Long-lived Particles Searches at CEPC

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This talk is based on K.C. Wang's talk @ CEPC New Physics and Flavor Physics Workshop in August, 2023

Physics Motivations

Long-lived particles (LLPs) are important ways to new physics

- **Relatively long lifetime naturally appear in many BSM models**
  - **feeble couplings to SM particles**
  - **phase space suppression**
  - **approximate symmetry**
  - **heavy mediators…**
- **Non-ambiguous signal for new physics**
  - **Leads to origin of dark matter, neutrino mass, baryogenesis…**
- **Distinct and detectable signature**
  - **Displaced vertex/object with a relatively long distance from main vertex (collision point)**
  - **For neutral particles: burst of energy appearing out of nowhere and far away from collision point**
  - **For charged particles: disappearing tracks, heavy/multi-charged particles**

LLPs Search Principle

$\lambda = \beta\gamma\, c\tau$

$\beta\gamma$: Kinematics

λ : decay length in the lab. frame

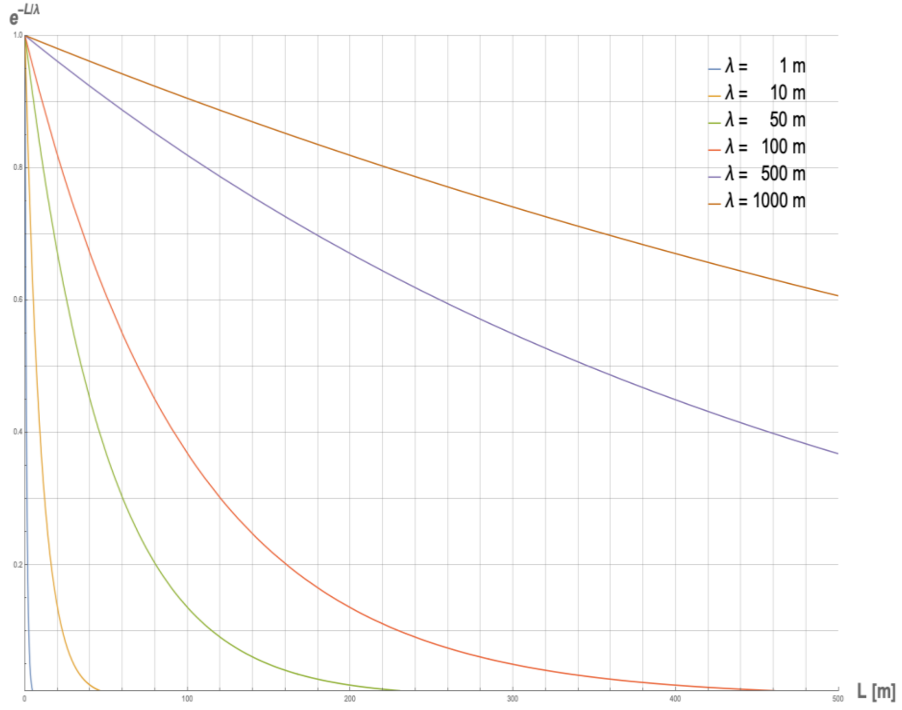
τ : lifetime in the rest frame

- **Probability of decaying between L_1 and L_2 ($L_1 < L_2$)**

$$P(\Delta L) = e^{-L_1/\lambda} - e^{-L_2/\lambda}$$

- **L_1 and L_2 : Determined by the detector (position, shape, volume, ...) and LLP's moving direction**

Exponential Decay



LLPs Search Principle

$\lambda = \beta\gamma\, c\tau$

λ : decay length in the lab. frame

$\beta\gamma$: Kinematics

τ : lifetime in the rest frame

$N_{\mathrm{exp}} = N_{\mathrm{prod}} \cdot P(\Delta L) \cdot \mathrm{Br} \cdot \epsilon$

N_{prod} : number of LLPs produced

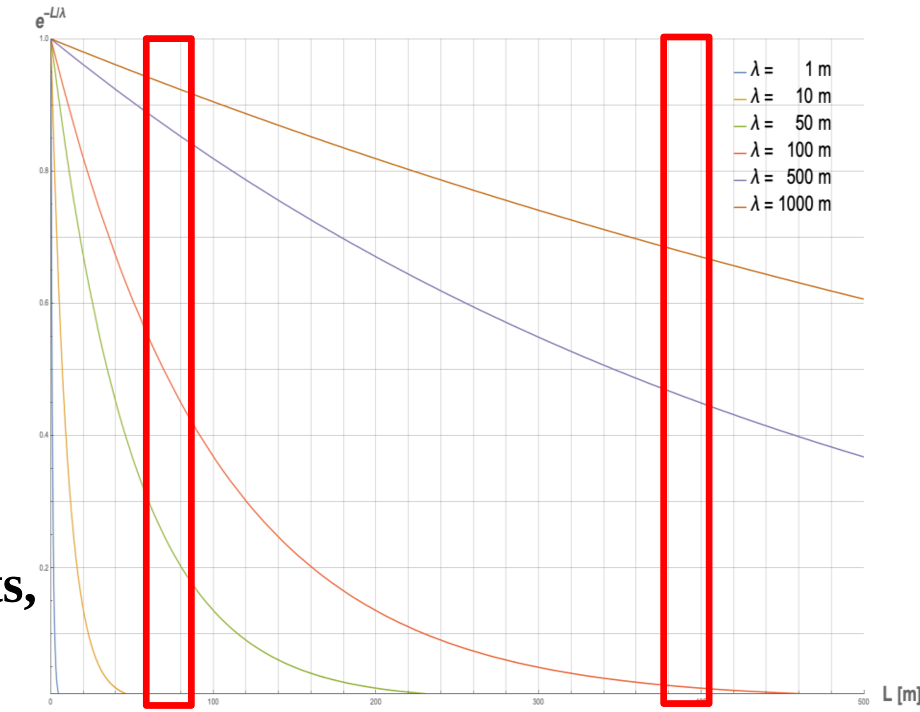
$P(\Delta L)$: probability of LLPs decaying inside the detector’s fiducial volume

Br: branching ratio of LLP decaying into visible final state

ϵ: detector efficiency

N_{exp}: number of expected signal events, depends on theory model parameters (mass, lifetime, kinematics), detector geometry and performance (position, shape, volume, efficiency)

Exponential Decay



Near detector

Far detector

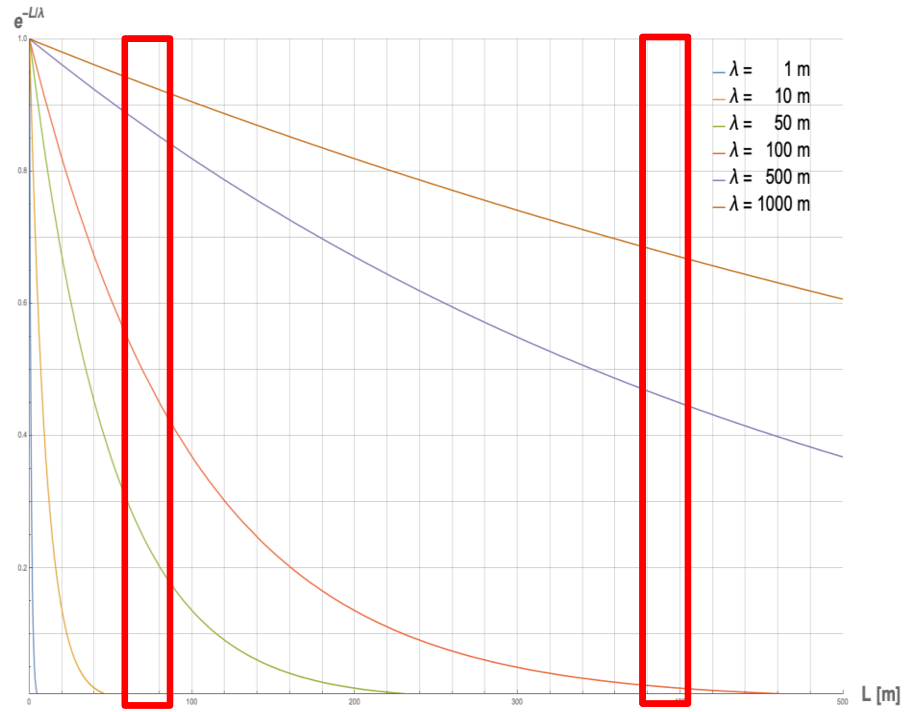
LLPs Search Principle

$\lambda = \beta\gamma\, c\tau$ λ : decay length in the lab. frame

$\beta\gamma$: Kinematics τ : lifetime in the rest frame

- Near detector: more signal yields but much more backgrounds
- Far detector: less signal yields but mostly background free
- Lepton collider: high lumi, clean environment, recoil strategy, triggerless, transverse direction
- Hadron collider: complex environment, forward direction

Exponential Decay



Near detector Far detector

Signatures in Near Detector

- **Mainly decay inside near detector :** $\boldsymbol{\lambda \sim \mathcal{O}(1)\ m}$

- **Mostly displaced vertex or objects**

- **Various final states with different decay products**

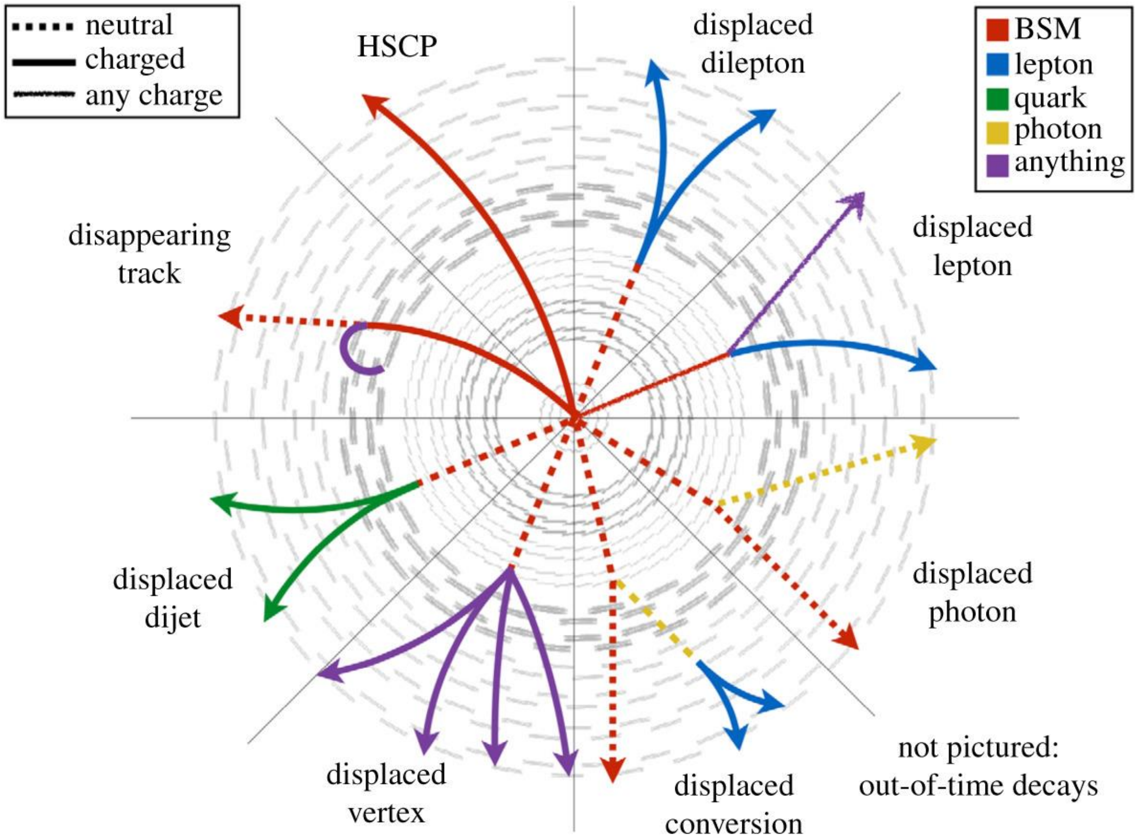
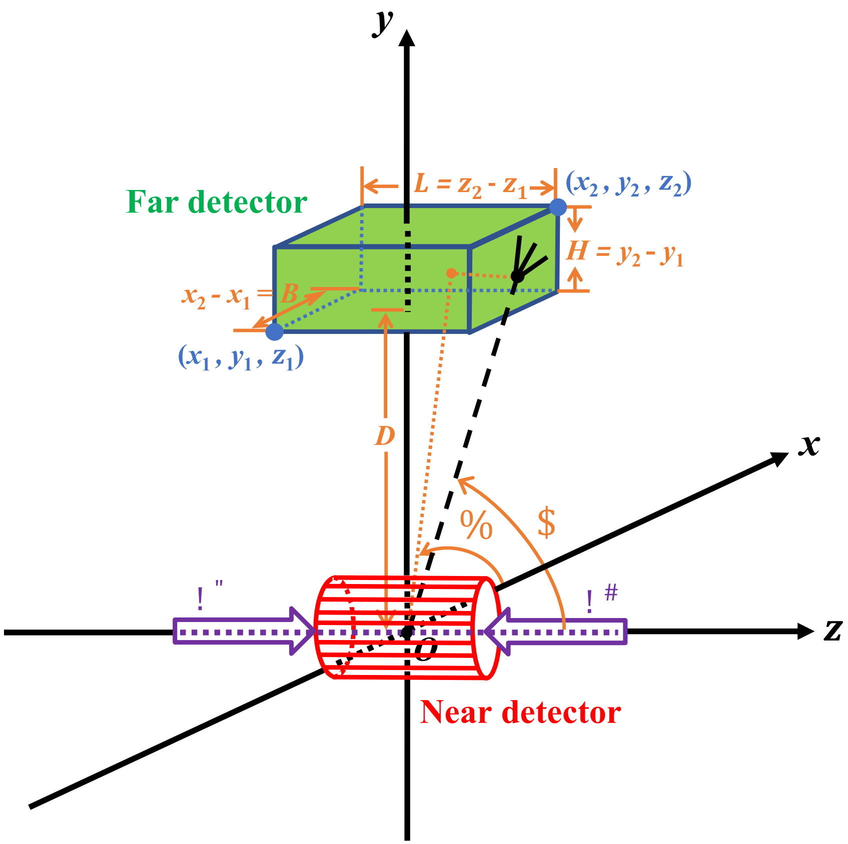


Figure from [A. De Roeck, Phil. Trans. Roy. Soc. Lond. A 377, 20190047 (2019)]

Signatures in Far Detector

- Mainly travel through and acts as missing energy in near detector
- Far detector $\lambda \sim \mathcal{O}(100)m$ is more likely to observe the decay process, and reconstruct the time, position, direction, momentum, mass, etc.
- Far detector can enhance the discovery potential for LLPs with extra long decay length



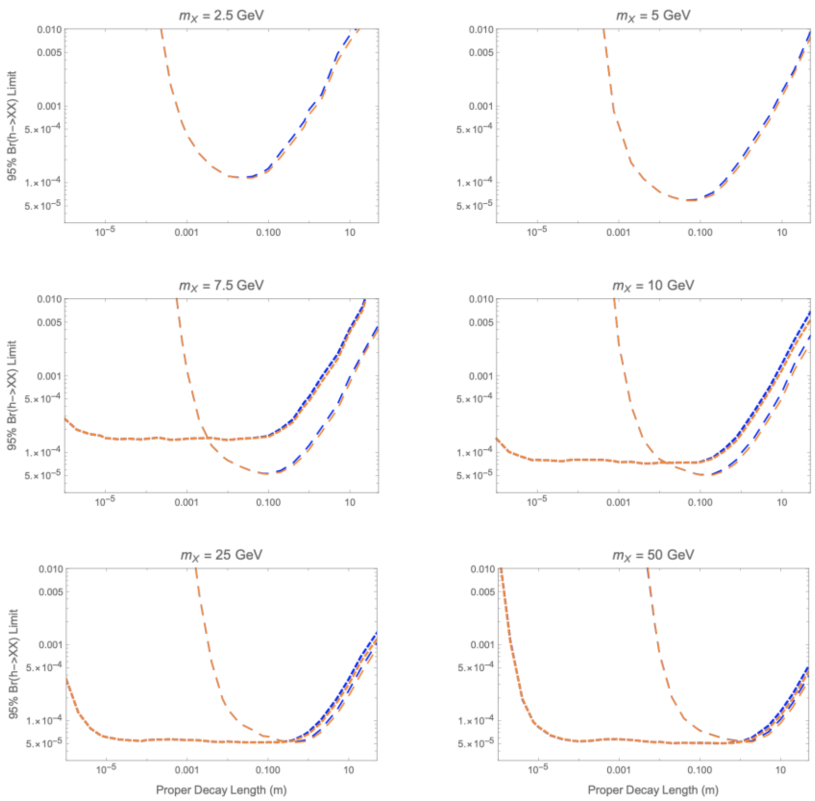
[1911.06576, Zeren Simon Wang and Kechen Wang, Physics with far detectors at future lepton colliders]

LLPs Searches at CEPC (Lepton Colliders)

- **Near detector searches**
- **Far detector searches**
- **Beam dump searches**
- **Discussions**

New Scalars in Higgs Decay

$$e^- e^+ \rightarrow HZ \rightarrow (XX)\,(l^- l^+) \;@\; \sqrt{s} = \textbf{250 GeV}$$



In the zero-background regime, Poisson statistics rules out model points which predict 3 or more signal events to 95% confidence (or better) if no signal is detected. We may then find a projected 95% upper limit on branching ratio as

$$\mathrm{Br}(h \to XX)^{95} = \frac{N_{sig}}{\mathcal{L} \times \sigma(e^+e^- \to hZ) \times \mathrm{Br}(Z \to \ell\ell) \times A \times \varepsilon}, \tag{3.1}$$

with $N_{sig} = 3$ and $A \times \varepsilon$ the result of our simulations. For both the CEPC and FCC-ee, the most recent integrated luminosity projections [4, 39] give $\mathcal{L} \times \sigma(e^+e^- \to hZ) = 1.1 \times 10^6$ Higgses produced.

Figure 1: Projected 95% $h \to XX$ branching ratio limits as a function of proper decay length for a variety of X masses. Blue lines are for CEPC and orange lines are for FCC-ee, and where only one is visible they overlap. The larger dashes are the 'long lifetime' analysis and the smaller dashes are the 'large mass' analysis.

[1812.05588, Samuel Alipour-Fard, Nathaniel Craig, Minyuan Jiang, and Seth Koren, Long Live the Higgs Factory: Higgs Decays to Long-Lived Particles at Future Lepton Colliders]

New Scalars in Higgs Decay

$h \to h_s h_s, h_s \to \mu^- \mu^+, \pi^- \pi^+$ @ $\sqrt{s} = 240$ GeV

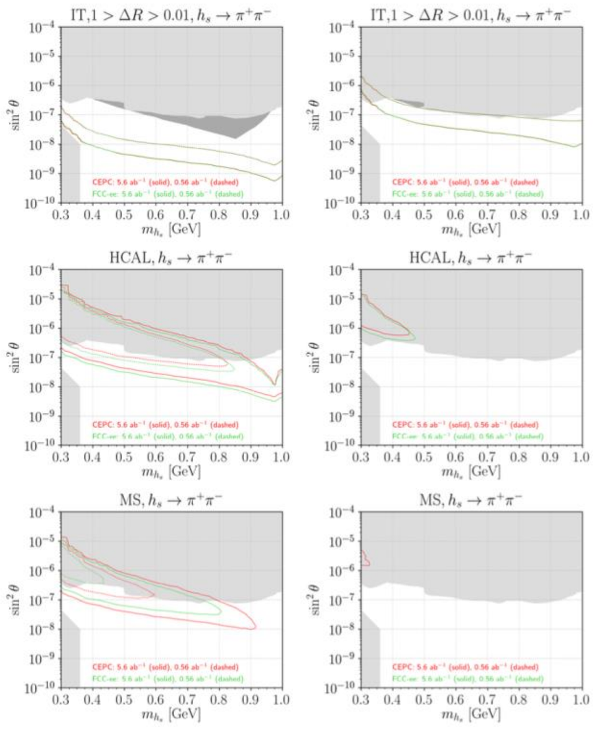


FIG. 5. Sensitivity reaches at the CEPC and FCC-ee for $h_s \to \pi^+\pi^-$. The left panels correspond to $\langle\chi\rangle = 10$ GeV while the right ones to $\langle\chi\rangle = 100$ GeV. The light gray area is experimentally excluded while the dark gray part shown in the upper row can be probed at the LHC with 300 fb^{-1} integrated luminosity.

Mirror glueballs: $h \to 0^{++}0^{++}, 0^{++} \to \xi\xi$ @ $\sqrt{s} = 240$ GeV

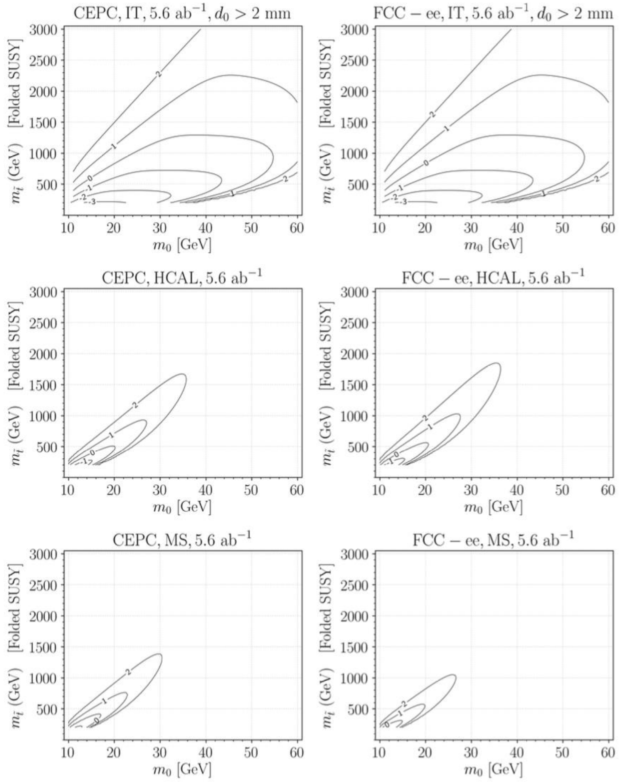
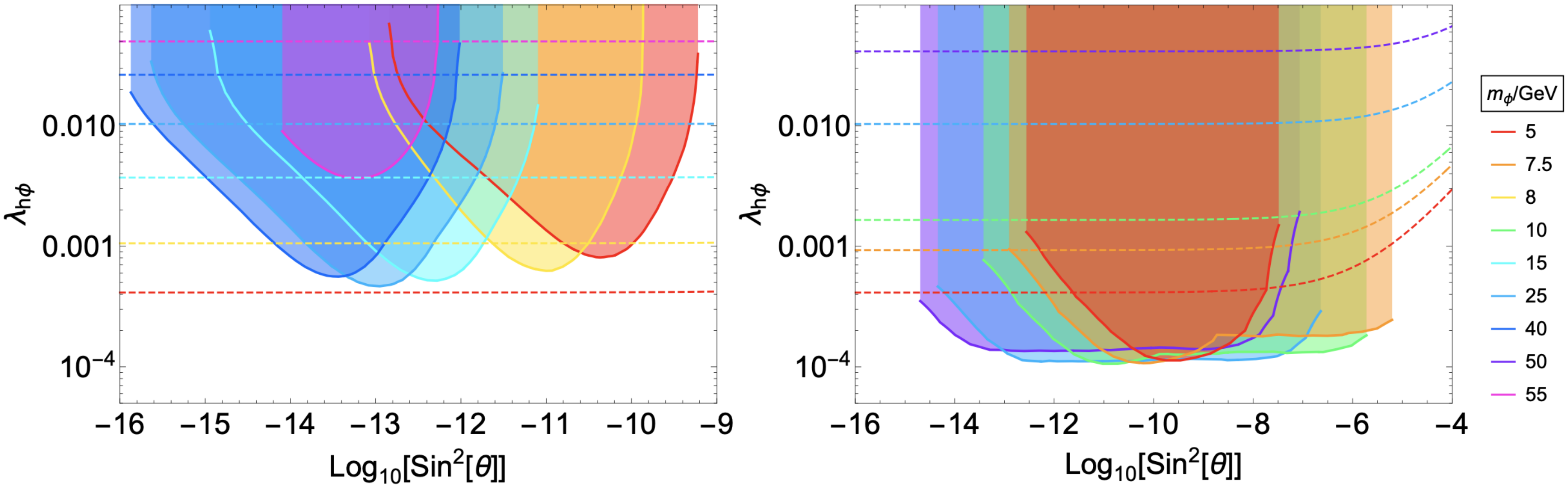


FIG. 7. Sensitivity reaches of $\log_{10}(\kappa)$ at the CEPC and FCC-ee for the Folded SUSY model for $N_{\text{signal}} = 10$.

[1911.08721, Kingman Cheung and Zeren Simon Wang, Probing Long-lived Particles at Higgs Factories]

New Scalars in Higgs Decay

$h \to \phi\phi$ @ $\sqrt{s} = 240$ GeV



(a) ATLAS $\sqrt{s} = 13$ TeV with 36 fb^{-1}. (b) FCC-ee $\sqrt{s} = 240$ GeV with 5 ab^{-1}.

Figure 4. Bounds on $\lambda_{h\phi}$ and $\sin^2\theta$ for various singlet masses arising from searches for displaced jets in Higgs decays. The dashed lines show the upper naturalness limit $\lambda_{h\phi}^{\max} = m_\phi^2/v^2 + 4\pi m_\phi s_\theta/v$.

[2008.12773, Elina Fuchs, Oleksii Matsedonskyi, Inbar Savoray, Matthias Schlaffer, Collider searches for scalar singlets across lifetimes]

Hidden Valley Particles in Higgs Decay

$H \to \pi_V^0 \pi_V^0 \to (b\bar{b})(b\bar{b})$ @ $\sqrt{s}$ = 350 GeV & 3 TeV

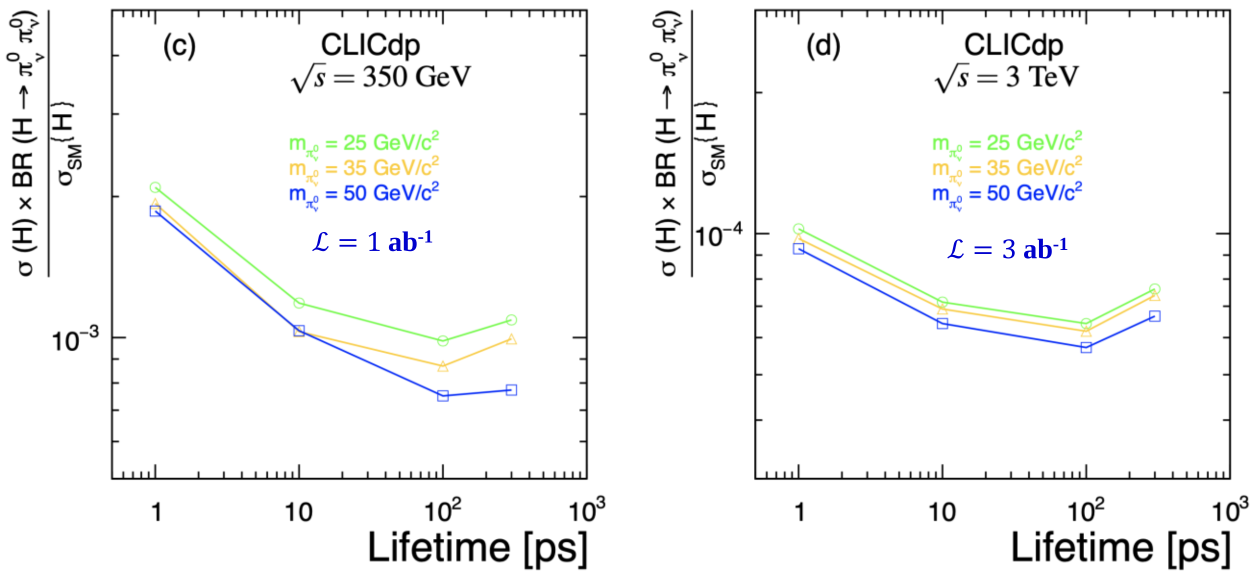


Figure 7: Expected 95% CL cross-section upper limits on the $\sigma(H) \times BR(H \to \pi_v^0 \pi_v^0)$, within the model [2], for three different π_v^0 masses: 25 GeV/c^2 (green), 35 GeV/c^2 (yellow), 50 GeV/c^2 (blue), as a function of π_v^0 lifetime for $\sqrt{s} = 350$ GeV (a) and $\sqrt{s} = 3$ TeV (b). The bottom row shows the upper limits normalized to the Standard Model production cross-section of the Higgs boson at $\sqrt{s} = 350$ GeV (c) and $\sqrt{s} = 3$ TeV (d).

[2212.04147, Marcin Kucharczyk and Mateusz Goncerz, Search for exotic decays of the Higgs boson into long-lived particles with jet pairs in the final state at CLIC]

Dark Photons in Higgs Decay

$$e^- e^+ \to HZ,\ H \to \gamma_D\gamma_D, \gamma_D \to f\bar{f}, l^- l^+ \text{ @ } \sqrt{s} = 250 \text{ GeV}$$

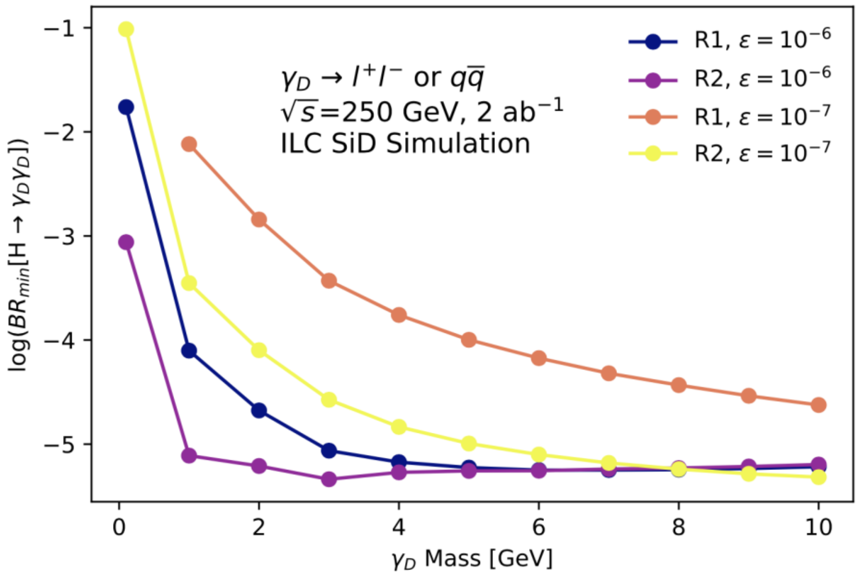


FIG. 6: The minimum branching ratio $H \to \gamma_D\gamma_D$ to which SiD will be sensitive for $\sqrt{s} = 250$ GeV and 2 ab^{-1}, when both leptonic and hadronic decays are reconstructed within the regions $R1$ and $R2$, for $\epsilon = 10^{-6}, 10^{-7}$.

[2203.08347, Laura Jeanty, Laura Nosler, and Chris Potter, Sensitivity to decays of long-lived dark photons at the ILC]

Neutralinos in Z decay

RPV-SUSY neutralinos: $Z \to \tilde{\chi}_1^0 \tilde{\chi}_1^0,\ \tilde{\chi}_1^0 \to e^{\mp} K^{(*)\pm}, e^{\mp} jj$ @ $\sqrt{s} = 91.2$ GeV

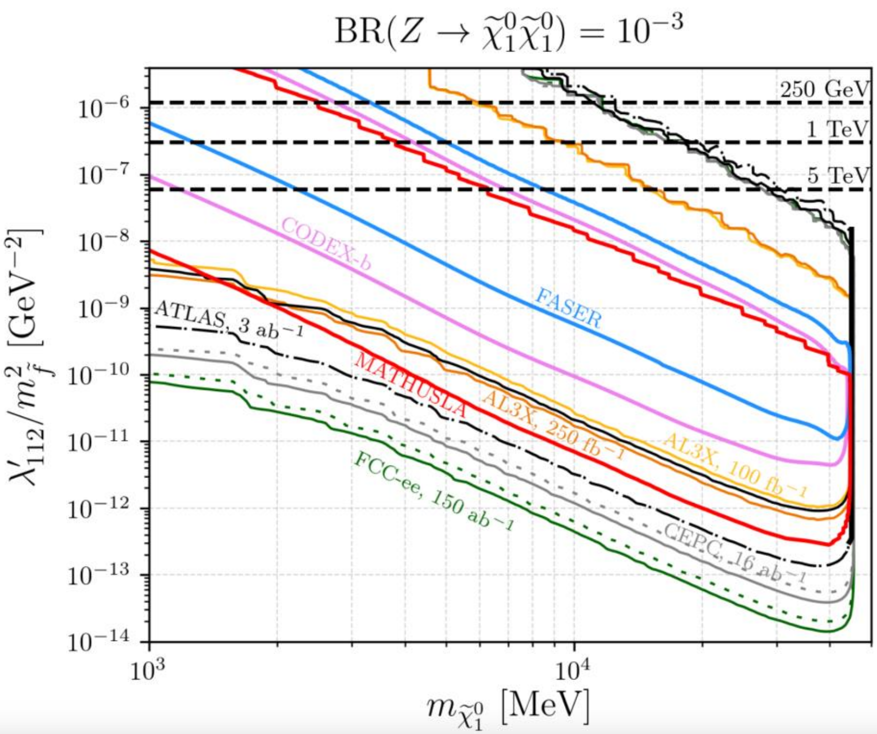
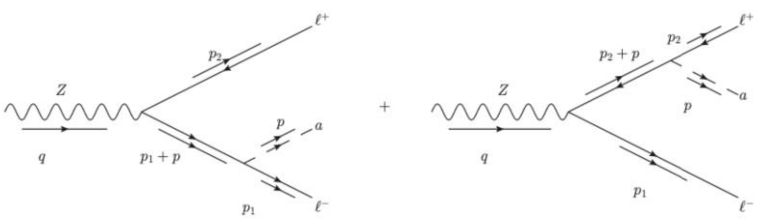


FIG. 1. The discovery limits of long-lived neutralinos for the near detector of CEPC/FCC-ee [7]. The solid contour curves correspond to three decay events in the fiducial volume when considering all decay modes of $\tilde{\chi}_1^0$, while the dashed lines include only visible/charged decay modes ($K^{(*)\pm} e^{\mp}$, $e^- us$ or $e^+ \bar{u}\bar{s}$). The estimates for experiments at the LHC: AL3X, CODEX-b, FASER and MATHUSLA, are reproduced from Refs. [8, 9]. The ATLAS results correspond to HL-LHC for $\sqrt{s} = 14$ TeV and 3 ab^{-1} integrated luminosity. The black horizontal dashed lines correspond to the current RPV bounds on the single coupling λ'_{112} [10] for three different degenerate sfermion masses $m_{\tilde{f}} = 250$ GeV, 1 TeV, and 5 TeV as labelled.

[1904.10661, Zeren Simon Wang, and Kechen Wang, Long-lived light neutralinos at future Z−factories]

Axion-like Particles in Z Deay

$$e^-e^+ \rightarrow Z^{(*)} \rightarrow l^-\, l^+ a\ @ \sqrt{s} = 91\ \text{GeV}$$



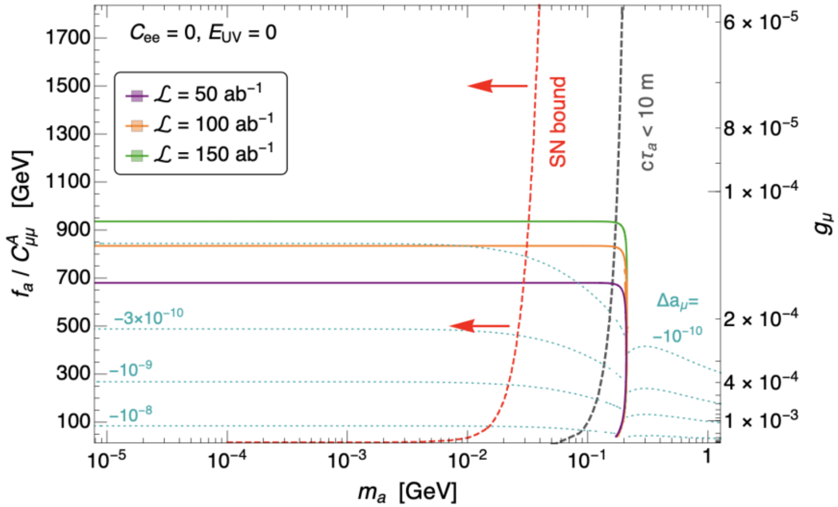
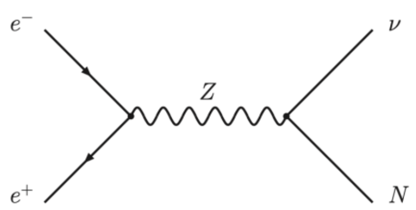


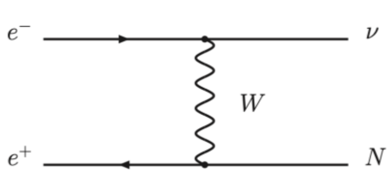
Figure 4: Prospected CEPC/FCC-ee 95% CL exclusion on the $(m_a,\ f_a/C^A_{\mu\mu})$ plane for a muonic ALP ($C^A_{ee} = 0$, $E_{\rm UV} = 0$) with different assumptions for the integrated luminosity $\mathcal{L}$, as indicated. On the right side of the dashed grey line the proper decay length of the ALP, as calculated using Eq. (8), is $c\tau_a < 10$ m. The region to the left of the red dashed line is excluded by SN1987A data, according to the analysis in [35]. The dotted cyan contours show the ALP contribution to the anomalous magnetic moment of the muon, $\Delta a_\mu \equiv (g-2)_\mu/2$. See the main text for details.

[2212.02818, Lorenzo Calibbi, Zijie Huang, Shaoyang Qin, Yiming Yang, and Xiaoyue Yin, Testing axion couplings to leptons in Z decays at future e-e+ colliders]

Heavy Neutral Leptons

$$e^-e^+ \to \nu\, N \;@\; \sqrt{s} = 240, 350, 500\ \text{GeV}$$





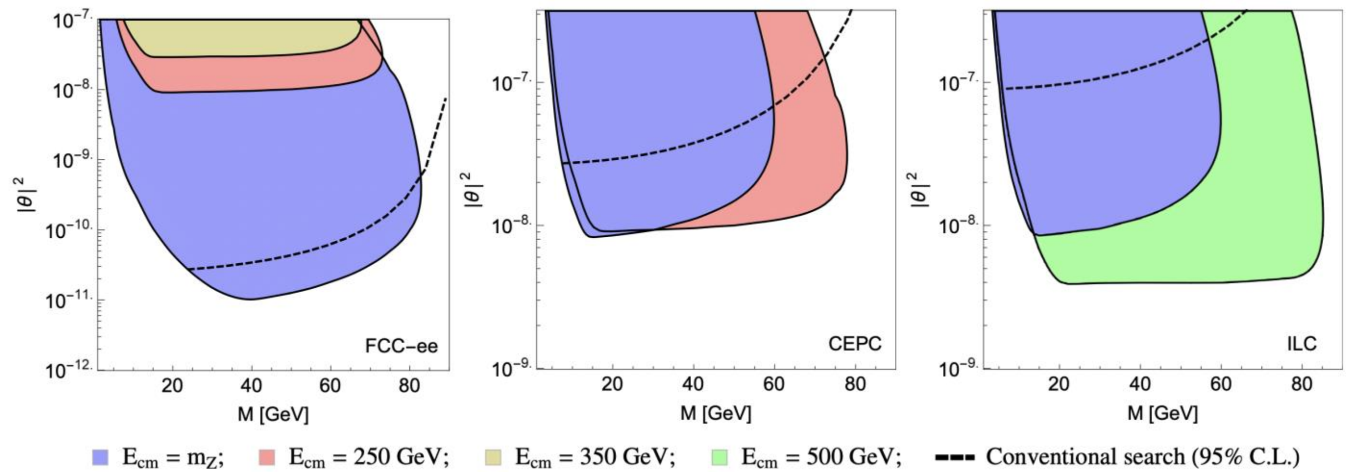


Figure 8: Sensitivity at 2σ for sterile neutrino searches via displaced vertices at the FCC-ee, the CEPC, and the ILC, assuming 100% signal efficiency. The colors denote the different modi operandi from fig. 4. The sensitivities for $E_{cm} \neq m_Z$ are understood for $|\theta|^2 = |\theta_e|^2$ (and θ_μ, $\theta_\tau = 0$). The SiD is used as benchmark detector for all the lepton collider experiments, for which we found heavy neutrino signals with vertex displacements between 10 μm and 249 cm to be essentially free of irreducible background, cf. section 4.2. The black dashed lines denote the conventional Z pole searches (cf. [10]).

[1604.0242, Stefan Antusch, Eros Cazzato, Oliver Fischer, Displaced vertex searches for sterile neutrinos at future lepton colliders]

Heavy Neutral Leptons

$e^- e^+ \to \nu\, N, NN; N \to \nu\gamma, 3f$ @ $\sqrt{s}$ = 91.2 GeV, 240 GeV, 3 TeV

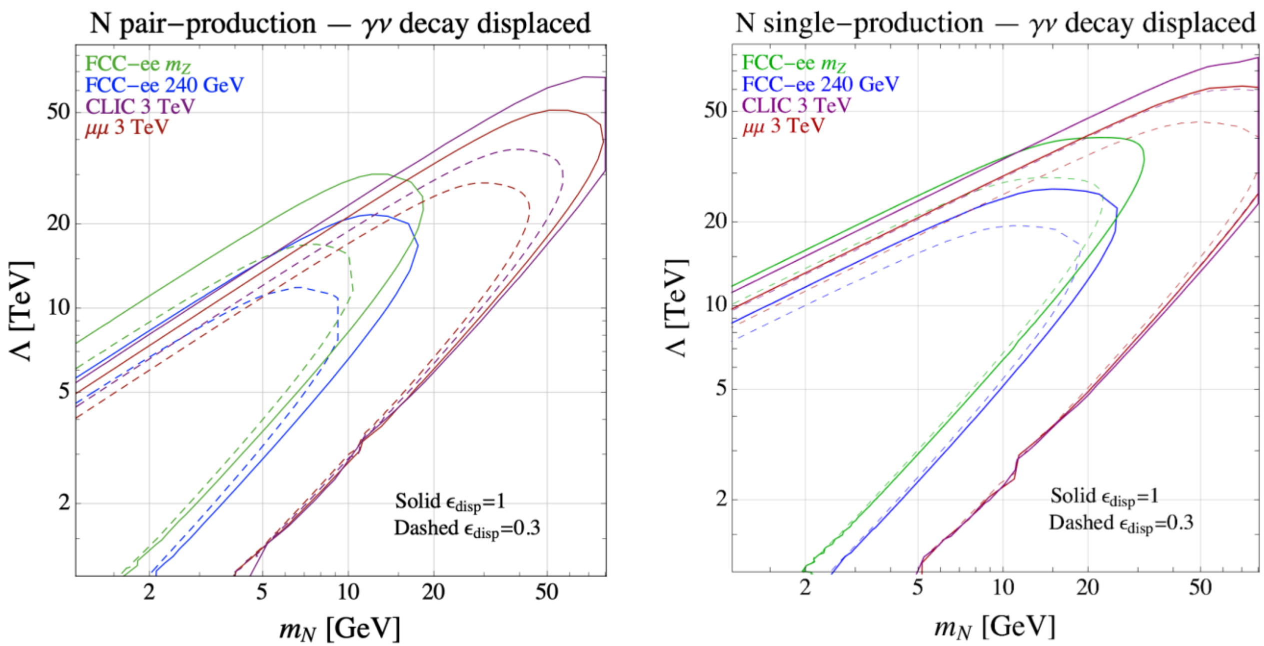
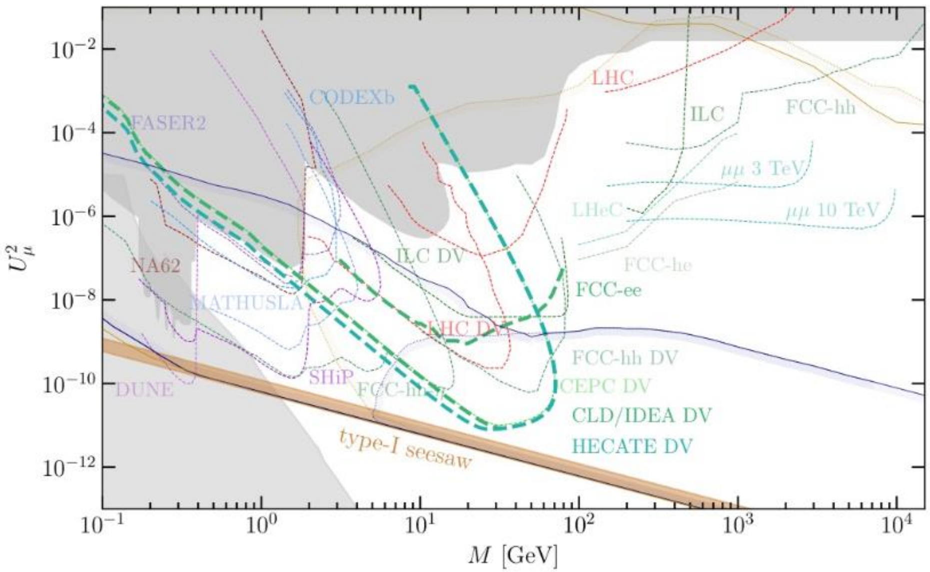


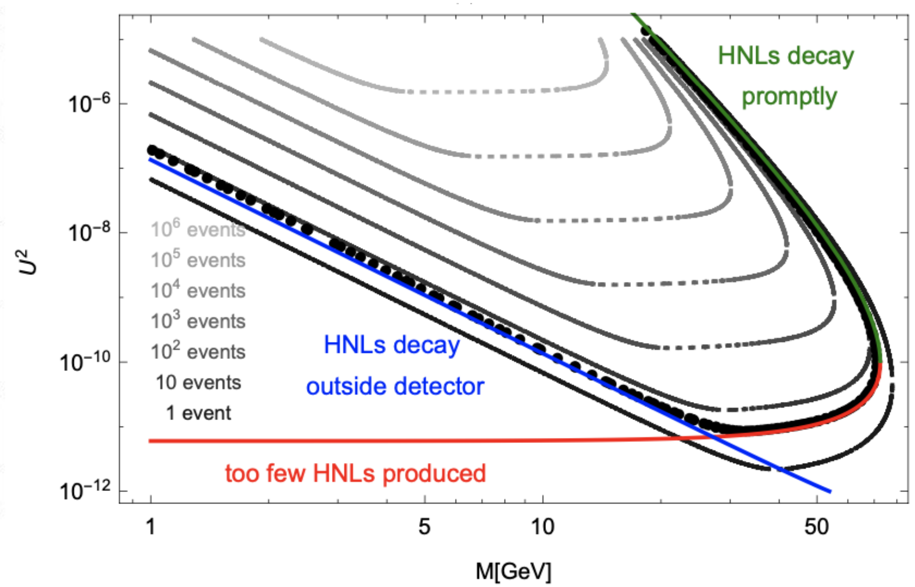
Figure 6. 95% CL exclusion limits for the displaced decay into a $\nu\gamma$ final state for pair produced (left) and singly produced (right) RH neutrinos. The solid lines correspond to $\epsilon_{\rm disp} = 1$ while the dashed ones to $\epsilon_{\rm disp} = 0.3$.

[2201.11754, Daniele Barducci and Enrico Bertuzzo, The see-saw portal at future Higgs factories: the role of dimension six operators]

Heavy Neutral Leptons

$$e^-e^+ \to \nu\, N \;@\; \sqrt{s} = 91.2\ \text{GeV}$$





[2210.1711, Marco Drewes, Distinguishing Dirac and Majorana Heavy Neutrinos at Lepton Colliders]

Heavy Neutral Leptons

$$e^- e^+ \rightarrow Z,\ Z \rightarrow \nu\, N, N \rightarrow l^-\, l^+ \nu, \gamma\nu \text{ @ } \sqrt{s} = 91.2\ \text{GeV}$$

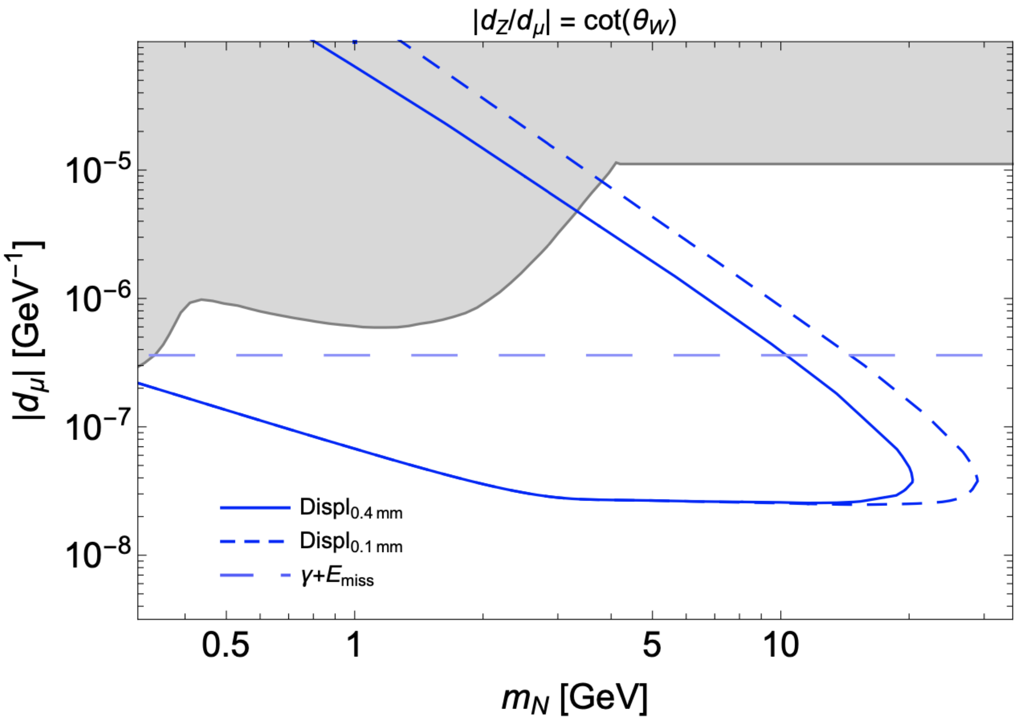


Figure 8: The potential of FCC-ee to probe the parameter space of the HNLs with the dipole coupling, see Sec. II B 2. The solid and short-dashed dark blue lines show the 90% CL sensitivity corresponding to the displaced decay signature, assuming the event selection considered in this paper (see Sec. IV A and Table III). The long-dashed lighter blue line denotes the sensitivity corresponding to the γ+missing energy signature.

[2301.08592, Maksym Ovchynnikov and Jing-Yu Zhu, Search for the dipole portal of heavy neutral leptons at future colliders]

SUSY Particles

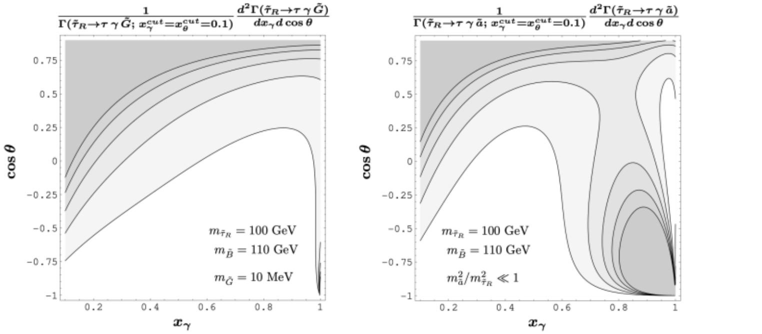


Figure 2: The normalized differential distributions of the visible decay products in the decays $\tilde{\tau} \to \tau\gamma\widetilde{G}$ for the gravitino LSP scenario (left) and $\tilde{\tau} \to \tau\gamma\tilde{a}$ for the axino LSP scenario (right) for $m_{\tilde{\tau}_1} = 100\,\mathrm{GeV}$, $m_{\widetilde{B}} = 110\,\mathrm{GeV}$, $m_{\tilde{a}}^2/m_{\tilde{\tau}_1}^2 \ll 1$, and $m_{\widetilde{G}} = 10\,\mathrm{MeV}$. The contour lines represent the values 0.2, 0.4, 0.6, 0.8, and 1.0, where the darker shading implies a higher number of events. Taken from [13].

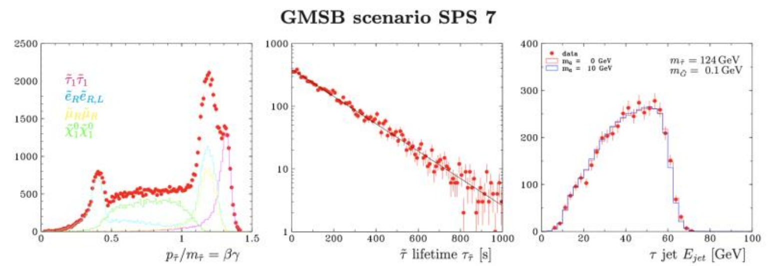


Fig. 3. SPS 7 scenario, assuming $\mathcal{L} = 100\,\mathrm{fb}^{-1}$ at $\sqrt{s} = 410\,\mathrm{GeV}$: (a) $\tilde{\tau}$ production spectra of scaled momentum $p/m = \beta\gamma$ with contributions from various processes; (b) $\tilde{\tau}$ lifetime distribution; (c) τ jet energy spectrum of the decay $\tilde{\tau}_1 \to \tau\widetilde{G}$ compared with simulations of $m_{\widetilde{G}} = 0\,\mathrm{GeV}$ and $10\,\mathrm{GeV}$

[1211.21950, Jan Heisig, Long-lived charged **sleptons** at the ILC/CLIC]

[0709.1030, Hans-Ulrich Martyn, Detection of long-lived **staus and gravitinos** at the ILC]

We analyze the prospects of observing lepton flavour violation in future e^-e^- and e^+e^- linear colliders in scenarios where the gravitino is the lightest supersymmetric particle, and the stau is the next-to-lightest supersymmetric particle. The signals consist of multilepton final states with two heavily ionizing charged tracks produced by the long-lived staus. The Standard Model backgrounds

[JHEP 0705:059,2007 Alejandro Ibarra and Sourov Roy, Lepton flavour violation in future linear colliders in the long-lived **stau** NLSP scenario]

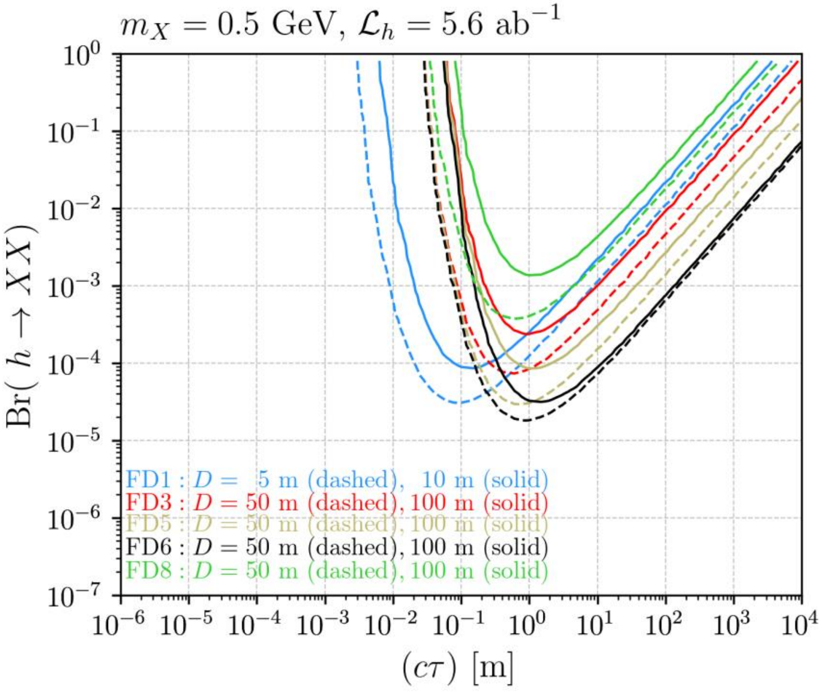
Searches with Far Detectors

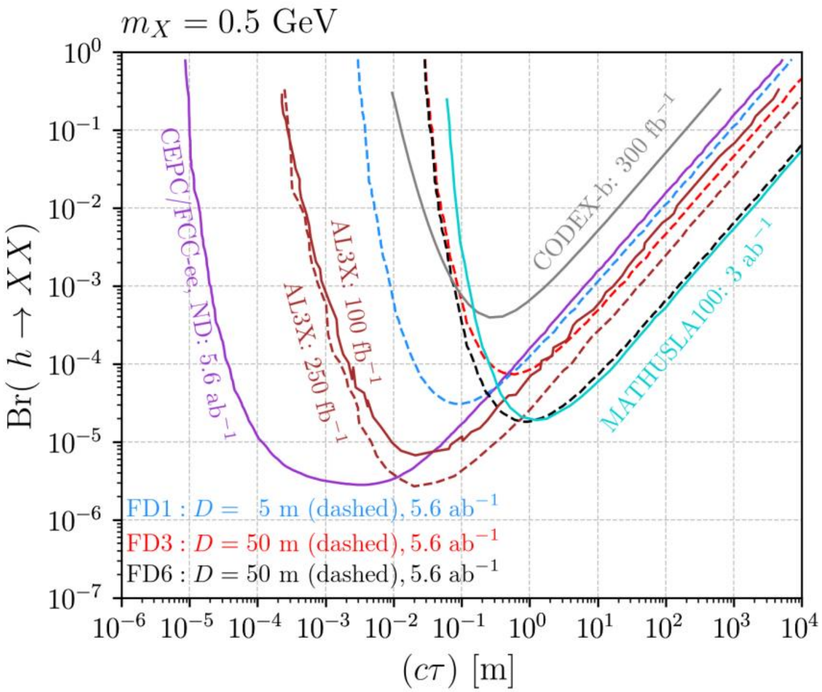
Scenario		Exotic Higgs Decay $h \to XX$	Heavy Neutral Leptons $Z \to N\nu$	RPV SUSY Light Neutralinos $Z \to \tilde{\chi}_1^0 \tilde{\chi}_1^0$
LLP		X (light scalar)	N	$\tilde{\chi}_1^0$ (light fermion)
production $e^- e^+ \to$		Zh (main) $\nu\nu h, e^- e^+ h$ (VBF)	Z	
$\sqrt{s}$[GeV]		240	91.2	
N_h	CEPC	1.14×10^6	-	
	FCC-ee			
N_Z	CEPC	-	1.5×10^{12}	
	FCC-ee		5.0×10^{12}	

[1911.06576, Zeren Simon Wang and Kechen Wang, Physics with far detectors at future lepton colliders]

Exotic Higgs Decays in FD

$$h \to XX \ @ \ \sqrt{s} = 240 \text{ GeV}$$

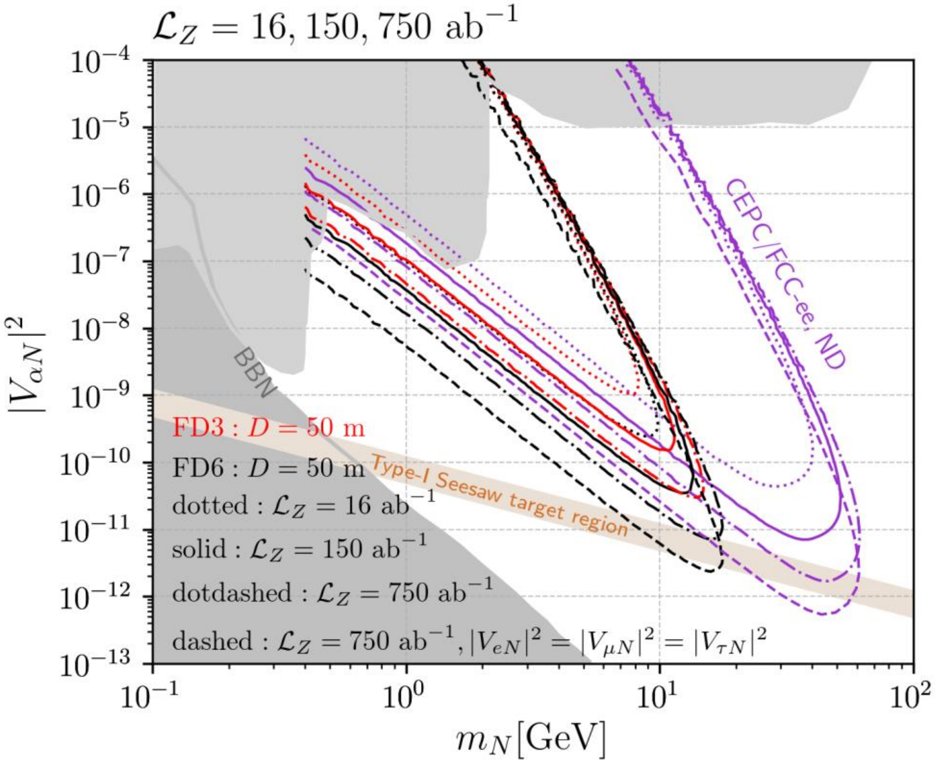




[1911.06576, Zeren Simon Wang and Kechen Wang, Physics with far detectors at future lepton colliders]

Heavy Neutral Leptons in FD

$$Z \to N\nu \; @ \sqrt{s} = 91.2 \text{ GeV}$$



750 ab^{-1}, 10 years, 4 IPs;

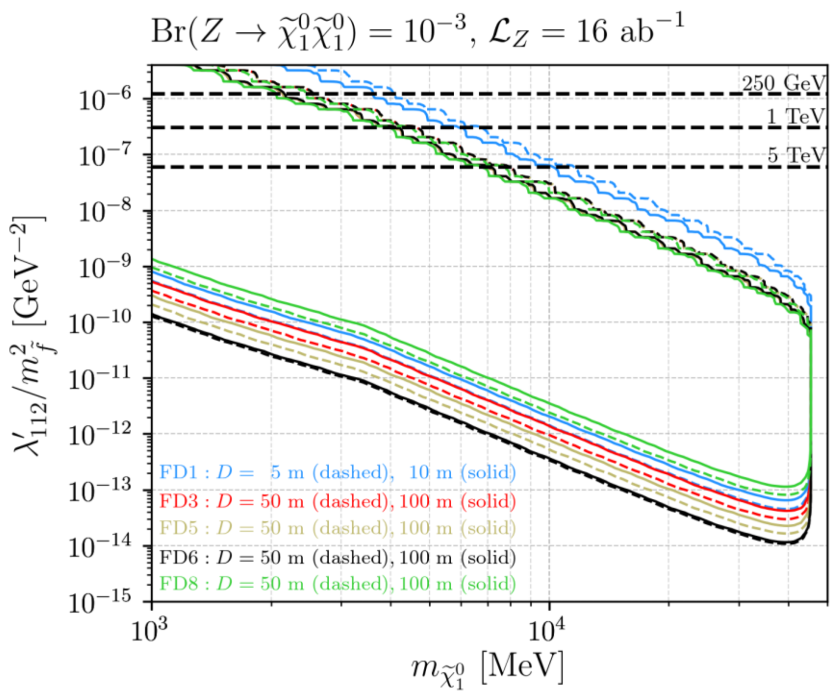
- **Increase luminosity**
- **Relax the theoretical assumptions**

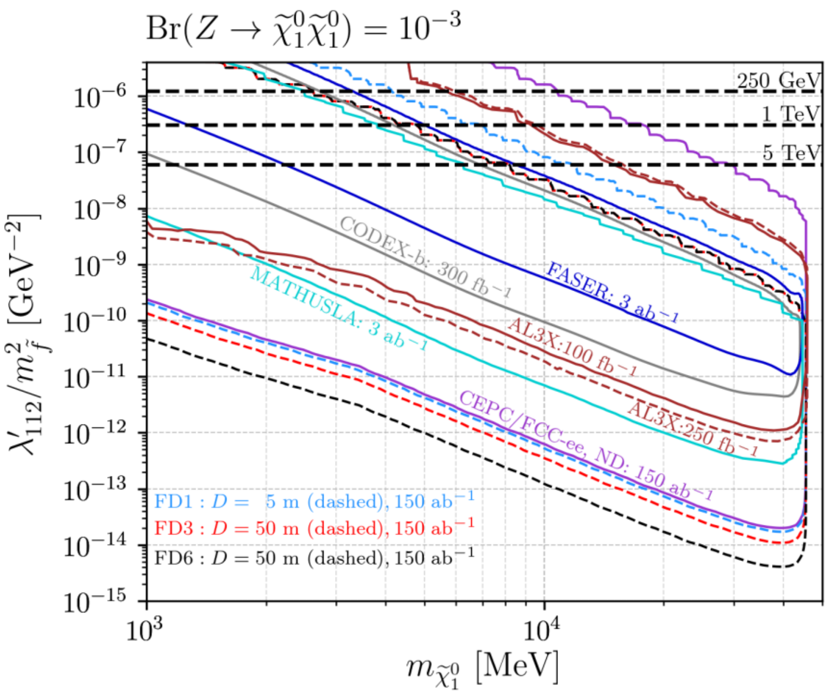
Test the Type-I seesaw directly!

[1911.06576, Zeren Simon Wang and Kechen Wang, Physics with far detectors at future lepton colliders]

RPV-SUSY Neutralinos in FD

$$Z \to \tilde{\chi}_1^0 \tilde{\chi}_1^0 \; @ \sqrt{s} = 91.2 \text{ GeV}$$

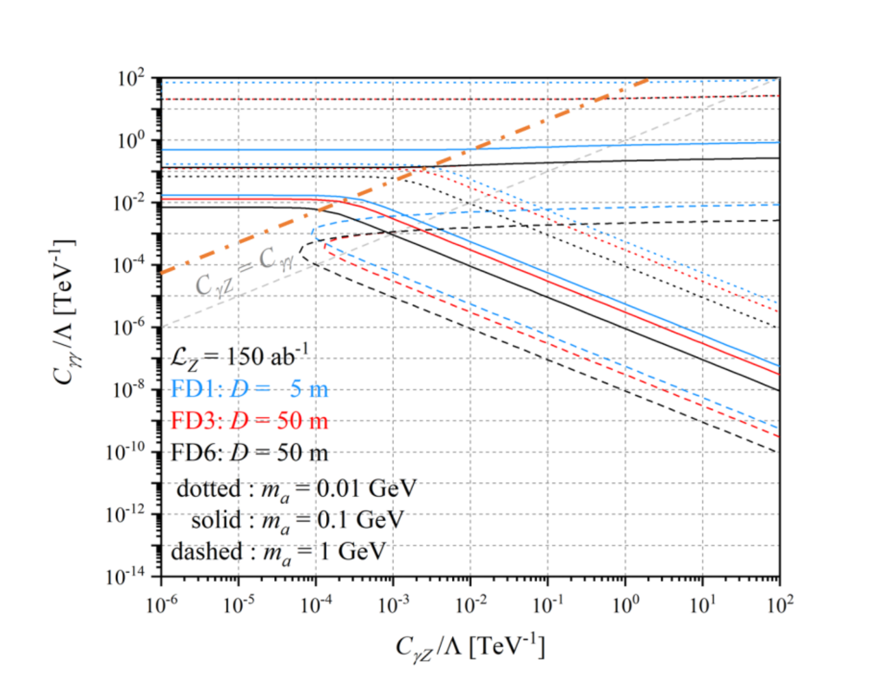


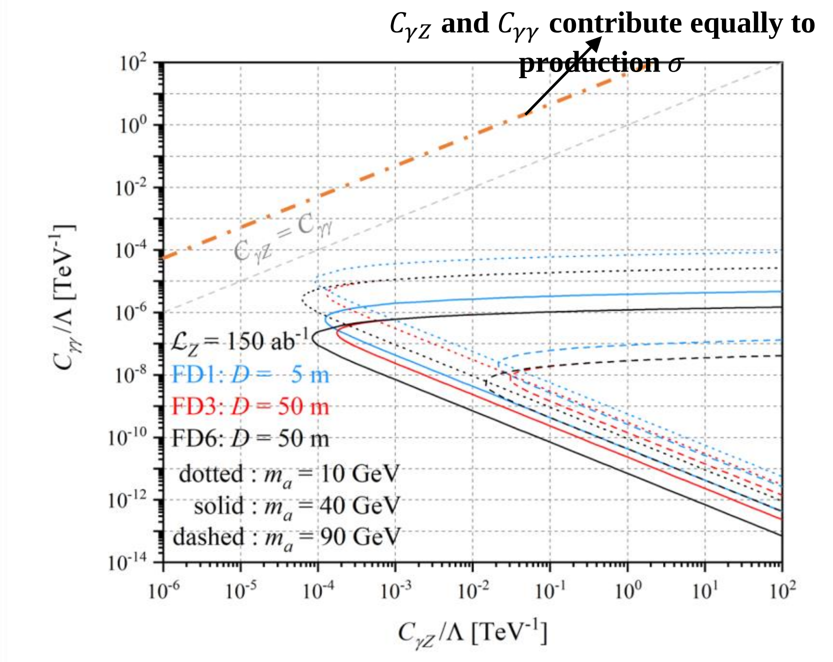


[1911.06576, Zeren Simon Wang and Kechen Wang, Physics with far detectors at future lepton colliders]

Axion-like Particles in FD

$$e^-e^+ \to \gamma\, a,\;\; a \to \gamma\gamma \;@\; \sqrt{s} = 91.2\ \text{GeV}$$



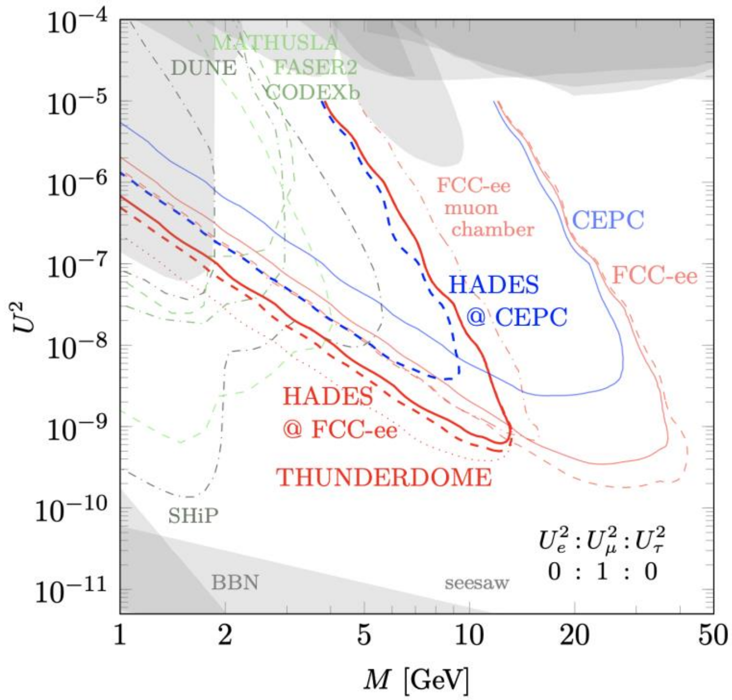


- **Discoverable regions shift downward with increasing m_a**
- **Discovery regions shift rightward when m_a > 40 GeV**

[2201.0896, Minglun Tian, Zeren Simon Wang and Kechen Wang, Search for long-lived axions with far detectors at future lepton colliders]

Heavy Neutral Leptons in FD

$$Z \to N\nu \;@\; \sqrt{s} = 91.2\ \text{GeV}$$



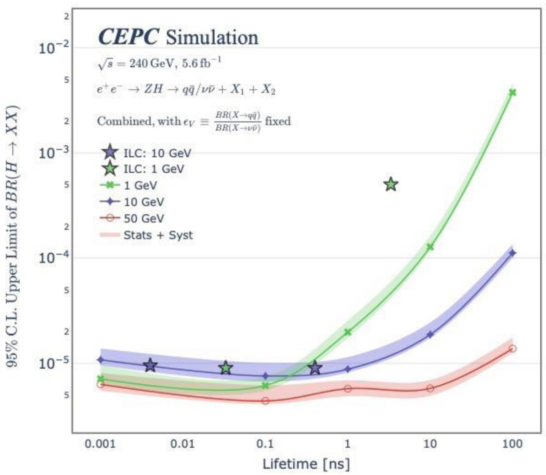
- **HADES detector would consist of scintillator plates located around the cavern walls forming a 4π detector.**

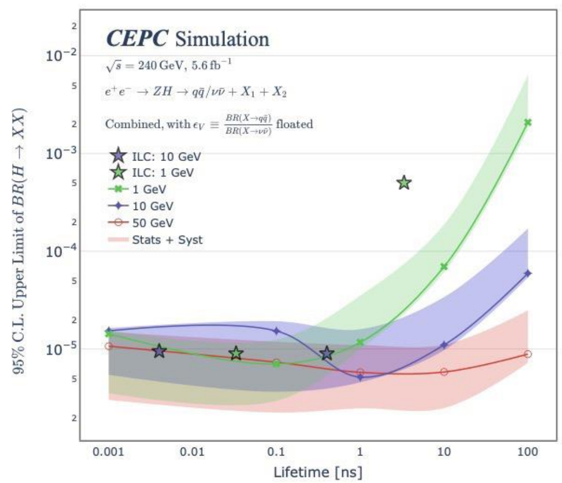
Figure 1: Comparison of the sensitivities (9 events) that can be achieved at the FCC-ee with $2.5 \cdot 10^{12}$ Z-bosons (red) or CEPC with $3.5 \cdot 10^{11}$ Z-bosons (blue).

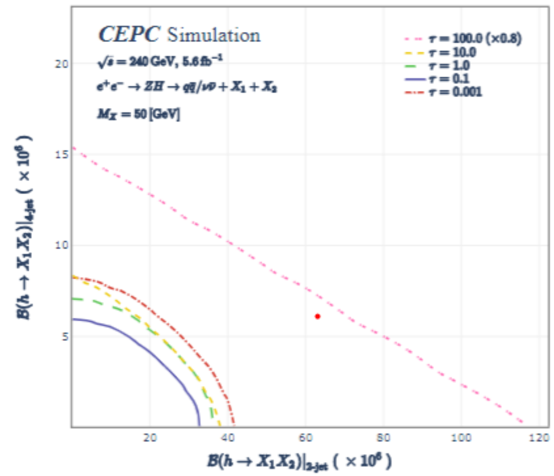
[2011.01005, Marcin Chrzaszczz, Marco Drewes, and Jan Hajer, HECATE: A long-lived particle detector concept for the FCC-ee or CEPC]

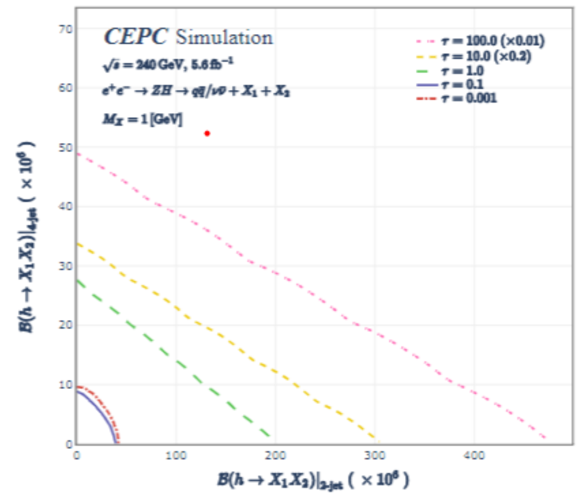
Enhancement from Far Detectors and Machine Learning Techniques

$e^-e^+ \to$ ZH (Z $\to$ inclusive, H $\to$ X1 + X2)









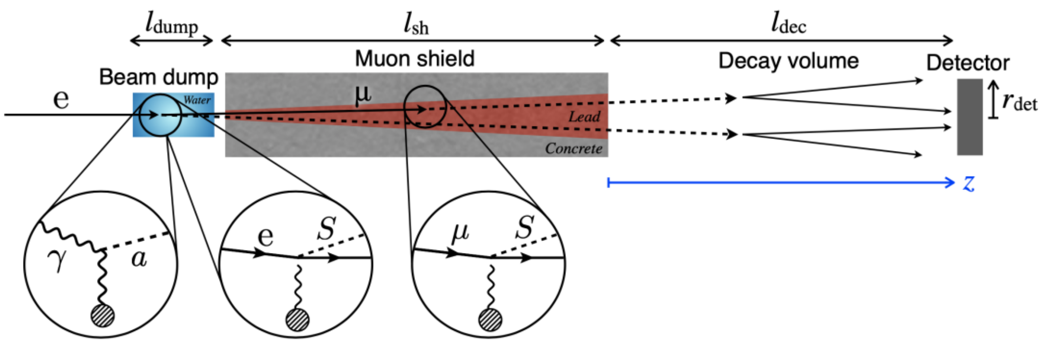
- **Exclusion limit improved by up to 16.2 times**

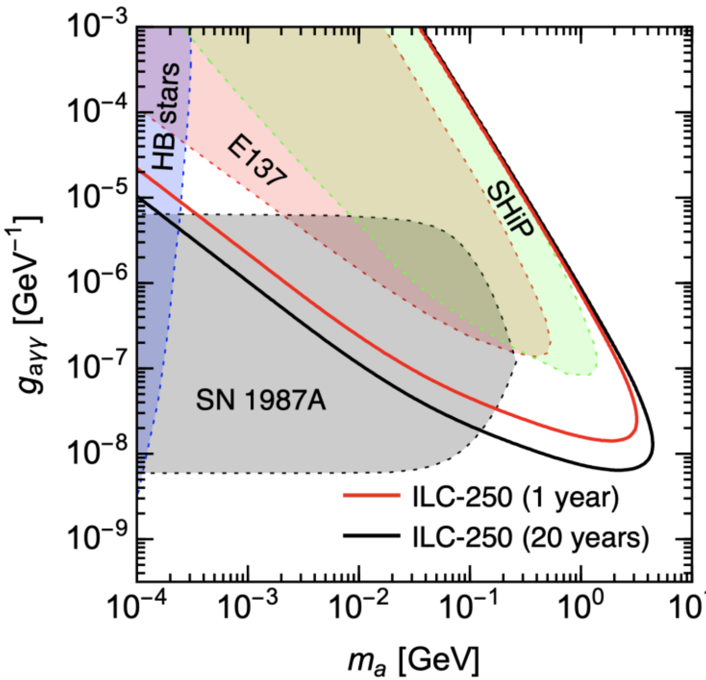
-	Gain	Lifetime [ns]				
	Mass [GeV]	0.001	0.1	1	10	100
Ext. Detector	1	1	1	3.2	11.6	16.2
	10	1	1	1	3.3	11.8
	50	1	1	1	1.1	3.6

[Talk@ 2023 CEPC workshop. Yulei Zhang, Cen Mo, Xiang Chen, Bingzhi Li, Hongyang Chen, Jifeng Hu, Liang Li: Search for Long-lived Particles at Future Lepton Colliders Using Deep Learning Techniques]

ALP in Beam Dump Experiment

ALP & new scalar @ E_{beam} =125 GeV





[2009.13790, Yasuhito Sakaki, Daiki Ueda, Searching for new light particles at the international linear collider main beam dump]

Leptophilic Gauge Boson in BD

$e^{\pm}N \to e^{\pm}N'X$ @ E_{beam} =125, 250, 500 GeV

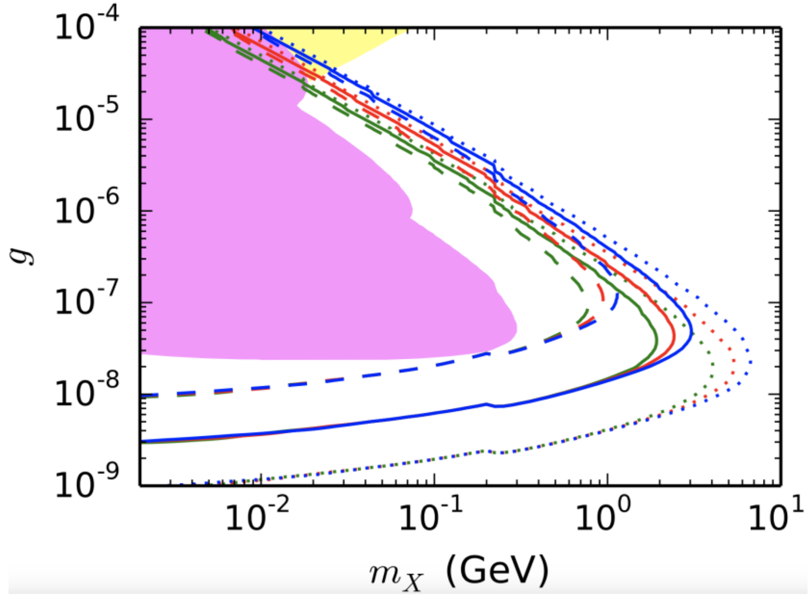


Figure 1: Contours of expected number of signal events for the $U(1)_{e-\mu}$ model. The beam energy is taken to be $E_{\text{beam}} = 125$ (green), 250 (red), and 500 GeV (blue). The dotted, solid, and dashed lines are for $N_{\text{sig}} = 10^{-2}$, 1, and 10^2, respectively, taking $N_e = 4 \times 10^{21}$. The mixing parameter is taken to be $\kappa_\epsilon = 1$. The pink and yellow shaded regions are excluded by beam dump and neutrino-electron scattering experiments, respectively.

[2104.00888, Kento Asai, Takeo Moroi and Atsuya Niki, Leptophilic Gauge Bosons at ILC Beam Dump Experiment]

Neutral Gauge Boson in BD

Z' @ E_{beam} =125 GeV

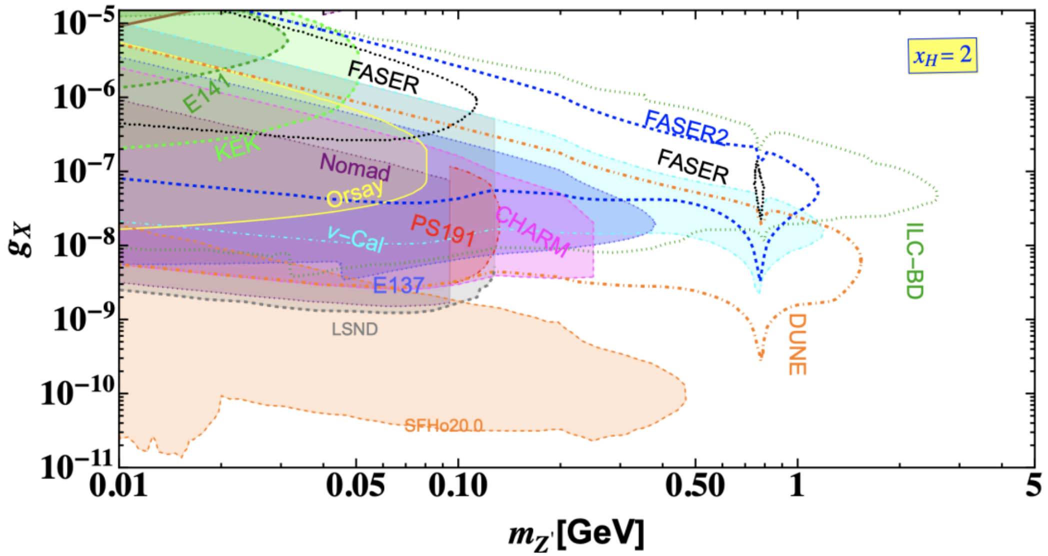


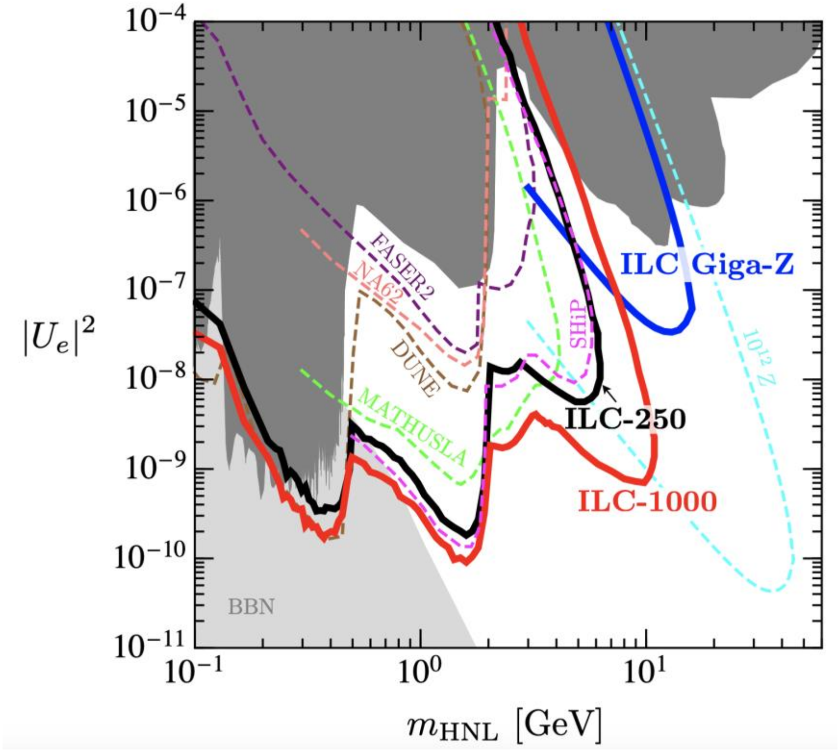
FIG. 6. Limits on $g_X - m_{Z'}$ plane for $x_H > 0$ and $x_\Phi = 1$ considering 10 MeV $\leq m_{Z'} \leq$ 5 GeV showing the regions could be probed by FASER, FASER2, ILC-Beam dump, and DUNE. We compare the parameter space with existing bounds from different beam dump experiments and a cosmological observation of supernova SN1987A (SFH020.0), respectively.

- Light Z′ produced via bremsstrahlung process
- Rare decay of π_0 and η mesons
- Pair annihilation at various beam dump experiments

[2206.12676, Kento Asai, Arindam Das, Jinmian Li, Takaaki Nomura and Osamu Seto, Chiral Z' in FASER, FASER2, DUNE, and ILC beam dump experiments]

Heavy Neutral Leptons in BD

E_{beam} = 45.6,125, 500 GeV



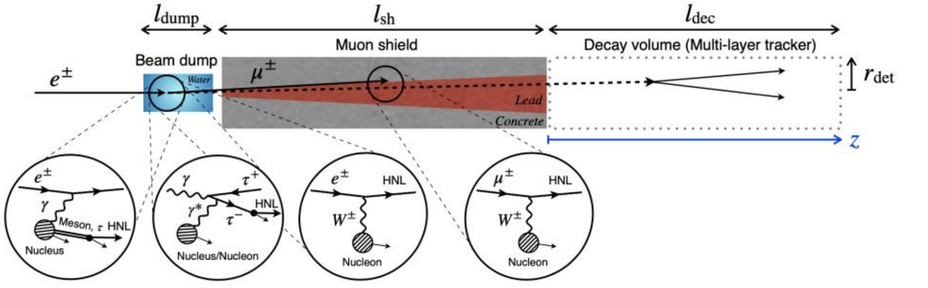


Figure 1. A setup for ILC beam dump experiments. It consists of the main beam dump, a muon shield, and a decay volume. We assume a multi-layer tracker is placed in the decay volume so that the charged tracks are measured.

Figure 5. Sensitivity reach of ILC beam dump experiment to HNLs mixing with the electron neutrino in the mass and mixing plane, assuming 10 year run at ILC-250 (black solid) and ILC-1000 (red solid). The number signal events more than 5.5 (9.1) is required at ILC-250(1000), which corresponds to the 95% C.L. sensitivity. The discussion about the background is in Sec. 4.1. The current exclusion bounds are shown in the gray region, see Sec. 4.3. The darker grey region is from the laboratory bounds, and the lighter gray region is the BBN bound for the HNL, which is roughly $\tau_{\mathrm{HNL}} > 0.02$ s [30]. Sensitivity reach through 10^9 Z-decays at ILC is shown as a blue solid line. See Sec. 4.2. For a comparison, dashed lines show a sensitivity reach of the DUNE experiment [40] (brown), the FASER2 experiment [41] (purple), the NA62 experiment [1] (orange), and the SHiP experiment [8] (magenta), the MATHUSLA experiment[42] (green), and 10^{12} Z-decays that could be realized at the FCC-ee experiment (cyan).

[2206.13523, Mihoko M. Nojiri, Yasuhito Sakaki, Kohsaku Tobioka, and Daiki Ueda, First evaluation of meson and τ lepton spectra and search for heavy neutral leptons at ILC beam dump]

Summary and Outlook

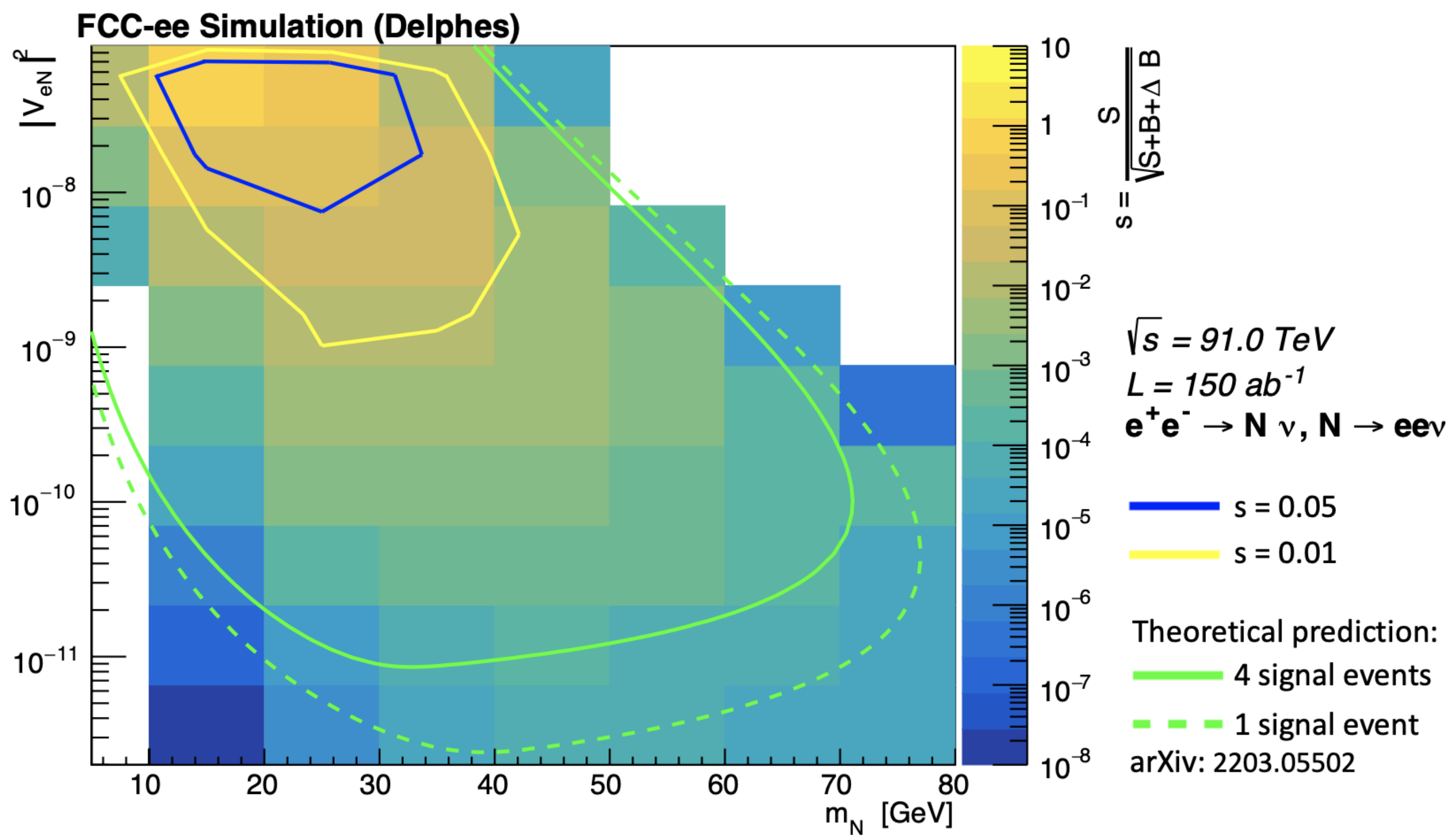
✓ **LLPs searches at CEPC have unique features**

- **Important ways to BSM physics**
  - **New scalars, glue balls, dark photons, heavy neutral leptons, ALP, SUSY, hidden valley particles, new gauge bosons …**
- **Clean environment with distinct detector signature**
- **Improvement from detector technology**
  - **Timing detectors: precise timing information**
  - **Trackers: better track resolution**
  - **Far detectors: economical solution for big volume detectors**
- **Machine learning techniques seem promising**

Backup

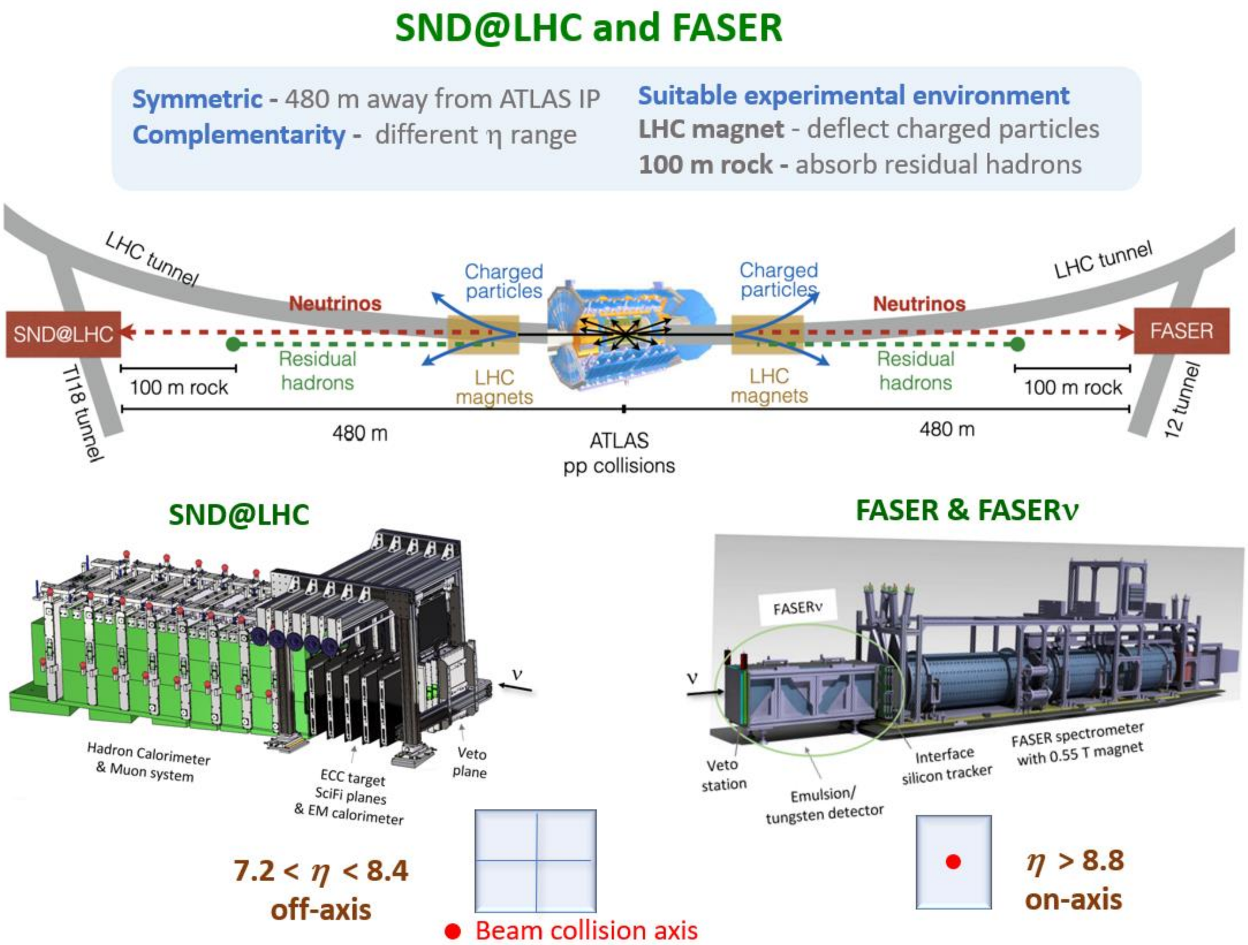
Heavy Neutral Leptons

$$e^-e^+ \rightarrow \nu\, N,\ \ N \rightarrow ee\nu\ @\ \sqrt{s} = \textbf{91 GeV}$$



[220601Thesis, Lovisa Rygaard, Long-Lived Heavy Neutral Leptons at the FCC-ee]

Far Detector Experiments



[http://www.ship-korea.com/SND.html]

[https://faser.web.cern.ch/index.php/]

[https://snd-lhc.web.cern.ch/]

[2210.02784, SND@LHC: The Scattering and Neutrino Detector at the LHC]

Future Far Detector Experiments

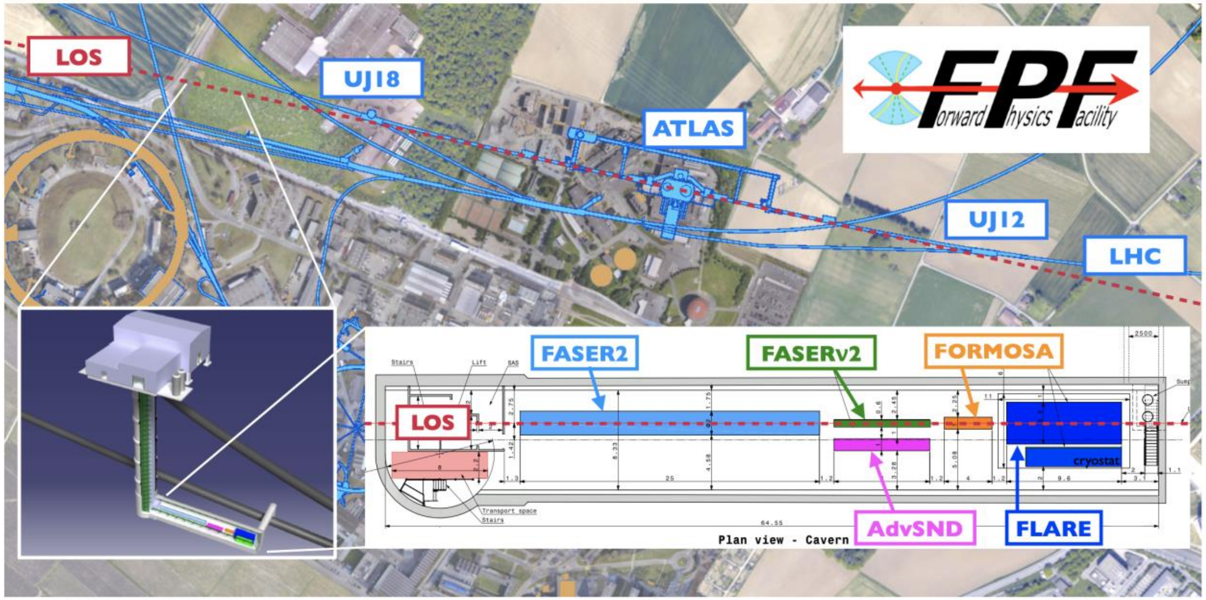


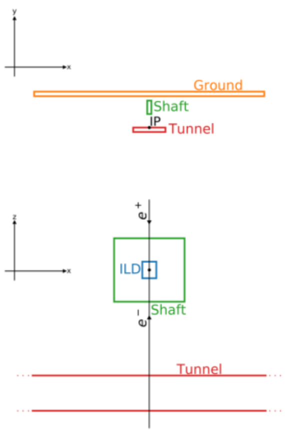
Figure 1: The preferred location for the Forward Physics Facility, a proposed new cavern for the High-Luminosity era. The FPF will be 65 m-long and 8.5 m-wide and will house a diverse set of experiments to explore the many physics opportunities in the far-forward region.

[2203.05090, The Forward Physics Facility at the High-Luminosity LHC]

Proposed FD experiments：
MATHUSLA;
FASER2**,** FASERv2**,** AdvSND**,** FLArE**,** FORMOSA；
CODEX-b；AL3X**; ...**

Axion-like Particles in FD

$$e^-e^+ \to \gamma a, a \to \gamma Z \to \gamma\,(\gamma a)\ @\ \sqrt{s} = 250\ \text{GeV}$$



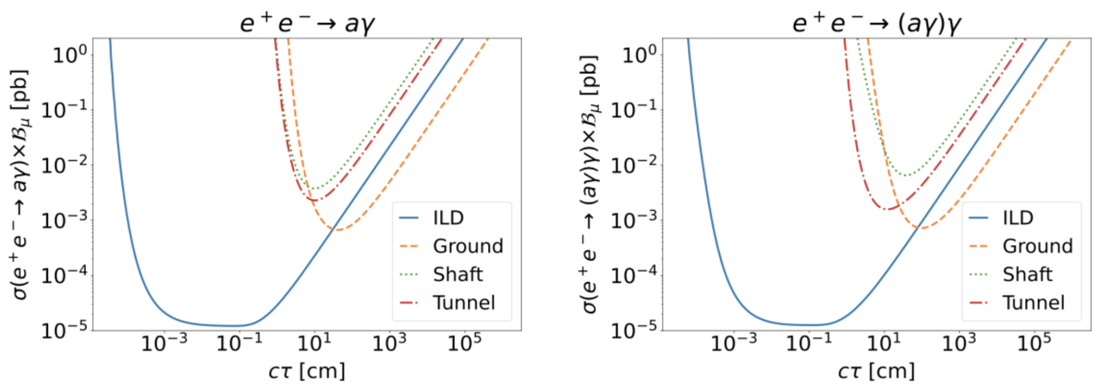


Figure 3: Far detector options around the ILC interaction point (IP). Shown are a side view (left) and top view (right) of the projected far detectors in the Shaft (S, blue), in the Tunnel (T, purple), and on the Ground (G, red), as well as the main detector ILD (green). The Ground detector is centered around $(x, z) = (0, 0)$ and is too large to appear in the top view.

- Shaft (S): $18 \times 30 \times 18\,\text{m}$, centered around $(0, 45, 0)\,\text{m}$
- Tunnel (T): $140 \times 10 \times 10\,\text{m}$, centered around $(0, -5, -35)\,\text{m}$
- Ground (G): $1000 \times 10 \times 1000\,\text{m}$, centered around $(0, 75, 0)\,\text{m}$.

Figure 5: Contours of $N_a = 3$ ALPs with $m_a = 300\,\text{MeV}$ decaying within various ILC detectors, as a function of the production cross section, σ, and the proper lifetime, $c\tau_a$. Shown are the production channels $e^+e^- \to a\gamma$ (left) and $e^+e^- \to Z\gamma \to (a\gamma)\gamma$ (right) at $\sqrt{s} = 250\,\text{GeV}$ and with $\mathcal{L} = 250\,\text{fb}^{-1}$. Predictions are made for the ILD (blue, plain) and far detectors placed in the Shaft (green, dotted), in the Tunnel (red, dot-dashed) and on the Ground (orange, dotted). The branching ratio of the ALP into muons is indicated by $\mathcal{B}_\mu$.

[2202.11714, Ruth Schäfer, Finn Tillinger, Susanne Westhoff, Near or far detectors? A case study for long-lived particle searches at electron-positron colliders]