

Mahmoud Al-Thakeel on behalf of the BSM group
Special Thanks to Nicolo Valle, Patrizia Azzi, and G. Polesello.

BSM at FCC-ee ITALIAN EFFORTS

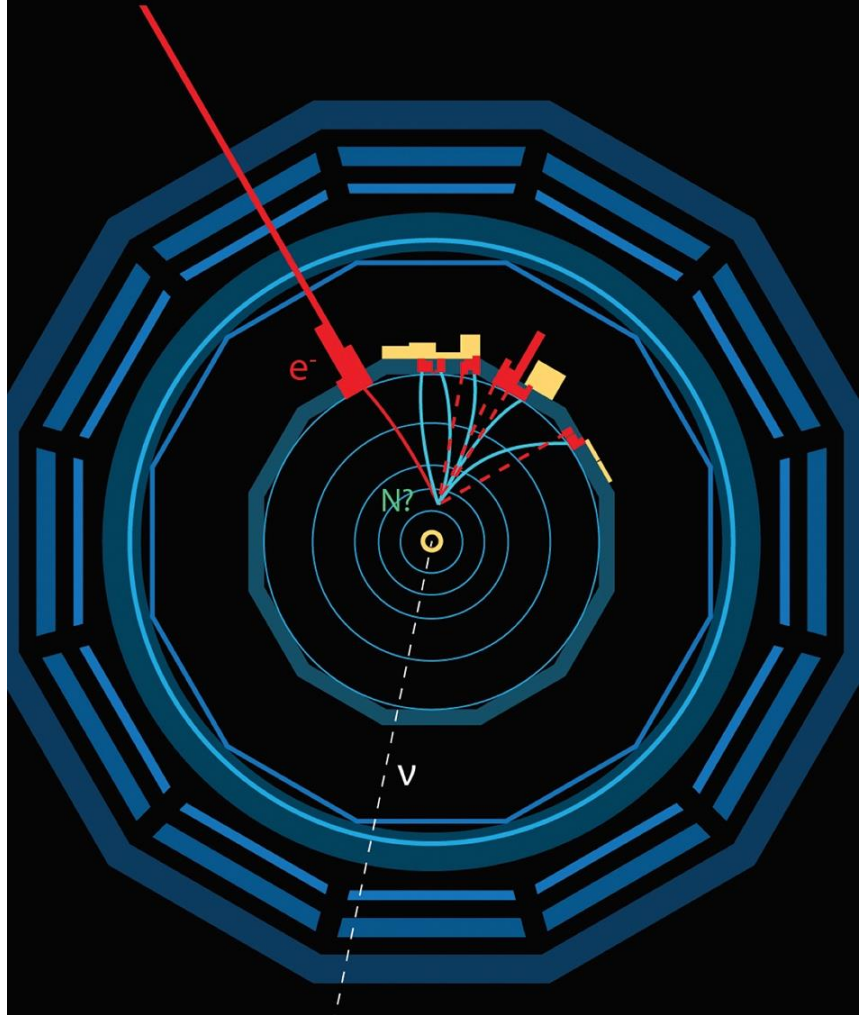
R&D-FCC Collaboration Meeting, Dec 17, 2025.



ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA



Istituto Nazionale di Fisica Nucleare

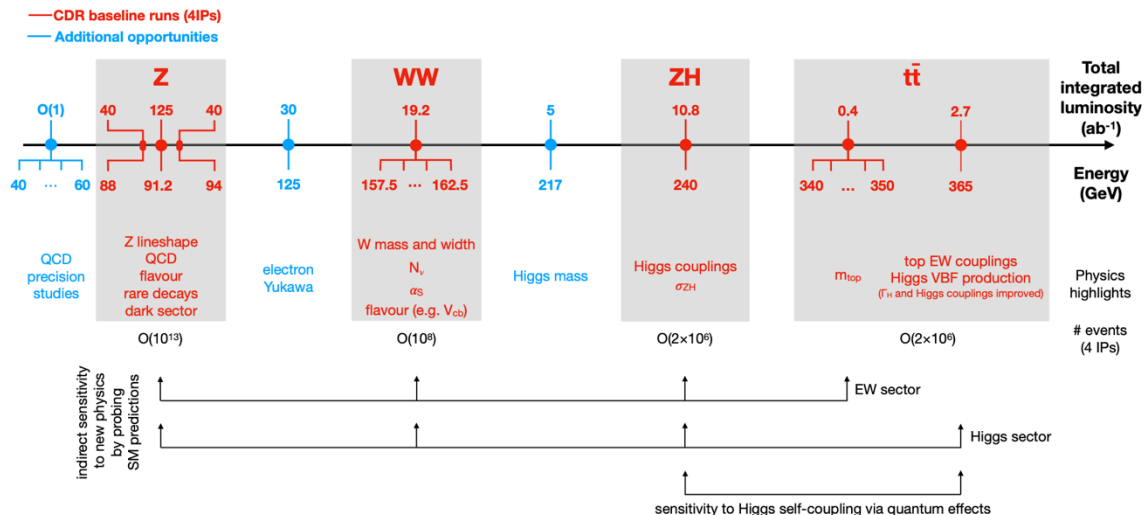


Discovery potential: An artistic rendering of the production and decay of a long-lived heavy neutral lepton at FCC-ee. Credit: norest.design/FCC

FCC-ee: Precision Tool

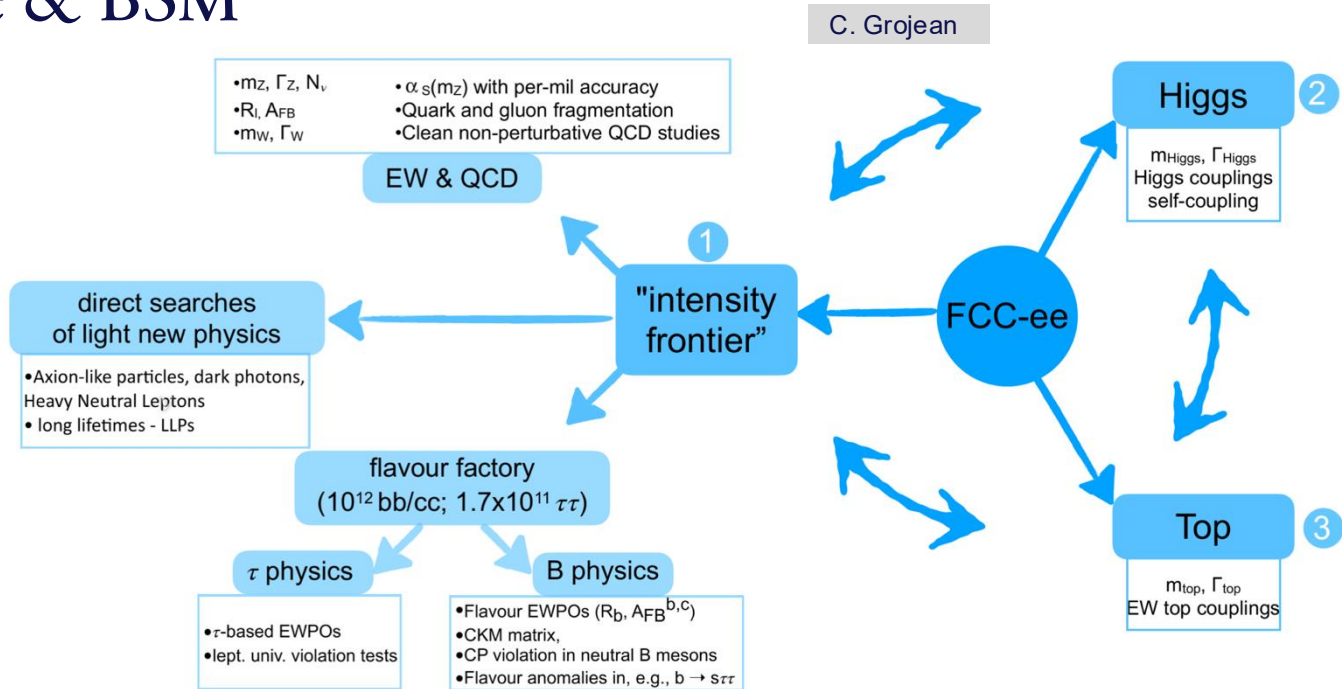
FCC-ee Potential

- Z, W, Higgs, top factories
- Huge dataset $\sim 10^5 \times$ LEP dataset
- Orders-of-magnitude precision improvement
- Clean environment & well-defined initial state



FCC-ee provides a high-precision, high-statistics platform to probe tiny deviations and rare processes, connecting precision electroweak & Higgs measurements with direct and indirect BSM searches.

FCC-ee & BSM



Feebly Interacting BSM Particles

Dark Photons (A')

Vector portal mediator
 $e^+e^- \rightarrow \gamma A' \rightarrow \gamma \mu^+ \mu^-$

Axion-Like Particles

Pseudoscalar bosons
 $Z \rightarrow \gamma a \rightarrow 3\gamma$

Heavy Neutral Leptons

Neutrino portal states
 $Z \rightarrow \nu N \rightarrow \nu \mu j j$



Axion-Like Particles (ALPs)

Axion-Like Particle Searches at FCC-ee:

G. Polesello

Model

ALP couples to U(1) gauge fields
BR($a \rightarrow \gamma\gamma$) = 100%

Production

$e^+e^- \rightarrow Z \rightarrow \gamma a$

Mass Range

0.1 – 90 GeV

Three-Photon Analysis ($\gamma\gamma\gamma$)

ALP decays inside detector $\rightarrow 3\gamma$ final state

Background: QED $e^+e^- \rightarrow \gamma\gamma\gamma$

Challenge: Separating collimated photons at low m_a

Mass Coverage

1 – 90 GeV

Monophoton Analysis (γ + invisible)

ALP decays outside detector ($L_a > 450$ cm)

Background: $e^+e^- \rightarrow \gamma Z, Z \rightarrow \nu\nu$

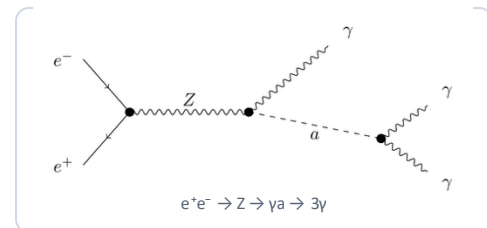
Crystal calorimeter resolution critical

Mass Coverage

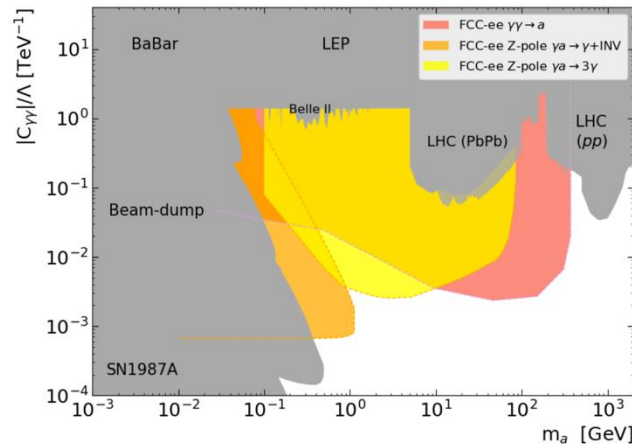
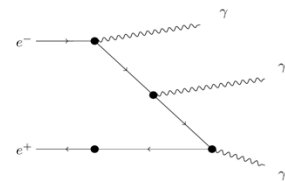
0.1 – 1 GeV

Key Results

- ✓ Coupling sensitivity: $C_{\gamma\gamma}/\Lambda \sim \text{few} \times 10^{-3} \text{ TeV}^{-1}$
- ✓ Monophoton extends beyond beam dump reach



ALP Background: $e^+e^- \rightarrow \gamma\gamma\gamma$



ALP Decay to Muon Pairs: $a \rightarrow \mu^+\mu^-$

G. Polesello, S. Naseem, R. Soualah, F. Arneodo

Production and Decay

$e^+e^- \rightarrow Z \rightarrow \gamma a$ followed by $a \rightarrow \mu^+\mu^-$

Final state: $\gamma + \mu^+\mu^-$ (prompt or displaced)

Analysis Strategy

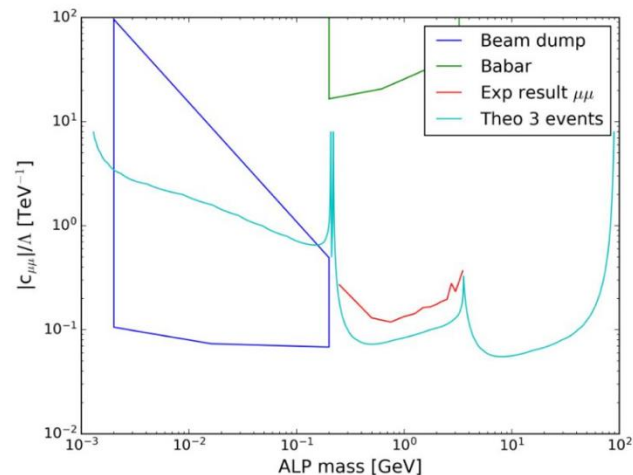
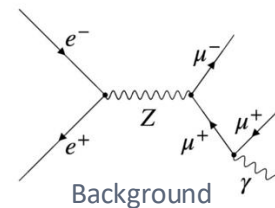
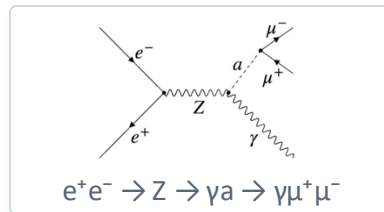
XGB classifier on kinematic variables

Discriminants: $E_\gamma > 42$ GeV, p_T^μ , $\Delta\alpha_{\mu\mu}$, missing momentum

Background: $Z \rightarrow \mu\mu$.

Status

Finalizing the $a \rightarrow \mu^+\mu^-$ analysis is ongoing.



See also [Nicolo talk](#)



Dark Photons

Dark Photon Searches at FCC-ee

G. Polesello

The Dark Photon Model

Vector mediator in dark sector models (hypercharge portal)

Kinetic mixing between $U(1)_D$ and $U(1)_Y$ with strength ϵ^2

Couples to SM via photon-like interactions

Production Process

$$e^+e^- \rightarrow \gamma A' \text{ followed by } A' \rightarrow \mu^+\mu^-$$

Associated production with ISR photon | Muon channel provides best sensitivity

Mass Range

0.4 – 360 GeV

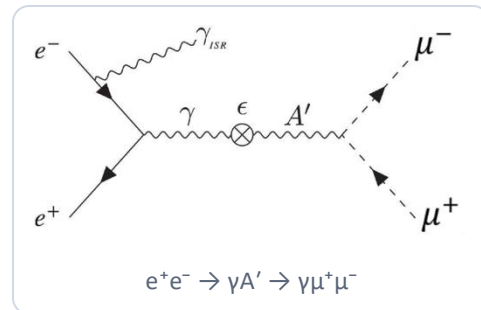
FCC-ee Runs

Z, WW, ZH, $t\bar{t}$

Analysis Strategies

Prompt: Full kinematic reconstruction, XGBoost classifier

Long-lived: Displaced vertex (r_{vx}), virtually zero background



Dark Photon: Prompt Analysis

G. Polesello

Prompt Decay Search Strategy

No requirement on decay vertex displacement (d_{vx})

Background: SM $e^+e^- \rightarrow \gamma\mu^+\mu^-$ (suppressed using full event kinematics)

XGBoost classifier trained on 5 kinematic variables achieves $\sim 35\%$ signal efficiency with $5\times$ background rejection

Discriminant Variable M_{cut}

$$M^2_{cut} = (m_{\mu\mu} - m_{A'})^2/\sigma^2 + (E_\gamma - E)^2/\sigma^2$$

Measures compatibility with signal kinematics for given test mass

Kinematic Variables

$\cos\theta_{A'}$, $E_{\mu 2}/E_{\mu 1}$, $\cos\Delta\alpha_{\mu\mu}$, $\phi_{\mu 1}$

Angular distributions sensitive to A' spin

95% CL Sensitivity by FCC-ee Run

Z-pole (91 GeV)
Best at 10-85 GeV

WW (160 GeV)
Extends to ~ 140 GeV

ZH (240 GeV)
Extends to ~ 220 GeV

$t\bar{t}$ (365 GeV)
Extends to ~ 360 GeV

Key Results

95% CL sensitivity on mixing: $\epsilon = (0.5 - 0.85) \times 10^{-3}$ across 0.5-360 GeV mass range

Combined FCC-ee reach surpasses HL-LHC extrapolations in 20-365 GeV interval

Dark Photon: Long-Lived Analysis

G. Polesello

Long-Lived Particle (LLP) Search Strategy

Requires observable flight path: transverse vertex distance r_{vx} selection
 A' decay displaced by 0.5 mm – 4 m from interaction point
 Virtually eliminates prompt SM background \rightarrow nearly zero-background search

Key Selection Variable

Transverse vertex distance r_{vx}
 Reconstructed from two collimated muon tracks

Background Suppression

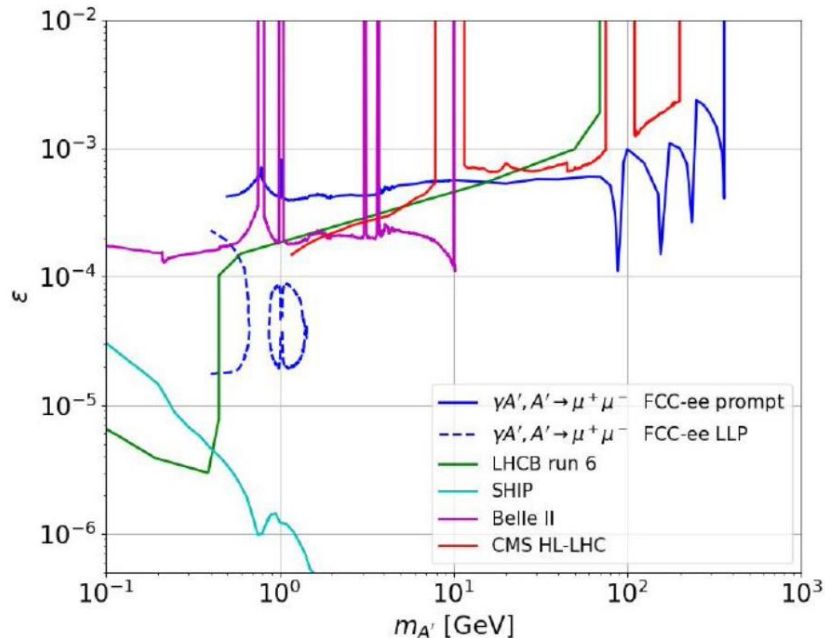
Cuts on $E_{\mu 2}$, $|\eta|$, vertex direction
 Exponential background suppression with r_{vx}

Parameter Space Coverage

Mass range: 0.4 – 1.4 GeV
 Mixing reach: $\epsilon \sim 2 \times 10^{-5}$ for $m_{A'} \sim 1$ GeV

Critical detector requirement:

High-precision vertexing for two collimated tracks



Heavy Neutral Leptons (HNLs)

Heavy Neutral Lepton Searches at FCC-ee

G. Polesello, N. Valle, L. Bellagamba, A. Pareti

The HNL Model (Neutrino Portal)

Heavy neutral leptons mix with SM neutrinos via mixing parameter $U_{\alpha N}$
 Benchmark: single HNL (N_1) mixing only with muon neutrino ($U_{\mu N}$)
 Model parameters: M_{N1} (mass) and $U^2_{\mu N}$ (mixing strength)

Production and Decay

$$e^+e^- \rightarrow Z \rightarrow \nu N_1$$

HNL produced via mixing with ν_{μ} | Decays via virtual W or Z

Decay Channels Studied

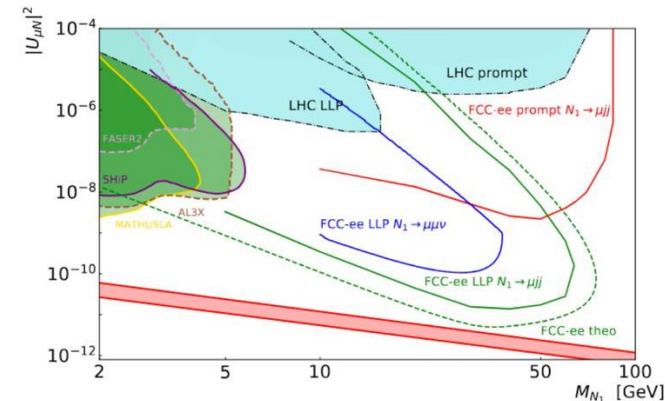
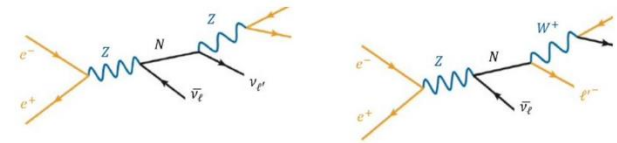
Semi-leptonic: $N \rightarrow \mu j j'$

BR \sim 50% | Full kinematic reconstruction
 Prompt + LLP analyses

Fully leptonic: $N \rightarrow \mu^+ \mu^- \nu$

BR \sim 5% | Very clean signature
 LLP analysis only

Mass range: 5 – 85 GeV | **Kinematic limit:** $M_{N1} < M_Z$



HNL: Prompt and Long-Lived Analyses

G. Polesello, N. Valle, L. Bellagamba, A. Pareti

Prompt Analysis ($\mu j j'$ channel)

Full kinematic reconstruction of M_{N1}
 Backgrounds: $Z \rightarrow \tau\tau$, $Z \rightarrow q\bar{q}$
 Cut-and-count optimized for each mass

Coverage: M_{N1} up to 85 GeV
 Higher $U^2_{\mu N}$ values accessible
 Necessary for high-mass region

Long-Lived Particle Analysis

$\mu j j'$ channel:

High track multiplicity \rightarrow precise vertex
 $D_{xy}^{vx} > 0.5$ mm selection

$\mu^+ \mu^- \nu$ channel:

Very clean, 2 tracks from displaced vertex
 Transverse distance from IP

LLP Background Suppression

$D_{xy}^{vx} > 0.1$ mm: < 1 event expected
 $D_{xy}^{vx} > 0.5$ mm: zero-background

Selection Efficiency

Kinematic cuts: 75-100% efficient
 Dominated by vertex reconstruction in tracker

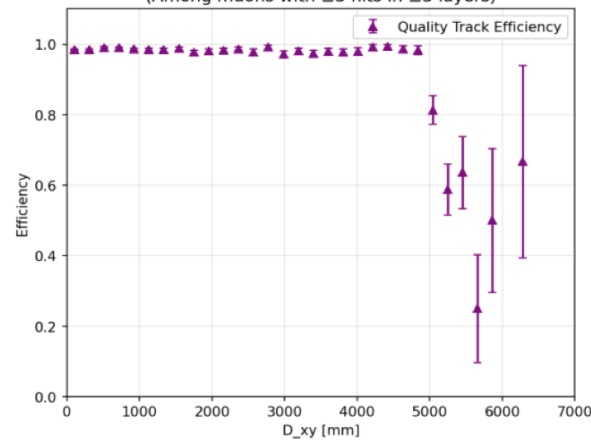
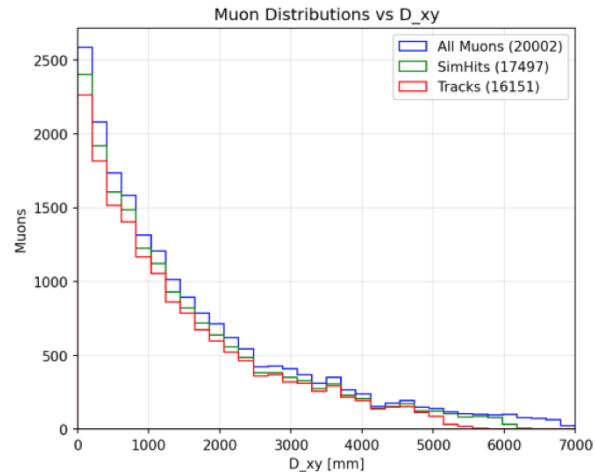
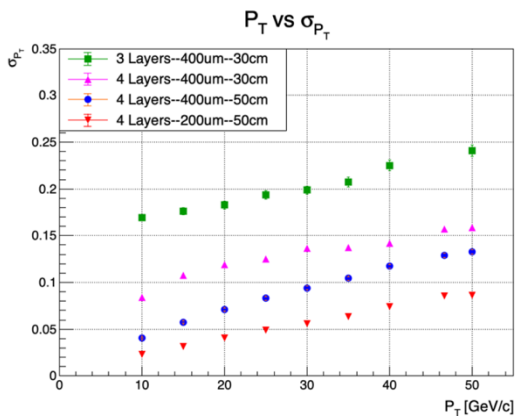
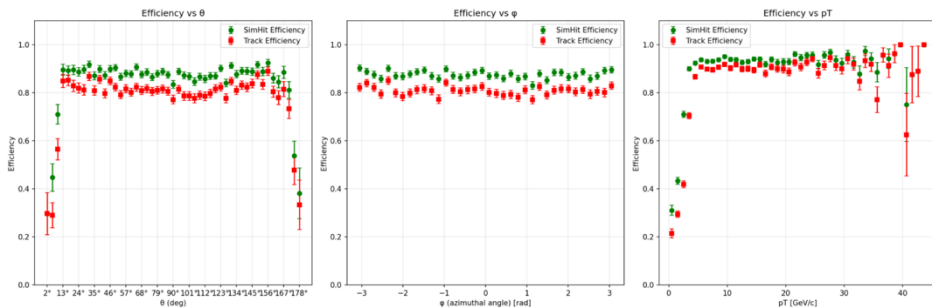
Exceptional LLP Sensitivity

Combined LLP channels reach $U^2_{\mu N} \sim 10^{-11}$ for $M_{N1} = 5-65$ GeV
 Z-pole statistics enable exploration of extremely low couplings unreachable by any other experiment

Standalone Muon-system displaced-tracking

Fully leptonic: $N \rightarrow \mu^+ \mu^- \bar{\nu}$

By studying the same model as before but in full-SIM and using only standalone IDEA Muon-LLP analysis only





Summary

Summary: FCC-ee BSM Discovery Potential

Comprehensive BSM Program at Z-Pole

Dark Photons

$\epsilon \sim 10^{-3}$ (prompt)

$\epsilon \sim 10^{-5}$ (LLP)

Surpasses HL-LHC 20-360 GeV

ALPs

$C_{\gamma\gamma}/\Lambda \sim 10^{-3} \text{ TeV}^{-1}$

3γ : 1-90 GeV | Mono γ : 0.1-1 GeV

Extends beyond beam dumps

HNLs

$U^2 \sim 10^{-11}$ (LLP)

Mass + nature determination

Unique parameter space

LLP Searches Dominate

6×10^{12} Z bosons enable access to extremely low couplings
unreachable elsewhere

Beyond Discovery

Timing-based mass, oscillations, Dirac/Majorana — full
characterization possible

IDEA Detector: Enabling Technology

Large decay volume | High-precision vertexing ($D_{xy} \sim 0.1 \text{ mm}$) | Timing resolution $\sim 30 \text{ ps}$ | Crystal ECAL option | No trigger limitations

Conclusion: FCC-ee acts as an ultra-sensitive probe for feebly interacting particles — detecting faint signals (low couplings) in mass ranges where powerful surface experiments (LHC) are blinded by backgrounds, while providing unique tools for complete characterization of any discovery.



THANK YOU
FOR YOUR ATTENTION.



BACKUP

Dark Photon: Combined Sensitivity

FCC-ee Sensitivity Summary (95% CL)

Prompt Analysis

Mass: 0.5 – 360 GeV
 $\epsilon \sim (0.5-0.85) \times 10^{-3}$

LLP Analysis

Mass: 0.4 – 1.4 GeV
 ϵ down to $\sim 2 \times 10^{-5}$

Comparison with Other Experiments

vs HL-LHC (CMS, LHCb)

FCC-ee surpasses in 20-365 GeV

vs Belle II

Complementary at low mass

vs SHIP

LLP covers unique region

Clean Environment

e^+e^- collisions with known \sqrt{s} allow full kinematic reconstruction and powerful background suppression

Multiple Runs

Statistical combination of Z, WW, ZH, $t\bar{t}$ runs extends mass coverage to 360 GeV

Future Developments

Additional sensitivity expected from $A' \rightarrow e^+e^-$, $A' \rightarrow \tau^+\tau^-$, and hadronic decay channels | Full detector simulation studies in progress

HNL Oscillations: pSPSS Model

Symmetry Protected Seesaw Scenario (pSPSS)

Two quasi-degenerate Majorana HNL states with small mass splitting Δm
HNLs oscillate into each other as they propagate (HNL-anti-HNL oscillations)
Oscillation period τ_{osc} determined by Δm

Conditions for Observable Oscillations

Requirement 1:

$\tau_{\text{osc}} \sim \tau_{\text{dec}}$ (comparable timescales)

Requirement 2:

$\tau_{\text{osc}} >$ experimental precision on decay path

Experimental Observable

Average $\cos \theta_{\text{vis}}$ in bins of decay path measures oscillation
 θ_{vis} : angle of visible decay products relative to HNL momentum direction

Pure Dirac Limit

$\tau_{\text{dec}} \ll \tau_{\text{osc}}$: No oscillation visible

Two Majorana Limit

$\tau_{\text{dec}} \gg \tau_{\text{osc}}$: Fully averaged out

Physics Significance

Observation of oscillations would probe lepton number violation and provide insight into the seesaw mechanism for neutrino mass generation

HNL Nature: Dirac vs Majorana Discrimination

Fundamental Question

If HNL is discovered, what is its nature?

Critical when oscillation is NOT directly observable ($\tau_{\text{dec}} \ll \tau_{\text{osc}}$ or $\tau_{\text{dec}} \gg \tau_{\text{osc}}$)

Dirac HNL

Lepton number conserved

No $N \leftrightarrow \bar{N}$ oscillations

$\tau_{\text{dec}} \ll \tau_{\text{osc}}$ regime

Majorana HNL

Lepton number violated

$N = \bar{N}$ (self-conjugate)

$\tau_{\text{dec}} \gg \tau_{\text{osc}}$ regime

Discrimination Method

Z boson polarization: HNL inherits spin information from Z decay

Angular distributions: Decay product angles sensitive to HNL polarization

Different predictions for Dirac vs (averaged) Majorana scenarios

Key Observable: $\cos \theta_{\mu}^{\text{HNL}}$

Angle of muon in HNL rest frame relative to HNL momentum | Distribution differs between Dirac and double-Majorana limits

Physics Implications

Determining Majorana vs Dirac nature directly probes whether neutrinos acquire mass through the seesaw mechanism with lepton number violation

Beyond Discovery: Timing-Based Mass Measurement

Novel Mass Measurement Technique

Mass of long-lived particle can be determined by combining:

- (1) Measured position of decay vertex (δd_L)
- (2) Measured timing of decay vertex (δt_L)
- (3) Known center-of-mass energy ($E_{CM} = 91.2 \text{ GeV}$)

Kinematic Principle

$$p_L = M_L \gamma \beta \quad (\text{relativistic momentum})$$
$$\beta = \delta d_L / (c \cdot \delta t_L)$$

Detector Requirements

Timing resolution: \sim few tens of ps
IDEA design: 30-50 ps achievable

Expected Performance

Long decay paths ($> 200 \text{ mm}$):

Mass precision: few %

Resolution dominated by:

Uncertainty in time and position of initial IP

Minimum Decay Length for 20% Mass Resolution

$M_L < 20 \text{ GeV}$: requires $d \sim 1 \text{ m}$ | $M_L \sim 40 \text{ GeV}$: requires $d \sim \text{few cm}$ | $M_L > 60 \text{ GeV}$: $d \sim 1 \text{ cm}$ sufficient

First Practical Implementation

This study formalizes and quantifies for the first time the performance of this technique in the FCC-ee context | Complements visible mass reconstruction

HNL: Combined Discovery Potential

FCC-ee Z-Pole Sensitivity (95% CL)

Prompt $\mu j j'$

M_N1: 5-85 GeV
Higher U^2 values

LLP $\mu j j'$

M_N1: 5-65 GeV
 $U^2 \sim 10^{-11}$

LLP $\mu \mu \nu$

M_N1: 10-50 GeV
~10% gain combined

Comparison with Other Experiments

vs LHC (CMS, ATLAS)

Orders of magnitude better at low U^2

vs FASER2, MATHUSLA

Complementary mass coverage

vs SHIP, AL3X

Similar reach, different systematics

Approaching Theoretical Limit

Analysis of all visible decay channels could reach ~70% of theoretical limit
Theoretical: 3 events with HNL decaying within IDEA detector volume (4.5m × 11m)

Unprecedented Sensitivity

FCC-ee can probe mixing values down to $U^2_{\mu N} \sim 10^{-11}$ — exploring parameter space unreachable by any other current or proposed experiment