Searches for direct BSM signals with the ILD concept at Higgs factories

Emanuela Musumeci (University of Alabama)

on behalf of the ILD Concept Group

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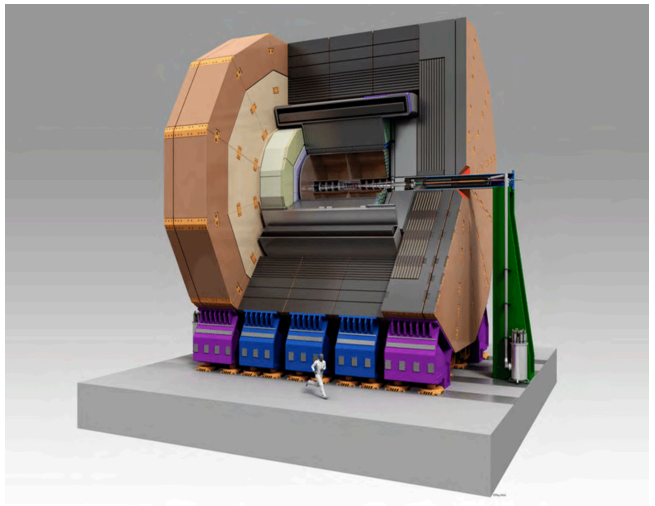
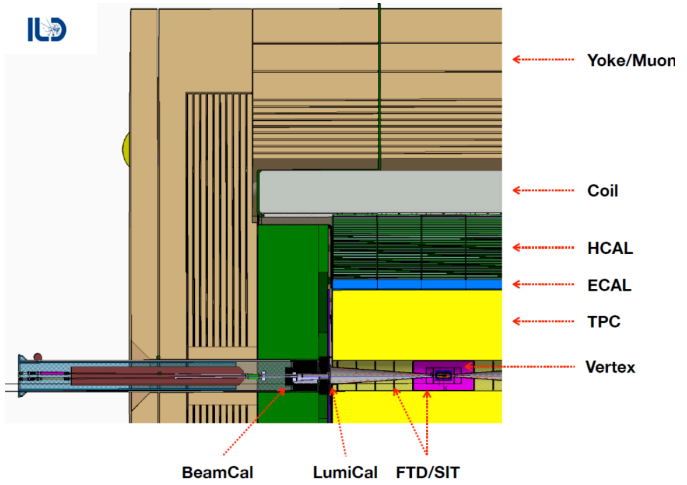
The International Large Detector (ILD)

See T. Mori's talk

- Multi-purpose detector for an e^+e^- Higgs factory, originally conceived for the International Linear Collider (ILC)
- Now also proposed for:
  - Linear Collider Facility (LCF) @ CERN (See C. Hensel's talk)
  - the FCC-ee
- Optimised for *Particle flow*
- Nearly 4π coverage, hermetic down to ~5 mrad
- Time Projection Chamber (TPC) as the main tracker: continuous tracking and dE/dx PID. TPC suitable for LLP searches
- Highly granular calorimeters inside a 3.5 T solenoid; minimal material in front

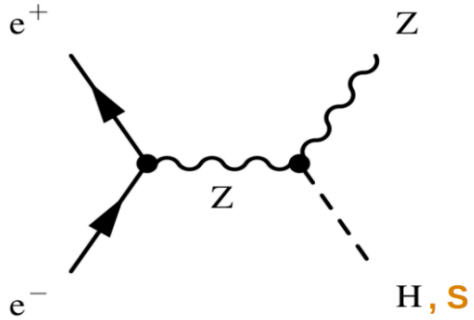


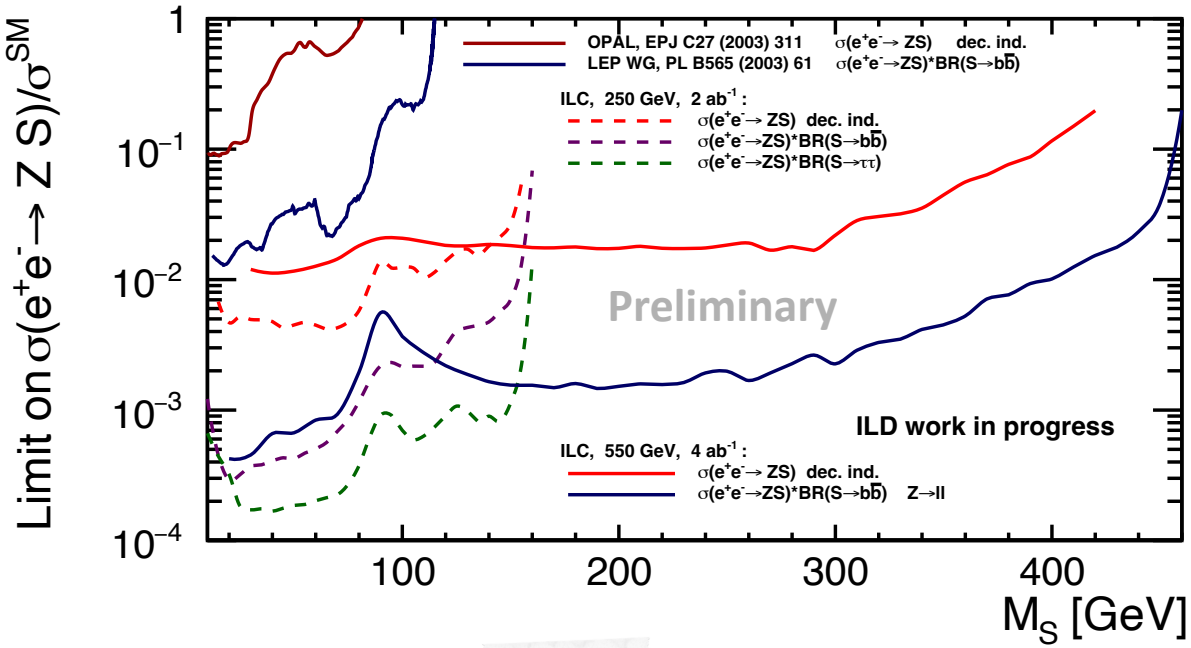


Results presented in this talk are the ILD contributions to the ECFA Higgs/EW/top study report and assume ILC running conditions

Extended scalar sector

- **Light additional scalars S^0** still allowed by LEP/LHC (singlet ext., 2HDM/N2HDM, IDM, triplets…)
- **Scalar-strahlung $e^+e^- \rightarrow Z\,S$**,
  - $Z \rightarrow e^+e^-/\mu^+\mu^-$ (and $q\bar{q}$): search in recoil mass against the Z — no assumption on S^0 decay
  - Specific channels ($b\bar{b}, \tau\tau$)
- **250 GeV, 2 ab-1** (dashed lines): previous ILD results, full sim/SGV
- **550 GeV, 4 ab-1** (solid lines): NEW ILD preliminary results, full sim / SGV
- **Reach:** couplings down to sub-percent of σ_{SM}— up to 2 orders of magnitude beyond OPAL, probing the full allowed parameter space



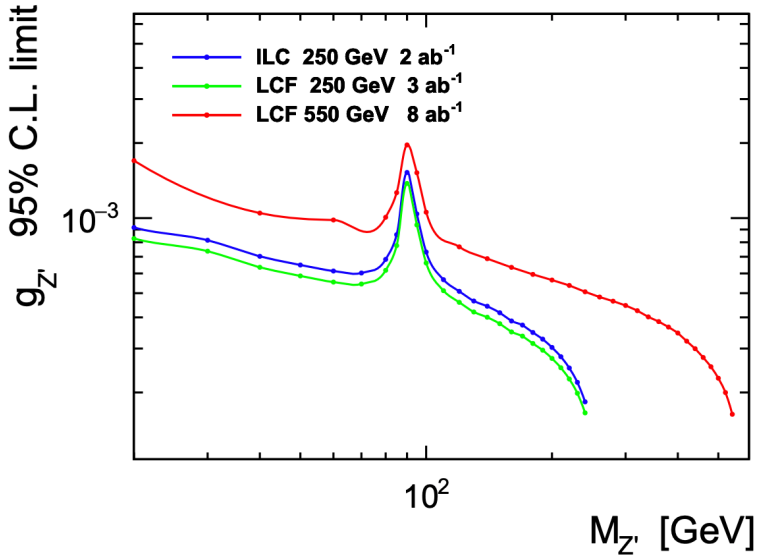


A Higgs factory with ILD can probe scalar couplings at the sub-percent level, covering a vast parameter space that no hadron collider can access

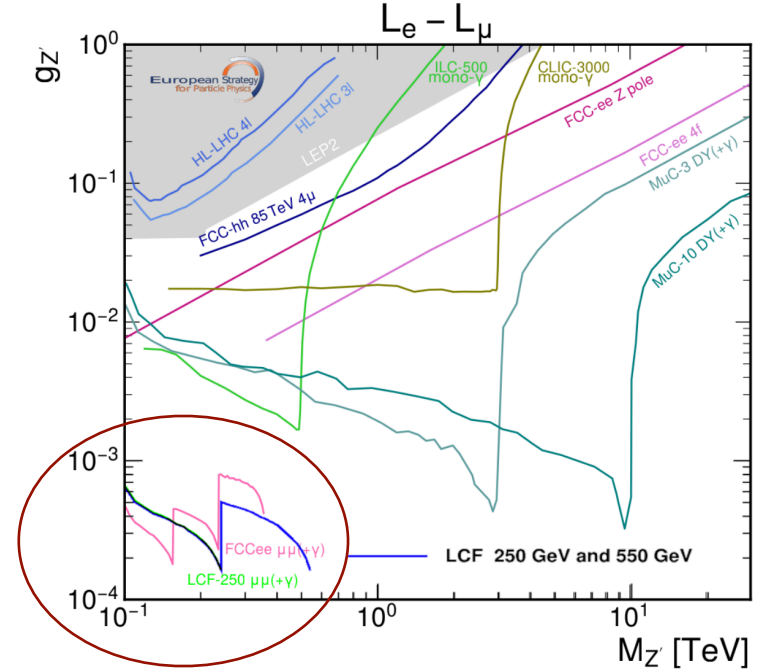
Leptophilic Z' in the $L_e - L_\mu$ model

Selected for ESPP Briefing Book (CERN-ESU-2025-001)

- **Signal: $e^+e^- \rightarrow Z'\gamma \rightarrow \mu^+\mu^-\gamma$; radiative-return approach:** select on di-muon kinematics (pT, Eμμ + $|p_{Z\mu\mu}|$ balance), no photon required
- *Fast simulation: WHIZARD 3.1.6 + Delphes*
- multi-photon ISR and ISR-ME matching included;
- ±1 GeV (2.5 GeV) mass window at 250 (550) GeV
- ±80%/±30-60% e^-/e^+ polarisation. Running scenarios:
  - ILC 250 GeV / 2 ab^{-1}
  - LCF 250 GeV / 3 ab^{-1}
  - LCF 550 GeV / 8 ab^{-1}
- **Result:** g' limits down to ~10^{-3} across m(Z') range — slightly better than FCC-ee direct search; polarisation is a key driver

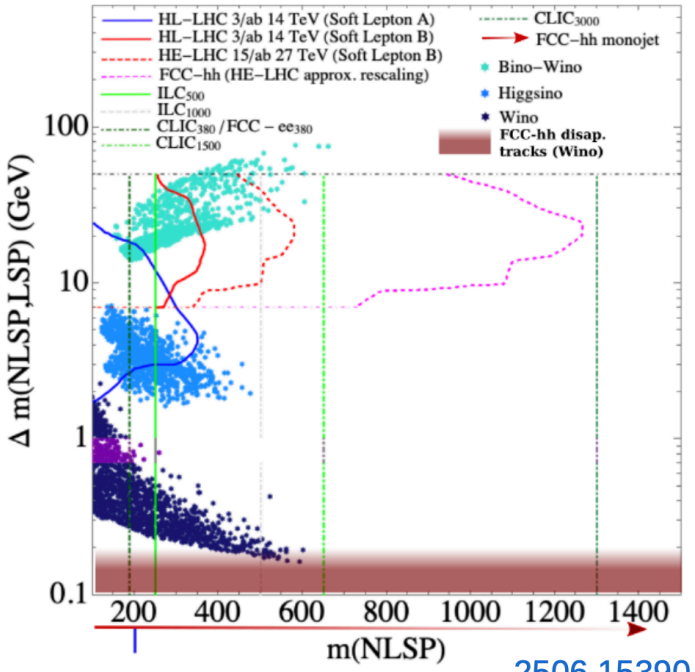


Comparison with Briefing Book results



SUSY

SUSY is still far from being excluded… and e^+e^- colliders may be the tool to settle it



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- Naturalness, DM relic density and (g−2)μ prefer light EW-inos and sleptons with compressed spectra — exactly where LHC searches lose sensitivity
- e^+e^- colliders can exclude all (N)LSP candidates in the whole m-Δm plane

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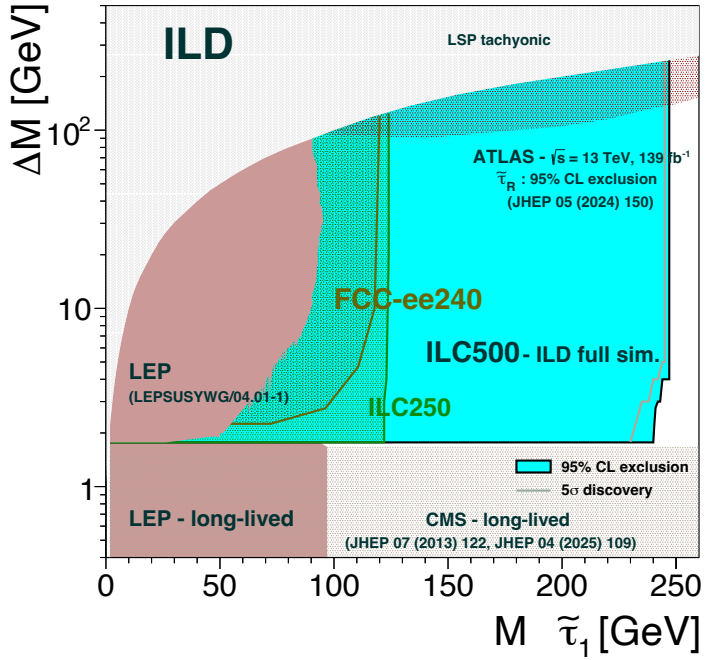
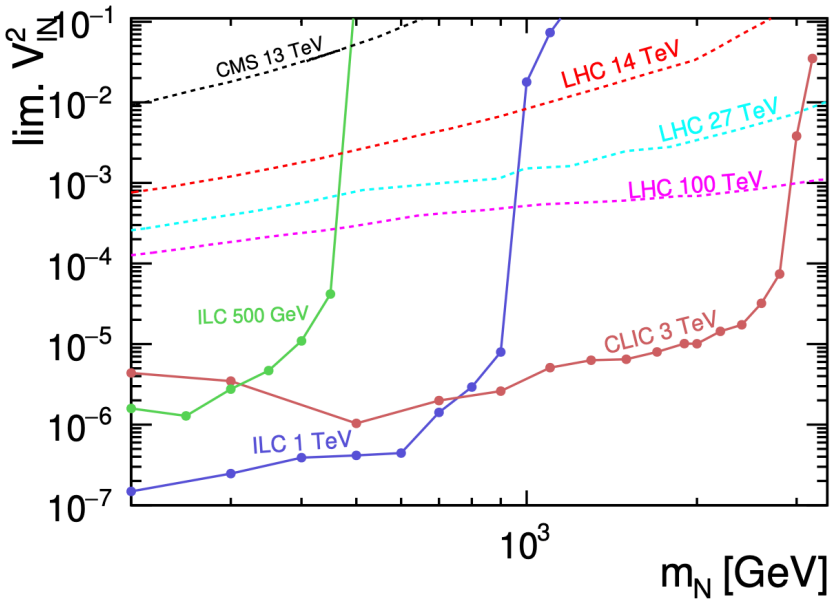


- $\tilde{\tau}$ NLSP (co-annihilation): *full-simulation* search at √s = 500 GeV incl. γγ overlay;
- Recasts for ILC250, ILC1000, FCC-ee240
- Discovery reach ≈ exclusion reach — no holes, no model-dependent assumptions, no trigger thresholds

Heavy Neutral Leptons: production & reach

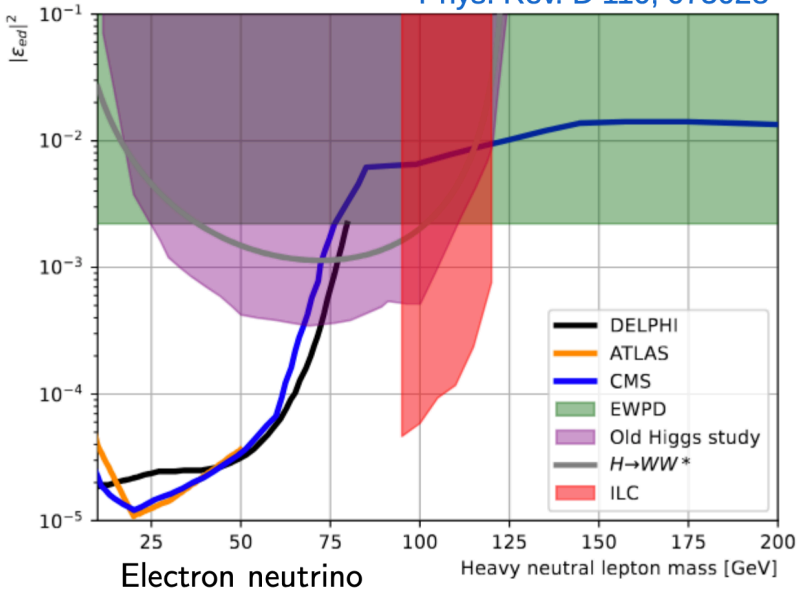
HNLs address neutrino masses, baryon asymmetry and DM — sensitivity to two complementary production mechanisms

JHEP 06 (2022) 010



- **Direct production: $e^+e^- \rightarrow N\nu$, $N \rightarrow \ell^\pm W^\mp \rightarrow \ell^\pm q\bar{q}$**
- Sensitivity to V^2_{lN} nearly flat up to the kinematic limit — observation expected almost to √s/2
- Full reconstruction of HNL mass from decay products;
- *Fast simulation* including eγ and γγ backgrounds
- Beam polarisation enhances signal and allows coupling structure diagnostics

Phys. Rev. D 110, 075028

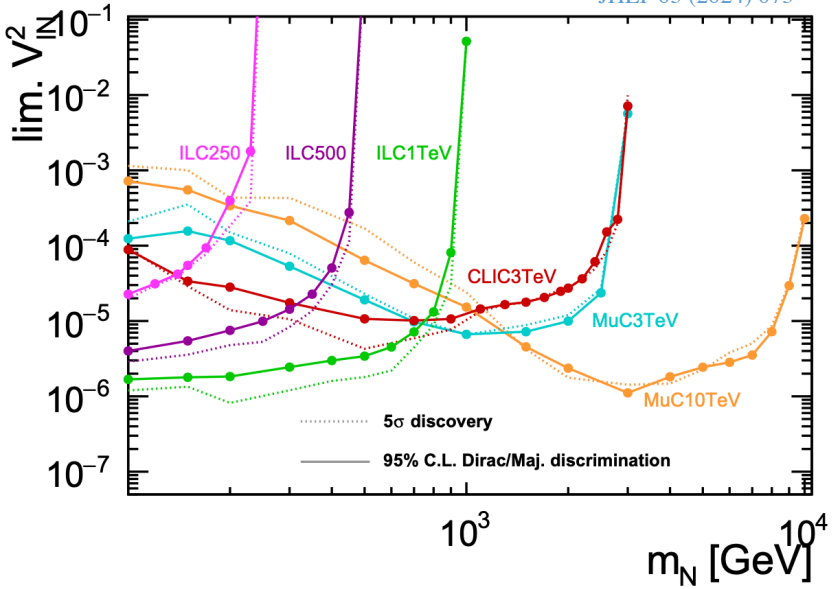


- **Search in Higgs decays: $e^+e^- \rightarrow ZH$, $H \rightarrow N\nu \rightarrow q\bar{q}\ell\nu$**
- Unique window: m(N) = 95–120 GeV — between Z and Higgs mass, below LEP reach and difficult for LHC
- *Full ILD simulation;* staged ML-based selection; both polarisation schemes studied
- Complementary to direct production: together cover the full accessible mass range

HNLs: discovery reach & nature determination

ILD could determine their Dirac or Majorana nature — and complementarity between colliders is key

JHEP 03 (2024) 075



- **5σ discovery (dotted) and Dirac/Majorana discrimination at 95% CL (solid) nearly coincide**
- Sensitivity scales with energy: ILC250 < ILC500 < ILC1TeV; CLIC and MuC extend reach to much higher masses
- Universal mixing assumed: $V_{eN} = V_{\mu N} = V_{\tau N}$
- *Fast simulation with Delphes*
- Discrimination uses BDT on angular variables and lepton-charge information — a qualitative statement about lepton number violation

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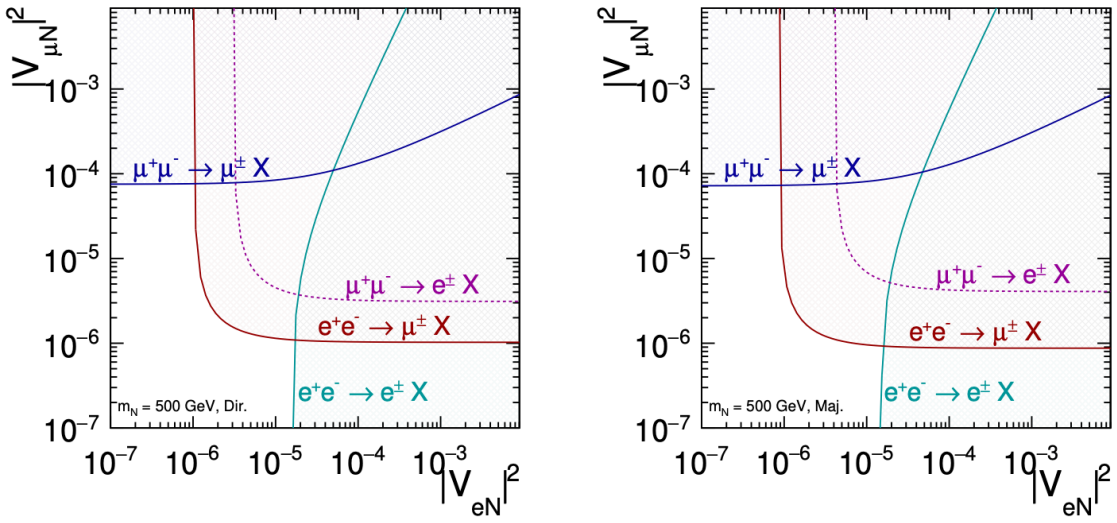
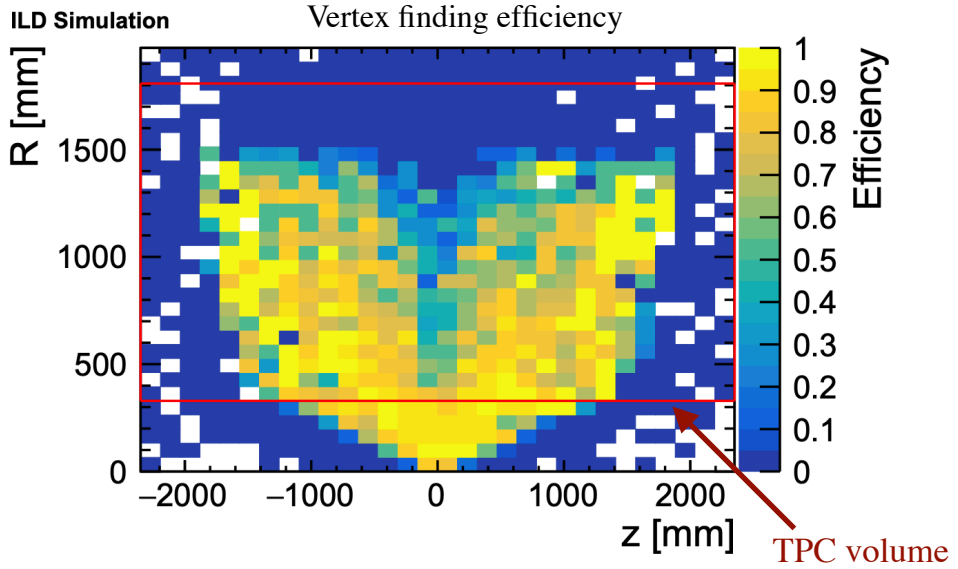


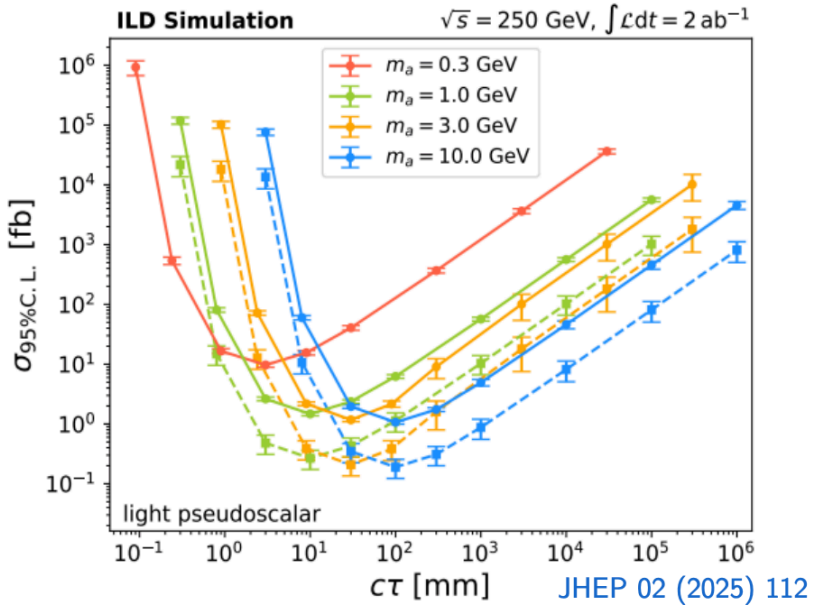
(a) Dirac neutrino. (b) Majorana neutrino.

- **The 1D universal-mixing picture is a special case — the full coupling space is 3D**
- e^+e^- and $\mu^+\mu^-$ colliders are sensitive to different coupling combinations: complementarity is essential
- A complete picture of HNL couplings requires measurements at different machines and energies
- Additional production channels explored: $e^+e^- \to NW^\pm e^\mp$ (arXiv:2308.02240); virtual effects in W^-W^+ (arXiv:2411.09418)

Long-lived particles in the ILD TPC

- LLPs generic in SUSY, ALPs, dark photons, HNLs, exotic scalars
- Higgs factory probes small masses, couplings and mass splittings, complementary to LHC
- **Model-independent:** two tracks from a displaced vertex in the TPC, no further assumptions on the final state
- **Full ILD simulation;** $\sqrt{s} = 250$ GeV @ 2 ab^{-1}
- **Two extreme benchmarks:** heavy scalar pair (Δm ≈ 1–2 GeV, soft, non-pointing) and boosted light pseudoscalar (m ≈ 0.3–1 GeV, collinear)
- **Optimised for H → LLP decays**; dedicated vertexing + cuts against γγ overlay; charged-LLP results in progress

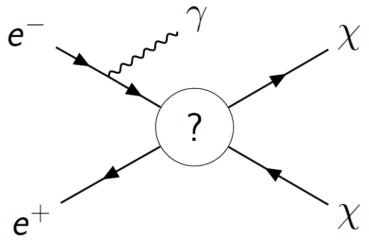




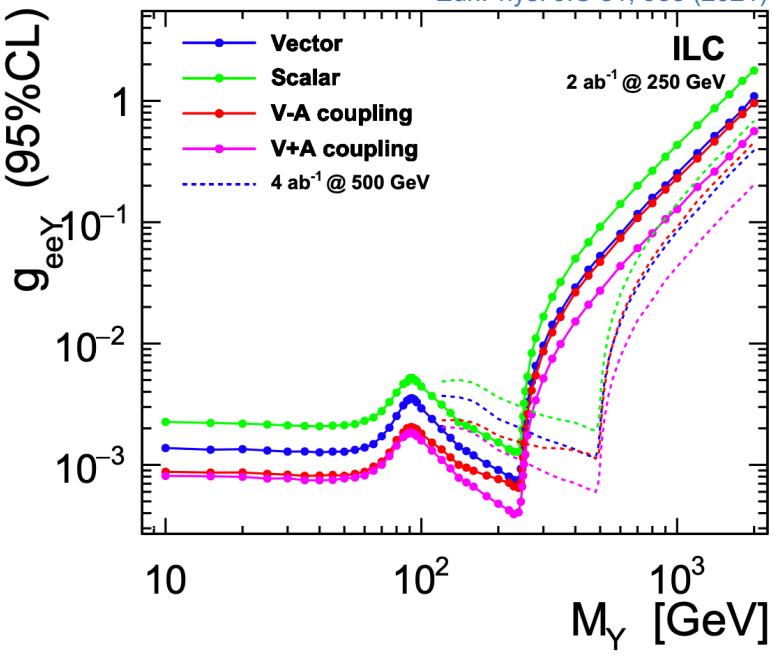
JHEP 02 (2025) 112

Dark matter: mono-photon search

The most general way to look for DM — hard ISR photon tags invisible DM pair production

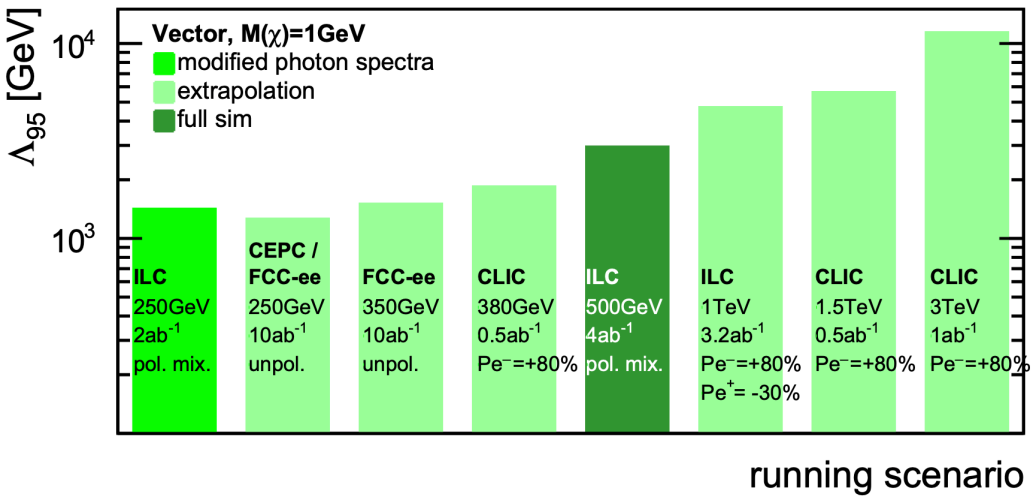


Eur.Phys. J.C 81, 955 (2021)



- **O(10^{-3}–10^{-2}) limits on mediator coupling g_{eeY} up to the kinematic limit $M_Y \leq \sqrt{s}$**
- Different coupling structures considered: vector, scalar, V-A, V+A
- Limits can be more stringent than from direct resonance searches
- Results for ILC 250 GeV (2 ab^{-1}) and 500 GeV (4 ab^{-1})

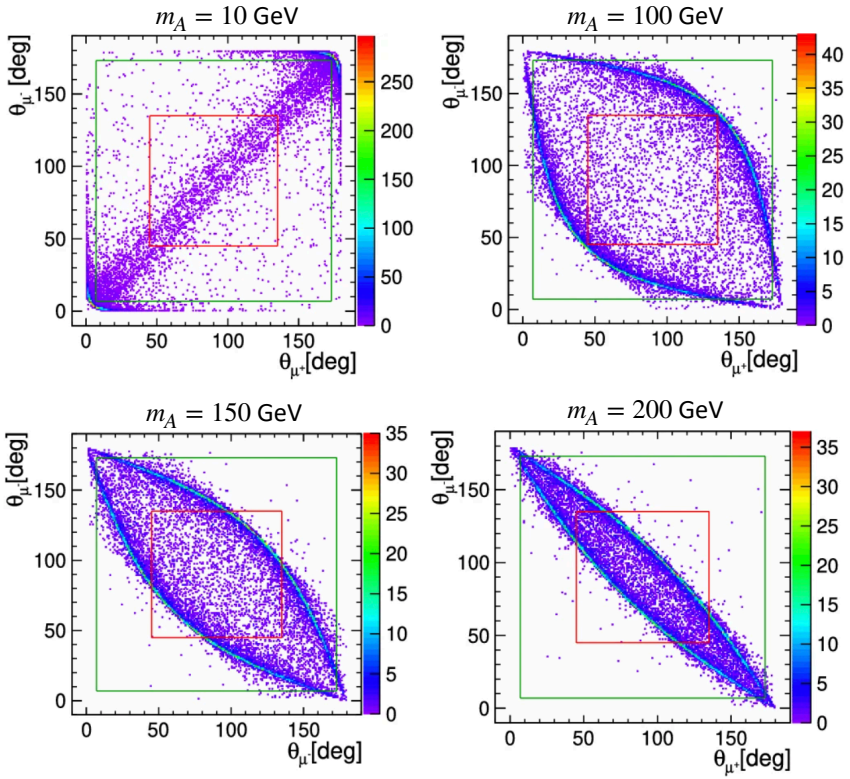
Phys. Rev. D 101, 075053 (2020)



- **EFT analysis at 500 GeV ILC: Λ probed up to ~4 TeV for vector coupling (with systematics)**
- Beam polarisation decisive: significantly enhances sensitivity vs unpolarised CEPC/FCC-ee — and allows identification of the BSM scenario (scalar vs vector mediator)
- Sensitivity to mediator masses far beyond √s

Dark Photons

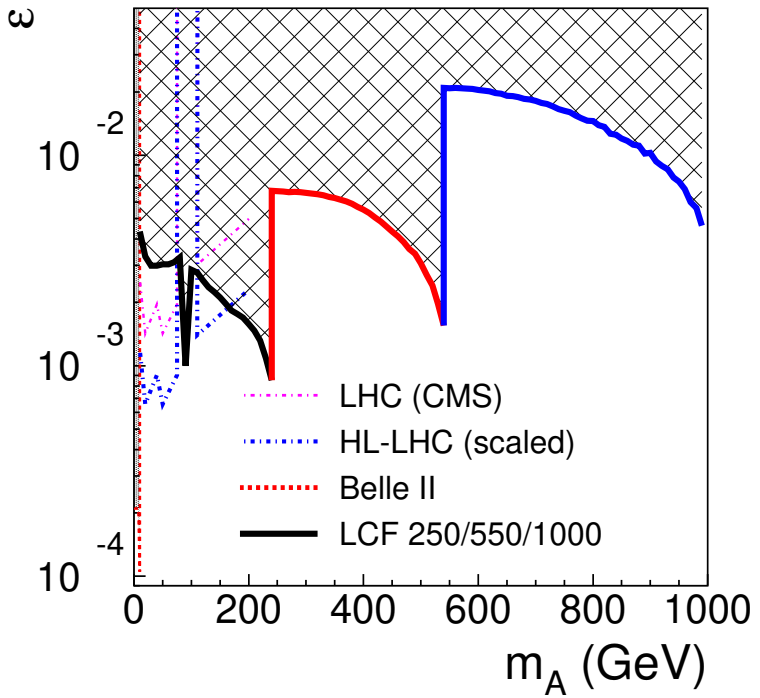
$e^+e^- \to \gamma_{ISR} A_D \to \mu^+\mu^-\gamma_{ISR}$ — kinetic mixing portal to the dark sector



Green = tracking acceptance
Red = barrel region

- **U(1) dark photon coupled to SM photon via kinetic mixing ε —** produced via radiative return, decays promptly to $\mu^+\mu^-$
- Limited probability of detecting both muons within acceptance — especially at low m(A_D) : wide angular coverage of ILD is essential
- Di-muon mass resolution ~0.2% including all detector effects — theory-level estimates too optimistic by factor 2–4

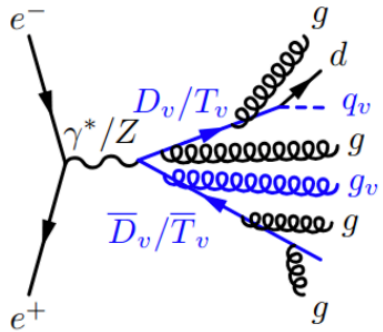
EPJP 141, 812 (2026)



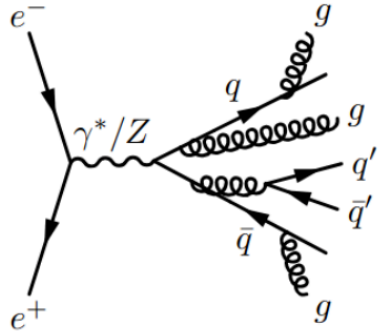
- Full simulation performed
- LCF recasts from ILC250 full simulation: ε limits reach ~few × 10^{-4} above M_Z — better than HL-LHC across the full mass range
- LCF250 → LCF550 → LCF1000: each energy stage extends reach to higher masses
- Linear colliders (ILC, LCF, C3) can perform an energy scan — additional sensitivity if E_{CM} tuned to m(A_D)

Hidden Valley

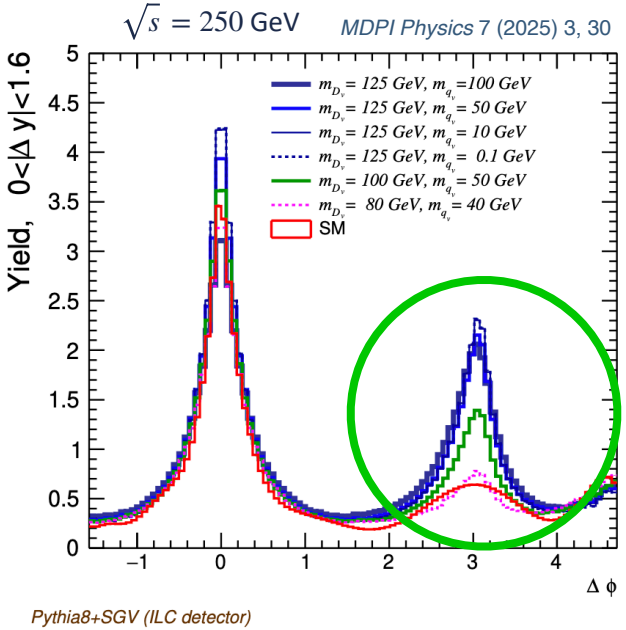
- Two-particle azimuthal correlations as a probe of hidden-sector production
- Multiple mass scenarios for dark communicators (D_v, T_v) and hidden-sector quarks q_v — broad parameter space coverage
- Study based on Pythia 8 and SGV simulation
- Clear peaks at Δϕ ~ π in the azimuthal yield Y(Δϕ) — visible above the SM background for a wide range of communicator and q_v masses
- ILD sensitivity validated for both ILC and FCC-ee running conditions



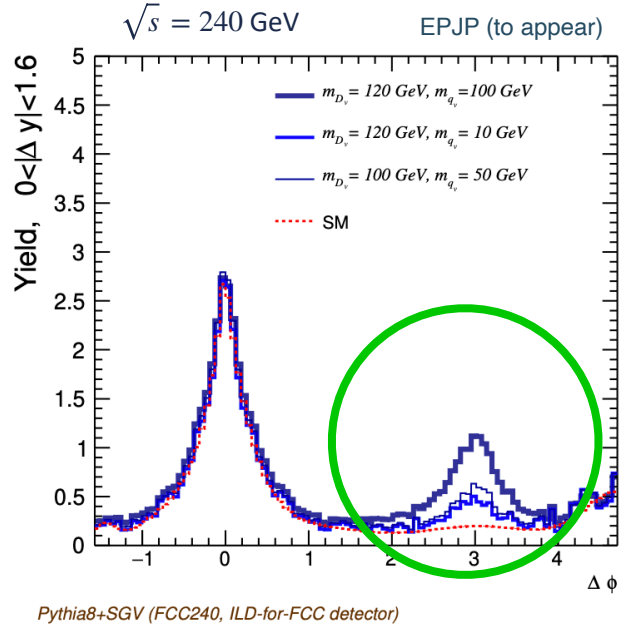
(a) Hidden valley



(b) SM light quarks



Pythia8+SGV (ILC detector)

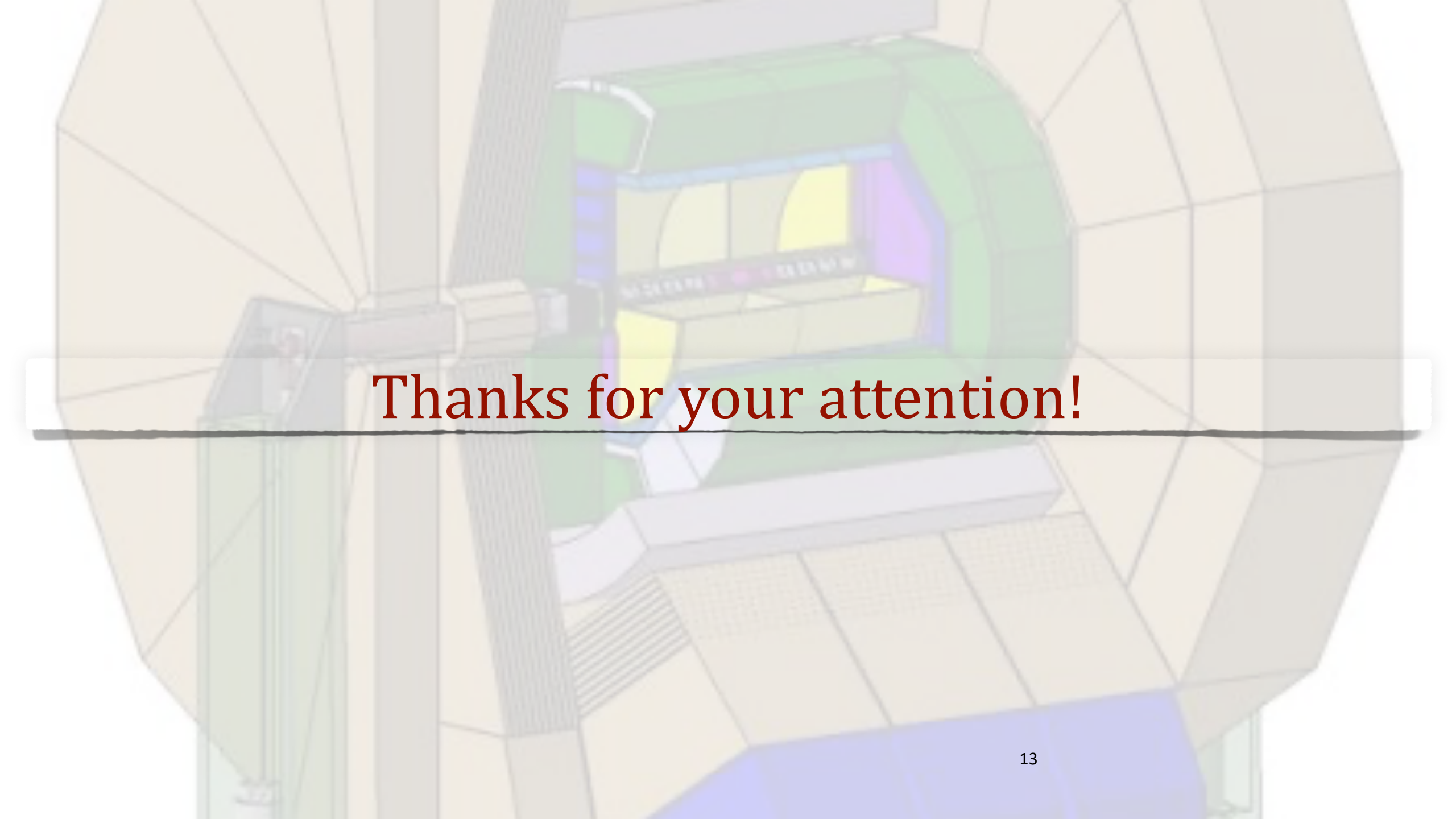


Pythia8+SGV (FCC240, ILD-for-FCC detector)

Summary & outlook

ILD at a Higgs factory: a broad and well-motivated direct BSM programme

- **Exotic scalars** — new ILD preliminary results at 550 GeV; limits down to $10^{-3} - 10^{-4} \times \sigma_{SM}$, two orders of magnitude below LEP, across all channels *(ILD preliminary)*
- **Leptophilic Z'** — first ILC/LCF direct result in Le–Lμ model; g' limits ~10^{-3}, competitive with FCC-ee; selected for ESPP Briefing Book
- **SUSY** — full ILD simulation covers the complete m–Δm plane to √s/2 for staus and higgsinos — no holes, discovery ≈ exclusion reach
- **Heavy Neutral Leptons** — reach to kinematic limit; Dirac/Majorana discrimination simultaneous with 5σ discovery; full 3D coupling space requires complementary colliders
- **Dark matter** — mono-photon: g_{eeY} limits O(10^{-3}) to kinematic limit; EFT scale Λ up to ~4 TeV; polarisation enables mediator scenario identification
- **Long-lived particles** — Higgs decays to LLPs: BR(H→ss) limits 10^{-4}–10^{-5}; TPC covers cτ from mm to ~10 m — four orders of magnitude in lifetime
- **Dark sectors**
  —Dark photons: full ILD simulation of A_D → $\mu^+\mu^-$; ε limits ~few × 10^{-4} above M_Z, better than HL-LHC;
  —Hidden Valley azimuthal correlations: clear signal peaks for wide range of communicator and qv masses; validated for ILC and FCC-ee configurations



Thanks for your attention!