[arXiv:2111.03653]

Testability of CP-even ALP at ILC

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Axion/Axion like particles (ALPs)

- Axion/ALPs are prominent candidates of light new particle.

- They emerge as pseudo Nambu Goldstone boson by spontaneous symmetry breaking of global U(1) symmetry.

- While axion was originally proposed to solve the strong CP problem, ALPs may rerate to BSM phenomena.

  - Dark matter
  - Baryogenesis
  - Neutrino mass
  - Inflation

  etc.

We can pursue new physics model by studying axion.

Axion/ALPs couplings

Usually, interactions of ALPs are assumed to be CP conserving.

$$\mathcal{L}_{\rm int.} \ni \quad \cancel{- g_{af} a \bar{f} f} \quad - i g_{af} a \bar{f} \gamma_5 f$$

The couplings such as g_{ae} and g_{an} have been surveyed in various laboratory experiments and astrophysical environments.

E.g., Stellar energy losses, direct/indirect detection of DM, meson decays, etc.

How about CP violating case?

Short summary

We consider the CP violation in the dark sector and construct a simple renormalizable model that only involves a dark Higgs singlet field.

- The predicted ALP has CP-even scalar couplings.
- The ALP couplings are controlled by the mass of ALP.
- At ILC, the ALP can be probed thorough the SM-like Higgs boson decay into ALPs.

  Various signals: Higgs invisible decay, displaced vertex, Higgs exotic decay
- The ALP can be DM in keV-MeV range and probed by the Higgs invisible decay.

Scalar potential : CP symmetric dark sector

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:

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

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

- In the potential, global dark U(1) symmetry is imposed.
  - Spontaneously broken by $\langle\Phi\rangle$. → ρ and s mix
  - Massless nambu Goldstone boson a' is obtained.
- The potential has accidental discrete symmetries.

C_{dark} **symmetry:** SM fields do not transform, $\Phi(t,\vec{x}) \to \Phi^*(t,\vec{x})$

CP **symmetry:** SM fields transform as in the SM, $\Phi(t,\vec{x}) \to \Phi^*(t,-\vec{x})$

Scalar potential : CP violating dark sector

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

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

- κ corresponds to the order parameter of breaking of dark U(1).
  - It scales the mass of ALP $m_a^2 \sim \mathcal{O}(\kappa)v_\Phi^2 \sim \mathcal{O}(\kappa)m_s^2$ ($v_\Phi \sim m_s \gtrsim v$)
- The accidental discrete symmetries are broken by δV.

C_{dark} **symmetry:** SM fields do not transform, $\Phi(t,\vec{x}) \to \Phi^*(t,\vec{x})$

CP **symmetry:** SM fields transform as in the SM, $\Phi(t,\vec{x}) \to \Phi^*(t,-\vec{x})$

CP violating dark sector predicts a CP-even ALP!

- The ALP fields mix 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

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

c_h is function of c_i .

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

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

→ ALP has the couplings of CP-even scalar.

→ The couplings scale with the mass of ALP.

Why is ALP CP-even?

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

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

- In *κ≠0* (i.e. *δV≠0*),

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

$C_{\rm dark}\cdot CP$: Conserved

The potential has the C$_{\rm dark}$ ・ CP symmetry.

- Actually, g_{af} breaks $C_{\rm dark}\cdot CP$.

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

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

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.

$$(a\bar{f}f) : \quad -\underbrace{\theta_{ah}}_{\sim c_h \frac{m_a^2}{m_h m_\Phi}} \frac{m_f}{v} a\bar{f}f$$

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

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

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

Numerical result for BR(h→ *aa*)

- Input parameters

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

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

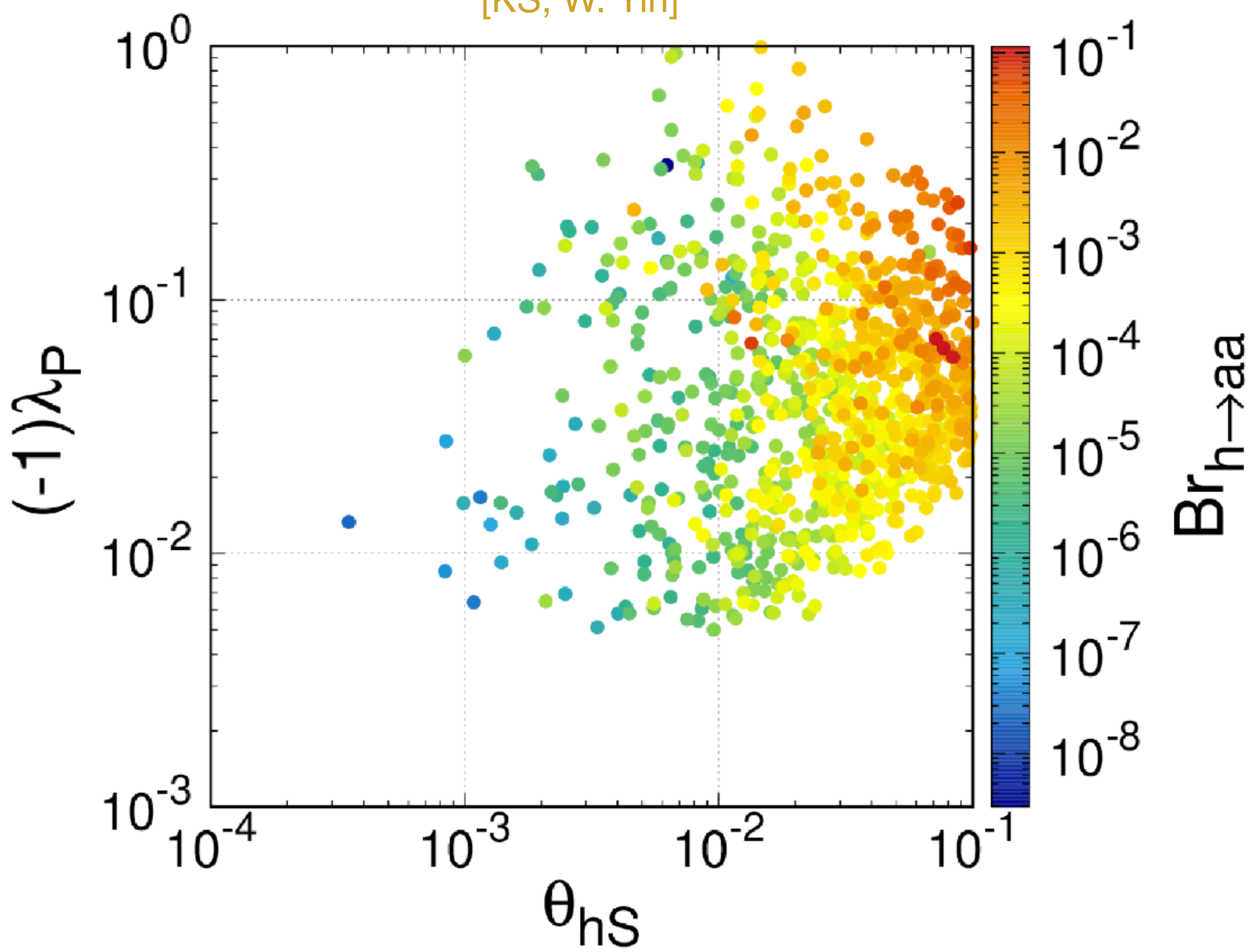
- Branching ratio

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

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

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

[KS, W. Yin]

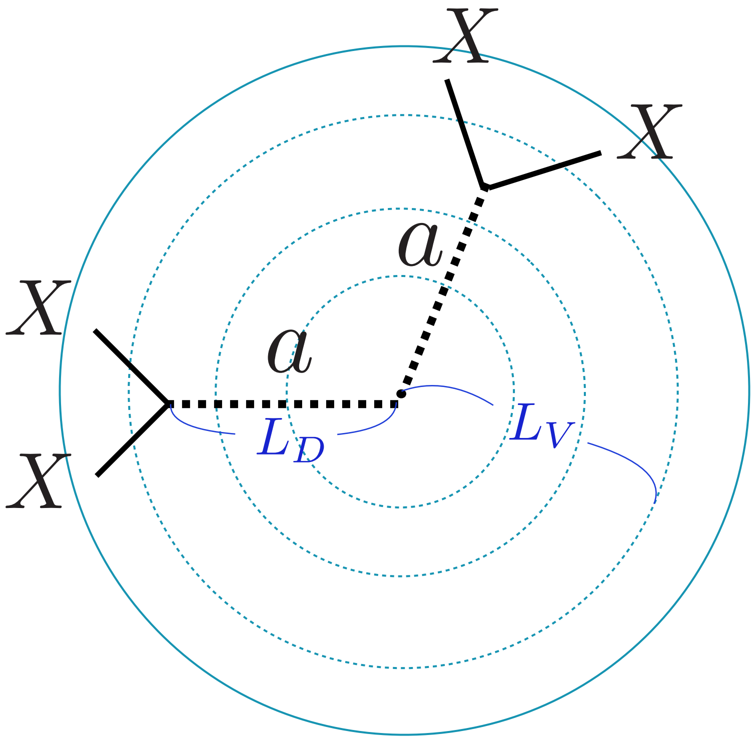


→ If the mixing angle between *h* and *s*, θ_{hs} is 1% ~10%, BR(h—>aa) can exceed 1%

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 collider 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 ×2, Higgs invisible decay or/and Displaced vertex+missing energy
$L_V > L_D > L_R$	Displaced vertex ×2
$L_V > L_R \gtrsim L_D$	Exotic Higgs decay

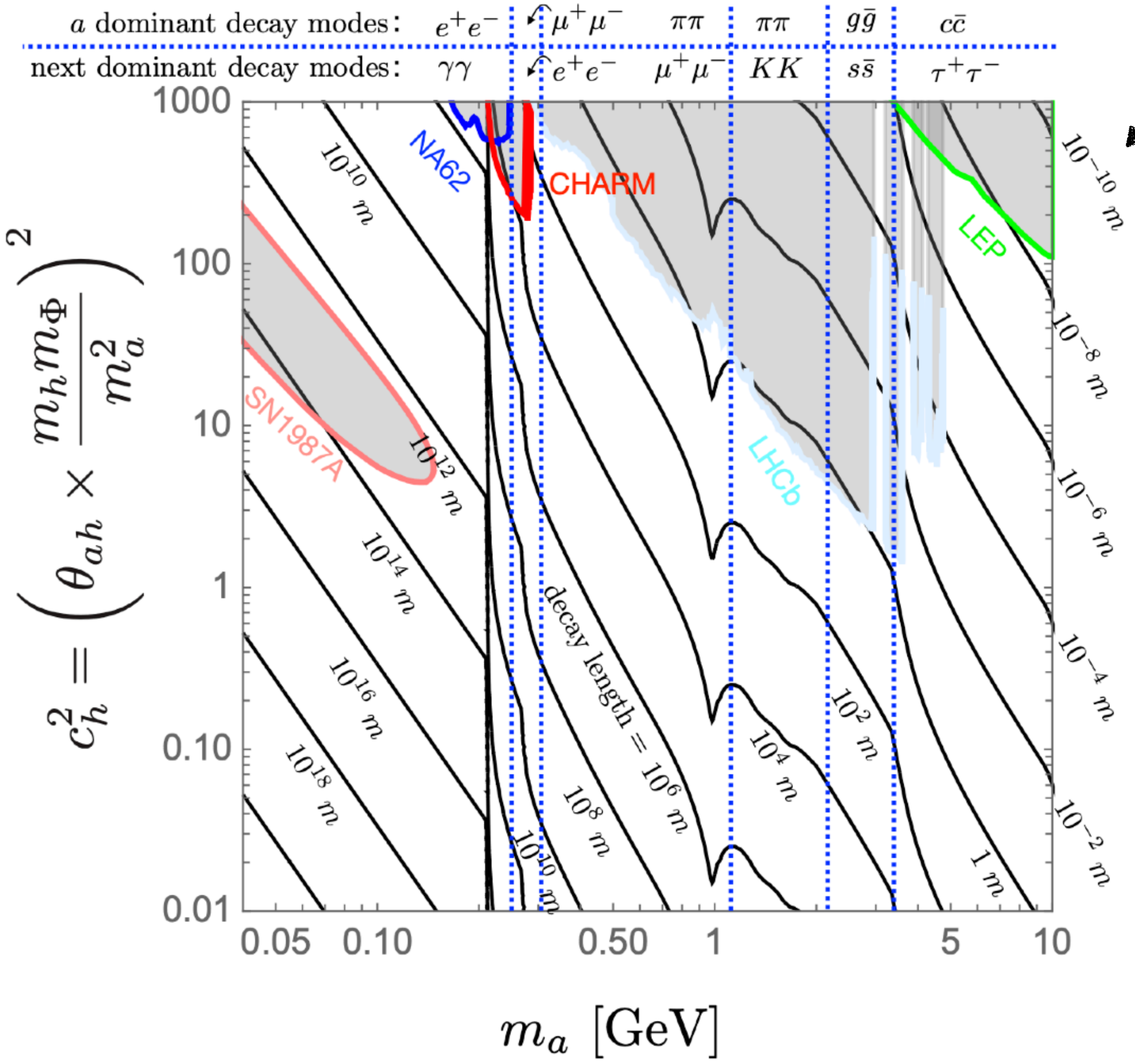
L_D : Decay length of ALP

L_V : Detector size

L_R : Resolution of vertex detector

Probe of CP-even ALP[1/5]

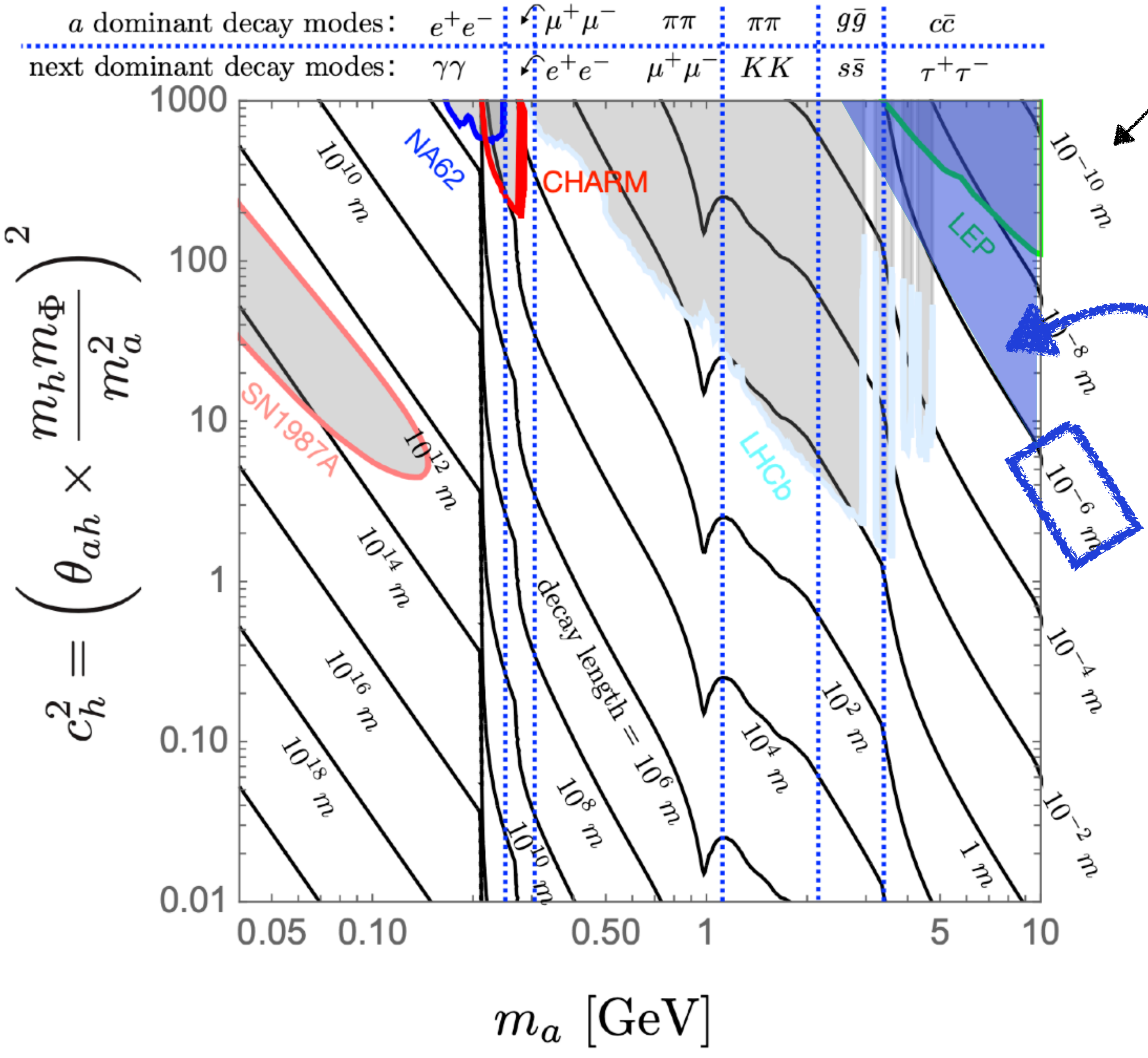
[KS, W. Yin]



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)

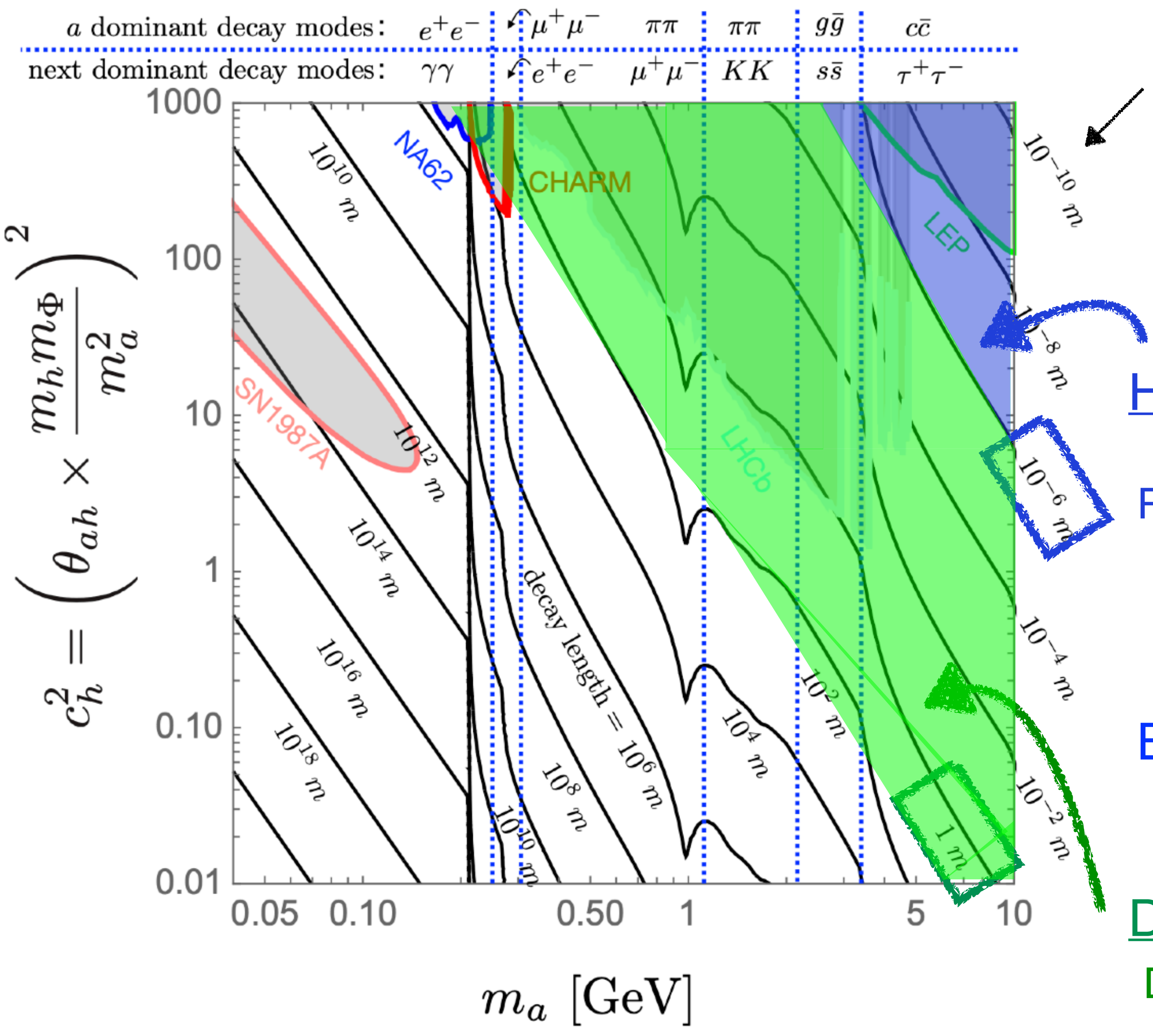
ILD: $L_R^{\mathrm{ILD}} \sim 4\mu m$ [ILD, 1912.04601]

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

[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)

Higgs exotic decays

Resolution of vertex detector (L_R)

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

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

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

Displaced vertex

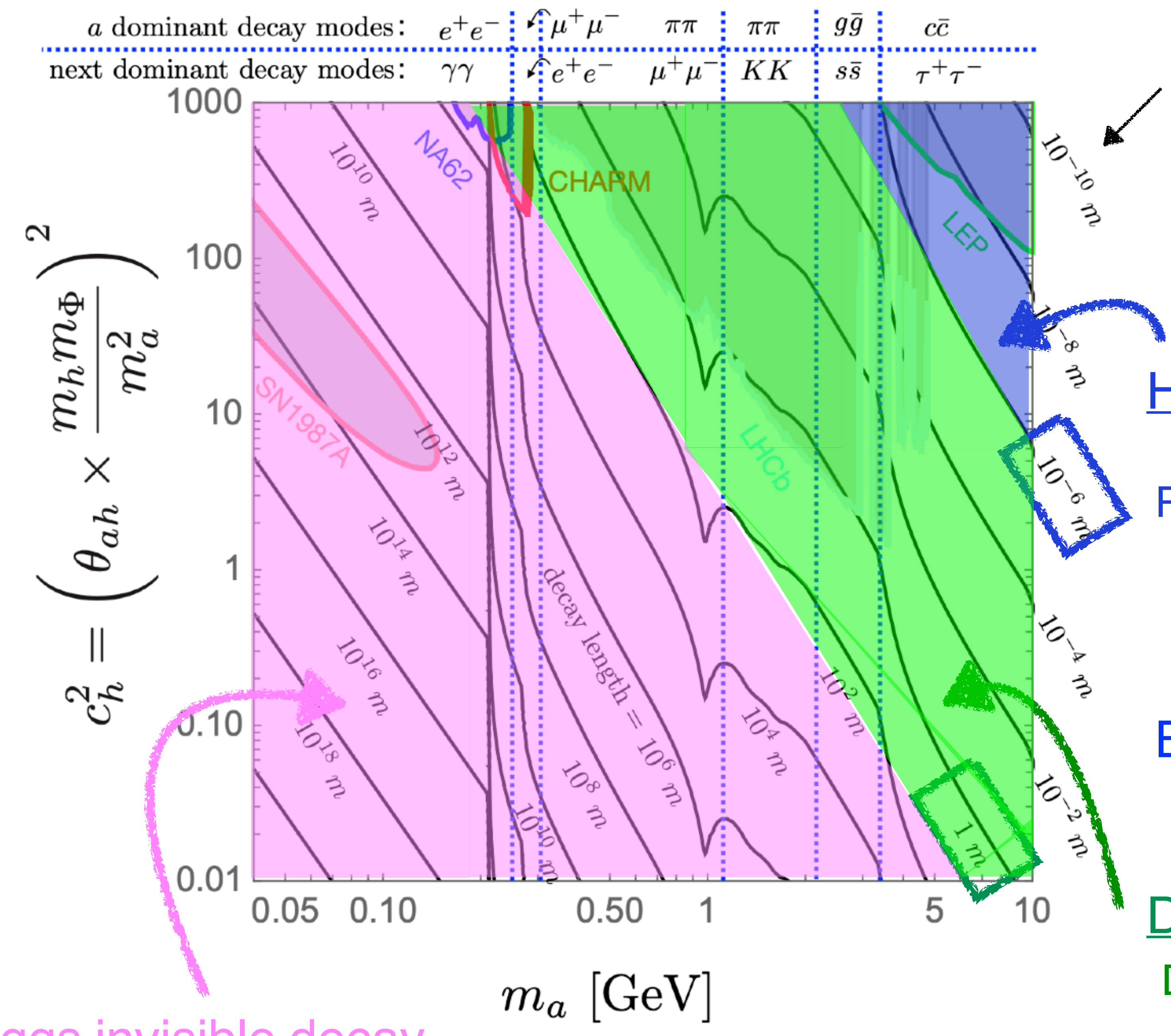
Detector size (L_V)

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

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

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]

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

Higgs invisible decay

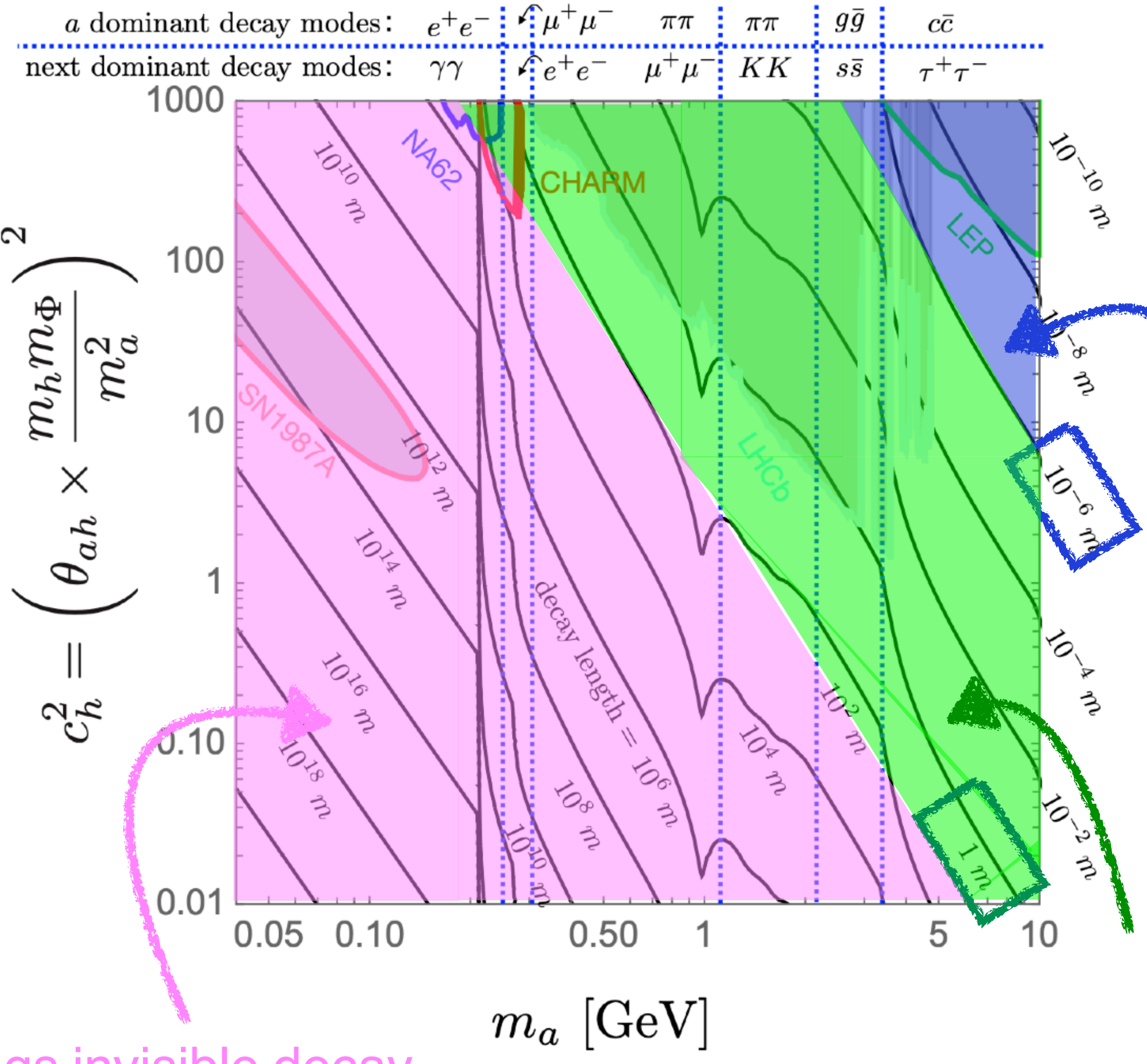
$$L_D \gg L_V \quad \text{or} \quad L_D \gtrsim L_V$$

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

[Y. Kato, 2002.12048]

Probe of CP-even ALP[5/5]

[KS, W. Yin]



Higgs invisible decay

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

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

[Y. Kato, 2002.12048]

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} (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]

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

CP-even ALP as DM

The ALP can be thermally produced through the interaction:

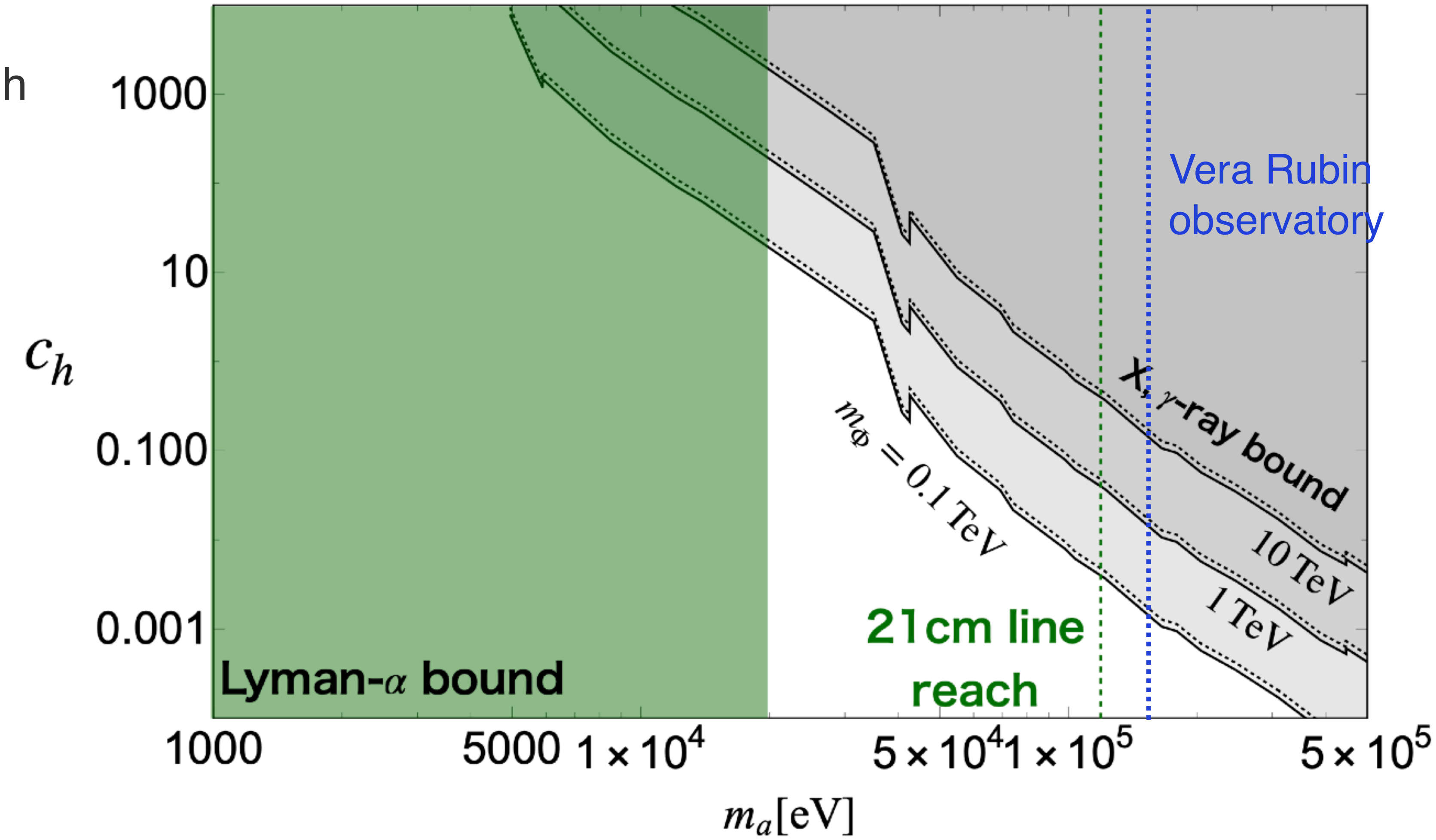
$$\delta\mathcal{L} = -\frac{\sqrt{2}m_\psi}{\Lambda_H^2 m_h^2}\partial a \partial a \bar{\psi}\psi$$

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

The correct relic density can be obtained:

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

[KS, W. Yin]



→ The ALP DM can be probed by the future 21 cm line measurements,
Vera Rubin observatory (structure formation limit).

→ Future X-ray and γ-ray observatories also has sensitivity in this parameter region.

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

Summary

- We discussed a simple renormalizable model with CP violation in the dark sector.

- The model predict ALP being CP-even.

- The ALP can be probed by ILC though *h—> aa* .

  - Depending on the decay length, different signatures are possible:

    Higgs invisible decay, displaced vertex, Higgs exotic decay

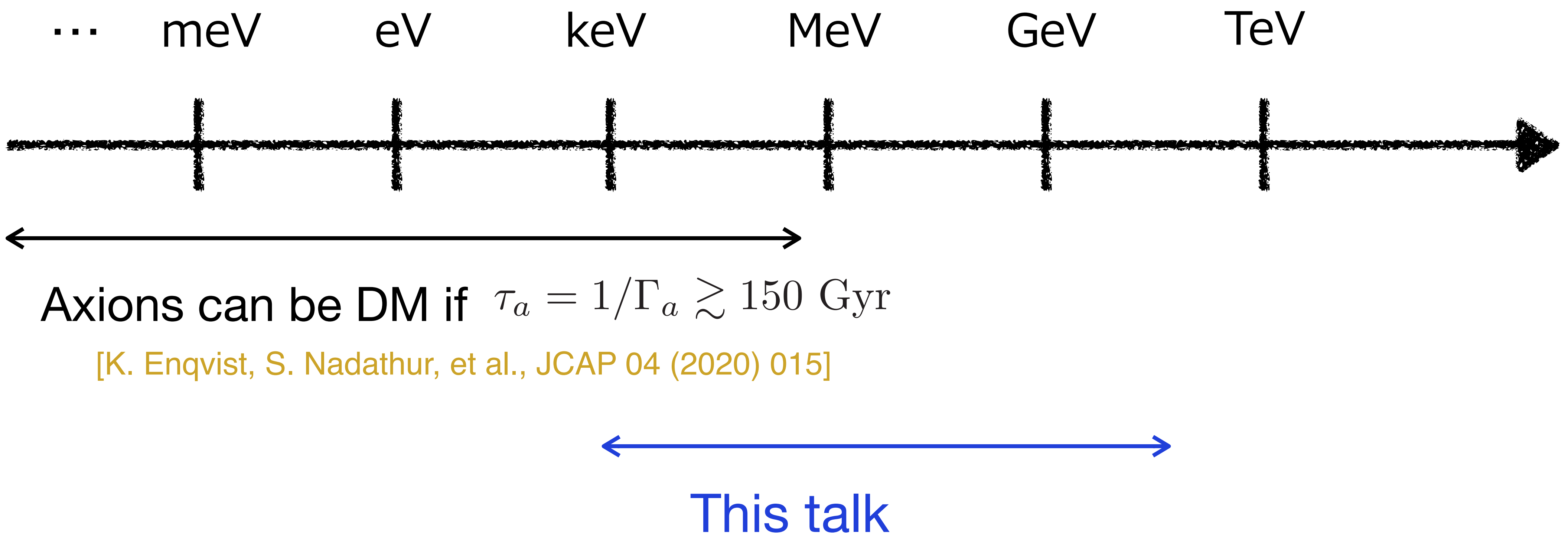
- In case of $m_a \lesssim 1\mathrm{MeV}$, the ALP can be searched by future 21 cm line measurements, Vera Rubin observatory as well as future X-ray, γ-ray observatories.

  - Also, the Higgs invisible decay can probe ALP in this mass range.

Buck up

Coupling of ALP with Higgs boson

- Axion/ALPs are prominent candidates of light DM.
- They emerge as pseudo Nambu Goldstone boson by spontaneous symmetry breaking of global U(1) symmetry.
- The general mass range



Axions can be DM if $\tau_a = 1/\Gamma_a \gtrsim 150\ \mathrm{Gyr}$

[K. Enqvist, S. Nadathur, et al., JCAP 04 (2020) 015]

This talk

Relations for scalar couplings in the limit κ=0

$$\lambda_P = \frac{\sin(2\alpha_1)(m_s^2 - m_h^2)}{4vv_\Phi} \,,$$

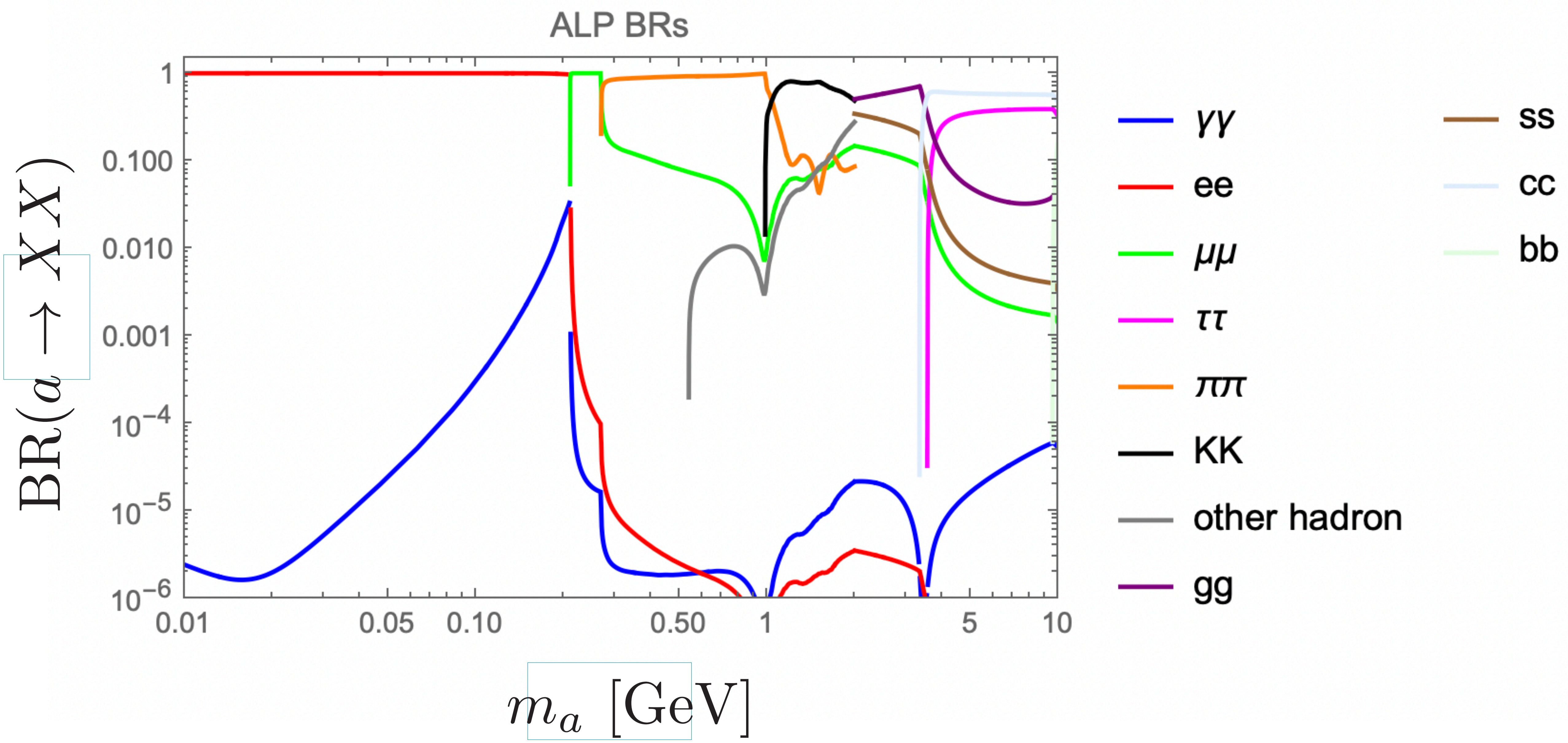
$$\lambda_s = \frac{\cos(2\alpha_1)(m_s^2 - m_h^2) + m_h^2 + m_s^2}{8v_\Phi^2} \,,$$

$$\lambda_h = \frac{\cos(2\alpha_1)(m_h^2 - m_s^2) + m_h^2 + m_s^2}{8v^2} .$$

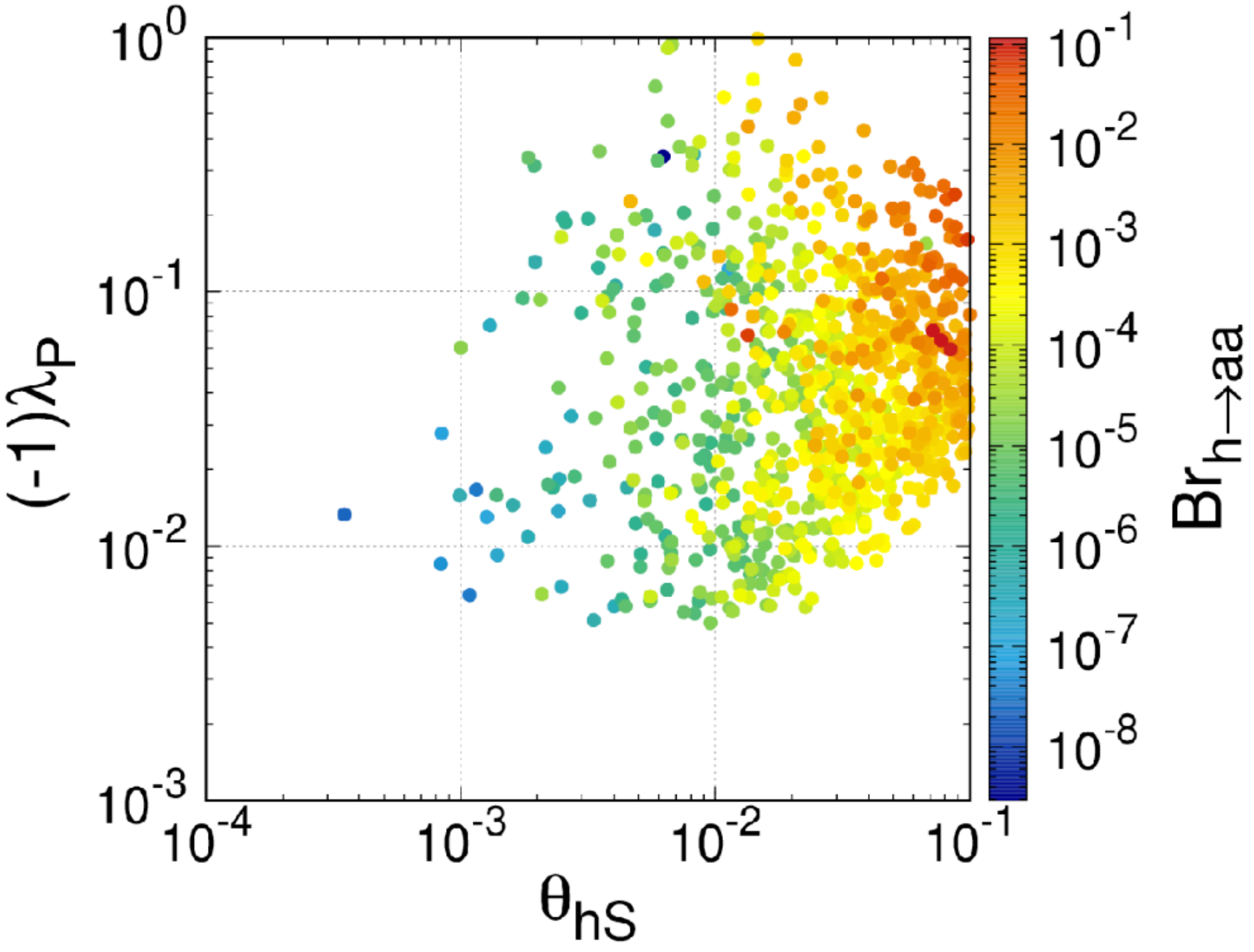
$$V = -m_\Phi^2|\Phi|^2 + \lambda|\Phi|^4 + \lambda_P|H|^2|\Phi|^2 + \lambda_H|H|^4 - \mu_H^2|H|^2 \,,$$

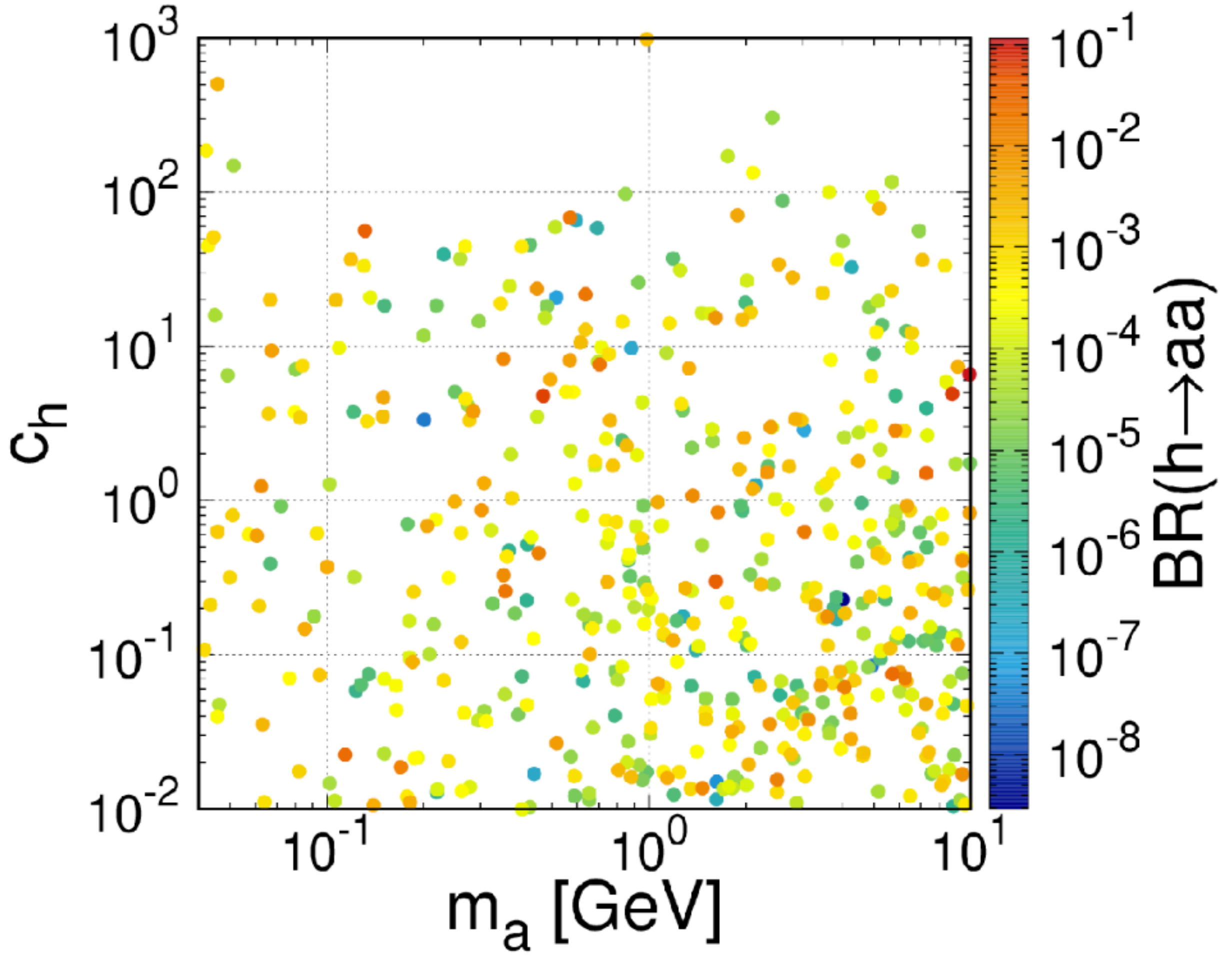
$$\begin{pmatrix} h \\ s \\ a \end{pmatrix} = R_{\alpha_1} \begin{pmatrix} \phi_r \\ \rho \\ a' \end{pmatrix} \quad R_{\alpha_1} = \begin{pmatrix} \cos\alpha_1 & \sin\alpha_1 & 0 \\ -\sin\alpha_1 & \cos\alpha_1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Branching ratios for the ALP



Branching ratios

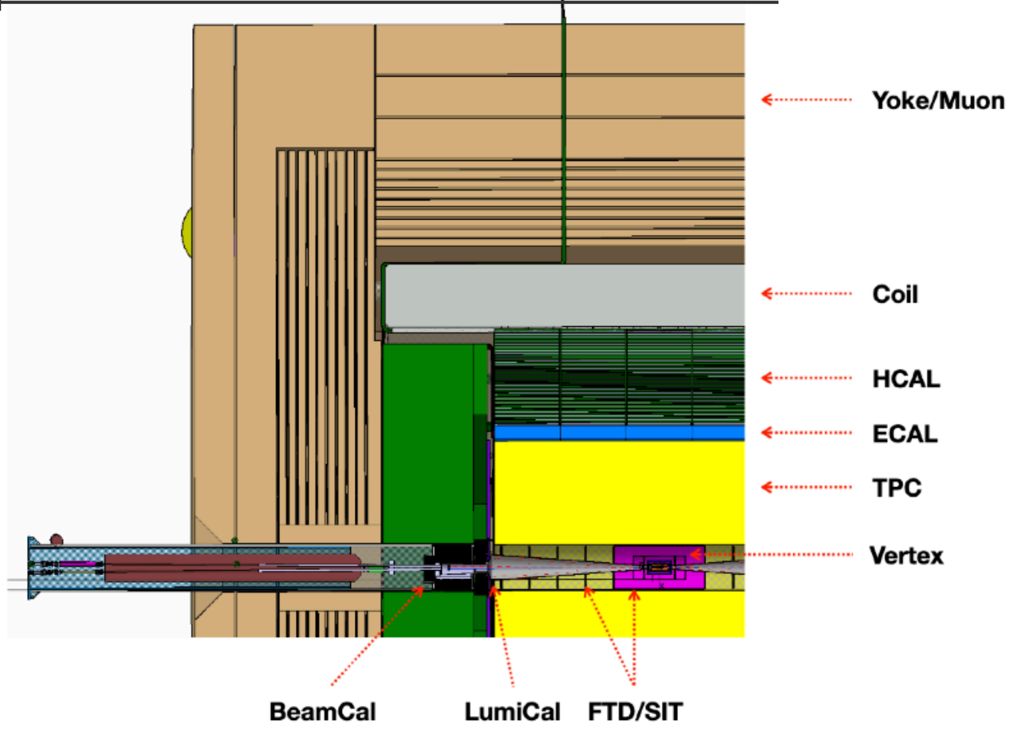




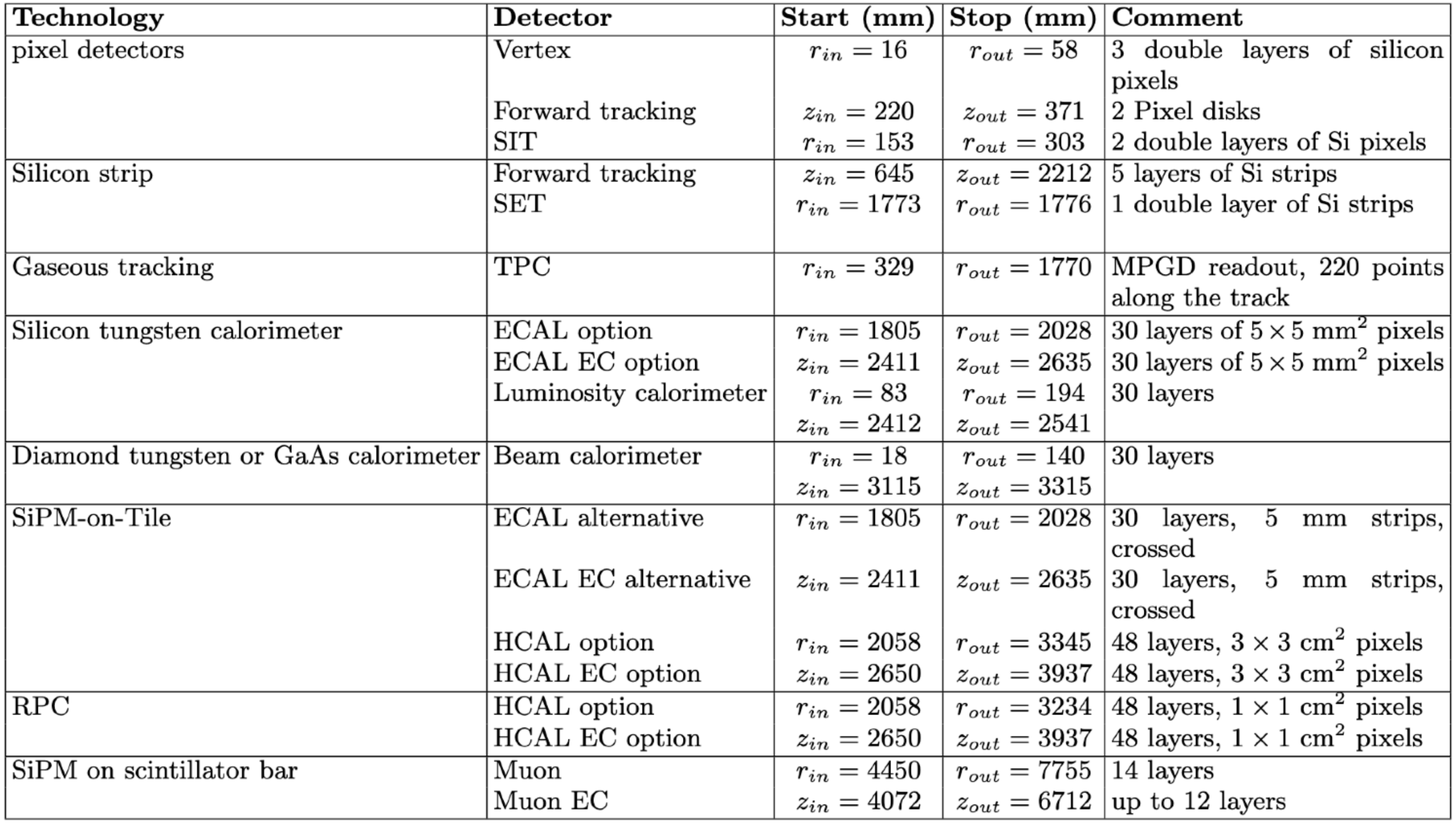
ILD detector

[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 5×5 mm^2 pixels
	ECAL EC option	$z_{in} = 2411$	$z_{out} = 2635$	30 layers of 5×5 mm^2 pixels
	Luminosity calorimeter	$r_{in} = 83$ $z_{in} = 2412$	$r_{out} = 194$ $z_{out} = 2541$	30 layers
Diamond tungsten or GaAs calorimeter	Beam calorimeter	$r_{in} = 18$ $z_{in} = 3115$	$r_{out} = 140$ $z_{out} = 3315$	30 layers
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, 3×3 cm^2 pixels
	HCAL EC option	$z_{in} = 2650$	$z_{out} = 3937$	48 layers, 3×3 cm^2 pixels
RPC	HCAL option	$r_{in} = 2058$	$r_{out} = 3234$	48 layers, 1×1 cm^2 pixels
	HCAL EC option	$z_{in} = 2650$	$z_{out} = 3937$	48 layers, 1×1 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