"KLM" Subdetector Concept for the EIC and Muon ID

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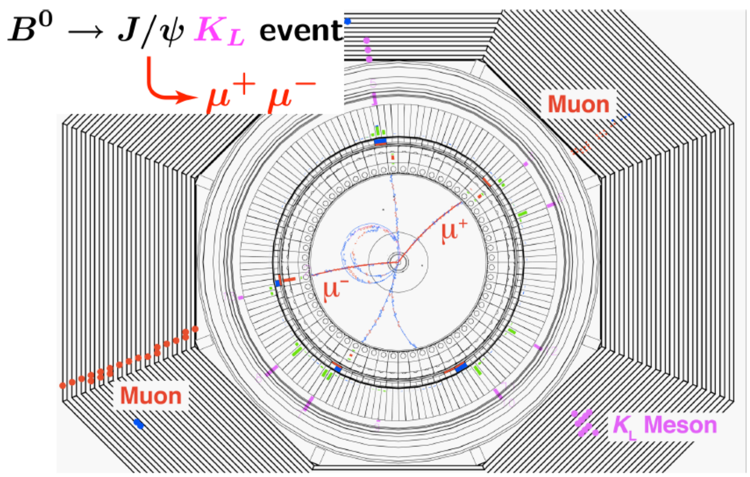
2^{nd} Detector W.G. / 14 Oct. 2022

Given Title: "Muon ID with a KLM like Detector" and Issues

Comments / prologue



Belle Detector

- 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 => consider a combined optimization/discussion.
- KLM (barrel and electron endcap) was incorporated into the EIC **CORE proposal** ... these efforts (and slides I will show) have wider application as we continue to develop ideas for detector #2.
- A "**EIC KLM R&D Proposal**" was submitted to the EIC Generic R&D program to address issues of further development of the KLM concept and optimization to EIC (funding TBD) ... will give/discuss objectives

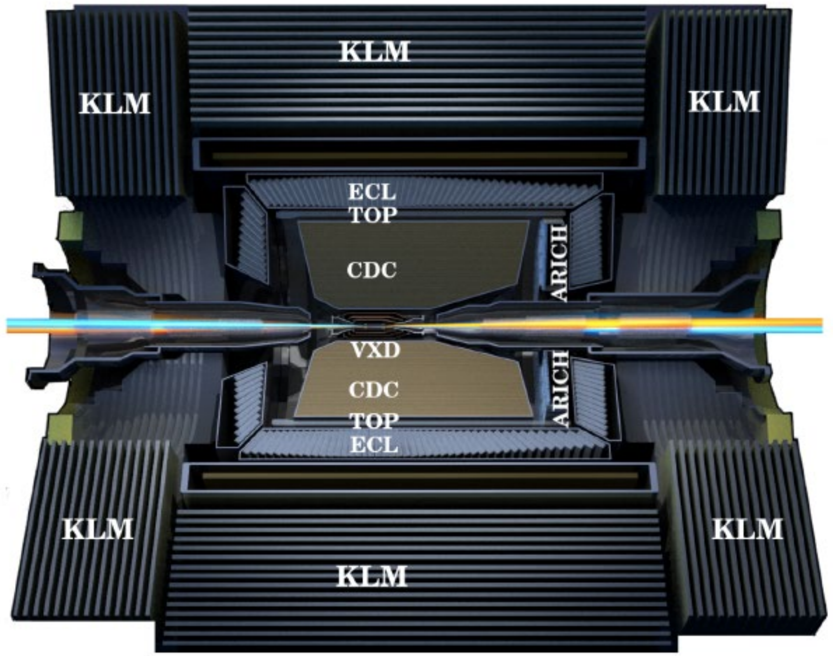
KLM @ Belle II: a Useful Starting Point

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

- The KLM subsystem is an important and successful part of the Belle II experiment; it presented a useful baseline/starting point for EIC application (**EIC EOI #26, CORE**)

Belle II and Prior Design Performance Requirements:

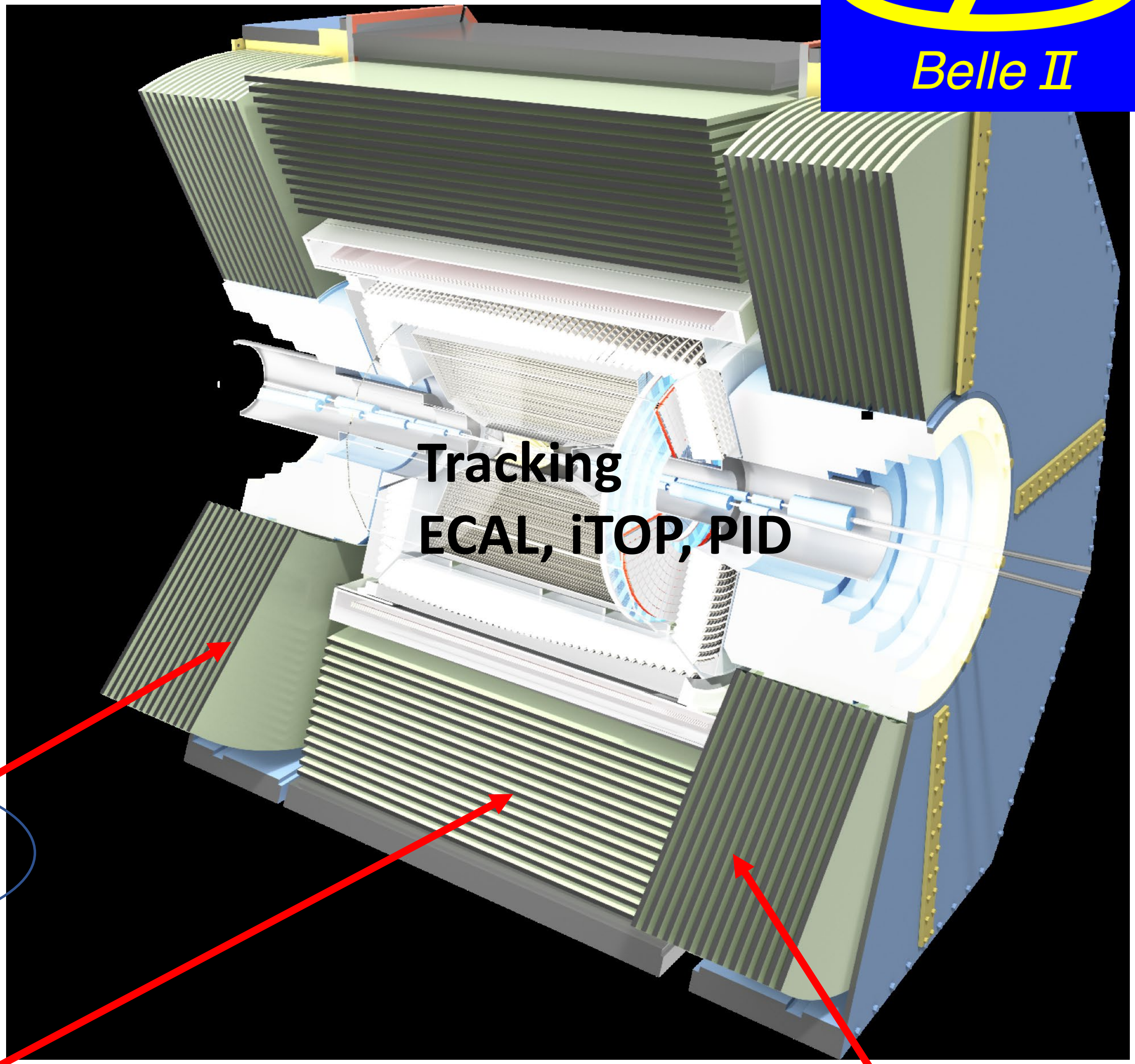
- Detect K_L mesons and muons
- Identify the muons and K_L mesons with high efficiency and purity
  - for muons above ~ 0.6 GeV momenta
  - good angular resolution (~ 2 deg) for the K_L's



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

Belle II KLM det. and upgrades at Super KEKB

- Active "2D" readout elements interleaved with 1.5 T solenoid magnet return steel
- <u>Optimized for μ and K_L detection and ID</u>
- Relatively inexpensive, technically simple construction, robust operation
- Not a full-fledged/proper EM or Hadron calorimeter (and generally not used as such)
- <u>Upgrade planned for Barrel w/ scint. layers along with readout/FEE update</u>

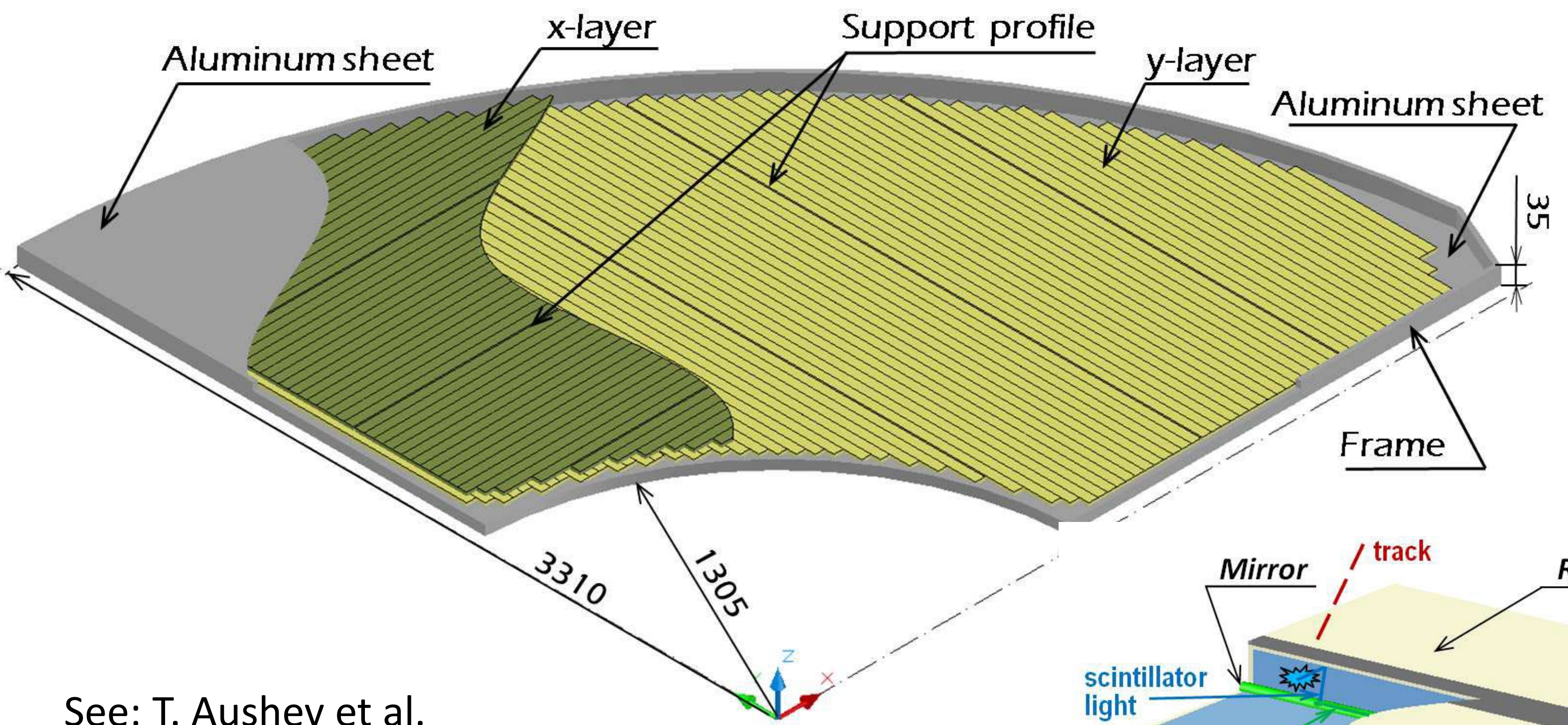


Octagonal Iron yoke structures:

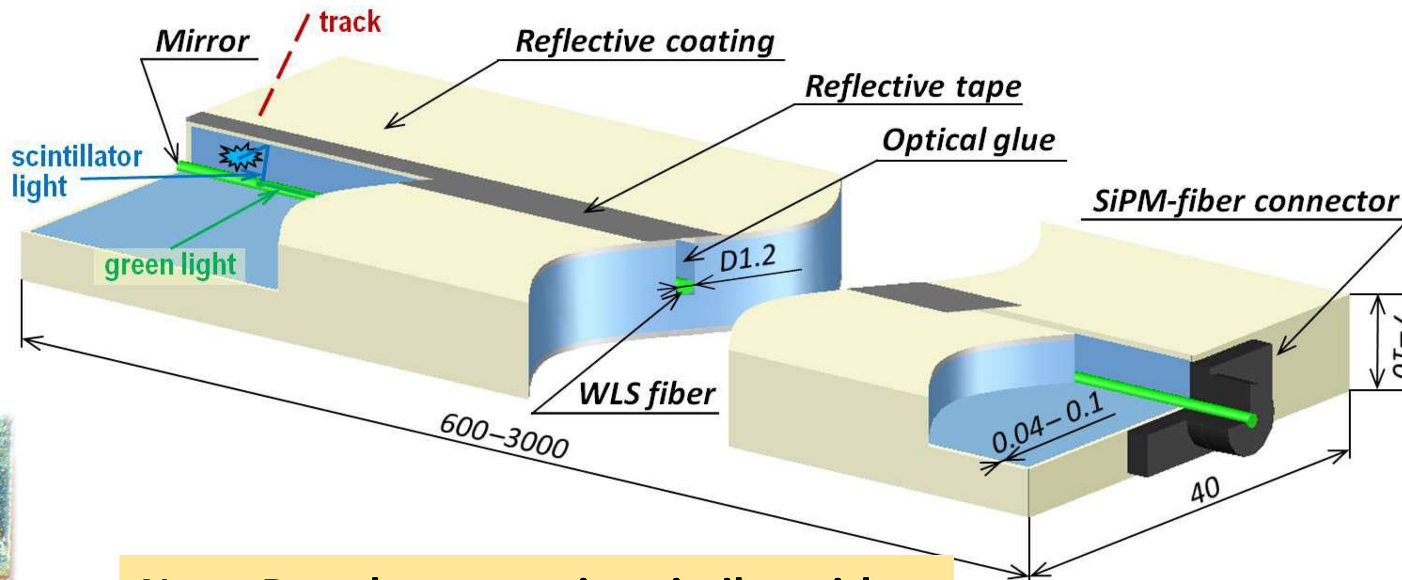
- 14 layers of ~ 47 mm thick steel plates
- ~ 40 mm thick air slots => 15 barrel, 14 Forward , 12 Back instrumented

	X_0 (cm)	λ_I (cm)
return steel	~ 37.5	~3.9
scintillator	~ 1.4	~0.7

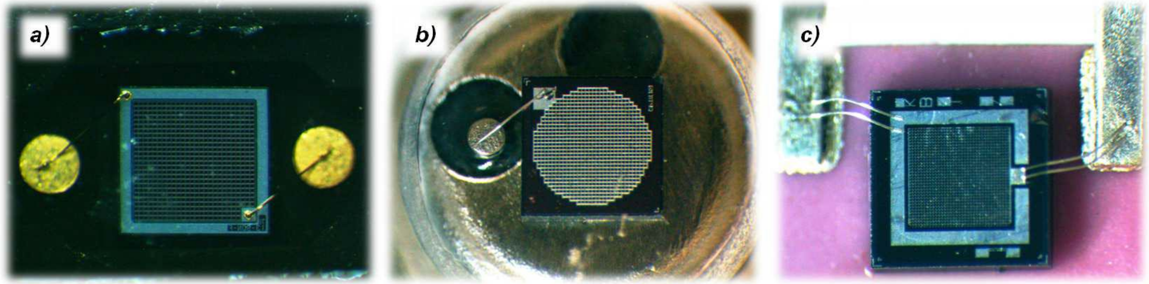
Endcap layers upgraded to scintillator at start of Belle II



- 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

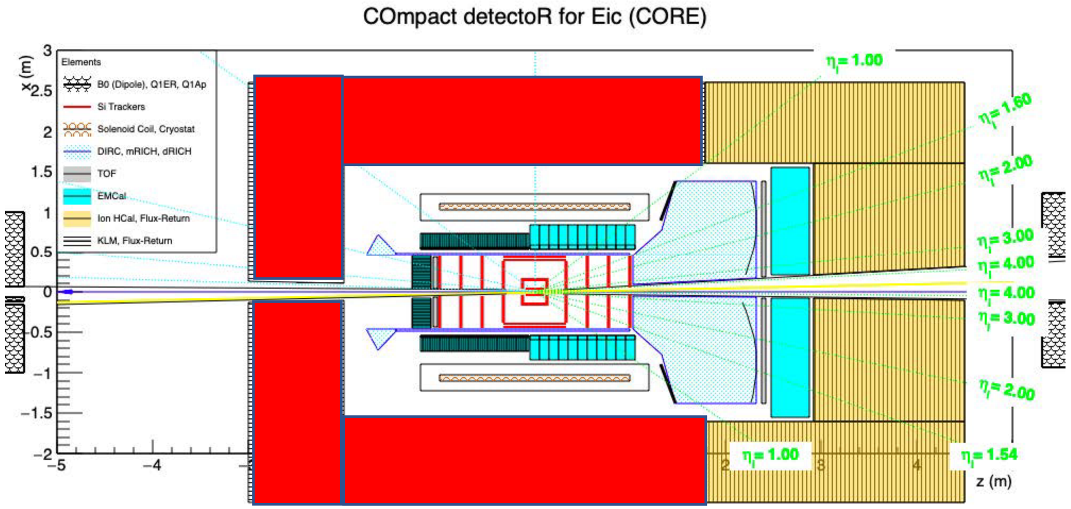


See: T. Aushev et al. arXiv:1406.3267v3 (2015) for details

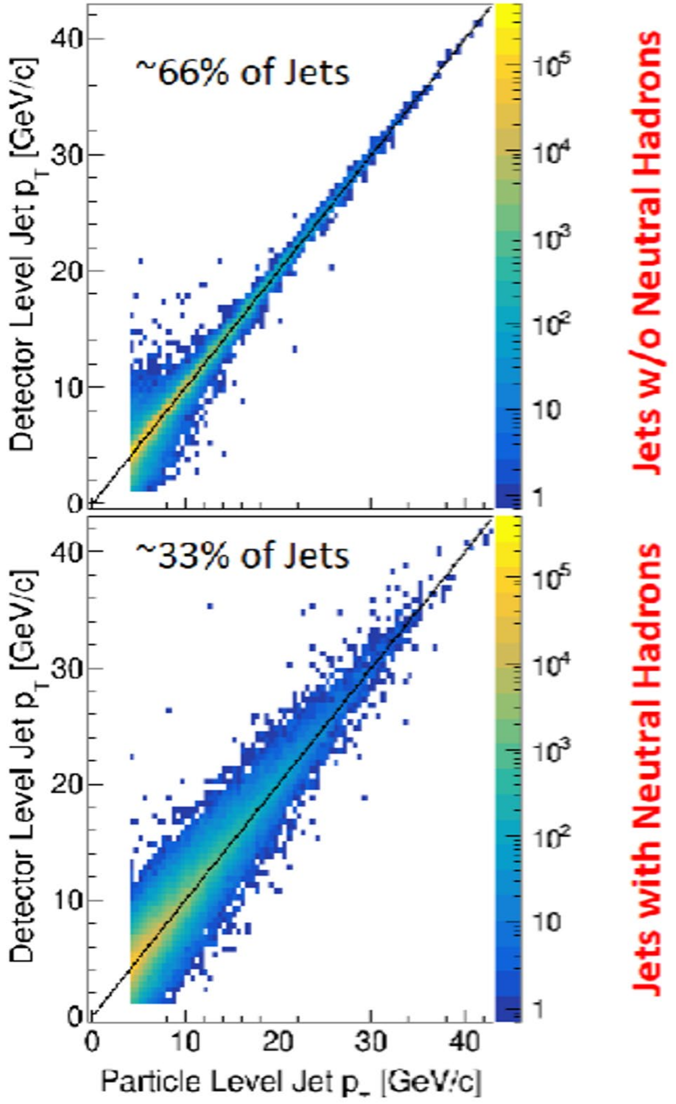


Note: Barrel construction similar with crossed scintillator strips – first 2 layers

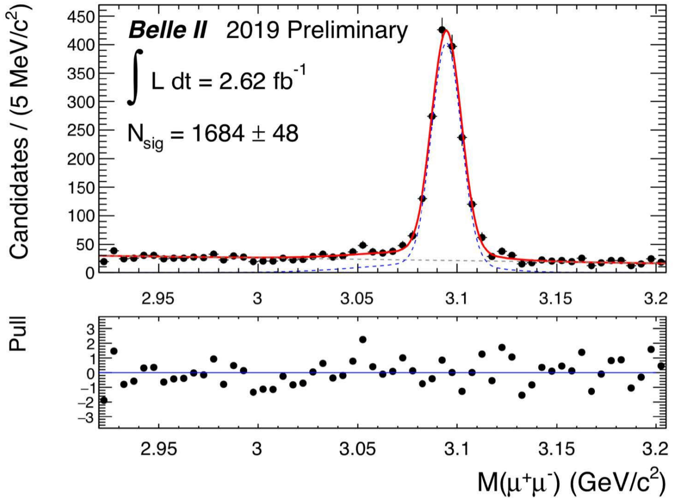
Flashback March 2021: Idea of a KLM (K_L & Muon subdetector) at EIC



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



- High efficiency and high purity μ detection and ID:



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

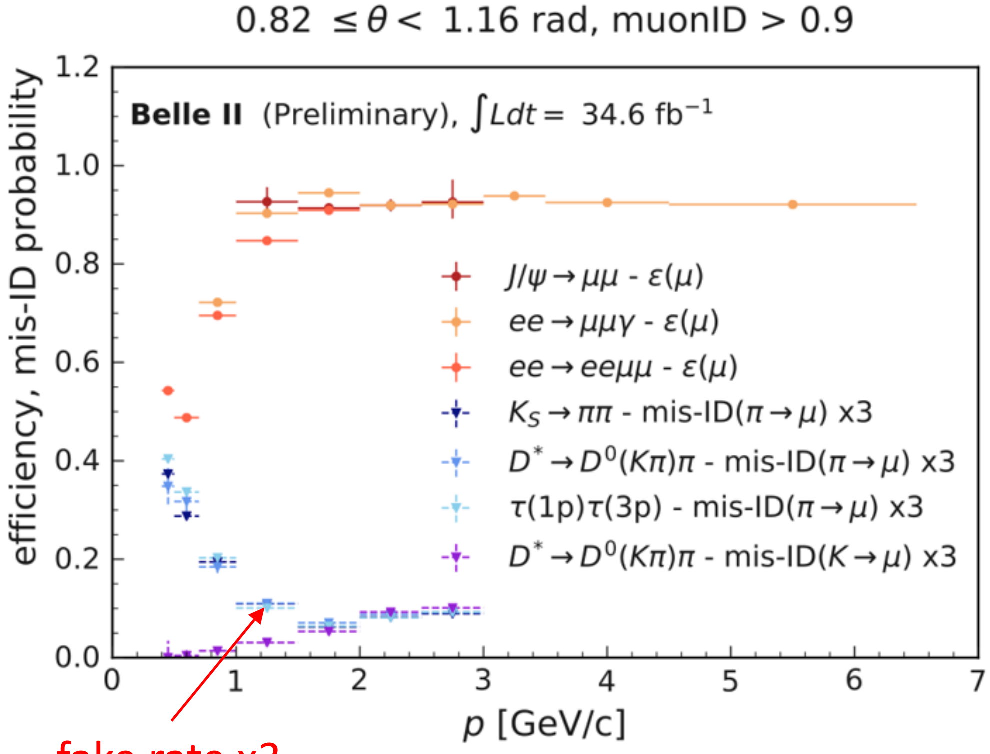
- e.g., for di-lepton production (J/ψ) and time-like Compton scattering processes and other.

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

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

Electron-Muon Identification and Analysis Techniques at Belle II

BELLE2-NOTE-PL-2020-027.pdf

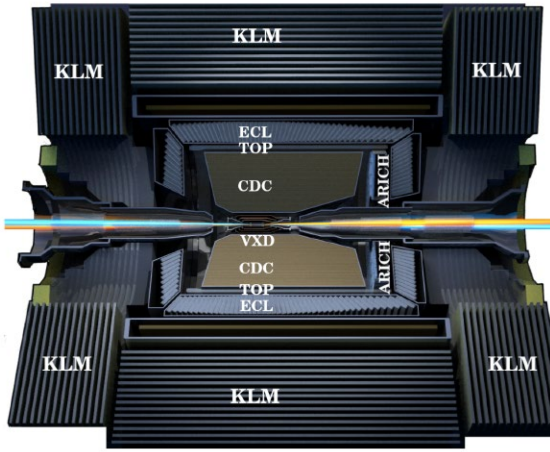


fake rate x3

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

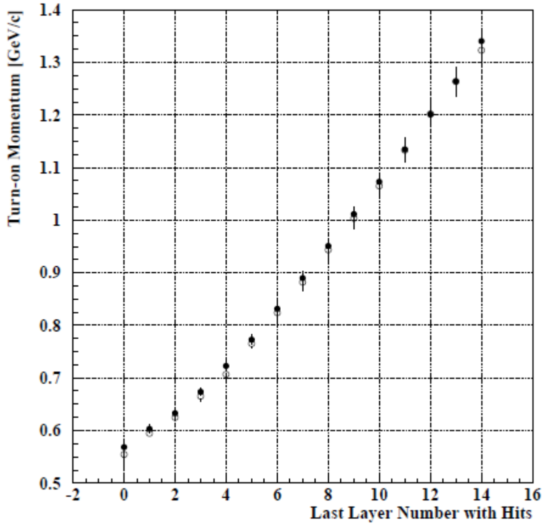
- Independently determine likelihood for each charged particle hypothesis
- construct a combined likelihood ratio.

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



- 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)

<u>Turn on momentum vs. KLM layer (data and MC)</u>



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

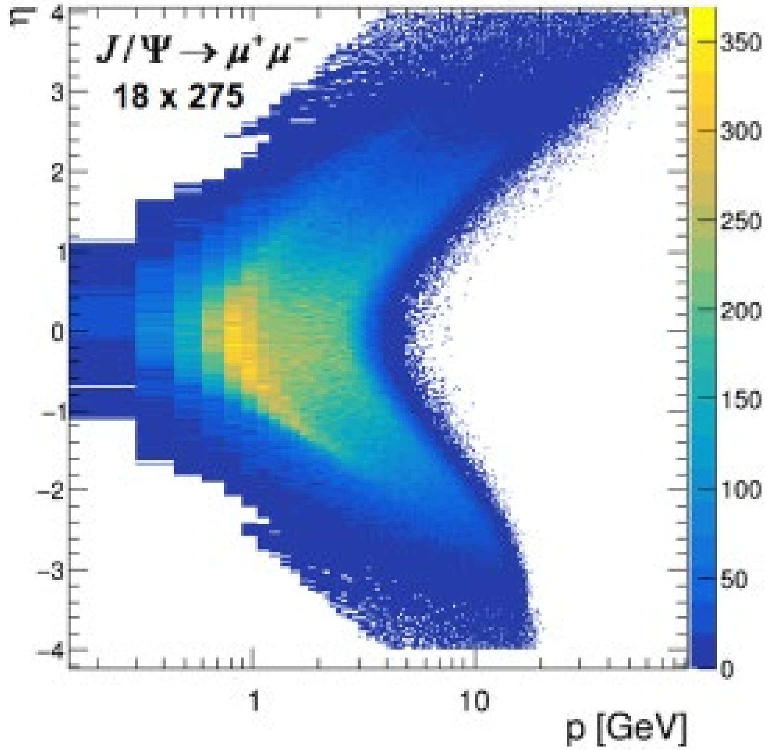
- Other techniques for analyzing & combining subdetector data, have been developed for Belle II but not covered in 2020 BELLE2-NOTE

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)

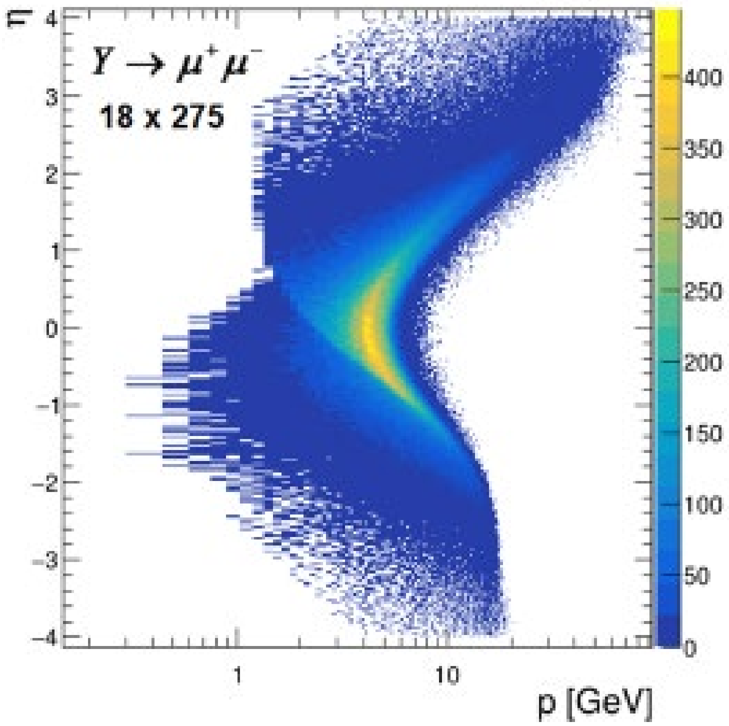
Muons from J/ψ decay



- 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

- **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



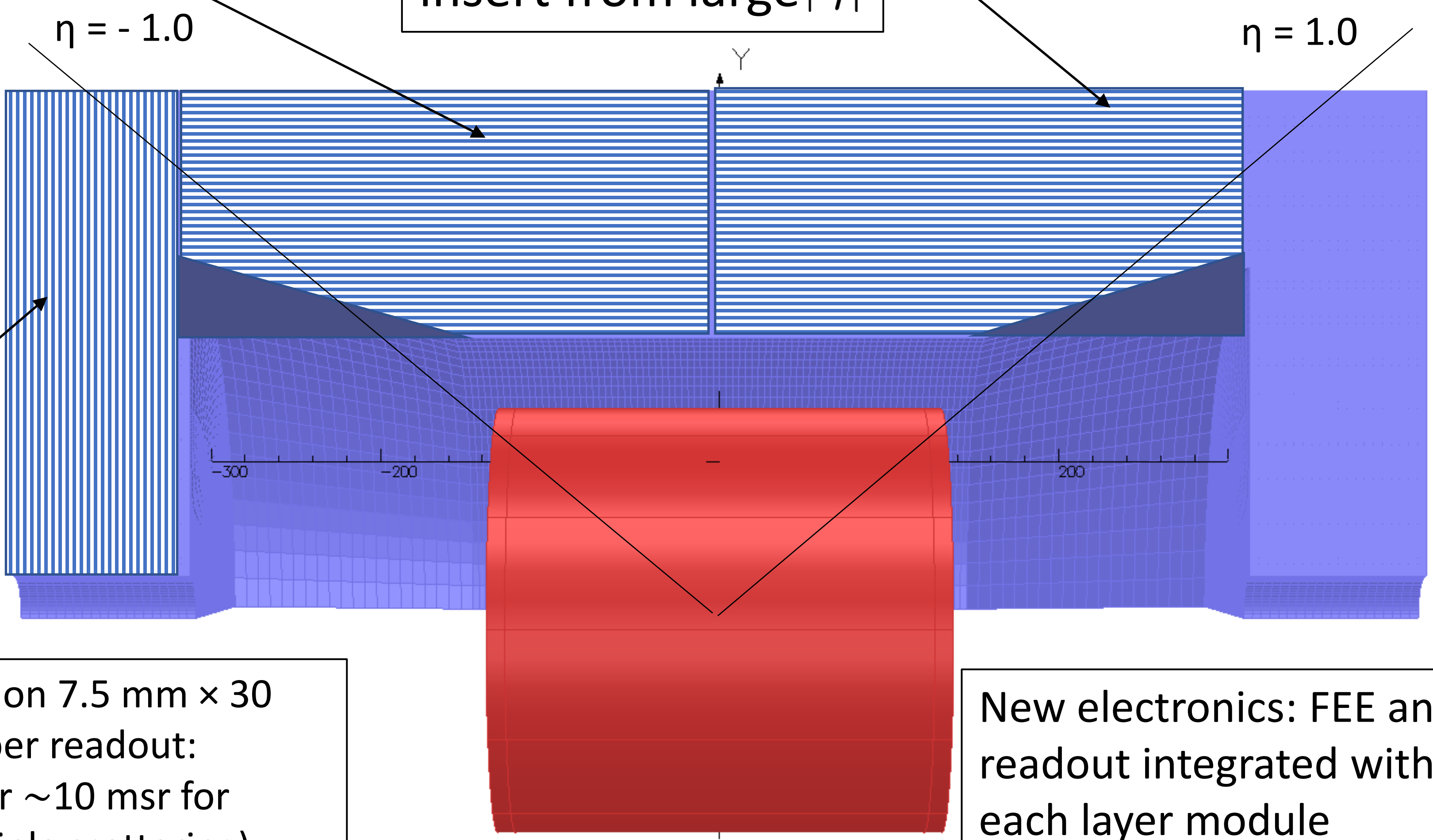
- Barrel: clean muon identification from 1.5 – 10 GeV/c is needed
- Endcaps: clean muon identification needed from 3 – 20 GeV/c
- in both cases, while muons complement the electron decay channels, they can be more rebust

EIC (CORE) “KLM” Implementation with Symmetric Solenoid Model

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

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

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

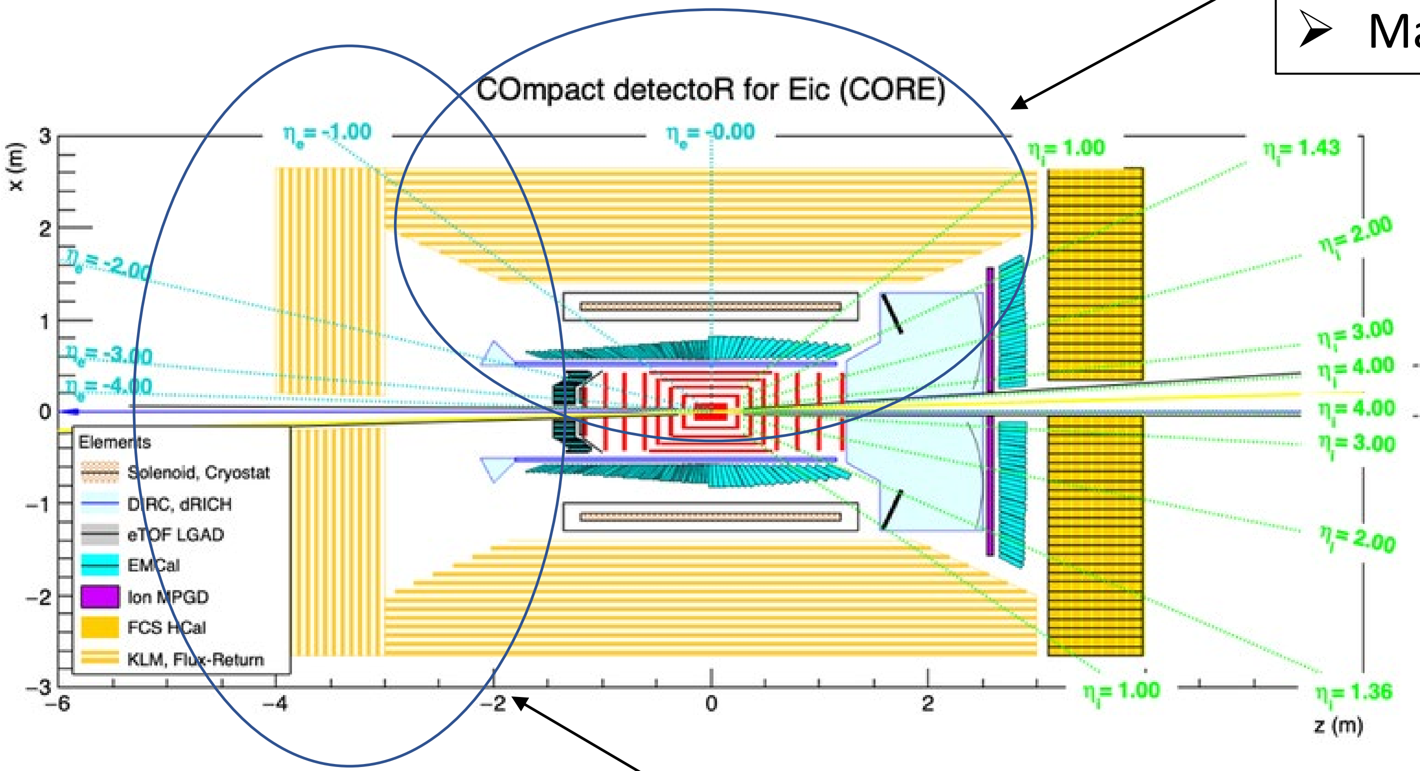
N.B.: maximum scintillator readout strip length < ~ 3m in all layers

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

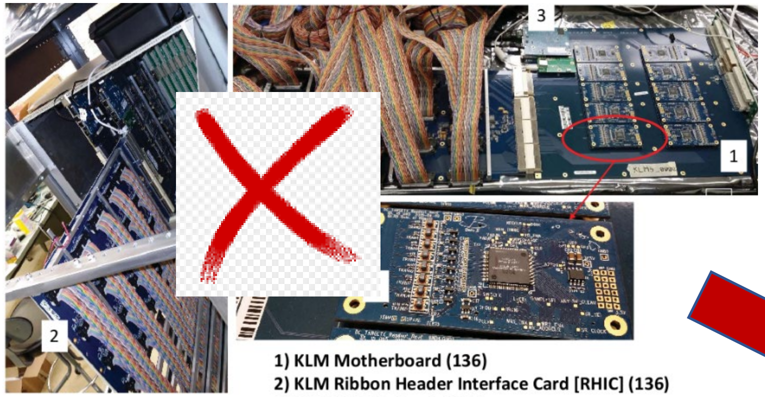
- Inner vacuum vessel ~ 4 cm Al, density 2.5
- Inner radiation shield ~ 2 mm Cu, density 9
- **Coil 6 cm - a 5:1 mix of Cu and NbTi (i.e., with Nb =Ti, a 10:1:1 mix of Cu, Nb, and Ti)**
- Coil support cylinder ~ 7 cm Al, density 2.5
- Outer radiation shield ~ 2 mm Cu, density
- Outer vacuum vessel Al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

KLM Endcap::

- 12 active layers (current)
- Material burden: electon-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

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

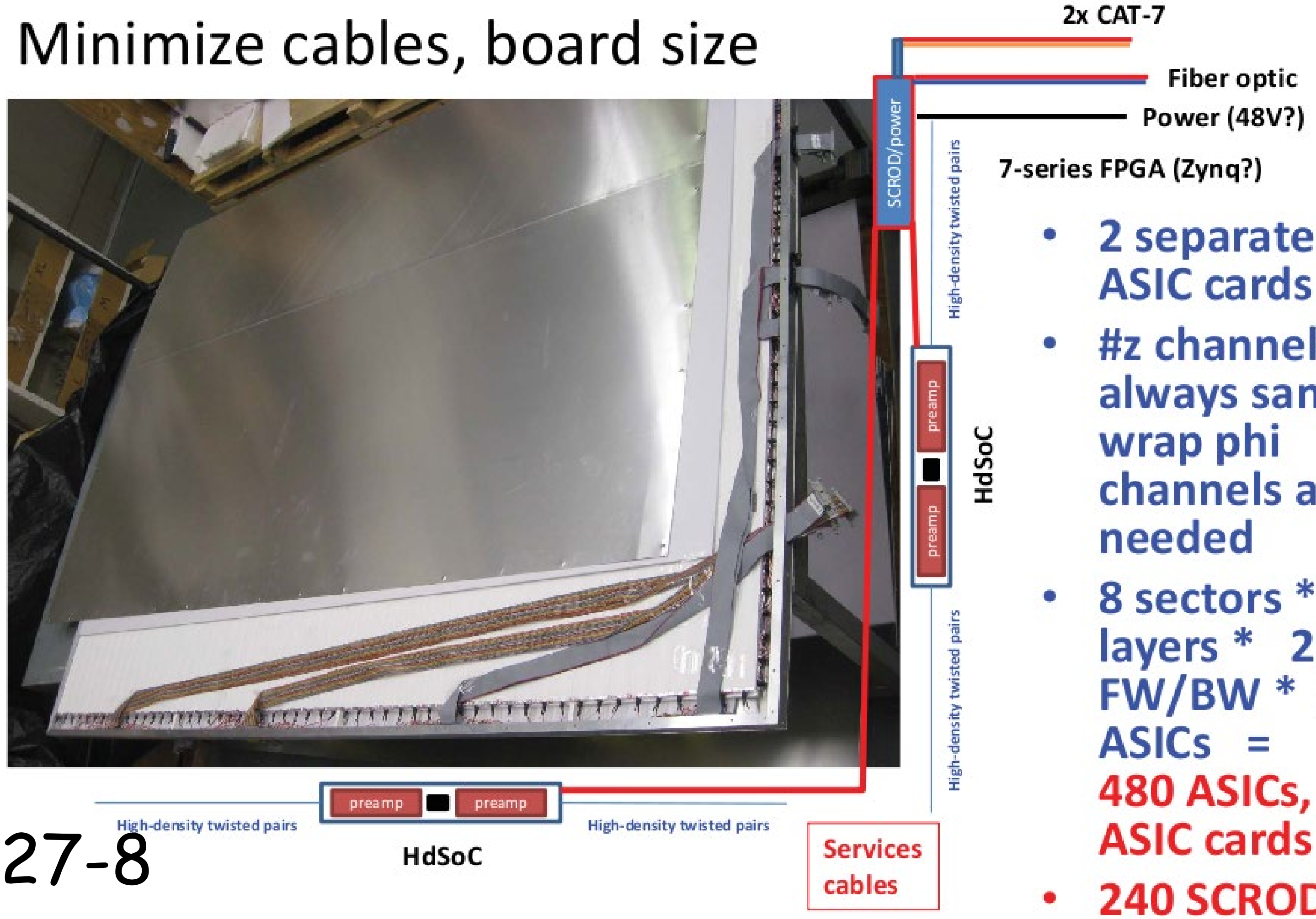


104 Endcap sets
32 Barrel

1) KLM Motherboard (136)
2) KLM Ribbon Header Interface Card [RHIC] (136)
3) KLM SCROD Rev A (136)
4) TARGETX Daughtercards (1288)

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

Minimize cables, board size



- 2 separate ASIC cards
- #z channels always same; wrap phi channels as needed
- 8 sectors * 15 layers * 2 FW/BW * 2 ASICs = 480 ASICs, ASIC cards
- 240 SCROD

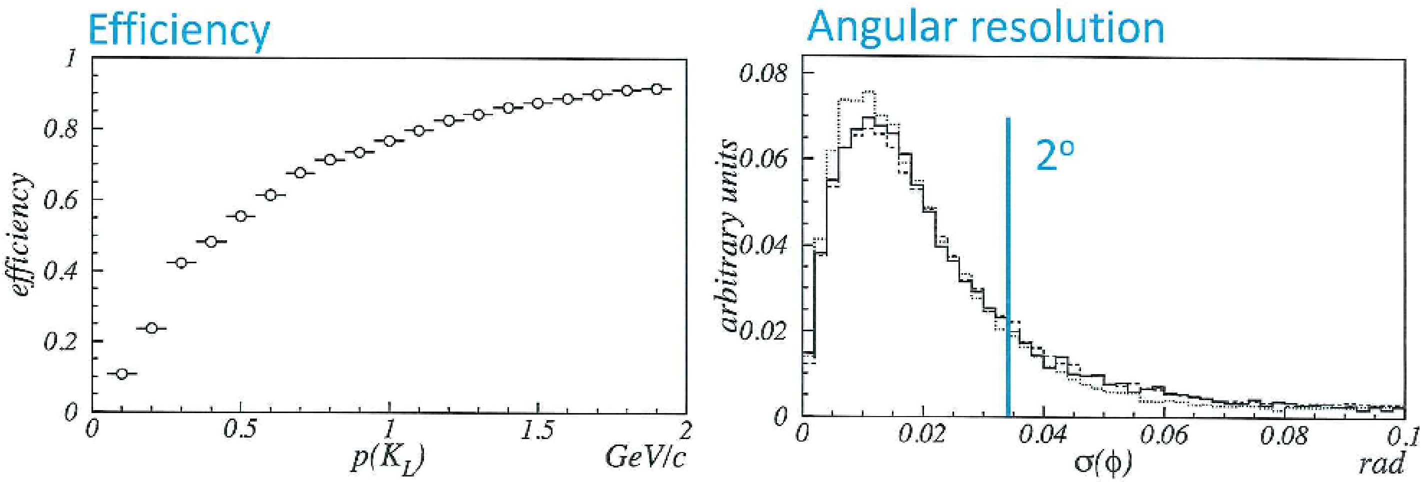
- ➢ Move digitizing front end electronics into detector panel
- ➢ Developments: embedded ASIC; compact SCROD; 64-chn readout; several different preamp options
- ➢ K_L time-of-flight possible?

Expected installation ~ 2027-8

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

Recall KLM performance: K-long detection and kinematics

- Belle II analyses and algo/FW implementation for K-long continue to be in progress; proposal (CORE) expectations (& plots below) were based on 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.**

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

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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Objectives of Proposed R&D Program

- **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** and calorimetry beyond the state-of-the-art (Belle II).
  - Use **pulse-shape analysis** based on recent advances in SiPMs and "Oscilloscope on a chip" readouts.
  - Use **timing resolution** (strive for 10's of picosec's) for time-off flight info for hadron ID and momentum measurement (w/ double-sided readout, could enable a more compact design).
- **Will a KLM double as a cost effective HCAL, also invertigate a dedicated HCAL using KLM (longitudinal & transverse readout) principles .**
- Can pulse shape, timing and longitudinal plus horizontal segmentation, be exploited AI in reconstruction for muons & hadron ID and calorimetery?

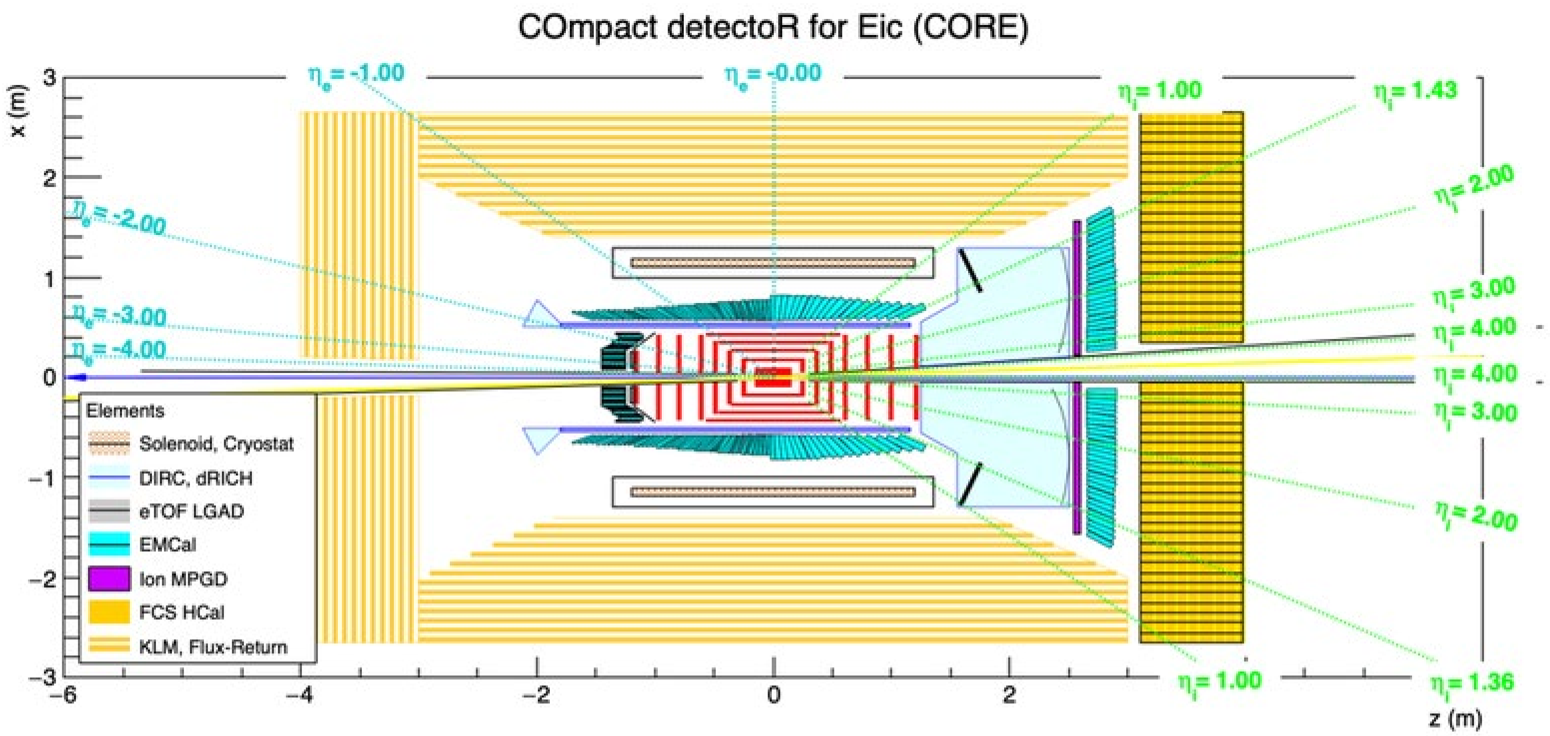
Summary and Future Directions

- Adding clean muon detection to any EIC 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, or drive a dedicated HCAL using KLM principles (longitudinal and transverse readout granularity).
- 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 to provide a cost-effective generic baseline detector design guide.

Thanks !

BACKUP SLIDES

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