Some exotic Higgs decay from NMSSM at the CEPC

Based on：
arXiv: 2002.05554 [hep-ph] K. Wang and Jingya Zhu, JHEP 06, 078 (2020)
arXiv: 2003.01662 [hep-ph] K. Wang and Jingya Zhu, Phys.Rev.D 101 (2020) 9, 095028
arXiv: 2006.03527 [hep-ph] Shiquan Ma, K. Wang and Jingya Zhu, Chin.Phys.C 45 (2021) 2, 023113

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CEPC味物理-新物理和相关探测技术研讨会

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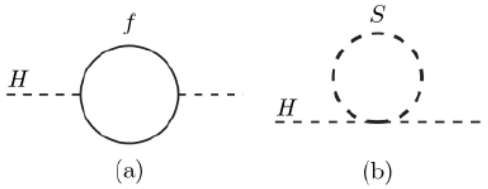
Outline

- Introduction: Why Supersymmetry (SUSY) ?
- Model: Semi-constrained NMSSM (scNMSSM)
- Our works: Higgs invisible decay
  Higgs decay to light scalars
- Summary

Introduction: Why SUSY ?

- **Problems in the SM:**
- Fine-turning



Martin, arXiv:9709356

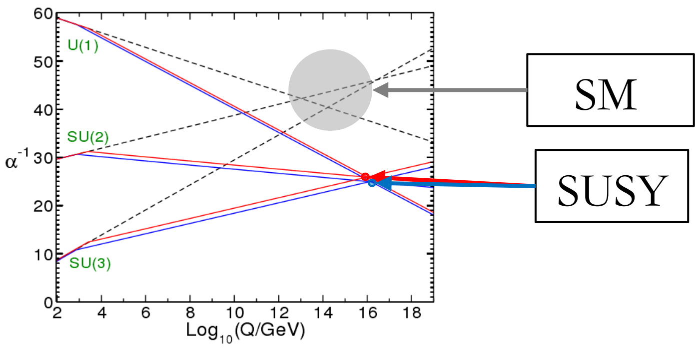
- Gauge couplings can’ t be unified at GUT scale

- Without dark matter candidate

- **How SUSY solve these:**

$$\Delta m^2_{H(a)} = -\frac{|\lambda_f|^2}{8\pi^2}\Lambda^2_{\rm UV} + \ldots$$

$$\Delta m^2_{H(b)} = \frac{\lambda_S}{16\pi^2}\left[\Lambda^2_{\rm UV} - 2m_S^2\ln(\Lambda_{\rm UV}/m_S) + \ldots\right]$$

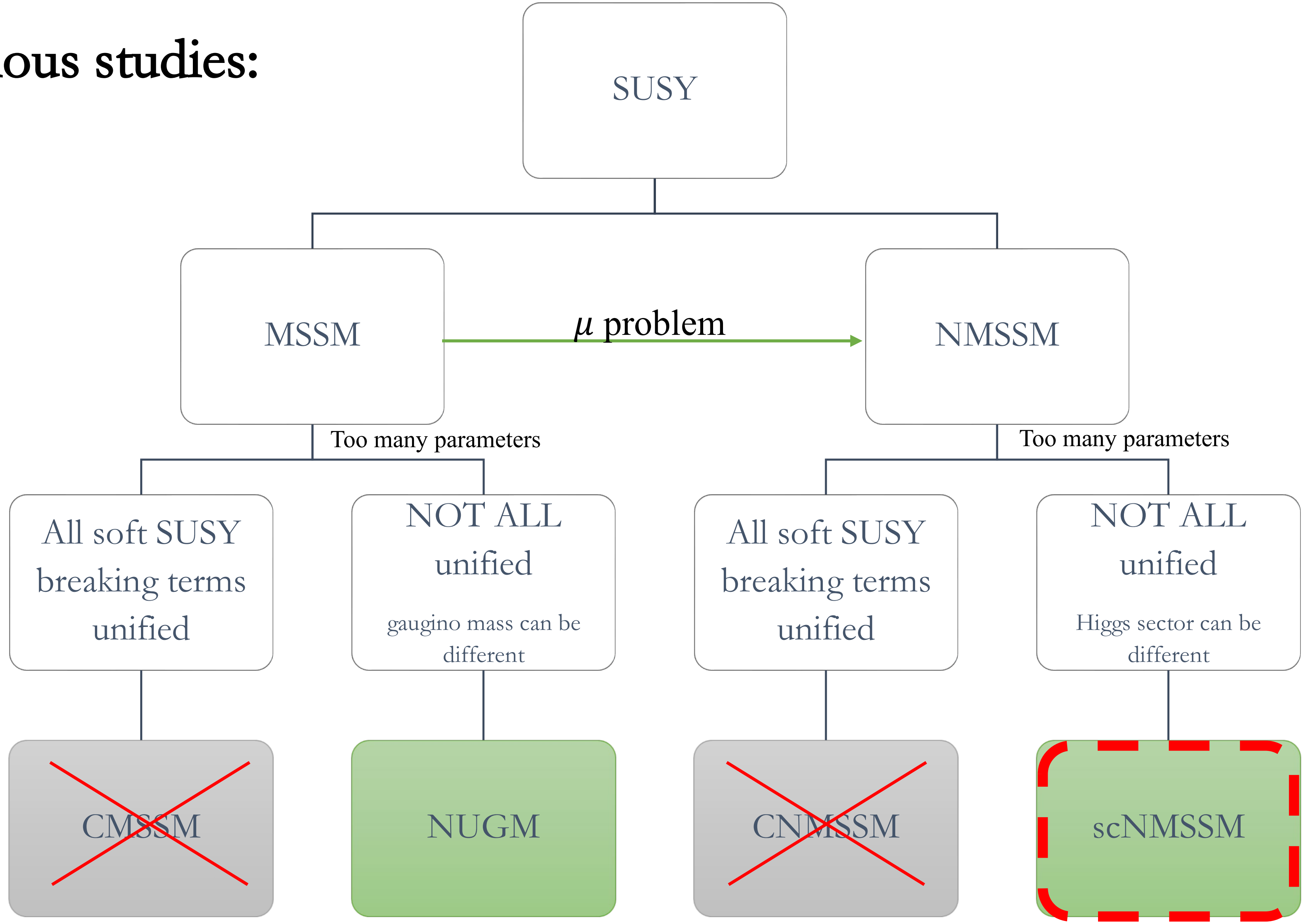


- R parity:

The Lightest Supersymmetric Particle (LSP) is absolute stable, which can be dark matter candidate.

Introduction: Why scNMSSM ?

- **Our previous studies:**



Model: Semi-constrained NMSSM

- The superpotential of NMSSM:

$$W_{\mathrm{NMSSM}} = y_u \hat{Q} \cdot \hat{H}_u \hat{u}^c + y_d \hat{Q} \cdot \hat{H}_d \hat{d}^c + y_u \hat{L} \cdot \hat{H}_d \hat{e}^c + \lambda \hat{S} \hat{H}_u \cdot \hat{H}_d + \frac{\kappa}{3} \hat{S}^3$$

- The effective μ"−term":

$$\mu_{\mathrm{eff}} = \lambda v_s$$

- The soft breaking term:

$$-\mathcal{L}^{\mathrm{soft}}_{\mathrm{NMSSM}} = -\mathcal{L}^{\mathrm{soft}}_{\mathrm{MSSM}}|_{\mu=0} + m_S^2 |S|^2 + \lambda A_\lambda S H_u \cdot H_d + \frac{1}{3} \kappa A_\kappa S^3 + \mathrm{h.c.}$$

- Semi-constrained: The Higgs sector are considered non-universal, the Higgs soft mass and trilinear couplings are allowed to be different at GUT scale.
- In the scNMSSM, the complete parameter sector is:

$$\lambda,\ \kappa,\ \tan\beta = \frac{v_u}{v_d},\ \mu,\ A_\lambda,\ A_\kappa,\ A_0,\ M_{1/2},\ M_0$$

Model: Electro-Weak Sector

- Higgs

CP-even Higgs

Light Higgs → h_1; SM-like → h_2

$$\begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix} = S_{ij} \begin{pmatrix} H_1 \\ H_2 \\ S^R \end{pmatrix}$$

CP-odd Higgs

Light Higgs → a_1

$$\begin{pmatrix} a_1 \\ a_2 \end{pmatrix} = P_{ij} \begin{pmatrix} A \\ S^I \end{pmatrix}$$

Charged Higgs

$$H^{\pm}$$

- Neutralino & Chargino

In scNMSSM, the Bino and Wino are very heavy, so they can be decoupled from the light sector.

LSP → $\tilde{\chi}_1^0$

NLSP → $\tilde{\chi}_2^0$, $\tilde{\chi}_3^0$, $\tilde{\chi}_1^+$

Will decay to LSP

$$\begin{pmatrix} \tilde{\chi}_1^0 \\ \tilde{\chi}_2^0 \\ \tilde{\chi}_3^0 \\ \tilde{\chi}_4^0 \\ \tilde{\chi}_5^0 \end{pmatrix} = N_{ij} \begin{pmatrix} \tilde{B} \\ \tilde{W}^0 \\ \tilde{H}_d \\ \tilde{H}_u \\ \tilde{S} \end{pmatrix}$$

$$\begin{pmatrix} \tilde{\chi}_1^+ \\ \tilde{\chi}_2^+ \end{pmatrix} = V_{ij} \begin{pmatrix} \tilde{W}^+ \\ \tilde{H}_u^+ \end{pmatrix}$$

Our works

- **Higgs invisible decay：**

125GeV Higgs (h_2) decay to Dark Matter (LSP)

So, we focus on:

$$m_{\text{Higgs}} \geq 2\, m_{\text{LSP}}$$

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- **Higgs decay to light scalars:**

125GeV Higgs can be: h_1 , h_2

Light scalars can be: h_1 , a_1

3 types:
$$\begin{cases} h_2 \to a_1 a_1 \\ h_1 \to a_1 a_1 \\ h_2 \to h_1 h_1 \end{cases}$$

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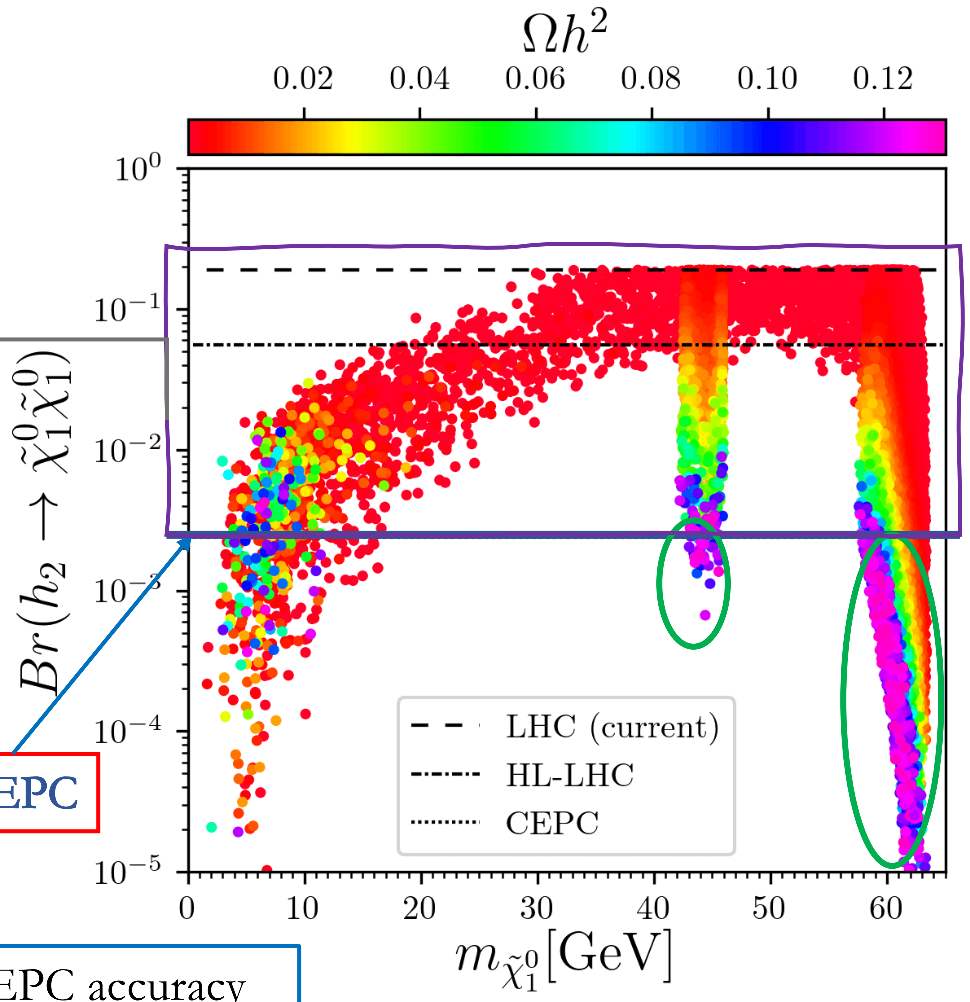
Higgs invisible decay

can be checked by CEPC



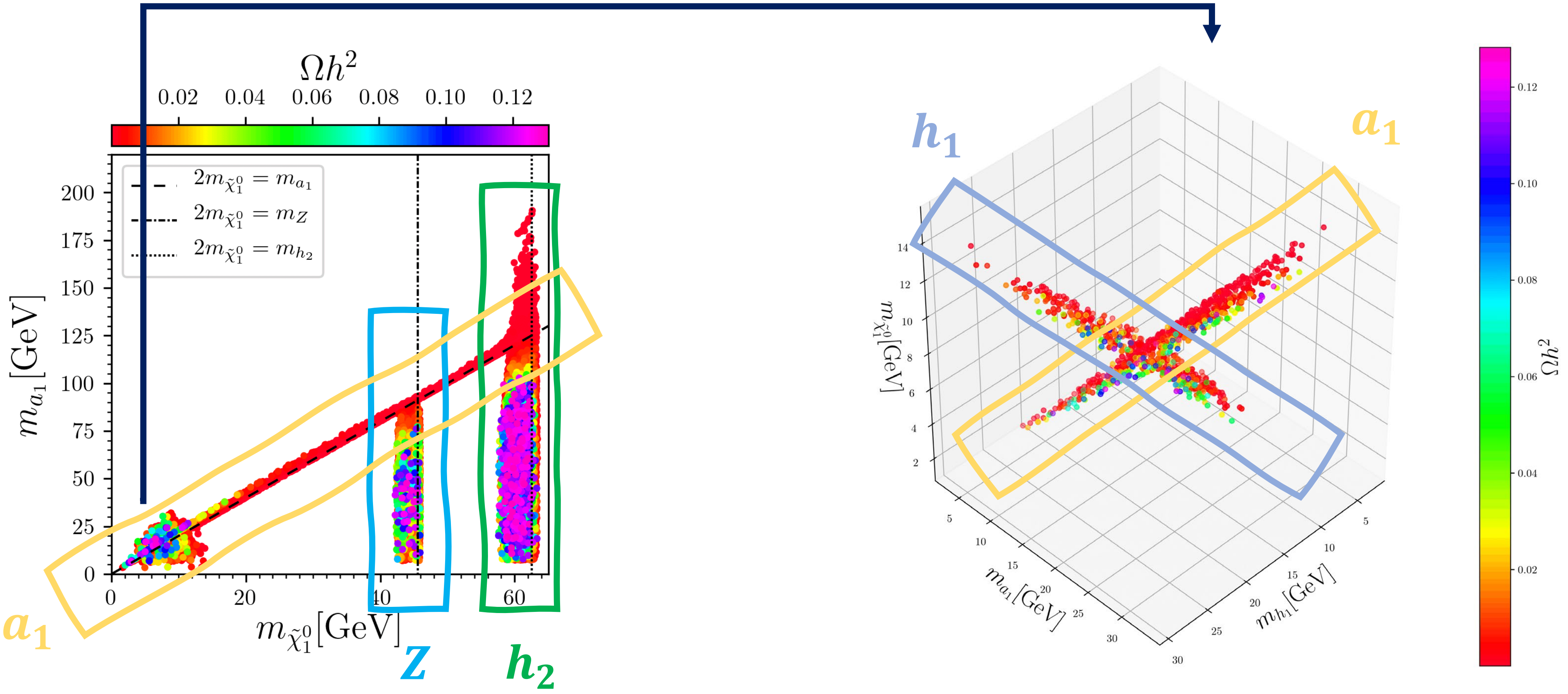
CEPC

CEPC accuracy is 0.24%

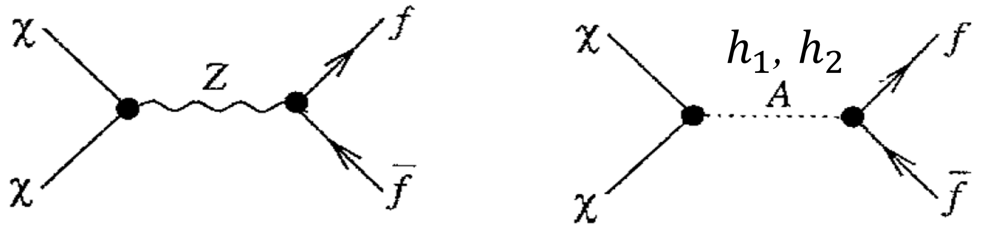
$$m_{\text{Higgs}} \geq 2\, m_{\text{LSP}}$$

- With right DM relic density, Higgs invisible decay is small, that because λ is small, Higgs couples very weak with DM.

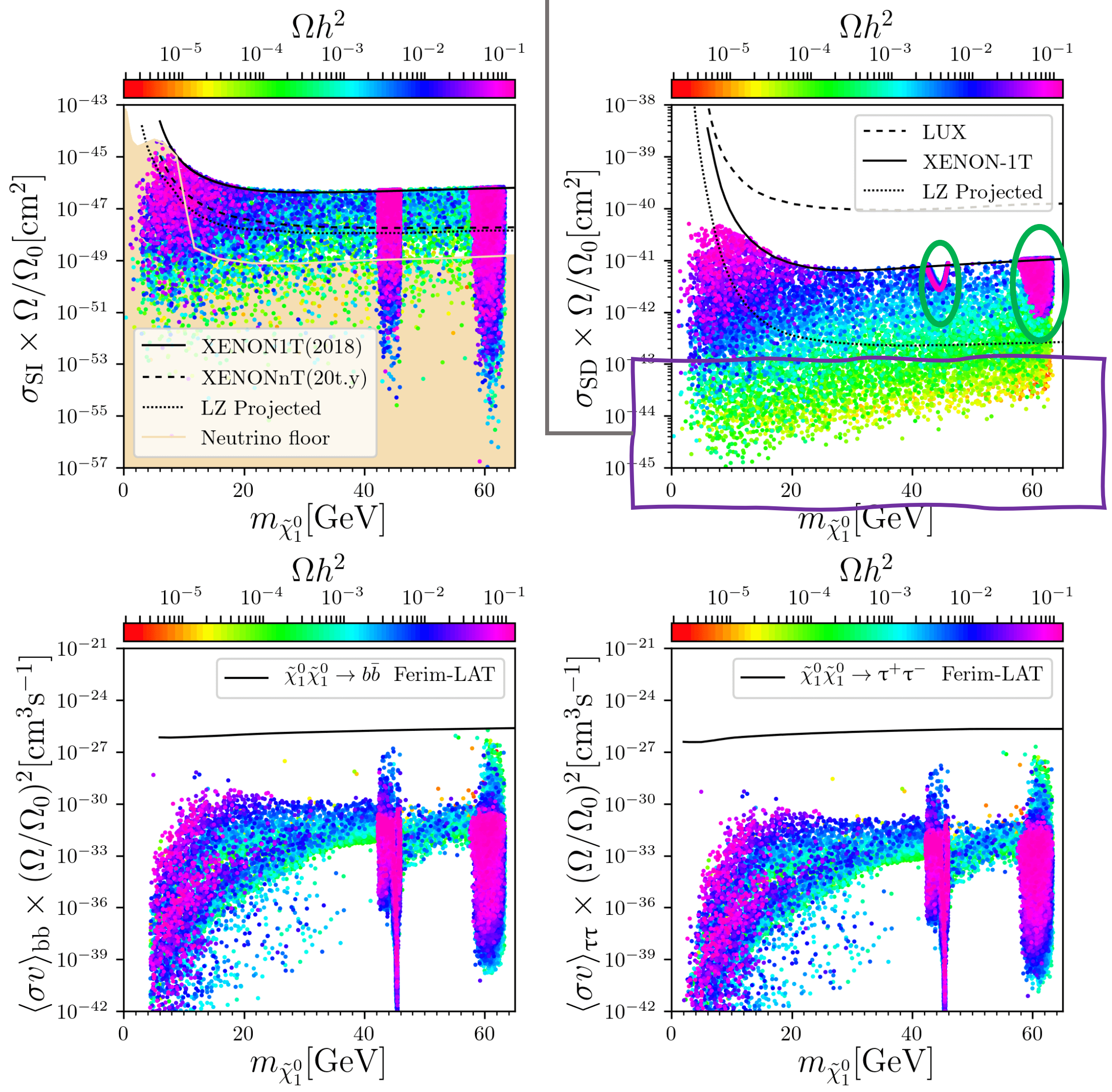
- If invisible decay was discovered at CEPC, probably DM is not mainly singlino in the scNMSSM.



4 funnel-annihilation mechanisms



can be checked by CEPC



- For LSP with right DM relic density, it can be checked by SD experiment
- For LSP without right DM relic density it can be checked by CEPC.

- For higgsino LSP, SD is large, when it have right DM relic density, it will be excluded.
- For singlino LSP, SD is small, so it can have right DM relic density.

Higgs decay to light scalars

- Three scenarios:

  - Scenario I: h_2 is the SM-like Higgs, and the light scalar a_1 is CP-odd;
  - Scenario II: h_1 is the SM-like Higgs, and the light scalar a_1 is CP-odd;
  - Scenario III: h_2 is the SM-like Higgs, and the light scalar h_1 is CP-even.

$h_2 \to a_1 a_1$

$h_1 \to a_1 a_1$

$h_2 \to h_1 h_1$

	Scenario I	Scenario II	Scenario III
$m_{\tilde{\chi}_1^0}$/GeV	$3 \sim 129$	$98 \sim 198$	$3 \sim 190$
m_{h_1}/GeV	$4 \sim 123$	$123 \sim 127$	$4 \sim 60$
m_{h_2}/GeV	$123 \sim 127$	$127 \sim 5058$	$123 \sim 127$
m_{a_1}/GeV	$4 \sim 60$	$0.5 \sim 60$	$3 \sim 697$

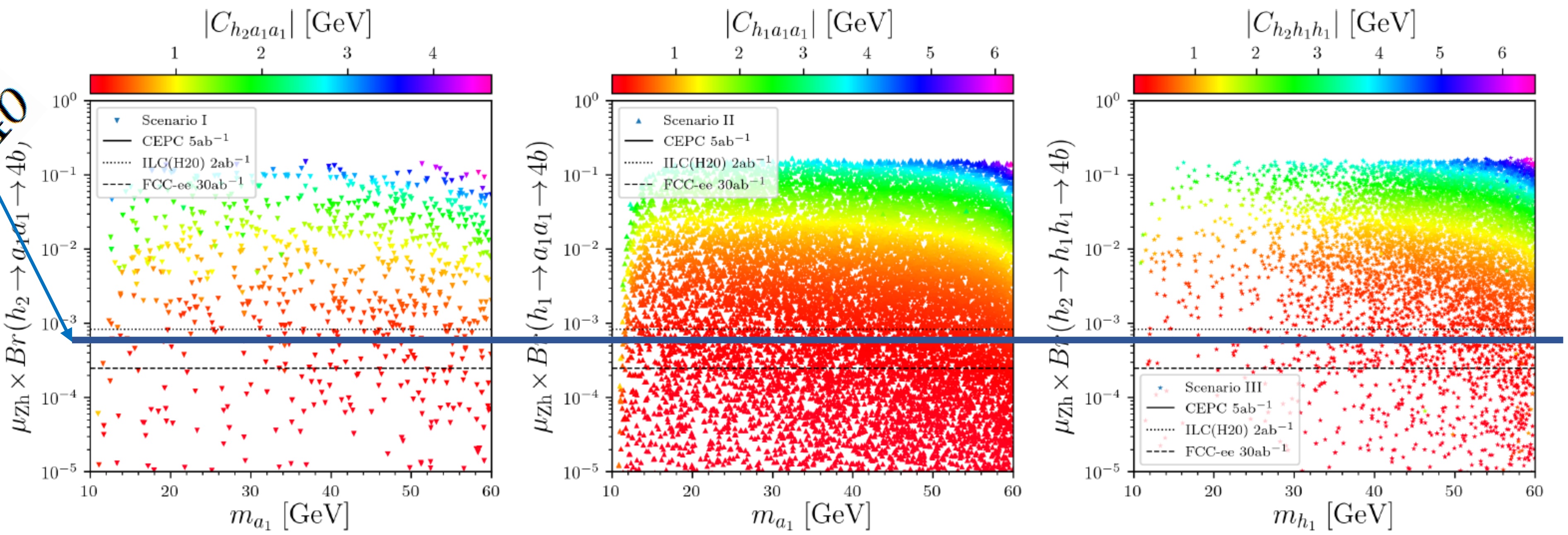
Detections at future lepton colliders

- Decay channels:

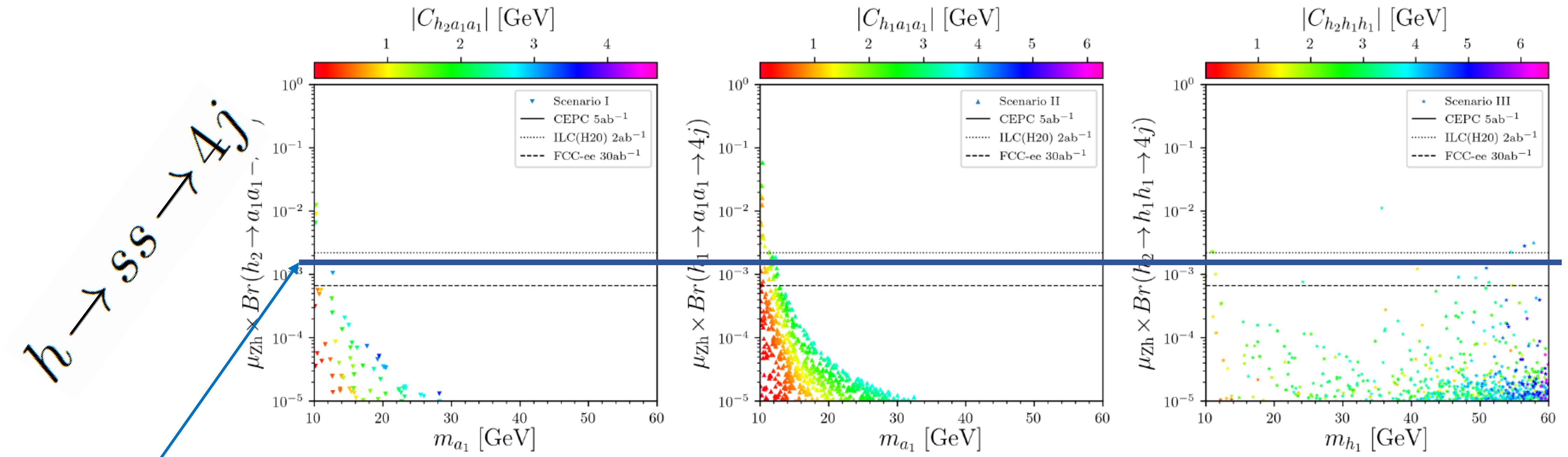
$$h_{\rm SM} \to ss \to 4b$$
$$h_{\rm SM} \to ss \to 4j$$
$$h_{\rm SM} \to ss \to 2b2\tau$$
$$h_{\rm SM} \to ss \to 4\tau$$

CEPC with $5\,\mathrm{ab}^{-1}$

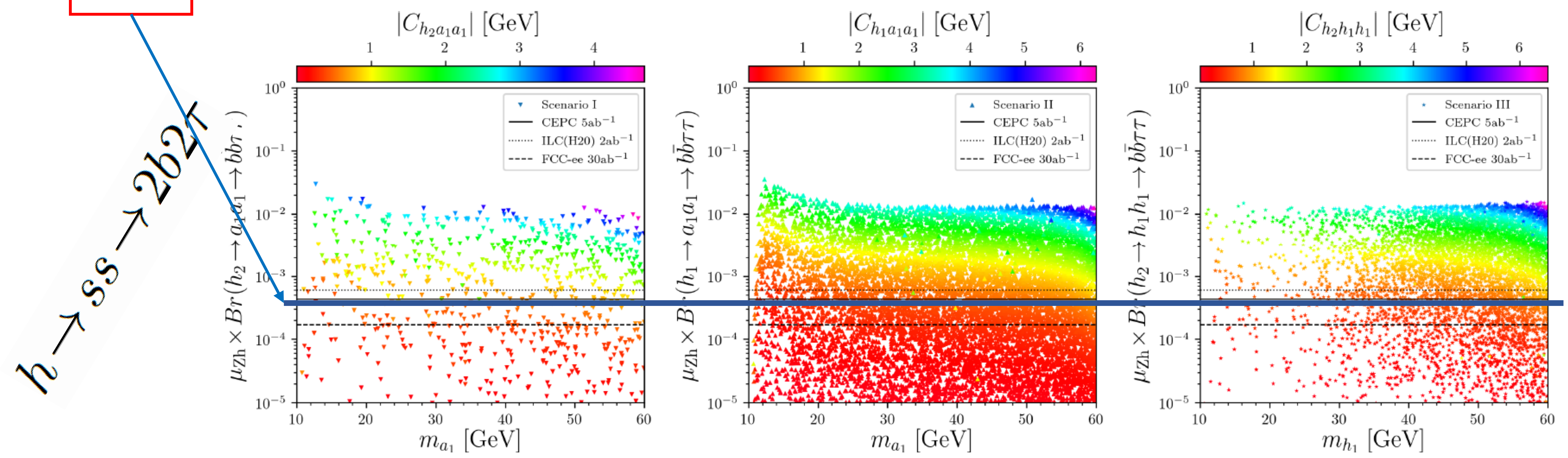
$h \to ss \to 4b$



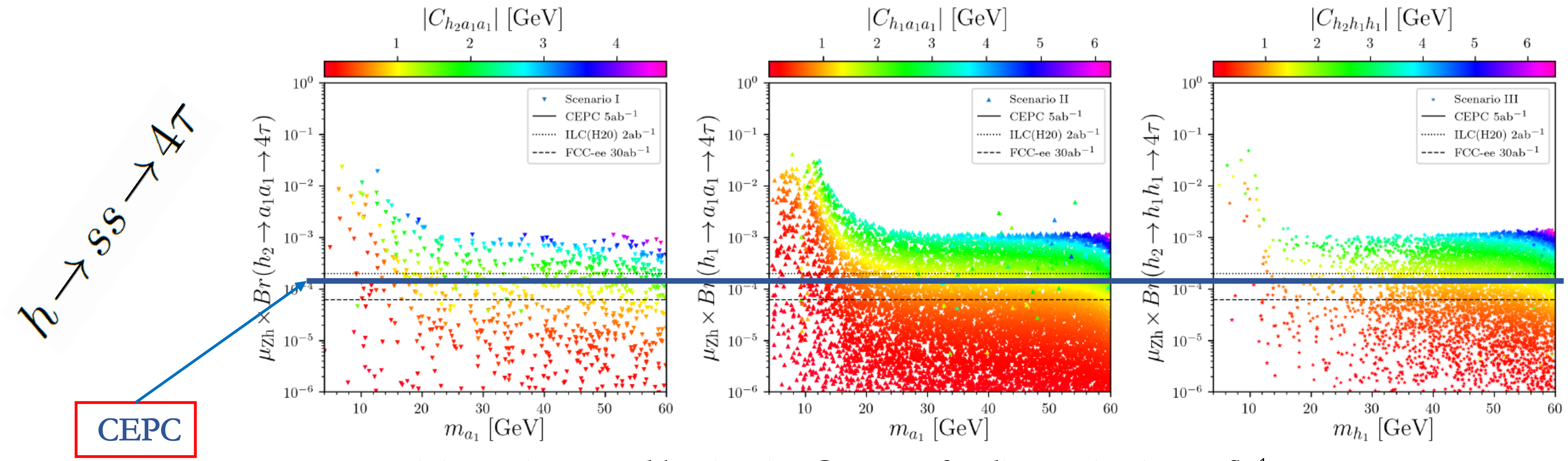
Minimum integrated luminosity @ CEPC for discovering is 0.42fb^{-1}



Minimum integrated luminosity @ CEPC for discovering is 21fb^{-1}



Minimum integrated luminosity @ CEPC for discovering is 4.6fb^{-1}



Minimum integrated luminosity @ CEPC for discovering is 0.26fb^{-1}

Deacy Mode	HL-LHC	Futrue colliders	
		CEPC	FCC-*ee*
$(b\bar{b})(b\bar{b})$	650 fb^{-1}(@II)	0.42 fb^{-1}(@III)	0.41 fb^{-1}(@III)
$(jj)(jj)$	-	21 fb^{-1}(@II)	18 fb^{-1}(@II)
$(\tau^+\tau^-)(\tau^+\tau^-)$	-	0.26 fb^{-1}(@III)	0.22 fb^{-1}(@III)
$(b\bar{b})(\tau^+\tau^-)$	1500 fb^{-1}(@II)	4.6 fb^{-1}(@II)	3.6 fb^{-1}(@II)
$(\mu^+\mu^-)(\tau^+\tau^-)$	1000 fb^{-1}(@II)	-	-

Summary

- Higgs invisible decay：
  - There are 4 funnel-annihilation mechanisms;
  - If Higgs invisible decay was discovered at CEPC, probably DM is not mainly singlino in the scNMSSM;
  - With right DM relic density, Higgs invisible decay is small, and they could be checked by SD experiment (LZ).

- Higgs decay to light scalars:
  - There are 3 scenarios about $h_{\rm SM} \to ss$
  - 95% E.L.@ CEPC is showed in $4b, 4j, 2b2\tau, 4\tau$
  - The most effective way is in 4τ channel(0.26fb-1)
  - Minimum IL for discovering @CEPC is close to FCC

Thanks!

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