Higgs Decays to Long-Lived Particles at *ee* Colliders

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-based on work with S. Alipourd-fard, N. Craig and S. Koren

Outline

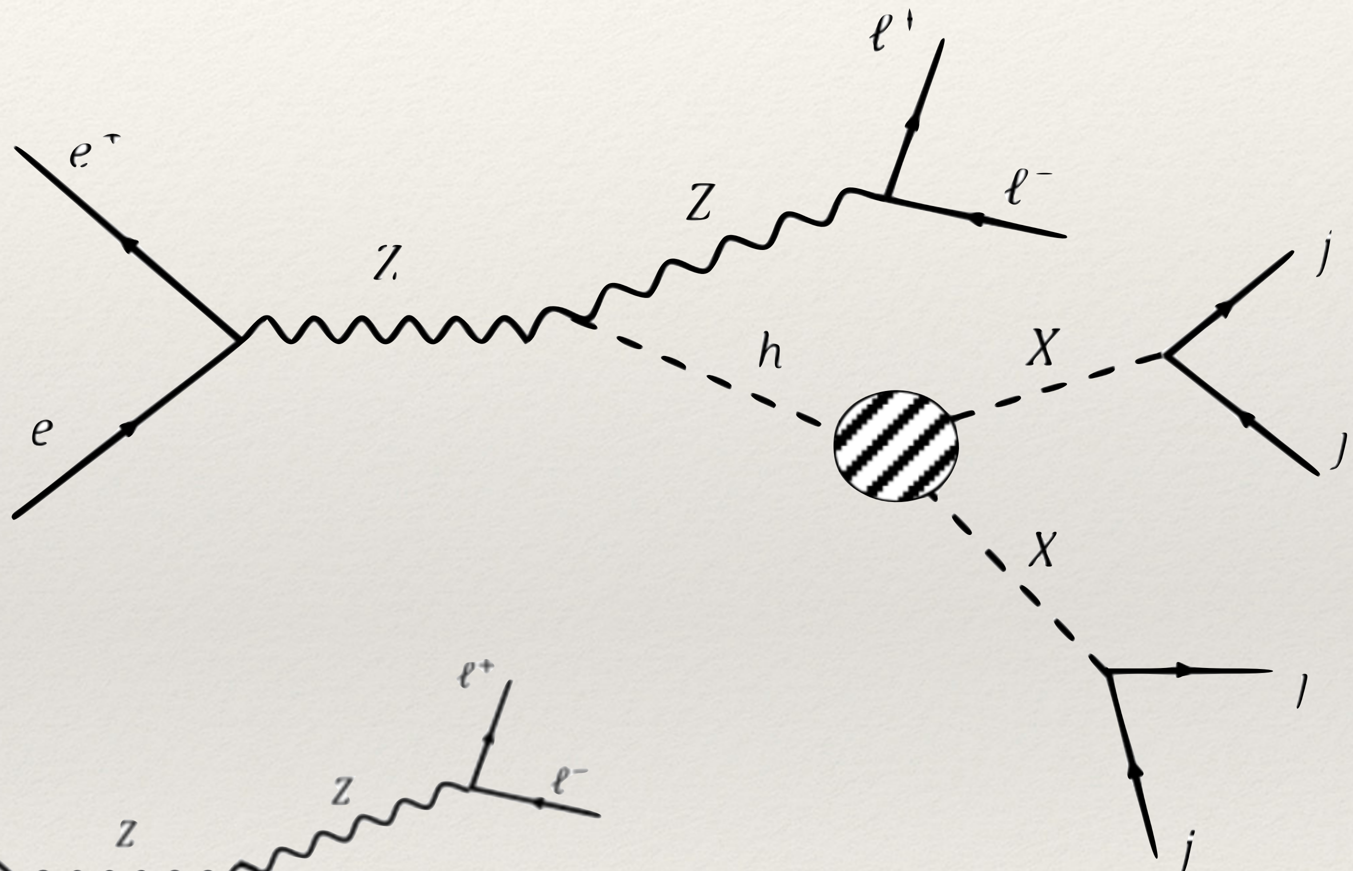
- Introduction: why Long-Lived Particles?
- Signal&background, analysis strategy and results
- Signal interpretations: Higgs portal & Neutral Naturalness
- Summary

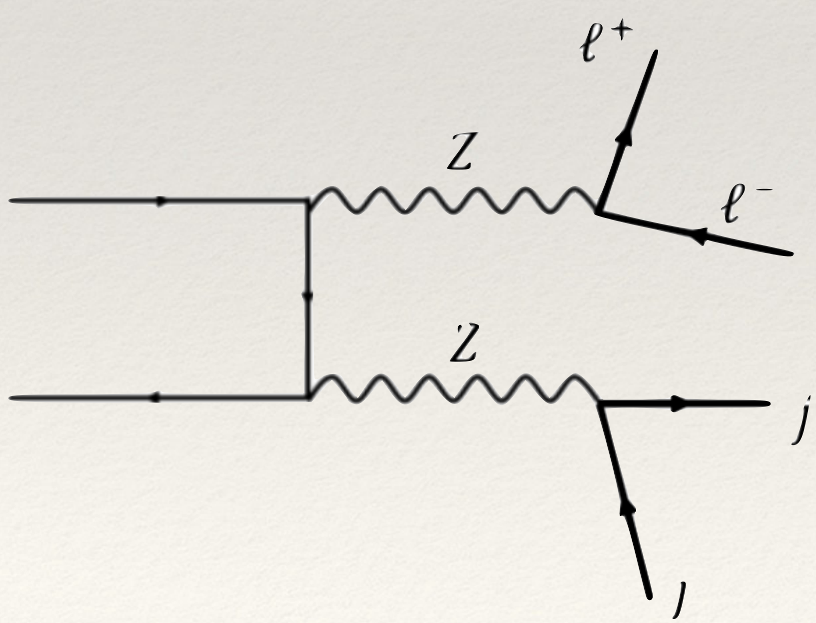
ee collider: precisely measure the Higgs property

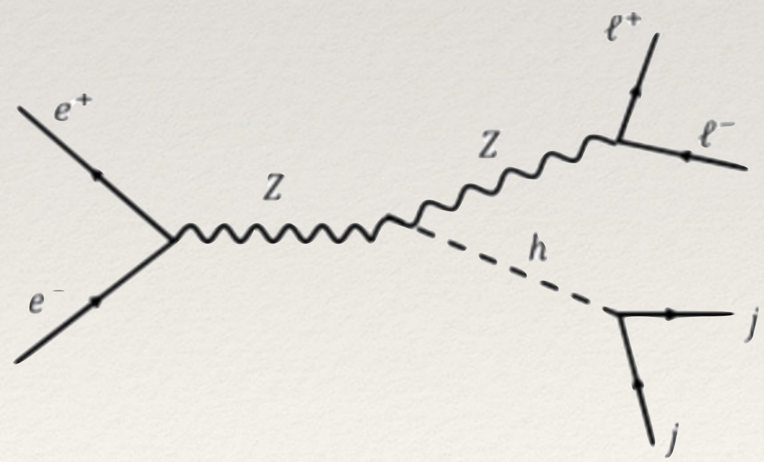
- Higgs coupling to itself or other SM states
- Higgs exotic decays
  - Long-Lived Particles(LLP)
    - Well motivated
      - Mass-degenerate spectra;
        Small coupling;
        Off-shell decay;
        Approximate symmetry;
      - SUSY;
        Neutral Naturalness;
        DM (free in/asymmetric..);
    - Novel search strategies:
      delayed detector signals/
      displaced vertex...
  - Prompt: extensively explored

Signal: $e^+e^- \to hZ \to XX + l\bar{l}$ X: neutral scalar

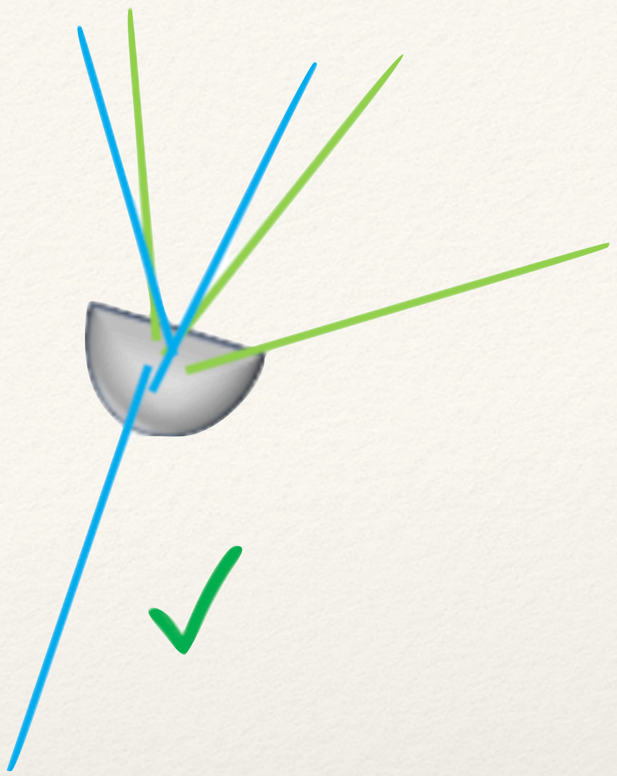
Background: $e^+e^- \to hZ$ with $Z \to l\bar{l}$ and $h \to b\bar{b}$;
$e^+e^- \to ZZ \to b\bar{b} + l\bar{l}$







Search strategy



- 1. Select the Higgstrahlung event

  $70 \leq M_{ee} \leq 110 GeV \ \ (81 \leq M_{\mu\mu} \leq 101 GeV); \ \ 120 \leq M_{recoil} \leq 150 GeV$

- 2. Use tracker information and cluster tracks together to form candidate vertices of X decay $|\vec{d}_{\text{cluster}}| < r_{\text{tracker}}$ (CPEC :1.81m; FCC-ee: 2.14m)

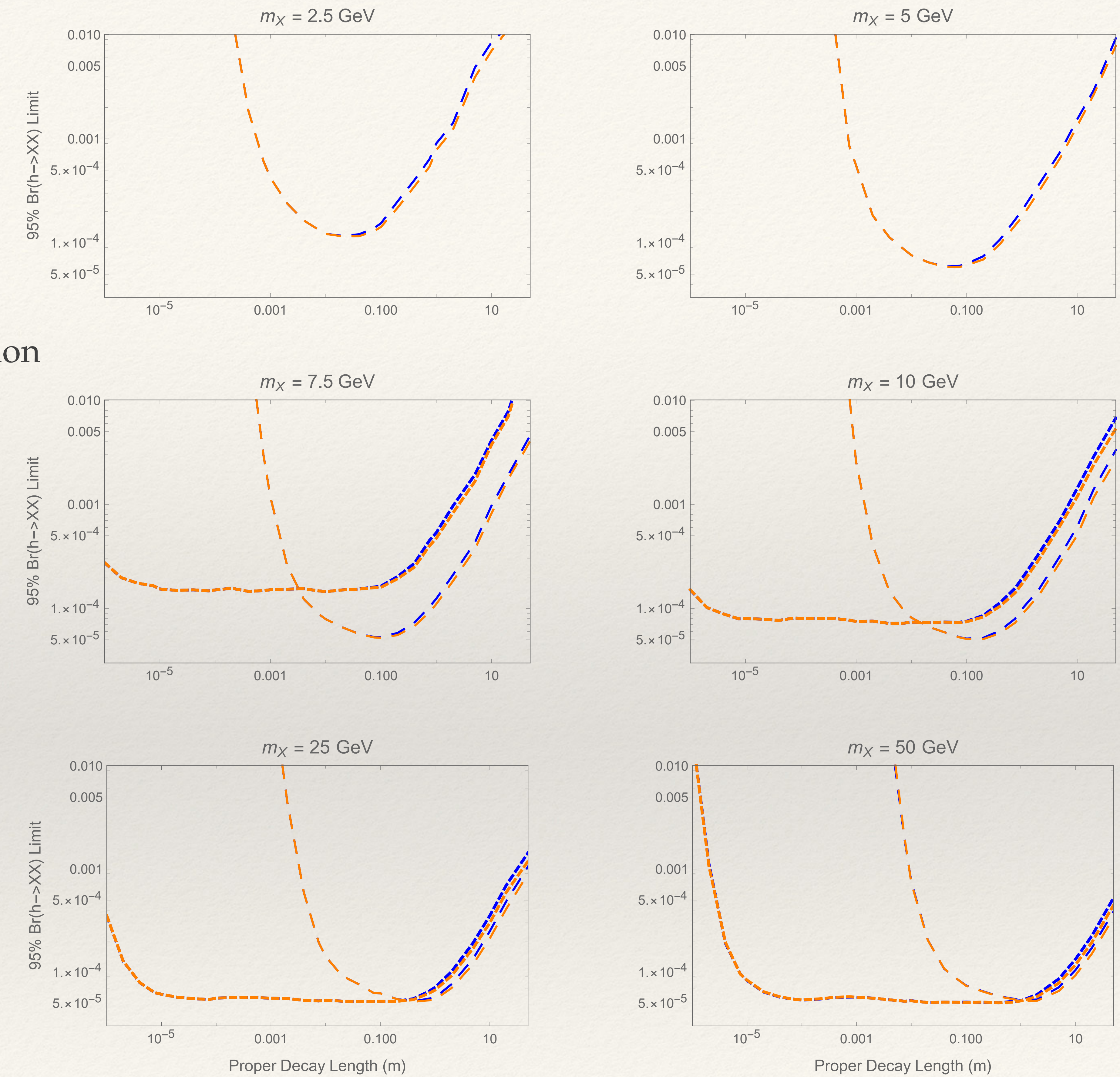
  - 'large mass' analysis: $|\vec{d}_{\text{cluster}}| > 5\mu m; \ M_{\text{charged}} > 6$ GeV
  - 'long-lifetime' analysis: $|\vec{d}_{\text{cluster}}| > 3cm; \ M_{\text{charged}} > 2$ GeV

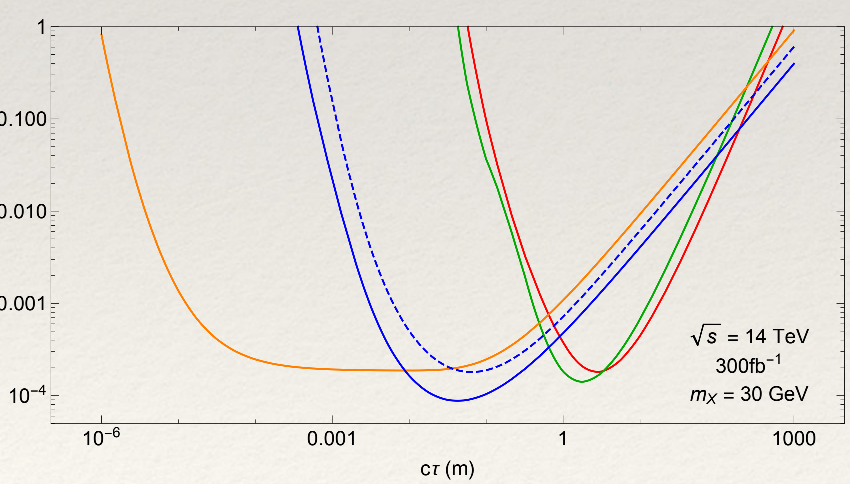
- 3. Select the vertex closest to the beam line among the candidate vertices
- 4."Pointer track" cut

Results

CEPC advantages:
Better impact parameter resolution and vertex reconstruction;
Lower backgrounds

(Curtin & Verhaaren, `15)





- Blue: CEPC; Orange: FCC-ee; Larger dashes : 'long lifetime'; Smaller dashes: 'large mass'

Higgs portal

$$\mathscr{L} \supset \frac{1}{2}(\partial_\mu \phi)^2 - \frac{1}{2}M^2\phi^2 - A|H|^2\phi - \frac{1}{2}\kappa|H|^2\phi^2 - \frac{1}{3!}\mu\phi^3 - \frac{1}{4!}\lambda_\phi\phi^4 - \frac{1}{2}\lambda_H|H|^4.$$

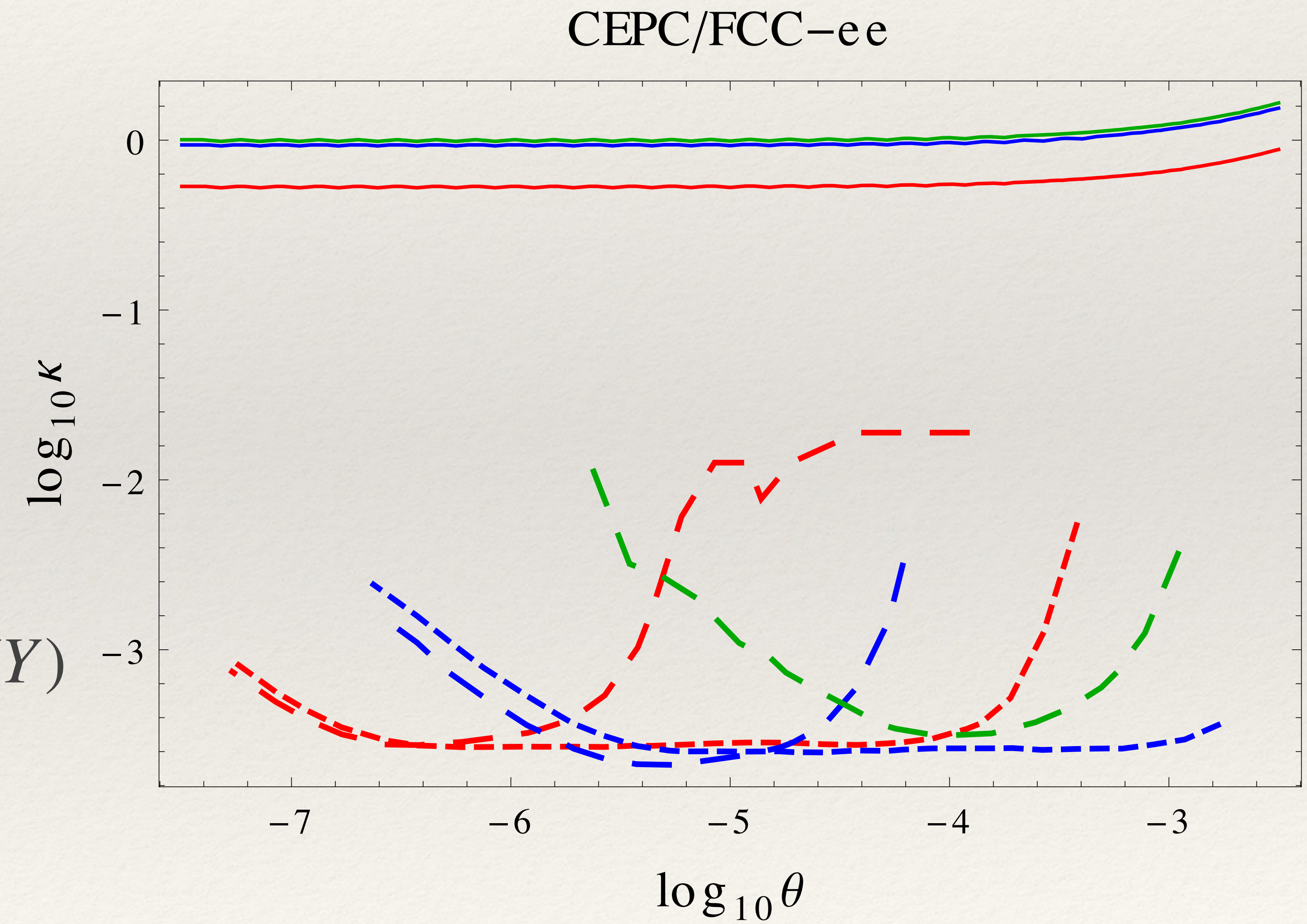
- Higgs coupling shift: tree level mixing ($A \neq 0$) and one-loop wave-function renormalization

$$\frac{\delta\sigma_{hZ}}{\sigma_{hZ}^{\rm SM}} \approx -\theta^2 - {\rm Re}\frac{d\mathscr{M}_{hh}}{dp^2}\bigg|_{p^2=m_h^2}$$

- Higgs exotic decay:

$$\Gamma(h \to ss) \approx \frac{\kappa^2 v^2}{32\pi m_h}\sqrt{1-4\frac{m_s^2}{m_h^2}},$$

$$\Gamma(s \to YY) = \sin^2\theta \times \Gamma(h_{\rm SM}[m_s] \to YY)$$



- Green: m_s=2.5 GeV; Blue: m_s=10 GeV; Red: m_s=50 GeV;

Neutral Naturalness

- Neutral naturalness models generally have top parters charged under additional $SU(3)_B$

- Fraternal twin Higgs:
  SM neutral twin top;   Tree level Higgs coupling shift $\sim v/f$

- Folded SUSY:
  Electroweak charged s-tops;   One loop $h\gamma\gamma$ shift

- Hyperbolic Higgs:
  SM neutral scalar top partner; Tree level Higgs coupling shift $\sim v/v_H$

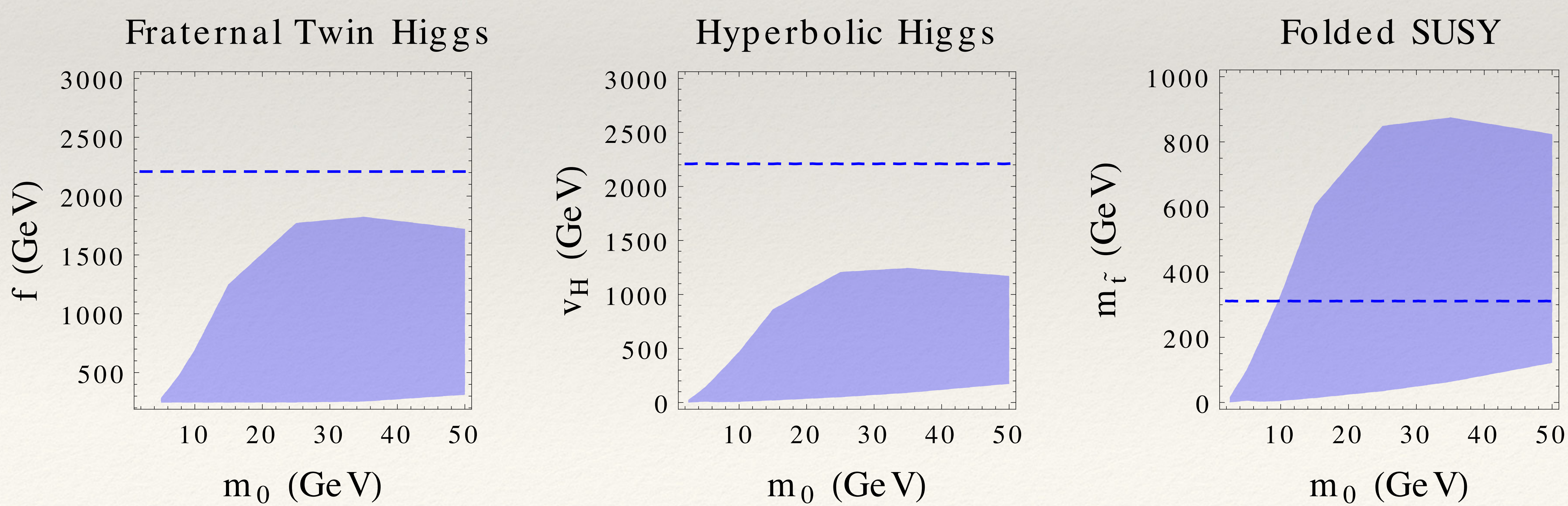
- LLPs are glueballs of $SU(3)_B$, with $J^{PC} = 0^{++}$ being lightest

- $$\mathscr{L}^{(6)} = \frac{\alpha_s^B}{6\pi}\left[\frac{y^2}{M^2}\right]|H|^2 G^B_{\mu\nu}G^{B\mu\nu}$$

$$\left[\frac{y^2}{M^2}\right] \approx \begin{cases} -\frac{1}{2v^2}\frac{v^2}{f^2} & \text{Fraternal Twin Higgs} \\ \frac{1}{4v^2}\frac{m_t^2}{m_{\tilde{t}}^2} & \text{Folded SUSY} \\ \frac{1}{4v^2}\frac{v}{v_{\mathcal{H}}}\sin\theta & \text{Hyperbolic Higgs} \end{cases}$$

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

- $$\Gamma(0^{++} \to YY) = \left(\frac{1}{12\pi^2}\left[\frac{y^2}{M^2}\right]\frac{v}{m_h^2 - m_0^2}\right)^2 \left(4\pi\alpha_s^B F^S_{0^{++}}\right)^2 \times \Gamma(h_{SM}[m_0] \to YY)$$



Summary

- Exotic Higgs decays to LLPs are a well-motivated place to look for new physics and probe Higgs properties , complementary to the precision Higgs coupling measurement.
- CEPC can improve on the LHC in searching for such rare decays. Need more comprehensive studies!
  (other signals; timing layers / calorimeters / muon chambers)