Continuation of EIC KLM R&D Proposal

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(Dated: July 2023)

This R&D program aims to demonstrate the capability of the KLM detector concept to provide muon identification in a compact design, and to evaluate and extend its capability for hadron identification and calorimetry beyond the state-of-the-art (Belle II). The goal is to provide a cost-effective generic baseline detector design for muon and/or neutral hadron (K_L and neutron) identification based on successive layers of scintillator-absorber sandwich integrated in the central solenoid flux return that can be implemented, *e.g.*, in a second EIC detector or future extensions elsewhere. The program brings a new collaborating institution, Ramaiah University of Applied Sciences (Bangalore, India), to the EIC project and explores synergies between the participating institutions as well as with other R&D programs at EIC and elsewhere.

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CONTENTS

I. EXECUTIVE SUMMARY

The objective of the proposed R&D program is to demonstrate the capability of the KLM detector concept to provide muon identification in a compact design and to extend it for hadron identification and calorimetry beyond the state-of-the-art (Belle II). The program aims to provide a cost-effective generic baseline detector design for muon and neutral hadron (K_L and neutron) identification based on successive layers of scintillator-strip-absorber sandwich integrated in the central solenoid flux return that can be implemented, *e.g.*, in a second EIC detector or future extensions elsewhere. One key aspect of the program is 10's of picosecond timing resolution.

The superior timing resolution will provide time-of-flight information for hadron identification and momentum measurements. Together with a double-sided readout, the timing resolution will also provide position information on one strip, removing the need for two orthogonal strips per layer and thus enabling a more compact design. We will investigate how this wealth of information from pulse shape and timing measurements, together with the longitudinal and horizontal segmentation, can be exploited by AI reconstruction algorithms for hadron ID and calorimetery. Adding muon detection to any EIC detector has recently been identified as being of high interest by the community as it can extend the physics reach of the EIC. This aspect has been emphasized in the discussion of the physics case for a 2nd detector at the recent topical workshop [1]. That such a detector could double as a cost effective HCAL is an exciting prospect for cost reduction. The proposed program takes advantage of synergies with existing R&D efforts for the EIC as well as for the Belle II KLM.

II. INTRODUCTION AND OVERVIEW

For ease of reading, the physics and project overview as well as the general description of the detector have been moved to the appendix and more details can be found in last year's proposal. Here we only highlight changes that were necessary due to the funding shortfall in the first year (about 50%), new insights and other developments. The general progress report can be found in Sec. III below. Based on the adapted project plan and schedule we ask for a continuation of funding, concentrating on simulation, scintillator evaluation and readout chain development for the Barrel KLM. This work will take place at Duke University, Indiana University and the University of South Carolina with the involvement of a new collaborator from Ramaiah University who is visiting U of SC to work on this project. The proponents of this project will still consult with the groups from the University of California which are not part of this proposal anymore but have relevant expertise.

A. Adaptions of original project plan

This section highlights the main changes with respect to the plan outlined in the proposal submitted in 2022.

1. *Simulation*

Initially the plan foresaw an implementation in fun4all only. Given feedback from the review committee and the EIC software group, we decided to focus on an implementation in DD4hep, the same framework used for the project detector. It is also the standard framework for other HEP experiments. The advantages are:

- Synergy with developments for the project detector (e.g., adaption of other subsystems in the simulation)
- Possibility to use the design of the KLM integrated with the solenoid magnet as a base for a second detector prototype design.
- Facilitation of contributions from groups familiar with the framework e.g., from work on ePIC.
- Integration in the project organization structure proposed by the EIC software group.

While the main thrust of the development is now the use of DD4hep, we still decided to invest some effort in the existing fun4all implementation based on the CORE design. This is relatively cost effective and educational as it is being done by an undergraduate student and will be helpful in cross-checking the DD4hep implementation initially. As shown further below, some new features have been implemented in the fun4all implementation as well. We want to stress though that this is not a duplication of work as geometry from fun4all can be ported to DD4hep.

2. *Electronics*

The plan for the electronics for Year 2 has changed substantially compared to the original project plan.

Due to personnel health reasons, there are uncertainties relating to the availability of the HDSoC readout and auxiliary SiPM boards from Hawaii. While still hoping to evaluate these electronics in the future, we will focus in the near and intermediate term on the more basic capability needed for obtaining test results to guide the design. The electronics to be used in the initial scintillator test stand measurements should be relatively simple and also adaptable to easily accommodate various configurations of scintillator bar and SiPM readout geometry.

For the SiPM carrier and amplifier, this means using an adaptation of the boards in the HELIX experiment (this design by Visser/IU is the basis for the UH readout scheme that was considered in the original plan, thus changes will be small). For the readout unit we plan ultimately to use a PSI – DRS4 or similar, based on availability. Initially, however, this will likely be the available vme-based system at USC that has been used in similar scintillator-timing development work. For details on the planned electronics, see Sec. IV B 4 below.

3. *Scintillators*

Initial scintillator strips for the test setup have been ordered from year one funding. They are from ELJEN and have a side cross sectional area of 1cm x 3 cm and lengths of 10 cm, 1.5m, and 2.5m. We may want to add one or two of the 2.5-m length strips with a different scintillator material in FY24, TBD.

4. Forward HCAL

Due to the delays getting the funding in place and then in recruiting students, the work on the forward HCAL is delayed and only started recently during the summer. Therefore we do not request additional funding for this part of the previous proposal at this point.

III. PROGRESS REPORT

Despite delays in contracting and hiring, a significant amount of the planned simulation work has been progressing as described below. Most of the hardware work will be carried out in the second half of this year. As of the writing of this document, the project is on track to accomplish the goals that were set out and deliver the promised milestones.

A. Simulation Work (Duke University, USC)

Graduate Student Simon Schneider (Duke) has taken the lead implementing the KLM system in DD4hep, the framework used by the project detector and which has been recommended by the EIC Software Working group. One of the goals of the simulation is also to provide a framework for a 2nd detector. Therefore the setup of the code, including repositories, has been coordinated with the EIC software group and designed with this use in mind. While the medium term goal for the simulation is to demonstrate the concept with the achieved performance of the scintillators measured in the lab, year 1 milestones for the software included integration and validation of the EIC KLM design, a first MuID ROC curve using muon ID modeled after the Belle II algorithm as well as a study of the KLM response to hadrons. As shown in Fig. III A the current simulation already includes a preliminary geometry of the KLM as based on the CORE design and enables a first estimate of the detected muon and pion range depending on the magnetic field. Also shown in the Figure is the combined simulation with subdetectors implemented for ePIC enabled by the DD4hep framework, in this case tracking and vertexing. The KLM in this implemention is built using a flexible parametrization which enables an optimization of the design by hand or using AI/ML.

At variance to the initial proposal, we decided to implement the simulation in DD4hep for the reasons outlined above. However, we also decided to continue the development of the existing fun4all simulation to cross-check the DD4hep simulation. This work has been done by undergraduate students at the University of SC.

The simulation work at USC has been making use of the existing CORE simulation in fun4all, which has the advantage of containing a realistic magnet design (Copper for the results shown here) and detector materials in the volume enclosed by the flux return where the KLM detector is located. This allows one to determine accurately the minimum momentum a muon, produced at the interaction point, needs to reach the barrel KLM detector, $p_{\mu,thr}$. Undergraduate student Preston White generated 5000 muons at the center of CORE with discrete momenta spanning the range from 0.5 GeV/c to 10 GeV/c and values

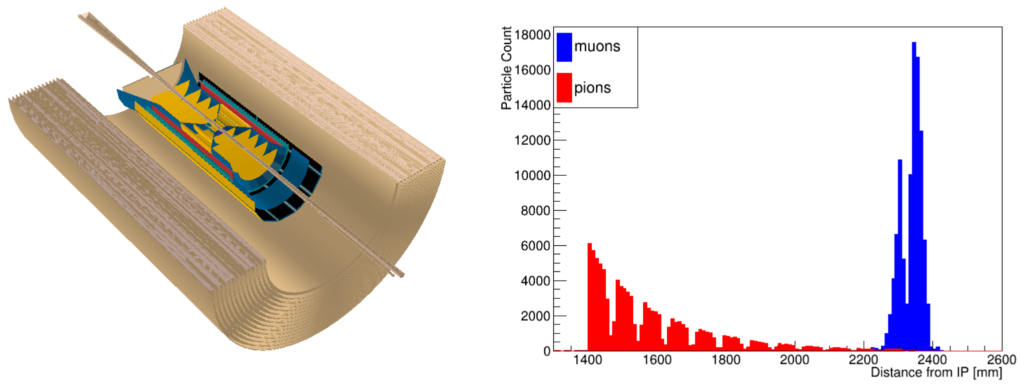

FIG. 1. Implementation of the 14 layer KLM in DD4hep with vertexing and tracking systems adapted from ePIC (left). Penetration depths of pions (red) and muons at 1 GeV. They can be clearly separated.

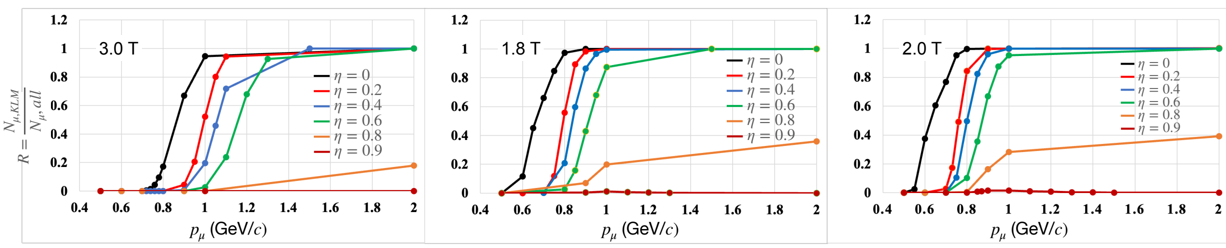

FIG. 2. Ratios of the number of muons reaching the barrel KLM to the number of muons generated at the center of CORE, for various values of central magnetic field and pseudo-rapidity.

of pseudo-rapidity from 0 to 0.9, just below the maximum coverage of the barrel. Due to the symmetry of the field, the obtained results are valid also for negative pseudo-rapidities covered by the barrel. The muon hits were read out by two virtual detectors located just at the inner element of the magnet (referred to as inner detector) and just outside the most outer element of the magnet (referred to as outer detector), respectively. The number of primary muons, $N_{\mu,KLM}$, reaching the outer detector was counted and normalized to the number of generated muons. This ratio $R = \frac{N_{\mu,KLM}}{N_{\mu,all}}$ is reported in Fig. 2 for three values of the central magnetic field: 3 T, 1.8 T, and 1.5 T, which are values considered for the EIC detectors. For low values of *eta*, *i.e.*, polar angles of 90° or somewhat smaller, the muons are well within the geometric coverage of the barrel and muon loss from the vertex to the KLM is primarily driven by the curving in the magnetic field. Larger field causes more loss, as expected. The energy loss in the Copper augments that effect. Replacing the Copper with Aluminum (which has been discussed as an alternative technology for the central magnet), shifts the curves down by about 100 MeV/c. As η increases, the muons scatter closer to the edge of the barrel and detector acceptance becomes an important factor for muon loss. At $\eta = 0.9$ muons scatter at the edge of the barrel, which explains the very small number that that reache the KLM location.

As an estimate of the muon thresholds for the KLM, we have fitted the rising part of R and have taken the value of momentum at $R = 0.5$ as $p_{\mu,thr}$. These estimates are shown in

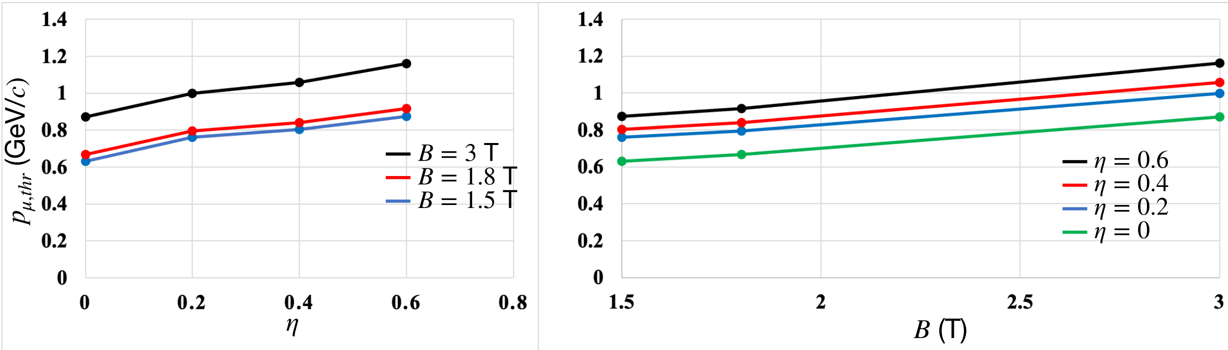

FIG. 3. Muon thresholds as a function of *eta* for various B (left) and as a function of B for several η (right). The value of $p_{\mu,thr}$ is the muon momentum at which 50% reach the barrel KLM.

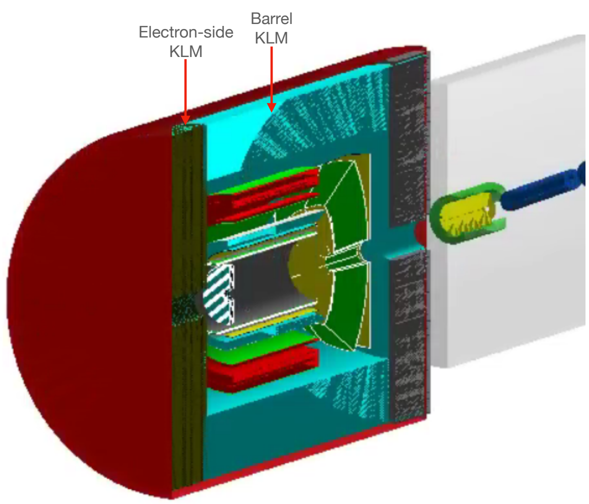

FIG. 4. The figure shows the implementation of a layered KLM structure- stacks of scintillator and steel layers on the electron-side of an EIC detector. One can see the volume of the flux return in the barrel where work to implement a KLM layered structure is in progress.

Fig. 3. The thresholds could be decreased by decreasing the radius of the magnet, which is a possibility within the CORE design, and the 2nd detector design in general, given that we are in the very early design stage. In any case, we will evaluate the muon thresholds with a shorter magnet radius during the rest of this year.

With funding from this project, Dr. Tapasi Ghosh spent one month at USC this summer and made the very first implementation of a simplified KLM, a sandwich of steel and scintillator cylindrical volumes on the electron-side, in fun4all. Figure 4 visualizes this work. Work has began to implement a simple steel-scintillator multi-layered sandwich in the barrel. The validation of these new geometries, as well as the analysis of muon and pion hits in the sandwich will be completed within the current year. In year 2, the focus will be on further developing the simulation by the implementation of a realistic bar structure in at least one KLM plane, with a focus on the barrel KLM. This structure would be easily exportable to a DD4hep simulation of a second EIC detector to support the further simulation work that will be done by DukeU.

B. Scintillator Evaluation Teststand (USC)

Due to the long contracting process between USC and JLab, which was concluded in early May, work on establishing the evaluation setup at USC will primarily take place in the second half of the year. The purchase of scintillator bars of side area of 1cm$\times$3cm and lengths of 0.1 m, 1.5 m, and 2.5 m and different material is in process and we expect the bars to be delivered in August. Work afterwards will be focused on preparing the bars for measurements and establishing the readout and DAQ system.

C. Electronics (UH/IU)

The contract for UH is still held up. We have proceeded with discussions and now plans for SiPM carrier and amplifier board support and fabrication at IU (e.g., based on the IU design for the HELIX experiment) for the year-two continuation of this project.

D. Forward HCAL (UCL/UCR)

The forward HCAL is for the time being not part of this proposal anymore due to delays in the first phase and an anticipated re-evaluation of the architecture pending the outcome of the first year studies.

IV. MULTIPURPOSE-KLM PROPOSED R&D PROGRAM

A. Motivation

This R&D proposal is aimed at developing a **Multipurpose KLM**, built on the state of the art KLM design, *e.g.*, the Belle II KLM, in which the active elements are scintillator strips. Note that the previous proposal included a separate forward instrumentation part. Due to delays in funding and graduate student recruiting, this is not part of the present continuing proposal.

As anticipated, the proposed R&D will address several open questions and shortcomings of the current state of the art of the KLM concept with respect to an application at the EIC. This project exploits the expertise of the Duke and IU groups with the Belle II KLM, and the USC group with fast scintillator detectors and offer opportunities for substantial synergies. Collaboration with the UC groups will continue and we will profit from their expertise on hadronic calorimeters. The Multipurpose KLM would be a good solution for the barrel and likely the electron-side endcap. At the same time, the project is generic and the delivered baseline design could be implemented in any specific EIC detection system. As part of the R&D program, we also plan to develop AI/ML algorithms that can make use of the additional information, namely, the longitudinal and transverse segmentation as well as the timing and pulse shape.

Characterization of neutral hadron response: The Belle II KLM was designed for the identification of K_L's. However, since the rest of the event is usually reconstructed, the initial state is known, and backgrounds are low, the focus of the Belle II R&D was only on the accurate reconstruction of the K_L's position. The energy of the kaon is reconstructed from the missing energy in the considered decay. Therefore, an important aspect of this R&D program is the characterization of the hadronic response to K_L and neutrons, that cannot be measured otherwise at the EIC. While we plan to address this point, at least initially, with detailed simulations that might be benchmarked against results with thin HCALs [2, 3], an eventual beam test will be highly valuable to verify the simulations.

Improved timing for ToF and hadronic momentum determination, and horizontal hit localization: In principle, plastic scintillators enable excellent timing down to 10s of ps. However, the current Belle 2 KLM design uses wavelength shifting fibers, introducing timing uncertainties, and TDCs with relatively coarse timing (several ns). Additional R&D on scintillators, readout geometry, and electronics is needed to achieve the desired resolutions. For a flight path of 1.4 m to the first KLM active layer in the barrel (such as the shortest flight path in the barrel of the CORE detector), a momentum resolution of 10% can be achieved via time-of-flight for 1.2-GeV/c K_Ls with a timing resolution of $\sim$ 60 ps. For neutrons, the same timing resolution yields 10% momentum resolution at 1.8 GeV/c. 50% momentum resolution for the same flight path of 2-GeV/c K_L (comparable to the resolution of conventional HCALs) is achievable with the same timing resolution as above. For neutrons under the same conditions, the momentum is 3 GeV/c. Since this is the shortest flight path, the estimates above quantify the most demanding case of timing resolution. The above estimates suggest, that momentum determination of K_L and neutrons in the barrel and the electron endcap could be done via the time-fo-flight technique over the momentum range of interest there. Thus, the timing, together with the longitudinal and horizontal segmentation, will be an important input for hadronic calorimetry.

Using double-sided readout, *i.e.*, SiPMs coupled to each end of the scintillator strip, the envisioned timing resolution could be sufficient to locate a hit within a few cm on the scintillator strip. If, this resolution is comparable to the strip width, instead of using two orthogonal layers to determine the hit position in a plane, only one layer would be needed. This would enable a much more compact construction.

Suitability as a thin HCAL In addition to characterizing the neutral hadron response, R&D is needed to investigate the capability of the whole system to work as a thin HCAL. This includes the use of additional information such as longitudinal segmentation, fine in-plane segmentation, and timing. This likely means the development of ML/AI algorithms to correlate this information with the sought after hadronic response.

Feasibility of integration in an EIC central magnet: The core tenet of the KLM concept is the integration in the flux return. Therefore, the integration into a conceptual design of the central magnet of a second EIC detector is planned to be part of the R&D.

B. R&D Program

As stated previously, the objectives of the proposed R&D are to (a) demonstrate that a radially-compact KLM design can provide clean muon ID satisfying the physics goals of the EIC and (b) extend the capability of the KLM state of the art in providing neutral hadron ID and characterization.

To achieve these objectives the R&D program will (a) study the proposed design in detailed simulations to demonstrate that an integrated solution can achieve the necessary sensitivity; (b) demonstrate that the proposed technical solution can provide the performance needed and is technically feasible. This includes R&D on thin scintillators that allow the detection of direct photons with a sufficient efficiency paired with 10's ps timing resolution.

A pulse shape discrimination using the novel HDSoC electronics might open new possibilities. One such avenue would be hadronic energy reconstruction using this new information in conjunction with AI/ML methods. Such studies could be potentially done in Year 3 or Year 4 of the project.

We plan to investigate if a two-sided readout combined with good timing resolution provides good enough position resolution along the strip that a single plane layout (with possibly different strip orientations in each layer) is workable. This would enable a more compact design, reducing the cost for the flux return. An improved timing measurement would also open the possibility of determining the momentum of a KLM-ID'ed neutral by means of time of flight.

1. Simulation of compact design

The scope of this part of the program is to implement and validate the compact EIC KLM geometry in an EIC-detector simulation. As discussed above, in Year 1 of the project, we are using a dual route with using the existing fun4all framework as well as starting a DD4hep implementation. With this approach we are balancing timely results, the use of existing EIC resources, and preparing for the future, as well as attracting additional collaborators. The KLM-specific simulation code will be modular and portable, so that it can be easily transferred between frameworks.

As the integration into the flux return is key for the KLM design, this work will be carried out in conjunction with the development of the magnet design for the second interaction region. A working relationship with the JLab magnet design group, responsible for the latter development, has been already established within the context of ongoing comparative studies of the impact of Al vs Cu coils on muon-track resolutions. While the magnet-material studies are not part of this R&D, their results have been relevant for the muon ID by the KLM and are being fed in the KLM simulation studies. The simulation will be used to demonstrate and optimize the performance of the compact KLM for muon ID and to establish muon detection thresholds.

2. Tests of Scintillator Bars with Direct Readout by multiple SiPMs

Ongoing Belle II R&D has indicated, along with results from other studies in the literature [4], that there are strong limitations to the achievable timing resolution using WLS fibers. Thus, an important part of the R&D proposed here is an extension of this design to direct readout with a group of SiPMs directly coupled to the scintillator. We will investigate if the direct SiPM coupling will enable the recording of 'direct' photons (not reflected) and, thus, improve timing significantly. This makes a careful selection of the scintillator material necessary, as the light output has to be large enough while the attenuation length cannot be too small. Bench-test results for 3-cm-thick, 120-cm-long EJ-204 scintillators at USC, done for the MUSE experiment, showed that with a double readout, ~ 45 ps resolution can be reached this way just using standard leading-edge discrimination and applying time-walk

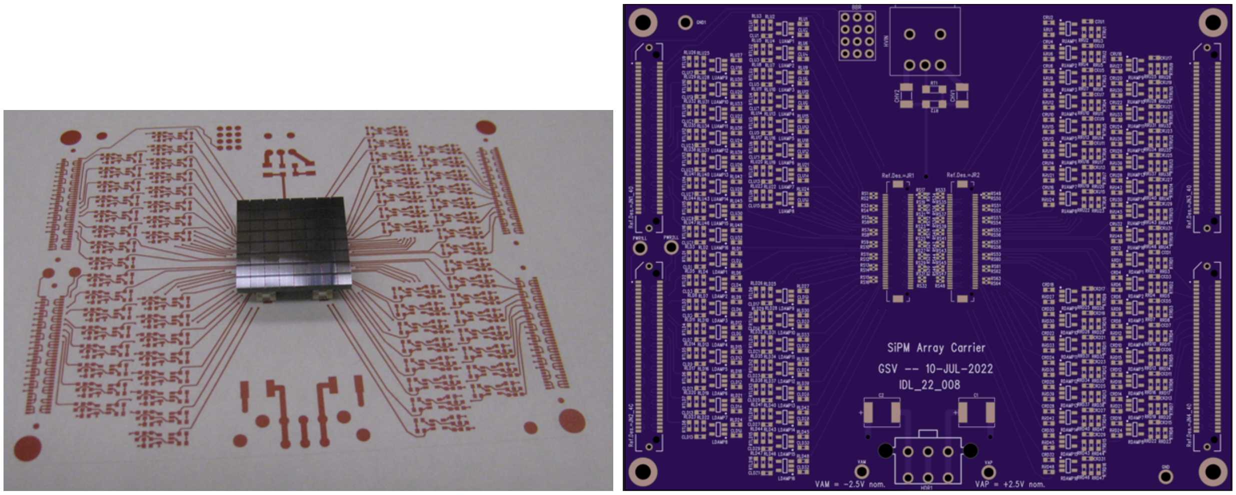

FIG. 5. Prototype SiPM carrier board adapted from an IU design for HELIX [5]. Here a configuration for 64 SiPMs to be used at the Univ. of Hawaii is shown; a version with a lower number of SiPMs will be used for this proposal.

corrections in post-processing. Thicker (6-cm thick) and longer bars (220-cm long), used in MUSE and CLAS12, have yielded $\sim$ 55 ps timing resolution. The new aspects motivating this R&D are the different size of scintillator strips, which in the initial EIC KLM design discussed in Sec. II-A are thinner and longer (7.5-mm thick and 1.5-m – 3-m long), as well as the SiPM readout, which due to the standard sizes of the SiPMs will allow us to cover a fraction of the side area of the bar. Our tests will determine the timing resolution that is achievable with this setup.

Another component of this proposal is to assess the hit position resolution along the length of a KLM scintillator strip that can be achieved when the strip is readout on both ends. If a good position resolution can be reached, a design with only one layer of strips (as opposed to two orthogonal layers) per layer can be enabled. For the construction of the scintillator detectors at MUSE and CLAS12, the USC group developed methodologies and techniques to determine the position of a hit along the scintillator bar. This R&D capitalizes on this expertise. This study will be carried out in bench measurements.

A strip width of 30 mm gives an angular resolution of order $\sim$10 msr for the inner most layers of the barrel (comparable to the muon multiple scattering in *e.g.*, Belle), and this width would be a starting point for this proposal for both the barrel and endcap implementations, as a compromise between total channel number and lateral strip response.

3. *Investigation of Scintillator Materials to optimize Timing Performance*

The attributes that would make an ideal scintillator material for obtaining good timing resolution from bulk readout of long thin strips, are often largely at odds with one another. One needs a long attenuation length, at least roughly comparable to the strip length, but also a good light yield. Added to this are signal rise and decay times from different scintillator composition choices that can affect the ultimate timing obtainable. SiPM characteristics also play a role. Recent high-resolution timing studies, although for small samples/bars, give some data-based guidance for estimating how performance depends on some of the relevant characteristics [6].

For our initial bench studies, necessarily involving relatively few samples, we have been selecting a standard commercial option. For the short, 10-cm long bar, we will study EJ-204, which is the fastest of the EJ-2xx series and has an attenuation length much longer than the length of the bar. For the 1.5-m bars, we will evaluate EJ-200, EJ-200, and EJ-208. For the 2.5-m bars, we will measure EJ-204 and EJ-208. Our comparative measurements will identify the most optimal solution for the various length ranges of KLM scintillator bars. In Year 3 we may consider scintillators with different attenuation-length vs rise time, such as the BC420 scintillator (available from *e.g.*, Saint-Gobain) is a long-attenuation-length good-timing-characteristic candidate. We will keep our eyes open for other samples with promising characteristics.

4. Electronics

The electronics to be used in the initial scintillator test stand measurements should be relatively simple and also adaptable to easily accommodate various configurations of scintillator bar and SiPM readout geometry. Because of uncertainties (due to personnel health reasons) relating to the availability of the HDSoC readout and auxillary SiPM boards from Hawaii, we will focus on more the more basic capability needed for obtaining test results to guide the design.

For the SiPM carrier and amplifier, this means using an adaptation of the boards in the HELIX experiment (this design by Visser/IU is the basis UH readout scheme). Figure 6 shows the HELIX carrier preamp board in several views.

The HELIX board handles the output of four SiPMs (pictured in the lower part of the figure) and provides both a fast and a slow signal output which can then be further processed in a separate readout unit. Modification of this design to accommodate more (or a different configuration) sensors is fairly straight forward with each SiPM divided into two (a fast and a slow signal) paths. The fast signal is of course used for timing and the slow one for charge determination. In the current design, each fast path is connected to a fast amplifier that amplifies the signal by a factor of 18, then the four amplified signals are combined and further amplified by an additional fast amplifier. All four signals of the slow path are combined and form the slow output of the carrier board.

The operational bias voltage of each SiPM is set to achieve a uniform gain. Since temperature-dependent gain changes are similar between SiPMs, a common temperature sensor located on the SiPM carrier board drives a common automatic voltage adjustment for gain stabilization.

The HELIX experiment used Hamamatsu S13360-6-50VE SiPMs. They were selected because of their good dynamic range, high photon-detection efficiency and relatively low transit time skew. For application in the KLM test bench, their 6x6mm size presents a relatively large collection area for the thin scintillator bars we plan to test. There are of course various tradeoffs in performance, size, and summed readout complexity which at this writing are still under discussion. Note: reworked carrier boards for test bench use will likely just mount at right angles to the bars to simplify fabrication cost and make any subsequent modifications easier.

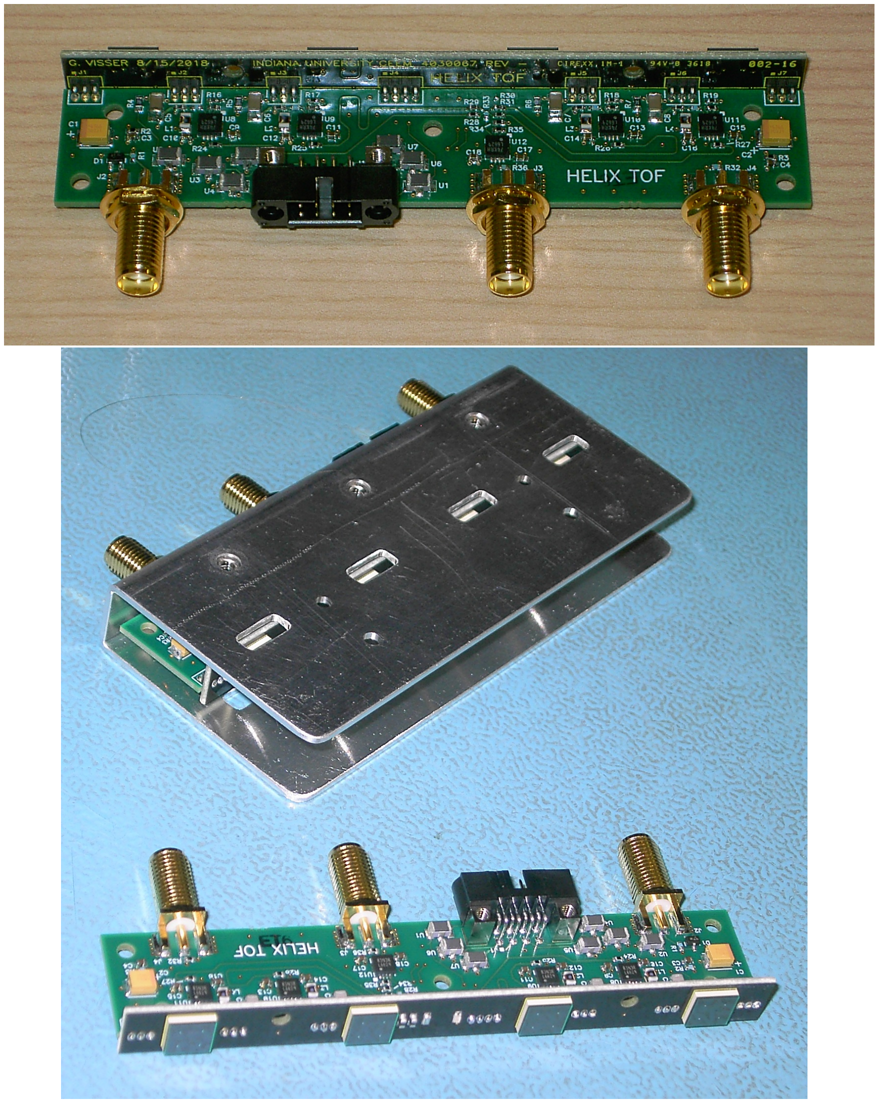

FIG. 6. Top: Carrier/preamp board from the HELIX [5] readout design. Fast and slow outputs as well as a pulsing input connector are visible. LV power is input on the central black connnector. Bottom: In upper view, the encapsulation the carrier/preamp board for HELIX use; in the lower view the scintillator interface side is pictured with 4 mounted SiPM sensors. Initial KLM test bench readout with use a custom adaptation of this design by G. Visser at IU.

C. Timelines and Deliverables

The proposed program was originally structured around a planned period of three years. Given the reduced funding profile, not all envisioned goals might be reached in three years. As partially outlined in Section III, Year 1, which is currently ongoing, is primarily concentrated on simulations. Setting up lab spaces also begins in this year by procuring scintillator strips and equipping them with adapted off-the-shelf readout. In accordance with existing local expertise, lab space at the University of South Carolina is currently being set up to be used to evaluate timing and position resolutions of scintillator strips. The setup of lab space at the University of Hawaii to construct HDSoC readout boards is also planned, albeit will be delayed due to health reasons. Given the reduced funding profile for Year 1, some of the originally envisioned activities will be moved into Year 2 for which we request funding here. One example is the planned setup to evaluate the full readout chain at Duke University. This will be pushed back to the end of Year 2 once off the shelf electronics has been evaluated. In the year relevant for this proposal, Year 2 of activities, simulation efforts will continue and be focused on detailed simulations of the readout. This work will be led by Duke. The goal is to converge towards a realistic design including the magnet that can also serve as a base for the second detector. Based on this geometry, more details of the design and readout will be implemented informed by the test stand set up at the University of South Carolina. The simulation will then be used to develop and evaluate muon and hadron identification algorithms and thus benchmark the expected performance of the system.

Using the test stand, the scintillators ordered in year 1 will be evaluated. We will use an off-the shelf electronics setup for this as described above. A viable readout configuration for timing and position resolution studies has to be developed after an initial evaluation of the electronics. Year 3 will include bench, and potentially test beam, evaluation of the chosen readout configuration with adapted carrier boards and readout firmware as well as the integrated design of the solenoid steel configuration. A detailed plan of activities for each year is given below. We indicate which tasks were originally in Year 1 but had to be pushed back due to the reasons discussed below. For completeness we also show the tasks that are still planned to do in Year 1 and thus bridge the gap between the status report and the proposed Year 2 activities.

Remaining Year 1 Activities

- Integration and validation of the initial compact EIC KLM design in fun4all and DD4hep. In Year 1, we will focus on the barrel KLM. The work will be done by the USC and Duke groups with support by SBU. This task is already well underway as discussed in Sec III Milestone: Implemented and validated KLM layer structure (in progress). Determination of muon detection thresholds within the CORE detector layout (done).

- Using the fun4all simulation of a stack of the KLM and a parametrized performance of a typical EIC silicon tracker [7], the MuID ROC curve for the proposed design will be calculated. We will use Belle II MuID algorithms to create a first-version of hit reconstruction and MuID algorithm for the EIC KLM. It is anticipated that the readout will not yet be fully simulated but parameterized based on Belle II performances[1] This work will be done primarily by the Duke group with support from RUAS. Milestone: Initial muon ID.

- SiPM boards will be designed based on the HELIX design. A readout chain will be established. This work will be done at IU. Milestone: First SiPM board assembled.

- For the test-stand at USC, thin scintillator strips have been ordered and will be prepared for bench tests. If SiPM readout boards are available, they will be coupled

[1] This simulation aspect will evolve in Year 2 as the readout chain evaluations in this project progress.

to each end of the strips with an optical glue. These preparations will follow procedure protocols established during scintillator detector construction for MUSE and CLAS12. The readout for these tests will be with simpler electronics and an existing DAQ. Milestone: Lab setup and DAQ ready.

Year-1 Deliverables: (a) KLM simulation class and basic methods validated and available on github, (b) first SiPM readout board assembly and commissioning.

Year 2 Activities

- Refinement of the MuID algorithm in simulations
- Study of the KLM response to hadrons in simulation. An initial investigation of the impact of the availability of the longitudinal shower shape on hadron energy measurements and efficiencies to detect neutral hadrons as a function of momentum will be done. Since in-plane segmentation is a key feature for the MuID, it will also be investigated how this information helps with hadron ID. This work will be done primarily by the Duke group. **This tasks has been moved back from year 1** Milestone: Initial clustering and reconstruction software. [2]
- SiPM readout boards based on the HELIX design will be assembled at IU
- Bench tests at USC of scintillator strips using the HELIX-based SiPM readout boards and simple electronics. The primary objective is to determine the timing resolutions for various scintillator types and lengths; compare with data-based expectations.
- Based on the initial results from the readout bench-tests, the simulation of the readout will be refined. The physics performance of selected configurations will be studied (*e.g.*, optimized for muons, neutral hadrons). We plan to investigate the possible improvements from full waveform sampling which is not provided by the initial HELIX based readout. If the HDSoC is not available in time, we consider procuring commercial electronics likely in Year 3.
- Clustering and MuID algorithms will be refined. In the full simulation, a track matching algorithm will be implemented.
- A readout chain test at Duke will be established. This test stand might be extended to include scintillators as well, so that some of the test suite could be done at Duke. Establishment of pulse shape readout and timing characteristics have to be established **This task has been moved back from Year 1**.
- Any needed optimization and validation of the KLM design in simulation as the magnet return yoke design will progress, with input from the ongoing R&D and Detector 2 progress. Electron-endcap KLM design implementation.
- Simulation/reconstruction - implement cluster SiPM in reconstruction
- Begin optimization of most promising configurations that are "buildable".

[2] It is planned to compare the simulation results for hadrons with available data on thin calorimeters from baloon experiments, *e.g.*, Refs [2, 3]. This will allow an initial verification of the hadron response in the absence of a beam test.

Year-2 Deliverables: (a) First timing resolutions results with off-the-shelf readout, (b) SiPM readout board assembly and commissioning, (c) detailed simulation of the KLM (d) muon reconstruction algorithms (e) hadron reconstruction algorithm (f) first readout chain implementation

Year 3 Activities

- A full simulation of the final configurations will be performed. Muon and hadron response will be studied. The results will be the base for an eventual beam test.
- Position resolution determination in bench tests of the bars procured in Year 1.
- If position resolution of at least 30-mm is achieved in the bench tests, the single-plane configuration will be implemented in simulation.
- Optimization of the readout chain based on test stand data.
- In simulation, the performance of KLM with single-strip-plane configuration will be compared to the performance in two-strip-plane configuration to tune the minimum position resolution needed for comparable response. This will inform on what further readout optimizations may be needed.
- The expectation is that the design of the magnet return yoke will be finalized so the KLM geometry in the simulation is finalized as well.
- To evaluate the hadronic response of the developed system and the impact on hadronic energy reconstruction using the achieved timing and longitudinal and in-plane segmentation, a beam test is desirable. This test could be prepared in year 3, given appropriate progress in the R&D program. The actual beam test could then be performed at the end of year 3 or beginning of year 4.

Year-3 Deliverables: (a) Quantified detector performance for muons and hadrons in simulation, (b) Position resolution of scintillator bars procured in Year 1 with HELIX readout and simple electronics (c) SiPM readout board assemblies, (d) Optimized readout chain. Depending on the situation at UH, this could be the initially envisioned HDSoC or a readout chain based on the HELIX readout developed in Year 2. The later case will have to be evaluated with respect to feasibility for a final design. Note that this milestone might move to Year 4 due to the uncertainties discussed above. (e) timing and position resolutions from bench tests with optimized readout.

V. BUDGET AND BUDGET SCENARIOS

A. Budget Request

The table below summarizes the budget request for the multipurpose KLM. It reflects the tasks lists discussed above.

Funding is requested for 50% postdoc at Duke to support the proposed simulation and reconstruction software development as well as implementation of the readout chain. This researcher will work on location at Duke and will be supervised by A. Vossen. Additional

	100%	80%	60%
Undergraduate students, USC	$12.5k	$7.8k	$7.8k
Postdoc (50%), Duke	$59.7k	$47.8k	$35.8k
Undergraduate students, Duke	$12.5k	$6.5k	$3.6k
Test Bench: carrier-bias bds and EE support, IU	$16.0k	$16.0k	$16.0k
SiPMs, LV Unit, Cables and Parts USC	$15.6k	$15.6k	$15.6k
Travel to U.S., RUAS	$9.7k	$9.7k	$0k
Travel for meetings between Duke/USC	$5k	$3k	$1k
Computational resources (laptop), RUAS	$2k	$0k	$0k
Total	$133.0k	$106.4k	$79.8k

TABLE I. Budget for Multipurpose KLM. The budget includes institutional overhead.

funding is requested for undergraduate students that will help during the summer particular on hardware tasks. We also request funding for travel for meetings mainly between Duke and USC personnel which will become more important in the 2nd year as the results of the work have to be disseminated between the institutions and a new test stand be established.

The personnel at USC and Duke funded by the program will be supported in the simulation and software work by SBU and RUAS.

We ask for support of two undergraduate students at USC who will work on bench test measurements. The travel budget for RUAS will support the travel of one colleague to spend a month working on the project at Duke or USC. RUAS requests a modest support for a laptop where they can carry out simulation and software work on the project. We are also in contact with a colleague from JU who is interested in participating in the project. Since the exact form of this collaboration is more uncertain, we do not request budget for this.

The engineering and material support for IU requested will be used to adapt the SiPM readout boards and amplifier as well as well as for the acquisition of a readout module.

1. *Money Matrix*

The tables below summarize the budget according to each project and institution. Each table shows one budget scenario.

Under the reduced budget scenarios, the project will take longer to carry out and some tasks planned for Year 2 will be delayed and not completed. A reduction of the budget by 20% will likely mean that deliverables (c, detailed simulation) and (e, hadronic response) will not be reachable. A reduction by 40% will mean that additionally milestone (f, readout chain implementation) will not be feasible. We did not apply a reduction to the readout electronics, instead reduced the budget elsewhere, as these are absolutely essential to progress the project.

VI. DIVERSITY, EQUITY, AND INCLUSION

This program provides excellent opportunities for training and career development through engagement in research of undergraduate and graduate students from a broad

Institution	Multipurpose KLM Budget
Duke	$77.2k
IU	$16k
USC	$28.1k
RUAS	$11.7k
Total	$133.0k

TABLE II. Budget, 100% scenario, separated by institution. Institutional overheads are included.

Institution	Multipurpose KLM Budget
Duke	$57.3k
IU	$16.0k
USC	$23.4k
RUAS	$9.7k
Total	$106.4k

TABLE III. Budget, 80% scenario, separated by institution. The budgets include institutional overheads. See text for milestones in this scenario.

pool of talent in physics, such as from economically disadvantaged communities or first-generation college students. The funds requested for support of undergraduates are critical, as students from these backgrounds cannot afford to work as research assistants for free instead of being paid for a non-physics job. The project will also be used to engage undergraduate students from a diverse background participating in the summer Duke REU program. During their research on the project, these students will be integrated in the research groups of the senior personnel committed to the project, where they will receive training in nuclear instrumentation, simulations, and data reduction techniques. Students will be also trained in how to communicate their research to an audience of peers and will be encouraged to present at collaborative meetings and workshops where they will be able to benefit from networking with other senior and junior researchers. The program also provides training and career opportunities for qualified postdoctoral fellows and, thus, supports retention of highly-skilled individuals in nuclear physics. Overall, the proposed program supports the commitment of the participants to educate and mentor a diverse work force through research. The participation of international collaborators supports retention of female physicists in research and provides opportunities for our students to network internationally.

VII. PARTICIPATING INSTITUTIONS

Center for the Exploration of Energy and Matter (CEEM), Indiana University: The group at IU has over the years been involved in the construction and oversight of many large-scale pieces of experimental apparatus. CEEM is housed in the former IU Cyclotron Facility building, retaining some essential infrastructure and expertise, and allowing IU to take on major project roles. Jacobs is a long-standing member of the local IU group, has considerable project experience and actively contributes to Belle/Belle II and STAR collabo-

Institution	Multipurpose KLM Budget
Duke	$40.4k
IU	$16k
USC	$23.4k
RUAS	$0k
Total	$79.8k

TABLE IV. Budget, 60% scenario, separated by institution. The budgets include institutional overheads. See text for milestones in this scenario.

ration upgrades, operations and physics efforts. One focus of recent such activities has been in electronics support. Our electronics group with two senior EEs (G. Visser, B. Kunkler[3]), has extensive experience in developing detector readout electronics and associated firmware for numerous HEP and nuclear experiments. Besides contributing to the original Belle II KLM and iTOP upgrades, they have been significantly engaged in projects for STAR/BNL, ATLAS/CERN, HELIX, NOvA and others. A current big effort for the STAR forward upgrade is the FEE readout of SiPMs for the Electromagnetic and Hadronic calorimeters. Relevant to the present proposal, they will play essential roles in the new electronics readout systems for the anticipated next Belle II Barrel KLM upgrade to an all scintillator strip readout from the present RPC modules.

University of Hawaii: The UH group and particularly its Instrumentation Development Laboratory have a long and established successful track record in fielding world-class, discovery experiments in particle and astroparticle physics. Most relevant to the KLM endeavor is that UH provided the ASICs and readout system for the Belle II KLM scintillator upgrade. In particular UH has been responsible for the design, fabrication, installation and support of the 20,000 channels of KLM scintillator readout. Two postdoctoral fellows that were key to the success of fielding the UH-developed ASICs for the iTOP and KLM subsystems, are the principles that subsequently formed Nalu Scientific. Nalu staff have a long history of working with UH and also developing next generation commercially available waveform digitizing ASICs. Dr. Kevin Flood, UH Affiliated Graduate Faculty member and Nalu Senior Scientist, convened the Babar PID group for several years, is a PID algorithms/software expert and has experience leading the salvage of another major Babar subdetector (EM Calorimeter). Close collaboration allows for the utilization of fungible engineering resources, which are simply no longer viable at a university level, in the era of projectization and a rather limited number of very large projects. In addition to excellent facilities for electronics design, evaluation and verification, university-subsidized CNC machine shop capabilities are available in support of detector components, in particular in support of the readout electronics.

Duke University: The Duke University group is led by Vossen and was started in 2018 when Vossen moved from Indiana University to Duke. While at IU, Vossen and Jacobs led the IU group to join Belle II and then led the development of the Barrel KLM RPC front-end-electronics. Vossen coordinated the IU contributions to the KLM commissioning. The KLM is also part of the institutional responsibility of Vossen's Duke group. Vossen's group has extensive experience in software development and simulations for the Belle II KLM. The Duke group was very active in the Yellow Report process as well as in the subsequent

[3] now deceased

detector collaborations and has gained extensive experience in fast simulations for the EIC in the process. At Duke University the group has access to significant technical resources of the University and the Triangle Universities Nuclear Laboratory located on the Duke University campus. In particular, this extends to laboratory space and mechanical and electrical technicians. The Duke group has also extensive experience with ML/AI methods.

University of South Carolina: The USC group consists of three senior faculty, graduate and undergraduate students. The group has extensive expertise in designing, testing, optimization, and construction of scintillation detectors having delivered the Forward Time Of Flight detector for CLAS12 and the SPS, beam monitor, and veto detectors for the MUSE experiment. We also have expertise in characterization of small photosensors through the previous generic EIC R&D program. Another aspect of the past work of the USC group that is available for this project is local infrastructure, including laboratory space and equipment.

Center for Frontiers in Nuclear Science, Stony Brook University: The mission of the CFNS at SBU is to promote and facilitate the realization of the U.S.-based EIC by enhancing the science case and collaborations amongst the scientists around the world interested in the EIC. The group has been heavily involved with EIC simulations and software development and brings significant, hardware, software, and simulation expertise to the project.

Ramaiah University of Applied Sciences: The group at RUAS has diverse software experience in HEP/nuclear physics, such as developing track reconstruction framework based on Kalman Filter, Cellular Automata algorithms, detector simulation by Geant4, applied ANN for identifying muons from hadrons. The group has performed physics studies and optimization of detector parameters. This is a new group for the U.S. EIC brought to the EIC community due to the collaborative opportunities provided by the program proposed here.

VIII. IN-KIND CONTRIBUTIONS

Duke: Duke provides in-kind 0.5 FTE grad student labor. The PI and postdocs experienced with EIC simulation work and KLM software and simulation at Belle II will also contribute at a fraction which is TBD. The group at Duke has lab space that is appropriate for the proposed R&D. The Duke group also has access to mechanical and electronics engineering resources of the department and the Triangle University Nuclear Laboratory.

University of South Carolina: USC provides in-kind partial faculty FTE, detector-lab space, DAQ system and equipment for scintillator timing- and energy-resolution evaluation, and know-how for scintillation detector evaluation, performance optimization, and construction.

Ramaiah University of Applied Sciences: RUAS will provide in-kind partial faculty FTE and software expertise.

Indiana University: IU provides partial faculty FTE; misc. test bench components as needed (specifically STAR forward calorimeter and EPD spares and test fixtures are potentially relevant and available); limited EE technical consultation.

Stony Brook University: SBU provides extensive know-how with EIC simulations and 20% of a postdoc to support the software work on the multipurpose KLM.

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Appendix A: Physics Motivation

Studies done for the Yellow Report and the CORE proposal, pointed out the importance of muon detection for an EIC program. This point was reiterated during the 1st workshop on a 2nd detector where muon detection was identified as a prime candidate for complementarity between the project detector and a potential 2nd detector [].

channels, such as TCS, DDVCS, HEMP and exclusive Quarkonium production. Figure 7 shows example momentum distributions of muons from J/ψ and Υ decays in exclusive production. The figure shows that for J/ψ, clean muon identification of up to ~ 4 GeV/c is needed in the barrel and is desirable over the range of 1 – 10 GeV/c in the electron and hadron endcaps. For Υ, a coverage of 1.5 – 10 GeV/c is required in the barrel and of 3 – 20 GeV/c in the endcaps. Small cross sections are characteristic for these processes, and the increase of collected statistics by measuring their muon decay channel, in addition to

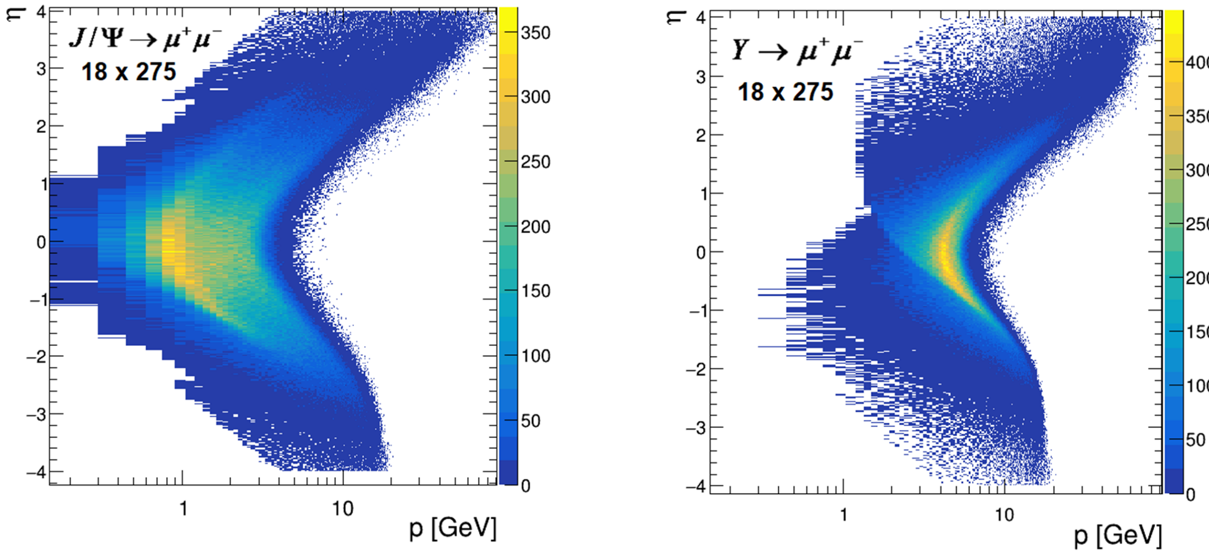

FIG. 7. Event distributions of muons produced in $J/\psi \to \mu^+\mu^-$ and $\Upsilon \to \mu^+\mu^-$, where the charm mesons originate in exclusive production off proton at beam configuration 18GeV×275GeV. The pseudorapidity versus momentum of each decay particle is shown. Figure from [8].

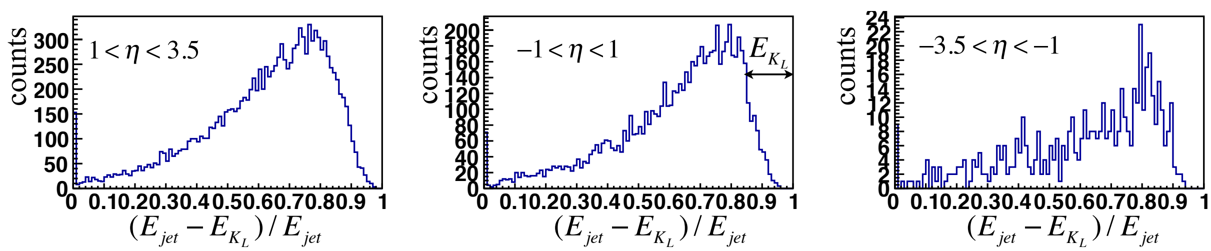

FIG. 8. Energy fraction of the total jet energy excluding the energy carried by K_L in the jet. The left, middle, and right distributions show the pseudorapidity of the jet in the hadron endcap, barrel, and electron endcap, respectively. The beam energy configuration is 10GeVx275GeV.

the electron channel, has the potential to increase the physics reach of the EIC program on GPDs. The EIC program on gluon imaging of nuclei by means of diffractive charmonium production will also benefit from muon identification detection for the same reason. Another aspect of the EIC detection capabilities discussed in the YR and relevant to this proposal, is the recognition that neutral-hadron calorimetry will significantly help jet reconstruction by enabling neutral-hadron identification for veto or reconstruction [9, 10]. A sample of 1M Pythia8-generated electron-proton collision events shows that $\sim 10\%$ of the jets produced at pseudorapidities above -1 (*i.e.*, scattered in the barrel or the hadron endcap of an EIC central detector) contain at least one K_L. These kaons carry at least 10 – 15% of the total jet energy (see Fig. 8) with the energy fraction exhibiting a wide variation. Figure 9 shows the momentum distribution of K_L produced in jets. One can see that in the barrel, detection of K_L with momenta up to ~ 3 GeV/c is needed and is somewhat narrower in the electron endcap. In the hadron endcap, one needs to cover a much broader range of kaon momenta, up to ~ 30 GeV/c. Jet reconstruction is essential for a large part of the

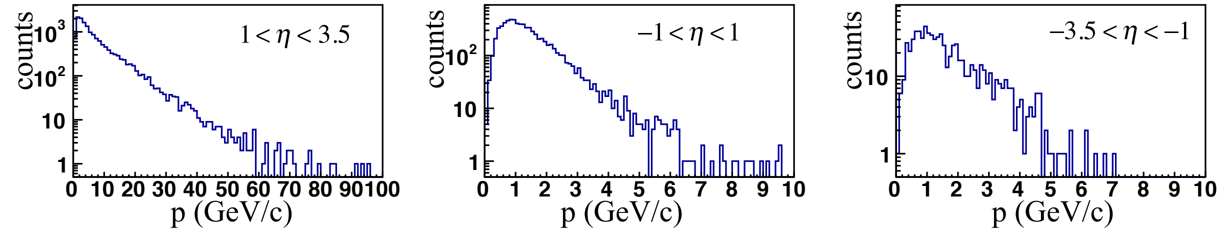

FIG. 9. Momentum distributions of K_L produced in a jet scattered in the electron endcap (left), barrel (middle), and hadron endcap (right). The pseudorapidity here is that of the kaon.

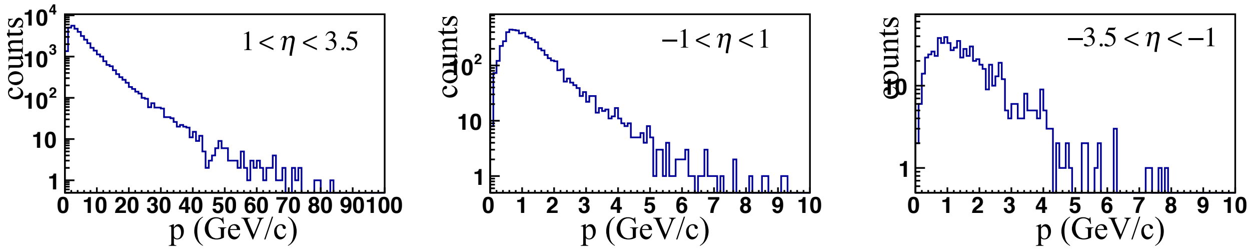

FIG. 10. Momentum distributions of neutrons produced in e-p collisions from Pythia8 for the electron endcap (left), barrel (middle), and hadron endcap (right).The beam energy configuration is 10x275.

EIC physics program [7]. Identification, and especially, precise measurement of the K_L momentum has the potential to improve the jet energy resolutions and is worth exploring. The other neutral hadron of interest is the neutron. Figure 10 shows neutron momentum distributions obtained from the same Pythia8 sample. All neutrons, in jets and otherwise, are included. The momentum ranges of interest for neutron detection are similar as for K_L on the two endcaps and the barrel.

The proposed program explores alternative (and compact) muon and neutral-hadron detection in the barrel and the electron endcap, where the momenta of these particles are relatively low, as a cost-effective alternative to hadronic calorimeters (HCAL). In the hadron endcap, HCALs would be a preferred solution, in comparison. The requirement for a radially-compact detector in the second EIC interaction region that can not only deliver the baseline EIC physics program, but also extend the physics reach by means of advanced complementary technologies, opens the R&D opportunity to explore the possibilities to extend the scintillator-based KLM design technology beyond the state of the art. An avenue that has not been explored previously, but would provide additional capabilities at the EIC, is for the KLM to act as an HCAL as well as a TOF (for low-momentum neutral hadrons). While the reverse is true, namely that in the absence of a dedicated muon detection system (*e.g.*, in the EIC project detector), muons can be identified by means of the combined ECAL/HCAL response, since at EIC energies most hadrons shower in the calorimeters, whereas muons are MIPs, the solution addressed by this R&D program will lead to significant cost savings, as a traditional HCAL is more expensive and for muon detection would have to have a high segmentation for track matching, increasing its complexity. To that extent, the KLM concept (described further below) can be a cost-effective complementary solution satisfying many of the above physics goals.

Appendix B: The KLM Concept

The KLM system proposed here is based on the Belle KLM ($K_L - \mu$) detector concept [11], and its subsequent upgrades at Belle II [12]. The proposal builds also on initial work done by the CORE Collaboration [8]. The Belle II system comprises layers of orthogonal scintillator strip planes with embedded wave-length-shifting (WLS) fibers and a single-end SiPM readout, interleaved with plates of the solenoid flux return steel.

In such a detector, muon identification with high purity is achieved by measuring their range in the scintillator-steel detector stack. Neutral hadrons (mostly K_L) are identified by the localized readout layer response following their interaction in a preceding steel plate. Segmentation in the readout along the z (beam axis) and ϕ (azimuth) directions, allows for a spatial coordinate measurement. Some aspects of the Belle KLM performance are shown in Fig. 11. The muon efficiency from early Belle II data in the lower panel, shows a steady rise from a turn on at ~ 0.6 GeV (determined by the material burden before the first readout layer, the magnetic field of the spectrometer magnet (1.5 T) and the radial location of the KLM.) to a high-efficiency plateau; the mis-identification rate decreases with layer number out to ~ 7 layers. The muon momentum is determined by the inner tracking detectors.

The upper plots demonstrate the efficiency for K_L detection along with the angular resolution from tagged K_L's using Belle data. Results from the Belle II scintillator upgrade are not yet available, but are expected to be as good or better.

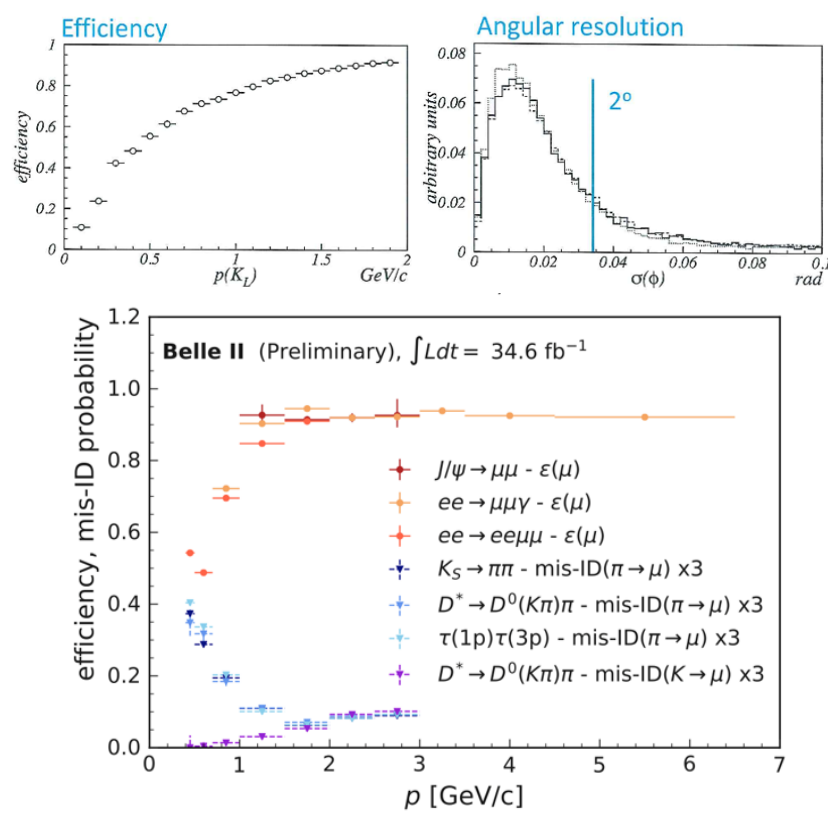

FIG. 11. Top: K_L efficiency (left) and angular resolution (right) from Belle data. Bottom: muon ID and fake rate vs. layer number from early Belle II data.

While the Belle KLM provides a feasible design with validated performance, the EIC has specific constraints that require adaptation. Such initial adaptation for EIC was carried out in the CORE detector proposal [8].

Besides the somewhat different overall geometry (a more elongated and compact barrel and smaller-radius endcap encircling the beam pipe), a major modification of the Belle design for the EIC was the shrinking of radial extent of the readout gaps to achieve overall radial compactness, necessitated by the space limitations at the second interaction region. However, the scintillator strip layer [4] implementation generally follows that used at Belle, namely an octagonal steel plate structure of the barrel return iron that accommodates the readout planes slid into air gaps created for each layer. The barrel layer panels are rectangular, each panel comprising two orthogonal layers of scintillator strips glued onto a thin common substrate, enclosed by an aluminum frame and covered with additional support/protective sheaths.

Two rectangular detector panels are placed in each layer of a barrel octant, one at the ion side and the other at the electron end, each inserted, respectively, where the barrel-endcap junction also provides service connections. For the endcap (on the electron-side), the scheme can be similar, but with the matching endcap plated structure divided in halves (for easy removal to the side) and the active scintillator strip layers inserted at the outer radius in quadrant-shaped panels.

As an example, the KLM design within CORE [8] uses an initial choice for the insertion gap of 21.5 mm interleaved with 55.5 mm steel plates (∼72% steel) for the entire implementation. This provides a workable solution that also enables a sampling frequency similar to a standard HCal – but with an individual layer response incorporating 3D positional readout - and thus can be a starting point for this project. As a further guidepoint, the implementation for CORE identified a suitable scintillator strip geometry with a cross sectional area of 7.5 mm × 30 mm, read out by a 1 mm diameter Wavelength Shifting (WLS) fiber. Following the Belle II design, the SiPM was directly recording the WLS light from the fiber mirrored at the far end. As demonstrated by Belle II, this gives an adequate number of photo-electrons, and can be extended out to 300 cm strip lengths [4].

The initial KLM design within the CORE detector is the starting point for the development of a baseline Multipurpose KLM for EIC and the HCAL KLM will leverage what has been learned about improving HCAL response to low energy neutral hadrons by emphasizing the longitudinal granularity of the readout.

[4] Compared to legacy RPC based Belle muon detectors, the design with scintillating material can be more compact and does not need a gas supply. This is an important advantage due the evolving environmental and safety standards for gas-based detectors. It also saves the infrastructure needed for the gas supply and reduces operating costs. The integration in the flux return is necessary, as the alternatives, i.e., having the detector inside or outside the magnet steel, are not viable. For a detector outside of the return steel, the threshold for muon detection would be too high and for both muons and hadrons, position and energy resolutions would be severely degraded due to multiple scattering and showering (for hadrons). A detector location inside the magnet steel would increase significantly the overall cost of the detector as the magnet cannot be compact anymore.