This project is supported from the European Union's Horizon 2020 research and innovation program under grant agreement No 951754.

Direct BSM at the FCC-ee

Juliette Alimena (DESY), on behalf of the FCC BSM group

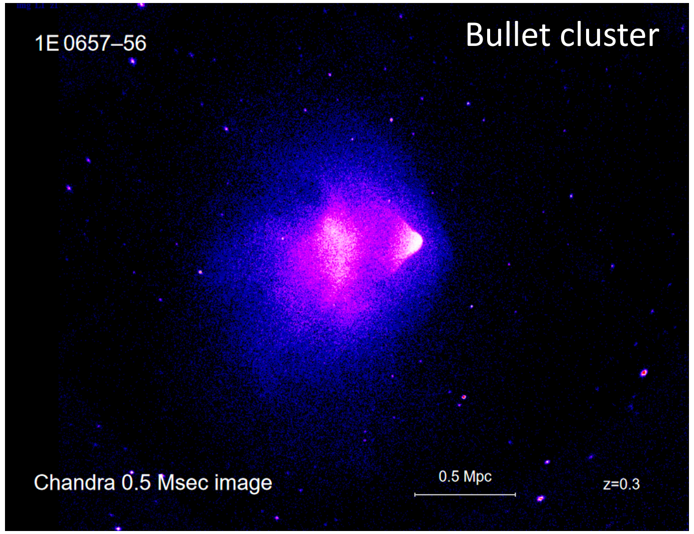
7th FCC Physics Workshop

LAPP Annecy, France

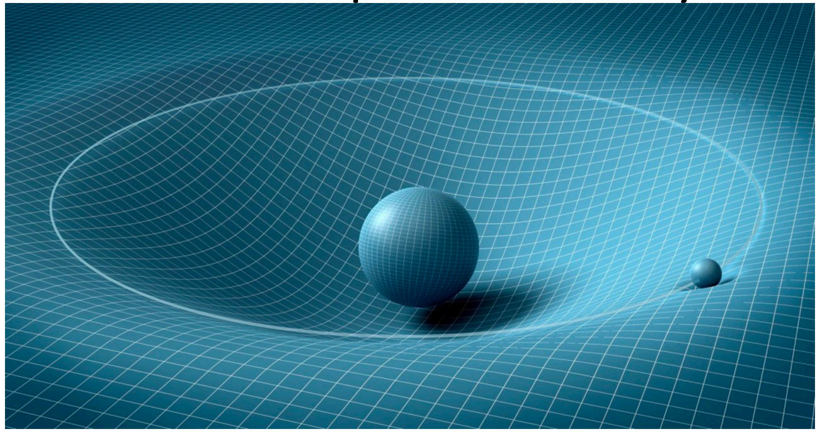
February 1, 2024

Unanswered Questions in Physics

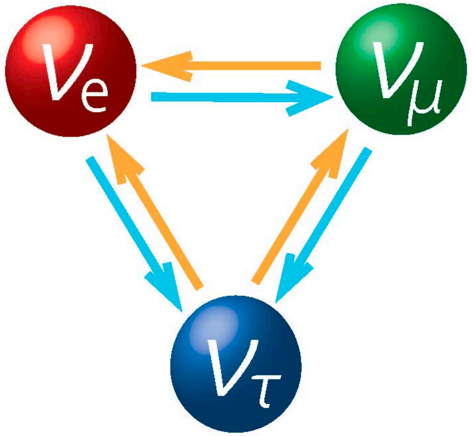
What is the particle nature of dark matter?



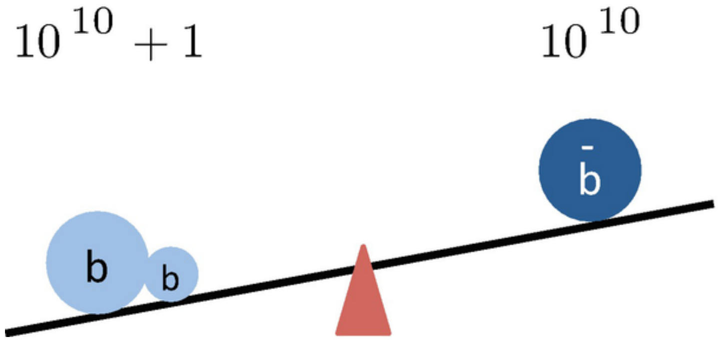
How do we incorporate gravity into a consistent particle theory?



How do neutrinos have mass?

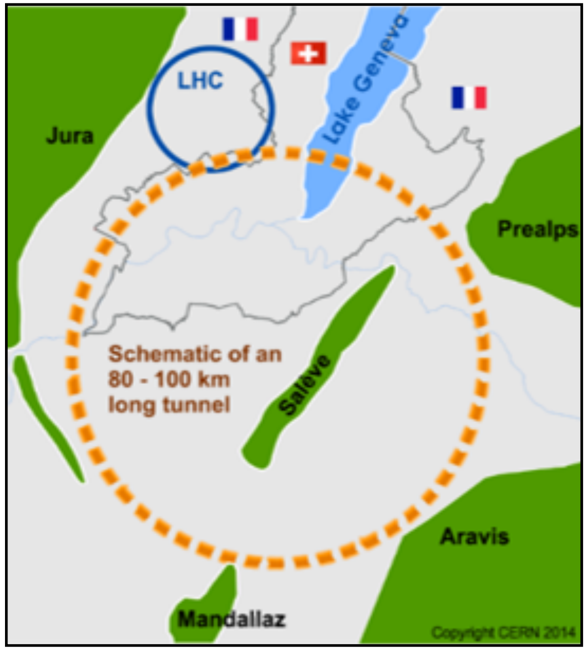


Why is there more matter than antimatter in the universe?

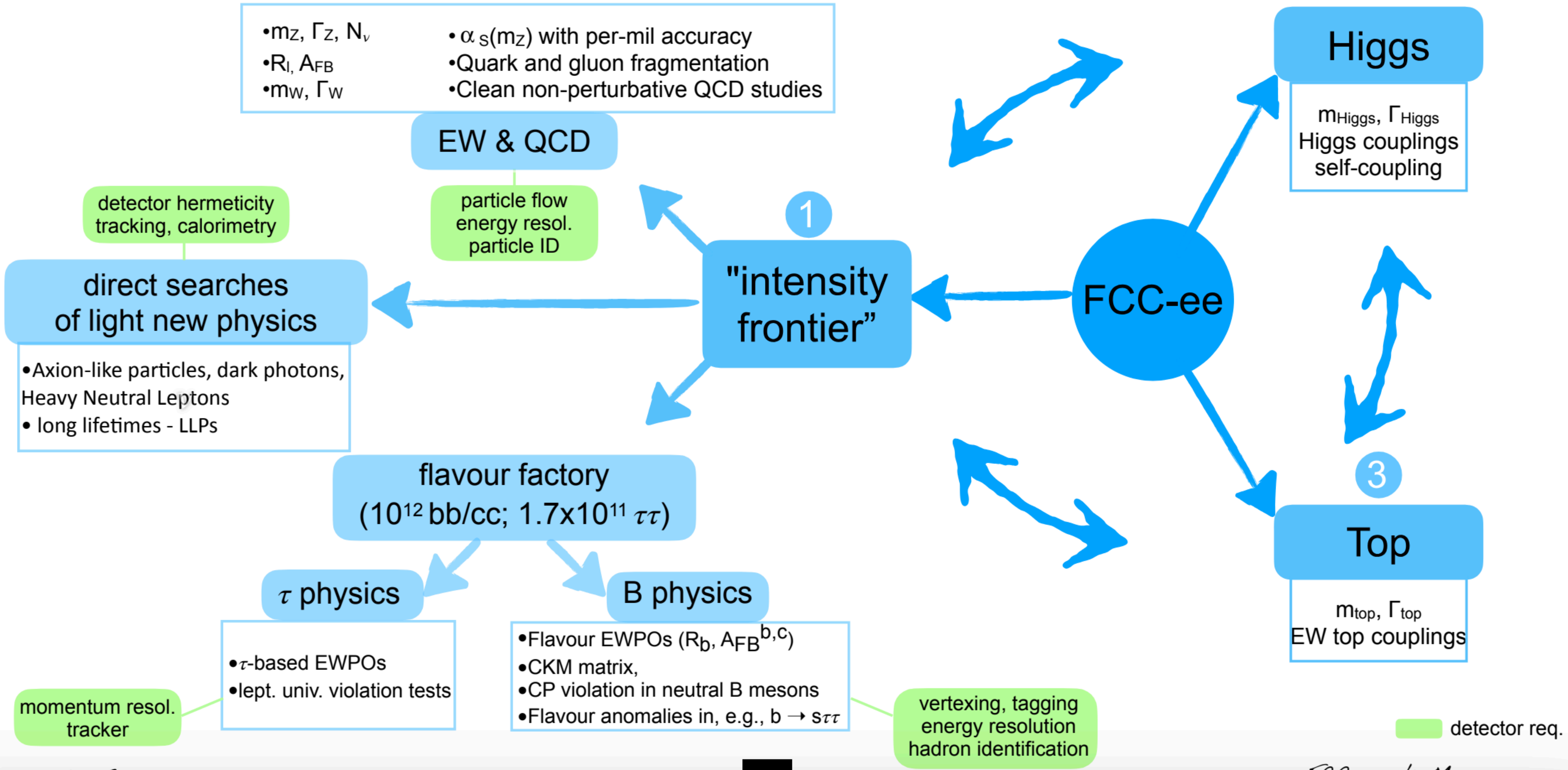


FCC: A Unique Machine

- The FCC will provide a **unique opportunity** to learn more about **how nature works**
- There's **no other way** besides colliders to explore the **Higgs** boson!
- The FCC is is a frontier Higgs, top, electroweak, and flavor factory where we can **directly discover new physics!**

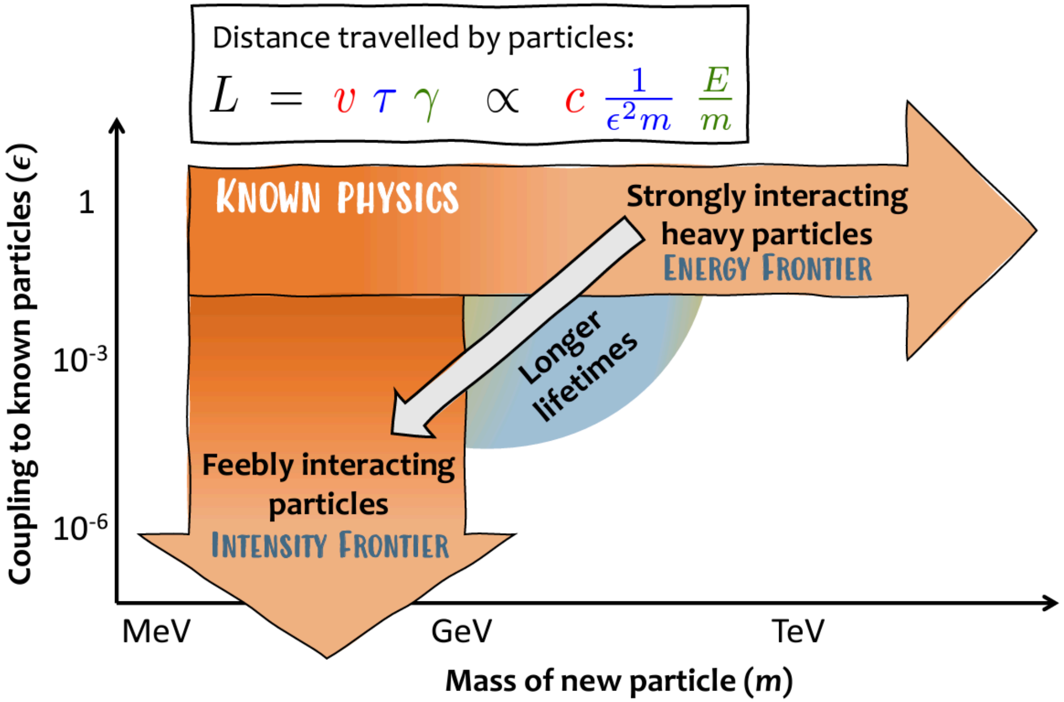


FCC-ee Physics Program



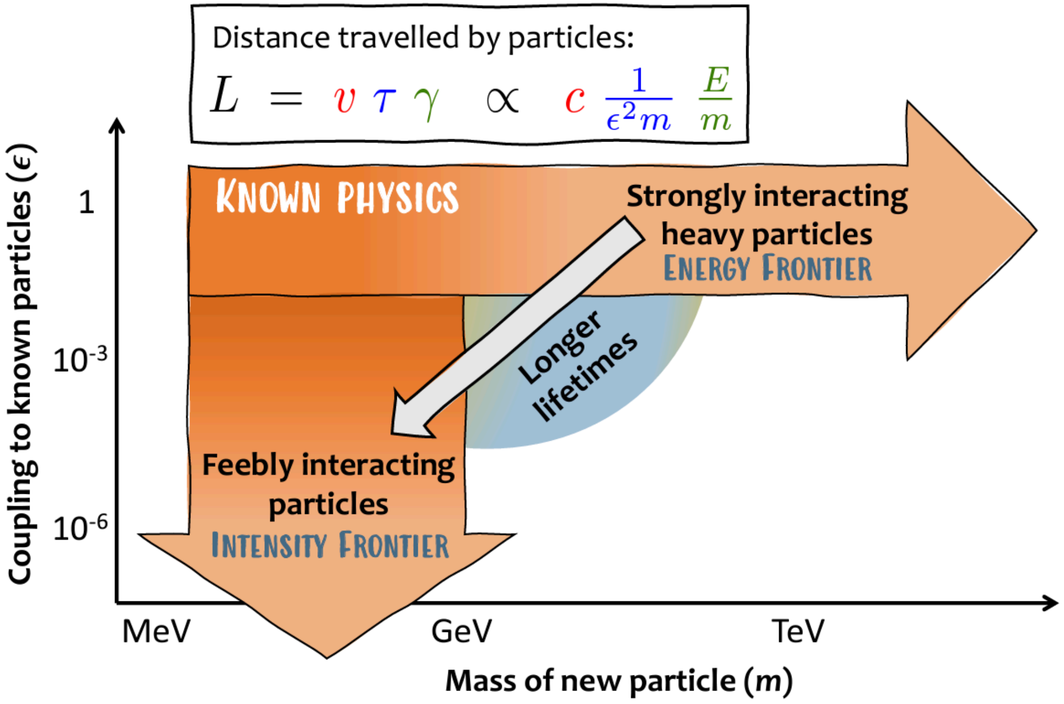
Feebly Interacting Particles (FIPs)

- Due to interacting feebly, they are linked to a “hidden sector”
- Couplings between SM and hidden sector result from “portal” operators



Feebly Interacting Particles (FIPs)

- Due to interacting feebly, they are linked to a "hidden sector"
- Couplings between SM and hidden sector result from "portal" operators
- Large number of specific models, can be simplified:



1. SM Higgs h — h ----- $(\mu S + \lambda S^2)H^\dagger H$ ----- S — Dark Higgs S

New scalar: **Dark Higgs**; couplings to SM μ, λ

3. SM EM A — A 〰 $-\frac{\epsilon}{2\cos\theta_W}F'_{\mu\nu}F_Y^{\mu\nu}$ 〰 A_D — Dark EM A_D

New vector: **Dark photon**; coupling to SM $\propto \epsilon Q$

2. SM 2γ or $2f$ — 2γ --- $\frac{\alpha}{f_\alpha}F_{\mu\nu}\tilde{F}^{\mu\nu}$; $2f$ --- $\frac{\partial_\mu \alpha}{f_\alpha}\bar{\psi}\gamma^\mu\gamma^5\psi$ ----- α — ALP α

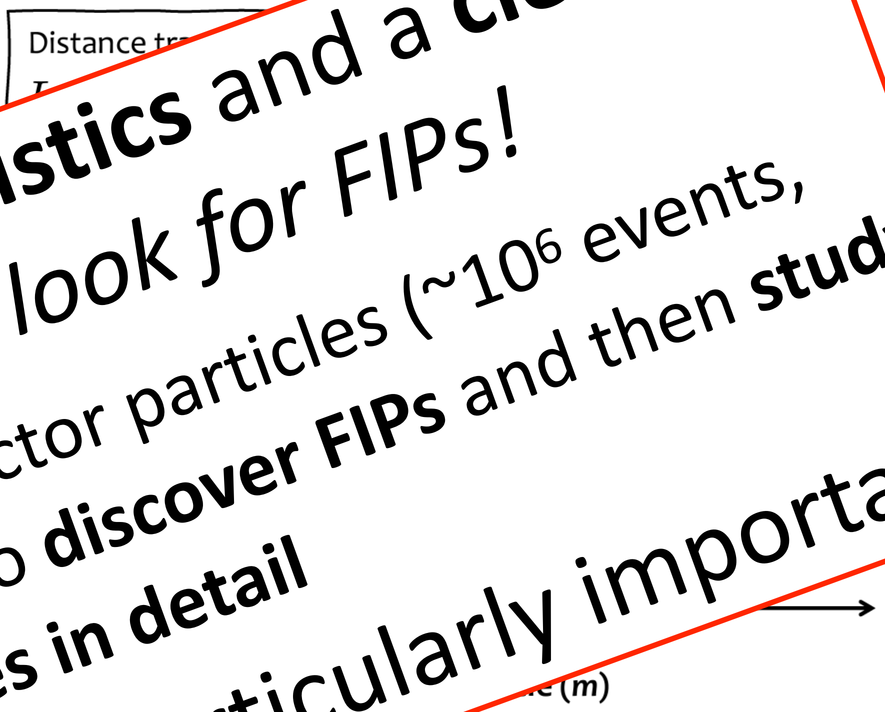
New pseudo-scalar: **ALP**; coupling to SM suppressed
(Axion Like Particle)

4. SM LH ν — ν — $y_N h L \psi_D$ — N — HNL N

New fermion: **HNL**; coupling to LH SM and h $\propto y_N$
(Heavy Neutral Lepton)

Feebly Interacting Particles (FIPs)

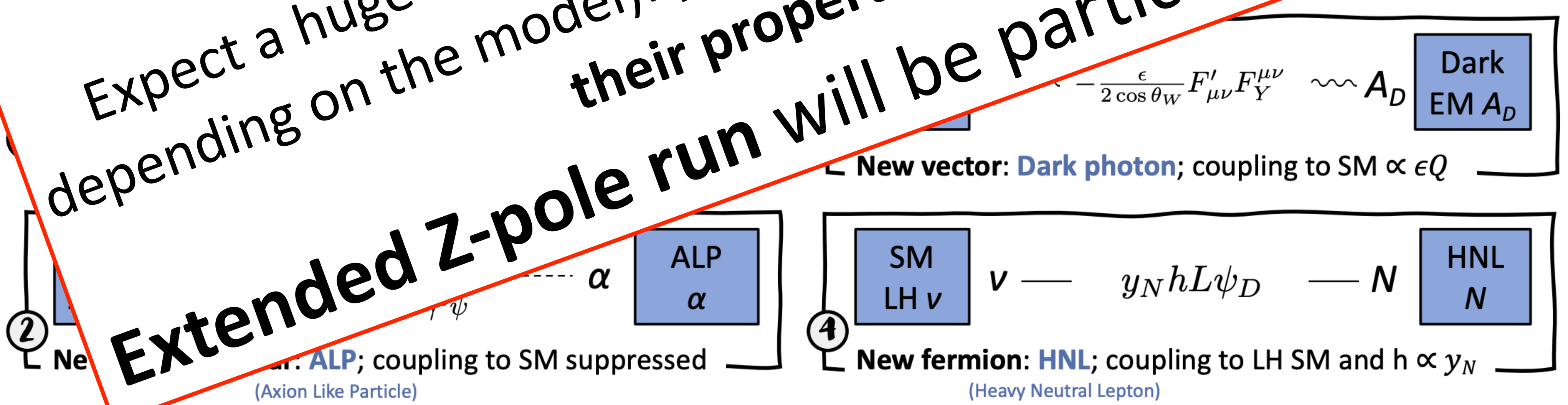
- Due to interacting feebly, they are linked to a “hidden sector”
- Couplings between SM and hi… sector result from “p… operators
- Lar… ca…



FCC-ee will give us huge statistics and a clean environment: *great to look for FIPs!*

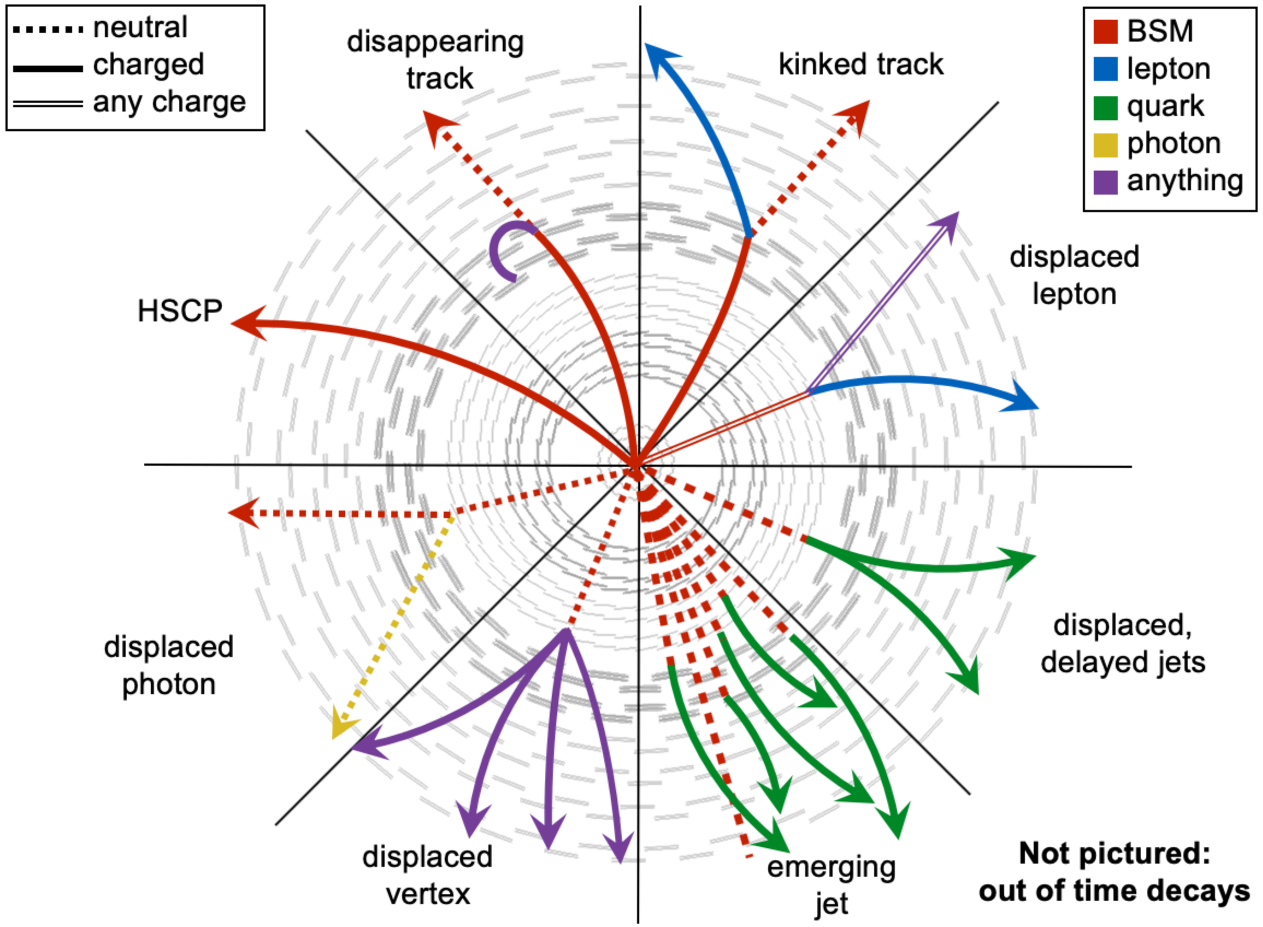
Expect a huge number of hidden sector particles (~10^6 events, depending on the model): potential to **discover FIPs** and then **study their properties in detail**

Extended Z-pole run will be particularly important



Long-Lived Particle Searches

- Design **signature-driven** searches with a wide variety of final states and lifetimes
- **Challenges of the LHC:** main detectors, triggers, offline reconstruction not designed for displaced particles
- **Big opportunity to do something different at the FCC!**
- Can design **general-purpose detectors with LLPs in mind!**



Past and Ongoing Work

Several Masters student theses on FIPs 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)
- Dimitri Moulin (University of Geneva, 2023)
- Daniel Beech (University of Cambridge, 2023)
- Sofia Giappichini (University of Perugia, 2023)
- Thomas Critchley (University of Geneva, 2024)

Snowmass LLPs:

- LOI
- White paper (Front. Phys. 10:967881 (2022) / arXiv:2203.05502)

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

C. B. Verhaaren[1], J. Alimena[2]*, M. Bauer[3], P. Azzi[4], R. Ruiz[5], M. Neubert[6,7], O. Mikulenko[8], M. Ovchynnikov[8], M. Drewes[9], J. Klaric[9], A. Blondel[10], C. Rizzi[10], A. Sfyrla[10], T. Sharma[10], S. Kulkarni[11], A. Thamm[12], A. Blondel[13], R. Gonzalez Suarez[14] and L. Rygaard[14]

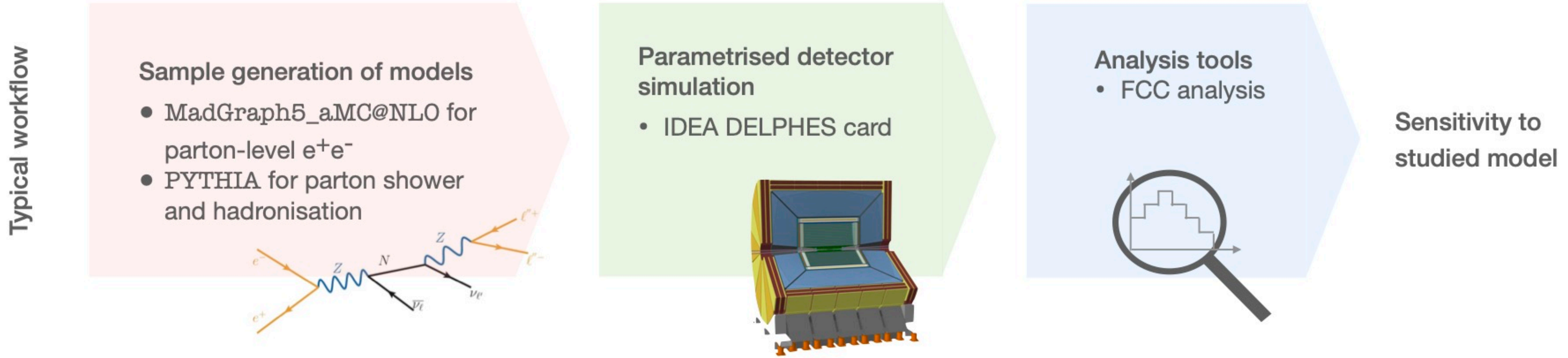
FIPs are also included in the midterm report

BSM group focusing on 3 physics cases:

1. Heavy Neutral Leptons (HNLs)
2. Axion-like Particles (ALPs)
3. BSM Higgs

I'll present the latest activities of several BSM FCC analyses

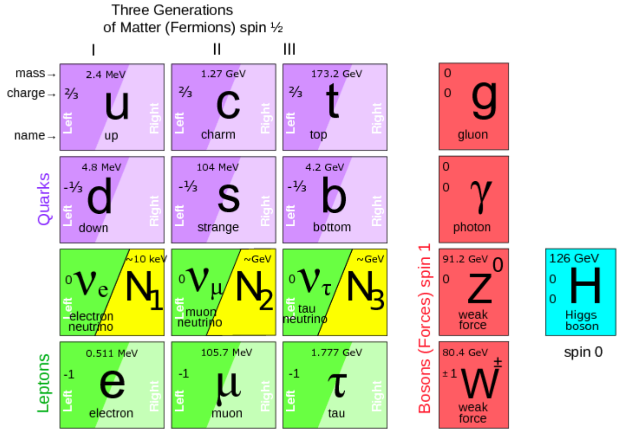
Workflow



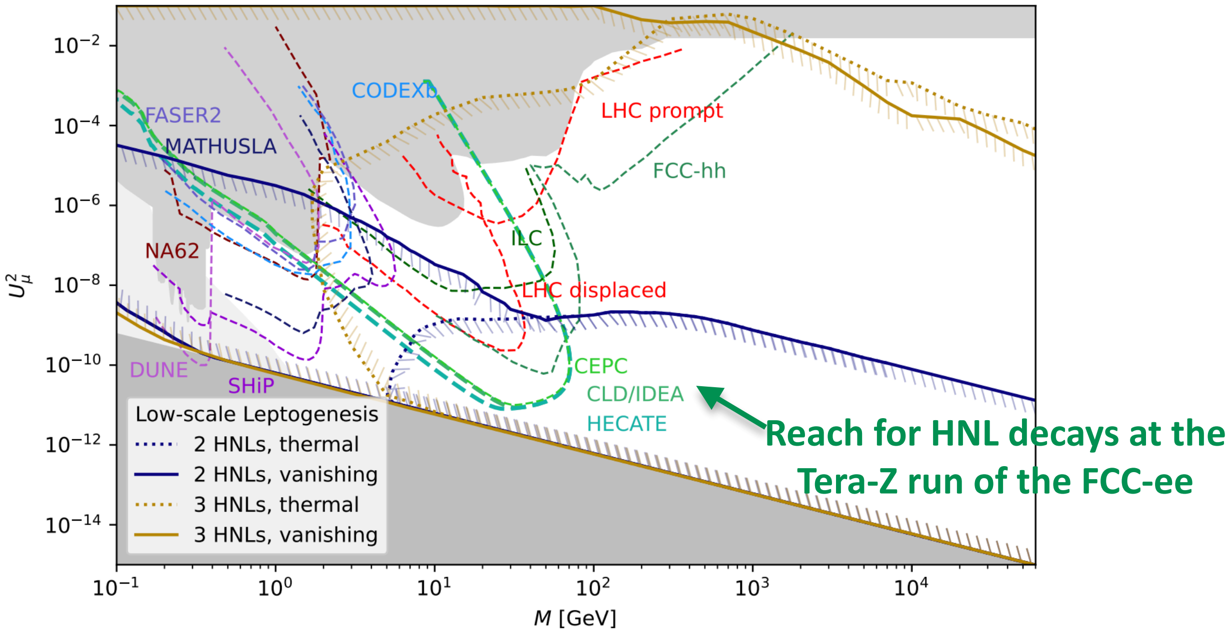
- Perform an FCC case studies with the **“official” analysis tools and framework** available for the FCC
  - **Use FCCAnalysis software** to analyze centrally-produced **EDM4HEP** samples with the **IDEA** detector in **Delphes**, although some signal samples produced privately
  - Dedicated tutorial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

1st Physics Case: Heavy Neutral Leptons (HNLs)

- **Sterile neutrinos** with **very small mixing** with active neutrinos
- **Could provide answers** to some open questions of the SM: Neutrino masses, Baryon asymmetry, Dark matter
- Get **long-lived HNLs** when coupling and mass are small
- Besides the studies I will mention in the next slides, also studying:
  - **HNLs in the CLD design** (Jeremy Andrea, Gaelle Sadowski)
  - **Neutrino oscillations** (see Jan's talk and Nicolo's talk in parallel sessions)



arXiv:2203.05502



Dimitri Moulin, Tanishq Sharma, Pantelis Kontaxakis, Anna Sfyrla

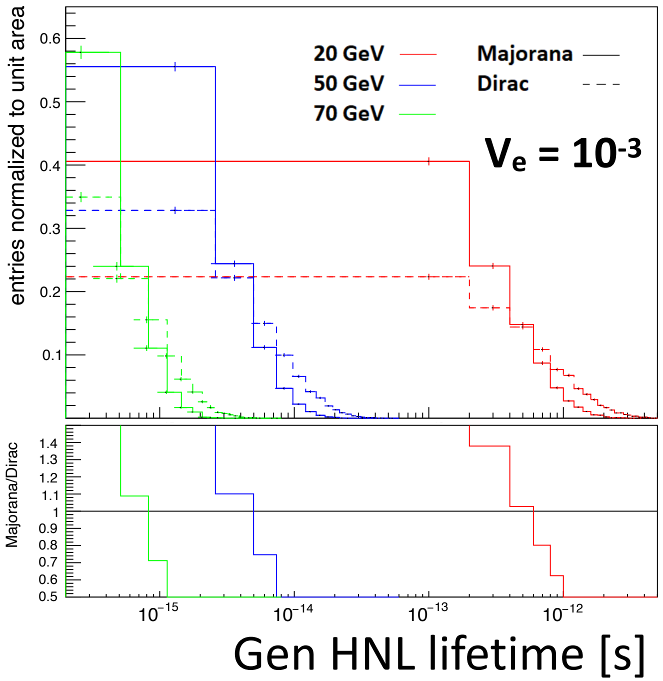
$N \rightarrow ee\nu$: HNL Properties

The extreme Dirac (LNC) and Majorana (LNC+LNV) benchmark model limits produce different kinematic distributions: arXiv:2105.06576

Example variables that can measure the amount of LNV:

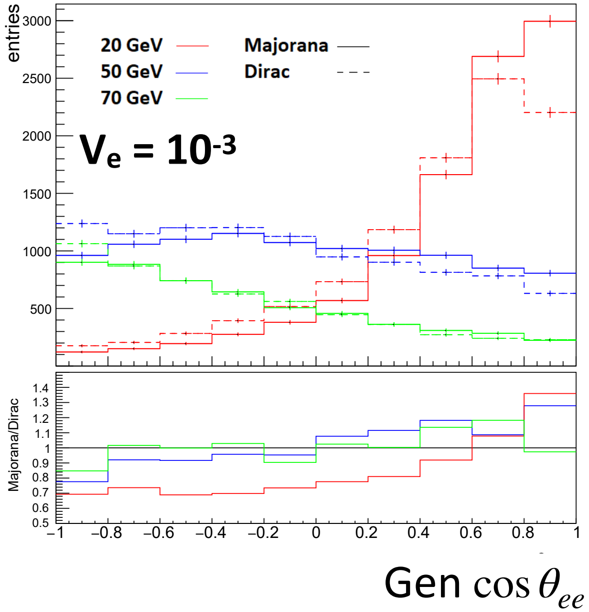
HNL Lifetime

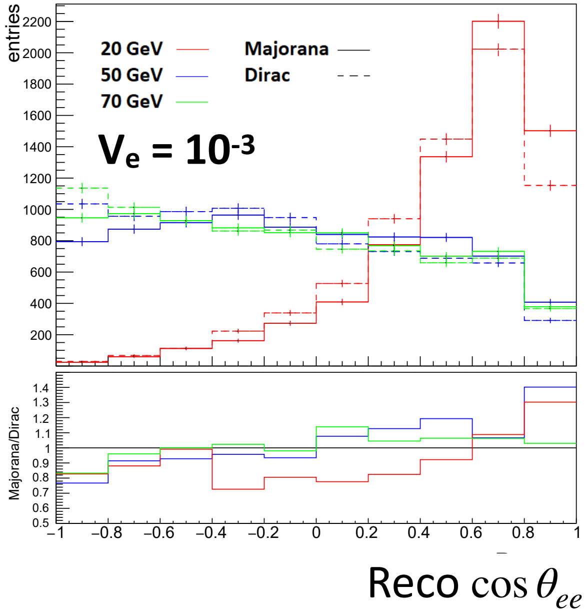
(model-dependent)



$\cos\theta_{ee}$

(opening angle between final state electron/positron)

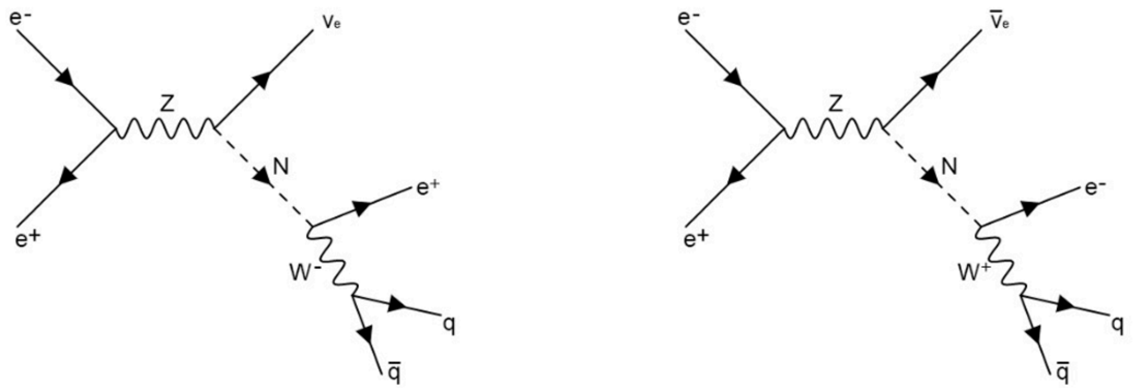




$N \to ejj$

Tom Critchley, Pantelis Kontaxakis,, Anna Sfyrla

- First performed a **cut and count** study, then compared with using **XGBoost** with TVMA
  - First use of ML in LLPs at FCC group
  - **Much improved limits**, especially at high mass
- **Just the beginning!** More to come:
  - Adding discriminating variables, using DNN instead of BDT, better MC statistics, …



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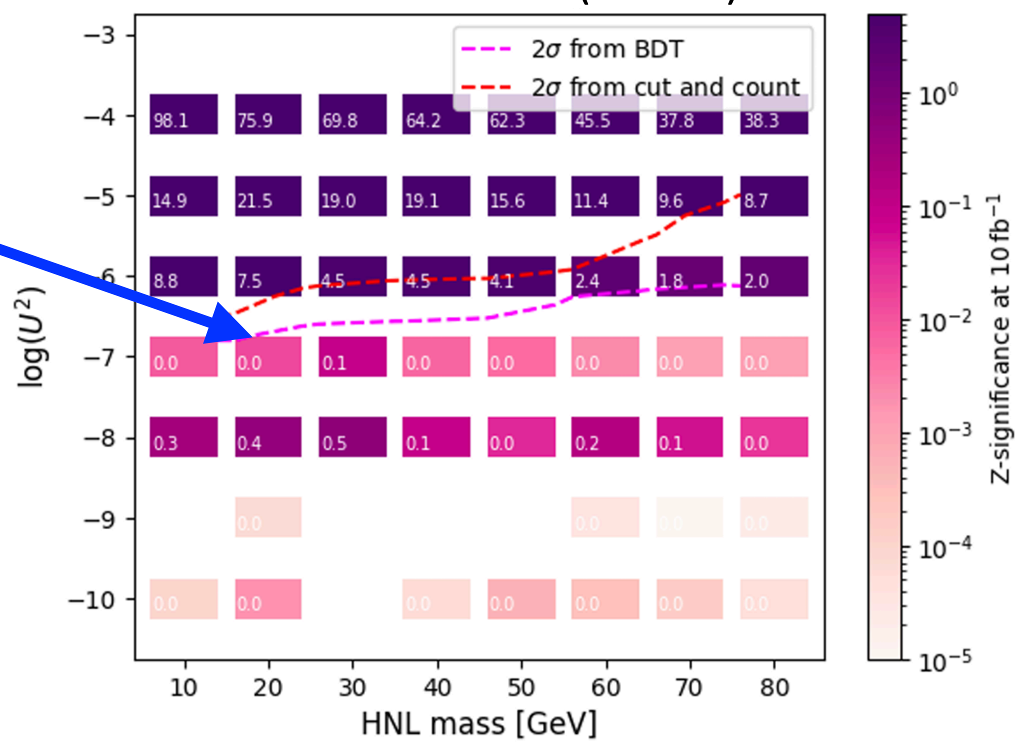
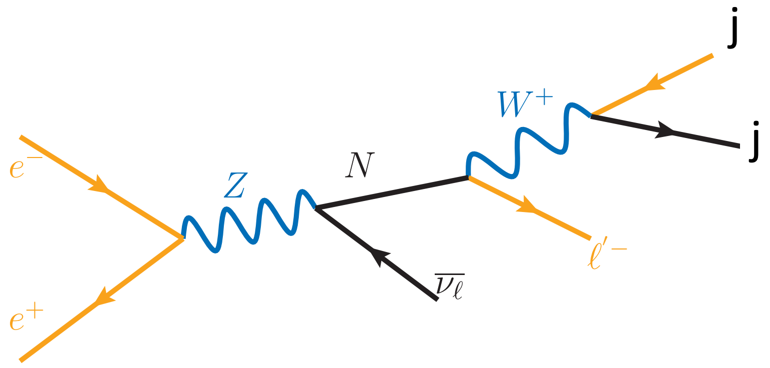
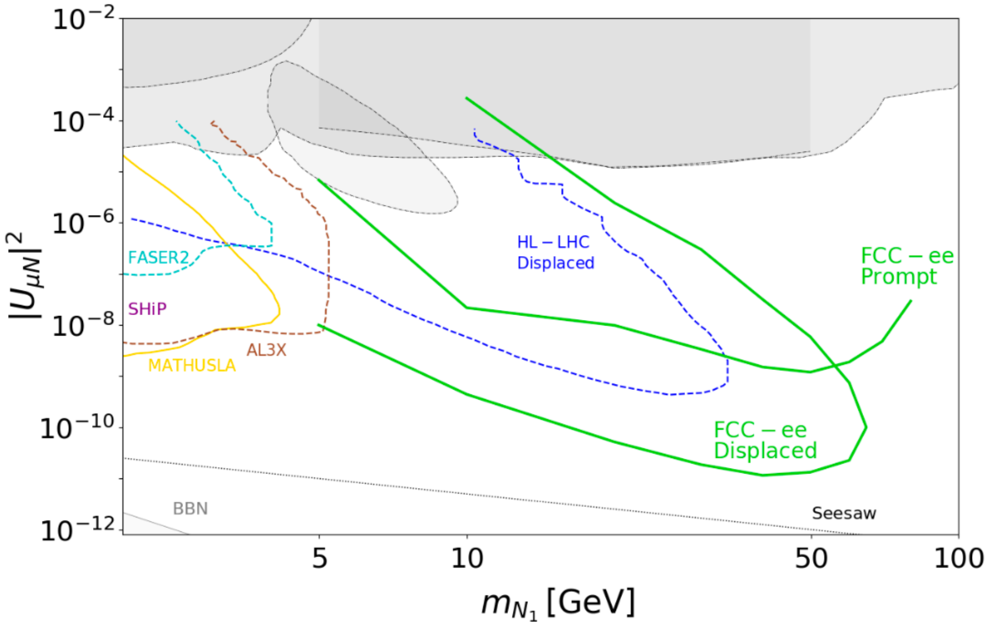


$N \to \mu jj$

Nicolò Valle, Giacomo Polesello



- High branching fraction: ~50%
- Two subanalyses:
  - **Prompt analysis** targeting **high HNL mass (> 50 GeV)**
    - Require vertex radius < 0.5 mm
  - **Long-lived analysis** targeting **low HNL mass**
    - Require vertex radius > 0.5 mm
- See Nicolo's talk in parallel session for more, also on neutrino oscillations

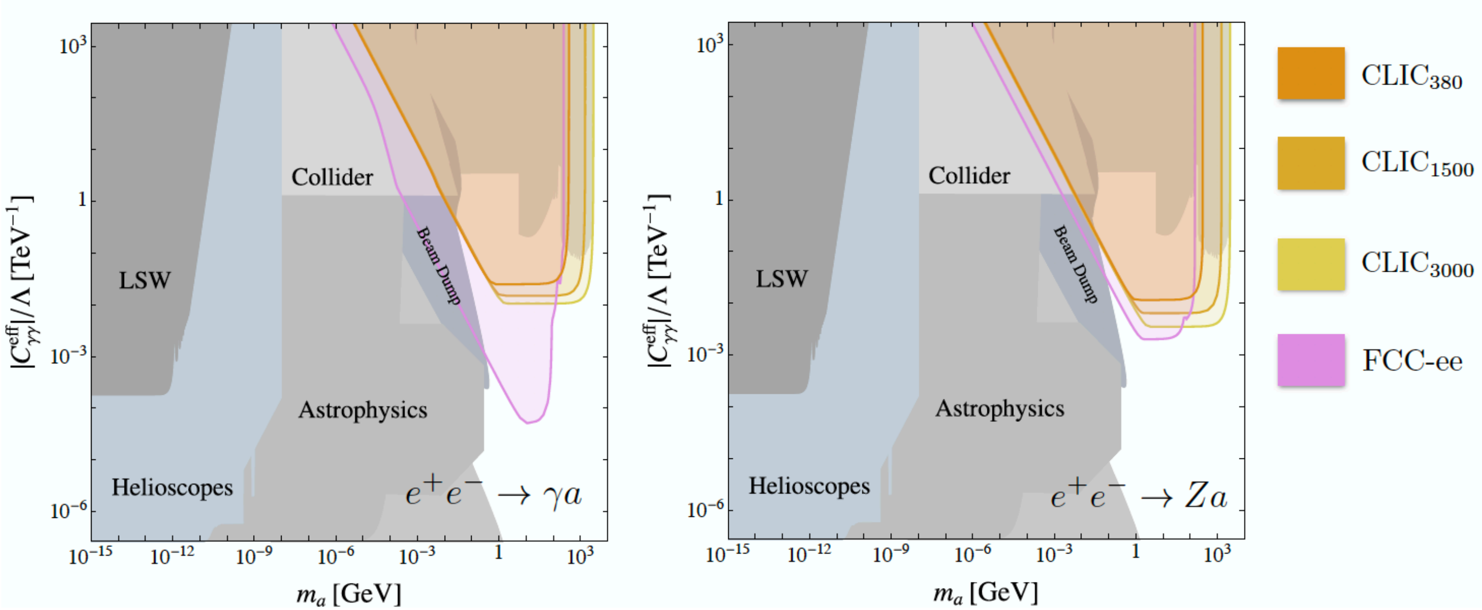


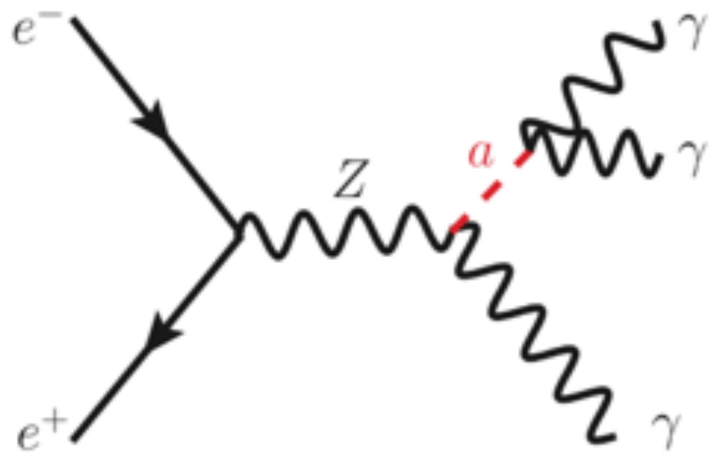
FCC note under approval

2nd Physics Case: Axion-Like Particles (ALPs)

- Axion-like Particles (ALPs) are pseudoscalars in models with spontaneously broken global symmetries
- 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

arXiv:1808.10323, arXiv:2108.08949

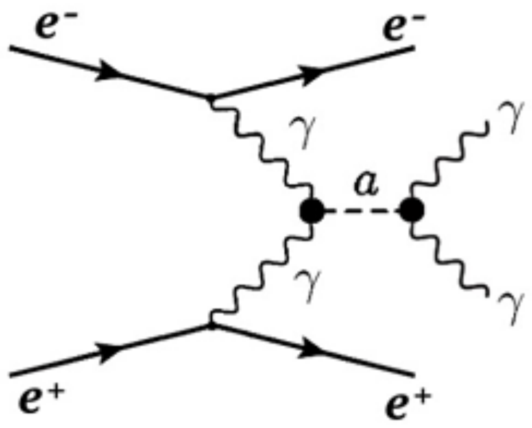


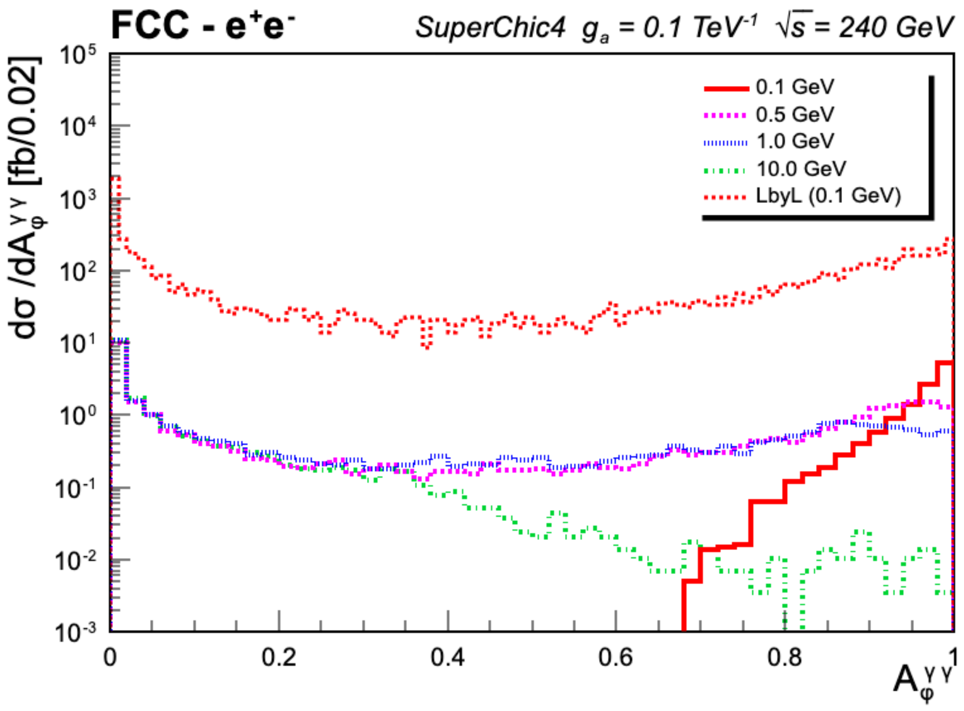


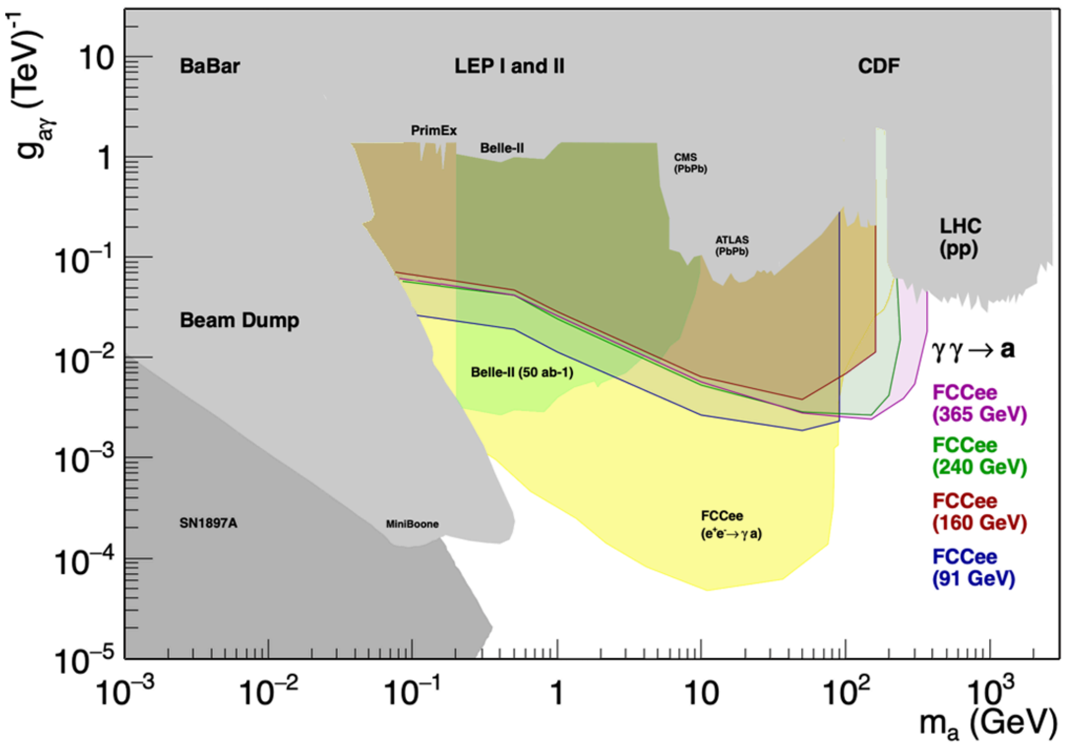
Patricia Rebello Teles, David d'Enterria, Victor Gonçalves, Daniel Martins
arXiv:2310.17270

ALPs via Photon Fusion

- ALPs produced in e+e- collisions via photon-photon fusion
- Irreducible background: light-by-light continuum
- Delphes-only, not yet using full edm4HEP/FCCAnalyses machinery
- See Patricia's talk in the parallel session for more







Axel Gallén, Giulia Ripellino, Magdalena Vande Voorde, Rebeca Gonzalez Suarez

3rd Physics Case: Exotic Higgs Decays to LLPs

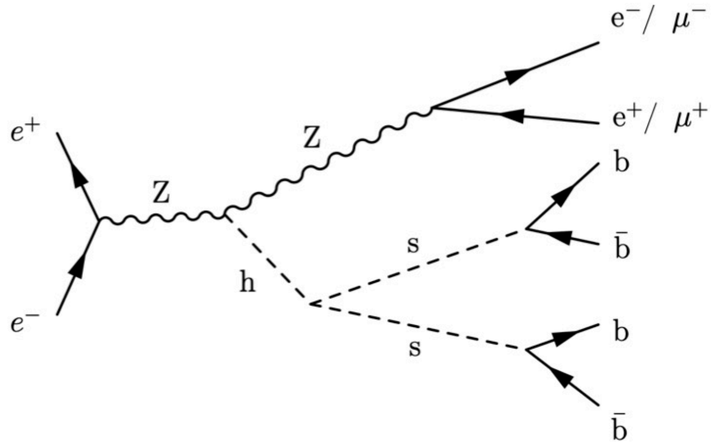
- Higgs bosons could undergo **exotic decays** to e.g. **scalars that could be long-lived**
- New scalar could be a **portal between the SM and a dark sector (HAHM)** ([arXiv:1312.4992](), [arXiv:1412.0018]())
- Higgs boson (h) and the scalar (s) mix with a mixing angle sin θ
- **For sufficiently small mixing, the scalar can be long-lived**
  - cτ ~ meters if θ < 1e-6

[Magda's master thesis]()

FCC note under approval

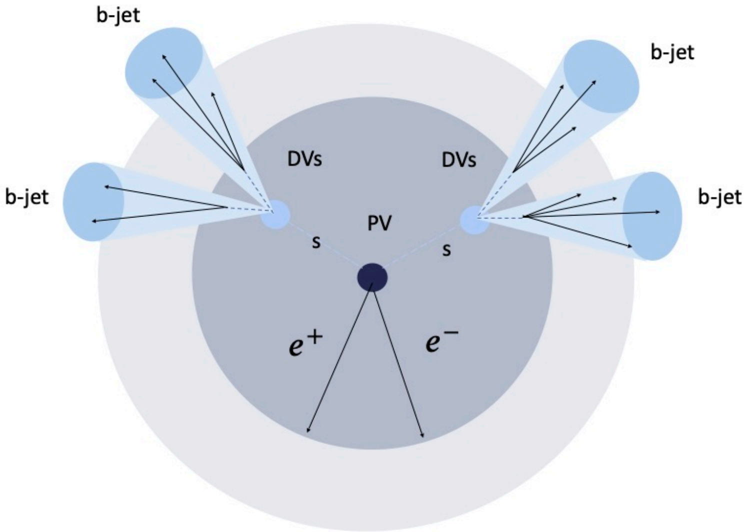
Target FCC-ee **Zh stage** (240 GeV):

$e^+e^- \to Zh$ with $h \to ss \to b\bar{b}b\bar{b}$ and
$Z \to ll$ (2 electrons or 2 muons)



Experimental signature

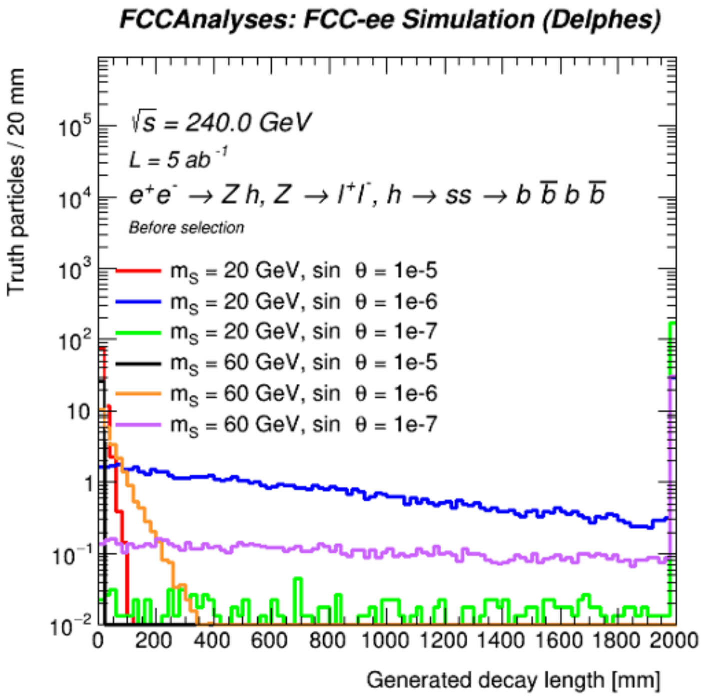
2 displaced vertices (DVs) +
Z boson from ee or mumu



Axel Gallén, Giulia Ripellino, Magdalena Vande Voorde, Rebeca Gonzalez Suarez

Exotic Higgs Decays: Gen-Level Study

- Select events with **at least 1 scalar** within the **acceptance region** $4 < r < 2000$ mm
- All signal points have $\geq$ **4 events** except the shortest and longest lifetimes probed



Signal Sensitivity:

Number of expected events given by
$N = L \times \sigma$ with $L = 5\ ab^{-1}$ and
$\sigma = \sigma_{ZH} \times BR(h \rightarrow ss) \times BR(s \rightarrow b\bar{b})^2 \times BR(Z \rightarrow l^+l^-)$

Mass of Scalar m_S [GeV]	Mixing angle $\sin\theta$	Mean proper lifetime $c\tau$ [mm]	Branching Ratio $BR(h \rightarrow ss)$	Total expected events	Expected selected events
20	1×10^{-5}	3.4	6.98×10^{-4}	55.20	50.19
20	1×10^{-6}	341.7	6.98×10^{-4}	55.20	53.87
20	1×10^{-7}	34167.0	6.98×10^{-4}	55.20	2.09
60	1×10^{-5}	0.9	2.06×10^{-4}	16.32	0.01
60	1×10^{-6}	87.7	2.06×10^{-4}	16.32	16.15
60	1×10^{-7}	8769.1	2.06×10^{-4}	16.32	10.66

Axel Gallén, Giulia Ripellino, Magdalena Vande Voorde, Rebeca Gonzalez Suarez

Exotic Higgs Decays: Reco-Level Study

- Select events with a **Z boson** and **at least two DVs**
- **Z boson:** 2 oppositely charged electrons or muons, with $70 < m_{ll} < 110$ GeV
- **DV:**
    - Inside tracker volume, but not in innermost region to reduce bkg from HF decays
    - DV mass > 1 GeV

Signal Sensitivity:

m_s, sin θ	$c\tau$ [mm]	BR($h \to ss$)	Before selection	Pre-selection	$70 < m_{ll} < 110$ GeV	n_DVs ≥ 2
20 GeV, 1e-5	3.4	6.98×10^{-4}	55.2 ± 0.552	52.84 ± 0.538	49.02 ± 0.520	5.0 ± 0.166
20 GeV, 1e-6	341.7	6.98×10^{-4}	55.2 ± 0.552	52.44 ± 0.538	49.02 ± 0.521	37.1 ± 0.453
20 GeV, 1e-7	34167.0	6.98×10^{-4}	55.2 ± 0.552	52.38 ± 0.540	49.68 ± 0.524	0.8 ± 0.067
60 GeV, 1e-5	0.9	2.06×10^{-4}	16.32 ± 0.163	15.62 ± 0.127	14.59 ± 0.154	0.0033 ± 0.0023
60 GeV, 1e-6	87.7	2.06×10^{-4}	16.32 ± 0.163	15.62 ± 0.196	14.61 ± 0.196	10.96 ± 0.167
60 GeV, 1e-7	8769.1	2.06×10^{-4}	16.32 ± 0.163	15.52 ± 0.159	14.62 ± 0.155	6.49 ± 0.103

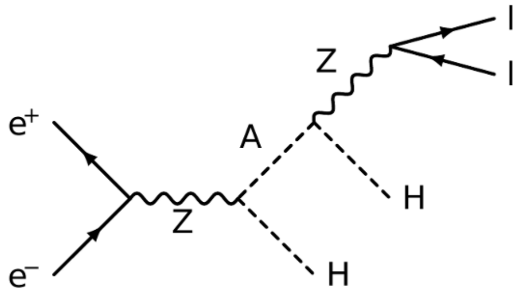
- **Need more bkg statistics** to draw conclusions: winter 2023 samples in progress
- Also working on **changing choice of kappa parameter for signal**, with less modification of Higgs width
- **Next step: paper!**
- **See Magda's talk in parallel session for more**

Anne-Marie Magnan, Nick Wardle, Gavin Davies, Alex Tapper

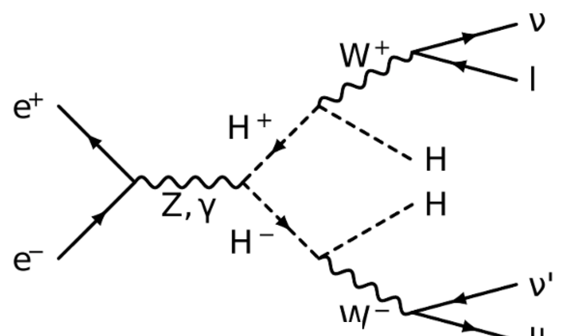
Inert 2HDM Scalar Pair Production: A First Look

- Inert Two-Higgs-Doublet model: add Z2 symmetry to 2HDM
- Set of 20 benchmark points relevant for FCC-ee, after existing experimental constraints
- Target FCC-ee **Zh stage** (240 GeV), using Winter 2023 samples
- First reproducing CLIC study (cut and count, gen-level only). Similar yields achieved
- Then new BDT selection for FCC: good significance at detector-level
- Working on limits now
- Should also investigate FCC-hh

$ee \rightarrow llHH$

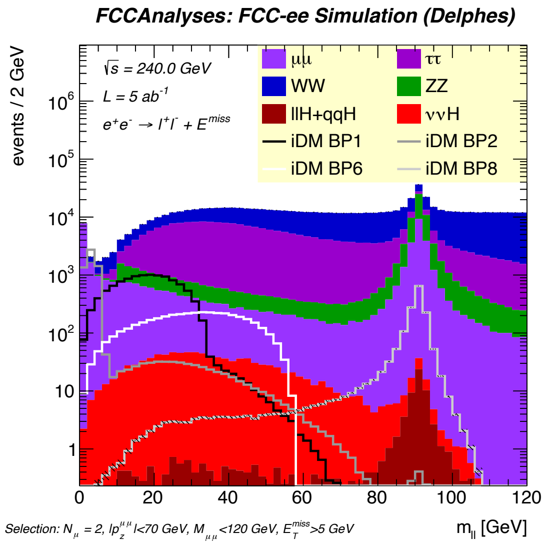


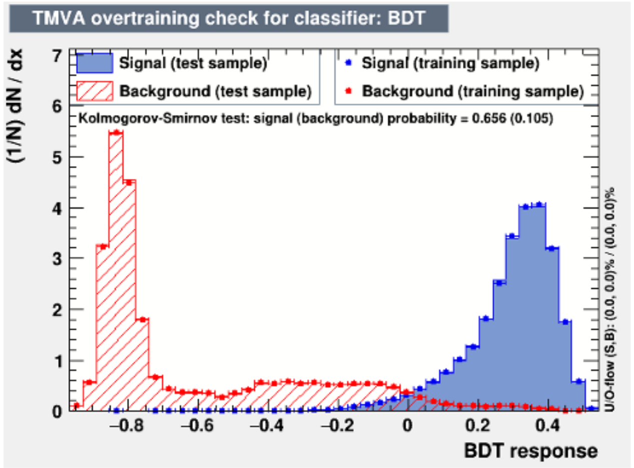
$ee \rightarrow ll\nu\nu HH$



arXiv:2002.11716

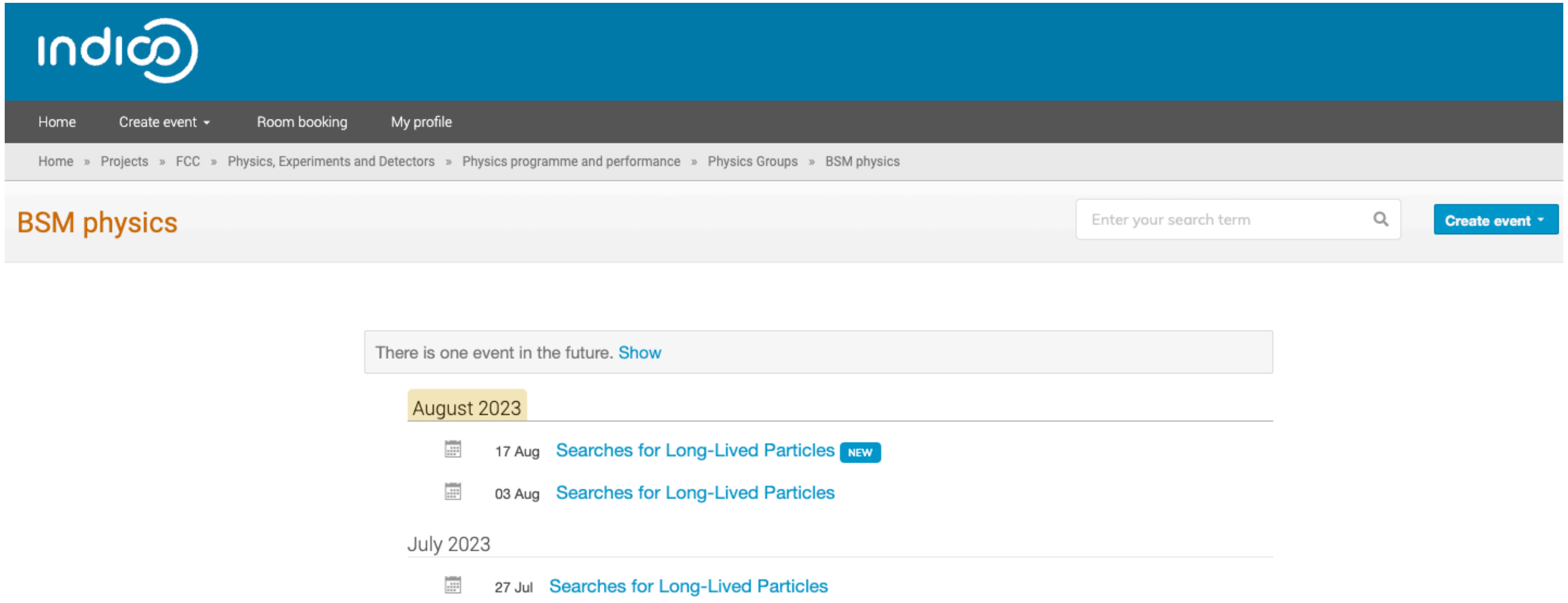
Sample	CLIC yield (380 GeV)	FCC yield
Sum bkg	5400	$\simeq$ 6800
BP1	1810	1571
BP2	1290	1023
BP7	540	480





BSM & LLPs at the FCC

- Informal group with:
  - Meetings: 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!**



Some Other Talks on BSM This Week:

Tuesday:

- Jan's talk on heavy neutrino-antineutrino oscillations
- Nicolo's talk on HNLs and Oscillations
- Giacomo's talk on HNL mass reconstruction from timing measurements

Wednesday:

- Sebastian's talk on new physics in the forward region
- Baibhab's talk on Z' models
- Yoxara's talk on 3-3-1 symmetry

Thursday: Come back to this room after coffee!

- Magda's talk on Exotic Higgs Decays to LLPs
- Patricia's talk on ALPs in photon-photon fusion

Summary

- A circular Higgs factory like the FCC-ee has a rich potential: Direct and indirect sensitivity to new physics
- 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
- Could discover FIPs and then study their properties at the FCC-ee!
    - Z pole run would be particularly important
- Plenty of phase space to explore at the FCC! Let’s make sure we don’t miss new physics!

Backup

LL HNLs

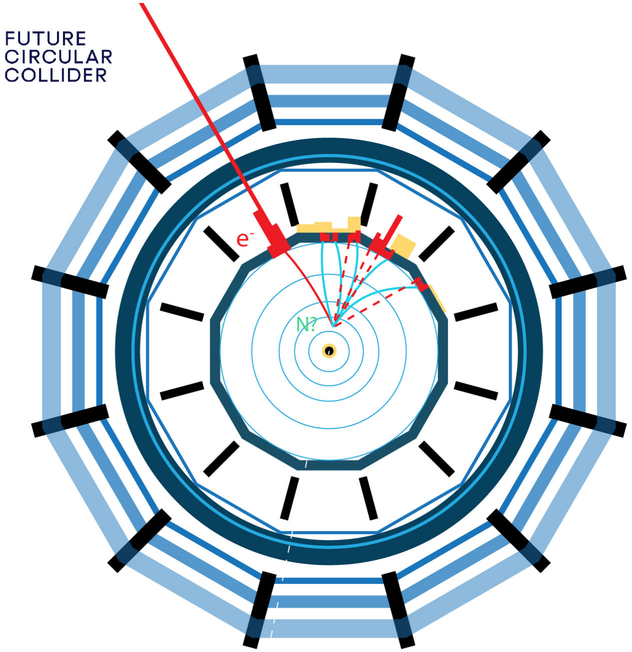
$$\lambda_N = \frac{\beta\gamma}{\Gamma_N} \simeq \frac{1.6}{U^2 c_{\rm dec}} \left(\frac{M}{\rm GeV}\right)^{-6} \left(1 - (M/m_Z)^2\right) {\rm cm}$$

c_{dec} = 1 (Majorana) or 1/2 (Dirac)

[arXiv:2210.17110]

$e^+e^- \to Z \to \nu N$

$N \to e^- + \{W^{+*} \to jj\}$

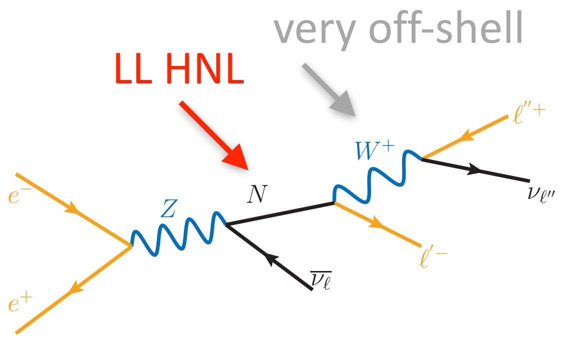


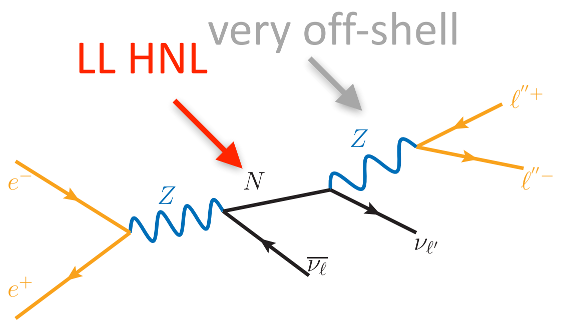
Get long-lived HNLs when coupling and mass are small

Experimental signature of LL HNLs: displaced vertex

JA, Suchita Kulkarni, Rebeca Gonzalez Suarez, Lovisa Rygaard

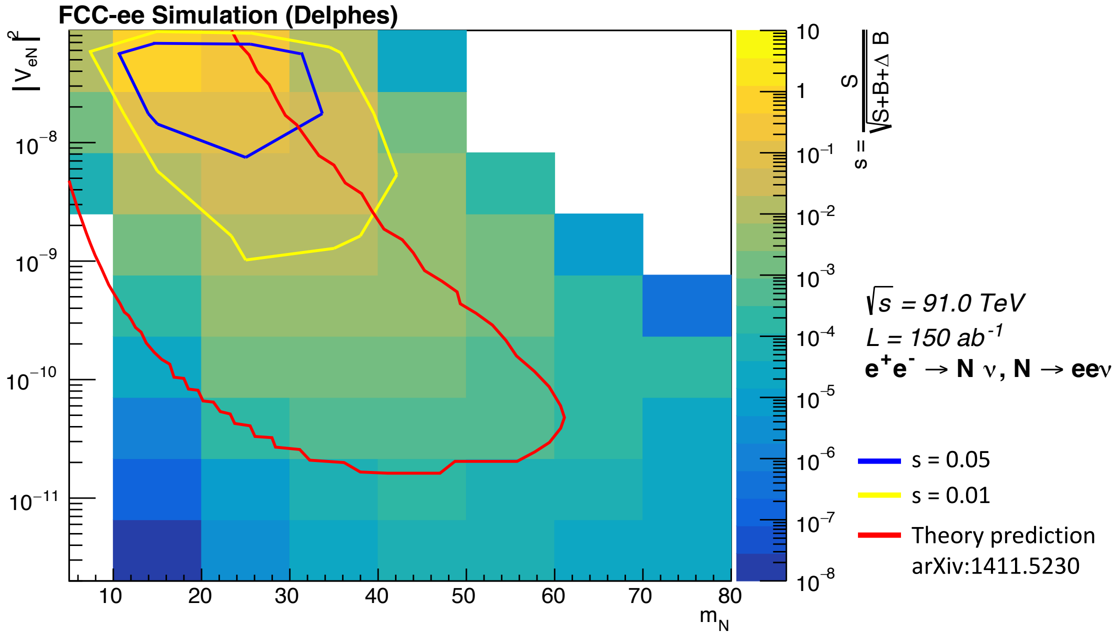
$N \to ee\nu$: Snowmass Results



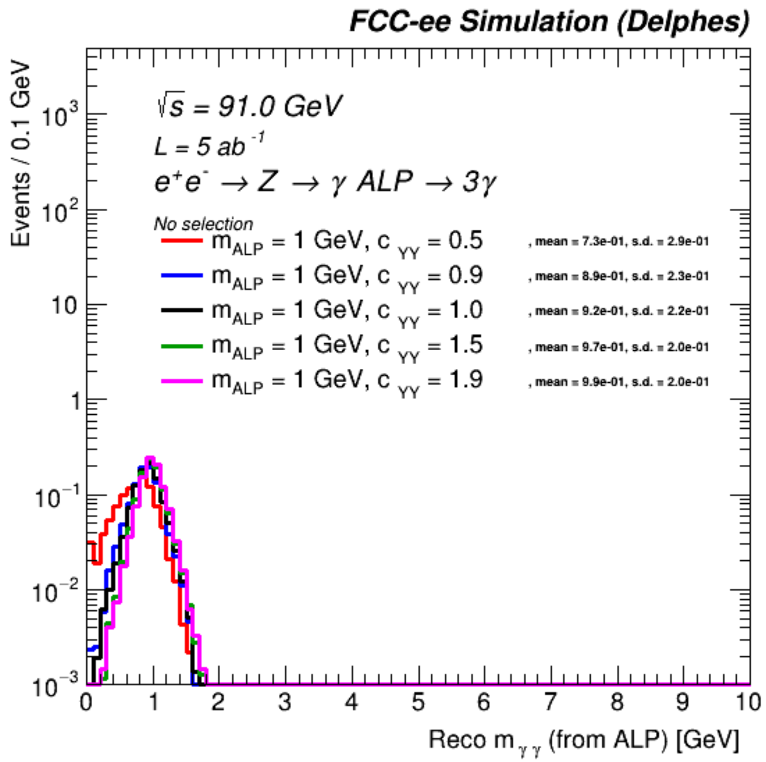


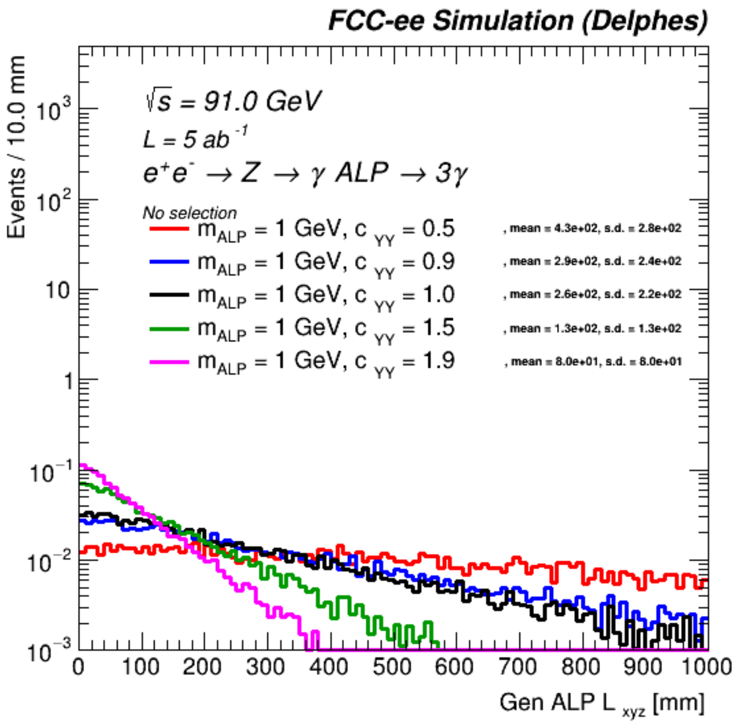
- Preliminary sensitivity shown with $\frac{S}{\sqrt{S+B+\Delta B}}$
- **This analysis:** $N \to ee\nu$
  - Contours show where FOM = 0.01 and 0.05
- Theory prediction from arXiv:1411.5230
  - Includes all HNL decay modes, not only electrons

- **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)



ALPs: Variables to Explore





- 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!**

Magdalena Vande Voorde, Giulia Ripellino

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
  - **SV finder** from **LCFI+ algorithm** (arXiv:1506.08371)
  - Added **vertex merging** to reconstruct the scalar DVs
    - Need to understand goodness of fit results (see Magda's talk at ECFA WG1-SRCH meeting)