

Beyond Standard Model Searches at FCC-ee

Student: Matej Haviernik

Supervisor: Mgr. Jana Faltova, PhD.

Institute of Nuclear and Particle Physics

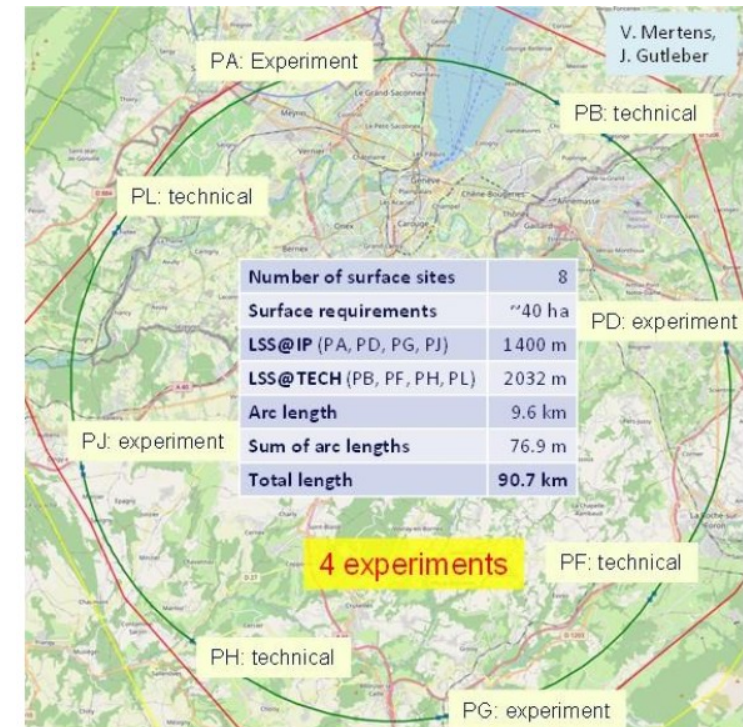
Charles University

Prague

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FCC-ee overview

- **FCC-ee** – high luminosity $e^+ e^-$ collider
- 90.7 km long tunnel with 8 surface points & 4 experiments
- Rich 15-years long physics program
 - Precision studies thanks to high luminosity and clean interaction environment
 - W, Z, H, t properties
 - BSM searches
- **Physics program outlook: operate at 4 working points**
 - Collisions at energies in the range from ~91 GeV to 365 GeV
 - Room for some flexibility in WP ordering during FCC-ee operation



WW threshold

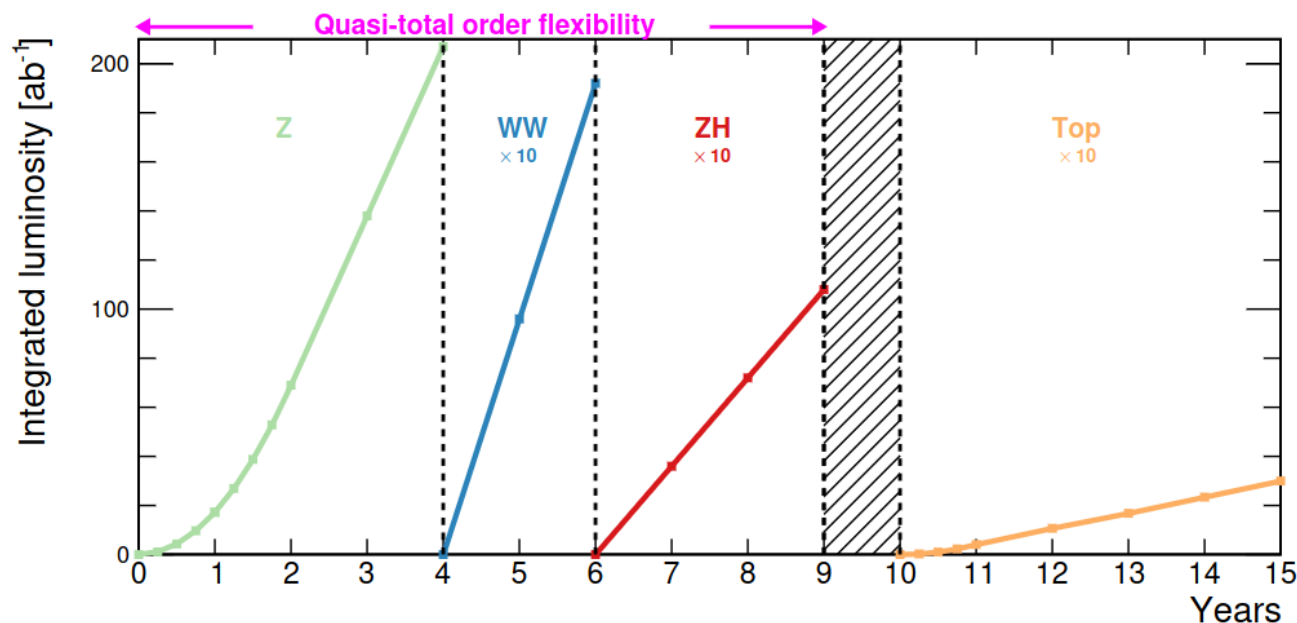
- Sub-MeV precision on m_W
- N_ν measurements
- α_s at $\sqrt{s} \approx 160 \text{ GeV}$

ZH pole

- Model-independent ZH coupling measurement from Higgstrahlung process
- Γ_H determination from $H \rightarrow ZZ^*$ decay

Z pole: Tera-Z

- Precise measurements of Z lineshape and couplings
- Flavour physics (c , b , τ)
- QCD - $\alpha_{QED/S}(m_Z)$
- exotic decays of Z



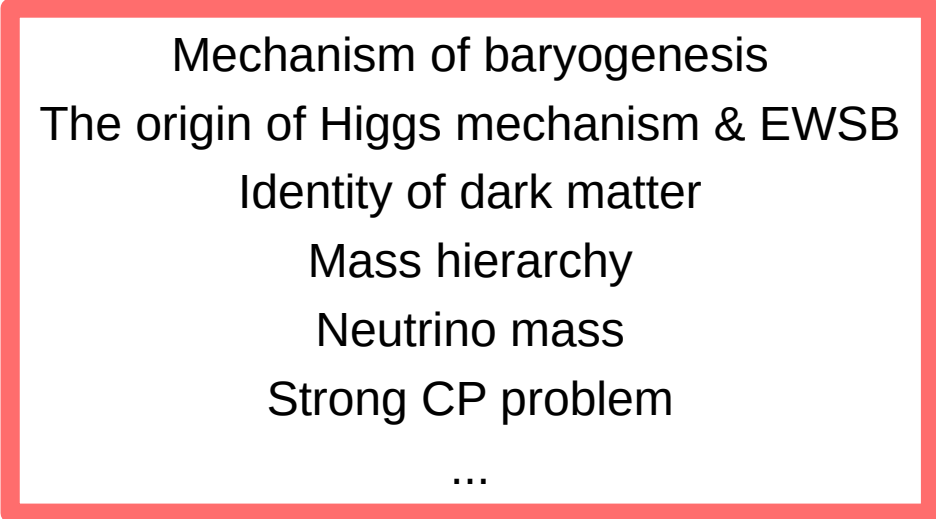
$t\bar{t}$ threshold

- Scan at $\sim 365 \text{ GeV}$
- Precise m_t measurement at $O(10 \text{ MeV})$ (necessary for EWPO)
- Study of Higgs self-coupling from measuring $\sigma(e^+e^- \rightarrow ZH)$ dependence on $\sqrt{s}$

Working point	Z pole	WW thresh.	ZH	$t\bar{t}$	
$\sqrt{s}$ (GeV)	88, 91, 94	157, 163	240	340–350	365
Lumi/IP ($10^{34} \text{ cm}^{-2}\text{s}^{-1}$)	140	20	7.5	1.8	1.4
Lumi/year (ab^{-1})	68	9.6	3.6	0.83	0.67
Run time (year)	4	2	3	1	4
Integrated lumi. (ab^{-1})	205	19.2	10.8	0.42	2.70
Number of events	6×10^{12} Z	2.4×10^8 WW	2.2×10^6 ZH	2×10^6 $t\bar{t}$	
			+ 65k WW $\rightarrow$ H	+ 370k ZH + 92k WW $\rightarrow$ H	

BSM at FCC-ee

- **Standard model still doesn't offer answers to all questions**



Mechanism of baryogenesis
The origin of Higgs mechanism & EWSB
Identity of dark matter
Mass hierarchy
Neutrino mass
Strong CP problem
...

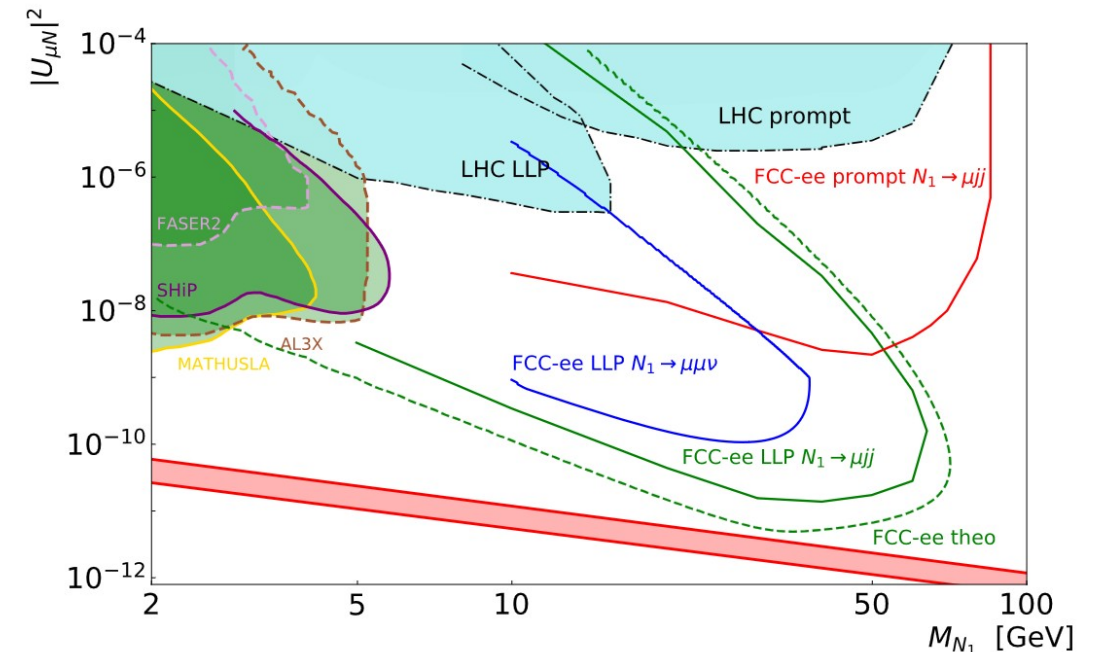
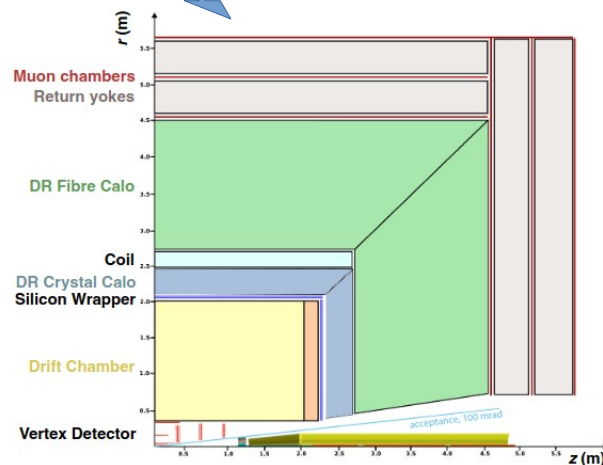


Obtain hints of new physics thanks to
large statistic & improved precision

- FCC BSM group has many fields of interest – not all of them fully occupied
- **Goal of this talk:** give a flyover view of some of the analyses the BSM group at FCC-ee is doing
 - 4 topics presented today: HNLs, Dark photons, Exotic H and Z decays and ALPs
 - Plus motivation for ALP studies at ALLEGRO

Heavy Neutral Leptons

- Appearing in SM extensions aiming to accommodate massive neutrinos
- **Tera-Z run** - large sample of Z bosons allows FCC-ee to search for **resonant HNL production**
 - Production channel of interest: $Z \rightarrow \nu_L + \text{HNL}$
- **Sensitivity studies:**
 - Prompt decays and long-lived HNL
 - Fully leptonic and semileptonic modes
- Toy model utilized for studies with signal simulated using Pythia & Delphes in the IDEA detector



Heavy Neutral Leptons

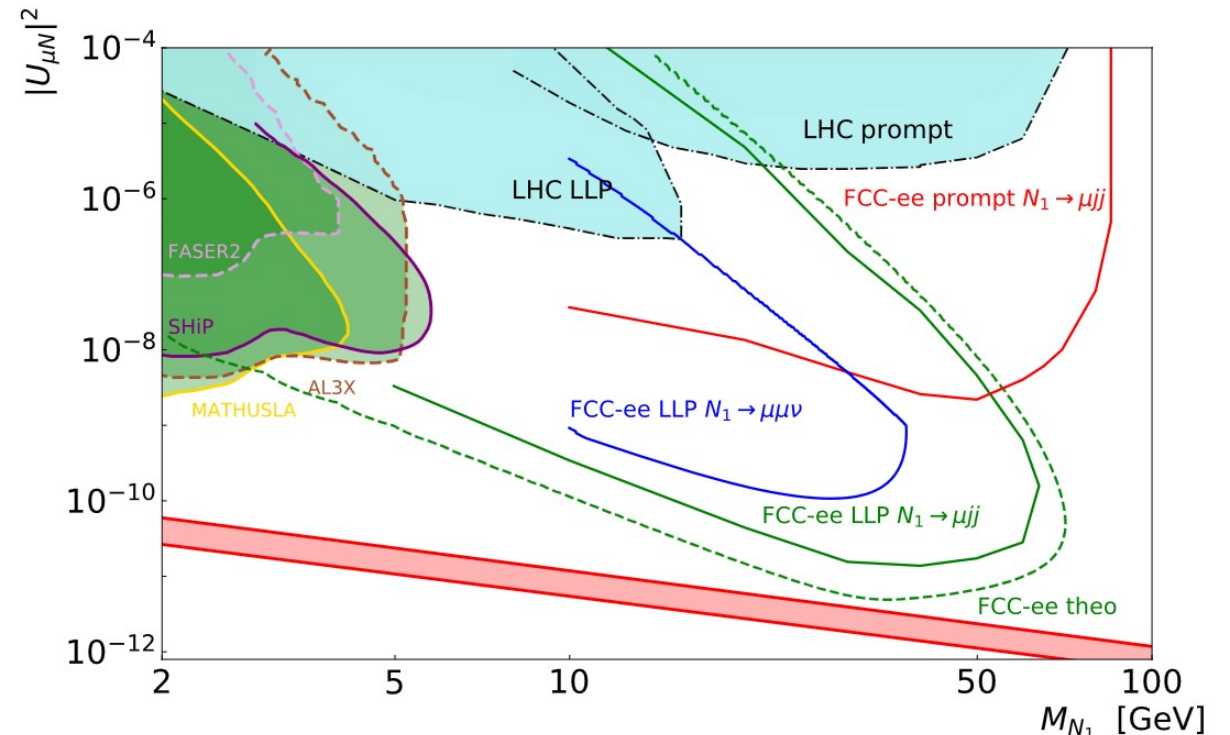
Semileptonic decay simulations

- High BR ($\sim 50\%$)
- Final state: $e/\mu + \nu + 2j$
- Dominant backgrounds of $Z \rightarrow b\bar{b}/c\bar{c}$

- Current reach in parameter state estimated from **simple models** with **one Majorana HNL** mixing with **one flavor of neutrino**
- Studies ongoing with a more realistic model (**two Majorana HNLs** mixing with all **three neutrino flavors**)

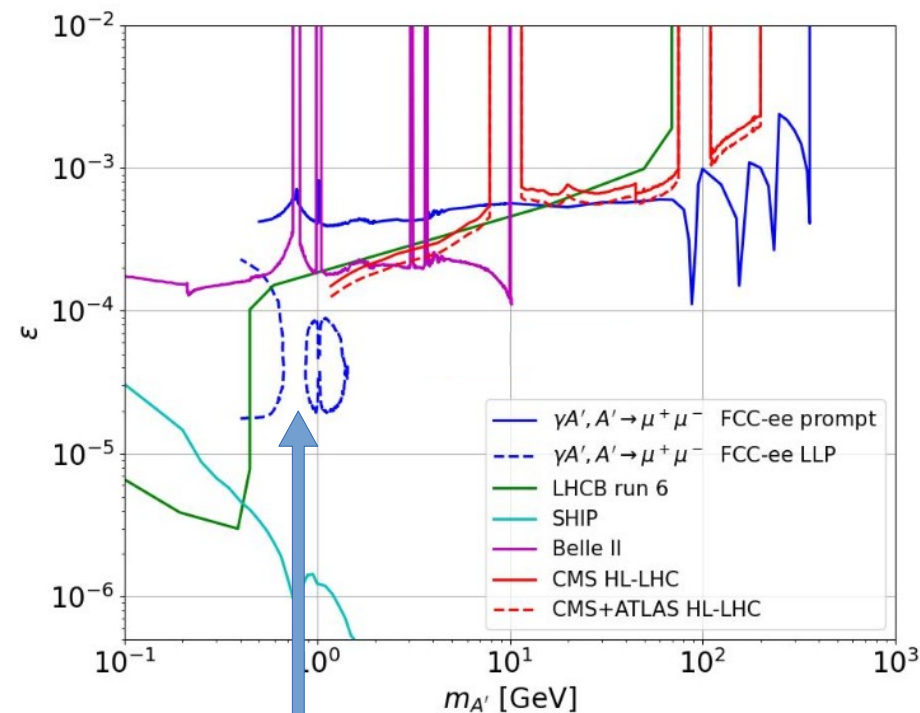
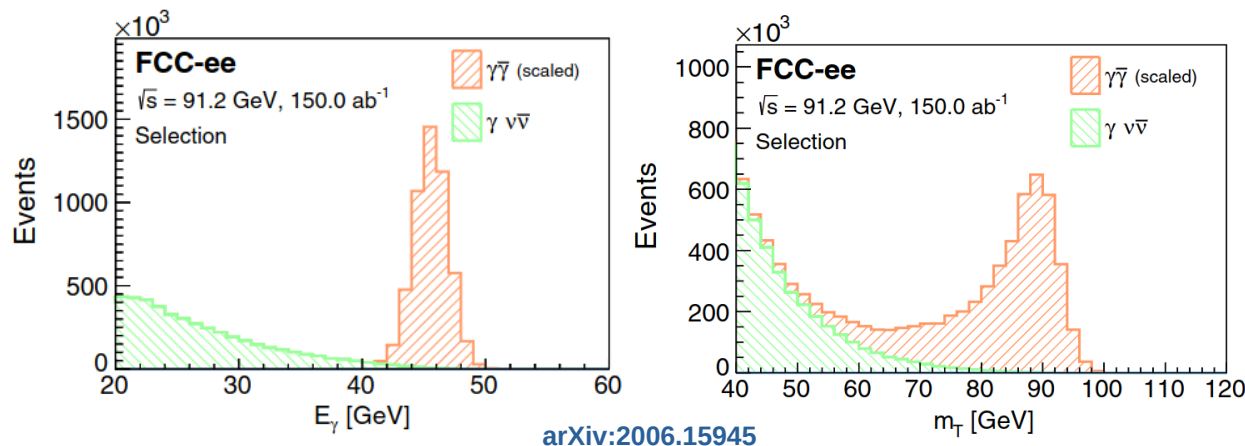
Fully leptonic decay simulations

- Clean signal, good for LLP studies
- Final state: $\mu^+ \mu^- \nu_\mu$
- Dominant background $Z \rightarrow \mu^+ \mu^- / \tau^+ \tau^-$



Dark photons

- Ambitions of FCC-ee: search for DM candidates in the **mass range of 1-100 GeV**
- Particular example – **dark photon** searches
 - Channel $e^+e^- \rightarrow A'\gamma$ with $A' \rightarrow \mu^+\mu^-$ decays
 - Sensitivity studies done for both prompt and long-lived scenarios



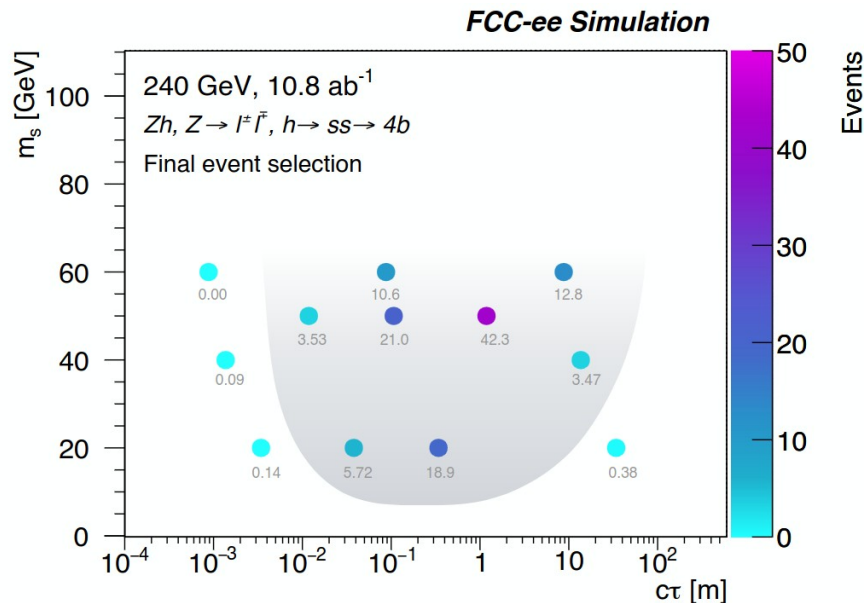
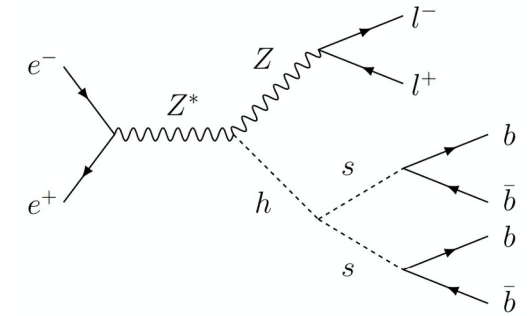
Discontinuities due to hadronic decays

[arXiv:2511.23337](https://arxiv.org/abs/2511.23337)

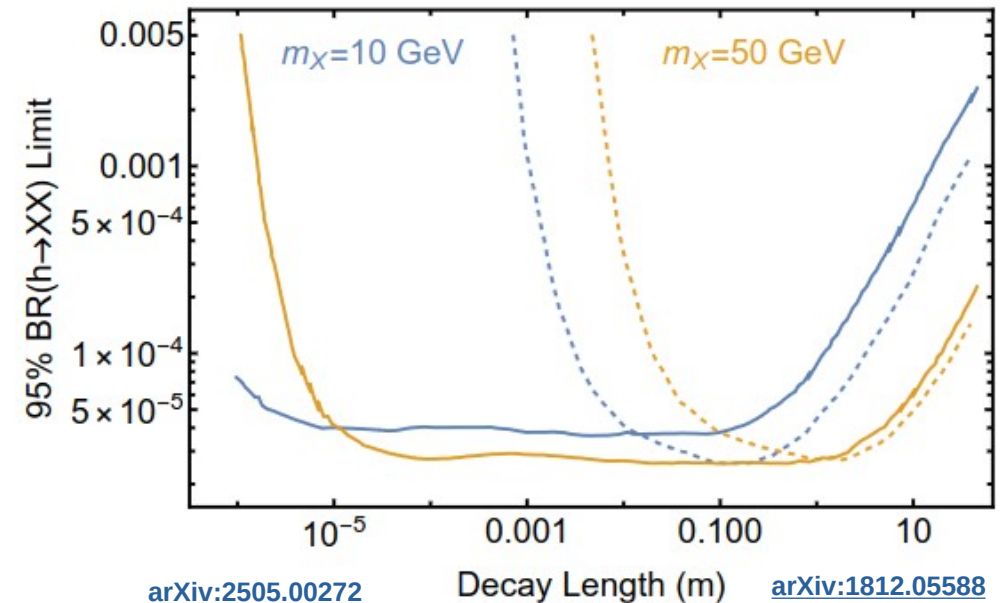
- For decays of Z into massless dark photon, Tera- Z expects to achieve sensitivity down to $\text{BR} = 6 \times 10^{-11}$ (current upper limit from LHC at $\sim 10^{-6}$)
- **Alternative processes being considered:** $e^+e^- \rightarrow A'H$ beyond the WW threshold or via exotic Higgs decay $H \rightarrow A'A'$ at the ZH pole

Exotic Higgs and Z decays

- **Ambition:** Large amounts of Z and H allows for **direct searches** of exotic decays
- **Exotic Higgs decays**
 - At the **ZH pole**, more than 2 million Higgs produced over ~3 years
 - Simulations with decays to long-lived scalars further decaying to primarily $b\bar{b}$ - good sensitivity for decay lengths between 1mm to 10m
 - Up to four orders of magnitude of improvement in BR over HL-LHC



[arXiv:2412.10141](https://arxiv.org/abs/2412.10141)



[arXiv:2505.00272](https://arxiv.org/abs/2505.00272)

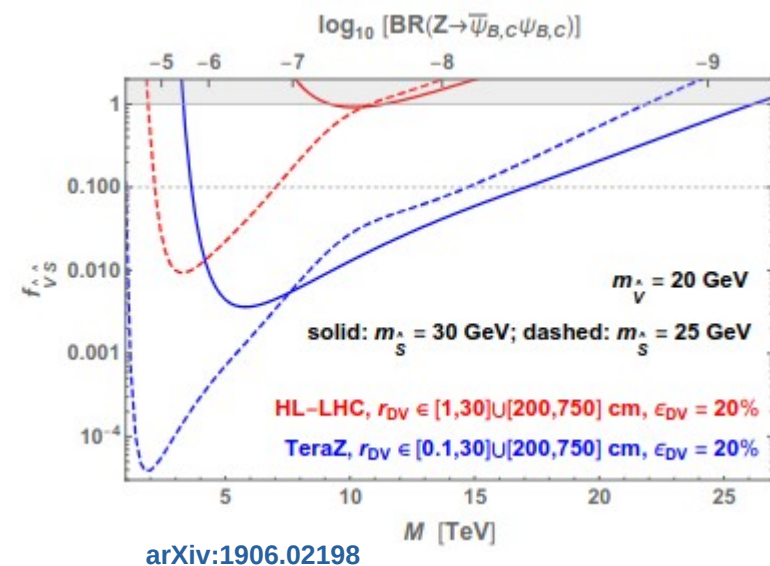
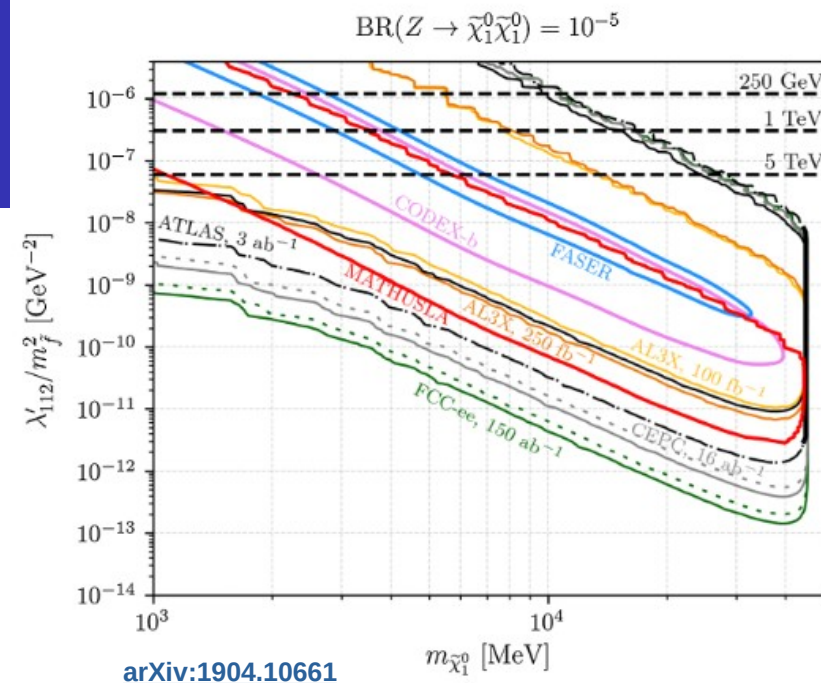
Decay Length (m)

[arXiv:1812.05588](https://arxiv.org/abs/1812.05588)

Exotic Higgs and Z decays

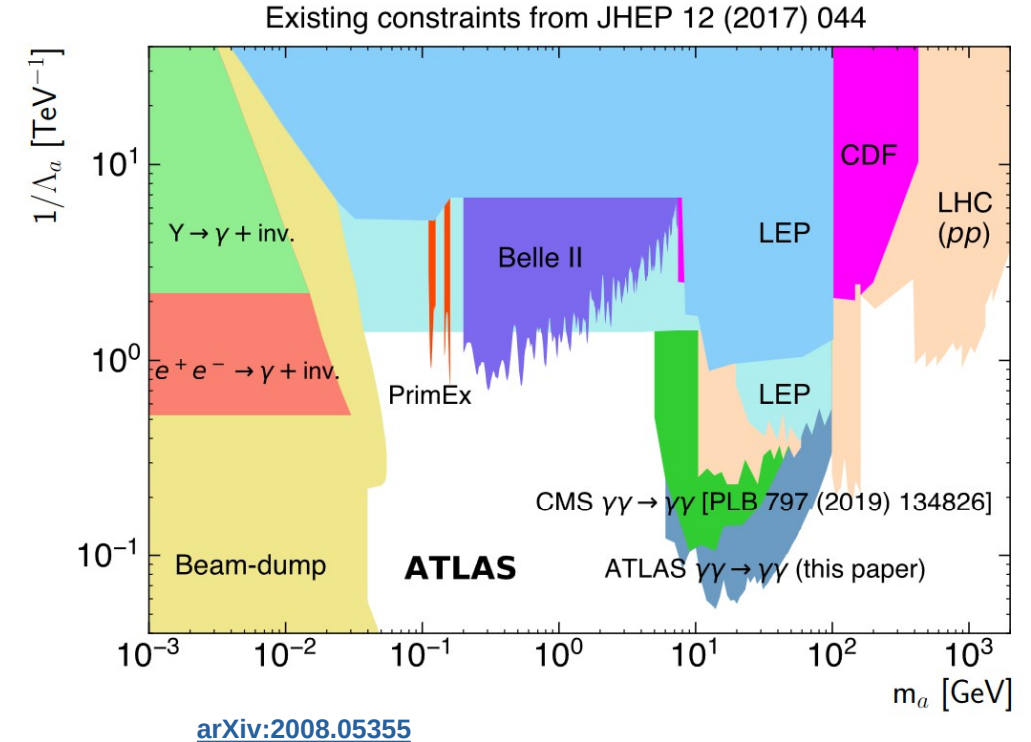
- **Exotic Z decays**

- Studies carried out with searches for decays to LLPs – **light neutralinos** and **hidden mesons**
- Light **neutralino** decays – occurring in some SUSY models
 - FCC-ee offers highest sensitivity to $Z \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0$ decays with 150 ab^{-1} of L_{int} for masses at $O(1\text{-}10 \text{ GeV})$
- Hidden **meson** searches
 - Study exploring Z decays to two hidden mesons
 - Tera-Z expects to probe up to $M \sim 10 \text{ TeV}$ in hidden meson mass and improve sensitivity by ~ 3 magnitudes over HL-LHC



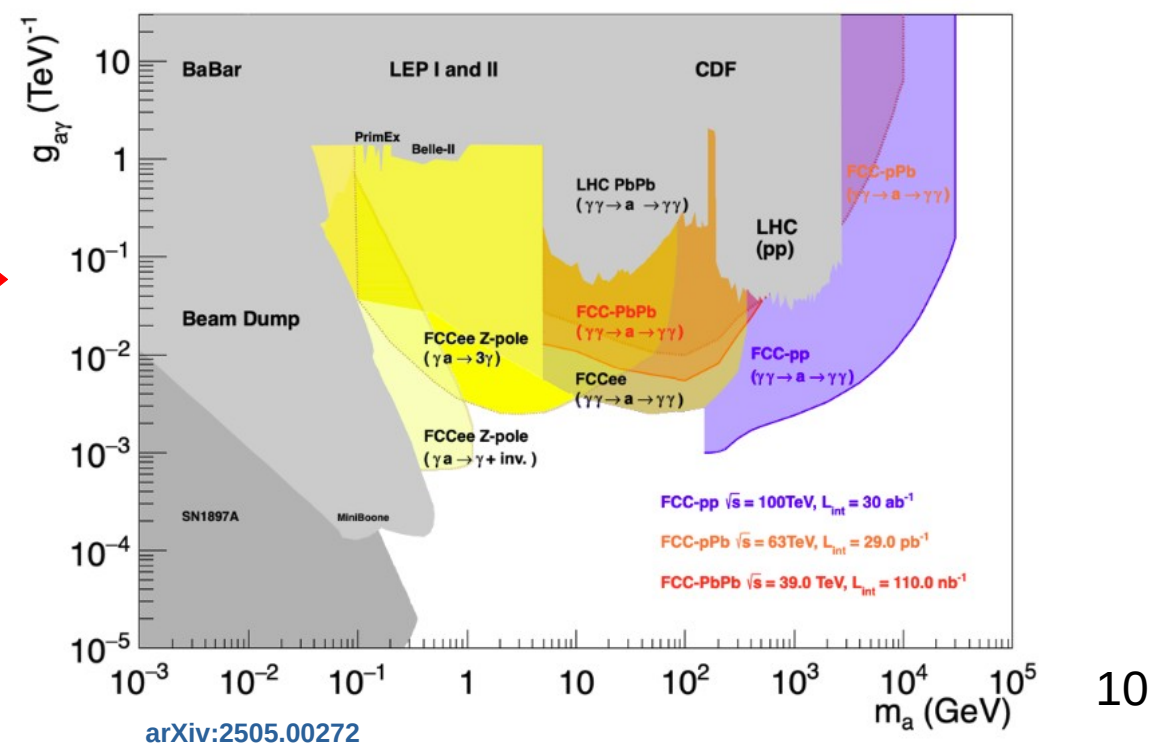
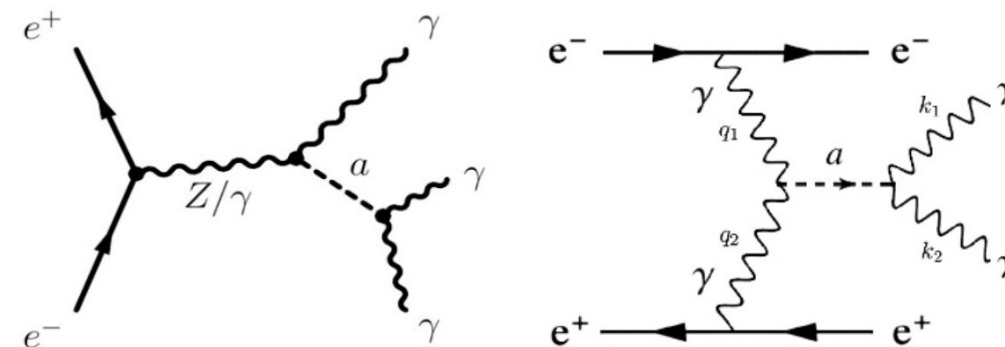
Axion-like particles

- **Axion-like particles (ALPs)** – often appear in BSM extensions
 - Originally proposed as a solution to strong CP problem
 - Nowadays extended to heavier ALP candidates - **mediators to dark sector**
- **Current state of things:**
 - Beam dump and astrophysical studies put constraints on ALP couplings at low masses
 - Data from LEP and LHC give upper limits for m_{ALP} at $O(1\text{ TeV})$
- **Outlook for FCC-ee:**
 - FCC-ee aims to search for ALPs primarily during the **Tera-Z** run in Z decays
 - Beyond FCC-ee - further extension in parameter space with pp and $PbPb$ collisions



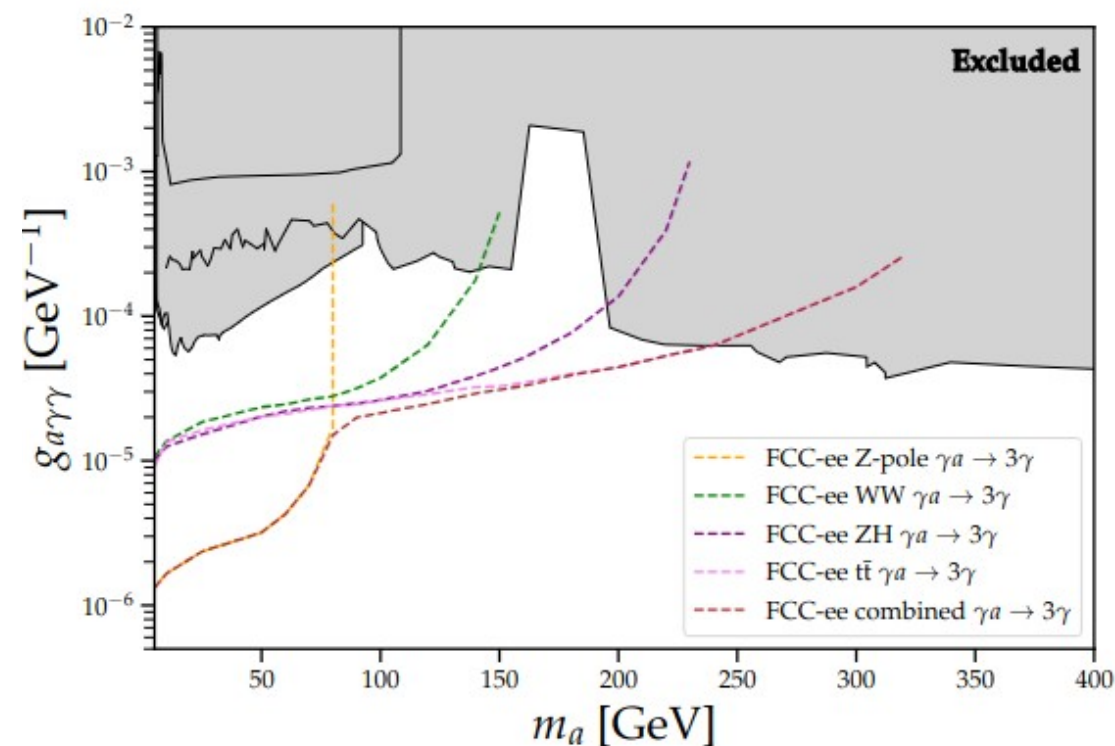
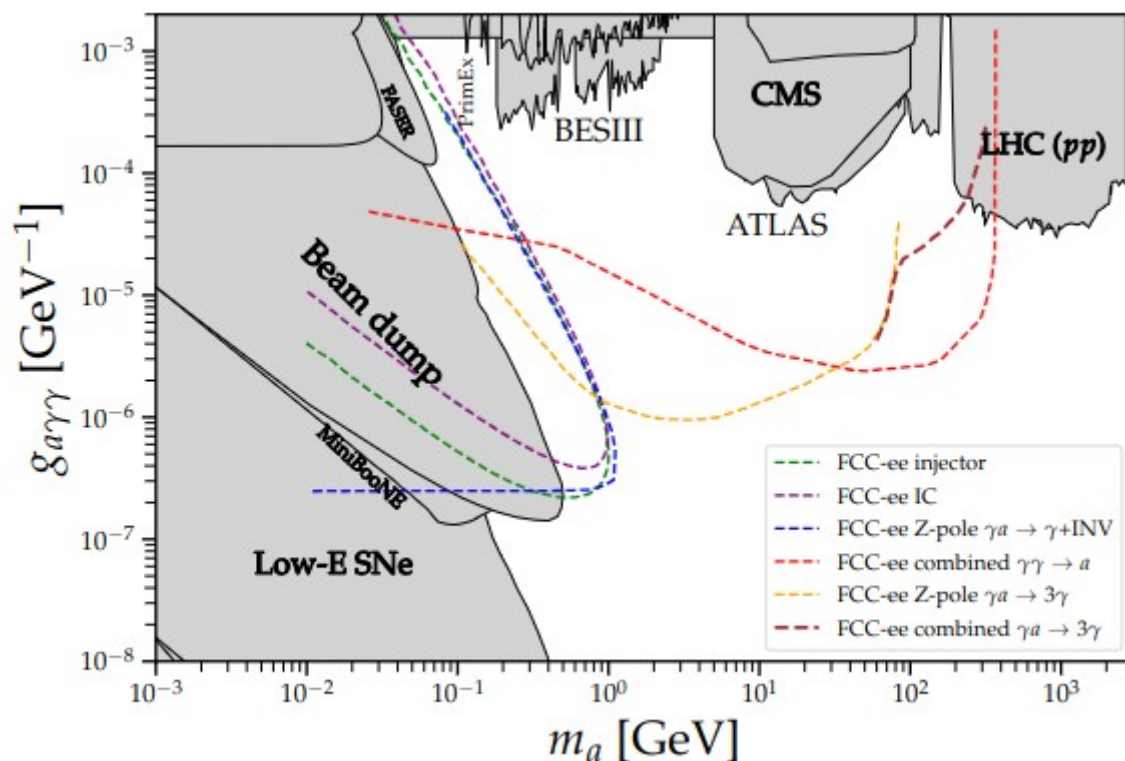
Axion-like particles

- **Primary process of interest:** $e^+e^- \rightarrow \gamma a$ with further $a \rightarrow \gamma\gamma$ decay
- Several scenarios considered
 - **Prompt decay** with a 3γ signature
 - **Delayed decay** – 3γ signature with a pair of non-pointing photons
 - **Decay outside the detector** – recoiling γ with $E_{T,miss}$
- ALP production via $\gamma\gamma \rightarrow \gamma\gamma$ also considered
- Sensitivity studies for ALPs - available with parametrized simulations of the IDEA detector
 - Plans to access the $m_{ALP} \sim 0.1$ -100 GeV range during the **Tera-Z** run
 - Predicted overall increase in sensitivity by two orders
 - Very recent results: [arXiv:2605.21452](https://arxiv.org/abs/2605.21452)



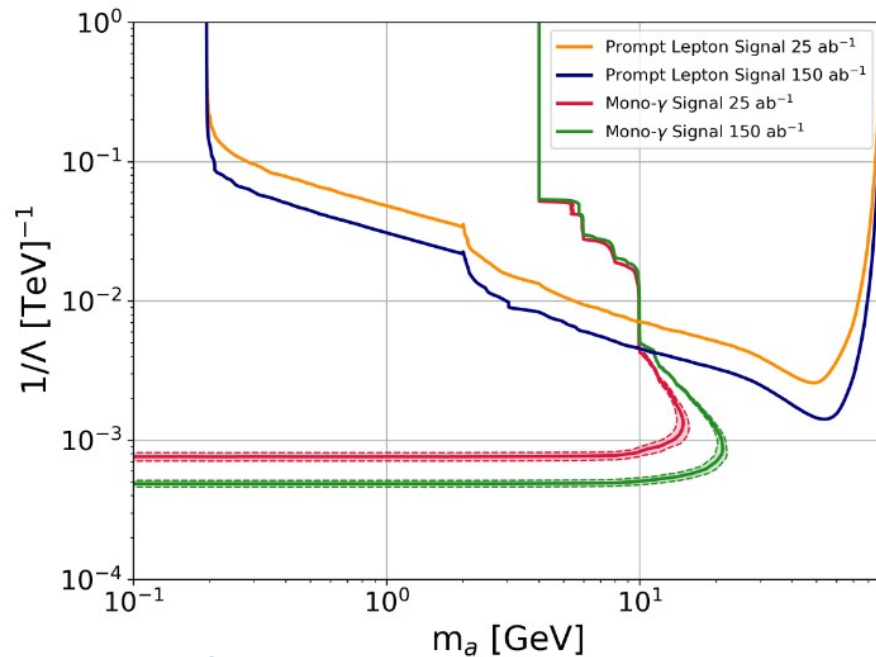
Axion-like particles – recent results

- Very recent results: [arXiv:2605.21452](https://arxiv.org/abs/2605.21452)
 - 3γ signatures at all 4 energies (prompt decays only) with IDEA detector
 - Improved sensitivity in the 100-200 GeV mass range

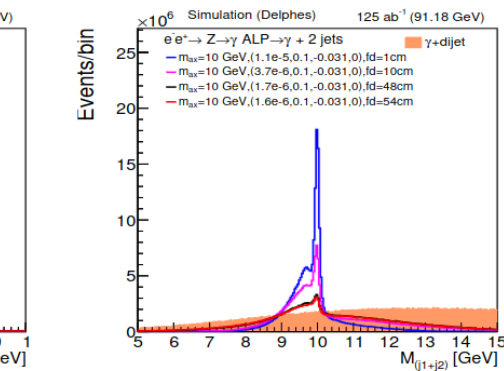
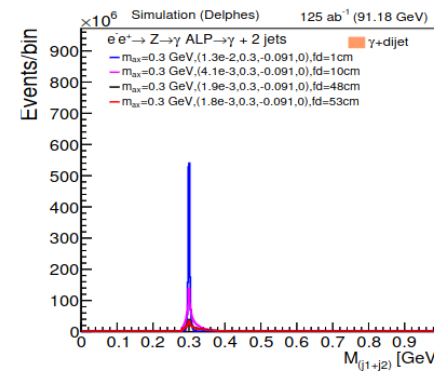


Axion-like particles – other processes

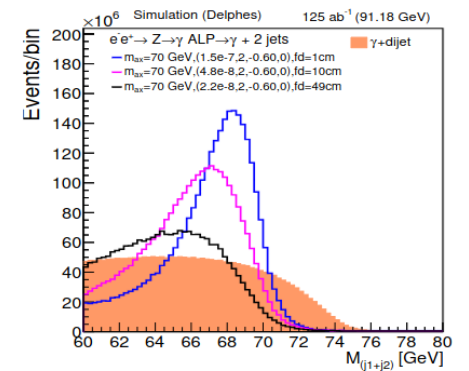
- Other ALP processes under consideration – coupling to Z and H , decays to **lepton pairs/jets**
 - Less constrained than decays to photons – room for exploration



[arXiv:2509.1771](https://arxiv.org/abs/2509.1771)



[doi:10.17181/2zh7p-v9a72](https://doi.org/10.17181/2zh7p-v9a72)

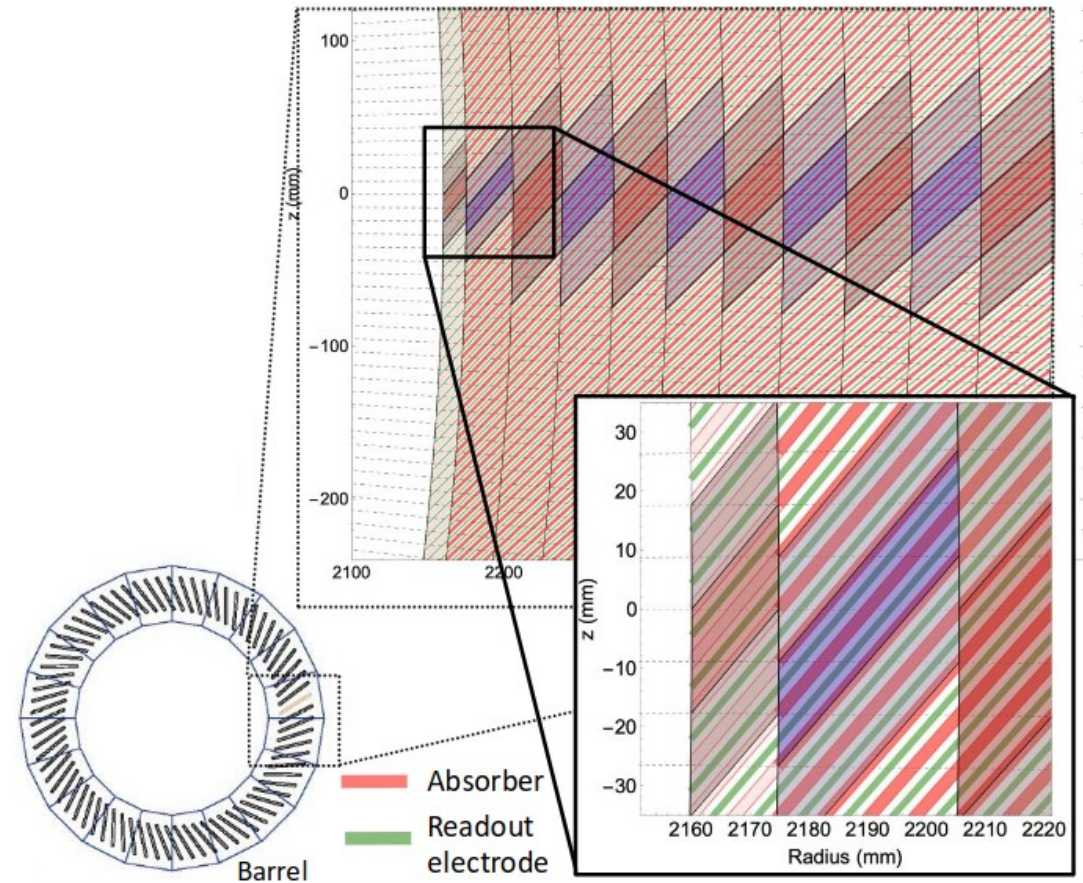


- Early sensitivity study with $a \rightarrow \mu^+ \mu^- / \tau^+ \tau^-$ decays in $\gamma\gamma$ production

- Simulated di-jet invariant mass distribution in $a \rightarrow gg$ decays for different ALP masses

Axion-like particles at ALLEGRO

- **Current status at ALLEGRO:** full simulations necessary to provide a satisfying sensitivity study
 - Fast-sim – parametrized detector response and simplified particle transport
 - Full-sim – fully simulated particle interactions with the detector environment
- Decay inside the ALLEGRO detector
 - 3γ signal with primary background of $e^+e^- \rightarrow 3\gamma$
 - Some experience with $\pi^0 - \gamma$ discrimination in ALLEGRO ECal, we'd like to apply the same expertise here
- **Challenge ahead of us:** Reconstruction of displaced vertex from non-pointing photons in ALLEGRO – currently not incorporated
 - IDEA sensitivity study assumes prompt decays in the detector center
 - Incorrect vertex calculation → underestimated diphoton angle and invariant mass



Conclusion

- There is a vibrant BSM community at FCC-ee with plenty of available topics for anyone interested
- **Room for improvement:** taken from [presentation by Rebeca Gonzalez Suarez](#) 
- Workshop focusing on FCC-ee BSM studies planned for Sep 23-25 at CERN
- Comprehensive write-up of the FCC-ee BSM discovery potential available in:
 - [FCC Feasibility Study - vol 1](#)
 - [European Strategy for Particle Physics Update 2025-2026 - contribution](#)

For the next two years:

– Closer theory-experiment alignment in our main topics: ALPs, HNLs (dark photons, exotic Higgs to a lesser extent)

– **Full-sim studies**

– Comprehensive set of final states (incl. taus)

– Signature-based analyses (displaced vertex, timing, non-pointing photons) to provide **detector requirements**

– New channels

Thank you for your attention!