[*JHEP* 04 (2022) 113]
[arXiv:2204.01739]

# A new renormalizable model for axion-like particle and its phenomenology

Kodai Sakurai (Tohoku U. )

Collaborator:

Wen Yin (Tohoku U.)

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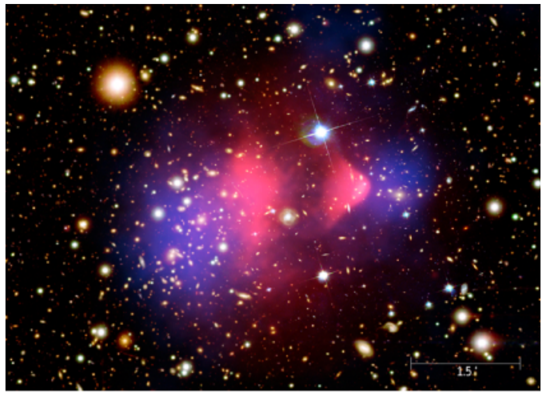
# Contents

# Dark Matter (DM)

- Existence of dark matter has been confirmed in many astrophysical observations.

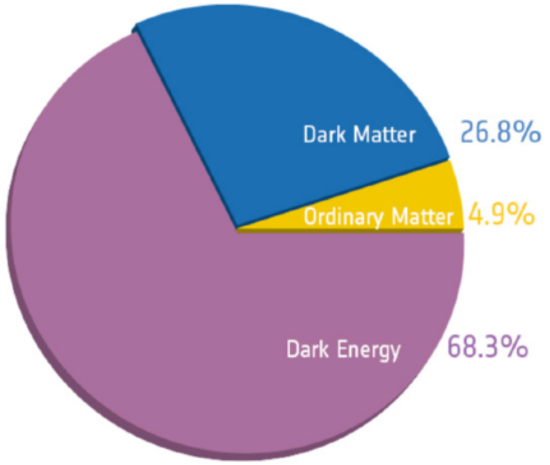
  Rotation curves of galaxies, gravitational lens, etc.



https://chandra.harvard.edu/index.html

- DM constitutes about 26% of the Universe.

- There is no candidate of DM in the standard model (SM).

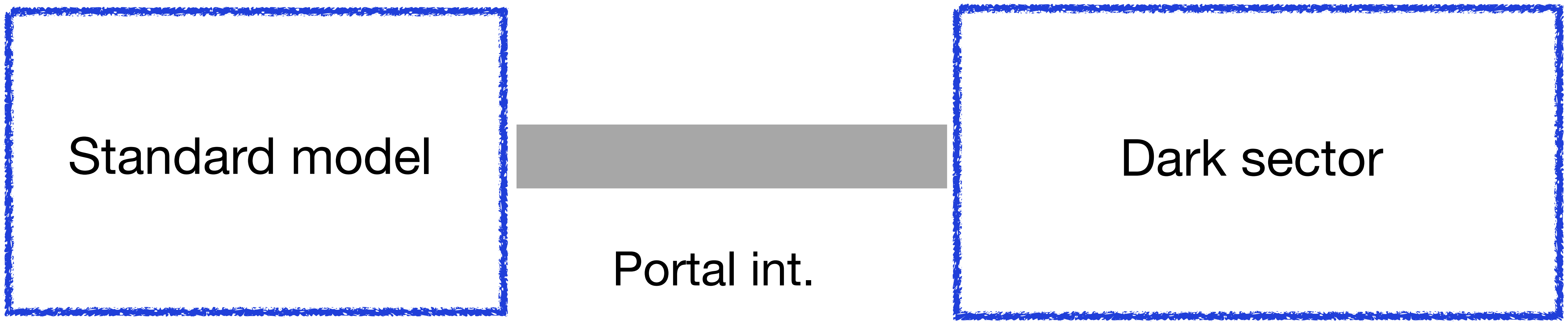



https://plancksatellite.org.uk/

Mysteries of DM:

- Spin
- The scale of mass
- Production mechanism

# Light dark sector




[ mediator
- SM particle
- New particle ]

Candidates of light DM :

- Sterile neutrino
- Axion/ axion-like particle (ALP)
  We focus
- Dark photon

# Feature of ALPs/ axion

- Stability of DM directly links to the lightness.

[ c.f ) WIMP DM
To stabilize it, some assumptions would be needed such as discrete symmetry or higher SU(2) representations. ]

⇨ Assuming that ALP is light ensures the stability of DM.

$$\tau_a = 1/\Gamma_a \sim \frac{1}{m_a^{3+n}} \gtrsim \text{(Age of Universe)}$$

- ALP couple with photons.

⇨ Rich phenomenology especially for Astrophysics

e.g) X-ray, γ-ray, Supernova cooling, …

- If one consider QCD axion, strong CP problem is solved.

$$\mathcal{L} \subset (\theta + \frac{a}{f})\frac{g^2}{32\pi^2}G_{\mu\nu}\tilde{G}^{\mu\nu}$$

$$\begin{matrix}(a \to a - \theta f) \\ (<a>=0)\end{matrix} \quad = (\theta - \theta + \frac{a}{f})\frac{g^2}{32\pi^2}G_{\mu\nu}\tilde{G}^{\mu\nu}$$

# Mass of ALP

- ALP is pseudo NG boson originated from the global U(1) symmetry breaking.
- ALP mass terms generate from the explicit U(1) breaking terms.

e.g) $$m^2\Phi^2 + \mathrm{h.c.} \to m^2 a^2$$

$$\Phi = \left(v_\Phi + \frac{s}{\sqrt{2}}\right) e^{i\frac{a}{v_\Phi}}$$

- $m^2 \to 0$ , U(1) symmetry is conserved. Corresponding to this, axion becomes massless NGB.

# Interaction of ALP in CP conserving case

ALP interactions enjoy shift symmetry $a \to a + C$ at the classical level.

$$\mathcal{L}^{\text{eff}}_{\text{int.}} = c_{f_L}\frac{\partial^\mu a}{f_a}\bar{f}_L\gamma_\mu f_L + c_{f_R}\frac{\partial^\mu a}{f_a}\bar{f}_R\gamma_\mu f_R + c_\phi\frac{\partial^\mu a}{f_a}(\phi^\dagger i\overleftrightarrow{D}_\mu\phi) + \frac{\alpha_{\text{em}}}{4\pi}\frac{a}{f_a}F_{\mu\nu}\tilde{F}^{\mu\nu}$$

- While ALP-fermion (Higgs) couplings respect the shift symmetry, ALP-photon coupling does not.
- ALP only has pseudoscalar coupling with fermions in the CP conserving case.

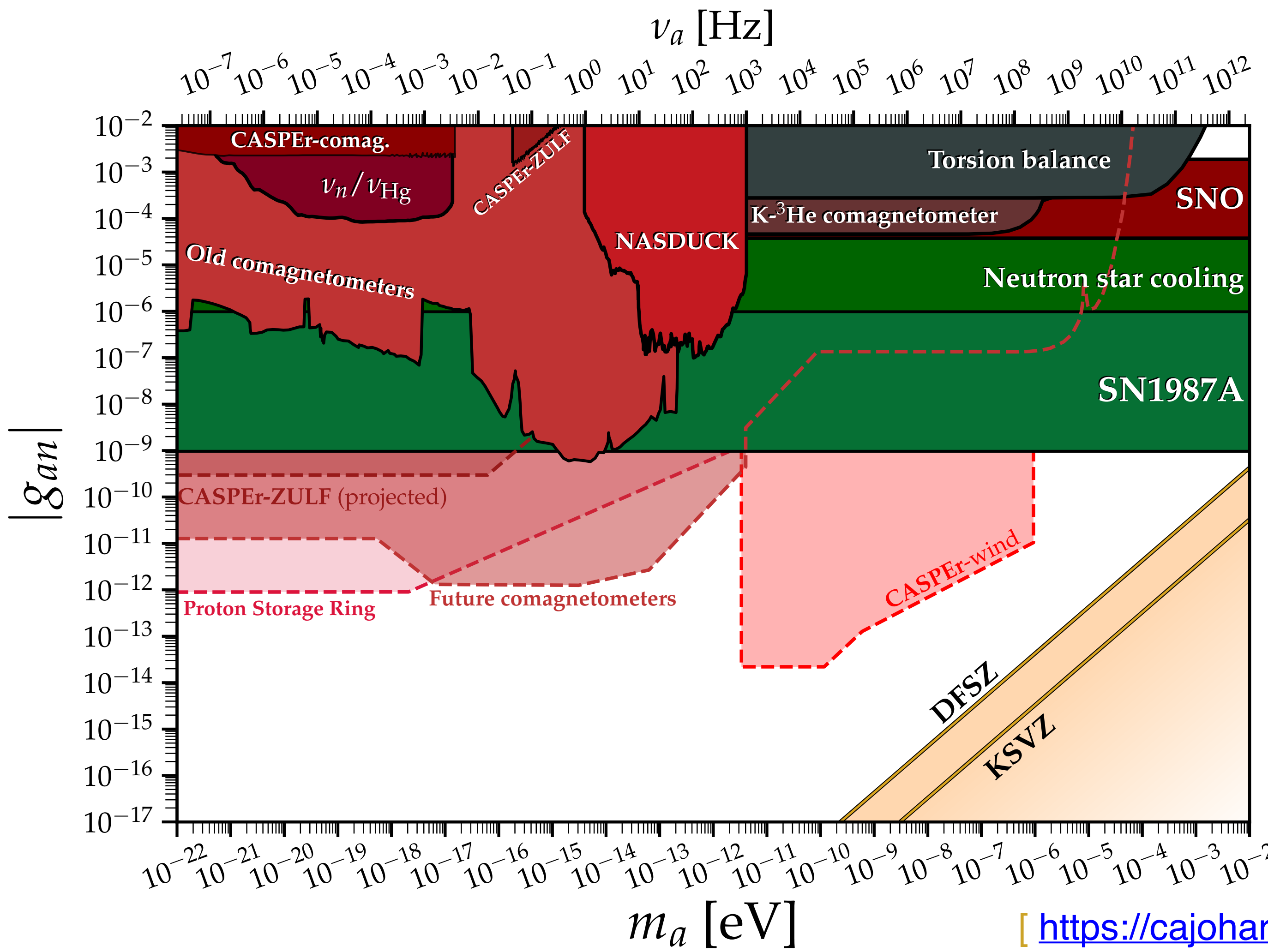
$$c_{f_L}\frac{\partial^\mu a}{f_a}\bar{f}_L\gamma_\mu f_L + c_{f_R}\frac{\partial^\mu a}{f_a}\bar{f}_R\gamma_\mu f_R \Rightarrow \frac{\partial^\mu a}{f_a}\left(c_{f_V}\bar{f}\gamma_\mu f + c_{f_A}\bar{f}\gamma_\mu\gamma_5 f\right)$$

$$c_{f_V}\bar{f}\gamma_\mu f\text{-term} = 0 \quad \left[\, a\partial^\mu(\bar{f}\gamma_\mu f) = 0 \,\right]$$

$$c_{f_A}\bar{f}\gamma_\mu\gamma_5 f\text{-term} = \frac{a}{f_a}\left(-2m_f c_{f_A}\bar{f}\gamma_5 f\right)$$

# Current bounds for the ALP-fermion coupling

ALP-neutron coupling: $\mathcal{L} = g_{aN} \frac{\partial^\mu a}{f_a} \bar{n}\gamma_\mu\gamma_5 n$ ←ALP interacts with the spin of fermion.




[ https://cajohare.github.io/AxionLimits/]

- The strongest current bound comes from SN1987A.
- CASPEr experiments survey $g_{an}$ ~$10^{-14}$ at $m_a$~$0.1$ neV.

# ALP interaction with CP violation

We consider the scalar coupling

$$\mathcal{L}^{\rm CPV} = -g^S_{af} a \bar{f} f$$

→ Nucleon receives a new force mediated by ALP.

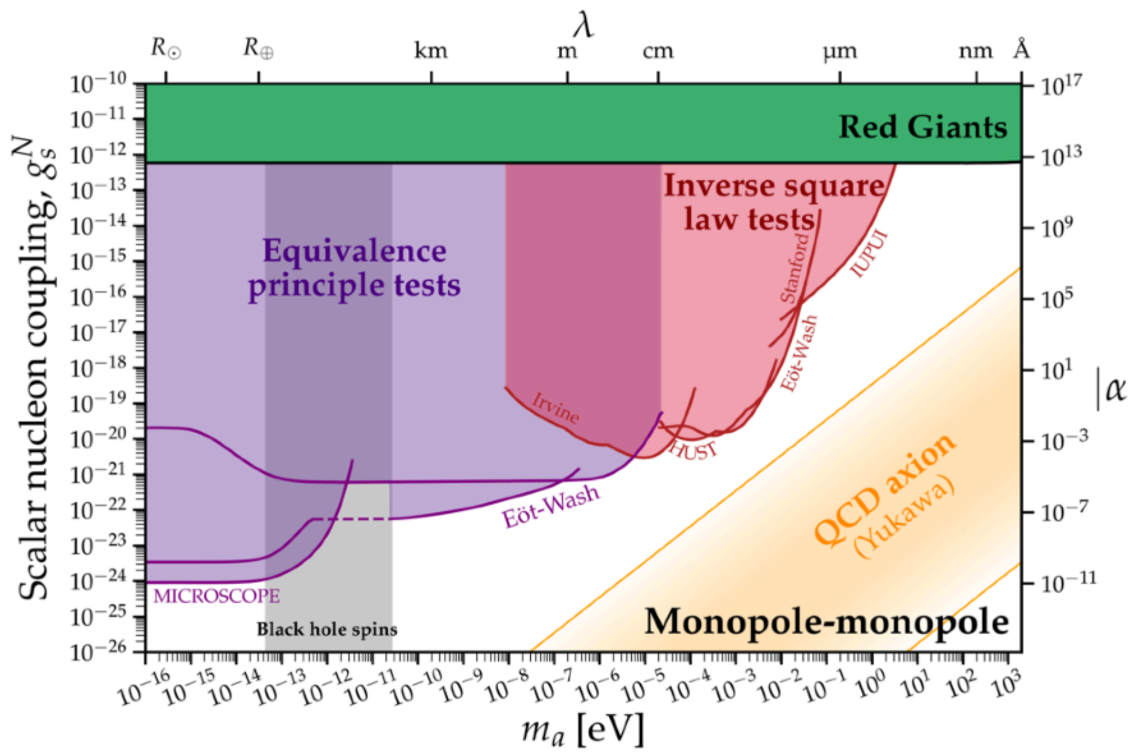
The potential in the non-relativistic limit

$$V(r) = -\frac{g^S_{N_1} g^S_{N_2} e^{-m_a r}}{4\pi r}$$

[C.O'Hare, E.Vitagliano, PRD 102, 115026 (2020)]

→ The gravitational potential is modified as

$$V_G(r) = -\frac{G_N m_1 m_2}{r}\left(1 + e^{-m_a r}\right), \quad \alpha = \frac{(g^S_N)^2}{4\pi G_N m_u^2}$$




$g^S_N$ constrained by long-range force experiments.

- When $m_a$< *1eV*, this gives significant contributions.
- The constraint is much tighter than $g_{aN}$ (~$10^{-9}$).

# What we are interest

- The CPV coupling is disfavored by the bounds from the long-range force.

  [ For QCD axion, CPV source spoils the virtue of the PQ mechanism. ]

- This would be the reason why UV models with CPC dark sector are popular.

- However, if $m_a$> eV, the limit of the long-range force is weaker.

Open question: How are the properties of ALP changed in the case we introduce CPV in the dark sector?

In this talk, we consider a simple renormalization model with CPV in dark sector.

- Properties of ALP
- ALP phenomenology

1. Phenomenology of ALP

- Introduction
- Model with CPV in dark sector
- Testability of ALP
  - Future colliders, astrophysical observations

2. Phenomenology of Higgs boson

- Suppression of the mixing effect in the strong coupling regime

3. Summary

# Scalar potential: CP symmetric dark sector [1/2]

SM Higgs doublet field: $H = \begin{pmatrix} G^+ \\ v + \frac{1}{\sqrt{2}}(\rho + iG_0) \end{pmatrix}$ , Dark Higgs field: $\Phi = v_S + \frac{1}{\sqrt{2}}(s' + ia')$

U(1) symmetric part:

$$V = -m_\Phi^2|\Phi|^2 + \lambda|\Phi|^4 + \lambda_P|H|^2|\Phi|^2 + \lambda_H|H|^4 - \mu_H^2|H|^2 \ ,$$

Soft breaking terms: CPV can be included only in this part.

$$\delta V = \kappa\left(\sum_{j=1}^{4} c_j \Phi m_\Phi^{4-j}\Phi^j + \sum_{j=1}^{2}(\tilde{c}_j^H m_\Phi^{2-j}\Phi^j|H|^2 + \tilde{c}_j^\Phi m_\Phi^{2-j}\Phi^j|\Phi|^2)\right) + \text{h.c.}$$

- Global dark U(1) symmetry is imposed in the potential.
  - Spontaneously broken by $\langle\Phi\rangle$ . → $\rho$ and $s$ mix
  - Nambu Goldstone boson $a$ is massless.

# Scalar potential: CP symmetric dark sector [2/2]

SM Higgs doublet field: $H = \begin{pmatrix} G^+ \\ v + \frac{1}{\sqrt{2}}(\rho + iG_0) \end{pmatrix}$ , Dark Higgs field: $\Phi = v_S + \frac{1}{\sqrt{2}}(s' + ia')$

U(1) symmetric part:

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Soft breaking terms: CPV can be included only in this part.

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- Accidental discrete symmetry:

*CP* : $(CP)H(t,\vec{x})(CP)^\dagger = H^*(t,-\vec{x})$

$(CP)\Phi(t,\vec{x})(CP)^\dagger = \Phi^*(t,-\vec{x})$

$C_{dark}$ : $(C_{dark})H(t,\vec{x})(C_{dark})^\dagger = H(t,\vec{x})$

$(C_{dark})\Phi(t,\vec{x})(C_{dark})^\dagger = \Phi(t,\vec{x})^*$

Both of *CP* and $C_{dark}$ are conserved in *V*.

# Scalar potential: CP violating dark sector

SM Higgs doublet field: $H = \begin{pmatrix} G^+ \\ v + \frac{1}{\sqrt{2}}(\rho + iG_0) \end{pmatrix}$ , Dark Higgs field: $\Phi = v_S + \frac{1}{\sqrt{2}}(s' + ia')$

U(1) symmetric part:

$$V = -m_\Phi^2 |\Phi|^2 + \lambda |\Phi|^4 + \lambda_P |H|^2 |\Phi|^2 + \lambda_H |H|^4 - \mu_H^2 |H|^2 \ ,$$

Soft breaking terms: CPV can be included only in this part.

$$\delta V = \kappa \left( \sum_{j=1}^{4} c_j \Phi m_\Phi^{4-j} \Phi^j + \sum_{j=1}^{2} (\tilde{c}_j^H m_\Phi^{2-j} \Phi^j |H|^2 + \tilde{c}_j^\Phi m_\Phi^{2-j} \Phi^j |\Phi|^2) \right) + \text{h.c.}$$

- $\kappa$ corresponds to the order parameter of breaking of dark U(1).
  - We assume $\kappa$ <<1. This may be natural in the sense that U(1) is restored in $\kappa \to 0$.
    [Gerard 't Hooft, NATO Sci.Ser.B 59 (1980) 135-157]
  - It scales the mass of ALP $m_a^2 \sim \mathcal{O}(\kappa) v_\Phi^2 \sim \mathcal{O}(\kappa) m_s^2$ ( $v_\Phi \sim m_s \gtrsim v$ )
- *CP* and C$_{dark}$ are violated in $\delta V$.

*CP* : $(CP)H(t,\vec{x})(CP)^\dagger = H^*(t,-\vec{x})$
$(CP)\Phi(t,\vec{x})(CP)^\dagger = \Phi^*(t,-\vec{x})$

C$_{dark}$ : $(C_{dark})H(t,\vec{x})(C_{dark})^\dagger = H(t,\vec{x})$
$(C_{dark})\Phi(t,\vec{x})(C_{dark})^\dagger = \Phi(t,\vec{x})^*$

# CP violating dark sector predicts a CP-even ALP!

- The ALP field mixes with the CP-even components *ρ* and *s'*.

$$\begin{pmatrix} h \\ s \\ a \end{pmatrix} = R(\theta_{hs}, \theta_{sa}, \theta_{ah}) \begin{pmatrix} \rho \\ s' \\ a' \end{pmatrix}$$

SM Higgs doublet : $H = \begin{pmatrix} G^+ \\ v + \frac{1}{\sqrt{2}}(\rho + iG_0) \end{pmatrix}$

Dark Higgs singlet: $\Phi = v_S + \frac{1}{\sqrt{2}}(s' + ia')$

$h:$ SM-like Higgs boson , $s:$ dark Higgs boson , $a:$ ALP

- The mixing angle between *h* and *a* can be expressed by

$$\theta_{ah} \simeq \frac{2\mathcal{M}_{ah}^2}{\mathcal{M}_{hh}^2 - \mathcal{M}_{aa}^2} \sim c_h \frac{m_a^2}{m_h m_\Phi}$$

$c_h$ is function of $c_i$ .

- Though the mixing with the SM Higgs boson, couplings of ALP with SM fields are generated.

$$\mathcal{L}_{\text{int.}} \ni -\theta_{ah} \frac{m_f}{v} a\bar{f}f \quad - i g_{af} a\bar{f}\gamma_5 f$$

→ ALP has the couplings of CP-even scalar.

→ The couplings scale with the mass of ALP.

counter exapmple of this coupling?

# Why does pseudo scalar couplings vanish?

$$C_{\rm dark}\cdot CP: \quad \text{the SM fields transform as in the SM, } \Phi[t,\vec{x}]\to\Phi[t,-\vec{x}]$$

$$\delta V=\kappa\left(\sum_{j=1}^{4}c_j\Phi m_\Phi^{4-j}\Phi^j+\sum_{j=1}^{2}(\tilde{c}_j^H m_\Phi^{2-j}\Phi^j|H|^2+\tilde{c}_j^\Phi m_\Phi^{2-j}\Phi^j|\Phi|^2)\right)+\text{h.c.}$$

In $\kappa\neq 0$ ( i.e. $\delta V\neq 0$ ),

$C_{\rm dark}$ : Broken, $CP$ : Broken

$C_{\rm dark}\cdot CP(\equiv C_{\rm eff}P)$ : Conserved

⇕

But $(C_{\rm eff}P)(-ig_{af})a\bar{f}\gamma_5 f(C_{\rm eff}P)^\dagger$
$\to +ig_{af}a\bar{f}\gamma_5 f$

→ The simple model involving dark Higgs singlet predict CP-even ALP.

# CP-even ALP couplings

U(1) symmetric part:

$$V = -m_\Phi^2|\Phi|^2 + \lambda|\Phi|^4 + \lambda_P|H|^2|\Phi|^2 + \lambda_H|H|^4 - \mu_H^2|H|^2\ ,$$

Explicit breaking terms: CPV can be included only in this part.

$$\delta V = \kappa\left(\sum_{j=1}^{4} c_j \Phi m_\Phi^{4-j}\Phi^j + \sum_{j=1}^{2}(\tilde{c}_j^H m_\Phi^{2-j}\Phi^j|H|^2 + \tilde{c}_j^\Phi m_\Phi^{2-j}\Phi^j|\Phi|^2)\right) + \text{h.c.}$$

U(1) symmetric part: ➡ $\mathcal{L}_{\text{eff}} \sim \frac{\mathcal{O}_{\text{SM}}}{m_\Phi^2}(\partial a)^2$

- $C_{dark}$ and *CP* symmetric
- Non-renormalizable

Explicit breaking terms: ➡

$$\mathcal{L}_{\text{eff.}} \ni -\theta_{ah} g_{hXX} aXX \sim \frac{m_a^2}{m_h m_\Phi} g_{hXX} aXX$$

- It realizes through the mixing between *h* and *a.*
- It vanishes at κ → 0 ($m_a^2$ → 0) .
- Renormalizable

1. Phenomenology of ALP

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# Search of CP-even ALP

The interaction between ALP and the SM-like Higgs boson is not necessary small, differently from the interaction with fermions.

$$(a\bar{f}f) : \quad -\theta_{ah}\frac{m_f}{v}a\bar{f}f$$

$$\sim c_h \frac{m_a^2}{m_h m_\Phi}$$

$$(h(\partial a)^2) : -\frac{\lambda_P v}{m_s^2 - m_h^2}h(\partial a)^2$$

If $\lambda_P \sim \mathcal{O}(1)$ , the coupling can be sizable.

→ The SM-like Higgs boson decays into ALPs can be significant.

- In case that ALP can decay, characteristic decay pattern of ALP can be predicted.
- The Higgs invisible decay can be also useful, even if ALP is DM. $\Gamma_{a\to\gamma\gamma} \simeq \frac{m_a^7}{\pi^5 v^2 m_h^2 m_\Phi^2}$

( QCD axion $m_a \sim m_\pi^2 \frac{f_\pi^2}{f_a^2}$ $f_a \gg v$ shoud be satisfied. $\longrightarrow$ $(h(\partial a)^2) : \sim \frac{cv}{f_a^2}h(\partial a)^2$ is suppressed. )

# Numerical result for BR(h→ *aa*)

- Input parameters

$$500\text{GeV} < m_s, v_s < 10\text{TeV}$$

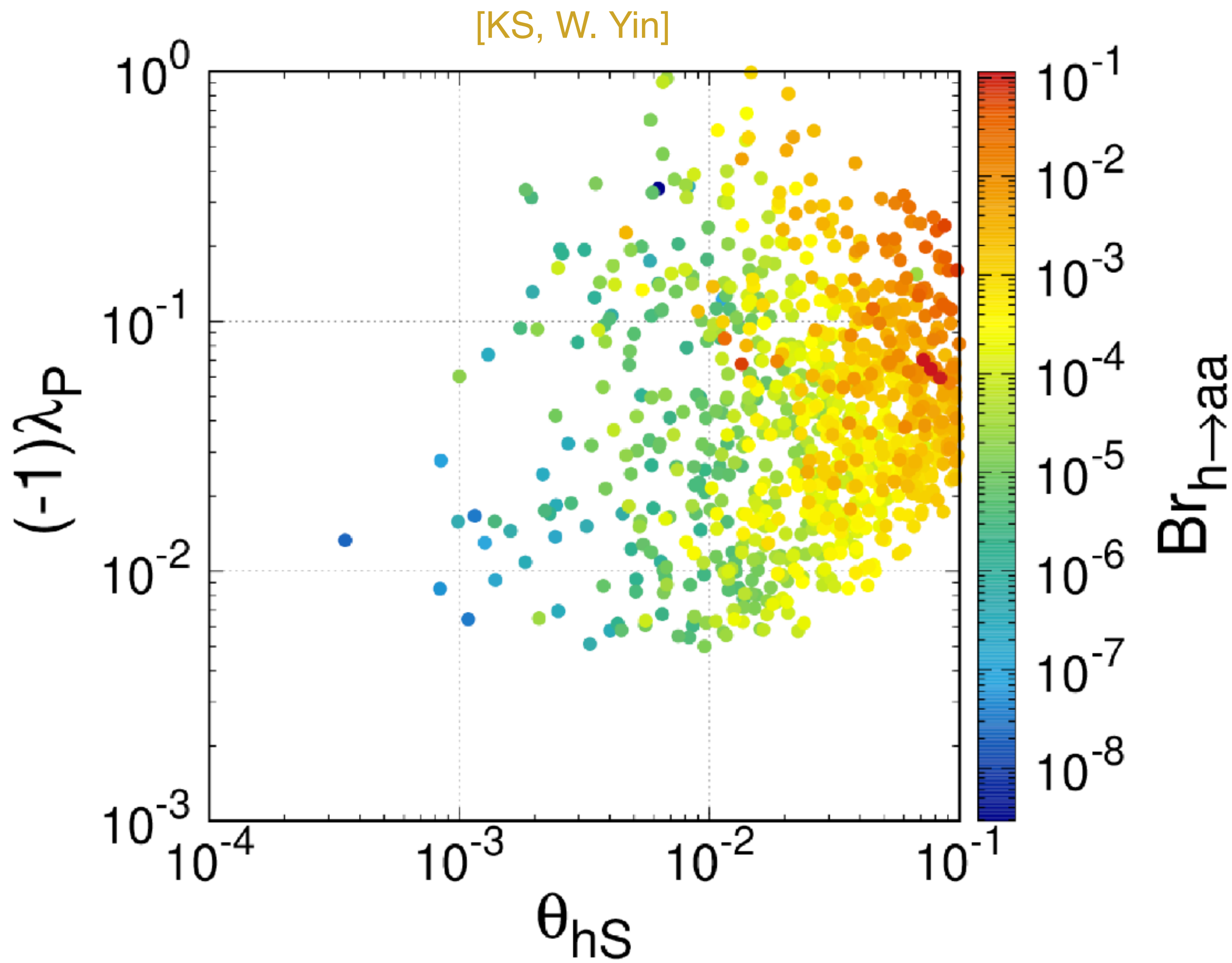
$$0 < c_i < 1, \quad 10^{-10} < \kappa < 10^{-2}$$

- Branching ratio

$$BR(h \to aa) \simeq \frac{|\lambda_{haa}|^2}{8\pi m_h \Gamma_h}$$

$$\lambda_{haa} \simeq \frac{\lambda_P}{2} v \cos\theta_{hs} + \frac{v_s}{\sqrt{2}} \lambda_H \sin\theta_{hs} + \mathcal{O}(\kappa)$$

$$V \ni +\lambda_P |H|^2 |\Phi|^2 + \lambda_H |H|^4$$

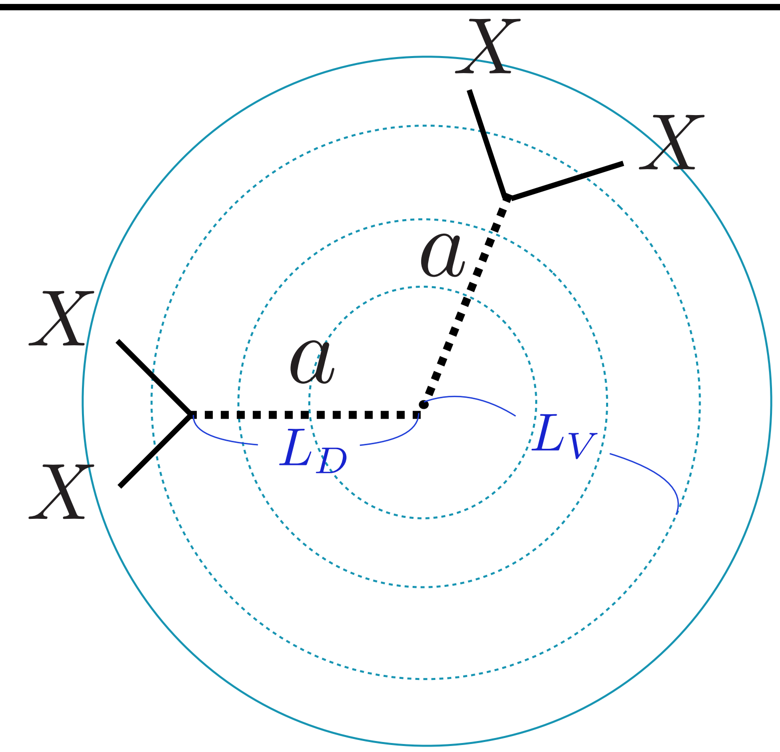



→ If the mixing angle between *h* and *s*, $\theta_{hs}$ is 1% ~10%, BR(h—>aa ) can exceed 1%

# Collider signature at the ILC

- At the ILC with $\sqrt{s} = 250\ \mathrm{GeV}$ , the ALP can be produced via $e^+e^- \to Zh$ , followed by $h \to aa$ .

- Different signatures are possible depending a relation between $L_D$ and $L_V$ (also $L_R$).




$a$ : ALP

$X$ : SM particle

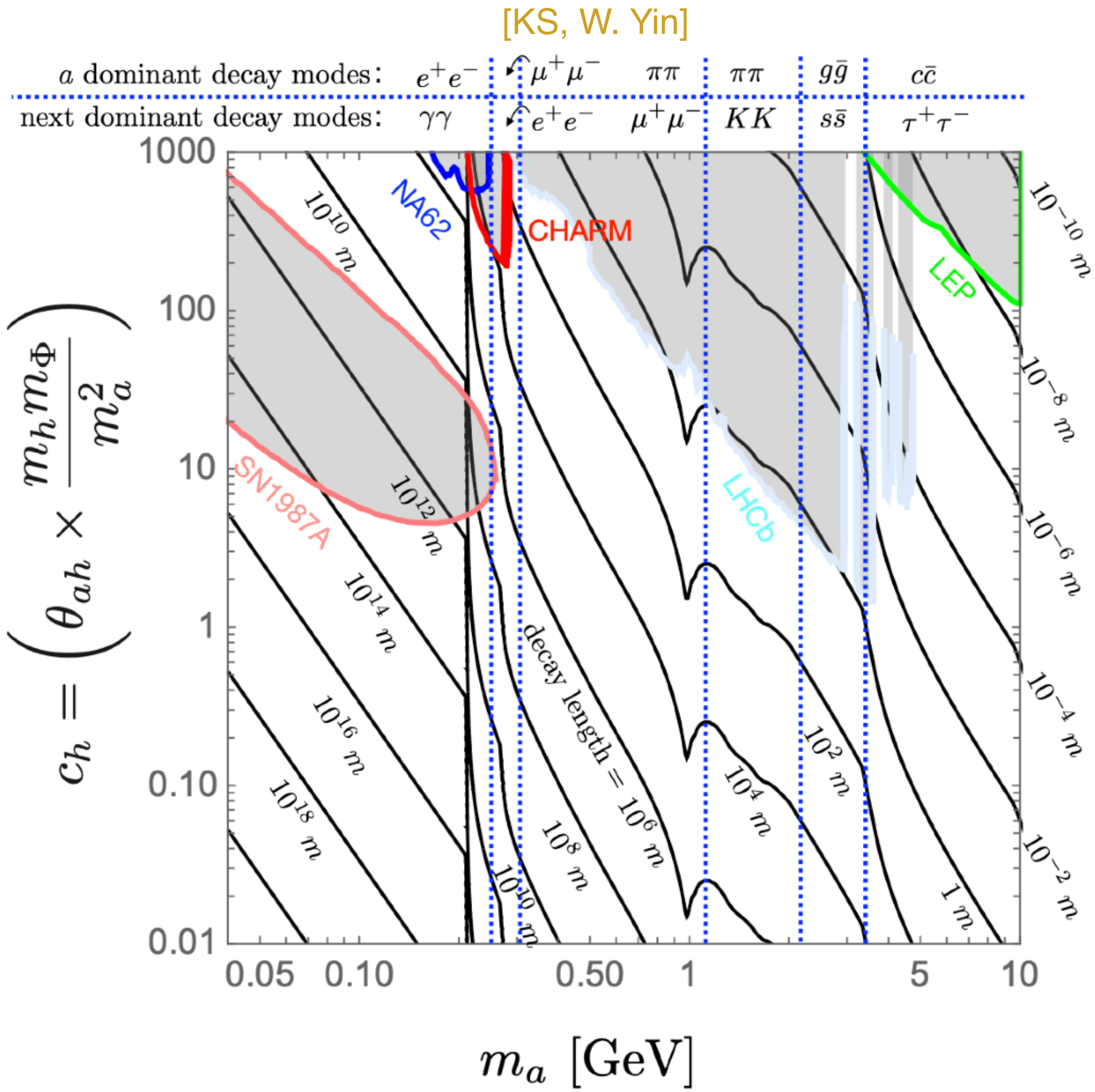
| Condition | Signals in Higgs factory |
|---|---|
| $L_D \gg L_V > L_R$ | Higgs invisible decay |
| $L_D \sim L_V > L_R$ | Displaced vertex $\times 2$, Higgs invisible decay<br>or/and Displaced vertex+missing energy |
| $L_V > L_D > L_R$ | Displaced vertex $\times 2$ |
| $L_V > L_R \gtrsim L_D$ | Exotic Higgs decay |

$L_D$ : Decay length of ALP

$L_V$ : Detector size

$L_R$ : Resolution of vertex detector

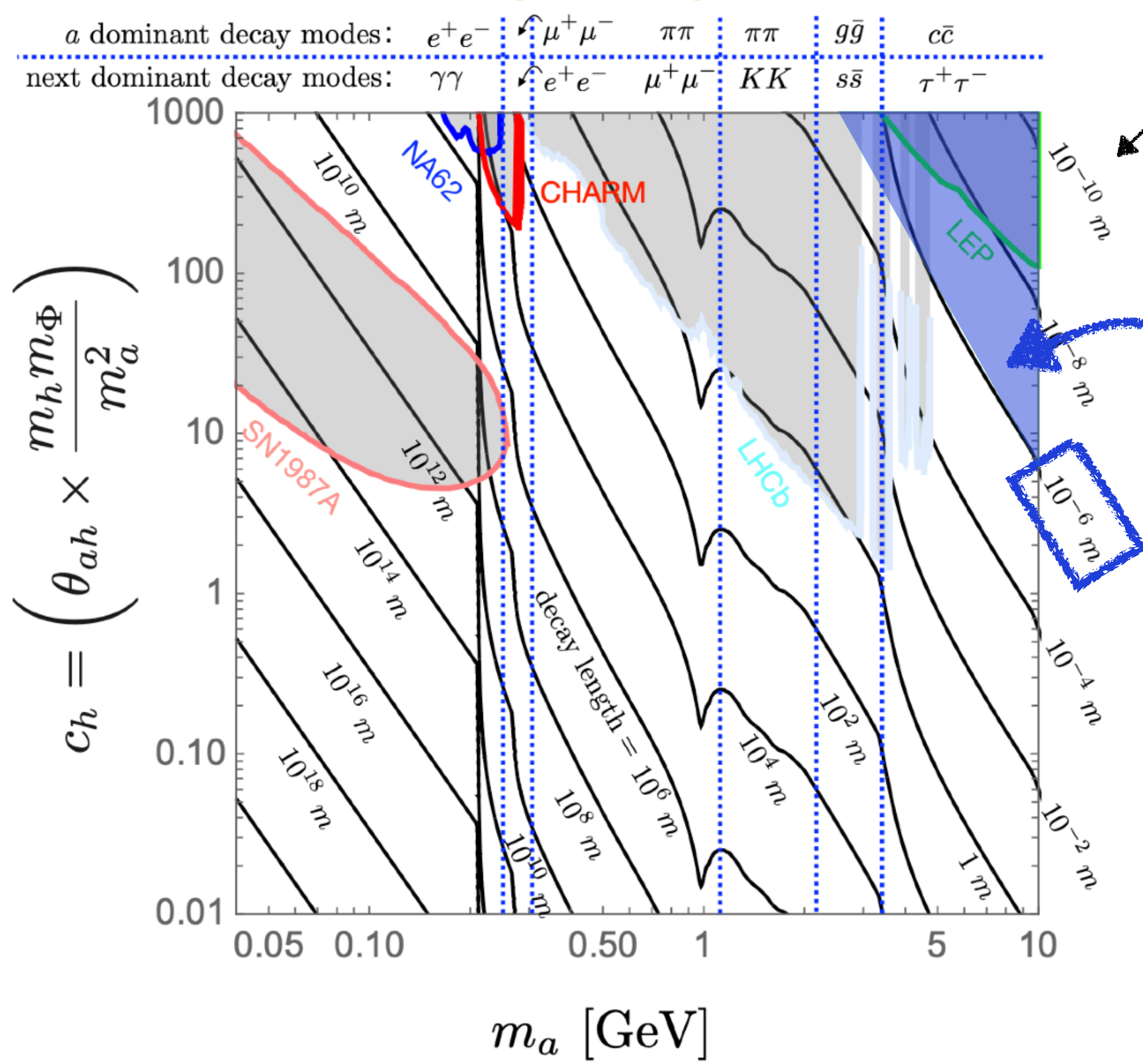
# Probe of CP-even ALP[1/5]




Decay length ($L_D$)

# Probe of CP-even ALP[2/5]

[KS, W. Yin]




Decay length ($L_D$)

Higgs exotic decays

Resolution of vertex detector ($L_R$)

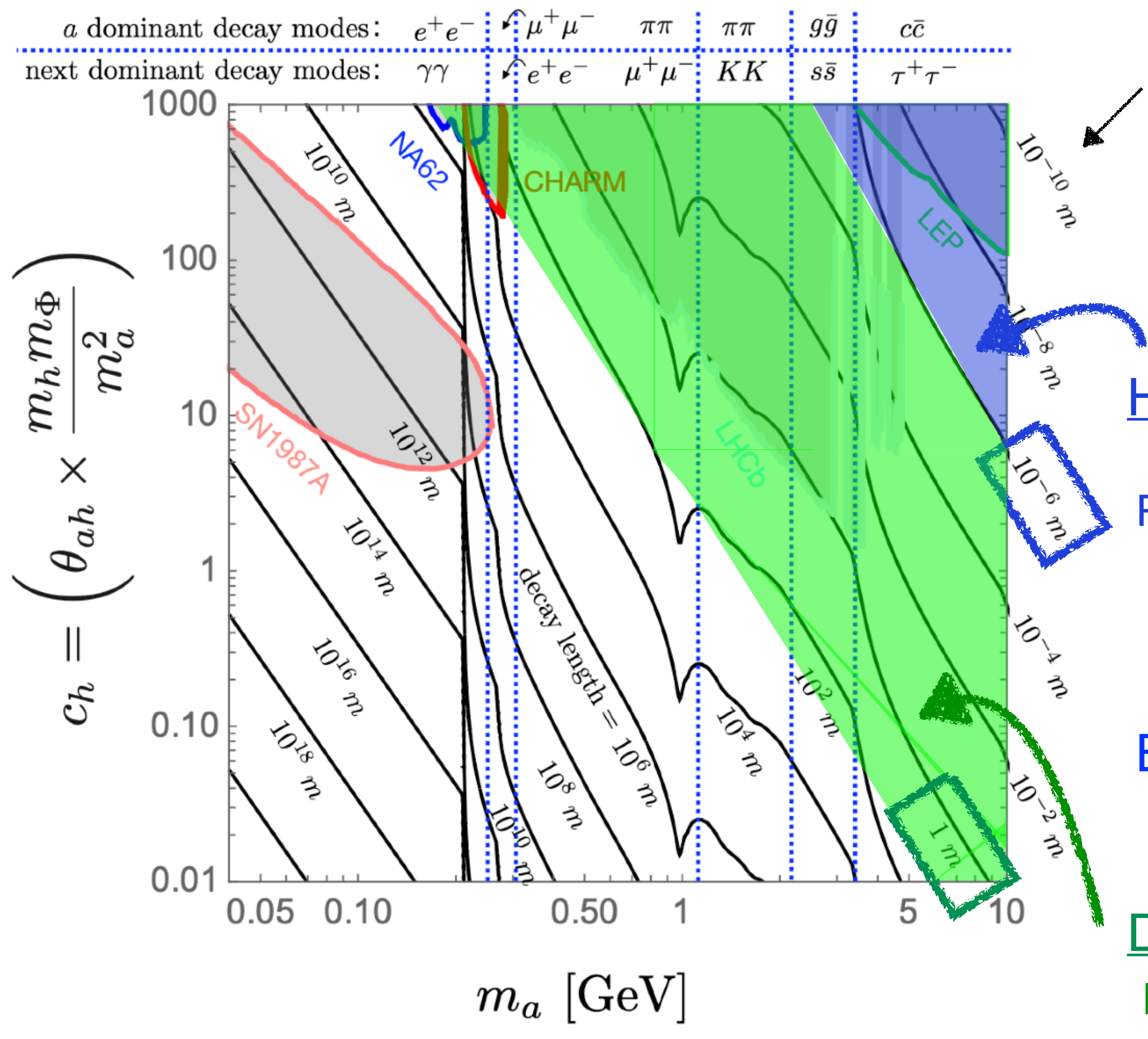
ILD: $L_R^{\mathrm{ILD}} \sim 4\mu m$ [ILD, 1912.04601]

BR($h \to aa \to c\bar{c}c\bar{c}$)< $10^{-3}$ ($2\sigma$, $2\mathrm{ab}^{-1}$ )

[Z. Liu, et al., Chin.Phys.C 41 (2017) 6, 063102]

# Probe of CP-even ALP[3/5]

[KS, W. Yin]




Decay length ($L_D$)

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[Z. Liu, et al., Chin.Phys.C 41 (2017) 6, 063102]

Displaced vertex

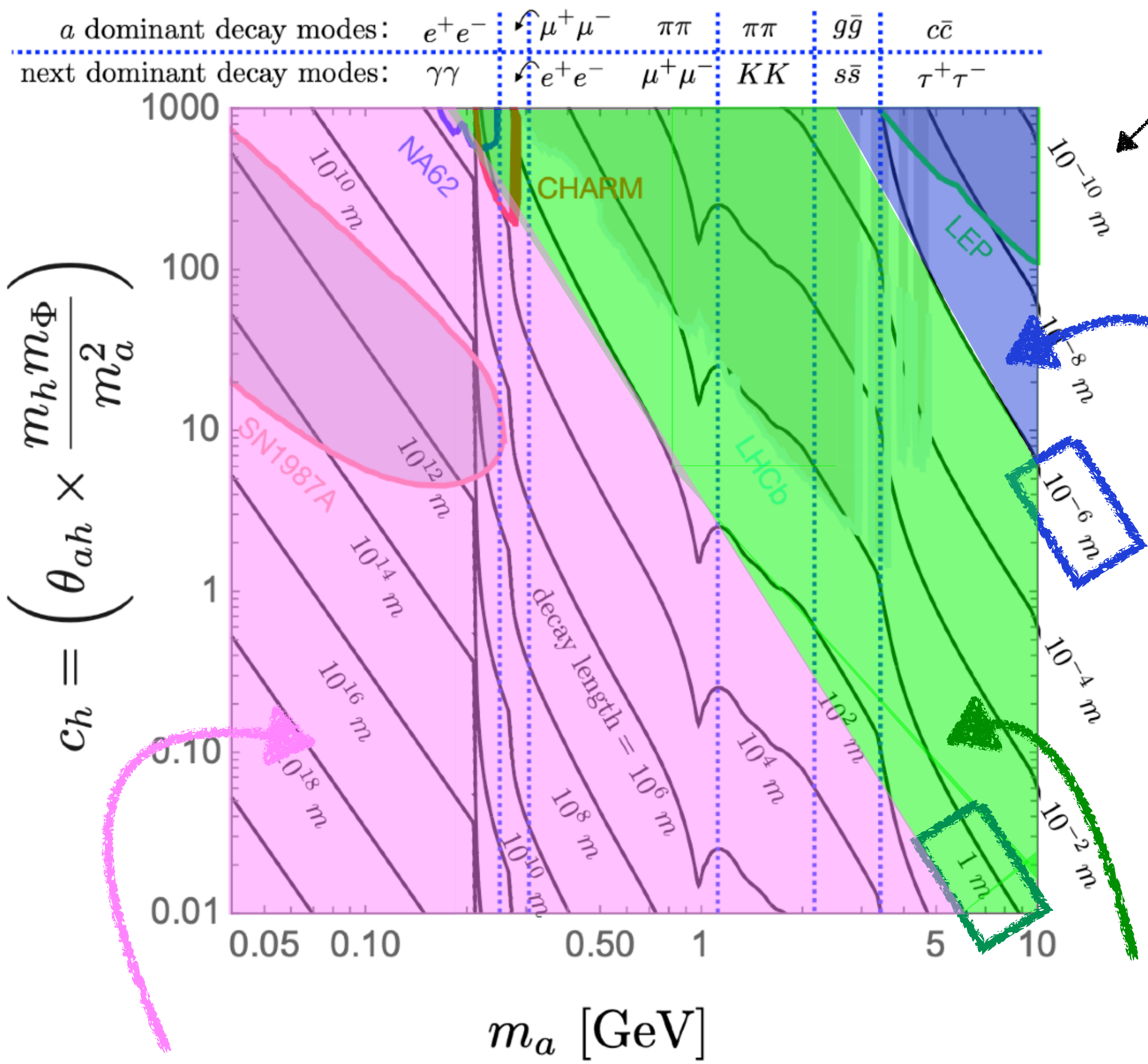
Detector size ($L_V$)

TPC (ILD): 180 cm [ILD, 1912.04601]

$$\mathrm{BR}(h \to aa) \lesssim 2 \times 10^{-4} \left(\frac{10^6}{N_H}\right) \ (2\sigma)$$

# Probe of CP-even ALP[4/5]

[KS, W. Yin]




Decay length ($L_D$)

Higgs exotic decays

Resolution of vertex detector ($L_R$)

ILD: $L_R^{\rm ILD} \sim 4\mu m$ [ILD, 1912.04601]

BR($h \to aa \to c\bar{c}c\bar{c}$)< $10^{-3}$ (2σ, 2ab$^{-1}$ )

[Z. Liu, et al., Chin.Phys.C 41 (2017) 6, 063102]

Displaced vertex

Detector size ($L_V$)

TPC (ILD): 180 cm [ILD, 1912.04601]

$$\mathrm{BR}(h \to aa) \lesssim 2 \times 10^{-4} \left(\frac{10^6}{N_H}\right) \ (2\sigma)$$

Higgs invisible decay

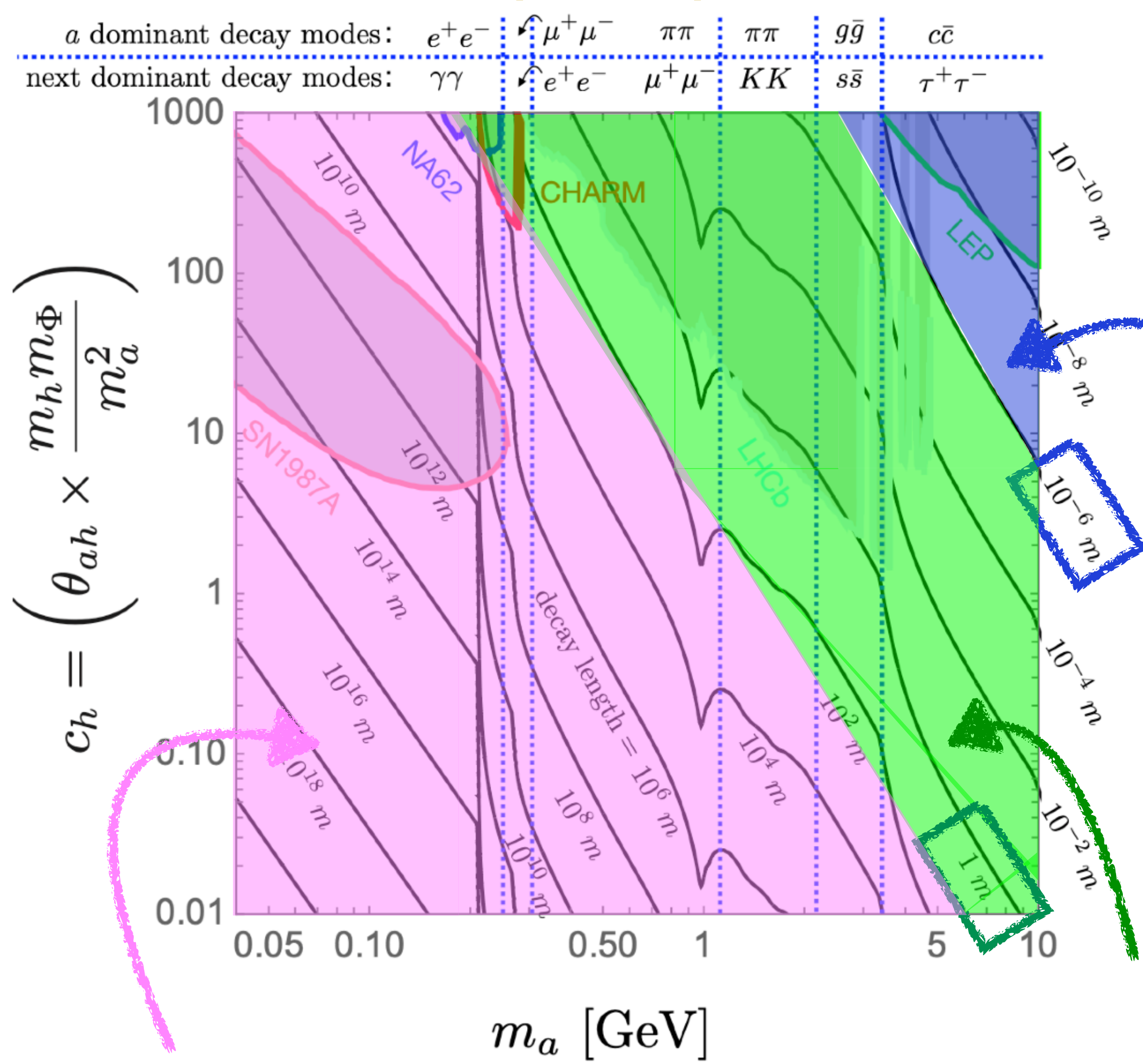
$$L_D \gg L_V \quad \text{or} \quad L_D \gtrsim L_V$$

$$\mathrm{BR}(h \to aa) \lesssim 2.3 \times 10^{-3} \ (2\sigma,\ 900\mathrm{fb}^{-1})$$

[Y. Kato, 2002.12048]

# Probe of CP-even ALP[5/5]

[KS, W. Yin]




## Higgs invisible decay

$L_D \gg L_V$ or $L_D \gtrsim L_V$

$\mathrm{BR}(h \to aa) \lesssim 2.3 \times 10^{-3}$ $(2\sigma,\ 900\mathrm{fb}^{-1})$

[Y. Kato, 2002.12048]

## Model predictions

$$BR(h \to aa) \simeq \frac{|\lambda_{haa}|^2}{8\pi m_h \Gamma_h}$$

$$\lambda_{haa} \simeq \frac{\lambda_P}{2} v \cos\theta_{hs} + \frac{v_s}{\sqrt{2}} \lambda_H \sin\theta_{hs} + \mathcal{O}(\kappa)$$

**CP-even ALP can be probed by *h→aa.***

## Higgs exotic decays

Resolution of vertex detector ($L_R$)

ILD: $L_R^{\mathrm{ILD}} \sim 4\mu m$ [ILD, 1912.04601]

BR($h \to aa \to c\bar{c}c\bar{c}$)< $10^{-3}$ ($2\sigma$, $2\mathrm{ab}^{-1}$ )

[Z. Liu, et al., Chin.Phys.C 41 (2017) 6, 063102]

## Displaced vertex

Detector size ($L_V$)

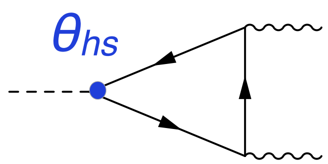
TPC (ILD): 180 cm [ILD, 1912.04601]

$$\mathrm{BR}(h \to aa) \lesssim 2 \times 10^{-4} \left(\frac{10^6}{N_H}\right) \ (2\sigma)$$

# CP-even ALP as DM

- The lifetime can be larger than the age of the Universe in $m_a \lesssim 1\text{MeV}$ .

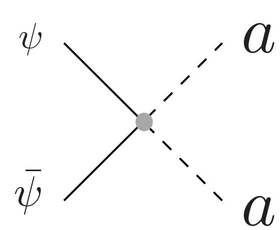
$$\Gamma_{a\to\gamma\gamma} \simeq \frac{m_a^7}{\pi^5 v^2 m_h^2 m_\Phi^2}$$




- The ALP can be thermally produced through the interaction:

$$\delta\mathcal{L} = -\frac{\sqrt{2}m_\psi}{\Lambda_H^2 m_h^2}\partial a \partial a \bar{\psi}\psi$$

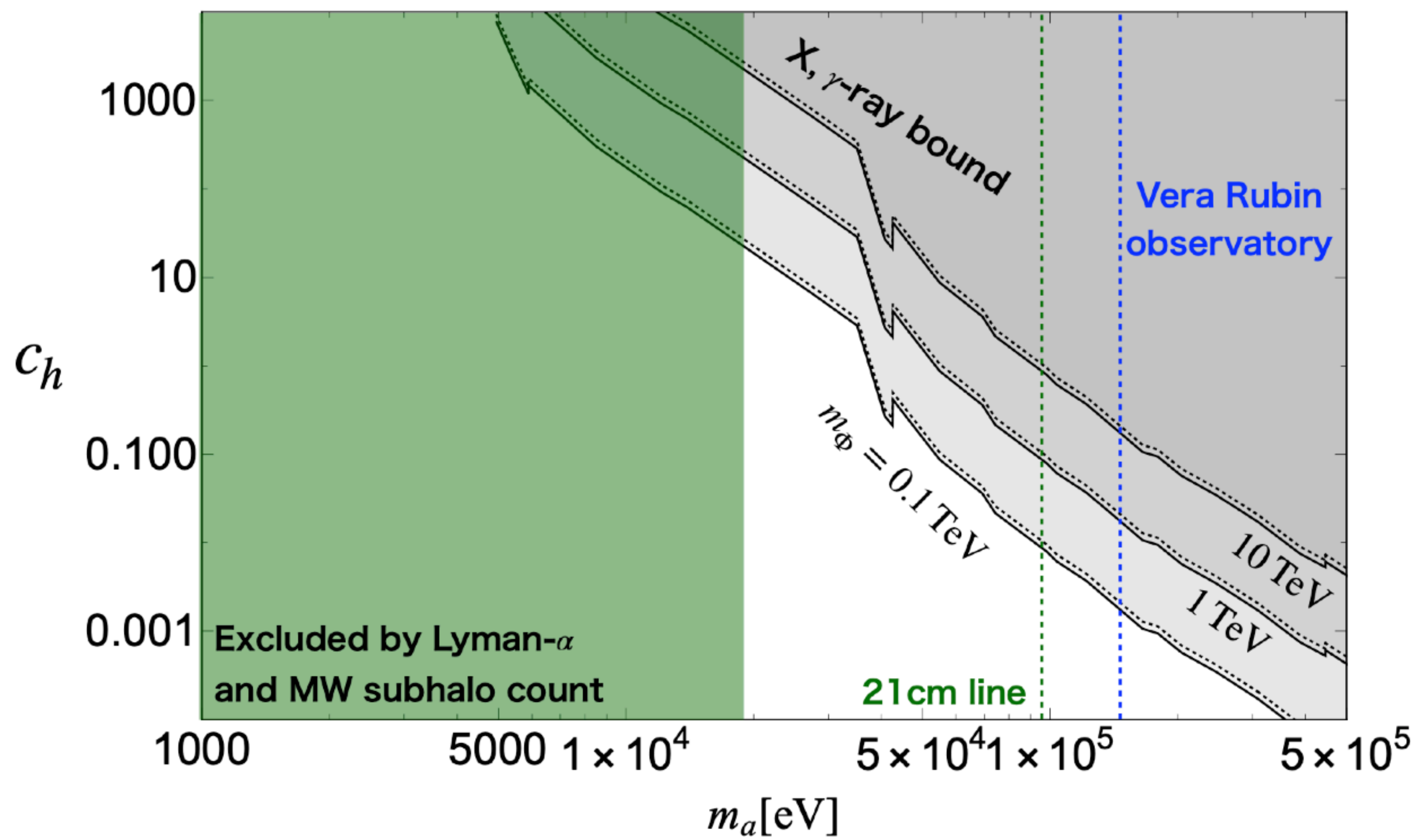
$$\frac{1}{\Lambda_H^2} \equiv -\frac{\lambda_P}{m_s^2 - m_h^2}$$




- The correct relic density can be obtained:

$$\Omega_a \sim 0.35\frac{m_a}{20\,\text{keV}}\left(\frac{m_\psi}{\text{GeV}}\right)^2\left(\frac{T_R}{2\,\text{GeV}}\right)^5\left(\frac{3\,\text{TeV}}{\Lambda_H}\right)^4$$

[KS, W. Yin]




→ The ALP DM can be probed by the future 21 cm line measurements, Vera Rubin observatory (structure formation limit) as well as future X,γ-ray observatories.

→ Higgs boson invisible decay can also probe ALP DM with $m_a \lesssim 1\text{MeV}$ .

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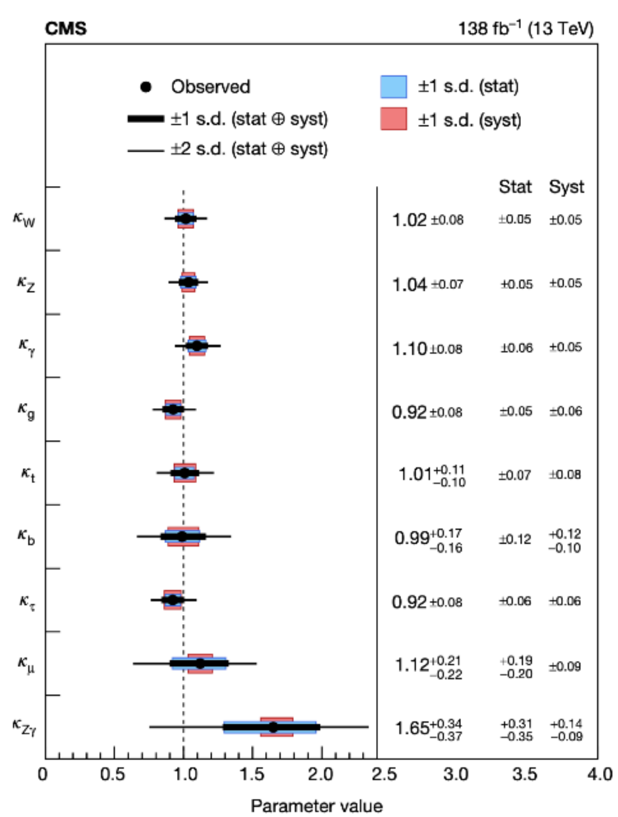
3. Summary

# Introduction [1/2]

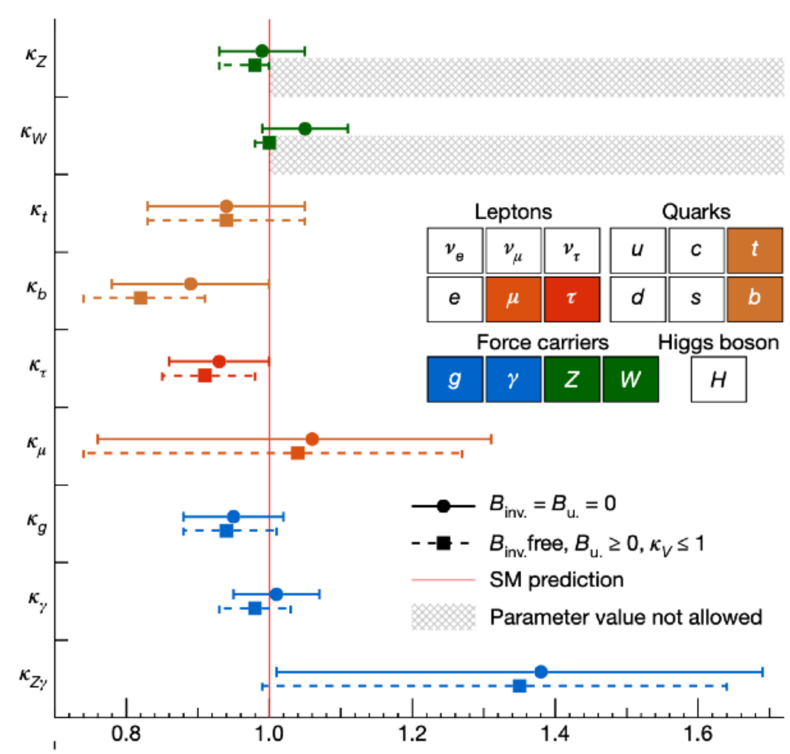
- What we found from the discovery of the Higgs boson *H*

1. Mass: 125 GeV, Spin: 0
2. *H* is mainly produced by the ggF process.
3. *H* decays into γγ, VV, bb, ττ
4. The properties of *H* is consistent with the SM (SM-like)

[CMS, Nature607,60]

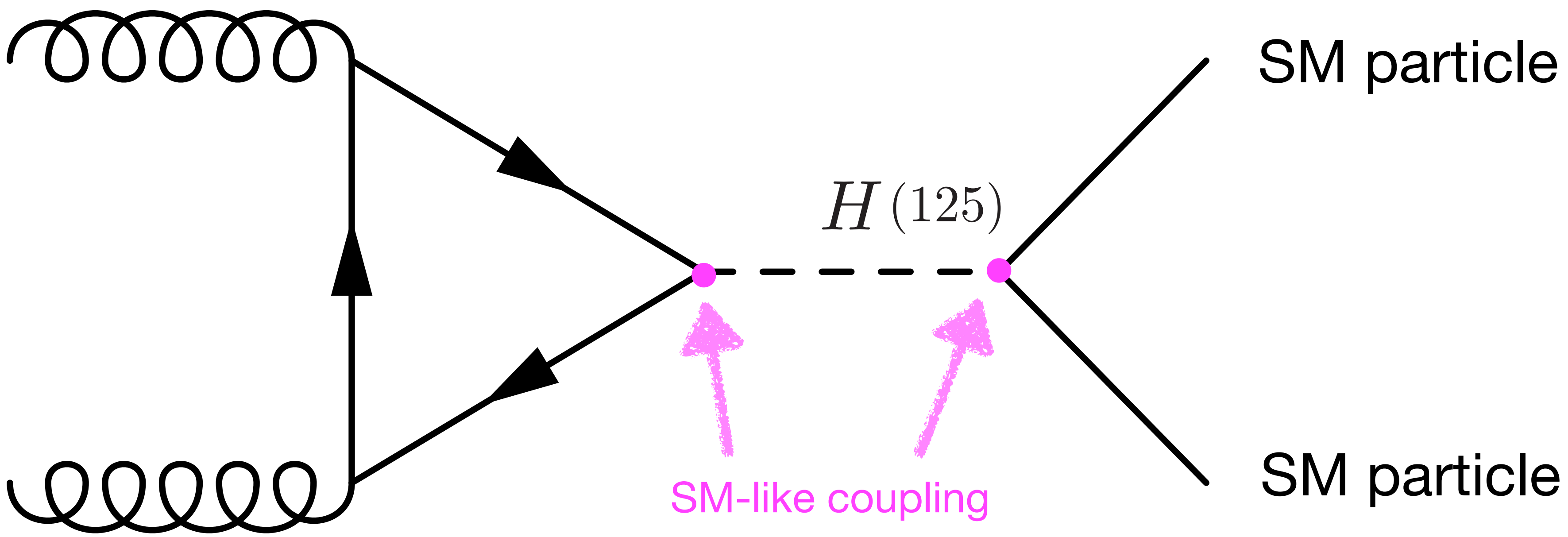



[ATLAS, Nature607,52]



# Introduction [2/2]

- What we found from the discovery of the Higgs boson *H*

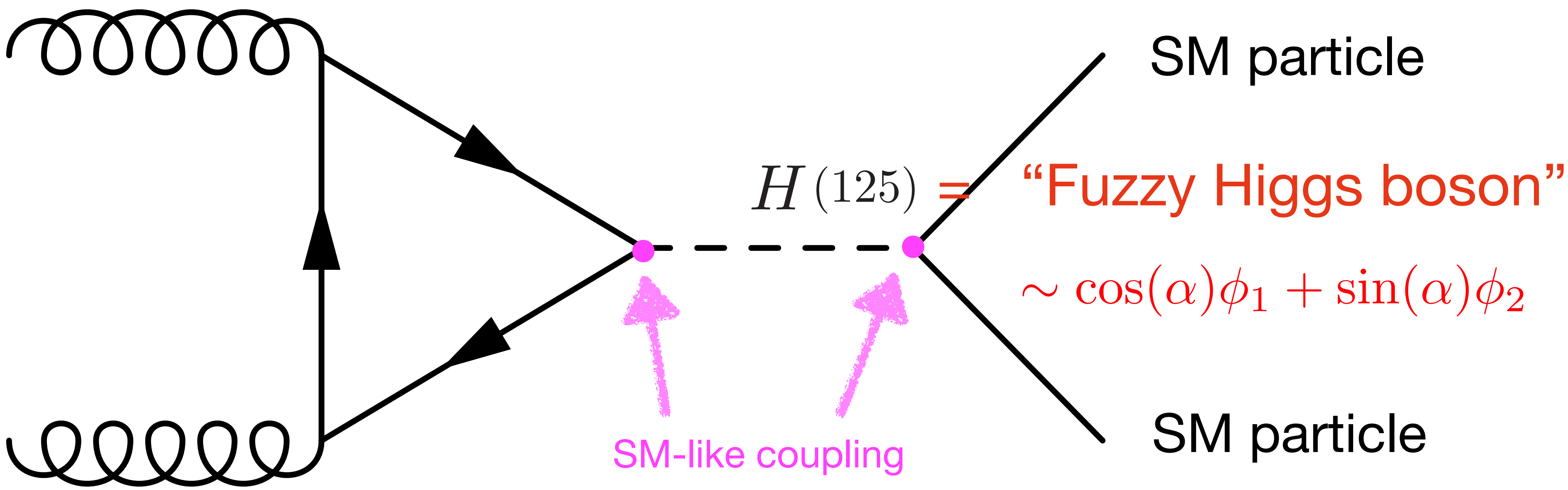



Did we really observe the SM-like Higgs boson?

- In this talk, we propose a new picture that gives observed properties of the Higgs boson.
- As a concrete example, we focus on the CP-even ALP model with κ=0.

# Introduction [2/2]

- What we found from the discovery of the Higgs boson *H*

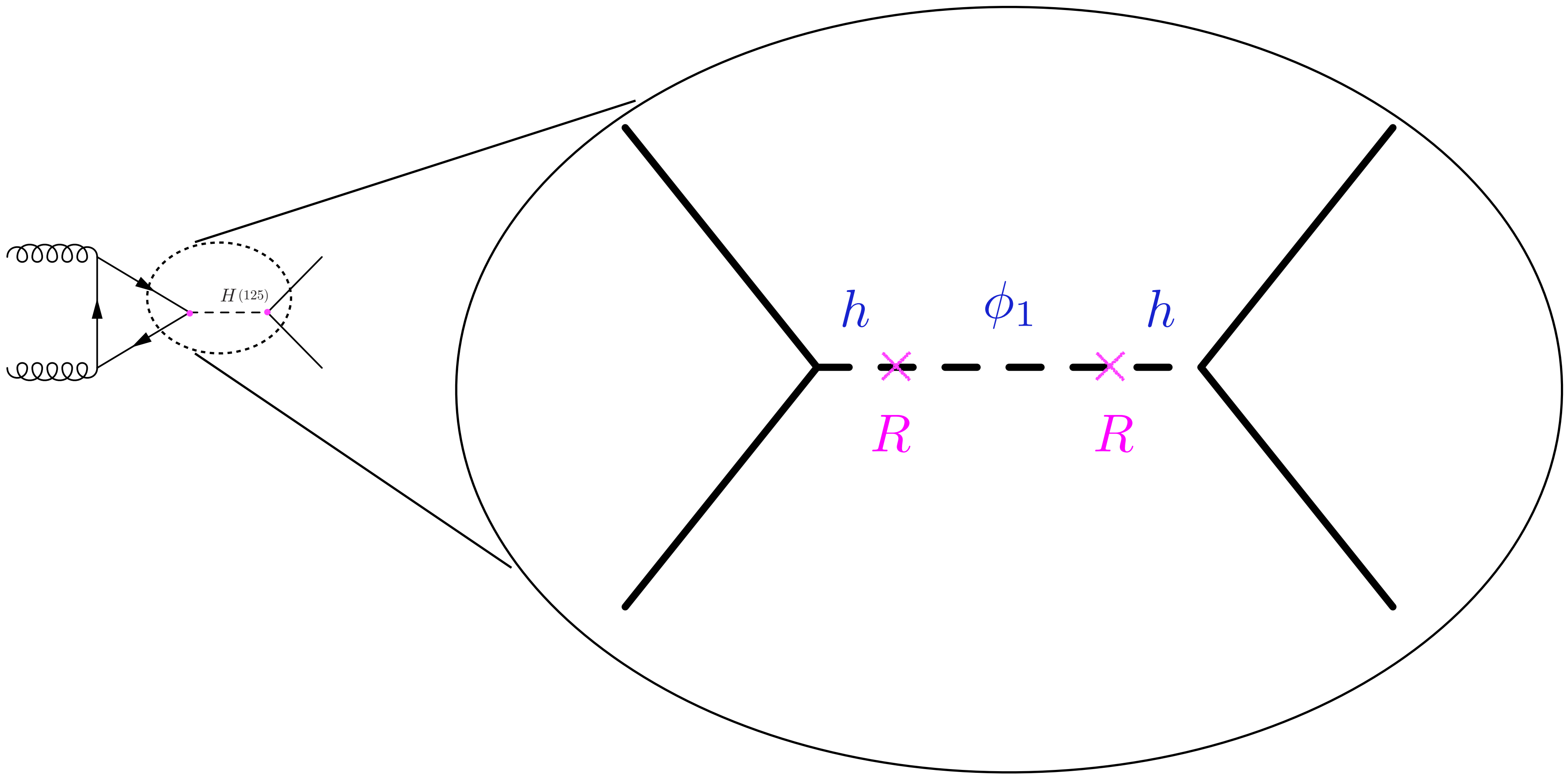



Did we really observe the SM-like Higgs boson?

- In this talk, we propose a new picture that gives observed properties of the Higgs boson.

- As a concrete example, we focus on the CP-even ALP model with κ=0.

# Usual picture




$m_{\phi_1} = 125\text{GeV}$

$m_{\phi_2} \gg m_{\phi_1}$

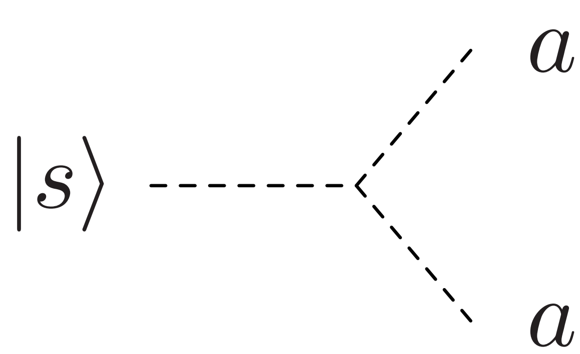
$$\begin{pmatrix} h \\ s \end{pmatrix} = R \begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix} \qquad R = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix}$$

Flavor (interaction) basis    Mass basis

We can interpret the mass eigenstate $\phi_1$ as the observed Higgs.

# In case that *s* promptly decays into dark sector

*s* invisible decay :

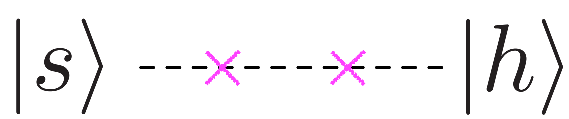



$$\Gamma_s \sim \frac{m_{\phi_2}^3}{32\pi^2 v_s^2} \sim \frac{\lambda_s m_2}{8\pi} \qquad \lambda_S \sim \mathcal{O}(1)$$

$(\alpha \simeq 0)$

Analog of ν oscillations

Transition of *s* to *h* :



$$P(t) \sim \left|\langle s|\, e^{-iHt}\, |h\rangle\right|^2$$

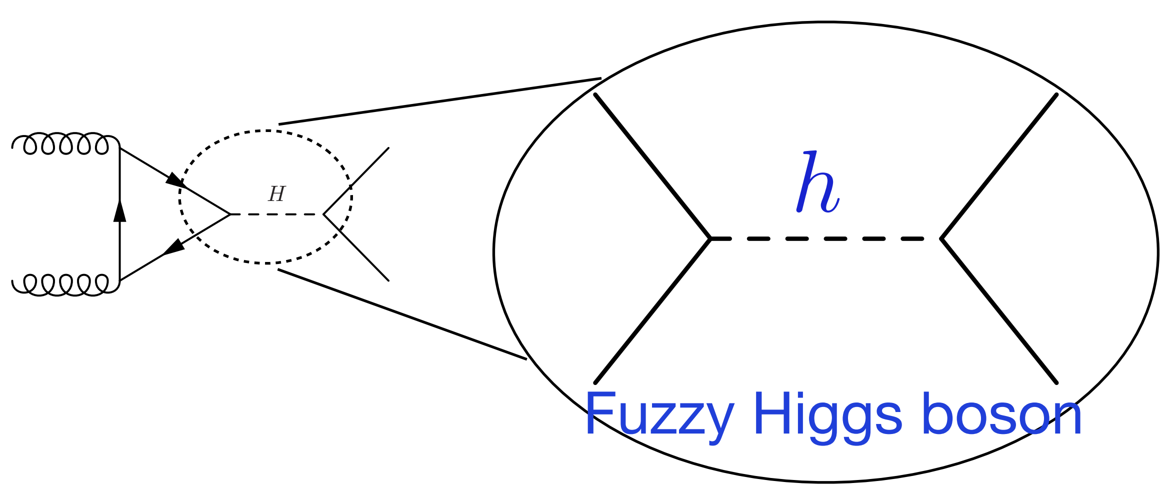
$$\sim \sin^2(2\alpha)\sin^2\left(\frac{\epsilon}{4|\vec{p}|}t\right)^2 \qquad \epsilon \equiv m_1^2 - m_2^2$$

<u>Typical time scale</u>

*s* invisible decay : $t_s \sim \dfrac{|\vec{p}|}{m_2\Gamma_s}$ Transition of *s* to *h* : $t_{osc.} \sim \dfrac{|\vec{p}|}{\epsilon/4}$

→ If $t_s << t_{osc.}$, i.e., $\Gamma_S >> |m_1 - m_2|$, *s* decays before converting to *h*.

In this case, we can not define the mass eigenstates as the asymptotic states because the s promptly decays.



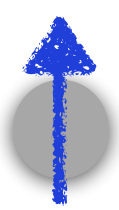
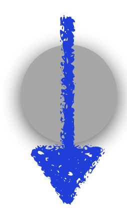

Observed Higgs boson can be understood as the flavor state, which is linear combination of $\phi_1$ and $\phi_2$.

# Quantum Zeno effect [1/2]

[J. Phys. A: Math. Theor.41 (2008) 493001(Review)]

"Frequent measurements slow the evolution of a quantum system, hindering transitions to states different from the initial one".

To demonstate this, let us consider the spin system (Rabi oscillation) as a concrete example.

 $: |1\rangle$  $: |2\rangle$

Initial state : $|\psi(0)\rangle = |1\rangle$

Time evolution : 
$$\begin{aligned} |\psi(t)\rangle &= e^{-iH_t}\,|1\rangle \\ &= \cos(\Omega t/2)\,|1\rangle + i\sin(\Omega t/2)\,|2\rangle \end{aligned}$$

$$H = \frac{\Omega}{2}\Big(\,|2\rangle\langle 1| + |1\rangle\langle 2|\,\Big)$$

Ω: Rabi frequency

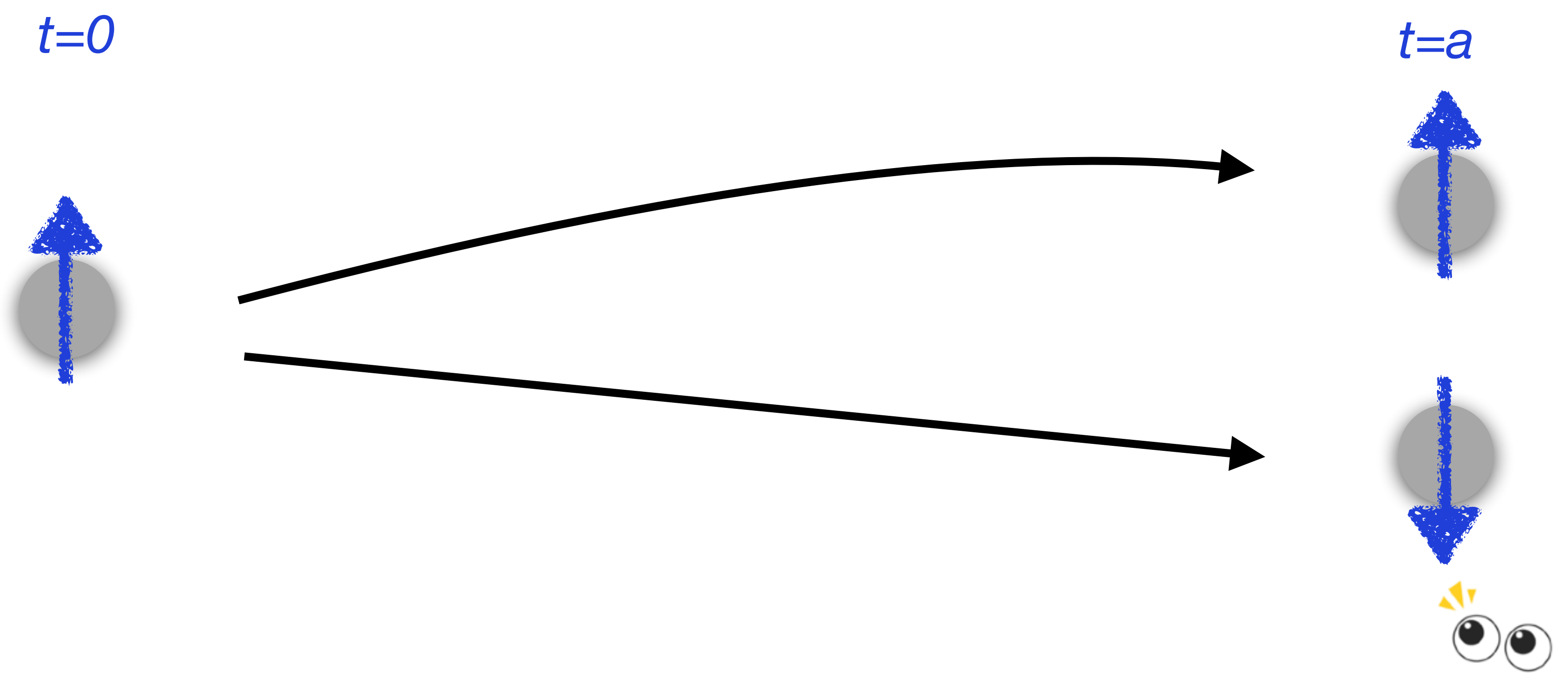
# Quantum Zeno effect [2/2]

Initial state : $|\psi(0)\rangle = |1\rangle$

Time evolution : $|\psi(t)\rangle = \cos(\Omega t/2)\,|1\rangle + i\sin(\Omega t/2)\,|2\rangle$

## ✻ Measurement at *t=a*

[J. Phys. A: Math. Theor.41 (2008) 493001(Review)]

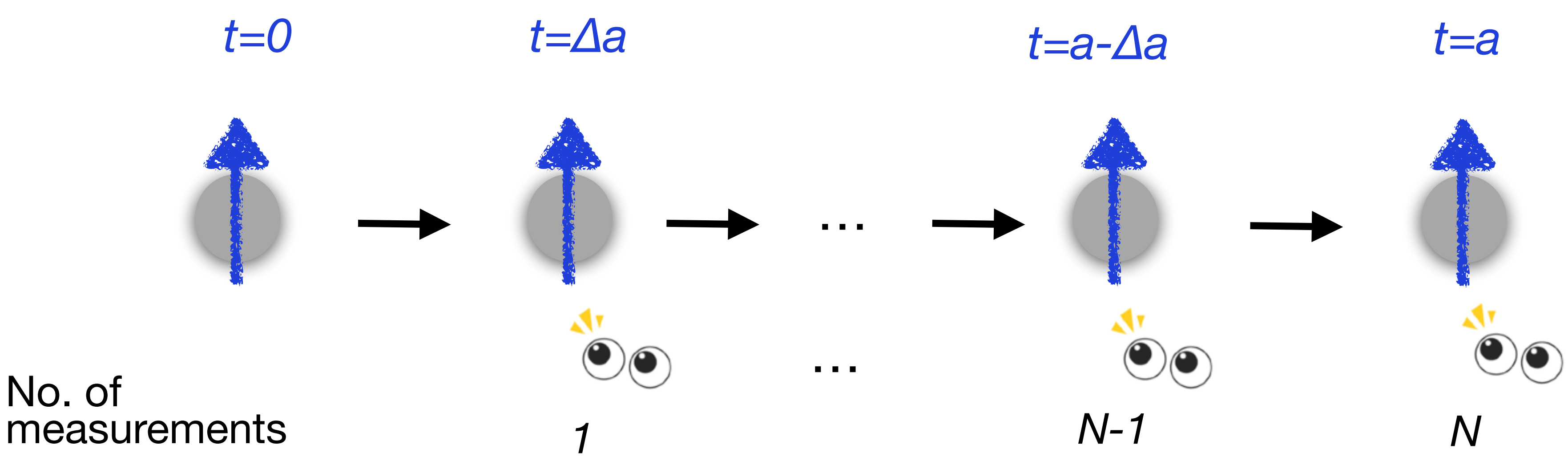



$$\left|\langle 1|\psi(a)\rangle\right|^2 = \cos^2(\Omega a/2)$$

$$\left|\langle 2|\psi(a)\rangle\right|^2 = \sin^2(\Omega a/2)$$

## ✻ Frequent measurement up *t=a*

$$\Delta a = \frac{a}{N}$$




$$\left|\langle 1|\psi(\Delta a)\rangle\right|^2 = \left(1 - \frac{\Omega^2 a^2}{4N^2}\right)^{2N}$$

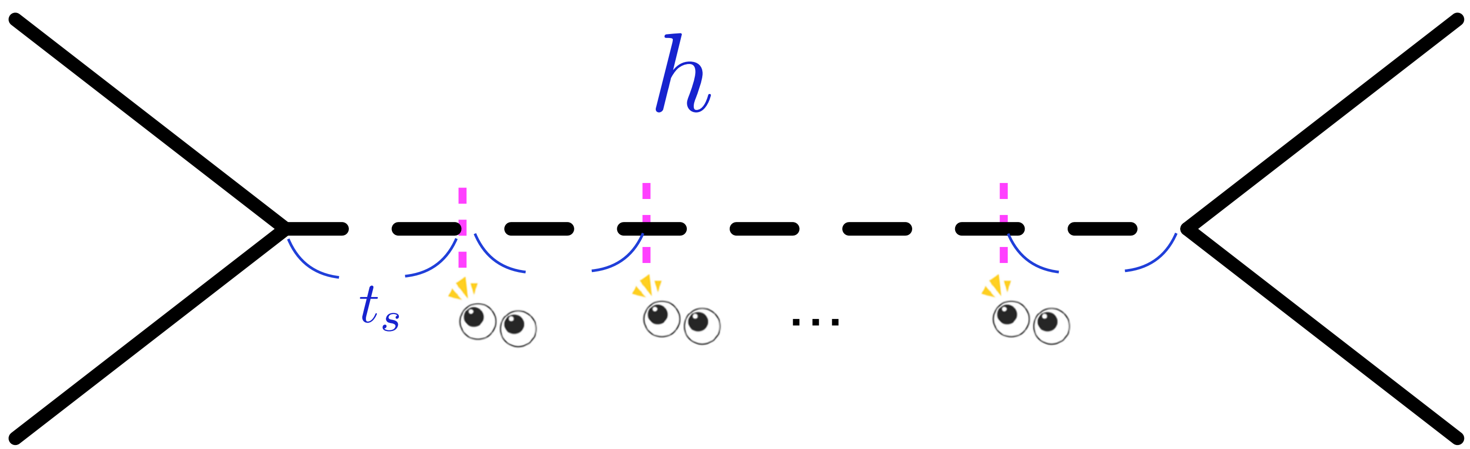
$$= \exp\left[-\frac{\Omega a^2}{2N}\right] = 1$$

$(2N \to \infty)$

If one measures the system frequently the transition of the spin is suppressed (Quantum Zeno effect).

# Similarity with the system of the Higgs boson

If we assume that s→aa is the measurement of the system on the dark sector side, the appearance of fuzzy Higgs can be understood ad the quantum Zeno effect.




$$P_{h\to h} \sim \exp(-t_s/t_{osc.}) \sim 1$$

$$(t_s \ll t_{osc.})$$

*s* decay : $t_s \sim \dfrac{|\vec{p}|}{m_2\Gamma_s}$ Transition of *s* to *h* : $t_{osc.} \sim \dfrac{|\vec{p}|}{\epsilon/4}$

→ If $t_s$ << $t_{osc.}$, i.e., $\Gamma_S$ >> $|m_1 - m_2|$, the state |h> evolves itself by the frequent measurement by the dark sector.

We confirm this effect by strict calculation in the quantum theory.

We will see that suppression of mixing between *s* and *h* happens.

# Breit-Wigner formulation

$$R = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix}$$

$$\hat{\Delta} = \frac{i}{\Delta_s} R \cdot \begin{pmatrix} Q^2 - m_2^2 + \hat{\Pi}_{22} & -\hat{\Pi}_{12} \\ -\hat{\Pi}_{21} & Q^2 - m_2^2 + \hat{\Pi}_{22} \end{pmatrix} \cdot R^T$$

$\Pi_{ij}$ : Renormalized self-energies

( i,j= 1,2 )

$$\Delta_s = (Q^2 - m_1^2 + \hat{\Pi}_{11})(Q^2 - m_2^2 + \hat{\Pi}_{22}) - \hat{\Pi}_{12}\hat{\Pi}_{21}$$

The position of the pole is determined by $\Delta_s = 0$.

(i) : $\hat{\Pi}_{12}, \hat{\Pi}_{21} \ll 1$ :

$$Q^2 = m_1^2 + \Pi_{11},\ m_2^2 + \Pi_{22}$$

$\Pi_{11} = i m_1 \Gamma_1$, $\Pi_{22} = i m_2 \Gamma_2$

(ii) : $\hat{\Pi}_{12}, \hat{\Pi}_{21}$ are not negligible :( $\epsilon = m_1^2 - m_2^2$ )

$$Q^2 = \frac{1}{2}\Big\{ m_1^2 + m_2^2 - \hat{\Pi}_{11} - \hat{\Pi}_{22} \pm \sqrt{(\epsilon - \Pi_{11} + \Pi_{22})^2 + 4\Pi_{12}\Pi_{21}} \Big\}$$

Position of the pole is nontrivial in this case.

Analytical formula of $\Pi_{ij}$ (only DM loop) :

$$\hat{\Pi}_{ij} \simeq \frac{i}{32\pi v_s^2} \begin{pmatrix} \sin^2(\alpha) m_1^4 & \sin\alpha\cos\alpha m_1^2 m_2^2 \\ \sin\alpha\cos\alpha m_1^2 m_2^2 & \cos^2(\alpha) m_2^4 \end{pmatrix}$$

When $v_S \ll 1$, $\Pi_{12,21}$ can be sizable.

# Result with α=π/4

$$m_{h\text{eff}} \equiv \sqrt{m_1^2 \cos^2\alpha + m_2^2 \sin^2\alpha}$$

$$R = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix}$$

$$\epsilon = m_2^2 - m_1^2$$

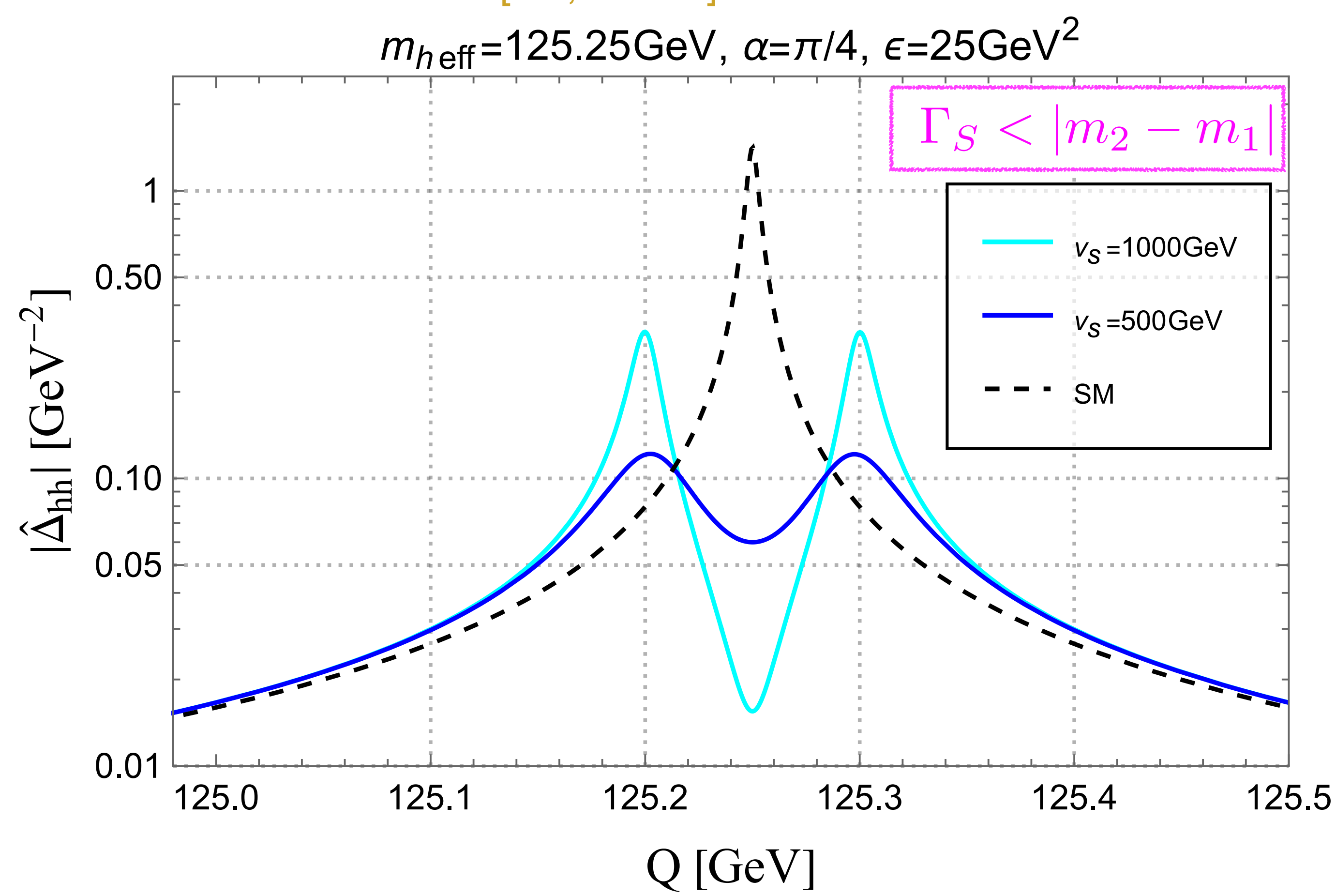
Using the BW formulation, we numerically calculate the $\Delta_{hh}$ with the different values of $v_s$.

[ $v_S$ controls the size of $\Gamma_S$

$$\Gamma_s \sim \frac{m_2^3}{32\pi^2 v_s^2} \sim \frac{\lambda_s m_2}{8\pi}$$
]

→ Two separated poles appear.

[KS, W. Yin]



# Result with α=π/4

$$m_{heff} \equiv \sqrt{m_1^2 \cos^2\alpha + m_2^2 \sin^2\alpha}$$

$$\epsilon = m_2^2 - m_1^2$$

$$R = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix}$$

Using the BW formulation, we numerically calculate the $\Delta_{hh}$ with the different values of $v_s$.

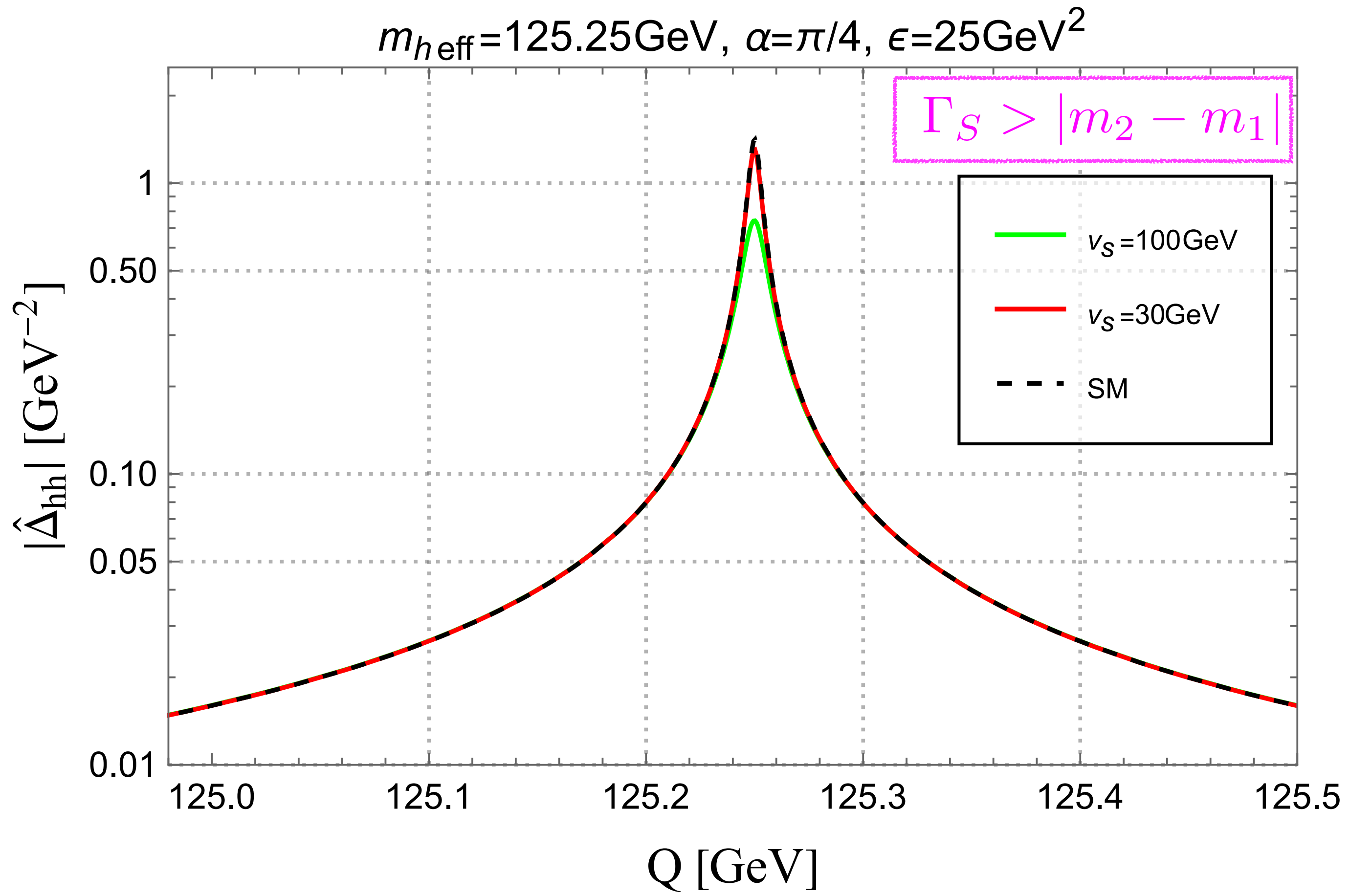
[ $v_S$ controls the size of $\Gamma_S$

$$\Gamma_s \sim \frac{m_2^3}{32\pi^2 v_s^2} \sim \frac{\lambda_s m_2}{8\pi}$$ ]

→ Single pole appears at Q=mH.

→ The propagator with vs = 30 GeV is coincide with the SM. (Fuzzy Higgs boson)

[KS, W. Yin]



# Result with α=π/4

$$m_{heff} \equiv \sqrt{m_1^2 \cos^2\alpha + m_2^2 \sin^2\alpha} \qquad R = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix}$$

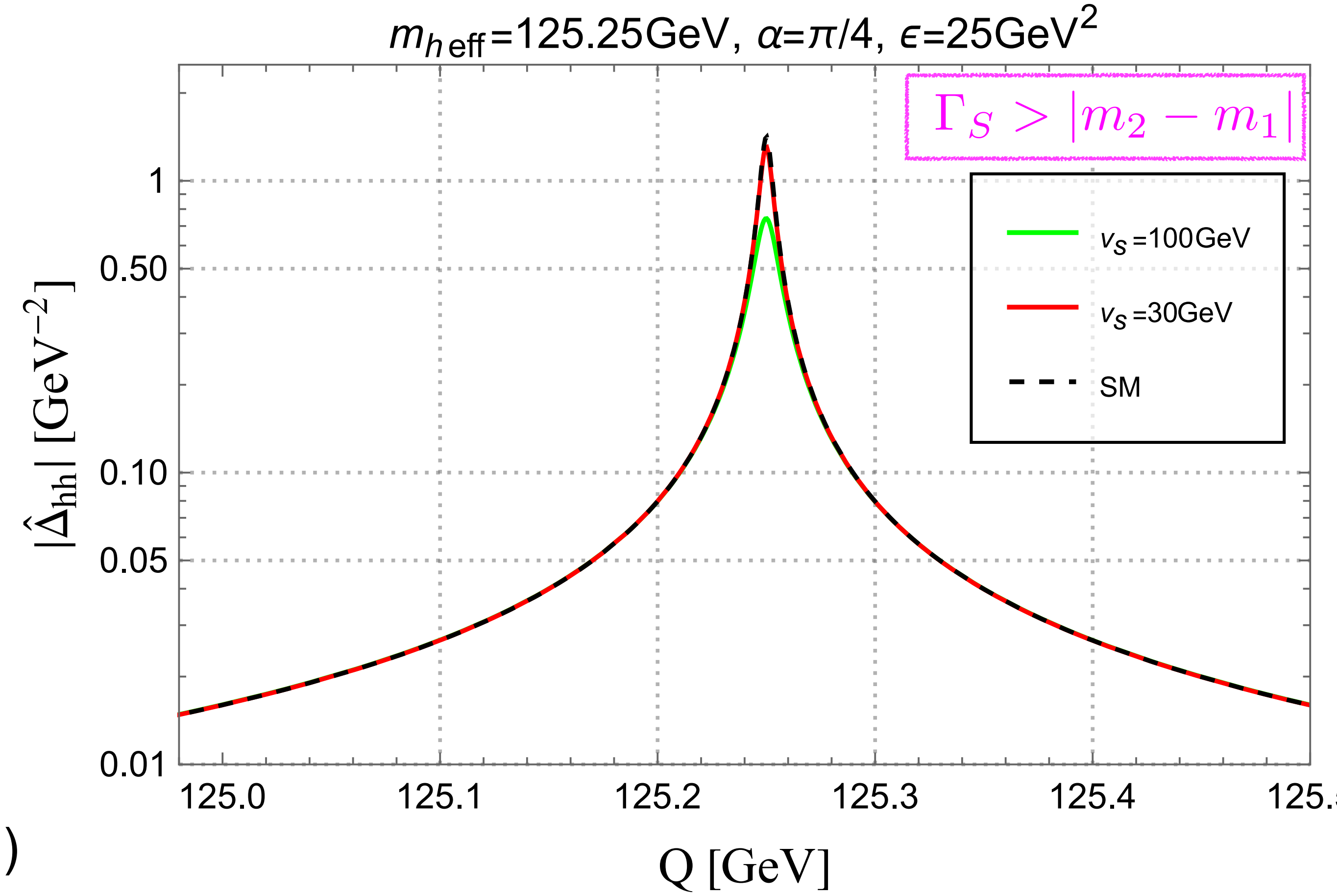
$$\epsilon = m_2^2 - m_1^2$$

Using the BW formulation, we numerically calculate the $\Delta_{hh}$ with the different values of $v_s$.

[ $v_S$ controls the size of $\Gamma_S$

$$\Gamma_s \sim \frac{m_2^3}{32\pi^2 v_s^2} \sim \frac{\lambda_s m_2}{8\pi}$$ ]

[KS, W. Yin]




<u>Analytical result of $\Delta_{hh}$</u> ( SM loops are neglected )

$$\hat{\Delta}_{hh} \simeq \frac{i(1+\delta)}{Q^2 - m_{heff}^2 + \frac{\epsilon^2 \sin^2(2\alpha)}{2m_{heff}^2} + i\frac{8\pi\epsilon^2 \sin^2(2\alpha) v_s^2}{m_{heff}^4}}$$

Position of pole

$$\Gamma_{heff\to dark} = \frac{\epsilon^2 \sin^2(2\alpha)}{4m_{heff}^2 \Gamma_s[m_{heff}]}$$

c.f) $\Gamma_{\phi_1 \to dark} = \frac{m_1^3 \sin^2\alpha}{32\pi v_S^2} \sim \frac{\Gamma_S}{32\pi^2} \frac{m_1^3}{m_2^3} \frac{\sin^2\alpha}{\cos^2\alpha}$

In case of $\Gamma_S < |m_2 - m_1|$, $\Gamma_{\phi_1\to dark} \gg 1$ at strong coupling regime. But $\Gamma_{heff\to dark} \ll 1$ .

$\delta$ : correction at $\epsilon^2$. $\mathcal{O}(10^{-5})$ at $v_s = 30$ GeV.

# Suppression of mixing by quantum Zeno

$$\Gamma_S > |m_2 - m_1| : \quad \Gamma_{heff\to \text{dark}} = \frac{\epsilon^2 \sin^2(2\alpha)}{4m_{heff}^2 \Gamma_s[m_{heff}]}$$

$$\Gamma_S < |m_2 - m_1| : \quad \Gamma_{\phi_1 \to \text{dark}} = \frac{m_1^3 \sin^2\alpha}{32\pi v_S^2} \sim \frac{\Gamma_S}{32\pi^2} \frac{m_1^3}{m_2^3} \frac{\sin^2\alpha}{\cos^2\alpha}$$

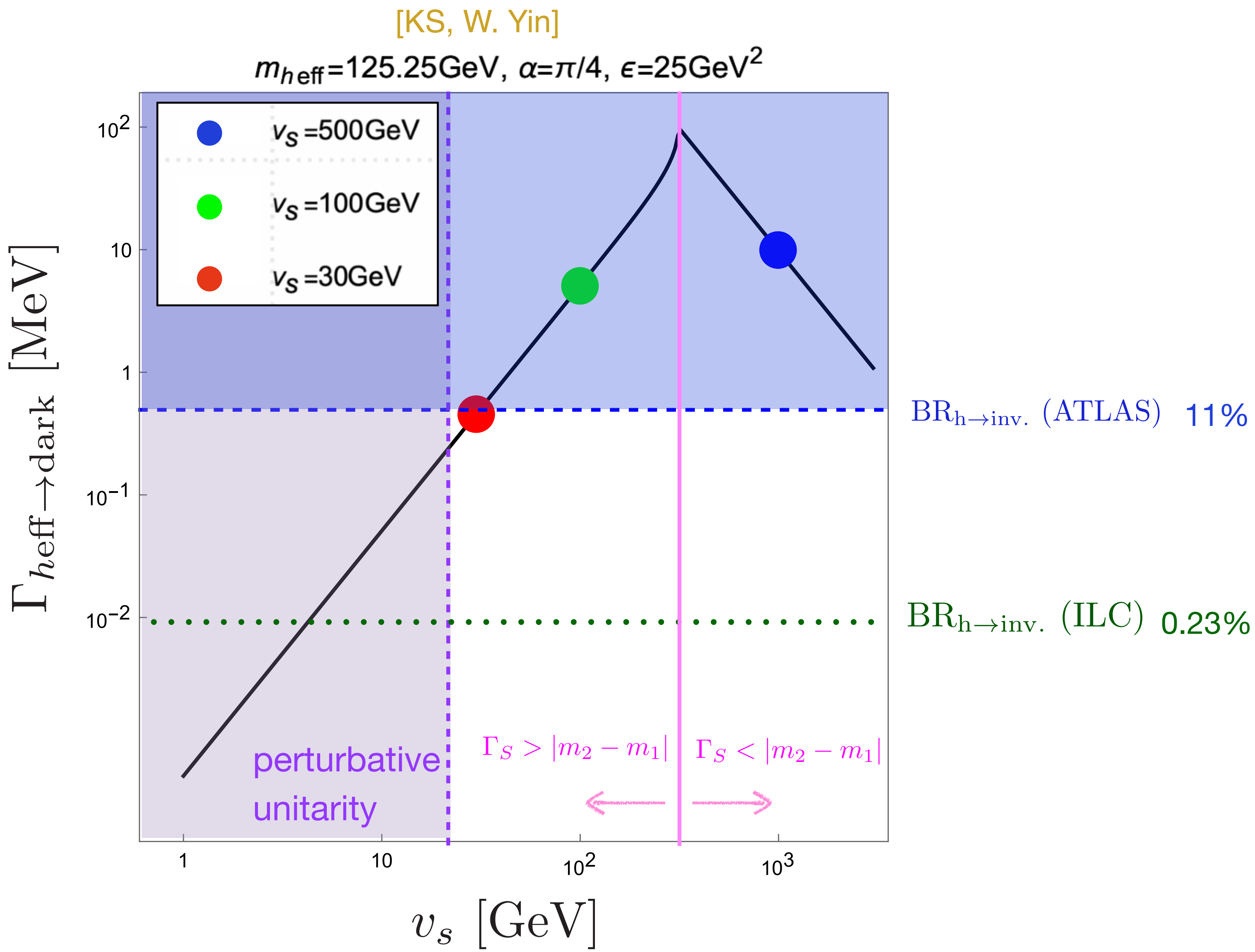
Comparing these equations, we can define the effective mixing angles for the fuzzy Higgs boson.

$$\Gamma_{heff\to \text{dark}} = \frac{\epsilon^2 \sin^2(2\alpha)}{4m_{heff}^2 \Gamma_s[m_{heff}]} = \frac{m_{heff}^3}{32\pi v_s^2} \underbrace{\frac{\epsilon^2 \sin^2(2\alpha)}{4m_{heff}^2 \Gamma_s^2}}_{\equiv \sin^2\alpha_{\text{eff}}}$$

→ If $s$ promptly decays into the dark sector, $\alpha_{\text{eff}}$ is suppressed, i.e., $\sin\alpha_{\text{eff}} \to 0 \ (\Gamma_s \gg 1)$ .

→ The suppression of the invisible decay rate is due to the suppression of the mixing.

# Numerical result for $\Gamma_{heff \to \mathrm{dark}}$



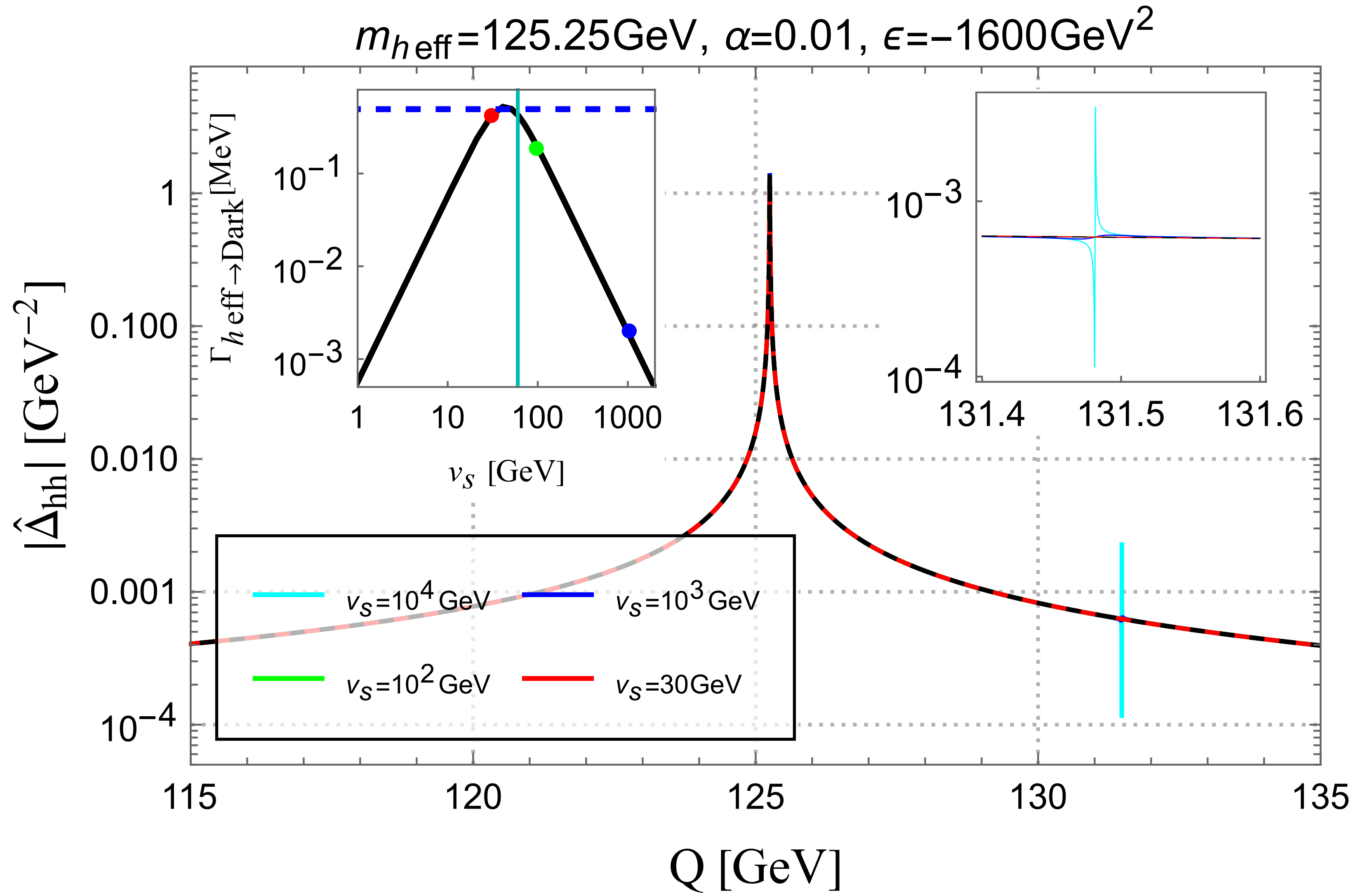

Deviations of Higgs coupling: $\kappa_V - 1 = \cos\alpha_{\mathrm{eff}} \sim -0.01\%\ (v_s = 30\ \mathrm{GeV})$

It is difficult to measure the deviation in the future exp.

→ *heff can be surveyed by the future experiment of Higgs inv. decay.*

# Result with α=0.01

[KS, W. Yin]




- In case of α=0.01, the fuzzy Higgs boson also appears.

→ Therefore, the suppression of the mixing effect happens even if $|m_1-m_2|$~O(1) GeV.

1. Phenomenology of ALP
    - Introduction
    - Model with CPV in dark sector
    - Testability of ALP
        - Future colliders, astrophysical observations

2. Phenomenology of Higgs boson
    - Suppression of the mixing effect in the strong coupling regime

3. Summary

# Summary

- We discussed a simple renormalizable model with CP violation in the dark sector.
- The model predicts ALP with CP-even scalar coupling.
- ALP can be probed by future collider experiments and astrophysical observations.

| | | |
|---|---|---|
| Long lived particle | ( in GeV ) | Higgs invisible decay, displaced vertex, Higgs exotic decay |
| DM | ( in keV-MeV ) | Higgs invisible decay, 21 cm line measurements Vera Rubin observatory, X,γ-ray observatories |

- If decay width of $s$ is larger than $|m_1 - m_2|$, the suppression of mixing between $s$ and $h$ happens.
  - The observed Higgs $\simeq$ $\cos(\alpha)\phi_1 + \sin(\alpha)\phi_2$ (Fuzzy Higgs)
  - The scenario can be tested by Higgs invisible decay.

# Buck up

# Relations for scalar couplings in the limit κ=0

$$\lambda_P = \frac{\sin(2\alpha_1)(m_s^2 - m_h^2)}{4vv_\Phi} \; ,$$
$$\lambda_s = \frac{\cos(2\alpha_1)(m_s^2 - m_h^2) + m_h^2 + m_s^2}{8v_\Phi^2} \; ,$$
$$\lambda_h = \frac{\cos(2\alpha_1)(m_h^2 - m_s^2) + m_h^2 + m_s^2}{8v^2} .$$

$$\alpha_1 = \theta_{hs}$$

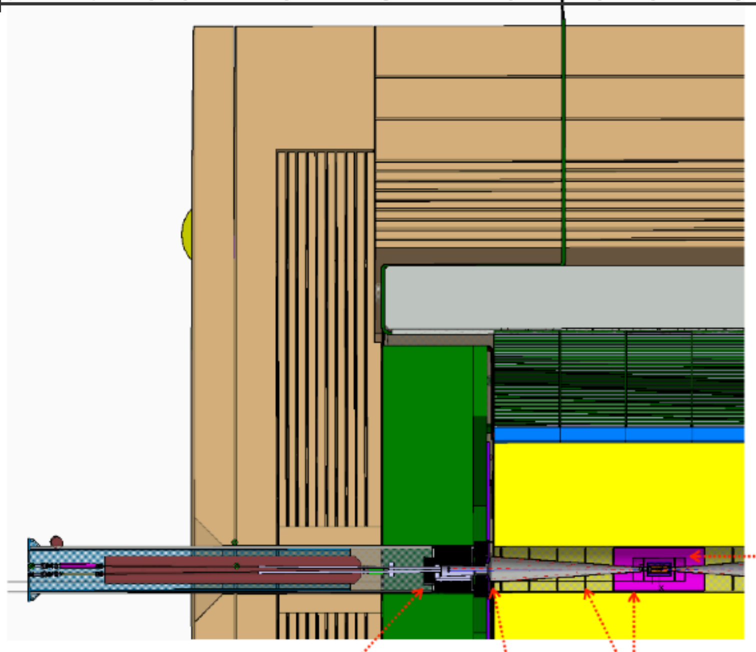
$$V = -m_\Phi^2 |\Phi|^2 + \lambda |\Phi|^4 + \lambda_P |H|^2 |\Phi|^2 + \lambda_H |H|^4 - \mu_H^2 |H|^2 \; ,$$

$$\begin{pmatrix} h \\ s \\ a \end{pmatrix} = R_{\alpha_1} \begin{pmatrix} \phi_r \\ \rho \\ a' \end{pmatrix} \qquad R_{\alpha_1} = \begin{pmatrix} \cos\alpha_1 & \sin\alpha_1 & 0 \\ -\sin\alpha_1 & \cos\alpha_1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

# ILD detector

[ILD, 1912.04601]

Amputated view of the detector

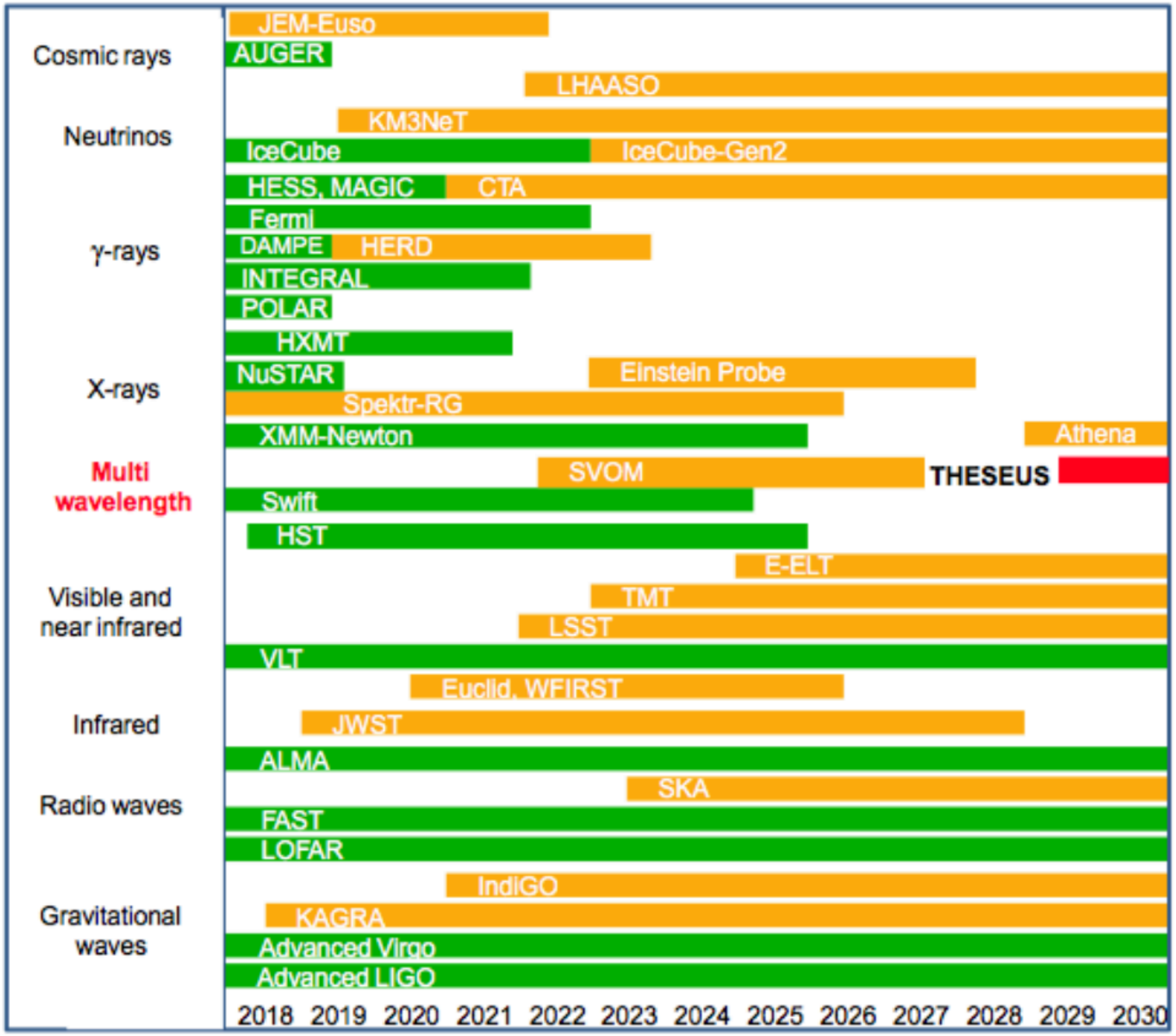



Detector sizes

| Technology | Detector | Start (mm) | Stop (mm) | Comment |
|---|---|---|---|---|
| pixel detectors | Vertex | $r_{in} = 16$ | $r_{out} = 58$ | 3 double layers of silicon pixels |
| | Forward tracking | $z_{in} = 220$ | $z_{out} = 371$ | 2 Pixel disks |
| | SIT | $r_{in} = 153$ | $r_{out} = 303$ | 2 double layers of Si pixels |
| Silicon strip | Forward tracking | $z_{in} = 645$ | $z_{out} = 2212$ | 5 layers of Si strips |
| | SET | $r_{in} = 1773$ | $r_{out} = 1776$ | 1 double layer of Si strips |
| Gaseous tracking | TPC | $r_{in} = 329$ | $r_{out} = 1770$ | MPGD readout, 220 points along the track |
| Silicon tungsten calorimeter | ECAL option | $r_{in} = 1805$ | $r_{out} = 2028$ | 30 layers of $5 \times 5$ mm$^2$ pixels |
| | ECAL EC option | $z_{in} = 2411$ | $z_{out} = 2635$ | 30 layers of $5 \times 5$ mm$^2$ pixels |
| | Luminosity calorimeter | $r_{in} = 83$ | $r_{out} = 194$ | 30 layers |
| | | $z_{in} = 2412$ | $z_{out} = 2541$ | |
| Diamond tungsten or GaAs calorimeter | Beam calorimeter | $r_{in} = 18$ | $r_{out} = 140$ | 30 layers |
| | | $z_{in} = 3115$ | $z_{out} = 3315$ | |
| SiPM-on-Tile | ECAL alternative | $r_{in} = 1805$ | $r_{out} = 2028$ | 30 layers, 5 mm strips, crossed |
| | ECAL EC alternative | $z_{in} = 2411$ | $z_{out} = 2635$ | 30 layers, 5 mm strips, crossed |
| | HCAL option | $r_{in} = 2058$ | $r_{out} = 3345$ | 48 layers, $3 \times 3$ cm$^2$ pixels |
| | HCAL EC option | $z_{in} = 2650$ | $z_{out} = 3937$ | 48 layers, $3 \times 3$ cm$^2$ pixels |
| RPC | HCAL option | $r_{in} = 2058$ | $r_{out} = 3234$ | 48 layers, $1 \times 1$ cm$^2$ pixels |
| | HCAL EC option | $z_{in} = 2650$ | $z_{out} = 3937$ | 48 layers, $1 \times 1$ cm$^2$ pixels |
| SiPM on scintillator bar | Muon | $r_{in} = 4450$ | $r_{out} = 7755$ | 14 layers |
| | Muon EC | $z_{in} = 4072$ | $z_{out} = 6712$ | up to 12 layers |

TABLE I. Key parameters of the ILD detector. All numbers from [4]. "Star" and "Stop" refer to the minimum and maxiumum extent of subdetectors in radius and/or $z$-value .

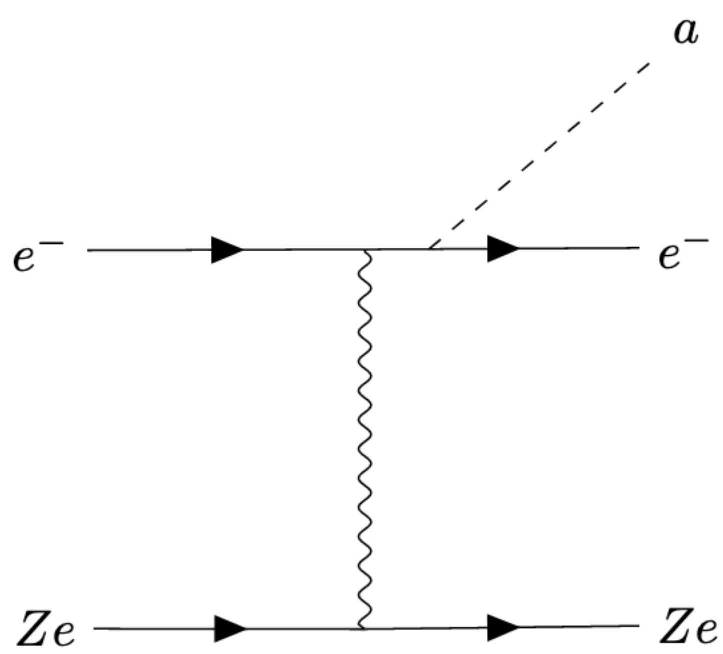
# Time schedule of the future X, gamma ray obsearvatries



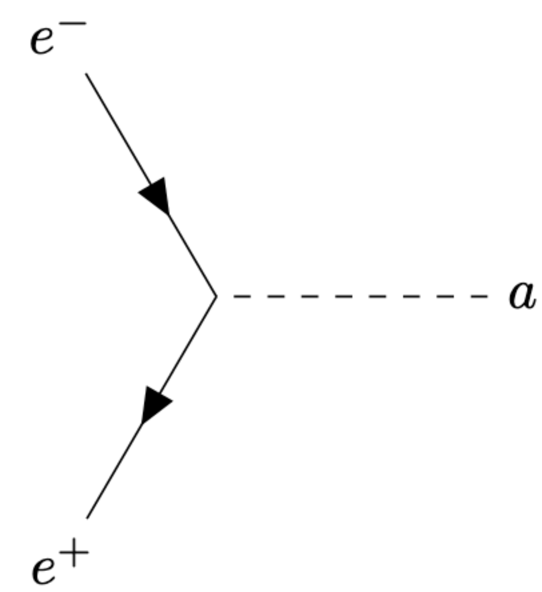
# Contents

- Introduction
- Model with CPV in dark sector
- Phenomenology of ALP
  - Testability of ALP at future collider
  - ALP DM search by astrophysical observations
- Phenomenology of Higgs boson
  - Suppression of the mixing effect in the strong coupling regime
- Summary

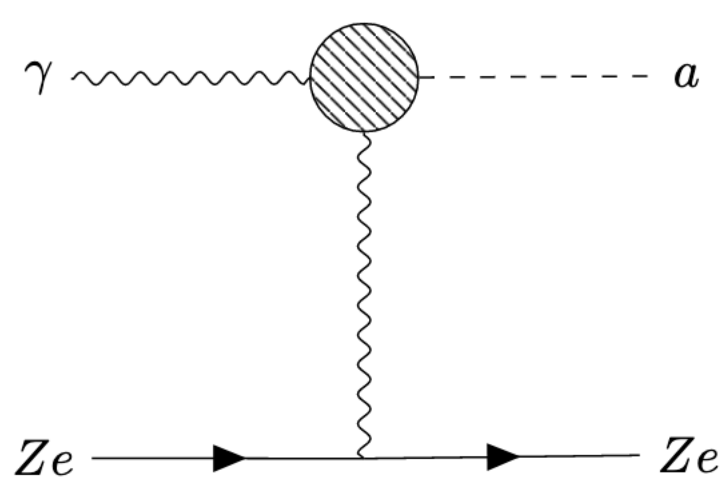
# ALP production ins Supernova



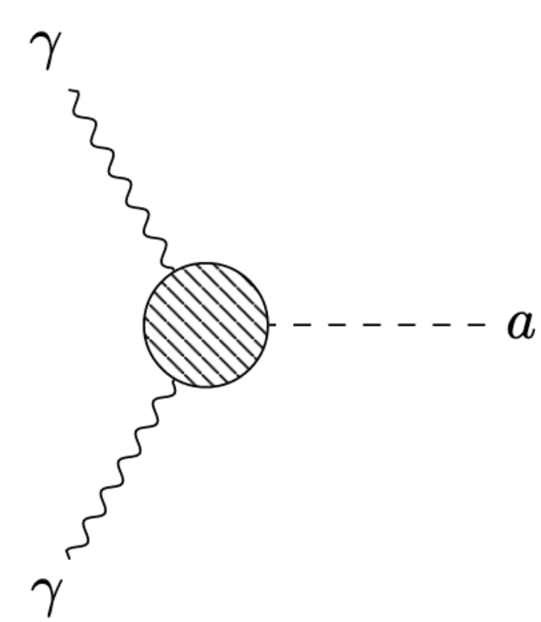

(a) Bremsstrahlung




(b) Electron-positron fusion




(c) Primakoff process




(d) Photon coalescence

# Axion-nucleon (QCD axion)

[G. Cortona,E. Hardy, et. al, JHEP01(2016)034]

$$\frac{\partial_\mu a}{2f_a} c_N \bar{N}\gamma^\mu\gamma_5 N$$

$$c_p = -0.47(3) + 0.88(3)c_u^0 - 0.39(2)c_d^0 - 0.038(5)c_s^0 \\ - 0.012(5)c_c^0 - 0.009(2)c_b^0 - 0.0035(4)c_t^0\,,$$

$$c_n = -0.02(3) + 0.88(3)c_d^0 - 0.39(2)c_u^0 - 0.038(5)c_s^0 \\ - 0.012(5)c_c^0 - 0.009(2)c_b^0 - 0.0035(4)c_t^0\,,$$

$$c_p^{\rm KSVZ} = -0.47(3)\,, \qquad c_n^{\rm KSVZ} = -0.02(3)$$

$$c_p^{\rm DFSZ} = -0.617 + 0.435\sin^2\beta \pm 0.025\,, \qquad c_n^{\rm DFSZ} = 0.254 - 0.414\sin^2\beta \pm 0.025$$

# Long lived particle search at HL-LHC

[B. Bhattacherjee, S. Matsumoto, R. Sengupta, 2111.02437]

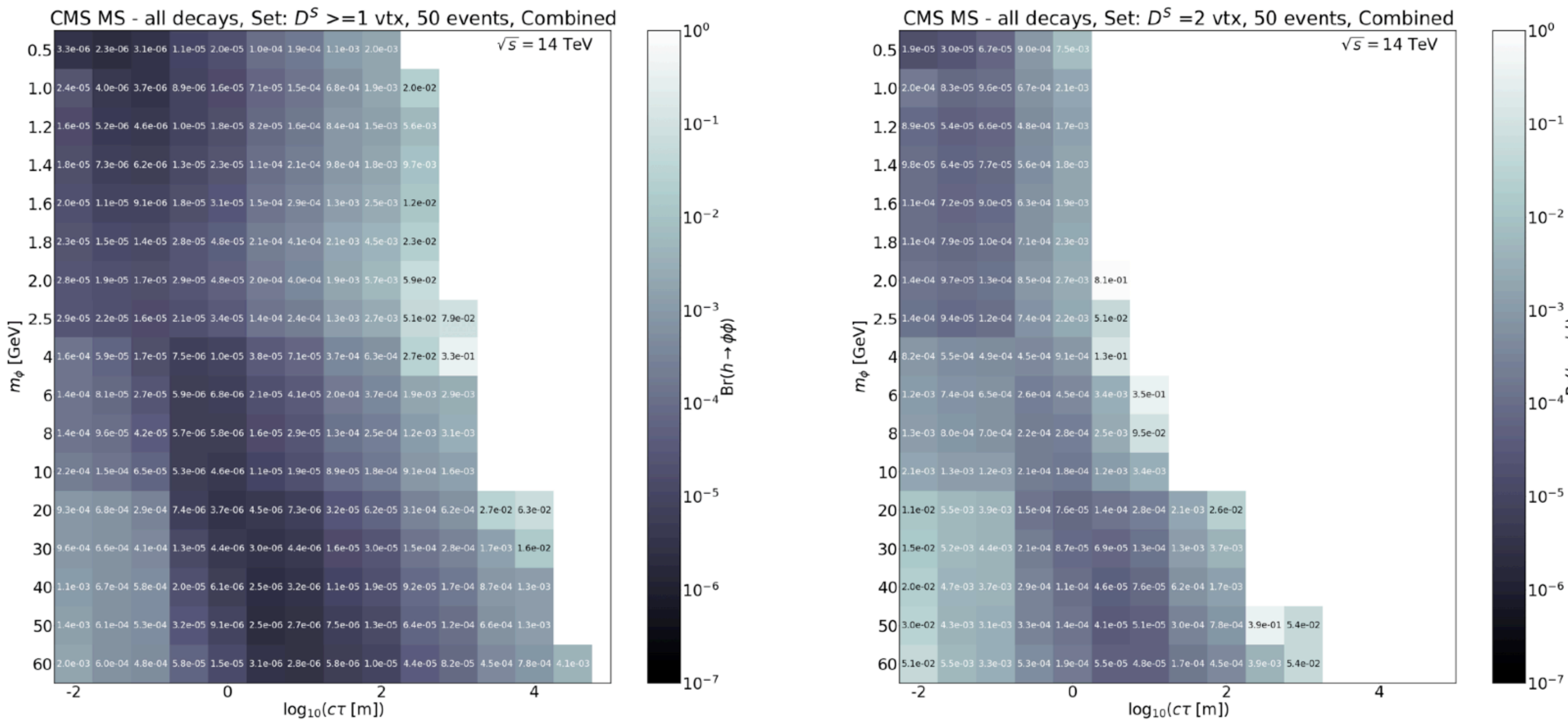



**Figure 24**: *Projected upper limits on the branching fraction, Br($h \to \phi\phi$), for 50 observed decays of long-lived mediator particles using the CMS MS when events are selected by applying softer cuts on the displaced particles only. The shown limits are obtained by combining the ggF, VBF and Vh modes for the Higgs boson production at the 14 TeV HL-LHC experiment with an integrated luminosity of 3000 fb$^{-1}$ and the decay modes of $\phi \to \mu^+\mu^-$, $\pi^+\pi^-$, $K^+K^-$, $c\bar{c}$, $\tau^+\tau^-$ and $b\bar{b}$ according to the branching ratios in Fig. 4.*

# LLP searches from Higgs decays in the future e+e- colliders

[S. Alipour-Fard et al., 1812.05588]

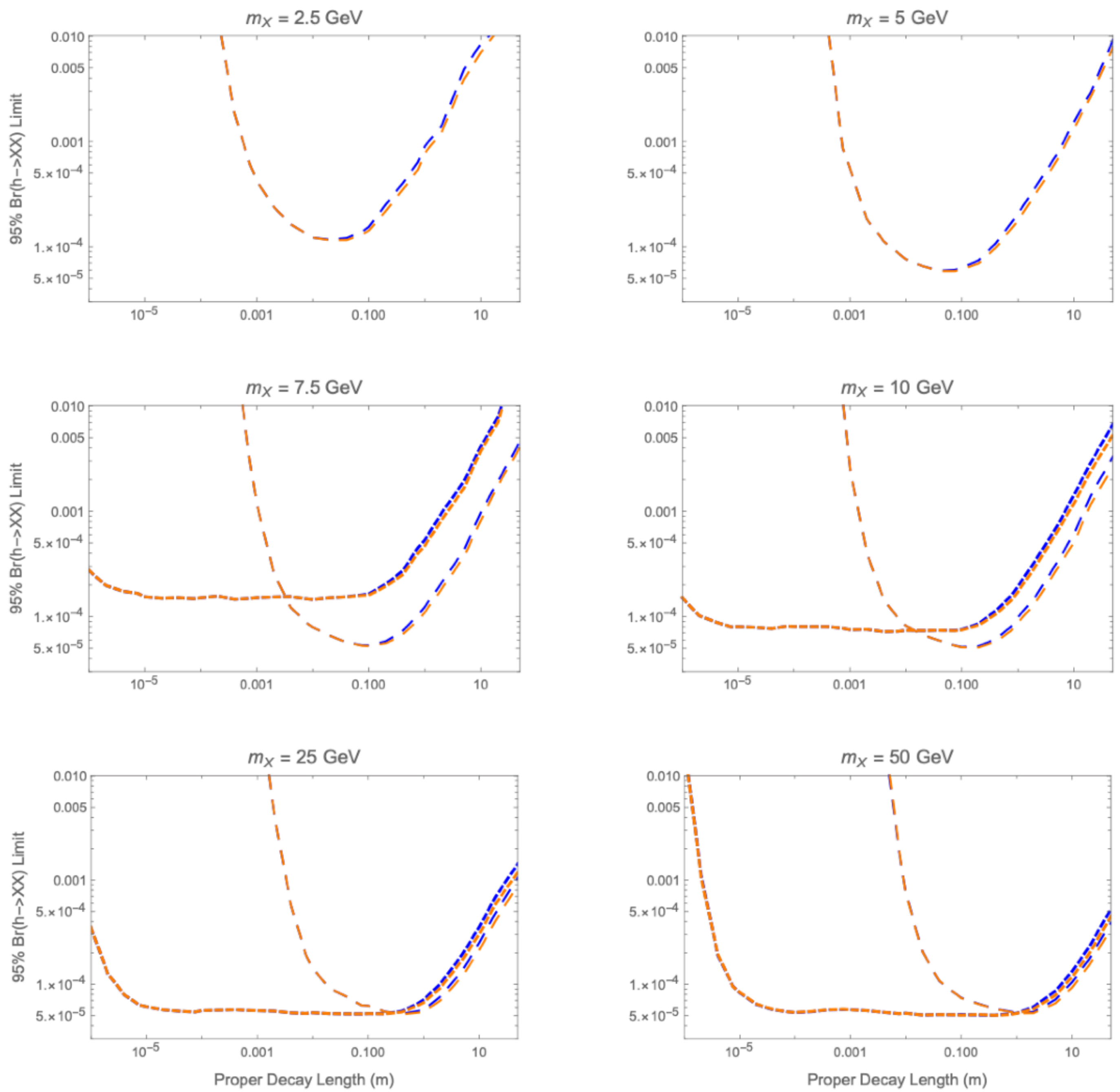


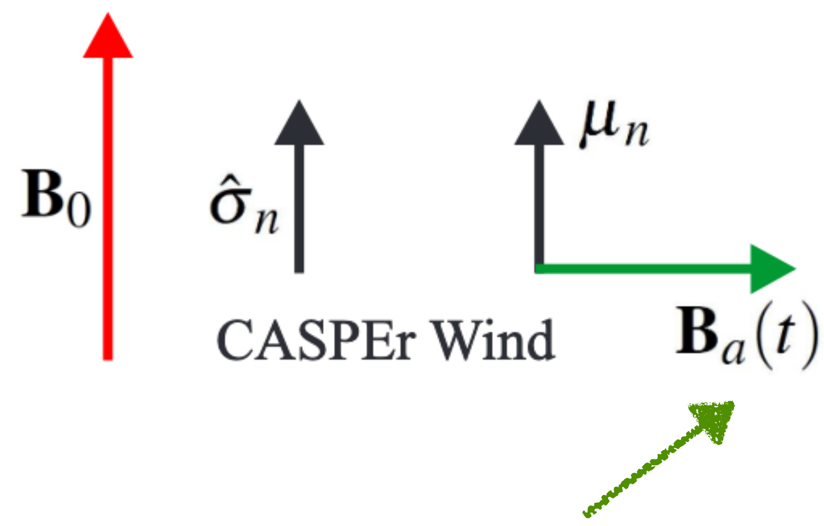

**Figure 1**: Projected 95% $h \to XX$ branching ratio limits as a function of proper decay length for a variety of $X$ masses. Blue lines are for CEPC and orange lines are for FCC-ee, and where only one is visible they overlap. The larger dashes are the 'long lifetime' analysis and the smaller dashes are the 'large mass' analysis.

# Cosmic Axion Spin Precession Experiment (CASPEr)

[1711.08999]

Lagrangian

$$\mathcal{L}_{\rm spin} \approx g_{aNN}[\partial_\mu a(\vec{r},t)]\overline{\Psi}_n\gamma^\mu\gamma_5\Psi_n \ ,$$




Magnetic field constacted by ALP DM

$$B_a[\mathrm{T}] \approx 10^{-7} \times \frac{g_{aNN}\left[\mathrm{GeV}^{-1}\right]}{g_n} \ ,$$

Hamiltonian

$$H_{\rm spin} = g_{aNN}\vec{\nabla}a(\vec{r},t)\cdot\hat{\vec{\sigma}}_n \ ,$$

$$H_{\rm wind} \approx g_{aNN} m_a a_0 \cos(\omega_a t)\vec{v}\cdot\hat{\vec{\sigma}}_n \ , \quad (16)$$

$$\approx g_{aNN}\sqrt{2\hbar^3 c\rho_{\rm DM}}\cos(\omega_a t)\vec{v}\cdot\hat{\vec{\sigma}}_n \ , \quad (17)$$

The existence of axion field affects to spin of the nucleon.
Thereby, the $g_{aNN}$ is constrained.

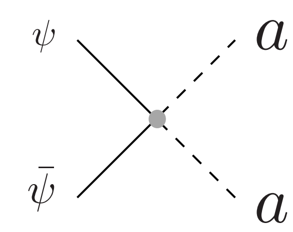
# Thermal production

- Thermal production rate

$$\Gamma_{\rm th} \sim \frac{1}{4\pi}\frac{m_\psi^2}{\Lambda_H^4 m_h^4}T^7$$

$$\delta\mathcal{L} = -\frac{\sqrt{2}m_\psi}{\Lambda_H^2 m_h^2}\partial a \partial a \bar{\psi}\psi$$

$$\frac{1}{\Lambda_H^2} \equiv -\frac{\lambda_P}{m_s^2 - m_h^2}$$




- For the ALP is not to be thermalized, Γ< H should be satisfied.
  We then obtain the conditions for the cosmic temperature:

$$T \lesssim 7\,{\rm GeV}\left(\frac{g_\star}{100}\right)^{1/10}\left(\frac{\Lambda_H}{3\,{\rm TeV}}\right)^{4/5}\left(\frac{4.18\,{\rm GeV}}{m_\psi}\right)^{2/5}$$

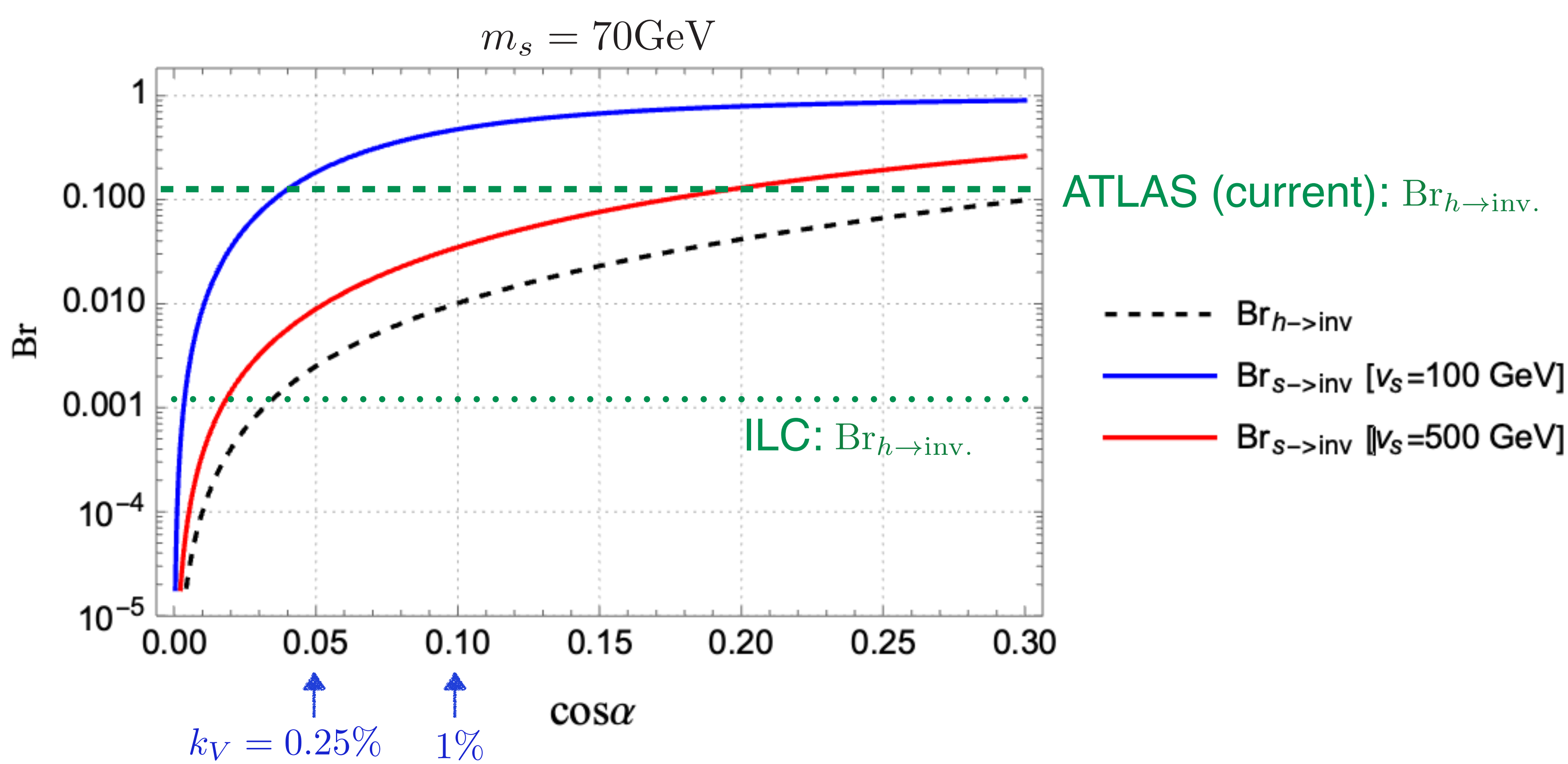
# Invisible decay for SM-like Higgs boson

- Br(s—> inv.)≠0の時は、SM-like ヒッグスの invisible decayも開いている

$$\Gamma_{h\to aa} \simeq \frac{m_h^3}{32\pi v_s^2}\cos^2\alpha \qquad \Gamma_{s\to \mathrm{inv}} \sim \frac{m_s^3}{32\pi v_s^2}$$

→ $\Delta M_W$を最大化するパラメタ領域は、$v_S << v$, $\cos a \sim 0.3$ で$\Gamma$(h—> inv)も大きくなる

- h—>inv.の $v_S$ 依存性はキャンセルする
- $\Delta M_W \sim$4MeVはcurrent boundに対応




→ $\Delta M_W$のtentionを緩和し得るシナリオでは常に h—>inv.が開いており、ILCで検証可能。

# Current bounds for the mass difference in the degenerate Higgs scenario

[CMS,Eur.Phys.J.C 74 (2014) 10, 3076]

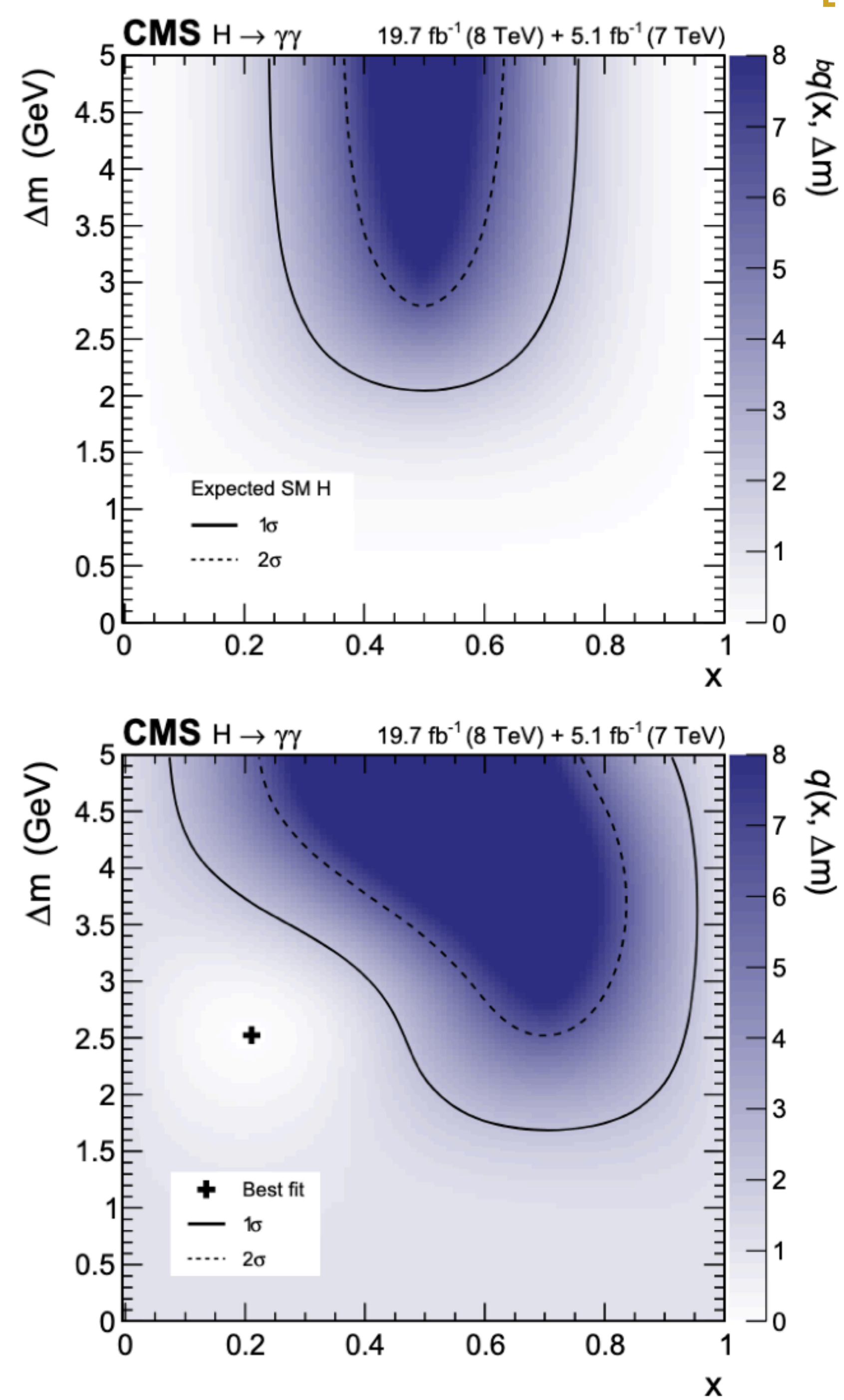
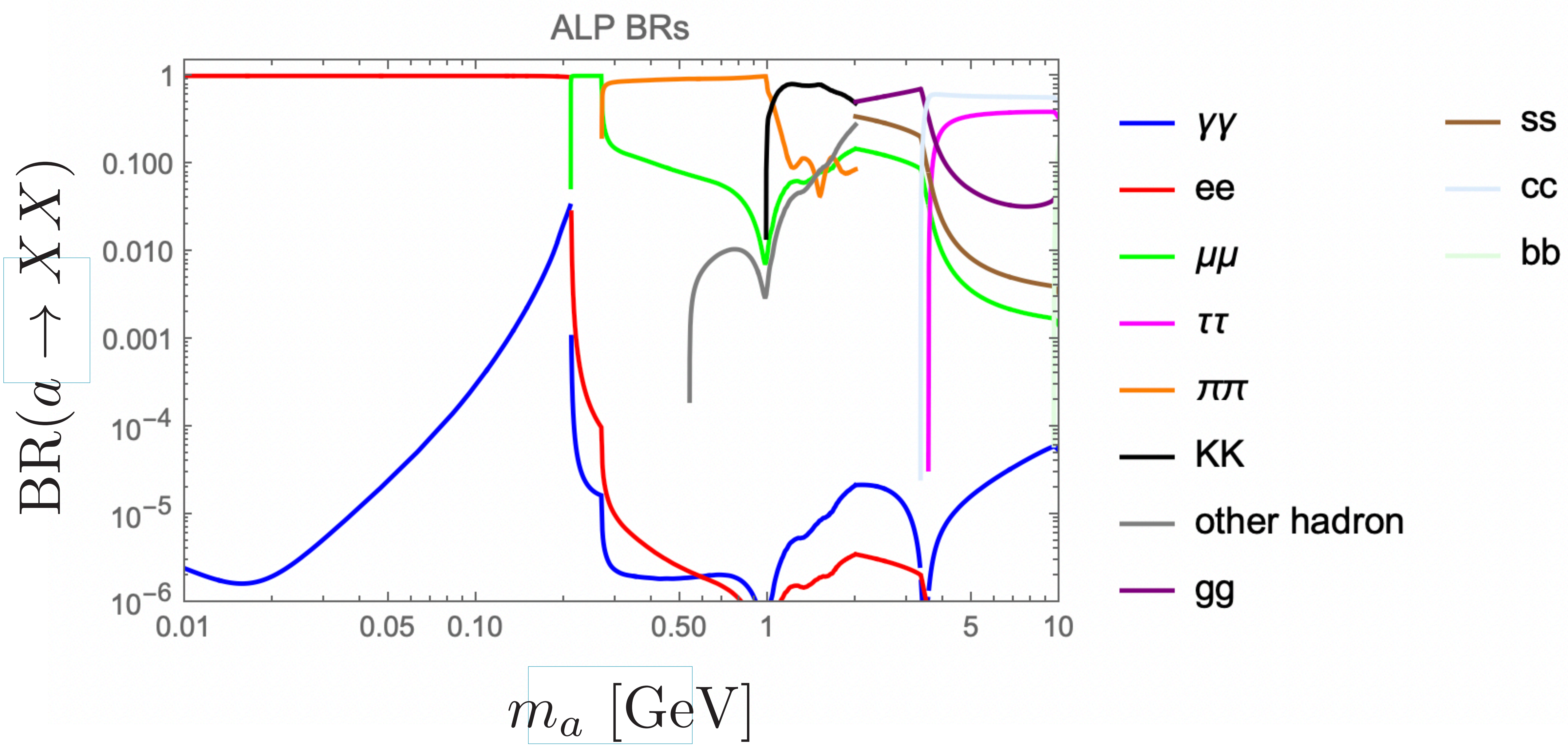


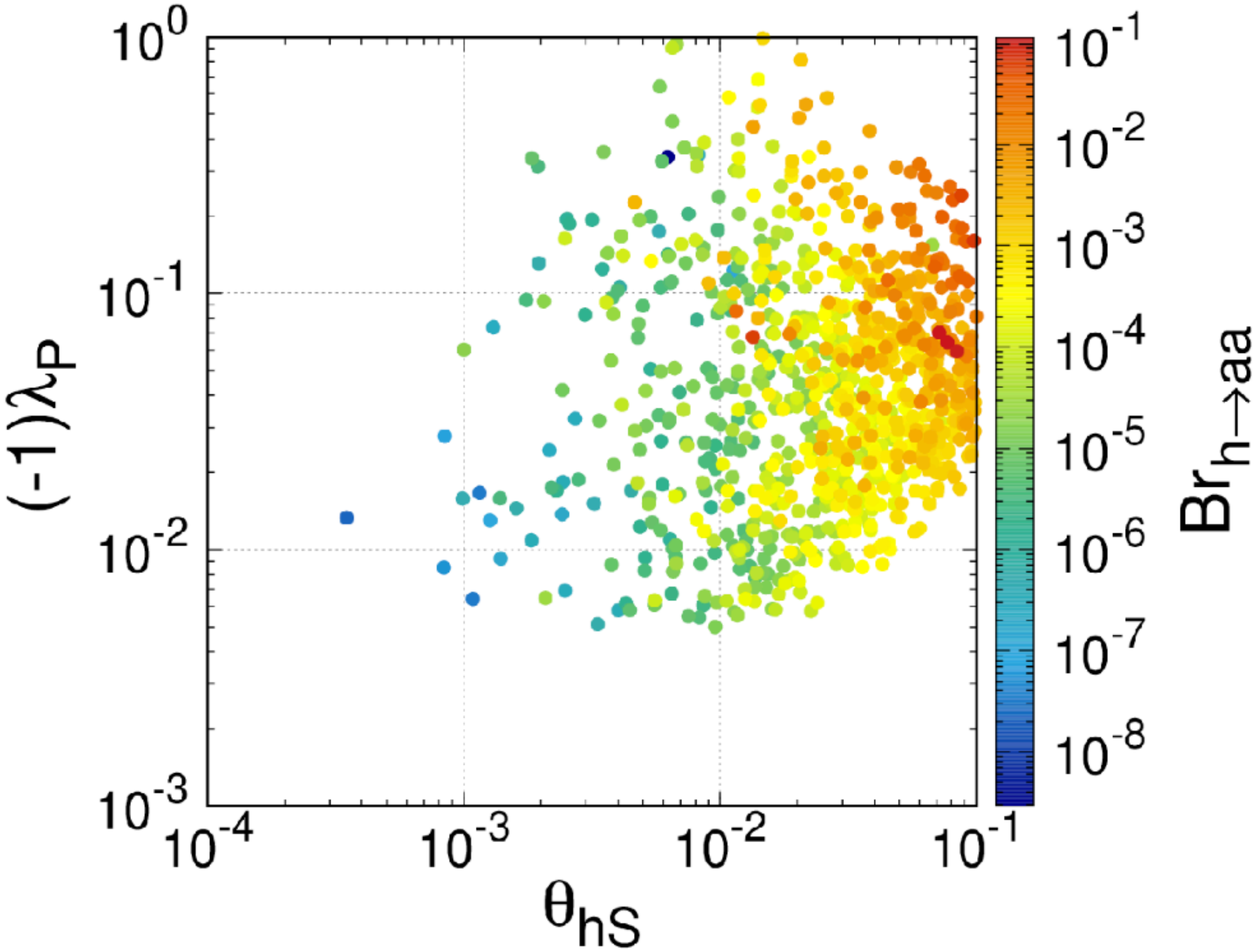

**Fig. 29** Map of the values of the likelihood ratio $q(x, \Delta m)$ for two near mass-degenerate states parameterized by $x$ (the fraction of signal in the lower mass state) and $\Delta m$ (the mass difference between the states). The *black cross* shows the best-fit value, and the lines correspond to the $1\sigma$ and $2\sigma$ uncertainty contours for the SM (single state) expectation (*upper plot*) and the observation (*lower plot*)

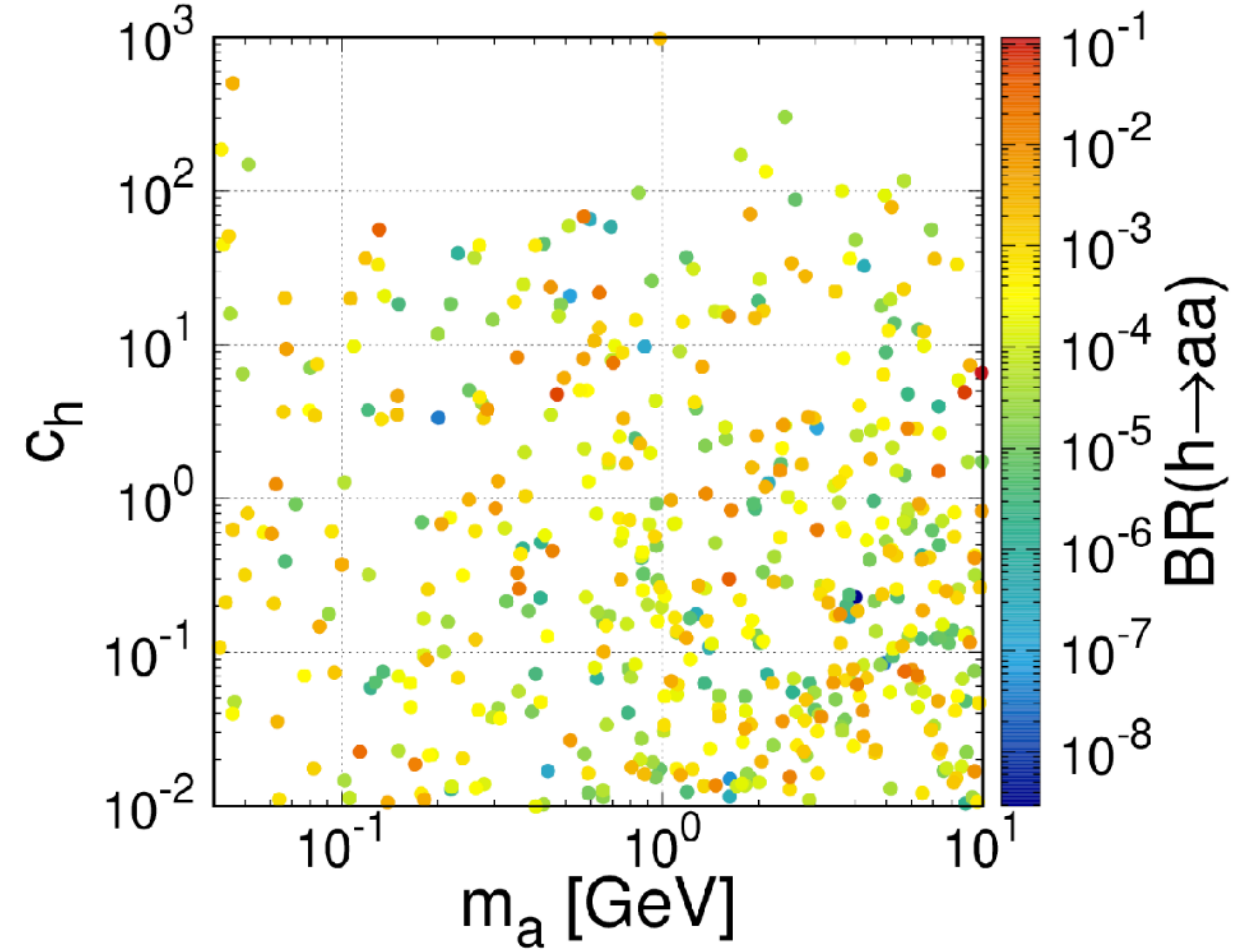
# Other plots

# Branching ratios for the ALP



# Branching ratios



# Result with α=π/4

$$m_{heff} \equiv \sqrt{m_1^2 \cos^2\alpha + m_2^2 \sin^2\alpha} \qquad R = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix}$$

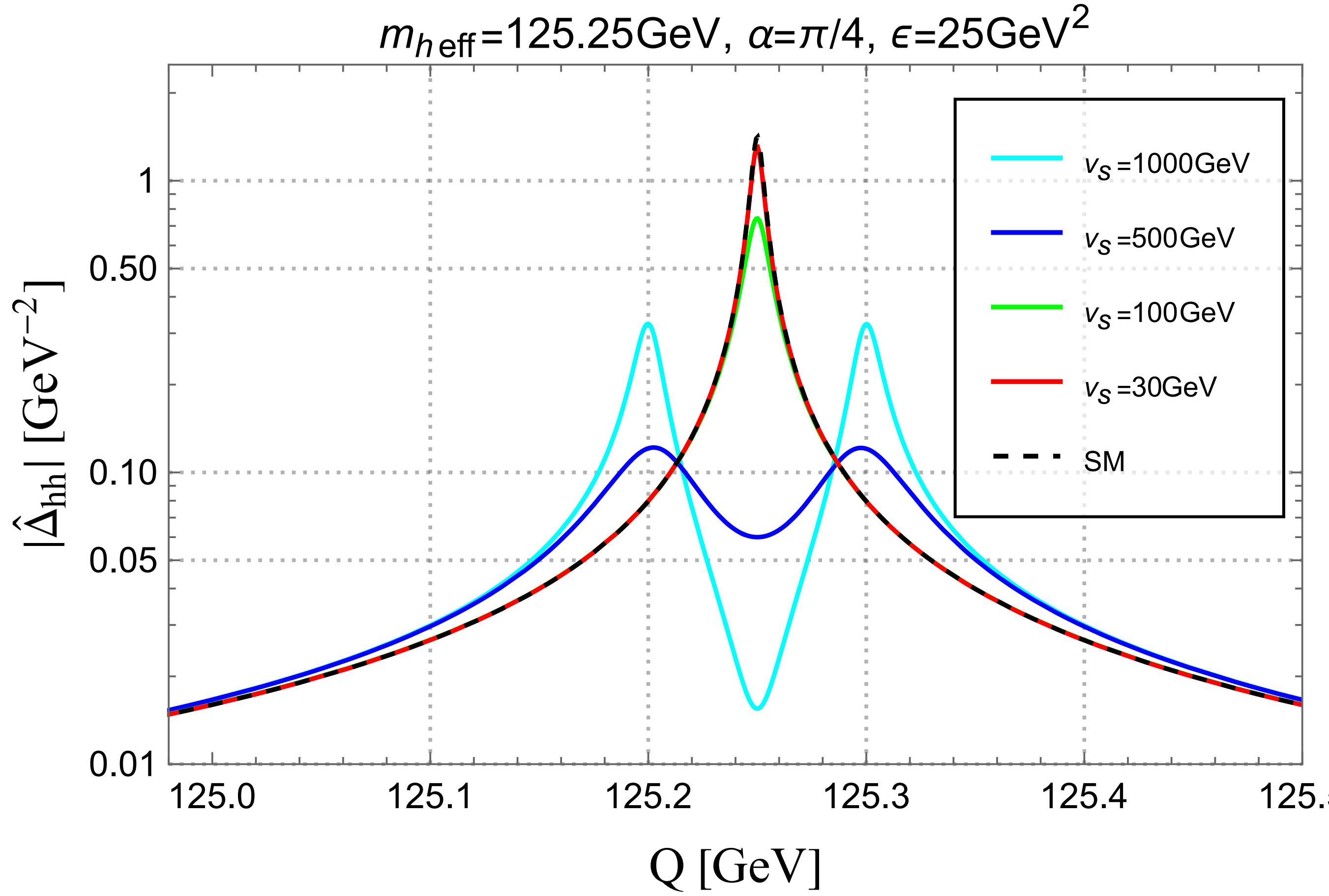
$$\epsilon = m_2^2 - m_1^2$$

Using the BW formulation, we numerically calculate the $\Delta_{hh}$ with the different values of $v_s$.

[ $v_S$ controls the size of $\Gamma_S$

$$\Gamma_s \sim \frac{m_2^3}{32\pi^2 v_s^2} \sim \frac{\lambda_s m_2}{8\pi}$$ ]

[KS, W. Yin]




Analytical result of $\Delta_{hh}$ ( $\Gamma_{h,s}$ → SM is neglected )

$$\hat{\Delta}_{hh} \simeq \frac{i(1+\delta)}{Q^2 - m_{heff}^2 + \frac{\epsilon^2 \sin^2(2\alpha)}{2m_{heff}^2} + i\frac{8\pi\epsilon^2\sin^2(2\alpha)v_s^2}{m_{heff}^4}}$$

Position of pole

$$\Gamma_{heff\to dark} = \frac{\epsilon^2 \sin(2\alpha)}{4m_{heff}^2 \Gamma_s[m_{heff}]}$$

c.f) $\Gamma_{\phi_1\to dark} = \frac{m_1^3 \sin^2\alpha}{32\pi v_S^2} \sim \frac{\Gamma_S}{32\pi^2}\frac{m_1^3}{m_2^3}\frac{\sin^2\alpha}{\cos^2\alpha}$

In case of $\Gamma_S < |m_2 - m_1|$, $\Gamma_{\phi_1\to dark} \gg 1$ at strong coupling regime. But $\Gamma_{heff\to dark} \ll 1$ .

$\delta$ : correction at $\epsilon^2$. $\mathcal{O}(10^{-5})$ at $v_s = 30$ GeV.