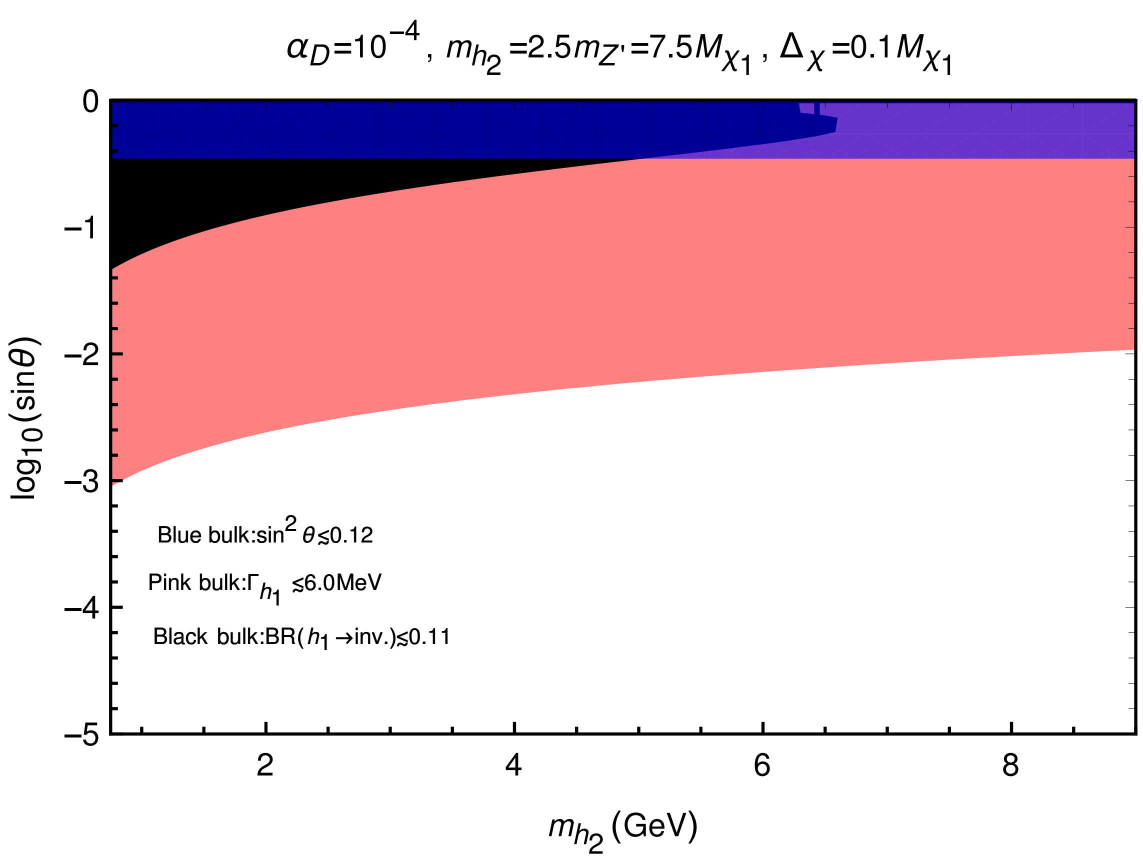
- Similar studies at ILC, CEPC, HL-LHC and FCC-hh in progress (The current version of FCC CDR does not include this interesting case.)

Dark Higgs search@colliders



Work in progress with Chih-Ting Lu, Youngjoon Kwon





In either case, the bound on the SM Higgs decay width Γ_{h_1} is the most stringent

Dark pion DM : WIMP vs. SIMP

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.)

Nicety of QCD

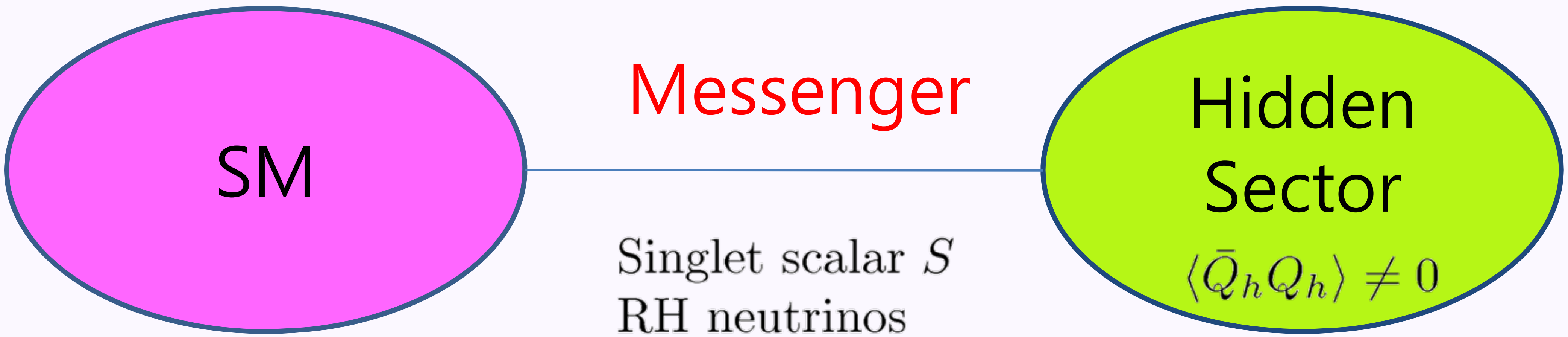
- Renormalizable
- Asymptotic freedom : no Landau pole
- QM dim transmutation :
- Light hadron masses from QM dynamics
- Flavor & Baryon # conservations : accidental symmetries of QCD (pion is stable if we switch off EW interaction; proton is stable or very long lived)

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

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

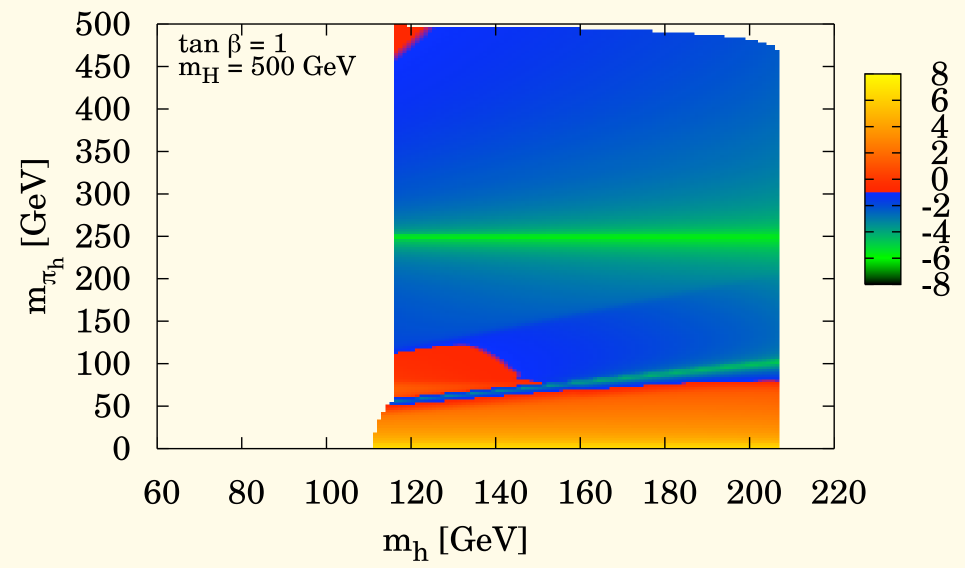
Not present in the two-Higgs Doublet model

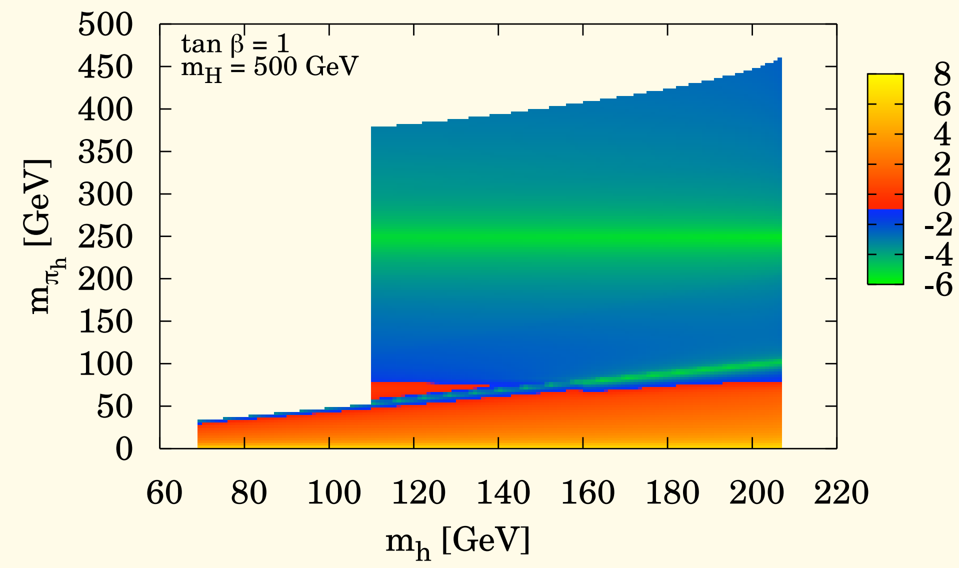
- Stability : $\lambda_{1,2} > 0$ and $\lambda_1 + \lambda_2 + 2\lambda_3 > 0$
- Consider the following phase:

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

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

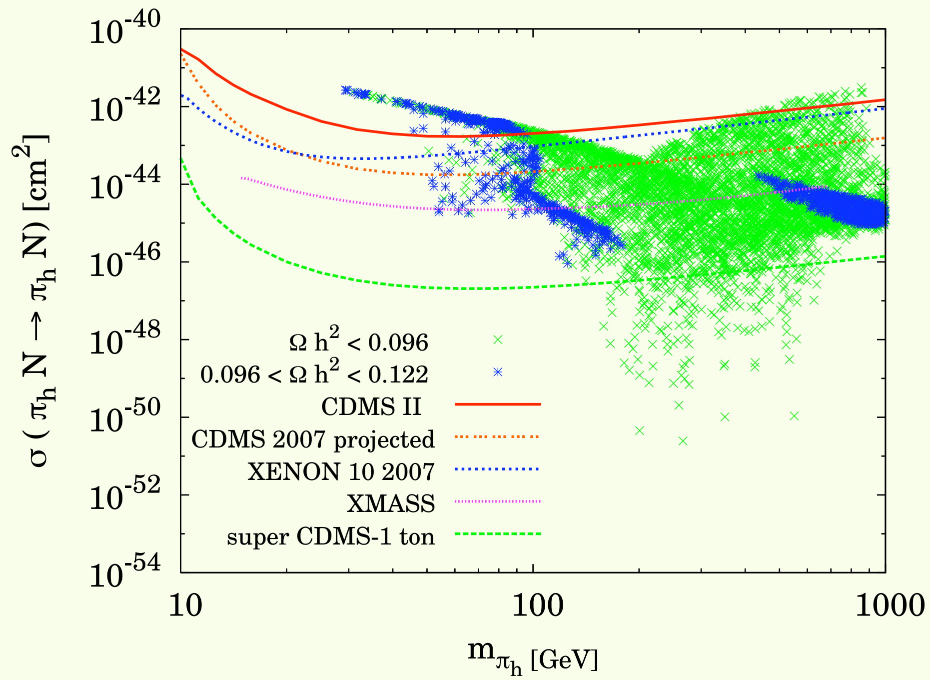
Relic Density

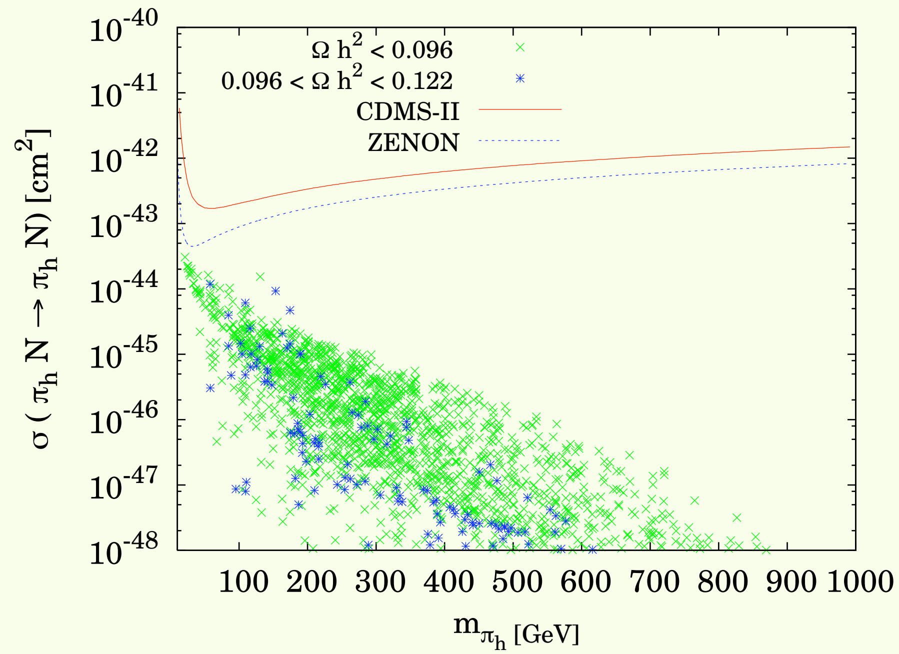




- $\Omega_{\pi_h} h^2$ in the (m_{h_1}, m_{π_h}) plane for $\tan\beta = 1$ and $m_H = 500$ GeV
- Labels are in the $\log_{10}$
- Can easily accommodate the relic density in our model

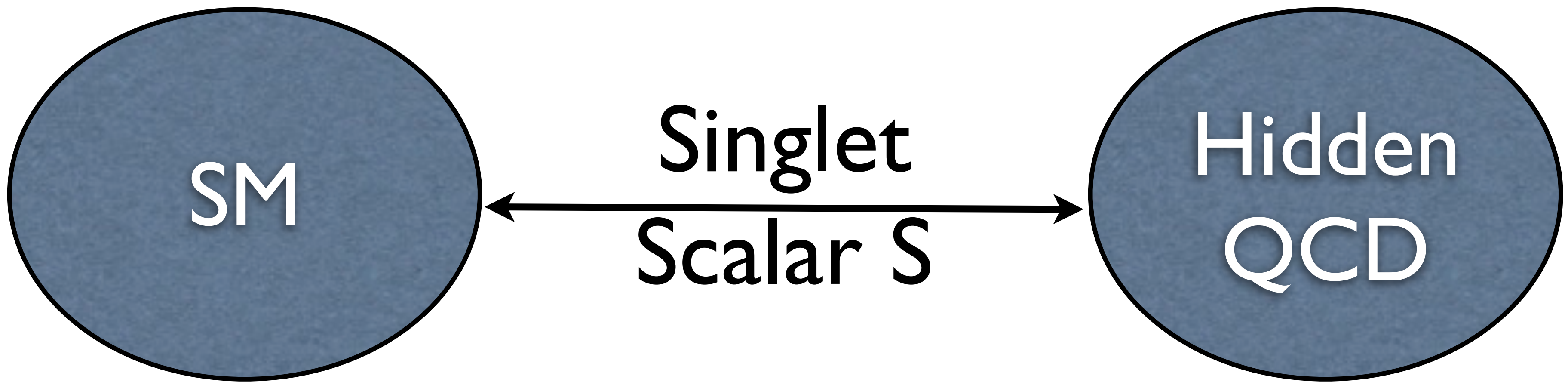
Direct detection rate





- $\sigma_{SI}(\pi_h p \to \pi_h p)$ 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)



- 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

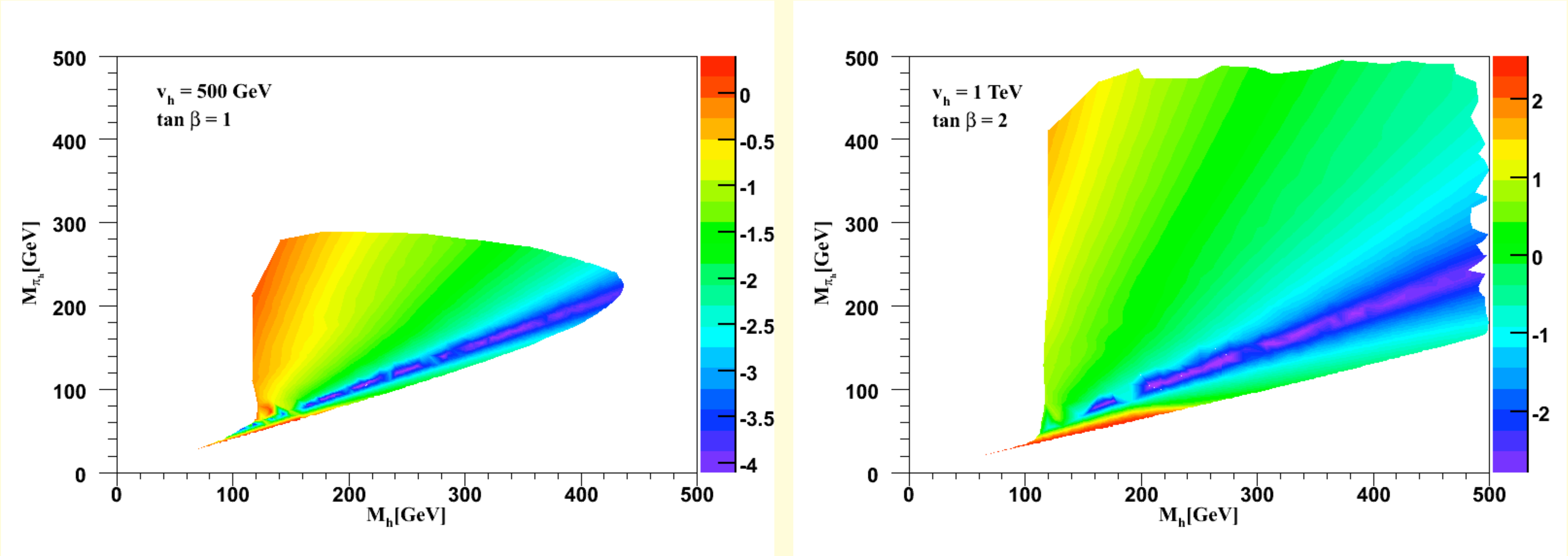
$$\mathcal{L}_{\rm hidden} = -\frac{1}{4}\mathcal{G}_{\mu\nu}\mathcal{G}^{\mu\nu} + \sum_{k=1}^{N_{HF}} \overline{\mathcal{Q}}_k (i\mathcal{D}\cdot\gamma - \lambda_k S)\mathcal{Q}_k$$

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

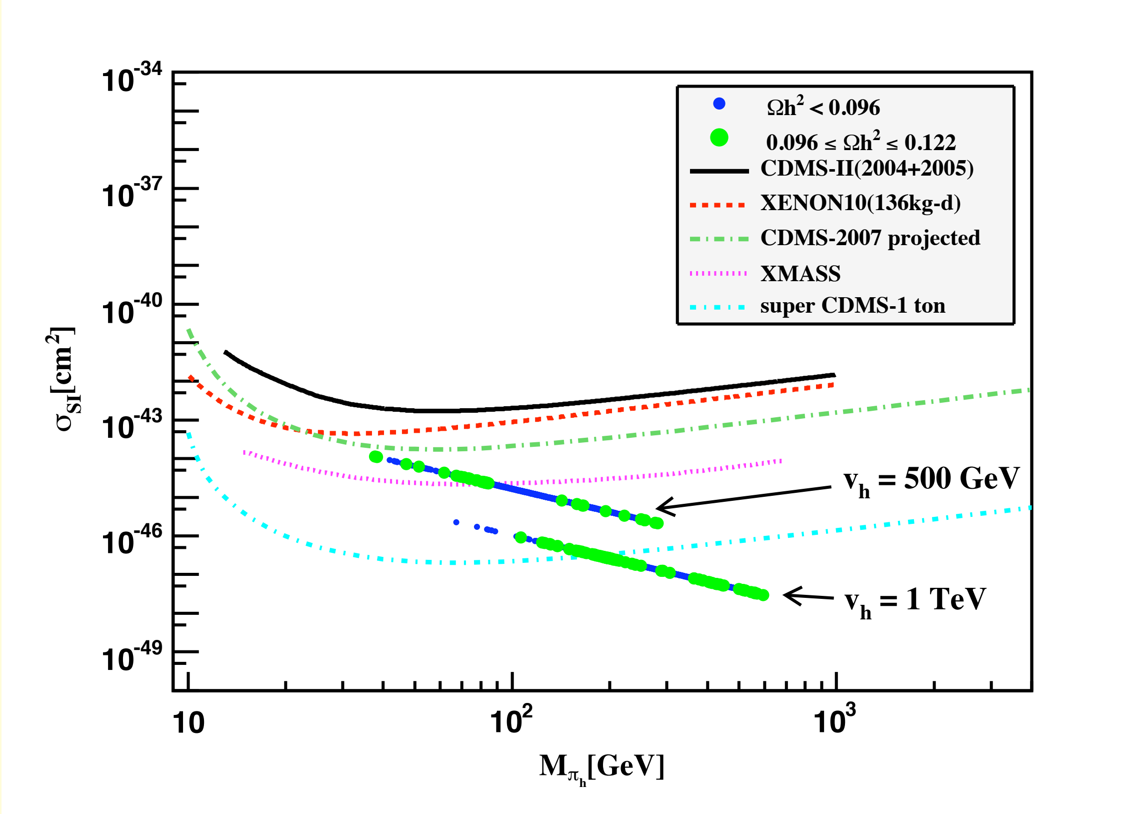


$\Omega_{\pi_h} h^2$ in the (m_{h_1}, m_{π_h}) plane for

(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 in Dark QCD

SIMP paradigm

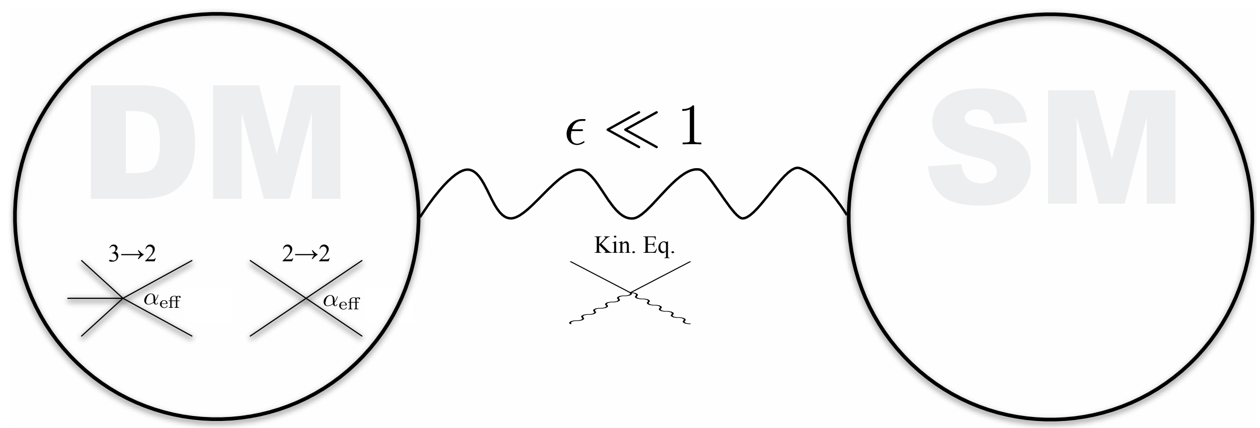


FIG. 1: A schematic description of the SIMP paradigm. The dark sector consists of DM which annihilates via a $3 \to 2$ process. Small couplings to the visible sector allow for thermalization of the two sectors, thereby allowing heat to flow from the dark sector to the visible one. DM self interactions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

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

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

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

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 $\pi_5(G/H) = Z$ (Nf > 2)

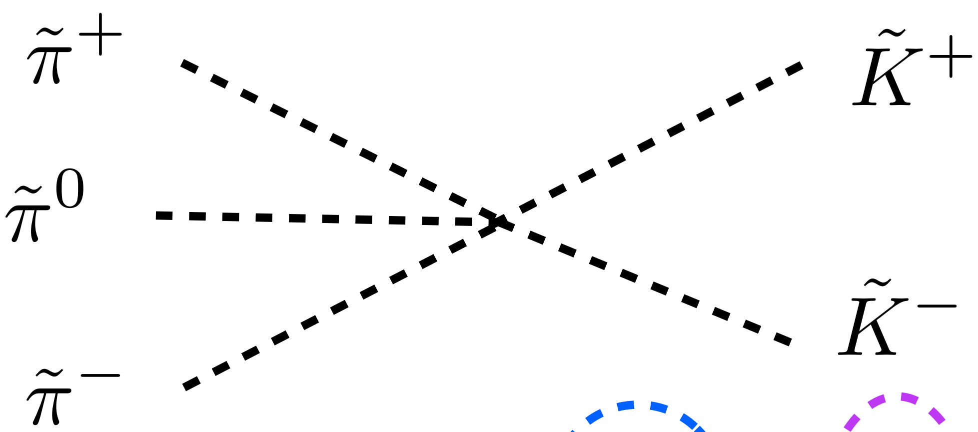
$$\Gamma_{\rm WZ} = C \int_{M^5} d^5x \; {\rm Tr}(\alpha^5) \qquad {\rm with} \quad \alpha = dUU^\dagger.$$

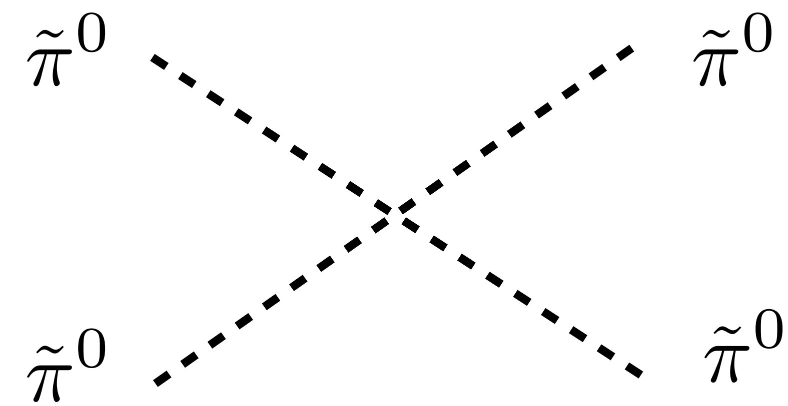
$$U = e^{2i\pi/F}$$

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

in the absence of external gauge fields

SIMP Dark Mesons





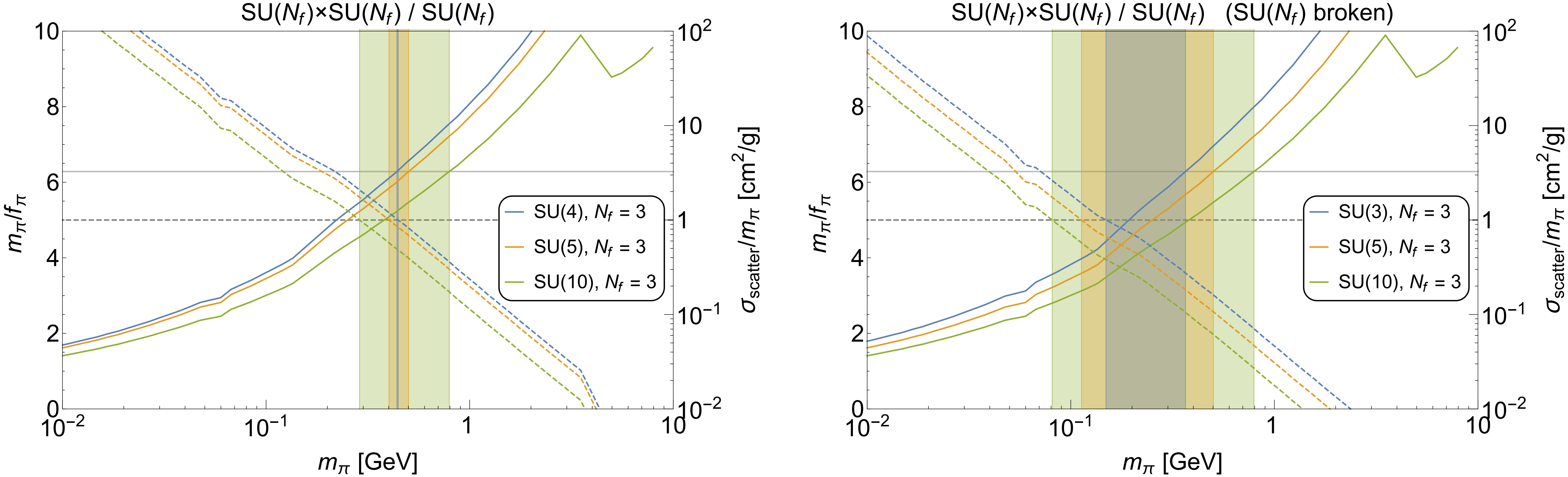
~const ~const

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

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 pions can help.)

SIMP + VDM

With Soo Min Choi, Hyun Min Lee, Alexander Natale,
arXiv:1801.07726, PRD (2018)

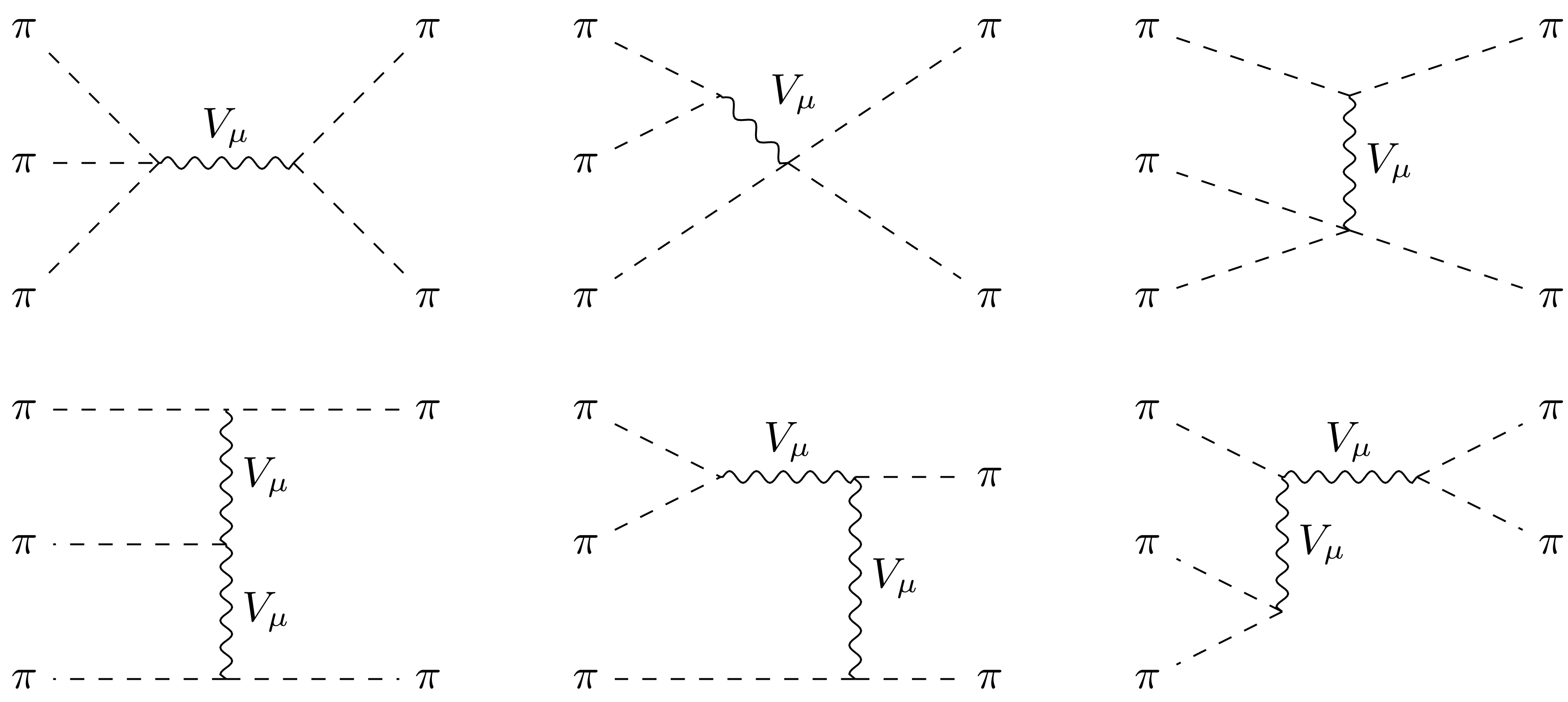


FIG. 1: Feynman diagrams contributing to $3 \to 2$ processes for the dark pions with the vector meson interactions.

SIMP + VM

New diagrams involving 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

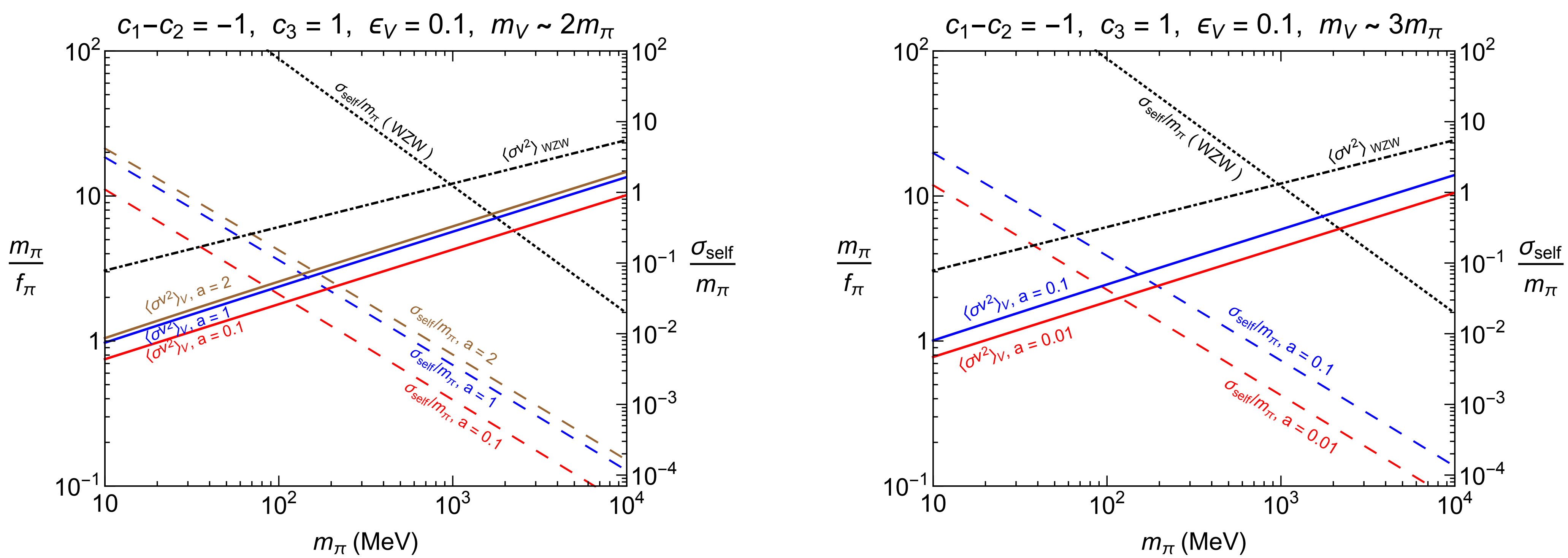


FIG. 2: Contours of relic density ($\Omega h^2 \approx 0.119$) for m_π and m_π/f_π and self-scattering cross section per DM mass in cm^2/g as a function of m_π. The case without and with vector mesons are shown in black lines and colored lines respectively. We have imposed the relic density condition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

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)

DQCD+dark photon ($m_{\gamma'} \neq 0$)

Work with Chih-Ting Lu, Ui Min

- So far I considered only dark mesons with singlet scalar, ignoring dark photon with nonzero mass
- Assume dark photon get massive by dark Higgs mechanism
- Question : Dark U(1)' charge of dark Higgs ?
- Should be careful not to induce operators that can induce dark matter decays unto dim-5 without severe fine-tuning

Dark meson DM

- Consider 3 flavor DQCD : $q = (u, d, s)$ with U(1)' charges equal to $Q' = (2/3, -1/3, -1/3)$ or $Q' = (1, -1, -1)$

- Assume $q_\phi = q_u - q_d = q_u - q_s$. Then the following Yukawa term is allowed : $\mathscr{L} \supset -\phi(y_{ud}\overline{u}d + y_{us}\overline{u}s)$

- Note that U(1)' charge is not conserved : FCCC @ tree level (unlike in the SM where FCNC ($K \to \pi\gamma^* \to \pi l^+ l^-$) occurs only at loop levels)

- Physical dark meson : linear combination of different U(1)' charges

- Is it good or not ? Let's first consider $\pi^0 \to \gamma'\gamma'$

$\pi^0, \eta \to \gamma'\gamma'$ in DQCD

- The leading order $O(p^4)$ contribution from the WZW $\propto \mathrm{Tr}[Q^2\lambda^a] \to 0$, for $Q' = (1, -1, -1)$

- However, this is not the end of the story, since there are $O(p^6)$ terms

WZW term at $O(p^4)$

$$\mathcal{L} = i\frac{N_C e^2}{8\pi^2 f_{\pi'}} \mathrm{Tr}[Q'^2 \Pi'] F'_{\mu\nu} \widetilde{F}'^{\mu\nu}$$

Beyond the WZW term at $O(p^6)$: also describes $\pi^0 \to \gamma'\gamma'$

Also there are $O(p^6)$ operators for $\eta \to \pi^0\gamma\gamma$

One can not make both vanish in QCD-like theories, and π^0, η will eventually decay

Main points

- Dark $\pi^0, \eta \to \gamma'\gamma'$ will occur any way at $O(p^4)$ or $O(p^6)$
- If mesons mix, then most of dark pion DM will decay
- Need to suppress this channel by some ways
- Dark Higgs charge should be taken with great care, in order not to have dark matter decay fast
- If this can be achieved, one can have interesting collider signatures and cosmological consideration of Dark pion DM will be affected
- Stay tuned !

Conclusion

- Dark Higgs plays important roles in particle/astroparticle/cosmology
- Galactic center gamma ray excess, DM searches@LHC and other colliders, Higgs portal assisted Higgs inflation
- Dark Higgs is also important in inelastic DM models : P-wave annihilation with correct relic density, without conflict with CMB bound (e.g., XENON1T excess)
- Some parameter regions can be probed at colliders