HECATE

A long-lived particle detector concept for the FCC-ee or CEPC

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Abstract The next generation of circular high energy collider is expected to be a lepton collider, FCC-ee at CERN or CEPC in China. However, the civil engineering concepts foresee to equip these colliders with bigger detector caverns than one would need for a lepton collider, so that they can be used for a hadron collider that may be installed in the same tunnel without further civil engineering. This opens up the possibility to install extra instrumentation at the cavern walls to search for new long-lived particles at the lepton collider. We use the example of heavy neutral leptons to show that such an installation could improve the sensitivity to the squared mixing parameter by almost half an order of magnitude.

1 Introduction

Future lepton colliders such as the FCC-ee [1] or CEPC [2] have an extremely rich physics program [3,4]. In particular, they are outstanding intensity frontier machines that can not only study the properties of the electroweak and Higgs sector at unprecedented accuracy, but they can also search for feebly coupled hidden particles that have escaped detection at the LHC due to their low production cross section. Due to their small interaction strength hidden particles can have comparably long lifetimes. Such new long-lived particles (LLPs) appear in many extensions of the Standard Model (SM) of particle physics that can address open questions in particle physics and cosmology, such as the Dark Matter (DM), neutrino masses or baryogenesis, cf. e.g. [5]. In recent years many studies have investigated the sensitivity of the LHC [6] and other experiments [7] to LLPs. The clean environment of a lepton collider would offer even better perspectives for such searches [1,3].

LLPs are typically searched for at colliders through displaced signatures [6]. One constraint in this context is the volume of the main detectors, which limits the potential to search for particles with very long lifetimes. For the LHC, several dedicated detectors have been proposed to extend the reach to larger lifetimes, including FASER [8], MATHUSLA [9], CODEX-b [10], A13X [11], MAPP [12], and ANUBIS [13]. While MATHUSLA would be placed at the surface, the other proposals take advantage of existing cavities that can be instrumented. At a future lepton collider the detectors will be smaller than those of the LHC, which limits the sensitivity to long lifetimes. However, the current planning for the FCC-ee and CEPC foresees to build a hadron collider in the same tunnel, namely the FCC-hh or SPPC [14,15]. For this reason, it has been proposed and is widely accepted that the detector caverns for the FCC-ee will be much bigger than needed for a lepton collider, so that the FCC-hh and its detectors can be installed in the same tunnel without major civil engineering effort. In this Letter we point out that instrumenting this extra space could considerably increase the sensitivity of the FCC-ee (or likewise the CEPC) to LLPs at a cost of only a few million Swiss franc (CHF). We therefore propose to include such a *HERmetic CAvern TrackEr* (HECATE) in future FCC-ee and CEPC studies.¹

2 Possible implementation and cost estimate

A possible implementation of the HECATE detector would consist of resistive plate chambers (RPCs) or scintillator plates, constructed from extruded scintillating bars, located around the cavern walls and forming a 4π detector. Such an hermetic detector design maximizes the fiducial volume

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¹ In a first version of the manuscript the detector concept was called HADES. The names has been changed to HECATE to avoid confusion with the existing experiment at GSI.

and allows to discriminate against events originating from outside the detector cavern. The inner detector and muon chambers act as a veto able to reject SM particles from the primary vertex. In order to obtain timing information and to distinguish particles from cosmic background, the HECATE detector should have at least two layers of detector material separated by a sizable distance. For reliable tracking, at least four layers, along with a smaller size and/or optimised geometry of the detector plates, would be required. The biggest challenge of such detector is the control of the background that will originate from two sources: cosmics and neutrinos produced at collision point. The first can be handled using timing information, which permits to distinguish particles coming from within the cavern from ones coming from outside the cavern. We expect neutrinos that are produced from cosmic rays and decay within the cavern volume to be more problematic. However, this background requires a detailed Monte Carlo simulation, which lies beyond the scope of this Letter. On the other hand, the feasibility of such a rejection is studied for the MATHUSLA detector, see [16] and references therein. We expect a lower background for HECATE, as MATHUSLA would be exposed to more cosmics due to its location on the surface. More dangerous is the background from SM neutrinos produced in process such as $e^+e^- \rightarrow Z \rightarrow \nu\bar{\nu}$, as neutrinos may interact with the detector material resulting in detectable charged particles. These type of events can be rejected in different ways, depending on where the interaction takes place. Events originating from the beam pipe can be rejected by using the tracker as a veto and interactions within the inner detectors can be rejected using its outer layers. Additionally, in the case that the background remains too large, one could install an additional tracker layer outside the detector as a veto system, that would be able to reject SM neutrino interactions in the outer layers of the usual detector. The present Letter is a simple proof-of-principle, and we postpone a detailed investigation of such backgrounds to future work. We note in passing that the MATHUSLA collaboration, which faces similar issues, has concluded that they are under control, see [16] and references therein.

For a horizontally cylindrical cavern with a radius of 15 m and length of 50 m, plates of 1 m² surface would provide ~ 6000 readout channels for the scintillating bars. The main cost of such detector would then be the cost of the scintillators. Assuming a thickness of 1 cm for a single panel the cost would amount to 3–5 MCHF with current prices. This assumes that the used scintillator is EJ-200, which has a long optical attenuation length and fast timing. The cost could be significantly reduced if a cheaper alternative is used that still matches the specifications required for such a detector design. The cost of the readout electronics can be estimated based on the Sci-Fi detector from LHCb [17]. On this basis, the readout electronics together with the clear and wave-

shifting fibers needed for the scintillator would cost around 30 CHF per channel. Hence, the total cost of the detector would be below 5 MCHF per layer. This estimate assumes present day technology and one can expect that better technology can be purchased at lower prices at the time the FCC-ee will be built.

3 Sensitivity estimate

We estimate the HECATE sensitivity for right-handed neutrinos, a type of *heavy neutral leptons* (HNLs). The existence of these HNLs is predicted by well-motivated extensions of the SM, in particular the type-I seesaw mechanism [18–23], leptogenesis [24], and as DM candidates [25]. They have been a benchmark scenario for FCC-ee sensitivity estimates from early stages [26]. The properties of HNLs are characterised by their Majorana mass M and the mixing angles θ_a that determine the suppression of their weak interactions relative to that of ordinary neutrinos. The implications of the heavy neutrinos' existence strongly depend on the magnitude of M , see e.g. [27] for a review.² The seesaw mechanism requires at least two HNLs to explain the light neutrino oscillation data. However, for the purpose of the present study a simplified model with a single HNL denoted by N suffices,

$$\mathcal{L} \supset -\frac{m_W}{v} \bar{N} \theta_a^* \gamma^\mu e_{La} W_\mu^+ - \frac{m_Z}{\sqrt{2}v} \bar{N} \theta_a^* \gamma^\mu \nu_{La} Z_\mu - \frac{M}{v} \theta_a h \bar{\nu}_{La} N + \text{h.c.}, \quad (1)$$

where e_{La} and ν_{La} are the charged and neutral SM leptons, respectively, Z and W are the weak gauge bosons with masses m_Z and m_W , and h is the physical Higgs field after spontaneous breaking of the electroweak symmetry by the expectation value v .

At a lepton collider the HNLs are primarily produced from the decay of on-shell Z -bosons. The HNL production cross section in the process $Z \rightarrow \nu N$ can be estimated as [26]³

$$\sigma_N \simeq 2\sigma_Z \text{BR}(Z \rightarrow \nu\bar{\nu}) U^2 \left(1 - \frac{M^2}{m_Z^2}\right)^2 \left(1 + \frac{M^2}{m_Z^2}\right), \quad (2)$$

their decay rate is roughly $\Gamma_N \simeq 12U^2 M^5 G_F^2 / (96\pi^3)$ with G_F the Fermi constant and $U^2 = \sum U_a^2$ with $U_a^2 = |\theta_a|^2$.⁴

² For further details on specific aspects we refer the reader to reviews on leptogenesis [28,29] and the perspectives to test it [30], sterile neutrino DM [31,32] and experimental searches for heavy neutrinos [33–36].

³ The sub-dominant N production in the decay of B -mesons generated in the process $Z \rightarrow b\bar{b}$ has e.g. been studied in [37].

⁴ The decay rates of HNLs into SM particles have been computed by many different authors [33,38–45], they overall more or less agree with each other.

The number of events that can be observed in a spherical detector with an integrated luminosity L can then be estimated as⁵

$$N_{\text{obs}} \simeq L \sigma_N \left[\exp\left(-\frac{l_0}{\lambda_N}\right) - \exp\left(-\frac{l_1}{\lambda_N}\right) \right]. \quad (3)$$

Here $\lambda_N = \beta\gamma/\Gamma_N$ is the HNL decay length in the laboratory frame, l_0 and l_1 denote the minimal and maximal distance from the interaction point (IP) where the detector can detect an HNL decay into charged particles. If the Z-boson decays at rest we can set $\beta\gamma = (m_Z^2 - M^2)/(2m_Z M)$.⁶ We then replaced one of the neutrinos with the HNL with a given mass. We have considered masses spanning from 1 GeV up to m_Z in steps of 1 GeV.⁷

In Fig. 1 we show the expected gain in sensitivity that can be achieved with HECATE (thick curves; red and blue encoding the FCC-ee and CEPC, respectively; solid and dashed, corresponding to $l_1 = 15$ m or $l_1 = 25$ m) in comparison to using only the inner detector (faint red and blue curve for FCC-ee and CEPC) with 2.5×10^{12} and 3.5×10^{11} Z-bosons, respectively. These numbers refer to the expected integrated luminosity during the Z-pole run at one IP. We display lines for nine detected signal events approximately corresponding to the 5σ discovery region under the assumption of a single background event. The actual sensitivity of HECATE should lie somewhere between the two thick red curves, as the approximately cylindrical detector extends from the IP 15 m in radial direction and 25 m in beam direction. The improvement with HECATE is almost half an order of magnitude in U^2 for given M . This can be understood by recalling that the region on the lower left side of the sensitivity region corresponds to decay lengths that greatly exceed the detector size. In this regime the exponentials in (3) can be expanded in l_1/λ and l_0/λ . For $l_1 \gg l_0$ the number of events is simply given by

$$N_{\text{obs}} \simeq L \sigma_N \frac{\Gamma_N l_1}{\beta\gamma} \propto L U^4 \frac{M^5 l_1}{\beta\gamma}. \quad (4)$$

Hence, the value of U^2 that leads to a given number of events for fixed M scales as $\propto 1/\sqrt{l_1}$. For the inner detector we assume a radius of 1.22 m within which displaced vertices can be detected. This corresponds to the size of the ECAL designed for the ILC [58], we use it as an estimate for the dimensions of the FCC-ee or CEPC detectors, which are to

⁵ In [46] we have confirmed in a proper simulation that the estimate (3) works reasonably well even at the LHC main detectors if one takes the average over the HNL momentum distribution. In the much cleaner environment of a lepton collider we expect that it works even better.

⁶ We confirmed that this is a good approximation by generating the HNL momentum distribution with PYTHIA 8.2 [47] (including initial state radiation) and averaging (3) over this distribution.

⁷ Natural units with $c = 1$ are used throughout this Letter.

Fig. 1 Comparison of the sensitivities for nine signal events that can be achieved at the FCC-ee with 2.5×10^{12} Z-bosons (red) or CEPC with 3.5×10^{11} Z-bosons (blue). The faint solid curves show the main detector sensitivity ($l_0 = 5$ mm, $l_1 = 1.22$ m). The faint dash-dotted curve indicates the additional gain if the muon chambers are used at the FCC-ee ($l_0 = 1.22$ m, $l_1 = 4$ m). The thick curves show the sensitivity of HECATE with $l_0 = 4$ m, $l_1 = 15$ m (solid) and $l_0 = 4$ m, $l_1 = 25$ m (dashed), respectively. Finally, the faint dashed red line shows the FCC-ee main detector sensitivity with 5×10^{12} Z-bosons, corresponding to the luminosity at two IPs. For comparison we indicate the expected sensitivity of selected other experiments with the different green curves as indicated in the plot [8–10,45,48]. The gray areas in the upper part of the plot show the region excluded by past experiments [49–57], the grey areas at the bottom mark the regions that are disfavoured by BBN and neutrino oscillation data in the ν MSM (‘seesaw’)

be determined.⁸ Hence, one can expect relative sensitivity gains $\propto \sqrt{1.22 \text{ m}/l_1}$. Relation (4) also permits to estimate the sensitivity gain by increasing the integrated luminosity L (e.g. by extending the Z-pole run or by considering more than one IP): Increasing L by a given factor has the same effect as increasing l_1 by the same factor. Hence, for given M , the value of U^2 needed to achieve a given number of events scales as $\propto 1/\sqrt{L}$. As an example we display the gain in sensitivity that could be achieved with the inner detector by doubling the integrated luminosity of the Z-pole run (faint dashed red curve). The scaling of all lines in the plot with increased integrated luminosity can be estimated by comparing the faint dashed red line to the faint solid red curve, and with relation (4). All HECATE lines would scale with the number of Z-bosons in the same way as the main detector line, we omit them here to keep the plot readable. We further do not show

⁸ In [59] the number 2.49 m was used, corresponding to the dimensions of the ILC HCAL. The gain in sensitivity can be estimated with (4), as outlined below, and lies somewhere between our main detector and muon chamber lines in Fig. 1.

all lines for the CEPC, the omitted ones would give similar relative sensitivity gains as for FCC-ee.

Further, we estimate the potential sensitivity gain from performing a search in the muon chambers at the FCC-ee (faint dash-dotted red curve). This idea, originally proposed in [60,61], has been applied to HNL searches at the LHC in [62,63]. As suggested by the scaling above, the gain is considerably lower than what could be done with HECATE. Finally, one may wonder whether it is worth to dig even bigger caverns to host dedicated LLP detectors. The scaling $\propto 1/\sqrt{l_1}$ of the sensitivity to U^2 for given M implies that the costs for civil engineering would quickly grow. For illustrative purposes we add the sensitivity that could be achieved with the very unrealistic *Totally Hyper-UNrealistic DETector in a huge DOME* (THUNDERDOME) concept at FCC-ee ($l_0 = 4$ m, $l_1 = 100$ m, dotted red line). However, for other LLP models with a different scaling the return of investment might be better.

It should be said that Fig. 1 is very conservative as far as the sensitivity gain with HECATE relative to the inner detector is concerned because we have assumed 100% efficiency and no backgrounds for both. For HECATE these assumptions are semi-realistic, as the inner detector can be used as a veto. In contrast, in the inner detector the reconstruction efficiency for displaced vertices rapidly decreases as a function of displacement. This dependence has been studied for the LHC [57,64,65] and LEP [51,66], but a realistic estimate for the FCC-ee detectors would require detailed simulations. In the present note, which is a proof-of-principle, we therefore choose to make the same assumptions for HECATE and the inner detector and therefore underestimate the relative sensitivity gain that could be achieved with HECATE.

It is instructive to compare the HECATE sensitivity to existing constraints and to the reach of other upcoming or proposed experiments. An updated summary of relevant experimental constraints can be found in [67].⁹ In Fig. 1 we display the exclusion region of several experiments under the assumption that the HNL exclusively mix with the second SM generation ($U^2 = |\theta_\mu|^2$) [49–57]. Indirect searches, on the other hand, strongly depend on the properties of light neutrinos, cf. e.g. [67,69–74] for a detailed discussion. In particular, lower bounds on the individual $|\theta_a|$ from neutrino oscillation data can only be imposed under specific model assumptions, and the lower bound on their sum U^2 scales as

m_{lightest}/M . As an indicator, we add the corresponding lower ‘seesaw’ bound in the Neutrino Minimal Standard Model (ν MSM) [75,76] as a gray area, assuming normal ordering of the light neutrinos. There is also a bound on the lifetime of the N from the requirement to decay before big bang nucleosynthesis (BBN) in the early universe, which again depends on the flavour mixing pattern. We here display the bound from [77] under the assumption $U^2 = |\theta_\mu|^2$.¹⁰

To put HECATE into the context of the future experimental program in particle physics, we indicate the sensitivity of selected other proposed or planned experiments, as indicated in the plot [8–10,45,48]. HECATE would be complementary to other proposals and help to fill the sensitivity gap between the reach of future lepton colliders limited by the volume of their detectors and fixed target experiment limited by the D -meson threshold, cf. Fig. 1.

Finally, one may compare the reach to the parameter region where leptogenesis is possible in well-motivated scenarios. The most updated parameter space scans for the ν MSM (practically $n = 2$) and the model with $n = 3$ can be found in [83,84], respectively. In both cases HECATE can probe regions deep inside the leptogenesis parameter space. In the future, it would be interesting to study how well HECATE could measure the HNL properties, so that, in case any HNLs are discovered, one could address the question whether or not these particles are indeed responsible for the origin of matter in the universe. For the FCC inner detector this has been done in [85,86].

4 Discussion and conclusions

In this Letter we point out that an instrumentation of the large detector caverns that are planned at future circular lepton colliders could considerably increase the sensitivity of searches for LLPs. The main difference between the HECATE concept and other proposals (such as surface detectors [9,87], forward detectors [9] or installations on the cavern ceiling [87]) lies in the approximate 4π solid angle coverage that can be achieved by covering the cavern walls with detectors. The possibility to install a far detector that is sensitive to displacements over 20 m with such large angular coverage without extra civil engineering is a unique opportunity result-

⁹ The sensitivity of some experiments depend on the number n of HNL flavours, the mass of the lightest SM neutrino m_{lightest} , and on the flavour mixing pattern, i.e. the relative size of the mixings $|\theta_a|^2$ with individual SM generations. It is therefore difficult to make an apple-to-apple comparison. The sensitivity of direct searches for displaced searches at accelerators in good approximation only depends on the flavour mixing pattern. In contrast to that, searches that rely on lepton number violating signatures strongly depend on the HNL mass spectrum and light neutrino properties [68].

¹⁰ In the recent works [77,78] it was assumed that the HNLs are in thermal equilibrium in the early universe, which is in general not true for small U^2 . In [79] it was, however, pointed out that smaller mixing angles are ruled out by the cosmological history between BBN and the cosmic microwave background (CMB) decoupling [80], and various other effects of HNL decays (dissociation of nuclei [79], effect the CMB anisotropies [81] heating up the intergalactic medium [82]). In the mass range considered here, the bounds from [77,78] can therefore be regarded as ‘hard’ unless one considers U^2 that are so tiny that the HNL are never produced in significant quantities.

ing from the fact that the caverns for FCC-ee or CEPC are expected to be designed to host a hadron collider. In addition to the large caverns, there will also be large vertical shafts over the chambers for the detector installation (16 m diameter planned for the CEPC, and over 20 m for the FCC at least two IPs), which could be used to install further instrumentation (as proposed for the LHC with ANUBIS).

The proposed solution based on scintillators should be regarded as an example and proof-of-principle. There are many other detectors that will reach timing and efficiency requirements, such as RPCs. The final choice would be based on detailed study of balance between the cost and the detector performance.

Using this example, we estimate that a detector of the HECATE type could increase the FCC sensitivity to heavy neutrinos (or HNLs) with masses below m_Z by almost half an order of magnitude at a cost of the order of ten million CHF, conservatively assuming present detector technology and prices. This improvement would help to fill the sensitivity gap for HNL masses between the B -meson mass (below which fixed target experiments are highly sensitive) and the regime that can be covered by the FCC-ee or CEPC main detectors. Heavy neutrinos are only one example for LLPs, which we have chosen for illustrative purposes here. HECATE could open many other portals to dark sectors that can potentially address some of the ‘big questions’ in particle physics and cosmology, including DM, baryogenesis, cosmic inflation and neutrino masses.

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