Probing long-lived particles at Higgs factories

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1. Motivation

Motivation

- New-physics (NP) models including SUSY predict new heavy fields
- No new fundamental particles found yet at the LHC
- More stringent limits placed on NP models, e.g. $m_{\tilde{q},\tilde{g}} \gtrsim 1$ TeV
- LHC focus: **promptly decaying** NP particles

Perhaps this assumption is wrong

$\rightarrow$ Long-Lived Particles!

LLP and CEPC/FCC-ee

- LLPs: produced, travel a macroscopic distance, and then decay $\rightarrow$ Displaced Vertices
- LLPs appear in many extensions of the SM:
  heavy neutral lepton, dark photon, neutralino, light Higgs, ...
- Often motivated by the small neutrino masses or dark matter
- Causes of the long lifetime:
  - **Feeble** couplings
  - **Heavy** mediators
  - **Small** phase space
  - ...
- CEPC/FCC-ee: large and clean samples of Higgs bosons

2. LLP searches at Higgs factories

Future lepton colliders and the Higgs mode

- LHC has been a huge success
- Next-generation e^-e^+ colliders: CEPC, FCC-ee, ILC, etc.
- $\sqrt{s}$ =91.2 GeV ($Z-$pole), 160 GeV (WW mode), 240 GeV (Higgs mode), etc.

production $e^-e^+ \rightarrow$		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 exotic Higgs decays $h \rightarrow XX$. X a long-lived scalar
    - a Higgs-portal model: a light scalar
    - neutral-naturalness models: the lightest mirror glueball

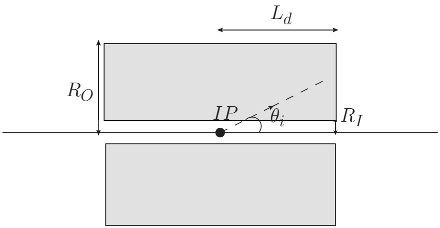
General calculation procedure

$$
\begin{aligned}
N_{\text{s.e.}}^{\text{IT}} &= \mathcal{L}_h \cdot \sigma_h \cdot \text{Br}(h \to XX) \cdot \langle P[s.e.\text{ in IT}] \rangle \cdot \epsilon^{\text{IT}} \\
N_{\text{s.e.}}^{\text{HCAL}} &= \mathcal{L}_h \cdot \sigma_h \cdot \text{Br}(h \to XX) \cdot \langle P[s.e.\text{ in HCAL}] \rangle \\
N_{\text{s.e.}}^{\text{MS}} &= \mathcal{L}_h \cdot \sigma_h \cdot \text{Br}(h \to XX) \cdot \langle P[s.e.\text{ in MS}] \rangle
\end{aligned}
$$

- ϵ^{IT}: cut efficiency of the IT
- For the IT, require at least one DV to constitute a signal event
- For the HCAL/MS, require two DVs

$$
\begin{aligned}
\langle P[s.e.\text{ in IT}] \rangle &= \frac{1}{N^{\text{MC}}} \sum_{i=1}^{N^{\text{MC}}} \Big(P[X_i^1 \text{ in IT}] + P[X_i^2 \text{ in IT}] - P[X_i^1 \text{ in IT}] \cdot P[X_i^2 \text{ in IT}] \Big) \\
\langle P[s.e.\text{ in HCAL}] \rangle &= \frac{1}{N^{\text{MC}}} \sum_{i=1}^{N^{\text{MC}}} \Big(P[X_i^1 \text{ in HCAL}] \cdot P[X_i^2 \text{ in HCAL}] \Big) \\
\langle P[s.e.\text{ in MS}] \rangle &= \frac{1}{N^{\text{MC}}} \sum_{i=1}^{N^{\text{MC}}} \Big(P[X_i^1 \text{ in MS}] \cdot P[X_i^2 \text{ in MS}] \Big)
\end{aligned}
$$

Inner Tracker



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

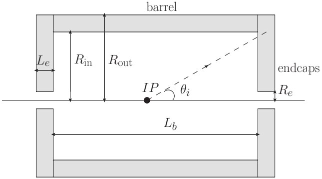
$$P[X_i \text{ in IT}] = e^{-L_i/\lambda_i^t} \cdot (1 - e^{-L'_i/\lambda_i^t})$$

$$L_i \equiv \begin{cases} R_I, & \text{if } |L_d \tan\theta_i| \leq R_I \\ d_{\text{res}} = 5\ \mu m, & \text{else} \end{cases}$$

$$L'_i \equiv \min(\max(R_I, |L_d \tan\theta_i|), R_O) - L_i$$

$$\lambda_i^t = \beta_i^t \gamma_i \tau_X$$

HCAL and Muon spectrometer



Detector	L_b [m]	L_e [m]	R_e [m]	$R_{\rm in}$ [m]	$R_{\rm out}$ [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

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

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

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

A Higgs-portal model

- Add a real SM-singlet scalar field to the SM Lagrangian, which mixes with the SM Higgs doublet field
- May connect the SM and the dark sectors
- Three parameters: m_{h_s}, $\sin^2\theta$, $\langle\chi\rangle$
- Consider *sub-GeV* h_s: decay products are collimated
- Production:

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

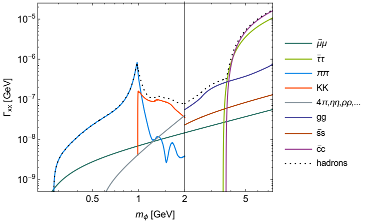
- $\text{Br}(h \to h_s h_s)$:

$$\text{Br}(h \to h_s h_s) = \frac{\Gamma(h \to h_s h_s)}{\Gamma(h \to h_s h_s) + \Gamma_h^{\text{SM}}}$$

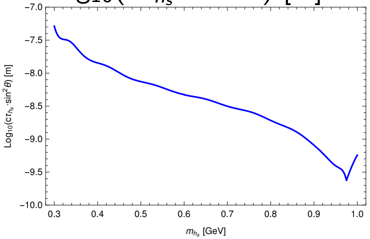
- Decay: $h_s \to \mu^+\mu^-$, $\pi\pi$, 4π (with $m_{h_s} \in [0.3, 1.0]$ GeV)

h_s decay calculation

Decay widths for $\sin^2\theta = 1$:



[Winkler,'18]



- Analytically calculate $\Gamma(h_s \to \ell^+\ell^-)$

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

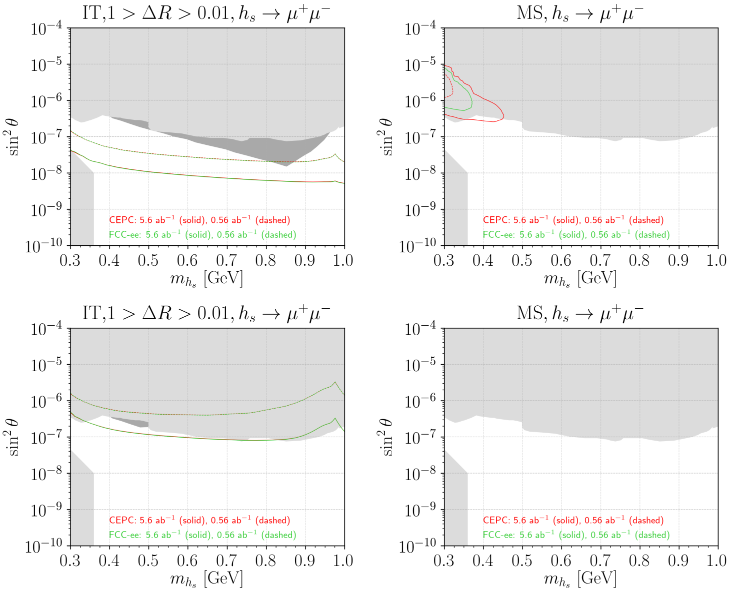
- Numerically extract $\Gamma(h_s \to \pi\pi)$ and $\Gamma(h_s \to 4\pi)$ from [Winkler,'18]

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%

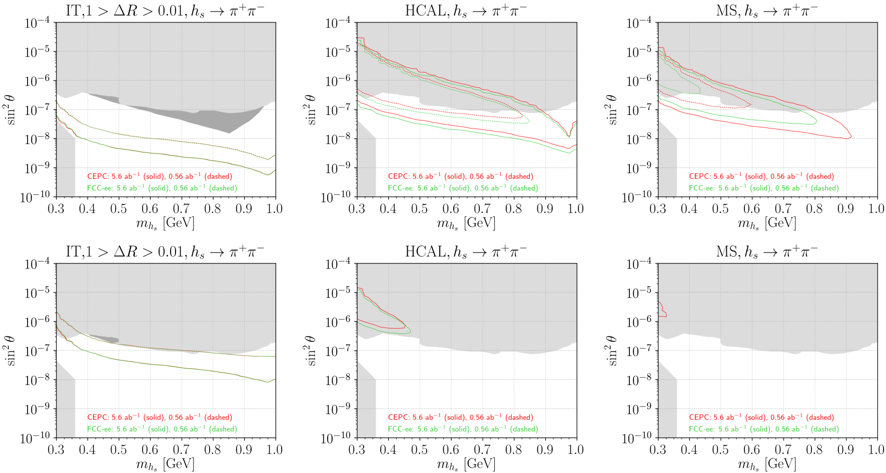
Results: dimuon channel

$\langle \chi \rangle = 10$ GeV

$\langle \chi \rangle = 100$ GeV



Results: dijet channel



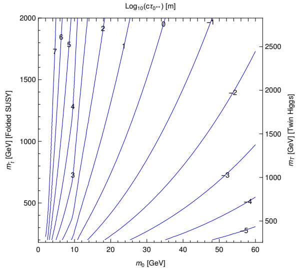
Neutral-naturalness models

- Hierarchy problem in the SM
- Neutral Naturalness: predict uncolored top partners to protect the Higgs mass up to $\sim$ 5-10 TeV
- The top partners can be either SM singlet or only charged in the EW sector, and charged under a *mirror* QCD sector $SU(3)_B$
- Examples: folded SUSY, (fraternal) twin Higgs, quirky little Higgs, hyperbolic Higgs, etc.
- 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 decay

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

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



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

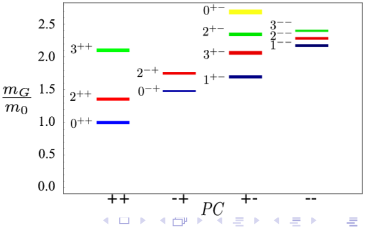
- Two parameters: m_0 and $m_{\tilde{t}}$ for folded SUSY

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

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

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

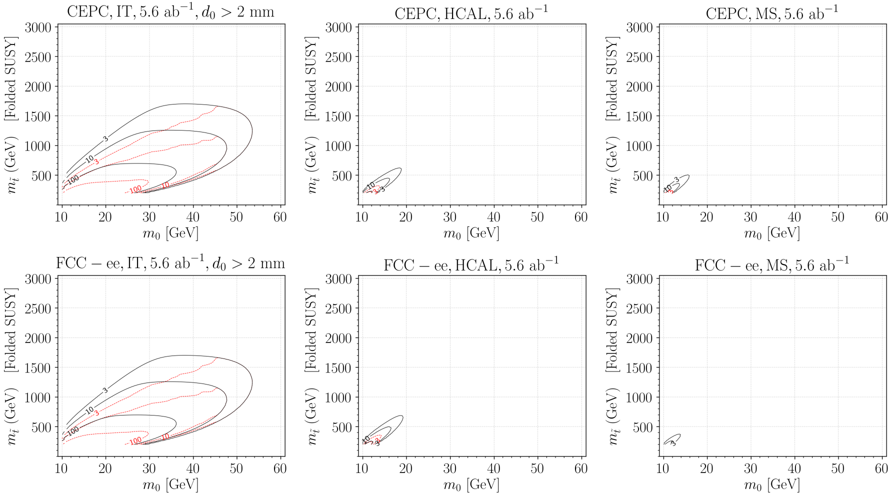
[Juknevich,'09]



Signatures and background

- Interested mass range: $\sim 10 - 60$ GeV
- Focus on $0^{++} \to b\bar{b}$
- Consider all of IT, HCAL, and MS
- Major backgrounds:
  - $e^- e^+ \to ZZ \to (\ell^+\ell^-, jj)(b\bar{b})$
  - $e^- e^+ \to Zh \to (\ell^+\ell^-, jj)(b\bar{b})$
- Make use of $\mathrm{Br}(Z \to \ell^+\ell^-/jj) \sim 0.8$: impose an invariant mass cut on the lepton or jet pair to identify the $Z-$boson
- Recoil-mass cut in order to remove the ZZ background: $M^2_{\mathrm{recoil}} = s - 2\sqrt{s}(E_{\ell^+} + E_{\ell^-}) + M^2_{\ell\ell}$; $120\ \mathrm{GeV} < M_{\mathrm{recoil}} < 150\ \mathrm{GeV}$
- Invariant-mass cut on $b\bar{b}$ pair: 10 GeV $< M_{b\bar{b}} <$ 80 GeV (no effect on the signal events)
- Require $d_0 > 2$ mm for both $b-$jets stemming from any secondary vertex in the IT
- Assume negligible SM background for the HCAL and MS

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



3. Outlook & Conclusions

Outlook for LLP searches at Higgs factories

- Truth-level study and Delphes 3 with displaced objects
- Other colliders such as the *LHeC* with 10^5 Higgs bosons
- For reviews of LLPs, see: 1806.07396, 1810.12602, 1903.04497, ...

Conclusions

- The assumption of prompt decay might be wrong
- NP hidden in LLPs?
- LLP searches at future Higgs factories
  - Sub-GeV light scalar at a Higgs portal model
  - The lightest mirror glueball and neutral-naturalness models
- A lot more models of LLPs and a lot more search avenues available!

Thank You!

MC simulation

- Higgs generation:
  HiggsProcess module in Pythia8
  Higgs decay exclusively to a pair of scalars
  New scalars further decay to specified states