Long-Lived Particles at the FCC-ee

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FCC Phenomenology Workshop

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Future Circular Collider

Future Circular Collider (FCC) will have one 100 km tunnel, two stages:

• Stage 1: FCC-ee (Z, W, H, tt) as Higgs EW and top factory at high luminosities

• Stage 2: FCC-hh (~100 TeV) as natural continuation at energy frontier, with ion and eh options

The FCC is a frontier Higgs, top, electroweak, and flavor factory where we can **directly discover new physics**

Enter LLPs!
Long-Lived Particles (LLPs)

Standard model particles span a wide range of lifetimes ($\tau$)
Long-Lived Particles (LLPs)

Standard model particles span a wide range of lifetimes ($\tau$)

We expect new phenomena to have a wide range of lifetimes as well.

But conventional searches for new phenomena at the LHC are for promptly decaying particles.

We also need to look for new particles with long lifetimes!
Long-Lived Particle Searches

- **Wide variety** of:
  - Charges
  - Final states
  - Decay locations
  - Lifetimes
- Design **signature-driven** searches
- Often interpret results with a **benchmark model**, but can expand to a **variety of scenarios**
- **Challenges of the LHC**: main detectors, triggers, offline reconstruction not designed for displaced particles

Big opportunity to do something different at the FCC!
Detectors at the FCC-ee

A few detector concepts being used for integration, performance, and cost estimates:

CLIC-like Detector (CLD)
- Full silicon vertex-detector + tracker
- 3D high-granularity calorimeter
- Solenoid outside calorimeter

Innovative Detector for an Electron-Positron Accelerator (IDEA)
- Silicon vertex detector
- Short-drift chamber tracker
- Dual-readout calorimeter (solenoid inside)

Noble Liquid
- High-granularity noble liquid calorimeter
- LAr or Lar + Lead or Tungsten absorber
- Newest proposal

Have the opportunity to design general-purpose detectors with LLPs in mind!
- Can prioritize e.g. displaced tracking and precision timing information
- Can also prioritize LLPs in the online filtering and offline reconstruction
Past and Ongoing Work

Several Masters student theses done or in progress:

- **Sissel Bay Nielsen** (University of Copenhagen, 2017)
- **Rohini Sengupta** (Uppsala University, 2021)
- **Lovisa Rygaard** (Uppsala University, 2022)
- **Tanishq Sharma** (University of Geneva, 2022)
- **Magdalena Vande Voorde** (Uppsala University, 2023)
- **Daniel Beech** (University of Cambridge, 2023)
- **Dimitri Moulin** (University of Geneva, 2023)
  - defending thesis today!

Snowmass:

- **LOI**

Searches for long-lived particles at the future FCC-ee


**LLP group focusing on 3 physics cases:**

1. Heavy Neutral Leptons (HNLs)
2. Axion-like Particles (ALPs)
3. Higgs bosons with exotic decays to LLPs

I’ll present the latest activities of several LLP FCC analyses
## Overview of Analyses

<table>
<thead>
<tr>
<th>Physics scenario</th>
<th>FCC-ee signature</th>
<th>Studies for snowmass</th>
<th>Ongoing work</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heavy neutral leptons (HNLs)</td>
<td>Displaced vertices</td>
<td>Generator validation and reco-level analysis for $ee\nu\nu$. First look at Dirac vs Majorana HNLs</td>
<td>• Update $ee\nu\nu$ studies with winter23 samples.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Dirac vs Majorana in $e\nu jj$ channel</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• First look at $\mu\mu\nu\nu$ channel</td>
</tr>
<tr>
<td>Axion-like particles (ALPs)</td>
<td>Displaced photon/lepton pair</td>
<td>Generator-level validation for $a\rightarrow\gamma\gamma$ at Z-pole run</td>
<td><strong>No studies continuing at the moment</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>-&gt; <strong>Opportunities to get involved!</strong></td>
</tr>
<tr>
<td>Exotic Higgs decays</td>
<td>e.g.</td>
<td>Theory discussion and motivation for studies at ZH-pole</td>
<td>• Reco-level analysis (inc. vertexing) for $h\rightarrow ss \rightarrow bbbb$</td>
</tr>
</tbody>
</table>
Workflow

- Perform an FCC case studies with the “official” analysis tools and framework available for the FCC
  - Use FCCAnalysis software to analyze centrally-produced EDM4HEP samples with the IDEA detector in Delphes, although some signal samples produced privately
  - Dedicated tutorial available for LLP studies
- Try to be as realistic as possible, with high stats background samples
1st Physics Case: Heavy Neutral Leptons

- Dirac or Majorana sterile neutrinos with very small mixing with active neutrinos
- Heavy enough to not disrupt the simplest BBN bounds and/or unstable on cosmological timescales
- Could provide answers to some open questions of the SM: Neutrino masses, Baryon asymmetry, Dark matter
- FCC will probe space not constrained by astrophysics or cosmology, complementary to fixed target, neutrino, and 0vbb prospects
- HNLs at the FCC-ee are right in the parameter region that is good for baryogenesis! [arXiv:2106.16226]

Reach for HNL decays at the Tera-Z run of the FCC-ee
LL HNLs

\[
\lambda_N = \frac{\beta \gamma}{\Gamma_N} \simeq \frac{1.6}{U^2 c_{\text{dec}}} \left( \frac{M}{\text{GeV}} \right)^{\frac{-6}{}} \left( 1 - (M/m_Z)^2 \right) \text{ cm}
\]

\[c_{\text{dec}} = 1 \text{ (Majorana)} \text{ or } 1/2 \text{ (Dirac)}\]

[arXiv:2210.17110]

Get long-lived HNLs when coupling and mass are small

Experimental signature of LL HNLs: displaced vertex

e+e- \rightarrow Z \rightarrow vN
N \rightarrow e^- + \{W^* \rightarrow jj\}
$N \rightarrow ll\nu$ Generation

- FCC-ee, $\sqrt{s} = 91$ GeV
- Generated in Madgraph5 v3.2.0 + Pythia8 + Delphes, with the latest IDEA card

FCC-ee Simulation (Delphes)

$$e^+e^- \rightarrow N\nu, N \rightarrow e\nu$$

HNL lifetime
**N \rightarrow eev**: Snowmass Results

- **Used centrally-produced “spring2021” background samples**

- **Main selections:**
  - Exactly 2 electrons, veto on additional photons, muons, and jets
  - Missing energy > 10 GeV (reduce Z->ee background with fake missing momentum)
  - Electron $|d_0| > 0.5$ mm (remove most of the rest of SM background)

- **Preliminary sensitivity shown with** $\frac{S}{\sqrt{S + B + \Delta B}}$

- **This analysis: N \rightarrow eev**
  - Contours show where FOM = 0.01 and 0.05
  - Theory prediction from arXiv:1411.5230
    - Includes all HNL decay modes, not only electrons
$N \to e e \nu$: Dirac vs Majorana

Dirac (LNC) and Majorana (LNC+LNV) HNLs produce different kinematic distributions: [arXiv:2105.06576](arXiv:2105.06576)

Variables that can distinguish between Majorana and Dirac HNLs:

**HNL Lifetime**
(model-dependent)

**$\cos \theta_{ee}$**
(opening angle between final state electron/positron)

Next: improve reconstruction, find more discriminating variables
$N \rightarrow \mu jj$: Ongoing Studies

- High branching fraction: ~50%
- Target HNL masses from 5 to 85 GeV, with scan over couplings
- Performing two subanalyses:
  - **Prompt analysis** for high HNL mass (> 50 GeV)
    - Studied jet energy resolution and prompt vertex performance
    - Detailed analysis largely complete
    - See more in Nicolo's talk at FCC week
  - **Long-lived analysis** for low HNL mass
    - Bkg suppressed by displaced vertex
    - Will study vertex and timing performance requirements
    - Will focus on this analysis on the next slide

$N \rightarrow \mu jj$: LL Analysis

- Kinematic selections kept the same as the prompt analysis:
  - 1 muon with $p > 3$ GeV
  - $\geq 3$ tracks
  - $E_{\text{miss}} > 5$ GeV
- Additionally, suppress prompt backgrounds by requiring muon $|d_0| > 1$ mm
- Preliminary results for LLP analysis at $\sqrt{s} = 91$ GeV, assuming 240 ab$^{-1}$
- Investigating further selection requirements using vertex fitter
$N \rightarrow \mu\mu\nu$: Ongoing Studies

- Early studies of sensitivity with $N \rightarrow \mu\mu\nu$ channel looking for DV + missing energy
- Optimizing search based on the distance from the 2-muon decay vertex to the IP
- DV reconstruction efficiency a promising area for further improvements
Another Physics Case: Exotic Higgs Decays to LLPs

- Higgs bosons could undergo exotic decays to e.g. scalars that could be long-lived
- New scalar could be a portal between the SM and a dark sector ([arXiv:1312.4992], [arXiv:1412.0018])
- Higgs boson (h) and the scalar (s) mix with a mixing angle $\sin \theta$
- For sufficiently small mixing, the scalar can be long-lived
  - $c\tau \sim \text{meters if } \theta < 1\text{e-6}$
- Probe $h \rightarrow ss \rightarrow bbbb$ in events with 2 displaced vertices and Z boson reconstructed from ee or mumu pair
Exotic Higgs Decays: Displaced Vertex Reconstruction

- Studied options of **DV reconstruction implemented in the FCCAnalyses framework** with extra constraints and functions inspired by **ATLAS DV reconstruction**


- Added **vertex merging** to reconstruct the scalar DVs

  - Need to understand goodness of fit results (see Magda’s talk at ECFA WG1-SRCH meeting)

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**Diagram:**

- **Selected tracks with pT > 1 GeV and |d0| > 2 mm**
- **SVs within 10σ or 1 mm**
- **Primary Vertex Finding**
- **Secondary Vertex Finding**
- **Vertex Merging**
- **Displaced Vertex**

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**Graphs:**

- **FCCAnalyses: FCC-ee Simulation (Delphes)**
  - DVs vs. 20 mm
  - mS = 240.0 GeV
  - l^+ l^- \rightarrow Z, Z \rightarrow l^+ l^-, h \rightarrow s \bar{s}, b \bar{b}

- **Number of DVs**
  - Peak = 2-3
  - Peak = 4
  - mS = 20 GeV, sin θ = 1e-6

- **Graph:**
  - no selection
  - pT > 1 GeV
  - pT > 1 GeV and |d0| > 2 mm
  - pT > 1 GeV and |d0| > 2 mm + merging
Exotic Higgs Decays: Sensitivity

Selection:

<table>
<thead>
<tr>
<th>Type</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Track Selection</td>
<td>$p_T$</td>
<td>1 GeV</td>
</tr>
<tr>
<td></td>
<td>$</td>
<td>d_0</td>
</tr>
<tr>
<td>Vertex Reconstruction</td>
<td>$V^0$ rejection</td>
<td>True</td>
</tr>
<tr>
<td></td>
<td>Max $\chi^2$</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>Max $M_{nmv}$</td>
<td>40 GeV</td>
</tr>
<tr>
<td></td>
<td>Max $\chi^2$ added track</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Vertex merging</td>
<td>False</td>
</tr>
<tr>
<td>Vertex Selection</td>
<td>$\tau_{DV-PV}$</td>
<td>4 mm</td>
</tr>
<tr>
<td></td>
<td>$\tau_{DV-PV}$</td>
<td>2000 mm</td>
</tr>
<tr>
<td></td>
<td>$M_{charged}$</td>
<td>1 GeV</td>
</tr>
</tbody>
</table>

Sensitivity:

- Backgrounds:

<table>
<thead>
<tr>
<th></th>
<th>Before selection</th>
<th>Pre-selection</th>
<th>$70 &lt; m_H &lt; 110$ GeV</th>
<th>n_DVs ≥ 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>WW</td>
<td>8.22e+07 ± 7.45e+06</td>
<td>2.11e+06 ± 4.16e+04</td>
<td>4.69e+05 ± 1.96e+04</td>
<td>0 (≤ 1.96e+04)</td>
</tr>
<tr>
<td>ZZ</td>
<td>6.79e+06 ± 1.77e+03</td>
<td>8.91e+05 ± 7.78e+03</td>
<td>5.85e+05 ± 6.31e+03</td>
<td>0 (≤ 8.31e+03)</td>
</tr>
<tr>
<td>ZH</td>
<td>1.01e+06 ± 1.01e+04</td>
<td>5.97e+04 ± 7.76e+02</td>
<td>4.75e+04 ± 6.93e+02</td>
<td>0 (≤ 8.93e+02)</td>
</tr>
</tbody>
</table>

- Signals:

<table>
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<tr>
<th>$m_H$, $\sin \theta$</th>
<th>Before selection</th>
<th>Pre-selection</th>
<th>$70 &lt; m_H &lt; 110$ GeV</th>
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<tr>
<td>20 GeV, 1e-5</td>
<td>44.3 ± 0.0295</td>
<td>29.8 ± 0.363</td>
<td>28.9 ± 0.358</td>
<td>3.55 ± 0.125</td>
</tr>
<tr>
<td>20 GeV, 1e-6</td>
<td>44.3 ± 0.0295</td>
<td>30.4 ± 0.367</td>
<td>29.7 ± 0.363</td>
<td>22.4 ± 0.315</td>
</tr>
<tr>
<td>20 GeV, 1e-7</td>
<td>44.3 ± 0.0295</td>
<td>36.3 ± 0.401</td>
<td>35.6 ± 0.397</td>
<td>0.531 ± 0.0485</td>
</tr>
<tr>
<td>60 GeV, 1e-5</td>
<td>13.1 ± 0.00474</td>
<td>8.38 ± 0.105</td>
<td>8.12 ± 0.103</td>
<td>0 (≤ 0.103)</td>
</tr>
<tr>
<td>60 GeV, 1e-6</td>
<td>13.1 ± 0.00474</td>
<td>8.34 ± 0.104</td>
<td>8.09 ± 0.103</td>
<td>6.43 ± 0.0917</td>
</tr>
<tr>
<td>60 GeV, 1e-7</td>
<td>13.1 ± 0.00474</td>
<td>9.69 ± 0.113</td>
<td>9.45 ± 0.111</td>
<td>4.10 ± 0.0732</td>
</tr>
</tbody>
</table>

Selection:

- Pre-selection
- Z boson tag
- Multiplicity of DVs

- $\geq 2$ oppositely charged electrons or muons
- $70 < m_H < 110$ GeV
- n_DVs ≥ 2

All but 2 signal points could be excluded at 95% CL

See more in Magda’s talk at ECFA WG1-SRCH meeting
Dedicated LLP Detectors at Future Facilities?

- FCC-ee baseline is consistent with having 2 or 4 detectors
- Opportunities for new, creative designs!

**Lepton collider ideas:**
  - Instrument cavern walls with scintillators or RPCs
- **Study at ILC** ([PRD 107 (2023) 076022 / arXiv:2202.11714](https://doi.org/10.1103/PhysRevD.107.076022))
  - Conclude that ILD still does better for LL ALPs

**Hadron collider ideas:**
- **DELIGHT** ([PRD 106 (2022) 095018 / arXiv:2111.02437](https://doi.org/10.1103/PhysRevD.106.095018))
  - Transverse detector
  - Numerical package to simulate sensitivity of far-forward detectors
- **FOREHUNT** ([arXiv:2306.11803](https://arxiv.org/abs/2306.11803))
  - Forward detector
  - See next slide
FOREHUNT

- Brand new proposal (June 20, 2023)
- Place dedicated LLP detector in the forward region at the FCC-hh
- Target LLPs from B-meson decays

- Assume main FCC-hh detector at $z \in [-25, 25]$ m and sufficient shielding
- Put FOREHUNT at at least 50 m in $z$
- Option: put FOREHUNT-C slightly off z-axis
  - 1 m off z-axis: acceptance drops by factor of 2
  - 5 m off z-axis: acceptance falls drastically

Dark Higgs scalar:

$$B^\pm \rightarrow K^\pm \phi$$

HNLs:

$$B^0 \rightarrow D^{\pm\tau^\pm}N_\tau,$$

$$B^\pm \rightarrow D^0\tau^\pm N_\tau,$$

$$B^\pm \rightarrow \tau^\pm N_\tau.$$
... to all who provided input for this talk

- Anna Sfyrla (University of Geneva)
- Daniel Beech (University of Cambridge)
- Dimitri Moulin (University of Geneva)
- Giacomo Polesello (INFN)
- Giulia Ripellino (Uppsala University)
- Juliette Alimena (DESY)
- Lorenzo Bellagamba (INFN)
- Magdalena Vande Vorde (KTH)
- Nicolo Valle (INFN)
- Pantelis Kontaxakis (University of Geneva)
- Rebeca Gonzalez Suarez (Uppsala University)
- Sarah Williams (University of Cambridge)
- Suchita Kulkarni (University of Graz)
LLPs at FCC-ee group

- Informal group with:
  - Meetings: [https://indico.cern.ch/category/5664/](https://indico.cern.ch/category/5664/)
  - Mailing lists:
    - LLP-FCCee-informal@cern.ch
    - FCC-PED-PhysicsGroup-BSM@cern.ch —> meetings announced here

- We welcome new people, join us!
Summary

• The FCC will have the ability to uniquely probe LLP areas of phase space, and discovery potential!
• Many interesting signals: Heavy Neutral Leptons, hidden sectors, axion-like particles, exotic Higgs decays, and more
• We now have the opportunity to design detectors and algorithms with LLPs in mind
• Also to consider: dedicated LLP detectors at the FCC
• Plenty of phase space to explore at the FCC! Let’s make sure we don’t miss new physics!
Backup
• At the FCC-ee, should look at total momentum, $\theta$, and total missing energy!
• Generator-level distributions look as expected
  • Momentum decreases as HNL mass increases
  • Slightly more central events as HNL mass increases
Confirmed HNL signal kinematics behave as expected, at gen and reco level

For example, for $m = 50$ GeV, $V_e = 1.41e-6$, the mean of the generated lifetime is $1.5E-9$ s $\rightarrow$ 45 cm, which is what we expected.

On the other hand, $m = 90$ GeV, $V_e = 1.41e-6$ is pretty prompt.

Reco $L_{xyz}$ (3D decay length) and vertex $\chi^2$ distributions are also understood.

- $m = 30$ GeV, $V_e = 1.41e-6$ is fairly displaced, so less isolated electrons are reconstructed.
Selection

- Preliminary event selection
- Tables show the expected number of events at 150 ab\(^{-1}\), cumulative after each cut (on reco variables)
  - Here used \(10^7—10^9\ (5\times10^4)\) raw/unscaled events for background (signal)
    - Will need to generate larger samples for some background
  - Most discriminating variables explored so far: missing energy and \(|d_0|\)

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<td>Most discriminating variables explored so far: missing energy and (</td>
</tr>
</tbody>
</table>

| Selection | Before selection | Exactly 2 reco e | Veto photons, muons, and jets | \(p > 10\) GeV | \(|d_0| > 0.5\) mm |
|-----------|------------------|-----------------|--------------------------------|----------------|-----------------|
| \(Z \rightarrow ee\) | \(2.19 \times 10^{11} \pm 6.94 \times 10^7\) | \(1.75 \times 10^{11} \pm 6.19 \times 10^7\) | \(1.53 \times 10^{11} \pm 5.80 \times 10^7\) | \(7.07 \times 10^8 \pm 3.94 \times 10^6\) | \(\leq 3.94 \times 10^6\) |
| \(Z \rightarrow bb\) | \(9.97 \times 10^{11} \pm 4.14 \times 10^7\) | \(5.64 \times 10^8 \pm 9.85 \times 10^5\) | \(3.25 \times 10^5 \pm 2.36 \times 10^4\) | \(1.22 \times 10^5 \pm 1.45 \times 10^4\) | \(1.72 \times 10^3 \pm 1.72 \times 10^3\) |
| \(Z \rightarrow \tau\tau\) | \(2.21 \times 10^{11} \pm 7.00 \times 10^7\) | \(5.49 \times 10^9 \pm 1.10 \times 10^7\) | \(5.10 \times 10^9 \pm 1.06 \times 10^7\) | \(2.52 \times 10^9 \pm 7.47 \times 10^6\) | \(6.64 \times 10^4 \pm 3.84 \times 10^4\) |
| \(Z \rightarrow cc\) | \(7.82 \times 10^{11} \pm 2.61 \times 10^7\) | \(1.69 \times 10^7 \pm 1.21 \times 10^5\) | \(5.22 \times 10^3 \pm 2.13 \times 10^3\) | \(1.74 \times 10^3 \pm 1.23 \times 10^3\) | \(\leq 1.23 \times 10^3\) |
| \(Z \rightarrow uds\) | \(2.79 \times 10^{12} \pm 8.83 \times 10^7\) | \(2.30 \times 10^7 \pm 2.54 \times 10^5\) | \(2.79 \times 10^3 \pm 2.79 \times 10^3\) | \(\leq 2.79 \times 10^3\) | \(\leq 2.79 \times 10^3\) |

| \(m_N\) | \(10\) GeV, \(|V_{cN}| = 2 \times 10^{-4}\) | \(2534 \pm 11\) | \(1006 \pm 7\) | \(996 \pm 7\) | \(951 \pm 7\) | \(907 \pm 7\) |
|----------|---------------------------------|--------------|-----------------|----------------|----------------|----------------|
| \(m_N\) | \(20\) GeV, \(|V_{cN}| = 9 \times 10^{-5}\) | \(458 \pm 2\) | \(313 \pm 2\) | \(308 \pm 2\) | \(293 \pm 2\) | \(230 \pm 1\) |
| \(m_N\) | \(20\) GeV, \(|V_{cN}| = 3 \times 10^{-5}\) | \(51.0 \pm 0.2\) | \(34.7 \pm 0.2\) | \(34.2 \pm 0.2\) | \(32.6 \pm 0.2\) | \(31.2 \pm 0.2\) |
| \(m_N\) | \(30\) GeV, \(|V_{cN}| = 1 \times 10^{-5}\) | \(5.01 \pm 0.02\) | \(3.85 \pm 0.02\) | \(3.76 \pm 0.02\) | \(3.54 \pm 0.02\) | \(3.39 \pm 0.02\) |
| \(m_N\) | \(50\) GeV, \(|V_{cN}| = 6 \times 10^{-6}\) | \(1.23 \pm 0.01\) | \(0.99 \pm 0.01\) | \(0.96 \pm 0.01\) | \(0.92 \pm 0.01\) | \(0.729 \pm 0.004\) |
2nd Physics Case: LL Axion-Like Particles

- Axion-like Particles (ALPs) are pseudo Nambu-Goldstone bosons of spontaneously broken global symmetries in BSM scenarios
- Very weakly coupled to the dark sector
- Get long-lived ALPs when couplings and mass are small
- At the FCC-ee:
  - Orders of magnitude of parameter space accessible
  - Especially sensitive to final states with at least 1 photon

- Privately generated ALPs in Madgraph5 v3.2.0 + Pythia8 + Delphes, with the latest IDEA card, $\sqrt{s} = 91$ GeV

• Started with simulating 1 GeV ALP mass, vary the coupling
• ALP mass confirmed with the reco invariant mass from the 2 photons coming from the ALP
• ALP decay length will also be a nice discriminating variable
• Ready for more personpower to step in and complete an analysis, guidance available!