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

→ Long-Lived Particles!
LLPs: produced, travel a macroscopic distance, and then decay → *Displaced Vertices*


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.

<table>
<thead>
<tr>
<th>Production</th>
<th>$Zh$ (main)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e^- e^+ \rightarrow$</td>
<td>$\nu\bar{\nu}h, e^- e^+ h$ (VBF)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$\sqrt{s}$ [GeV]</th>
<th>240</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_h$</td>
<td>$CEPC$</td>
</tr>
<tr>
<td></td>
<td>$FCC$-ee</td>
</tr>
<tr>
<td></td>
<td>$1.14 \times 10^6$</td>
</tr>
</tbody>
</table>

- 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

\[ N^{\text{IT}}_{\text{s.e.}} = \mathcal{L}_h \cdot \sigma_h \cdot \text{Br}(h \rightarrow XX) \cdot \langle P[\text{s.e. in IT}] \rangle \cdot \epsilon^{\text{IT}} \]
\[ N^{\text{HCAL}}_{\text{s.e.}} = \mathcal{L}_h \cdot \sigma_h \cdot \text{Br}(h \rightarrow XX) \cdot \langle P[\text{s.e. in HCAL}] \rangle \]
\[ N^{\text{MS}}_{\text{s.e.}} = \mathcal{L}_h \cdot \sigma_h \cdot \text{Br}(h \rightarrow XX) \cdot \langle P[\text{s.e. in MS}] \rangle \]

- \( \epsilon^{\text{IT}} \): 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

\[ \langle P[\text{s.e. in IT}] \rangle = \frac{1}{N^{\text{MC}}} \sum_{i=1}^{N^{\text{MC}}} \left( P[X_1^i \text{ in IT}] + P[X_2^i \text{ in IT}] - P[X_1^i \text{ in IT}] \cdot P[X_2^i \text{ in IT}] \right) \]
\[ \langle P[\text{s.e. in HCAL}] \rangle = \frac{1}{N^{\text{MC}}} \sum_{i=1}^{N^{\text{MC}}} \left( P[X_1^i \text{ in HCAL}] \cdot P[X_2^i \text{ in HCAL}] \right) \]
\[ \langle P[\text{s.e. in MS}] \rangle = \frac{1}{N^{\text{MC}}} \sum_{i=1}^{N^{\text{MC}}} \left( P[X_1^i \text{ in MS}] \cdot P[X_2^i \text{ in MS}] \right) \]
Inner Tracker

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

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

\[ L_i' \equiv \min(\max(R_I, |L_d \tan \theta_i|), R_O) - L_i \]

\[ \lambda_i^t = \beta_i^t \gamma_i \tau X \]
HCAL and Muon spectrometer

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

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

\[
L_{\alpha}^i \equiv \min(\max(R_e, |(L_b/2 + L_e) \tan \theta_i|), R_{out}) - R_e
\]

\[
L_{\beta}^i \equiv \min(\max(R_e, |L_b/2 \tan \theta_i|), R_{in}) - R_e
\]
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:

$$\Gamma(h \rightarrow h_s h_s) \approx \frac{\sin^2 \theta (m_h^2 - m_{h_s}^2)^2}{32\pi m_h \langle \chi \rangle^2}$$

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

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

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

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

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

- **Analytically calculate $\Gamma(h_s \to \ell^+ \ell^-)$**
- **Numerically extract $\Gamma(h_s \to \pi\pi)$ and $\Gamma(h_s \to 4\pi)$ from [Winkler,'18]**

<table>
<thead>
<tr>
<th>$m_{h_s}$ (GeV)</th>
<th>0.3</th>
<th>0.4</th>
<th>0.5</th>
<th>0.6</th>
<th>0.7</th>
<th>0.8</th>
<th>0.9</th>
<th>1.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Br($\mu^+ \mu^-$)</td>
<td>20.6%</td>
<td>13.0%</td>
<td>10.3%</td>
<td>8.6%</td>
<td>7.1%</td>
<td>5.1%</td>
<td>2.5%</td>
<td>2.0%</td>
</tr>
<tr>
<td>Br($\pi\pi$)</td>
<td>79.4%</td>
<td>87.0%</td>
<td>89.7%</td>
<td>91.3%</td>
<td>91.2%</td>
<td>93.0%</td>
<td>96.3%</td>
<td>96.8%</td>
</tr>
<tr>
<td>Br(4$\pi$)</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0.1%</td>
<td>1.7%</td>
<td>1.9%</td>
<td>1.2%</td>
<td>1.2%</td>
</tr>
</tbody>
</table>
Results: dimuon channel

\[ \langle \chi \rangle = 10 \text{ GeV} \]

\[ \langle \chi \rangle = 100 \text{ GeV} \]
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

\[ \Gamma(0^{++} \rightarrow \xi\xi) = \left( \frac{1}{12\pi^2} \left[ \frac{y^2}{M^2} \right] \frac{v}{m_h^2 - m_0^2} \right)^2 \left( 4\pi \alpha_s^B F_0^{S+} \right)^2 \Gamma^{\text{SM}}_{h \rightarrow \xi\xi}(m_0^2), \]

- \(4\pi \alpha_s^B F_0^{S+} \approx 2.3 m_0^3\)
- \(\Gamma^{\text{SM}}_{h \rightarrow \xi\xi}(m_0^2)\) calculated with HDECAY 6.52

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

- Two parameters: \(m_0\) and \(m_\tilde{t}\) for folded SUSY
Mirror glueball production

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

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

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

[Juknevich, '09]
Signatures and background

- Interested mass range: $\sim 10 - 60$ GeV
- Focus on $0^{++} \rightarrow b\bar{b}$
- Consider all of IT, HCAL, and MS
- Major backgrounds:
  - $e^-e^+ \rightarrow ZZ \rightarrow (\ell^+\ell^-, jj)(b\bar{b})$
  - $e^-e^+ \rightarrow Zh \rightarrow (\ell^+\ell^-, jj)(b\bar{b})$
- Make use of $\text{Br}(Z \rightarrow \ell^+\ell^-/jj) \sim 0.8$: 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:
  \[ M_{\text{recoil}}^2 = s - 2\sqrt{s}(E_{\ell^+} + E_{\ell^-}) + M_{\ell\ell}^2 ; 
  120 \text{ GeV} < M_{\text{recoil}} < 150 \text{ GeV} \]
- Invariant-mass cut on $b\bar{b}$ pair: $10 \text{ GeV} < M_{b\bar{b}} < 80 \text{ GeV}$ (no effect on the signal events)
- Require $d_0 > 2 \text{ mm}$ 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, ...
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