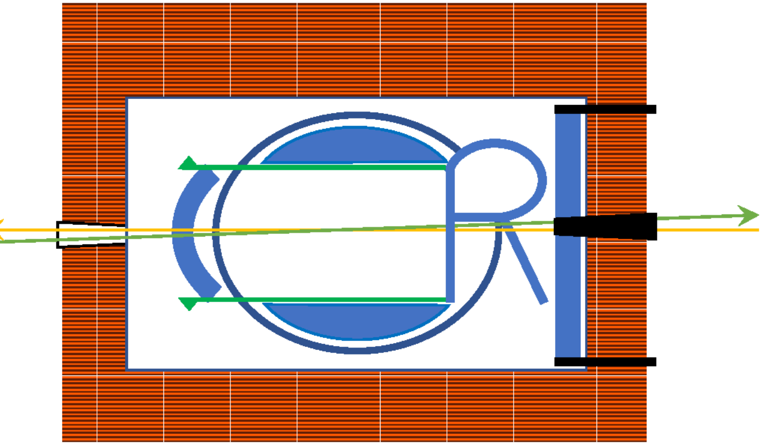
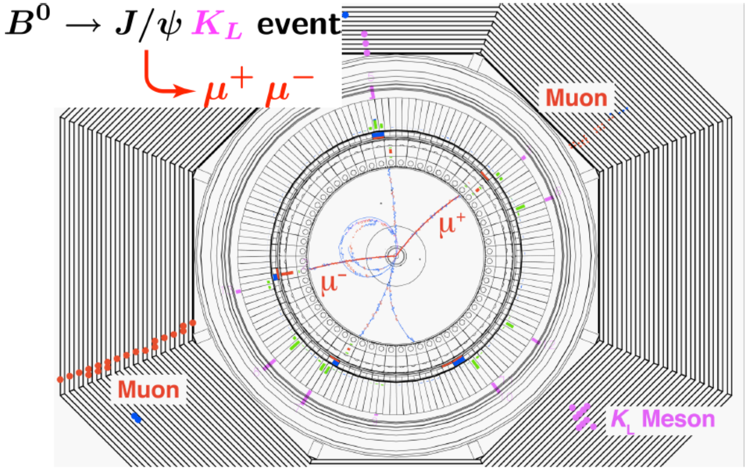


CORE KLM Subdetector Status and Update

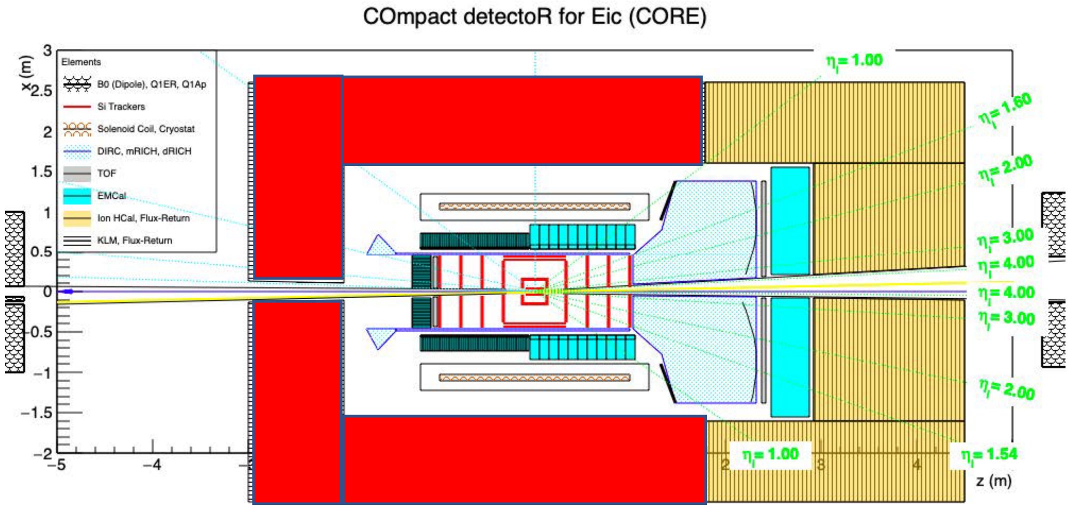


Belle Detector

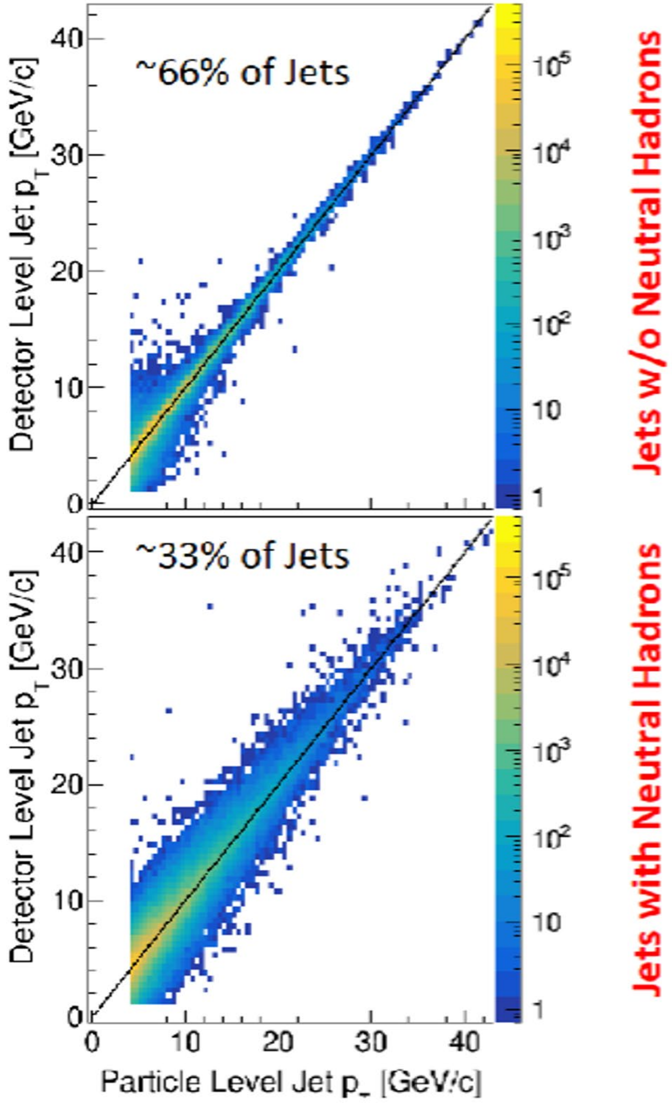
W. W. Jacobs

CORE Meeting 21 June 2022

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

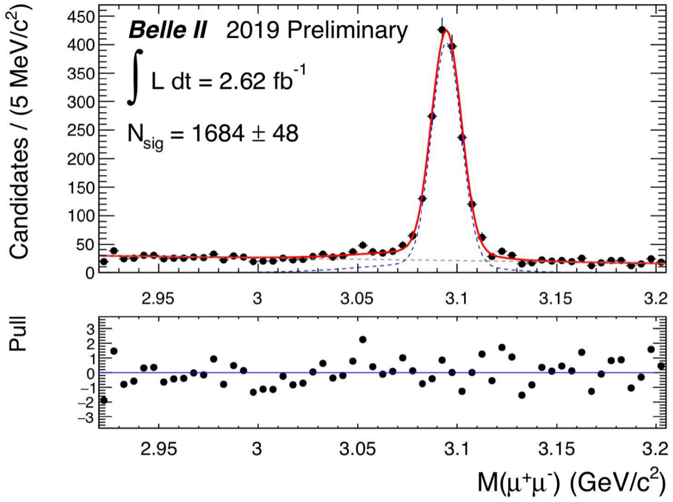


- Identify K_L and other neutral particles in jets … correct or veto



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



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

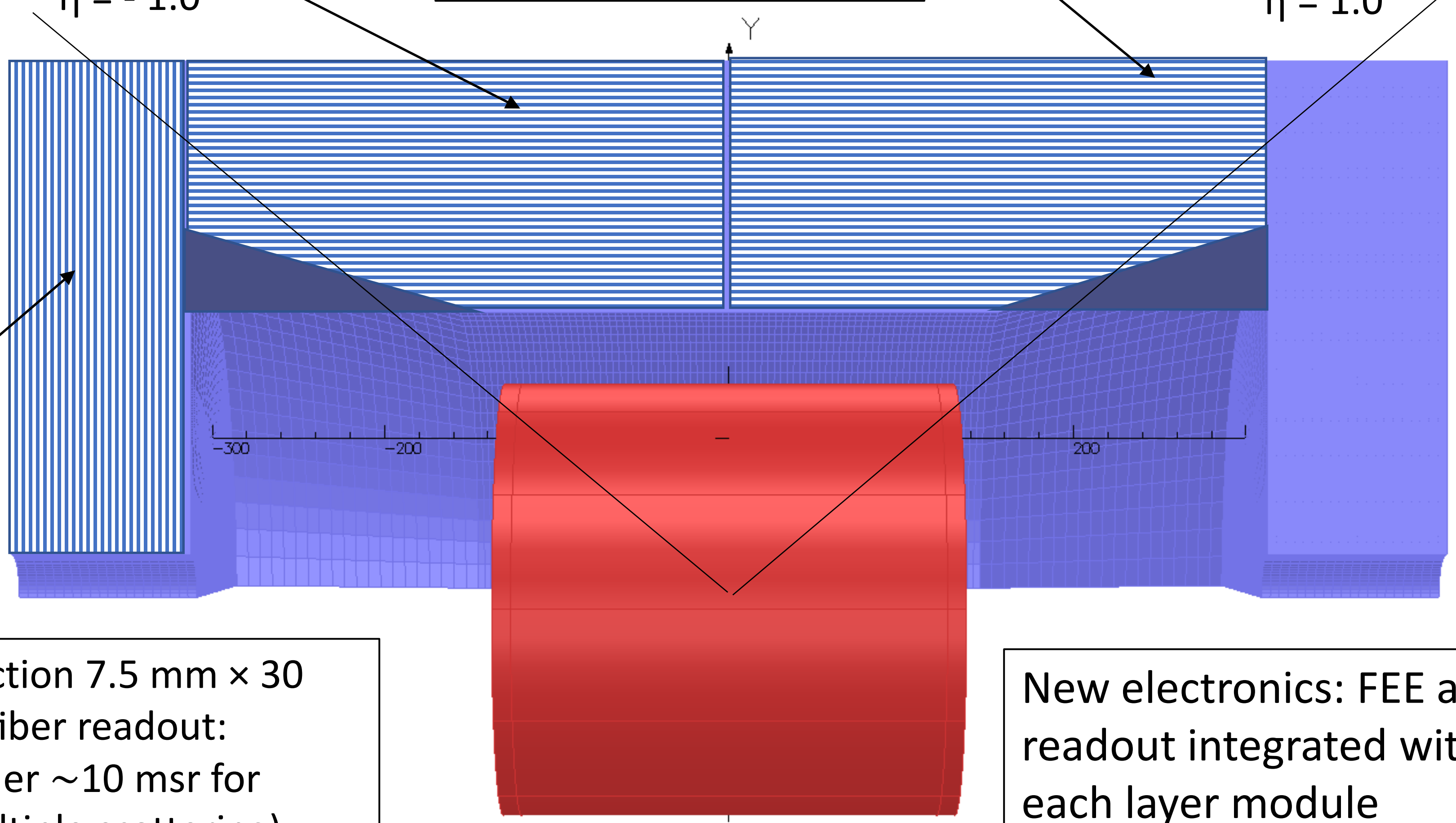
- Provide additional detector response and coverage for verification or veto.

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

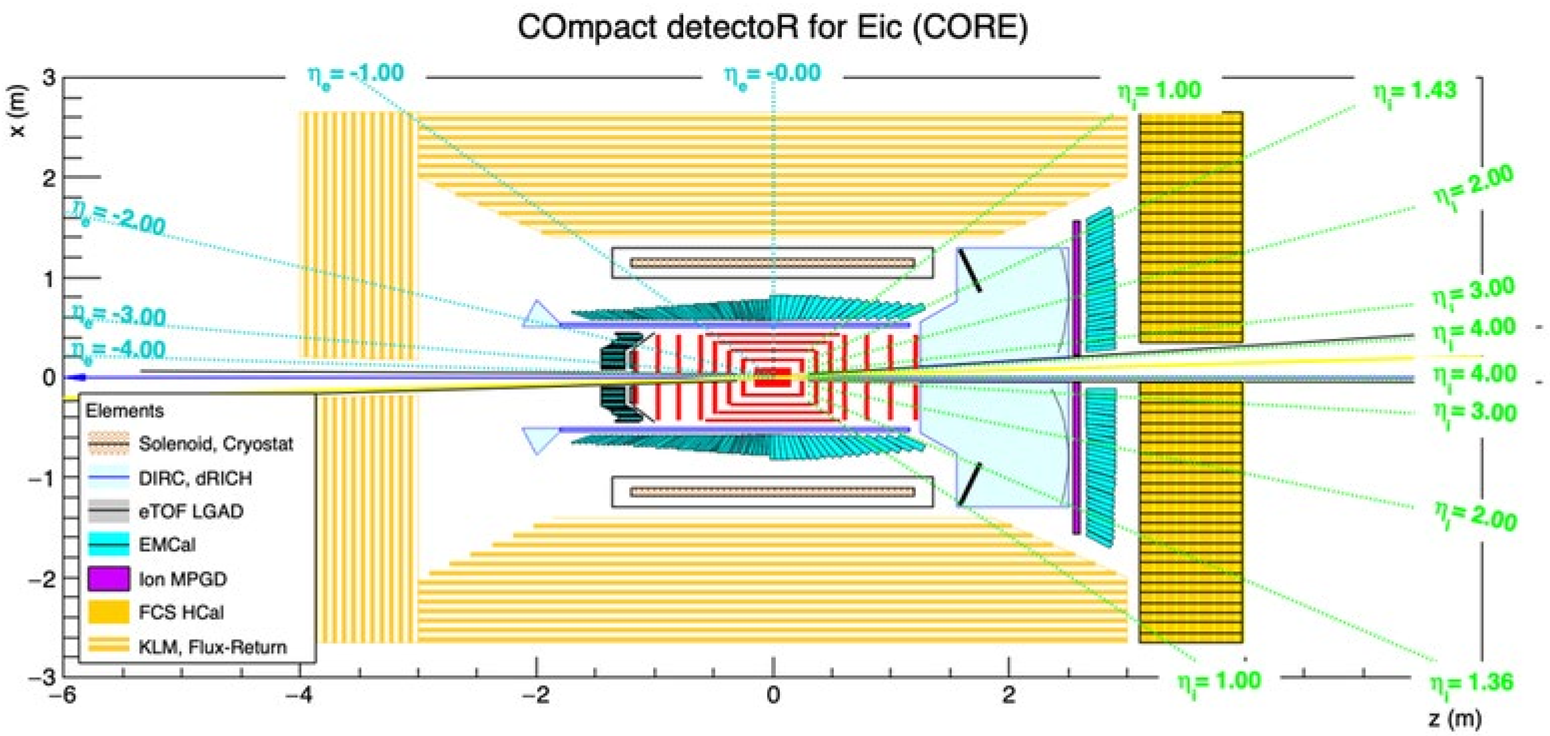


Strip geometry: cross section 7.5 mm × 30 mm w/ 1 mm dia. WLS fiber readout: angular resolution of order ~10 msr for inner barrel (~ muon multiple scattering)

New electronics: FEE and readout integrated with each layer module

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

KLM 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.

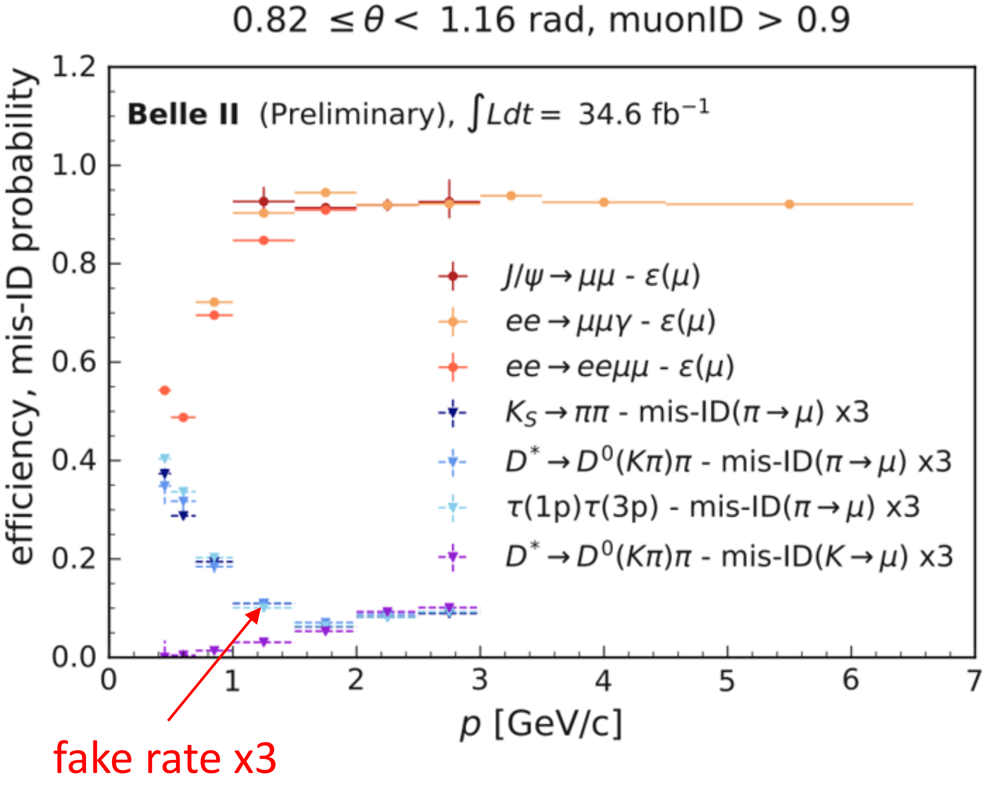
Barrel (electron & ion sides) nominal strip count:

- 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

Electron-Muon Identification and Analysis Techniques at Belle II

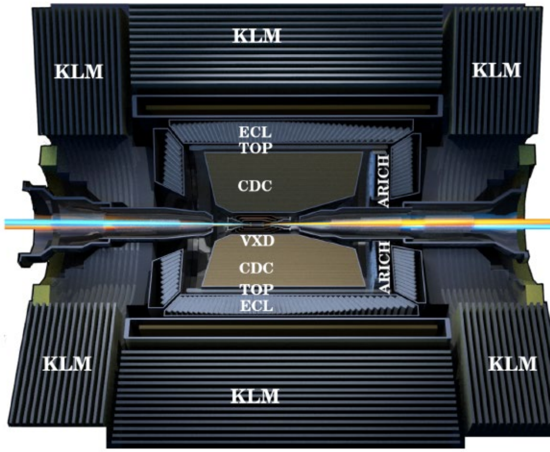
BELLE2-NOTE-PL-2020-027.pdf



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

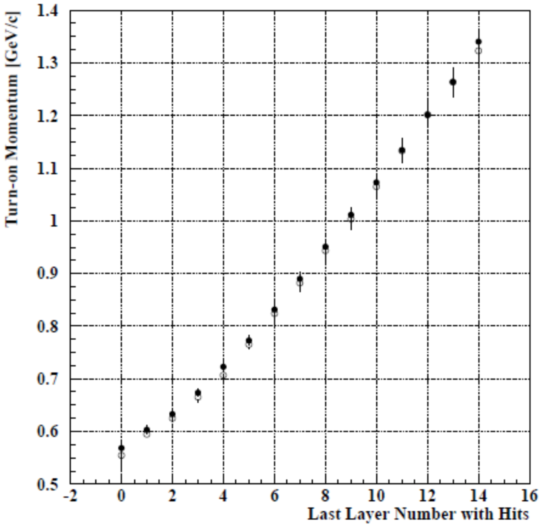
- Independently determine likelihood for each charged particle hypothesis
- construct a combined likelihood ratio.

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



- 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

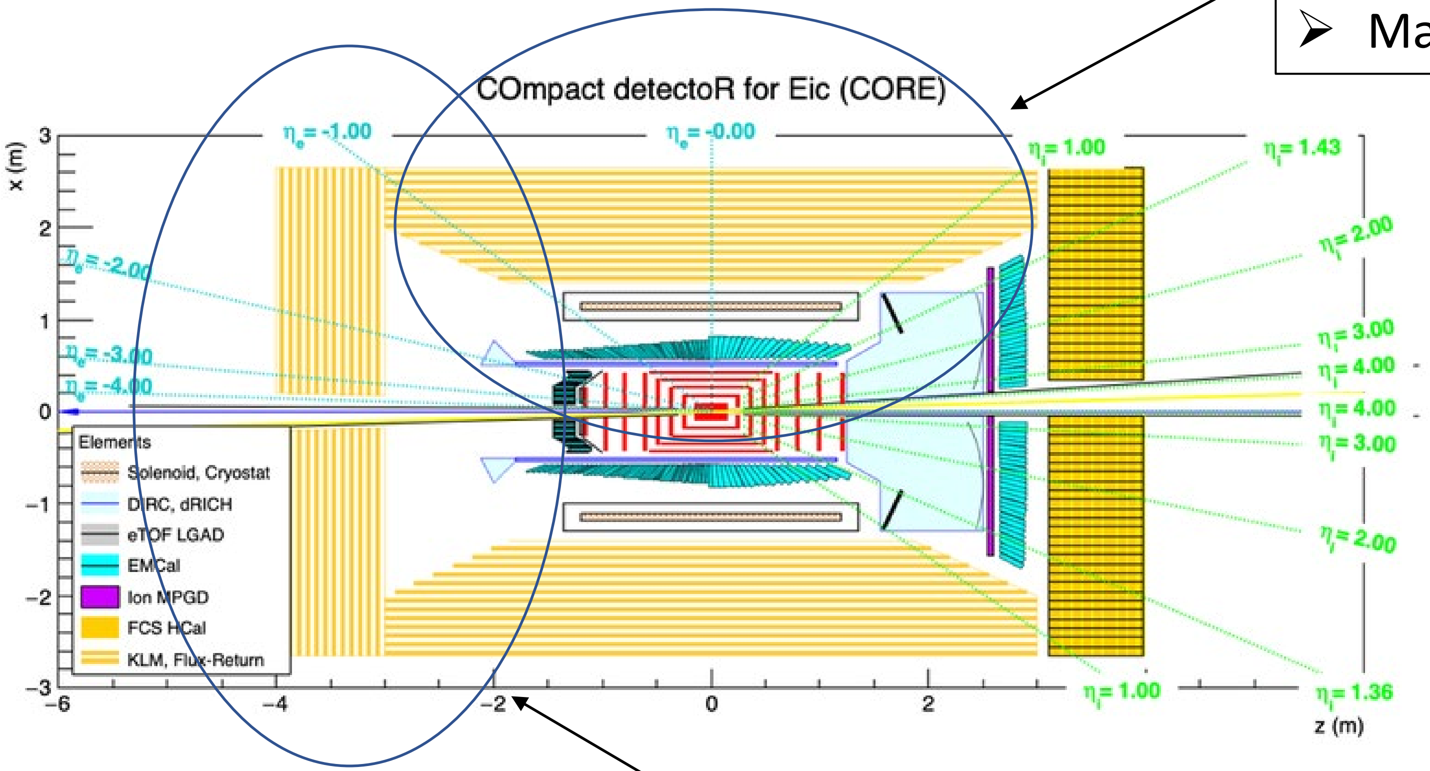
Lower momentum μ w/ tracking + ECL (Wave Form) info and BDT analysis (Bryan Fulsom, EIC Muon Detection and Quarkonium Reconstruction Workshop, 2022).

CORE 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 (Paul)

- 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

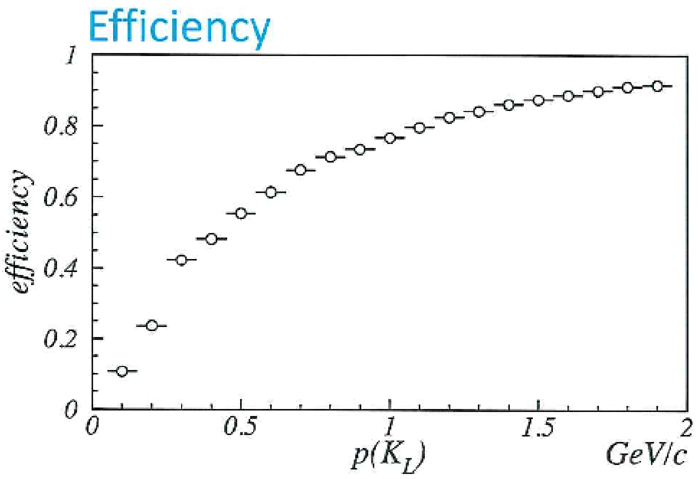
KLM Endcap::

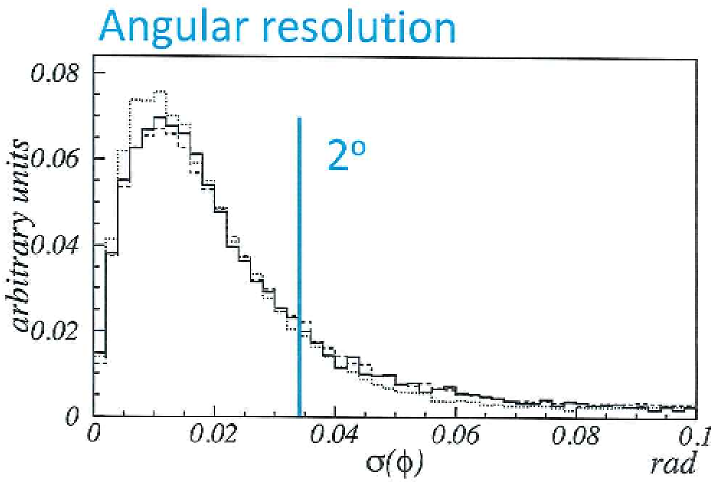
- 12 active layers (current)
- Material burden: electon-side inner dets (significantly varying with location)

- **Less material burden may lower Muon KLM detection threshold, but may also attenuate less background and fake contributions? … TBD (expect to be comparable or < Belle)**

Recall KLM performance: K-long detection and kinematics

- Belle II analyses and algo/FW implementation for K-long continue to be in progress; CORE proposal expectations 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 the CORE implementation could be studied and optimized in a suitable simulation environment.**

Concurrent / Ongoing and Projected Related Activities and CORE

- **Belle II KLM barrel KLM upgrade LOI under consideration for long shutdown in '28**
  - Switch (all) remaining RCP layers to scintillator strips and update all electronics
  - In an upgrade, is a rough K-long momentum determination by TOF possible? (e.g., ~ 100ps gives ~13% resolution for ~ 1. GeV/c K_L and ~ 2 m flight path)
  - R&D effort at (Belle II) Fudan Univ. to get good timing from long scintillator bars and SiPMs w/o using WLS to get the light out.
  - On-module FEE readout upgrades (including possible ASICs development) envisioned w/ specification (in updated form might need to address add'tl timing requirements).
- **CORE KLM**
  - Impact of above (Belle II) developments on implementation / design update for CORE
  - How to effectively pump up CORE KLM effort and coordinate with other developments?
  - Effort on more "traditional" (or innovative) HCAL solutions instead of a KLM?

Summary and Future Directions

- A KLM implementation with the "symmetric 3T" solenoid model was presented and costed for the CORE detector proposal submission … little DPAP feedback on idea.
- Useful now to incorporate KLM structure into a "full" CORE simulation environment (fun4all? or other) for further update and optimization for physics needs and practical implementation with solenoid/CORE.
- Investigate muon ID, efficiency and response in more detail: optimize geometry and include updated analysis techniques (machine learning, etc.) from other detectors
- Can a K-long momentum via TOF be effectively included? Could it impact KLM readout implementation and layer design (single layer with position by timing)?
- Investigate utility of wave form information added to analyses from KLM and other detectors

Thanks ! … volunteers /suggestions welcome!

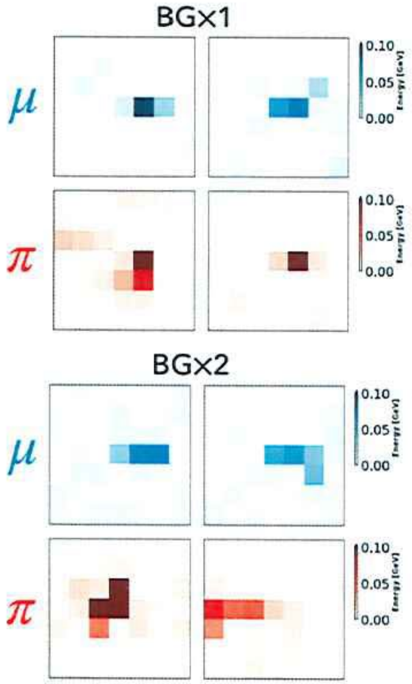
BACKUP SLIDES

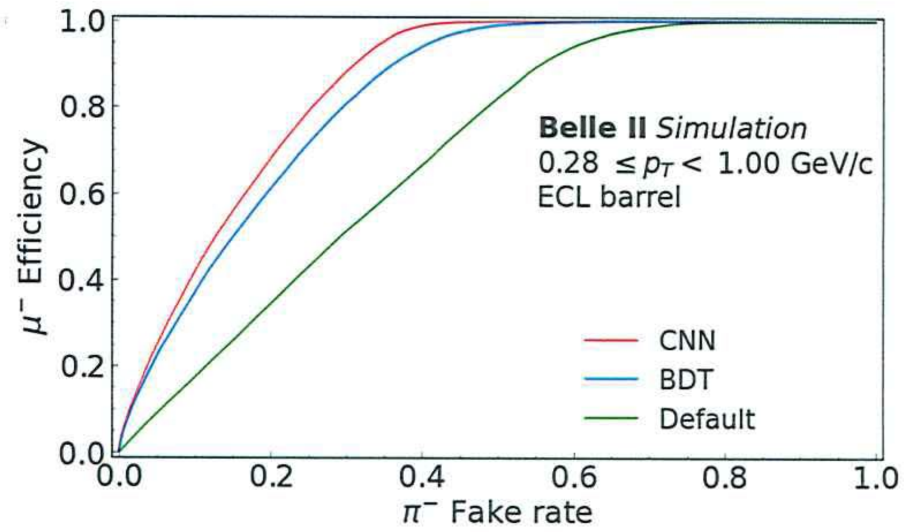
Future Developments

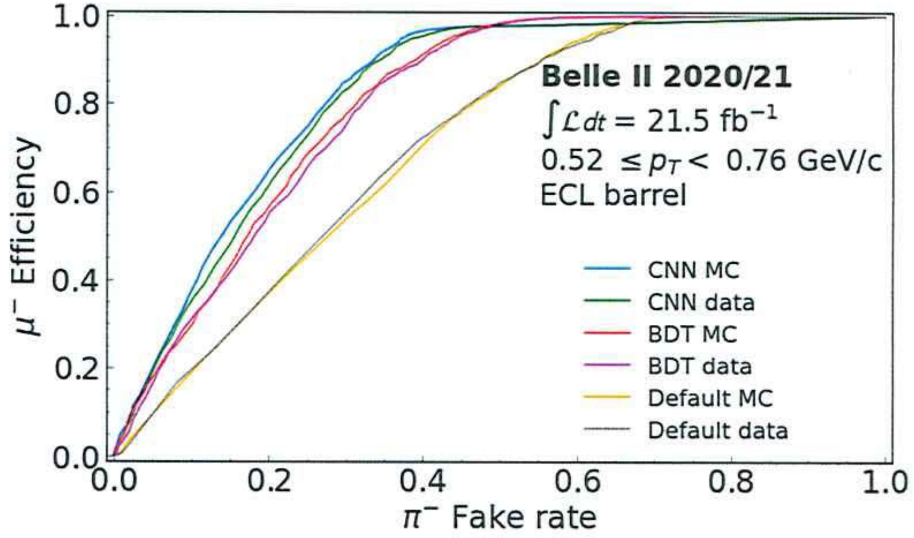
- Low-momentum μ reconstruction
  - Muons do not reach KLM
  - Use tracking and/or ECL information
  - BDT and CNN of variables/shape

Variable	Range	Description
E/p [c]	–	Ratio of cluster energy over track momentum.
$E_{cluster}$ [GeV]	–	Cluster energy.
E_1/E_9	–	Ratio of the energy of the seed crystal over the energy sum of the 9 surrounding crystals.
E_9/E_{21}	–	Ratio of the energy sum of 9 crystals surrounding the seed over the energy sum of the 25 surrounding crystals (minus 4 corners).
$\lvert Z_{40}\rvert$	–	Zernike moment $n = 4$, $m = 0$, calculated in a plane orthogonal to the EM shower direction.
$\lvert Z_{51}\rvert$	–	Zernike moment $n = 5$, $m = 1$, calculated in a plane orthogonal to the EM shower direction.
Z_{MVA}	–	Score of BDT trained on 11 Zernike moments.
ΔL [mm]	–	Projection on the extrapolated track direction of the distance between the track entry point in the ECL and the cluster centroid.
$\Delta \log \mathcal{L}(\ell/\pi)_{CDC}$	–	Log-likelihood difference between $\ell - \pi$ hypothesis in the CDC.
$\Delta \log \mathcal{L}(\ell/\pi)_{TOP}$	ECL barrel	Log-likelihood difference between $\ell - \pi$ hypothesis in the TOP.
$\Delta \log \mathcal{L}(\ell/\pi)_{ARICH}$	ECL FWD endcap	Log-likelihood difference between $\ell - \pi$ hypothesis in the ARICH.
$\Delta \log \mathcal{L}(\mu/\pi)_{KLM}$	$p > 0.6$ GeV/c	Log-likelihood difference between $\mu - \pi$ hypothesis in the KLM.

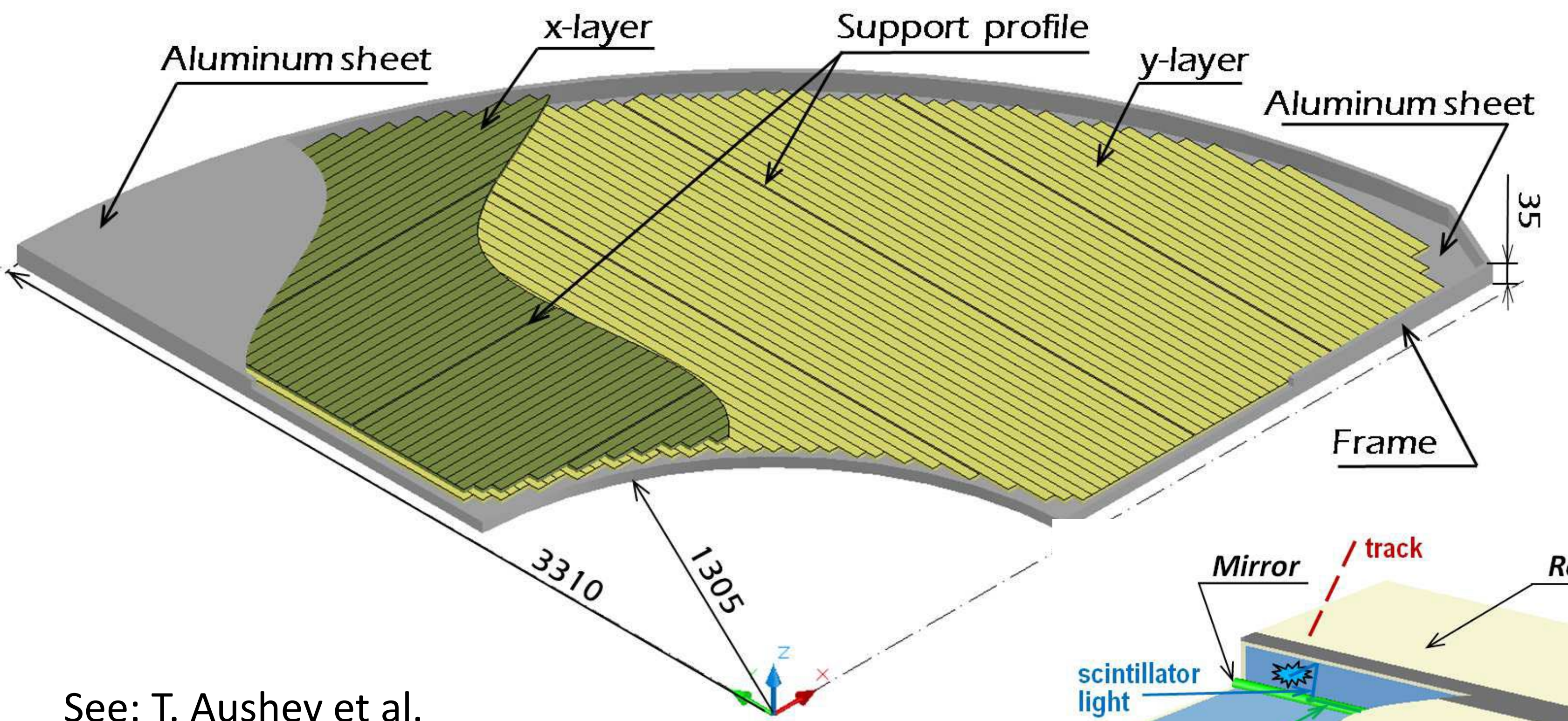
EPJ Web Conf., 245 (2020) 06023



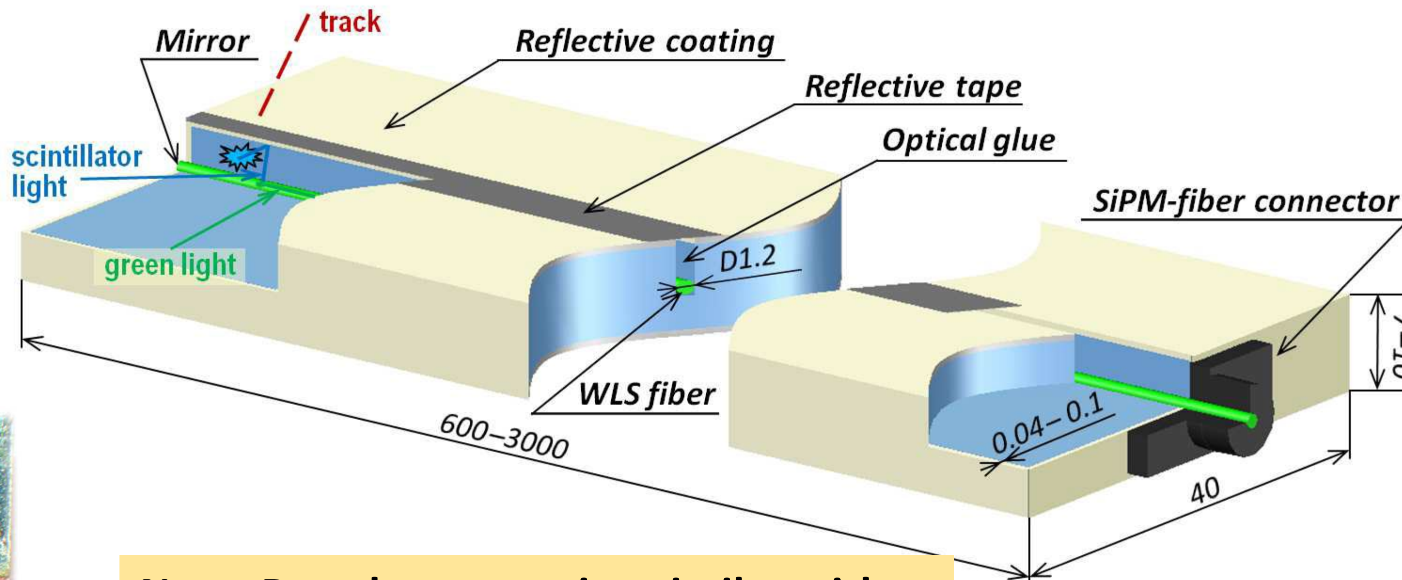




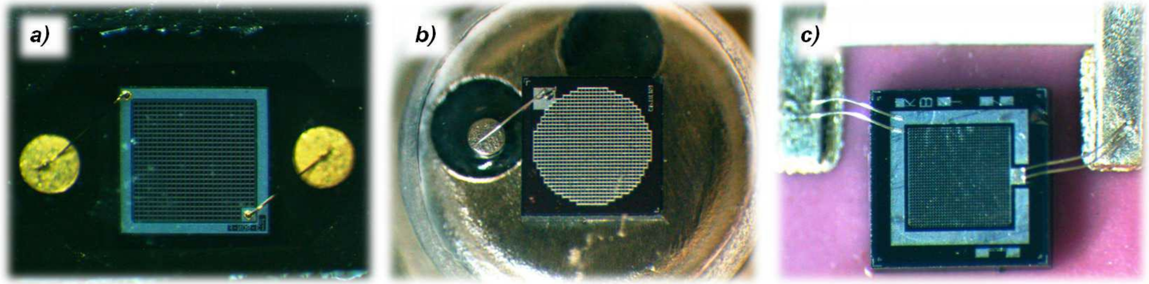
All Endcap layers upgraded to scintillator at start of Belle II



- Similarly, 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

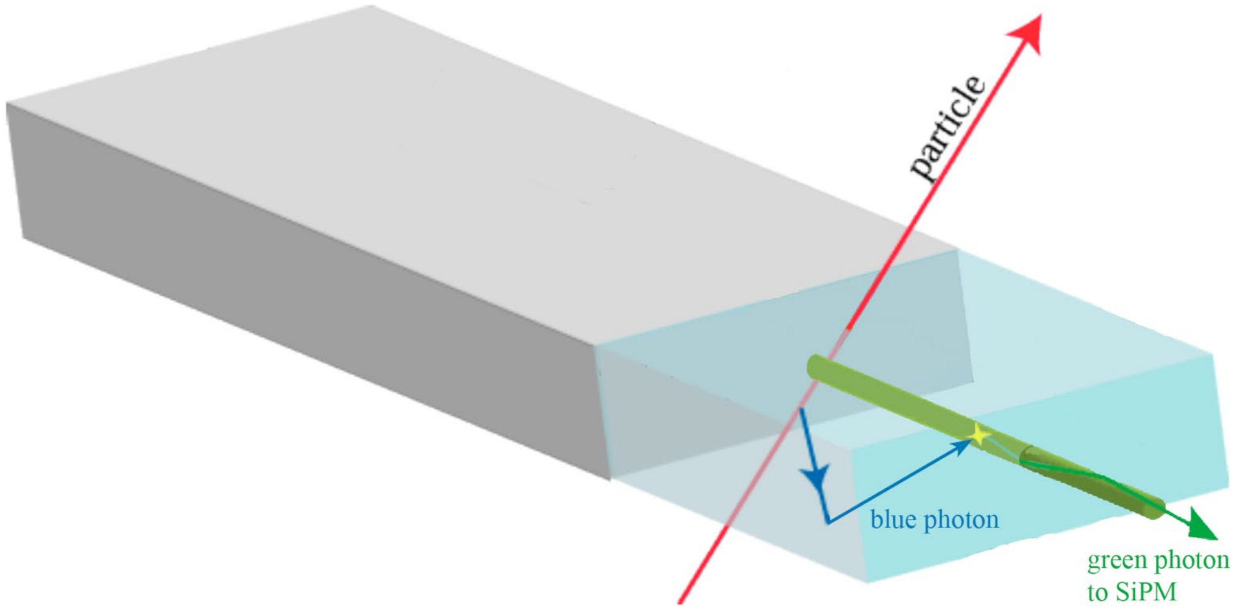


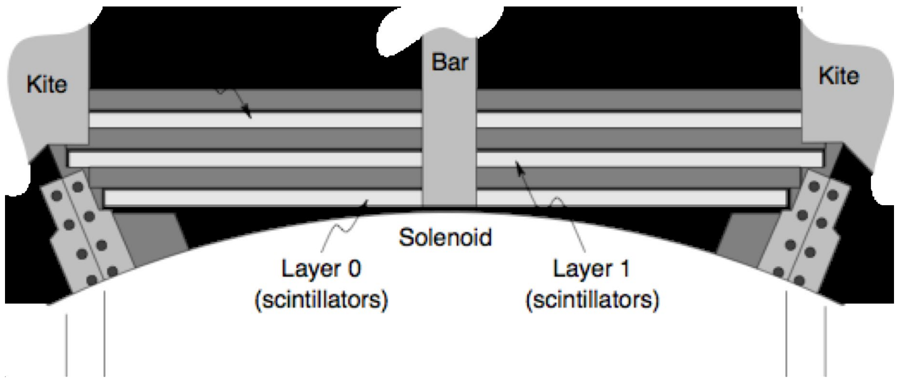
See: T. Aushev et al. arXiv:1406.3267v3 (2015) for details



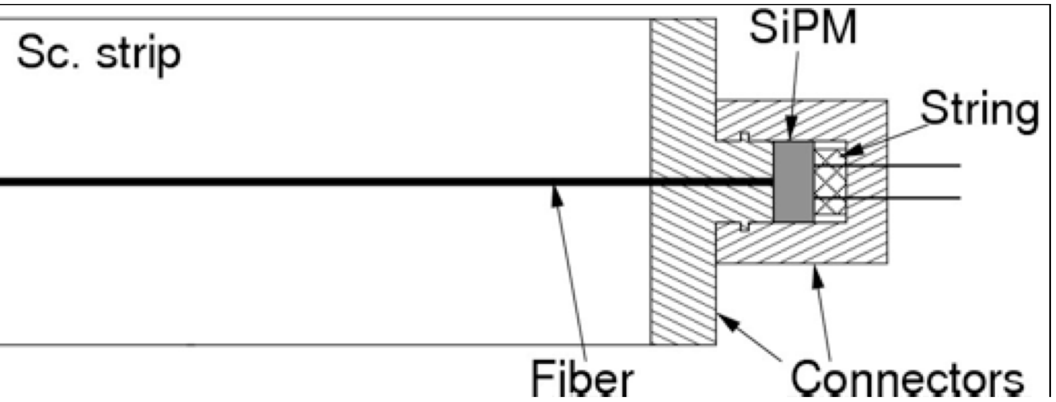
Note: Barrel construction similar with crossed scintillator strips – first 2 layers

Now: first 2 Barrel layers are scintillator based (replace RPC)

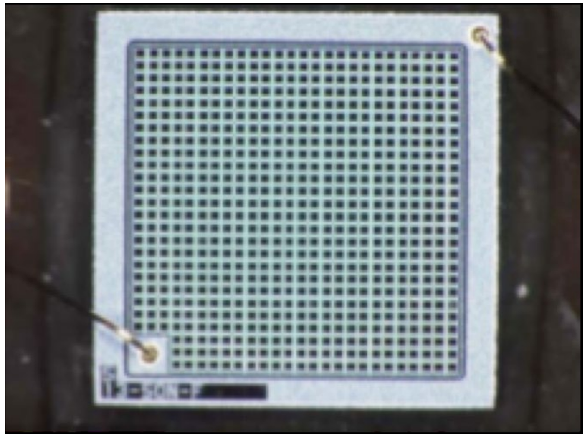




- Scintillator strips: ~ 1x2 cm cross section extruded with fiber hole or machined w/ cut
- Hamamatsu SiPM attached to fiber (mirrored at far end)

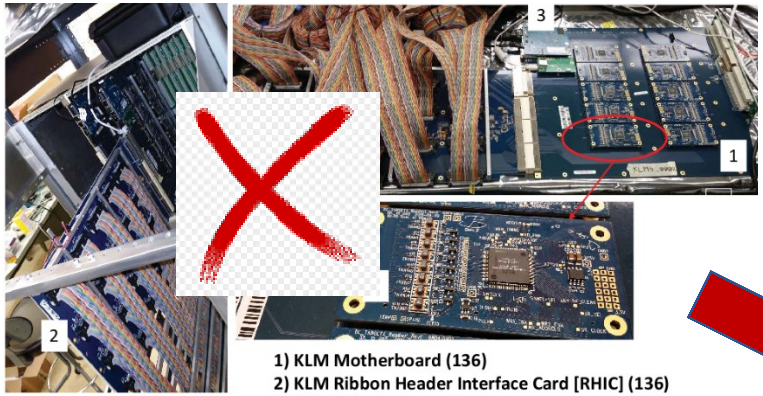


- 1.5 T field operation
- rad-hard (est. >10-year lifetime @ Belle II)
- 8-pixel threshold => >99% efficiency



~ 1.3 x 1.3 mm2
667 pixels

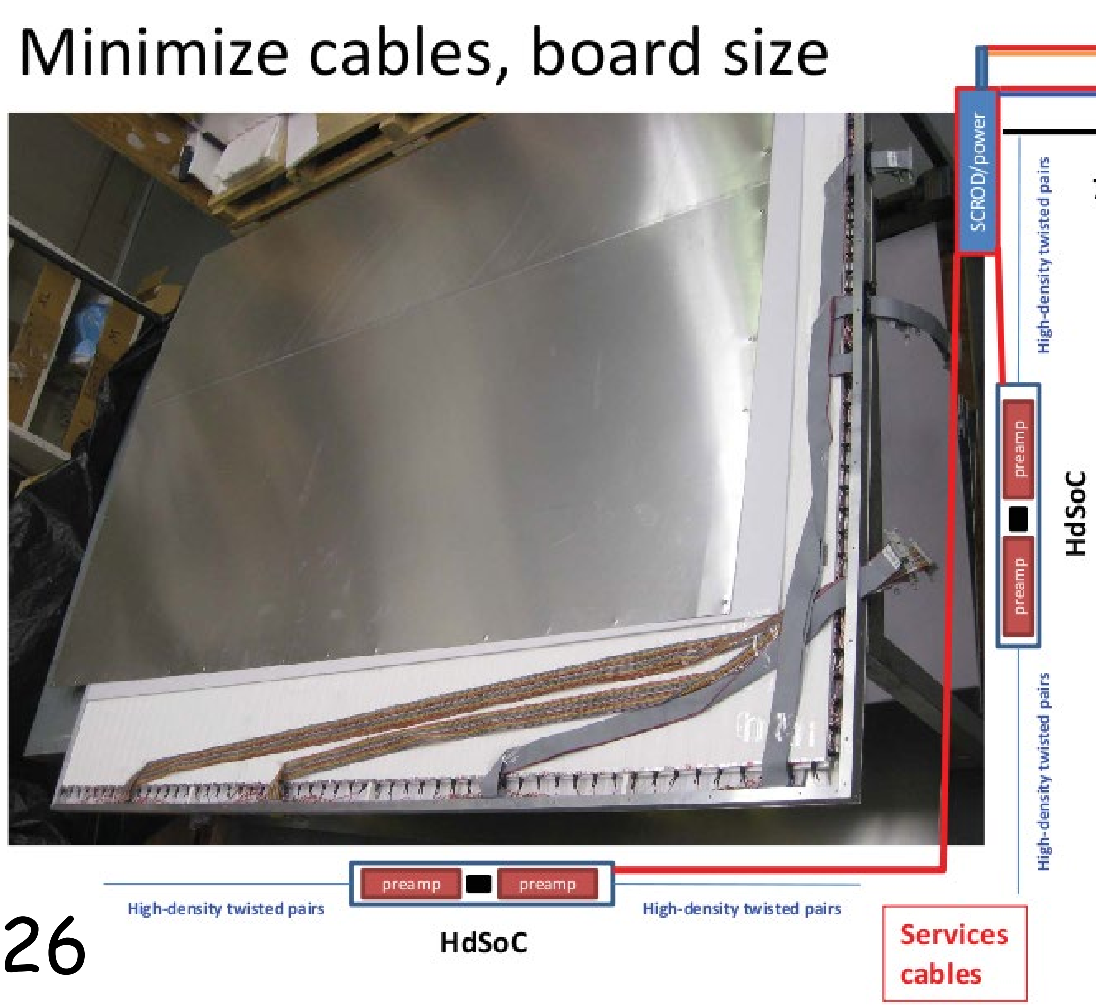
Plans (EOI to Belle II): replace 13 remaining Barrel RPC layers



104 Endcap sets
32 Barrel

- ➢ 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 ~ 2026

- ➢ ~ 26k channels: initial cost est. ~1.4-1.8M elec., ~4.8M det., w/ some reuse of crates, etc.

Example: upgraded Belle II detector at Super KEKB

- Active readout elements interleaved with 1.5 T solenoid magnet return steel
- Configuration optimized primarily for μ and K_L detection and ID
- Relatively inexpensive, technically simple construction, robust operation
- It is not a full-fledged/proper EM or Hadron calorimeter

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