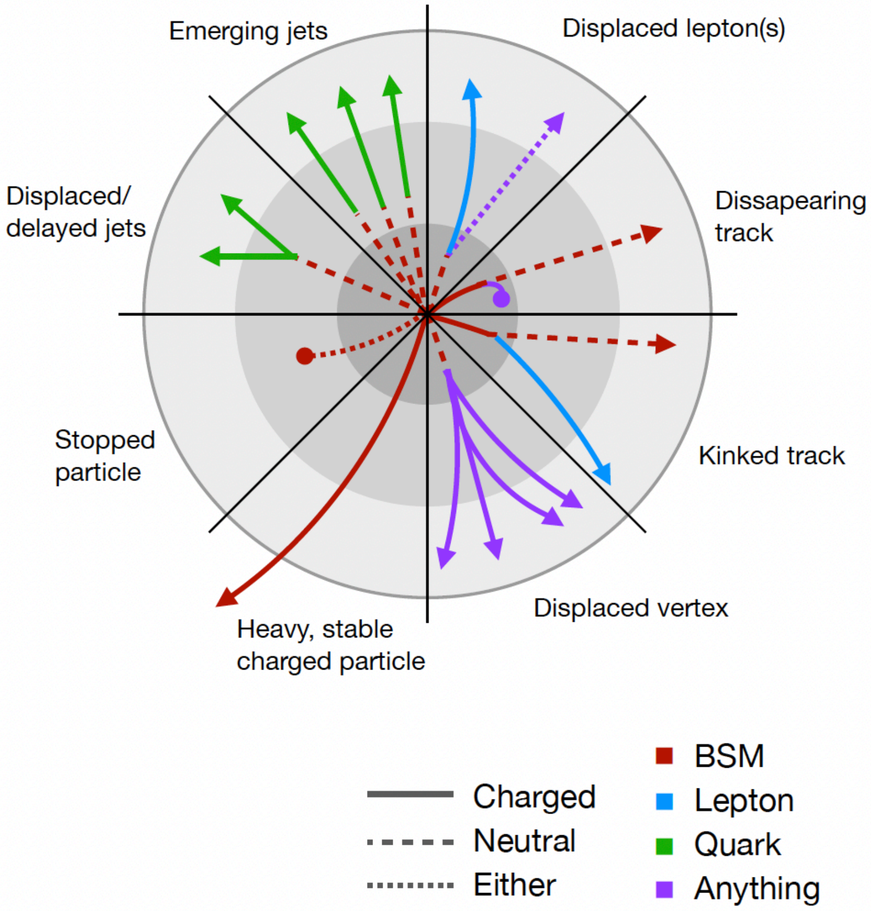
REBECA GONZALEZ SUAREZ - UPPSALA UNIVERSITY

# Searches for long-lived particles

Focus Topic: WG1-SRCH

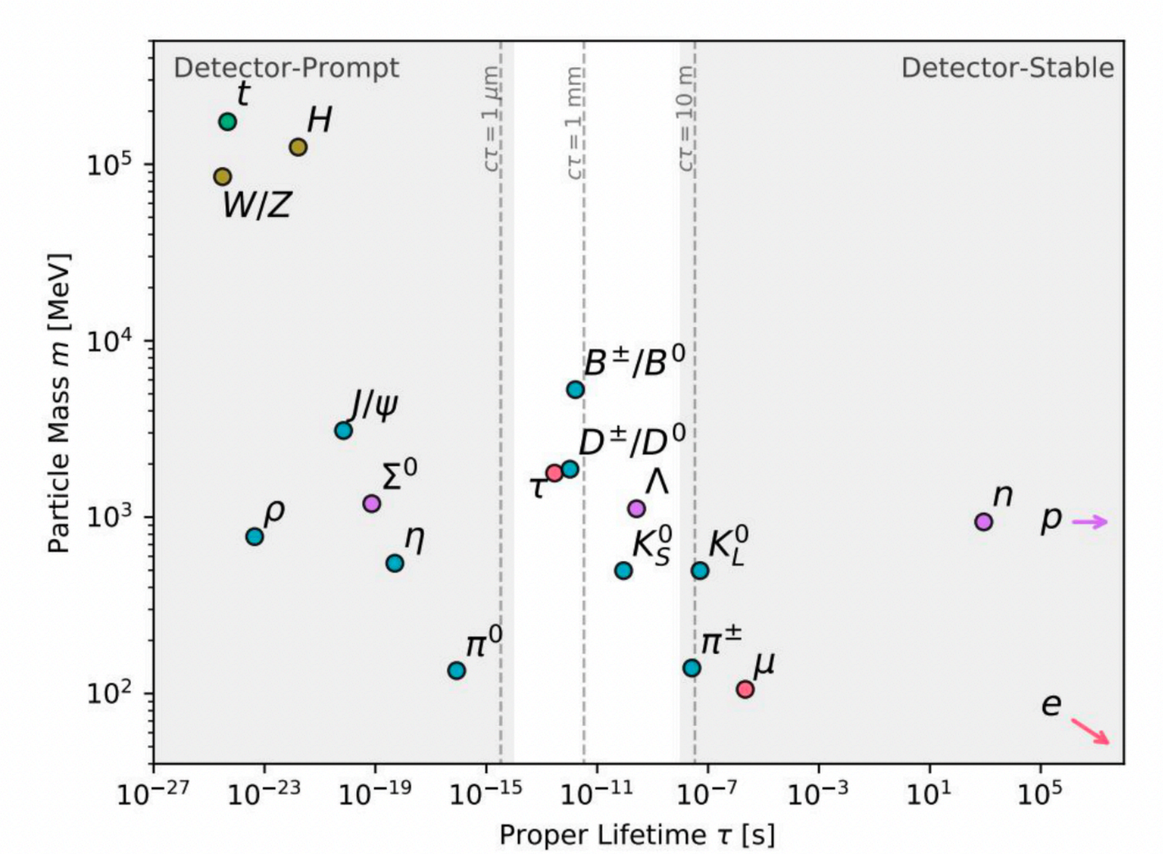
# We all know about LLPs

- Particles with relatively long lifetimes, that decay after going through the detectors some distance
  - They produce unconventional experimental signatures (displaced, but also delayed, emerging, disappearing, kinked…)
  - They have in general low backgrounds
  - Due to the experimental focus on prompt decays in high energy colliders: trigger, reconstruction, and analysis algorithms can miss them
  - Require customization and out-of-the-box approaches



# What makes a LLP

- Particles are long-lived due to e.g. small couplings or a suppressed decay phase space
  - same for SM or BSM particles
- New LLPs are a generic signature of BSM physics
- They connect to central physics questions
  - Neutrino masses, dark matter, baryon asymmetry of the universe etc



# LLPs are ~~becoming~~ very popular

- Explosion of LLP searches and models in the last few years
- Reasons:
  - Lack of mainstream BSM signals ➔ LLPs open access to uncovered areas, e.g. hidden sectors with new particles and forces
  - Searches for LLPs can bridge gaps of sensitivity between experiments (eg. dark matter searches between colliders and astro)
  - LLP searches can be model independent, since any LLP observed is a sign of new physics
  - LLP searches gives us the opportunity to think outside the box, to be creative and to propose new ways to solve problems
    - Innovation: in methods and experimental setups

A solid bet to find new physics

LLP2025 June 2-6, Valencia

# To find an LLP

- Hermetic detectors with large active volumes, to maximize geometric acceptance
- High granularity at large radii for reconstruction efficiency of displaced tracks/vertices
- Particle ID capabilities:  dE/dx, time-of-flight, good vertex & timing resolution

- *Dedicated triggers (or data acquisition)*
- Custom reconstruction algorithms
- Custom data analysis methods

- Shielding: for background mitigation

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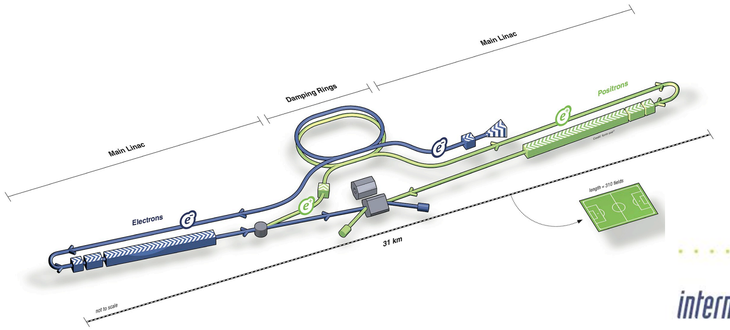
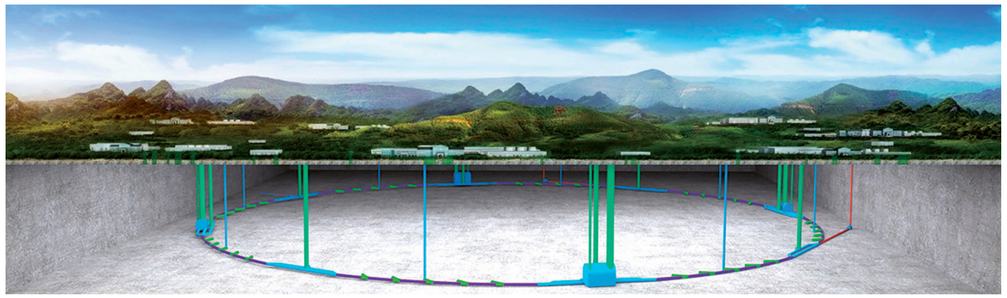
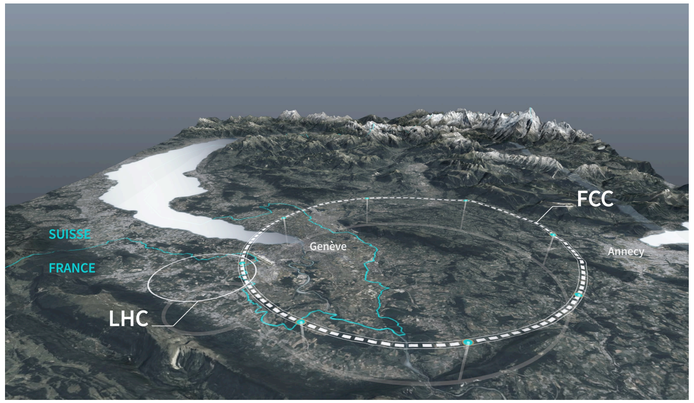
Additional detectors

# In EVERY Higgs/EW/Top factory

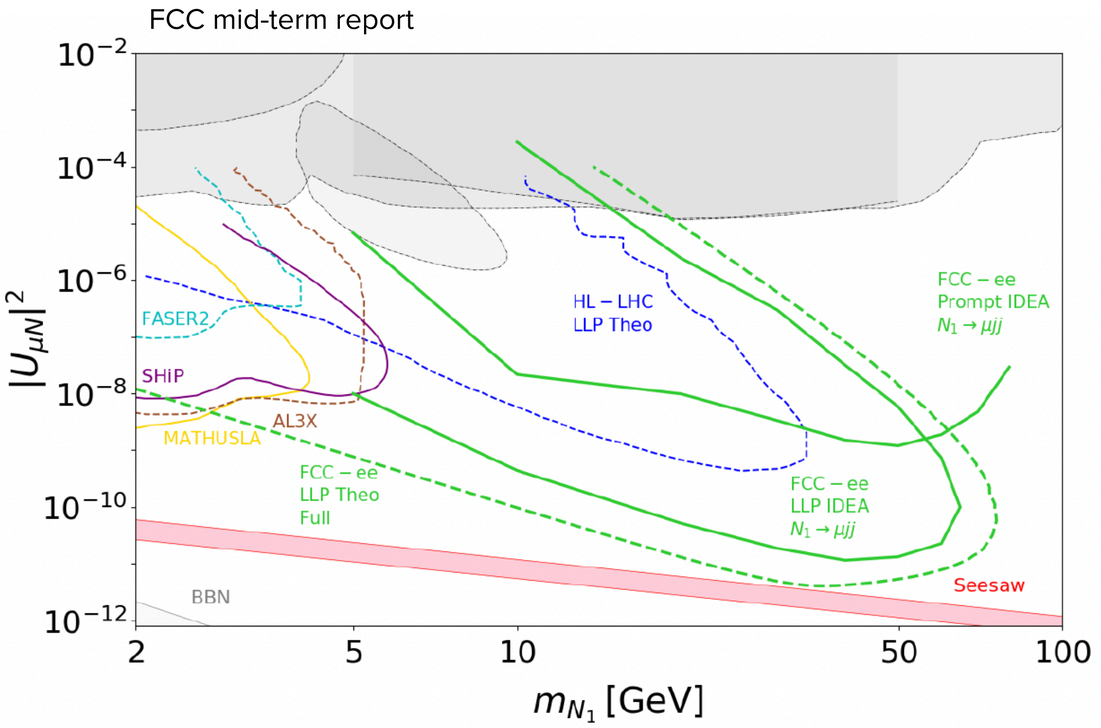
- There are LLP searches in place
- Three central physics cases where small couplings give rise to LLPs
  - **Heavy Neutral Leptons (HNLs)**
  - **Axion-Like Particles (ALPs)**
  - **Exotic decays of the Higgs boson**
- Plus additional LLP sources e.g. SUSY





# HNLs

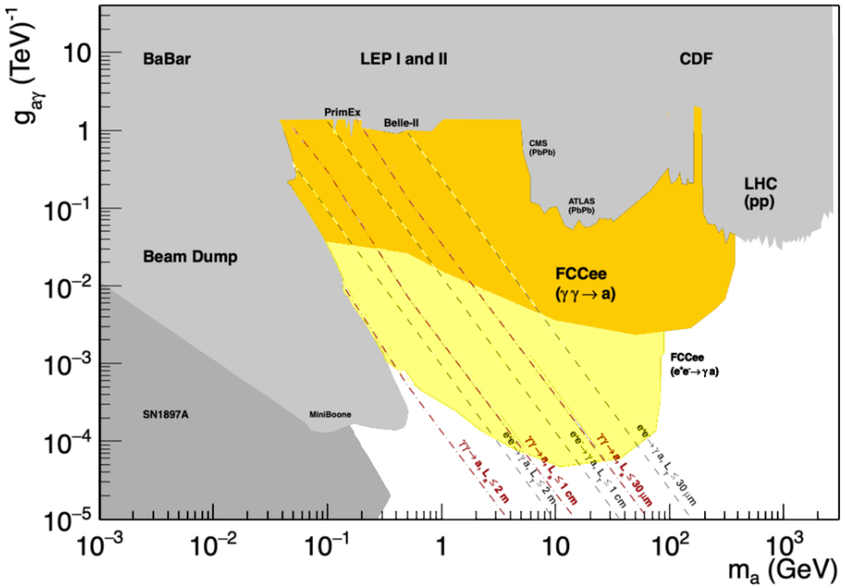



- During this workshop:
  - Heavy Neutral Leptons Search in a Realistic Neutrino Oscillation Model at FCC-ee (S. Giappichini)
  - Searching for Heavy Neutral Leptons and measuring them with the IDEA detector at the FCC-ee (N. Valle)

- Since last year's workshop the LLP/HNL community has been very active
  - Sensitivity to discovery from a few GeV to close to the Z boson mass (G. Polesello, N. Valle)
  - Prompt and displaced studies
    - The closest you get to the see-saw line, the more likely it is to get a displaced vertex
  - In all final states (S. Williams, E. Bellagamba)
  - With fast and full-simulation (G. Sadowski et al)
  - Using Machine Learning (P. Kontaxakis, T. Critchley)
  - Estimating their properties
  - Informing detector design, e.g. timing (arXiv:2406.05102)

# ALPs

- Another exciting case at Higgs factories, that can show up in many final states
  - Prompt and long-lived (again, LLP signature when couplings are feeble)
  - But mostly involving photons
- Work in progress at different future facilities (e.g. M. Meena et all)




ALPs via photon fusion
P. Rebello Teles et al
arXiv:2310.17270

- During this workshop:
  - Search for LLP in Z decays in association with a prompt photon at Tera-Z / Z boson decay into a light scalar boson and a photon: study of the FCC/CEPC sensitivities (G. Cacciapaglia et al)

# Exotic Higgs decays

- Possible Higgs boson decays to LLPs couldn't be ignored at Higgs factories
- Small couplings to new scalars/pseudoscalars produce displaced signatures
- Promising sensitivity studies at FCC-ee: M. Vande Voorde, A. Gallén, G. Ripellino et al, and CLIC: JHEP 03 (2023) 131)
- Studies of different detector designs
  - (M. Larson, L. Skinnari)

- During this workshop:
  - Long-lived particles from exotic Higgs decays at the FCC-ee (M. Vande Voorde)

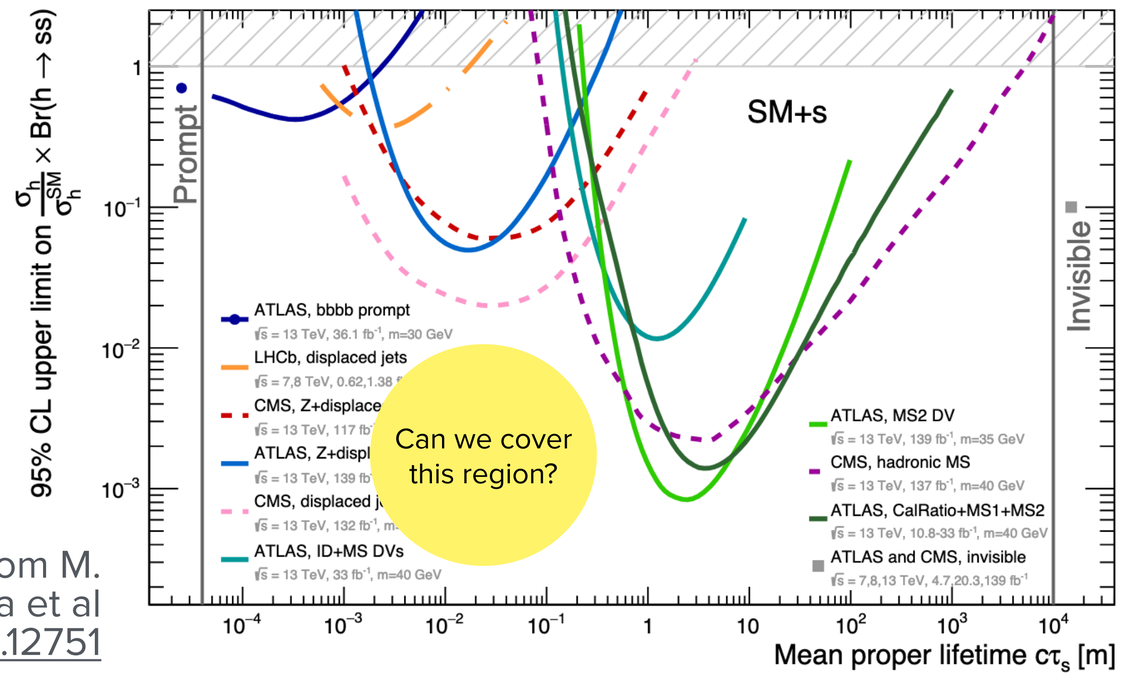



Figure from M. Cepeda et al arXiv2111.12751

# Detector studies

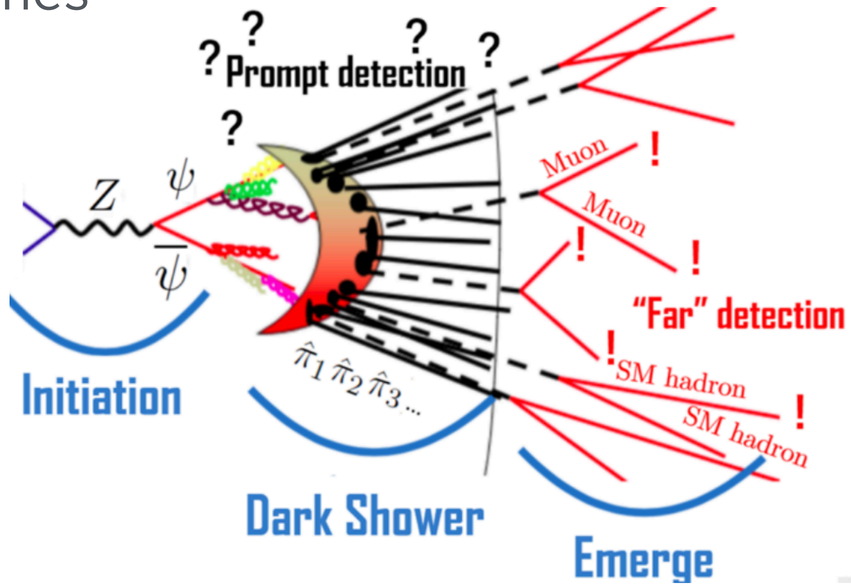
- LLPs are signature-driven: you make sure you can find an LLP and you don't need to think a lot about the new physics model behind.

- Different studies around future facilities are turning the question on the detector:
  - Some already mentioned
  - ILD: "Searching for displaced vertices with a gaseous tracker for a future e+e− Higgs factory" arXiv:2409.13492
  - From the round table Optimization of Pixel/Vertexing Detectors for LLPs (J. Gonski), including ML

- And other studies suggesting to just add more detectors:
  - Far detectors:  arXiv:2202.11714, arXiv:2201.08960, arXiv:1911.06576
  - HECATE arXiv:2011.01005
  - LAYCAST arXiv:2406.05770
  - Beam dump arXiv:2105.13768, arXiv:2009.13790

# New exciting LLP avenues

- The next LLP main question is dark
  - Electroweak Portal Dark Shower (X. Jiang) Virtual Overflow Session of 3rd ECFA WS
  - Dark jets signatures enriched in hadrons/photons/leptons (A. De Cosa) LLP round table
  - Dark photon studies considered in all facilities
  - Great area to link HL-LHC with future Higgs/EW/Top factories



# LLP targets

- Observables
  - Displacement
  - Distinct tracking patterns
    - disappearing tracks
    - uncommon energy loss
  - Non-pointing/delayed photons
  - Non-standard jets
  - Slow-moving/stopped jets/particles
  - Collimated muons with no tracks in the inner detector
- Methods
  - Displaced tracks and vertex reconstruction
    - Tracking and muon systems
  - Tracking for anomalous dE/dx patterns
  - Timing in the calorimeters and tracking
  - Jet reconstruction and “tagging”
  - Background estimation:
    - Instrumental (beam-induced background, pileup, and cavern noise) as well from cosmic-ray muons

# In short

- Long-lived particles are exciting to search for at current colliders and will play a central role in the BSM programs of future Higgs/EW/Top factories
  - Small couplings and low masses are usually behind LLP signatures, and that is the kind of new physics that we will be able to target
- LLPs could give answers to central physics questions
  - Neutrino masses, dark matter, baryon asymmetry of the Universe
- Work is ongoing in all future colliders
  - Three established physics cases with good potential for discovery/large exclusion
    - HNLs, ALPs, Exotic Higgs decays
  - New lines, related to e.g. dark matter, growing
- This is a focus topic that offer much more than sensitivity estimates
  - It has the potential to deeply influence detector design

# Working on LLPs and not here?

- Contact your expert from the LLP EXPERT TEAM!
  - Coordinator (Rebeca)
  - FCC-ee contact: Juliette Alimena (DESY)
  - ILD contact: Filip Zarnecki (Warsaw)
  - SiD / CLIC contact: Marcin Kucharczyk (Cracow)
  - Theory contact: Jan Hajer (Lisbon)
  - LHC contact: Emma Torro Pastor (Valencia)
  - Detector/Generator requirements: Sarah Williams (Cambridge)

ECFAWG1-ExpertTeam-LLP@cern.ch

Link to the round table