“KLM” Subdetector Concept for the EIC: Muon ID and Neutral Hadrons

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2nd Detector at IP8 Workshop
CFNS, 6-8 December, 2022

Aspects of Muon and Neutral Hadron Detection/ID at the EIC

➢ Muon Detection is an essential capability of collider detectors

- In particular for the EIC, muons play a crucial role in:
  - Diffractive J/ψ
  - access to gluon TM Ds
  - TCS, DDVCS and much more.
- Excellent muon ID will be complementary to capabilities at the ePIC detector

➢ Neutral hadron detection also an important collider detector capability

- Jet physics: --- Jet reconstruction essential for a large part of the EIC physics program
  - Improved resolution for physics extraction (using veto or via reconstruction)
  - measurement of neutral hadron e.g., K_L momentum
- Neutron detection – as produced in jets or otherwise

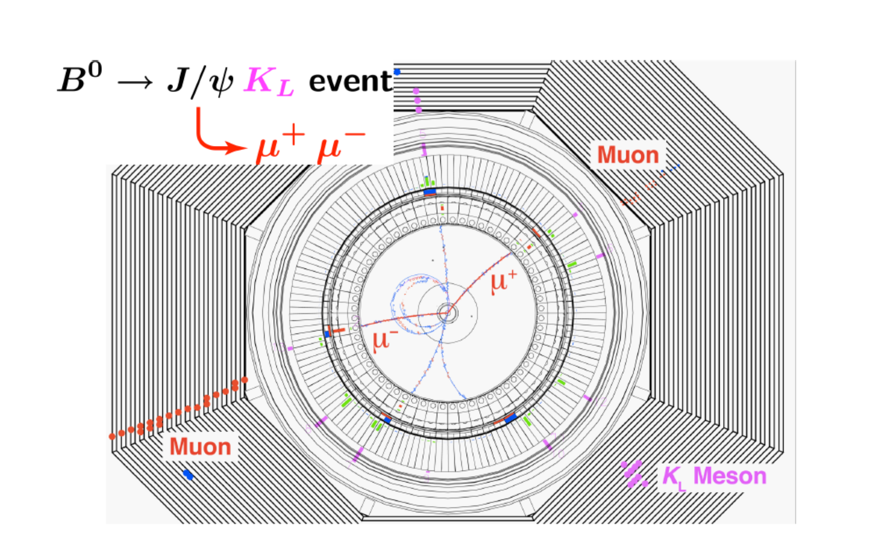
➢ Physics reach from upgraded or complementary detector capabilities

- Transverse and/or longitudinal readout pixelization of detector components
- Use of machine learning and other advanced analysis techniques

A KLM-Like Detector: Muon ID and Neutral Hadron Detection

Prologue / overview

- Idea originates from Belle/Belle II KLM (K_L and Muon) subdetector and its various upgrades.
- In this scheme, Muon ID capabilities (EIC priority) go hand-in-hand with good K_L / neutrals detection/ID => a combined optimization/discussion.
- Note: Belle implemented KLM is not a proper EM or Hadron calorimeter (generally so far not used as such even in a reduced capacity at Belle)

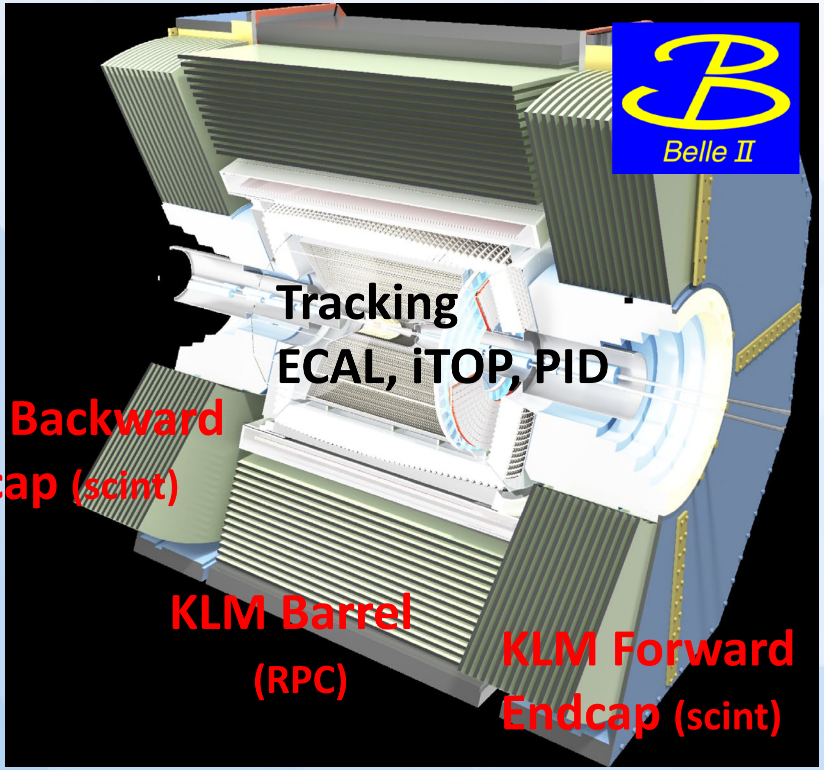


Belle Detector

- KLM (barrel + electron endcap) suggested in EIC EOI #26; later incorporated into the EIC CORE proposal ... efforts now have wider application in developing detector #2.
- An EIC KLM R&D Proposal was submitted to the EIC Generic R&D program (and initially funded) to address issues of further development of the KLM concept and optimization for the EIC

KLM @ Belle II: a Useful Starting Point

KEK: e^+e^- collider "B-factory" (Υ(4S)=10.58 GeV)



- The KLM subsystem is an important part of Belle II; it presents as useful starting point for EIC (**EOI #26, CORE)**
- Active "2D readout in 1.5T solenoid magnet return steel
- Relatively inexpensive , simple robust design/operation

Belle II and Prior Design Performance Goals:

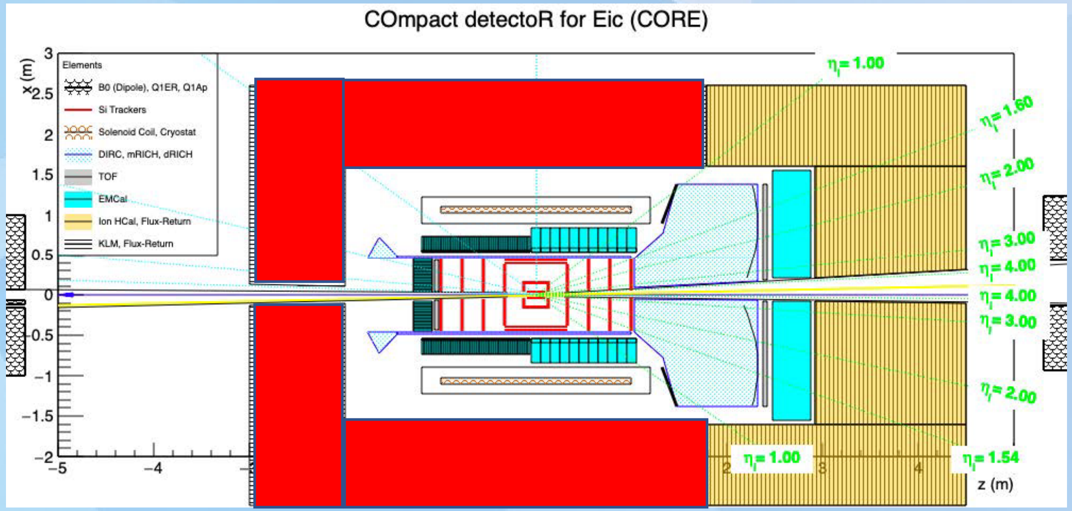
- ID muons and K_L mesons w/ high efficiency & purity
  - for muons above ~ 0.6 GeV momenta
  - good angular resolution (~ 2 deg) for the K_L's

- Currently under Belle II development are optimization of muon efficiency/fake rates at lower momenta; K-long efficiency and ID improvements in software and potentially FW/ML
- **Can a K_L momentum via TOF be effectively included in an (EOI) anticipated upgrade to all scintillator sensors with improved readout?**

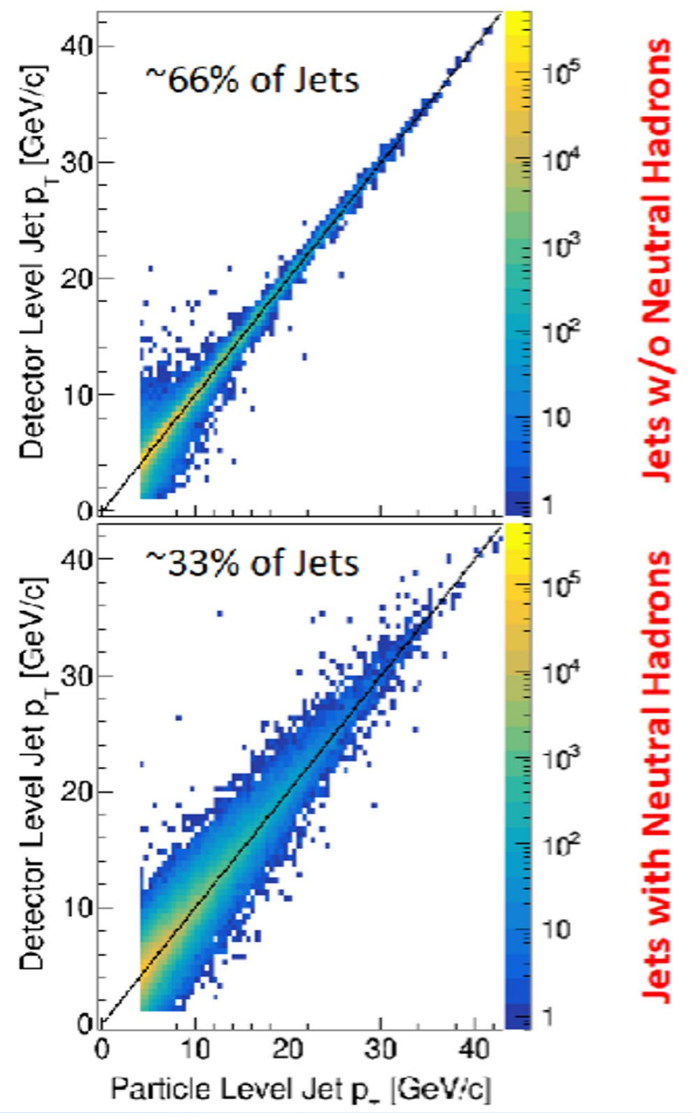
Belle octagonal Iron yoke structures:

- 14 layers of ~ 47 mm thick steel plates~ 40 mm thick air slots => readout 15 barrel, 14 Forward , 12 Back instrumented

Flashback March 2021: Idea of a KLM (K_L & Muon subdetector) at EIC

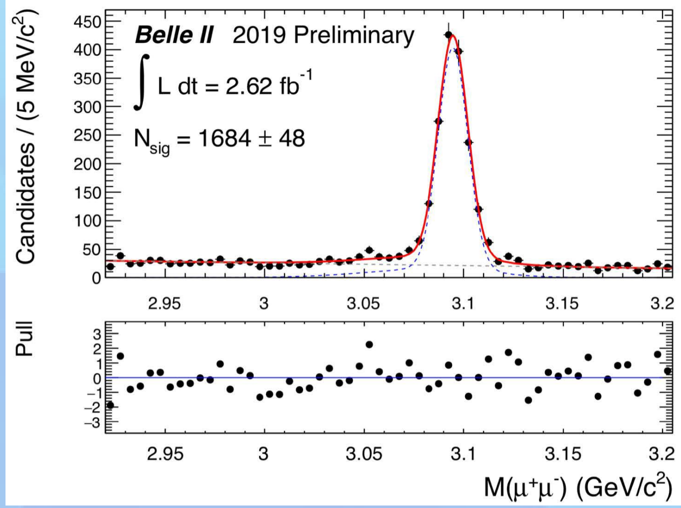


- Identify K_L and other neutral particles in jets … correct or veto



B.S. Page et al., arXiv.1911.00657 "Jet Physics at a Future EIC"

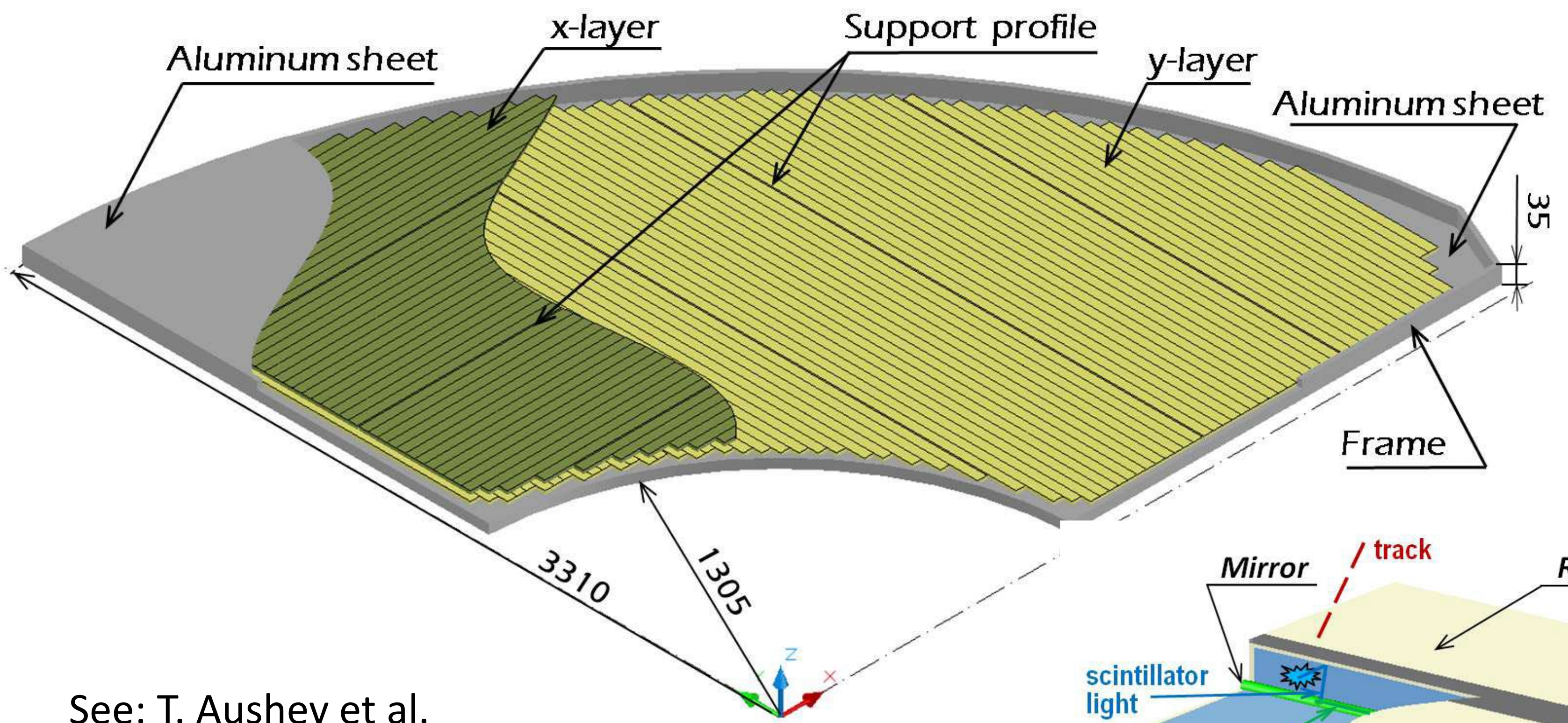
- High efficiency and high purity μ detection and ID:
  - e.g., for di-lepton production (J/ψ) and time-like Compton scattering processes and other.



J/ψ → $\mu^+\mu^-$ reconstruction with early running Belle II data

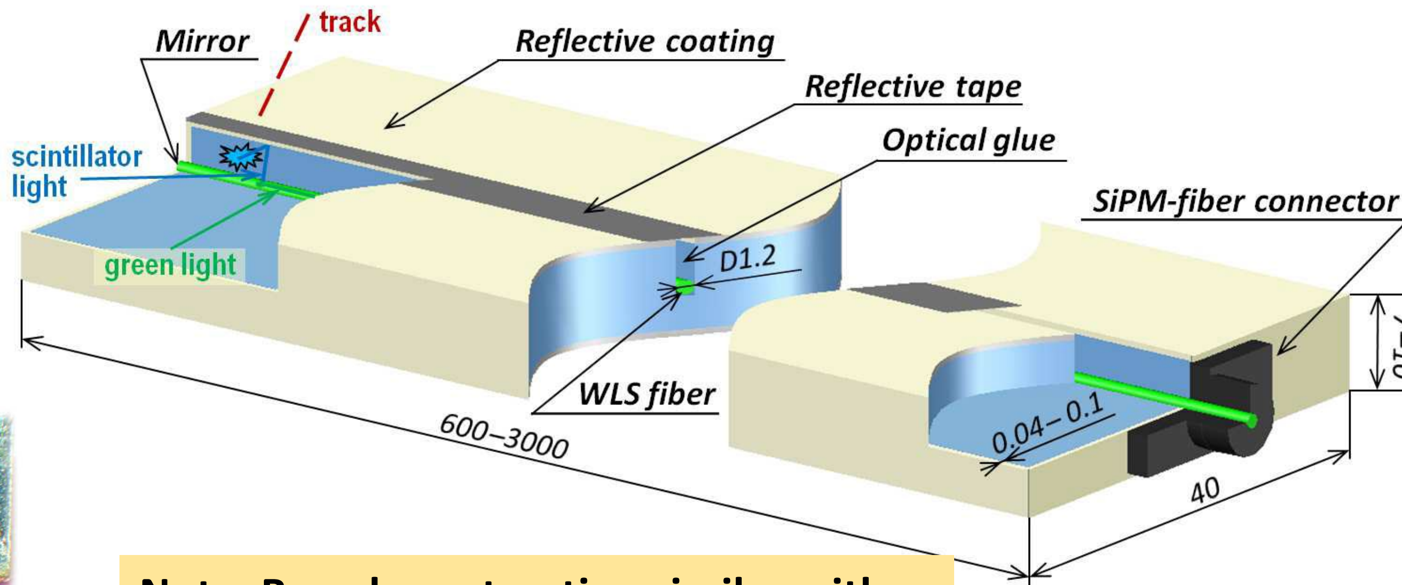
- Provide additional detector response and coverage for verification or veto.

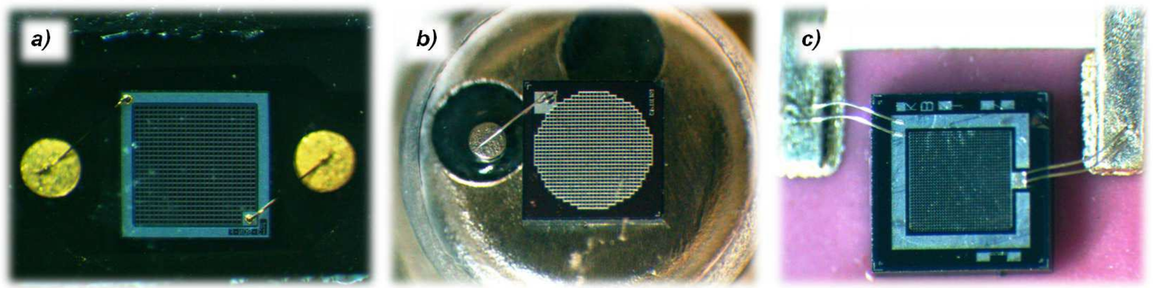
Endcap layers upgraded to scintillator at start of Belle II



- Scintillator strips ~ 0.7x4 cm^2 machined w/ cut)
- Single strip readout w/ SiPM
- FEE readout has pulse shape characterization capabilities … FW implementation (w/ barrel) under development

See: T. Aushev et al.
arXiv:1406.3267v3 (2015) for details

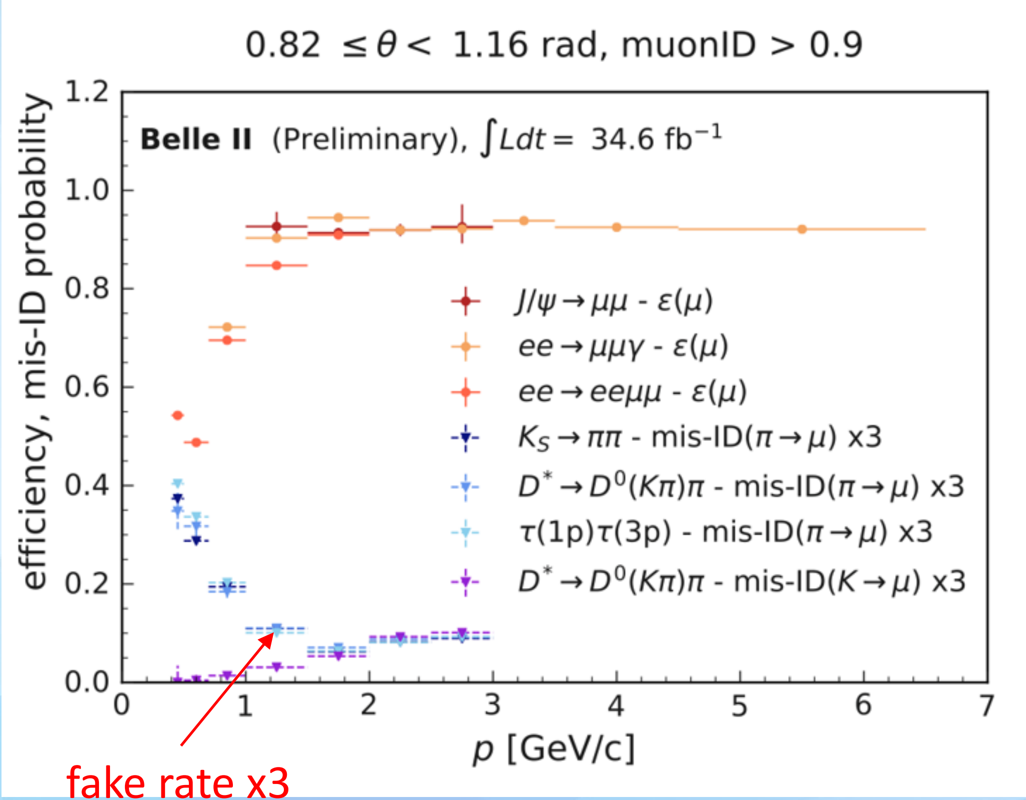




Note: Barrel construction similar with crossed scintillator strips – first 2 layers

Electron-Muon Identification and Analysis Techniques at Belle II

BELLE2-NOTE-PL-2020-027.pdf

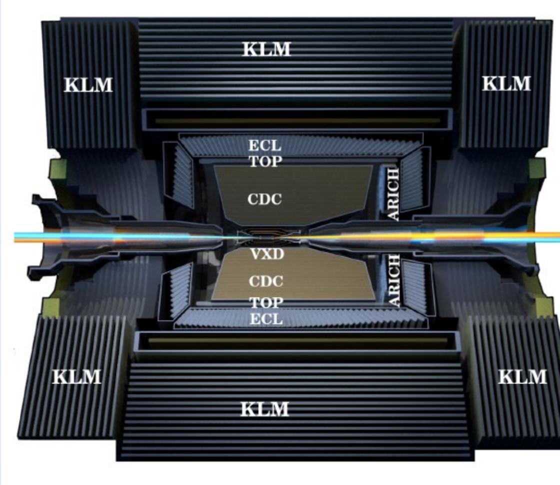


fake rate x3

Particle ID: CDC, TOP, ARICH, ECL (CsI), KLM

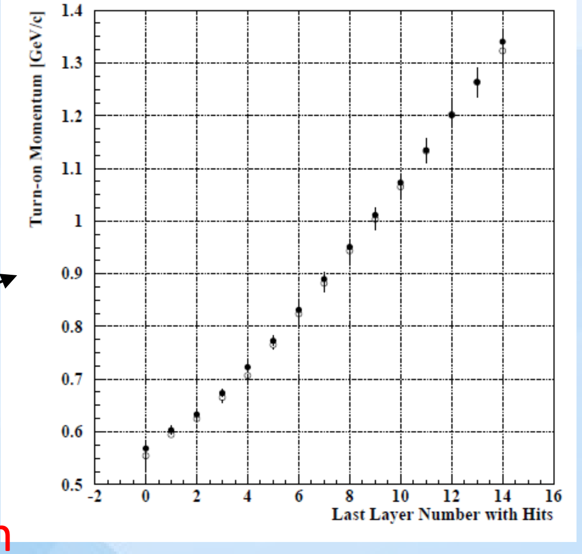
- Independently determine likelihood for each charged particle hypothesis
- construct a combined likelihood ratio.

$$\ell\mathrm{ID} = \frac{\mathcal{L}_\ell}{\mathcal{L}_e + \mathcal{L}_\mu + \mathcal{L}_\pi + \mathcal{L}_K + \mathcal{L}_p}$$



- reconstruct charged tracking (SVD + CDC)
- select suitable candidates -> extrapolate tracks to outer det.
- match to KLM "track" hit pattern
- Characterize range and track fit (layer turn on, etc.) => muon likelihood parameters
- optimization analysis (digital/logic)

Turn on momentum vs. KLM layer (data and MC)



A. Abashian *et al*, NIM ***A491***, 69 (2002)

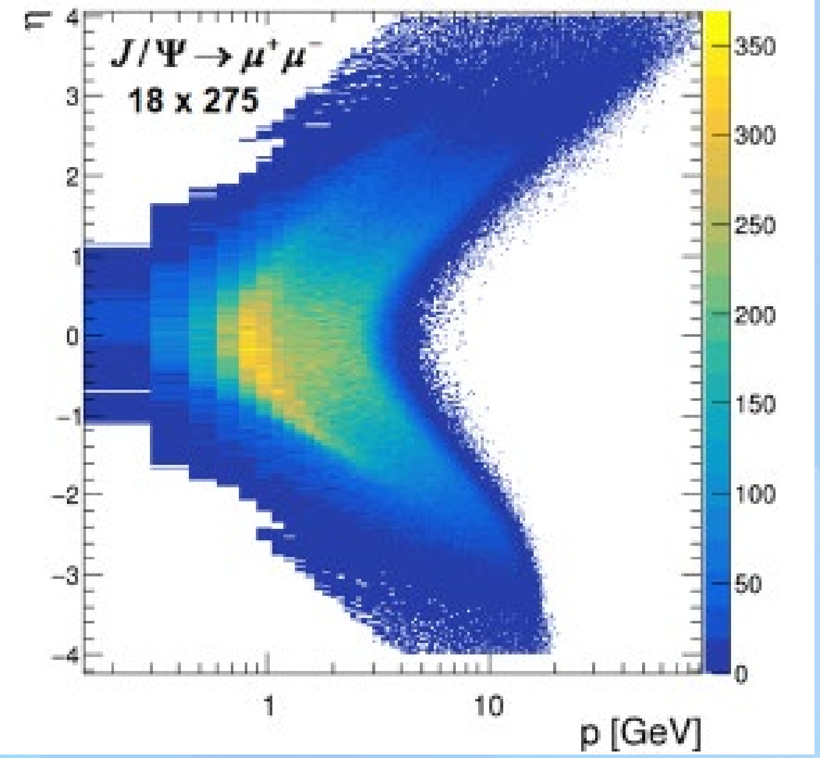
- Other techniques for analyzing & combining subdetector data, have been developed for Belle II but not covered in 2020 BELLE2-NOTE

Lower momentum μ w/ tracking + ECL (Wave Form) info and BDT analysis (Bryan Fulsom, EIC Muon Detection and Quarkonium Reconstruction Workshop, 2022).

Eta Dependence of Muon Momenta for Different Channels at the EIC

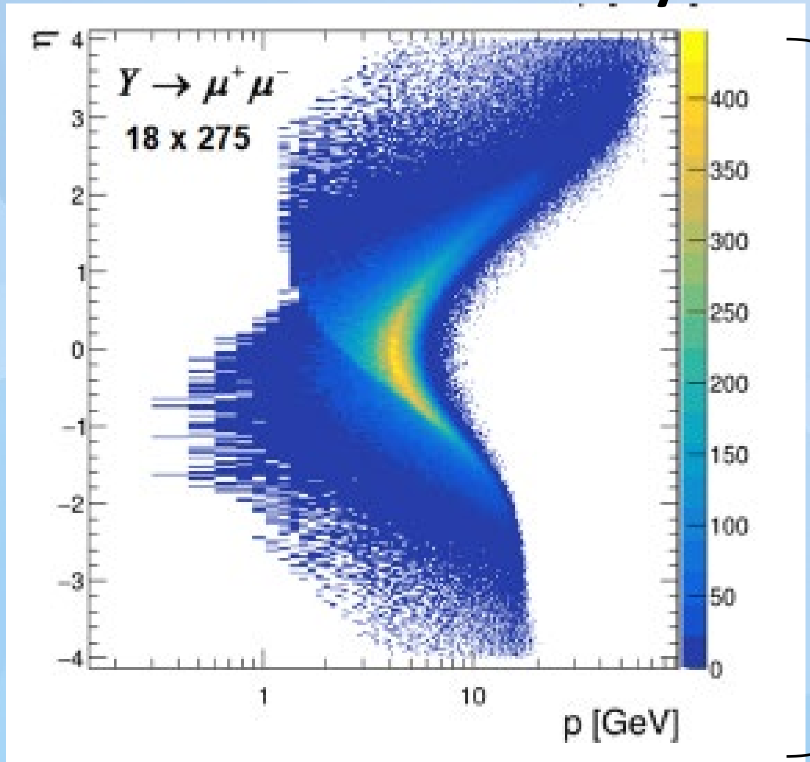
Simulations from arXiv2209.00494 (CORE)

Muons from J/ψ decay



- Moderately strong η vs. p dependence
- Lowest momentum Muons in Barrel region around η = 0
- Momenta from J/ψ less than those from Y decay

Muons from Y decay



J/ψ:

- Barrel: clean muon identification would be good to have below 1 GeV/c (especially near η=0) and up to ~ 4 GeV/c
- Endcaps: clean muon ID desirable over the range of 1 – 10 GeV/c

Y:

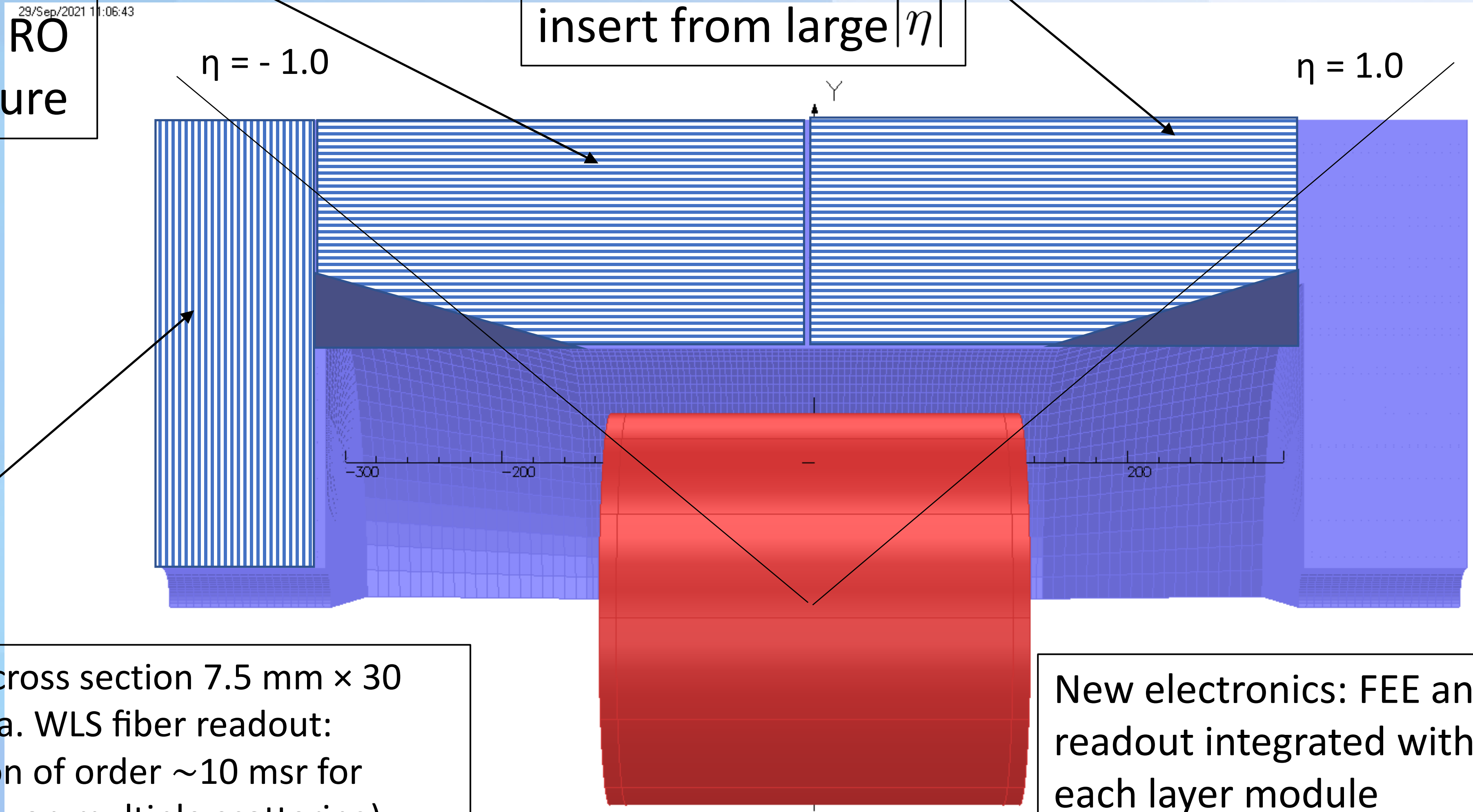
- Barrel: clean muon identification from 1.5 – 10 GeV/c is needed
- Endcaps: clean muon identification needed from 3 – 20 GeV/c
- in both cases, while muons complement the electron decay channels, they can be more rebust

EIC 3T Solenoid "KLM" Implementation using a Symmetric Model

Barrel e-side:
octant structure
w/ rectangular RO
modular structure

Barrel h-side:
octant structure;
insert from large $|\eta|$

P. Brindza, magnet calcs.
arXiv2209.00494 CORE



Endcap e-side:
quadrant RO
layers; endcap
vertically split in
halves for access
with radial insert

Strip geometry: cross section 7.5 mm × 30 mm w/ 1 mm dia. WLS fiber readout: angular resolution of order ~10 msr for inner barrel (~ muon multiple scattering)

New electronics: FEE and readout integrated with each layer module

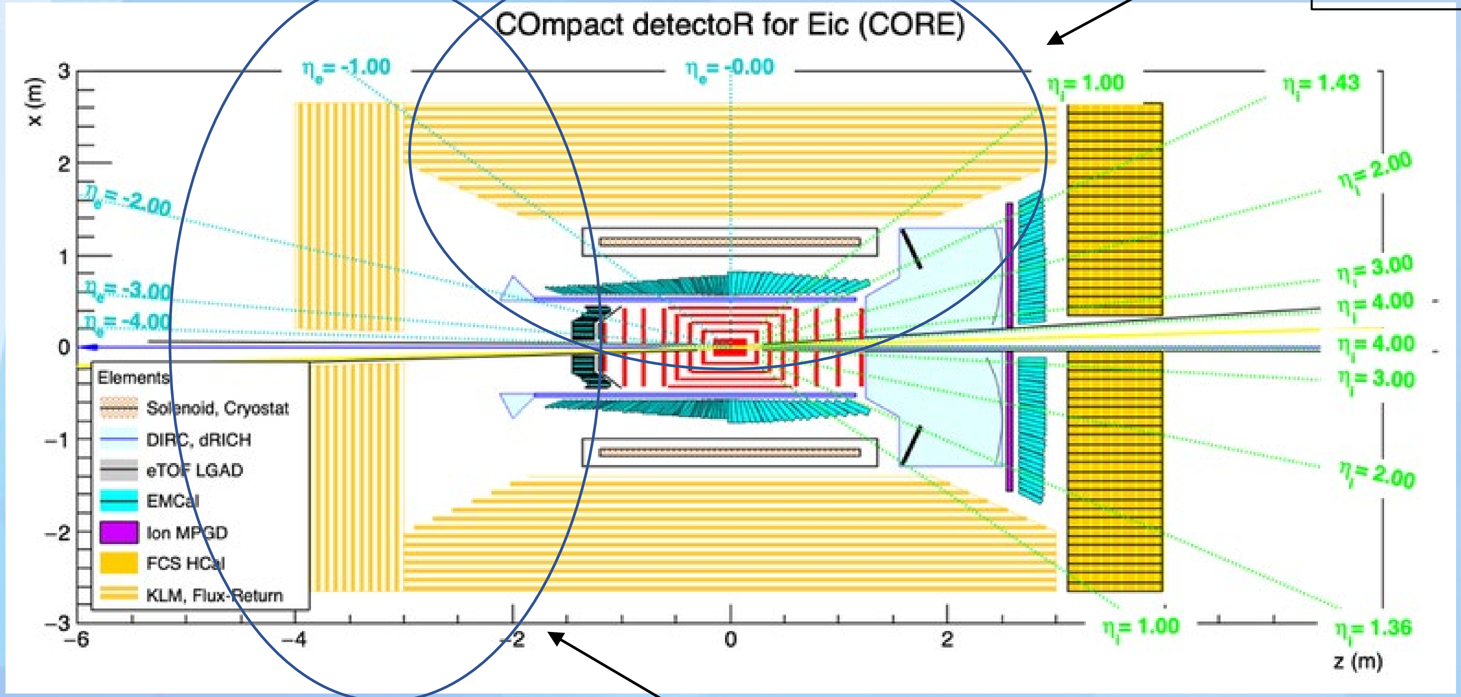
N.B.: maximum scintillator readout strip length < ~ 3m in all layers

KLM: Muon Threshold, ID and Purity Issues vs. Detector η

- **Thresholds (and perhaps purity) will vary across Barrel vs. Endcap regions => physics impact?**

KLM Barrel:

- 14 active layers (current)
- Material burden: inner dets + coils/cryostat



Inner Detector components

- Tracking: --
- DIRC: --
- $PbWO_{4}$: modules 20 cm, density 8.3
- W-shashlik: (modules 10 cm, density 17.2?)

Initial Coil and cryostat estimates & issues

- Inner vacuum vessel ~ 4 cm Al, density 2.5
- Inner radiation shield ~ 2 mm Cu, density 9
- **Coil 6 cm - a 5:1 mix of Cu and NbTi (i.e., with Nb =Ti, a 10:1:1 mix of Cu, Nb, and Ti)**
- Coil support cylinder ~ 7 cm Al, density 2.5
- Outer radiation shield ~ 2 mm Cu, density
- Outer vacuum vessel Al ~ 10 cm Al, density 2.5

KLM Endcap::

- 12 active layers (current)
- Material burden: electron-side inner dets (significantly varying with location)

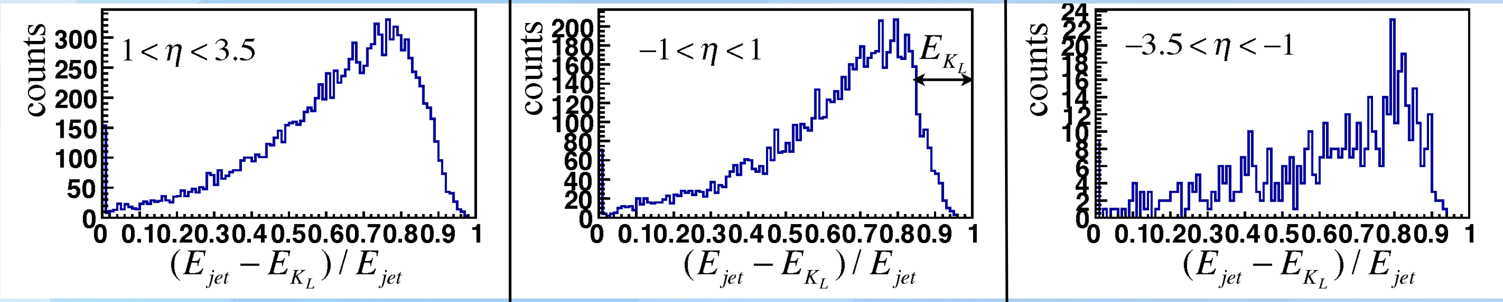
- **Less material burden may lower Muon KLM detection threshold, but may also attenuate less background and fake contributions? "curl up" threshold depends on field and KLM radial compactness**

Neutral Hadrons: K-long in jets and kinematics at EIC

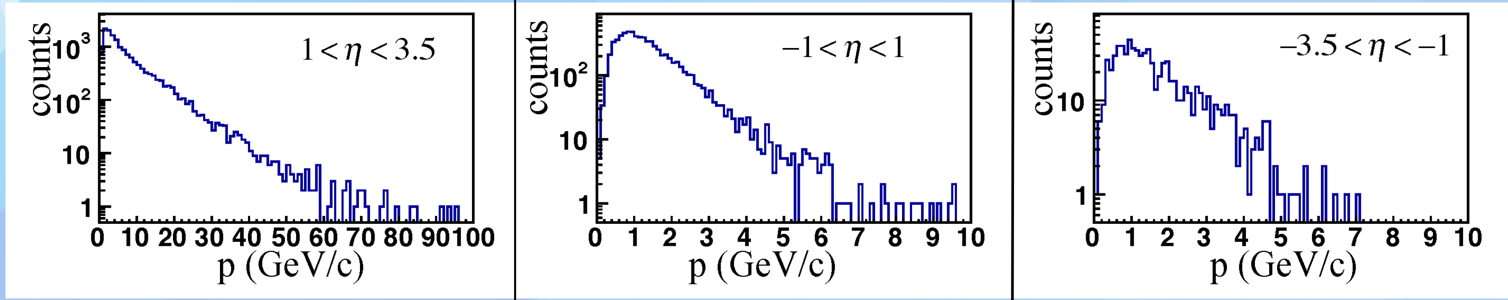
10GeV x 276 GEV

Pythia 8 generated events (1M) – from KLM EIC generic R&D proposal, M. Arratia et al., 2022

Energy fraction of total jet excluding K_L energy



K_L momentum in produced jets

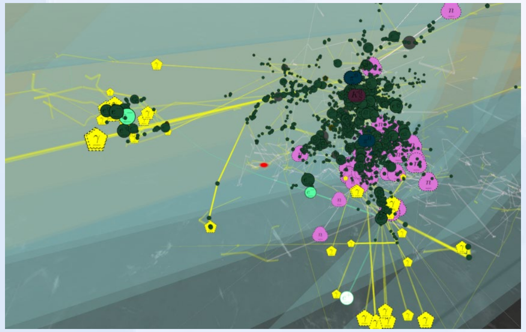


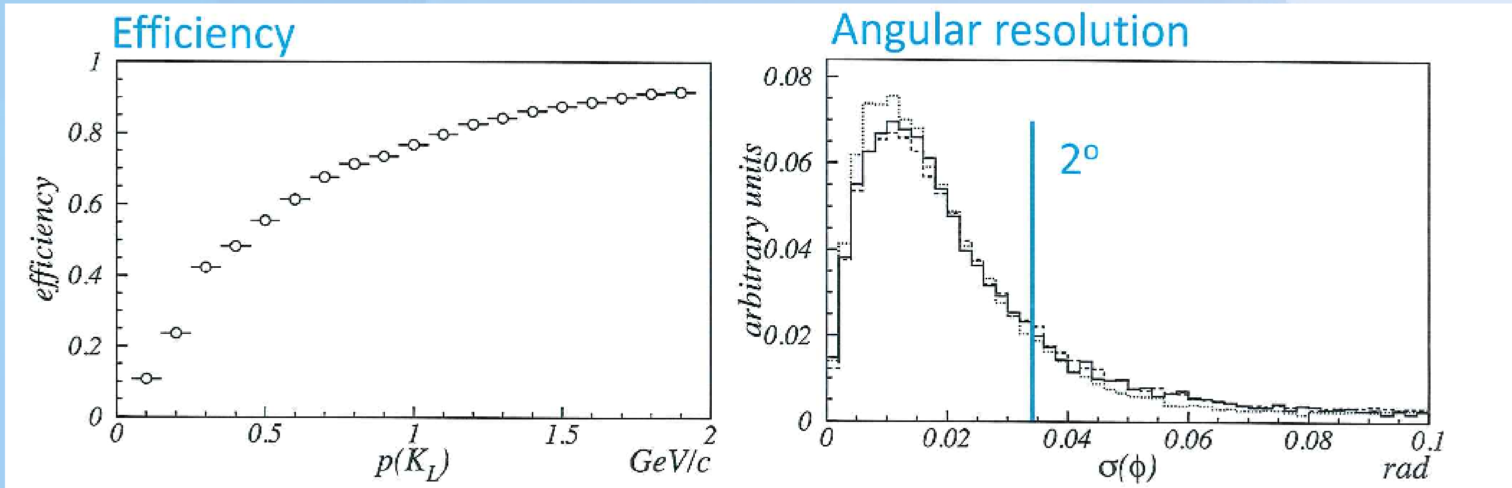
Hadron-side Endcap | Mid-rapidity Barrel | Electron-side Endcap

- ~ 10% of jets scattered into the barrel or the hadron endcap contain at least one K_L
- These kaons carry at least 10 –15% of the total jet energy (w/ wide variation of energy fraction)
- For barrel, detection of K_L with momenta up to ~ 3-4 GeV/c is needed (smaller in electron endcap); for hadron endcap, much broader range up to ~ 30 GeV/c required
- Note: The momentum ranges of interest for neutron are similar as for K_L for the two endcaps and the barrel region

Belle KLM performance: K-long detection and kinematics

- Belle II analyses and algo/FW implementation for K-long in progress; publlically available results results from Belle Data:



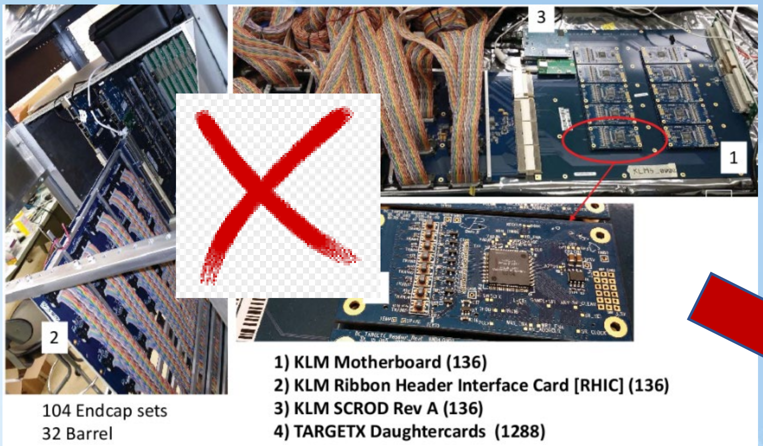


- Efficiency: fraction of reconstructed K-long clusters vs. K-long momentum in kinematically constrained decays … angular resolution from known K-long direction vs. measurement

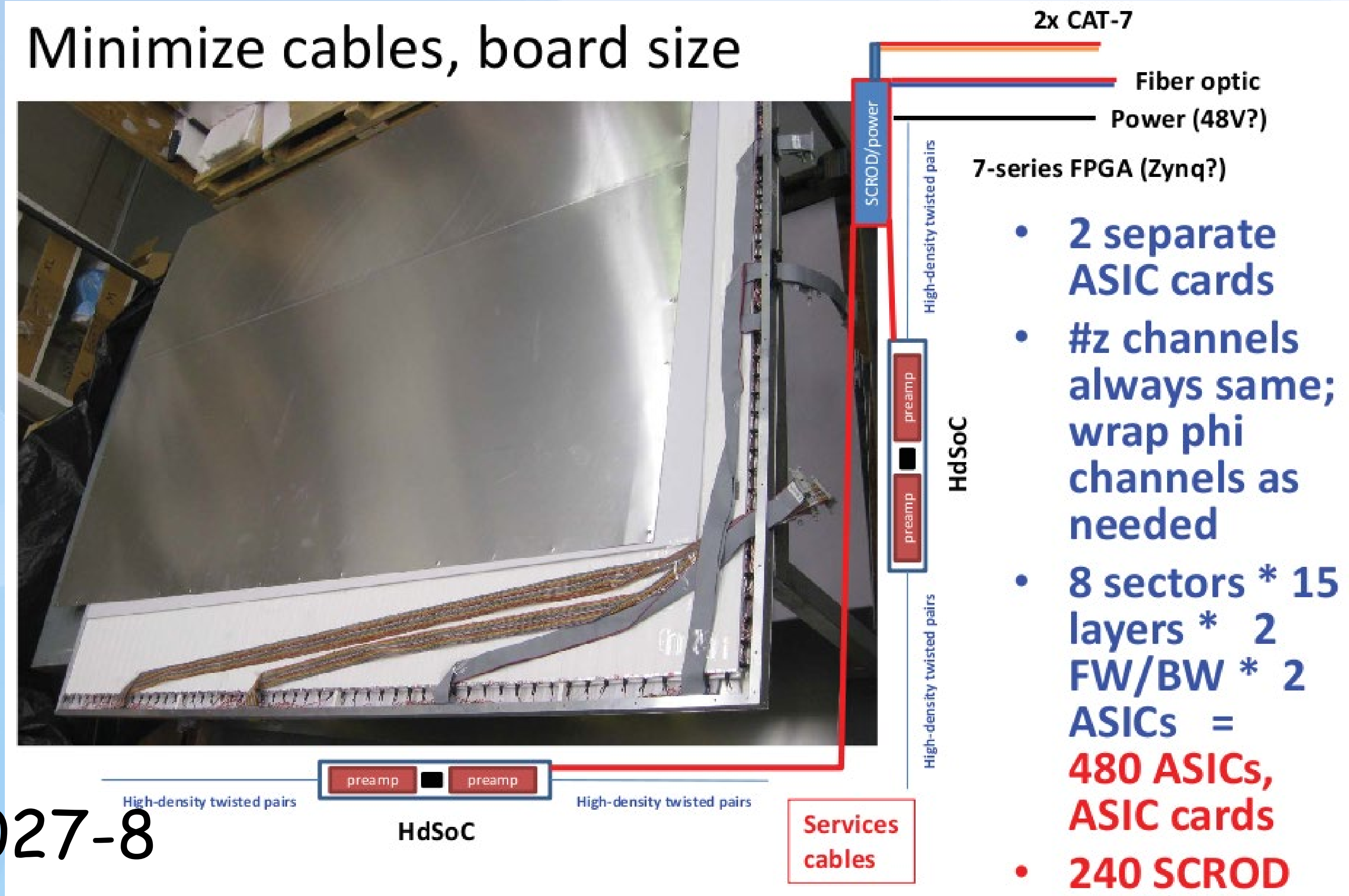
- Current Belle II efforts include: *using a trained BDT to distinguish K_L meson from background*; future use of FEE based signal shape characterization possible?

- As is the case for Muons, neutral/K_L response in an EIC KLM implementation could be studied and optimized in a suitable simulation environment.

Plans (EOI to Belle II): replace 13 remaining Barrel RPC layers



- ➢ Fabricate the new scintillator layers
- ➢ Redesign scintillator readout for all 15 layers

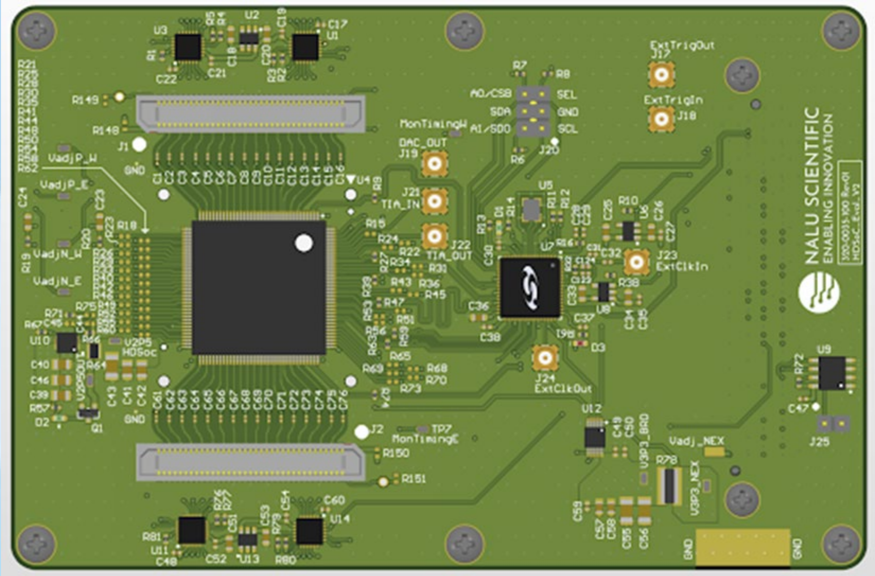


- ➢ Move digitizing front end electronics into detector panel
- ➢ Developments: embedded ASIC; compact SCROD; 64-chn readout; several different preamp options
- ➢ K_L time-of-flight possible?

Expected installation ~ 2027-8

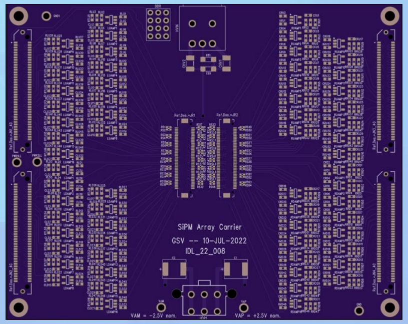
- ➢ ~ 26k channels: working on updating all readout electronics to state-of-art implementation

KLM Electronics Readout Upgrades: Belle II and EIC R&D



HDSoC board prototype

- Readout scheme: modest amplification and shaping is done with 32-channel amplifier ASICs, which then feed 64-channel transient waveform digitizer (HDSoC) ASICs.
- Individual hits from either one or two of these HDSoC ASICs per orthogonal coordinate, for both in a layer, and collected into a Readout Unit, known as a System Control and Read Out of Data (SCROD).

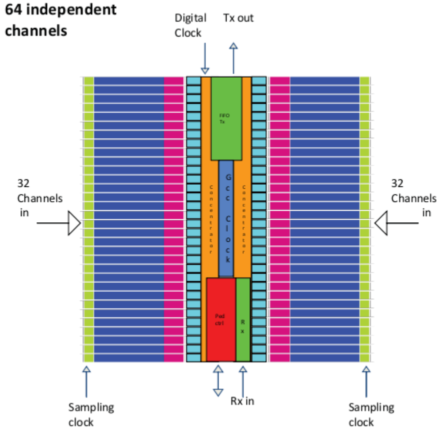


prototype carrier board for 64 SiPMs

TARGET ASIC upgrade

Nalu Scientific
Data Acquisition Systems

HdSoC Floorplan: 64 independent channels



Parameter	Specification
Channel no.	64
Sample rate	1-2 GSa/s
Bandwidth	1 GHz
No. bits	12
Supply Voltage	2.5V
Input noise	1mV
Gain stages	TBD -
Analog buffer length/channel	2048
Power/channel	20-40mW
Integration	SoC

- 4x integration
- Compact power/signal cabling to SCROD
- System on Chip (signal processing), reduce SCROD processing load
- "Data push" possible (reduces need for depth since don't wait for L1 trigger)
- Possibility to integrate amplification, Si-PM overbias adjustment
- Prototypes available early 2021

- HDSoC – High Density System on a Chip - -electronics are in development by the University of Hawaii in conjunction with Nalu Scientific
- HDSoC electronics will enable waveform sampling
- Digitization of SiPM signals allows one to manipulate and extract best possible timing and amplitude response

Generic R&D Proposal for "KLM" at the EIC (esp. 2nd Det) Objectives

EICGEBRandD 2022 ID 19

EIC KLM R&D Proposal

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(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.

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- **Demonstrate capability of the KLM detector concept for the EIC and provide cost-effective generic baseline detector design guide**
  - Provide **excellent muon identification in a compact design** (based on successive layers of scintillator-strip-absorber) .
  - Study **optimization of field, det radius and layer topology** for best muon efficiency vs. threshold and desired range.
- **For muon and neutral hadron (KL and neutron) identification:**
  - Extend concept for **hadron identification** /calorimetry beyond the state-of-the-art (Belle II), **including direct SiPM readout**
  - Use **pulse-shape analysis** based on recent advances in SiPMs and "Oscilloscope on a chip" readouts.
  - Use **timing resolution** for time-of flight info for hadron ID/ momentum (double-sided readout => a more compact design}?
- Can pulse shape, timing and longitudinal plus horizontal segmentation, be exploited in AI reconstruction for better muon ID and hadron ID/calorimetry?
- **Will a KLM double as a cost effective HCAL; also investigate a dedicated HCAL using KLM (longitudinal & transverse) readout principles .**

Summary and Future Directions

- Adding clean muon detection to anEIC 2nd detector has been identified as high interest by the community; it can extend the physics reach of the EIC.
- The KLM detector concept, based on readout layers of a scintillator-strip-absorber sandwich in the solenoid return steel, can provide clean muon identification in a cost effective and compact design.
- A KLM also includes neutral hadron (K_L and neutron) identification , whose capabilities can be optimized in conjunction with muon detection/ID.
- Separately, a KLM may double as a cost effective “thin” HCAL by using KLM principles (longitudinal/transverse readout granularity) and advanced analysis (AI) techniques.
- Investigations of muon detection and hadron/neutrals ID/calorimetry capabilities, beyond the state-of-the-art (Belle II), and matched to the needs of EIC physics are needed/planned to provide a cost-effective generic baseline detector design guide.

Thanks !

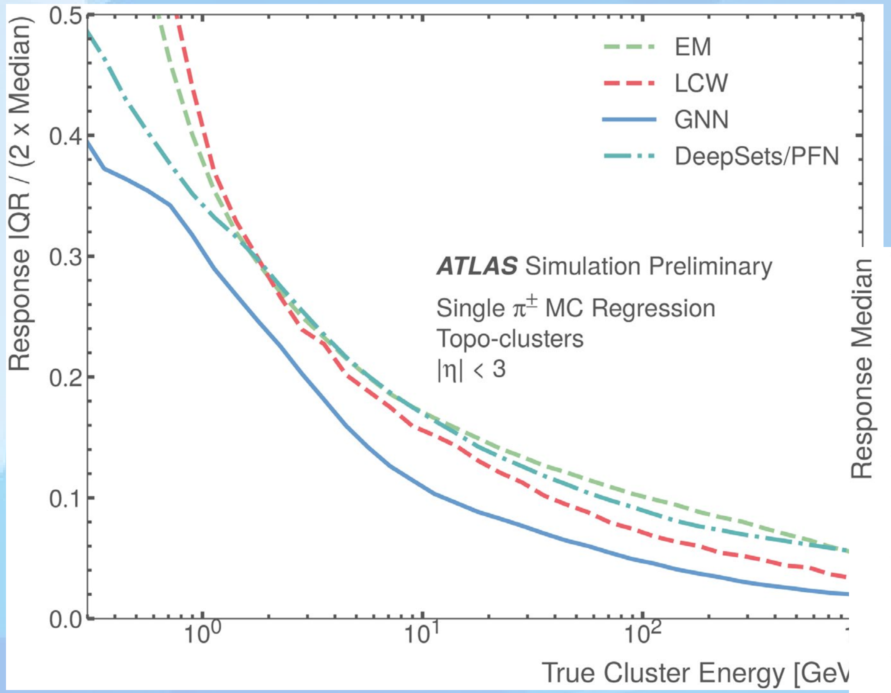
BACKUP SLIDES

KLM Concepts: Potential Advantages of HCAl with Granularity

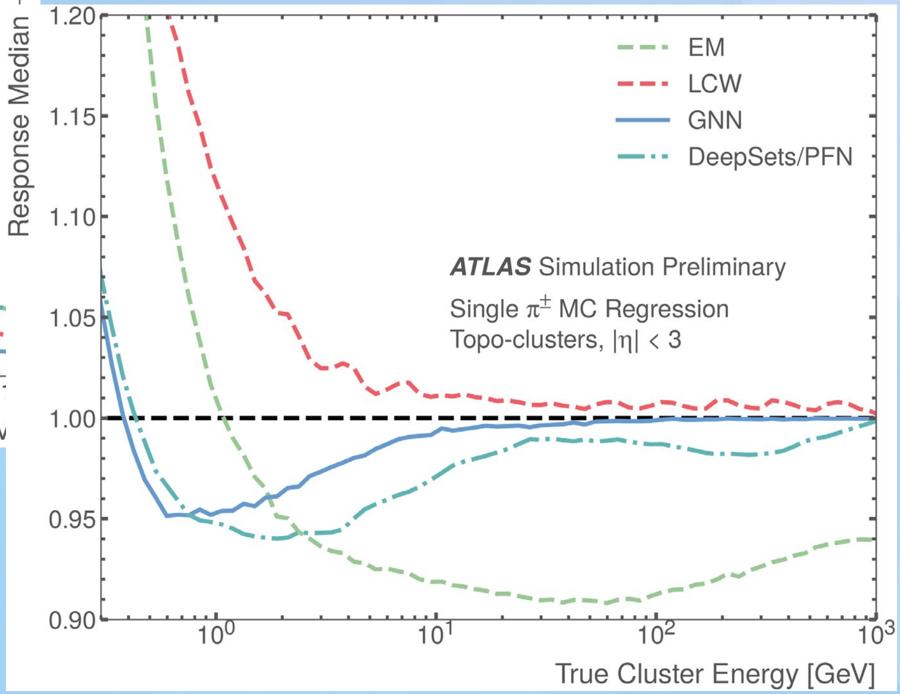
Deep Learning for Pion Identification and Energy Calibration with the ATLAS Detector

- suggests promising way to improving the energy resolution of a traditional HCAL design is by emphasizing its granularity, in particular the longitudinal one, and exploit with modern techniques

Relative resolution



Bias

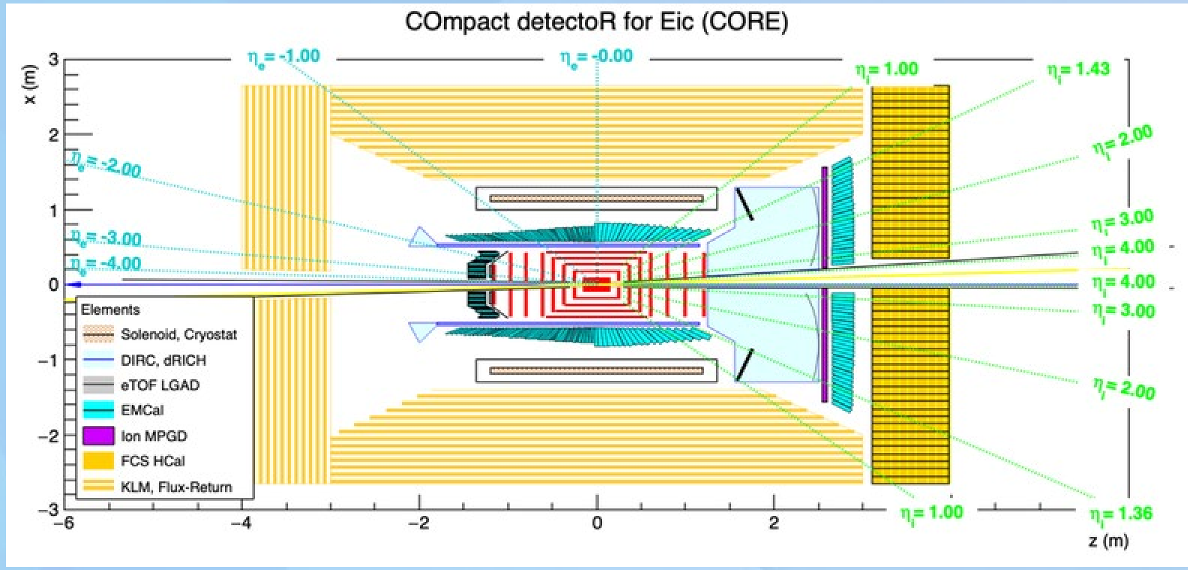


Various machine learning techniques for pion reconstruction using the ATLAS "Tile" calorimeter

- ATLAS study with ML gave improved energy resolution and reduced bias even in1–10 GeV range
- approach practical only in last decade w/ lowered cost and improvement of SiPM technology
- Can possibly exploit KLM transverse and longitudinal readout granularity for improved thin HCAL performance?

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PLOTS/JETM-2022-002/

KLM Subdetector Implementation at CORE (as in DPAP proposal)



- Instrument return steel of entire barrel and electron-side endcap
- Different than Belle geometry (more elongated/compact barrel; small-radius endcap encircling beam pipe)
- Shrink radial extent of the readout gaps from Belle for overall compactness
- Select insertion/readout gap of 21.5 mm interleaved w/ 55.5 mm steel plates (~72% steel in the return)

Endcap (electron side) nominal strip count:

- 12 readout layers
- 84 strips in each orthogonal plane per layer per octant
- lengths “x “ and “y” up to 2.4m
- Endcap total of ~ 8.1k strips.

Barrel (electron & ion sides) nominal strip count:

- 14 readout layers
- “ϕ” strips 36-64 (lengths 1.5-3m) per octant
- 48-98 “z” strips (lengths 1.2-2m) per octant
- full barrel total of ~ 30k strips

Belle design parameters adapted to CORE, chosen for “buildabilty” and not otherwise optimzed in proposal