Suplemento de la Revista Mexicana de Física **4** 021135 (2023) 1–7

Overview of the CODEX-b experiment

M. K. Wilkinson

Department of Physics, University of Cincinnati,
400 Geology/Physics Bldg., PO Box 210011, Cincinnati, OH 45221-0011, USA

Received 30 May 2023; accepted 9 January 2024

We present the motivation and use-case for the proposed CODEX-b detector, as well as its description. We also describe the design and status of a smaller demonstrator detector, CODEX-β, as of the time of the conference associated with these proceedings.

Keywords: Dark matter; long-lived particles; large hadron collider; beyond standard model; new physics; Higgs boson; resistive plate chamber; transverse detector; physics beyond colliders.

DOI: https://doi.org/10.31349/SuplRevMexFis.4.021135

1. Introduction

The continued lack of clear signals for physics Beyond the Standard Model (BSM) at particle colliders poses a major challenge for the future direction of the field. One of the most obvious shortcomings of the Standard Model (SM) is in the description of Dark Matter (DM) about which it says nothing. The existence of DM is known from astronomical observations of its gravitational effects, but searches for it at particle colliders have so far yielded no signal candidates, though limits have been placed [1-6]. This situation suggests the need for new approaches to detection.

That DM is known only from its gravitational interactions poses a challenge for searches at colliders, which are famously insensitive to the incredibly weak effects of gravity. Nonetheless, there remains the possibility of feeble interactions between the dark sector and the SM via various portals. The minimal models for such portals can be classified into four types, (1) the dark photon, (2) the dark Higgs, (3) the axion, and (4) the sterile neutrino [7], all of which may include Long-Lived Particles (LLPs) [8], that is, particles with $c\tau \gtrsim \mathcal{O}(1)$ cm. Indeed, LLPs are ubiquitous in many BSM scenarios, including baryogenesis, supersymmetry, neutral naturalness, and, of course, the SM itself, which contains both the short-lived Z boson with $\tau \sim 2\times10^{-25}$ s and the proton with $\tau \gtrsim 10^{34}$ years [1, 8, 9]. From a qualitative perspective, given the presence of LLPs in the SM, one naturally expects their presence in BSM scenarios as well, and sensitivity to such particles is therefore an important component of future searches for BSM physics [9].

There is already a rich physics program searching for LLPs at the Large Hadron Collider (LHC). As shown in Fig. 1, existing detectors are sensitive to LLPs with a wide range of masses, from below 10 mev to above 10 gev, and required collision energies, that is, the center-of-mass energy required to produce particles that couple to LLPs. Nonetheless, there is a crucial region of phase-space to which these detectors are not sensitive, namely low-mass LLPs that only couple to particles produced at high collision energies; in particular, they are not sensitive to low-mass LLPs that couple

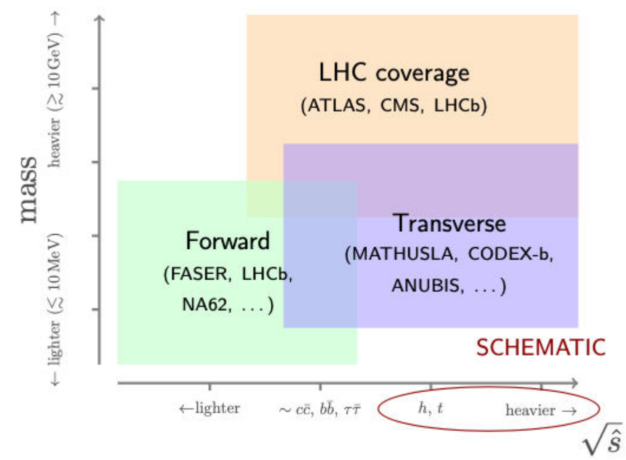

FIGURE 1. Sensitivity of some current, planned, or proposed experiments to various LLP masses as functions of the center-of-mass collision energy required to produce them, $\sqrt{\hat{s}}$. The energies only accessible at the LHChave been circled. Adapted from Ref. [10].

to the Higgs boson. These detectors are limited by a combination of high backgrounds, limiting their sensitivity to light LLPs, and geometry, since Higgs bosons are produced almost entirely in the central (not forward) region [8].

The Particle Data Group (PDG) currently places the upper limit on the branching fraction of the Higgs boson to invisible particles, including BSM particles, at about 19% [1]:

$$\mathrm{Br}[h \to \text{invisible}] \lesssim 19\%.$$

This leaves a substantial fraction of the width of the Higgs boson that could potentially decay to BSM particles (including LLPs) to which current LHC experiments, the only ones where Higgs bosons are produced, have only limited sensitivity.

This document is arranged as follows: Section 2 describes the design of the proposed CODEX-bdetector; Sec. 3 details a few of the BSM scenarios to which the CODEX-bdetector would be sensitive; Sec. 4 explains the planned CODEX-β demonstrator detector; and Sec. 5 summarizes the document.

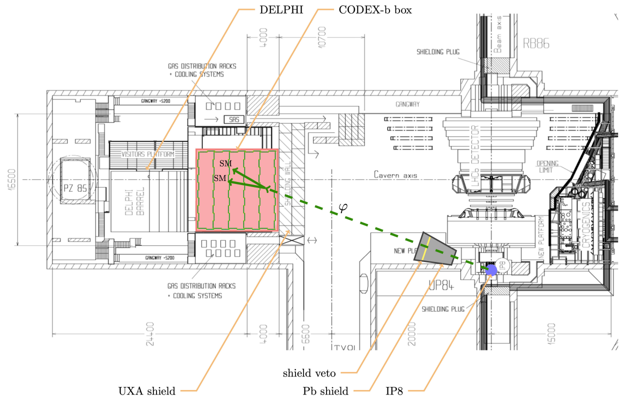

FIGURE 2. Layout of the LHCb experimental cavern at IP8, shown from above, overlaid with a schematic of the CODEX-b detector. Taken from Ref. [8].

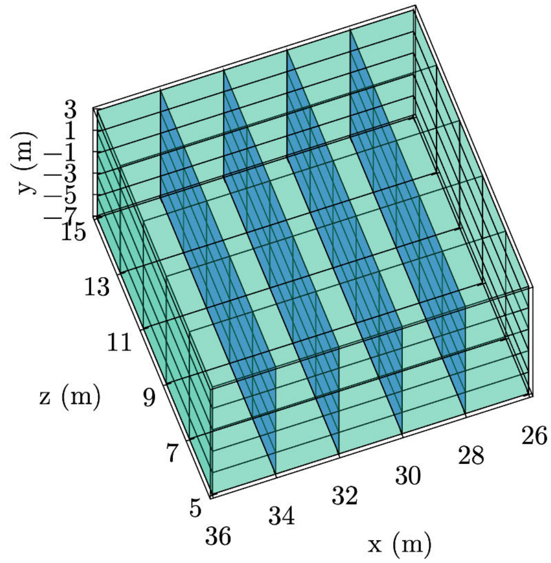

FIGURE 3. Schematic of the CODEX-b detector geometry, decomposed into 2×2 m pairs of triplet RPCs. The six external faces are shown in green, the four internal stations in blue. IP8 is at $x = y = z = 0$, and LHC beams travel along the z-axis at $x = y = 0$. Taken from Ref. [8].

2. CODEX-bdetector design

The COmpact Detector for EXotics at LHCb (CODEX-b) is a proposed LLP detector that would be placed in the area transverse to Interaction Point 8 (IP8), the LHC collision point in the LHCb detector cavern, as shown in Fig. 2, which already has many of the needed detector services in place. It would consist of a 10 m cube between the DELPHI exhibit and the LHCb detector. This would be a zero-background environment, ensured by the combination of a concrete (UXA), a lead (Pb), and an active shield, described below in Sec. 2.2. This shielding would ensure the absence of SM decays in the detector volume, meaning that any observed tracks would be compelling evidence of BSM LLP decay. This zero-background strategy for BSM LLP detection at the LHC is not unique to CODEX-b, and other proposed experiments using such a strategy include MATHUSLA, which would be located near the CMS interaction point [11], and ANUBIS, which would be located near the ATLAS interaction point [12]. (While CODEX-b and ANUBIS would be underground, MATHUSLA would be at the surface and therefore susceptible to background contributions from cosmic rays.)

A software-only trigger for LHCb was introduced for Run 3 of the LHC; every event is read out and reconstructed in real time (with buffering), enabling flexible decisions about which events to keep [13]. The CODEX-b readout would take advantage of this existing LHCb computing infrastructure, integrating with the LHCb trigger system. This would allow the full LHCb event reconstruction to be read out, complementing the information collected by CODEX-b itself and enabling detailed analysis of the underlying event. This feature is, to our knowledge, unique among proposed detectors.

Particle detection would be based on the use of 500 triplet Resistive Plate Chamber (RPC) panels, each with an area of 2×1 m. These would be built according to the ATLAS phase-II design [14], an established, inexpensive approach that minimizes the necessary research and development as well as costs. There would be no associated magnetic field or calorimeter, and mass measurements would be extracted using only the geometry of the tracks in the detector [15].

Each triplet-RPC panel would comprise three RPCs, and the panels would be arranged in a $10 \times 10 \times 10$ m cube with four internal stations, as shown in Fig. 3, for a total of 1,500 RPCs. As illustrated in Fig. 2, a signal LLP φ would travel through the shielding to decay to two (or more) charged SM particles inside the detector volume, producing no hits in the detector plane at $x = 26$ m (see Fig. 3) and producing hits in at least two of the other detector planes.

2.1. Resistive plate chambers

RPCs are planar capacitors whose parallel plates are separated by insulating spacers, which define a gas-filled gap [1], as shown in Fig. 4. This gas serves as the target for ionizing radiation, which creates electron-hole pairs in the gas; these electron-hole pairs then drift in opposite directions toward the readouts under the influence of the capacitor's electric field. The gas is kept at atmospheric pressure, simplifying their construction and maintenance. In practical terms, the thickness of the gas-gap determines the time to read out the electron-hole pairs and thus the timing resolution.

CODEX-b will rely on the BIS-7 RPC design developed by ATLAS for the High Luminosity LHC (HL-LHC) upgrade [14]. It is both well-tested and inexpensive, helping keep the overall cost of the CODEX-b detector low. It has more than sufficient spatial and timing resolutions, $\mathcal{O}$(1 mm) and $\mathcal{O}$(100 ps), respectively. The BIS-7 is a strip-based RPC; perpendicular strips on either side of the gas gap give two-dimensional information about the location of the ionizing

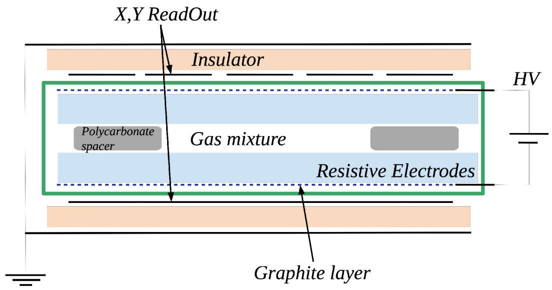

FIGURE 4. Schematic showing the cross-section of the BIS-7 RPC singlet design. Taken from Ref. [8].

particle. A schematic of the cross section of an RPC singlet is shown in Fig. 4.

As described above, the basic detector element of CODEX-b would be a *triplet* RPC [8]. Three independent singlet RPCs would be stacked face-to-face to form a triplet and packaged into a module. Each module would comprise a triplet and its mechanical supports and various services. This would provide three-point tracks to the reconstruction software (each module expects a hit in as many as three RPCs per track) and allow the modules to operate in self-trigger mode without any external reference system.

2.2. Zero background

The dominant sources of primary-collision (proton collisions at IP8) induced potential background in the CODEX-b detector volume are decays (or scatterings) of neutrons and K^0_L mesons to charged tracks [8]. These can be suppressed with passive shielding as

$$\sim e^{-L/\lambda},$$

where L is the shield thickness and λ is the nuclear interaction length of the material. The existing UXA wall is 3 m thick and made of concrete, corresponding to 7λ of shielding. An additional 25λ of shielding may be gained by the addition of a 4.5 m-thick Pb shield. Figure 2 shows the proposed positions of these shields in the LHCbcavern.

These shields may act as secondary sources of backgrounds by scattering muons or neutrinos produced in the primary collision [8], as shown in Fig. 5. If these leptons scatter in the Pb shield, their daughter neutrons or K^0_L mesons are likely suppressed by the remaining shielding, *e.g.*, the UXA wall. If, however, they make it through the Pb shield and scatter in the last ≈ 1 m of the UXA wall, their daughters may not be suppressed by the passive shielding and may decay inside the detector volume, becoming a source of background for the experiment.

These secondary daughters can be suppressed by embedding a single-layer scintillator (or similar) as an active veto layer in the Pb shield [10, 15], as shown in Fig. 5. The location of such a veto must be carefully optimized to reject most muons that produce secondaries without being so close to IP8 as to veto all events. This optimization was conducted using

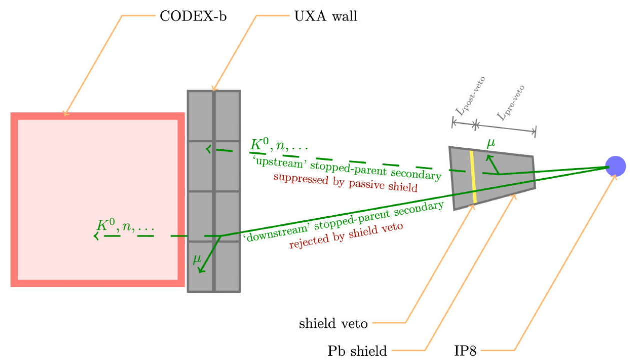

FIGURE 5. Shielding configuration for the CODEX-b detector. The Pb shield and concrete UXA wall are shown in grey, the active shield veto is shown in gold, and typical background topologies are shown as green arrows. Taken from Ref. [8].

simulation and later verified by measuring the flux rate in the LHCb cavern, as described below.

The simulation of the backgrounds was conducted using a combination of PYTHIA8 and GEANT4 [16-18], considering backgrounds from photons, electrons, protons, neutrons, π^+ mesons, π^0 mesons, K^+ mesons, K^0_S mesons, K^0_L mesons, muons, neutrinos, and (where applicable) their antiparticles [10]. All were found to produce $< \mathcal{O}(1)$ signal-like yields in the detector volume after collecting an integrated luminosity $\mathcal{L} = 300$ fb-1 with the shielding described above in place. The simulation of machine-induced background sources was underway at the time of the conference associated with these proceedings.

To verify the rates found in the above simulation, a validation campaign was carried out [19]. Existing scintillators were placed in six positions, shown in Fig. 6, and data was collected in a seventeen-day period during Run 2 of the LHC. All measured background rates were less than predicted by simulation; for example, at position 2, a flux rate of only 0.2 hz was measured while 5 hz had been predicted. The simulation described above was thus shown to be conservative, increasing confidence that the proposed design would indeed

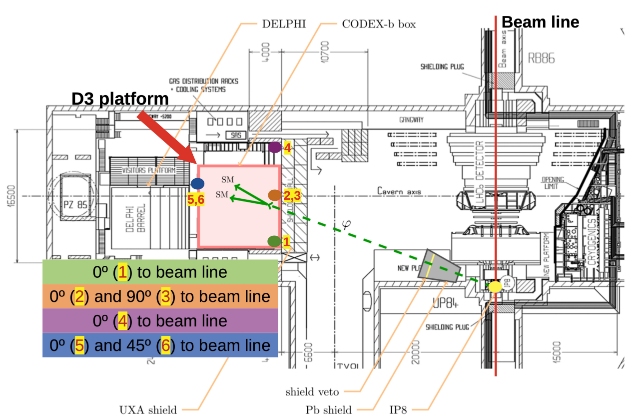

FIGURE 6. Measurement positions for background validation in the LHCb cavern. The D3 platform is part of the existing UXA-D barracks currently occupying the proposed location of the CODEX-b detector. Taken from Ref. [19].

result in a zero-background environment. At the time of the conference associated with these proceedings, further tests were scheduled to be carried out by the CERN radiation group during Run 3 of the LHC [8]. Final background validation would be carried out by the CODEX-β demonstrator, described below in Sec. 4.

3. CODEX-b model sensitivity

The CODEX-b detector would be sensitive to a wide range of BSM scenarios, many of which are detailed in Ref. [10]; we highlight a few of them here. Additional scenarios that CODEX-b would be able to probe include R-parity violating supersymmetry, relaxion models, neutral naturalness, inelastic DM, DM coscattering, DM from sterile coannihilation, asymmetric DM, baryogenesis, and hidden valleys. Across all models, a general picture emerges that CODEX-b would offer greatly increased coverage to existing detectors and complementary coverage to other proposed detectors at a lower cost with simplified construction and shorter installation time.

3.1. Abelian hidden sector

The Abelian hidden sector model is a minimal model postulating one new particle (A') and its associated Higgs boson (H'); the A' particle corresponds to (1) the dark photon mentioned in Sec. 1. Mixing between the H' boson and the SM Higgs boson (h) can lead to $h \to A'A'$ decay, which becomes the dominant production mode for the A' particle in the limit of small mixing between the A' particle and the SM photon. The A' particle may then decay to SM states via kinetic mixing. The CODEX-b detector would have good sensitivity to such a scenario, including a wide range of phase space to which ATLAS will have no sensitivity, as shown in Fig. 7.

3.2. Scalar-Higgs portal

The scalar-Higgs portal model is the most minimal extension of the SM and postulates a single additional scalar (S). From gauge invariance, the Lagrangian is restricted to

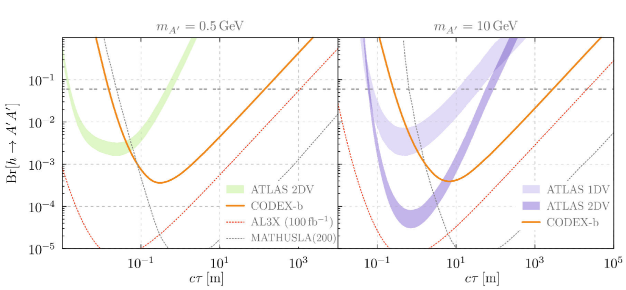

FIGURE 7. Estimated upper limits on $\mathrm{Br}[h \to A'A']$ from simulation as a function of A' lifetime. The horizontal dashed line is the estimated HL-LHC limit on $\mathrm{Br}[h \to \mathrm{invisible}]$. ATLAS estimates are shown for one or two displaced vertices (1DV or 2DV) and the corresponding bands range from conservative to optimistic. Taken from Ref. [10].

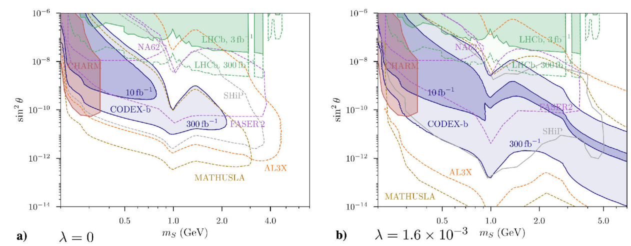

FIGURE 8. CODEX-b reach to investigate the scalar-Higgs portal by measuring $\sin^2\theta$, estimated from simulation. $\lambda = 0$ and $\lambda = 1.6 \times 10^{-3}$ correspond to the most conservative and optimistic scenarios, respectively. The latter case corresponds to $\mathrm{Br}[h \to SS] = 0.01$, the approximate future reach for $\mathrm{Br}[h \to \mathrm{invisible}]$ of ATLAS and CMS. Taken from Ref. [10].

$\mathcal{L} \supset \sin(\theta) S H^\dagger H + (\lambda/2) S^2 H^\dagger H + \cdots$, where θ is the mixing angle of S and the SM Higgs boson and λ is a constant. This mixing between the hidden S particle and the SM Higgs corresponds to (2) the dark Higgs mentioned in Sec. 1. The LHCb experiment is already sensitive to such models [20,21], and the CODEX-b detector would be dramatically more sensitive, as shown in Fig. 8.

3.3. Axion-like particles and heavy neutral leptons

Pseudoscalars coupling to the SM via dimension-5 operators, Axion-Like Particles (ALPs), are associated with a variety of BSM models, corresponding to (3) the axions mentioned in Sec. 1. Their highly suppressed couplings can lead to LLPs, which can couple to quarks, gluons, leptons, and photons. CODEX-b would be sensitive to a wide range of such scenarios.

Motivated by, *e.g.*, the presence of neutrino masses, DM, or semileptonic anomalies, heavy neutral leptons feature in a range of BSM scenarios and correspond to (4) the sterile neutrinos mentioned in Sec. 1. CODEX-b would have sensitivity complimentary to that of, *e.g.*, DUNE and the b-factories in many scenarios.

In the interest of brevity, the sensitivity plots for these models are not shown here; they can be found in Ref. [10].

4. CODEX-β

To validate the key concepts behind the CODEX-b detector design, a small-scale demonstrator detector called CODEX-β has been proposed to operate during Run 3 of the LHC. It would seek to

- Validate the background estimates described in Sec. 2.2, confirming that CODEX-b would operate in a zero-background environment.
- Integrate with the LHCb readout and trigger, proving the feasibility of this setup and building the expertise of the team.
- Demonstrate that the BIS-7 RPC design is suitable for this kind of detection and reconstruction.

- Reconstruct SM background decays to validate those used in simulation

- Test the suitability of the mechanical support structure design before scaling it to support the full-sized CODEX-b detector.

It is described in detail below.

4.1. CODEX-β design

The CODEX-β demonstrator would be similar to the proposed CODEX-b design in almost every way except scale, occupying just $2 \times 2 \times 2$ m and containing only one internal station, for a total of fourteen triplet RPCs, as shown in Fig. 9. It is proposed to be located inside the UXA-D barracks in the LHCb cavern, which the CODEX-b detector is proposed to replace. No Pb or active shield would be in place, only the existing UXA wall, allowing for detailed background validation studies (see Sec. 2.2).

From Run 3 of the LHC, LHCb will have a software-only trigger (see Sec. 2 above). The CODEX-βdemonstrator would integrate with the LHCb DAQ, sending hits to the LHCb event-builder and trigger-farm on the surface.

While both CODEX-b and CODEX-β would utilize the existing ATLAS BIS-7 singlet RPC design, a new module frame design is needed to support the RPCs in the unique cubic geometries of these detectors. Such a design has been drafted based on the BIS-7 module frame design, but it requires thicker aluminum and larger cross-supports, would provide more pick-points for hoisting, and would impose fewer space constraints, allowing the modules to be moved and positioned in a variety of positions without unduly stressing the triplet RPCs. It would be made entirely of 6063 aluminum extrusions with stainless steel fasteners, requiring no welding. A preliminary finite element analysis shows that these frames would be robust under load, and the design is depicted in Fig. 10.

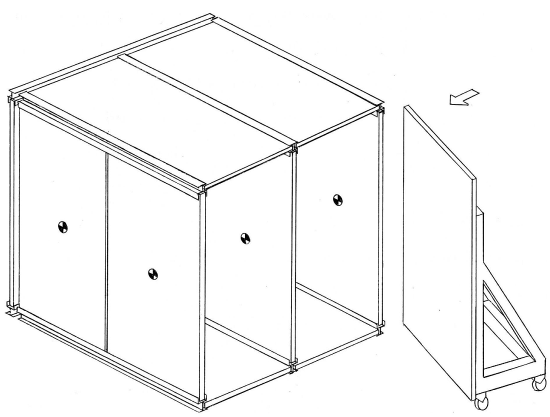

FIGURE 9. Schematic of the CODEX-β demonstrator geometry. The arrow indicates the direction of incoming particles. The open face would be closed by two modules on rolling carts, one of which is shown. Taken from Ref. [8].

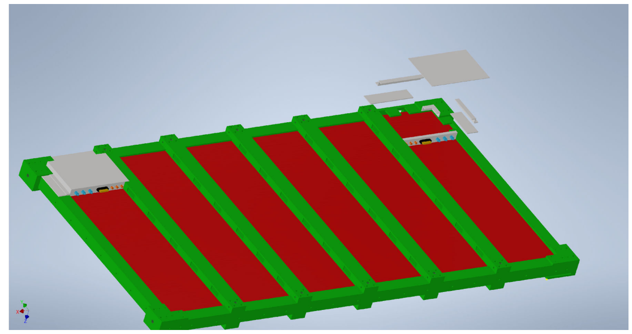

FIGURE 10. Schematic of the module support frame for CODEX-b and CODEX-β, along with the needed service boxes. Taken from Ref. [8].

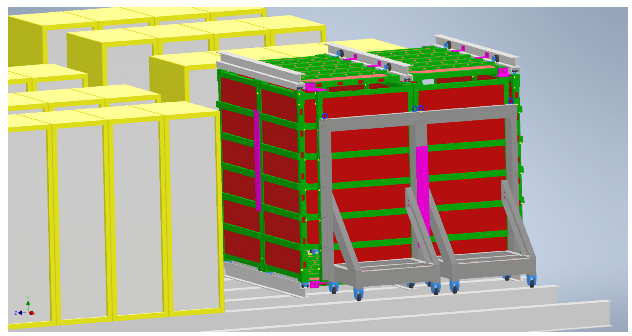

FIGURE 11. (Left) schematic of the CODEX-β demonstrator in place in the UXA-D barrack. The remaining servers are shown; the floor tiles covering the floor-supports and walls are not. Taken from Ref. [8]. (Right) the narrow door leading into the UXA-D barrack.

The support structure would need to support fourteen $\approx$ 200 kg modules in different orientations, necessitating three different installation procedures: (1) vertically mounted modules with rollers on the bottom and guides on the top, (2) horizontally mounted modules with rollers on both sides, and (3) vertically mounted modules on permanent carts, not supported by the structure. This would allow all the modules to be rolled into place while leaving one removable face, enabling access to the interior of the cube for maintenance and troubleshooting.

Its proposed location inside the UXA-D barrack would pose challenges for installation, as the server racks and walls greatly constrain the available space and all components must enter through a narrow door, as shown in Fig. 11. This necessitates creative approaches to installation. The support structure would be assembled entirely in-place, except for components that require welding. Rolling carts would be used to transport the modules into the barrack and would permanently support two of the modules (see Fig. 9). This would still be a tight operation in any case, requiring careful planning to execute.

4.2. CODEX-β model sensitivity

While primarily serving to validate the technical feasibility of the CODEX-b detector, the CODEX-β demonstrator would

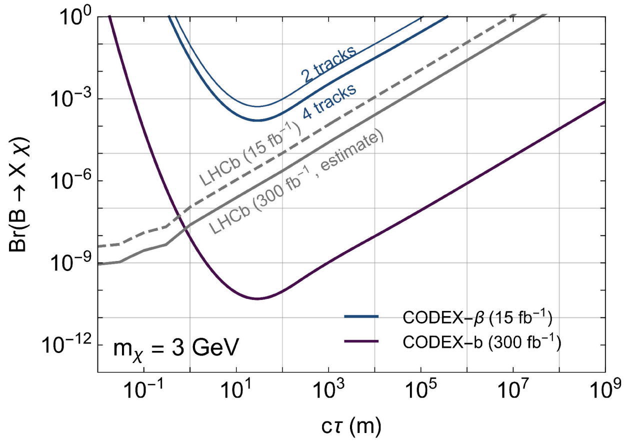

FIGURE 12. Sensitivity of the CODEX-β demonstrator to an LLP χ, produced in B-meson decays, decaying hadronically. Taken from Ref. [10].

itself have sensitivity to some BSM scenarios [10]. Billions of b-hadrons would be produced at IP8 while CODEX-β was in place, and some of them could decay to a BSM LLP. The CODEX-β demonstrator would be sensitive to a multi-track SM decay of such an LLP, even with its limited acceptance and relatively high levels of background, as shown in Fig. 12. It is even possible, though unlikely, that it could be the first to set limits on certain types of decays, despite the better reach of LHCb, because of the expected simplicity of analyses in CODEX-β.

4.3. CODEX-β production pipeline and status

This section is up-to-date as of the time of the conference associated with these proceedings.

The construction of CODEX-β is underway. Testing of 422 readout boards was conducted during the summer of 2022, and strip panels for the RPC singlets are being procured.

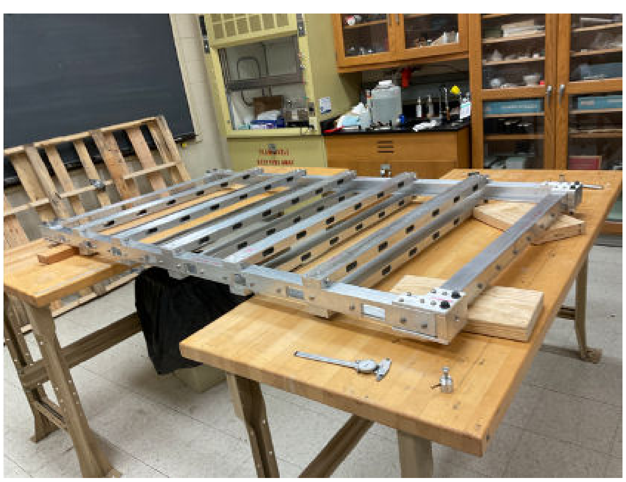

FIGURE 13. Assembled prototype module frame (top) without skins or shims and (bottom) with skins and shims placed around a mock triplet RPC.

A prototype module frame has been machined and assembled, shown in Fig. 13. It took about three hours for an inexperienced team to assemble using written procedures and was found to match the specified dimensions to high precision. Aluminum skins with 2.3 mm thickness are placed on either side of the triplet RPC to create a Faraday cage, reducing electronic noise and providing additional support. Aluminum shims of varying thicknesses can be placed between the skins and the frame to ensure the triplet RPC is slightly compressed and tightly held; mock triplet-RPC insertions were conducted using appropriately-sized foam to confirm the suitability of this scheme, also shown in Fig. 13. The stability of the frame was confirmed by hoisting it from multiple angles using eye hooks attached to the frame's pick points.

The CODEX-β production pipeline is foreseen to begin at the University of Cincinnati (UC), which would manufacture and test the module frames and support structure, and at an RPC lab at the European Organization for Nuclear Research (CERN), which would assemble the RPCs. The module frames would be sent from UC to the CERN RPC lab, where the modules would be assembled. The support structure, meanwhile, would be sent directly to IP8 for assembly. Final assembly, including module insertion and service installation, would naturally take place at IP8.

The production of CODEX-β is well underway. The support frame design is mature, and the final validation of the prototype module frame is in progress. The designs of the gas and electronics systems are mature, and final material procurement is ongoing. The needed measurements of the UXA-D barrack are complete, and a mock detector installation has been conducted. The preparations for installation, including the production of all components, are anticipated to be complete by the end of 2023.

5. Summary

To avoid large blind spots in the search for BSM physics, a transverse LLP detector at the LHC is necessary. CODEX-b is a proposed such detector that would have sensitivity to a wide range of BSM scenarios with complementary coverage to other proposed detectors at a lower construction and maintenance cost and a shorter construction timeline. Partial installation and data-taking are proposed to begin by Run 4 of the LHC (2027) with full installation by Run 5 (2032).

The CODEX-β demonstrator would validate the novel features of the CODEX-b detector. It would serve as a prototype, using the same technology and setup on a smaller scale, thus demonstrating the feasibility of CODEX-b and providing expertise to the team. It would also validate the background estimates in the area of the LHCb cavern in which the CODEX-b detector is proposed to be located and possibly probe BSM scenarios. It is currently under construction, and installation is proposed to begin during Run 3 of the LHC (ongoing).

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