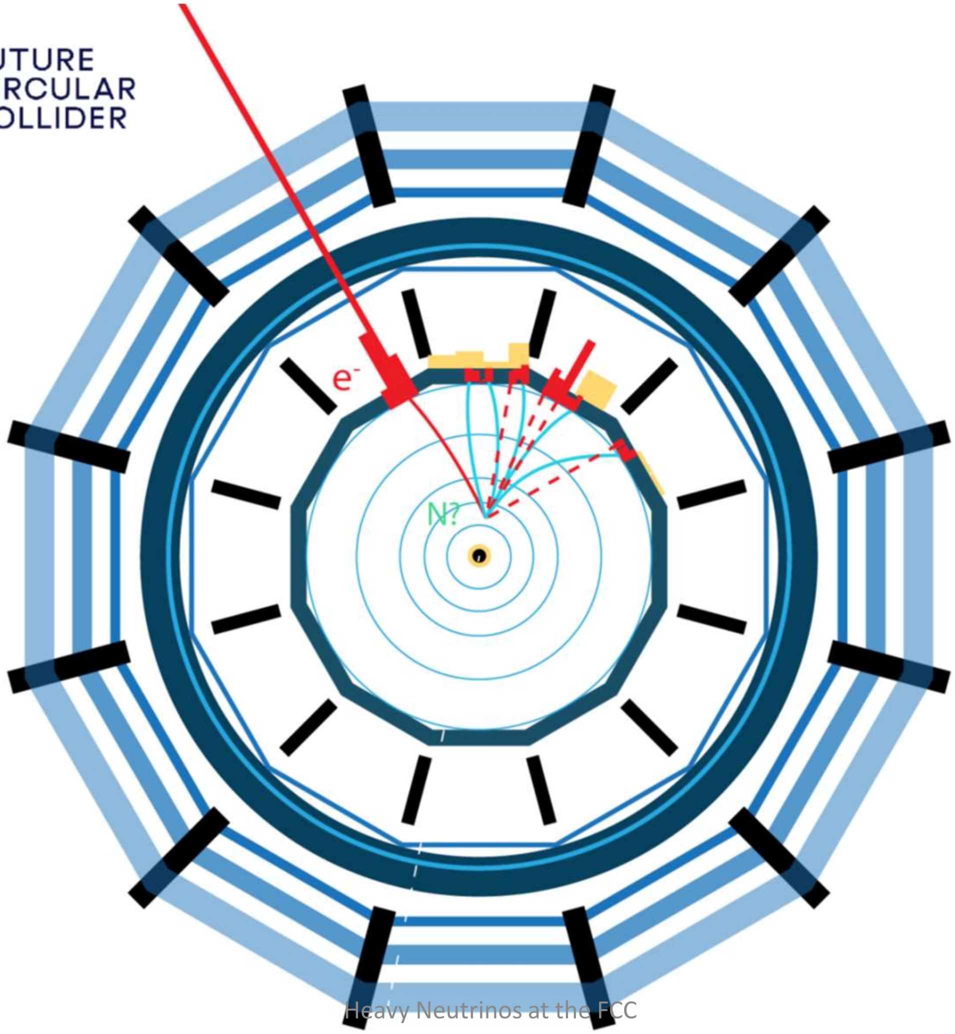
Heavy Neutral Leptons at FCC-ee

FUTURE CIRCULAR COLLIDER

courtesy
Panos Charitos



Heavy Neutral Leptons

High Energy Physics - Experiment

[Submitted on 10 Mar 2022 (v1), last revised 11 Mar 2022 (this version, v2)]

Searches for Long-Lived Particles at the Future FCC-ee

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The electron-positron stage of the Future Circular Collider, FCC-ee, is a frontier factory for Higgs, top, electroweak, and flavour physics. It is designed to operate in a 100 km circular tunnel built at CERN, and will serve as the first step towards $\geq$ 100 TeV proton-proton collisions. In addition to an essential and unique Higgs program, it offers powerful opportunities to discover direct or indirect evidence of physics beyond the Standard Model.
Direct searches for long-lived particles at FCC-ee could be particularly fertile in the high-luminosity Z run, where 5×10^{12} Z bosons are anticipated to be produced for the configuration with two interaction points. The high statistics of Higgs bosons, W bosons and top quarks in very clean experimental conditions could offer additional opportunities at other collision energies. Three physics cases producing long-lived signatures at FCC-ee are highlighted and studied in this paper: heavy neutral leptons (HNLs), axion-like particles (ALPs), and exotic decays of the Higgs boson. These searches motivate out-of-the-box optimization of experimental conditions and analysis techniques, that could lead to improvements in other physics searches.

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Subjects: **High Energy Physics - Experiment (hep-ex)**; High Energy Physics - Phenomenology (hep-ph); High Energy Physics - Theory (hep-th)
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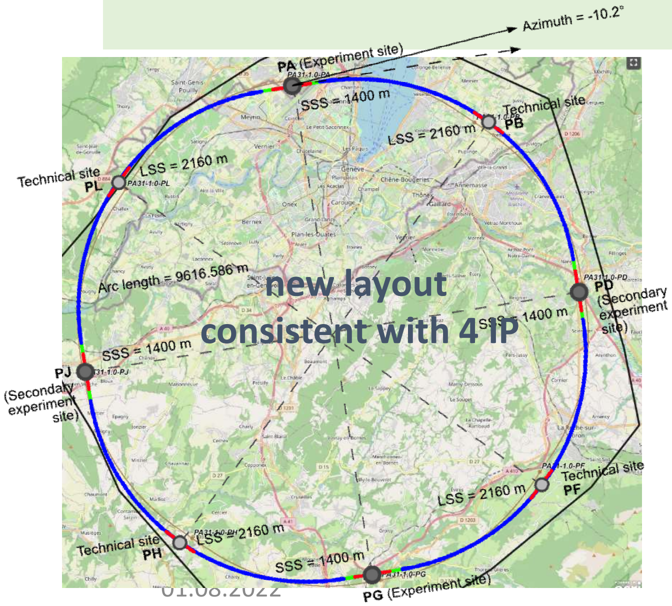
Synergy: The FCC integrated program at CERN

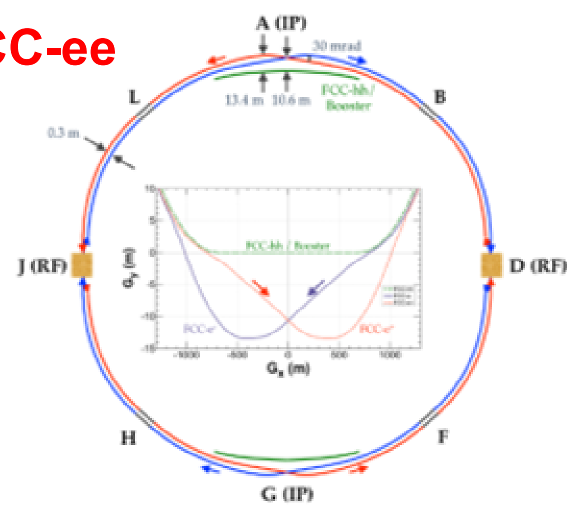
Comprehensive cost-effective program inspired by successful LEP – LHC success story

- **Stage 1: FCC-ee (Z, W, H, tt) as first generation Higgs EW and top factory at highest luminosities.**
- **Stage 2: FCC-hh (~100 TeV) as natural continuation at energy frontier, with ion and eh options.**
- **Maximizes physics output with strong complementarity**
- Integrating an ambitious high-field magnet R&D program
- Common civil engineering and technical infrastructures, building on and reusing CERN's existing infrastructure.
- Start construction early 2030's, start data taking shortly after HL-LHC completion
- **FCC-INT project plan is fully integrated with HL-LHC exploitation ➔ seamless continuation of HEP**
- **Feasibility study approved and funded at CERN (100MCHF/5yrs) + magnet R&D (120 MCHF/6yrs)**

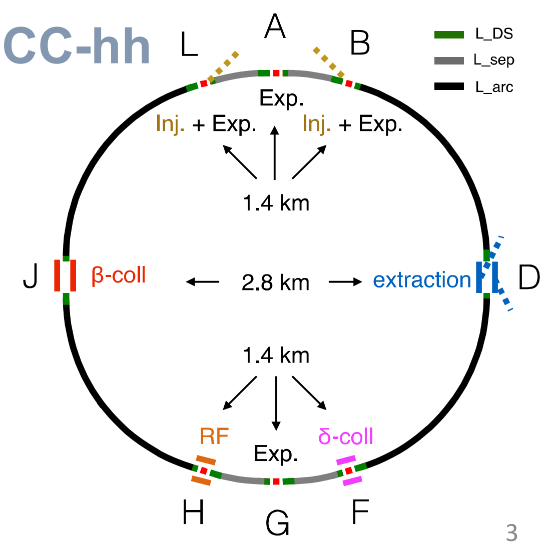
***** GLOBAL COLLABORATION *****



FCC-ee

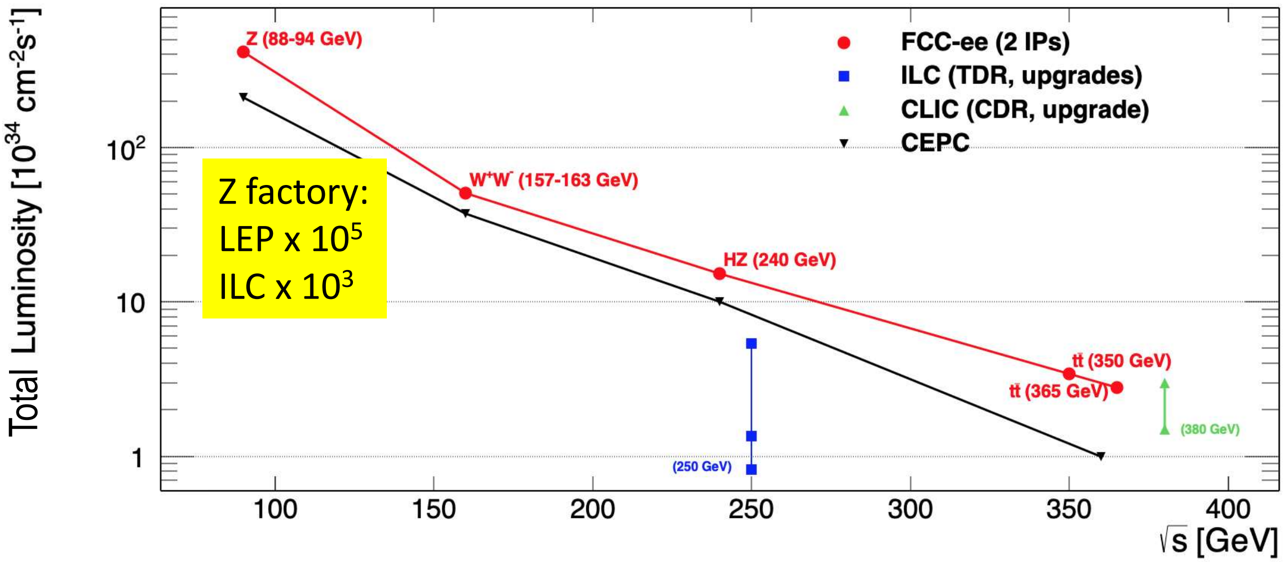


FCC-hh



FCC-ee

Great energy range for the heavy particles of the Standard Model



notes:
- -- 4IP increases Total Lumi by 1.7
- -- 2IP assumed in all numbers below
- -- order and duration of Z/WW/ZH can be decided at a later stage
- -- ee→ H must be after both Z and ZH and before tt

see back-ups for facility comparisons

Event statistics (2IP) for a 15 years data taking plan

					E_{CM} errors:
Z peak	**E_{cm} : 91 GeV**	4yrs	**5 10^{12} e+e- → Z**	**LEP x 10^5**	<100 keV
WW threshold	**$E_{cm} \geq$ 161 GeV**	2yrs	**>10^8 e+e- → WW**	**LEP x 2.10^3**	<300 keV
ZH maximum	**E_{cm} : 240 GeV**	3yrs	**> 10^6 e+e- → ZH**	**Never done**	1 MeV
s-channel H	***E_{cm} : m_H***	*(3yrs?)*	***O(5000) e+e- → H***	***Never done***	<< 1 MeV
$t\bar{t}$	**E_{cm} : $\geq$ 350 GeV**	5yrs	**10^6 e+e- → $t\bar{t}$**	**Never done**	2 MeV

A bit about motivation and communication

One of the first handicaps here is a matter of **name**

Sterile neutrinos ``ν_4" (and *no* it is *not* a fourth family of neutrino!)
Heavy Neutral Leptons
Right-Handed Neutrinos
Heavy Majorana neutrinos
are all the same....

Generically we are talking of the new degree of freedom that arises for each family of light neutrinos that is massive.
Massive neutrino → two helicity states,
which can be projected on Electroweak Left-handed ($\nu_L = \nu_- + m/E\ \nu_+$) Right-Handed ($\nu_R = \nu_+ + m/E\ \nu_-$) states.
At least two are needed to account for three family oscillations

Heavy Neutral Leptons

not a new concept!

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Extending limits on neutral heavy leptons

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(Received 12 January 1984)

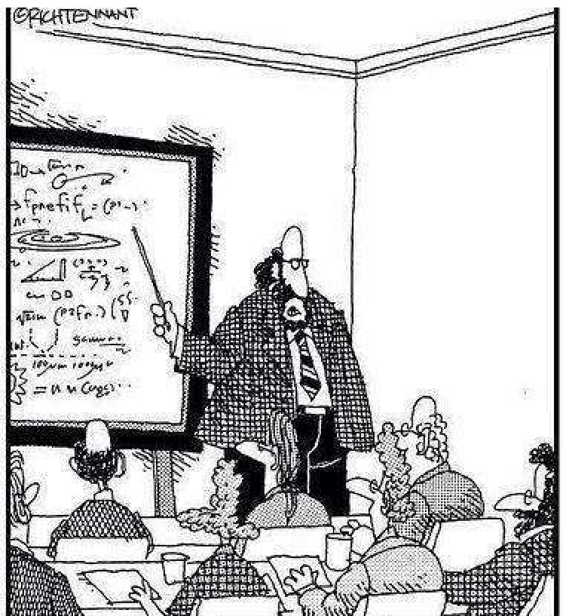
Neutral leptons corresponding to "right-handed neutrinos" are expected in many grand unified theories of the electroweak strong interactions. At present, the experimental limits on the masses and mixings with ordinary neutrinos of these leptons are very poor for masses above about 1 GeV. Suggestions are made for extending these limits, in experiments involving the production of b quarks, W and Z bosons, and any heavier gauge bosons that might exist, and via high-statistics studies of neutral-current neutrino interactions.

Heavy Neutral Leptons are right-handed neutrino partners to the Standard Model active neutrinos (Status of HNL, Snowmass HNL arXiv:2203.08039v1)
Original ideas linked to GUTs lead to notion that the right hande neutrinos were very heavy (up to 10^{10} GeV or more)

my SM training in 1976

Electroweak eigenstates

I = 1/2			I = 0			
$\begin{pmatrix} e \\ \nu_e \end{pmatrix}_L$	$\begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix}_L$	$\begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix}_L$	$(e)_R$	$(\mu)_R$	$(\tau)_R$	Q= -1
			$(\nu_e)_R$	$(\nu_\mu)_R$	$(\nu_\tau)_R$	Q= 0



"Along with 'Antimatter,' and 'Dark Matter,' we've recently discovered the existence of 'Doesn't Matter,' which appears to have no effect on the universe whatsoever."

Right handed neutrinos are singlets
no weak interaction
no EM interaction
no strong interaction

can't produce them
can't detect them
-- so why bother? –

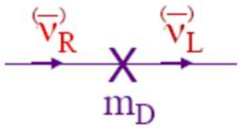
Also called 'sterile'

NB unlike for for ν_L, nothing distinguishes the particle and antiparticle of ν_R which is a singlet (no 'charge')

Neutrino masses occur via processes which are intimately related to the Higgs boson
This aspect is quite relevant for a « Higgs factory »?

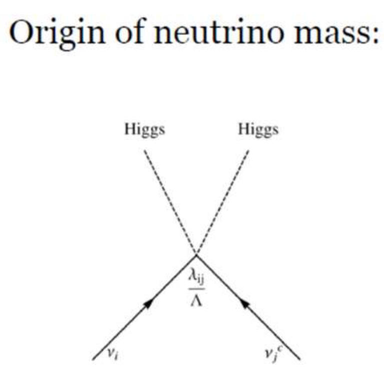
Adding masses to the Standard model neutrino 'simply' by adding a Dirac mass term

$m_D \overline{\nu_L}\, \nu_R$

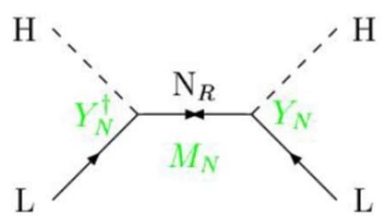


m_D is the **Yukawa coupling** (like everybody else). Then the right handed neutrinos are perfectly sterile.

Things become more interesting when a Majorana mass term arises. So-called **Weinberg Operator** (only Dim5 operator in EFT) and involves the Higgs boson and the neutrino Yukawa coupling



Pilar Hernandez, Granada 2019-05



Majorana mass term is extremely interesting as this is the **particle-to-antiparticle transition** that we want in order to explain **the Baryon asymmetry of the Universe** (+ CP violation in neutrinos)

This implies a decay H→ νN that would be worthwhile investigating -- can we see such a thing with 10^{10} Higgs decays @FCC-hh?
“Direct” observation of Yukaya coupling of neutrinos at FCC-hh

Mass eigenstates

See-saw type I :

$$\mathcal{L} = \frac{1}{2}(\bar{\nu}_L,\ \bar{N}_R^c)\begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix}\begin{pmatrix} \nu_L^c \\ N_R \end{pmatrix}$$

$M_R \neq 0$
$m_D \neq 0$
Dirac + Majorana mass terms

$$\tan 2\theta = \frac{2\, m_D}{M_R - 0} \qquad \ll 1$$

$$m_\nu = \tfrac{1}{2}\left[(0 + M_R) - \sqrt{(0 - M_R)^2 + 4\, m_D^2}\right] \qquad \simeq -m_D^2/M_R$$

$$M = \tfrac{1}{2}\left[(0 + M_R) + \sqrt{(0 - M_R)^2 + 4\, m_D^2}\right] \qquad \simeq M_R$$

general formula — if $m_D \ll M_R$

$M_R = 0$
$m_D \neq 0$
Dirac only, (like e- vs e+):

m ↑

I_{weak}=	ν_L	ν_R	$\bar{\nu}_L$	$\bar{\nu}_R$
	½	0	½	0

4 states of equal masses

Some have I=1/2 (active)
Some have I=0 (sterile)

$M_R \neq 0$
$m_D = 0$
Majorana only

m ↑

I_{weak}=	ν_L	$\bar{\nu}_R$
	½	½

2 states of equal masses

All have I=1/2 (active)

$M_R > m_D \neq 0$ see-saw

Dirac + Majorana

m ↑

dominantly:

I_{weak}=	ν	N	$\bar{\nu}$	N
	½	0	½	0

4 states , 2 mass levels

m_1 have ~I=1/2 (~active)
m_2 have ~I=0 (~sterile)

Manifestations of right handed neutrinos

one family see-saw :
$\theta \approx (m_D/M)$
$\boldsymbol{m_\nu} \approx \frac{m_D^{\,2}}{M}$
$m_N \approx M$
$|U|^2 \propto \theta^2 \approx \boldsymbol{m_\nu} / m_N$

$$\nu = \nu_L \cos\theta - \boldsymbol{N^c_R} \sin\theta$$

$$\boldsymbol{N} = \boldsymbol{N_R} \cos\theta + \boldsymbol{\nu_L}^c \sin\theta$$

what is produced in W, Z decays is:

$$\boldsymbol{\nu_L} = \boldsymbol{\nu} \cos\theta + \boldsymbol{N} \sin\theta$$

$\boldsymbol{\nu}$ = light mass eigenstate
N = heavy mass eigenstate
$\neq \boldsymbol{\nu_L}$, active neutrino which couples to weak inter.
and $\neq N_R$, which does'nt.

-- mixing with active neutrinos leads to various observable consequences
-- if very light (eV) , possible effect on neutrino oscillations ('eV sterile neutrino' (LSND/miniboone etc... ruled out since PLANCK mission MINOS/ICECUBE/DAYABAY but search still ongoing in broader region)
-- if in keV region (dark matter), monochromatic photons from galaxies with $E=m_N/2$
-- possibly measurable effects at High Energy
If N is heavy it will decay in the detector (not invisible)
➔ PMNS matrix unitarity violation and deficit in Z «invisible» width
➔ Higgs, Z, W visible exotic decays H➔ $\nu_i \bar{N}_i$ and Z➔ $\nu_i \bar{N}_i$, W-> $l_i \bar{N}_i$
➔ also in K, charm and b decays via W^*-> $l_i^{\pm} \bar{N}$, N ➔ $l_j^{\pm}$
with any of six sign and lepton flavour combination
➔ violation of unitarity and lepton universality in Z, W or τ decays
-- etc... etc...
-- Couplings are very small ($|U|^2 = \boldsymbol{m_\nu} / m_N$) *(but who knows?)* and generally seem out of reach at high energy colliders.

HNL RH neutrino production in Z decays

Production:

$$BR\left(Z^0 \to \nu_m \overline{\nu}\right) = BR\left(Z^0 \to \nu\overline{\nu}\right) |U|^2 \left(1 - \frac{m_{\nu_m}^2}{m_{Z^0}{}^2}\right)^2 \left(1 + \frac{1}{2}\frac{m_{\nu_m}^2}{m_{Z^0}{}^2}\right)$$

multiply by 2 for antineutrino and add contributions of 3 neutrino species (**→** $\Sigma_{\lambda=e,\mu,\tau}$ **$|U_\lambda|^2$**)

Decay

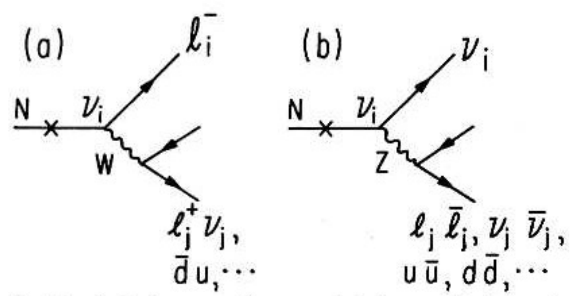


FIG. 2. Typical decays of a neutral heavy lepton via (a) charged current and (b) neutral current. Here the lepton l_i denotes e, μ, or τ.

Decay length:

$$L \approx \frac{3 \text{ cm}}{|U|^2 \left(m_{\nu_m}(\text{GeV}/c^2)\right)^6}$$

NB CC decay always leads to $\geq$ 2 charged tracks

Backgrounds : four fermion: e+e- → $W^{*+} W^{*-}$ e+e- → Z*(νν) + (Z/γ)*

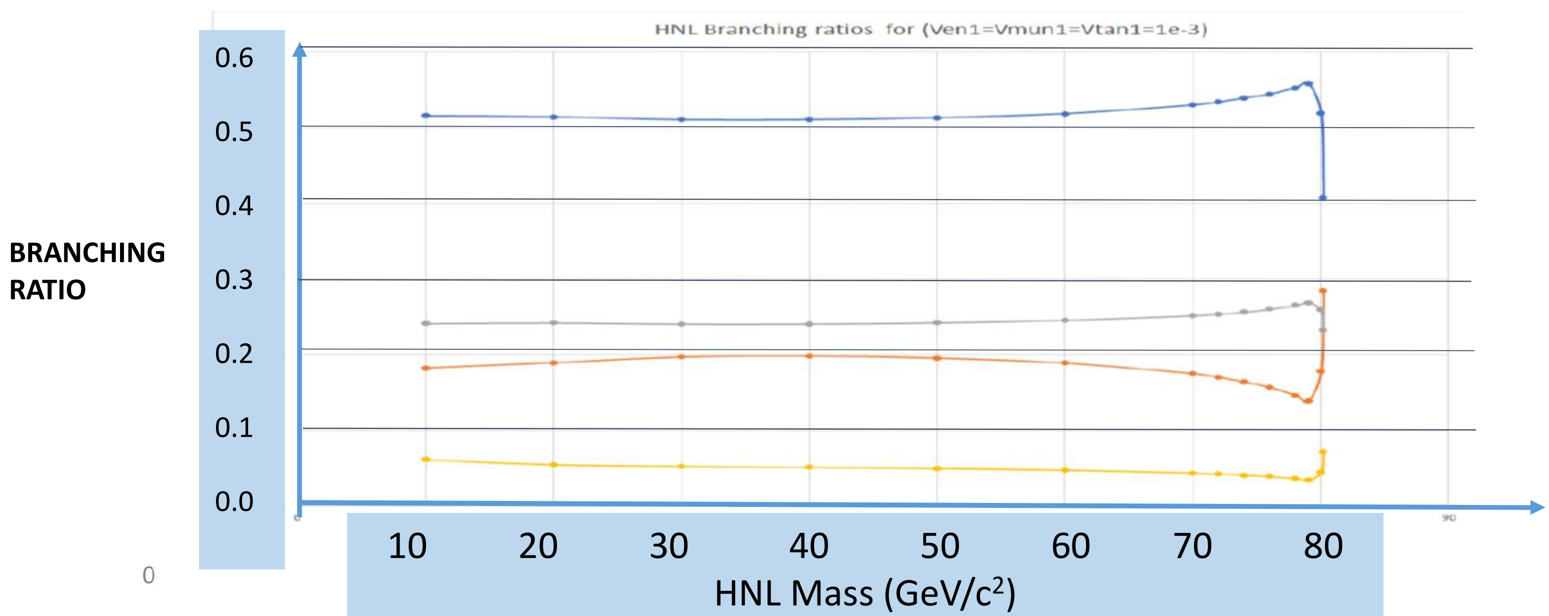
Long life time → detached vertex for ~<M_Z

Production of HNL at FCC-ee

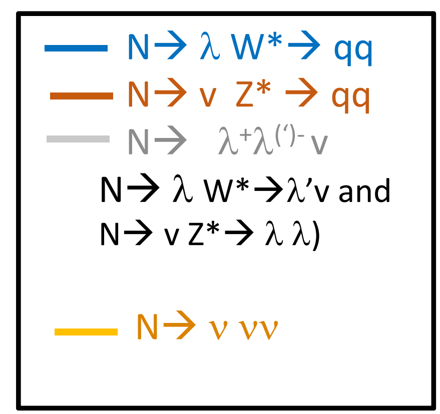
We begin experimentally by assuming HNL production one at a time.

This is an approximation of the more favored situation where two or three almost degenerate HNLs are produced, possibly generating a phenomenology akin to e.g. K_L and K_S or (K <-> $\bar{K}$) system with oscillations and other lifetime effects.
This is extraordinarily interesting and does not appear much in the discussion. We should program this.

In the simplified, <u>one-N-at-a-time</u> assumption the particle has one mass, one cross-section and one decay width/life time. and four decay modes N→ eW*, μW*, τW* (CC decays) and N→ νZ* (NC decay)-- two or more charged tracks except N->ννν



Tanishq Sharma



A bit of phenomenology

decay modes

-- ~50-55 % is made of N→ λ W*→ qq λ= e, μ, τ, each propto $|U_\lambda|^2$

-- ~22-28 % is made of N→ $\lambda\lambda$v (N→ λ W*→λ'v and N→ v Z*→ λ λ)

-- ~6% is made of N→ v v v (no chance)

-- ~18-20% is made of N→ v Z*→ qq

exact numbers vary with HNL mass (difference btw W and Z propagator)

-- > 50-55% has no missing energy in the decay (except for tau decay)
***and* is sign/helicity tagged (as coming from W decay).**

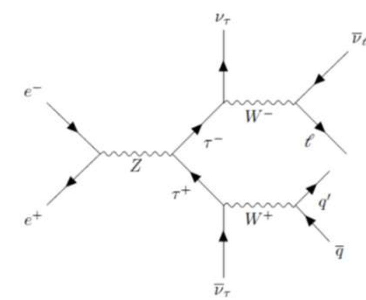
-- not to forget: the NC/CC ratio is independent of the individual $|U_\lambda|^2$ λ= e, μ, τ
« Neutral Current » topology can be enhanced in the HNL decays into a lighter HNL

Decay length LLP vs Prompt analysis vs EWPO

in a wide range of mass and small enough couplings we have **a long lived signature**
then things are nice and easy, because it is essentially background free.
NB in case this were really true one event would be enough to establish discovery – this needs to be carefully demonstrated taking into account the exact location of the cavern and the details of analysis (detector readout etc..)

-- The LLP signal would be required to have *no* particle originating from the main vertex.
a distance from the vertex of 400 microns would be
sufficient to eliminate the prompt background. No such cut is required for the prompt signal

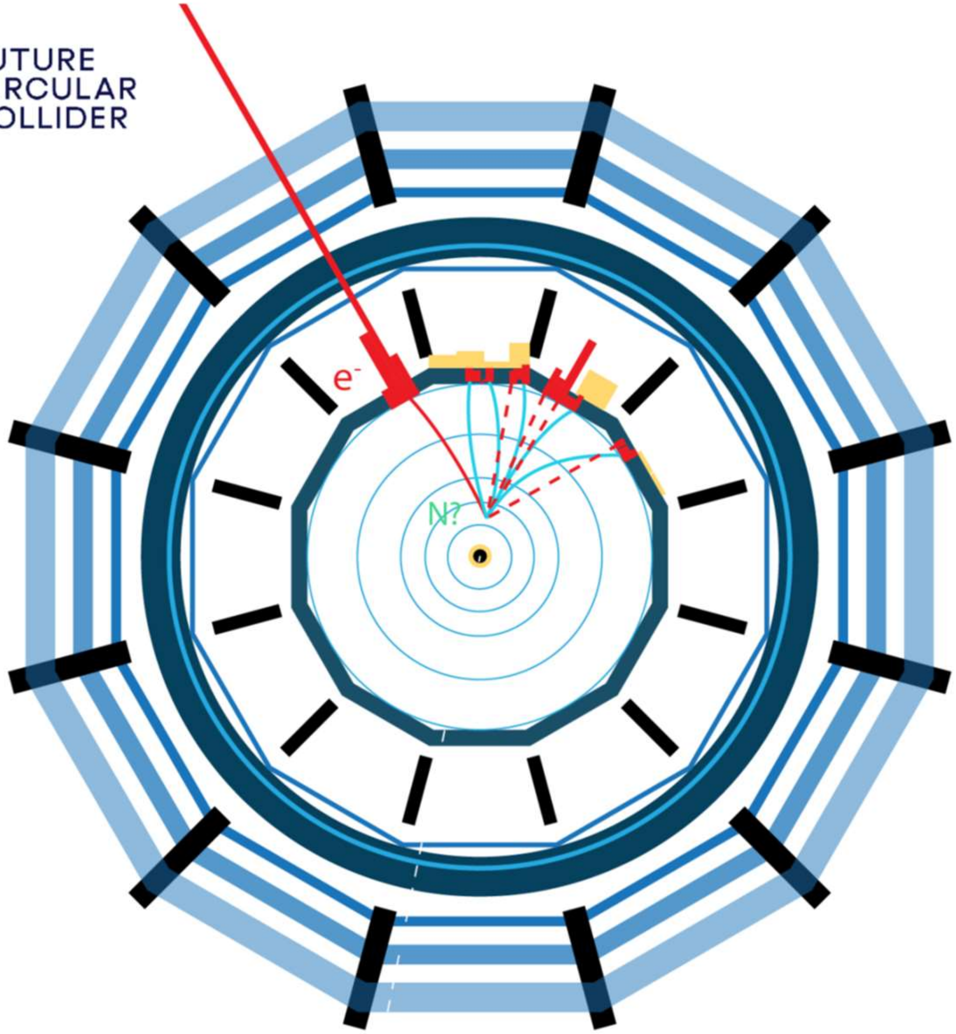
For higher masses and couplings we have a **prompt analysis**. **The boundary** depends critically
to separate the prompt signal from the irreducible backgrounds Z→ W*W* and Z→ Z*Z* incl
(S. Bay-Nilsen Master Thesis)

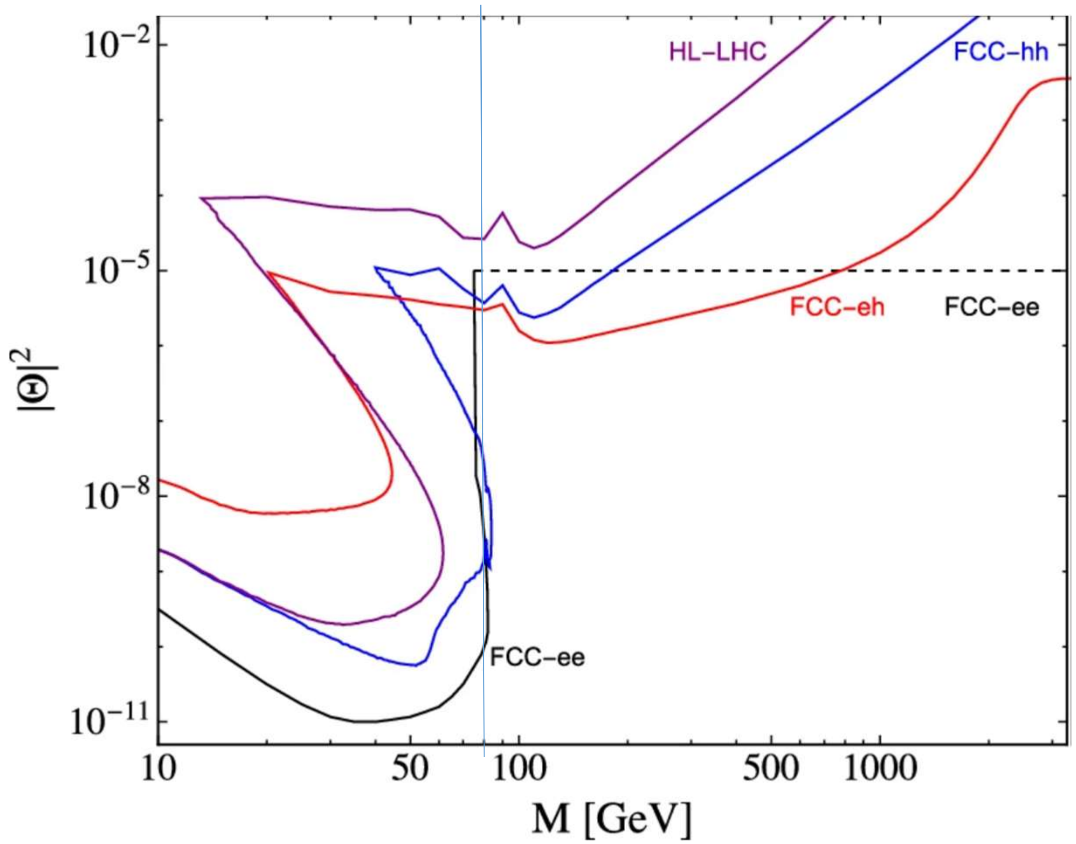


-- The prompt signal seems to be dominated by Z→ $\tau\tau$ background (at low mass)
see arXiv:2201.05831v1. (m_N = 5-15 GeV)

-- for the high mass the prompt signal was studied by Sissel Bay Nielsen Master's Thesis
and Oliver Fischer for the CDR curves, which are reproduced in the ESPP document

For large mixing angles, irrespectively of the HNL mass, a limit exists from precision measurements of


e-
N?



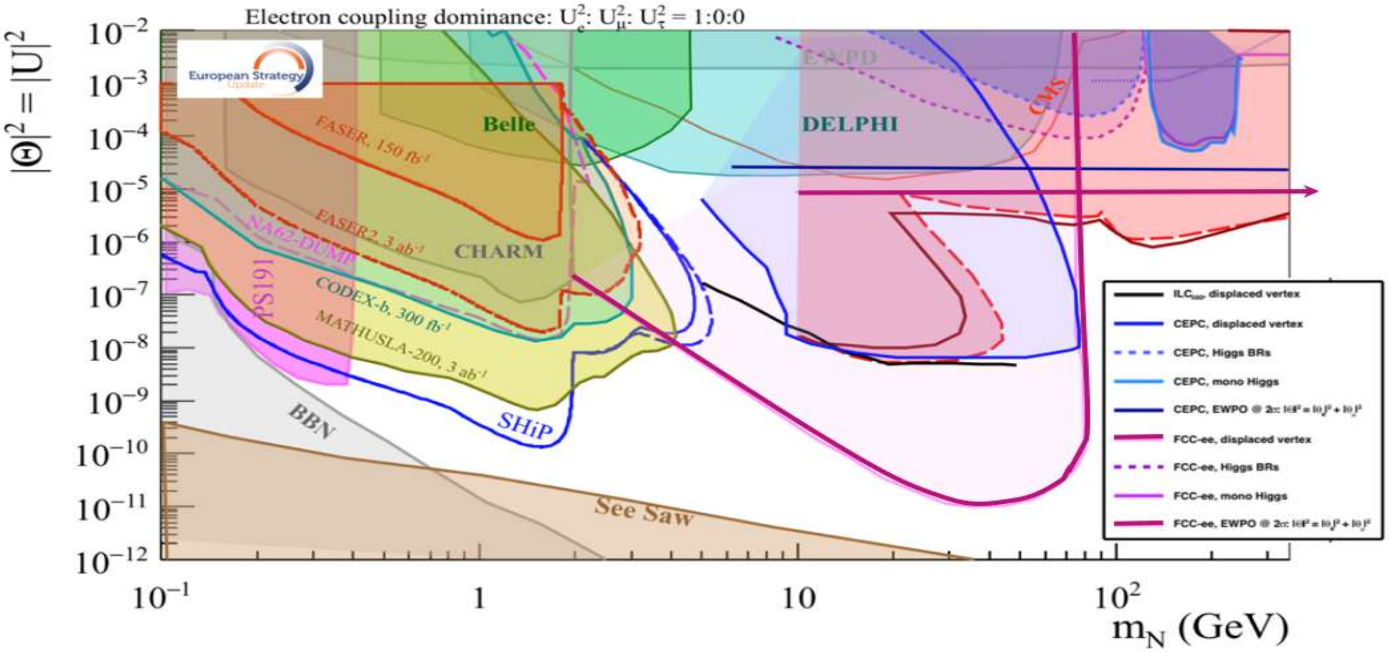
This is the FCC CDR plot – as anticipated the limit stops at the W mass, when life times get very short due to on-shell W decay.

The horizontal line corresponds to G_F effect on EWPO

This picture is relevant to Neutrino, Dark sectors and High Energy Frontiers.

FCC-ee (Z) compared to the other machines for right-handed (sterile) neutrinos

How close can we get to the 'see-saw limit'?



-- the purple line shows the 95% CL limit if no HNL is observed. (here for 10^{12} Z),

-- the horizontal line represents the sensitivity to **mixing of neutrinos** to the dark sector, using EWPOs (G_F vs $\sin^2\theta_W^{eff}$ and m_Z, m_W, tau decays) which extends sensitivity from 10^{-3} (now) to 10^{-5} (FCC) mixing all the way to very high HNL masses (500-1000 TeV at least). arxiv:2011.04725

65 GeV only?
CEPC goes to W mass

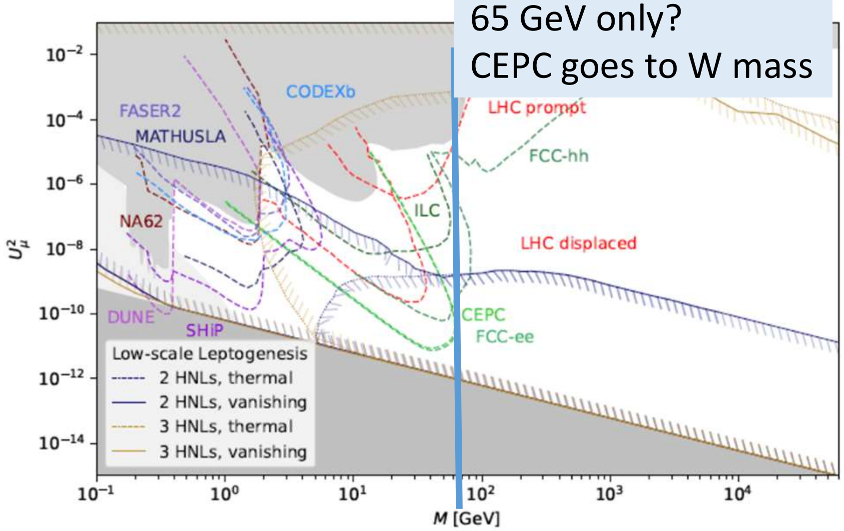


Figure 3: *Bold green line:* Sensitivity of displaced vertex searches at FCC-ee with 5×10^{12} Z bosons corresponding to 4 observed HNL decays, assuming no background and 75% reconstructed HNL decays with a displacement between 400μm and 1.22m. For comparison, we show what CepC can achieve with 4.2×10^{12} Z bosons for the same parameters. *Bold turquoise line:* Gain in sensitivity if the maximal observable displacement is increased to 5m with a HECATE-like detector [77]. *Dark gray:* Lower bound on the total HNL mixing from the requirement to explain the light neutrino oscillation data [72]. *Medium gray:* Constraints on the mixing $|V_{\mu i}|^2$ of HNLs from past experiments [78–88], obtained under the assumption $|V_{\ell N}|^2 = \delta_{\ell\mu} U_\mu^2$. *Light gray:* Lower bound on U_μ^2 from BBN [89,90]. *Hashed orange and violet lines:* Regions in which the observed baryon asymmetry of the universe can be explained with two [91, 92] or three [93] HNL flavours and different initial conditions, as explained in the legend. *Other colourful lines:* Estimated sensitivities of the LHC main detectors (taken from [94–96]) and NA62 [65] as well as the sensitivities of selected planned or proposed experiments (DUNE [97],FASER2 [98], SHiP [99, 100], MATHUSLA [101], Codex-b [102]) as well as FCC-hh [75].

this correctly says 'sensitivity with displaced vertex search'

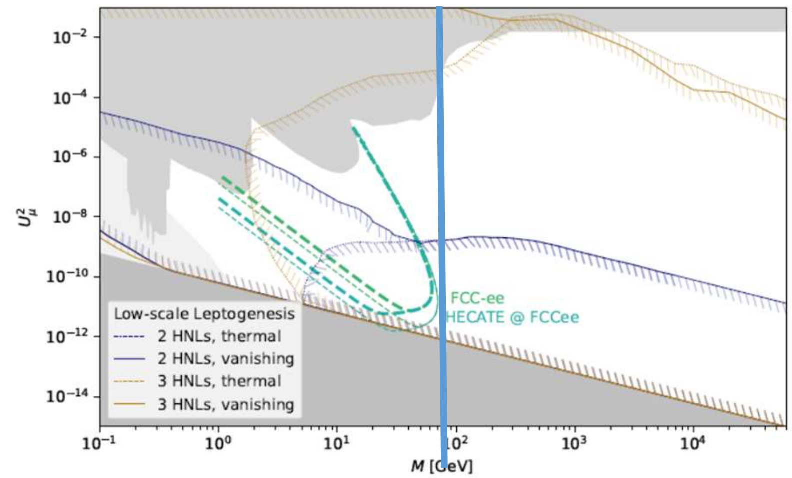


Figure 4: In this figure, similar to Fig. 3, the contours for 4 events (bold lines) and 1 event (non-bold lines) are shown for FCC-ee with a 1.2 m radius setup for the displaced vertex analysis only. In addition, the curves are also shown for a putative 5 m radius volume as in the HECATE [77] set-up, increasing the sensitivity for low mass and small coupling part of the parameter space.

NEW: show 4 event and 1 event curves for $5 10^{12}$ Z

4 events corresponds to, having not seen anything, excluding the regions where you would have 95% chance of seeing something if its there.
limit-setting oriented.
1 event corresponds to no background situation where you would have 63% chance of seeing one event.
discovery oriented

Dirac vs Majorana(I)

It has been emphasized by Matthew Mccullough that there exist ways to create models of Dirac HNL-like particles and that **the discovery of a RHv requires the observation of the Majorana nature of the particle.**

In any case Fermion number violation is of the greatest interest.

Several methods

1. Forwards backward asymmetry relic of the Z parity violating couplings. Dirac keeps it, Majorana washes it out.
   ➔ uses N→ λqq decay and requires lepton charge reconstruction.
2. Polarization (also relic of Z parity violation) of HNL leads to harder lepton spectrum for Dirac than for Majorana
   ➔ uses N→ λqq and requires lepton momentum reconstruction (but not the charge)
   NB analysis sensitive to detail W* mass distribution, esp. for small masse W* (in tau & D mass region and below)

3. W/Z diagram interference (Petcov) for N→ $\lambda\lambda$v Very elegant but less statistics and less easy

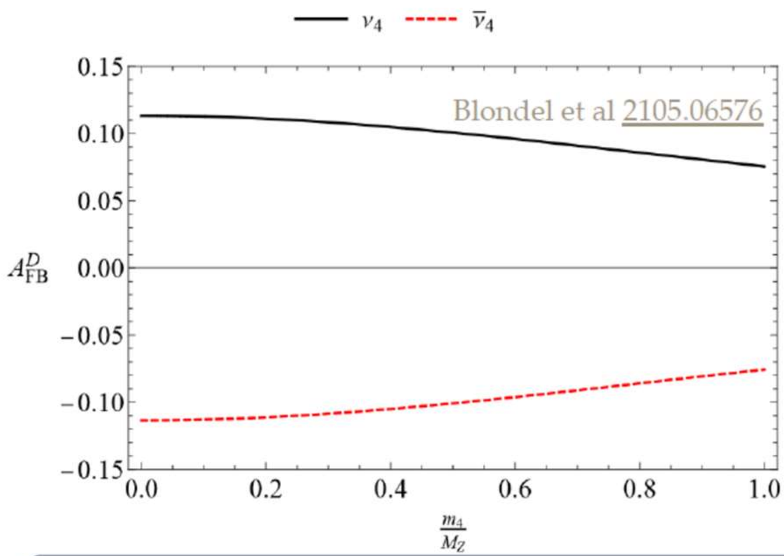
These methods work for the prompt analysis as well as for the LLP analysis within presumably a smaller radius.

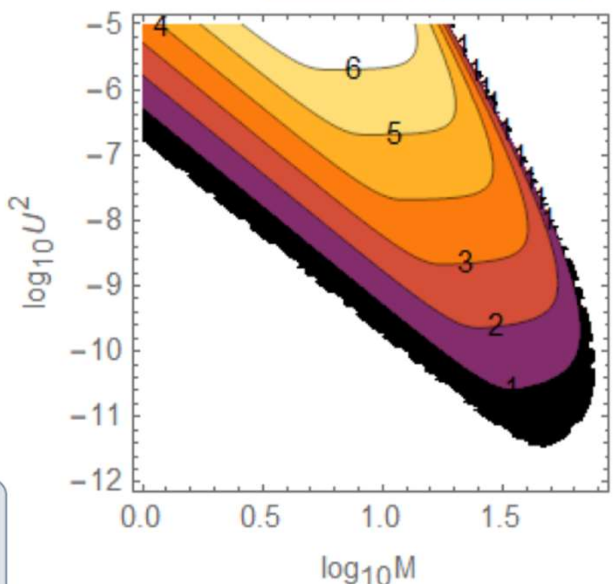
Forward-Backward Asymmetry

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

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

$$A^D_{\rm FB}(\bar\nu_4) = \frac{3}{2}\frac{M_Z^2}{(2M_Z^2+m_4^2)}\frac{(g_R^2-g_L^2)}{(g_L^2+g_R^2)}$$

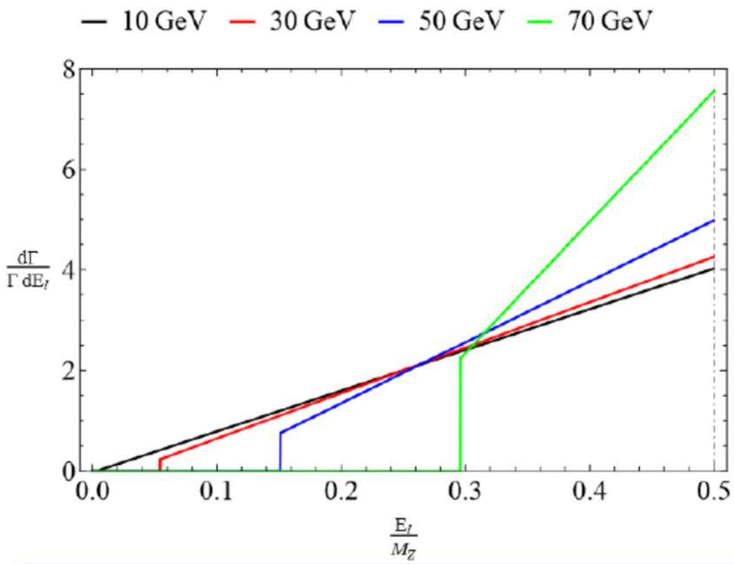


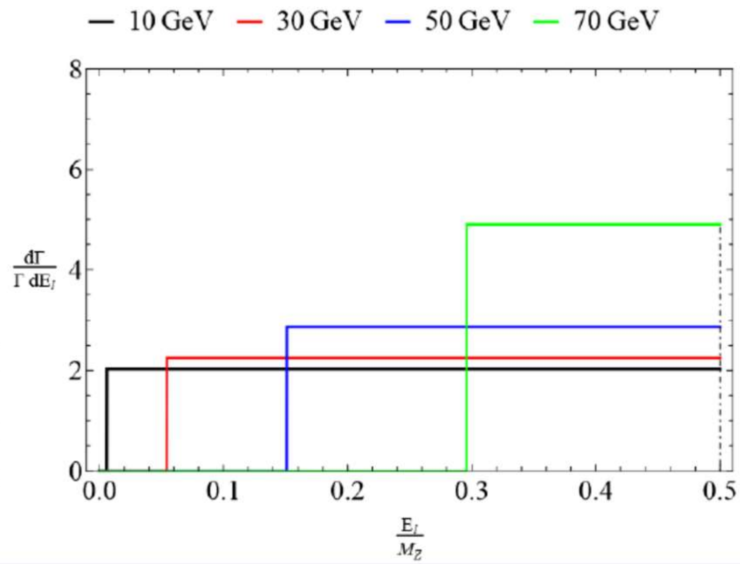


- Forward-backward asymmetry ~10%
- Needs hundreds of events for 2σ exclusion
- Estimate: doable for $U^2 > 10^{-9}$ at FCC-ee

Drewes, ICHEP

Polarisation Impact on Lepton Spectrum





- **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:

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

Blondel et al 2105.06576

Dirac vs Majorana(II)

the lifetime is reduced by a factor 2 for a Majorana vs Dirac particle

it is nicely visible in the plots prepared by T. Sharma *-->

C_{MD}= 1(Dirac), 2(Majorana)

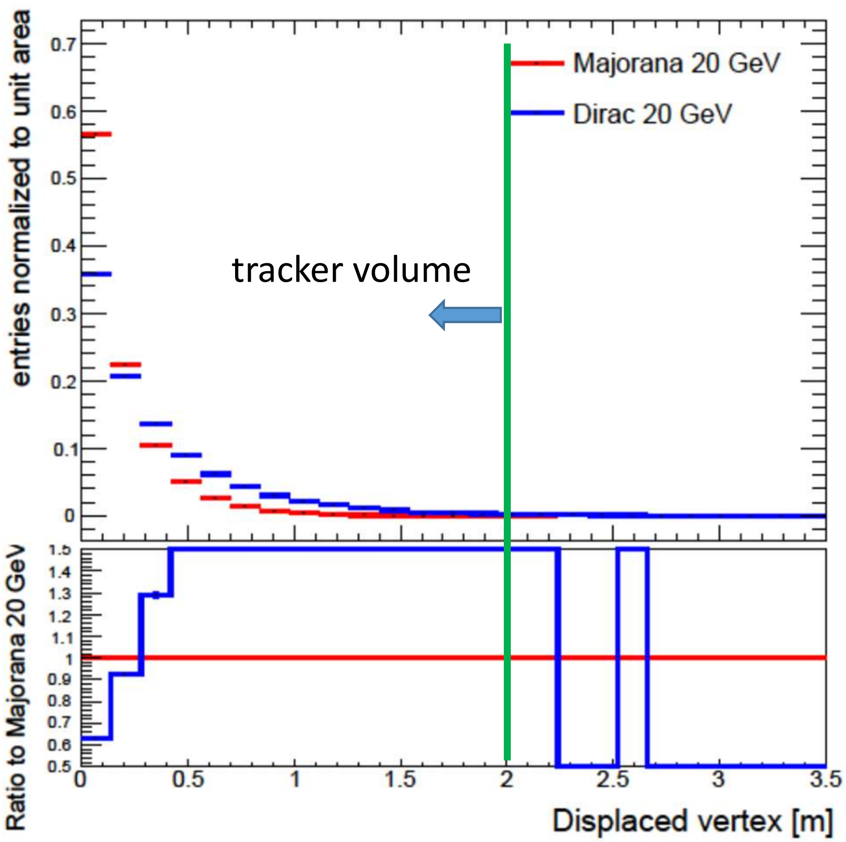
$$\mathrm{BR}(Z \to \nu N) = \frac{2}{3}|U_N|^2 \ \mathrm{BR}(Z \to \mathrm{invisible}) \ \left(1 + \frac{{m_N}^2}{2{m_Z}^2}\right) \left(1 - \frac{{m_N}^2}{{m_Z}^2}\right),$$

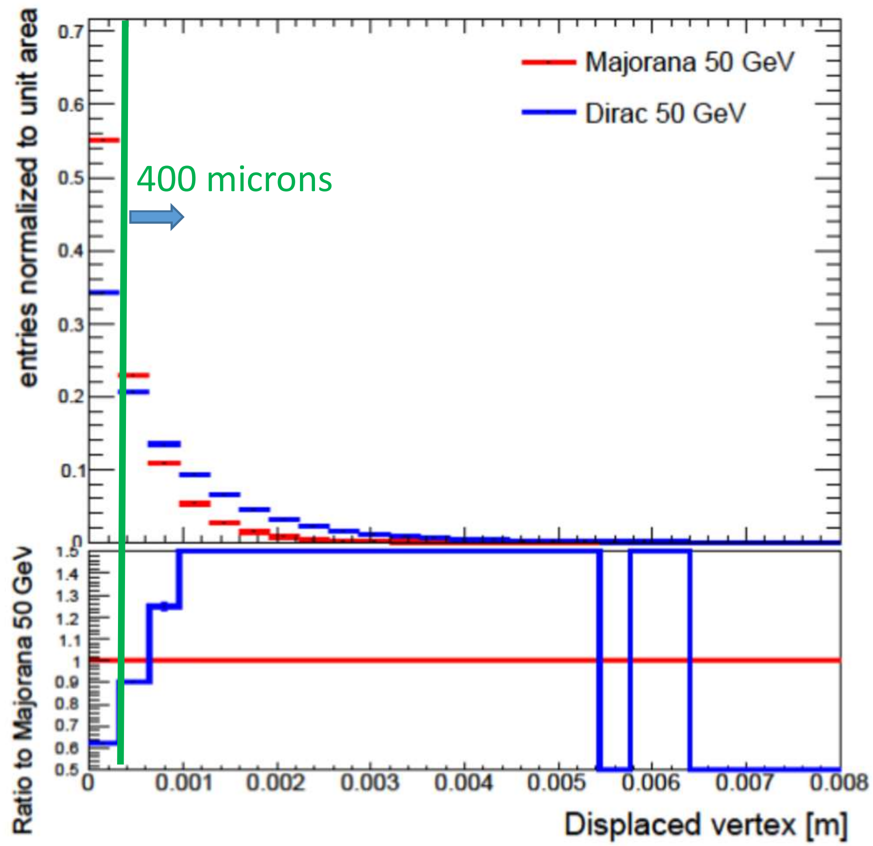
$$\Gamma_N = \frac{1}{c\tau_N} \simeq C_0 C_{MD} |U_N|^2 \ \left(\frac{m_N}{50\mathrm{GeV}}\right)^5 \times \left(\frac{3.10^9}{1 \ \mathrm{cm}}\right)$$

$$|U_N|^2 \equiv \sum_{\ell=e,\mu,\tau} |U_{\ell N}|^2$$

→ **At the Z** the production cross-section and the decay rate depend on the same combination of mixing angles!

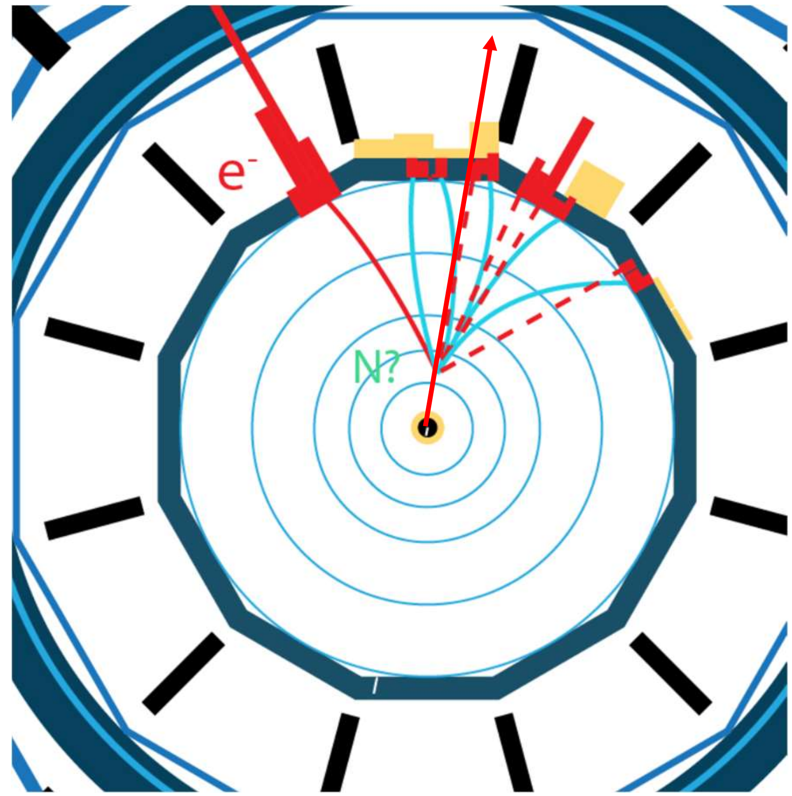
Of course this can only be used **if** we can measure the lifetime, however at larger mixing angle the other methods can be used.





decay length for mixing angle $|U|^2=10^{-6}$ in $N \rightarrow$ e+e- ν mode (10^4 events)

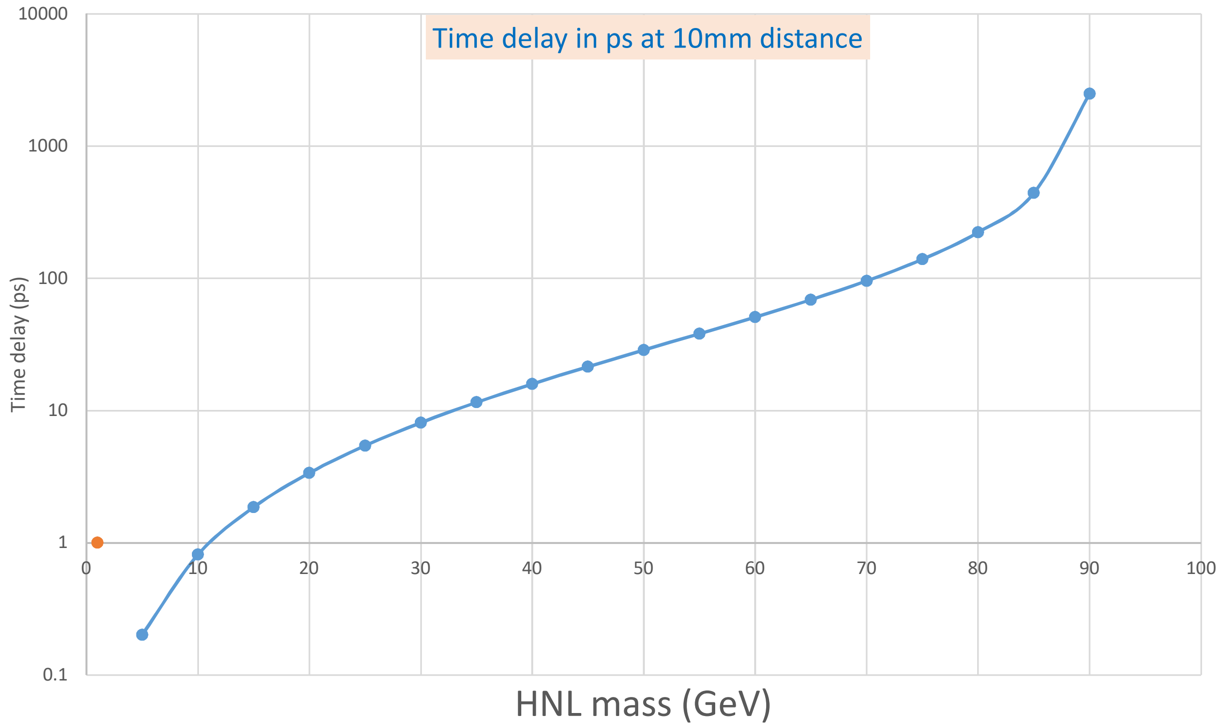
A little bit on timing studies



A. In an event like this, there is considerable amount of information for reconstruction.
-- primary vertex and secondary vertex give 3D direction of HNL and decay length
see table below for primary vertex 4D sigmas.
-- the final state reconstruction has therefore many constraints for a kinematic fit
--ECM and PCM
-- v_N and energy at secondary

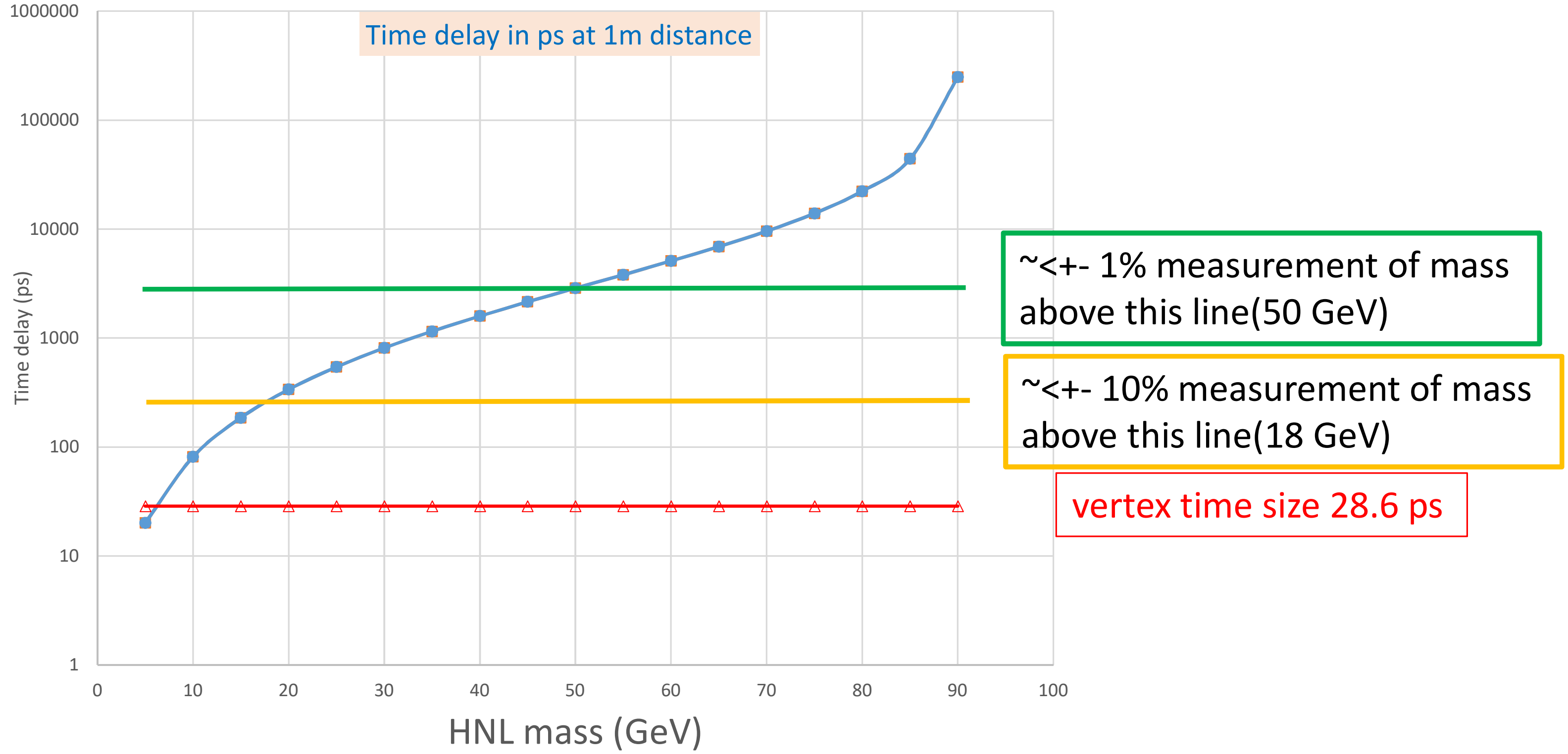
B However if precision timing is available, mass and velocity can be reconstructed on the basis only of
-- time-of-flight
-- and decay length

time of flight = E/M . τ
Decay length = P/M . cτ
knowning the two and applying the 2-body constraint at production $P^2 = (m^2_Z - m^2_N)/2m_Z$, $E^2 = (m^2_Z + m^2_N)/2m_Z$
will give the required information. This means that long lived particles can be reconstructed by timing



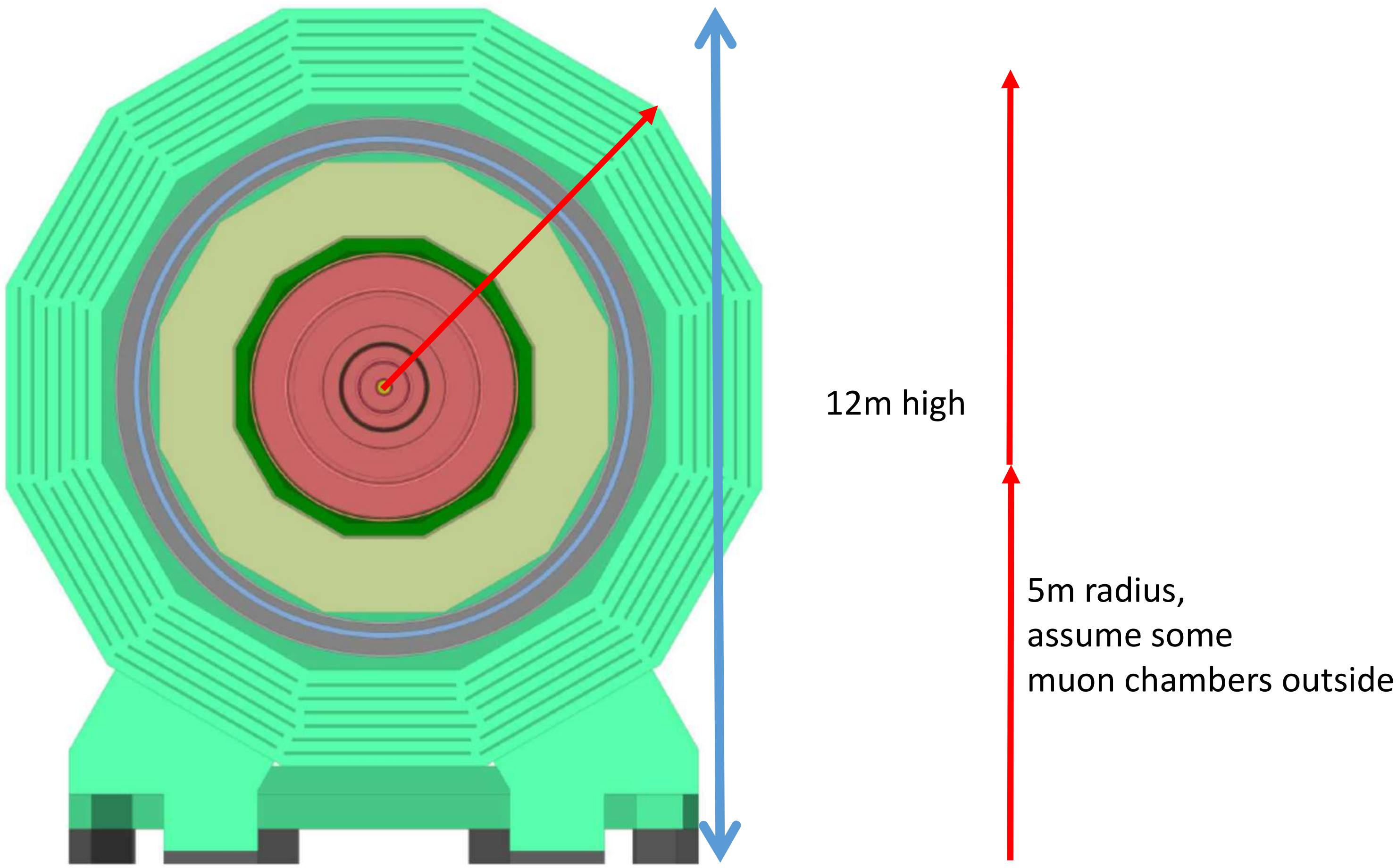
Time delay in ps at 10mm distance
10000
1000
100
10
1
0.1
Time delay (ps)
0
10
20
30
40
50
60
70
80
90
100
HNL mass (GeV)

Assuming a time resolution of 30 ps a very precise measurement of the HNL mass can be achieved from the timing alone



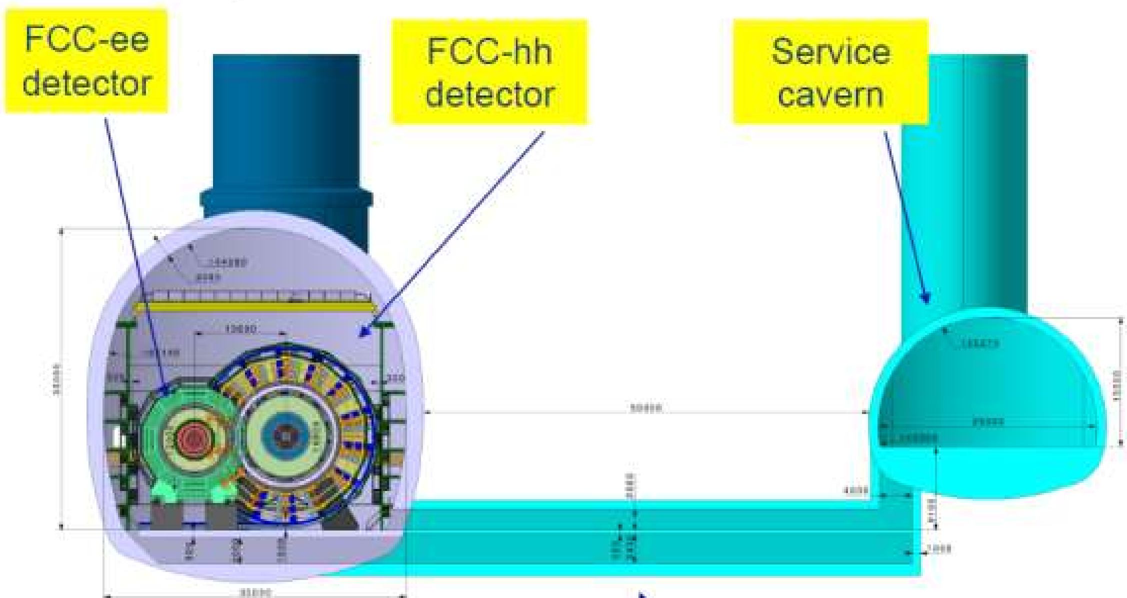
Increasing the detection efficiency with large detectors

CLD detector

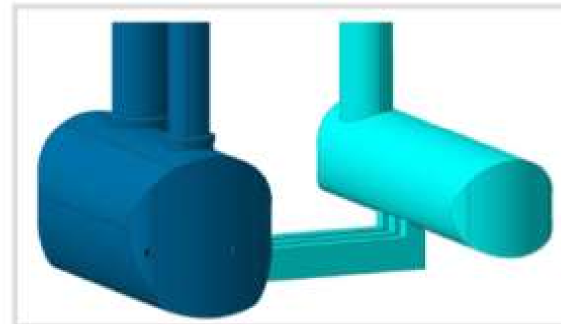


Common experimental points (A, G)

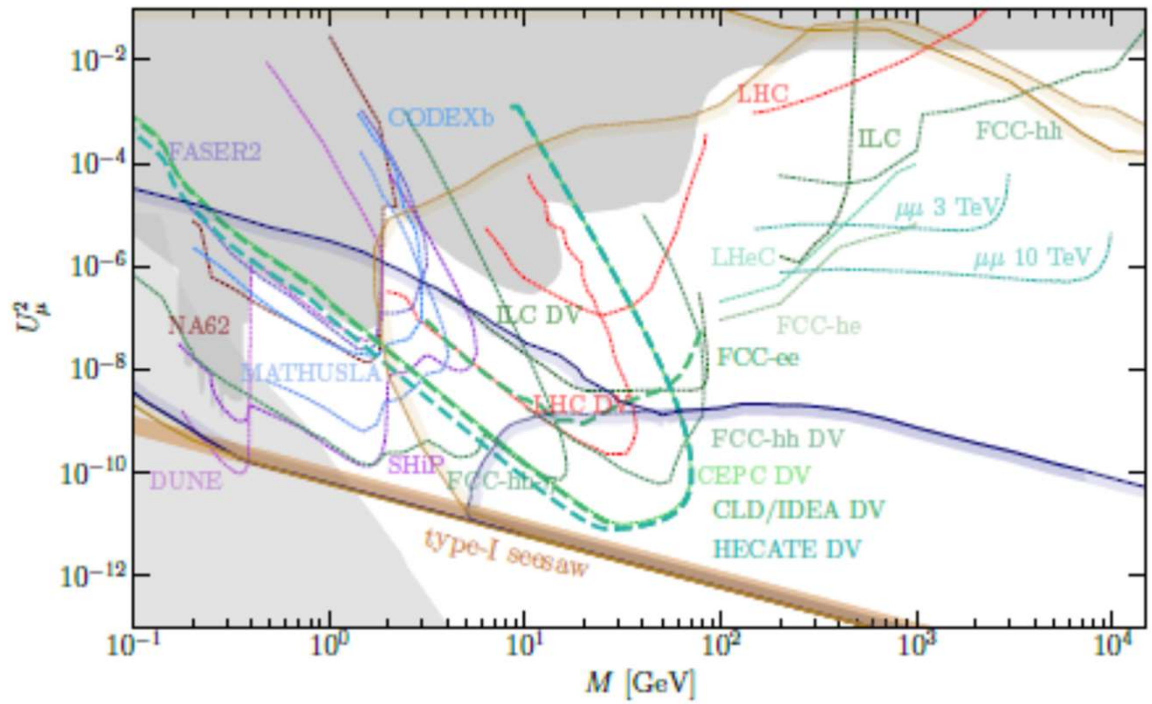
Distance between detector cavern and service cavern 50 m.
Strayfield of unshielded detector solenoid < 5mT.



Preliminary design of access and cable paths



HECATE DETECTOR TO FILL THE WHOLE CAVERN with e.g. RPC or Scintillator modules.



4 event lines for LLP signature (Exclusion if you do the search and find nothing!) 5 10^{12} events

Full legend of previous plot

see Alimena et al,

arXiv:2203.05502v3

Figure 1: *Bold green line:* Sensitivity of displaced vertex searches at FCC-ee. The parameter region inside the curves corresponds to more than four observed HNL decays with $|V_{\ell N}|^2 = \delta_{\ell\mu} U_\mu^2$ from 5×10^{12} Z bosons, assuming no background events and 95% reconstructed HNL decays (i.e., all decays except the invisible decay) inside the main detectors based on the IDEA or CLD design with a displacement of over 400 μm. Based on Tables 7.2 and 7.3 in [1] with 1 m of instrumentation required for detection, we assume a cylinder of length $l = 8.6$ m and radius $r = 5$ m (CLD) or $l = 11$ m and $r = 4.5$ m (IDEA) as fiducial volumes. The resulting curves for the CLD and IDEA detectors are visually indistinguishable. For comparison, we show what CEPC can achieve with 4.2×10^{12} Z bosons [2] for an IDEA-type detector [3]. *Bold turquoise line:* Gain in sensitivity if the maximal observable displacement is increased with HECATE-like detectors [4] with $l = 60$ m, $r = 15$ m at two IPs. *Medium gray:* Constraints on the mixing of HNLs from past experiments [5–15]. *Colourful lines:* Estimated sensitivities of the main HL-LHC detectors [16–18] and NA62 [19], compared to the sensitivities of selected planned or proposed experiments (DUNE [20], FASER2 [21], SHiP [22, 23], MATHUSLA [24], CODEX-b [25], cf. [26] for a more complete list), prompt searches at FCC-ee or CEPC [27, 28], and searches at selected other proposed future colliders (FCC-hh [18, 29–31], ILC [32, 33] LHeC and FCC-he [34], and muon colliders [35], with DV indicating displaced vertex searches). The curves from [16, 27, 28] were re-scaled for a consistent integrated luminosity with [17, 18, 36]. The sensitivity of FCC-ee and other future colliders can be further improved with dedicated long-lived particle detectors [4, 31, 37, 38]. *Brown band:* Indicative lower bound on the total HNL mixing $U_e^2 + U_\mu^2 + U_\tau^2$ from the requirement to explain the light neutrino oscillation data [39]. The band width corresponds to varying the light neutrino mass ordering and the lightest neutrino mass. The matter-antimatter asymmetry of the universe [40] can be explained by low scale leptogenesis [41–43] together with the light neutrino properties inside the mustard (violet) hashed contours with three [44] (two [45]) HNL flavours; solid and dashed contours indicate vanishing and thermal initial conditions in the early universe, respectively. *Light gray:* Lower bound on U_μ^2 from BBN [46, 47]. Plot adapted from [48].

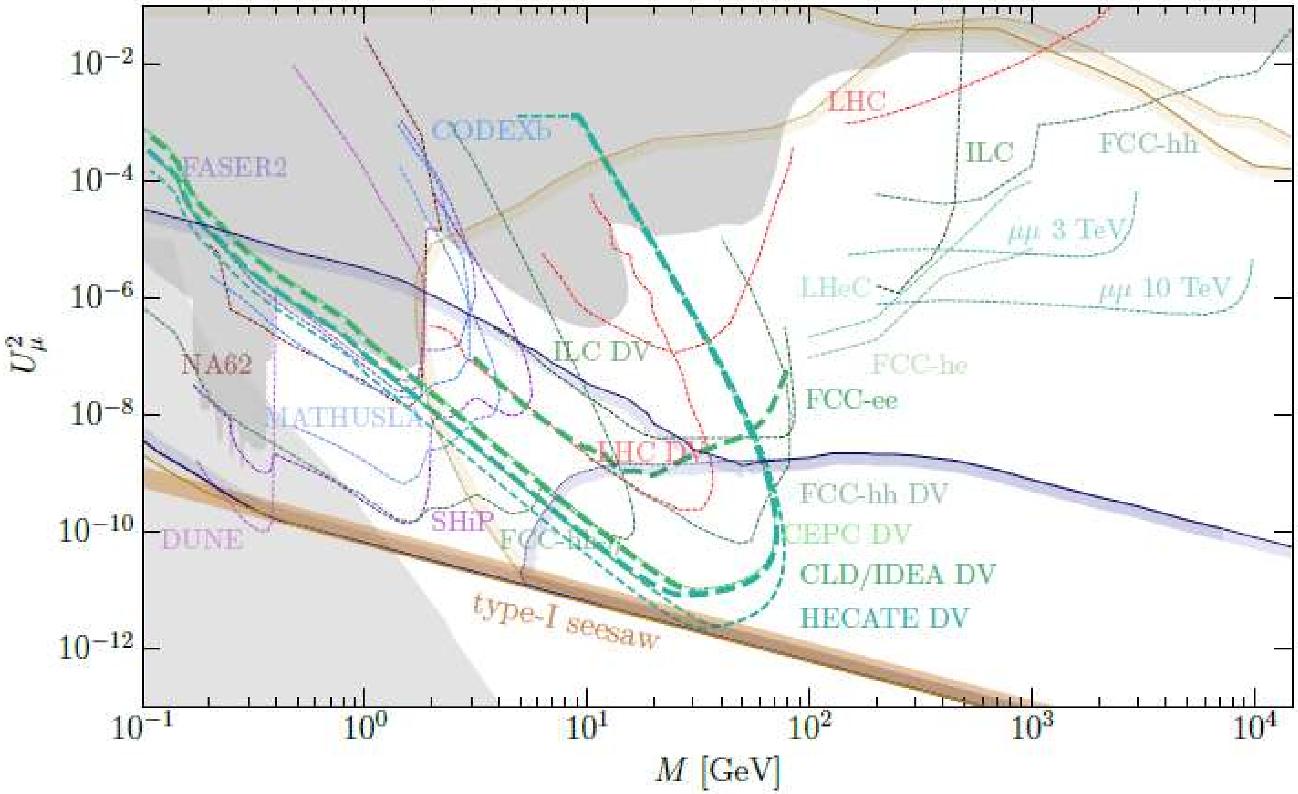
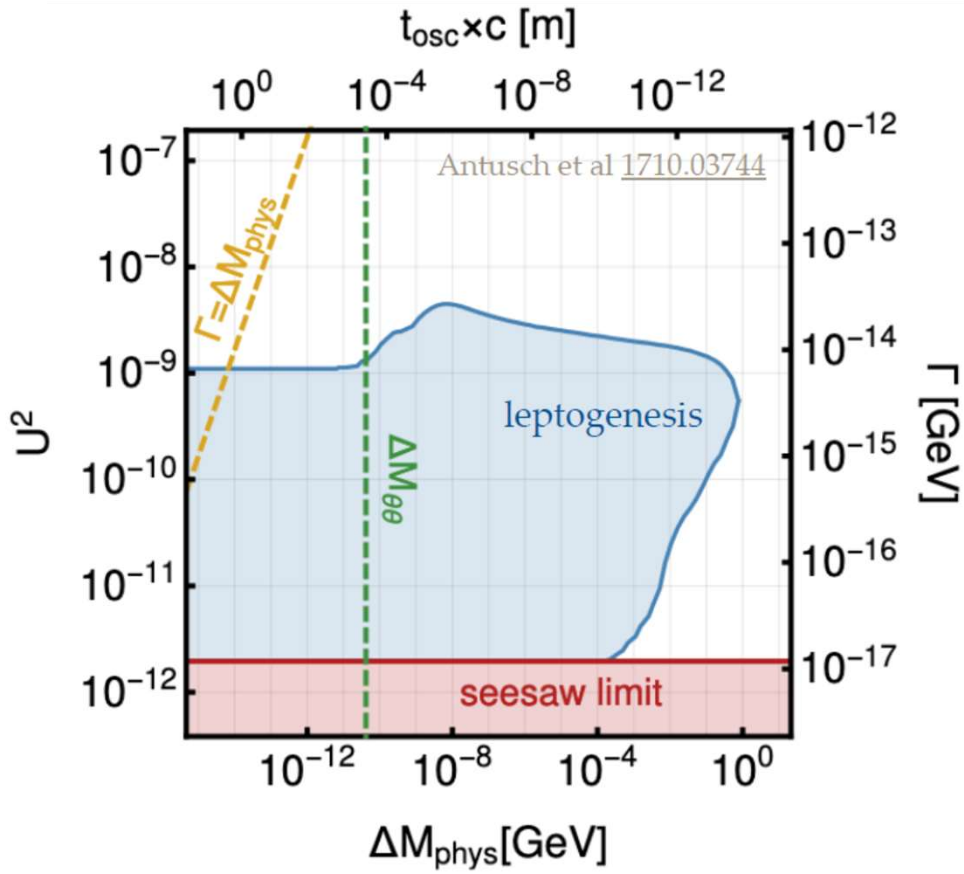
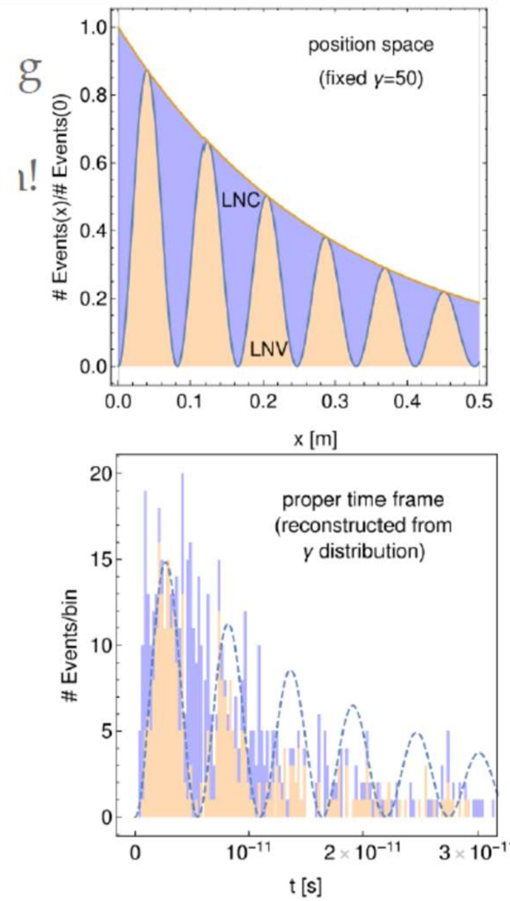


Figure 2: Comparison of the parameter regions in which four events (bold lines) and one event (non-bold lines) are expected in the IDEA/CLD detector or HECATE, with the same conventions and assumptions as in Fig. 2.

see M. Drewes presentation at ICHEP 2022

Testing Leptogenesis





Conclusions

0. as emphasized in 2021 NUFACT, **the FCC-ee is a heavy neutrino factory.**

1. We cannot overstate the importance of the HNL search – although large chance to be in vain
   the probability to appear below the W mass covers a fair fraction of the EW scale see-saw models.
   Directly related to the Higgs Yukawa coupling and extremely straightforward.

2. Right-handed neutrinos contain a very attractive solution to both the neutrino masses and the matter dominance in the Universe.
   -- it is also beautiful by its simplicity.

3. analysis contains many unpicked low-lying fruits and we keep finding new tricks.

JOIN US!