Overview of LLP Studies at Future e^-e^+ Colliders

Kechen Wang
Wuhan University of Technology

The 2024 European Edition of the International Workshop on the CEPC

April 8, 2024

White paper – LLP searches

VII. LONG-LIVED PARTICLE SEARCHES (LIANG LI, YING-NAN MAO, KECHEN WANG, ZEREN SIMON WANG)

Contents

Please feel free to contact me (kechen.wang@whut.edu.cn) if your studies are missed !

OUTLINE

LLP Searches @ ee Colliders

Studies with Near Detectors

Studies with Far Detectors

Studies with beam dump

Discussion

The talk in previous workshop [https://indico.ph.ed.ac.uk/event/259/contributions/2476/attachments/1370/2064/LLPs_eeColliders_v9.pdf]

Theory Motivation

LLP: Relatively long lifetime or equivalently decay length

New particles become long-lived because of:
→ feeble couplings to SM particles
→ phase space suppression
→ approximate symmetry
→ heavy mediators, ...

The discovery of LLPs could explain some fundamental problems:
neutrino mass, dark matter, baryogenesis, naturalness, ...

LLP searches are important ways to BSM physics.

Idea of LLP searches @ colliders

When a LLP produced at 0 (usually the IP),

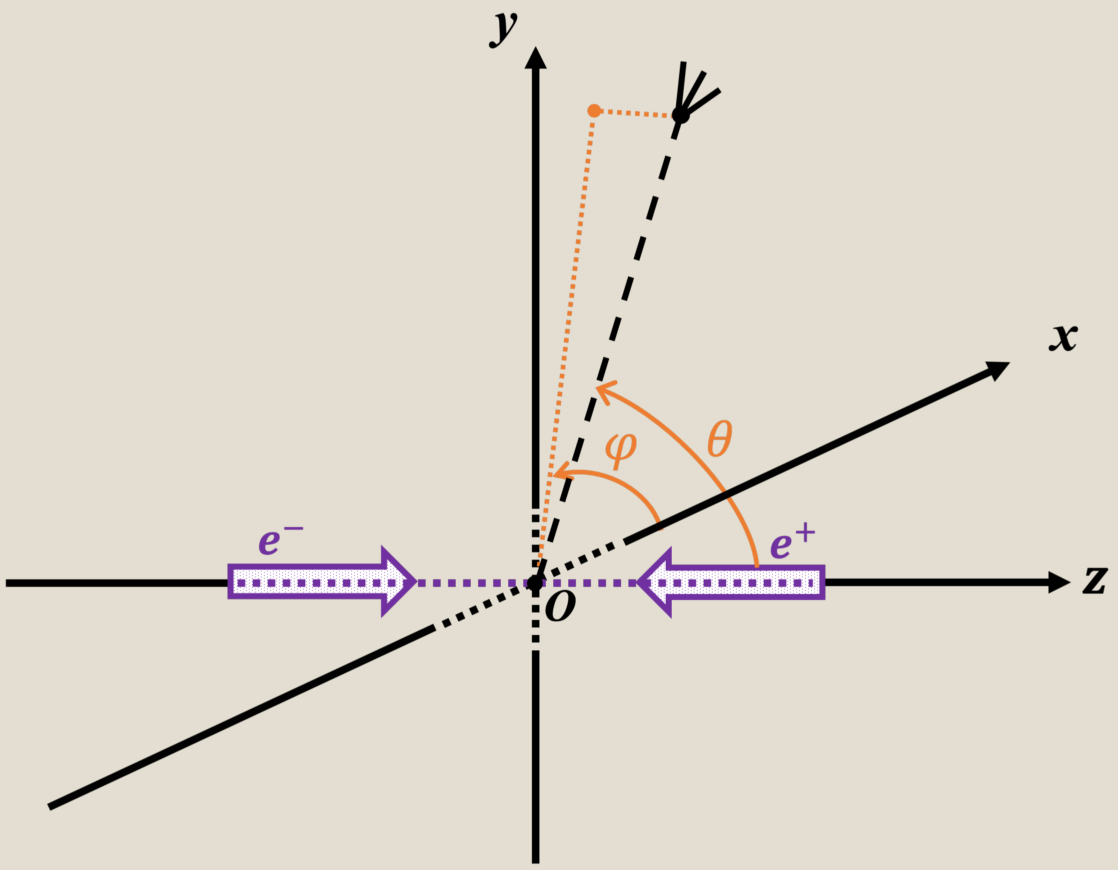
Probability of still existing (does not decay) at L

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

where decay length in the lab. frame

$$\lambda = \beta\gamma\, c\tau = \left(\frac{p}{m}\right)\ (c\tau)$$

Kinematics   lifetime in the rest frame



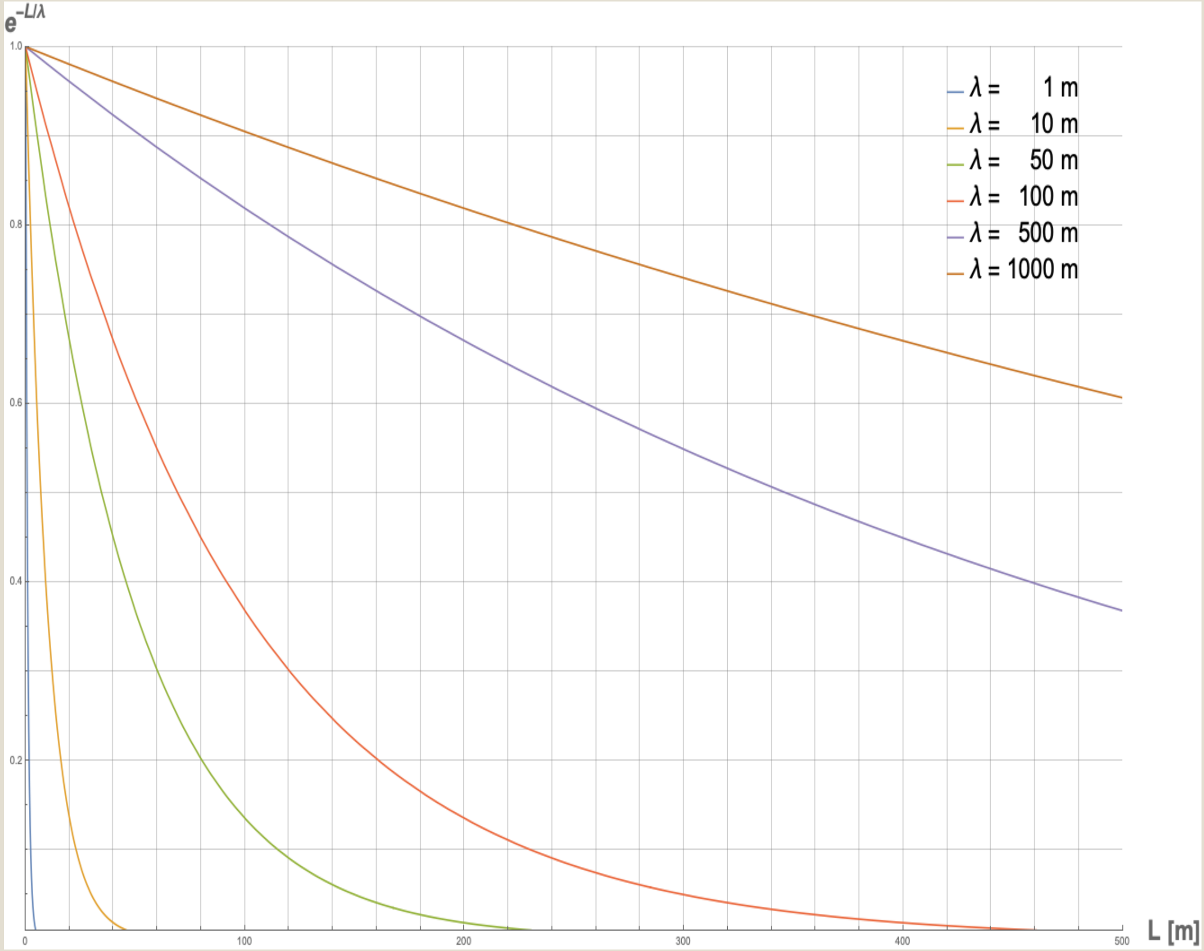
Idea of LLP searches @ colliders

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, ...) & LLP's moving direction

Exponential Decay



Idea of LLP searches @ colliders

$$N_{\mathrm{exp}} = N_{\mathrm{pro}} \cdot P \cdot \mathrm{Br} \cdot \epsilon$$

# of LLPs produced

probability of decaying inside the detector's fiducial volume

Branching ratio of LLP decaying into visible final state

detector efficiency

expected # of signal events:
depends on theory model parameters (mass, lifetime, kinematics) & geometry and performance of detector (position, shape, volume, efficiency)

@ *ee* vs. *pp*
***ee*:** high lum., clean environment, EW prod., transverse direction, recoil strategy
***pp*:** forward direction

Signatures of LLPs in ND

When $\lambda \sim \mathcal{O}(1)$ m,

Mainly decay inside the near detector

Appear as displaced vertex

Various final states depending on different decay products

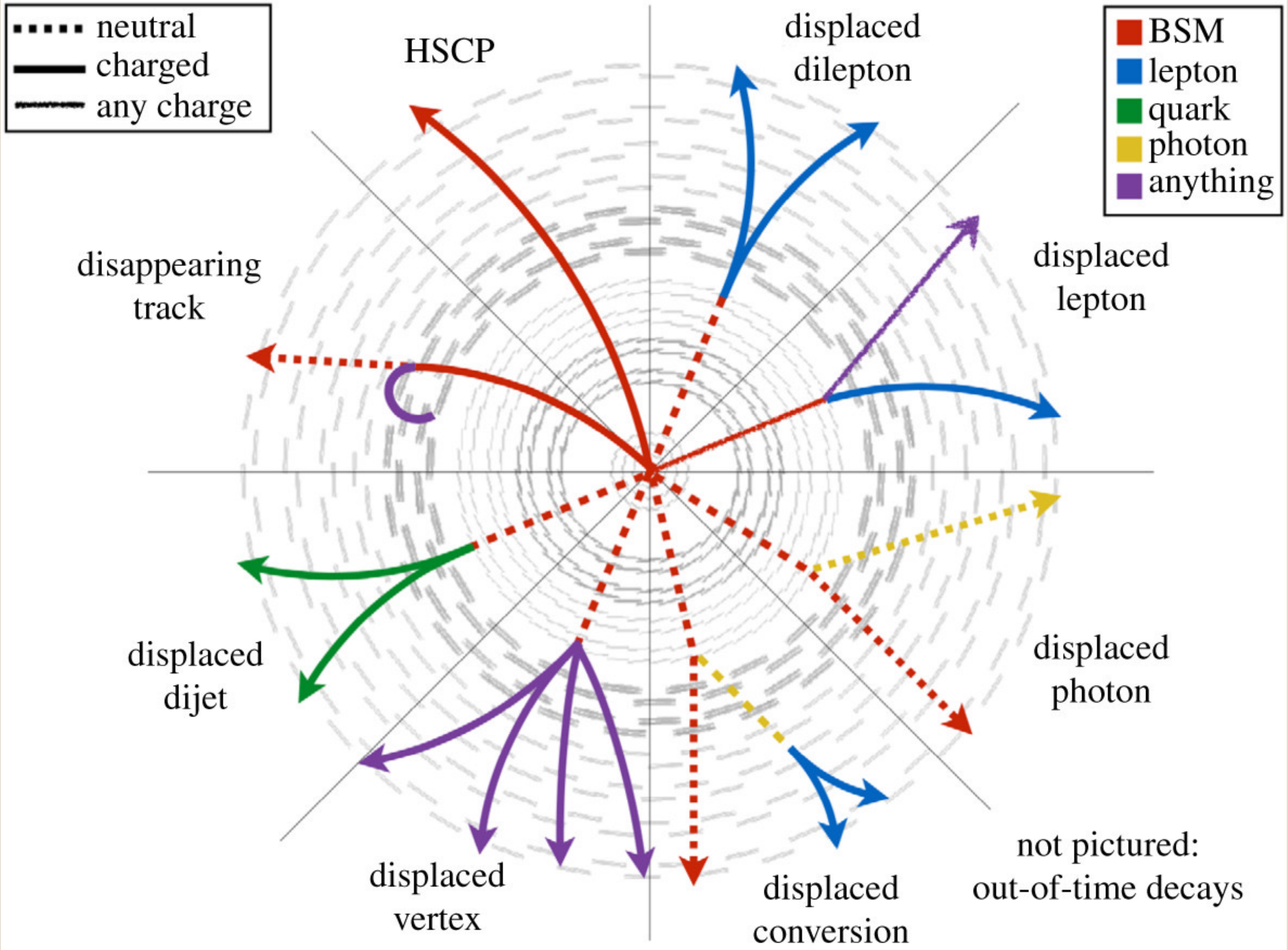


Figure from [A. De Roeck, Phil. Trans. Roy. Soc. Lond. A 377, 20190047 (2019)]

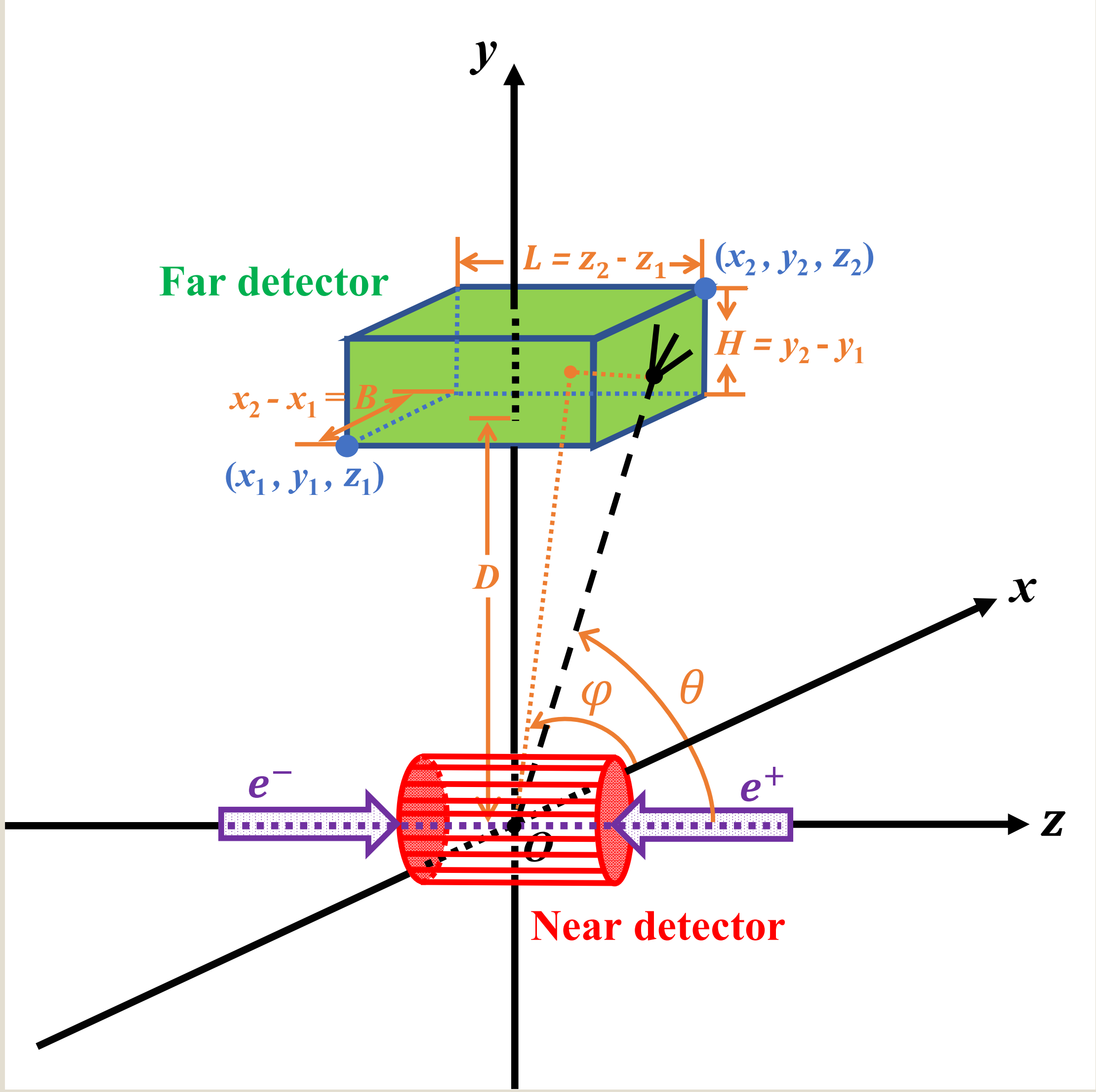
Signatures of LLPs in FD

When $\lambda \sim \mathcal{O}(100)$ m,

Mainly travel through and acts as missing energy in the near detector.

Far detector 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 very long decay length.



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

Higgs Decay

New scalars: $e^-e^+ \rightarrow HZ \rightarrow (XX)\ (l^-l^+)$ @ $\sqrt{s} = 250$ GeV

[**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: $h \rightarrow h_s h_s, h_s \rightarrow \mu^-\mu^+, \pi^-\pi^+$ @ $\sqrt{s} = 240$ GeV **Mirror glueballs:** $h \rightarrow 0^{++}0^{++}$, $0^{++} \rightarrow \xi\xi$ @ $\sqrt{s} = 240$ GeV

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

New scalars: $h \rightarrow \phi\phi$ @ $\sqrt{s} = 240$ GeV

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

Hidden valley particles: $H \rightarrow \pi_V^0\pi_V^0 \rightarrow (b\bar{b})(b\bar{b})$ @ $\sqrt{s} = 350$ GeV & 3 TeV

[**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: $e^-e^+ \rightarrow HZ,\ H \rightarrow \gamma_D\gamma_D, \gamma_D \rightarrow f\bar{f}, l^-l^+$ @ $\sqrt{s} = 250$ GeV

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

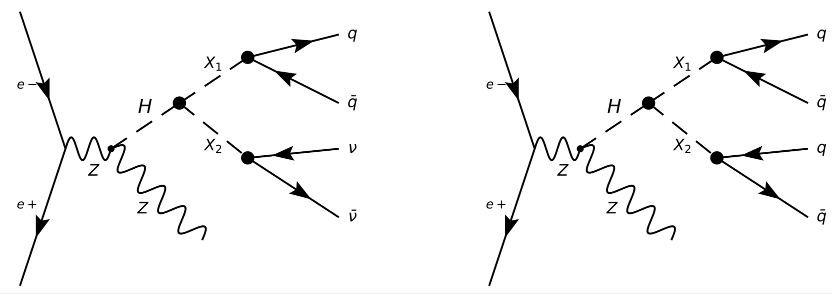
Details see the talk in previous workshop
[https://indico.ph.ed.ac.uk/event/259/contributions/2476/attachments/1370/2064/LLPs_eeColliders_v9.pdf]

Higgs Decays

New scalars: $e^-e^+ \to ZH \to (\text{incl.})(X_1X_2) \to (\text{incl.})(\nu\bar{\nu}\, jj)$ / $(\text{incl.})(jj\, jj)$, @ $\sqrt{s} = 240$ GeV

[**2401.05094, 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]

Signal production: long-lived X_1 , X_2



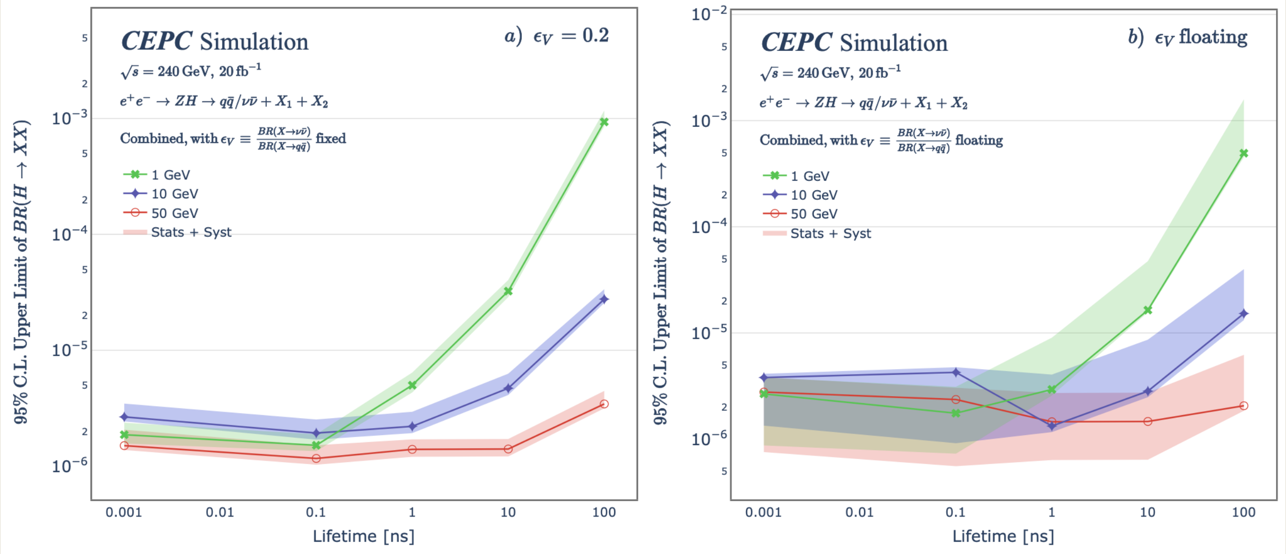


FIG. 6: One-dimensional constraints on Higgs boson decay to LLPs. 95% C.L. upper limit on the branching ratio (BR) for the Higgs boson (H) decay into pairs of LLPs (X_1X_2) via $e^+e^- \to ZH$, where ϵ_V is the ratio $\frac{BR(X\to\nu\bar{\nu})}{BR(X\to q\bar{q})}$. **a)**: a fixed ratio $\epsilon_V = 0.2$, **b)**: a floating ϵ_V. The shaded areas indicate statistical and systematic uncertainties combined.

Background processes:

$e^-e^+ \to q\,\bar{q}$

$e^-e^+ \to Z/W$

$e^-e^+ \to ZH \to$ incl.

pileup

cosmic rays

ML methods:
Convolutional Neural Networks (CNN) & Graph Neural Networks (GNN) performed to reject Bkg.

Z Decays

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

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

Axion like particles: $e^- e^+ \to Z^{(*)} \to l^- l^+ a$ @ $\sqrt{s} = 91$ GeV

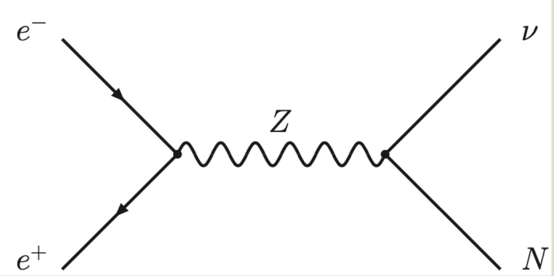
[**2212.02818, Lorenzo Calibbi, Zijie Huang, Shaoyang Qin, Yiming Yang, and Xiaoyue Yin**, Testing axion couplings to leptons in Z decays at future e-e+ colliders]

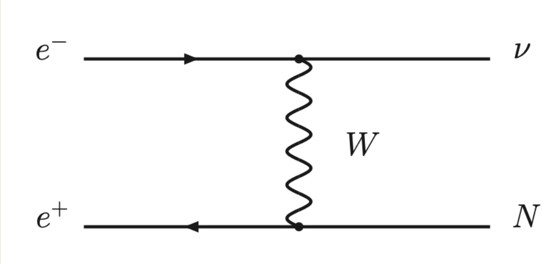
Details see the talk in previous workshop
[https://indico.ph.ed.ac.uk/event/259/contributions/2476/attachments/1370/2064/LLPs_eeColliders_v9.pdf]

Heavy Neutral Leptons

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

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





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

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

HNL: $e^- e^+ \to \nu\, N,\ \ N \to ee\nu$ @ $\sqrt{s} = 91$ GeV

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

Details see the talk in previous workshop [https://indico.ph.ed.ac.uk/event/259/contributions/2476/attachments/1370/2064/LLPs_eeColliders_v9.pdf]

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

[**2210.1711, Marco Drewes**, Distinguishing Dirac and Majorana heavy neutrinos at lepton colliders]

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

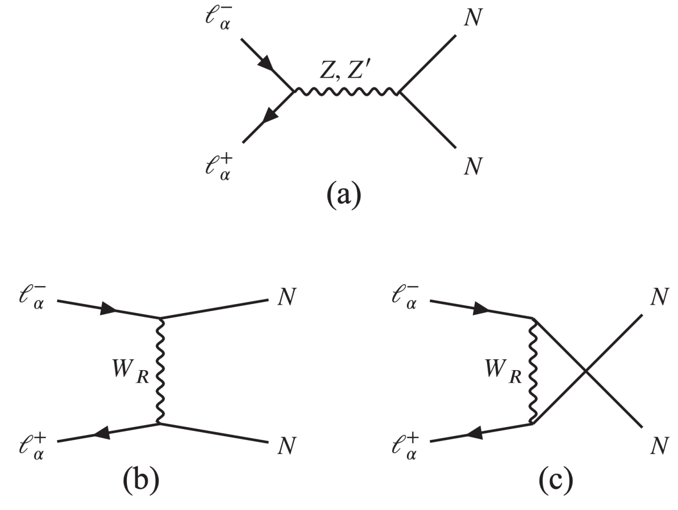
[**2301.08592, JHEP 07 (2023) 039, Maksym Ovchynnikov and Jing-Yu Zhu**, Search for the dipole portal of heavy neutral leptons at future colliders]

Heavy Neutral Leptons

HNL: $e^-e^+ \to N\,N \to \left(e^\pm W_R^{*\mp}\right)\left(e^\pm W_R^{*\mp}\right) \to (e^\pm j\,j)(e^\pm j\,j)$ @ $\sqrt{s} = 90$ GeV

[**2310.17406, PRD 109 (2024) 055002, Kevin A. Urquía-Calderón**, Long-lived heavy neutral leptons at lepton colliders as a probe of left-right-symmetric models]

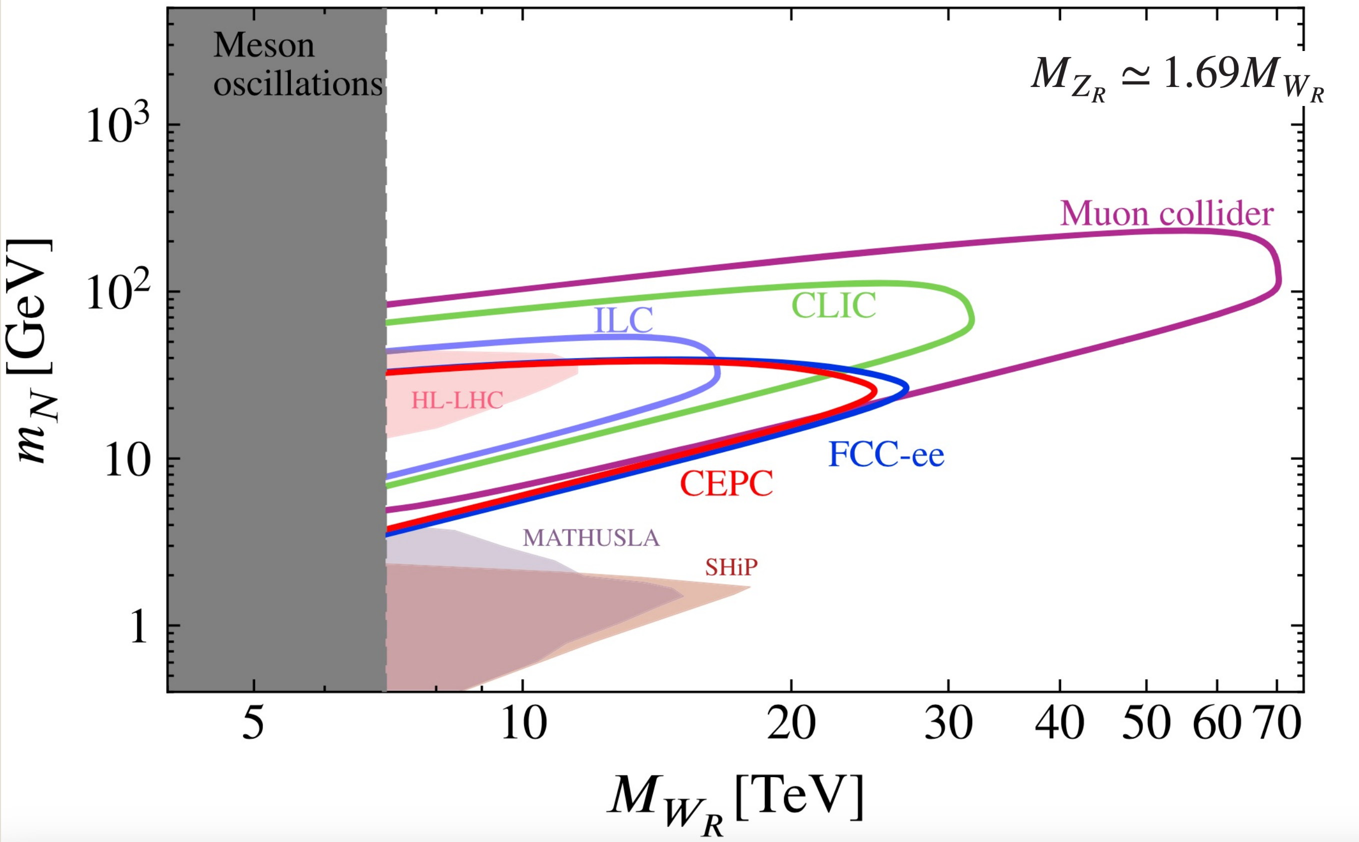
Signal *NN* production:



Experiment	Energy (GeV)	Luminosity (ab^{-1})
FCC-ee	90, 161, 240, and 350	150, 10, 5, and 1.7
CEPC	90, 161, 240, and 360	100, 6, 20, and 1
ILC	250, 350, and 500	2, 0.2, and 4
CLIC	380, 1500, and 3000	1, 2.5, and 5
Muon collider	3000 and 10 000	0.4 and 4 (per year)

Detector		z/R	$\langle L_{\max}(\theta)\rangle$
IDEA	Tracker	4.0 m/2.0 m	2.2 m
(FCC-ee, CEPC)	Muon system	13.0 m/5.0 m	6.4 m
SiD	Tracker	1.6 m/1.2 m	1.1 m
(ILC, CLIC)	Muon system	11.3 m/6.0 m	6.53 m

Sensitivity of future experiments vs our results (one displaced vertices)



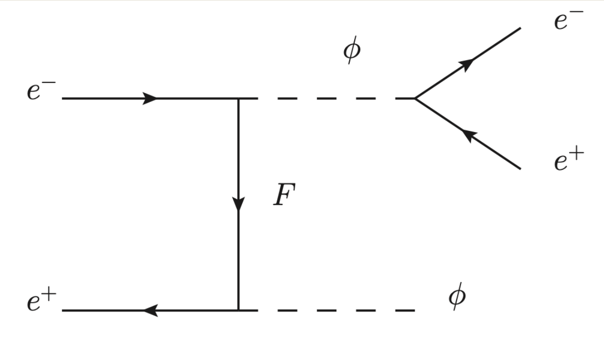
Sensitivity plots reach using the benchmark points presented in Tables I (FCC-ee and CEPC at the Z pole, and linear and muon colliders the values with the highest center-of-mass energies) with a minimum displaced length of 5 mm; and a maximum displaced length until the tracker volume for FCC-ee, CEPC, ILC, and CLIC, and until the muon system for a muon collider (all lengths are shown in Table II). The plots were made considering $\mathcal{N}_{\text{events}} = 3$, corresponding to a ~95% exclusion limit.

New scalars

HNL: $e^-e^+ \to \phi\,\phi \to (e^-e^+)(e^-e^+)$ @ $\sqrt{s} = 240$ GeV

[**2311.12934, Qing-Hong Cao, Jinhui Guo, Jia Liu, Yan Luo, Xiao-Ping Wang**, Long-lived searches of vector-like lepton and its accompanying scalar at colliders]

Signal production

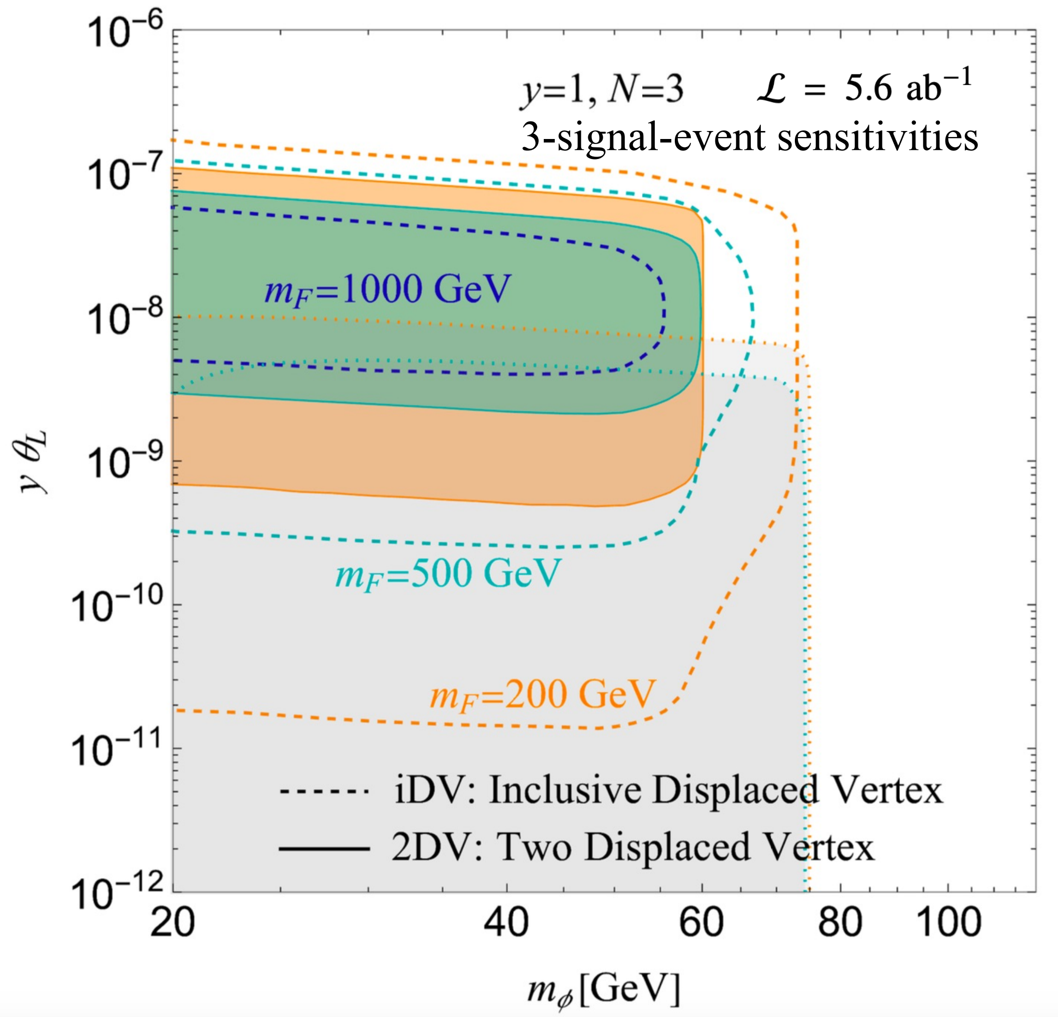


Selection cuts

Long-lived ϕ decay inside the inner tracker

DV-CEPC : $10\text{ cm} < |d_\phi \cdot \sin\theta_i| < 1.8\text{ m}, |d_\phi \cdot \cos\theta_i| < 2.35\text{ m},$

$p_T^{e_i} > 30\text{ GeV}, m_{e_1 e_2}(m_\phi) > 20\text{ GeV}, 1 > \Delta R > 0.01,$



SUSY

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

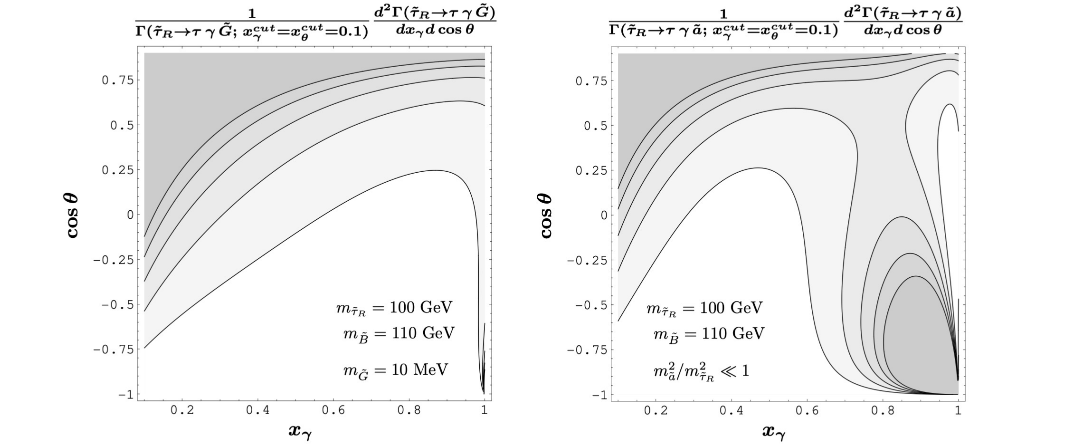


Figure 2: The normalized differential distributions of the visible decay products in the decays $\tilde\tau \to \tau\gamma\tilde G$ for the gravitino LSP scenario (left) and $\tilde\tau \to \tau\gamma\tilde a$ for the axino LSP scenario (right) for $m_{\tilde\tau_1} = 100\,\text{GeV}$, $m_{\tilde B} = 110\,\text{GeV}$, $m^2_{\tilde a}/m^2_{\tilde\tau_1} \ll 1$, and $m_{\tilde G} = 10\,\text{MeV}$. 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].

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

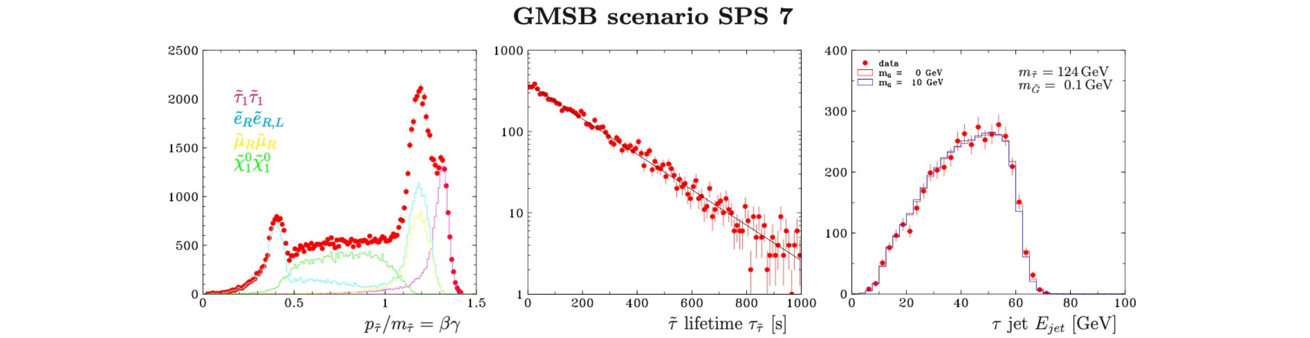
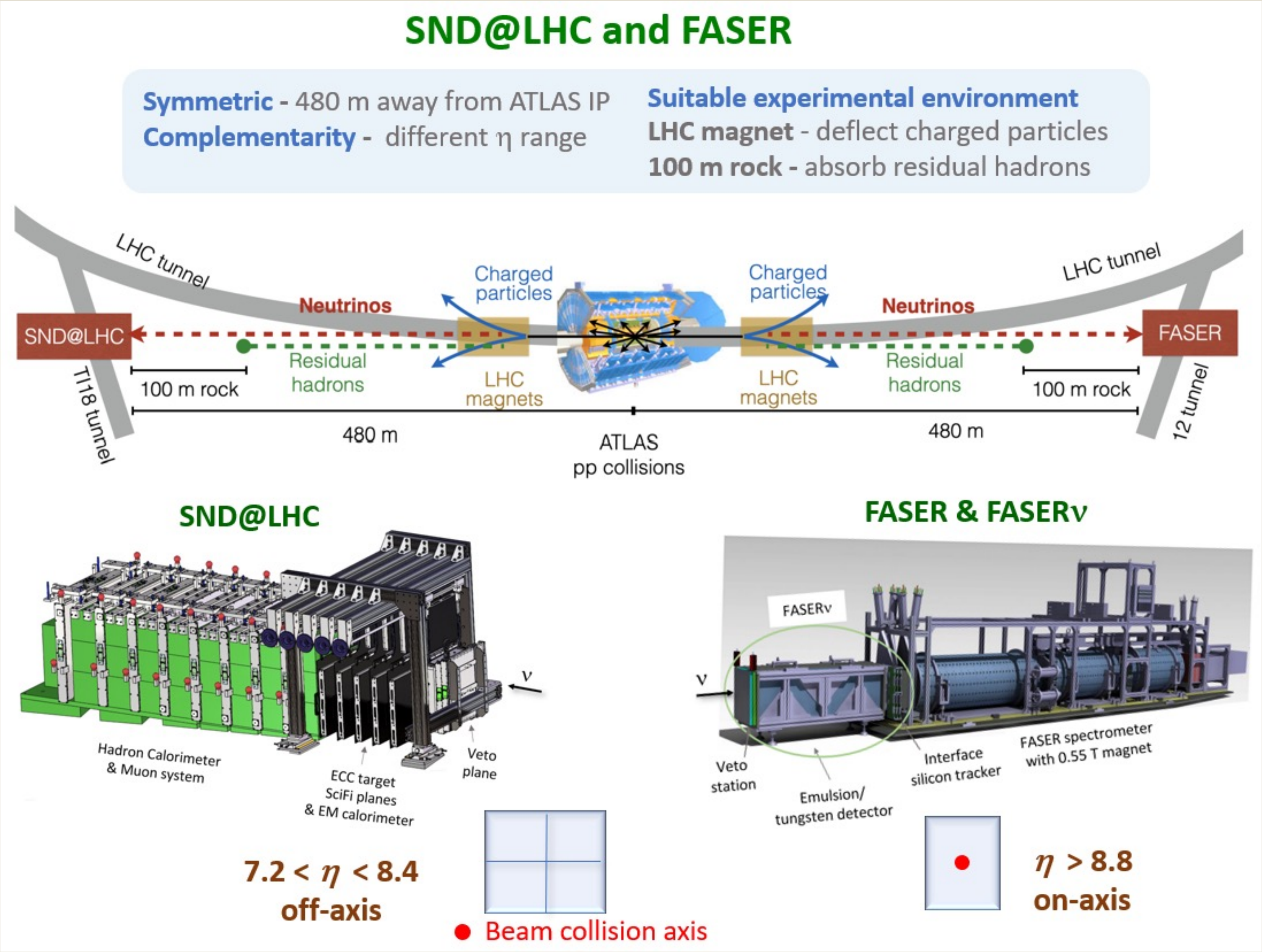


Fig. 3. SPS 7 scenario, assuming $\mathcal{L} = 100\,\text{fb}^{-1}$ at $\sqrt{s} = 410\,\text{GeV}$: (a) $\tilde\tau$ production spectra of scaled momentum $p/m = \beta\gamma$ with contributions from various processes; (b) $\tilde\tau$ lifetime distribution; (c) τ jet energy spectrum of the decay $\tilde\tau_1 \to \tau\tilde G$ compared with simulations of $m_{\tilde G} = 0\,\text{GeV}$ and $10\,\text{GeV}$

[**0606116, Alejandro Ibarra and Sourov Roy**, Lepton flavour violation in future linear colliders in the long-lived stau NLSP scenario]

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

Current running FD experiments @ LHC



[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]

Proposed FD experiments @ LHC

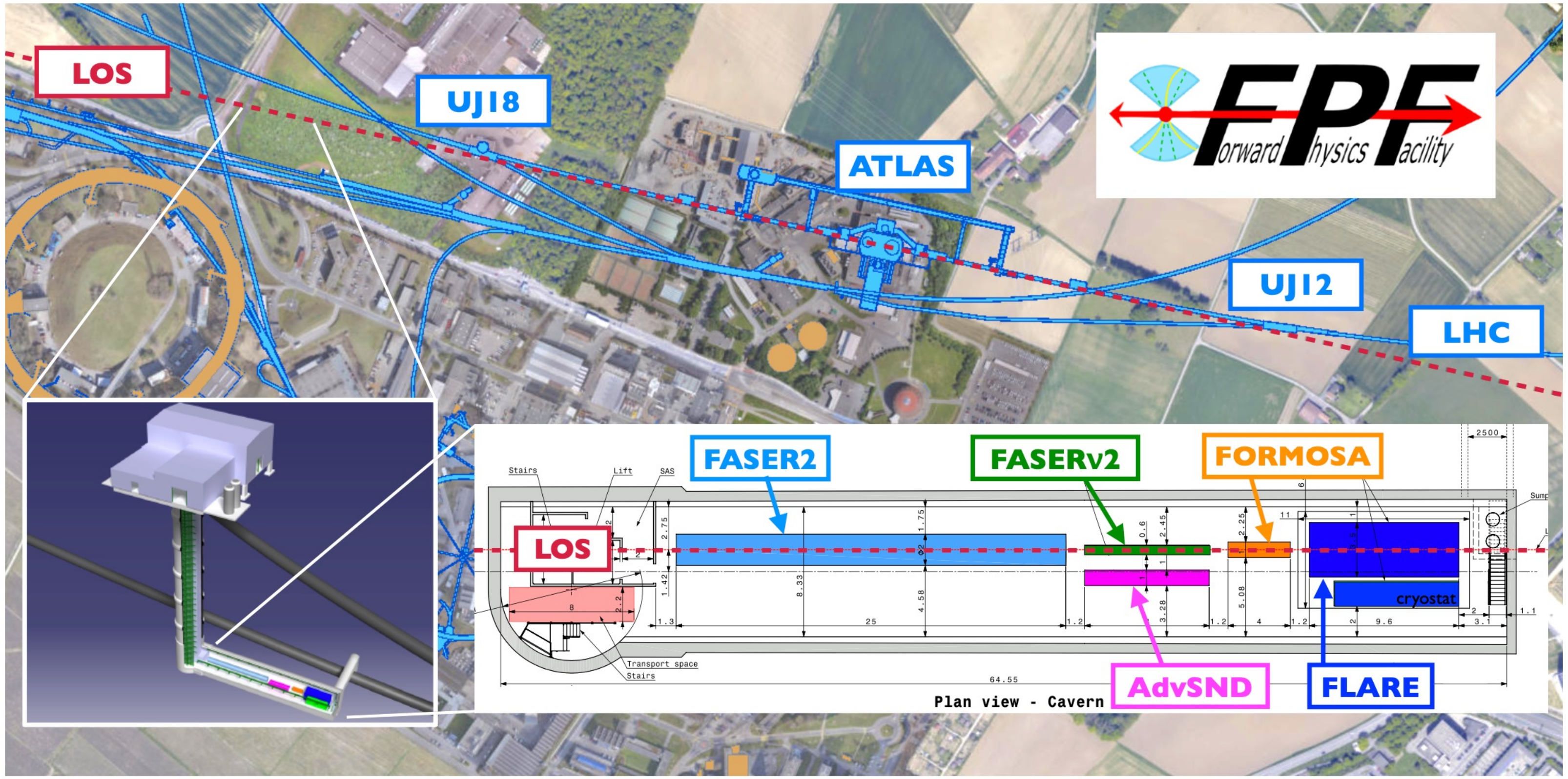


Figure 1: The preferred location for the Forward Physics Facility, a proposed new cavern for the High-Luminosity era. The FPF will be 65 m-long and 8.5 m-wide and will house a diverse set of experiments to explore the many physics opportunities in the far-forward region.

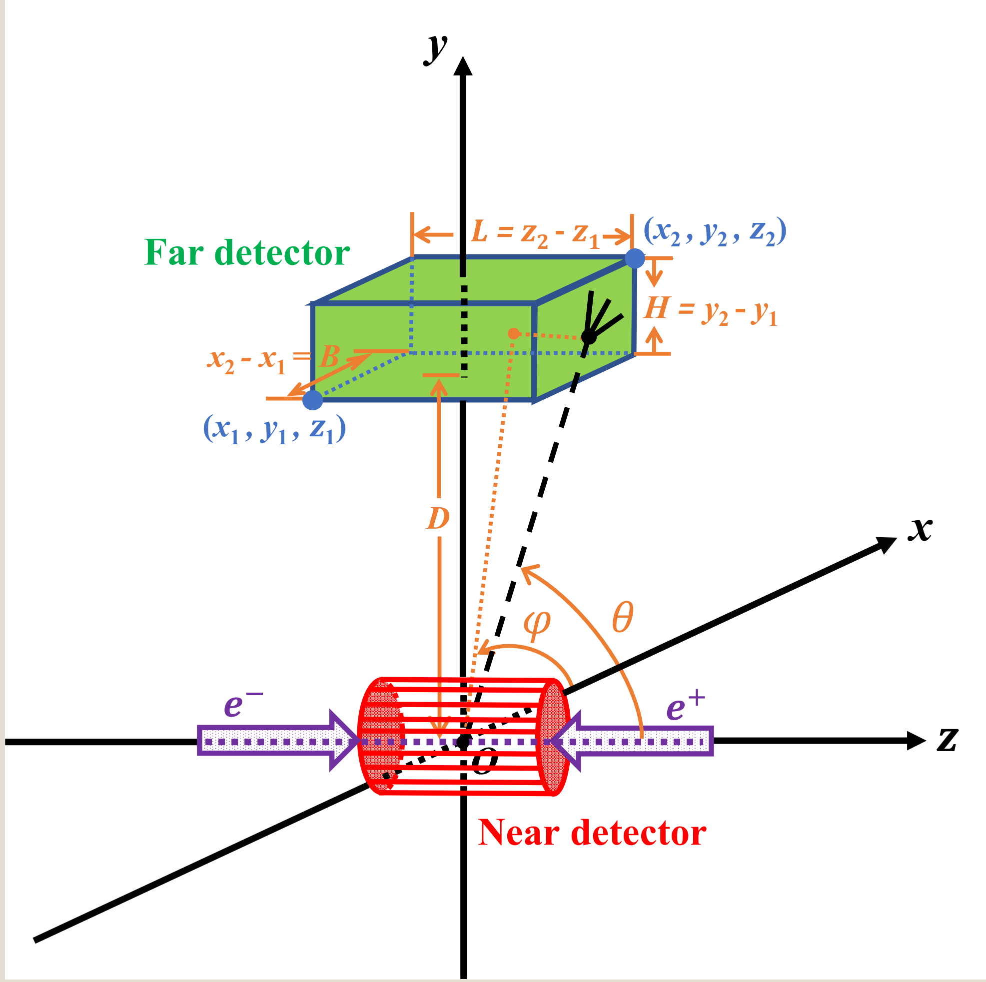
[2203.05090, The Forward Physics Facility at the High-Luminosity LHC]

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

FAr Detectors at the Electron Positron Collider (**FADEPC**)

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

	V [m^3]	B [m]	H [m]	L [m]	(x_1, y_1, z_1) [m]	(x_2, y_2, z_2) [m]	D [m]
FD1	5.0×10^3	10	10	50	(5, -5, -25)	(15, 5, 25)	5
					(10, -5, -25)	(20, 5, 25)	10
FD2	8.0×10^5	200	20	200	(-100, 50, 50)	(100, 70, 250)	50
					(-100, 100, 100)	(100, 120, 300)	100
FD3	8.0×10^5	200	20	200	(-100, 50, -100)	(100, 70, 100)	50
					(-100, 100, -100)	(100, 120, 100)	100
FD4	8.0×10^5	100	80	100	(-50, 50, -50)	(50, 130, 50)	50
					(-50, 100, -50)	(50, 180, 50)	100
FD5	3.2×10^6	200	80	200	(-100, 50, -100)	(100, 130, 100)	50
					(-100, 100, -100)	(100, 180, 100)	100
FD6	8.0×10^7	1000	80	1000	(-500, 50, -500)	(500, 130, 500)	50
					(-500, 100, -500)	(500, 180, 500)	100
FD7	8.0×10^5	2000	20	20	(-1000, 50, -10)	(1000, 70, 10)	50
					(-1000, 100, -10)	(1000, 120, 10)	100
FD8	8.0×10^5	20	20	2000	(-10, 50, -1000)	(10, 70, 1000)	50
					(-10, 100, -1000)	(10, 120, 1000)	100



Simple shape: cuboid, similar to MUTHUSLA
Varying: position & geometry size

Far Detector

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

		Exotic Higgs Decays	Heavy Neutral Leptons	Light Neutralinos in RPV SUSY
scenario		$h \to XX$	$Z \to N\nu$	$Z \to \tilde{\chi}_1^0 \tilde{\chi}_1^0$
LLP		X light scalar	N	$\tilde{\chi}_1^0$ light fermion
production $e^-e^+ \to$		Zh (main) $\nu\bar{\nu}h, e^-e^+h$ (VBF)	Z	
$\sqrt{s}$ [GeV]		240	91.2	
N_h	CEPC FCC-ee	1.14×10^6 [16] 5.6 ab^{-1}, 7 years, 2 IPs	-	
N_Z	CEPC FCC-ee	-	7.0×10^{11} [16] **16 ab^{-1}**, 2 years, 2 IPs 5.0×10^{12} [20] **150 ab^{-1}**, 4 years, 2 IPs	

has been updated to 1.5×10^{12}

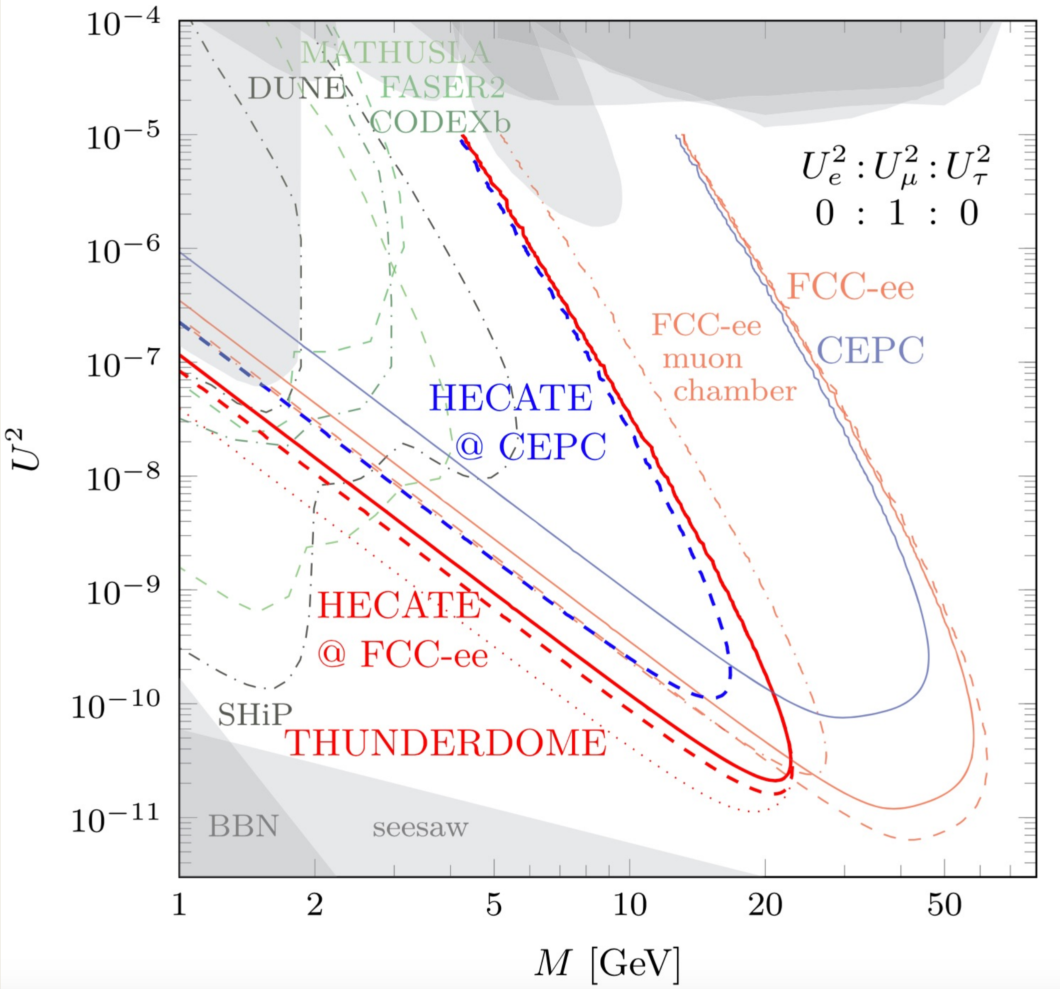
Axion like particles: $e^-e^+ \to \gamma\, a,\ a \to \gamma\gamma$ @ $\sqrt{s} = 91.2$ GeV

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

Far Detector

HNL: $Z \to N\nu$ @ $\sqrt{s} = 91.2$ GeV

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



the HECATE detector would consist of resistive plate chambers (RPCs) or scintillator plates, constructed from extruded scintillating bars, located around the cavern walls and forming a 4π detector.

the HECATE detector should have at least two layers of detector material separated by a sizable distance. For reliable tracking, at least four layers, along with a smaller size and/or optimised geometry of the detector plates, would be required.

Fig. 1 Comparison of the sensitivities for nine signal events that can be achieved at the FCC-ee with 2.5×10^{12} Z-bosons (red) or CEPC with 3.5×10^{11} Z-bosons (blue). The faint solid curves show the main detector sensitivity ($l_0 = 5\,\text{mm}$, $l_1 = 1.22\,\text{m}$). The faint dash-dotted curve indicates the additional gain if the muon chambers are used at the FCC-ee ($l_0 = 1.22\,\text{m}$, $l_1 = 4\,\text{m}$). The thick curves show the sensitivity of HECATE with $l_0 = 4\,\text{m}$, $l_1 = 15\,\text{m}$ (solid) and $l_0 = 4\,\text{m}$, $l_1 = 25\,\text{m}$ (dashed), respectively. Finally, the faint dashed red line shows the FCC-ee main detector sensitivity with 5×10^{12} Z-bosons, corresponding to the luminosity at two IPs. For comparison we indicate the expected

Far Detector

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

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

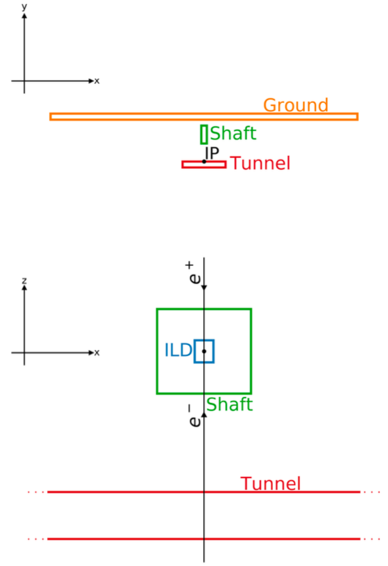


Figure 3: Far detector options around the ILC interaction point (IP). Shown are a side view (left) and top view (right) of the projected far detectors in the Shaft (S, blue), in the Tunnel (T, purple), and on the Ground (G, red), as well as the main detector ILD (green). The Ground detector is centered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

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

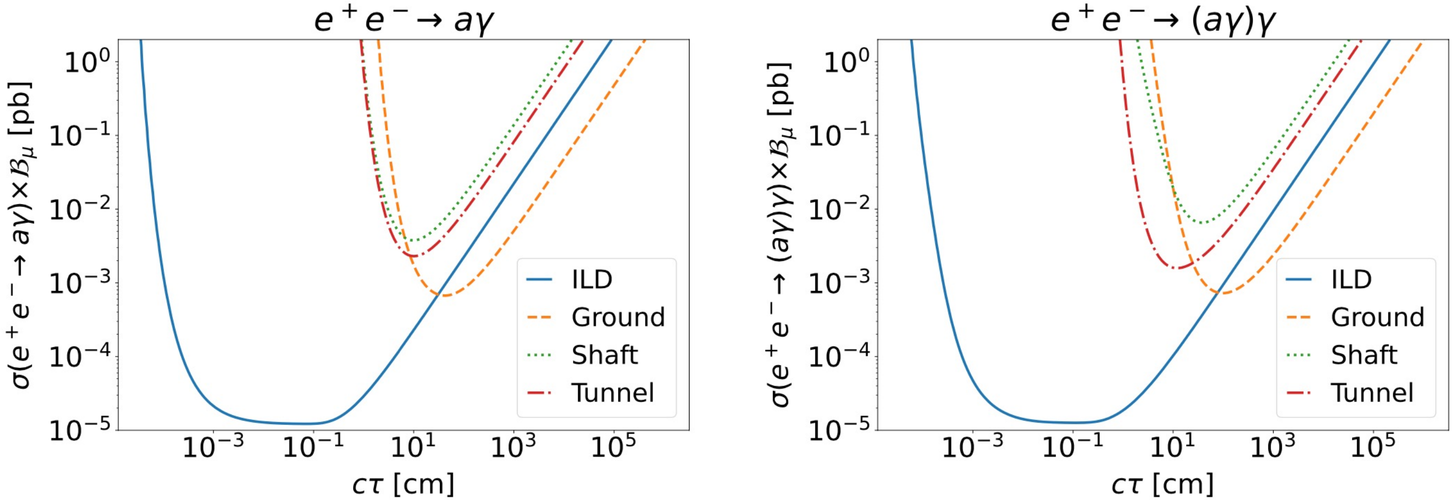
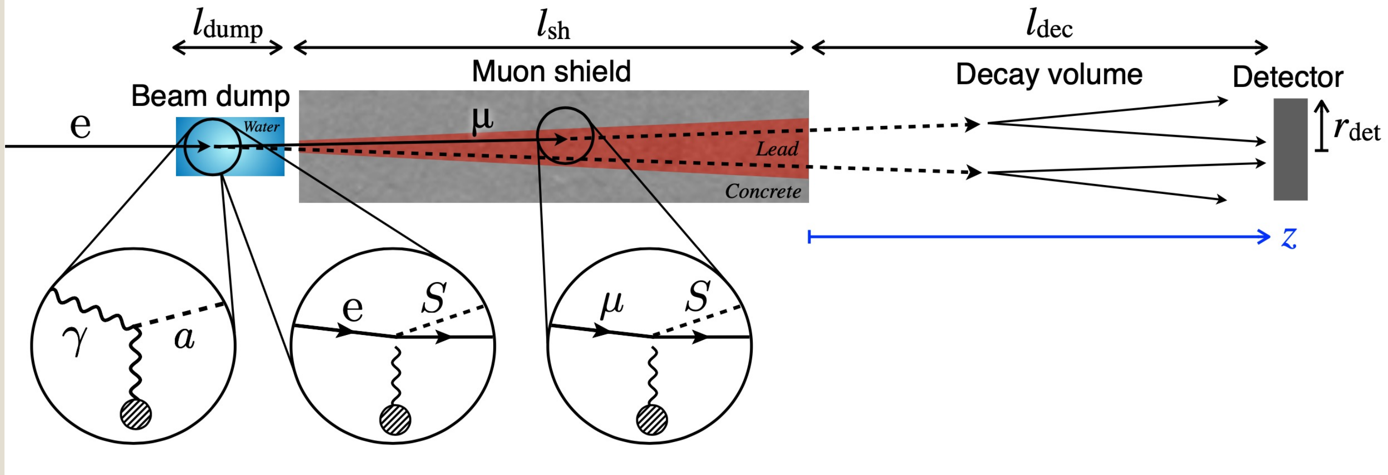


Figure 5: Contours of $N_a = 3$ ALPs with $m_a = 300$ MeV decaying within various ILC detectors, as a function of the production cross section, σ, and the proper lifetime, $c\tau_a$. Shown are the production channels $e^+e^- \to a\gamma$ (left) and $e^+e^- \to Z\gamma \to (a\gamma)\gamma$ (right) at $\sqrt{s} = 250$ 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 $\mathcal{B}_\mu$.

Beam Dump

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

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

New neutral gauge boson Z' @ E_{beam} =125 GeV

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

HNL @ E_{beam} = 45.6,125, 500 GeV

[**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]

[**2206.13745, JHEP 04 (2023) 046, Pierce Giffin, Stefania Gori, Yu-Dai Tsai, Douglas Tuckler**, Heavy neutral leptons at beam dump experiments of future lepton colliders]

Discussion

LLPs searches @ ee colliders have **unique characteristics** (high lum., clean environment, EW prod., transverse direction, recoil strategy) and are important ways to BSM physics.

Studies with Near Detectors

→ Higgs/Z decays, new scalars, dark photon, mirror glueballs

→ HNL, ALP, SUSY, hidden valley particles, vector-like leptons ...

Studies with Far Detectors

→ Different designs

→ Higgs decays, HNL, SUSY, ALP, ...

Studies with beam dump

→ ALP, new scalars, HNL, leptophilic gauge bosons, Z', ...

More studies are very welcome!

Discussion

Related to the Program Tools

→ LLP event fast simulation @ detector level:

no sophisticated and mature tools yet !

ND vs FD

→ FDs can be shielded, Bkg could be small

→ 3-signal-event sensitivities: background study for ND are needed

Related to the Detection Technology

→ Timing detectors: offers important timing info. for LLPs

→ Trackers: better track resol.

→ Cheap far detectors: particle ID, big volume