Long Lived Particles

at Higgs Factories and LHeC

Kingman Cheung 10/6/2020 based on the works

1. K.C. and Zeren Simon Wang, *Probing Long-lived Particles at Higgs Factories*, *Phys.Rev.D* 101 (2020) 3, 035003
2. K.C., Oliver Fischer, Zeren Simon Wang, Jose Zurita, *Exotic Higgs decays into displaced jets at the LHeC, 2008.09614.*

Motivations

1. Higgs boson is the Master Piece to understand the underlying physics of Electroweak Symmetry Breaking.

2. Among various avenues the rare Higgs decay is a useful one to search for exotic light particles.

$$H \to \Theta^\dagger\Theta, AA, \phi\phi, \chi\chi, \ldots \text{etc}$$

3. Especially, existence of hidden sectors that the Higgs boson acts as the portal to the dark world.

Motivations

1. Null results from search for BSM at the LHC raise the question if there is a systematic shortcoming.

2. Current hardware and software triggers are mostly based on PROMPT DECAYS, such as squarks, gluinos in SUSY, top partners in composite models, etc.

3. Another class of exotic particles — Long Lived Particles (LLP) may have escaped all detections.

4. Quite a number of BSM predict existence of LLP.

5. Decay lengths are targeted at

$$O(10\,\mu m) < c\tau < 10\,m < O(km)$$

LHC FASER, MATHUSLA

6. Specific triggers will be installed in future runs at ATLAS and CMS.

Signatures of LLP's

1. LLP's so produced travel a macroscopic distance before it decays. It can be electrically neutral or charged. For neutral ones

   —> Displaced Vertex

2. The easiest decay mode is into leptons, giving rise to displaced charged leptons or lepton-jets.

3. More arduous modes are fully hadronic, including emergent jets, dark jets, semi-visible jets, depending on the fraction of invisible decays.

Models that predict LLP's

1. RPV SUSY squarks and leptons with very small RPV couplings. Split SUSY, etc.
2. Heavy neutral leptons.
3. Z portals — dark photons.
4. Higgs portal models with a small enough mixing between the Higgs boson and the hidden scalar boson. (Focus of this talk.)

LLP Search at Higgs Factories

K.C. and Zeren Simon Wang 1911.08721, PRD

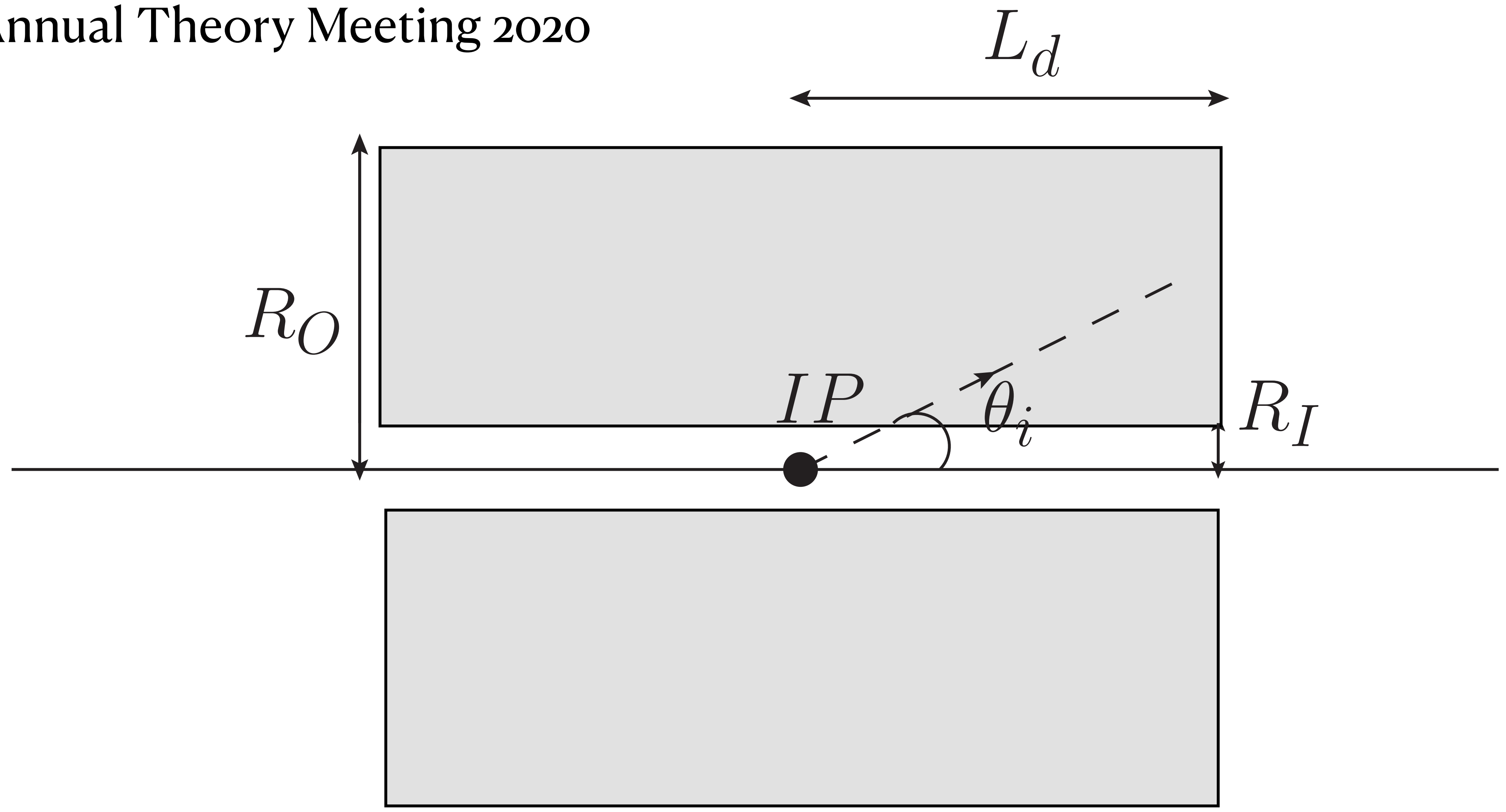
Higgs Factories

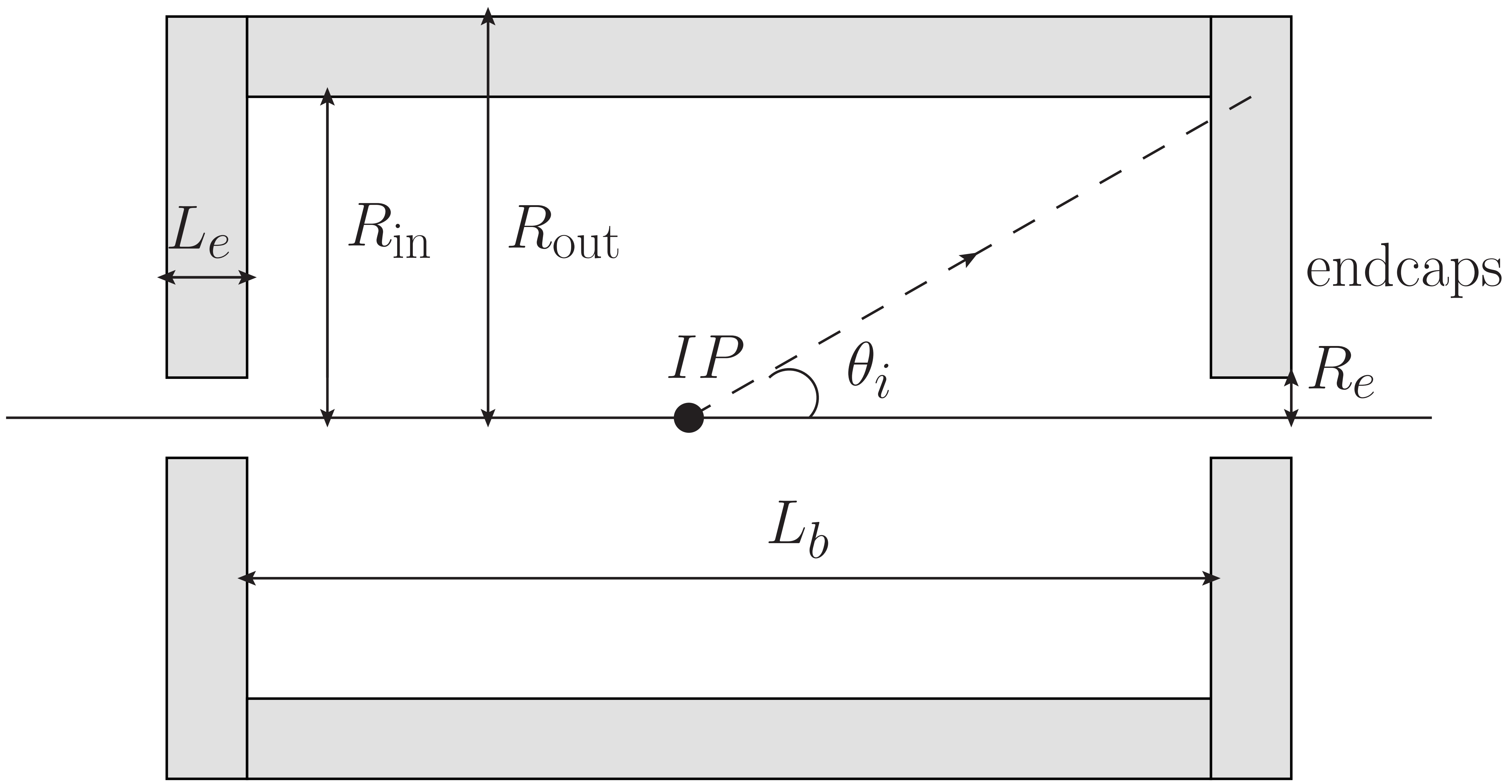
- Next generation e^+e^- colliders: CEPC, FCC-ee, ILC, etc
- They will run at $\sqrt{s} \simeq 240$ GeV (Higgs factory mode).

production $e^-e^+ \to$		Zh (main) $\nu\bar{\nu}h, e^-e^+h$ (VBF)
$\sqrt{s}$ [GeV]		240
N_h	CEPC FCC-ee	1.14×10^6

- Focus on rare Higgs decays:
  a Higgs-portal model: a light scalar h_s,
  a neutral-naturalness model: the lightest mirror glue ball

$$h \to h_s h_s, \;\; 0^{++}0^{++}$$





Detector	R_I [mm]	R_O [m]	L_d [m]	V [m^3]
CEPC	16	1.8	2.35	47.8
FCC-ee IDEA	17	2.0	2.0	50.3

Calculations Details

$$N^{\mathrm{IT}}_{\mathrm{s.e.}} = \mathcal{L}_h \cdot \sigma_h \cdot \mathrm{BR}(h \to XX) \cdot \langle P[s.e.\ \mathrm{in\ IT}] \rangle \cdot \epsilon^{\mathrm{IT}},$$

$$N^{\mathrm{HCAL}}_{\mathrm{s.e.}} = \mathcal{L}_h \cdot \sigma_h \cdot \mathrm{BR}(h \to XX) \cdot \langle P[s.e.\ \mathrm{in\ HCAL}] \rangle\,,$$

$$N^{\mathrm{MS}}_{\mathrm{s.e.}} = \mathcal{L}_h \cdot \sigma_h \cdot \mathrm{BR}(h \to XX) \cdot \langle P[s.e.\ \mathrm{in\ MS}] \rangle\ .$$

IT: Inner Tracker
HCAL: Hadronic Calorimeter
MS: Muon Spectrometer

For IT: requires at least one DV to form a signal event
For HCAL/MS: requires two DV's

$$\langle P[s.e.\ \text{in IT}] \rangle = \frac{1}{N^{\mathrm{MC}}} \sum_{i=1}^{N^{\mathrm{MC}}} \left(P[X_i^1 \text{ in IT}] + P[X_i^2 \text{ in IT}] - P[X_i^1 \text{ in IT}] \cdot P[X_i^2 \text{ in IT}] \right)$$

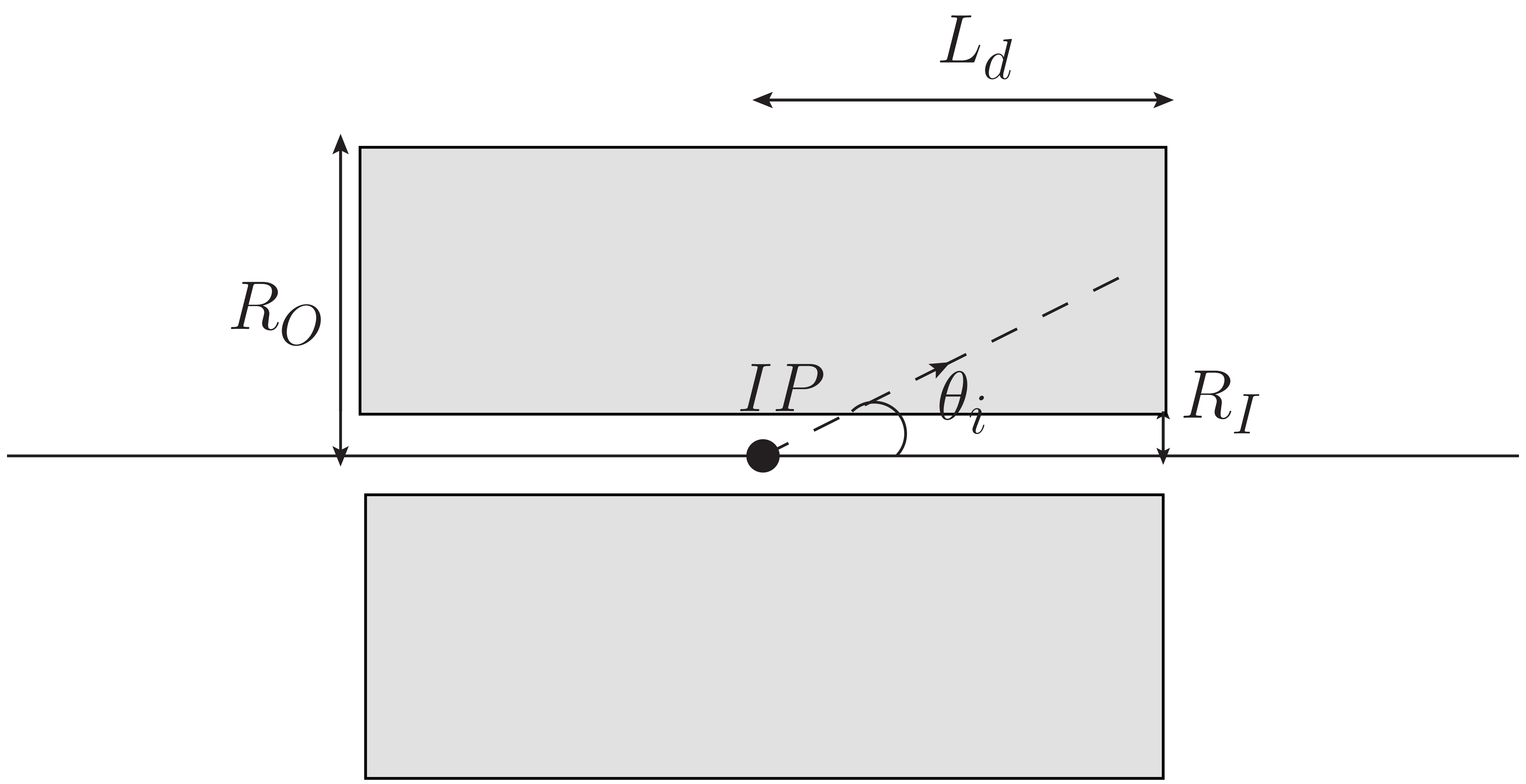
$$\langle P[s.e.\ \text{in HCAL}] \rangle = \frac{1}{N^{\mathrm{MC}}} \sum_{i=1}^{N^{\mathrm{MC}}} \left(P[X_i^1 \text{ in HCAL}] \cdot P[X_i^2 \text{ in HCAL}] \right)$$

$$\langle P[s.e.\ \text{in MS}] \rangle = \frac{1}{N^{\mathrm{MC}}} \sum_{i=1}^{N^{\mathrm{MC}}} \left(P[X_i^1 \text{ in MS}] \cdot P[X_i^2 \text{ in MS}] \right)$$

$P[X_i$ in IT/HCAL/MS$]$ is the decay probability inside the fiducial components

$$
\begin{aligned}
P[X_i \text{ in IT}] &= e^{-L_i/\lambda_i^t}\cdot\left(1-e^{-L_i'/\lambda_i^t}\right)\\
L_i &\equiv \begin{cases} R_I, & \text{if } |L_d \tan\theta_i| \le R_I \\ d_{\rm res} = 5\ \mu m, & \text{else}\end{cases}\\
L_i' &\equiv \min(\max(R_I, |L_d \tan\theta_i|), R_O) - L_i\\
\lambda_i^t &= \beta_i^t\, \gamma_i\, \tau_X
\end{aligned}
$$

Not decay before reaching IT, decay within IT



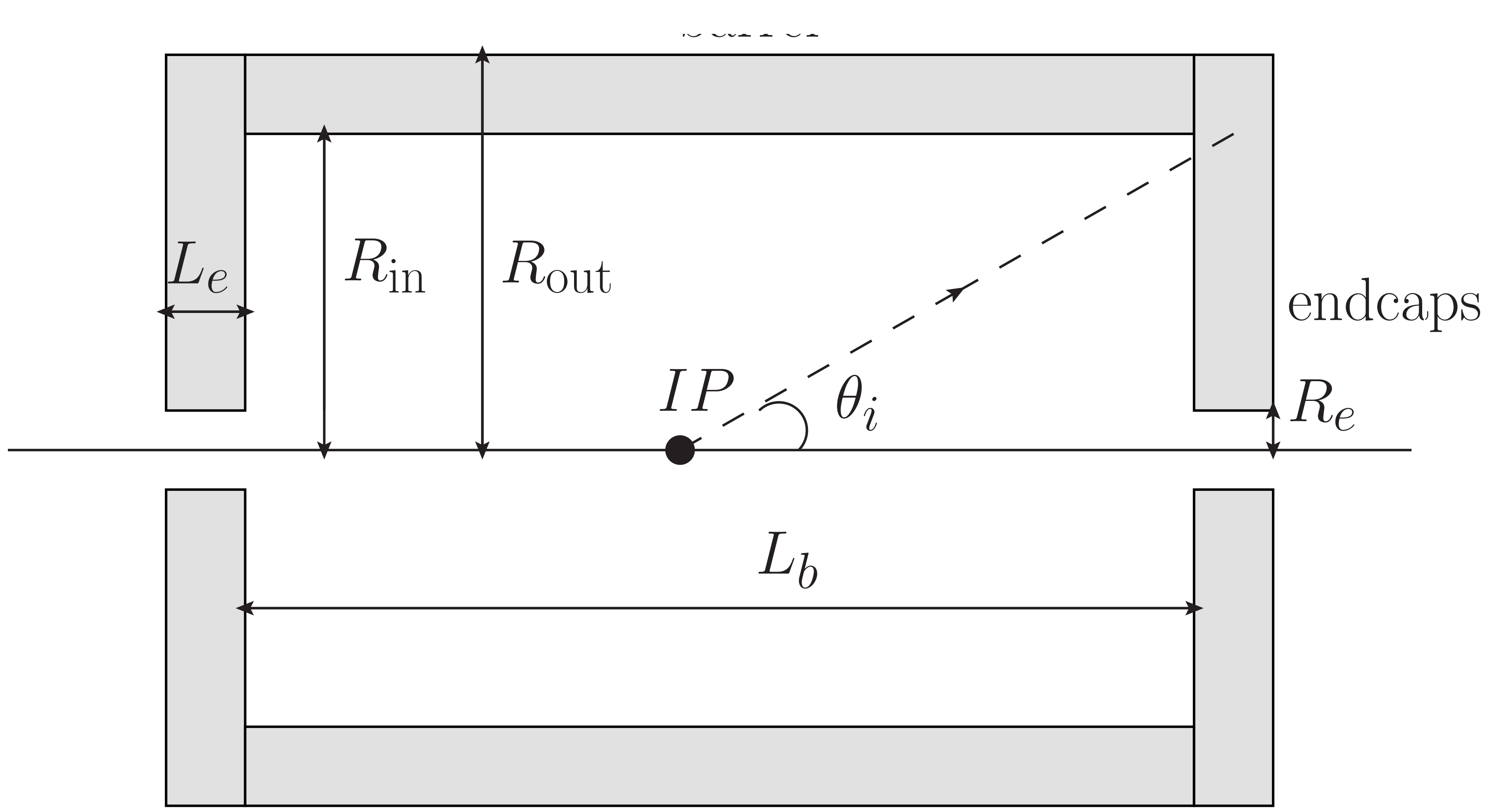
Detector	R_I [mm]	R_O [m]	L_d [m]	V [m^3]
CEPC	16	1.8	2.35	47.8
FCC-ee IDEA	17	2.0	2.0	50.3

$$P[X_i \text{ in HCAL/MS}] = e^{-R_e/\lambda_i^z} \cdot (1 - e^{-L_i^\alpha/\lambda_i^t}) - e^{-R_e/\lambda_i^z} \cdot (1 - e^{-L_i^\beta/\lambda_i^t}),$$

$$L_i^\alpha \equiv \min(\max(R_e, |(\frac{L_b}{2} + L_e)\ \tan\theta_i|), R_{\text{out}}) - R_e,$$

$$L_i^\beta \equiv \min(\max(R_e, |\frac{L_b}{2}\ \tan\theta_i|), R_{\text{in}}) - R_e,$$

Not decay before HCAL/MS,
decay within HCAL/MS



Detector	L_b [m]	L_e [m]	R_e [m]	R_{in} [m]	R_{out} [m]	V [m^3]
CEPC	5.3	1.493	0.50	2.058	3.38	224.5
FCC-ee IDEA	6	2.5	0.35	2.5	4.5	580.1
CEPC	8.28	1.72	0.50	4.40	6.08	854.8
FCC-ee IDEA	11	1	0.35	4.5	5.5	534.9

A Higgs Portal Model

Add a real singlet field to the SM

$$\mathcal{L} = \frac{1}{2}\partial_\mu X \partial^\mu X + \frac{1}{2}\mu_X^2 X^2 - \frac{1}{4}\lambda_X X^4 - \frac{1}{2}\lambda_{\Phi X}(\Phi^\dagger \Phi) X^2 + \mathcal{L}_{\mathcal{SM}} \ ,$$

$$\Phi(x) = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ \langle\phi\rangle + \phi(x) \end{pmatrix}$$

$$X(x) = \langle\chi\rangle + \chi(x)$$

$$\langle\phi\rangle^2 = \frac{4\lambda_X \mu^2 - 2\lambda_{\Phi X}\mu_X^2}{4\lambda\lambda_X - \lambda_{\Phi X}^2} \ ,$$

$$\langle\chi\rangle^2 = \frac{4\lambda \mu_X^2 - 2\lambda_{\Phi X}\mu^2}{4\lambda\lambda_X - \lambda_{\Phi X}^2}$$

$$m_h^2 \simeq 2\lambda\langle\phi\rangle^2 = (125.10 \text{ GeV})^2$$

$$m_{h_s}^2 \simeq 2\lambda_X\langle\chi\rangle^2$$

$$\begin{pmatrix} h \\ h_s \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}\begin{pmatrix} \phi \\ \chi \end{pmatrix}$$

$$\mathcal{L}_{hh_sh_s} = -\frac{1}{2}\lambda_{\Phi X}\langle\phi\rangle h h_s h_s$$

$$\theta \simeq \frac{\lambda_{\Phi X}\langle\phi\rangle\langle\chi\rangle}{m_h^2 - m_{h_s}^2} \ ,$$

- The mixing connects the dark sector with the SM
- 3 parameters: m_{h_s}, $\sin^2\theta$, $\langle X\rangle$
- Consider sub-GeV h_s, such that the decay products are collimated.
- Production of h_s

$$\Gamma(h \to h_s h_s) \simeq \frac{\sin^2\theta \left(m_h^2 - m_{h_s}^2\right)^2}{32\pi m_h \langle\chi\rangle^2}$$

- Decay of h_s for 0.3 GeV − 1 GeV.

$$h_s \to \mu^+\mu^-,\ \pi\pi,\ 4\pi$$

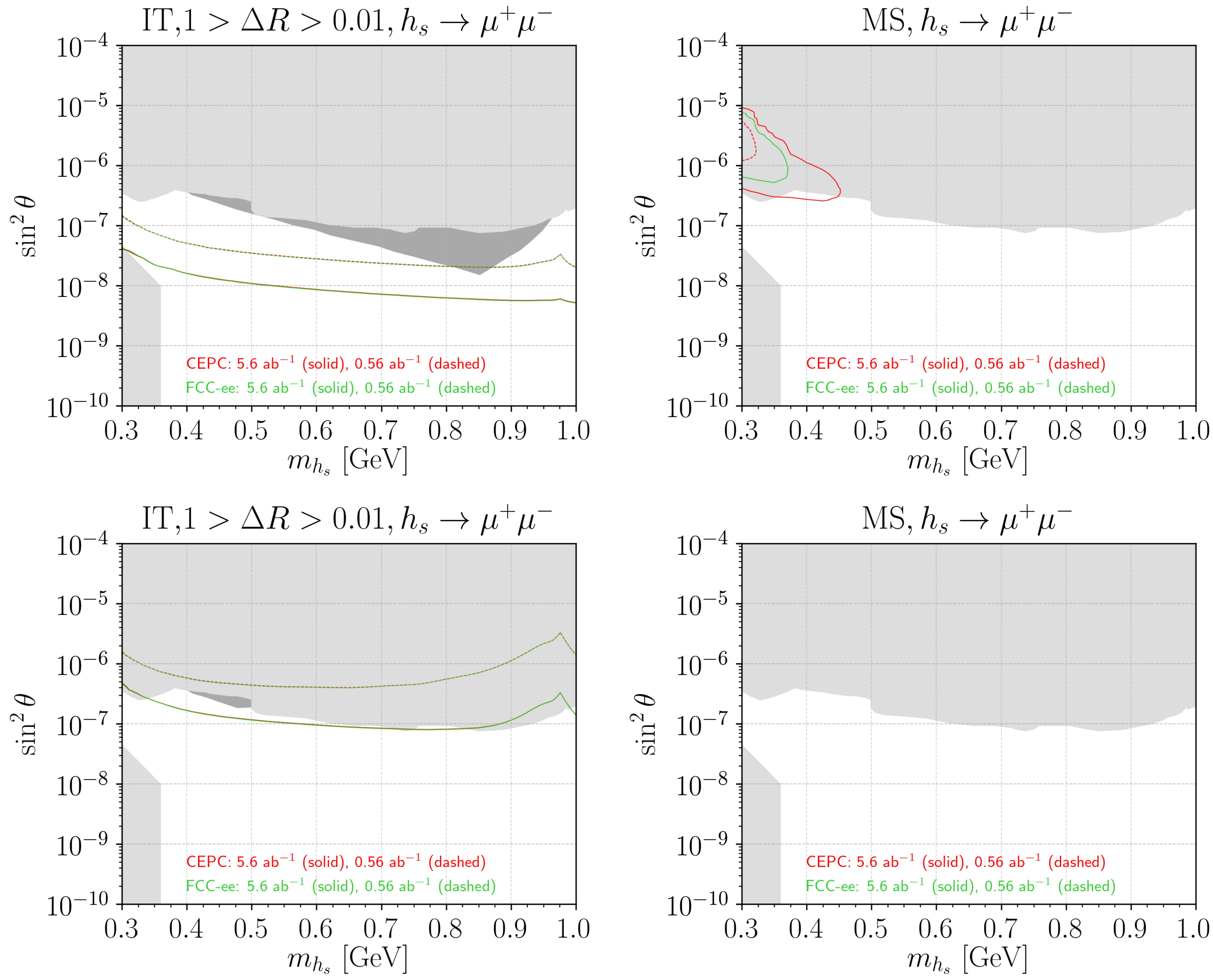
$$\Gamma(h_s \to \ell^+\ell^-) = \sin^2\theta \frac{m_\ell^2 m_{h_s}}{8\pi\langle\phi\rangle^2}\left(1 - \frac{4m_\ell^2}{m_{h_s}^2}\right)^{3/2} .$$

m_{h_s} (GeV)	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
$\mathrm{Br}(\mu^+\mu^-)$	20.6%	13.0%	10.3%	8.6%	7.1%	5.1%	2.5%	2.0%
$\mathrm{Br}(\pi\pi)$	79.4%	87.0%	89.7%	91.3%	91.2%	93.0%	96.3%	96.8%
$\mathrm{Br}(4\pi)$	0%	0%	0%	0.1%	1.7%	1.9%	1.2%	1.2%

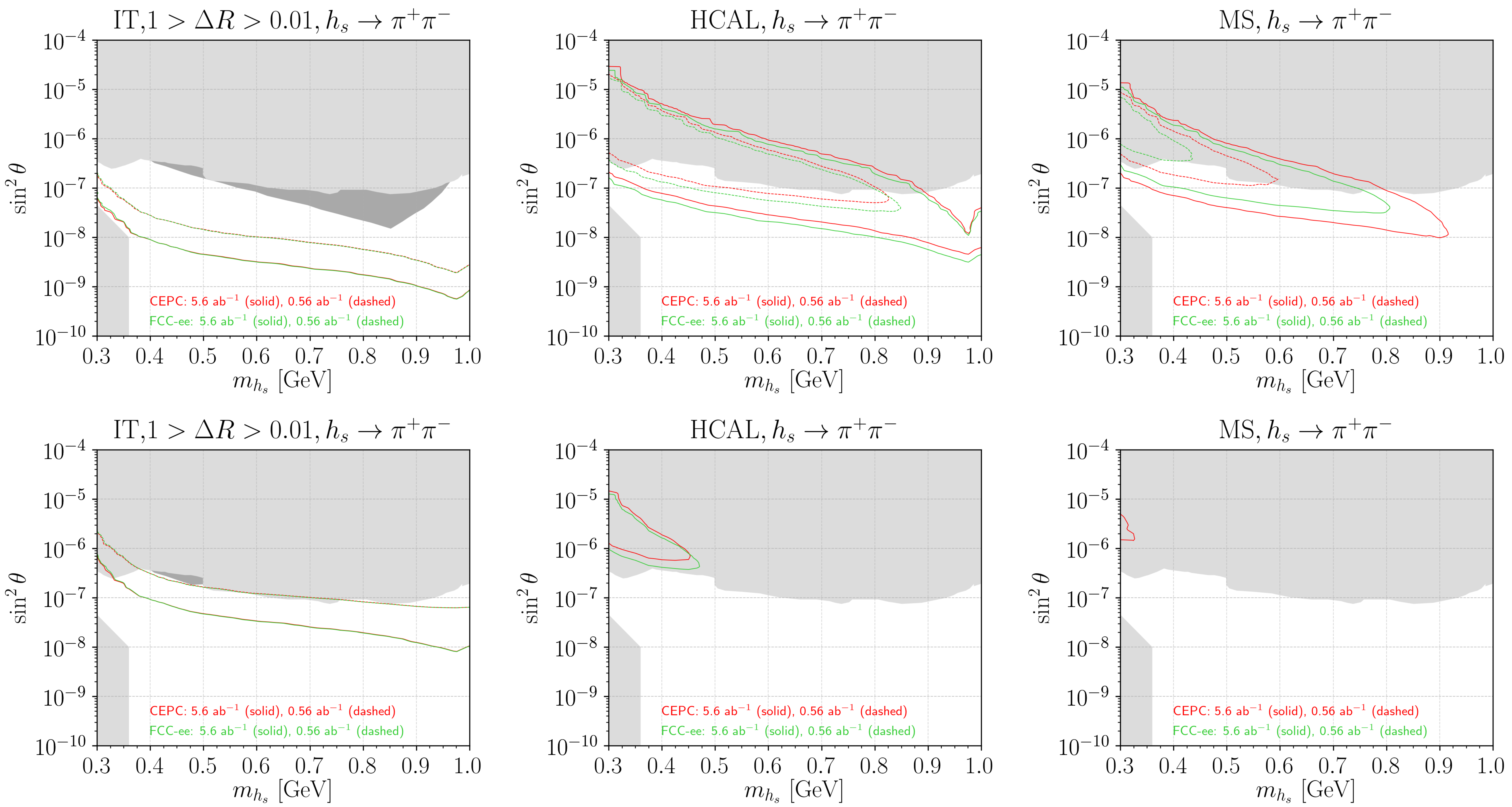
muon channel

$\langle\chi\rangle = 10$ GeV

$\langle\chi\rangle = 100$ GeV



ππ channel



IT,1 > ΔR > 0.01, $h_s \to \pi^+\pi^-$
HCAL, $h_s \to \pi^+\pi^-$
MS, $h_s \to \pi^+\pi^-$
$\sin^2\theta$
m_{h_s} [GeV]
CEPC: 5.6 ab^{-1} (solid), 0.56 ab^{-1} (dashed)
FCC-ee: 5.6 ab^{-1} (solid), 0.56 ab^{-1} (dashed)

Neutral Naturalness Models

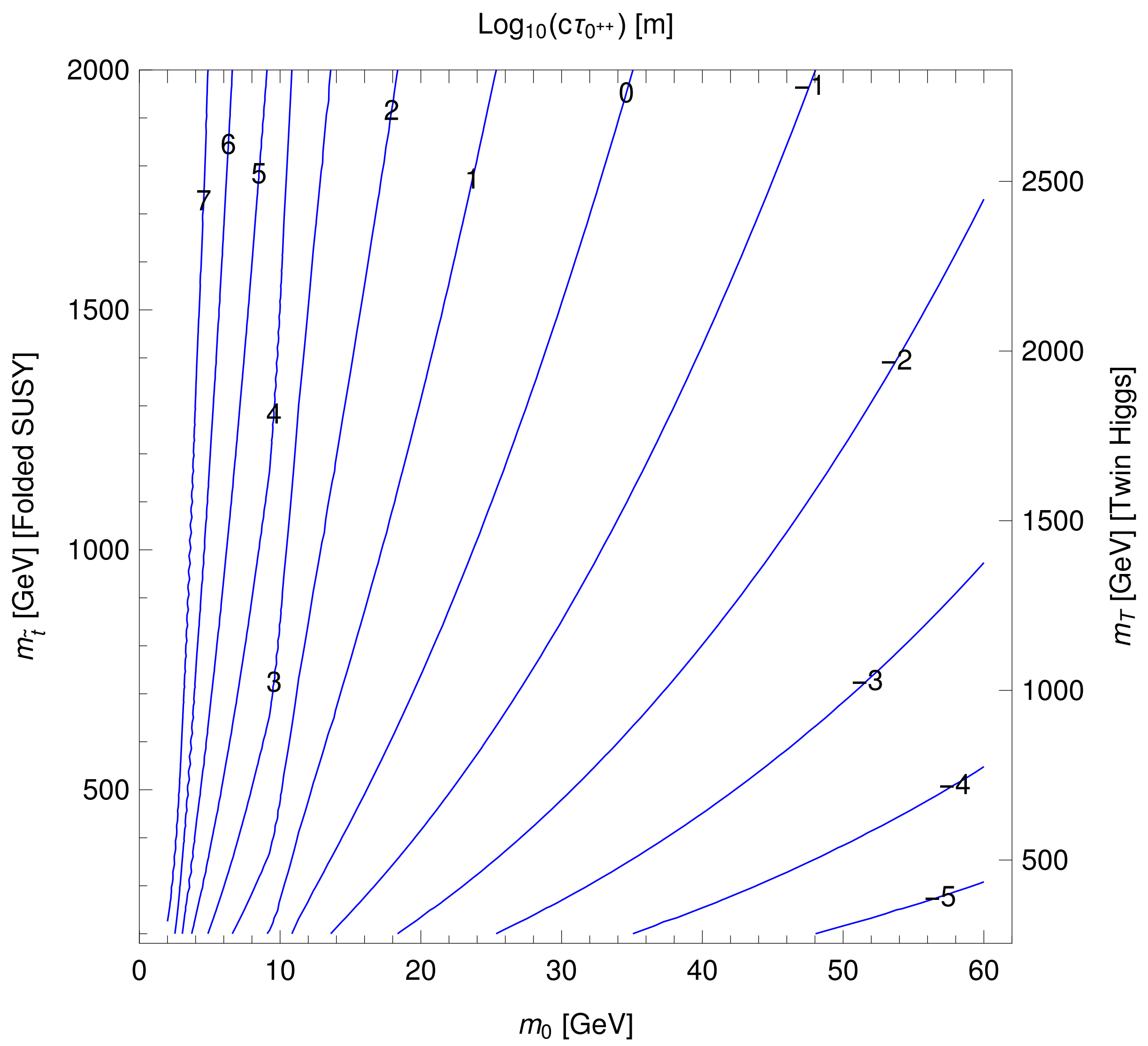
- Proposed to solve the gauge hierarchy problem.
- Predict uncolored top partners to protect the Higgs boson mass up to 5 – 10 TeV.
- The top partner is either a SM singlet or only charged in the EW sector, thus can avoid most existing constraints.
- The top partner is charged under a mirror QCD sector $SU(3)_B$
- Examples are folded SUSY, (fraternal) twin Higgs, quirky little Higgs, hyperbolic Higgs, …
- In the folded SUSY, squarks are charged under $SU(3)_B$, but not $SU(3)_C$. $SU(2)_L \times U(1)_Y$ is shared between the SM particles and superpartners.
- In the mirror sector mirror glueballs are supposed to be the lightest states

Mirror Glueball Decays

Partial decay width into a pair of SM particles:

$$\Gamma(0^{++} \to \xi\xi) = \left(\frac{1}{12\pi^2} \left[\frac{y^2}{M^2} \right] \frac{v}{m_h^2 - m_0^2} \right)^2 (4\pi\alpha_s^B \mathbf{F}^{\mathbf{S}}_{\mathbf{0}^{++}})^2 \Gamma^{SM}_{h\to\xi\xi}(m_0^2),$$

- $4\pi\alpha_s^B \mathbf{F}^{\mathbf{S}}_{\mathbf{0}^{++}} \approx 2.3\, m_0^3$
- $\Gamma^{SM}_{h\to\xi\xi}(m_0^2)$ calculated with HDECAY 6.52



$$\frac{y^2}{M^2} \approx \begin{cases} \frac{1}{4v^2} \frac{m_t^2}{m_{\tilde{t}}^2}, & \text{Folded SUSY} \\ -\frac{1}{2v^2} \frac{m_t^2}{m_T^2}, & \text{Fraternal Twin Higgs and Quirky Little Higgs} \\ \frac{1}{2v^2} \frac{v}{v_H} \sin\theta, & \text{Hyperbolic Higgs} \end{cases}$$

- Two parameters: m_0 and $m_{\tilde{t}}$ for folded SUSY

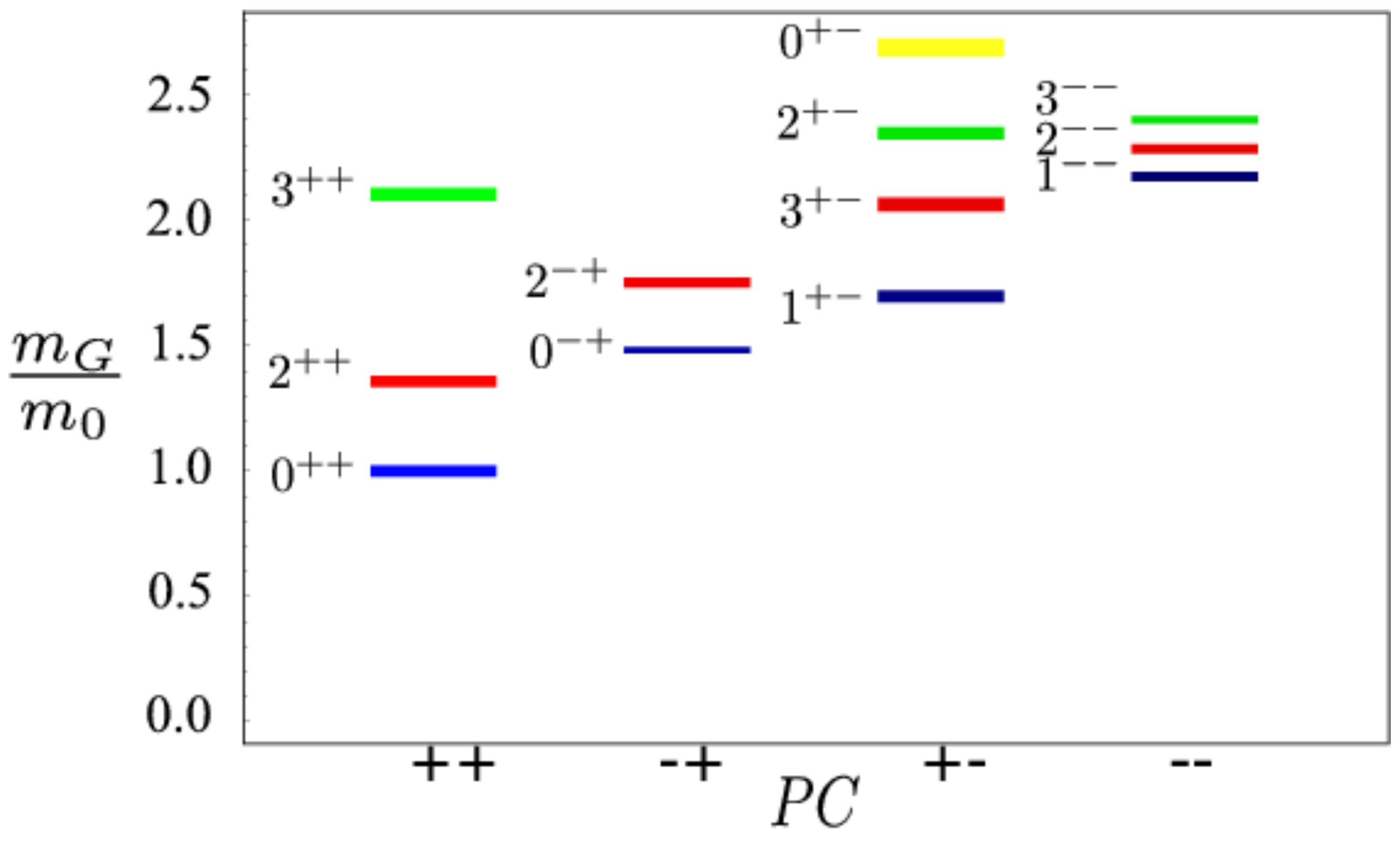
●Mirror Glueball Production

$$\mathrm{Br}(h \to 0^{++}0^{++}) \approx \mathrm{Br}(h \to gg)_{\mathrm{SM}} \cdot \left(\frac{\alpha_s^B(m_h)}{\alpha_s^A(m_h)}\, 2\, v^2 \left[\frac{y^2}{M^2}\right]\right)^2 \cdot \sqrt{1 - \frac{4m_0^2}{M_h^2}} \cdot \kappa(m_0),$$

- $\mathrm{Br}(h \to gg)_{\mathrm{SM}} \approx 8.6\,\%$
- $\alpha_s^B(m_h)/\alpha_s^A(m_h) \sim \mathcal{O}(1)$: ratio of the couplings of the hidden and SM QCD sectors
- $\kappa(m_0)$: the effect of the glueball hadronization mainly
- $\kappa_{\max} = 1$

$$\kappa_{\min}(m_0) = \frac{\sqrt{1 - \frac{4m_0^2}{m_h^2}}}{\sum_i \sqrt{1 - \frac{4m_i^2}{m_h^2}}}$$

[Juknevich,'09]

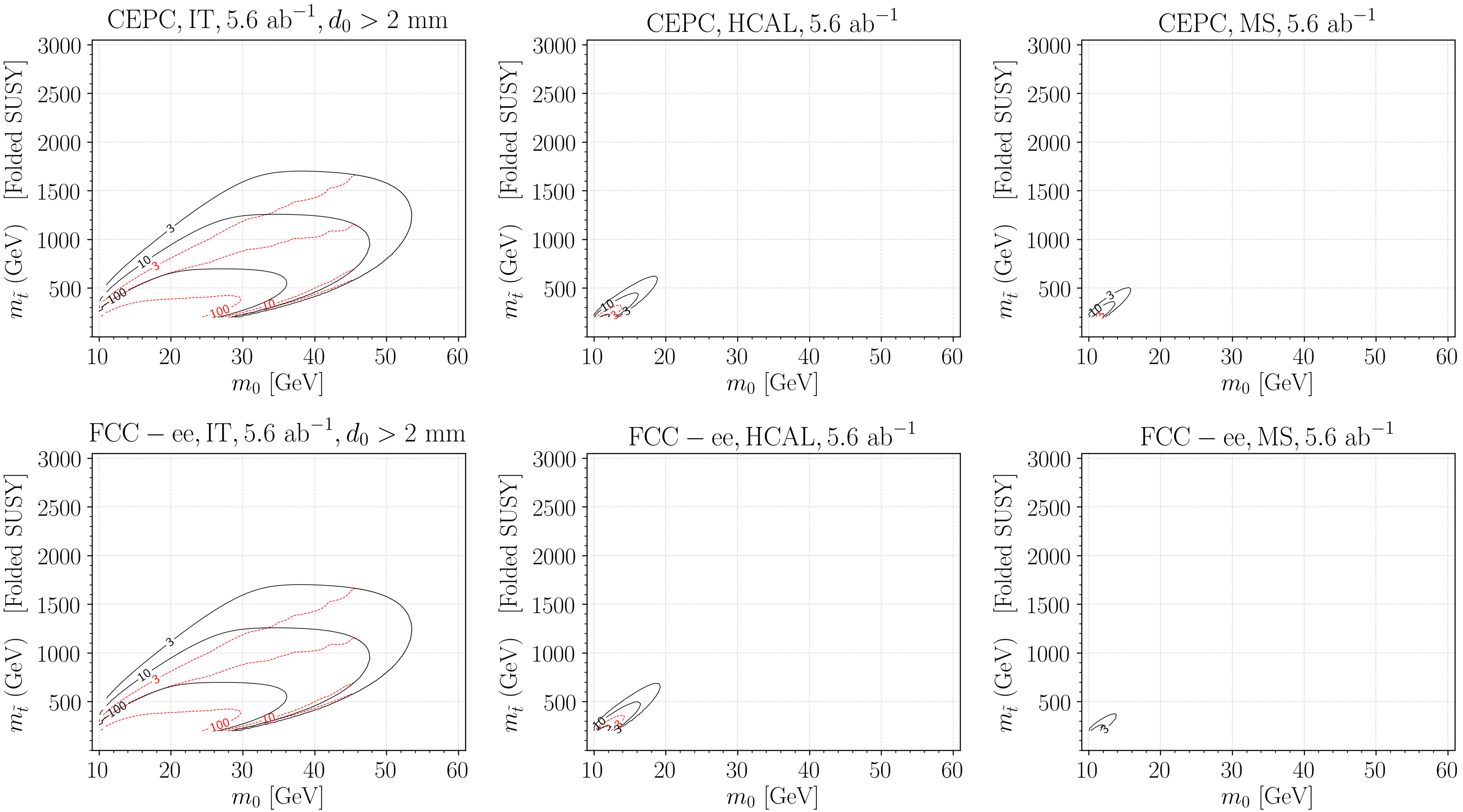


- Focus on

  $O^{++} \to b\bar{b}, \quad \text{with} \;\; M_{O^{++}} = 10 - 60 \text{ GeV}$

- Consider IT, HCAL, MS
- Require d_0 > 2 mm for both b-jets stemming from any secondary vertex
- Assume little backgrounds in HCAL and MC

$N_{\text{signal}} = 3, 10, 100$ events

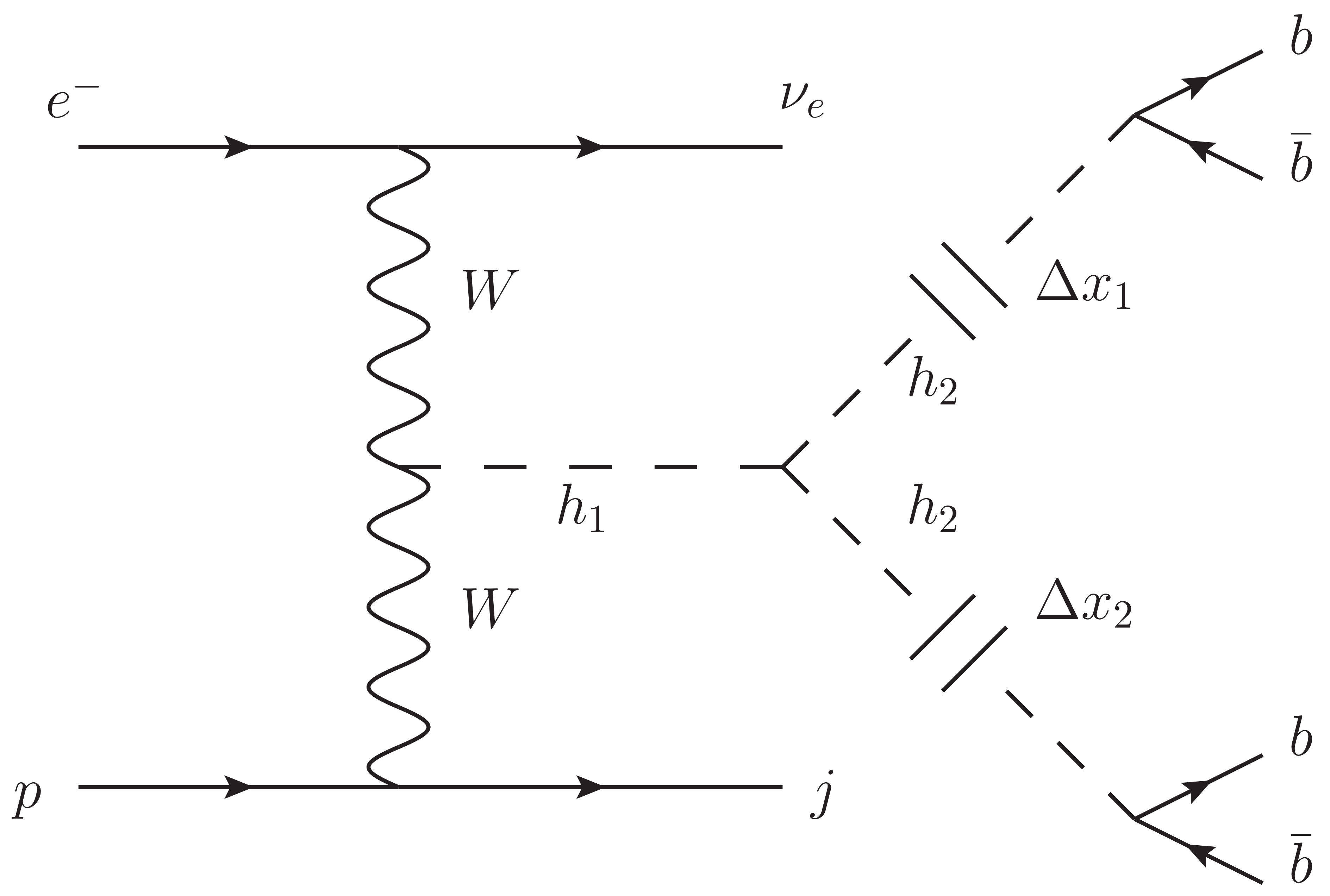


Exotic Higgs Decays into Displaced jets at LHeC

Reconstructed level study

K.C., Oliver Fischer, Zeren Simon Wang, Jose Zurita, 2008.09614

At ep Collisions, the dominant Higgs production



e- (60 GeV) onto proton (7 TeV)
Expect 1 ab^{-1}
1.1×10^5 Higgs bosons

Use the Higgs portal model with a complex singlet scalar

$$V(H,S) = -\mu_1^2 H^\dagger H - \mu_2^2\, S^\dagger S + \lambda_1 (H^\dagger H)^2 + \lambda_2 (S^\dagger S)^2 + \lambda_3 (H^\dagger H)(S^\dagger S)\,.$$

Production

$$\Gamma(h_1 \to h_2 h_2) \simeq \frac{1}{32\pi m_{h_1}}(\lambda_3 v)^2 \left(1 - \frac{4m_{h_2}^2}{m_{h_1}^2}\right)^{1/2} \simeq \frac{\sin^2\alpha(m_{h_1}^2 - m_{h_2}^2)^2}{32\pi m_{h_1} x^2}\left(1 - \frac{4m_{h_2}^2}{m_{h_1}^2}\right)^{1/2}.$$

Decay

$$\Gamma(h_2 \to f\bar{f}) = \frac{N_C (Y_f \sin\alpha)^2}{8\pi} m_{h_2} \left(1 - \frac{4m_f^2}{m_{h_2}^2}\right)^{3/2}$$

Decay length

$$c\tau = \frac{c}{\Gamma_{\text{tot}}} \approx 1.2 \times 10^{-5} \left(\frac{10^{-7}}{\sin^2\alpha}\right)\left(\frac{10\ \text{GeV}}{m_{h_2}}\right) \ \text{m}$$

Mass range

$$M_{h_2} = 10 - 60\,\text{GeV}, \qquad h_2 \to b\bar{b}$$

Signature

$$p\,e^- \to \nu_e\, j\, h_1 \to \nu_e\, j\, h_2\, h_2 \to \nu_e\, j\, (b\bar{b})_{\text{displaced}}\, (b\bar{b})_{\text{displaced}}.$$

Calculation details

Event generation

Use MadGraph with Pythia 6.4.28 patched for ep collisions with

$$10\,\mathrm{GeV} < m_{h_2} < m_{h_1}/2, \qquad 10^{-12}\,\mathrm{m} < c\tau < 100\,\mathrm{m}$$

$$p_T^{b,j} > 5\,\mathrm{GeV},\ |\eta^{b/j}| < 5.5,\ \Delta R(b, b/j) > 0.2$$

Detection Simulation

Customized Delphes 3.3.2 with modules that allow the definition of displaced jets. Specifically, the transverse displacement of a jet $d_T(j) = \sqrt{d_x^2(j) + d_y^2(j)}$ is defined to be the minimum dT of all the tracks associated to the jet. And $\Delta R(\mathrm{track}, j) < 0.4$, $p_T(\mathrm{track}) > 1$ GeV

Background processes

$$p + e^- \to \nu_e + j + n_b\, b + n_\tau\, \tau + n_j\, j,$$

$$N = n_b + n_\tau + n_j \leq 4$$

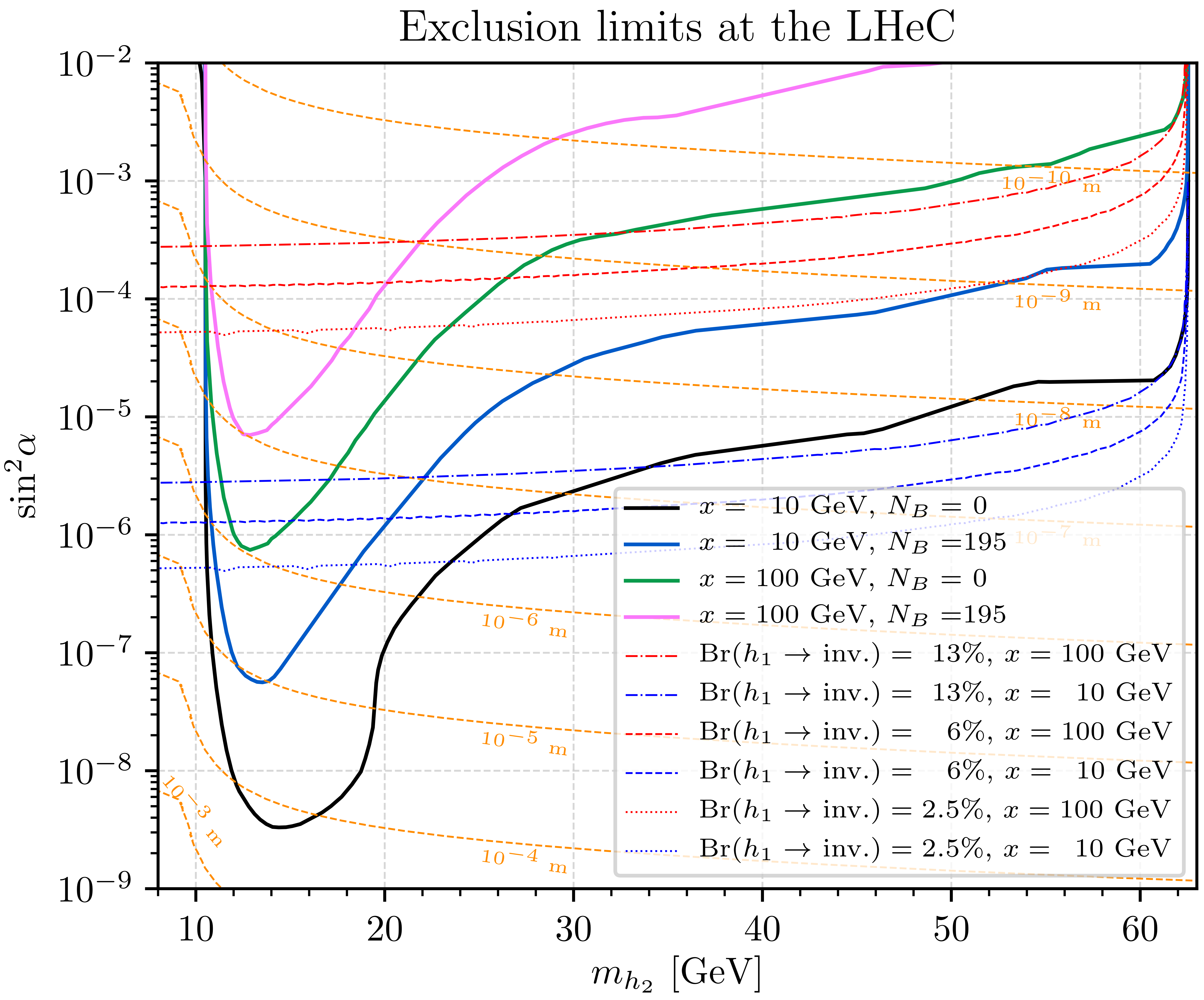
In principle, the prompt jet backgrounds (n_j>0) give no displaced objects. But a huge x-section multiplied to tiny efficiencies still generates a handful of events.

Event Selection

- Number of reconstructed jets $n_J \geq 5$
- A jet as displaced if $d_T(j) > 50\,\mu m$. Number of Displaced jets $n_{\text{disp},J} > 0$
- The displaced jets are grouped together into a so-called "heavy group" if their transverse displacements is < 50 μm. $n_{hG} \geq 1,\, m_{hG} > 6\,\text{GeV}$
- Invariant mass of all heavy groups $m_{SS} \in [100{,}150]\,\text{GeV}$

$$N_S = N_{h_1} \cdot \text{Br}(h_1 \to h_2 h_2) \cdot \left(\text{Br}(h_2 \to b\bar{b})\right)^2 \cdot \epsilon^{\text{pr-cut-XS}} \cdot \epsilon_S^{\text{cut}},$$

$$N_B = \sum_{i=1}^{12} \mathcal{L}_{\text{LHeC}} \cdot \sigma_{B_i} \cdot \epsilon_{B_i}^{\text{cut}}, \qquad N_B = 195$$



Higgs Portal Model Result

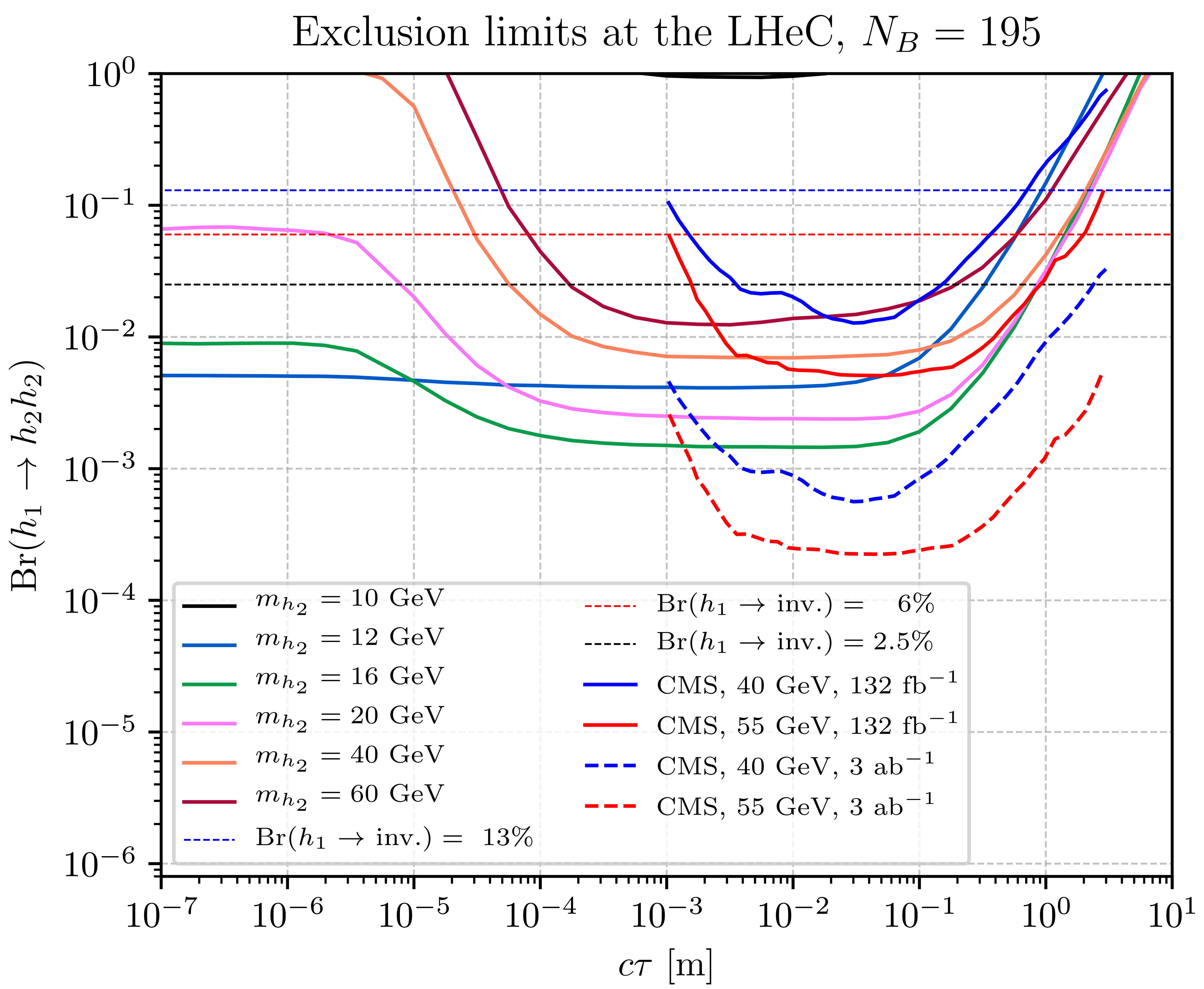
α = mixing angle

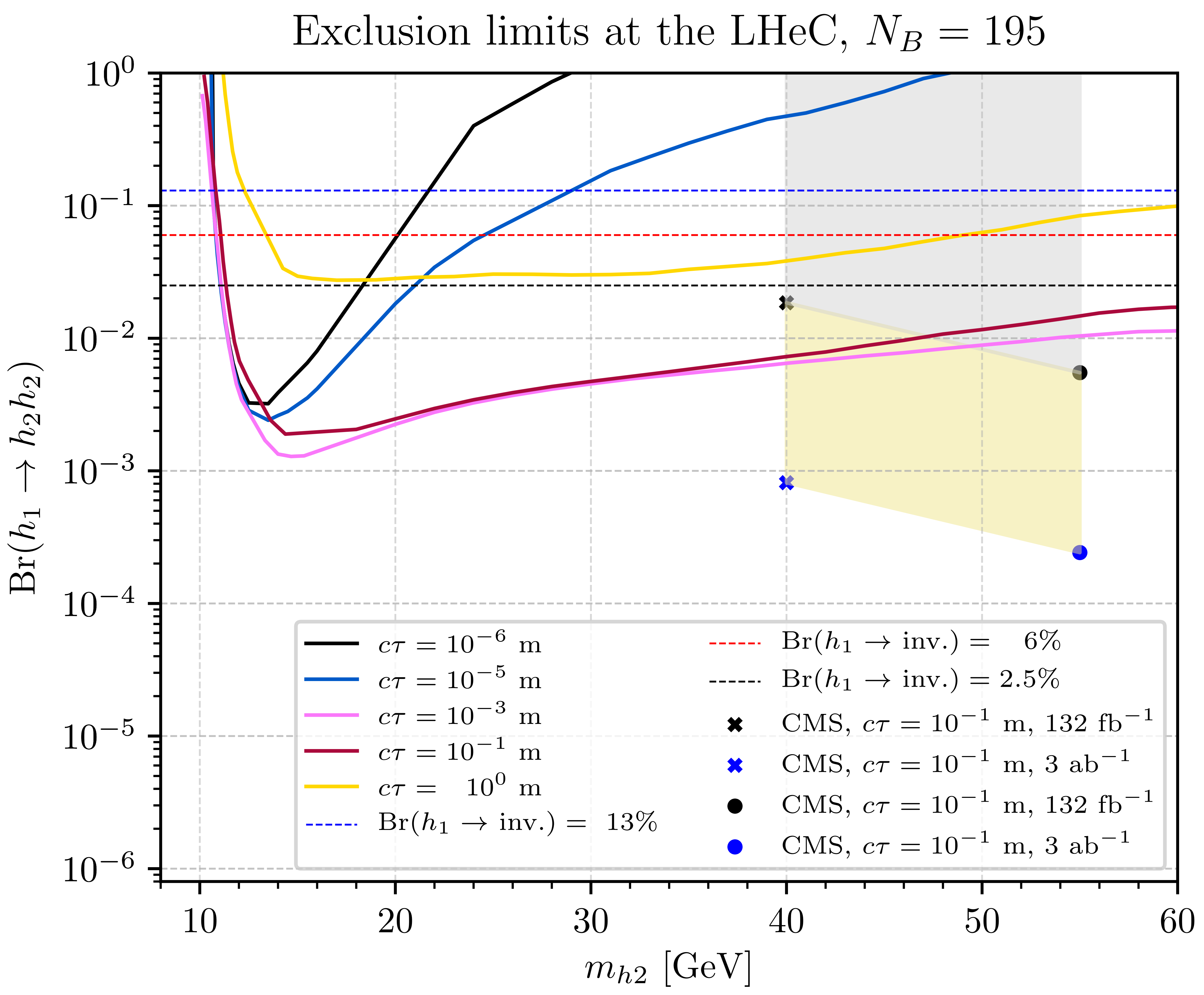
x = VEV

$N_B = 195, N_S = 2\sqrt{B} = 28$

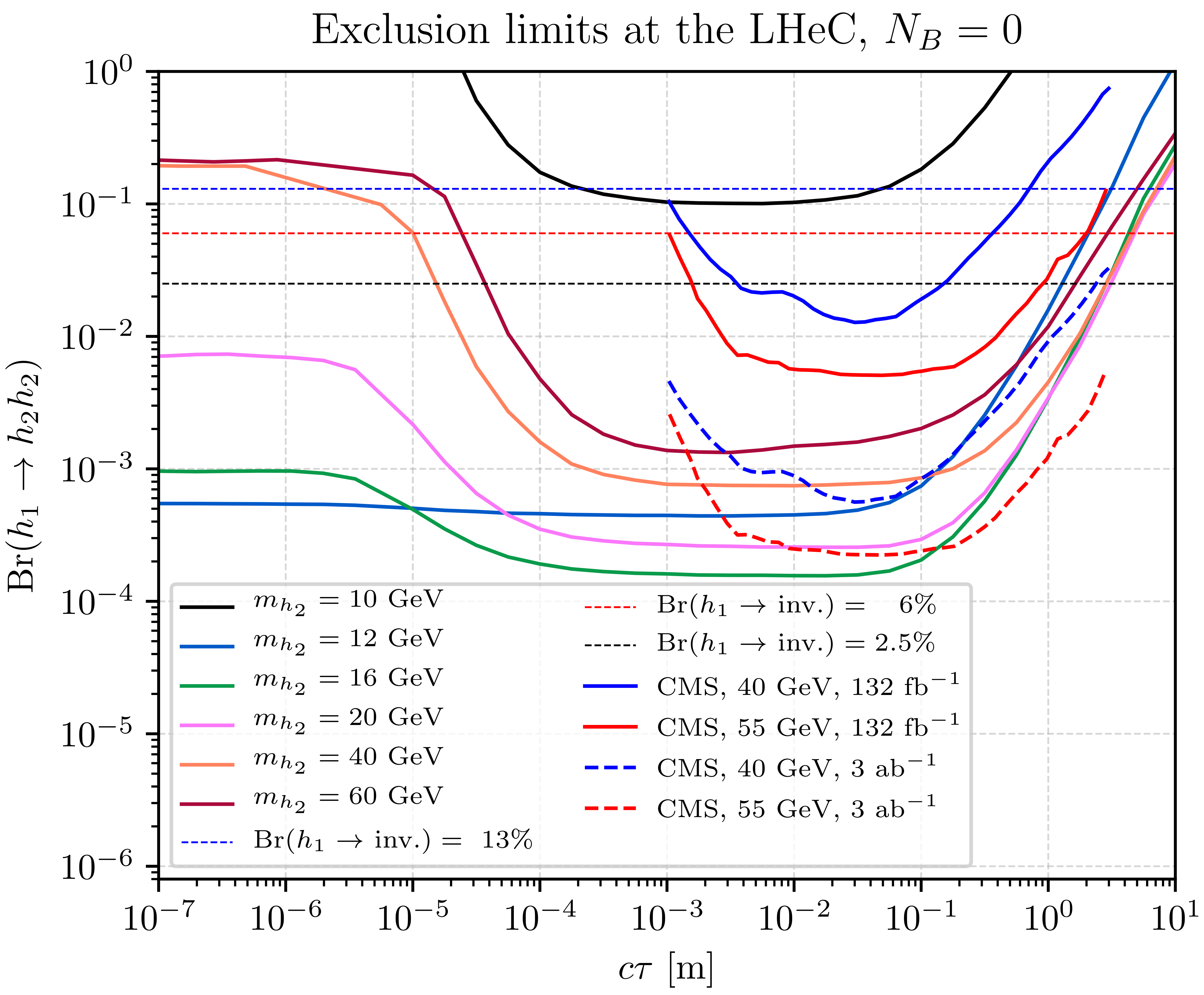
$N_B = 0, N_S = 3$

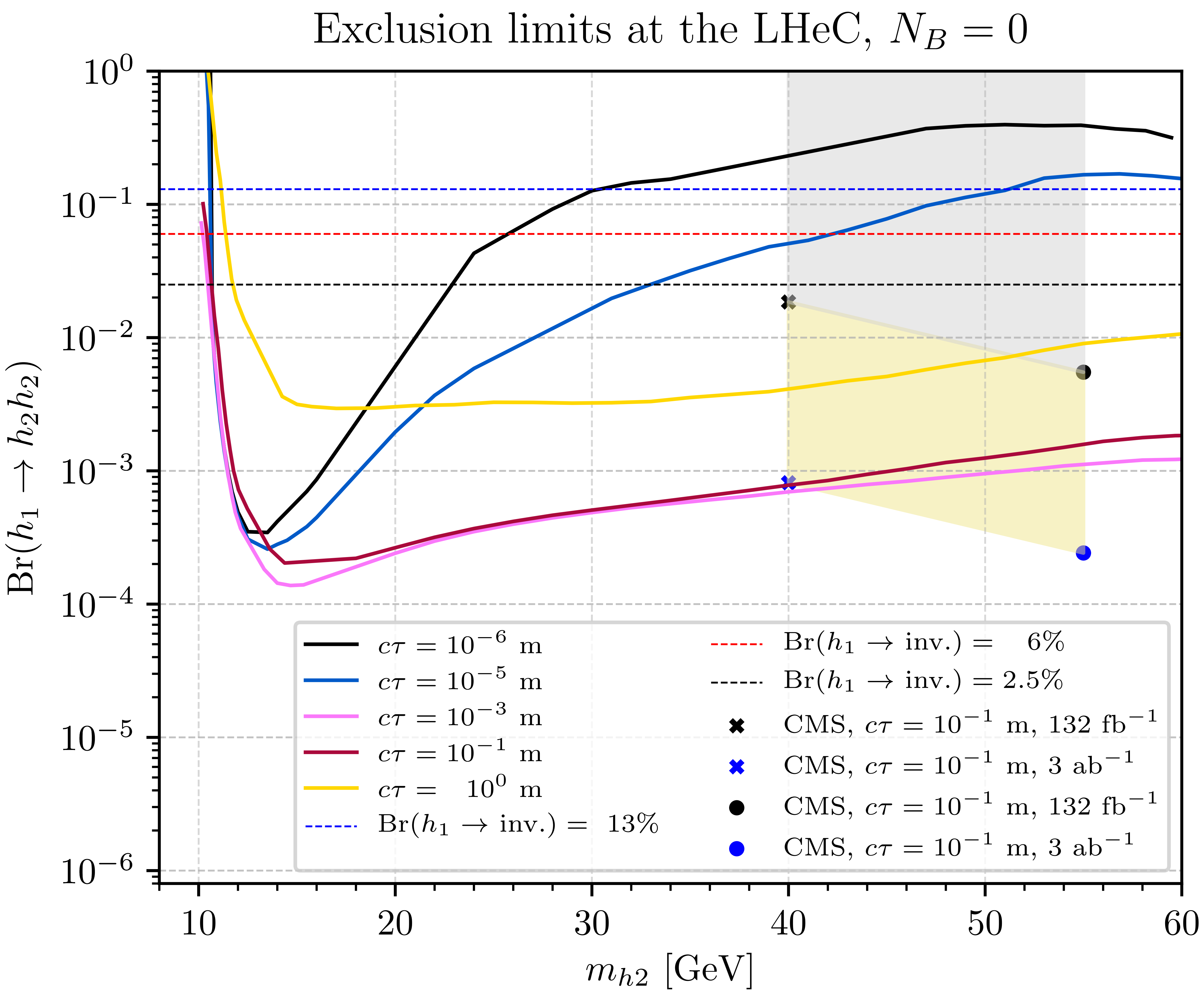
at 95%CL





Model Independent Results: Production rate vs Decay length





the ideal $N_B = 0$ case.

- Search for displaced jets can reach sensitivities down to $B(h_1 \to h_2 h_2) \sim 10^{-3}$, which is much better than the current LHC (HL-LHC) $B(h_1 \to \text{invisible}) \simeq 13\,\%$ (2.5%)
- The best sensitivity occurs at

  $10^{-4}\,\text{m} < c\tau < 10^{-1}\,\text{m}$, and $12\,\text{GeV} < m_{h_2} < 20\,\text{GeV}$
- For $c\tau < 1\,\mu\text{m}$ the h_2 decay is pratically prompt. The reconstructed displacement of the final state cannot be disentangled from displaced decays of B mesons. Thus, efficiencies are much lower than those of long lifetime.
- For those with $c\tau > 0.1\,\text{m}$, the decay of h_2 would be outside the IT.
- In ideal case $N_B = 0$, the sensitivity can reach $B(h_1 \to h_2 h_2) \sim 10^{-4}$

Conclusions

- Extending to search for LLP's can cover a larger parameter space for various models with feeble couplings.
- Branching ratio of the Higgs boson into a pair LLP's can be reached to $O(10^{-4} - 10^{-3})$
- Reconstructed level analysis, instead of geometric analysis, is important to establish the more realistic sensitivity reach.