FACULTY OF PHYSICS
UNIVERSITY OF WARSAW

Linear Collider Vision

BSM searches at the linear collider facility

EPS-HEP2025,
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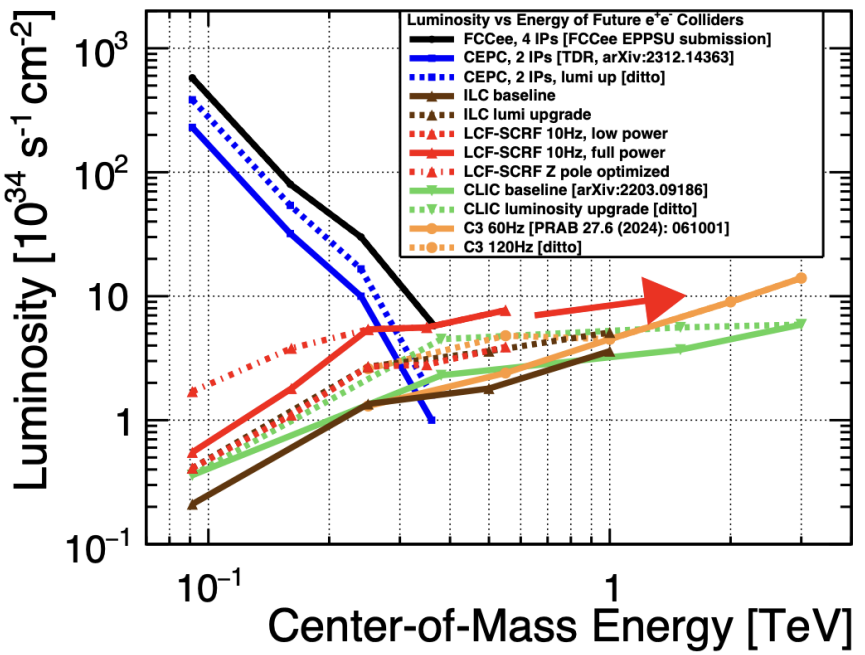
NATIONAL SCIENCE CENTRE
POLAND

Linear Collider Facility (LCF) at CERN

- A linear e^+e^- collider, with the energies from **91 GeV** to **1 TeV** or more
- Superconducting RF technology, proven and industrialised
- 2 interaction points, ±80% (±30-60%) electron (positron) beam polarisation
- First stage at **250 GeV** for Higgs measurements, followed by upgrade to **550 GeV**
- Affordable and flexible option:



→ First stage minimises the need to extend the CERN budget

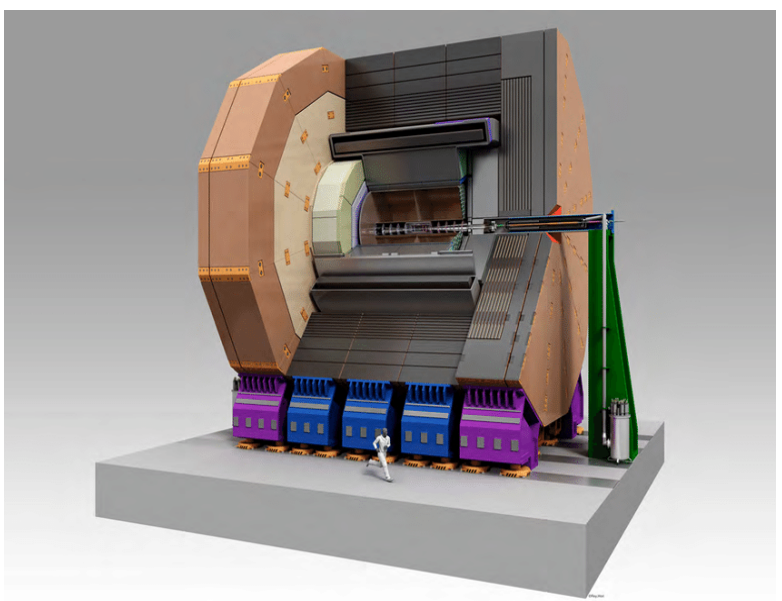
LCF and LCV documents

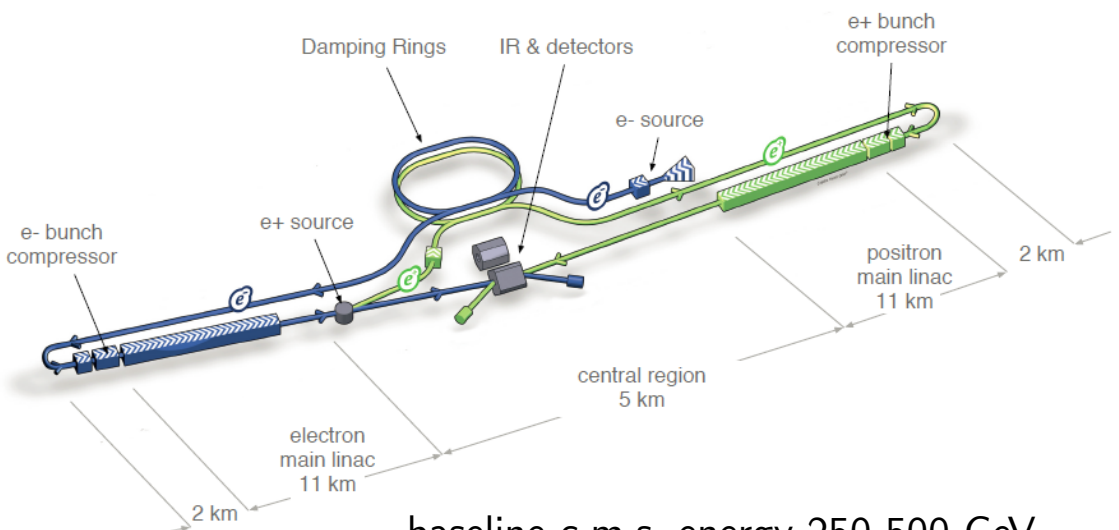
→ Adaptable in case of potential discoveries at HL-LHC or one of the early running stages

→ A variety of options for future high-energy or high-lumi upgrades, depending on the choice of technology (see Linear Collider Vision talk by Gudrid Moortgat-Pick)

International Large Detector (ILD)

- Multi-purpose detector for an e^+e^- Higgs factory, originally proposed for the International Linear Collider (ILC)
- Possible operation at circular e^+e^- machines currently under study
- Results presented in this talk are the ILD contributions to the ECFA Higgs/EW/top study report and assume **ILC running conditions** (very similar to LCF)

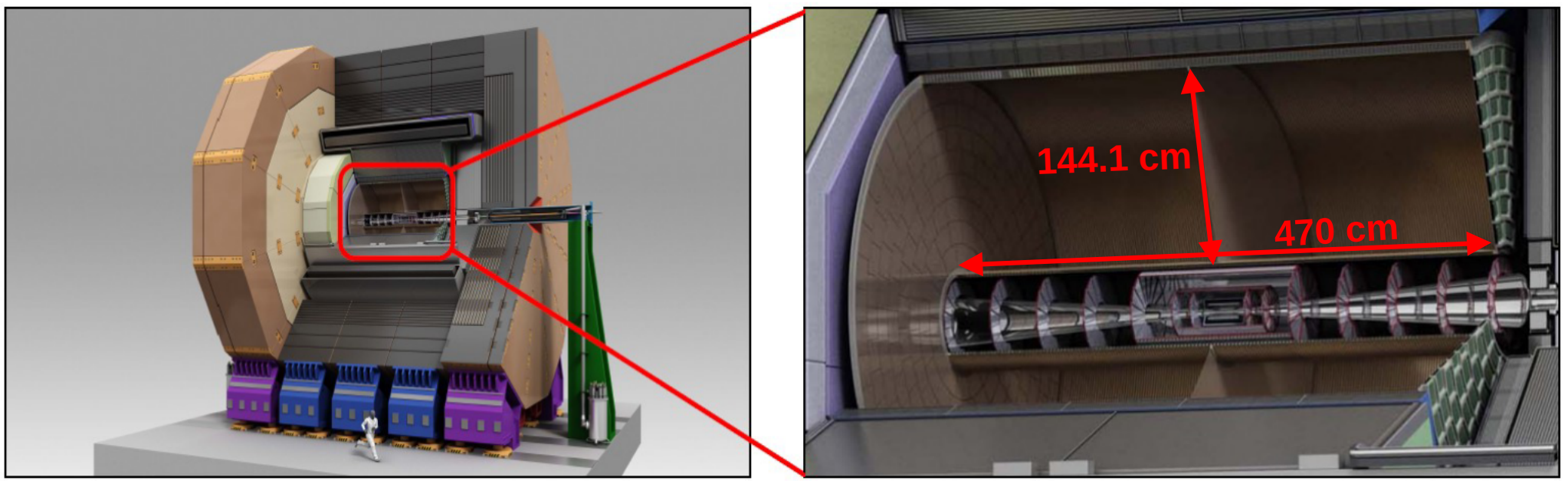




baseline c.m.s. energy 250-500 GeV

International Large Detector (ILD)

- Nearly 4π angular coverage, optimised for particle flow
- **Time projection chamber (TPC)** as the main tracker allowing for continuous tracking and dE/dx PID
- Highly granular calorimeters with minimal material in front inside of 3.5 T solenoid



See a dedicated talks by Vincent Boudry on the ILD and on the ECAL

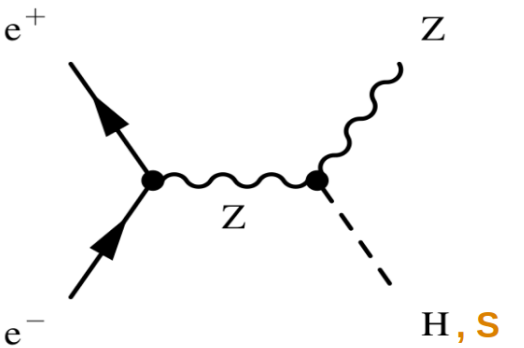
ILD and LCF at EPS-HEP2025

- Gudrid Moortgat-Pick, A Linear Collider Vision for the Future of Particle Physics
- Vincent Boudry,
  The ILD Detector: A Versatile Detector for an Electron-Positron Collider at Energies up to 1 TeV
- Krzysztof Mękała, Top and Electroweak physics at the linear collider facility
- Maria Teresa Nunez Pardo De Vera,
  Prospects for light exotic scalar measurements at the e+e- Higgs factory
- Maria Teresa Nunez Pardo De Vera, Stau searches at future e+e- colliders
- Vincent Boudry, A Silicon-Tungsten ECAL for Higgs Factory Detectors
- Krzysztof Mękała, Determination of the first-generation quark couplings at the Z-pole
- JK, Long-Lived Particle Searches at a Future Higgs Factory with the ILD experiment

Extended scalar sector

- Additional (light) scalars still not excluded by the LHC
- A number of models (singlet extensions, 2HDMs, N2HDM, IDM, scalar triplet, ...)

  → large parameter space allowed and accessible at e^+e^- colliders
- Can be produced in scalar-strahlung, or in SM Higgs decays
- Searches for S → bb, ττ, invisible, and decay-independent, with Z → ll (ee + μμ) or qq
- ILC can exclude new scalars at sub-percent level of the SM Higgs cross sections



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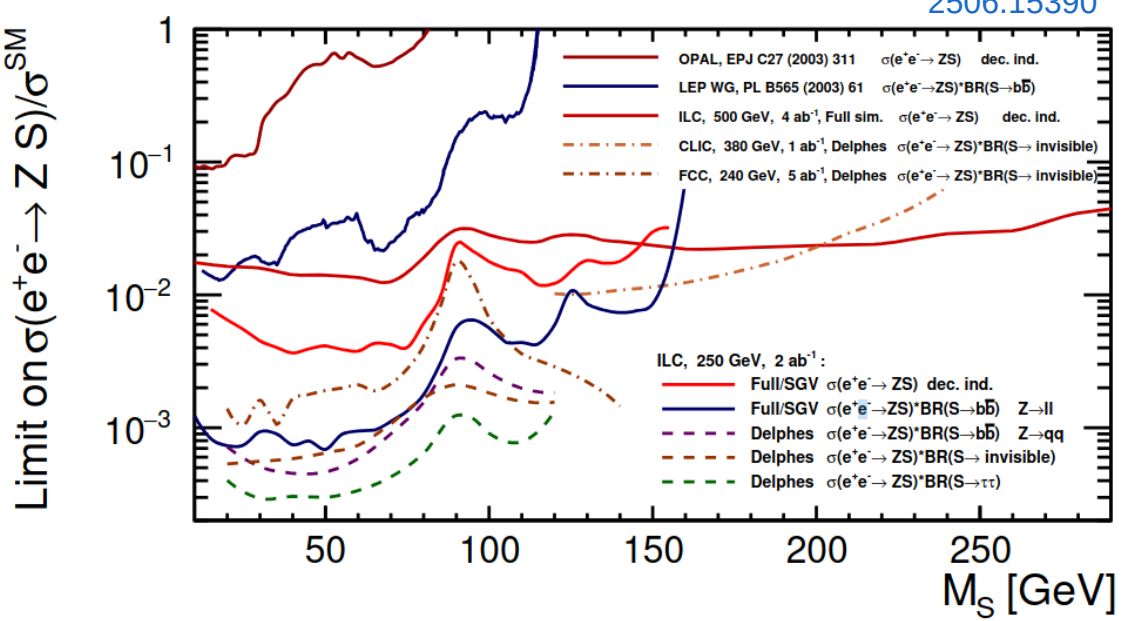
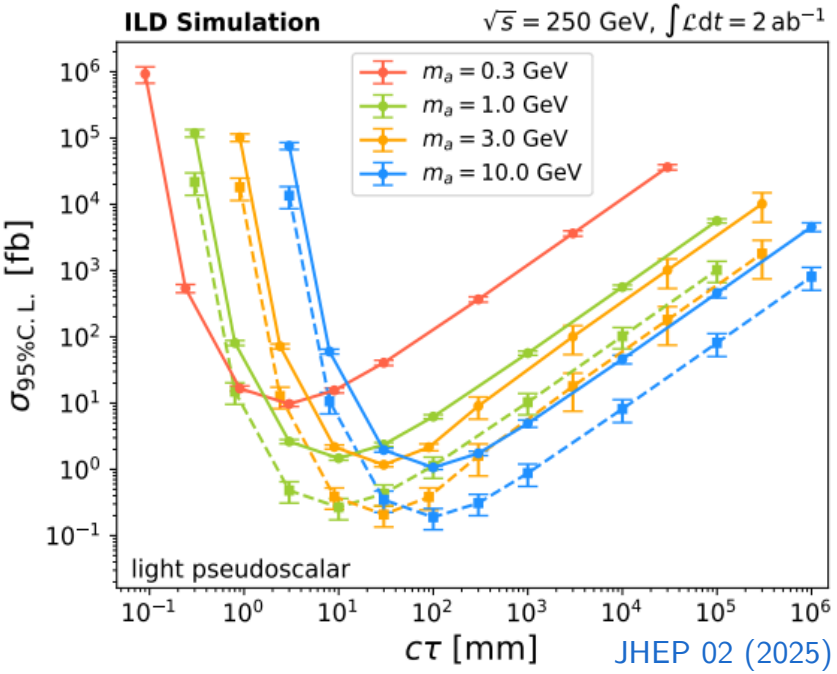


See a dedicated talk by M.T. Nunez Pardo De Vera on Wednesday

Long-lived particles



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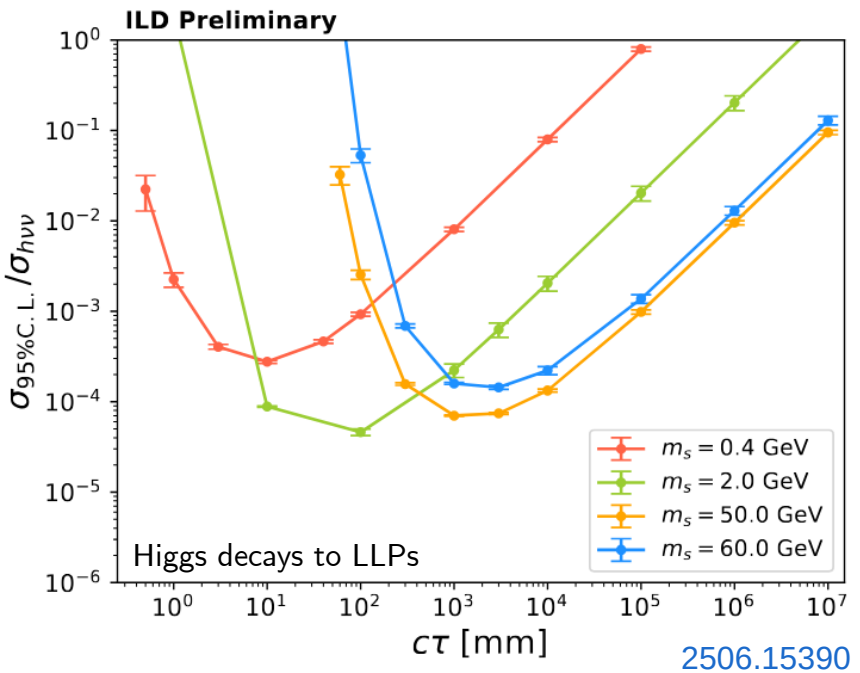

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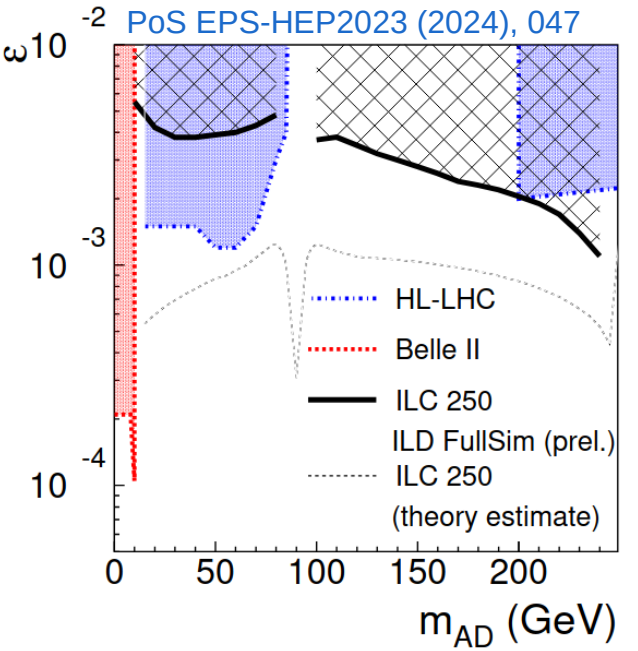
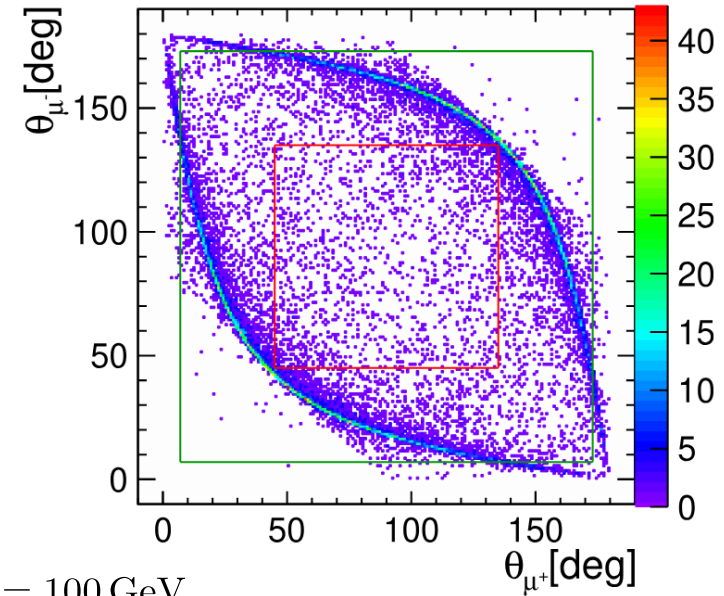
- Model-independent search for neutral long-lived particles in the ILD's TPC
- Search optimised for Higgs decays to LLPs, preliminary results for charged LLPs
- For details see the **next talk** in this session...

New gauge bosons

- U(1) dark photon is a good candidate for a messenger to dark sector
- Coupled to SM photon via kinetic mixing ε which must be small, could be produced in e^+e^- collisions



$$e^+e^- \to \gamma_{ISR} A_D \to \mu^+\mu^-\gamma_{ISR}$$



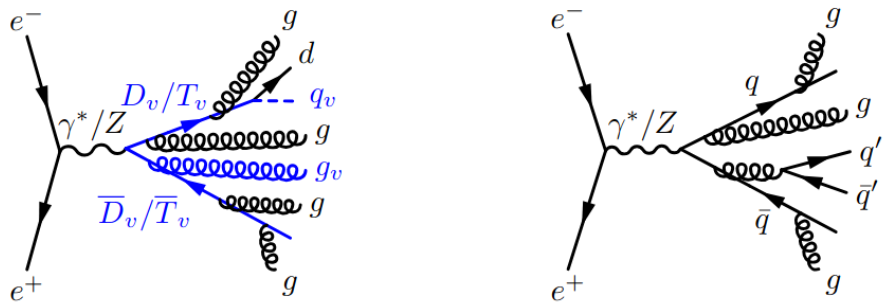
$m_{A_D} = 100\,\mathrm{GeV}$

Green: tracking acceptance
Red: barrel region acceptance

- Limited probability of detecting both muons within the acceptance

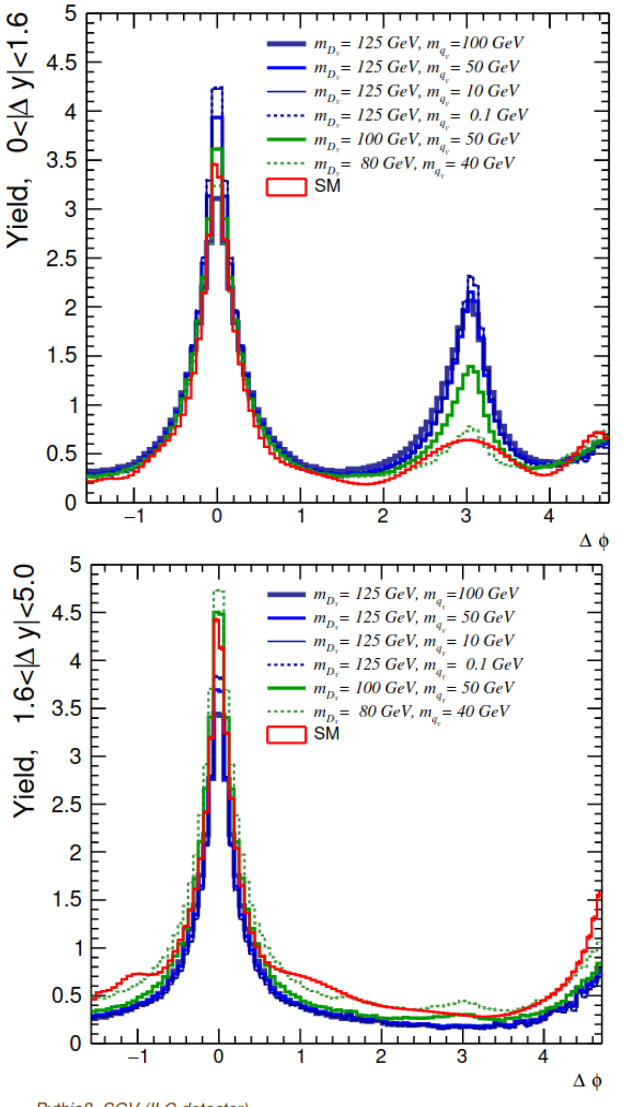
  → Importance of wide angular coverage and full detector simulation
- Mass resolution of ~0.2% including detector effects
- Sensitivity up to kinematic limit

New gauge bosons



(a) Hidden valley (b) SM light quarks

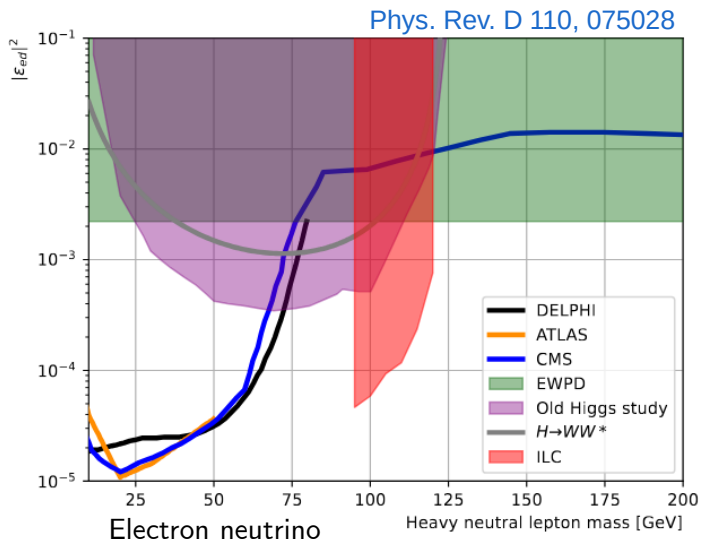
- Two-particle correlations can be used to discover dark sector particles in Hidden Valley (HV) models
- A range of masses for *communicators* (D_v/T_v) and hidden sector particles (q_v) considered
- Study based on Pythia 8 and SGV fast simulation
- Sizable peaks visible in distributions of azimuthal yield $Y(\Delta\Phi)$, defined by integrating over a range of rapidity differences

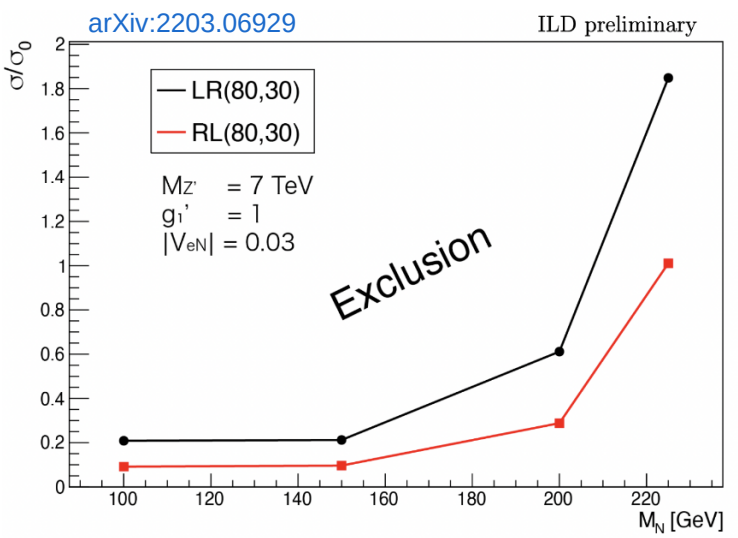


arXiv:2312.06526

Heavy Neutral Leptons (HNLs)

- HNLs could solve the neutrino mass and baryon asymmetry problems, or be dark matter candidates
- Full simulation studies show linear colliders are well-suited to search for HNLs above the Z mass

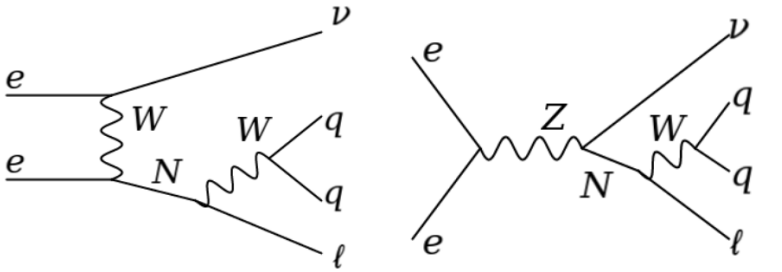




- Search in Higgs decays to HNLs via Higgsstrahlung, with Z → qq and H → Nν → qqlν
- 2 polarization schemes and 95-120 GeV mass range
- Staged selection including ML techniques

- $U(1)_{(B-L)}$ model: $e^+e^- \to NN$, with $N \to e^{\pm}W^{\mp} \to e^{\pm}qq$ channel
- Visible influence of the beam polarisation
- Exclusion for 100-220 GeV HNL masses

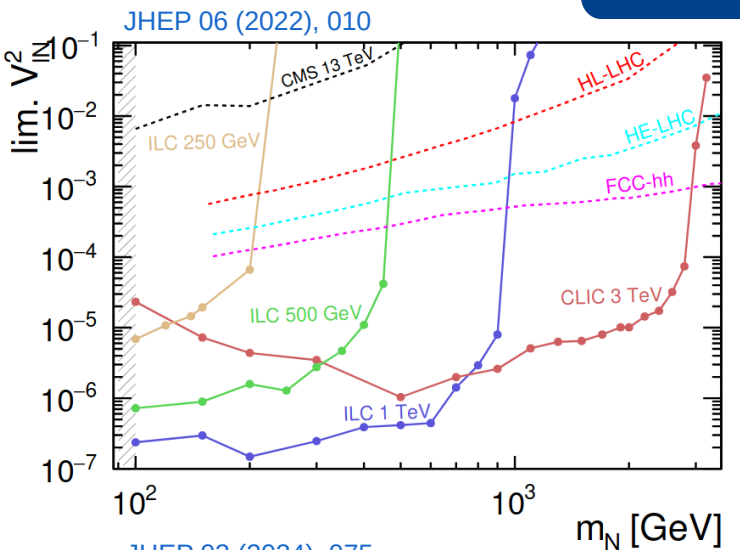
Heavy Neutral Leptons (HNLs)

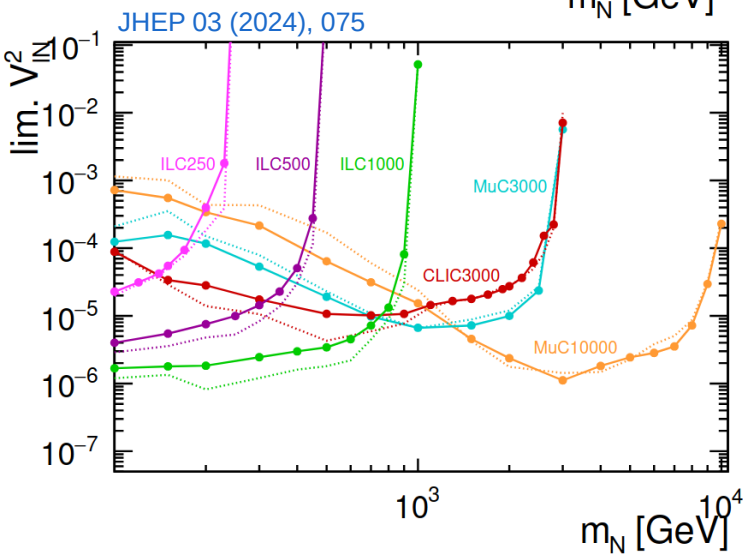


Full reconstruction of HNL mass possible

- Mixing V_{lN} set to the same value for all leptons
- Fast simulation study, including eγ, γγ backgrounds
- Observation expected almost up to the kinematic limit

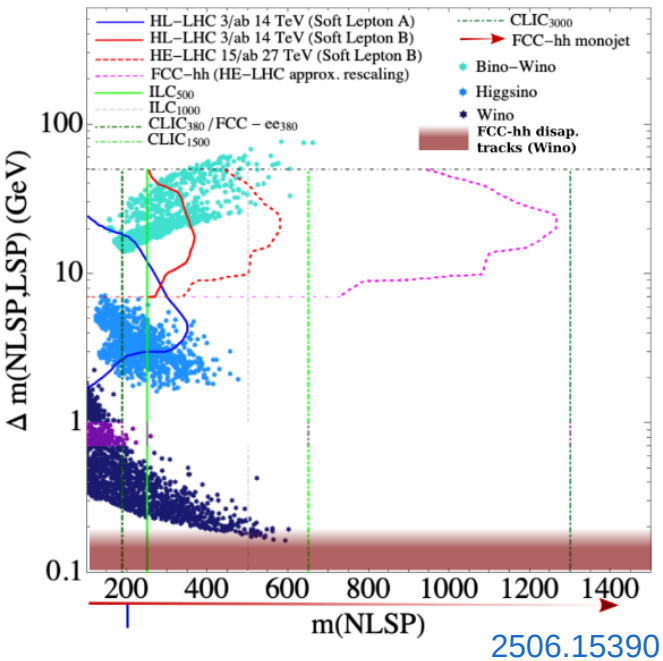
- Possibility of discriminating Dirac vs. Majorana nature of HNLs considered
- MVA (BDT) analysis involving angular variables
- Discrimination (dotted lines) following 5σ discovery (solid lines) possible at all linear colliders





SUSY

SUSY is still far from being excluded...



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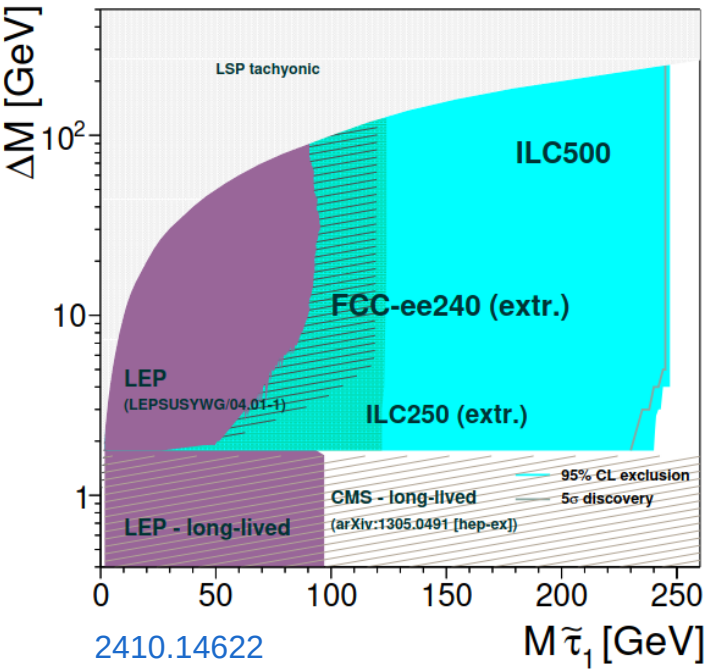

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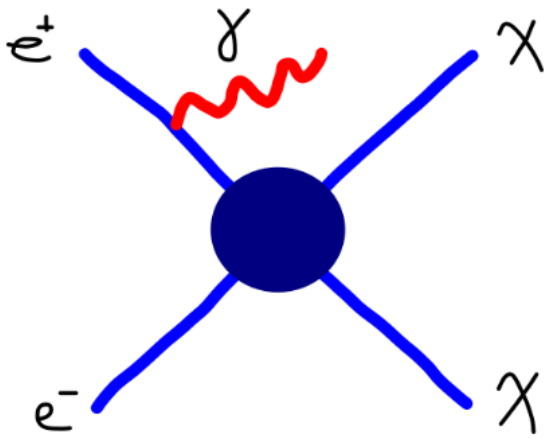
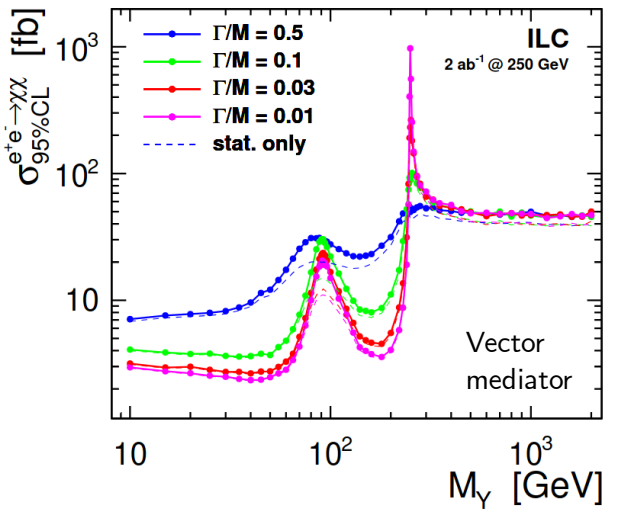
- Many scenarios favour compressed spectra (Higgsino/Wino LSP)
- e^+e^- colliders can exclude all (N)LSP candidates in the whole m-Δm plane

- Dedicated stau search at 500 GeV ILC, full simulation
- Recasts for ILC250, ILC1000, FCC-ee240
- More details in a talk by M.T. Nunez Pardo De Vera in this session

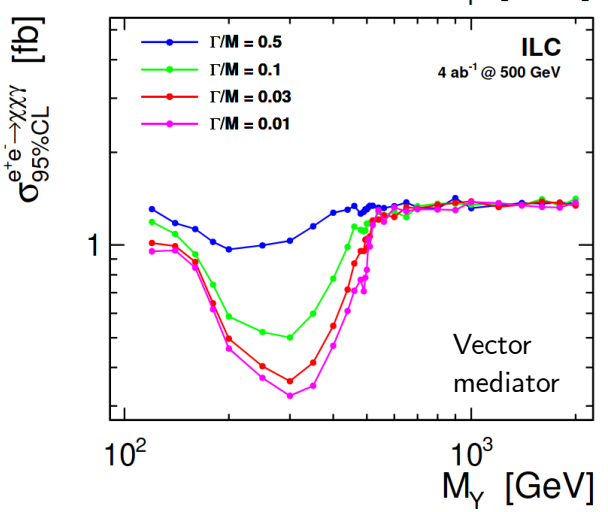
Dark Matter (DM) searches



- Mono-photon channel search assuming simplified DM model
- Small and moderate mediator masses
- Limits on cross sections and couplings, depending only on width and mass
- Fast simulation study based on 2D distributions



- Different coupling structures considered
- Best limits for light and narrow mediators
- For heavy mediators ($M_Y \gg \sqrt{s}$) weak dependence on mass and width
- For 500 GeV ILC expected limits on EFT mass scale from 2.6 TeV to 5 TeV, depending on coupling structure



$$\Lambda^2 = \frac{M_Y^2}{|g_{eeY}\, g_{\chi\chi Y}|}$$

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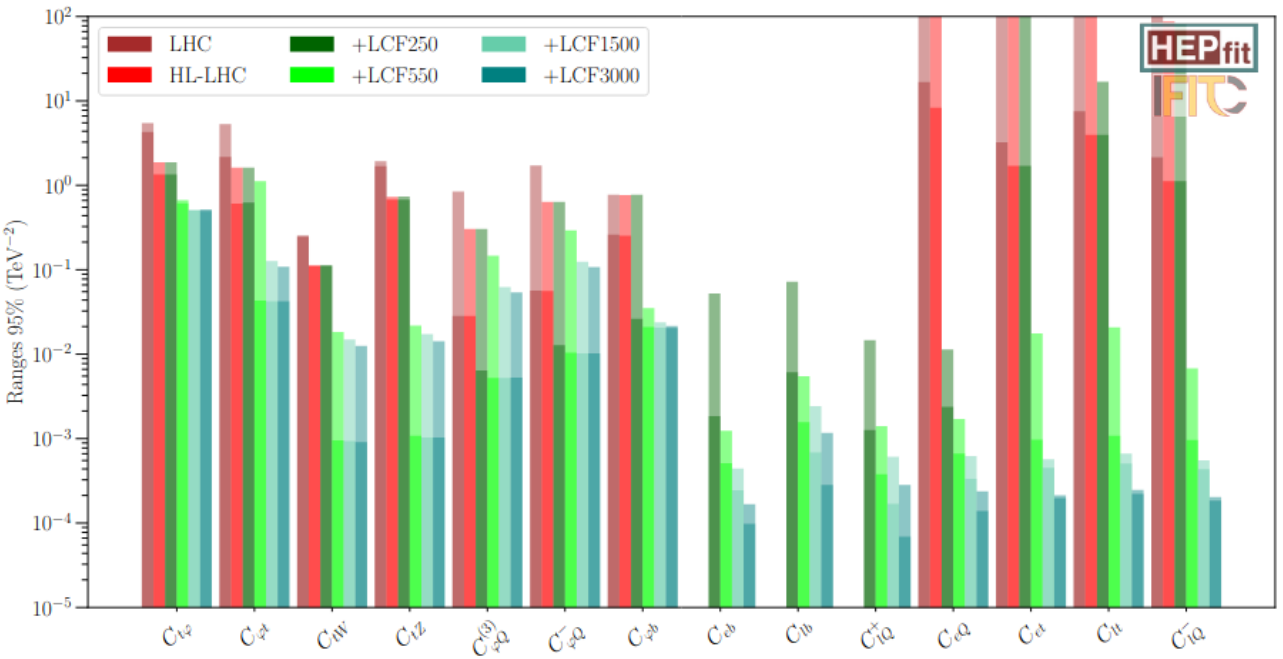
Reach via EFT and beam dump

Operators with top and bottom quarks



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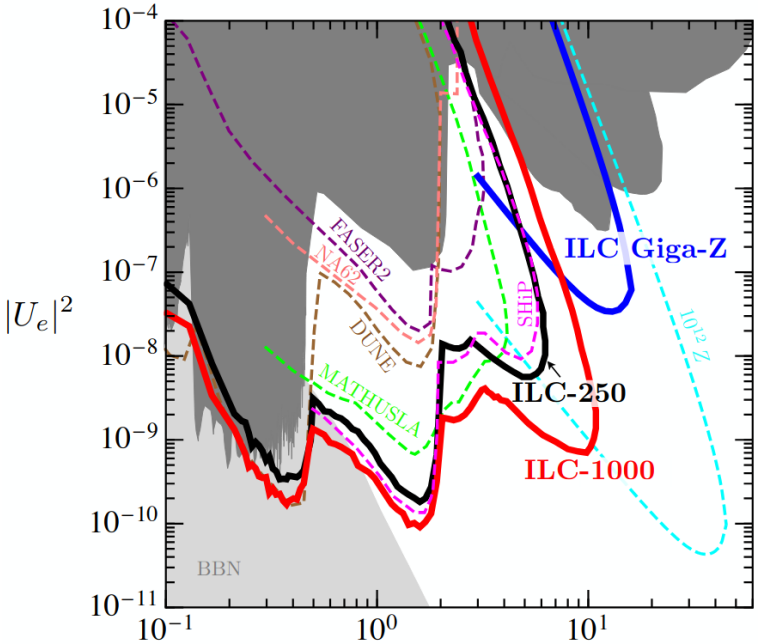
ILC beam dump reach to HNLs



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Thank you!