Searches for feebly interacting new particles at FCC-ee

65th ICFA Advanced Beam Dynamics Workshop on High Luminosity Circular e+e- Colliders (eeFACT2022)

12-15 September 2022 LNF Frascati (Rome)

Monica Verducci Universita’ e INFN Pisa (monica.verducci@cern.ch)

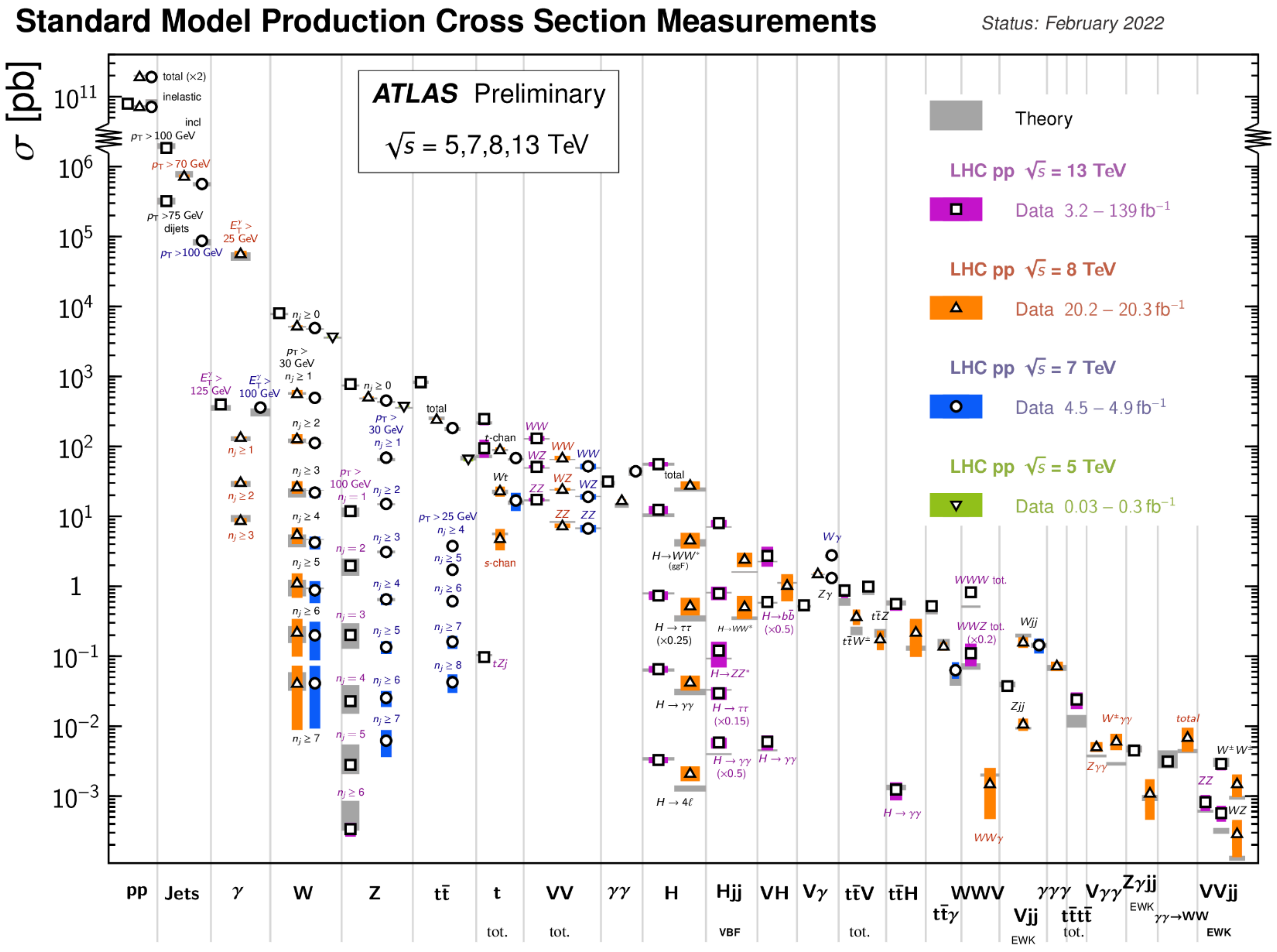
For the informal working group Long-lived particles at the FCC-ee

IN SUPREMÆ DIGNITATIS 1343
UNIVERSITÀ DI PISA

FCC

Motivation for Feebly Interacting Particles FIPs

- The SM theory has successfully explained almost all experimental results and precisely predicted a wide variety of phenomena!
  - The SM is currently the best description there is of the subatomic world, but it does not explain the complete picture. Still some open questions as hierarchy problem, the origin of neutrino masses or dark matter etc..
- Light new states as FIPs are present in many models that address the fundamental outstanding questions within the standard model (SM)!



Genesis of the feebly interacting particles FIPs

How to couple light degrees of freedom to the SM while being consistent with all possible constraints: its symmetries and mass spectra, respect the actual phenomenologies?

- Idea: add new particle feebly coupled to the SM via a portal term (suppressed).

$$\mathscr{L} = \mathscr{L}_{SM} + \mathscr{L}_{NON-SM} + \mathscr{L}_{INT}^{Portal}$$

Portal Type	SM Operator	FIP Operator	Dark Sector /FIP	
Scalar Portal	$\vert H\vert^2 (d=2)$	$\vert S\vert^2$	Dark Higgs	Mixes with standard Higgs
Vector Portal	$F_{\mu\nu}(d=2)$	$F'^{\mu\nu}$	Dark Photon	Mixes with photon
Neutrino Portal	$LH\ (d=5/2)$	N	HNL	Mixes with neutrino
Pseudoscalar Portal	$\bar{f}_i \Gamma^\mu f_j (d=3)$	$\partial_\mu a$	ALP	Direct interaction with fermion
Fermion Portal	$\bar{f}_i \Gamma^\mu f_j (d=3)$	$\Psi \Gamma_\mu \Psi$	dark fermion	

FIPs Searches @ FCC

- The FCCee provides an excellent opportunity to probe these new particles with masses between 1 and 100 GeV and their electroweak couplings.
  - Tera-Z run: Huge gain in sensitivity for feebly-coupled new particles with mass in ~ 1 — 91 GeV range (also in H decay)
  - The open parameter space is moreover still very large and provides an excellent opportunity for the FCCee.
  - **This mass range is difficult to access for the LHC and Tevatron due to trigger limitations and large backgrounds, while the particles are too heavy to be produced at Belle II**

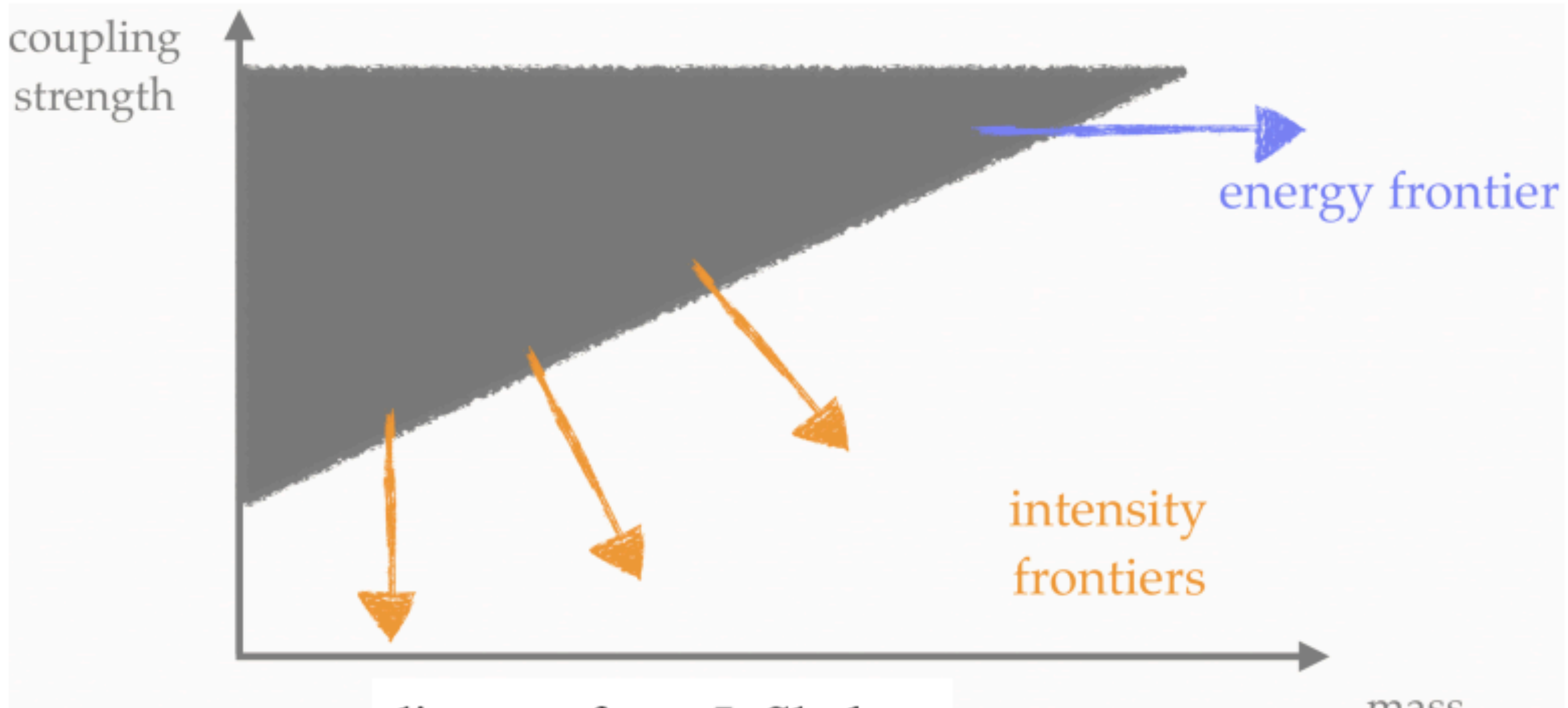


diagram from J. Shelton

Experimental approach:

- Broad model-independent search program
- Long-lived signatures are explored
- Today's talk: Axion-like particles (ALPs) and Heavy Neutral Leptons (HNL)

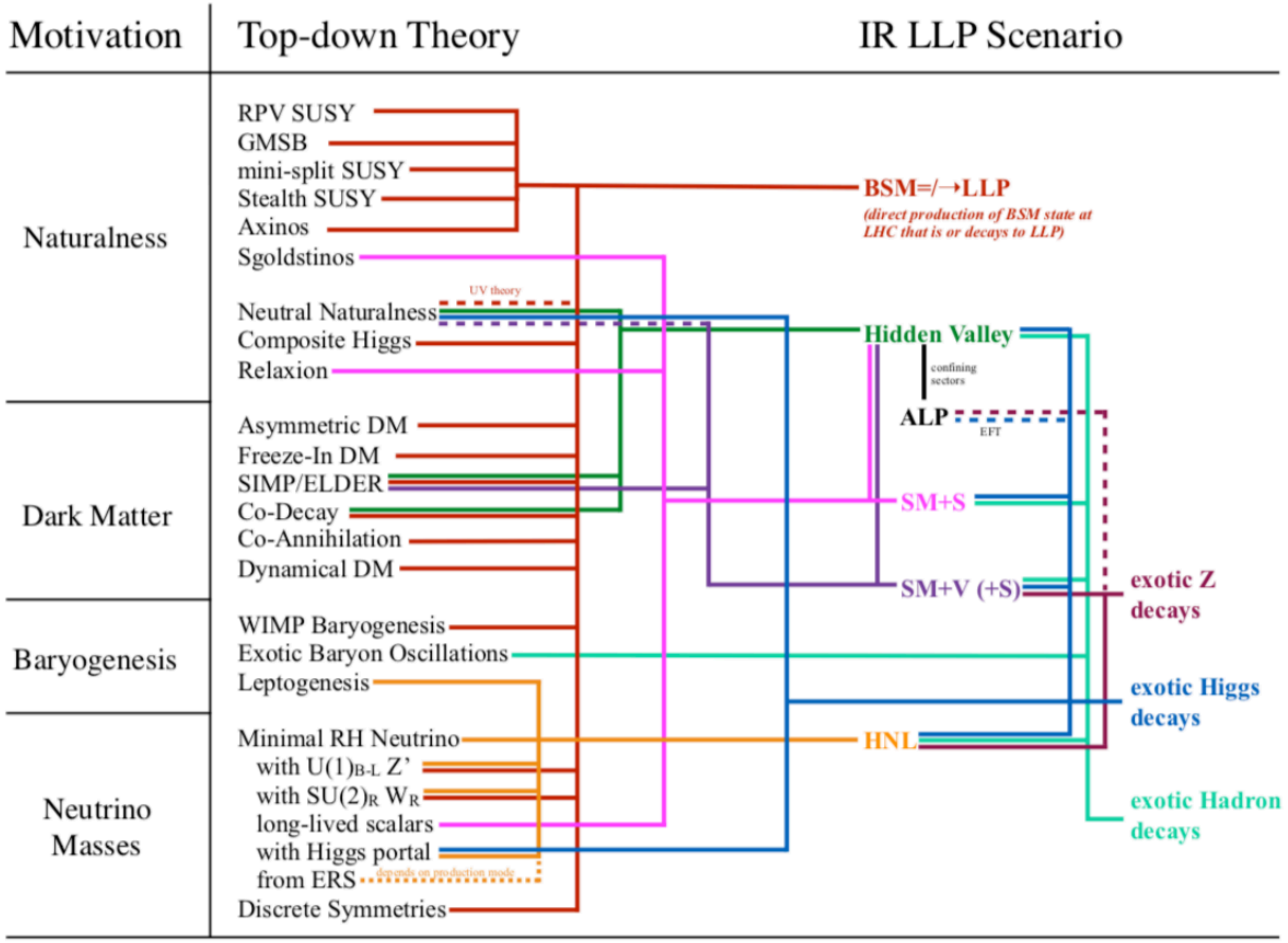
Distance travelled by particles:

$$L = v\,\tau\,\gamma \propto c\,\frac{1}{\epsilon^2 m}\,\frac{E}{m}$$

Phenomenology of the FIPs

A characteristic of weakly interacting (light) particles is the possibility to have a long lifetime

- Distinct signatures
- Opportunity for exploration in **future colliders** and dedicated experiments



Curtin et al, arXiv 1806.07396, *Rept.Prog.Phys.* 82 (2019) 11, 116201

large cτ, small Γ

- Large mass hierarchies
- Compressed spectra
- Small couplings

EW Baryogenesis
Dark Matter
Hierarchy Problem
Neutrino Masses

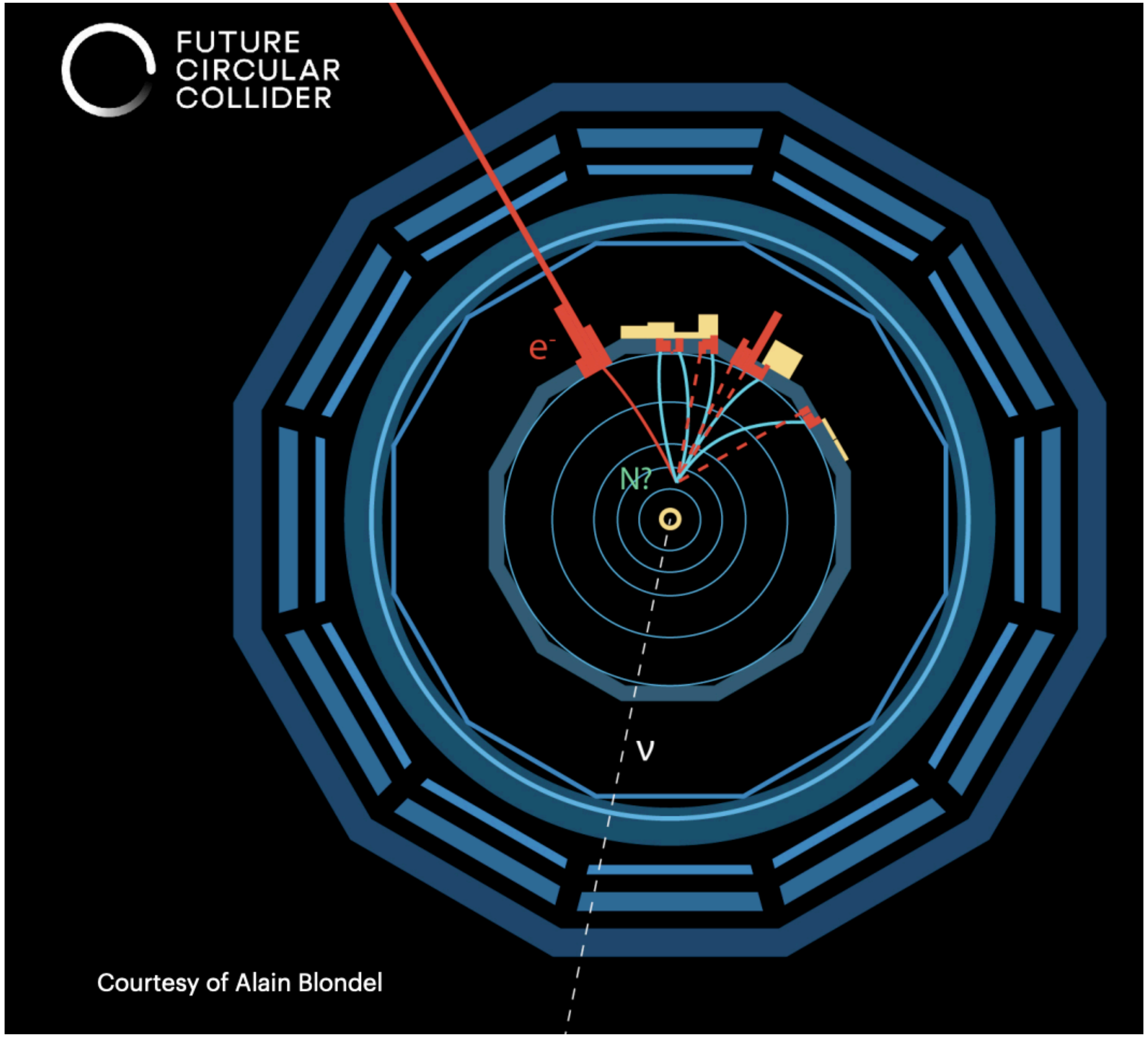
BSM Models: Supersymmetry, dark QCD, RH neutrinos , Neutral Naturalness, Higgs Portal, Z′ Portal, Hidden Valleys, ..

Challenges with Long-Lived Particles

- These unconventional signatures could be very complicated if the detectors are not built with LLPs as main target!

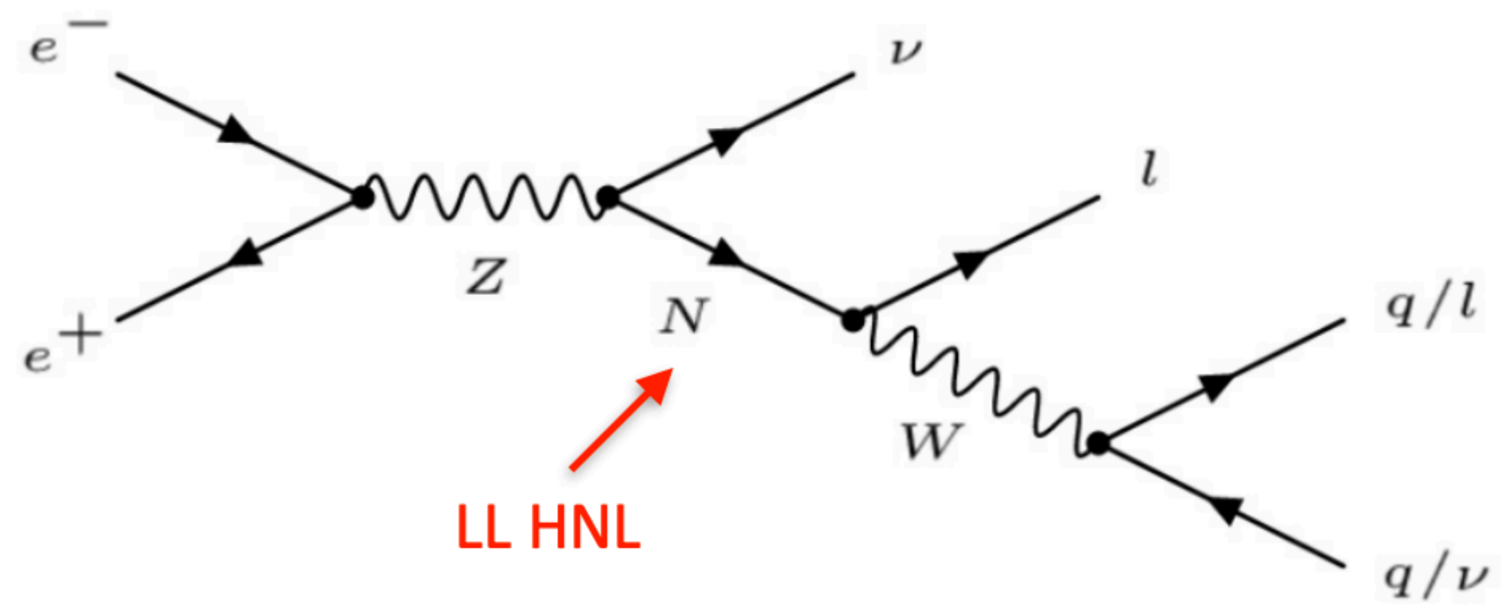
- The signal event reconstruction and selection, as the background estimation, need dedicated and very specialised techniques.
  - Require customised trigger and self-made objects reconstruction algorithm
  - Detector-signature based search. Experimentally very diverse, depending on particles' properties (dE/dx, Time-of-flight, displaced vertex)
  - Requires non-standard analysis strategies and tools
    - Non-standard background (cosmic-ray muons and Beam Induced background), generally data-driven estimation since complicated to simulate in Monte Carlo
    - Reinterpretation: Use search based on a benchmark model to set constraints on other models. Particularly difficult since there is no common definition of LLP objects.

Heavy Neutral Leptons



Heavy Neutral Leptons HNLs

- **HNLs** represent one renormalisable **"portals" to a BSM secto**r (e.g. "dark sector") and are predicted by many extensions of the SM (MaD 1303.6912 , Abdullahi et al 2203.08039).
  - Motivated by some open questions of the SM: Neutrino masses, Baryon asymmetry, Dark matter….
- **Production via $e^+e^- \rightarrow Z \rightarrow \nu N$, with long-lived $N \rightarrow lW*$**
  - Right-handed, sterile neutrinos: mixing limit extended down several orders of magnitude close to seesaw limit
  - N lifetime and lepton angular distribution to distinguish Majorana vs. Dirac nature of N
    - Dirac or Majorana: Symmetries of nature, identify underlying neutrino mass model and connection to baryogenesis/leptogenesis



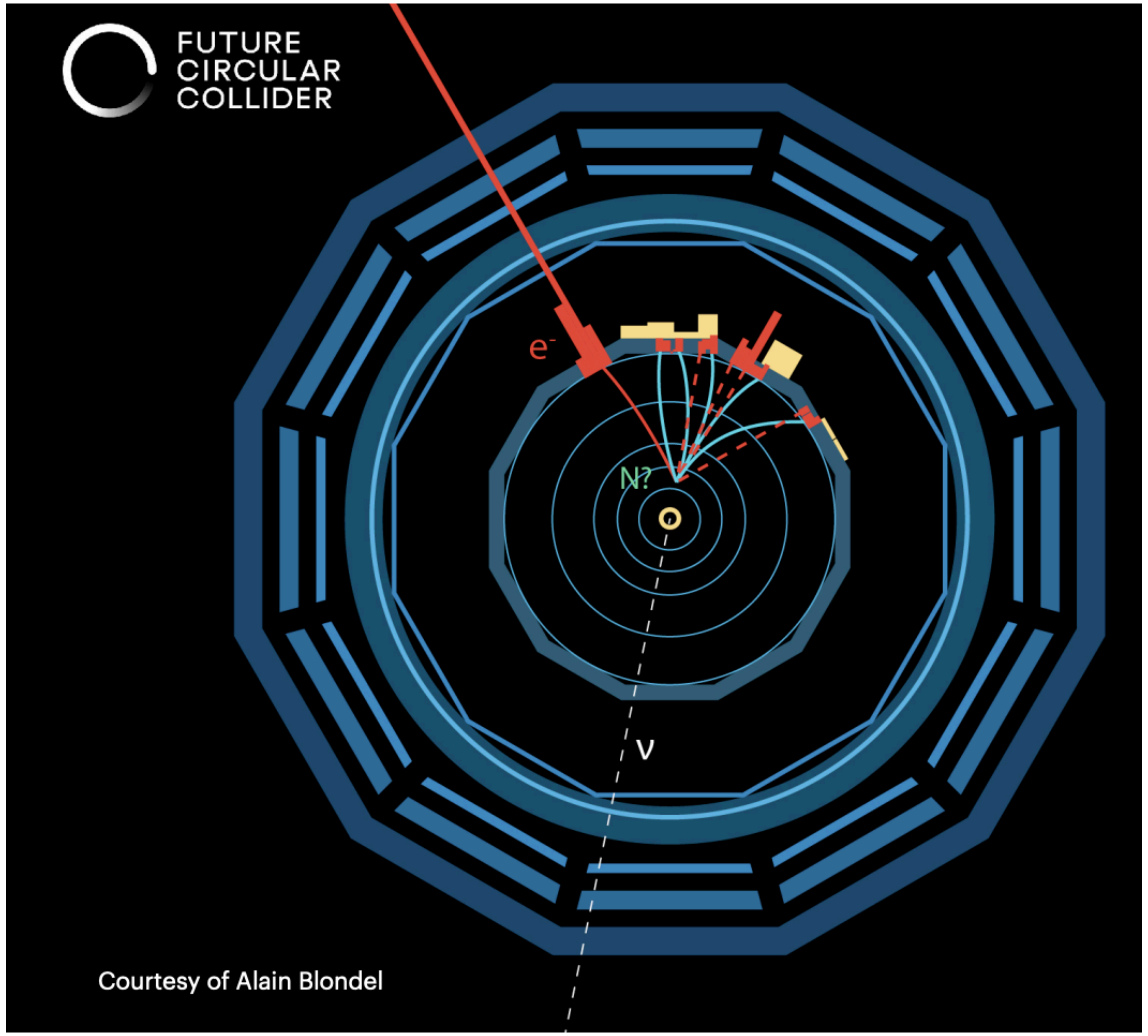
$$L \sim 0.025\text{m} \left(\frac{10^{-6}}{V_l}\right)^2 \left(\frac{100\ \text{GeV}}{m_N}\right)^5$$

- **Model**: One flavour of HNLs N, Couples to SM only through mixing θ with SM neutrinos (e, μ, τ) Model with five parameters : M, θ_e, θ_μ, θ_τ, and R_{ll}. (R_{ll} is ratio of lepton number violating (LNV) to lepton number conserving (LNC) N decays; R_{ll} = 1 for Majorana N and R_{ll} = 0 for Dirac N.)

HNL Long-lived

Blondel et al. 1411.5230

- Many of the current limits cover high neutrino mixing values
  - For low values of the neutrino mixing angle, the decay length of the heavy neutrino can be significant
- HNL could decay ~1m away from the collision point
  - Secondary vertex in the middle of the tracking system: displaced vertex search
- Background-free searches
  - Instrumental and cosmic background to be studied
- For HNL with long enough lifetime → oscillations can also be studied arXiv:1709.03797

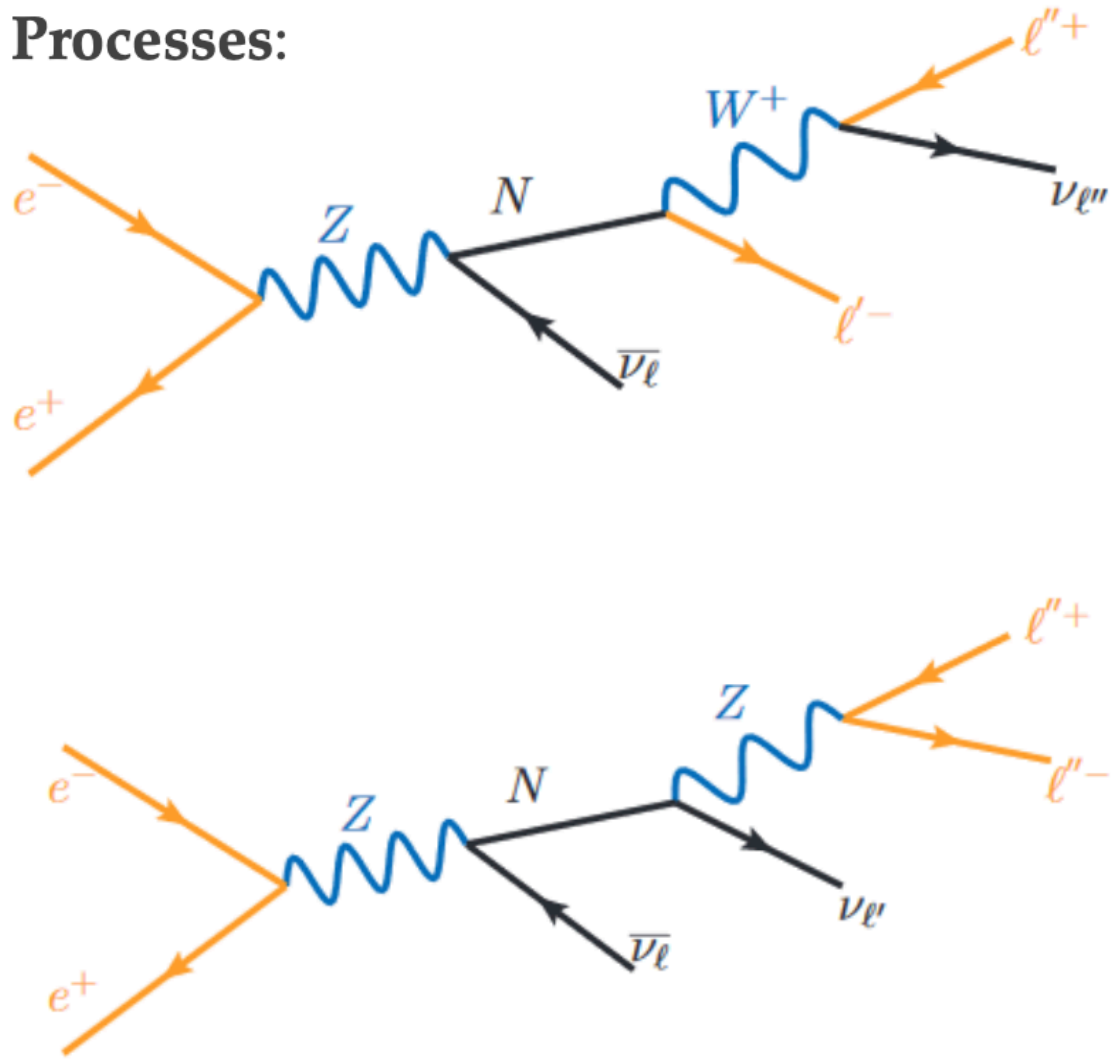


HNL Model

Generated Samples with Majorana and Dirac HNLs: full chain Madgraph5 v3.2.0 + Pythia8 + Delphes, with the latest IDEA card.

- $\sqrt{s} = 91$ GeV
- Get long-lived HNLs when coupling and mass are small. **Largest event numbers: displaced vertices in Z-pole run**
- Neutrino in final state unobservable, 4-momentum of N can still be fully reconstructed
- Maiorana/Dirac N: Angular distribution of final state particles and polarisation of final state particles [Blondel et al. 2105.06576]

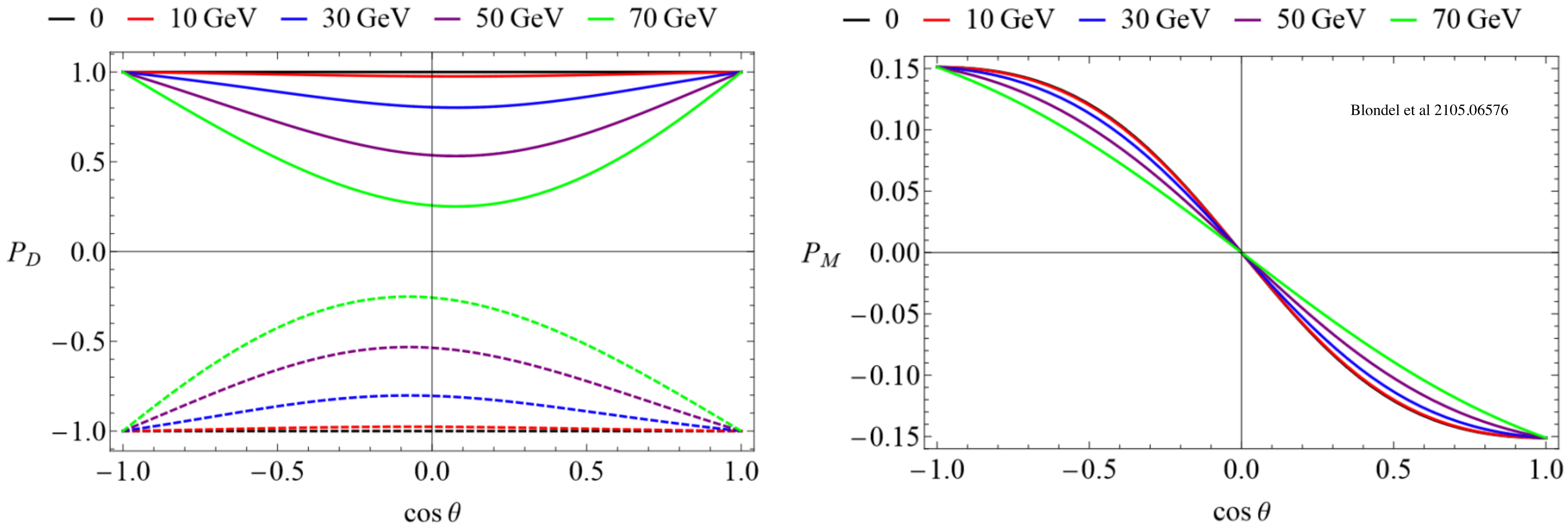
Processes:

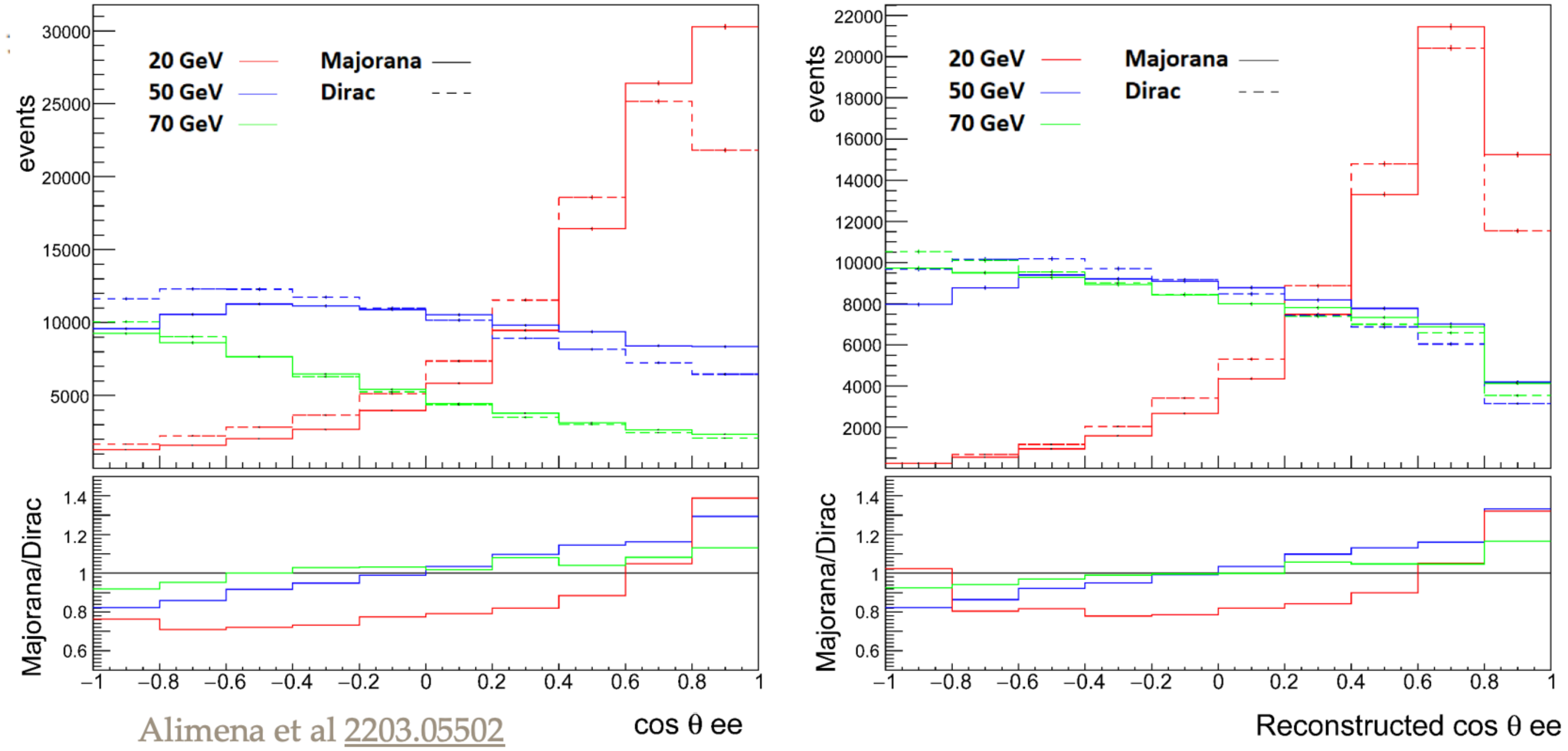


$$\textbf{Majorana } N: e^+e^- \to Z \to N\nu_e + N\overline{\nu_e}, \quad \text{with} \quad N \to e^+e^-\nu_e + e^+e^-\overline{\nu_e},$$
$$\textbf{Dirac } N: e^+e^- \to Z \to N\overline{\nu_e} + \overline{N}\nu_e, \quad \text{with} \quad N\ (\overline{N}) \to e^+e^-\nu_e\ (\overline{\nu_e}),$$

HNL Polarization impact on Leptons

- **Dirac N and anti-N individually are highly polarised**, can only decay into lepton or anti-lepton, respectively.
- Majorana N are only mildly polarised and decay into leptons of either charge
- Lepton spectrum in HNL decay depends on polarisations.





Alimena et al 2203.05502

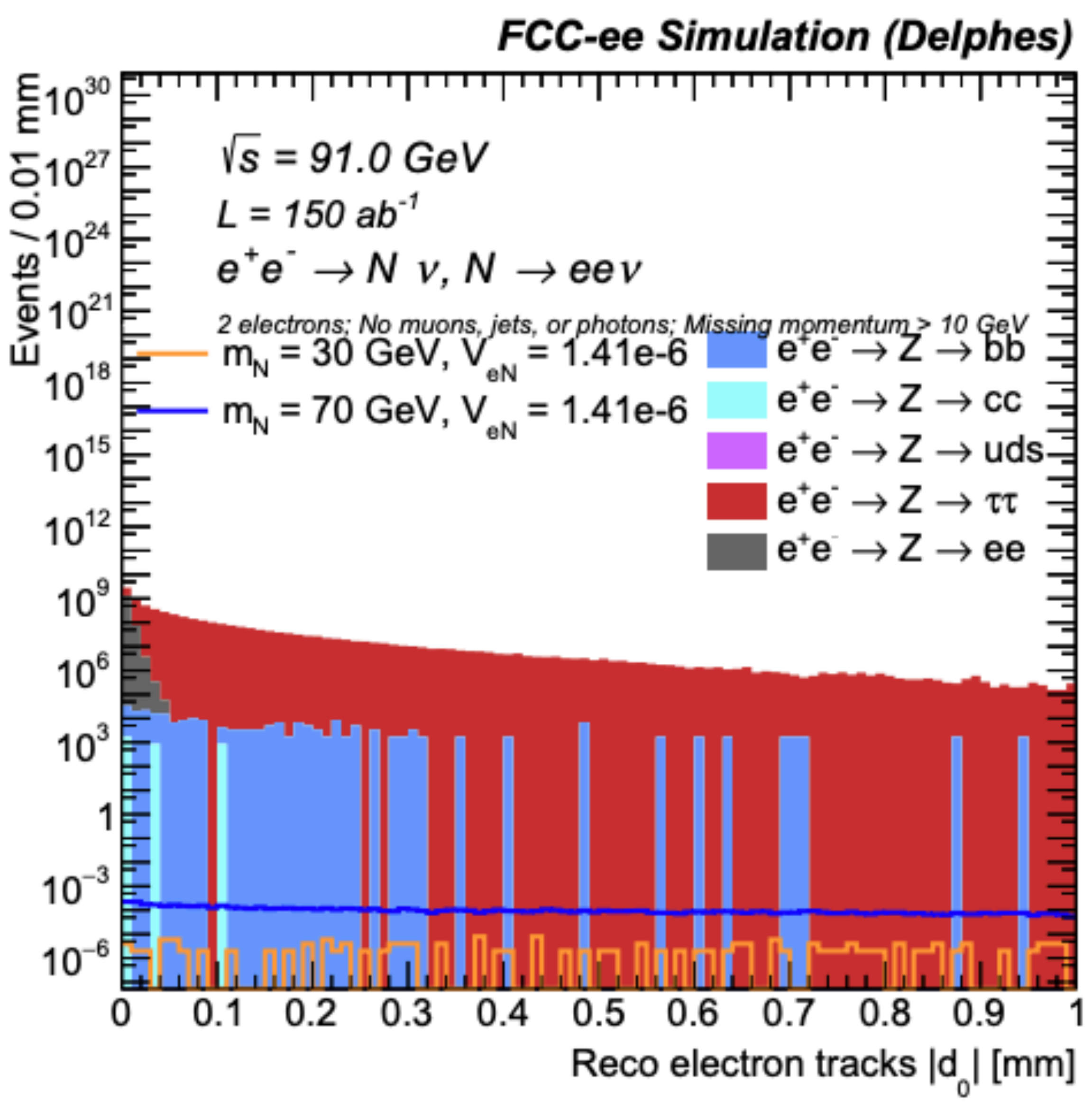
Simulated Samples

Analysis and Sample Produced

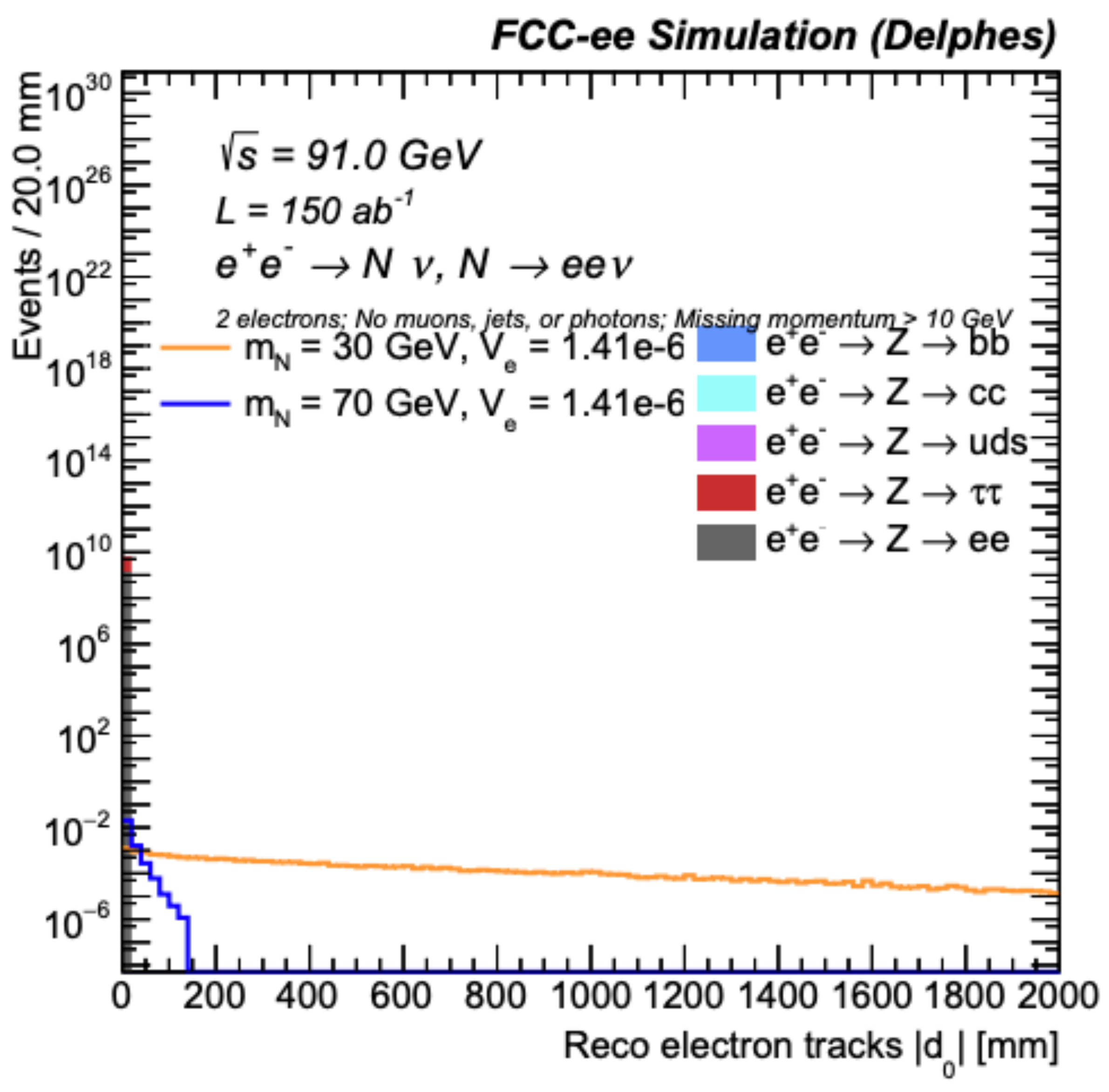
Event Selection Applied:

- **exactly two electrons, and no photons, jets, or muons.** These requirements substantially reduce the background from light and heavy quarks.
- **Missing Momentum> 10 GeV**, which is particularly effective at reducing Z → ee events with spurious missing momentum associated with finite detector resolution.
- **both electrons are displaced with $|d_0| > 0.5$ mm**

0–1 mm



0–2000 mm



axXiv:2203.05502

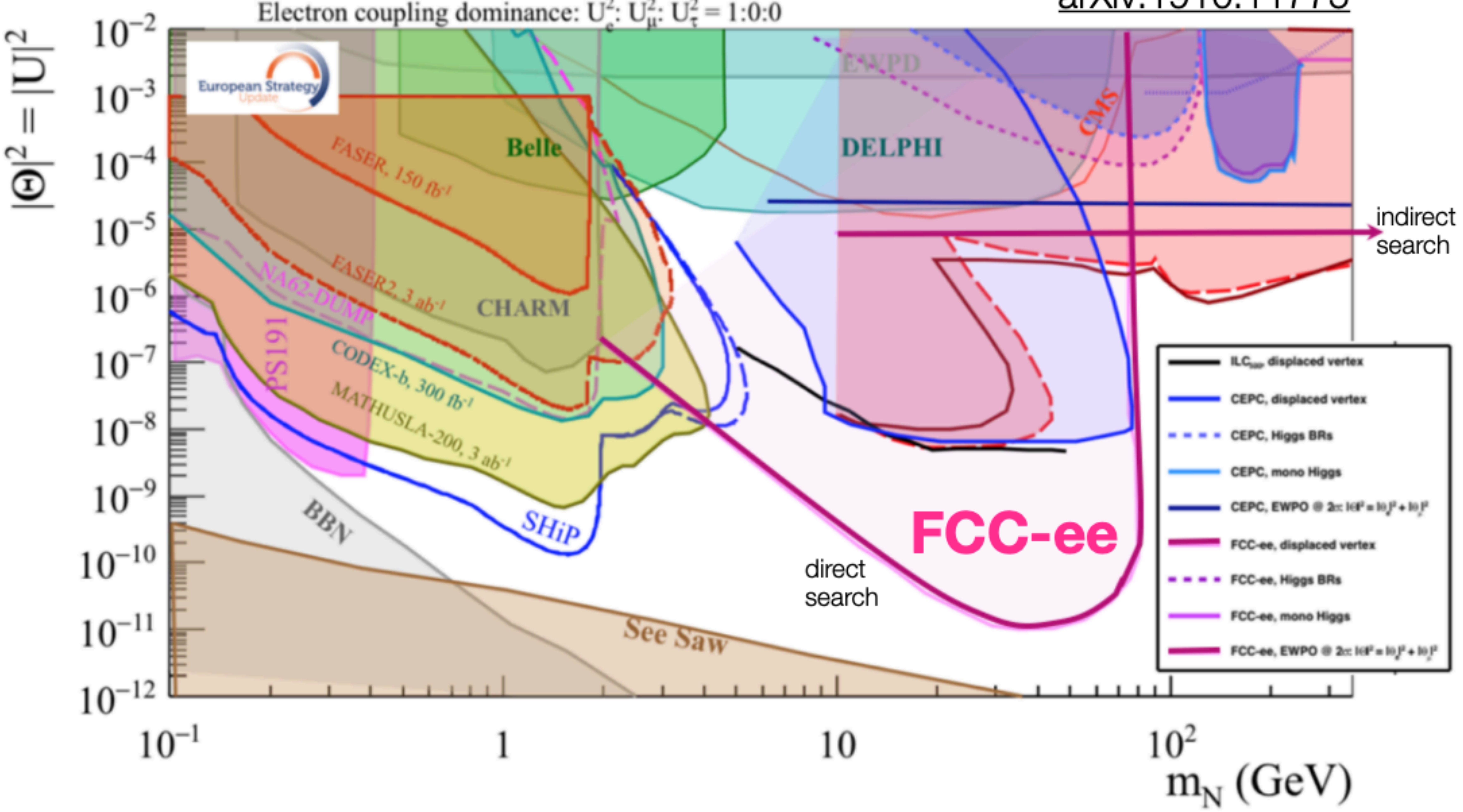
Background Samples

- $Z \to e^+e^-, \tau^+\tau^-, Z \to q\bar{q}$

FCC Prospects

FCC will probe space not constrained by astrophysics or cosmology, complementary to accelerator and neutrino prospects

arXiv:1910.11775



Complementary FCC-ee/-hh/-eh

FCC-ee:

- Direct search: single HNL production in Z decays
  Sensitive to 10^{-11} M below the W mass FCC-hh

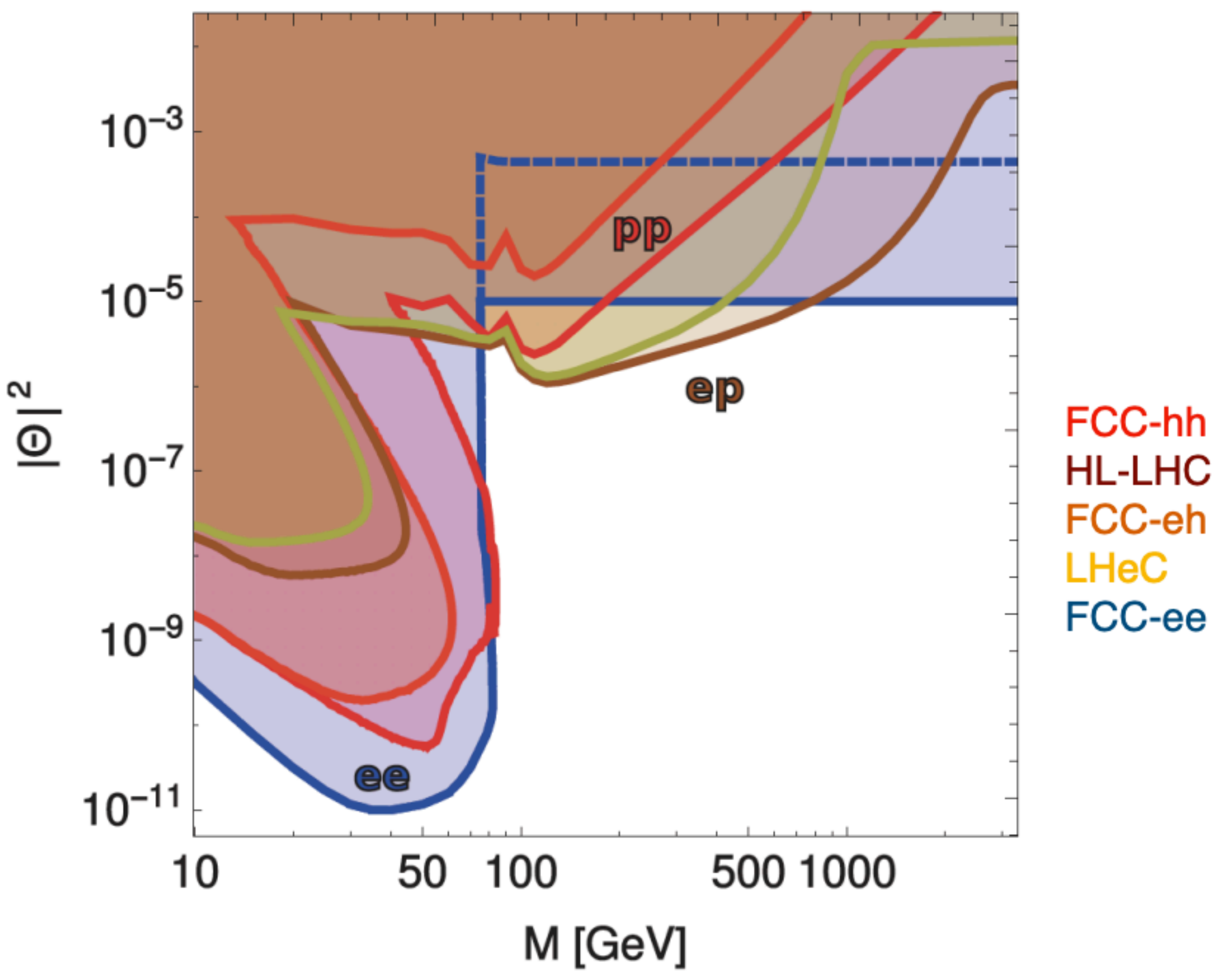
FCC-hh:

- Direct search: single HNL production in W/Z decays
  Lepton Number Violation, Lepton Flavor Violation can test heavy neutrinos with masses up to ~2 TeV

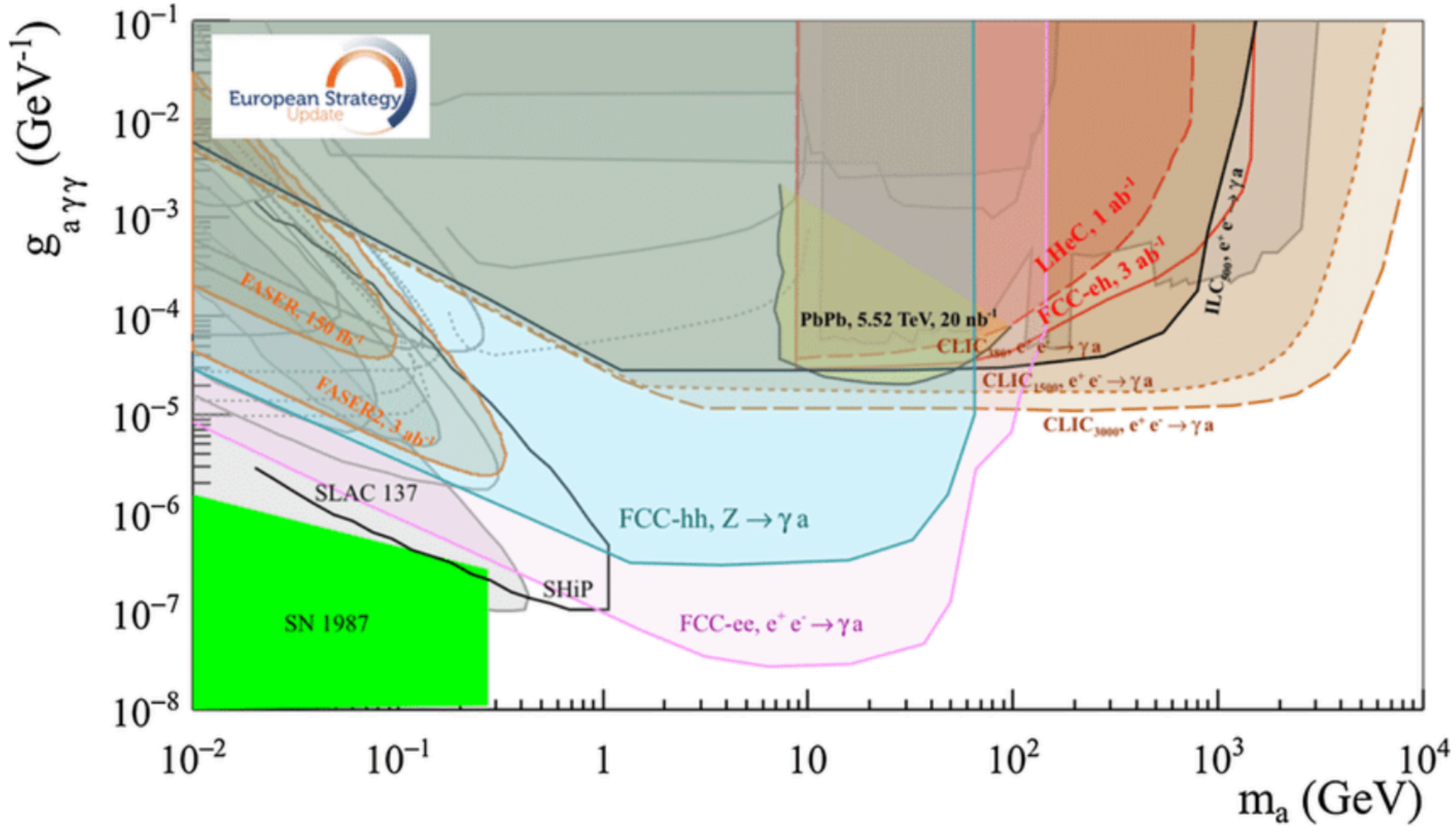
FCC-eh

- Can extend the reach of the FCC-hh up to ~2.7 TeV
  Best reach above W mass Sensitive to LFV and Lepton-Number-violation signatures

arXiv:1612.02728

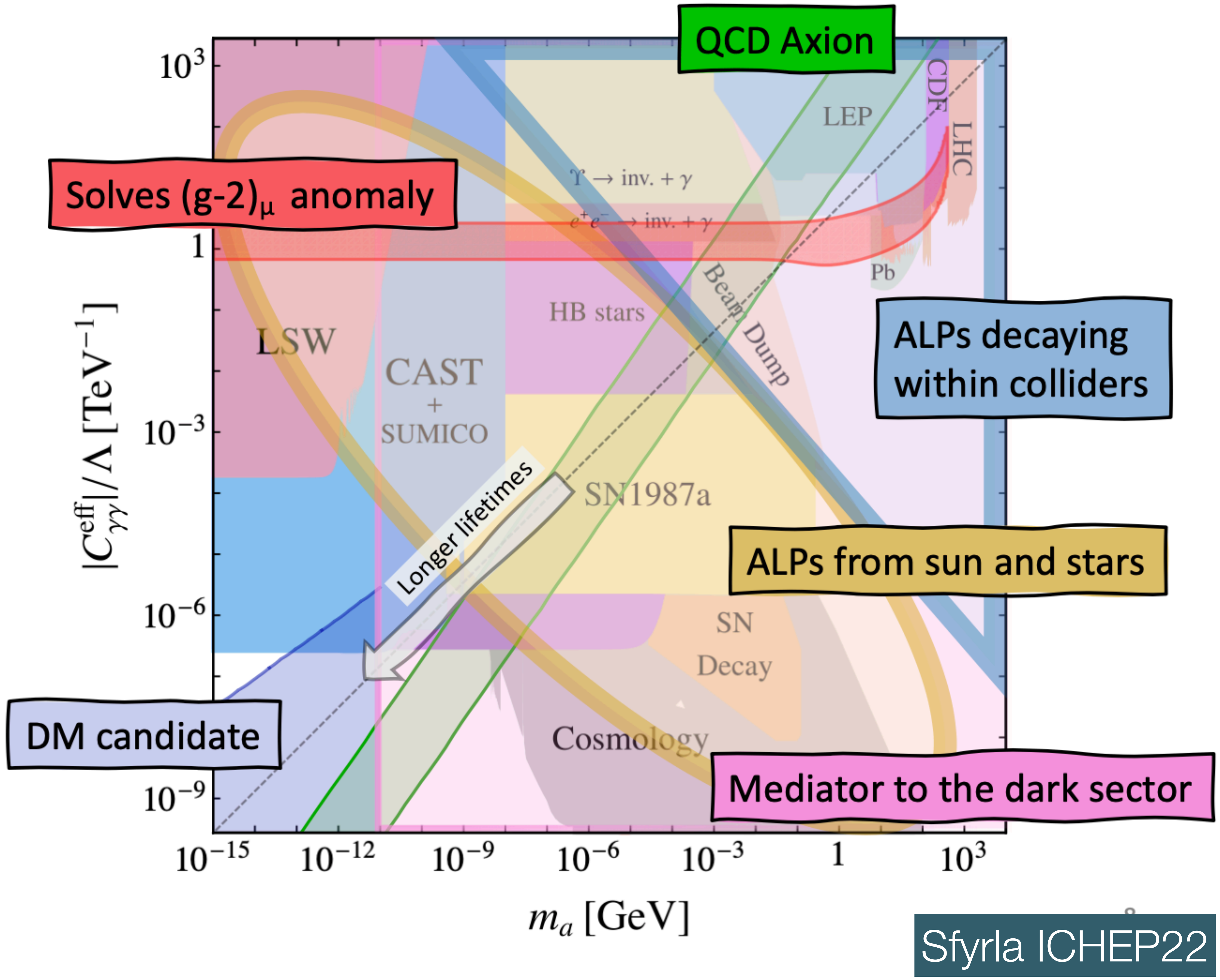


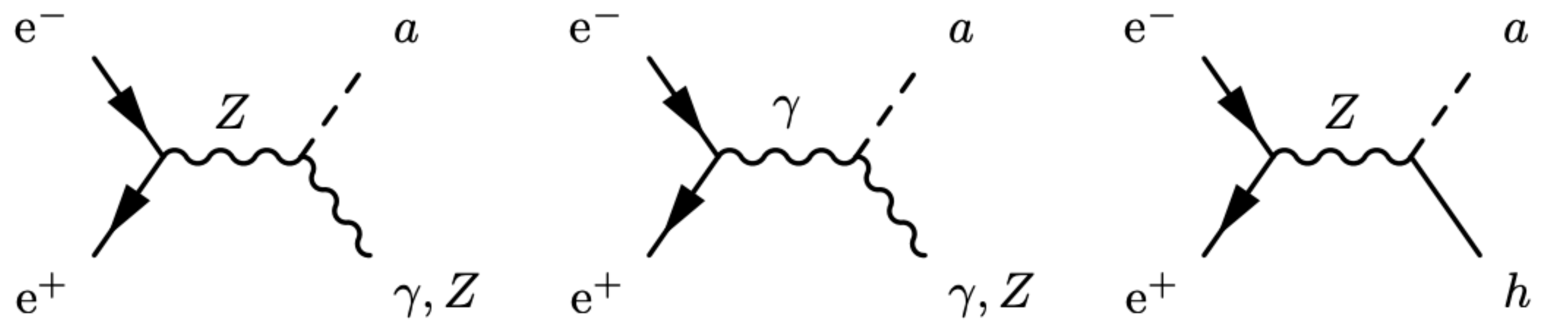
Axion-Like Particle

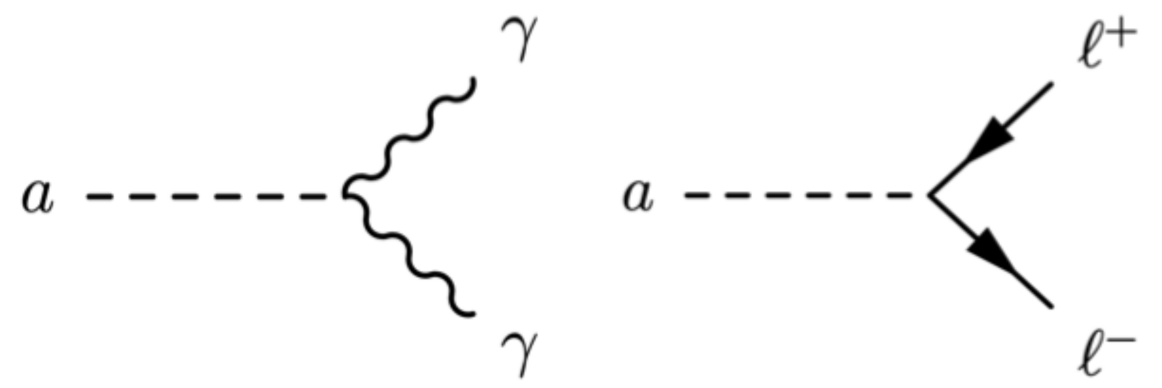


Axion-like Particles ALPs

- **Axion-like Particles (ALPs) are pseudo Nambu-Goldstone bosons** of spontaneously broken global symmetries in BSM scenarios, also in composite Higgs Model and EW baryogenesis.
- “Low” mass particles with suppressed couplings to SM: get long-lived ALPs
- BR to SM particles depends on their mass
- Especially sensitive to final states with at least 1 photon. Couplings to H accessible similar for couplings to Z. Resonant production suppressed.







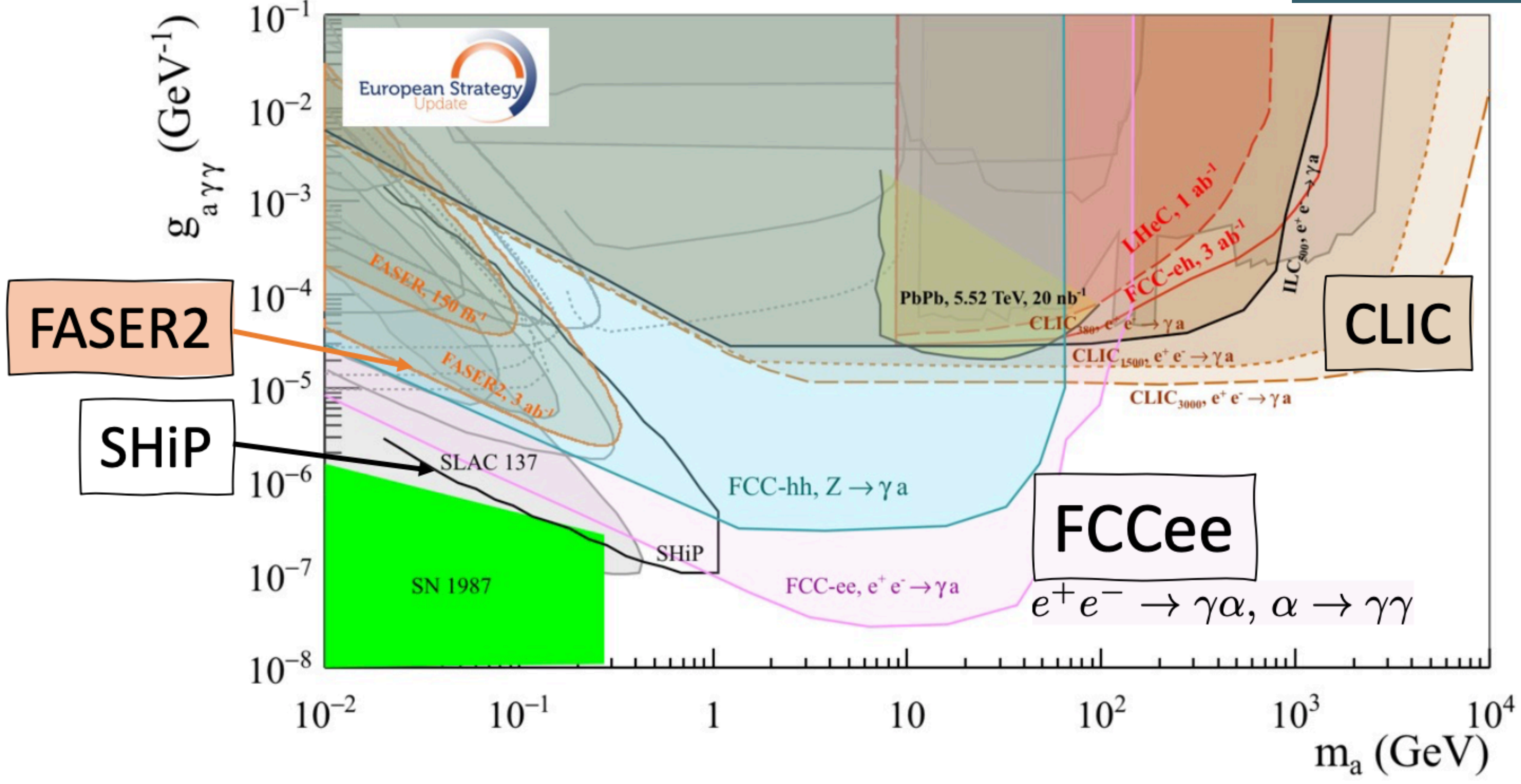
ALPS@FCC

Recent review – input to Snowmass – arXiv:2203.06520

Sfyrla ICHEP22

At the FCC-ee:

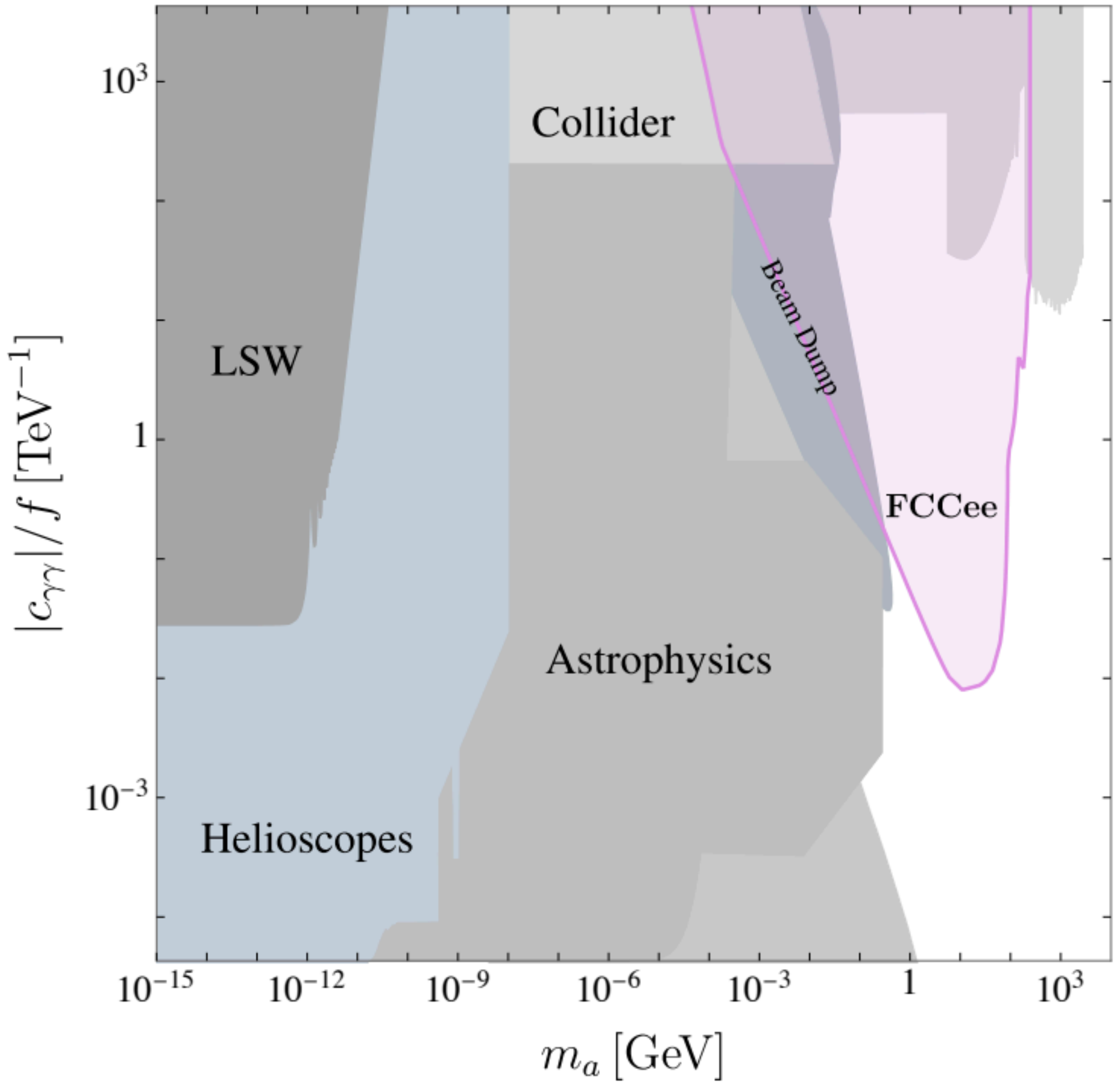
- Orders of magnitude of parameter space accessible
- Decays to SM particles other than photons are less constrained
- Status: implemented and tested baseline ALP configuration in FCC framework, starting to generate in Madgraph



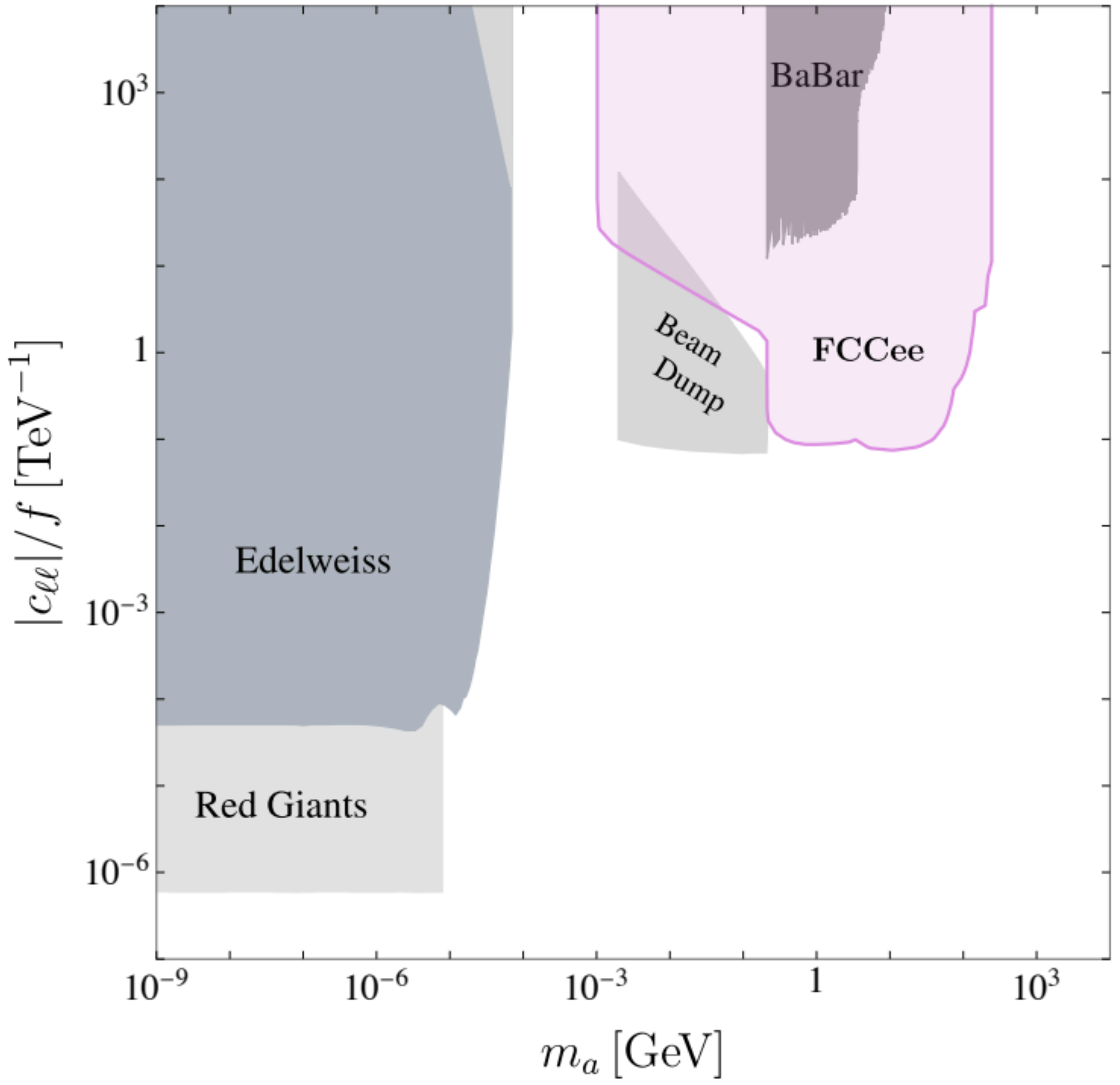
The sensitivity provided by FCC-ee uniquely extends other limits by up to four orders of magnitude in the 1-100 GeV mass range

ALPs: Projected sensitivity of FCC-ee for $e^+e^- \to \gamma a$

These searches are sensitive to ALP decay lengths of up to 1.5 m ($e^+e^- \to \gamma a \to 3\gamma$) and 2 cm ($e^+e^- \to \gamma a \to \gamma l^+l^-$). The search for long-lived ALPs may be significantly improved with the installation of a dedicated far detector that could probe decay lengths of up to 100 m.



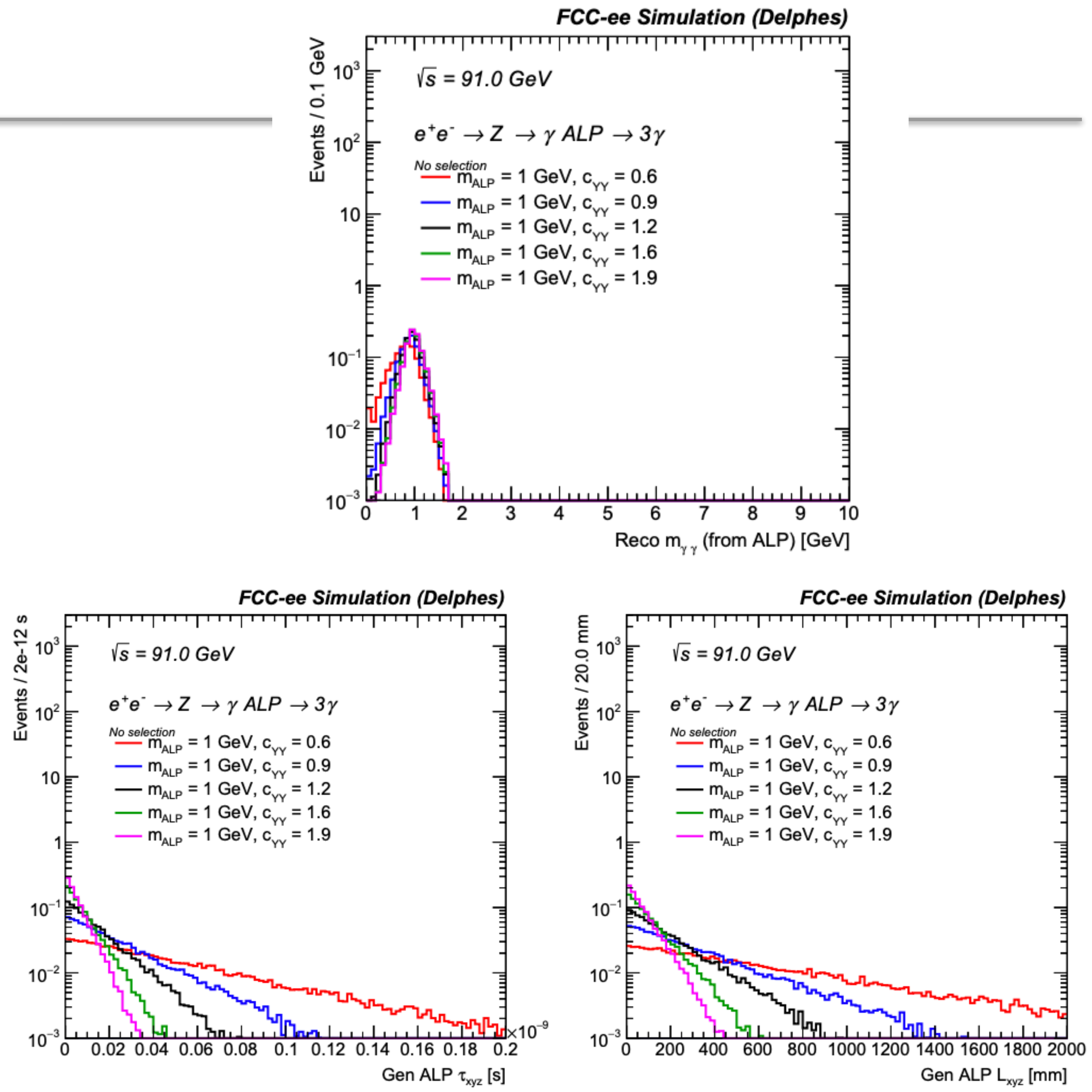
$e^+e^- \to \gamma a \to 3\gamma$



$e^+e^- \to \gamma a \to \gamma l^+l^-$

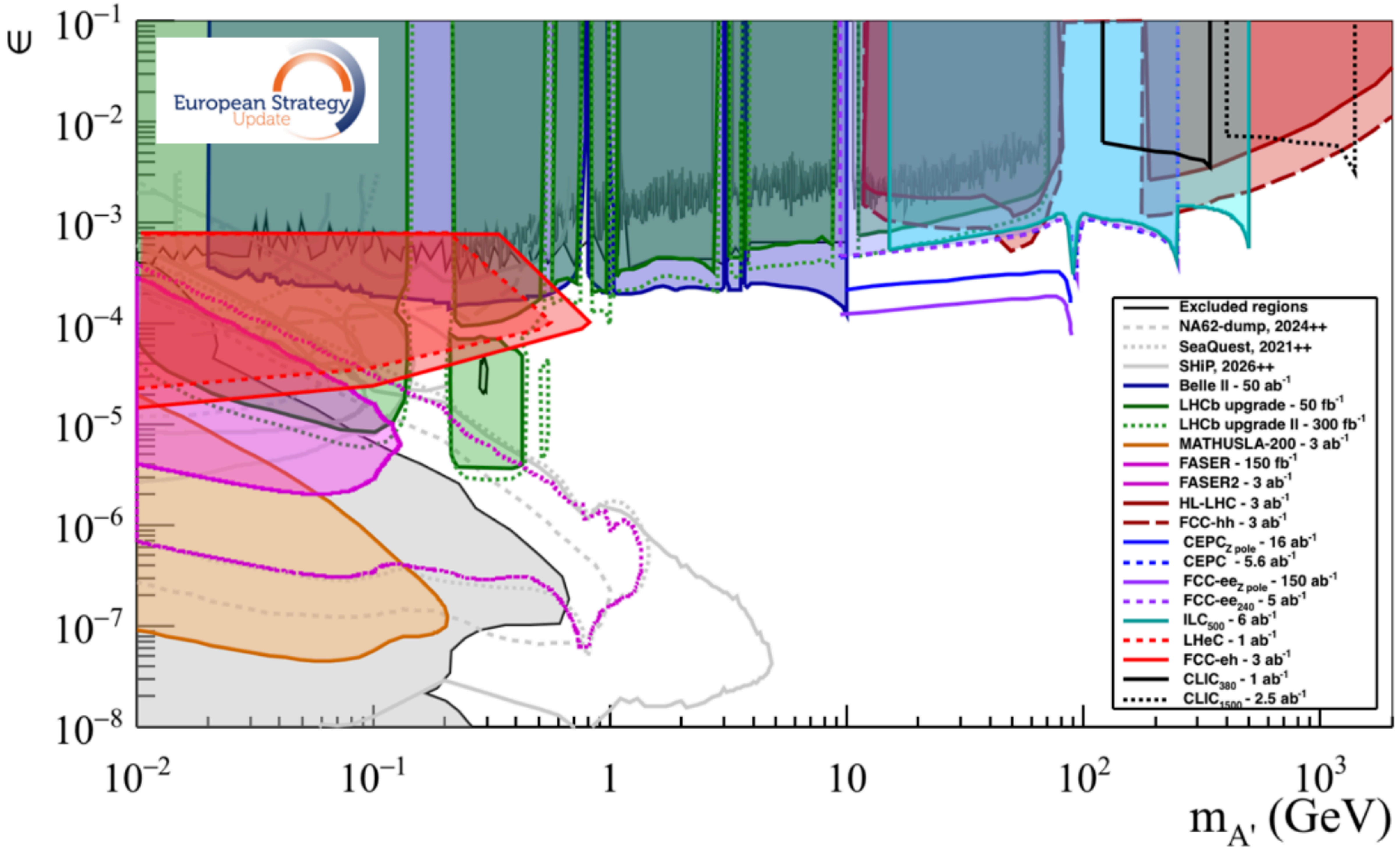
ALPs Analysis

- **Generated Samples: full chain Madgraph5 v3.2.0 + Pythia8 + Delphes, with the latest IDEA card.**
- ALP kinematics for m_{ALP} = 1 GeV and several benchmark choices of the coupling $c_{\gamma\gamma}$.
- Key Observables for distinguishing ALPs from background and different mass/couplings: $M_{\gamma\gamma}$, L_{xyz}, τ_{xyz}
- **Detector side:** Calorimeter and precision timing variables will be extremely helpful .

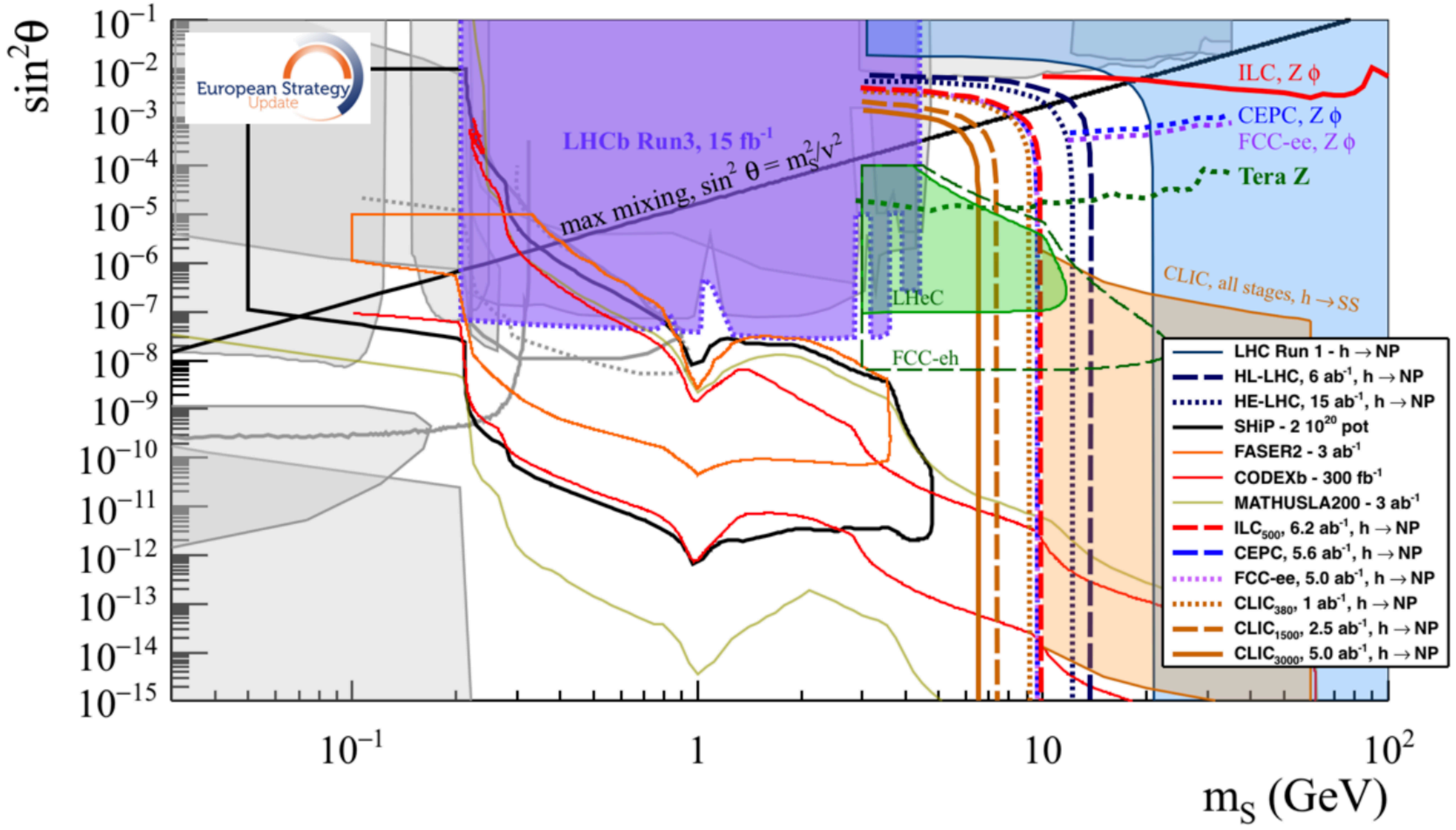


Sensitivity to other Portals

arXiv:1910.11775



Dark Photon



Dark Scalar mixing with the Higgs boson

Conclusions

- FCC-ee will push the intensity frontier of particle physics , in particular we expected to collect $5x10^{12}$ Z bosons at Z-Tera Runs
- **Feebly interacting new particles**, could be investigated in a phase space where no other experiment will ever have sensitivity
  - HNL and ALP sensitivity presented.
- **Detector requirements:**
  - Need to be sensitive to vertices from mm to m (displaced vertices identification)
  - Calorimetry system with high granularity.
  - Extended sensitive material (additional detectors?)
  - Trigger (online) selection prepared to filter these events

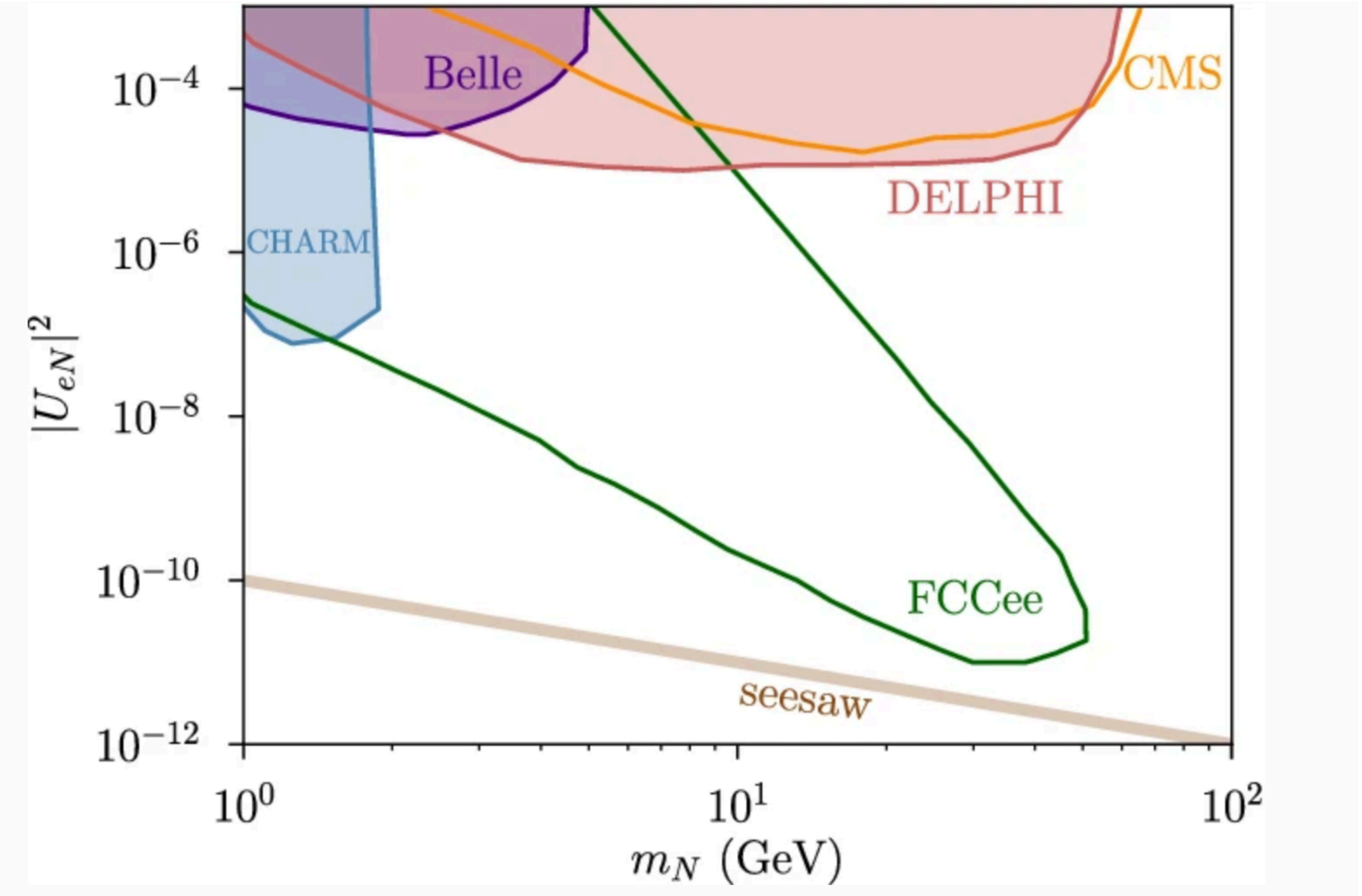
Backup

Portal Type	Operator	Dark Sector /FIP
Scalar Portal	$\mathcal{L}_S \supset \mu S H^\dagger H + \lambda S^2 H^\dagger H$	Dark Higgs
Vector Portal	$\mathcal{L}_{A'_\mu} \supset \epsilon F'_{\mu\nu} B_{\mu\nu}$	Dark Photon
Neutrino Portal	$\mathcal{L}_N \supset y_{ai}(L_a H) N^i$	HNL
Pseudoscalar Portal	$\mathcal{L}_a \supset a\left(\frac{F_{\mu\nu}\widetilde{F}^{\mu\nu}}{4f_\gamma} + \frac{G_{\mu\nu}\widetilde{G}^{\mu\nu}}{4f_g}\right) + \frac{\partial^\mu a}{f_f}\bar{f}_i\gamma^\mu\gamma^5 f^i$	ALP
Fermion Portal		dark fermion

HNL

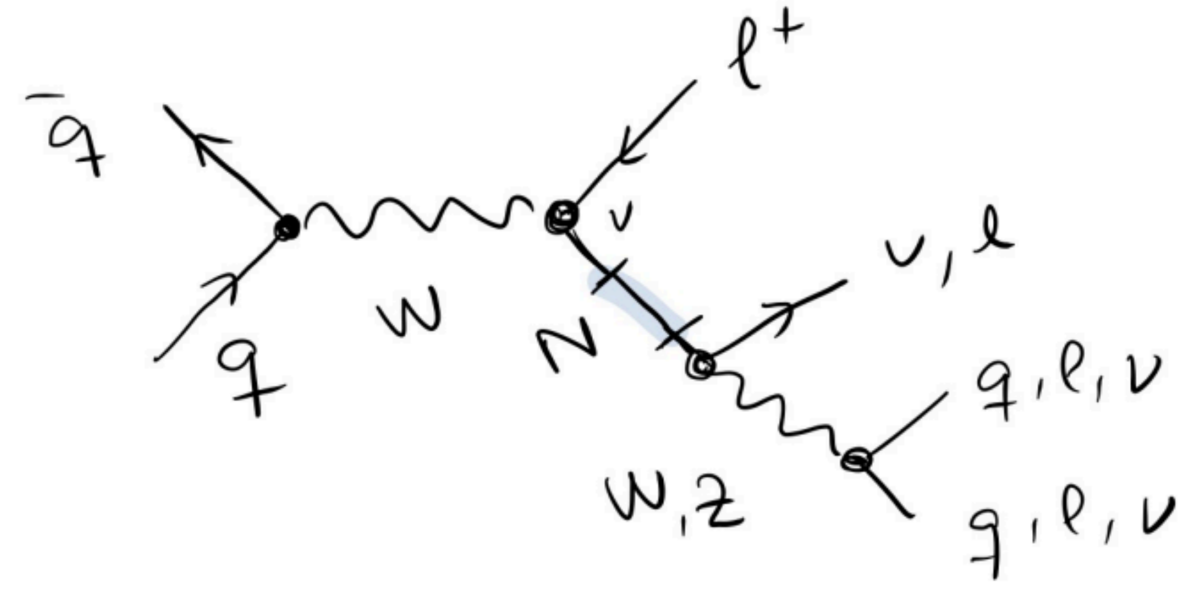
$$\mathcal{L} \supset -\frac{m_W}{v}\overline{N}\theta^*_\alpha\gamma^\mu e_{L\alpha}W^+_\mu - \frac{m_Z}{\sqrt{2}v}\overline{N}\theta^*_\alpha\gamma^\mu\nu_{L\alpha}Z_\mu - \frac{M}{v}\theta_\alpha h\overline{\nu_{L\alpha}}N + \text{h.c.}$$

single HNL with mass m_N, compared with the sensitivity of the FCCee, assuming couplings to the first lepton generation only



FCC hh -> HNL from W decay

- FCC-hh high luminosity and large centre of mass energy will help probe additional parameter space
  - High mass, but mixing angles of interest to neutrino mass models not accessible At the 100 TeV pp, 10^{13} W bosons → HNL produced in W decays
  - Discovery signatures: three leptons, displaced vertex
  - **More complex environment than FCC-ee: pile-up/backgrounds/ lifetime/trigger**
    - Allows for characterization both in flavour and charge of the produced neutrino, thus information of the flavour sensitive mixing angles and a test of the fermion violating nature of the intermediate(Majorana) particle.
- If we find hints for HNL at the FCC-ee, the FCC-hh will help understanding more about them1



Gonzalez S. Telescope Conferece 2021

Constraints on RII

Drewes_ICHEP2022

- HNL production cross section is same for Dirac and Majorana:

$$\mathrm{BR}(Z \to \nu N) = \frac{2}{3}|U_N|^2\,\mathrm{BR}(Z \to \text{invisible})\left(1 + \frac{m_N{}^2}{2m_Z{}^2}\right)\left(1 - \frac{m_N{}^2}{m_Z{}^2}\right)$$

- HNL decay rate differs:
  Dirac: : $C_{MD} = 1$
  Majorana: $C_{MD} = 2$

$$\Gamma_N = \frac{1}{c\tau_N} \simeq C_0 C_{MD}|U_N|^2\left(\frac{m_N}{50\mathrm{GeV}}\right)^5 \times \left(\frac{3.10^9}{1\ \mathrm{cm}}\right)$$

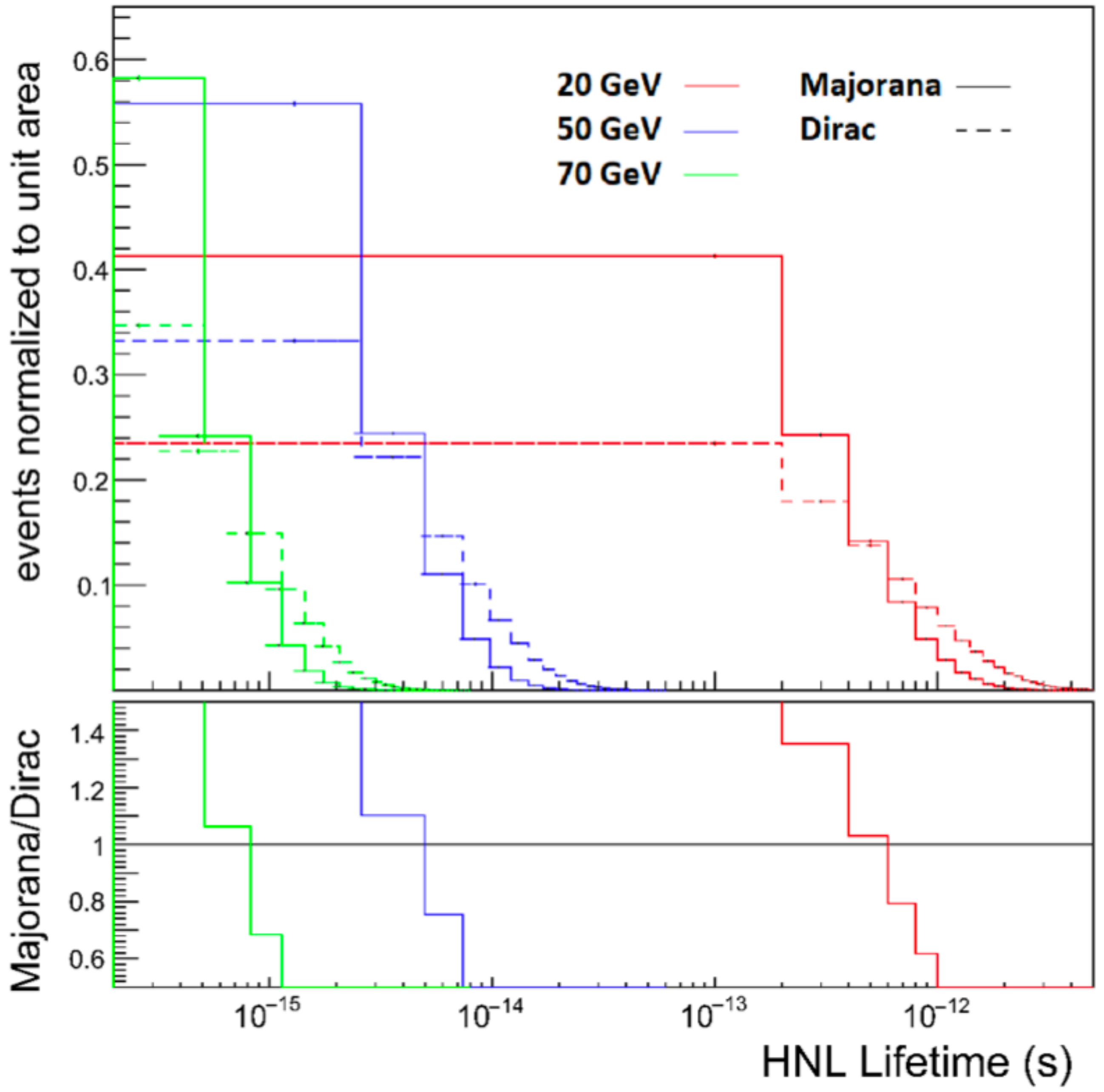
- HNL mass extracted from full 4-momentum reconstruction or from time-of-flight

➢ **Extract $U_a{}^2$ from total # decays ,**
C_{MD} from # decays between displacement l_0, l_1

$$N_{\mathrm{obs}} \simeq L\sigma_N\left[\exp\left(-\frac{l_0}{\lambda_N}\right) - \exp\left(-\frac{l_1}{\lambda_N}\right)\right]$$

$$\lambda_N = \beta\gamma/\Gamma_N \qquad \beta\gamma = (m_Z^2 - M^2)/(2m_Z M)$$

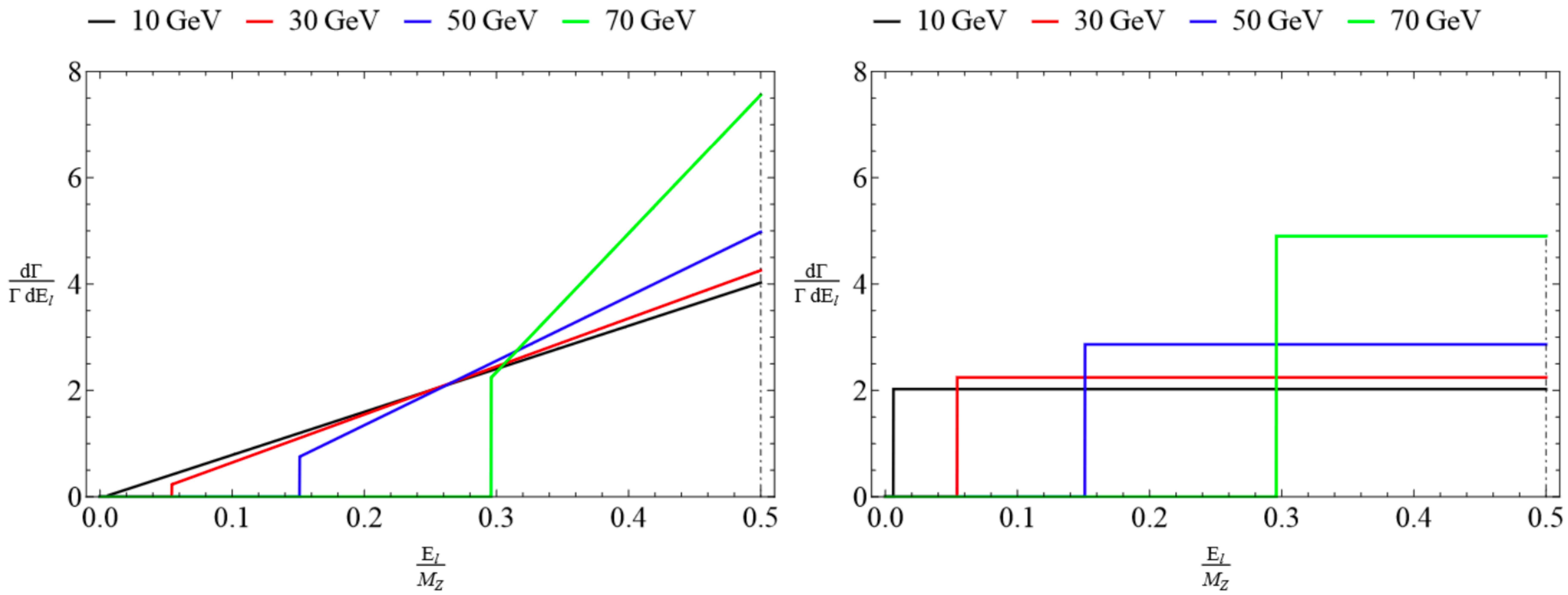
- Caveat: Dirac-HNL may be "faked" by pair of Majorana HNLs



Alimena et al 2203.05502

Polarisation Impact on lepton spectrum

Drewes_ICHEP2022

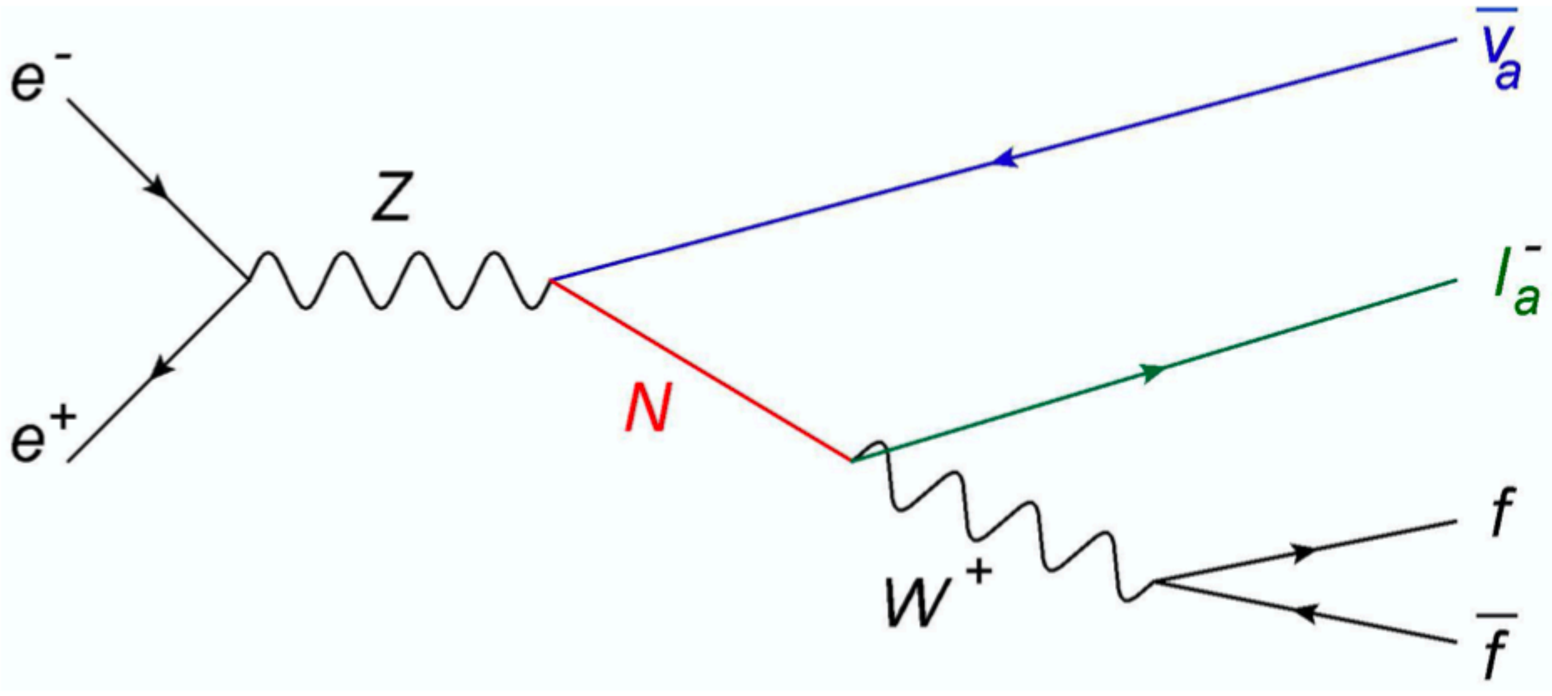


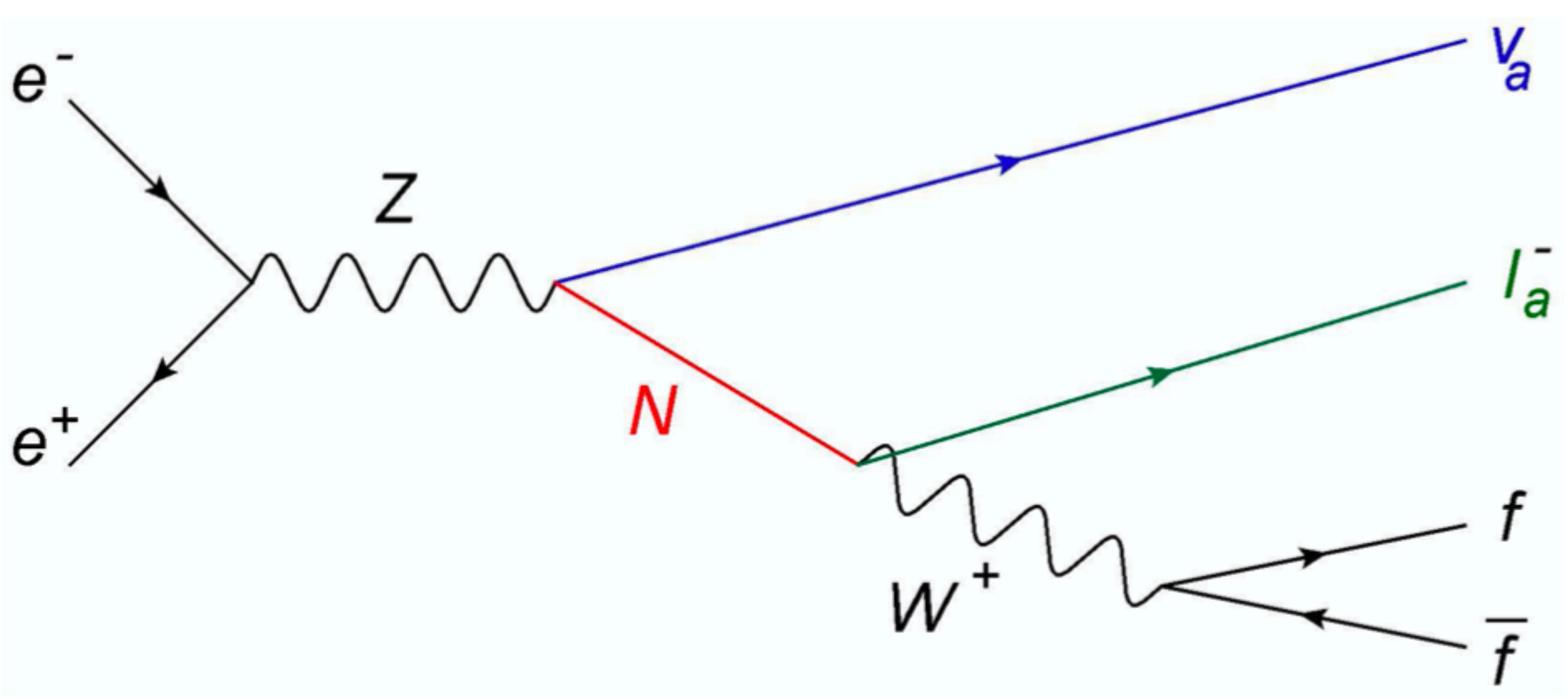
- **Dirac** N and anti-N *individually* are highly polarised, can only decay into lepton or anti-lepton, respectively
- **Majorana** N are only mildly polarised and decay into leptons of either charge
- Lepton spectrum in HNL decay depends on polariations, e.g. decay into pion+lepton:

$$\frac{1}{\Gamma(\ell^{\pm})}\frac{d\Gamma(\ell^{\pm})}{dE_\ell} = \frac{4}{\left(1-\frac{M^2}{m_Z^2}\right)^2}\left[\frac{(1\mp P)}{2} - \frac{M^2}{m_Z^2}\frac{(1\pm P)}{2} \pm 2P\frac{E_\ell}{m_Z}\right]$$

Blondel et al 2105.06576

Asymmetry

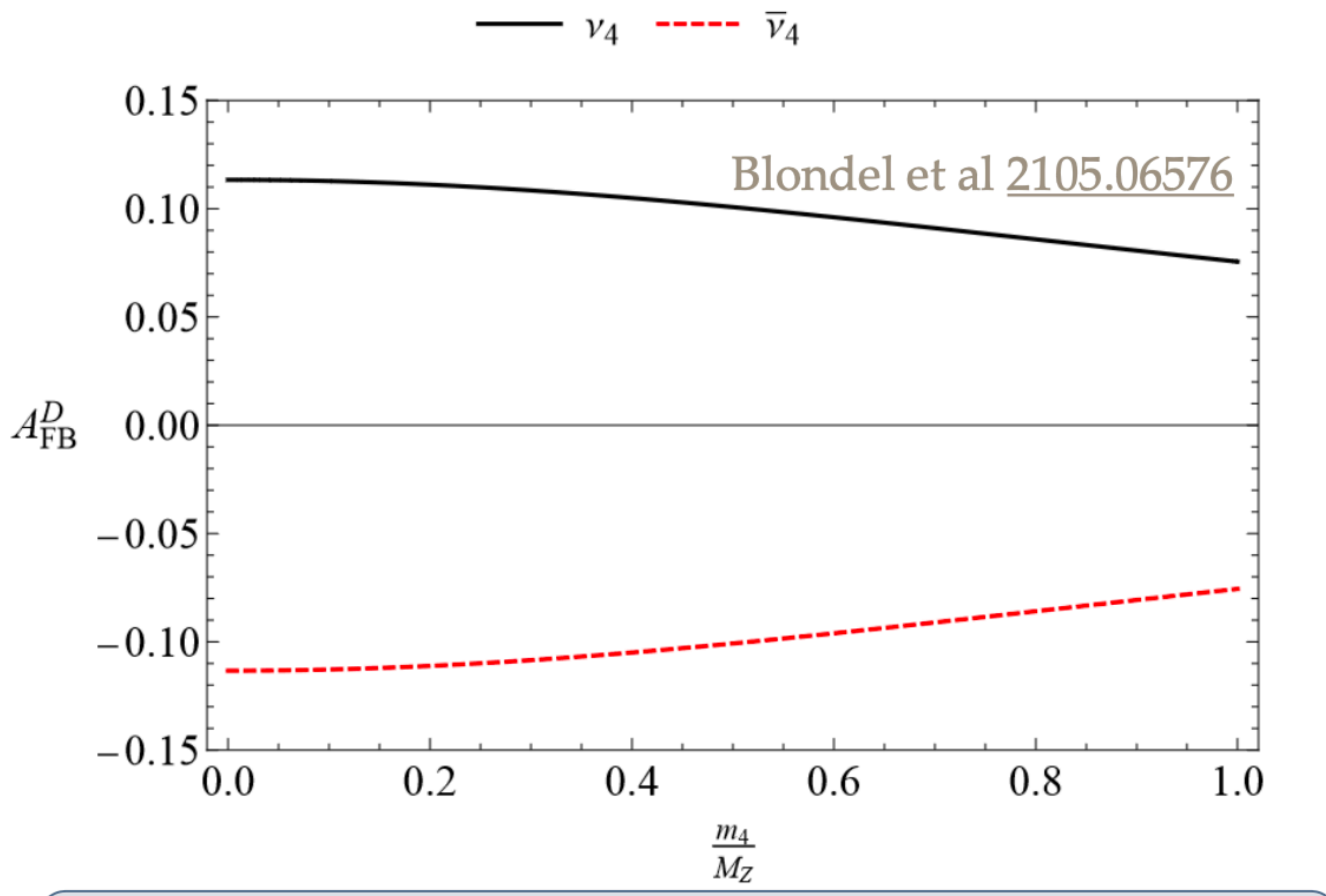




Z-bosons are polarised due to P-violation of weak interaction:

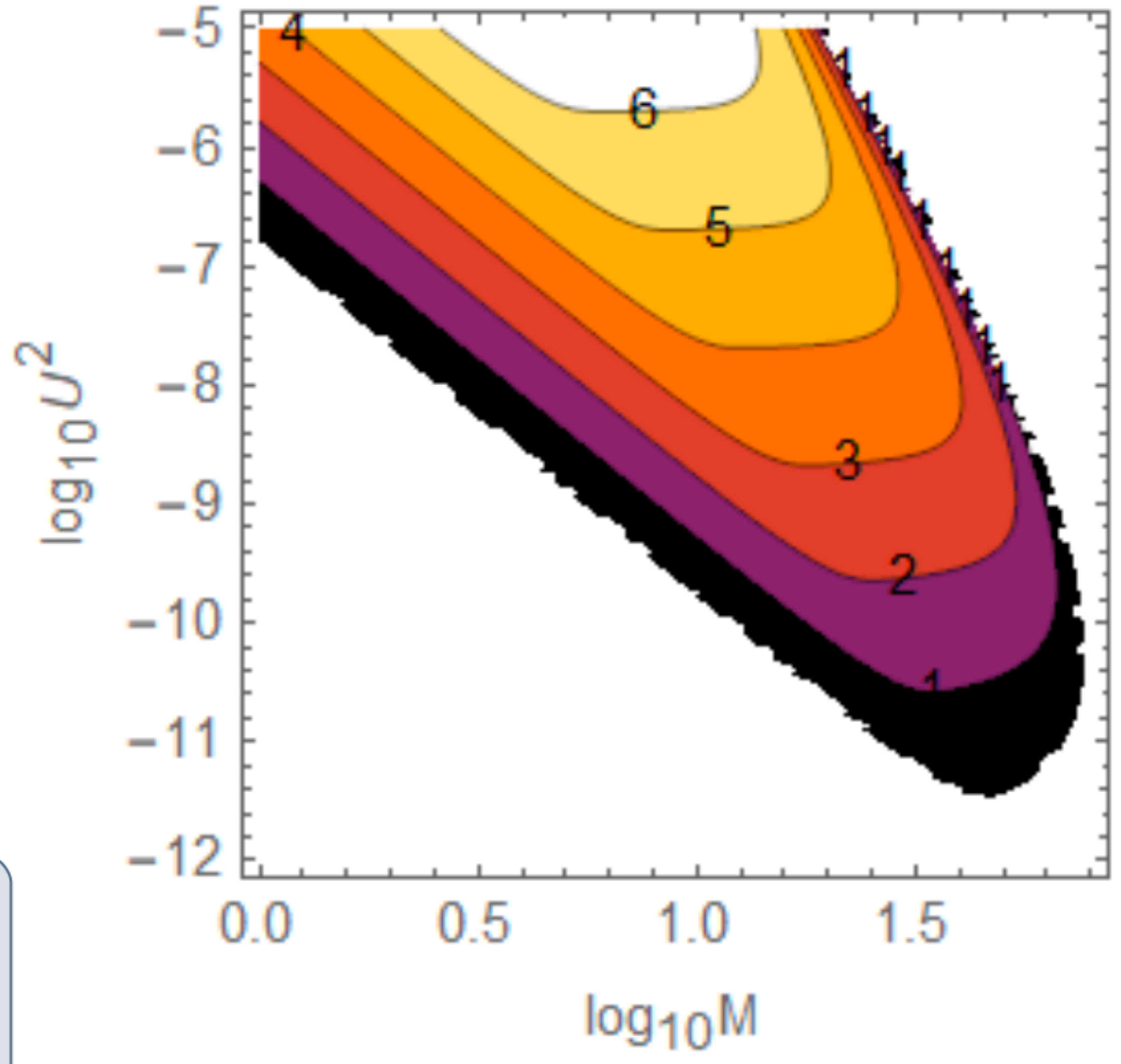
$$g_R = 2\sin^2\theta_W \qquad g_L = (1 - 2\sin^2\theta_W) \qquad P_Z = \frac{(g_R^2 - g_L^2)}{(g_L^2 + g_R^2)} \simeq -0.15.$$

$$A_{\rm FB} = \frac{1}{\sigma}\left[\int_0^1 \frac{d\sigma}{d\cos\theta} d\cos\theta - \int_{-1}^0 \frac{d\sigma}{d\cos\theta} d\cos\theta\right]$$



$$A_{\rm FB}^D(\nu_4) = \frac{3}{2}\frac{M_Z^2}{(2M_Z^2 + m_4^2)}\frac{(g_L^2 - g_R^2)}{(g_L^2 + g_R^2)},$$

$$A_{\rm FB}^D(\overline{\nu}_4) = \frac{3}{2}\frac{M_Z^2}{(2M_Z^2 + m_4^2)}\frac{(g_R^2 - g_L^2)}{(g_L^2 + g_R^2)}$$



Drewes_ICHEP2022

- Forward-backward asymmetry ~10%
- Needs hundreds of events for 2σ exclusion
- Estimate: doable for $U^2 > 10^{-9}$ at FCC-ee