PROCEEDINGS OF SCIENCE

Sensitivity to HNLs with ANUBIS

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Models of new physics often predict long-lived particles that would escape current Large Hadron Collider experiments unseen. Long-lived particles are predicted by extensions to the Standard Model where a new sector couples to known particles via portal interactions. Such extensions include Heavy Neutral Leptons (HNLs), axions, dark scalars and dark photons. With HNLs as an example, we evaluate the discovery potential of the ANUBIS Experiment to a rich array of final states. The ANUBIS setup places detector technology directly on the ATLAS cavern ceiling, extending our lifetime reach further from the interaction point while maintaining synergy with timing information from the main detector. Recent updates to this detector setup are showcased in our results, including a new geometry layout and improved isolation from hadronic radiation. Benchmark HNL models allow us to compare with other long-lived particle experiments, and provide examples of new physics with unique discovery potential at the ANUBIS Experiment.

12th Large Hadron Collider Physics Conference (LHCP2024)
3-7 June 2024
Boston, USA

*Speaker

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1. Long-lived particles at the High-Luminosity LHC

Beyond-Standard Model (beyond-SM) scenarios predict long-lived particles (LLPs) through well-motivated mechanisms, in answer to common questions such as the origins of dark matter and baryogenesis. Often, these LLPs are neutral, explaining why they escape the LHC detectors unobserved [1]. For example, a common type of neutral LLP model for benchmarking is the sterile neutrino or Heavy Neutral Lepton (HNL) class, where See-saw mechanisms can explain the relative sizes of observed neutrino masses and introduce additional sterile neutrinos with long lifetimes, presenting significant unexplored parameter space [2]. Typical HNL models can include a wide variety of production and decay combinations, causing them to appear in diverse new physics scenarios.

The Physics Beyond Colliders (PBC) initiative aims to streamline efforts to target LLPs at the LHC and focus new detector proposals towards covering areas of phase space with greatest remaining discovery potential [3]. HNLs are a prime target for upcoming experiments sensitive to new physics with mass in the MeV-GeV range with weak couplings to SM particles. We require a range of searches to target diverse hidden sector physics, such as HNLs, where the weak couplings are present in portals between the hidden sector and the SM. The PBC group offers a method of organising and comparing these targets for future experiments.

1.1 Project scope

The ANUBIS experiment is a detector proposed for increasing sensitvity to LLPs in the HL-LHC upgrade [4]. The design extends the reach of the ATLAS Experiment by implementing RPC technology directly on the ATLAS cavern ceiling, converting the cavern into additional fiducial volume. ANUBIS falls under the umbrella of the PBC, belonging to a selection of future accelerator-based experiments exploiting the high-energy and high-intensity beams at the HL-LHC.

The scope of the present project is to develop a framework that explores the effect of the improved geometrical design of ANUBIS and updates to its isolation requirements, motivated by recent demonstrations that tighter isolation and a wider solid angle are likely to boost our signal sensitivity [5]. Recent interest in HNLs at ANUBIS prompted discussion of our sensitivity with the outdated design, revealing competitive discovery potential for minimal model scenarios [6]. We create a modular, multi-purpose algorithm to explore the sensitivity of our proposed detector to HNLs, for the first time using the updated design.

1.2 Transverse detectors

A vital consideration for improving LLP searches at the LHC is the addition of transverse and forward detectors that aim to form part of the HL-LHC upgrade. By increasing the distance of our furthest detector materials from an interaction point, these experiments extend the lifetime reach beyond the sensitivity of the main detectors. The ANUBIS detector is a transverse experiment, targeting a different mass-coupling range compared with forward experiments.

LHC coverage falls short for various LLP lifetimes spanning between around 100 metres and the Big Bang nucleosynthesis limit, in particular for scenarios where the combination of lifetime, mass, couplings, kinematics and background pose a challenge. The main LHC detectors typically

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lose LLPs that fall outside the sensitive mass range, especially for LLP masses smaller than close to 10 GeV where the backgrounds in ATLAS and CMS are often prohibitive [7].

Other transverse LLP detectors proposed for the HL-LHC include MATHUSLA and CODEX-b [8, 9]. Alongside ANUBIS, these experiments observe similar sensitivity to Higgs portal models in previous sensitivity studies [10].

2. The ANUBIS Experiment

Resourceful use of the ATLAS cavern ceiling as a base for the ANUBIS detector permits RPC tracking layers to extend across a large solid angle coverage with comparatively small added cost. An added benefit of cavern ceiling is that these layers will be situated at approximately 20 metres from the interaction point, extending the lifetime reach without also accumulating the difficult additional backgrounds faced by a design that places the detector material much further from the beamline outside the range of natural rock shielding. The ANUBIS experiment plans to function in tandem with the ATLAS detector, synchronising timing and triggering such that events may be matched across the experiments, lending the new detector a unique range of sensitivity.

The signal for the ANUBIS detector includes charged particle final states produced by neutral LLPs which escape from ATLAS and decay within the cavern region. Most backgrounds are excluded by using the ATLAS detector as an active veto, and cosmics are eliminated by rock shielding. The most persistent backgrounds in this study are neutrons and neutral K-long particles, where the neutral long-lived kaon for example has a mean decay length of around 15.3 metres, and these are removed by isolating the signal from nearby jets and charged tracks with our updated isolation requirements. In addition, background estimation for the present project is derived from the ATLAS muon spectrometer search, which employs a data-driven estimate and includes pileup [11]. This technique permits a conservative estimate for ANUBIS, given that the probability of hadronic interactions is considerably higher in dense calorimeter matter than in air, and the fiducial region in air is much smaller for the ATLAS muon spectrometer search.

2.1 Pro-ANUBIS detector

A prototype detector for the ANUBIS Experiment was installed in the ATLAS cavern during 2023 and has taken data since March 2024, which is currently under analysis. The prototype is designed to confirm data quality, optimise data-taking and allow us to develop alignment with ATLAS. Analysis tools are maturing as we continue to develop clustering and track reconstruction algorithms. The design hinges on BIS-7/8 RPC technology, capable of measuring particle fluxes inside the ATLAS cavern during Run 3. The setup produces the effect of a single tracking station unit module belonging to the main detector, stationed at a comparable distance and therefore able to evaluate its eventual performance once installed for HL-LHC.

3. Heavy Neutral Leptons

We focus on PBC-defined benchmark HNL models where couplings to the SM are minimal; the HNL couples only to one SM lepton flavour, beginning with electron-coupled Majorana (with no unique antiparticle) HNLs. These scenarios offer benchmarks for comparing sensitivity [12].

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Sensitivity depends on the complexity of the model; more complicated models with obscure signals are more easily isolated from background, but minimal SM couplings ensure that we do not overestimate sensitivity by targeting signatures which are by design almost background-free.

The decay modes of a heavy Majorana neutrino depend on its mass [13]. In theory, ANUBIS has some sensitivity for all available decay modes excluding decays into the fully-invisible tri-neutrino final state, so we simulate a wide range of two- and three-body final states.

4. Sensitivity at ANUBIS

The sensitivity of the ANUBIS Experiment to new physics depends on the mechanisms in the theory model for production and decay of a long-lived particle, the final state signature, the selection criteria for background removal, and any other efficiencies associated with the detector design. ANUBIS provides optimal sensitivity for a distinct range of HNL masses, which we define by scanning the coupling and mass parameters, calculating the corresponding decay width, simulating the decay position and evaluating the direction and geometric requirements for the decay products to reach ANUBIS. We interpret our results in consideration of factors such as relative production cross-sections, dominant decay branching ratios, prevalence of two- and three-body decays, characteristics of associated radiation and others.

4.1 Physics cases

The experiment requires at least two charged products of the HNL to coincide with the detector material for a signal to register. Kinematically accessible production and decay modes at LHC energies open new channels at HNL masses above a certain value; for example, when the HNL mass is above the pion mass, we predict two-body decays into a lepton plus a meson, where the meson is likely to be a pion, eta, rho, omega or kaon. The charged decay products in this decay chain must coincide with ANUBIS.

Mesons are produced dominantly at the LHC, especially abundant lighter mesons such as D mesons [14]. However, despite larger production cross-sections, mesons are more likely to be produced as part of jets, appearing in association with collimated hadronic radiation such as pions, coinciding with backgrounds from neutral kaons and neutrons which we remove. Similar cases arise in other transverse detector proposals. In contrast, Drell-Yann modes where HNLs are produced by W or Z bosons are associated with radiation produced in any angular direction, which is therefore less likely to fall within the bounds of isolation criteria and less affected by background removal. Further, the Drell-Yann modes are more likely to produce strongly-boosted HNLs than the B or D meson modes, leading to complementary mass and lifetime ranges at a transverse detector, with sensitivity in general to heavier boosted signal. In the case where the HNL mass is much lower than the W boson mass, we expect charged and neutral current interactions to dominate HNL production via bosons.

A strong basis for our study is comparison with a dark scalar or scalar portal scenario, due to previous work [5]. Compared with a scalar model, HNL LLPs have non-zero branching ratio for fully or partially invisible final states, leading to a lower fraction of decays with two or more charged objects. In particular, we observe this effect for tau-coupled HNLs at higher masses, where the large tau mass forbids charged-current decays for HNL masses up to the GeV scale. At the same time,

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HNL signals in general are collimated with less hadronic activity than scalar portal signals due to electroweak decays producing a neutrino or lepton, favouring the HNLs in background isolation.

4.2 Sensitivity framework

The algorithm developed in the present project is multi-purpose, designed to explore the sensitivity of ANUBIS to additional models, extending to muon- and tau-coupled HNLs, alongside vector-portal, axion-portal and scalar-portal models, to add to those covered so far. Fast and efficient evaluation with a modular framework will lend advantage for targeting this slew of interesting new physics scenarios. Recent development of this framework permits us to visualise the benefit of the updated geometry design, as well as to implement the ANUBIS-specific isolation requirements with ease, compare with other transverse experiments and ultimately understand how we contribute to honing LHC LLP sensitivity as part of the PBC initiative.

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