EIC KLM R&D Proposal

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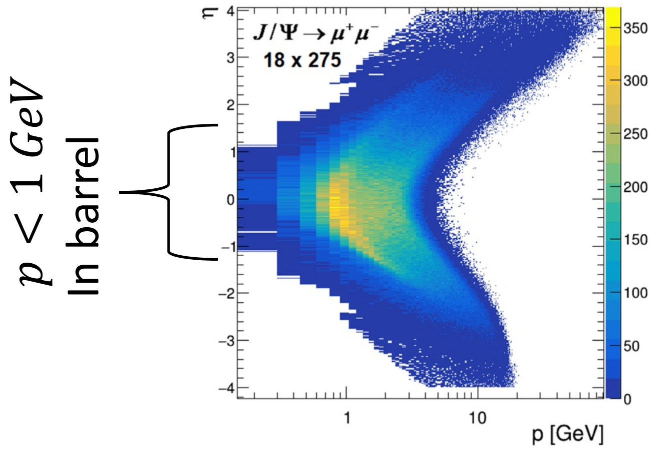
Project Motivation and Objectives

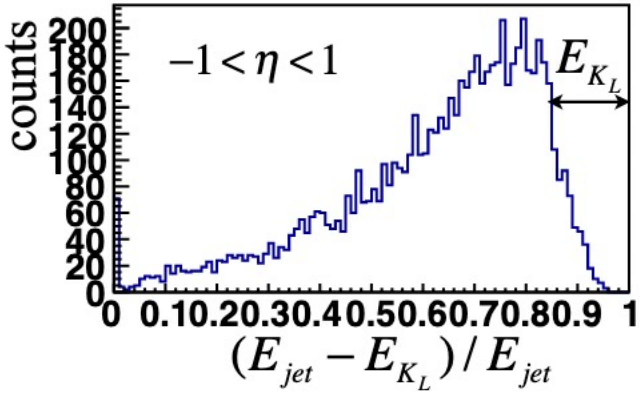
- Muon Detection is an essential capability of collider detectors
  - EIC: Diffractive J/Ψ, access of gluon TMDs, TCS, DDVCS and much more.
  - Excellent MuID will be complementary to ePIC

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 μ reqs.]
  - Muon ID capabilities designed with good K_L / neutrals detection/ID (ToF) in mind
    - ➔longitudinal segmentation can provide 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



Barrel ➔Multipurpose KLM

- Provide excellent muon identification in a compact design
- Extend concept for hadron identification and calorimetry

Endcap ➔focus on HCAL performance, cost/performance tradeoff

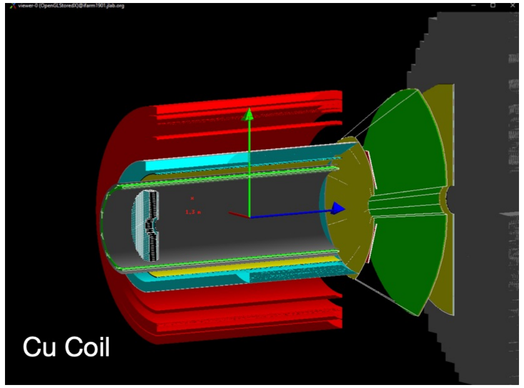
- Evaluate HCAL performance in relevant momentum region
- **Novel aspect: Use longitudinal segmentation+ state of the art Machine Learning Methods**

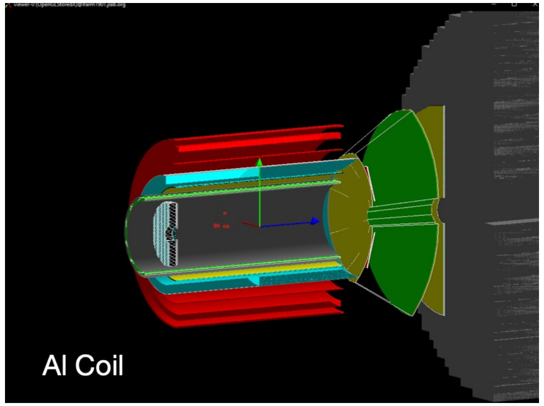
Project Scope

Significant effort in year 1

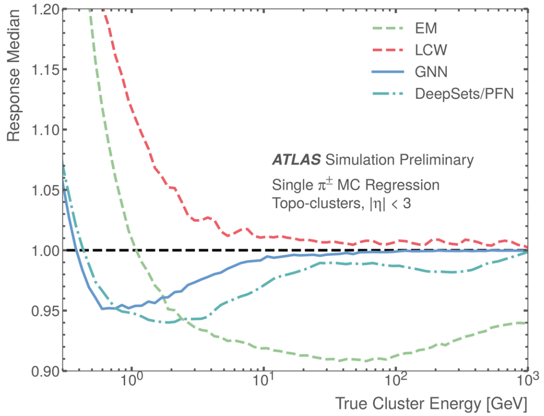
- Implementation of Barrel and Endcap KLM in Simulation to
  - Study optimization of field, det radius and layer topology for best muon efficiency vs. threshold and desired range.
  - Achieve a MP-KLM baseline integrated design (with magnet and tracker)
  - Adapt ML algorithms to KLM geometry
  - Interplay of geometry/ML performance
- R&D on thin scintillators
  - Demonstrate feasibility of compact design with direct readout
  - Timing (strive for 10s of picoseconds) for TOF info for hadron ID and momentum measurement
  - w/ double-sided readout of strip, good timing could enable a more compact design .
- R&D on fast, wave form sampling electronics to improve performance

  ➔Shift to year 2 based on committee response
- R&D on HCAL implementation with reusing existing components
  - Beam test





CORE magnet system simulations



Performance of GNN based HCAL rec

ATL-PHYS-PUB-2022-040

Committee Question on Simulation

Since EPIC has now decided on all parts of the software framework, how does the migration affect the proposed studies and timeline?

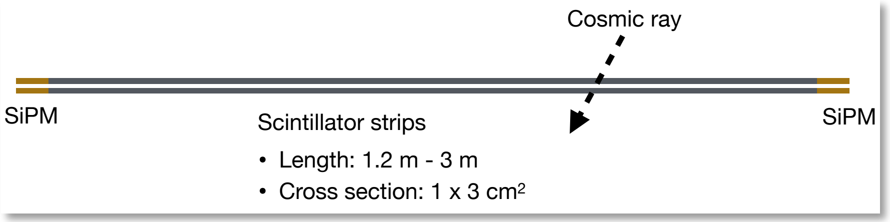
- *The R&D does not depend on the EPIC simulation framework. The proponents plan to use DD4HEP and have expertise with DD4HEP. We do not expect issues with migrating to DD4HEP. No funds are requested for software migration and no significant time investment is expected for the migration.*

- Compact magnet design for IP8 already exists in fun4all. Move from fun4all and dd4hep is not a major concern and expected as soon as practical.
- Groups have significant experience in fun4all and dd4hep
    - UCR significant experience implementing instrumention in dd4hep for Athena/EPIC
    - Duke: co-lead dRICH SW effort including simulations in fun4all and now dd4hep
    - UofSC and SBU: significant experience with fun4all for CORE (work on magnet studies for CORE and IP8)
- Develop most of the framework (in particular ML interface) framework agnostic →Maximum synergy

Instrumentation R&D year 1/Committee Q3

"What, exactly, is going to be prototyped?
The proposal would be helped by a few drawings of what might be prototyped.

- Multipurpose KLM
  - Single strips with double-ended strip readout w/ SiPMs
  - Readout with existing electronics (IU,UCR) and DAQ(UofSC)
  - Studies of various strips (funding request for 3)
    - scintillation material BC-420, BC-408, EJ-204; compromise between fast timing and attenuation length)
    - potentially different SiPMs (borrow from UCR and IU)
    - lengths (~1.5 m, ~ 2 m)
    - Double-ended direct readout for improved timing resolution (compared to WLS)
  - Test stand with two long strips
    - Prepare strips and bring setup in operation
    - Evaluate light yields, perform timing and energy calibrations, determine attenuation lengths
    - Prepare for timing and position resolution measurements in Year 2
    - Evaluate light yields (enough for < 100ps timing), timing, energy calibration



Schematics of bench setup withf thin, long scintillator strips at UofSC

State of the art scintillator laboratory developed previously at UofSC

- Endcap HCAL-KLM
  - Prototype setup with focus on reusing existing and off the shelf components (in-kind)

Year 1 Activities and Budget Request

Multipurpose KLM

- Simulation + Reconstruction work at Duke (overall SW work led by PD)
  - 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
- Electronics development at UH →move to Y2

UG students, USC	$\$12.5k$
Postdoc (50%), Duke	$\$53.7k$
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Postdoc (50%), UH	$\$50k$
HDSoC evaluation readout system, UH	$\$10k$
Test Bench: EE support, IU	$\$8.3k$
Scintillator strips, USC	$\$4.5k$
Travel to U.S., JU	$\$8k$
Travel to U.S., RUAS	$\$13k$
Laptop RUAS	$\$2k$
Total	$\mathbf{\$174.5k}$

80%, 60% reductions proportional but shift focus on simulations first

Year 1 Activities and Budget Request
Endcap HCAL

- Simulation and Teststand at UCR
  - Deliverables
    - Adaption of Graph Neural Network (GNN) to forward HCAL
    - Teststand setup, first proof of concept prototype (in-kind)
  - Milestones: First proof of concept of hadronic reconstruction performance
- Cal Poly SLO: Support teststand
- Simulation and reconstruction at UCLA
  - Deliverables
    - Simulation and reconstruction framework for forward HCAL in dd4hep
    - Evaluation of hadronic response in simulation
  - Milestone: Initial implementation of forward HCAL concept

Graduate student (50%), UCR	$\$28.4k$
Graduate student (50%), UCLA	$\$28.2k$
Undergraduate students, CPSU SLO	$\$12.0k$
Travel, UCR	$\$2.0k$
Total	$\mathbf{\$70k}$

$80\%, 60\%$ reductions proportional but shift focus on simulations first

Committee Question 2

The collaboration between the Multipurpose KLM and KLM-type HCAL is not specified at all.

What are the benefits for this combined proposal?

- Both project propose to conduct R&D on plastic scintillators readout by SiPMs for the purpose of hadron and muon ID
- Multiple synergies in software (simulation and ML), instrumentation and readout electronics
- Benefits of combined proposal:
  - Shared Reconstruction algorithms (standard and ML)
  - planning of tests,
  - Discussion of results, analysis techniques, pitfalls for measurements, etc.
  - Shared (in-kind) resources,
  - Shared expertise on simulations, materials, SiPMs.
  - Studies of different geometries and readouts: single- vs double-ended.
  - Potentially shared readouts
  - Potentially shared scintillator (depending on R&D outcome)
  - Synergies in lab capabilities

Committee Question 4

Reduced funding scales both detector parts equally.
Have other options been considered, e.g. focusing primarily on one part?

- Reducing funding scales for both detectors equally preferred
- Will consider shifting focus
  - on software/simulations
  - Push back R&D on forward HCAL prototype pending results from scintillator R&D

  However:
    - Forward HCAL mainly supported by in-kind contributions
    - Resources requested to support forward HCAL effort are modest

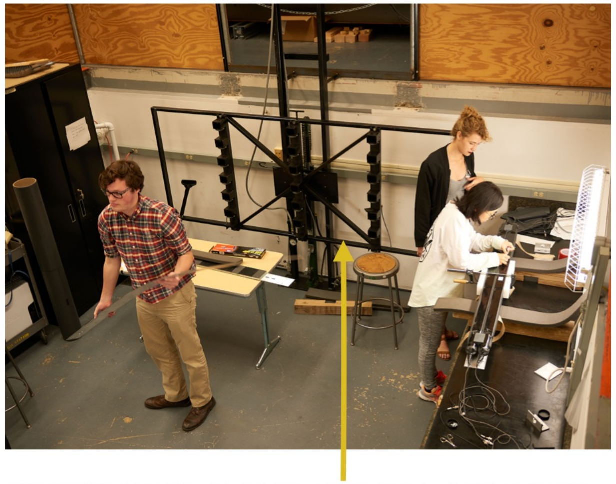
Thank you for your attention

Backup

Institutions/workforce (on project)

- CSU-SLO → work on endcap HCAL setup
  - Undergraduate student
- Duke → simulation/reconstruction. Teststand (in-kind)
  - Experience with simulations/reconstruction at EIC and KLM@Belle II
  - **Postdoc (50%), undergraduate student**
- Indiana → instrumentation
  - Expertise in construction/development of scintillator based calorimetry, SiPMs KLM@BelleII
  - considerable experience with SiPM readout for STAR
- SBU →Simulation support
  - Expertise in EIC software
- UCLA →endcap HCAL setup
  - Expertise in calorimetry for EIC, STAR,
  - **Grad student (50%)**
- UCR → simulation/ML development, teststand (in-kind)
  - Expertise in ML methods, simulation for EIC
  - **Grad student (50%)**
- UH → HDSoC electroics
  - Expertise in electronics
  - **Postdoc (50%)**
- UofSC → Scintillator R&D teststand
  - Expertise in Scintillator R&D, MUSE and Jlab experiments, simulations in CORE
  - **Undergraduate students**
- Jazan→travel to SBU/USC
- Ramaeiah→travel to SBU/UofSC

Scintillator testing at UCR



"Wind Mill" holder, allowing to hold vertically long (> 1 m) bars for PM glueing.

Answer to questions

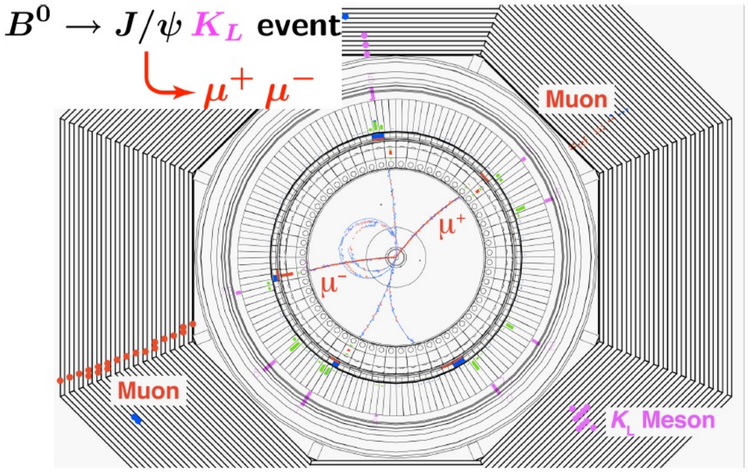
Scintillator strips

- Length: 1.2 m - 3 m
- Cross section: 1 x 3 cm^2

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

Comments / prologue

- 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.



Belle Detector

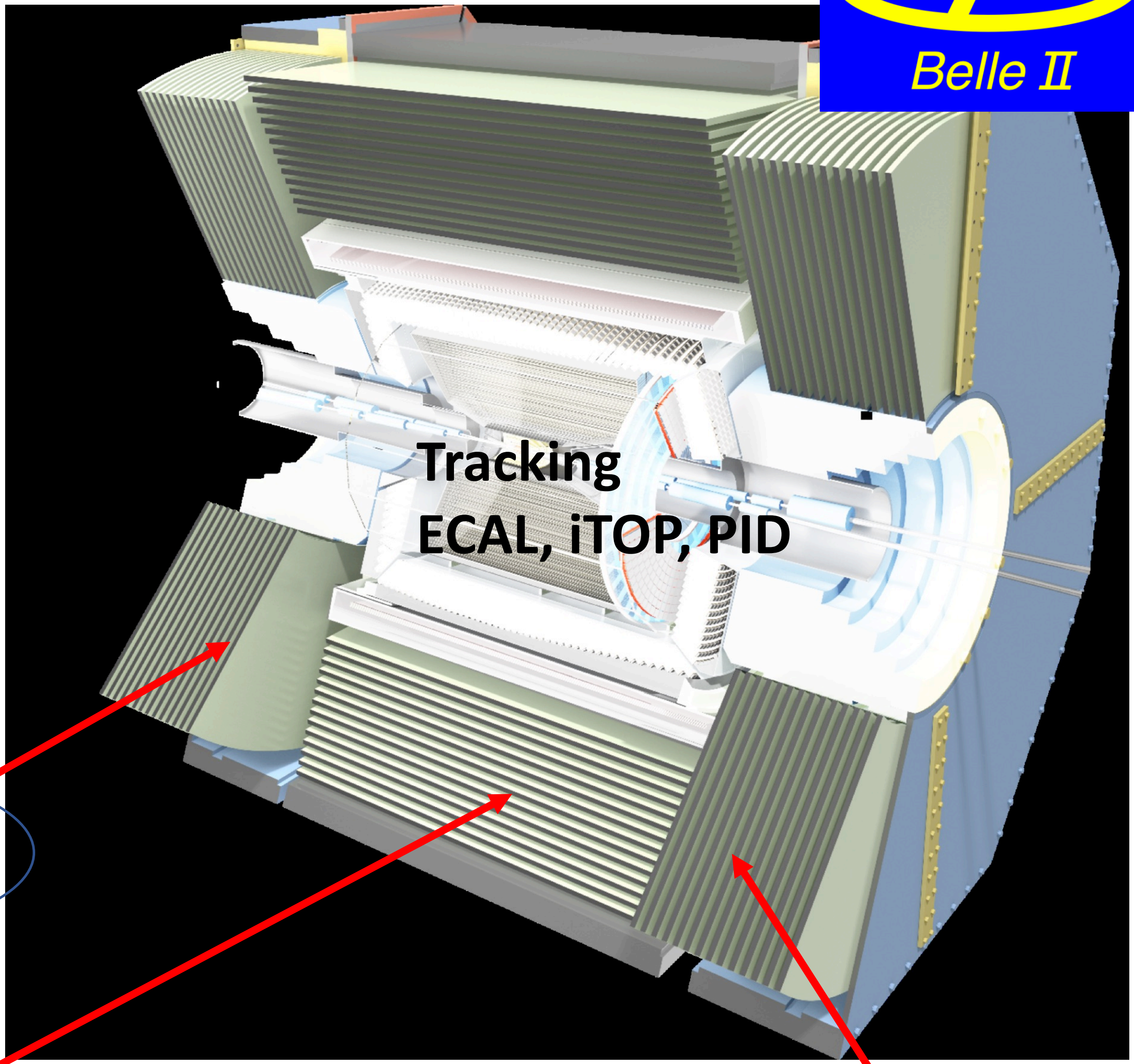
- KLM (barrel and electron endcap) was incorporated into the EIC **CORE proposal** ... these efforts (and slides I will show) have wider application as we continue to develop ideas for detector #2.
- A "**EIC KLM R&D Proposal**" was submitted to the EIC Generic R&D program to address issues of further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

Belle II KLM det. and upgrades at Super KEKB

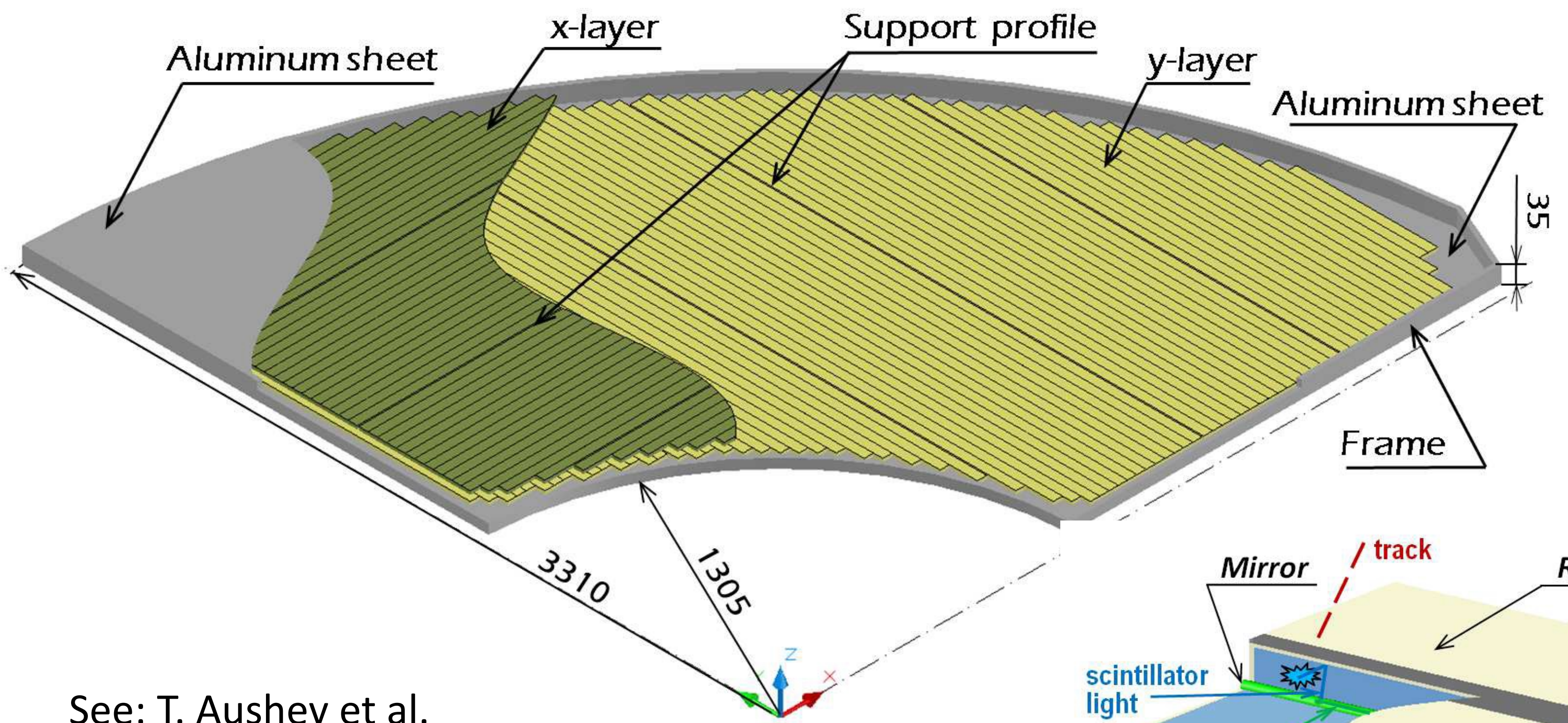
- Active "2D" readout elements interleaved with 1.5 T solenoid magnet return steel
- Optimized for μ and K_L detection and ID
- Relatively inexpensive, technically simple construction, robust operation
- Not a full-fledged/proper EM or Hadron calorimeter (and generally not used as such)
- Upgrade planned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

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

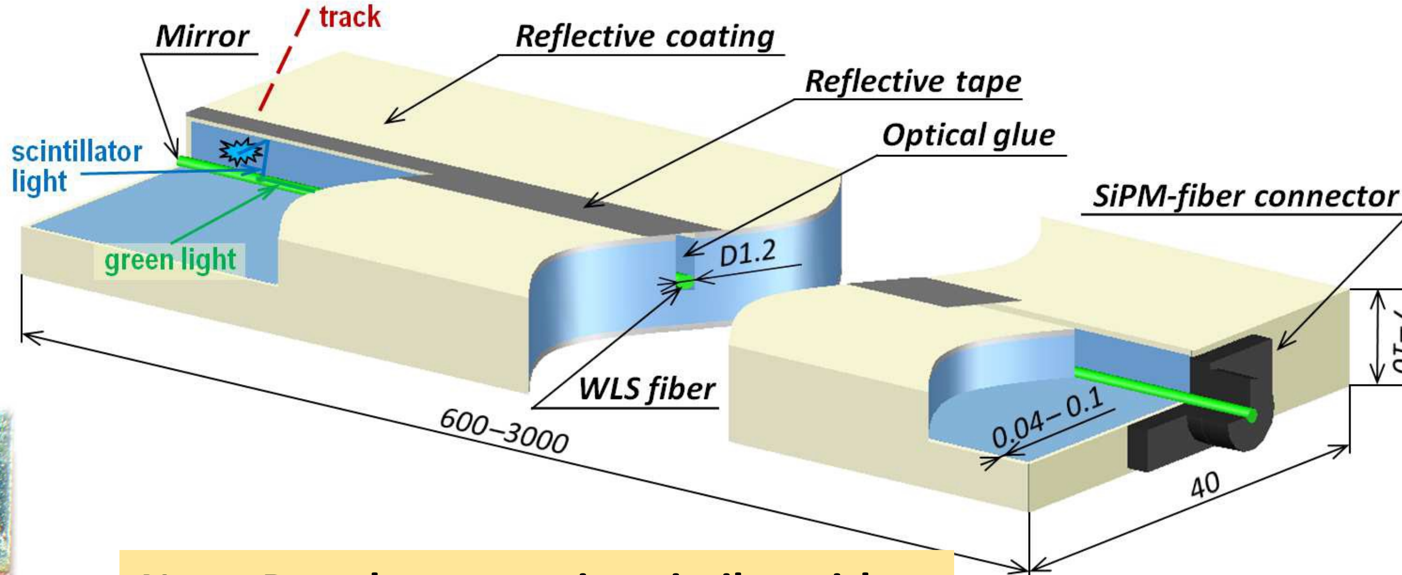
	X_0 (cm)	λ_I (cm)
return steel	~ 37.5	~3.9
scintillator	~ 1.4	~0.7



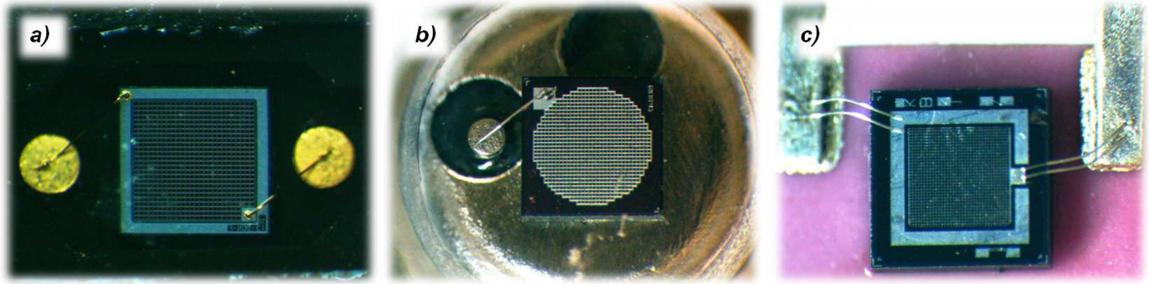
Endcap layers upgraded to scintillator at start of Belle II



- 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



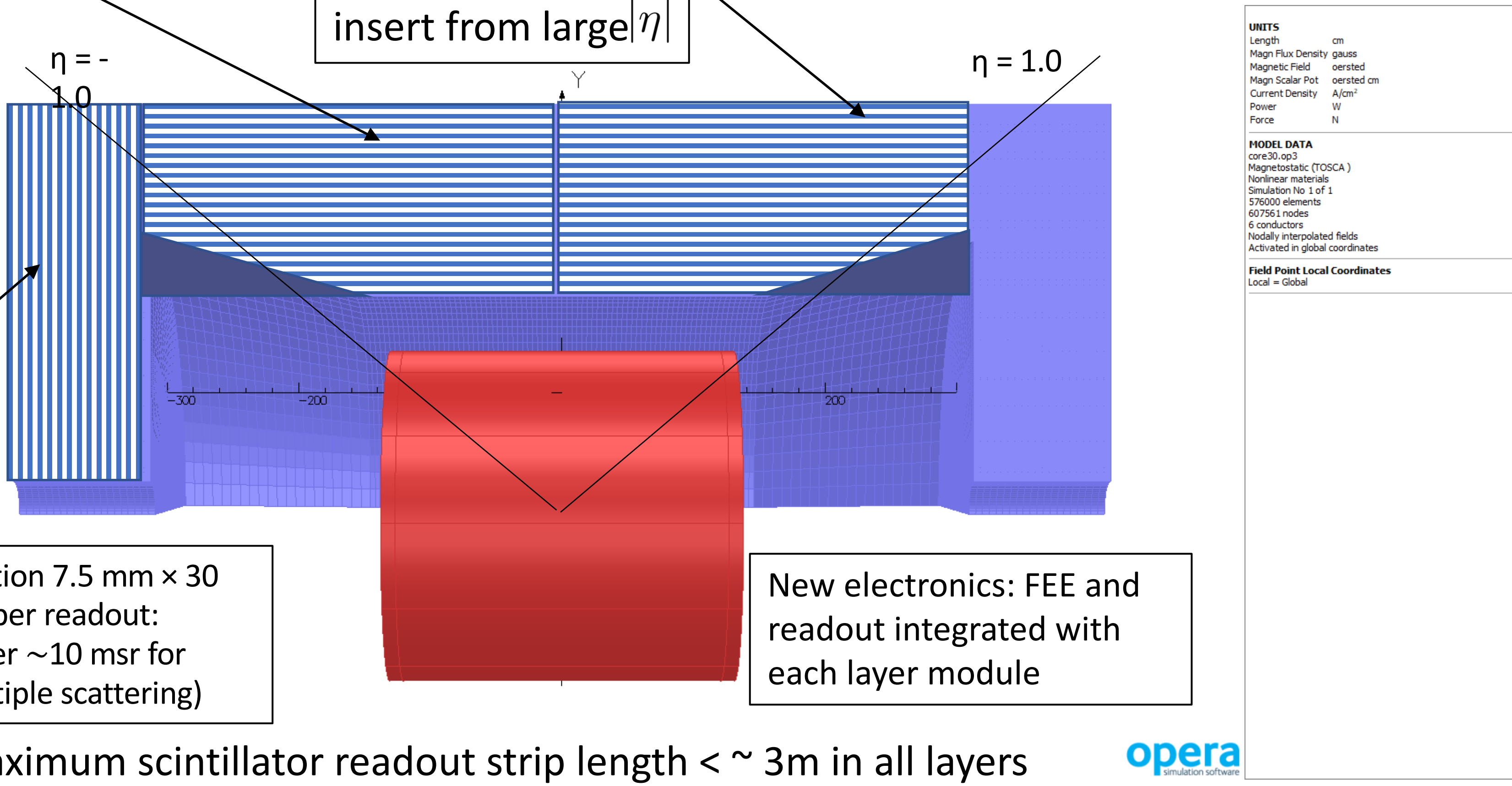
Note: Barrel construction similar with crossed scintillator strips – first 2 layers

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



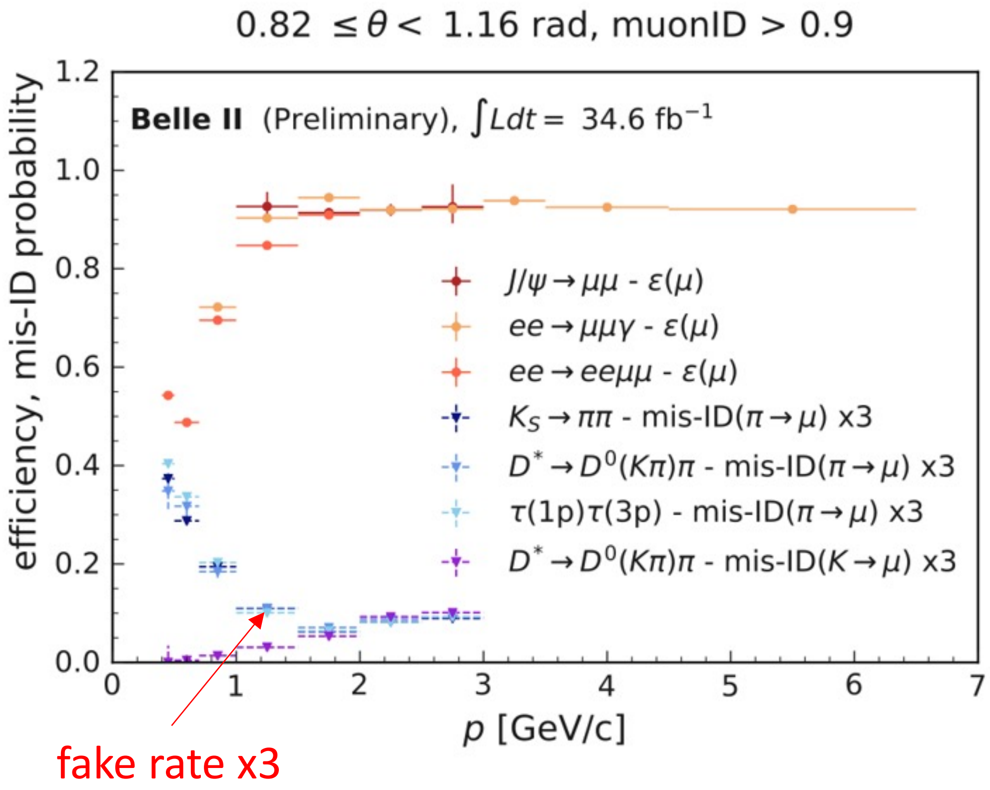
Strip geometry: cross section 7.5 mm × 30 mm w/ 1 mm dia. WLS fiber readout: angular resolution of order ~10 msr for inner barrel (~ muon multiple scattering)

New electronics: FEE and readout integrated with each layer module

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

Electron-Muon Identification and Analysis Techniques at Belle II

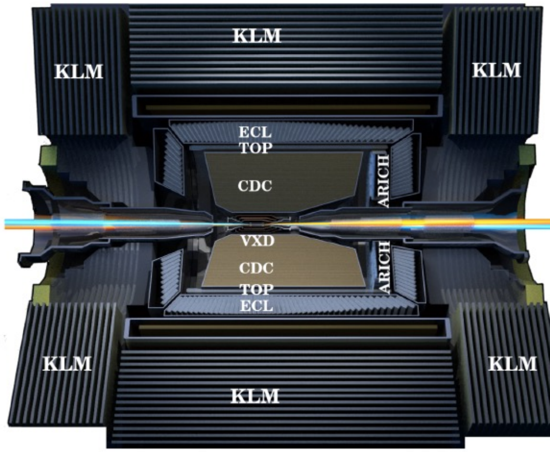
BELLE2-NOTE-PL-2020-027.pdf



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

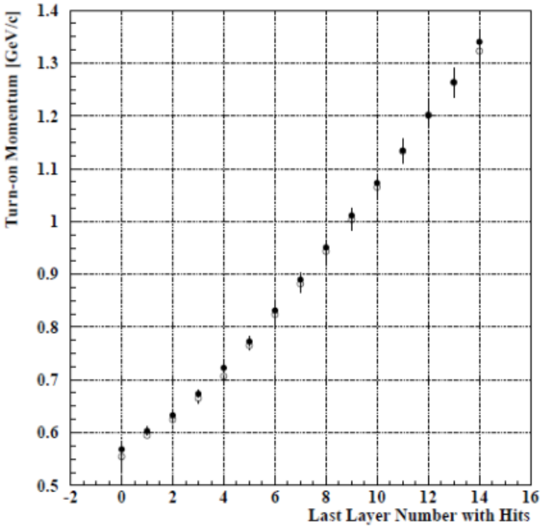
- Independently determine likelihood for each charged particle hypothesis
- construct a combined likelihood ratio.

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



- 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

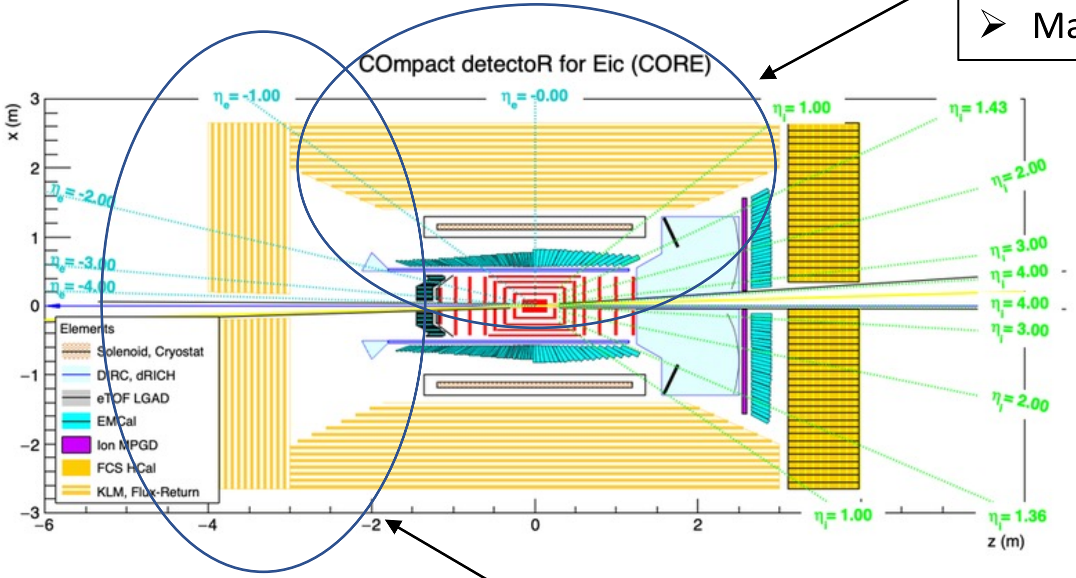
Lower momentum μ w/ tracking + ECL (Wave Form) info and BDT analysis (Bryan Fulsom, EIC Muon Detection and Quarkonium Reconstruction Workshop, 2022).

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

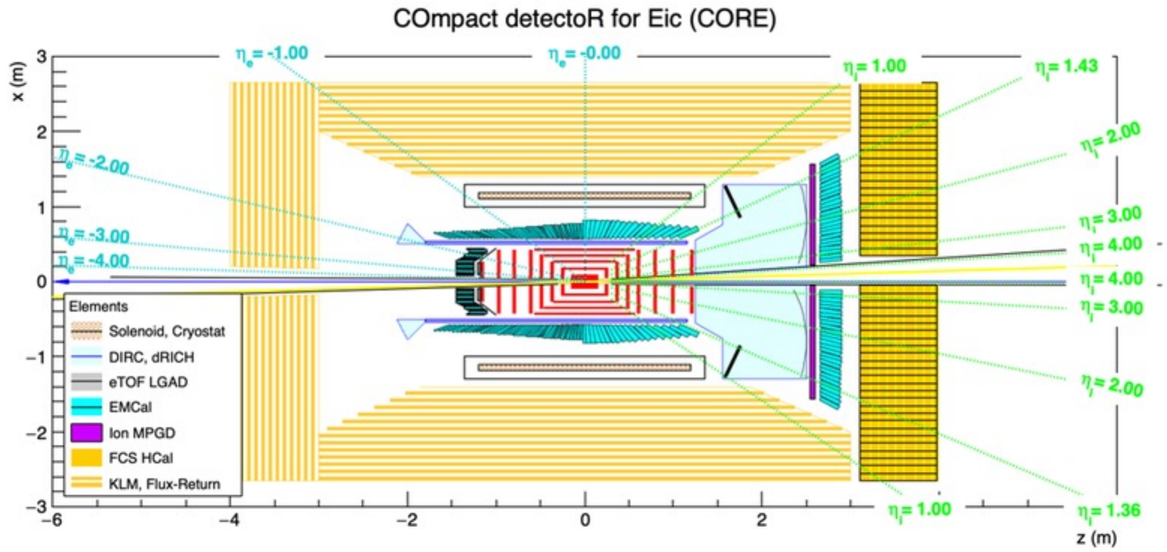
- Inner vacuum vessel ~ 4 cm Al, density 2.5
- Inner radiation shield ~ 2 mm Cu, density 9
- **Coil 6 cm - a 5:1 mix of Cu and NbTi (i.e., with Nb =Ti, a 10:1:1 mix of Cu, Nb, and Ti)**
- Coil support cylinder ~ 7 cm Al, density 2.5
- Outer radiation shield ~ 2 mm Cu, density
- Outer vacuum vessel Al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

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

<u>**Belle design parameters adapted to CORE, chosen for “buildabilty” and not otherwise optimzed in proposal**</u>

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- *Benefits of combined proposal: planning of tests, discussion of results, analysis techniques, pitfalls for measurements, etc. Shared expertise on simulations, materials, SiPMs. Studies of different geometries and readouts: single- vs double-sided. Potentially shared readouts.*
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