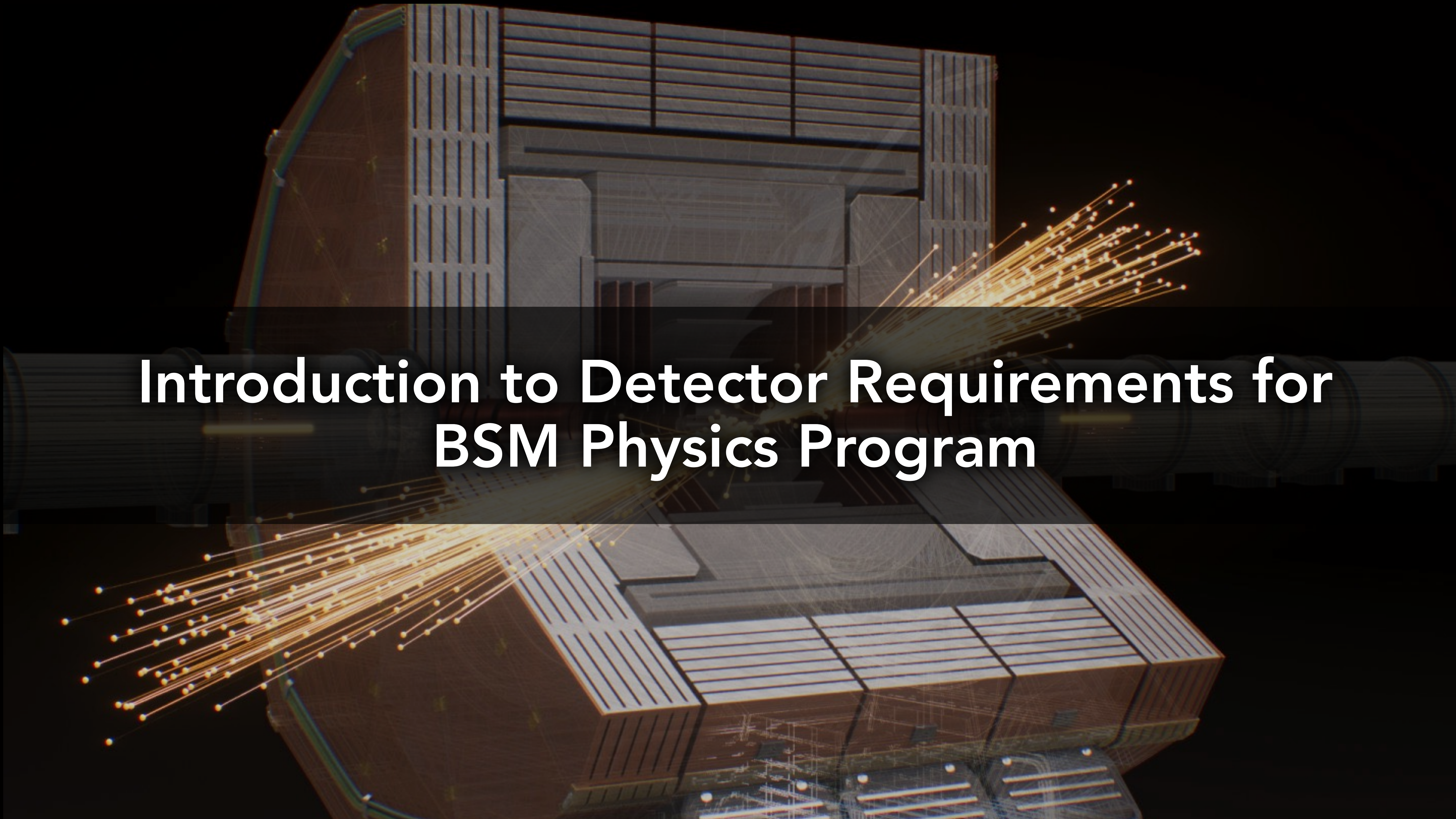


Introduction to Detector Requirements for BSM Physics Program

Louise Skinnari (Northeastern University)

Future Circular Collider (FCC) Week: San Francisco, June 10-15, 2024

Northeastern University

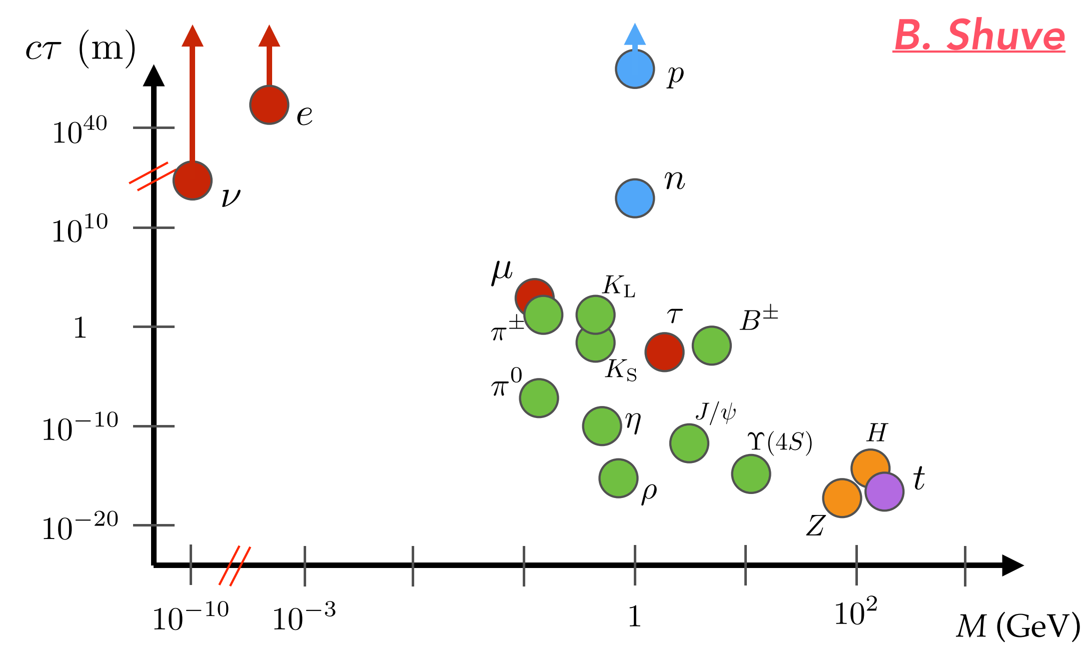
Introduction

- Clean FCC-ee environment => wide range of beyond-Standard Model (BSM) particle couplings and masses accessible
  - ✦ Probe BSM physics *indirectly* or *directly*

- Indirect searches: Sensitivity to BSM physics through precise measurements of SM observables

- Direct searches: Experimental signatures vary greatly depending on *lifetime* of new particles, consequently, detector requirements vary greatly
  - ✦ *Prompt decays*
  - ✦ *Decay in inner tracking detectors*
  - ✦ *Decay in calorimeter / muon systems*
  - ✦ *Escape detection altogether*

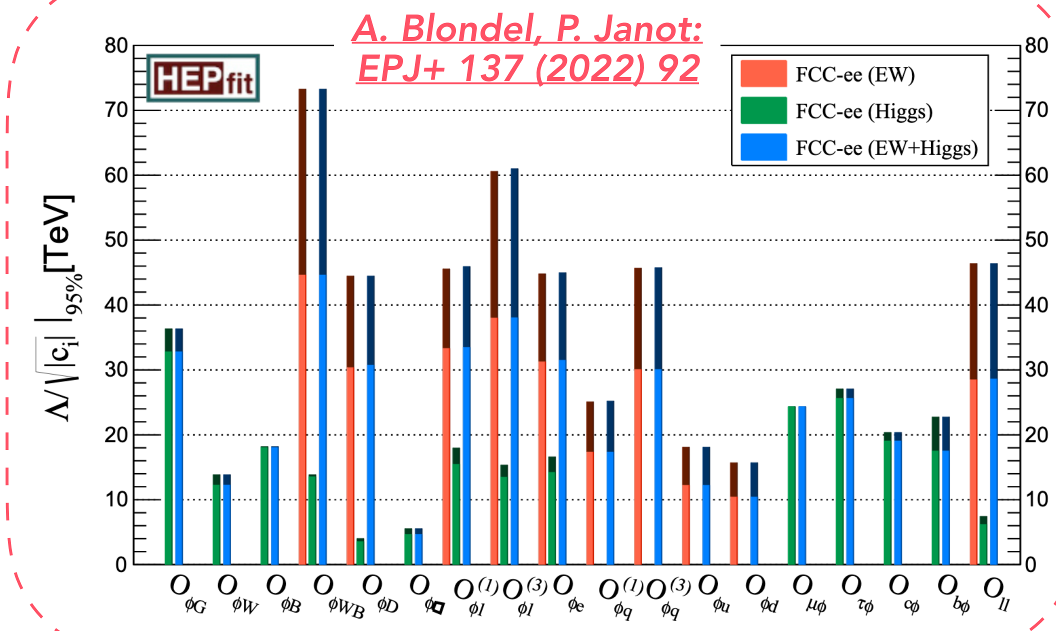
Lifetime vs mass for SM particles



Indirect probes

- Precise measurements of EW observables: Indirect sensitivity to up to ~70 TeV-scale sector connected to EW/Higgs

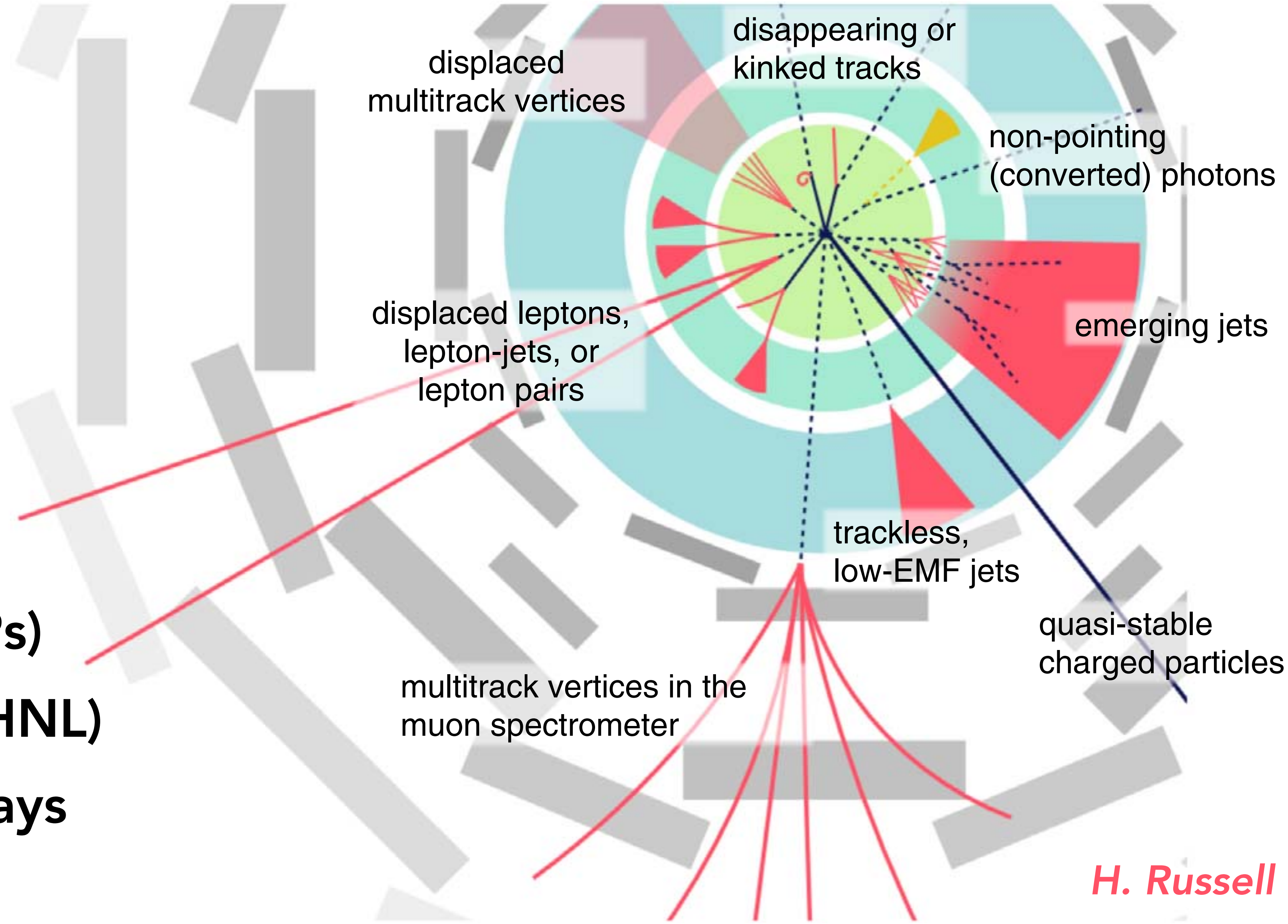
- Top sector: Search for FCNCs, sensitivity to Z′ bosons from top EW coupling



- Flavor (b/c/tau): Rare decays, LFV searches, tests of LFU

- *Associated detector requirements* similar to those from corresponding SM measurements, e.g.:
  - Excellent track momentum resolution (low X_0)
  - Vertex resolution & PID capabilities for flavor tagging
  - Particle flow, jet energy/angular resolution for hadronic final states
  - *See talks by J. Zhu and M. Selvaggi*

Direct BSM searches

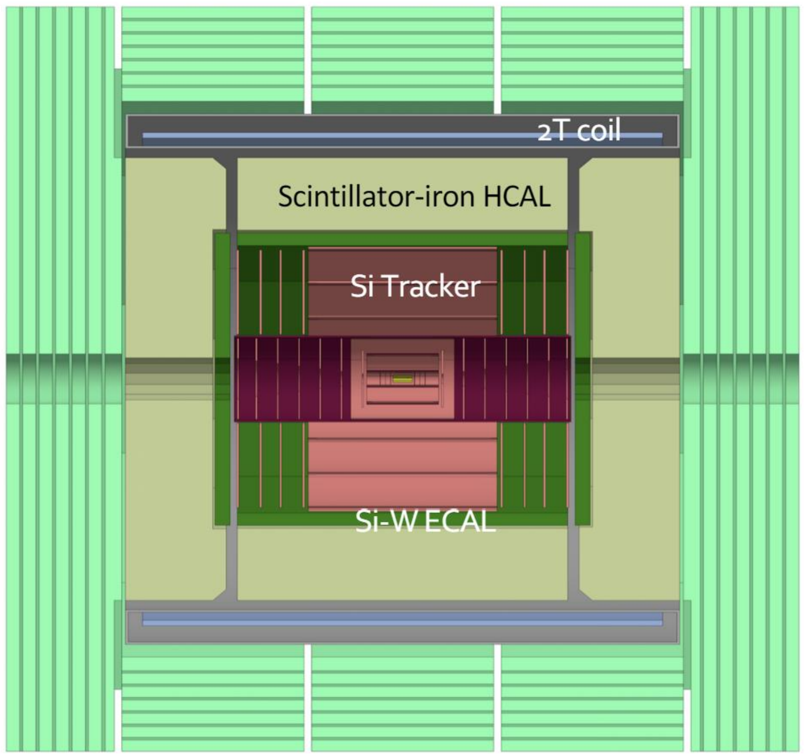


H. Russell

- Examples of studied BSM phenomena:
  - **Axion-like Particles (ALPs)**
  - **Heavy neutral leptons (HNL)**
  - **Exotic Higgs boson decays**
  - Dark photons (Z_D)
  - Z′
  - Light SUSY and light scalar scenarios
- Complementarity between prompt/long-lived searches!
- *BSM landscape discussed by Z. Demiragli*

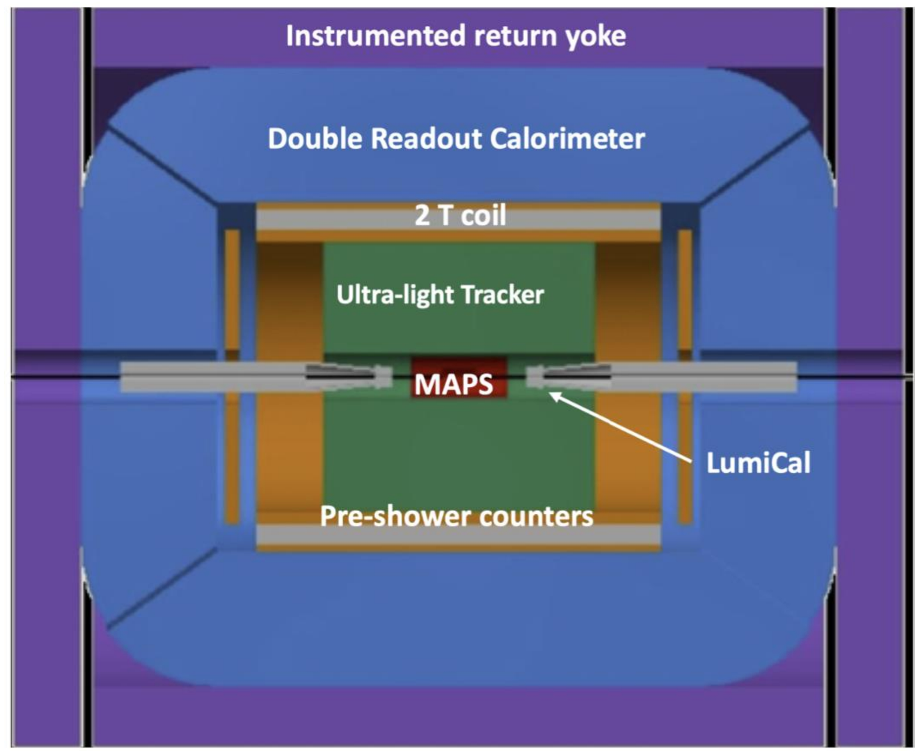
Detector concepts

CLD



- Full silicon vertex + strip tracker
- CALICE-like 3D-imaging high-granular calorimetry with Si-W for ECAL and Sci-iron for HCAL
- Muon system with RPCs
- Coil outside of calorimeters

IDEA



- Silicon vertex + ultra-light tracker
- Monolithic dual readout calorimeter with Cu-fibers (possibly augmented by dual-readout crystal ECAL)
- Muon system with μ-RWELL
- Coil inside calorimeters

ALLEGRO

- Silicon vertex + ultra-light tracker
- High granularity noble liquid ECAL (LAr or LKr with Pb or W absorbers)
- CALICE-like or TileCal-like HCAL
- Muon system
- Coil outside of ECAL

J. Zhu

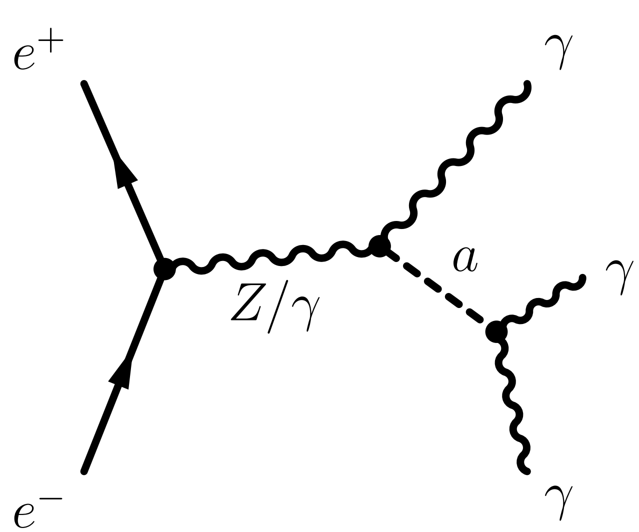
- *Studies so far primarily relied on Delphes fast simulation with IDEA card*

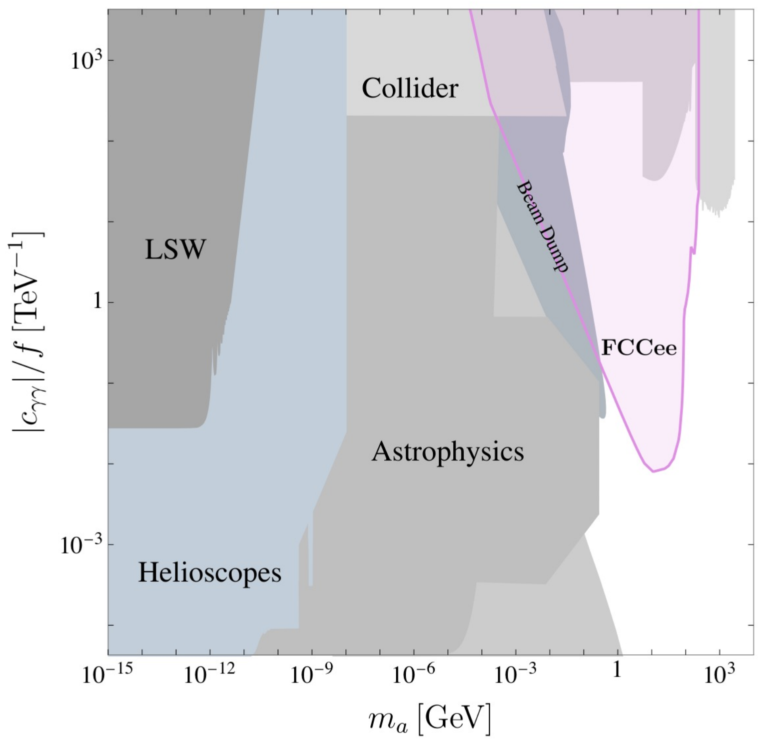
Detector requirements

- Identifying long-lived particles places distinct detector requirements
  - Impact parameter resolution for large displacements
  - Tracking detectors: additional layers / continuous tracking
  - Calorimetry: high radial segmentation, tracking capability
  - Muon detectors: standalone tracking capability
- Large decay lengths implies extended detector volume
- Invisible final states => hermetic detectors
- Triggerless readout
- Precise timing for velocity (mass) estimates
- *Next slides highlight select recent work within BSM group to illustrate detector requirements, not a complete overview of all BSM work done!*

Axion-like particles (ALPs)

- Hypothetical pseudoscalar appearing naturally in many SM extensions; mass and coupling can range over many orders of magnitude
- ALP associated production vs m_a and coupling to vector bosons ($C_{\gamma\gamma}$)
- Particularly relevant at FCC-ee is final state with **three photons**
  - ✦ Imposes requirements on **ECAL performance**
  - ✦ **Masses ≳5 GeV:** Sensitivity dominated by ECAL resolution, require high momentum prompt photons
    Masses ≲5 GeV: Large contribution from position resolution and photon-photon separation power (granularity)





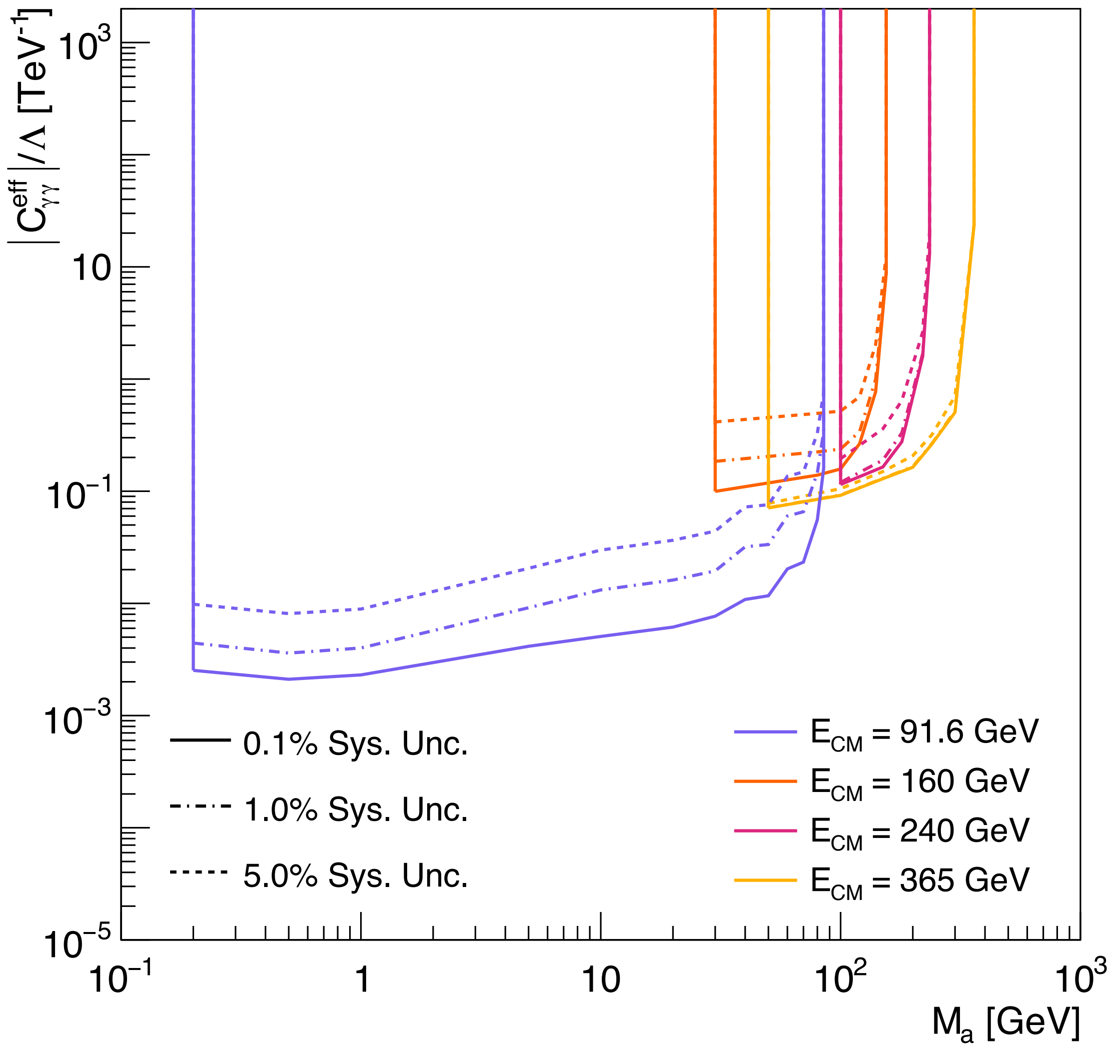
Axion-like particles

L. Pezzotti thesis

- Analysis considers m_a = 0.2–360 GeV at different √(s) in 3 photon channel
  - Signal/background: MG5 + Pythia8; DELPHES for IDEA fast simulation
  - Signal discrimination based on $\gamma\gamma$ invariant mass, opening angle and energy of third photon

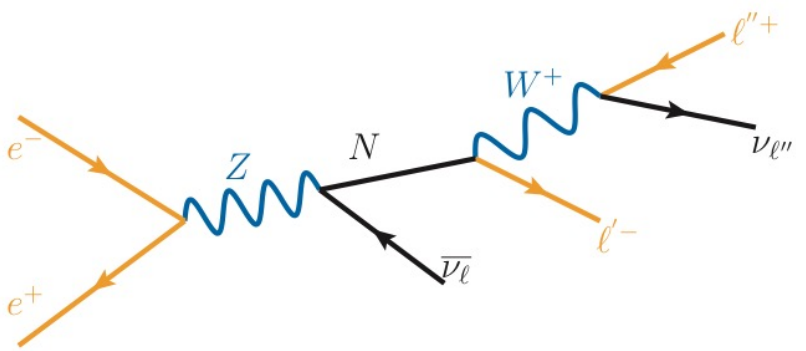
- Low mass ALPs (<5 GeV) sensitive to effective **separation of collimated photons** => excellent benchmark for detector optimisation

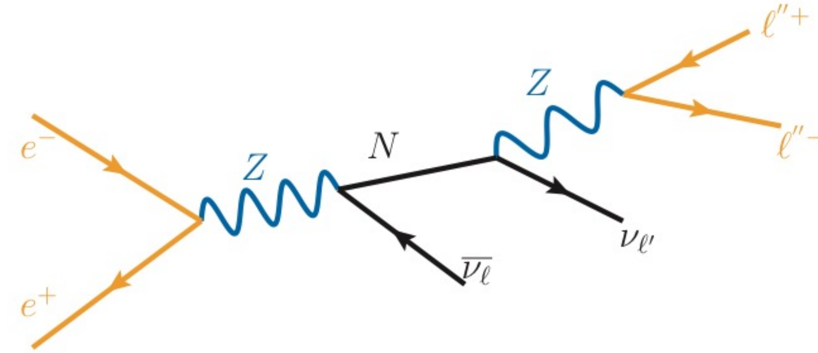
- Full simulation studies needed to assess sensitivity at low mass / potential for separating the two nearby photons



Heavy neutral leptons (HNLs)

- Dirac or Majorana fermions with sterile neutrino quantum numbers
  - ✦ Promising new physics channel at Z pole
  - ✦ Rich set of signatures, both prompt & long-lived



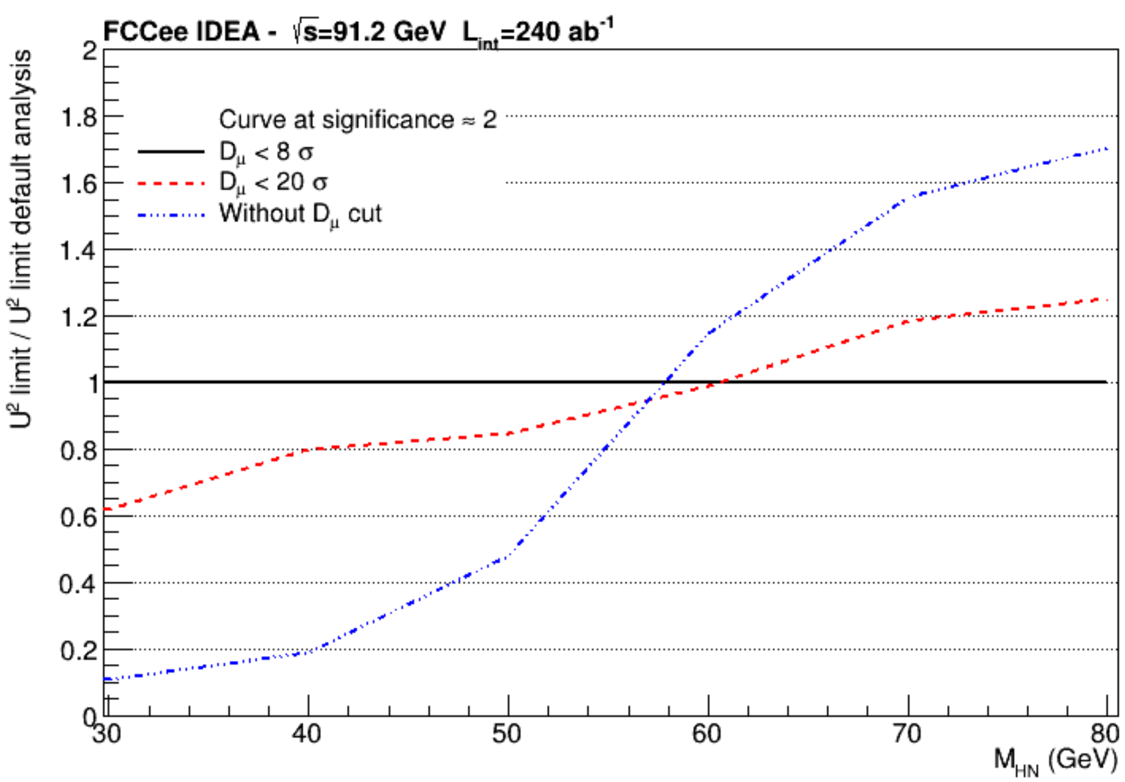


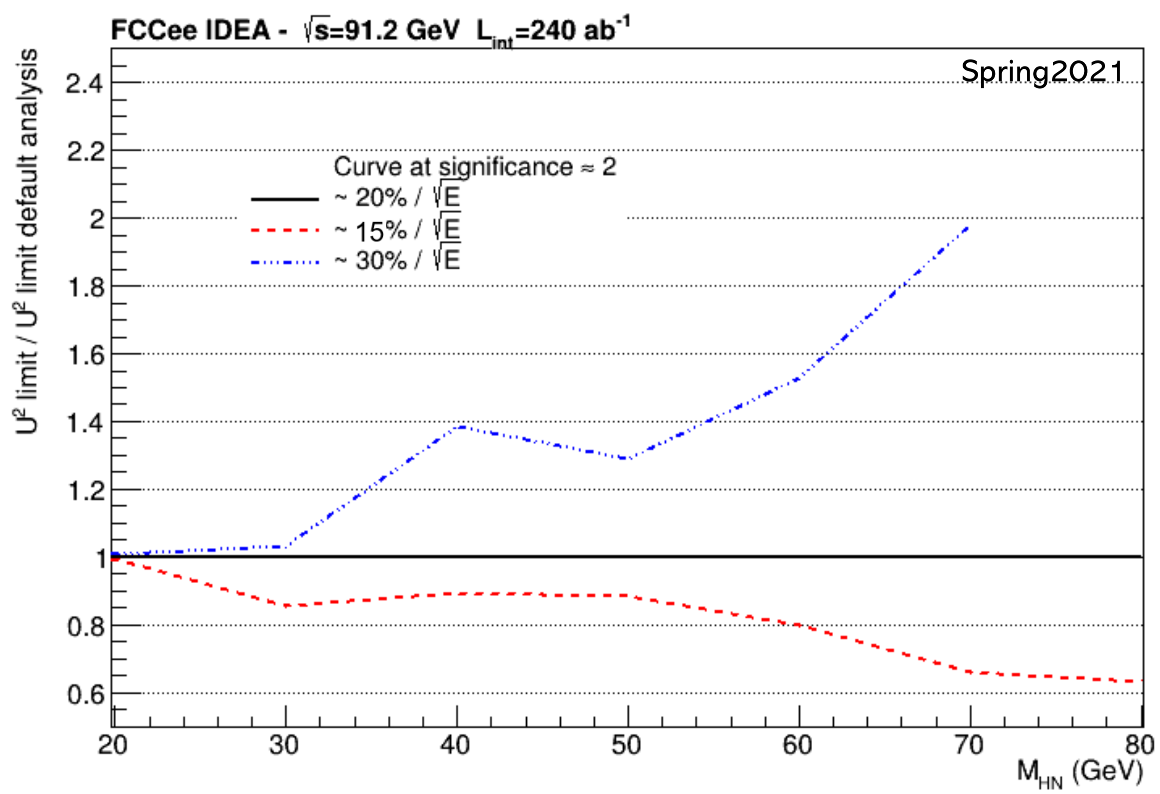
- **Analysis: HNL => μjj** Require one muon + two jets
  - ✦ High mass / prompt signal
    - Background rejection through constraints on HNL mass and missing energy
    - Requirements on **jet energy resolution** and **vertexing performance**
  - ✦ Low mass / displaced signal
    - Background suppression through displaced vertex
    - Requirements on **vertexing** and **timing performance**
  - ✦ Signal: MG5 + Pythia8; Delphes for IDEA fast simulation

HNL => μjj

G. Polesello, N. Valle

- Using sum of visible four-momenta to select HNL mass and ν recoil energy
- **Prompt analysis** uses selection on muon transverse impact parameter to suppress background ($d_{0,\mu}$ < 8σ; σ~5μm) => *tracker pointing resolution*
- Fast simulation with parametric particle energy resolution: **EM**~11%/√(E) ; **HAD**~30%/√(E) ; 1% constant term
  - ✦ Simplified approach to estimate impact of calorimeter resolution: estimate variation of background when varying mass window vs jet-jet mass resolution

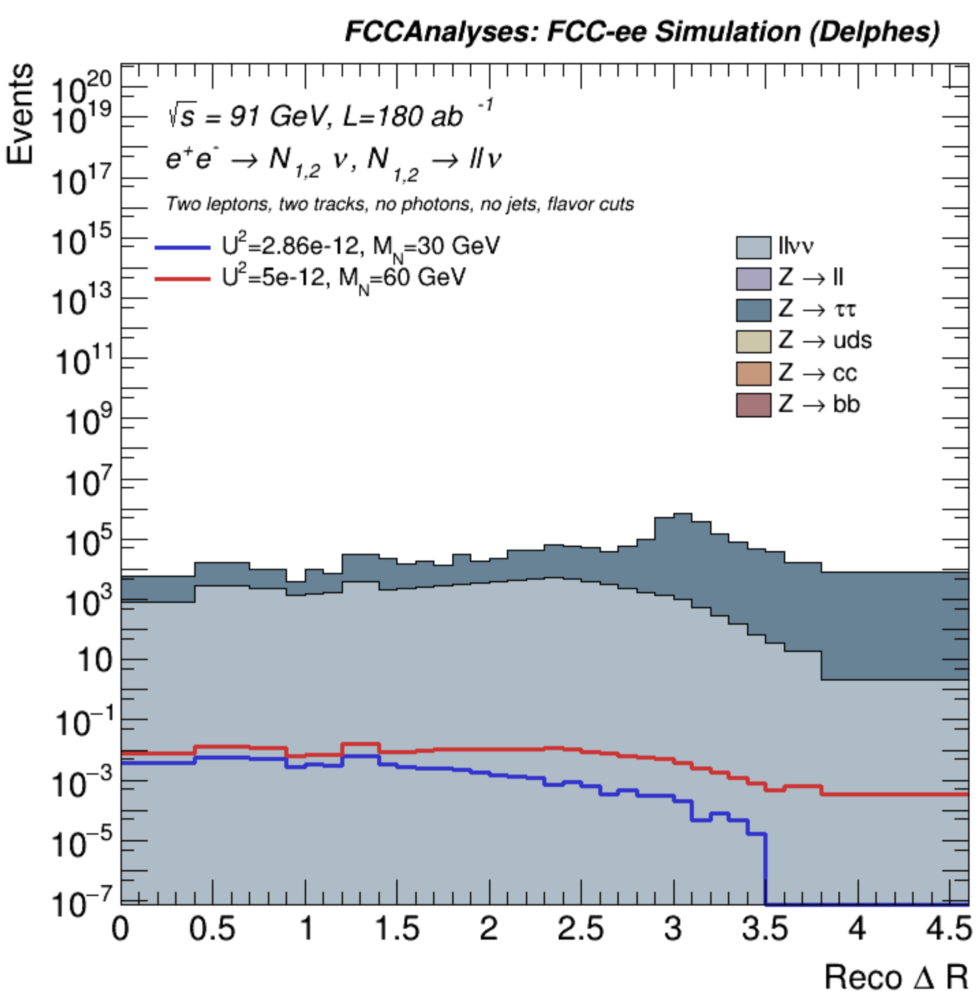


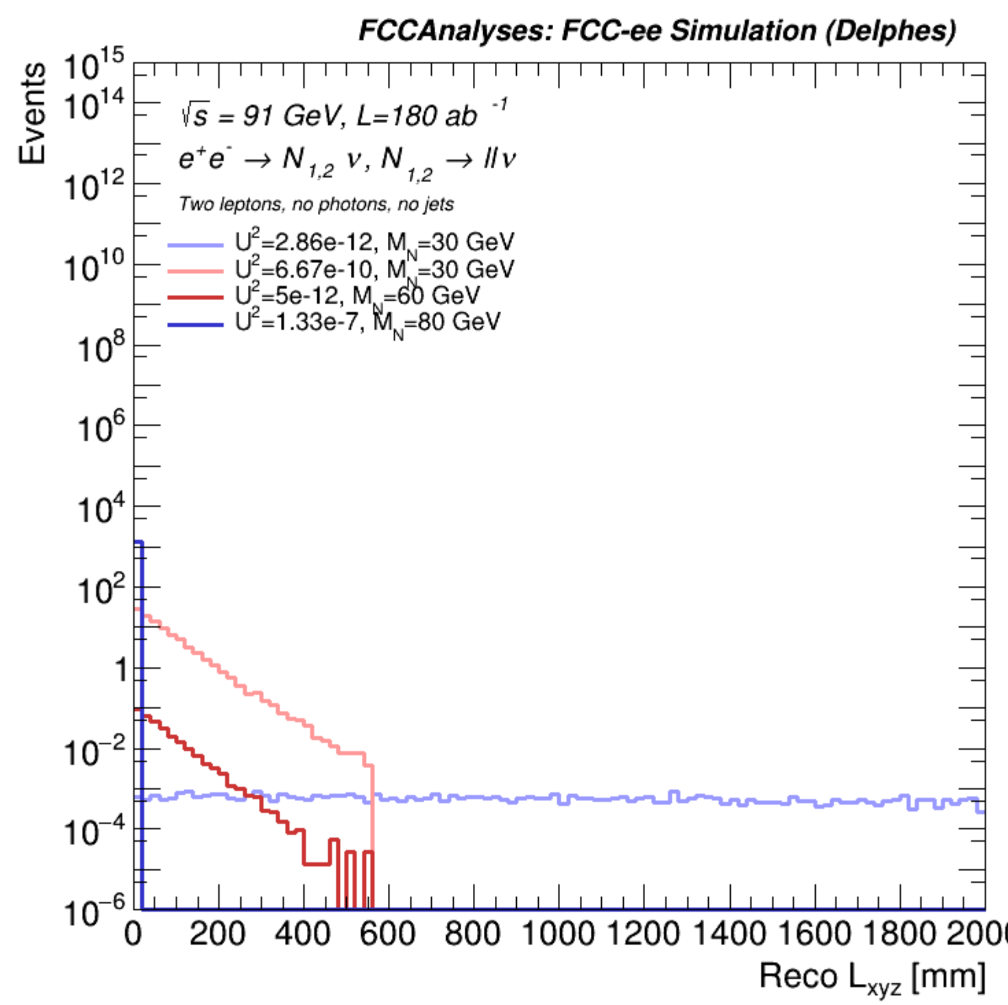


HNL => eev/μμν

S. Giappichini, M. Klute,
O. Panella, M. Presilla,
X. Zuo

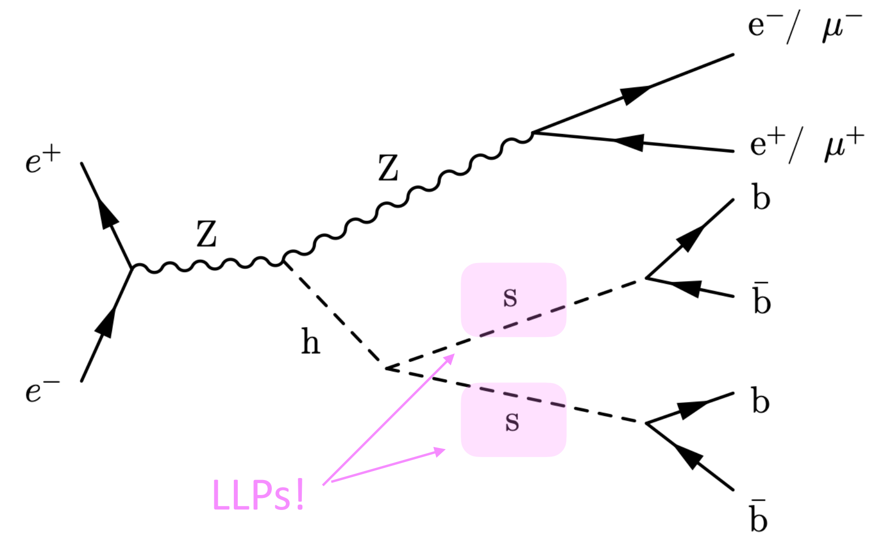
- Require two leptons (e/μ)
- Signal simulation: MG5+Pythia8 + Delphes with IDEA detector card
  - Shape-based analysis from dR with ML fit
- Requirements on reconstructed vertex incl. L_{xy} < 2000mm, $|d_0|$ > 0.55mm





Exotic Higgs decays

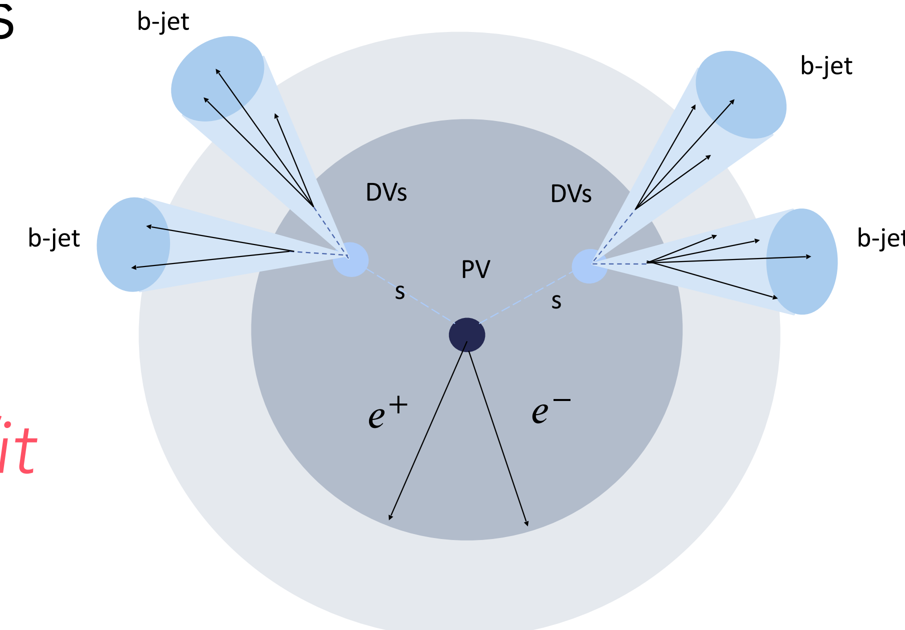
A. Gallén, G. Ripellino, M. Vande Voorde, R. Gonzalez Suarez



- Target Zh (240 GeV) run with signal process:

$$e^+e^- \to Zh \text{ with } Z \to e^+e^-/\mu^+\mu^- \text{ and } h \to ss \to b\bar{b}b\bar{b}$$

- Experimental signature: Reconstructed Z boson + displaced vertices from long-lived scalar decays
- Simulation: MadGraph v3.4.1 + Pythia8 + Delphes with winter2023 **IDEA vs CLD** card
- *Recent detector card comparison illustrate benefit of continuous tracking / many tracker layers*



M. Larson, LS

Mean proper lifetime cτ [mm]	3.4	341.7	34167.0	0.9	87.7	8769.1
$N_{DVs} \geq 2$ Events	20 GeV, 1e-5	20 GeV, 1e-6	20 GeV, 1e-7	60 GeV, 1e-5	60 GeV, 1e-6	60 GeV, 1e-7
IDEA	5.02	37.09	0.77	0.003	10.97	6.50
CLD (min. hits = 6)	5.08	6.02	0.11	0.003	10.67	0.82
CLD (min. hits = 5)	5.19	16.17	0.23	0.005	11.16	2.01
CLD (min. hits = 4)	5.30	24.34	0.31	0.003	11.21	2.99

Final # events selected

Conclusions

- Understanding the impact of detector design and performance is crucial given the broad range of unconventional signatures and rich phenomenology involved!
- Exciting opportunity to optimize detector designs specifically for long-lived particle searches
- Beyond optimizing general purpose detectors for BSM physics, options for targeted detectors and facilities, e.g.:
  - HErmetic CAvern TrackEr (**HECATE**): *M. Chrzaszcz, M. Drewes, J. Hajer, EPJC 81 (2021) 546*
    Proposes additional instrumentation on the cavern walls for large gain in sensitivity for LLPs (4π solid angle coverage for displacements of 20m)
  - Forward Physics Facility (**FPF**): See talk by S. Trojanowski (Anncey 2024)

Backup

FCC-ee machine parameters

M. Benedikt et al
Chamonix workshop 2024

Parameter	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45.6	80	120	182.5
beam current [mA]	1270	137	26.7	4.9
number bunches/beam	11200	1780	440	60
bunch intensity [10^{11}]	2.14	1.45	1.15	1.55
SR energy loss / turn [GeV]	0.0394	0.374	1.89	10.4
total RF voltage 400/800 MHz [GV]	0.120/0	1.0/0	2.1/0	2.1/9.4
long. damping time [turns]	1158	215	64	18
horizontal beta* [m]	0.11	0.2	0.24	1.0
vertical beta* [mm]	0.7	1.0	1.0	1.6
horizontal geometric emittance [nm]	0.71	2.17	0.71	1.59
vertical geom. emittance [pm]	1.9	2.2	1.4	1.6
horizontal rms IP spot size [μm]	9	21	13	40
vertical rms IP spot size [nm]	36	47	40	51
beam-beam parameter ξ_x / ξ_y	0.002/0.0973	0.013/0.128	0.010/0.088	0.073/0.134
rms bunch length with SR / BS [mm]	5.6 / 15.5	3.5 / 5.4	3.4 / 4.7	1.8 / 2.2
luminosity per IP [10^{34} $cm^{-2}s^{-1}$]	140	20	5.0	1.25
total integrated luminosity / IP / year [ab^{-1}/yr]	17	2.4	0.6	0.15
beam lifetime rad Bhabha + BS [min]	15	12	12	11
	4 years 5 x 10^{12} Z LEP x 10^5	2 years > 10^8 WW LEP x 10^4	3 years 2 x 10^6 H	5 years 2 x 10^6 tt pairs