EIC KLM R&D Proposal

M. Arratia[a],[1] J.C. Bernauer,[2] M. H. S. Bukhari,[3] R. Corliss,[2] J. Datta,[2] K. Dehmelt,[2] A. Deshpande,[2] P. Garg,[2] T. Ghosh,[4] Th. Hemmick,[2] Y. Ilieva,[5] W. W. Jacobs[b],[6] J. Klay,[7] P. Nadel-Turonski,[2] W. Li,[2] E. Shulga,[2] O. Tsai,[8] G. S. Varner,[9] G. Visser,[6] and A. Vossen[c][10,11]

[1]*Department of Physics and Astronomy, University of California, Riverside, CA 92521, USA*
[2]*CFNS, Stony Brook University, Stony Brook, New York 11794*
[3]*Department of Physics, Faculty of Science, Jazan University, Jazan 45142, Saudi Arabia*
[4]*Ramaiah University of Applied Sciences, New BEL Road, Bangalore-560054, India*
[5]*University of South Carolina, Columbia South Carolina 29208*
[6]*CEEM, Indiana University, Bloomington Indiana 47405*
[7]*California Polytechnic State University, San Luis Obispo, 93407*
[8]*Department of Physics and Astronomy, University of California, Los Angeles, CA 90095, USA*
[9]*University of Hawaii, Honolulu, Hawaii 96822*
[10]*Duke University, Durham, North Carolina, 27708*
[11]*Thomas Jefferson National Accelerator Facility, Newport News, Virginia 23606*

(Dated: June 2022)

This R&D program aims to demonstrate the capability of the KLM detector concept to provide muon identification in a compact design, to extend its capability for hadron identification and calorimetry beyond the state-of-the-art (Belle II), and to investigate the KLM principle in a dedicated HCAL using existing components. 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.

Proposal contact(s):
A. Vossen; anselm.vossen@duke.edu

[a] Principal Investigator; miguel.arratia@ucr.edu
[b] Principal Investigator; jacobsw@indiana.edu
[c] Principal Investigator; anselm.vossen@duke.edu

CONTENTS

I. Executive Summary 3

II. Introduction 3
A. The KLM Concept 6

III. Multipurpose-KLM Proposed R&D Program 8
A. Motivation 8
B. R&D Program 9
1. Simulation of compact design 9
2. Direct Readout by multiple SiPMs 9
3. Direct Double-Sided Readout by SiPMs 10
4. Investigation of Scintillator Materials to optimize Timing Performance 11
5. Use of High Density System on a Chip Electronics 11
C. Timelines and Deliverables 12

IV. Extending the concept of high-granularity "KLM" calorimeter to a cost-effective HCAL with potential for improved hadronic resolution 14
A. Motivation 14
B. Objective and potential benefits 15
C. Proposed activities 16
D. Timelines and Deliverables 16

V. Budget and Budget Scenarios 17
A. Budget Request 17
1. Multipurpose KLM 17
2. Money Matrix 18

VI. Diversity, Equity, and Inclusion 19

VII. Participating Institutions 20

VIII. In-kind Contributions 22

References 23

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. Key aspects of the program are 10's of picosecond timing resolution and pulse-shape analysis based on recent advances in SiPMs and "Oscilloscope on a chip" readouts. 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. That such a detector could double as a cost effective HCAL is an exciting prospect for cost reduction. In addition to this Multipurpose KLM, as part of the proposal we will also investigate a dedicated HCAL using the KLM principle, but with existing hardware components for cost effectiveness. This might be a solution in the hadron going direction of an EIC, where low threshold muon detection is not paramount and, thus, design requirements (like segmentation) can be relaxed. 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

Studies performed for the EIC Yellow Report (YR) [1] and more recently [2], showed the importance of clean muon identification at the EIC for a variety of channels, such as TCS, DDVCS, HEMP and exclusive Quarkonium production. Figure 1 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 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 [3, 4]. 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 –

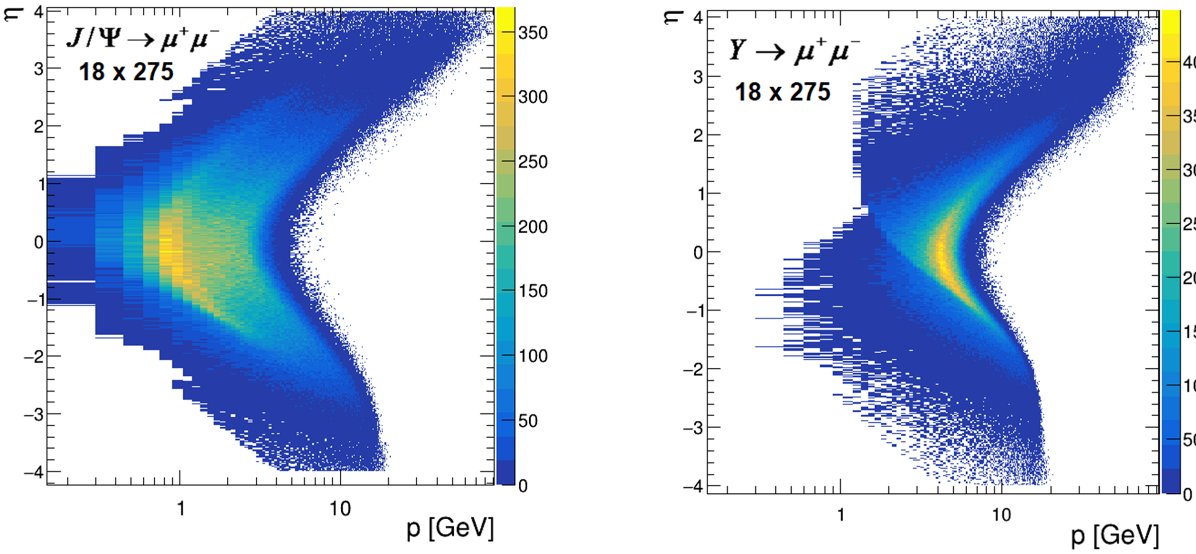

FIG. 1. Event distributions of muons produced in $J/\psi \to \mu^+\mu^-$ and $\Upsilon \to \mu^+\mu^-$, where the charm mesons originate in exclusive production off proton at beam configuration 18GeV×275GeV. The pseudorapidity versus momentum of each decay particle is shown. Figure from [2].

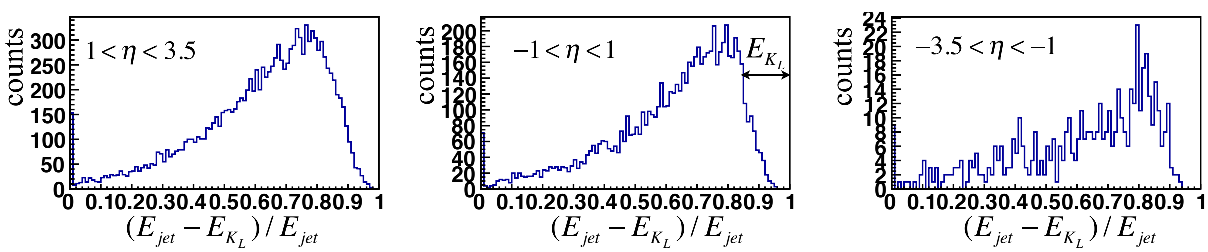

FIG. 2. Energy fraction of the total jet energy excluding the energy carried by K_L in the jet. The left, middle, and right distributions show the pseudorapidity of the jet in the hadron endcap, barrel, and electron endcap, respectively. The beam energy configuration is 10GeVx275GeV.

15% of the total jet energy (see Fig. 2) with the energy fraction exhibiting a wide variation. Figure 3 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 $\sim$ 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 $\sim$ 30 GeV/c. Jet reconstruction is essential for a large part of the EIC physics program [1]. 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 4 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

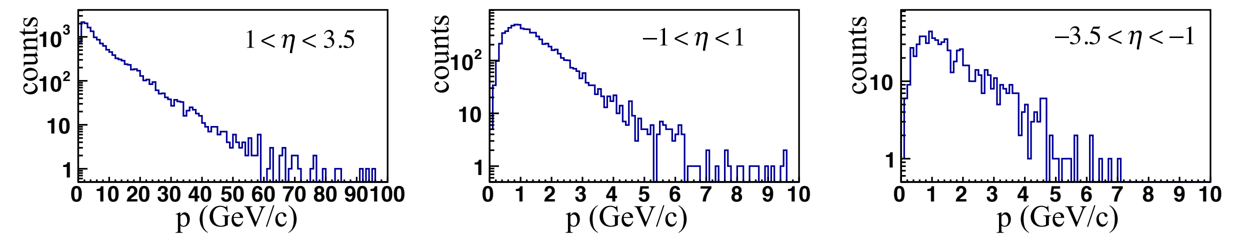

FIG. 3. Momentum distributions of K_L produced in a jet scattered in the electron endcap (left), barrel (middle), and hadron endcap (right). The pseudorapidity here is that of the kaon.

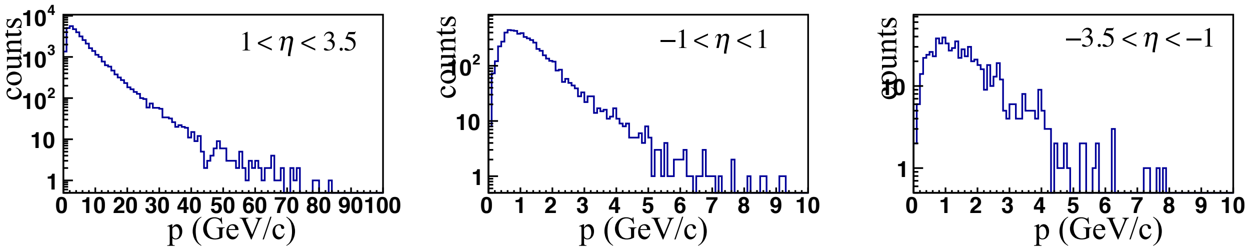

FIG. 4. Momentum distributions of neutrons produced in e-p collisions from Pythia8 for the electron endcap (left), barrel (middle), and hadron endcap (right).The beam energy configuration is 10x275.

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.

This R&D program approaches the problem at hand in two interrelated ways. In the first, referred to as a **Multipurpose KLM**, we build on the state of the art KLM design, *e.g.*, the Belle II KLM, in which the active elements are scintillator strips. In the second, referred to as a **KLM-type HCAL**, we build on a layered concept for HCAL tower design potentially reusing existing components. These two subprojects exploit the unique expertise of the UC collaborators with hadronic calorimetry, the Duke, IU, and HU with the Belle II KLM, and the USC with fast scintillator detectors and offer opportunities for substantial synergies. The Multipurpose KLM would be a good solution for the barrel and likely the electron-side endcap, whereas the KLM-type HCAL would be a good endcap solution. Both subprojects are generic and the delivered baseline designs 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.

A. The KLM Concept

The KLM system proposed here is based on the Belle KLM ($K_L - \mu$) detector concept [5], and its subsequent upgrades at Belle II [6]. The proposal builds also on initial work done by the CORE Collaboration [2]. 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. 5. 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.

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 [2].

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 [1] 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

[1] 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.

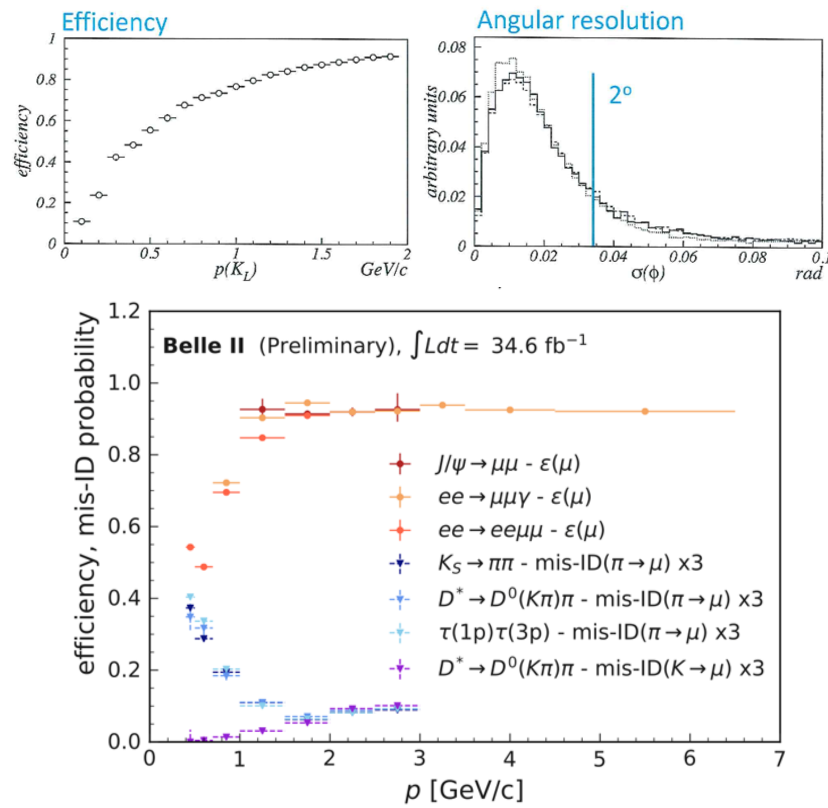

FIG. 5. Top: K_L efficiency (left) and angular resolution (right) from Belle data. Bottom: muon ID and fake rate vs. layer number from early Belle II data.

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 [2] uses an initial choice for the insertion gap of 21.5 mm interleaved with 55.5 mm steel plates ($\sim$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 $\times$ 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 [7].

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.

III. MULTIPURPOSE-KLM PROPOSED R&D PROGRAM

A. Motivation

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.

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 [8, 9], 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 has 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. In particular, R&D on thin scintillators that allow the detection of direct photons with a sufficient efficiency paired with 10's ps timing resolution and pulse shape discrimination using the novel HDSoC electronics might open new possibilities. One avenue is hadronic energy reconstruction using this new information in conjunction with AI/ML methods. It is also planned 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. Initially, the work will be done within the CORE-detector fun4all framework, which already exists and has been used by members of the participating groups. The KLM-specific simulation code will be modular and portable, so that it can be easily transferred to the common EIC simulation framework based on Detector-1 tools, which is expected to become available around the end of 2022. 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 are relevant for the muon ID by the KLM and will be fed in the KLM simulation studies. As a starting point, we will implement the design of the KLM in the CORE detector (as described in Sec. II-A). The simulation will be used to demonstrate and optimize the performance of the compact KLM for muon ID and to determine muon detection thresholds.

2. Direct Readout by multiple SiPMs

Ongoing Belle II R&D has indicated, along with results from other studies in the literature [7], that there are strong limitations to the achievable timing resolution using WLS fibers. Thus, an important part of 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,

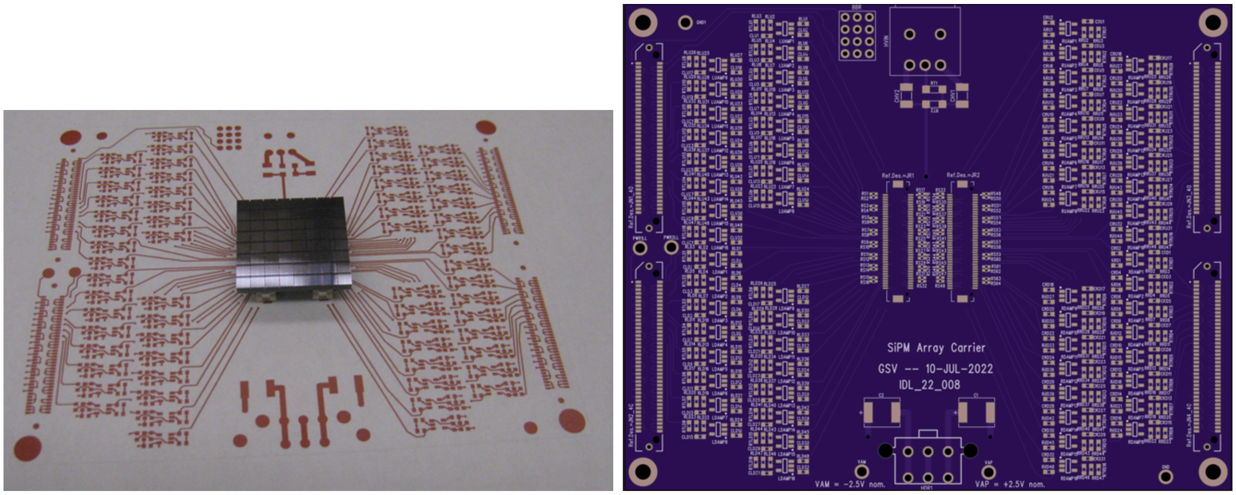

FIG. 6. Prototype SiPM carrier board adapted from an IU design for HELIX [10]. Here a configuration for 64 SiPMs to be used at the Univ. of Hawaii is shown; a version with a lower number of SiPMs will be used for this proposal.

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 corrections in post-processing. Thicker (6-cm thick) and longer bars (220-cm long), used in MUSE and CLAS12, have yielded ~ 55 ps timing resolution. The scintillator strips 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). The initial evaluation of the timing resolution of similar bars in a single-direct-coupled-SiPM readout configuration can be done in bench tests. For such tests, we would use waveform sampling electronics (provided by HU or IU), which is expected to help with timing and to provide pulse information for PID.

3. Direct Double-Sided Readout by SiPMs

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.

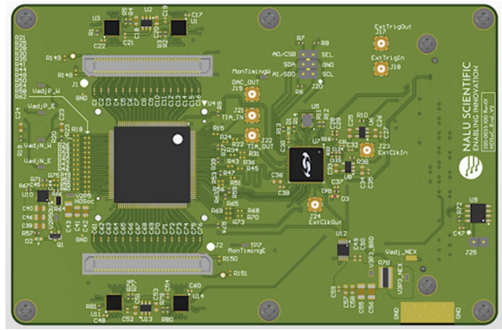

FIG. 7. HDSoC board prototype

4. 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 [11].

For our initial bench studies, necessarily involving relatively few samples, we will select a standard commercial option. For example. BC420 scintillator (available from *e.g.*, Saint-Gobain) is a long-attenuation-length good-timing-characteristic candidate. We will keep our eyes open for samples with promising characteristics that others might possibly have, but of course special order bulk suppliers are not likely to be able to help in the small quantity we need for initial tests. Looking to the future, the unavailability of production options from facilities in Russia and Ukraine may prove a challenge.

5. Use of High Density System on a Chip Electronics

As already anticipated, this proposal will commission High Density System on a Chip (HDSoC) electronics that will enable waveform sampling and several ps timing resolution. The HDSoC electronics are already developed by the University of Hawaii in conjunction with Nalu Scientific [12]. Figure 7 shows a current prototype. The initial development was supported by an SBIR grant [13], which was recently updated to a Phase II award. Since this is a generic platform, for the evaluation of this system for the given purpose, readout firmware is still needed and will be provided by this R&D. Other related work consists of construction of carrier boards and electronic/mechanical integration of the multi SiPM readout. As shown in Fig. 6, a prototype carrier board for 64 SiPMs already exists, which can easily be modified for the needs of this proposal.

Depending on the availability of funding, a modified prototype board with a simplified readout firmware can already made a available for bench tests in Year 1. Otherwise, the test stand for the scintillator and the initial evaluation could use a conventional setup with SiPMs and existing electronics.

C. Timelines and Deliverables

The proposed program is structured around a planned period of three years. Year 1 will primarily concentrate on simulations. Setting up lab space and infrastructure at the participating institutions will also begin in that year by procuring scintillator strips and equiping them with adapted off-the-shelf readout (HU and/or IU). In accordance with existing local expertise, lab space at the University of South Carolina will be used to evaluate timing and position resolutions of scintillator strips, lab space at the University of Hawaii will be used to construct HDSoC readout, and a setup to evaluate the full readout chain will be used at Duke University. In Year 2 the activities will be focused on detailed simulations of the readout and bench tests of viable readout configurations for timing and position resolution studies. Initial evaluation of the electronics will also take place in that year. 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.

Year 1 Activities

- Integration and validation of the initial compact EIC KLM design in fun4all. In Year 1, we will focus on the barrel KLM. The work will be done primarily by the USC group with support by SBU. Milestone: Implemented and validated KLM layer structure. Determination of muon detection thresholds within CORE detector layout.

- Using the fun4all simulation of a stack of the KLM and a parametrized performance of a typical EIC silicon tracker [1], 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[2]. This work will be done primarily by the Duke group with support from RUAS. Milestone: Initial muon ID.

- 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. Milestone: Initial clustering and reconstruction software. [3]

- The FPGA for the readout will start in UH, with support from IU, in addition to the design of needed auxiliary boards for the readout stack. For this, the necessary components (*e.g.*, HDSoC cards) will be procured. Hawaii will also design the SiPM package, several SiPMs are used to directly read out the scintillator without compromising timing performance. Milestone: First SiPM board assembled.

- For the test-stand at USC, thin scintillator strips will be procured and prepared for bench tests. If SiPMs are available, they will be coupled to each end of the strips

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

[3] It is planned to compare the simulation results for hadrons with available data on thin calorimeters from baloon experiments, *e.g.*, Refs [8, 9]. This will allow an initial verification of the hadron response in the absence of a beam test.

with an optical glue. These preparations will follow procedure protocols established during scintillator detector construction for MUSE and CLAS12. The readout for these tests could be with simpler, existing hardware and electronics. This work will also be supported by JU. Milestone: Lab setup and DAQ ready.

- At the end of the first year, contingent sufficient progress in Hawaii, a readout chain test can be established at Duke.

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

- Second SiPM readout board will be assembled at HU and will be commissioned with gen-2 firmware.
- Bench tests at USC of scintillator strips using the first SiPM readout board and simple firmware. Depending on the progress of the readout stack development, this might be a single or multiple SiPMs. Assessment of: timing resolutions of a single-sided and double-sided readout, position resolution with double-sided readout. Vary: scintillator type and dimensions if possible, SiPM type, readout techniques, *etc.*, scint wrapping, configs for SiPM clusters. Compare with other data-based expectations.
- If position resolution of at least 30-mm is achieved in the bench tests, the single-plane configuration will be implemented in simulation.
- 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.
- 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).
- 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.
- 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".

Year-2 Deliverables: (a) First timing and position resolutions results with generation-1 readout, (b) second SiPM readout board assembly and commissioning, (c) muon and hadron reconstruction algorithms

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.
- The readout FPGA code and setup will be finalized in Hawaii. Readout stack will be procured. Bench tests with final readout architectures will be run at USC and Duke and evaluated with respect to their muon performance. The performance measured will be fed into the simulations to evaluate the physics impact.
- 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) second SiPM readout board assembly and commissioning, (c) Gen 3 Firmware, including optimized feature extraction, (d) timing and position resolutions from bench tests with final readout.

IV. EXTENDING THE CONCEPT OF HIGH-GRANULARITY "KLM" CALORIMETER TO A COST-EFFECTIVE HCAL WITH POTENTIAL FOR IMPROVED HADRONIC RESOLUTION

A. Motivation

It is well known that the response of non-compensating calorimeters to low-energy hadrons is non-linear due to the fluctuations of electromagnetic fraction of hadronic showers [14]. However, modern reconstruction techniques can alleviate these issues, as demonstrated for example in a study [15] that used the ATLAS iron-scintillator "Tile" calorimeter that concluded:

> *Deep learning approaches outperform the classification applied in the baseline local hadronic calibration and are able to improve the energy resolution for a wide range in particle momenta, especially for low energy pions.*

In fact, this ATLAS study and subsequent ones [16] yielded an improved energy resolution and reduced bias even in the 1–10 GeV range [15], as shown in Fig. 8. This suggests that a promising way to improving the energy resolution of a traditional HCAL design is by emphasizing its granularity, specially the longitudinal one, to be exploited with modern techniques. Such an approach became practically only during the last decade, given the lowering of cost and dramatic improvement of SiPM technology.

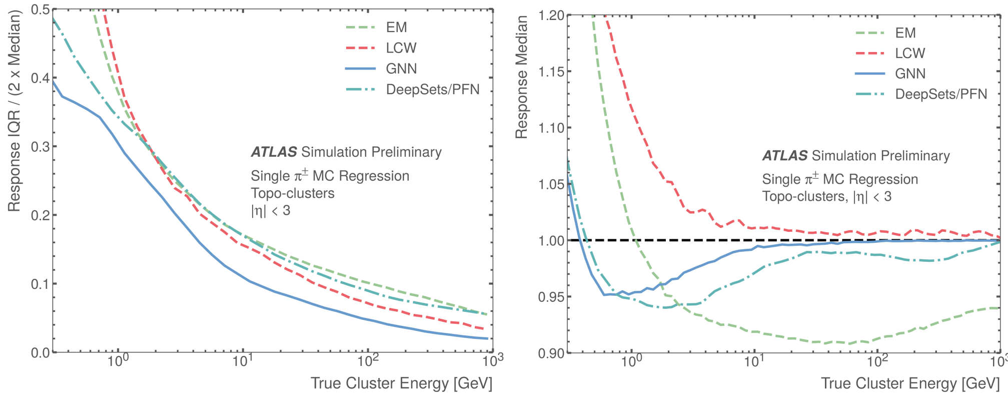

FIG. 8. Relative resolution (left) and bias (right) for pion reconstruction based on various machine-learning techniques that use the ATLAS "Tile" calorimeter. A graph-neural network (GNN) approach yields good resolution and low bias even in the 1-10 GeV range. Figure from Ref. [16].

B. Objective and potential benefits

We plan to design and test a low-cost, high-granularity Fe/Sc calorimeter that can be optimized to measure energy of low-energy hadrons. The main innovation with respect to traditional sampling designs is that every longitudinal layer will be readout independently, providing data that can be exploited to improve the response of low-energy neutral hadrons with energies relevant for the EIC. This approach would be a cost-effective alternative to expensive "imaging calorimeters" [17].

An improved measurement of low-energy neutral hadrons will boost inclusive DIS studies that use the hadronic final state (HFS), i.e. all particles but the scattered electron, to reconstruct x and Q^2 in low-y kinematics of neutral-current DIS or charged-current DIS. Moreover, measurements of HFS can account for unmeasured QED radiation by exploiting conservation of momentum in the entire event; this information can be used event-by-event to improve resolution and reduce bias [18]. An improved resolution for neutral hadrons would ensure the possibility to use low thresholds, which could become critical to reach the low-y region. For example, given that y is reconstructed as: $y = \Sigma\left(E_i - p_{z,i}\right)/2E_e$, loosing a 1 GeV neutron at large angles would induce a bias of $\Delta y \approx -1/20 = -0.05$ and completely spoil the measurement of low-y events.

Such a detector can be based on steel absorber and plastic scintillators readout with SiPMs. The active element geometry could be either megatiles or long bars. While, the KLM concept with long bars is the subject of the multipurpose KLM discussed previously, in this part of the proposed program, we focus on the megatile and short bars geometry. We expect synergy in various aspects of the studies. Such a design has potential not only for Detector 2, but also for Detector 1; in particular, to instrument the electron endcap. The possibility for reusing STAR HCAL Fe blocks or STAR barrel calorimeter megatiles could drive down the cost of materials substantially for use in either Detector 1 or 2. We expect to see an increased interest in a cost-effective solution for a combined calorimetry-muon tracking capabilities for both Detector 1 and Detector 2.

C. Proposed activities

First, a Geant4 Monte Carlo, running on the DD4Hep framework, will be used to simulate the expected performance using a basic reconstruction algorithm. We have preliminary results that indicate that the simulation can yield reasonable resolutions of Fe/Sc calorimeters by comparing to existing test-beam data. We then will implement a GNN approach similar to the ATLAS study [15, 16]. We note that we are actively developing similar approaches for a related project in collaboration with the authors of the ATLAS studies (from LBNL and LLNL) in the context of our California EIC consortium. The full testing and final adjustments are expected to take approximately three months, to be completed within one year of the project offset. An alternative simulation of the hadronic response with FLUKA will be investigated to estimate the systematic uncertainties of the simulations.

In addition, in order to test and develop these ideas, we plan to build and test a complete 64-channel 60× 60 cm^2, 3λ prototype, for which we have all building blocks (Fe blocks identical to those used in STAR HCAL, SiPMs, extruded scintillator bars, wave-shifting fiber) and a readout and bias system. The goal for this prototype is not to test any final design but rather to serve as a proof of principle for a HCAL design with high longitudinal granularity and low-cost. We will use cosmic rays and benchtop radiation sources to test the prototype and develop associated analysis software. Then, we plan to demonstrate the capabilities of the prototype under test-beam conditions. One attractive option is to do a parasitic test in Hall B at Jefferson Lab [19], which in principle could yield unique data with low-energy hadrons (1–10 GeV) tagged with the CLAS12 spectrometer. Several possible options for such a test exist, as described in Ref. [19]. The readout unit that we envision using for testing (CAEN FERS 5200) would enable to match its trigger timestamps with the Hall-B DAQ system in an offline analysis. This test would also provide crucial data on low-energy hadron response (<10 GeV) for Fe/Sc calorimeters that is not currently available, yet it is critical for the EIC domain.

D. Timelines and Deliverables

The deliverables related to this project include:

- Conceptual design of a cost-effective Fe/Sc HCAL with high longitudinal granularity and time capabilities, which is optimized for AI-reconstruction aimed for low-energy hadrons.
- Proof-of-concept prototype (60×60 cm^2, 3λ) including 64 channels with in-kind materials (Fe blocks, SiPMs, scintillator bars, WLS fiber, CITIROC readout and SiPM bias system).
- Test data at low hadron energies to demonstrate the concept.

More detailed list of planned activities is given below.

Year 1

- Use a well-established and validated simulation framework (DD4Hep) to estimate performance of a traditional sampling calorimeter highly-segmented in the longitudinal direction with various geometries and active elements (megatiles or plastic bars). Milestone: Simulation is validated against previous experiment's test beam data.

- Quantify performance gain for low-energy hadrons with AI-reconstruction exploiting high-granularity and time information. Milestones: GNN models trained and validated against performance reported in existing experiments.

- Perform measurements of light yield, attenuation and time resolution for scintillator bars with WLS fiber and SiPM readout using CITIROC ASIC readout (CAEN FERS-5200).
  Milestone: Measurements are incorporated into simulation.

- Start assembly of 64-channel prototype using Fe blocks (identical to STAR HCAL) and scintillator bars as active element.

Year 2

- Prototype bench top testing with cosmic ray and LED.
  Milestone: Muon track reconstruction achieved using bar "strip" coordinates and time information from dual-ended readout.

- Develop strategy for readout synchronization for parasitic testing at Hall B. Identify plan for possible setup.
  Milestone: plan for parasitic testing concrete and vetted by Hall-B experts.

- Finish assembly of 64-channel prototype.

- Move prototype to Jefferson Laboratory and perform tests with cosmics and LED on site.

- Parasitic testing of Hall B to test performance with low-energy hadrons of various types.

V. BUDGET AND BUDGET SCENARIOS

A. Budget Request

1. Multipurpose KLM

The table below summarizes the budget request for the multipurpose KLM subproject.

Funding is requested for 50% postdocs at Duke and HU to support the proposed reconstruction software development and readout adaptation, respectively, for the multipurpose KLM. These researchers will work on location at Duke and HU and will be supervised by A. Vossen and G. Varner, respectively. Funding is requested for graduate students at UCR, and UCLA to carry out software, simulation, and instrumentation work. The students will work on location at their institutions and will be supervised by M. Arratia, and O. Tsai, respectively.

The personnel at USC and Duke funded by the program will be responsible for the simulation and software work planned on the multipurpose KLM in Year 1 with support from SBU, RUAS, and JU. At USC, undergraduate students will work during summer on the determination of detection thresholds and simulation validation. At UCR, UCLA, and CPSU SLO, students will work on simulation, assembly of the prototype, and bench tests.

	100%	80%	60%
Undergraduate students, USC	$12.5k	$7.8k	$7.8k
Postdoc (50%), Duke	$53.7k	$43k	$32.2k
Undergraduate students, Duke	$12.5k	$10k	$7.5k
Postdoc (50%), UH	$50k	$40k	$30k
HDSoC based evaluation readout system, UH	$10k	$8k	$6k
Test Bench: config & readout EE support, IU	$8.3k	$6.6k	$5k
Scintillator strips, USC	$4.5k	$3.6k	$2.7k
Travel to U.S., JU	$8k	$6.4k	$0k
Travel to U.S., RUAS	$13k	$10k	$0k
Computational resources (laptop), RUAS	$2k	$0k	$0k
Total	$174.5k	$135.4k	$91.2k

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

	100%	80%	60%
Graduate student (50%), UCR	$28.4k	$22.7k	$17k
Graduate student (50%), UCLA	$28.2k	$22.6k	$16.9k
Undergraduate students, CPSU SLO	$12.0k	$9.6k	$7.2k
Travel, UCR	$2.0k	$1.6k	$1.2k
Total	$70.6k	$56.5k	$42.3k

TABLE II. Budget for KLM-type HCAL. The budget includes institutional overhead.

The travel budget for RUAS and JU will support the travel of one colleague from each university to spend a month working on the project at SBU and USC, respectively. RUAS requests a modest support for a laptop where they can carry out simulation and software work on the project.

2. 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 1 will be delayed or not completed. For example, the KLM strip layer structure will not be fully implemented and validated in simulation. Muon, K_L, and neutron detection thresholds would be evaluated with a simplified cylindrical layout. Progress on the study of the KLM response to hadrons will occur at a slower pace. Reduced funding for the postdoc at UH means that the first SiPM board with gen 2 firmware will not be made available in Year 1, which will delay significantly the bench tests of timing and position resolutions planned for Year 2. As these are key for extending the KLM technology beyond the state of the art, this postdoctoral support is critical.

Institution	Multipurpose KLM	KLM-type HCAL	Sum
Duke	$66.2k	$0k	$66.2k
HU	$60k	$0k	$60k
IU	$8.3k	$0k	$8.3k
USC	$17k	$0k	$17k
RUAS	$15k	$0k	$15k
JU	$8k	$0k	$8k
UCR	$0k	$30.4k	$30.4k
UCLA	$0k	$28.2k	$28.2k
CPSU SLO	$0k	$12k	$12k
Total	$174.5 k	$70.6k	$245.1k

TABLE III. Budget, 100% scenario, separated by project and institution. Institutional overheads are included.

Institution	Multipurpose KLM	KLM-type HCAL	Sum
Duke	$53k	$0k	$53k
UH	$48k	$0k	$48k
IU	$6.6k	$0k	$6.6k
USC	$11.4k	$0k	$11.4k
RUAS	$10k	$0k	$10k
JU	$6.4k	$0k	$6.4k
UCR	$0k	$24.3k	$24.3k
UCLA	$0k	$22.6k	$22.6k
CPSU SLO	$0k	$9.6k	$9.6k
Total	$135.4k	$56.5k	$191.9k

TABLE IV. Budget, 80% scenario, separated by project and institution. The budgets include institutional overheads. In this reduced scenario, the intermediate milestones are: KLM simulation class with incomplete segmentation geometry, initial muon ID, Lab setup and DAQ ready at USC, gen-2 firmware not fully debugged.

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 underrepresented groups in physics as well as from economically disadvantaged communities and 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

Institution	Multipurpose KLM	KLM-type HCAL	Sum
Duke	\$39.7k	\$0k	\$39.7k
UH	\$36k	\$0k	\$36k
IU	\$5k	\$0k	\$5k
USC	\$10.5k	\$0k	\$10.5k
RUAS	\$0k	\$0k	\$0k
JU	\$0k	\$0k	\$0k
UCR	\$0k	\$18.2k	\$18.2k
UCLA	\$0k	\$16.9k	\$16.9k
CPSU SLO	\$0k	\$7.2k	\$7.2k
Total	\$91.2k	\$42.3k	\$133.5k

TABLE V. Budget, 60% scenario, separated by project and institution. The budgets include institutional overheads. In this reduced scenario, the intermediate milestones are: KLM simulation class with a simple layered, but not segmented, cylindrical geometry, initial muon ID, lab setup and DAQ ready at USC, incomplete first SiPM readout board assembly and commissioning.

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.

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 collaboration 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), 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 ahttps://www.overleaf.com/project/62bca6ecc05eedc369fcbfaf 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 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.

UC Riverside: UCR has a fully equipped machine shop capable of small production runs. The rate is $36/hr for labor. At UCR, our group has about 750 sf laboratory space, which is equipped with modern electronic equipment, including fast digitizers, fast pulsed laser, low-noise power supplies, electrometers, etc. In addition, our lab space includes a separate 400 sf ISO 7 clean room.

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.

California Polytechnic State University San Luis Obispo: Cal Poly is a predominantly undergraduate institution with a vibrant learn-by-doing approach to education that involves undergraduates in the research areas of its faculty members. For fifteen years the PI has supervised undergraduate research projects with both the ALICE experiment at CERN, funded by NSF RUI and MRI grants, and the NIFFTE experiment at LANSCE, funded by DOE Office of Nuclear Energy and direct contracts to LLNL and LANL. Students work on simulations, software, data collection and analysis, as well as hardware component testing both locally and at CERN and the national labs. The PI has extensive experience in modeling and simulation of detectors and a shared 300 sq. ft. lab space with modern lab equipment and photo-sensor testing capabilities.

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.

UC Riverside: Materials that can become part of a small calorimeter prototype, which are worth not less than 50k: 1200 Fe blocks (identical to the STAR HCAL design), $O(100)$ SiPMs of various models and sizes, 64-channel readout and bias system, WLS fiber of various types. https://www.overleaf.com/project/62bca6ecc05eedc369fcbfaf

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.

University of Hawaii: UH provides in-kind FTE from EE M. Andrew, access to a CNC-capable machine shop and machinist support, access and expertise in use of programmable logic and Application Specific Integrated Circuit (FPGA and ASIC) design tools and implementation, and the significant lab infrastructure for test, evaluation and characterization of the internationally renown Instrumentation Development Laboratory.

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

REFERENCES

[1] R. Abdul Khalek *et al.*, "Science requirements and detector concepts for the electron-ion collider: Eic yellow report," (2021), arXiv:2103.05419.

[2] CORE Proto-Collaboration, "Core - a compact detector for the eic," `https://doi.org/10.5281/zenodo.6536630` (2021).

[3] B. S. Page, Xiaoxuan Chu, and E. C. Aschenauer, "Experimental aspects of jet physics at a future eic," Phys. Rev. D **101**, 072003 (2020).

[4] Miguel Arratia, Youqi Song, Felix Ringer, and Barbara V. Jacak, "Jets as precision probes in electron-nucleus collisions at the future electron-ion collider," Physical Review C **101** (2020), 10.1103/physrevc.101.065204.

[5] A. Abashian *et al.* (Belle), "The K(L) / mu detector subsystem for the BELLE experiment at the KEK B factory," Nucl. Instrum. Meth. A **449**, 112–124 (2000).

[6] T. Aushev *et al.*, "A scintillator based endcap K_L and muon detector for the Belle II experiment," Nucl. Instrum. Meth. A **789**, 134–142 (2015), arXiv:1406.3267 [physics.ins-det].

[7] W. Baldini *et al.*, "Measurement of parameters of scintillating bars with wavelength-shifting fibres and silicon photomultiplier readout for the SHiP muon detector," Journal of Instrumentation **12**, P03005–P03005 (2017).

[8] S. Avvakumov *et al.*, "Performance of the NuTeV fe-scintillator sampling calorimeter and implications for thin calorimeters," Nuclear Physics B - Proceedings Supplements **78**, 232–237 (1999).

[9] L. Pacini *et al.*, "CaloCube: an innovative homogeneous calorimeter for the next-generation space experiments," J. Phys. Conf. Ser. **928**, 012013 (2017).

[10] Nahee Park *et al.*, "Cosmic-ray isotope measurements with HELIX," PoS **ICRC2021**, 091 (2021).

[11] Alexey Stoykov and Tigran Rostomyan, "Time Resolution of BC422 Plastic Scintillator Read Out by a SiPM," IEEE Trans. Nucl. Sci. **68**, 1487–1494 (2021), arXiv:2103.11391 [physics.ins-det].

[12] Nalu Scientific LLC, Home website at: `https://www.naluscientific.com/`.

[13] Nalu Scientific SBIR, "Design and fabrication of the hdsoc - high density digitizer system-on-chips," Available at sbir.gov site: `https://www.sbir.gov/sbirsearch/detail/1711597`.

[14] Richard Wigmans, "Advances in hadron calorimetry," Ann. Rev. Nucl. Part. Sci. **41**, 133–185 (1991).

[15] "Deep Learning for Pion Identification and Energy Calibration with the ATLAS Detector," (2020).

[16] "Ddeep learning pion reco with point cloud," `https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PLOTS/JETM-2022-002/`, accessed: 2022-07-25.

[17] Felix Sefkow, Andy White, Kiyotomo Kawagoe, Roman Pöschl, and José Repond, "Experimental Tests of Particle Flow Calorimetry," Rev. Mod. Phys. **88**, 015003 (2016), arXiv:1507.05893 [physics.ins-det].

[18] Miguel Arratia, Daniel Britzger, Owen Long, and Benjamin Nachman, "Reconstructing the kinematics of deep inelastic scattering with deep learning," Nucl. Instrum. Meth. A **1025**, 166164 (2022), arXiv:2110.05505 [hep-ex].

[19] "Detector testing capabilities in hall b," `https://www.jlab.org/eiccenter/`

detector-testing-capabilities-hall-b, accessed: 2022-07-25.