The comprehensive search for CP violating Higgs portal WIMP

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work in progress

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About WIMP

- Weakly Interacting Massive Particle (WIMP)
- Very well-motivated dark matter candidate

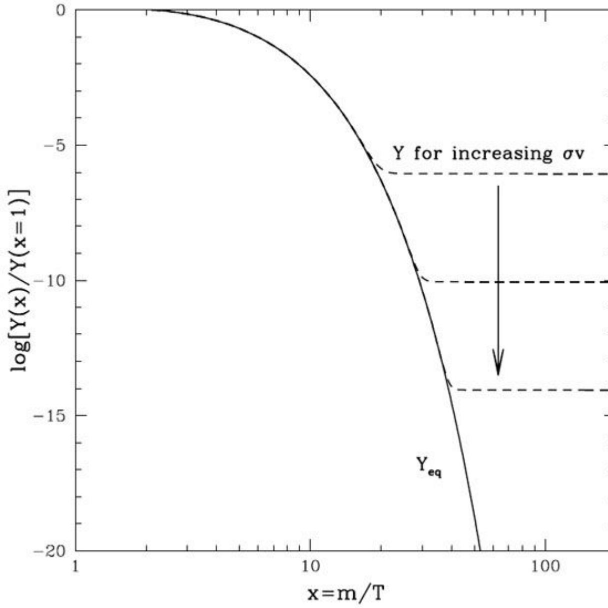
  (contained in many BSM theories)
- Stable particle, mass is around GeV~TeV
- Abundance is determined by freeze-out mechanism
- We can estimate abundance by solving Boltzmann Eq.

$$\frac{dn}{dt} + 3Hn \quad = \quad \langle \sigma v \rangle (n_{\mathrm{eq}}^2 - n^2)$$

n : Number density of DM

⟨σv⟩ : Annihilation cross section of DM

[E.W.Kolb, M.S.Turner]



Classification of WIMP

- There are many models which include WIMP
- It is convenient to classify WIMP by its gauge representation

Lorentz	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$
scalar		$\mathbf{1}$	0
or		$\mathbf{2}$	$-1/2, +1/2$
fermion	$\mathbf{1}$	$\mathbf{3}$	$-1, 0, +1$
or		$\mathbf{4}$	$-3/2, -1/2, +1/2, +3/2$
vector		$\mathbf{5}$	$-2, -1, 0, +1, +2$
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- Hypercharge is quantized by the condition that DM must be electrically neutral

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The interaction of SU(2)-multiplet WIMP is determined by gauge theory

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The interaction of SU(2)-singlet WIMP cannot be determined from gauge theory, and there can be various types of interaction

We focus on SM gauge singlet fermionic WIMP in this talk

Singlet fermionic WIMP

- We impose Z_2 symmetry to stabilize WIMP

WIMP(χ) : odd   SM particles : even

- Renormalizable operators cannot be written because of gauge symmetry and Z_2 symmetry

Mass dimension	Operator
4	None
5	$\bar{\chi}\chi\|H\|^2$ $\bar{\chi}i\gamma_5\chi\|H\|^2$
6	$\bar{\chi}\gamma_\mu\gamma_5\chi\bar{Q}\gamma^\mu Q$ $\bar{\chi}\gamma_\mu\gamma_5\chi\partial_\nu F^{\mu\nu}$ etc.

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We focus on CP violating Higgs Potral operator

[L.Lopez-Honorez, T.Schwetz, J.Zupen (2012)]   (The reason will be mentioned later)

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We need to introduce mediator field to connect WIMP and Higgs field for the UV-completion

The model

- New particles are WIMP and a mediator particle
- WIMP：SM gauge singlet fermion (χ)
- Mediator：SM gauge singlet CP odd scalar (A)
- Interaction of WIMP and mediator ： $A(\bar{\chi} i \gamma_5 \chi)$
- Interaction of Higgs and mediator ： $A|H|^2$
- Effective operator obtained by integrating out the mediator field ： $(\bar{\chi} i \gamma_5 \chi)|H|^2$

Lagrangian

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{2}\bar{\chi}(i\partial\!\!\!/ - m_\chi)\chi + \frac{1}{2}(\partial_\mu A)^2 - \frac{y_p}{2}A(\bar{\chi}i\gamma_5\chi) - V(A,H)$$

$$V(A,H) = \mu_{AH}A|H|^2 + \frac{\lambda_{AH}}{2}A^2|H|^2 + \mu_1^3 A + \frac{\mu_A^2}{2}A^2 + \frac{\mu_3}{3!}A^3 + \frac{\lambda_A}{4!}A^4$$

- Mass mixing of mediator and SM Higgs occurs after the symmetry breaking

- We call the neutral scalar fields a and h (125GeV) after the diagonalization

$$\begin{pmatrix} h \\ a \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} h' \\ a' \end{pmatrix}$$

h' ←Original SM Higgs

a' ←Expansion of A around the vacuum

Parameters of the model

- Mass of WIMP：m_χ
- Mass of mediator：m_a
- Coupling constant of WIMP and mediator：y_p (coefficient of $A(\bar{\chi} i \gamma_5 \chi)$)
- Mixing angle of mediator and Higgs：$\sin\theta$
- Scalar three point coupling ：C_{ahh}
- Another scalar three point coupling：C_{aah}
- Scalar four point coupling of mediator：λ_{aaaa}

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- Relic abandance
- Direct detection
- Collider physics

etc…

- Scalar three point coupling : C_{ahh}
- Another scalar three point coupling : C_{aah}

- Decay of the scalar particles

- Scalar four point coupling of mediator : λ_{aaaa}

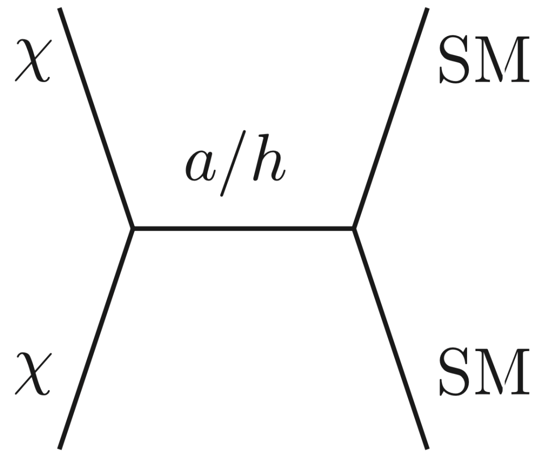
- Vacuum stability

Constraint on the model

- Vacuum stability condition
- Relic abundance condition
- Direct detection
- Collider experiment
- Indirect detection

Relic abundance condition

- $\chi\chi \to a/h \to \mathrm{SM}$s is main annihilation mode



$$\langle \sigma v \rangle \propto (y_p \sin\theta)^2$$

- $\chi\chi \to ah$ can happen for $2m_\chi > m_a + m_h$
- $\chi\chi \to aa$ can happen for $m_\chi > m_a$

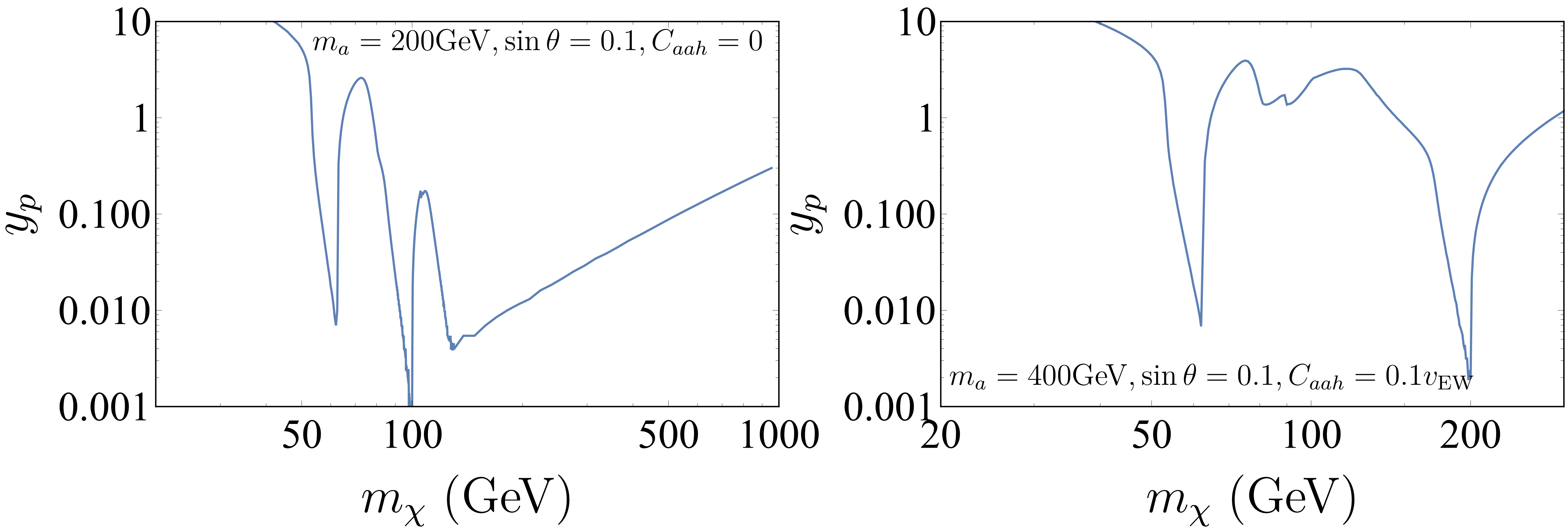
We mainly focus on $\chi\chi \to a/h \to \mathrm{SM}$ annihilation mode, which means the region $m_\chi < m_a$

Relic abundance condition

- Calculate the parameters to obtain $\Omega h^2 = 0.120$

(By micrOMEGAs)
[G. Belanger, F. Boujema, A. Pukhov, A. Semenov (2010)]

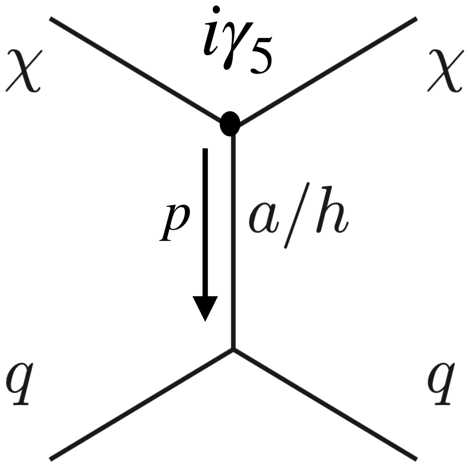
[Planck (2018)]



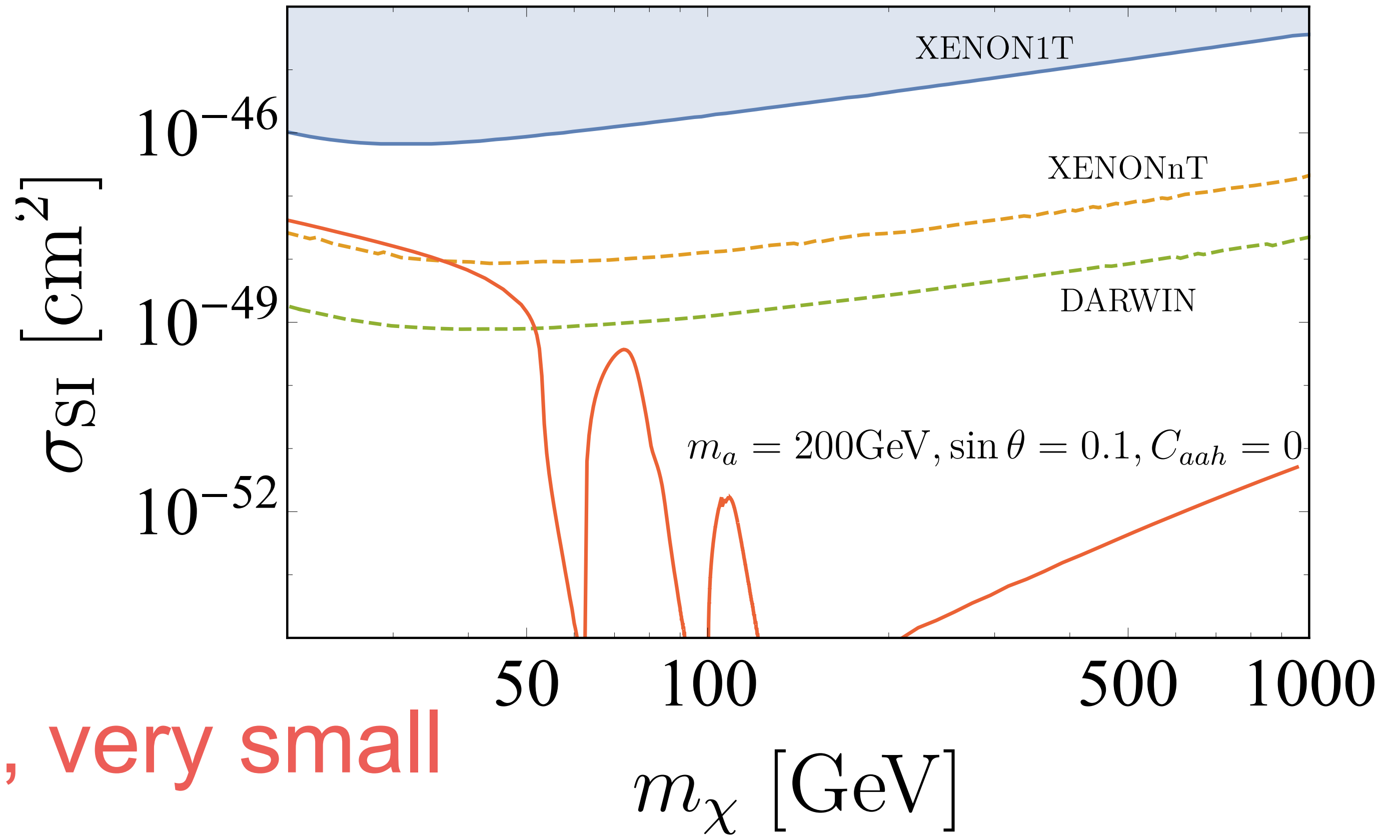
- In peaky region, h and a propagate on-shell for annihilation of DM

Direct detection

- Scattering cross section depends on the momentum transfer at the tree level

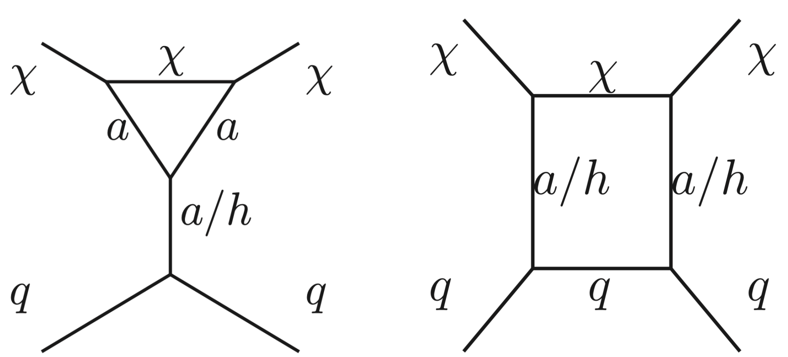


$$\sigma_{\rm SI} \propto \frac{p^2}{m_\chi^2}$$



Its depend on the velocity of DM, very small

- At 1-loop level, scattering cross section does not depends on the momentum transfer, but still small



[T. Abe, M. Fujiwara, J. Hisano (2019)]

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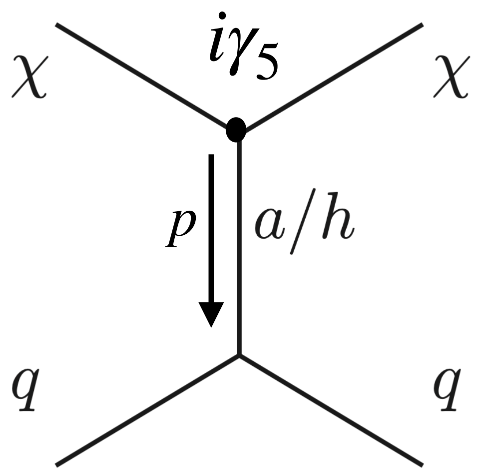

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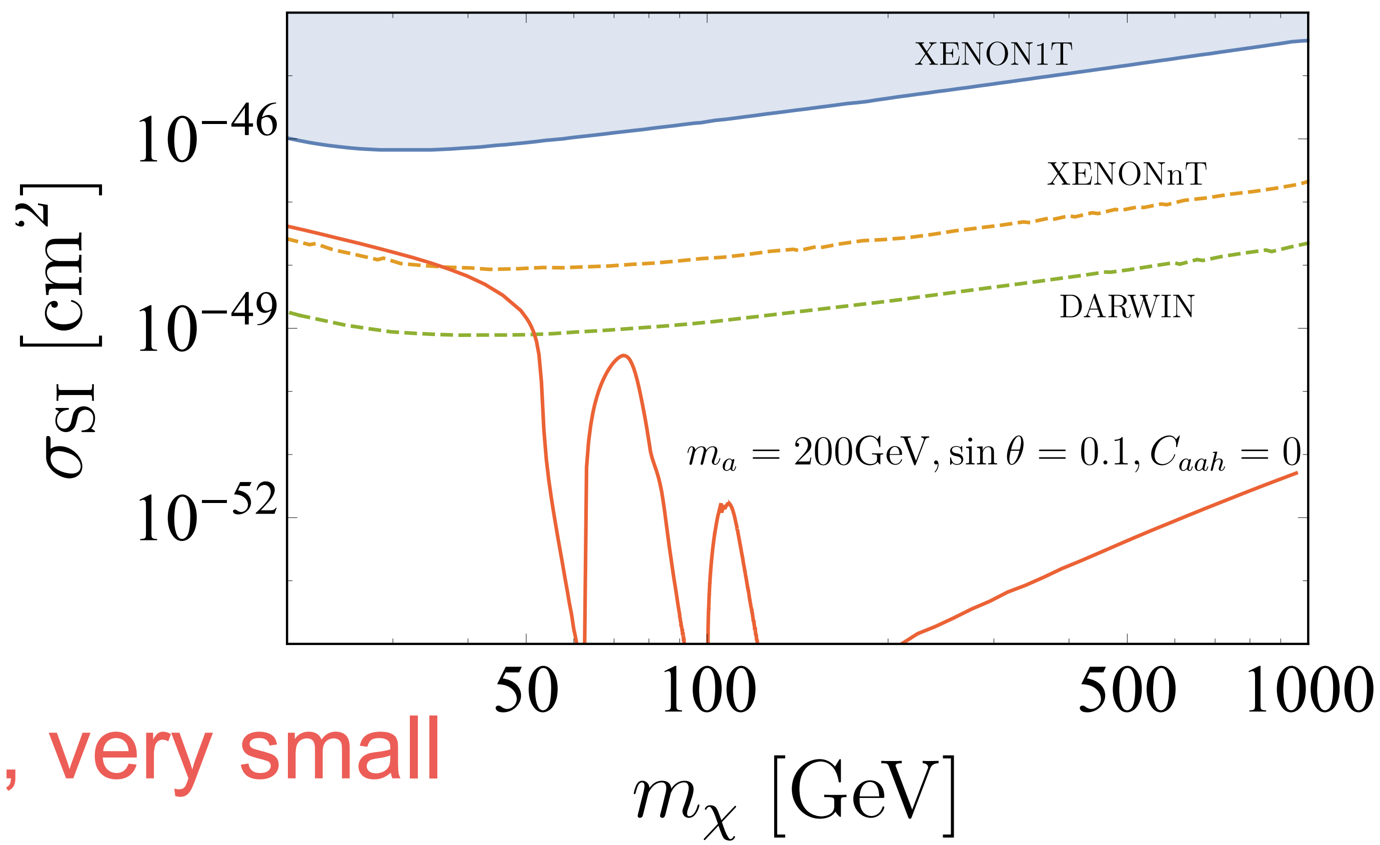

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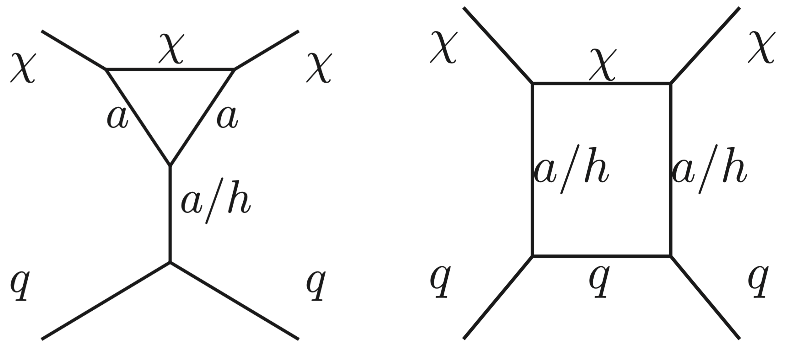


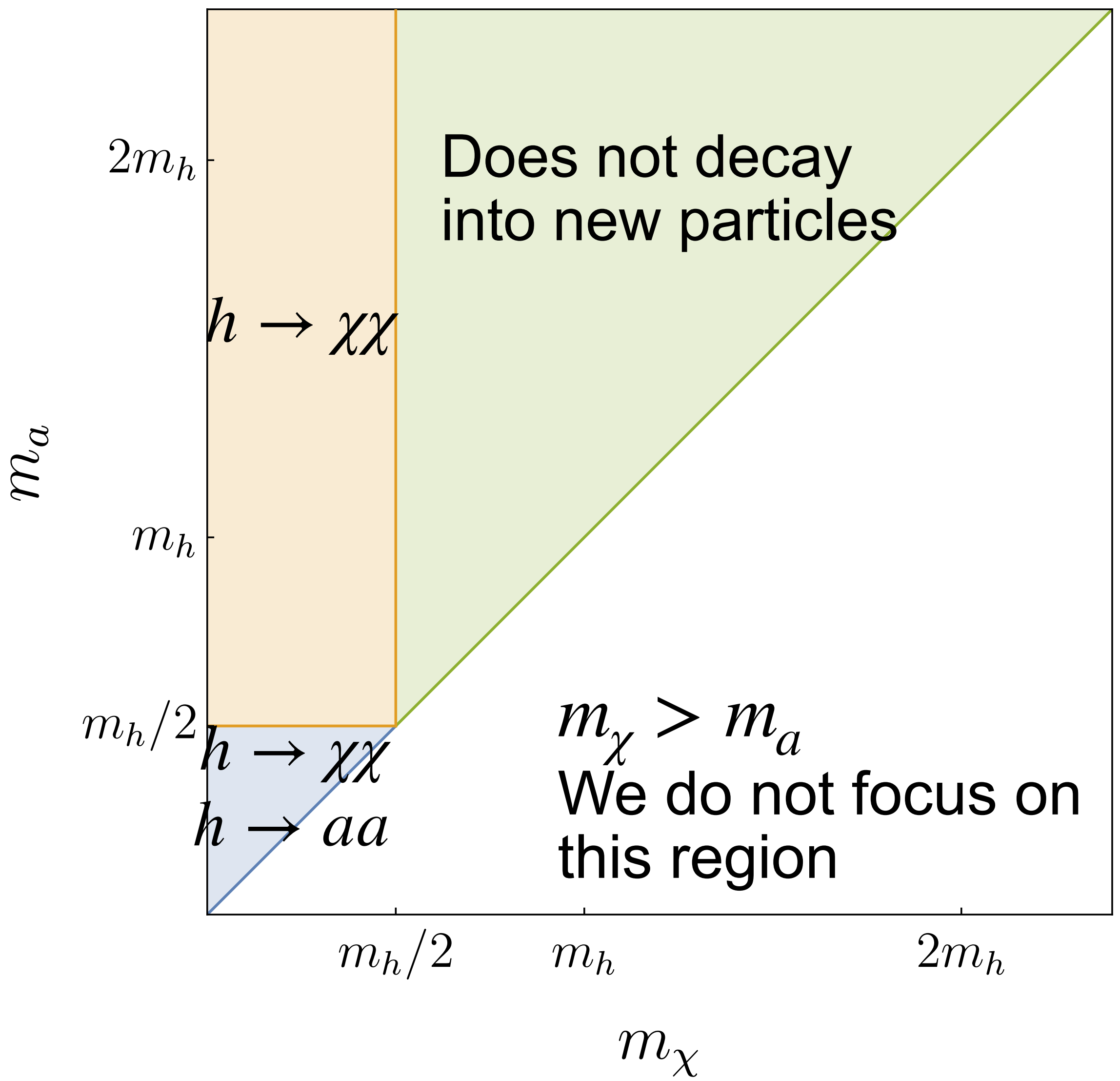
[T. Abe, M. Fujiwara, J. Hisano (2019)]

How can we detect WIMP?

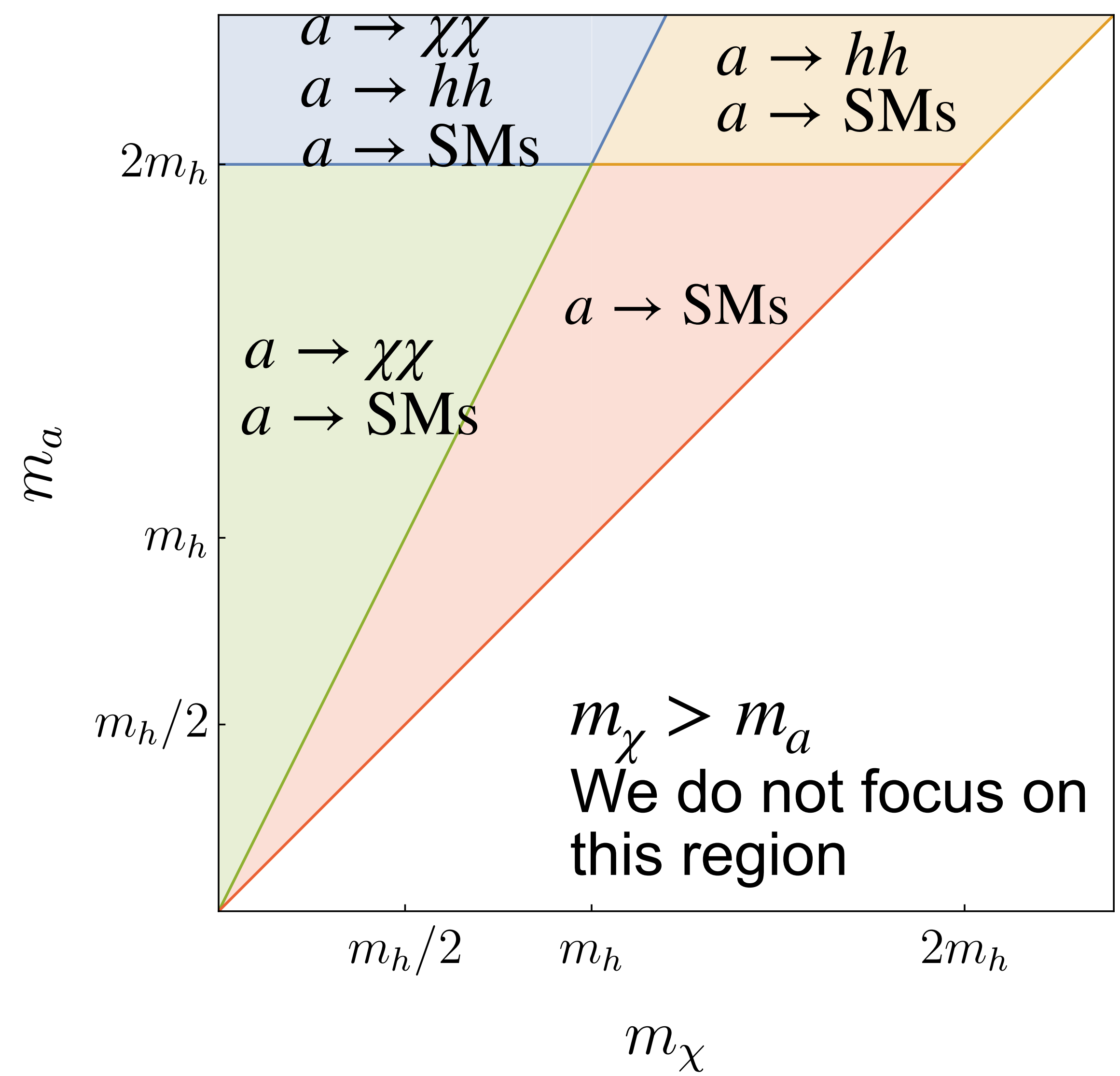
Collider experiment

- Look at the decay of 125 GeV Higgs and mediator

<u>New decay mode of h</u>



<u>Decay mode of a</u>



- Here, SMs stand for SM particles other than higgs

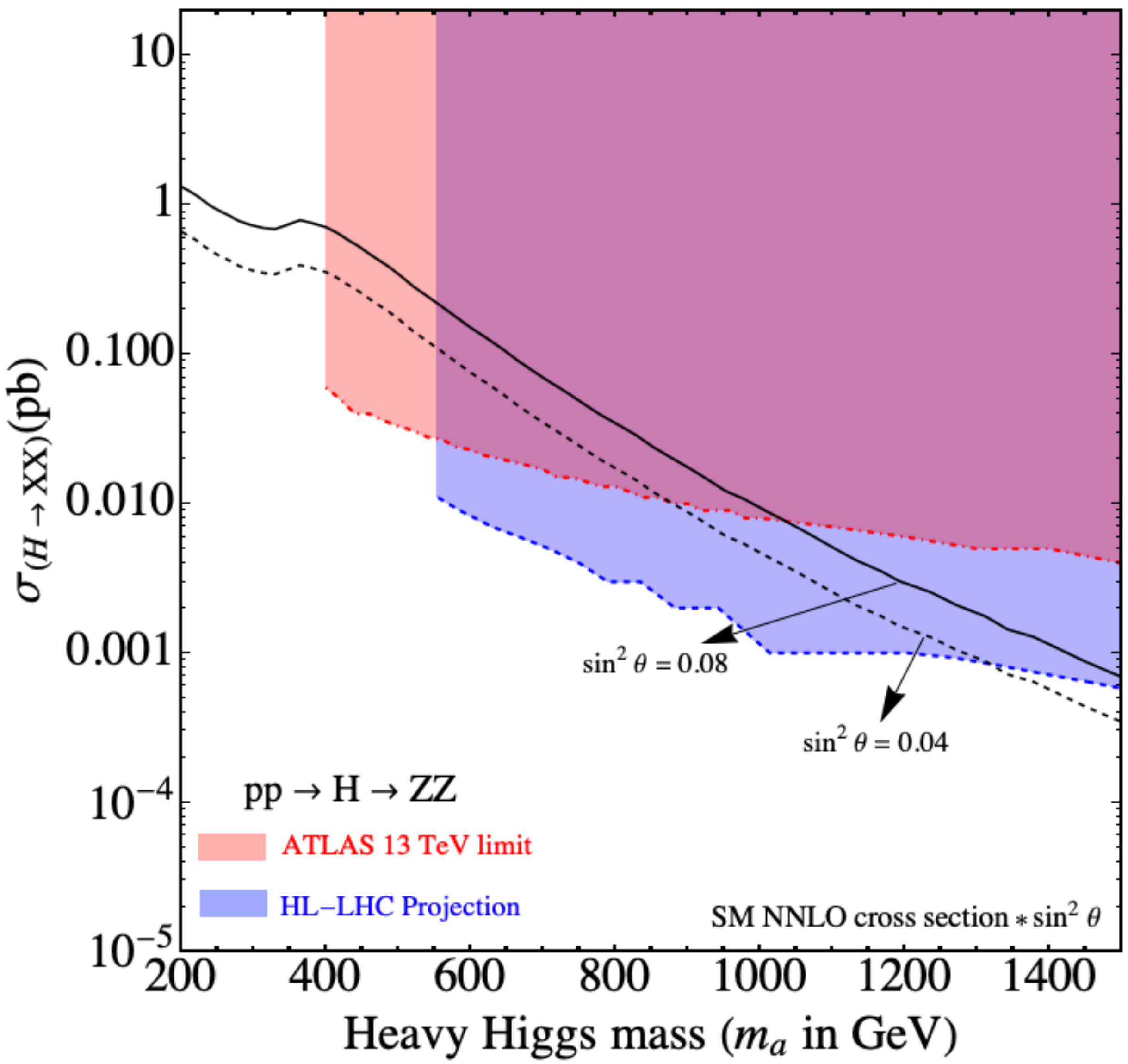
$a \to$ SMs depends on $\sin\theta$

$a \to hh$ depends on C_{ahh}

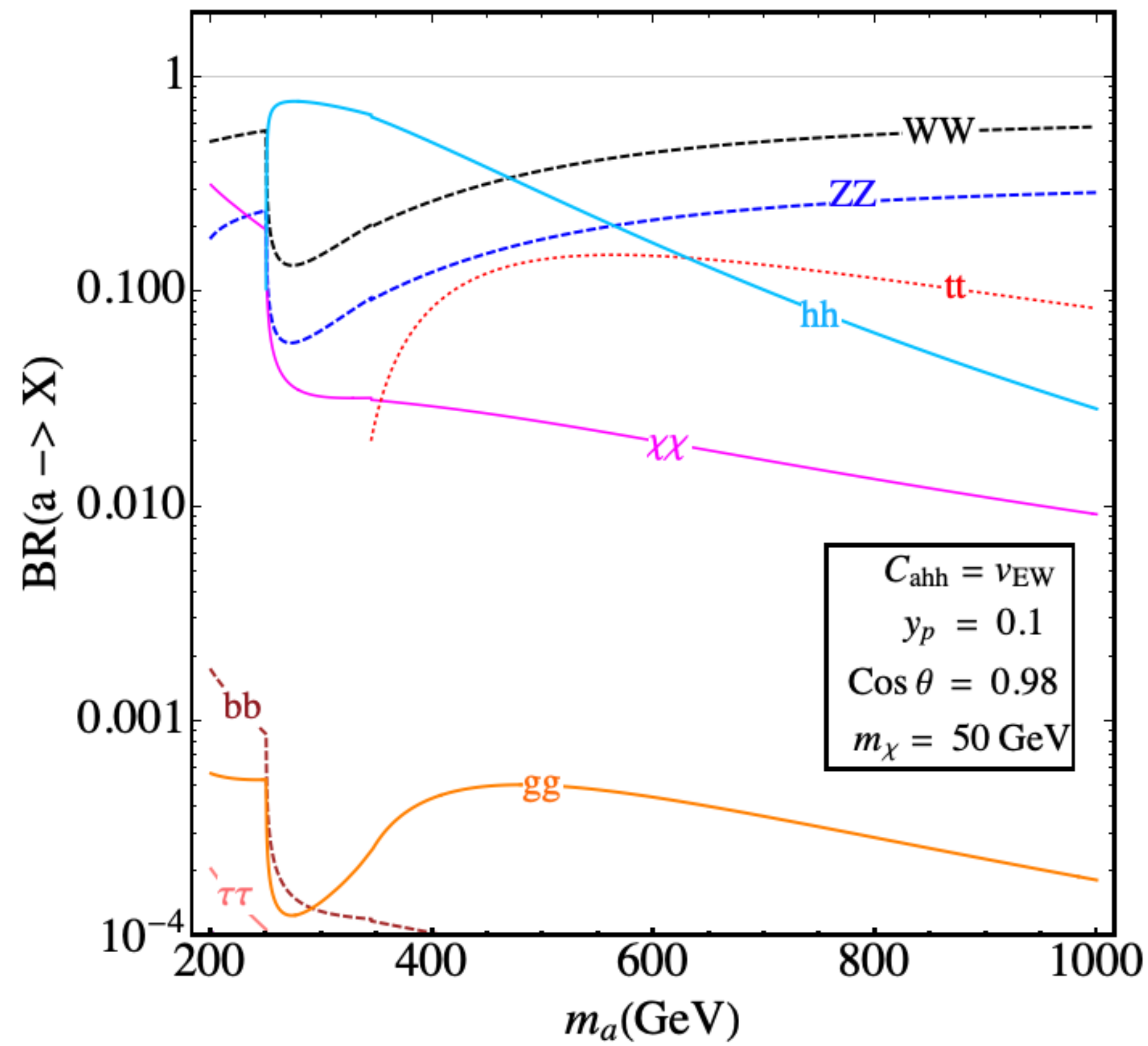
Collider experiment

- Looking at decay of a (taking some benchmark points)

Constraint from heavy higgs search at LHC

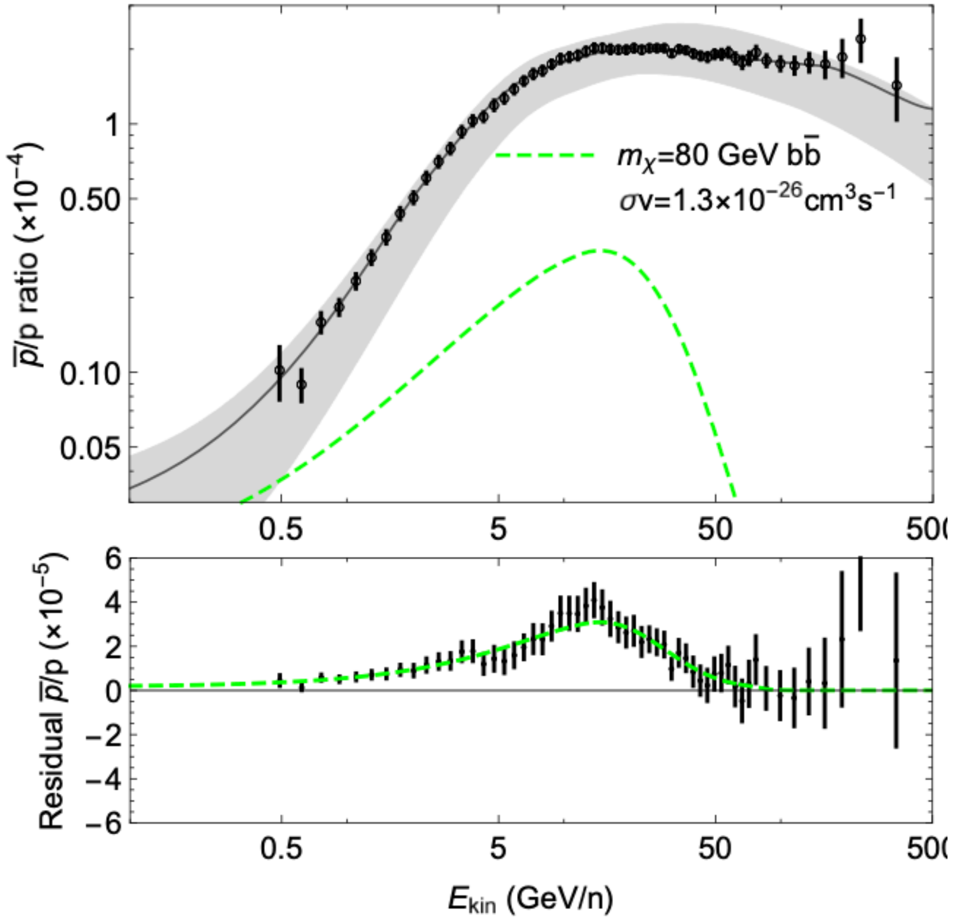


Branching ratio of a



Indirect detection

- Pair annihilation of WIMPs can occur in our galaxy
- $\chi\chi \to a/h \to \text{SMs} \to \gamma, e^+, e^-, P, \bar{P} \ldots$
- The remnant particles of this annihilation can be observed in cosmic rays



[I.Cholis, T. Linden, D.Hooper (2019)]

- Energy spectrum of $\bar{P}$ has a small excess aorund 10GeV [AMS-02]
- This can be explained by s-wave annihilation of DM, $\chi\chi \to b\bar{b}$ [A.Cuoco, J.Heisig D.Hooper,(2017)]
- Our model is a candidate of such an annihilating DM!!

$$\chi\chi \to a/h \to b\bar{b}$$

Summary

- We consider various experiments and observations for SM gauge singlet fermionic WIMP, assuming CP odd scalar mediator
- Direct detection experiments do not work effectively for this model, and large parameter region is remained uncovered
- Precision measurement of Higgs and direct production of mediator particles at collider experiments become very important
- As the implication from the indirect detection, the excess of anti-proton at a few 10GeV can be explained by this model