# Continuation of KLM R&D for the EIC

Anselm Vossen for the collaboration

University of Hawai'i Mānoa
University of South Carolina
Indiana University
Ramaiah University of Applied Sciences
Stony Brook University
Duke University
Jefferson Lab
Jazan University

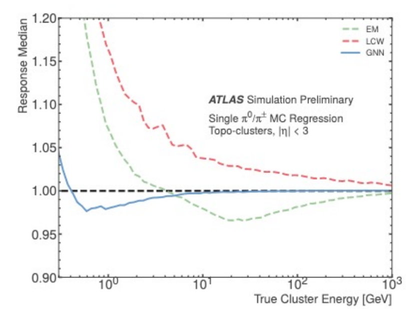
- AI/ML is mentioned a number of times in the proposal, but did not surface in the deliverables explicitly. What is the connection?

- AI/ML is not a deliverable per se, but a tool to optimize the deliverables.
- We see two potential uses of ML/AI
  - Energy reconstruction and PID
    - Established
    - Make use of longitudinal and lateral segmentation
    - Well established (e.g. ATLAS, ePIC), in particular for non-compensating calorimeters
  - Detector design
    - 2nd detector design optimization is one potential goal of the AIDE collaboration (Vossen co-PI)

9 layers

| p (GeV) | Edep/p cut | | | ML | | | Combined | |
|---|---|---|---|---|---|---|---|---|
| | Cut | e Eff. | pion Rej. | e:pion Weighting | e Eff. | pion Rej. | e Eff. | pion Rej. |
| 0.1 | > 0.055 @ $9X_0$ | 99.83% | 1.15 | 1:10 | 95.20% | 490.39 | 95.03% | 565 |
| 0.2 | > 0.070 @ $9X_0$ | 99.49% | 1.33 | 1:15 | 95.68% | 499.23 | 95.19% | 663 |
| 0.5 | > 0.085 @ $9X_0$ | 97.26% | 18.99 | 1:20 | 98.09% | 96.96 | 95.40% | 1841 |
| 1 | > 0.085 @ $9X_0$ | 97.70% | 44.28 | 1:40 | 97.27% | 87.15 | 95.04% | 3859 |
| 2 | > 0.085 @ $9X_0$ | 96.82% | 166.63 | 1:40 | 98.75% | 43.93 | 95.62% | 7320 |
| 5 | > 0.095 @ $20X_0$ | 99.06% | 184.44 | 1:40 | 96.84% | 35.95 | 95.92% | 6631 |
| 10 | > 0.095 @ $20X_0$ | 98.61% | 236.68 | 1:40 | 96.73% | 30.14 | 95.39% | 7134 |

Impact of ML/AI on ePIC barrel calorimeter performance (courtesy of C. Peng)




(a) $\pi^0$ and $\pi^\pm$ Median Energy Response

Performance of GNN based Steel/Scintillator tile HCAL recATL-PHYS-PUB-2022-040

- Some context, or comparison, of this proposal's device relative to the HCals of the LEP detectors, DELPHI, OPAL and ALEPH, would be useful. These were multi-plate steel-sensor stacks that served as magnet-barrel flux returns, hadronic calorimeters, and first stages of muon taggers.

| | ALEPH | DELPHI | OPAL | KLM(CORE) |
|---|---|---|---|---|
| magnetic field | 1.5T | 1.2T | 0.435 T | =< 3T |
| barrel R_inner | 300 cm | | 340 cm | 140 cm |
| barrel R_outer | 468 cm | | 440 cm | 265 cm |
| number of layers | 23 | 20 | 9 | 14 |
| slab thickness | 5 cm | 5 cm | 10 cm | 5.55 cm |
| gap width | 2.2 cm | 1.8 cm | 2.5 cm | 2.15 cm |
| interaction length | 7.16 | | >4 | $\approx 5$ |
| resolution | 0.84 /sqrtE | 1.12 /sqrtE | 1.2 /sqrtE | **TBD** |
| active layer | Streamer tubes | Streamer tubes | Streamer tubes | scint |
| readout | into towers 1-dim tract | into towers 1-dim tract | into towers 1-dim tract | **Flux in 3D** |

- Some context, or comparison, of this proposal's device relative to the HCals of the LEP detectors, DELPHI, OPAL and ALEPH, would be useful. These were multi-plate steel-sensor stacks that served as magnet-barrel flux returns, hadronic calorimeters, and first stages of muon taggers.

- Thank you for this suggestion. There are some similarities as the reviewer pointed out. In general the readout is using gas based detectors and sampling fractions are comparable. However, the KLM proposed here would be more compact and simpler to construct, would have finer longitudinal segmentation and operate in a higher B field. 3D shower shape information will improve on energy resolution ($\approx 100\%/\sqrt{E}$ ) cited for the LEP calorimeters (This resolution is the same as the requirement for the project detector HCAL from the Yellow report). Additionally, the proposed KLM would have a $ToF$ capabilities➔PID and energy measurement with 10-20% resolution between 1-2 GeV (complementary to calorimetry at higher energies)

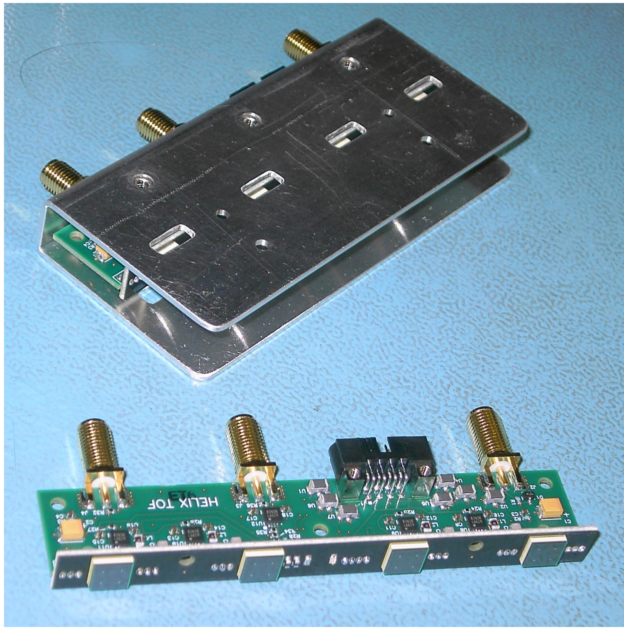
- Some detail about the HELIX experiment electronics would be helpful.

- A description of the full HELIX readout can be found in the reference: Nahee Park et al., “Cosmic-ray isotope measurements with HELIX,” PoS ICRC2021, 091

- Depending on particles, ToF has up to 50ps resolution.

- For KLM, plan to adapt carrier+preamp

- Slow and fast outputs (timing and charge)



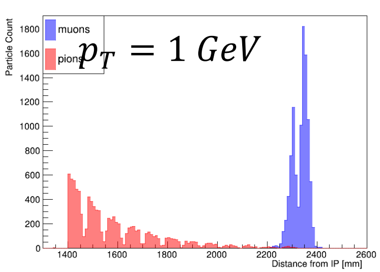
- Does ELJEN have access to needed chemicals to manufacture the required scintillators or are there any known supply chain issues? What type of scintillator is planned?

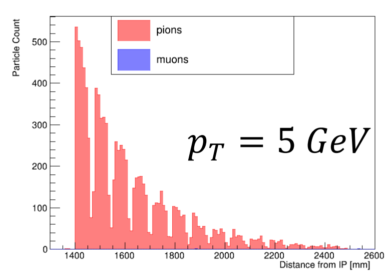
- According to their representative, there are no supply chain problems and they could deliver 30k scintillator bars if we were to order them.

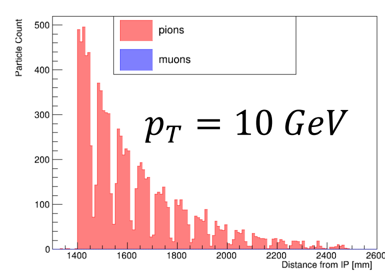
- Is Fig.2 right hand panel 1.5 T (text) or 2.0 T (legend on figure)?
- The correct value is 1.5 T, the labelling of the figure of 2. T is not correct.

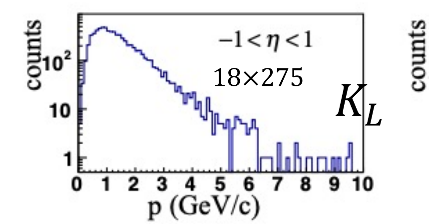
- What energy resolution sigma/E is forseen for the HCal? How many interaction lengths are planned? What is the relevant energy range for the hadrons, and is shower leakage a concern?

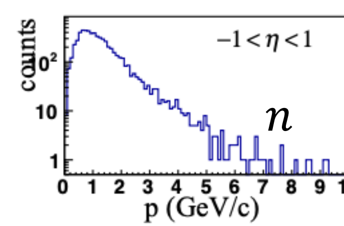
- Using ToF, the resolution is between 10% for $K_L$ and neutrons at 1.2/1.8 $GeV$ and 50% at 2/3 GeV $p_T$ respectively. The energy resolution has not been determined yet. Comparing to the LEP example we expect better than $100\%/\sqrt{E}$, which is the YR requirement and the ePIC HCAL performance. Improvements will come from the measurement of the 3D shower shape
- The reference design (CORE) uses 14 layers with $55mm$ thick steel plates, giving about 5 interaction length.
  Transverse shower leakage is not a concern due to the fine segmentation. Shower leakage in the longitudinal direction can lead to lower energy resolutions for an HCAL. We hope that the fine transverse and longitudinal segmentation allows to o












Last energy deposit in KLM for different $p_T$ ➔Shower is largely contained even at the highest momenta expected in the barrel

- The scintillator discussed is 7.5mm thick, a factor of 8 less than the 6 cm thick scintillator used in CLAS12, for which 55 ps timing resolution is noted. This suggests a factor of 8 fewer photons, modulo light collection issues. Some discussion of possible timing resolution and the means to achieve 50 ps or better would be useful.

- Timing will be used to get positional information for muons (MIPs) and ToF/position for neutrons/$K_L$
  - Expect bigger energy deposit for hadrons

- Some numbers:
  - 100ps timing resolution ➔ 1.9cm position resolution
  - 60ps timing resolution ➔10% ToF resolution for $K_L$ @ 1.2 GeV, neutrons @ 1.8 GeV

- Experience from MUSE, EJ-204 with $3cm$ thickness/$120cm$ length: $\sigma = 47 \pm 3$ ps
- Adjusting for thickness, SiPM coverage and QE in initial tests, we expect $\approx 100ps$ resolution
- MUSE like SiPM coverage (77%) → $\approx 70\ ps$ resolution. Further improvements will be explored with the testbench (e.g. applying overvoltage to SiPM)
- This is also consistent with extrapolations from state-of-the art measurements [6] (20 ps resolution for BC-422 at 10cm) and adjusting for $\tau_R, \tau_D$ and attenuation length (Given that he timing resolution is $\propto \sqrt{(\tau_R \cdot \tau_D)/N_\gamma}$, where $\tau_R, \tau_D$ are the rise and decay times of the scintillator)

[6] *IEEE Trans.Nucl.Sci.* 68 (2021) 7, 1487-1494, e-Print: 2103.11391 [physics.ins-det]

# Cont

- The scintillator discussed is 7.5mm thick, a factor of 8 less than the 6 cm thick scintillator used in CLAS12, for which 55 ps timing resolution is noted. This suggests a factor of 8 fewer photons, modulo light collection issues. Some discussion of possible timing resolution and the means to achieve 50 ps or better would be useful.

- Best timing will be achieved for neutrons and $K_L$
  - Higher light output
  - Neutral track, so position resolution via timing important
  - PID from shower shape and energy from ToF

- Muons will have less good timing resolution
  - Tracking helps with position resolution and momentum measurements
  - KLM mainly for muon PID

- A tentative goal of $70ps$ resolution is sufficient for
  - position resolution better than $2cm$ ($\approx$ strip width and multiple scattering
  - Energy resolution from ToF of few 10% up to $\approx 2\ GeV$

[6] *IEEE Trans.Nucl.Sci.* 68 (2021) 7, 1487-1494, e-Print: 2103.11391 [physics.ins-det]

- Will larger-area SiPMs than exhibited for HELIX in Figure 6 be tested? Some larger SiPMs were tested by C. Woody of BNL as part of prior R&D, in that case for reading out EMCal modules. Has contact with him been made?

- For the tests, we are considering to use 6x6 mm^2 SiPMs (max size from Hamamatsu). Depending on the results of the tests, we may need to consider potentially, further options that lead to a larger coverage of the area of the bar, where the light is collected,  Contact with C. Woody is to be established.

- Are there any representative waveforms already recorded for the signals from SiPMs coupled to the proposed scintillator(s), or is that part of this R&D?

- This is part of the proposed activities for FY24

- Have you calculated the threshold for a constant field by hand? Is this broadly consistent (within the deliberate choice of 0.5 for the efficiency)?

- Yes, we have and not accounting for energy loss in the material prior to the KLM. For example, the minimum momentum a muon would need to just reach the KLM in a 3-T field is 0.642 MeV/c. In a 1.5-T field, this momentum is 300 MeV/c. Due to energy loss, such muons do not make it to the detector. The 50% cutoff was chosen arbitrarily.

- The proposal reports on some test bench measurements from Belle-II. It seems that the numbers are not completely consistent between sections II-A-3 and IV-B-2. Can you summarize this and explain the purpose of the new scintillator sizes? Can you explain in more detail the plans to directly couple the SiPM to the scintillator? (Other experiments may still have some leftover spares with other dimensions, although details about the light collection may be helpful.)

- We could not quite follow this comment. The dimensions of the scintillators given in the two referenced sections are the same.
- There are no testbench measurements with Scintillators+SiPMs from Belle reported in the proposal.
- The dimensions of the scintillators are driven by the tradeoff between a compact design and sufficient photon yield for the target timing resolution.
- Coupling of the SiPMs: optical grease (likely for teststand) or cement (final detector)

- Is the delayed funding an independent problem to the workforce recruitment?

- Since only partial funding is provided recruitment has to be somewhat independent of the arrival of funds. However, work scheduling depends on the availability of funds.

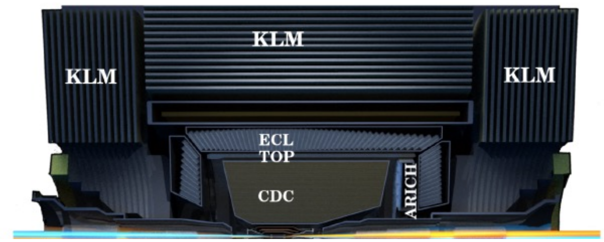
# Project Motivation and Objectives

**Muon Detection is an essential capability of collider detectors**

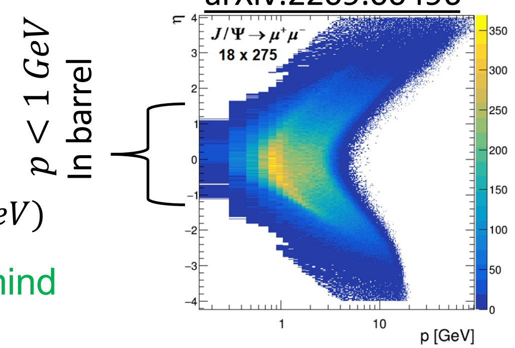
- EIC: Diffractive $J/\Psi$, access of gluon TMDs, TCS, DDVCS and more.
- Excellent MuID will be complementary to ePIC

➔Strong interest! See presentations at 2nd detector workshops and meetings

➔Active effort to work out the physics case




arXiv:2209.00496




Design based on **Belle/Belle II $K_L$Muon Id (KLM)**

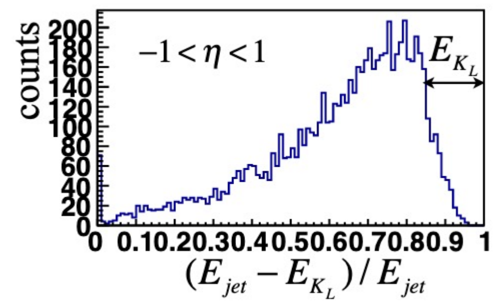
⇒MuID fulfills requirements for EIC:

- Good angular resolution ($\approx 2^{\circ}$)
- **Low** momentum threshold due to integration in magnet flux return: ($\approx 0.6\ GeV$) [match $\mu$ reqs.]

- Muon ID capabilities designed with good $K_L$ / neutrals detection/ID (ToF) in mind

  ➔longitudinal segmentation+timing ➔competitive HCAL performance

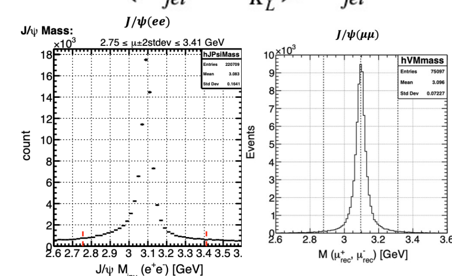
  ➔HCAL: Jet reconstruction, kinematic reconstruction at low $y$




Objective: **Demonstrate capability and cost-effectiveness of the KLM detector concept for the EIC**

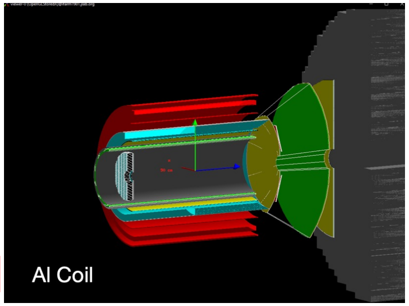
- Provide excellent muon identification in a compact design
- Extend concept for hadron identification and calorimetry
- Evaluate HCAL performance in relevant momentum region
- Evaluate $neutron/K_L$ PID performance (shower shape and ToF)
- Use timing, double sided readout for position determination

  →compact design
- **Novel aspect: Use longitudinal segmentation, excellent timing + state of the art Machine Learning Methods for PID, calorimetry and compact, cost effective design**



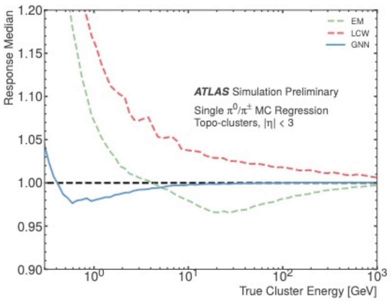
# Project Scope

- Implementation of Barrel KLM in Simulation to
  - Study optimization of field, det radius and layer topology for best muon efficiency vs. threshold and desired range.
  - Achieve a KLM baseline integrated design (with magnet and tracker)
  - Study hadronic response (energy, PID)
  - Adapt ML algorithms to KLM geometry
  - Interplay of geometry/ML performance




CORE magnet system simulations

- R&D on thin scintillators
  - Demonstrate feasibility of compact design with direct read
  - Timing (strive for 10s of picoseconds) for TOF info for hadron ID and momentum measurement
  - w/ double-sided readout of strip, evaluate timing for position determination
  
  ➔more compact design.
- Implementation of fast readout chain using SiPMs
- Integration of R&D results into simulations
- Beam test to verify hadronic response




(a) $\pi^0$ and $\pi^\pm$ Median Energy Response

Performance of GNN based HCAL rec
ATL-PHYS-PUB-2022-040

# Previous Year 1 Activities and Budget Request

- Simulation + Reconstruction work at Duke
  - Deliverables
    - MuID reconstruction/MuID
    - Study of hadronic shower shape
    - Clustering, hadronic reconstruction algorithms
  - Milestone: Initial characterization of MuonID, hadron reconstruction/ID
- Readout teststand at Duke (+ in kind contributions/REU)

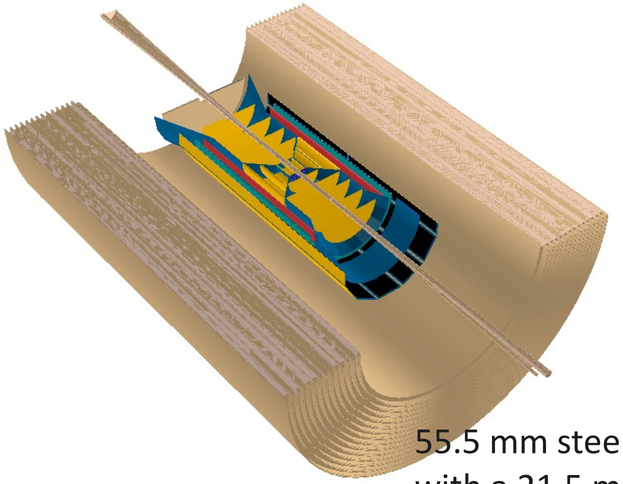
- Teststand for Scintillator R&D, UofSC
  - Deliverable:
    - Procurement of material
    - Preparation of teststand (including DAQ)
  - Milestone: Teststand ready
  - EE support by IU
- Simulation work at UofSC/SBU
  - Deliverables/Milestone: Implemented KLM layer structure

# Current Status

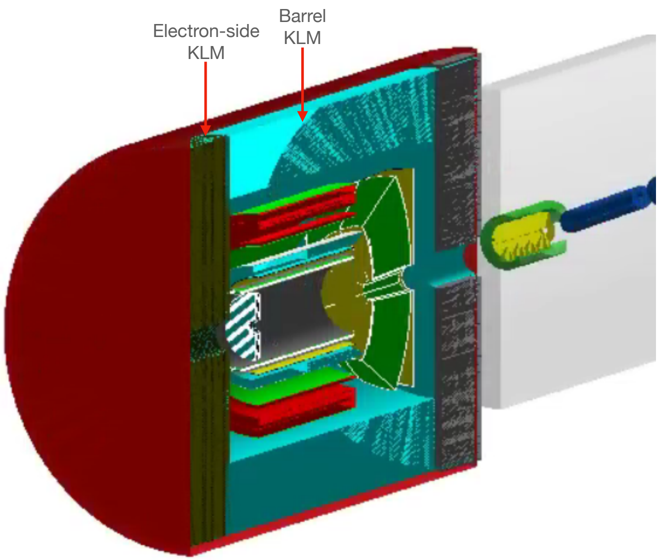
- Funding at $\approx 54\%$ level
- Delays in contracting an hiring
- Simulation + Reconstruction work at Duke
  - DD4HEP implementation
  - Study of hadronic and $\mu$ response
  - Milestone: Initial characterization of MuonID, hadron reconstruction/ID
- Teststand for Scintillator R&D, UofSC
  - Deliverable:
    - Procurement of material
    - Preparation of teststand (including DAQ)
  - Milestone: Teststand ready
  - EE support by IU
- Simulation work at UofSC/SBU
  - Deliverables/Milestone: Implemented KLM layer structure

# Simulations

- Implementation in DD4HEP
  - Synergy with 2nd detector and ePIC
    - E.g. 2nd IP implementation, study of muon physics

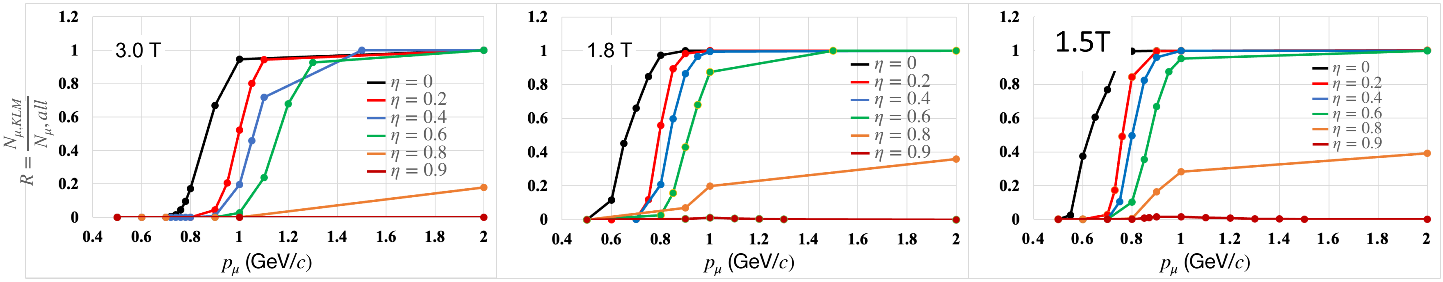


55.5 mm steel
with a 21.5 mm gap
14 layers



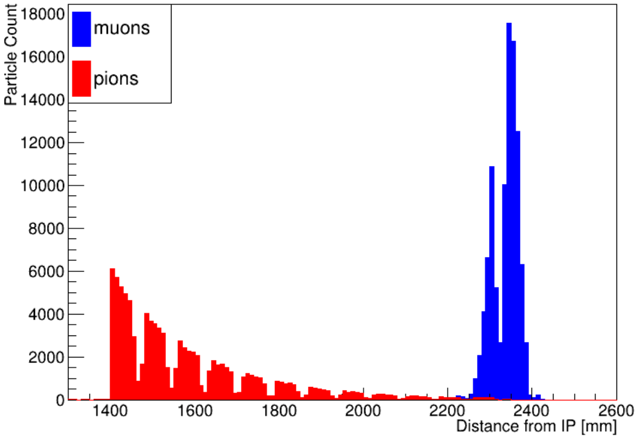

- Implementation in Fun4All
  - Existing CORE implementation
  - Minimal initial effort
  - Ways to export to DD4HEP

# Simulations, Cont



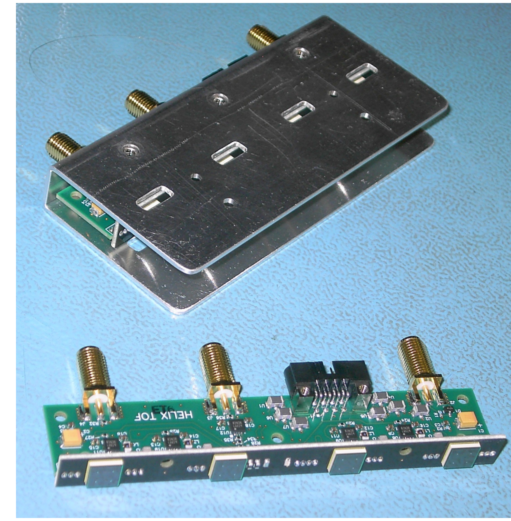

- Minimum Muon momentum for CORE configuration
  - 600 MeV is reached for lower central B field

- Muon vs pion response from DD4HEP simulation



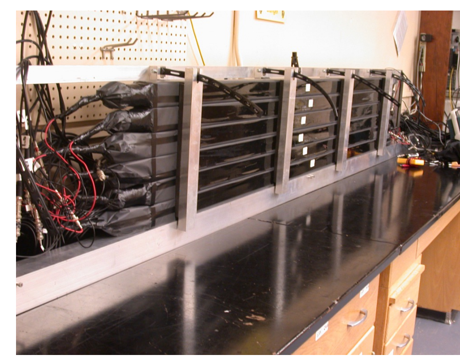
# Scintillator test and electronics

- Goal: thin scintillators with balanced attenuation/timing properties
  - use scintillator readily available commercially
  - $[1.5\mathrm{m} \mid 2.5\mathrm{m}] \times 1 \times 3\ \mathrm{cm}^2$ to be tested
  - EJ-204 (fastest)
  - EJ-200, EJ-208
  - BC420 (planned for Year 3)




HELIX carrier/preamp board

- Ordered…
- Pair with appropriate SiPM (QE max matched)
  - default  S13360-6050VE used by HELIX but consider others (e.g. S14160-6050HS)
  - Final detector might use custom solution to cover more area



Setup at USC

- Hawaii HDSoC plans on hold
- Use (slightly modified) HELIX carrier/preamps → $6\times6\ mm^2$ SiPMs (IU)
- Tentative readout chain: Couple to PSI – DRS4 or similar ($ps$ resolution)
- For teststand use evaluation electronics on hand

# Year 2 Activities and money matrix

- Refinement of MuID Algorithm
  - Include in fast simulations, physics impact
- Further study of KLM response to hadrons
  - Energy resolution, PID

- Clustering & MuID, track matching
- SiPM carrier/preamp assembled at IU

- Bench test HELIX and simple readout
  ➔feed back into simulations

- Readout chain test at Duke

- Optimization of buildable configurations

- Prioritize engineering/hardware in the budget

| | |
|---|---|
| UG students, USC | $\$12.5k$ |
| Postdoc (50%), Duke | $\$59.7k$ |
| UG students, Duke | $\$12.5k$ |
| Test Bench: EE support, IU | $\$16k$ |
| SiPMs, LVUnivt, Cables and Parts, USC | $\$15.6k$ |
| Travel for Meetings USC, Duke | $\$5k$ |
| Travel to U.S., RUAS | $\$9.7k$ |
| Laptop RUAS | $\$2k$ |
| **Total** | $\mathbf{\$133.0k}$ |

# Milestones Year 2

- Detailed KLM simulation, integration in
  - MuID algorithm
  - Hadronic energy resolution, $K_L$ PID

- Timing resolutions for select scintillator materials with off the shell electronics
- SiPM readout board assembly and commissioning

- First readout chain implementation

# Year 3 Activities

- Full simulation of final configuration
- Compare single/two strip in simulation
- Integrating in (final?) magnet return yoke
- Position resolution determined in test bench
  - Implement in simulations if better than 30mm
- PID performance from full simulations
- Optimization of readout chain
- Beam test to evaluate hadronic response

- Milestones
  - Quantified detector performance for muons & hadrons in simulation
  - Position resolution from test stand with HELIX electronics and simple digitizer
  - SiPM carrier/preamp assemblies
  - Optimized readout chain (HDSoC still on the table maybe for year 4)
  - Timing and position of optimized readout

# Backup

# Scintillator Tests at the University of South Carolina

**Objective:** To measure timing and position resolution of scintillator bars with design length, width, and thickness; and with SiPM readout on both ends.

Measurements will provide information about:

- The best scintillation material (fast response vs attenuation length) for various-length KLM bars
- Timing resolution with an initial SiPM readout
  - Can we reach the desired timing resolution to measure hadron momentum via time of flight and what minimum SiPM coverage is needed?
  - Do we need wave-form analysis electronics?
- Position resolution - can we use only one plane of scintillators per layer - cost and space budget

# Scintillators Acquired in FY23: side area of 1cm x 3cm

| Material | Rise Time (ns) | Decay Time (ns) | Photons/1MeV $e^-$ | Attenuation Length (cm) | Wavelength of Max. Emission (nm) | Scintillator Length (cm) |
|---|---|---|---|---|---|---|
| EJ-200 | 0.9 | 2.1 | 10,000 | 380 | 425 | 150, 250 |
| EJ-204 | 0.7 | 1.8 | 10,400 | 160 | 408 | 150 |
| EJ-208 | 1.0 | 3.3 | 9,200 | 400 | 435 | 150, 250 |

KLM Scintillator Bars Design (2023): side area of 0.75cm x 3 cm; Variable Length: 120 cm — <300 cm

# SiPM Options (FY24)

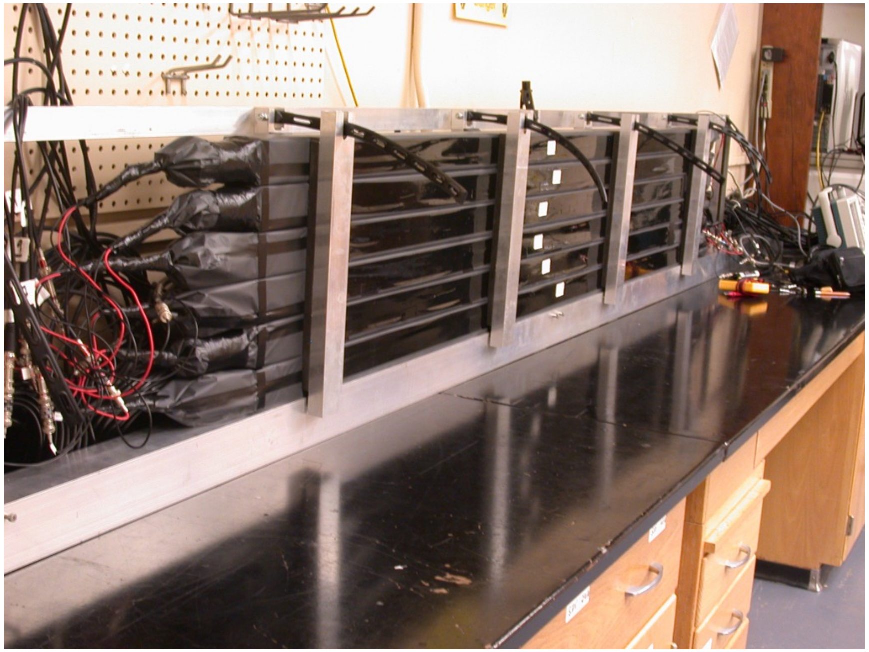
ends on the amount of light collected by the photocathode area of the photomultiplier. Ideally, we want to collect all the light at each of

e area SiPMs Hamamatsu offers are 0.6x0.6 $cm^2$.

| SiPM | Peak Sensitivity Wavelength (nm) | PDE at PSW | Gain | Recommended Operating Voltage (V) |
|---|---|---|---|---|
| S14160-6050HS | 450 | 50% | $2.5x10^6$ | 38+2.7 |
| S13360-6050VE | 450 | 40% | $1.7x10^6$ | 53+3 |

S14160-6050HS is a preferred choice due to its higher PDE and lower operating voltage

# Scintillator Tests at USC: Infrastructure



Scintillation bars for the CLAS12 FTOF detector under cosmic ray tests at USC

R. Gothe and E. Phelps, private communication.

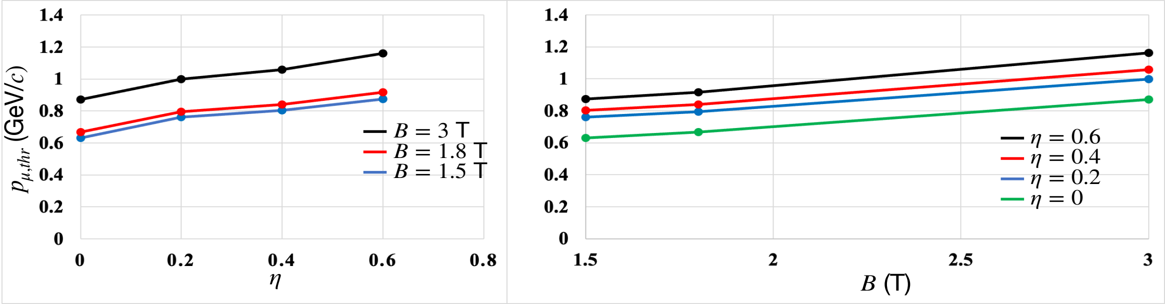
A state-of-the-art laboratory has been fully equipped to mount and test more than 500 large scintillators for the CLAS12 and MUSE projects.

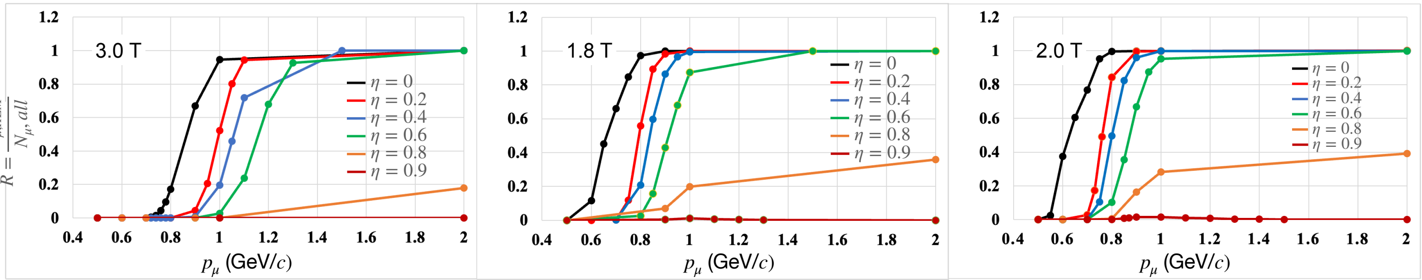
Scintillators are wrapped in Aluminized Mylar; Light tight DuPont Tedlar encases the entire counter.

Electronics:

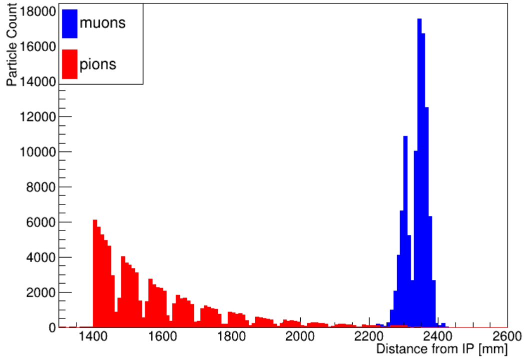
- Leading-edge discriminators: LeCroy 623B
- TDC (25 ps): CAEN V1290N
- QDC for time-walk correction: CAEN V792N

# Simulations, Cont



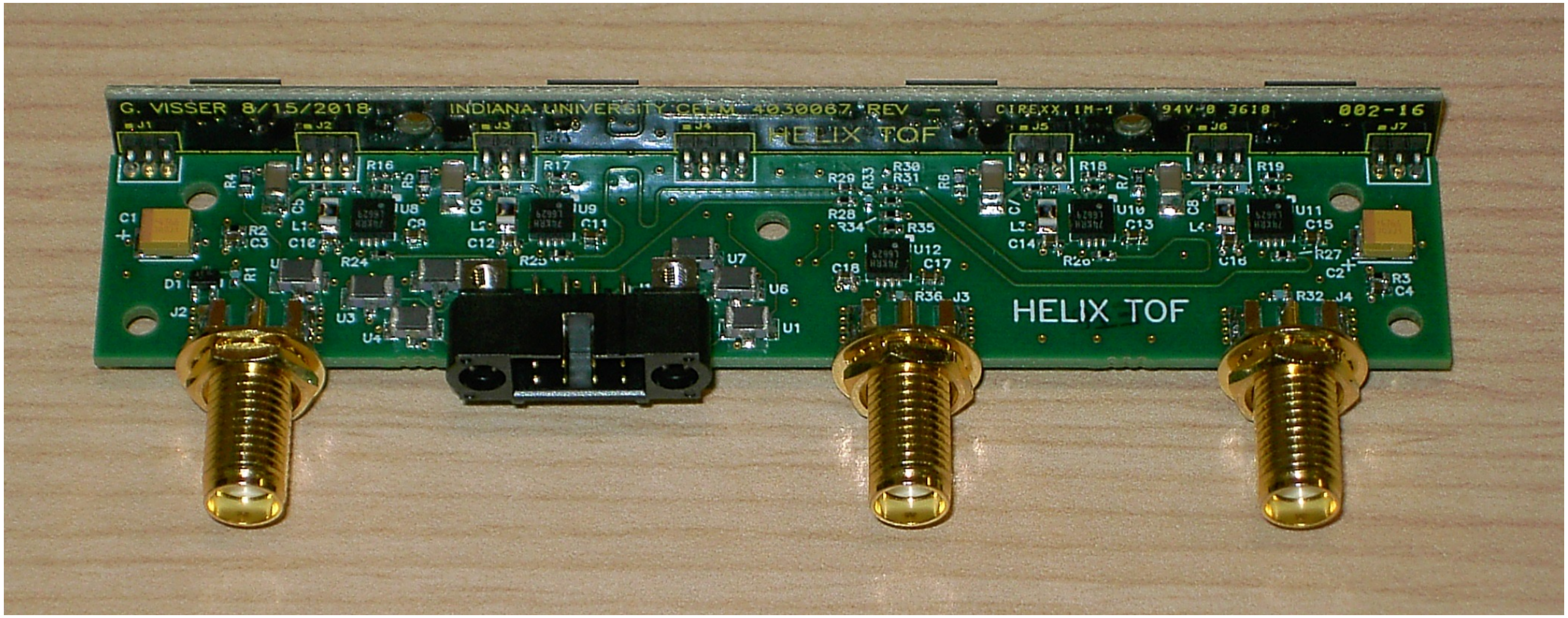




- Minimum Muon momentum for CORE configuration
  - 600 MeV is reached for lower B field central




- Muon vs pion response from DD4HEP simulation

- This is also consistent with extrapolations from state-of-the art measurements [6] (20 ps resolution for BC-422 at 10cm) and adjusting for $\tau_R, \tau_D$ and attenuation length (Given that he timing resolution is $\propto \sqrt{(\tau_R \cdot \tau_D)/N_\gamma}$, where $\tau_R, \tau_D$ are the rise and decay times of the scintillator)



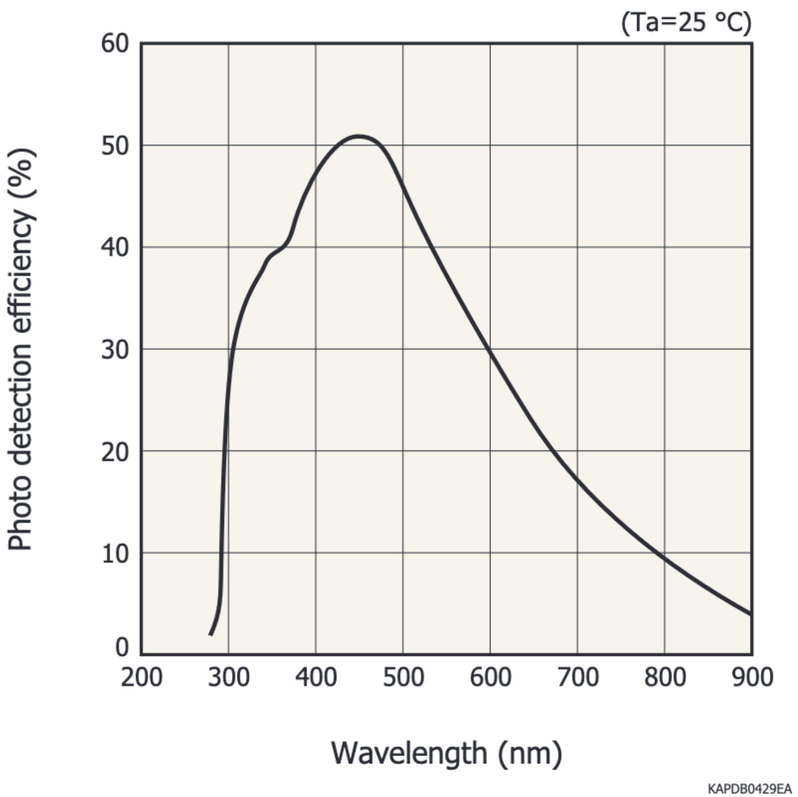
## Physical Constants

| Constant | BC-418 | BC-420 | BC-422 |
|---|---|---|---|
| Light Output, % Anthracene | 67 | 64 | 55 |
| Rise Time, ns | 0.5 | 0.5 | 0.35 |
| Decay Time, ns | 1.4 | 1.5 | 1.6 |
| Pulse Width, FWHM, ns | 1.2 | 1.3 | 1.3 |
| Light Attenuation Length, cm* | NA** | 140 | NA** |
| Wavelength of Max. Emission, nm | 391 | 391 | 370 |
| No. of H Atoms per $cm^3$, ($x10^{22}$) | 5.21 | 5.21 | 5.19 |
| No. of C Atoms per $cm^3$, ($x10^{22}$) | 4.74 | 4.74 | 4.71 |
| Ratio H:C Atoms | 1.100 | 1.100 | 1.102 |
| No. of Electrons per $cm^3$, ($x10^{23}$) | 3.37 | 3.37 | 3.34 |
| Principal uses | ultra-fast timimg | ultra-fast timimg | ultra-fast timimg |

* The typical 1/e attenuation length of a 1 x 20 x 200 cm cast sheet with edges polished as measured with a bialkali photomultiplier tube coupled to one end

** Scintillator recommended for use in small sizes; therefore, the 1/e attenuation length values are not applicable

# S14160/S14161 series




Photon detection efficiency does not include crosstalk and afterpulses.

## S13360-2050VE/-3050VE/-6050VE

**Photon detection efficiency vs. wavelength (typical example)**