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Probing light dark sector by invisible decays of dark and SM-like Higgs bosons at the ILC

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Motivations

There are many BSM models with the dark sector (DS).

- Dark sector connects with the SM sector via portal int.
- Most of them require small portal interactions.

Dark sector may be difficult to test…

- Can we construct models for the dark sector with sizable portal coupling?
- If yes, what is possible signals to probe the dark sector through the portal int.?

→ In this talk,

- We propose a simple renormalizable model that contains DS with sizable portal coupling.
- We show that (dark) Higgs invisible decays can probe light dark sector.

Simplest model of dark sector

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

We consider SM + Dark Higgs field:

Dark Higgs field: $< \Phi >= v_\Phi$

$$\boxed{V = -m_\Phi^2|\Phi|^2 + \lambda|\Phi|^4 + \underbrace{\lambda_P}_{\text{Portal coupling}}|H|^2|\Phi|^2 + \lambda_H|H|^4 - \mu_H^2|H|^2\ ,}$$

- There are two possibilities for the DS.

  - U(1) global symmetry → Axion like particle
  - U(1) local symmetry → Hidden photon (mass from $|D_\mu\Phi^2|$)

Discussion of ’t Hooft naturalness

We consider SM + Dark Higgs field:

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

Dark Higgs field: $< \Phi >= v_\Phi$

$$\boxed{V = -m_\Phi^2|\Phi|^2 + \lambda|\Phi|^4 + \underbrace{\lambda_P}_{\text{Portal coupling}}|H|^2|\Phi|^2 + \lambda_H|H|^4 - \mu_H^2|H|^2\ ,}$$

- The region with $\lambda_P \sim \mathcal{O}(1)$ is favored region by the argument of naturalness.

[Gerard 't Hooft, NATO Sci.Ser.B 59 (1980) 135-157]

  - In the limits $\lambda, \lambda_P, \lambda_H \to 0$, any symmetry is not restored.

    → $\lambda, \lambda_{P,H} \sim \mathcal{O}(1)$ is natural, following the arguments of ’t Hooft.

  - This follows that v_Φ and m_Φ should be at around the EW scale.

    Minimization conditions: $\mu_H^2 = \lambda_H v^2 + \frac{\lambda_P}{2} v_\Phi^2 \quad \mu_\Phi^2 = \lambda_\Phi v_\Phi^2 + \frac{\lambda_P}{2} v^2$

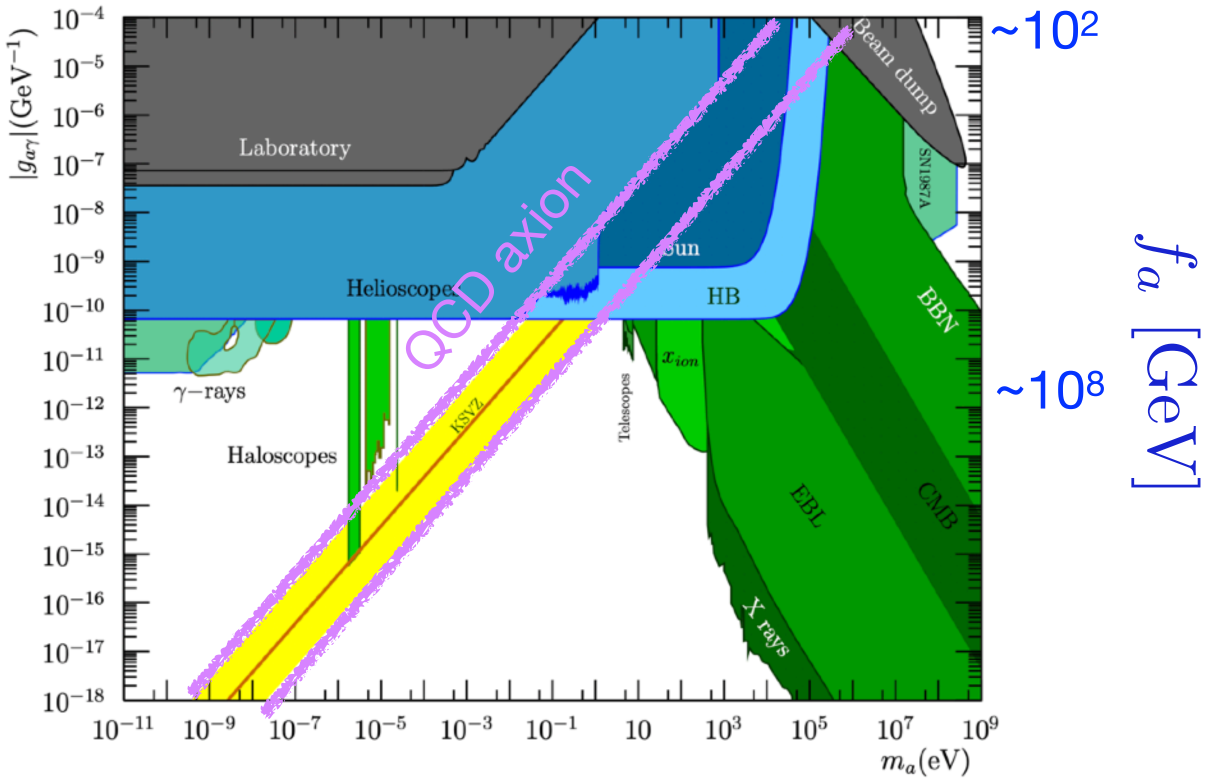
    → $100\mathrm{GeV} \sim \mu_H \sim v_\Phi \sim m_\Phi$

➡ v_Φ and $m_\Phi \sim v$ is favored parameter space by the naturalness.

Viable parameter space for axion/ALPs

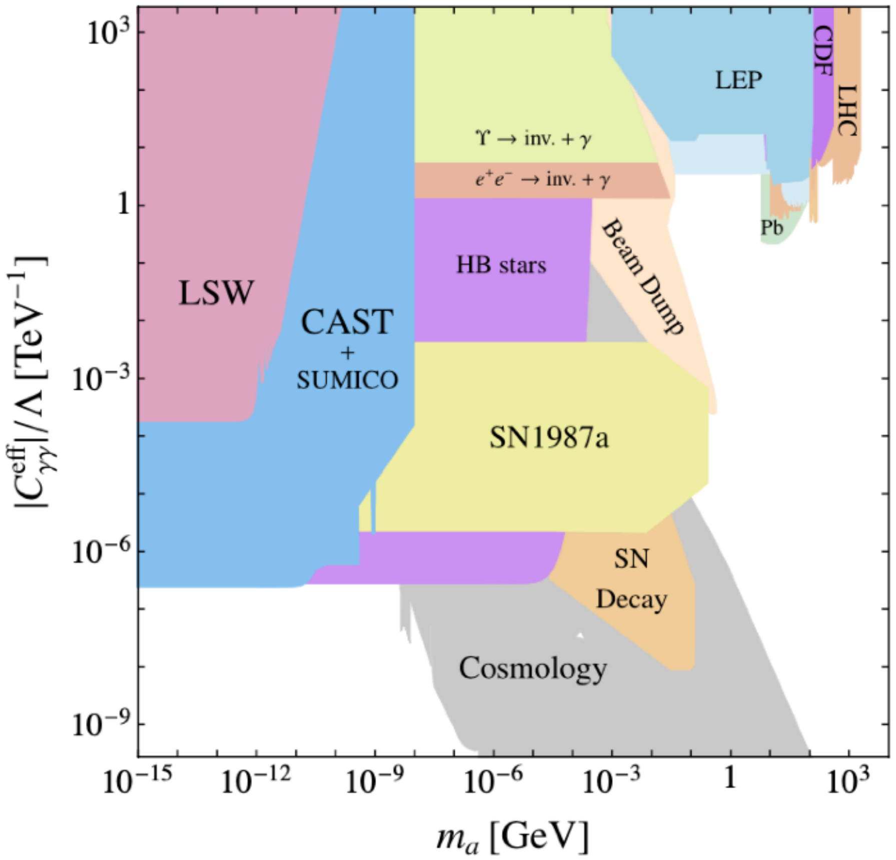
QCD axion

- f_a~100GeV are excluded Lab exp. (Beam dump, Kaon decays)
- Viable parameter space: $f_a > 10^8\mathrm{GeV}$
- This leads tiny portal coupling $\sim v^2/f_a^2$.



Axion-like particle (ALP)

- f_a can be 1 TeV.
- m_a >1 GeV.
- This ALP wouldn't be DM.



➡ Can we construct models for the dark sector while keeping the VEV EW scale ?

A simple renormalization model

U(1) symmetric potential + soft breaking terms:

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

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

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

- κ corresponds to the order parameter of U(1) breaking.
  - We assume κ <<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 $m_a^2 \sim \mathcal{O}(\kappa) v_\Phi^2 \sim \mathcal{O}(\kappa) m_\Phi^2$ ($v_\Phi \sim m_s \gtrsim v$)
- Higgs potential (V+δV) has CP symmetry

$$V = V(|H|^2, |\Phi|^2) \qquad \delta V = \delta V(|H|^2, s', a') \quad \longrightarrow \quad (CP)\delta V(|H|^2, s', a')(CP)^\dagger = \delta V(|H|^2, s', a')$$

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

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

$\mathcal{M}_{ah} \sim \kappa v v_\Phi \sim m_a^2$

c_h is function of c_i .

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

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

← The model (*V*+*δV*) has CP symmetry.

→ ALP has the couplings of CP-even scalar.

→ The couplings scale with the mass of ALP.

CP-even ALP as DM

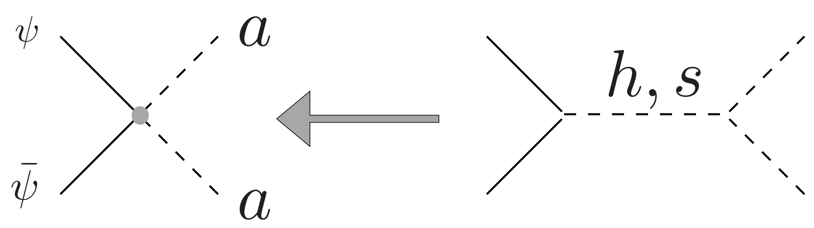
- The ALP-fermion couplings are suppressed by taking small m_a.

  → We can avoid constraints from laboratory exp. (Beam dump, meson decays ..)

  → The couplings are not controlled by the portal coupling λ_P

- If λ_P is not small, the ALP can be thermally produced:

$$\delta\mathcal{L} = -\frac{\sqrt{2}m_\psi}{\Lambda_H^2 m_h^2}\partial a \partial a \bar{\psi}\psi \qquad \frac{1}{\Lambda_H^2} \equiv -\frac{\lambda_P}{m_s^2 - m_h^2}$$

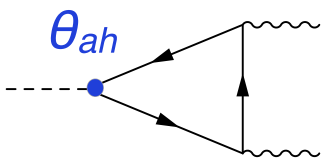


- The correct relic density can be obtained:

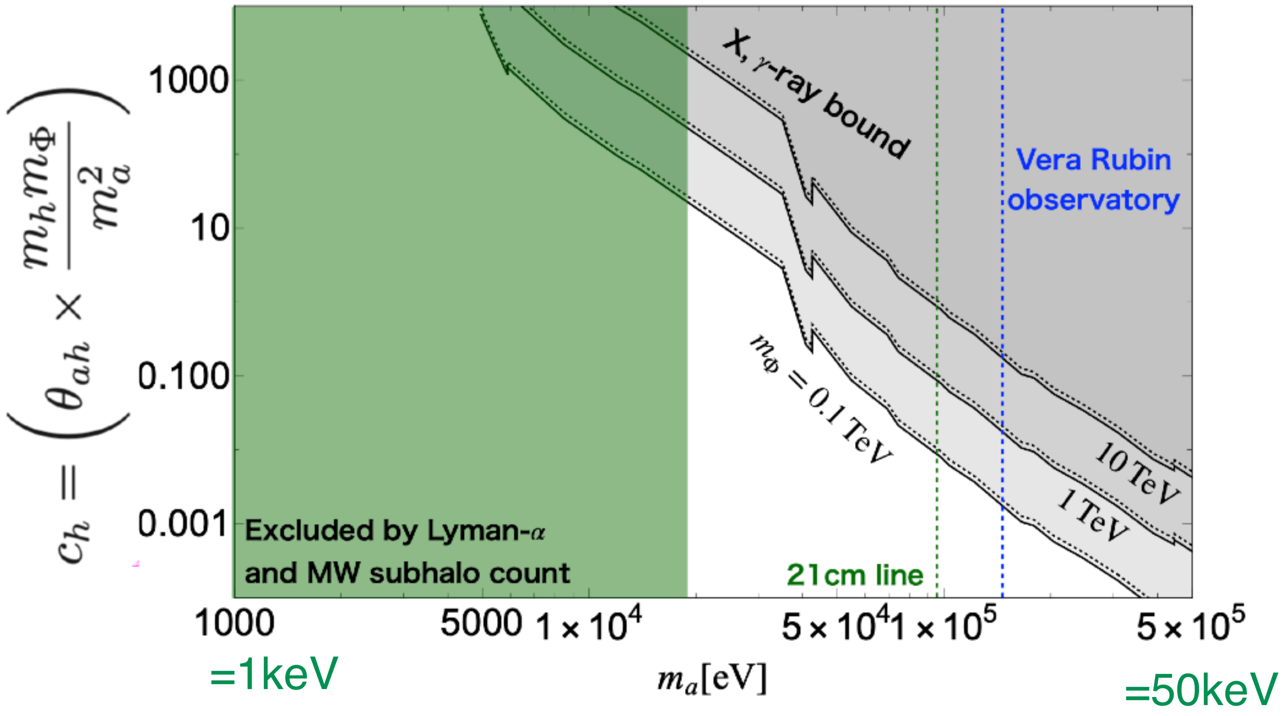
$$\Omega_a \sim 0.35 \frac{m_a}{20\,\mathrm{keV}} \left(\frac{m_\psi}{\mathrm{GeV}}\right)^2 \left(\frac{T_R}{2\,\mathrm{GeV}}\right)^5 \left(\frac{3\,\mathrm{TeV}}{\Lambda_H}\right)^4$$

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

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



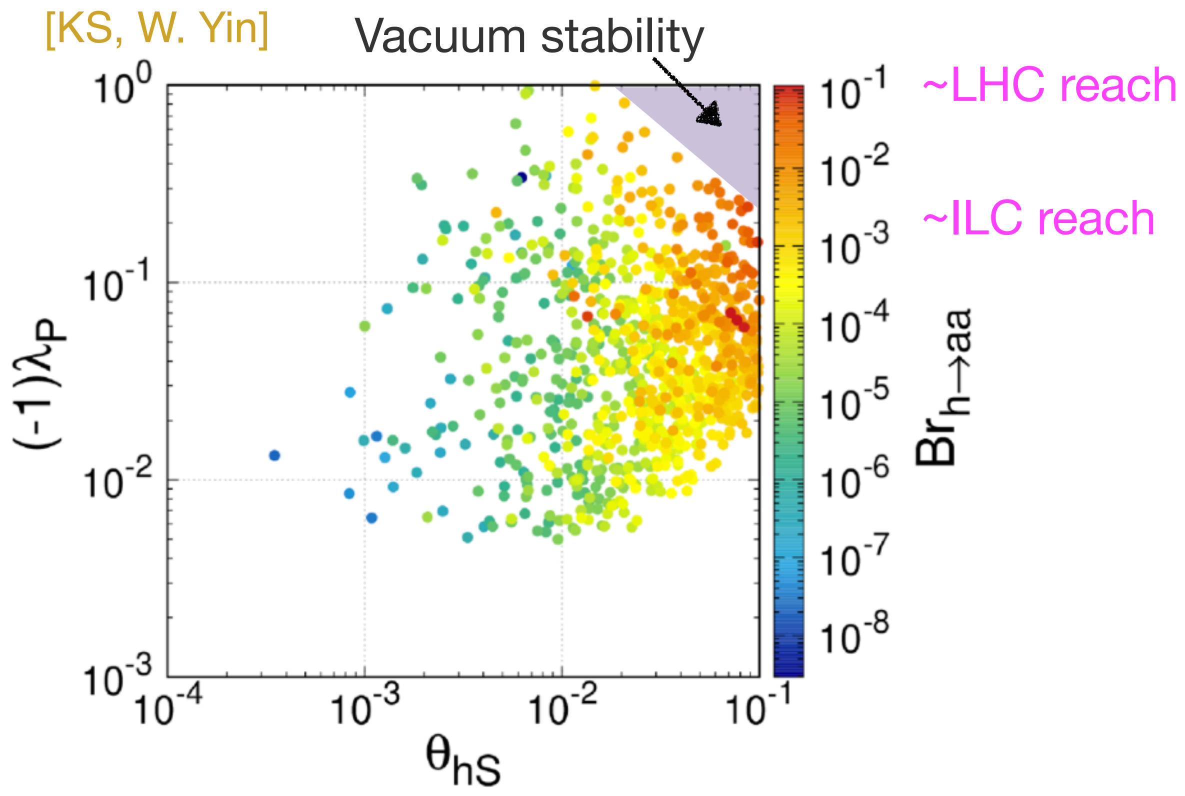
[KS, W. Yin]



How can we search CP even ALP?

The Higgs boson -ALP interaction is not small in the case of $\lambda_P \sim \mathcal{O}(1), \quad m_s \sim \mathcal{O}(100)\mathrm{GeV}.$

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


[KS, W. Yin]

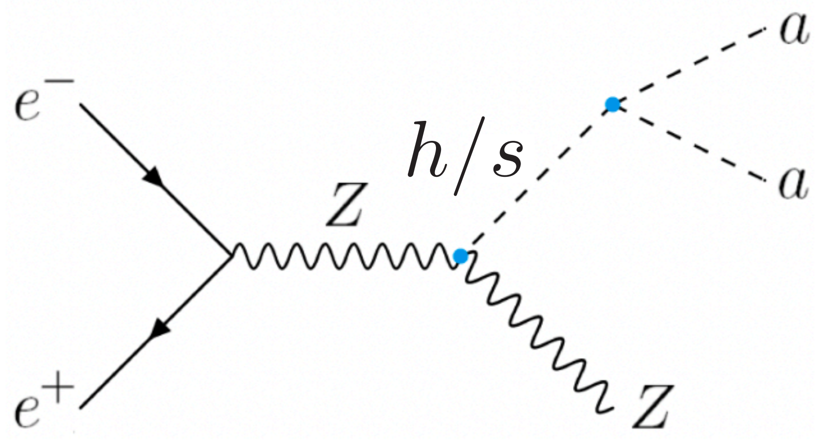
Vacuum stability

~LHC reach

~ILC reach

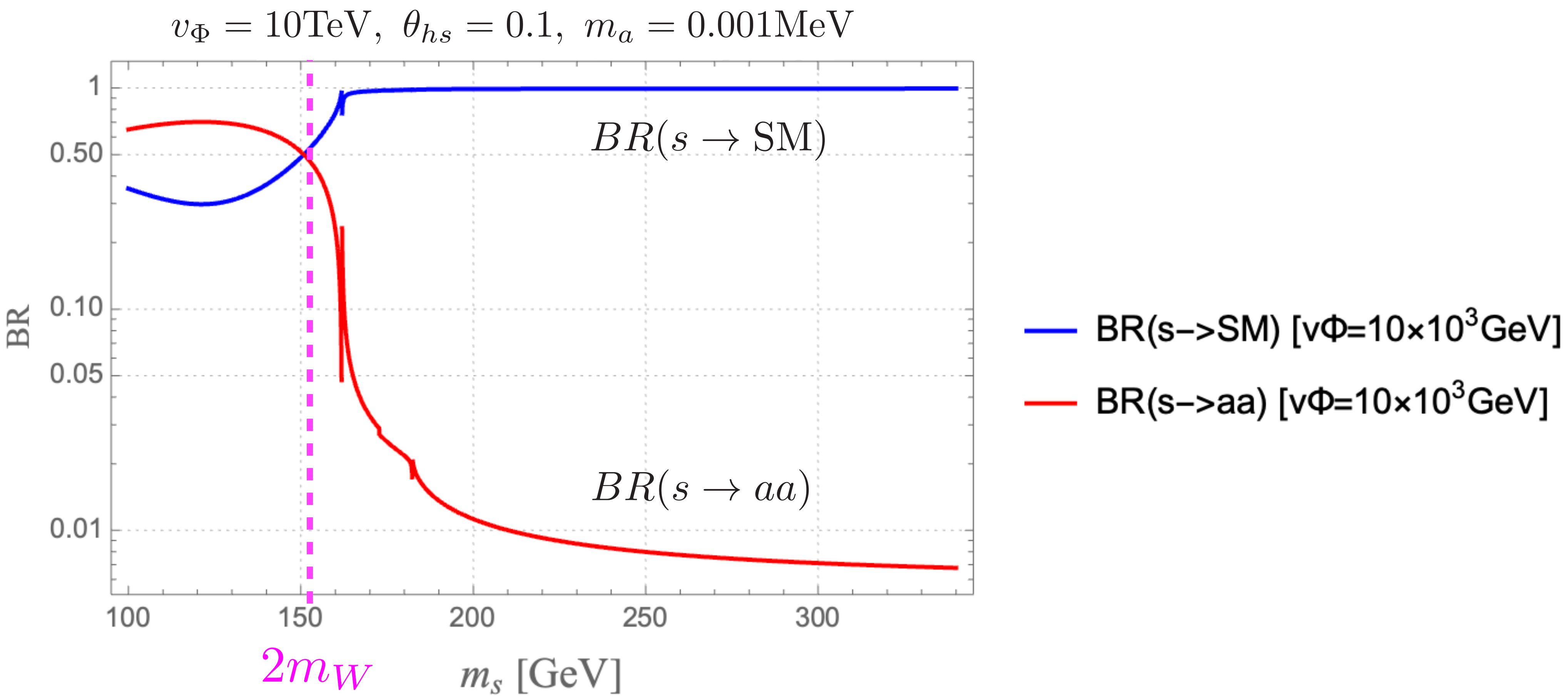
→ ALP can be tested by the Higgs boson invisible decay.

→ We have studied $e^+e^- \to Zh/s \to Zaa$ at the ILC with $\sqrt{s} = 250\ \mathrm{GeV}$.



When does the dark Higgs boson affect to the signal process?

We have two contributions (h,s) to $e^+e^- \to Zh/s \to Zaa$



In addition, above 2m$_W$ ($\sim 250 - m_h$) on-shell s is not produced.

→ We assume that *s* is enough light to be produced at the ILC 250 GeV

$$63\text{GeV} \lesssim m_s \lesssim 160\text{GeV}$$

Collider analysis

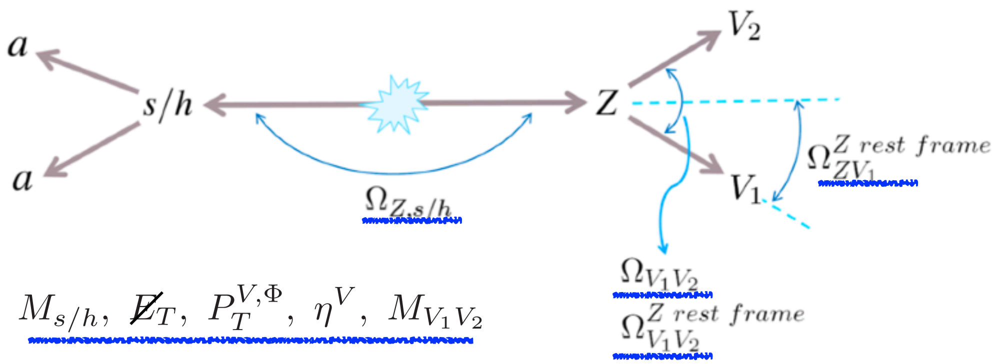
- We studied 7 signal regions (SR).

Signal region:	Decay mode	BR
SR1:	$q\bar{q}$	0.699
SR3:	e^-e^+	0.034
SR2:	$\mu^-\mu^+$	0.034
SR4:	$\tau^-\tau^+$(hadronic)	0.014
SR5,6:	$\tau^-\tau^+$(semileptonic)	0.015
SR7:	$\tau^-\tau^+$(leptonic)	0.004

- Collider simulation is performed by

  `Madgraph, Pythia, Delphes, FastJet.`

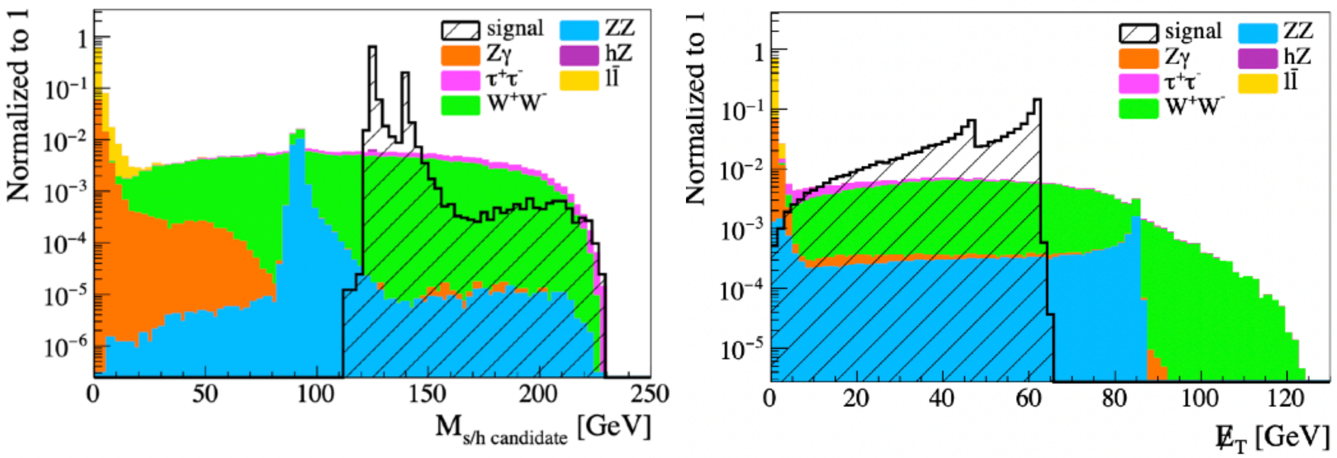
- To separate signal and backgrounds, we use 9 discriminating variables.



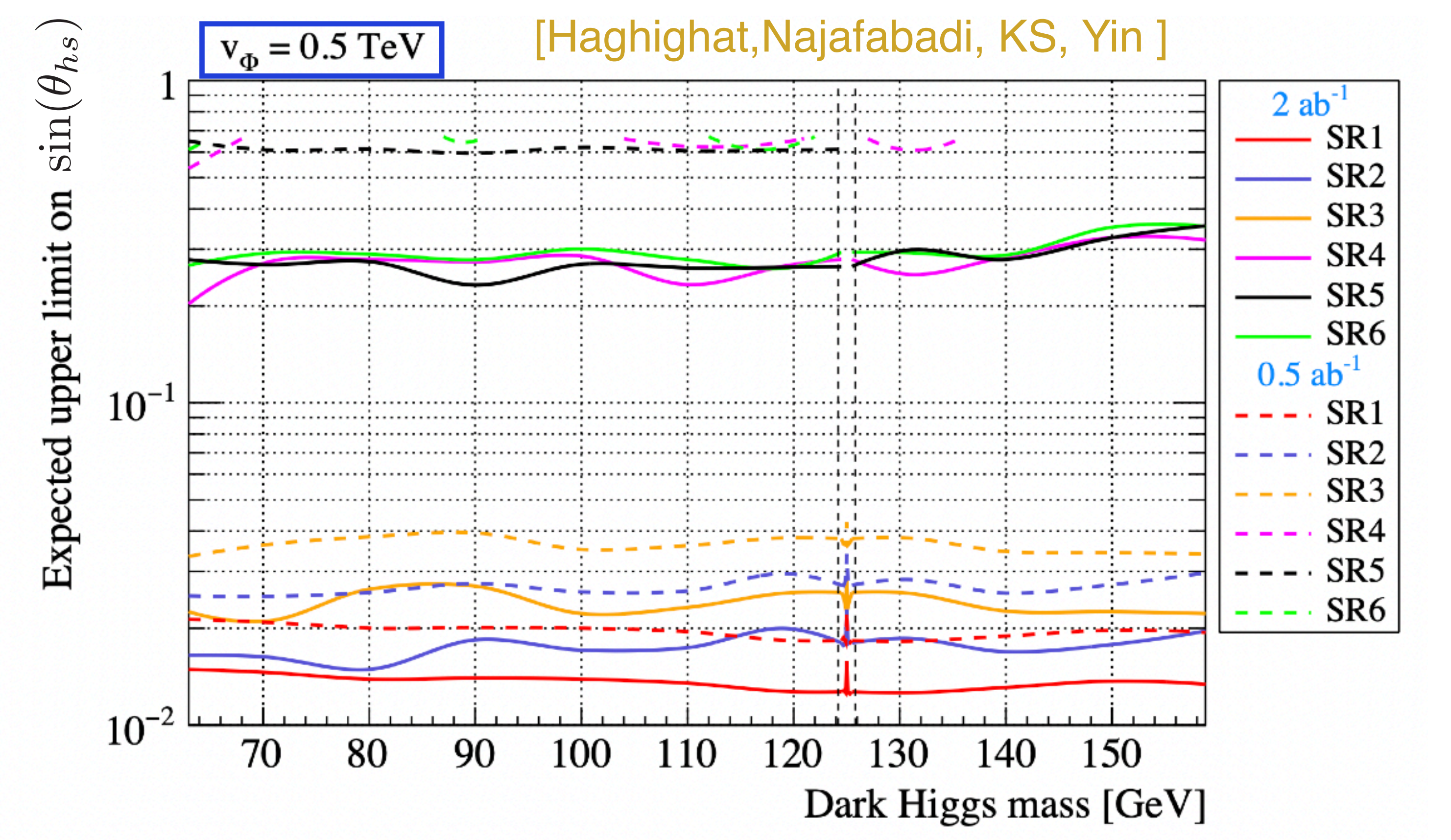
- To get better sensitivity, we employed a multivariate technique by utilizing the TMVA package. BDT algorithms are used.

→ Due to characteristic distributions, $M_{s/h}$, $\not{E}_T$, $\Omega_{\mu_1\mu_1}$ have the most discriminating powers.

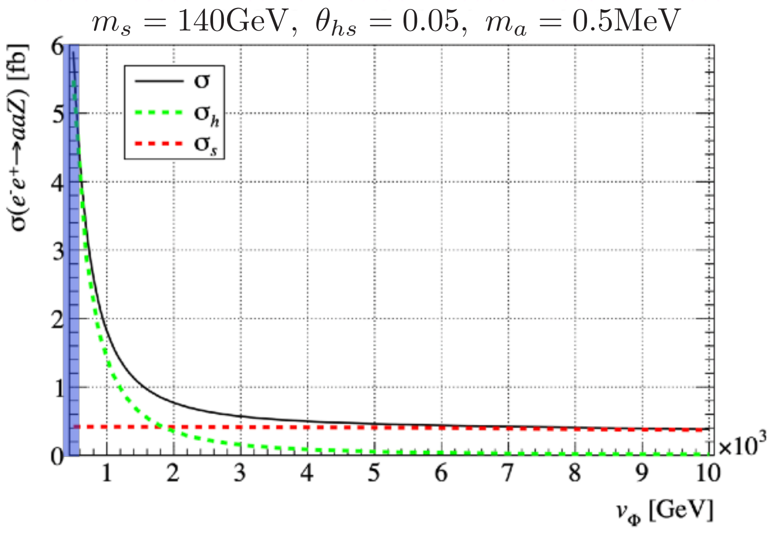
SR2 $v_\Phi = 1\text{TeV},\ m_s = 140\text{GeV},\ \theta_{hs} = 0.05$

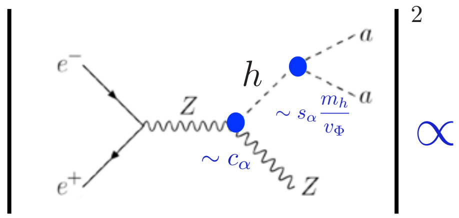


Sensitivity for the mixing angle for vΦ=500GeV



[Haghighat,Najafabadi, KS, Yin]





$\sigma_h \sim \left| \quad \right|^2 \propto s^2_{2\theta_{hs}} \frac{m_h^2}{v_\Phi^2}$

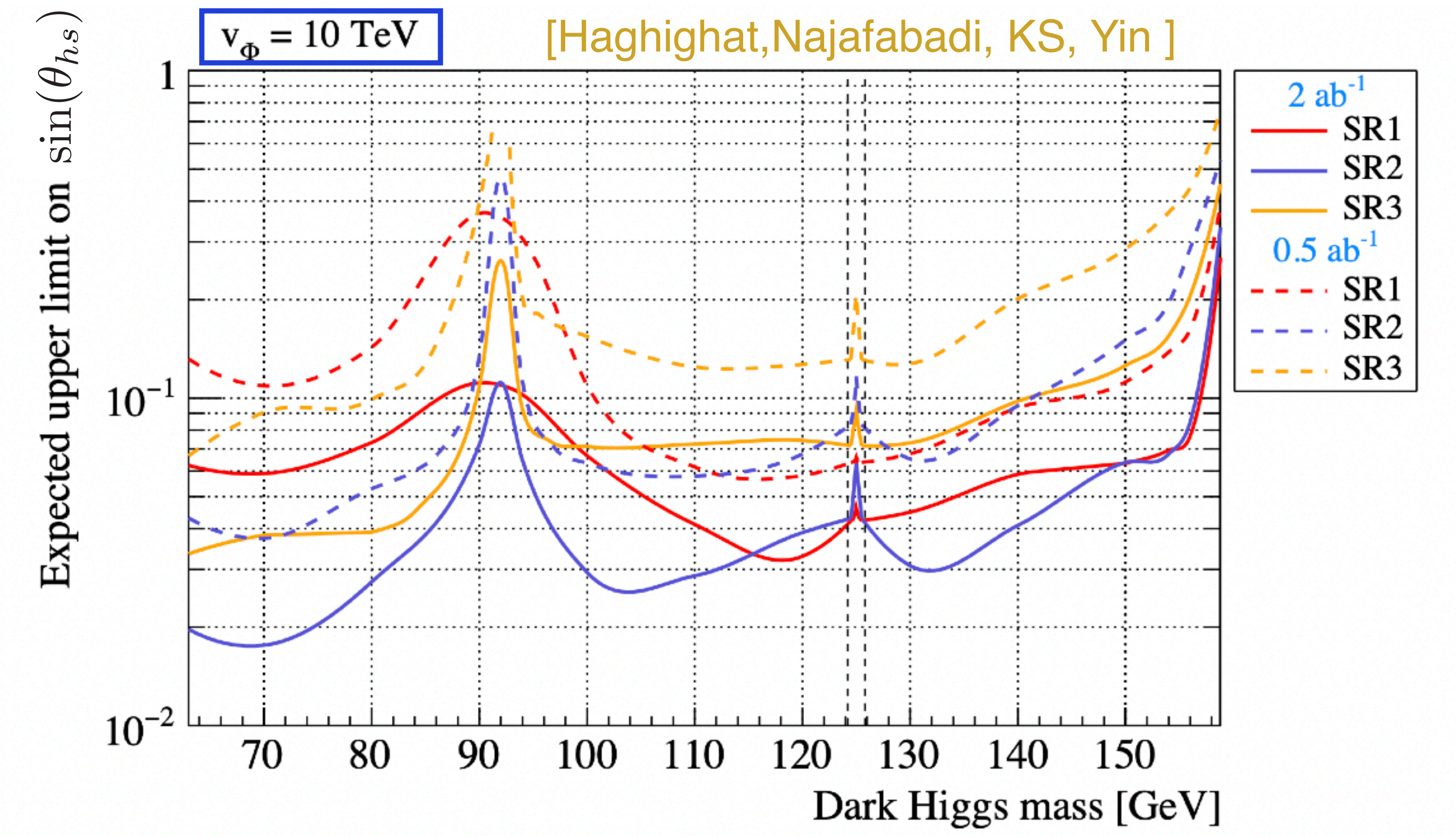
- Main contributions: $\sigma \sim \sigma_h$
- Strongest limit: SR1 $\sin\theta_{hs} \lesssim 0.015$

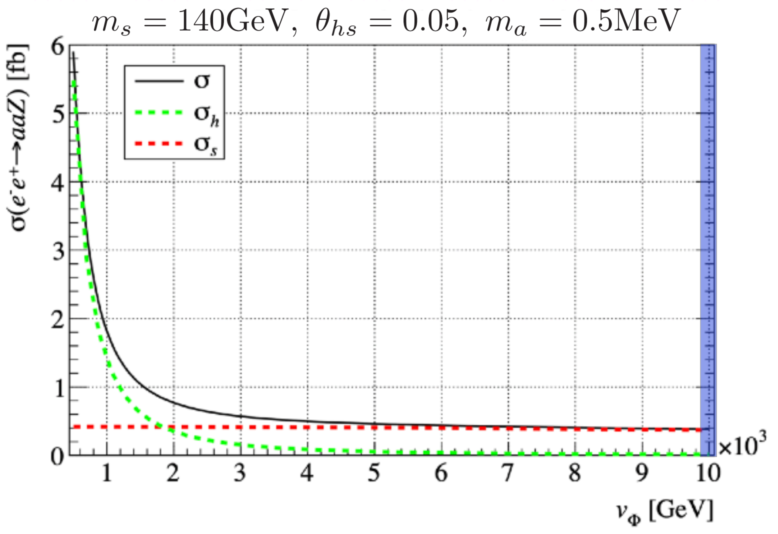
  (Large event selection efficiency)

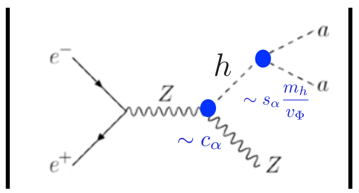
- The limits are almost independent of m_s .

Signal region:	Decay mode	BR
SR1:	$q\bar{q}$	0.699
SR3:	e^-e^+	0.034
SR2:	$\mu^-\mu^+$	0.034
SR4:	$\tau^-\tau^+$(hadronic)	0.014
SR5,6:	$\tau^-\tau^+$(semileptonic)	0.015
SR7:	$\tau^-\tau^+$(leptonic)	0.004

Sensitivity for the mixing angle for vΦ=10TeV







$$\sigma_h \sim \left| \quad \right|^2 \propto s^2_{2\theta_{hs}} \frac{m_h^2}{v_\Phi^2}$$

$$\sigma_s \simeq \sigma(e^+e^- \to Zs) \cdot \underline{\mathrm{BR}(s \to aa)}$$

$$= \Gamma_{s\to aa}/(\Gamma_{s\to aa} + \Gamma_{s\to SM})$$

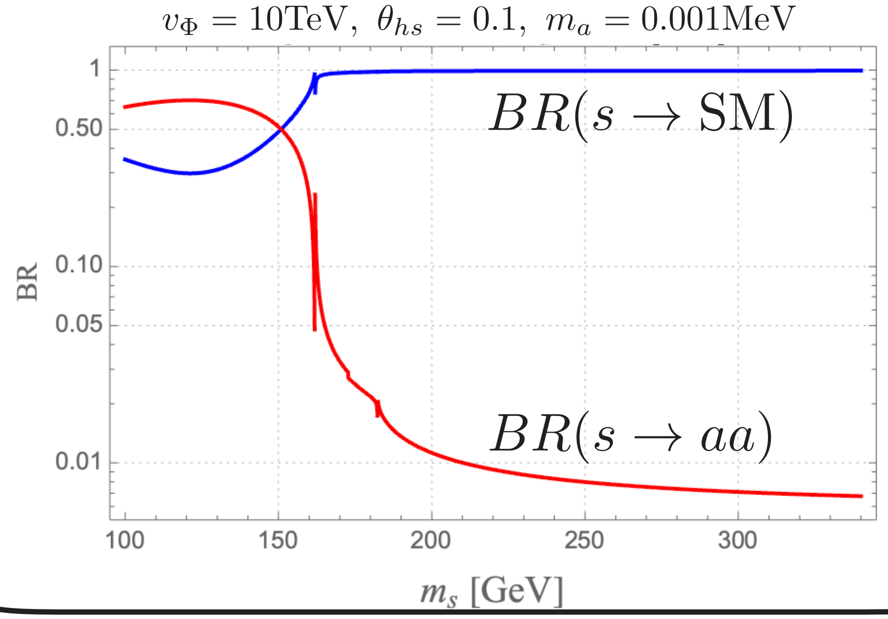
- Main contributions: $\sigma \sim \sigma_s$

- Strongest limit: SR2 $\sin\theta_{hs} < 0.02$ - 0.1

  (For SR1, separation of signal and BG is difficult due to small σ)

- The limits depend on m_s .

  → Even when BR(h—>aa)<<1, CP-even ALP can be probed by the invisible decays of *s.*



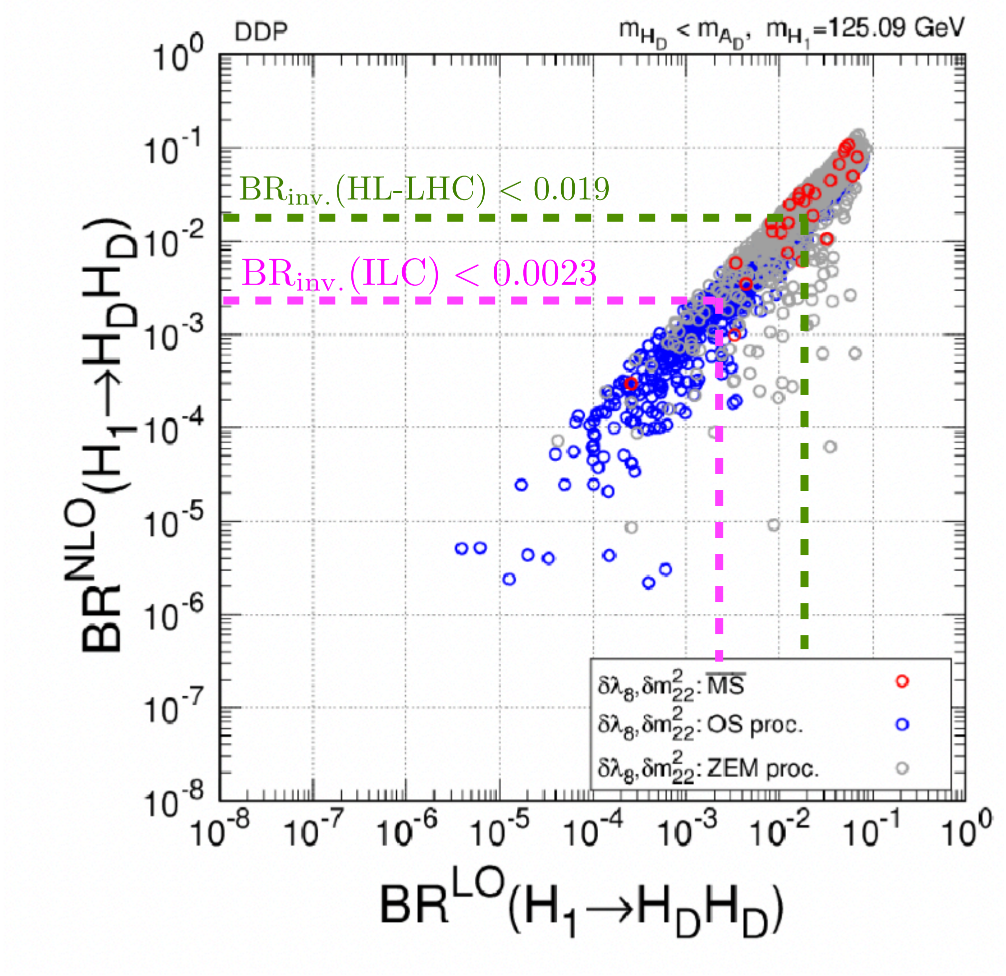
Impact of loop effects of extra scalars to h—> DM DM

$m_s < 2m_W$ → Invisible decays of *h,s*

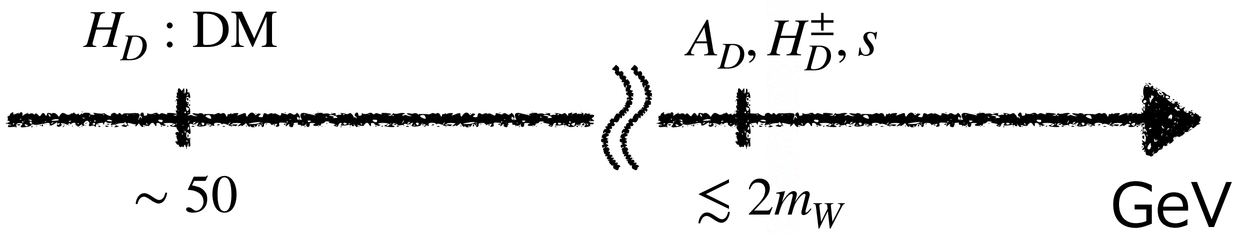
$2m_W < m_s$ → Loop effect of *s* to *h* invisible decay

Correlation between BR$^{\text{NLO}}$ and BR$^{\text{LO}}$ for h—>DM DM

[D. Azevedo P. Gabriel,M. Mühlleitner, KS, R. Santos]



The model with dark Higgs s
+ inert scalars $H_D, A_D, H_D^{\pm}$



→ There are points where BR NLO < BR LO.

→ Loop effect of extra scalars can be important in future measurements of Higgs invisible decays.

Summary

- We discussed a simple renormalizable model that involves dark Higgs field with the VEV at EW scale.

- The predicted ALP has the coupling like the CP-even scalar.

- It can be DM in the mass range of keV - MeV.

- We studied sensitivity regions by $e^+e^- \to Zh/s \to Zaa$ at the ILC 250GeV.

→ Dark Higgs *s* contribution is important, especially $v_\Phi \sim \mathrm{TeV}$.

→ Even if *s* is quite heavy, the loop corrections can affect to *h* invisible decay.