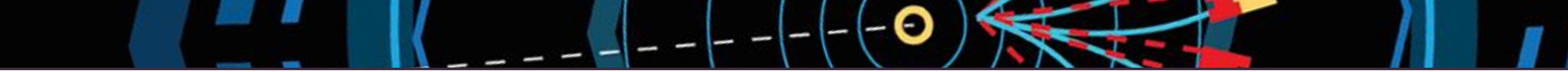
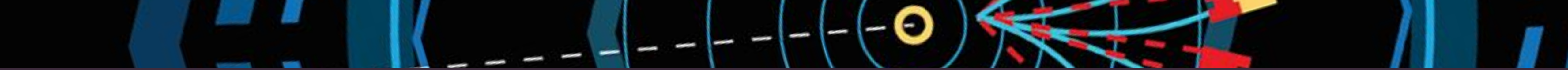


Dark sector perspectives at FCC-ee

Nicolò Valle, INFN Pavia

WIFAI 2025 12 Nov 2025, Bari

Istituto Nazionale di Fisica Nucleare



Dark sector perspectives at FCC-ee

- Introduction: BSM and FCC potential
- Scalar, pseudoscalar, neutrino, vector portals
- Case study: dark photons
- Challanges and summary

WIFAI 2025 **12 Nov 2025, Bari**

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The dark matter – evidence and unknowns

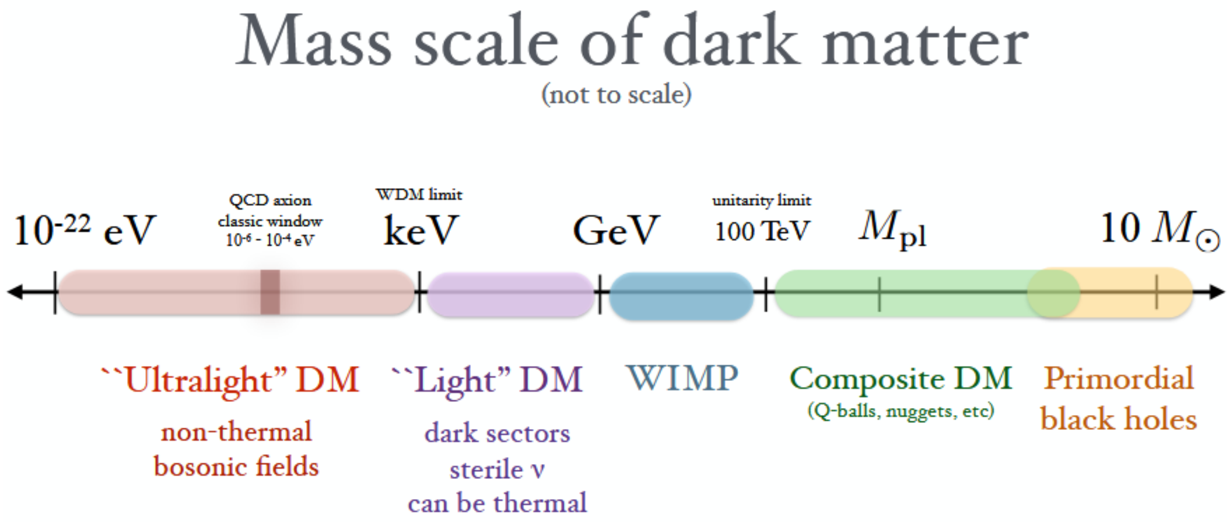
Astrophysical Evidence: *unseen mass dominates*

What is DM? No confirmed particle yet – **“WIMP”** searches so far negative

Paradigm Shift: Maybe DM isn’t *one* particle, but part of a broader **dark sector** with multiple new particles

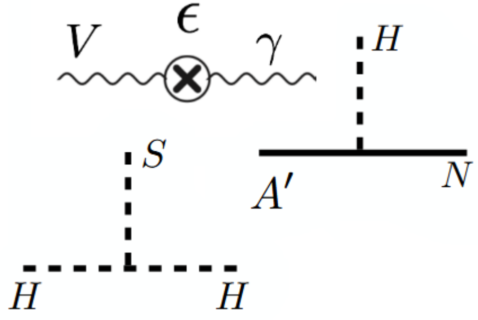
Rich Phenomenology Additional “dark” particles could be unstable but produce detectable signatures (e.g. decays back to SM particles)

Experimental Strategy Look not only for dark matter itself, but any “portal” particle that connects the dark sector to us



https://arxiv.org/pdf/1904.07915

Very economical extensions of the SM



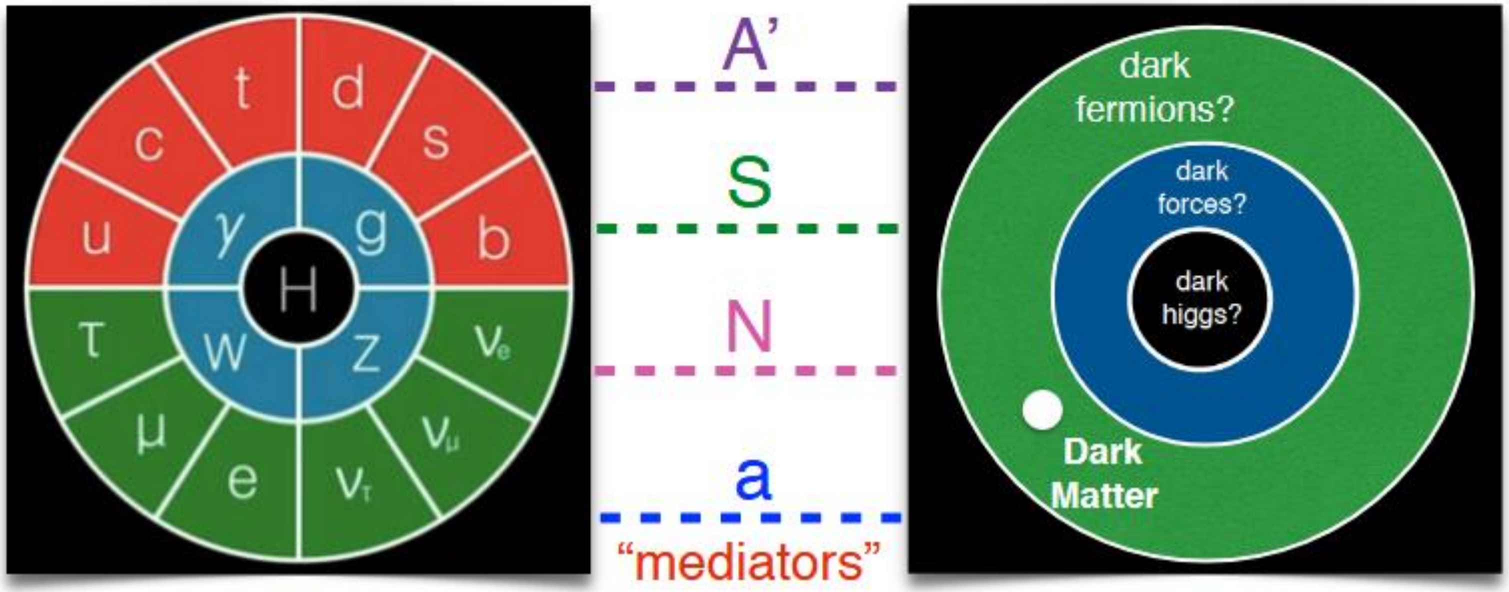
Portal models – connecting the Dark Sector to SM

Concept: Minimal renormalizable interactions linking new *gauge-singlet* states to the Standard Model.

Four Key Portals

- **Scalar (Higgs) Portal** — *A new scalar mixes with the Higgs (e.g. "dark Higgs"), allowing it decays into hidden states*
- **Pseudoscalar Portal (ALPs)** — *A pseudo-Goldstone boson (axion-like particle) couples to two photons or gauge bosons*
- **Neutrino Portal** — *Additional heavy neutral leptons (HNLs) mix with SM neutrinos*
- **Vector Portal** — *A dark U(1) gauge boson ("dark photon") kinetically mixes with the photon/Z boson*

(Other exotic possibilities exist, but portal framework covers broad scenarios)



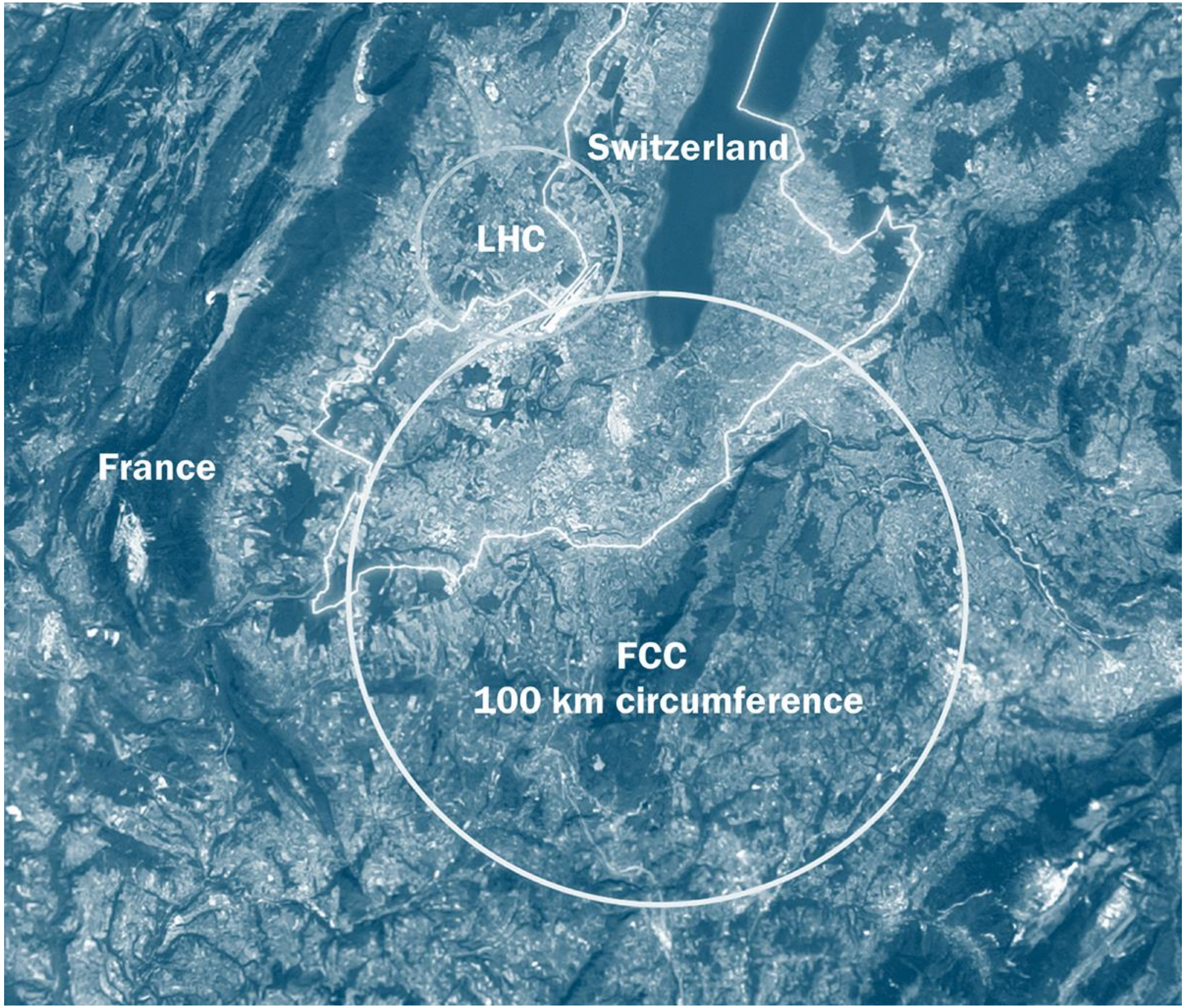
$$\epsilon B^{\mu\nu} A'_{\mu\nu}$$

$$\kappa |H|^2 |S|^2$$

$$y H L N$$

$$g_{a\gamma} a \tilde{F}_{\mu\nu} F^{\mu\nu}$$

BSM at FCC-ee



91 km circular e+e- collider at CERN (planned as first stage of FCC)

Energies from **m_Z = 91 GeV up to ~365 GeV** (t-tbar)

European Strategy Priority: FCC-ee feasibility study finished

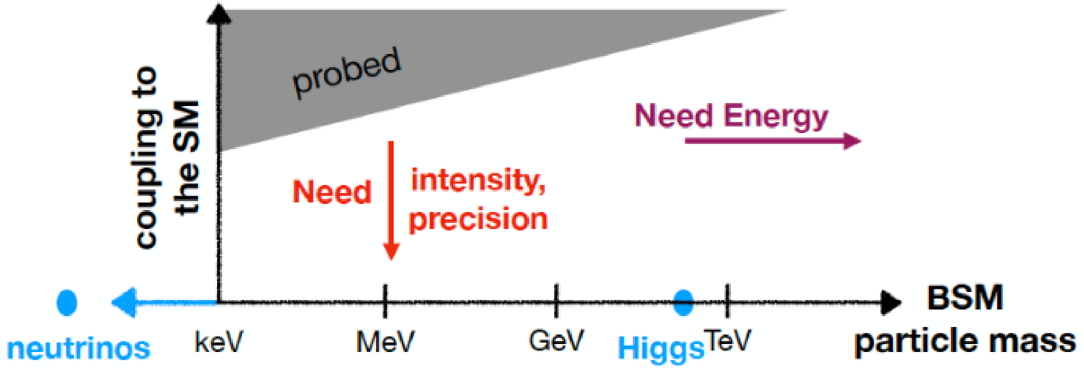
High priority to explore electroweak and dark sector frontiers

BSM at FCC-ee

We don't know what wil be next New Physics scale

↓

search as broadly as possible



Unprecedented Yields: Tera-Z run: ~5×10^12 Z bosons; ~10^8 W pairs, ~10^6 Higgs, 10^5 top pairs.

Clean Environment: Simple initial state (e, e), well-known $\sqrt{s}$ (~100 keV scale calibration), low backgrounds → ideal for tiny signals

Feebly interacting BSM particles

Heavy Neutral Leptons

Dark photons

Axion Like Particles

Exotic Higgs decays

Detector requirements

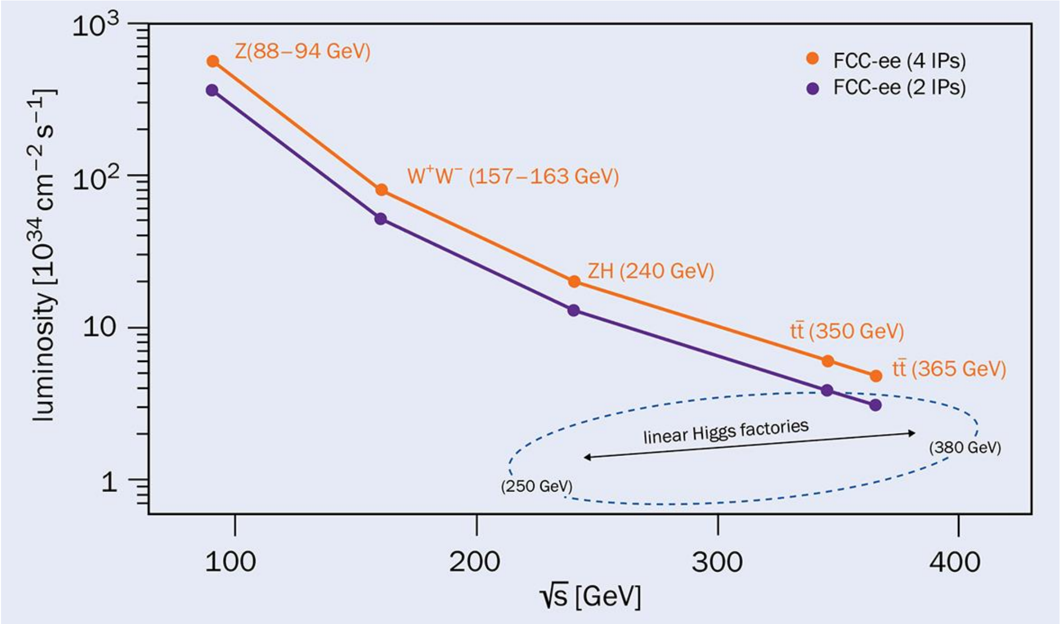
Large decay volume

High segmentation

IP resolution for large displacement

Timing

No limitations related to triggering



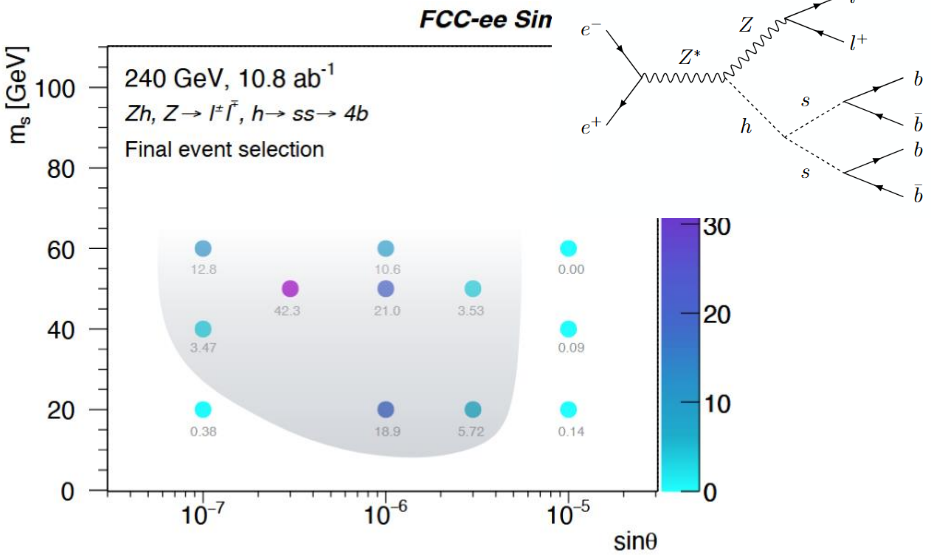
Scalar (Higgs) portal

New Scalar Field: singlet scalar S that mixes with the Higgs H, small mixing angle $\sin\theta$

S might decay to invisible or be stable itself if light.

Cosmology: A scalar portal mediating between DM and SM can generate the correct relic abundance (freeze-out or freeze-in).

https://arxiv.org/pdf/2412.10141



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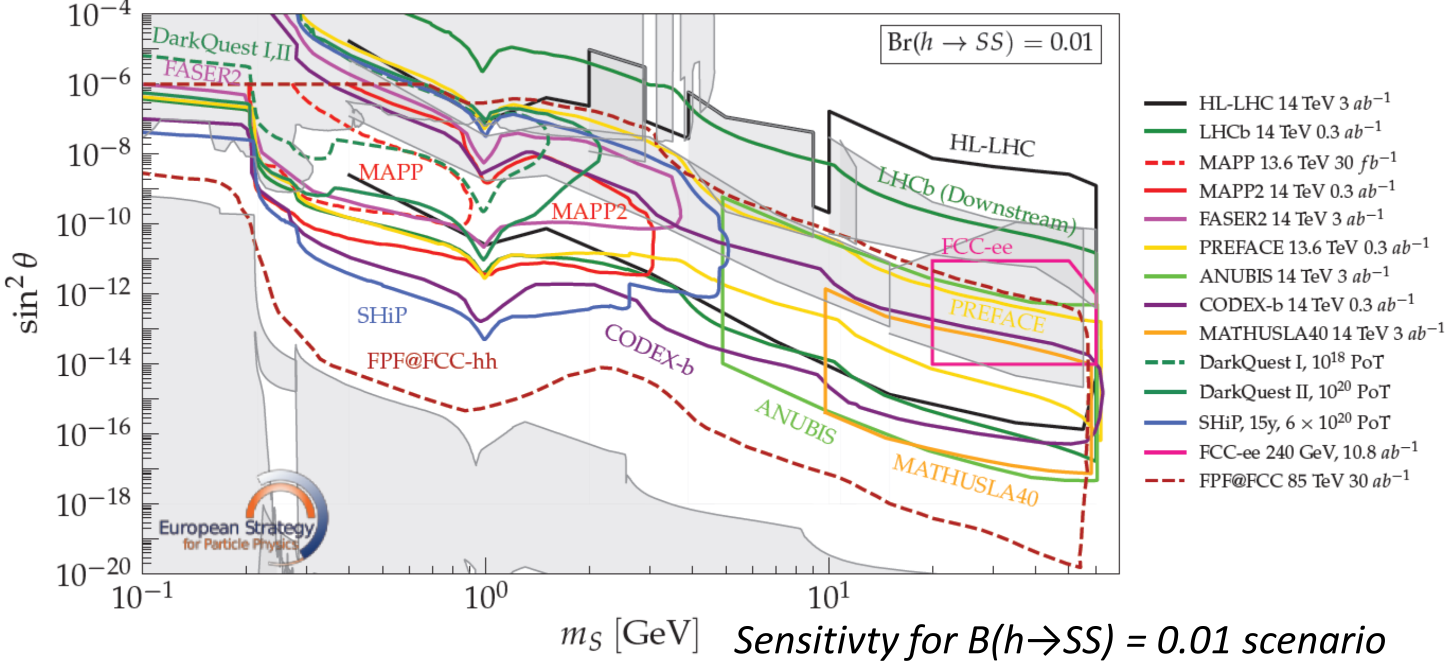


Sensitivty for B(h→SS) = 0.01 scenario

Scalar (Higgs) portal at FCC

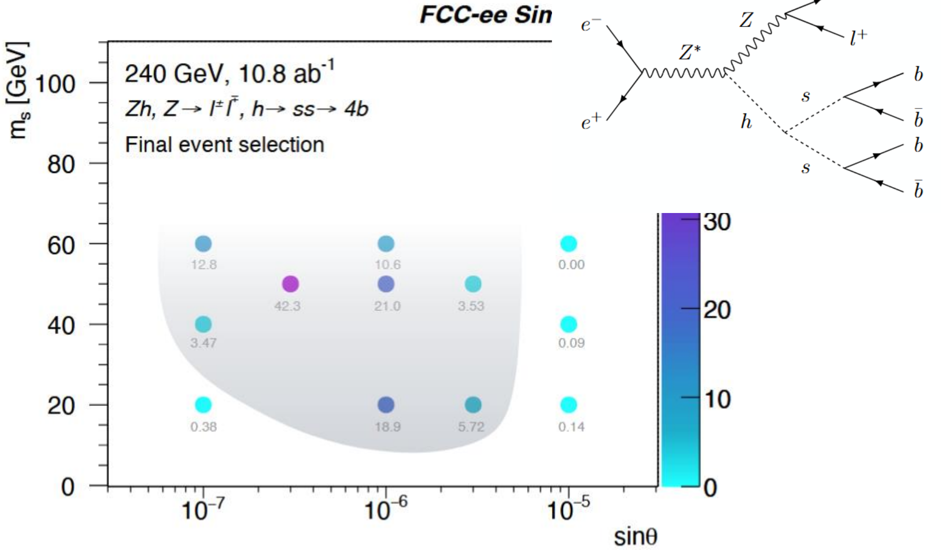
Higgs Invisible Decays: Key signature. Higgs → invisible is tightly constrained. **FCC-ee sensitivity:** an order of magnitude better than HL-LHC.

Exotic Higgs Decays: Higgs → XX (long-lived or visible), FCC-ee can discover decays with $B \sim 10^{-5}$ or smaller in clean channels

Direct S Production: If S is light, Higgsstrahlung-like, via mixing. Look for deviations in Z decays

Precision Effects: S mixing alters Higgs couplings (and width)

https://arxiv.org/pdf/2412.10141



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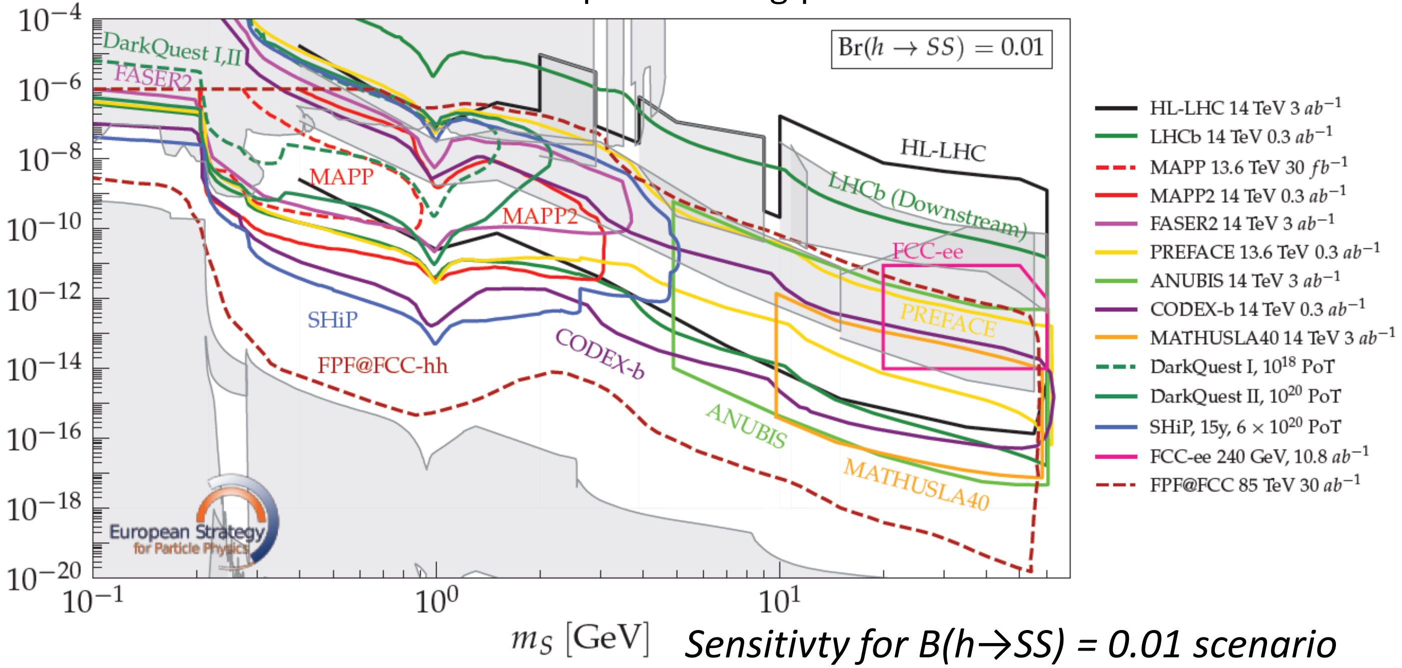


Sensitivty for B(h→SS) = 0.01 scenario

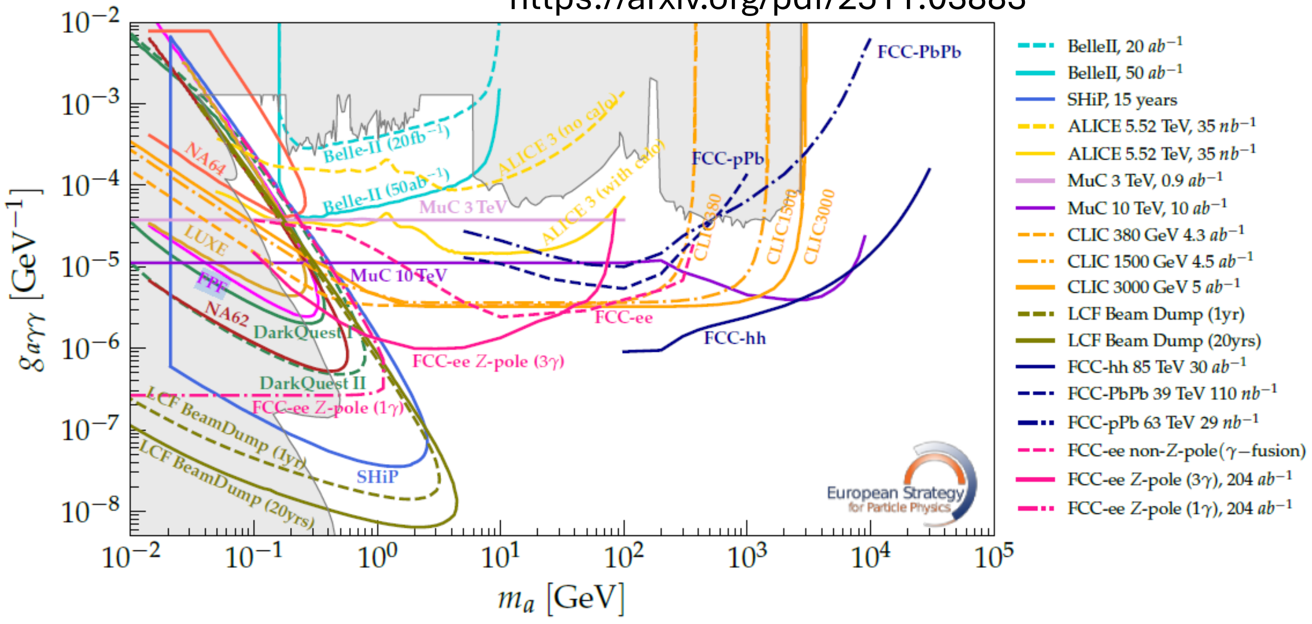
Pseudoscalar portal / ALPs

Axion-Like Particle (ALP): A light pseudo-scalar (spin-0) associated with a broken global symmetry. Couples to two photons (or W, Z) via anomalous interactions.

Role in Dark Sector: ALP could be a mediator or even dark matter itself if light

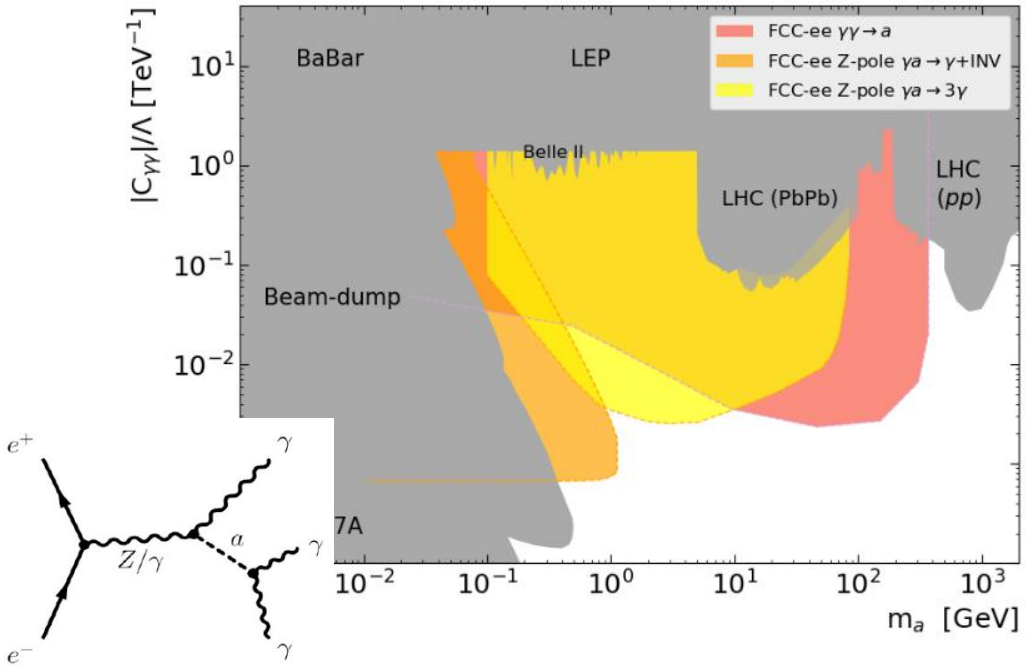
Signatures: Primarily $a \to \gamma\gamma$, (for $m_a > 2m_e,$ also $a \to ee$). Long lifetime if coupling scale is high → displaced signals.

https://arxiv.org/pdf/2511.03883



Sensitivity projections for ALPs coupling to photons as a function of the ALP mass

https://arxiv.org/abs/2502.08411



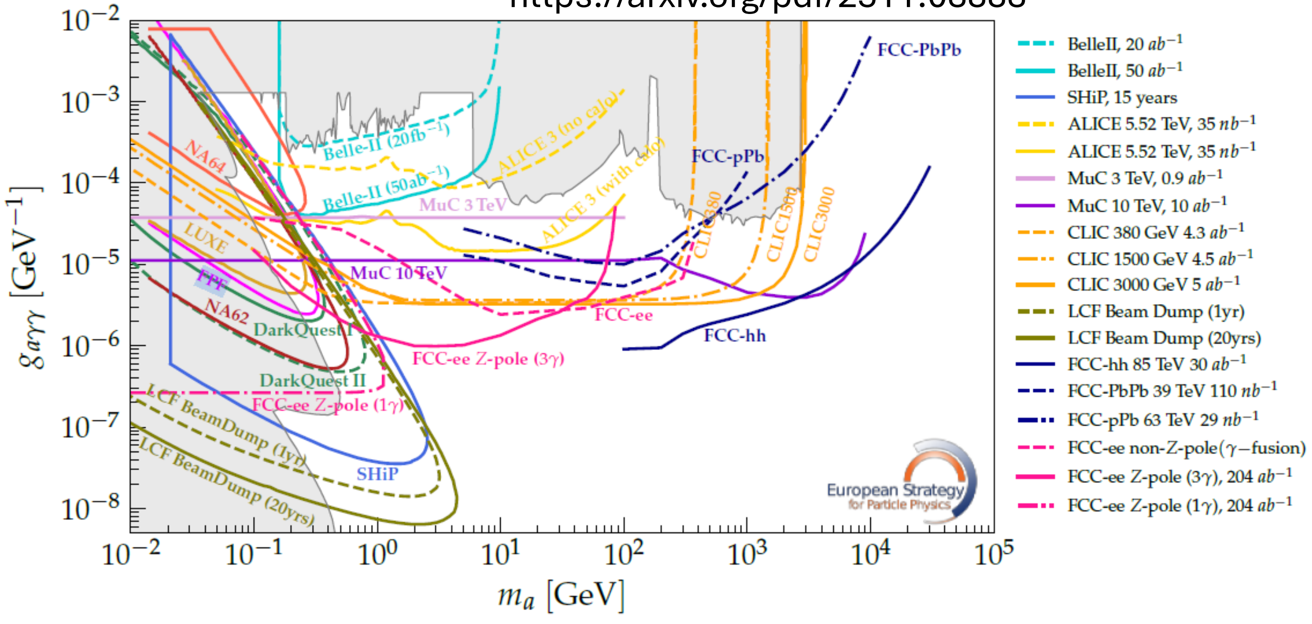
Pseudoscalar portal / ALPs at FCC

Z Boson Decays: Huge Z sample. Signature: single high-energy photon + **missing energy** (if a escapes) or γ+ **delayed di-photon**

Sensitivity: FCC-ee can probe ALP-photon coupling $g_{a\gamma}$ at least 2 order of magnitude smaller in strength than LHC

Long-Lived ALPs Fine calorimeter granularity helps distinguish two closely spaced photons (boosted low-mass ALP → collimated γ's). Timing layers can help identify delayed signatures.

https://arxiv.org/pdf/2511.03883



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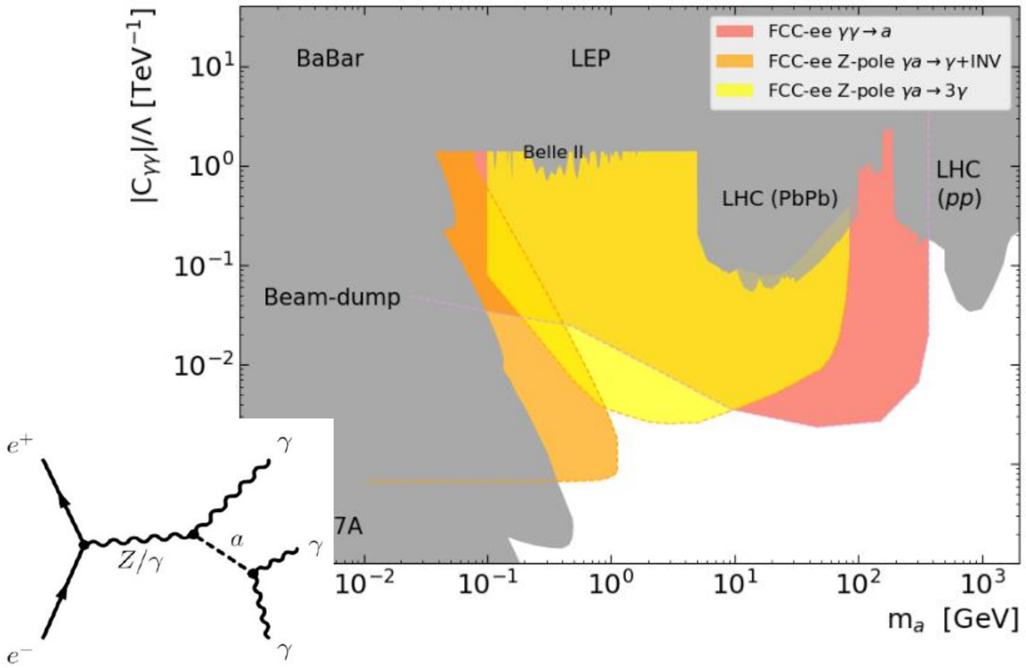


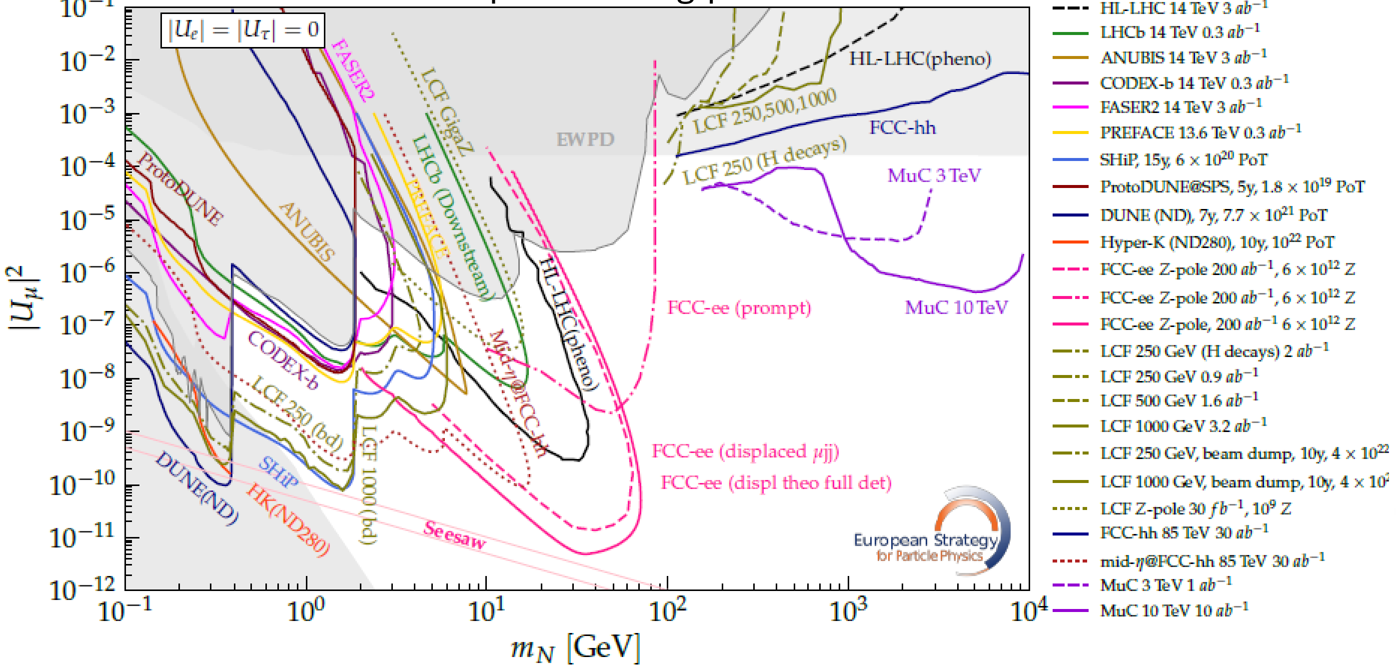
Neutrino Portal / HNLs

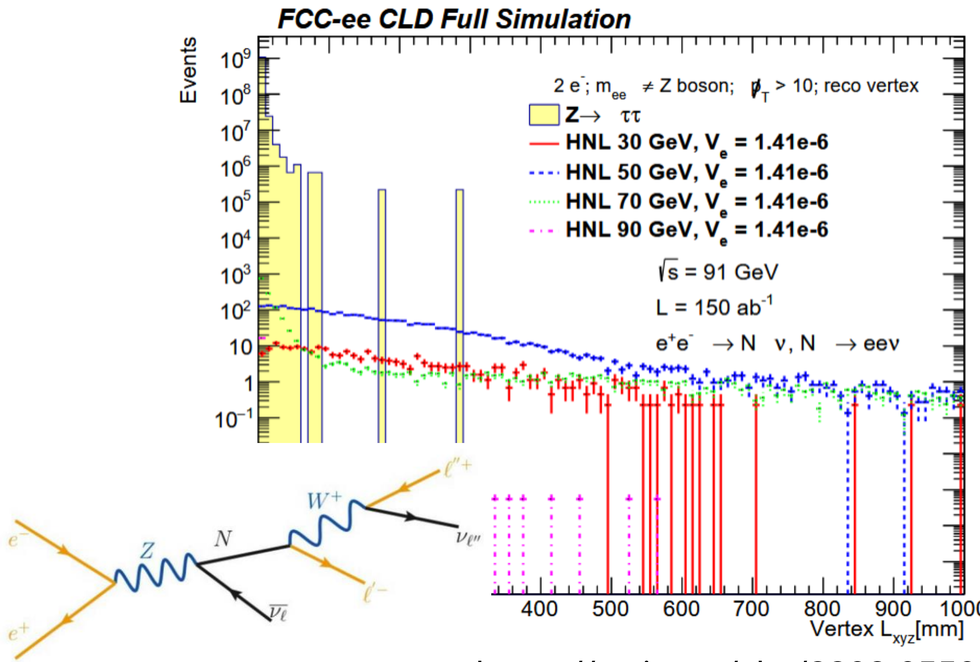
Sterile Neutrinos (HNLs): Gauge-singlet fermions that mix with SM neutrinos. Arise in see-saw models to explain tiny ν masses;

Mass Scale: Can range from eV to GeV–TeV. .
Interest at colliders typically ~100 MeV up to tens of GeV (so they can be produced in W/Z/H decays).

Baryogenesis Tie-in: HNLs with masses ~GeV and small mixings can also generate matter–antimatter asymmetry via leptogenesis

https://arxiv.org/pdf/2511.03883





https://arxiv.org/abs/2203.05502

Neutrino Portal / HNLs at FCCee

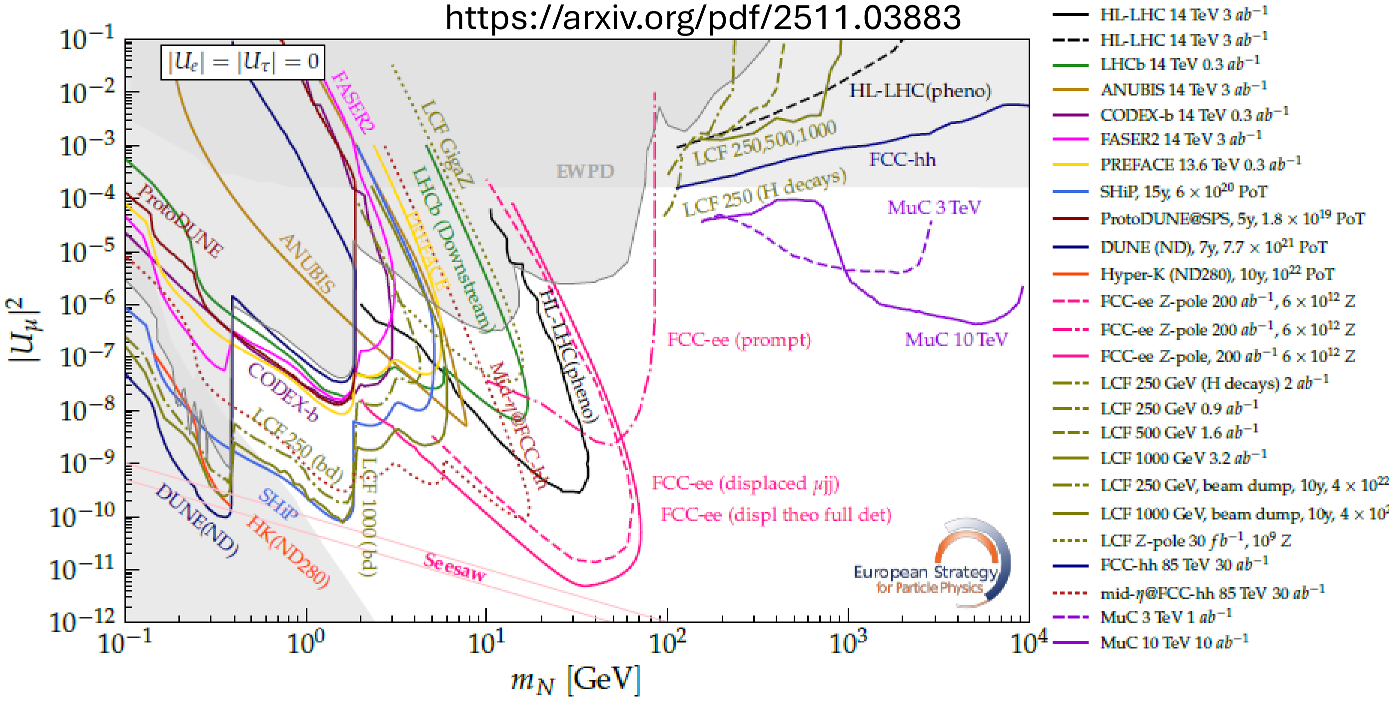
Z Decays: $Z \rightarrow \nu N$. With ~10^{12} Z decays, FCC-ee sensitive down to 10^{-11} – 10^{-12} mixing angle

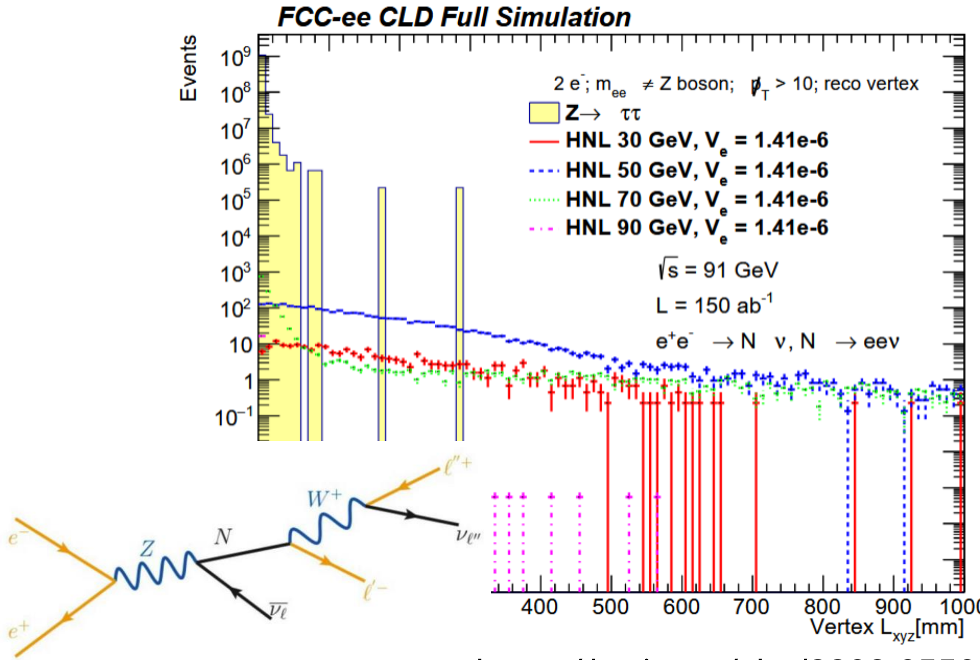
W Decays: $W \rightarrow \ell N$. Yields 10^{8} → sensitivity complementary to Z decays for heavier N

Higgs Decays: BR up to few %. FCC-ee's $H \rightarrow invisible$ limit (0.05%) constrains this strongly

Discovery potential: Long-lived HNLs give virtually background-free signals. FCC-ee detectors planned with superb vertex resolution to catch these

https://arxiv.org/pdf/2511.03883





https://arxiv.org/abs/2203.05502

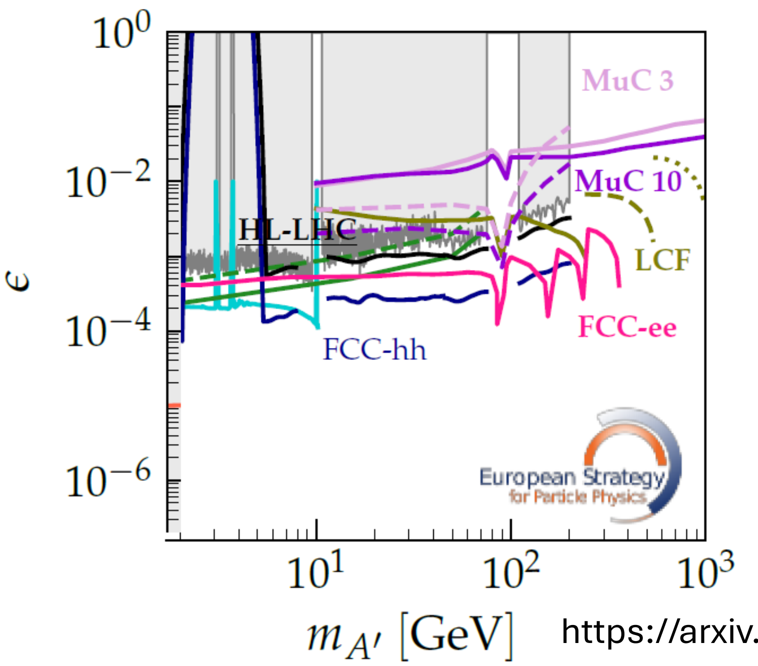
Vector portal / Dark photon

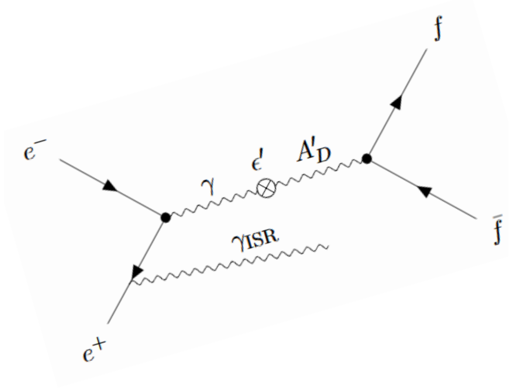
Dark Photon: Extra U(1) gauge boson with kinetic mixing with the ordinary photon (or Z).

Mass Range: Could be light (keV–GeV) or heavier. Often considered in MeV–GeV range as mediator of dark matter

Hidden Sector Force: Additional charge, A' a mediator between DM and SM through mixing.

Decay Channels: Long-lived if light (dominant decay might be to 3γ or not at all if stable).





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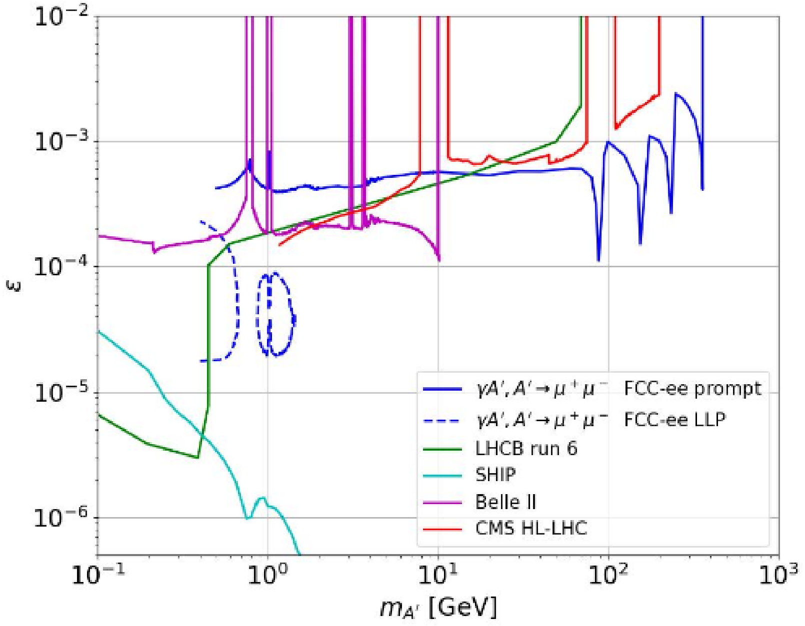
Courtesy of G.Polesello



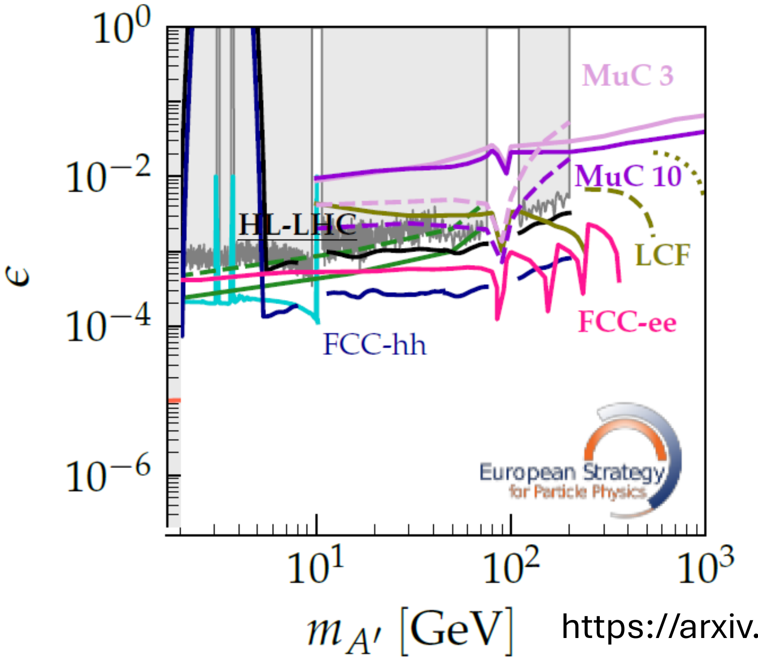
Vector portal / Dark photon at FCCee

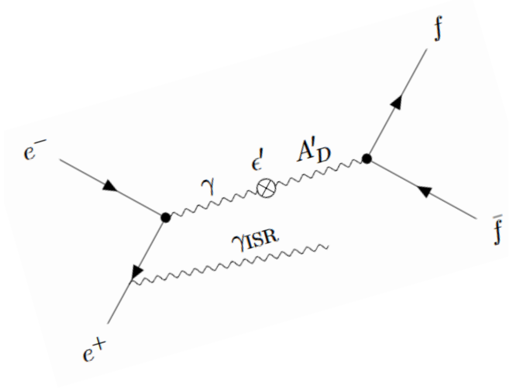
Mono-Photon Search: $e^+e^- \to \gamma A'$ with A' invisible (decays to dark matter). FCC-ee can push sensitivy to invisible down to 10^{-11} for a few tens GeV (competitive with dedicated experiments)

Displaced Decays: Low background and high trigger efficiency. FCCee better than LHC for ~GeV-scale long-lived bosons.

Resonance in Hadrons/Leptons: If A' decays promptly, could see a narrow resonance in di-lepton mass spectra. But FCC-ee at Z-pole has many events.

Projected Reach: FCCee covers significant new territory, especially for 1 MeV–10 GeV range. Fully unexplored region in invisible-decay case.





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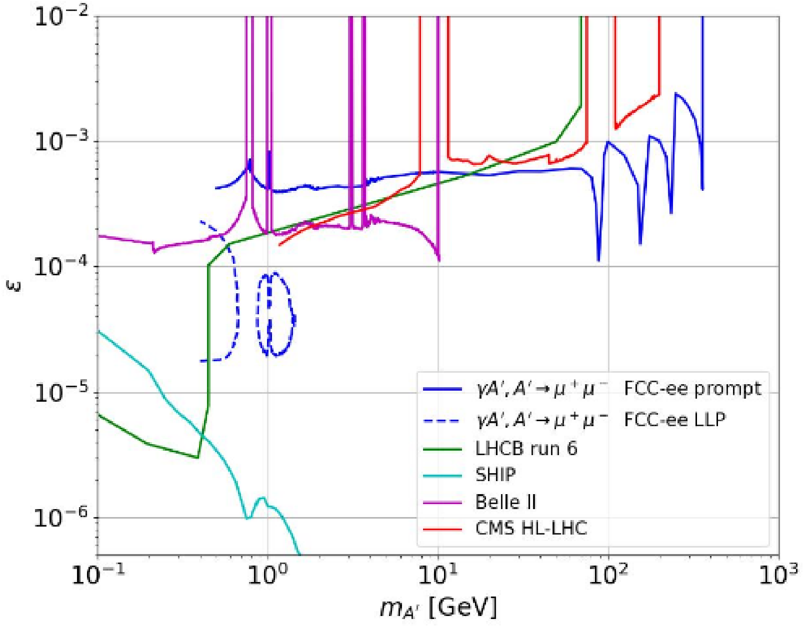


Signatures & Challanges

Missing Energy

Characteristic of invisible decays (Higgs → invis, Z→ $\gamma +$ invis, ,$A' \rightarrow$ dark matter, etc.). Need excellent hermiticity.

Displaced Vertices (LLPs)

Vertex detector: high granularity silicon pixels to locate decay ~10 μm accuracy.
Tracking volume: large radius to catch late decays.
Low beam backgrounds at FCC-ee simplify LLP searches.

Resonances

Peaks in invariant mass distributions (e.g. dilepton resonances from A’).
Requires high resolution tracking/calorimetry to distinguish narrow bumps.
Also large statistics and controlled systematics

Trigger/Timing

FCC-ee can likely run trigger-less. Picosecond timing layers in calorimeter and tracking can tag delayed decays and remove background

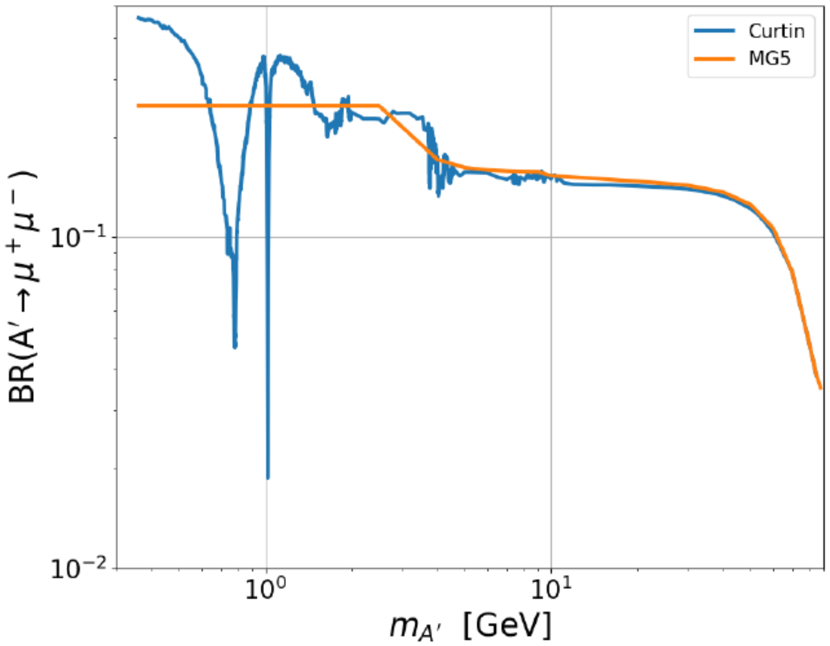
Case study: $A' \to \mu\mu$

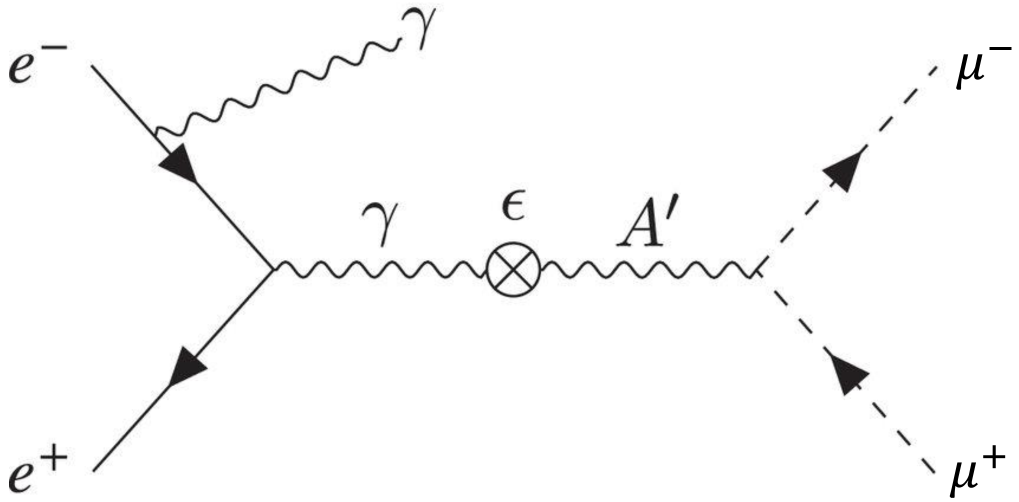
New – by G. Polesello
AN DOI

$e^+e^- \to \gamma A'$ followed by $A' \to \mu^+\mu^-$

Model: kinetic mixing between U(1)D and U(1)Y ; coupling strength $\propto \varepsilon^2$

Mass range: $m_{A'} = 0.4\text{–}360\ GeV$

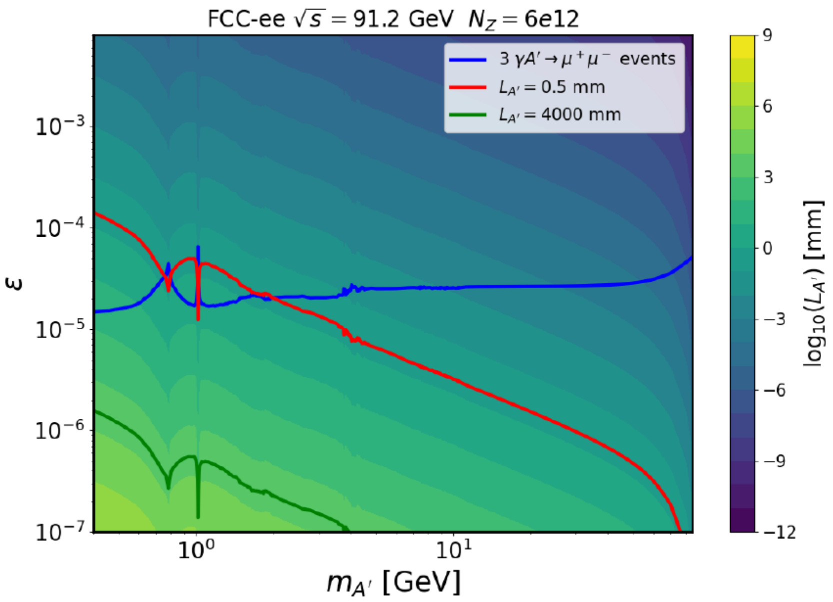




Tools:
MG5_aMC@NLO + PYTHIA8 + DELPHES
↑
IDEA detector fast simulation

Case study: $A' \to \mu\mu$

New – by G. Polesello
AN DOI

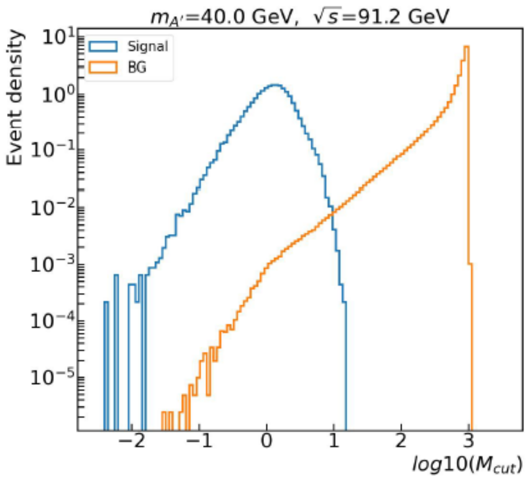


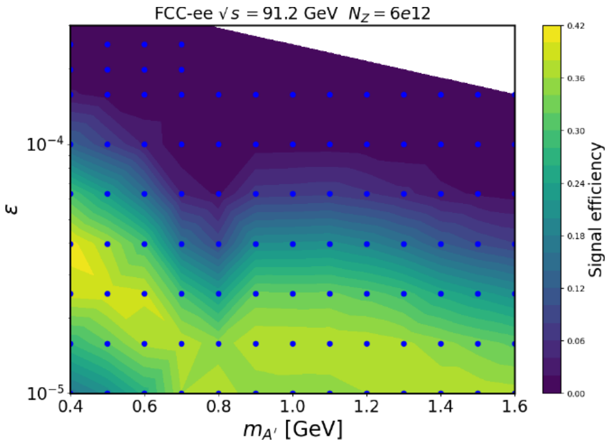
Main background: $e^+e^- \to \gamma\mu^+\mu^-$

Prompt analysis

Discriminant variable: $$M^2_{cut} = \frac{(m_{\mu^+\mu^-} - m_{A'})^2}{\sigma(m_{A'})^2} + \frac{(E_\gamma - E)^2}{\sigma(E)^2},$$

ML classifier: XGBoost → background rejection ×5, signal efficiency ≈ 35%





LL analysis

A' decay displaced by 0.5 mm – 4 m

Key variable: transverse vertex distance r_{vx}

Background suppressed via cuts on $E_{\mu 2}$, $|\eta|$, and vertex direction

Case study: $A' \to \mu\mu$

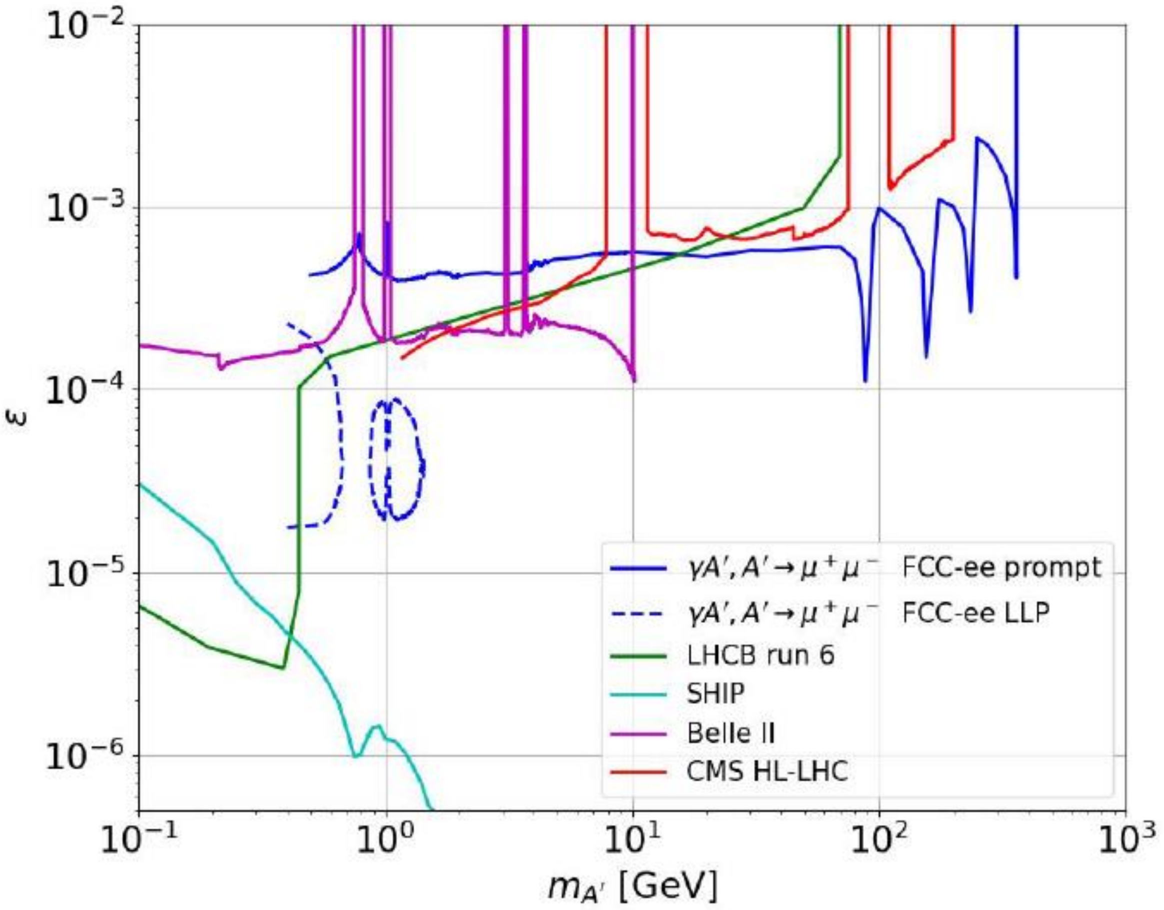
New – by G. Polesello
AN DOI

Prompt A' search:
95% CL sensitivity on ε $0.5 \times 10^{-3} < \varepsilon < 0.85 \times 10^{-3}$

Combined FCC-ee reach surpasses HL-LHC projections for $m_{A'} > 20\,GeV$

Long-lived A' search:
Sensitivity down to $\varepsilon \sim 2 \times 10^{-5}$ for $m_{A'} \sim 1\,GeV$
Extends coverage beyond LHC, SHiP, and Belle II

Take-home message:
FCC-ee offers **unprecedented reach** in both **prompt** and **displaced** dark photon decays — thanks to the **IDEA tracker and vertexing precision**



Summary

Theoretical Motivation: Dark sectors (multiple new states) offer solutions to major puzzles (DM, neutrino masses, baryogenesis). Portal frameworks (Higgs, ALP, HNL, dark photon) give clear targets

FCC-ee Strength: A "Tera-Z" and "Higgs factory" with superb precision, making it *the ideal hunting ground for feebly-coupled physics*. Rare decays and long-lived signals can be detected well below current limits

Discovery Potential: Orders-of-magnitude improvements in sensitivity:

- Scalar/Higgs portal: invisible BR down to 0.05%, exotic Higgs decays 10^{-5} level.
- ALP/axion portal: $Z \rightarrow \gamma a$ probing ALP-photon couplings ~10x beyond LHC reach
- Neutrino portal: HNL mixings U^2 down to 10^{-11} covering seesaw–leptogenesis parameter space.
- Vector portal: dark photon ε down to 10^{-5} in 1–10 GeV mass, plus unique sensitivity to long-lived light mediators

Even in absence of discovery, FCC-ee will set definitive constraints guiding future theory and the next collider (FCC-hh) to where new physics could lie