Karlsruhe Institute of Technology

FUTURE CIRCULAR COLLIDER

CERN

# BSM Physics Opportunities at FCC-ee

**Sofia Giappichini on behalf of the FCC collaboration**
Karlsruhe Institute of Technology

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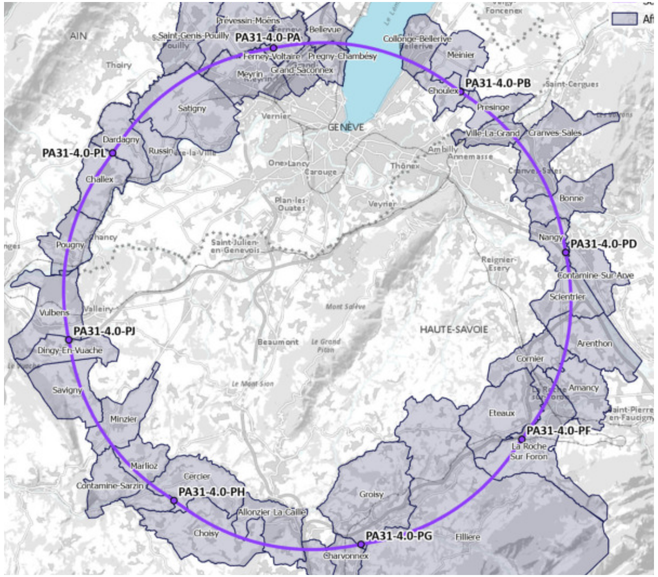
sofia.giappichini@cern.ch

# FCC-ee project

- Proposed to be built at CERN, operations from 2040s
- 90.7 km circumference with 4 experimental sites
- Feasibility study Vol. 1, Vol. 2, Vol. 3



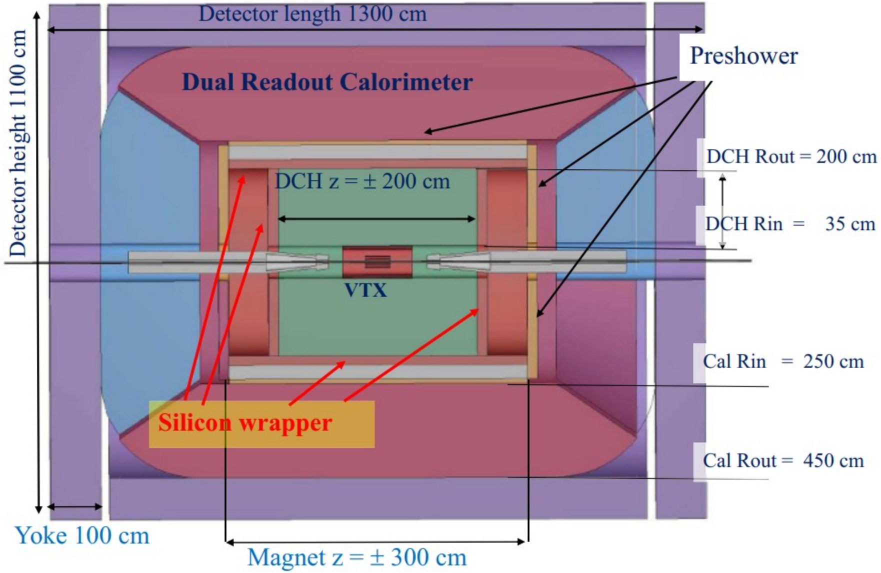

**FCC-ee run plan**
(from FCC final report)

| | Z | WW | ZH | tt |
|---|---|---|---|---|
| $\sqrt{s}$ (GeV) | 87.9 - 91.2 - 94.3 | 157.5 - 162.5 | 240 | 340→350 - 365 |
| $\mathcal{L}$ ($ab^{-1}$) | 40 - 125 - 40 | 19.2 | 10.8 | 0.41 - 2.65 |

- **Intensity frontier**: increase luminosity to find new physics in $e^+e^-$ rather than increase energy in pp collisions

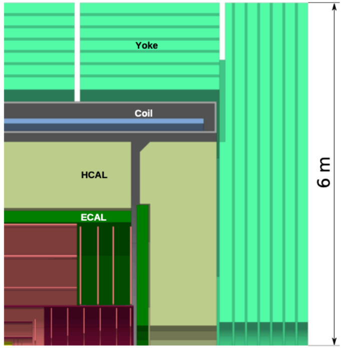
# Experimental setup

- **IDEA** detector concept arXiv:2502.21223
  - Drift chamber tracker
- Following studies with **parameterised simulation**

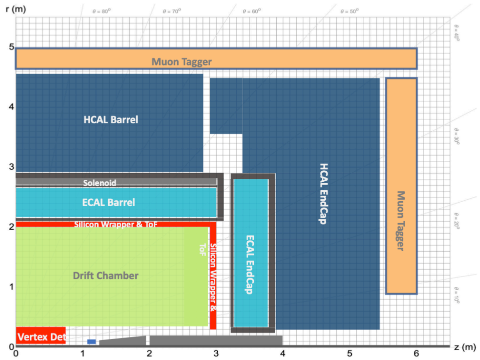



- Two other concepts for FCC-ee:
  - CLD, silicon tracker arXiv:1911.12230
  - ALLEGRO, noble liquid calorimeter Nucl. Instrum. Methods Phys. Res., A 1069 (2024) 169921

**CLD**

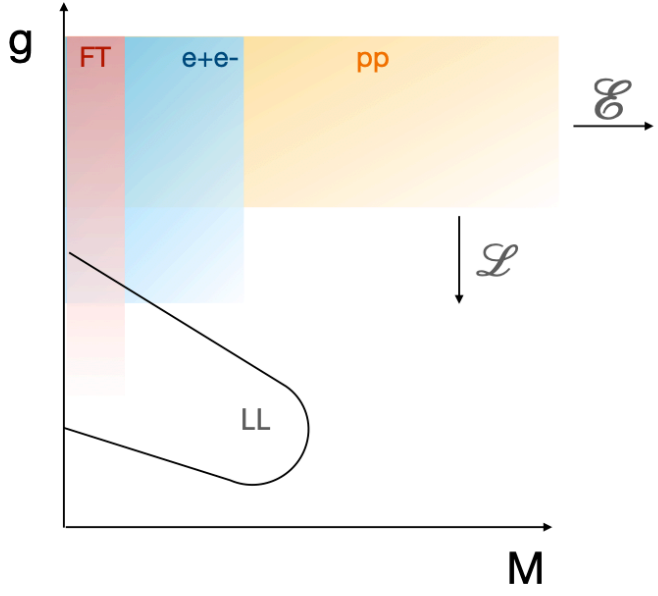



**ALLEGRO**



# Direct searches

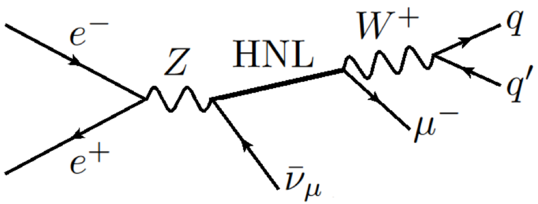
- **Classic benchmarks** of feebly interacting particles (weak interactions with SM particles):
  - Heavy Neutral Leptons (HNL)
  - Axion-Like Particles (ALP)
  - Scalars from exotic Higgs decay
- We can target the **long-lived** (decay length $\gtrsim$ 0.5 mm) parameter space with dedicated searches



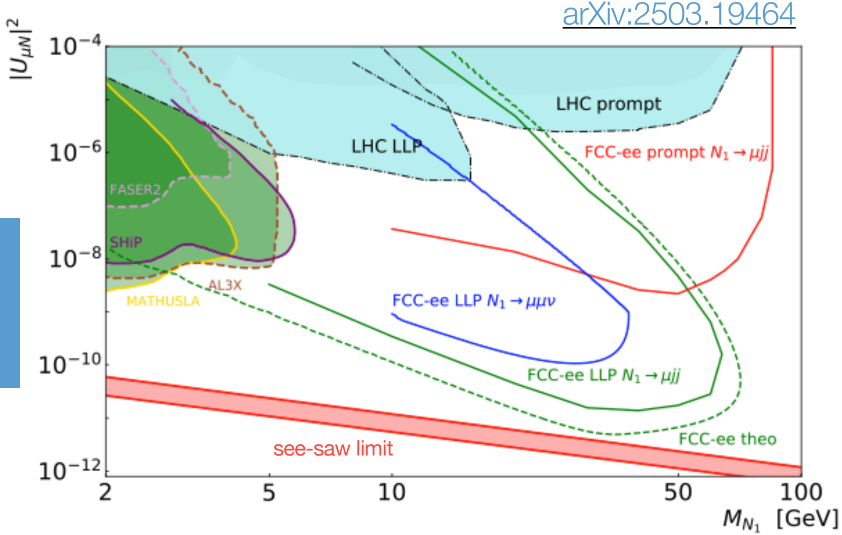

credit: F. Maltoni

# Single Majorana HNL

- Studies on semi-leptonic and fully leptonic channels with **single mixing**
- **Prompt** and **long-lived** (within tracker volume, background-free from simulation), with and without machine learning
- One study in full-sim CLD doi:10.17181/k3faq-d1f12



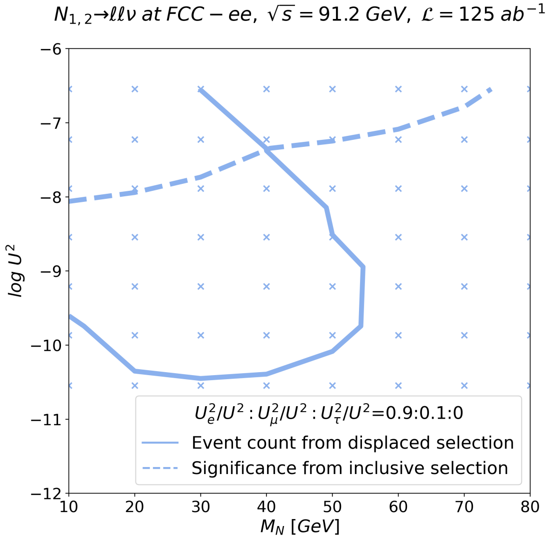

arXiv:2503.19464



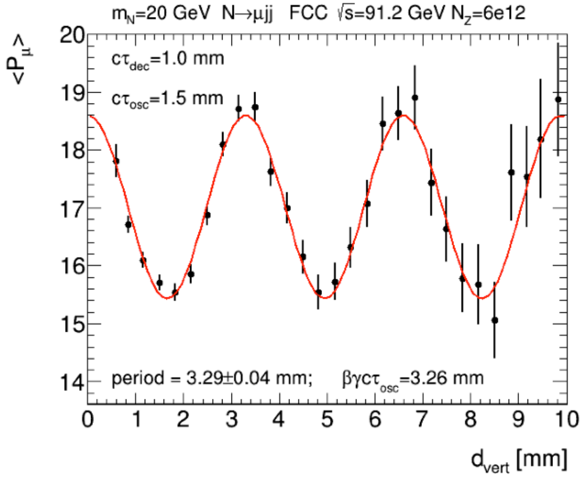

**HNL discovery at FCC-ee for a mass range beyond the reach of specialised detectors and smaller mixing angles**

# Realistic HNLs models

- **Two quasi-degenerate Majorana HNLs** with coupling to all active neutrinos, both mass hierarchies JHEP05(2025)054




- **Two pseudo-Dirac HNLs** mixing to muons, lepton flavour violation from $N\bar{N}$ **oscillations** and Dirac vs. Majorana limit doi:10.17181/hd9nb-zmg24

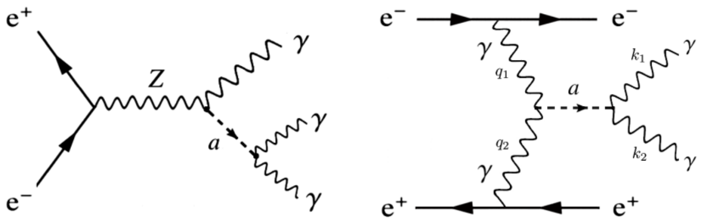


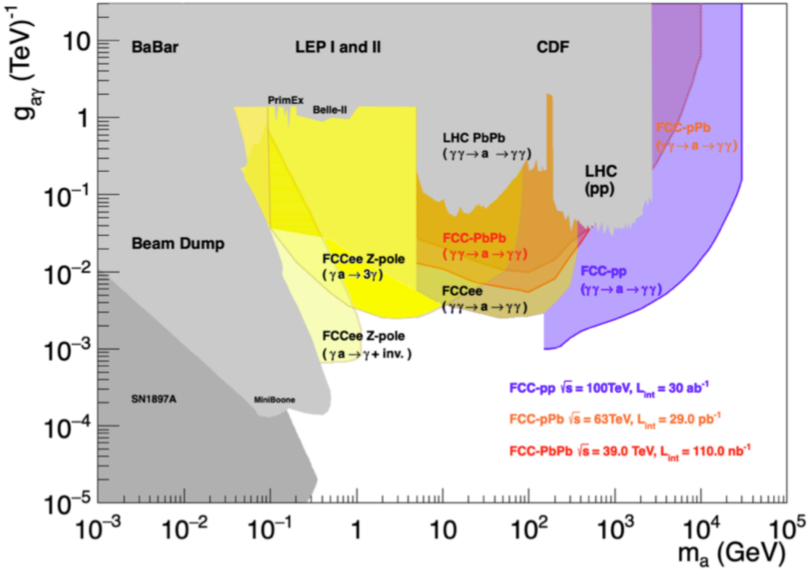

**Precise measurements at FCC-ee test the parameters and underlying symmetries**

# ALPs

- $Z \to a\gamma$ prompt (tri-photon) and long-lived (mono-photon) JHEP06(2025)239
- **Photon fusion** production from combination of all runs PhysRevD.109.055003
- Preliminary study on $a \to gg$ (with CLD fast-sim) doi:10.17181/2cj3g-x8h03

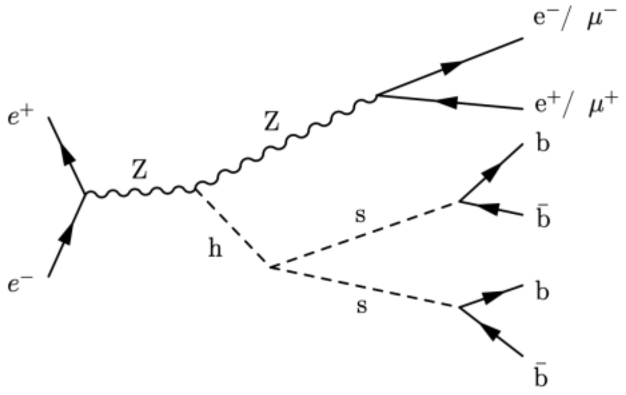
**FCC-ee can probe ALP-photon couplings in regions inaccessible to beam-dump experiments**



# Exotic Higgs

- Large Higgs sample at FCC-ee, for the first time at lepton colliders
- Direct searches with up to **four orders of sensitivity** in Higgs branching ratios compared to HL-LHC




**Background-free sensitivity at FCC-ee for scalars between 1 mm and 10 m decay length**

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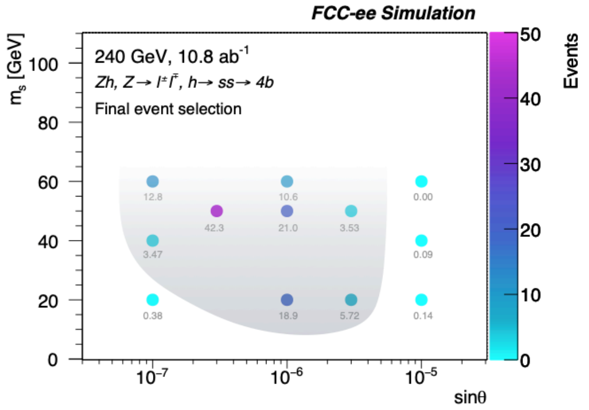
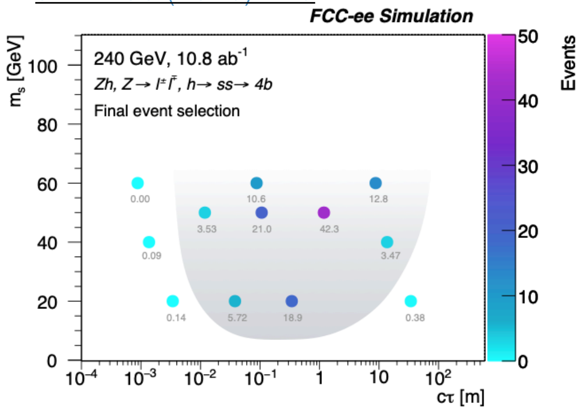
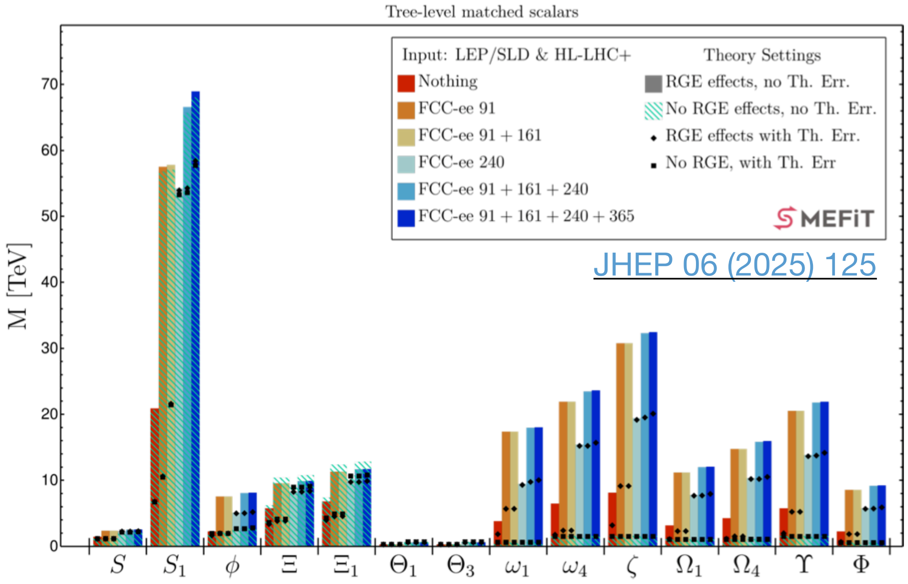


# Indirect searches

- Effective Field Theories connect measurements at different scales without knowledge of the UV
- The Tera-Z program is well placed to find indicators of **heavy new physics,** complementarity with Higgs run

**FCC-ee shows significant improvement in the reach of precision of electroweak observables in SMEFT framework**

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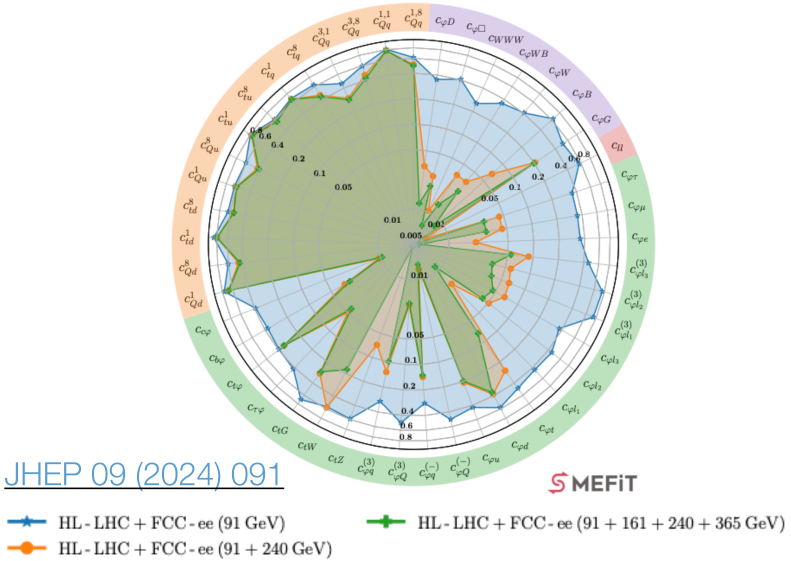


JHEP 09 (2024) 091

# Conclusions

**FCC-ee can directly probe the $\mathcal{O}$(1-100) GeV mass range of feebly interacting particles and high-precision SM measurements indirectly probe BSM in the $\mathcal{O}$(10-100) TeV range, thanks to a clean environment, high luminosity, and large acceptance**

- Strong interplay of prompt and long-lived signatures
- Tera-Z and Higgs runs are highly beneficial to the BSM program
- There is still work to be done in preparation for the TDR, get in touch!

- More details in the FCC-ee Feasibility study and ECFA report
- All inputs to the 2026 European Strategy for Particle Physics update

# Backup

# Other direct searches

- Not experimentally explored yet at FCC-ee but interesting:
  - Dark photons
  - Dark matter (monophoton, …)
  - Exotic Z decays
  - Z’

[arXiv:2405.03396](arXiv:2405.03396)

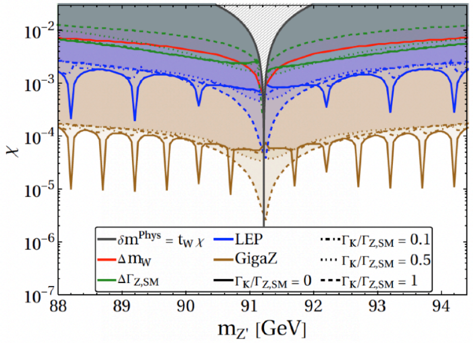


Figure 1: Constraints in the $(m_{Z'}, \chi)$ plane arising from excluded shifts in the W mass (red line) and Z-like width (green lines), as well as Bhabha scattering from LEP Run 1 [29] (blue lines) and a projection for a Giga-Z factory (light brown lines). The gray hatched region is unobtainable due to avoided-crossing.

[Phys. Rev. D 111, 035029 (2025)](Phys. Rev. D 111, 035029 (2025))

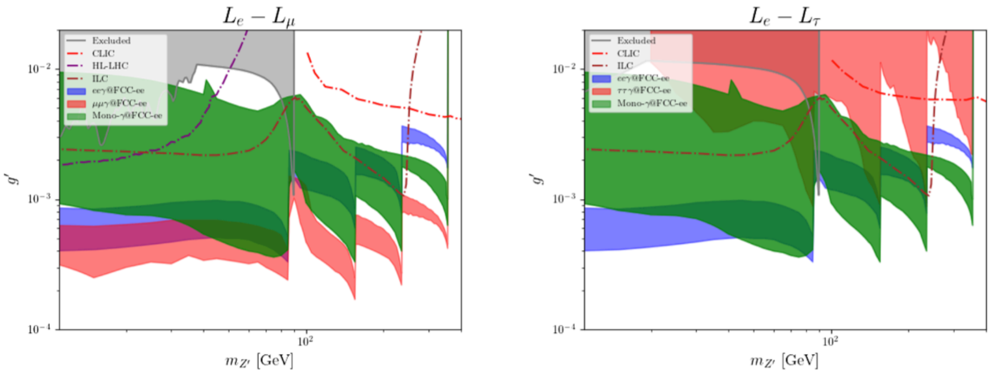


FIG. 13. Projected sensitivities of all four FCC-ee runs to the $L_e - L_\mu$ ($L_e - L_\tau$) model. The red, blue and green bands correspond to the $\mu\mu\gamma$ ($\tau\tau\gamma$), $ee\gamma$, and mono-$\gamma$ search channels respectively, and show the range of bounds set on this model by varying $\Delta_{ll}$ and $\Delta_\gamma$ for each search channel from 0.5 to 10 GeV.

# More on indirect searches (FCC FSR)

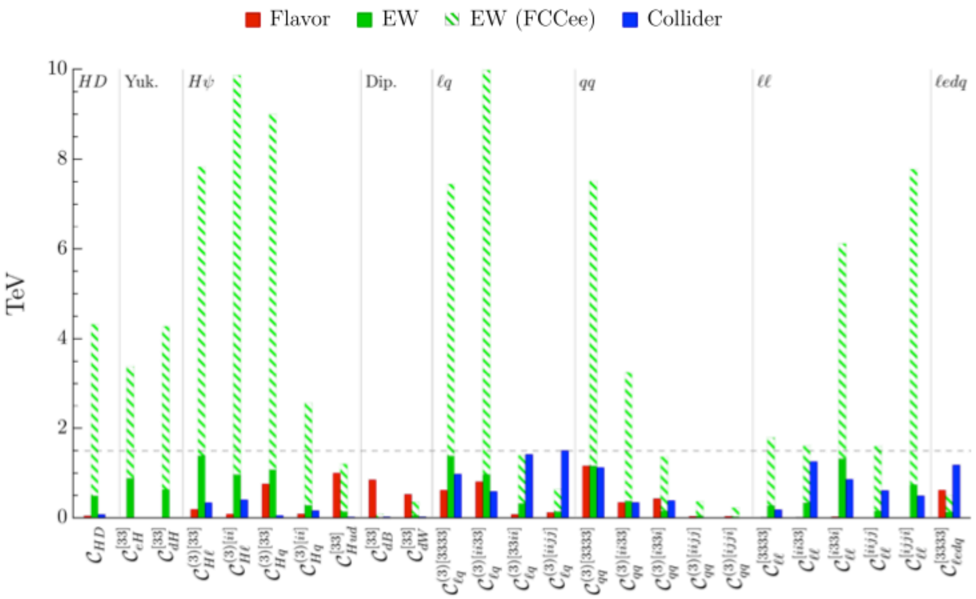


**Fig. 16:** The reach of FCC-ee precision electroweak observables (hatched) compared to present day flavour, electroweak, and high energy collider constraints, for all operators consistent with $U(2)^5$-symmetric flavour physics at the new physics matching scale. The bounds are $3\,\sigma$ single-parameter fits, obtained running from a scale of 3 TeV with full resummation of the logarithmic terms. Taken from Ref. [102].

# More on indirect searches

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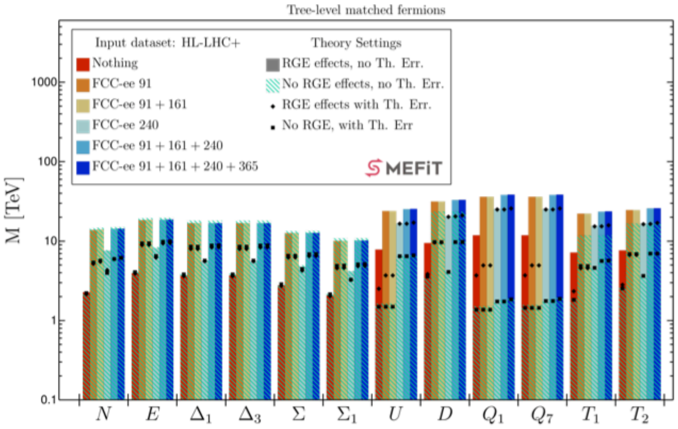
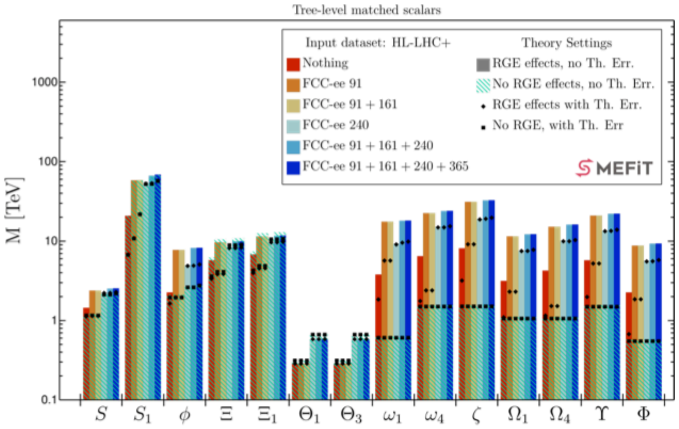
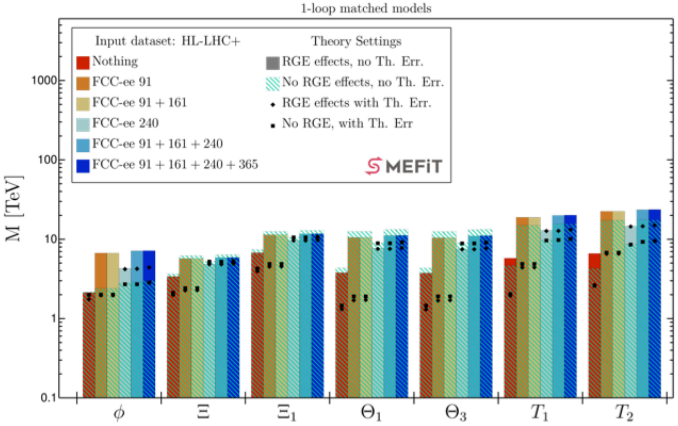
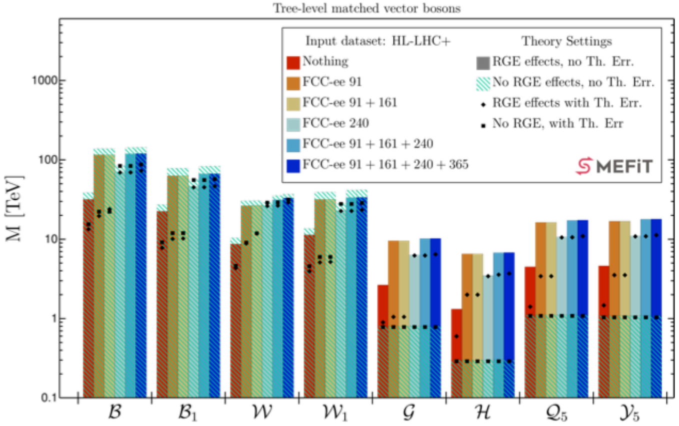


# FCC-hh (FCC FSR)

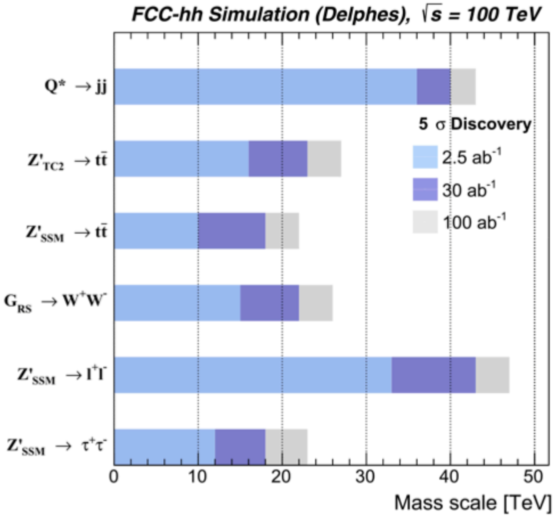



**Fig. 32:** Summary of the 5 $\sigma$ discovery reach, as a function of the resonance mass, for different FCC-hh luminosity scenarios. From Ref. [186].

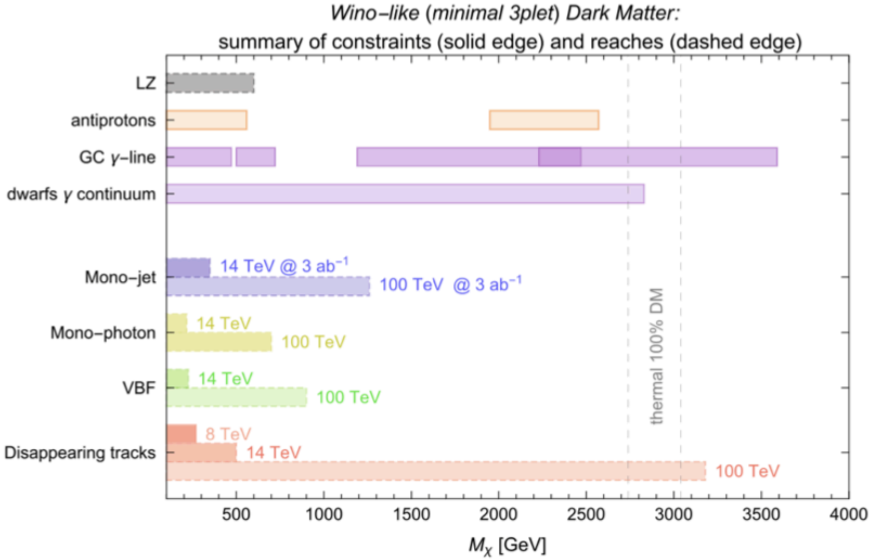
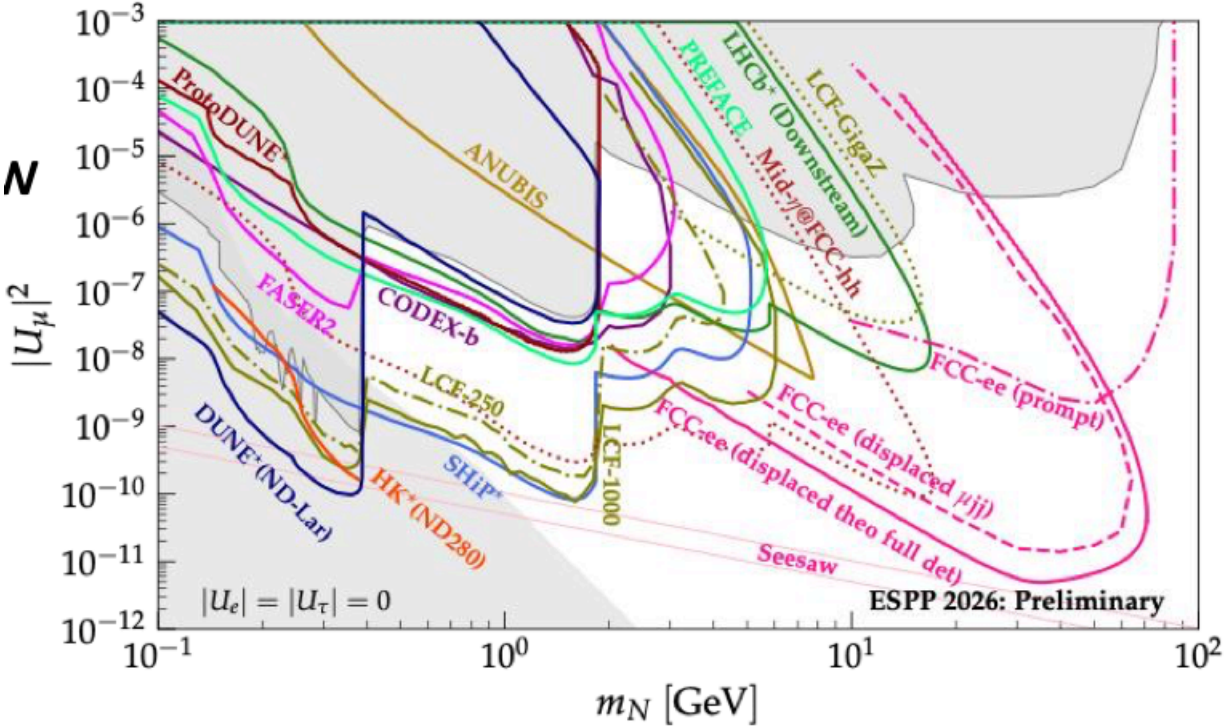



**Fig. 33:** The projected sensitivity of searches for a WIMP triplet DM candidate in final states with disappearing tracks at FCC-hh [10]. Adapted from Ref. [189].

# ESPP HNLs

Venice-ESPP-2025



# HNLs theory

- See-saw type 1 Phys. Rev. Lett. 128, 051801

$$\mathcal{L}_{type\ I} = \frac{1}{2}\sum_{i=1}^{n} \bar{N}_i(i\partial\!\!\!/ - M_i)N_i - \frac{g}{\sqrt{2}}\sum_{i=1}^{n}\sum_{\ell=e,\mu,\tau} \bar{N}_i U^*_{\ell i} W^+_\mu \gamma^\mu \ell^-_L$$

$$-\frac{g}{2\cos\theta_W}\sum_{i=1}^{n}\sum_{\ell=e,\mu,\tau} \bar{N}_i U^*_{\ell i} Z_\mu \gamma^\mu \nu_{L,\ell} - \frac{gHM_i}{2M_W}\sum_{i=1}^{n}\sum_{\ell=e,\mu,\tau} \bar{N}_i U^*_{\ell i}\nu_{L,\ell} + H.c.$$

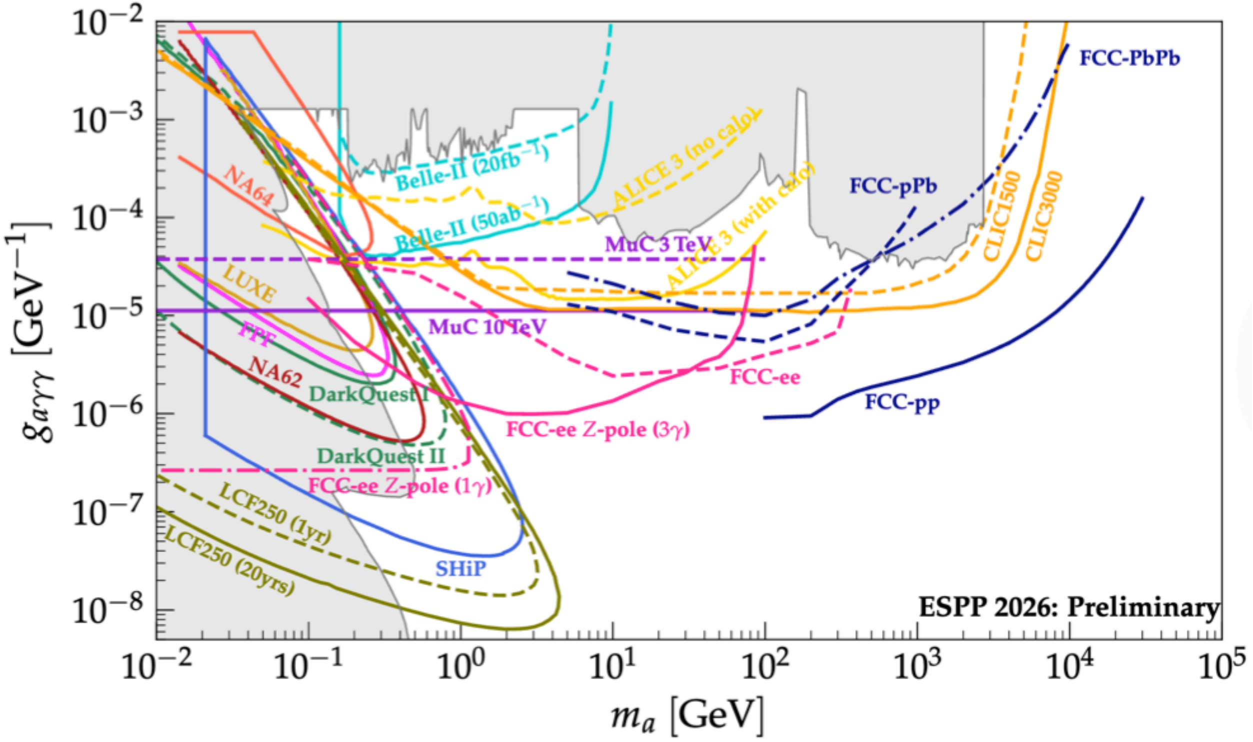
- Decay lenght PoS ICHEP2022 (2022) 608

$$L_{N_i} = \simeq \frac{1.6}{U_i^2}\left(\frac{M_i}{GeV}\right)^{-6}\left(1-(M_i/M_Z)^2\right)\ cm$$

- Pseudo-Dirac limit JHEP 12 (2021) 182 in agreement with leptogenesis JHEP 09 (2018) 124 and oscillation data JHEP 09 (2020) 178

# ESPP ALPs

Venice-ESPP-2025



# Generic ALPs

Wide range of masses and coupling strengths => span various energy scales and experimental setups at lepton & hadron colliders.

$$\mathcal{L}^{D=5}_{a-SM} \supset \sum_f C_{ff}\frac{\partial^\mu a}{\Lambda}\bar{f}\gamma_\mu\gamma_5 f + C_{GG}\frac{a}{\Lambda}G_{\mu\nu}\tilde{G}^{\mu\nu}$$

After EWSB

$$+C_{\gamma\gamma}\frac{a}{\Lambda}F_{\mu\nu}\tilde{F}^{\mu\nu} + C_{\gamma Z}\frac{a}{\Lambda}F_{\mu\nu}\tilde{Z}^{\mu\nu} + C_{ZZ}\frac{a}{\Lambda}Z_{\mu\nu}\tilde{Z}^{\mu\nu} + C_{WW}\frac{a}{\Lambda}W_{\mu\nu}\tilde{W}^{\mu\nu}$$

Exotic Z Decays

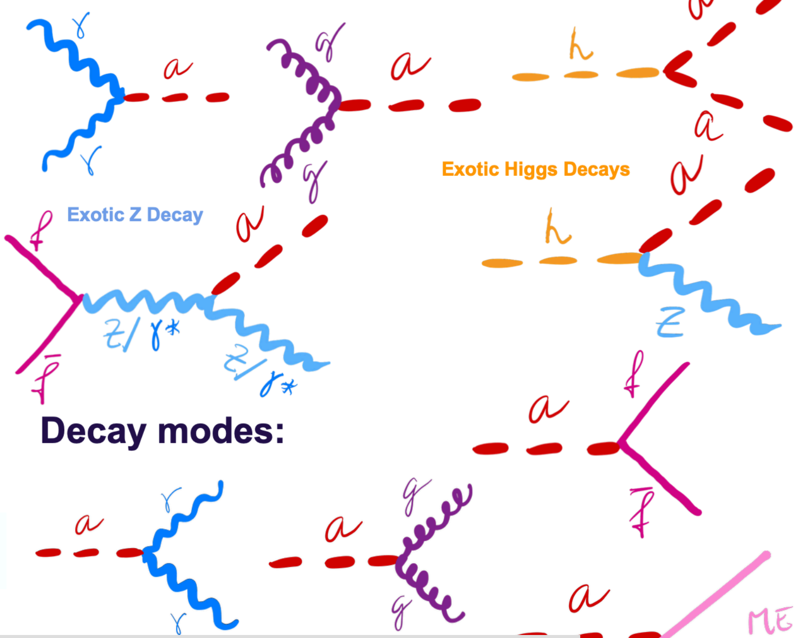
$$\mathcal{L}^{D\geq 6}_{\text{eff}} = \frac{C_{ah}}{\Lambda^2}(\partial_\mu a)(\partial^\mu a)\,\phi^\dagger\phi + \frac{C^{(7)}_{Zh}}{\Lambda^3}(\partial^\mu a)\left(\phi^\dagger\, iD_\mu\,\phi + \text{h.c.}\right)\phi^\dagger\phi + \dots$$

Exotic Higgs Decays

A. Thamm (2019) link; Bauer's UFO Model

## Production modes:

## Decay modes:




$$\Gamma_a = \frac{g^2_{a\gamma\gamma} m_a^3}{64\pi} \qquad L_a = 1/\Gamma_a$$

$$\langle L_T\rangle = \langle\gamma\beta\rangle\, L_a \sin\theta = \langle(\gamma\beta)_T\rangle\, L_a = 64\pi\,\langle p_T\rangle\, g^{-2}_{\gamma\gamma}\, m_a^{-4}$$

# Exotic Higgs

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This work considers an extension of the SM by a new real scalar field $S$ which interacts with the SM Higgs boson doublet $H$. The minimal renormalizable Lagrangian describing the scalar system is given by

$$\mathcal{L}_{\text{scalar}} = \mathcal{L}_{\text{kin}} + \frac{\mu_s^2}{2} S^2 - \frac{\lambda_s}{4!} S^4 - \frac{\kappa}{2} S^2 |H|^2 + \mu^2 |H|^2 - \lambda |H|^4 \,, \tag{2.1}$$

where a discrete symmetry taking $S \to -S$ is assumed. Depending on the choice of couplings, the two fields may acquire non-zero vacuum expectation values, and the two scalar states, corresponding to the SM Higgs boson $h$ and the dark scalar $s$, mix with a small mixing angle $\sin\theta$. The mixing allows for decays of the SM Higgs boson into pairs of dark scalars, as well as decays of the dark scalar back into SM states. The decay width of the dark scalar into SM states is equal to that of the SM Higgs boson with the mass of the dark scalar, reduced by a factor $\sin^2\theta$, according to

$$\Gamma(s \to X_{\text{SM}} X_{\text{SM}}) = \sin^2\theta \cdot \Gamma(h(m_s) \to X_{\text{SM}} X_{\text{SM}}) \,. \tag{2.2}$$

The mixing suppression $\sin^2\theta$ is common to all partial widths, and therefore does not affect the branching ratios if $s$ only decays to SM particles. For dark scalar masses above 10 GeV, the decay into $b\bar{b}$ is the dominant decay channel, with a branching ratio of 0.9 [1].

# Complementarity
## Between stages

- The FCC-hh will complement and substantially extend the FCC-ee physics reach in nearly all possible directions.
- The seven-fold centre-of-mass energy increase with respect to LHC enhances the potential for observing new particles at mass scales up to 40 TeV.
- Indirectly, it will be sensitive to energies well above its kinematic reach of 100 TeV, for example in the tails of Drell–Yan distributions.
- Should any deviations from SM expectations be observed at FCC-ee, FCC-hh has the potential to pinpoint its microscopic origin.

# LLP specialised detectors for FCC-ee

- Far detectors: arXiv:1911.06576 arXiv:2201.08960
- LAYCAST: LAYered CAvern Surface Tracker at future electron-positron colliders arXiv:2406.05770
- HECATE: A long-lived particle detector concept for the FCC-ee arXiv:2011.01005