Performance of the Belle II Aerogel-Based Ring-Imaging Cherenkov Counter system in SuperKEKB 2019 Phase 3 Operation

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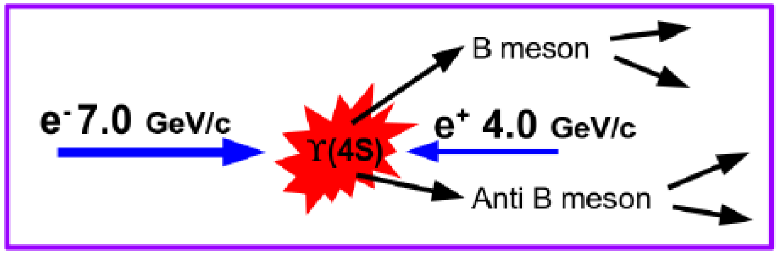
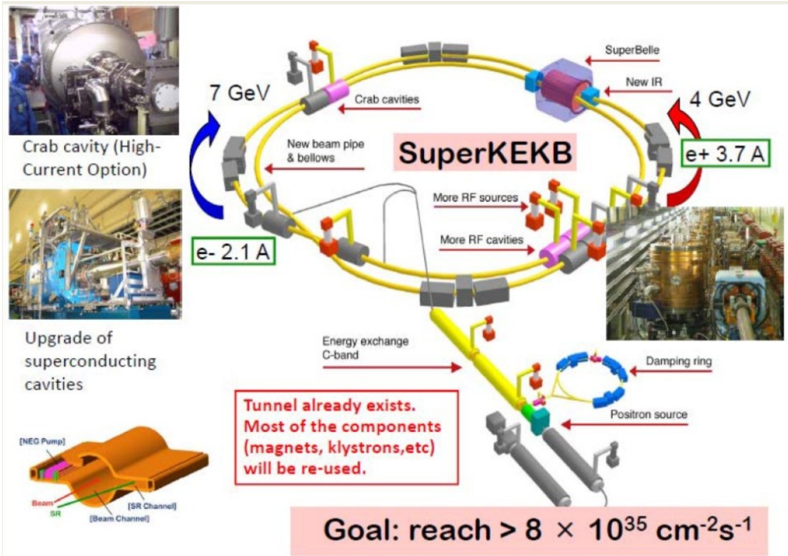
Outline

- Introduction to SuperKEKB and Belle II.
- ARICH system:
  - Detector design and PID scheme
  - HAPD.
  - Readout electronics.
  - New cooling system.
- Particle identification with ARICH:
  - PID Likelihood.
  - PDF calibration.
  - Performance study.

SuperKEKB

- SuperKEKB: Upgraded from KEKB.
  - 40 times larger luminosity of KEKB with nano beam scheme.
  - Asymmetric energy collider: 7.0 GeV e^- and 4.0 GeV e^+ for $\Upsilon(4S) \rightarrow B\bar{B}$.
  - Luminosity so far: L_{peak} = 1.1 x 10^{34} $cm^{-2}s^{-1}$ under I_{HER} = 370mA and I_{LER} = 450mA. L_{int} = 10.57 fb^{-1}.
  - Beam collision operation phase: Phase 2: Apr. to Jun. 2018. Phase 3: From Mar. 2019.



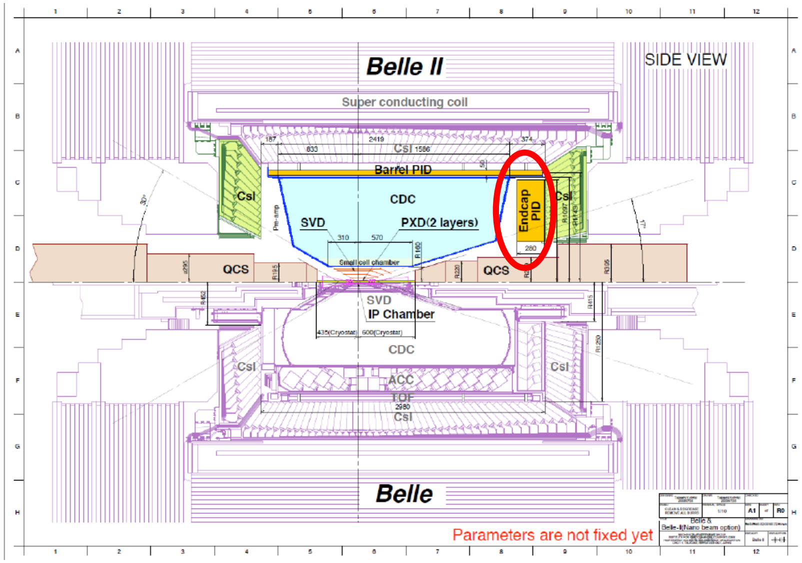


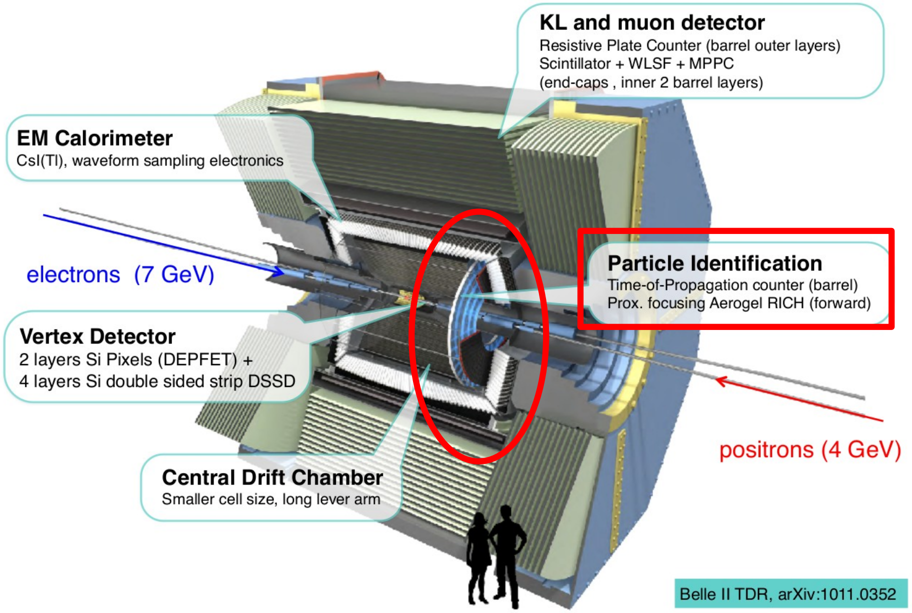
Parameter	LER	HER	Unit
E	4.000	7.007	GeV
I	3.6	2.6	A
β_x^*	32	25	mm
β_y^*	270	300	μm
σ_z	6	5	mm

Parameter	Value	Unit
N_b	2500	
C	3016.315	m
$2\phi_x$	83	mrad
L	8×10^{35}	$cm^{-2}s^{-1}$

Belle II detector

- Belle II: A newly-designed sub-detectors set to improve detection performance.
  - Physics target: Rare B, τ, charm physics, Dark Matter search and CP Violation.
- Requirements with high luminosity:
  - High trigger rate (~30 kHz).
  - High background.
  - Radiation tolerance.
- Particle ID:
  - Barrel: Time-Of-Propagation (TOP)
  - Forward Endcap: Aerogel RICH (ARICH)
- The goal of ARICH: to separate K and π up to > 4σ at momenta up to 4 GeV/c
  - Critical for physics search such as rare B and CP Violation in B decays.

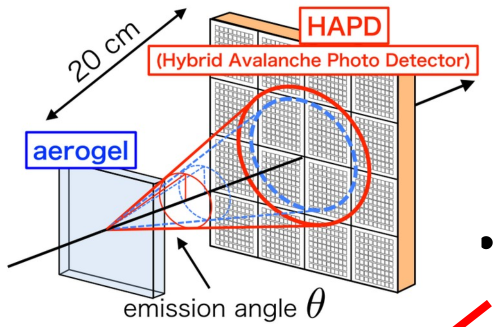




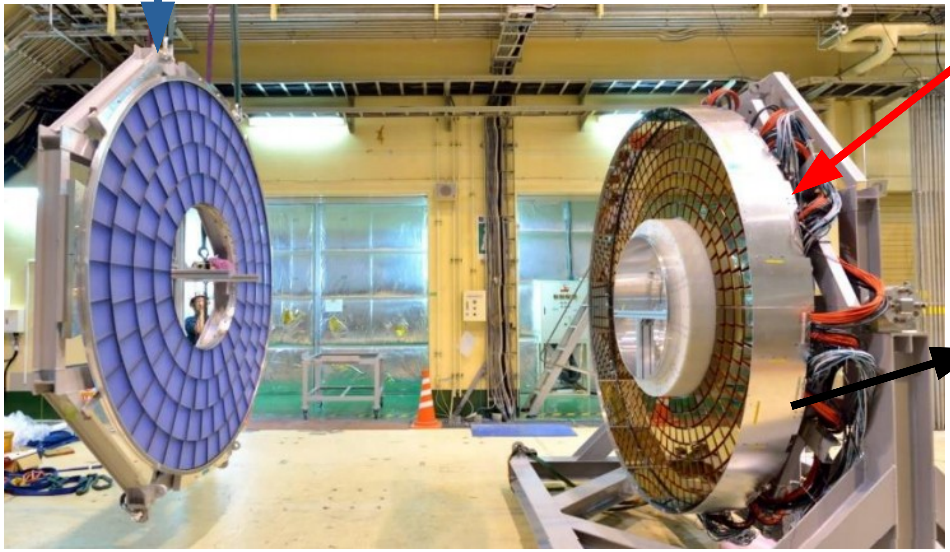
ARICH detector

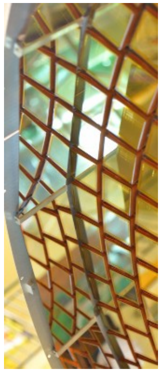
Two main structures in the ARICH detector:

- **Silica aerogel radiators:**
  to produce Cherenkov photons
  - 248 aerogel tiles in total.

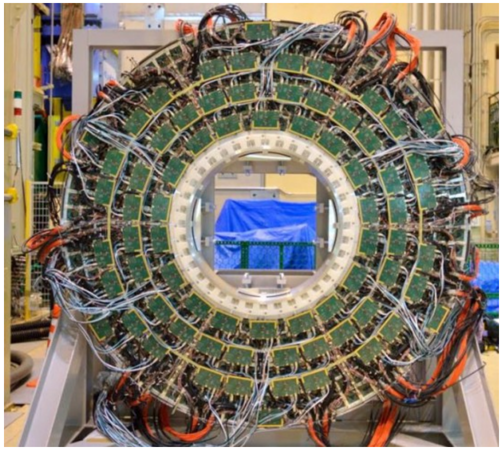


- **Photodetector:**
  Hybrid Avalanche Photo-Detector (HAPD) to detect Chrenkov photons
  - 420 HAPDs in total.
- **Readout electroincs:**
  Mounted on the backend to readout photon signals.





Mirror in the edge to increase photon detection efficiency.



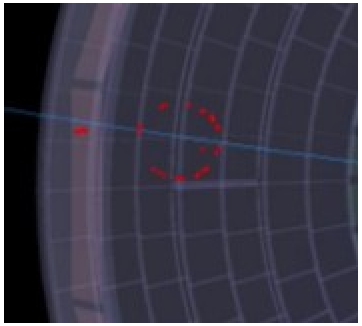
Installation is done in 2017 summer and commissioning has been done in Phase 2.

PID with ARICH

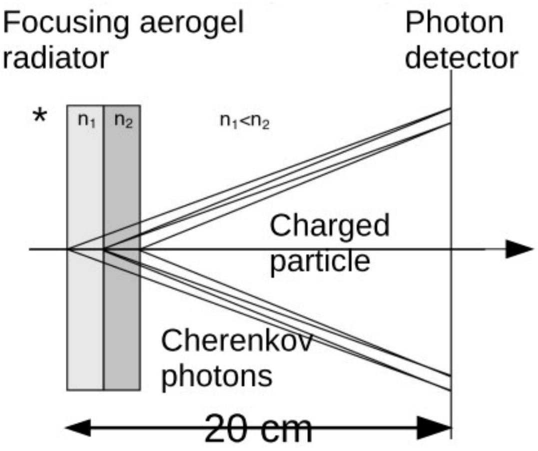
- The emitted Cherenkov photons would be detected by the HAPD plane as ring image. Radius of the ring image (Cherenkov angle) is the key to PID. Photon detector with high position resolution is critical.

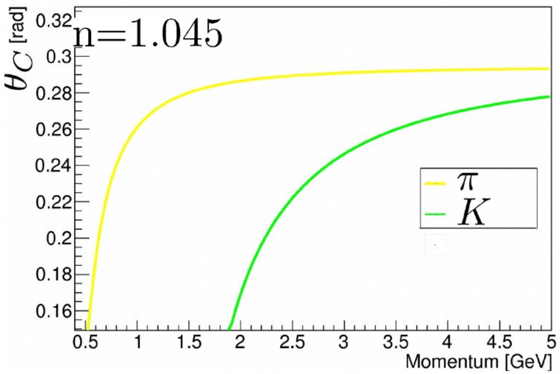
$$m = p\sqrt{n^2 \cos^2 \theta - 1}$$

m: particle mass
p: particle momentum
n: refractive index

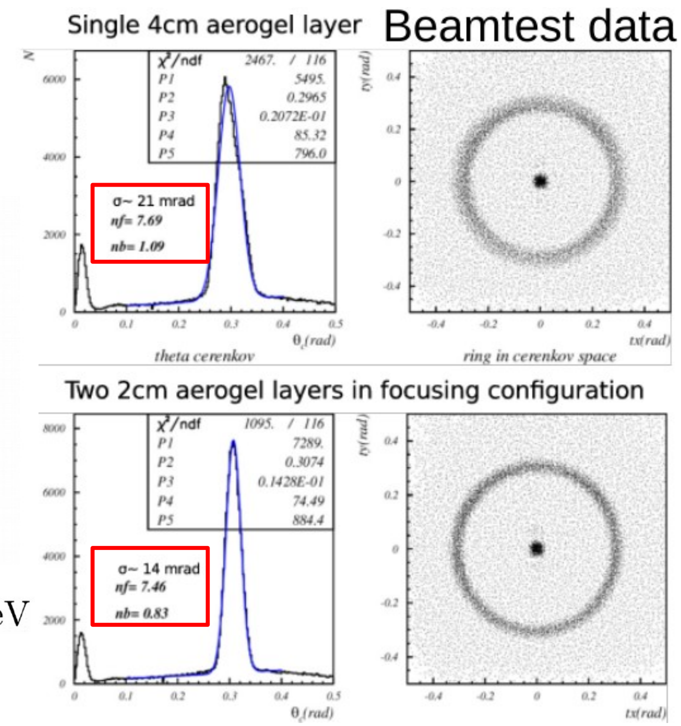


- Two 2 cm thick layers of aerogel radiator as a focusing configuration to enhance to position measurement resolution.
  (n_1 = 1.045 and n_2 = 1.055)





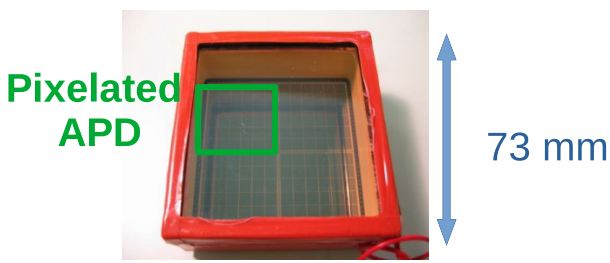
$\theta_C(\pi) - \theta_C(K) \sim 30$ mrad @ 3.5 GeV

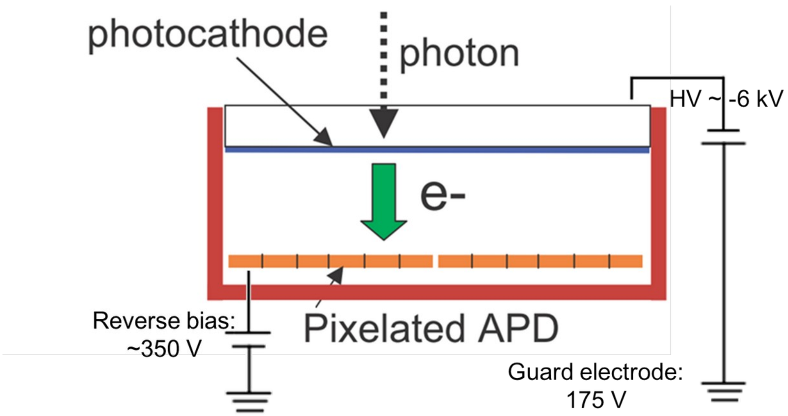


HAPD

- Hybrid Avalanche Photo-Detector (HAPD) is used to detect Chrenkov photons generated by aerogel tiles.
  - Single photon detection.
  - 4 APD chips.
  - Works in a magnetic field of 1.5T.
  - Radiation tolerance: 10^{12} neutron/cm^2 (1 MeV equiv.) ~10 years of Belle II.

Size	$73 \times 73 \times 28\,\mathrm{mm}^3$
Number of channels	$12 \times 12 = 144\,\mathrm{ch}$
Channel size	$4.9 \times 4.9\,\mathrm{mm}^2$
Effective area	$65\,\%$
Photo-cathode material	Bialkali
Quantum efficiency	$\sim 28\,\%$ at $400\,\mathrm{nm}$
Bombardment gain	$\sim$1800
Avalanche gain	$\sim$40
Total gain	72000
Capacitance	$80\,\mathrm{pF}$

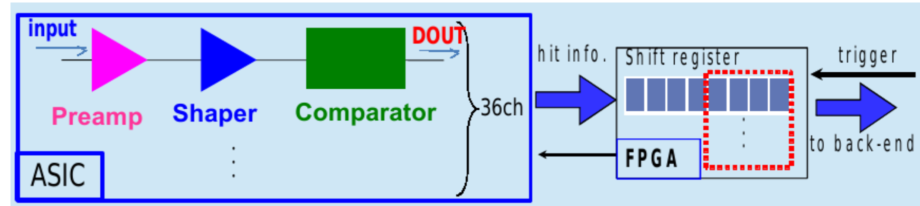




- Two types of voltage supply to HAPD:
  - HV: -6 kV
    448 ch in total.
  - Bias-Guard:
    175V for guard and 350V for bias.
    2160 ch in total.

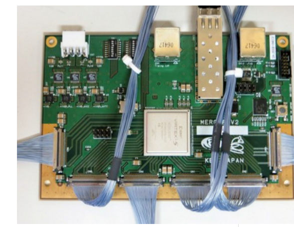
Readout electronics system

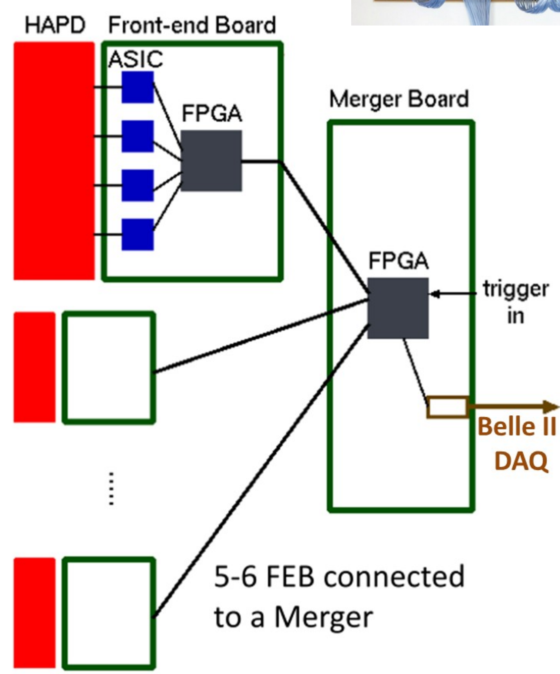
- Two types of FPGA chips:
- Front-end (FEB): Xilinx Spartan-6 FPGA
  - 420 in total.
  - Four 36-ch ASICs to digitize photon signals from HAPD.
- Merger: Xilinx Virtex-5 FPGA
  - 72 in total.
  - Controls up to 6 FEB: Firmware downloads and parameter settings.
  - Combine FEB data to central DAQ with zero suppression.
  - Slow monitoring/control of the system: Temperature, voltage, FPGA SEU, etc.
  - **New firmware design: Detection and self-repair on FEB SEU. Details in the next page.**



Front-end

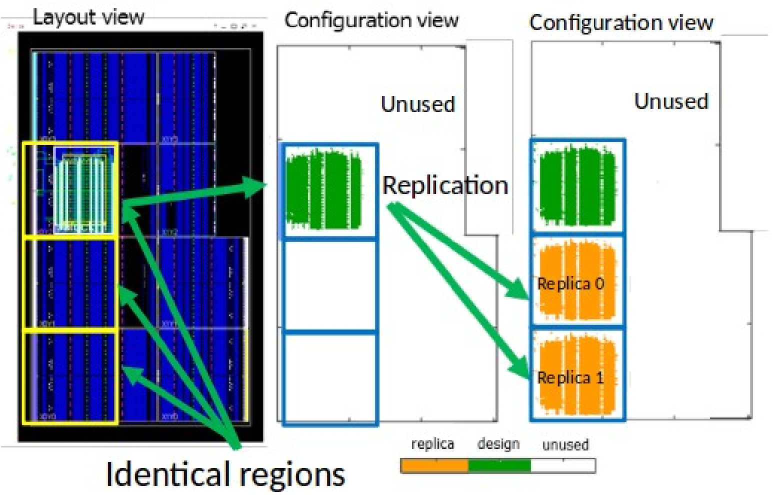
Merger

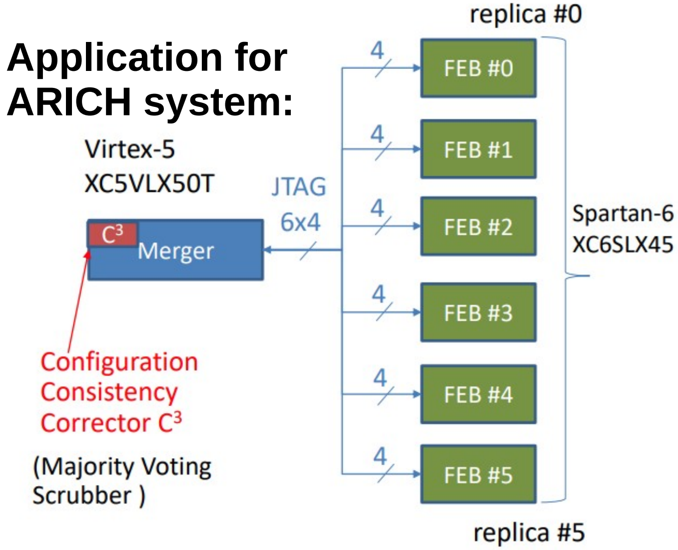




R. Giordano *et al.*, Instruments 2019, 3(4), 56

- Under peak luminosity of Belle II, Single-event-upset (SEU) on FEB is expected to be frequent.
  - Uncorrectable: 0.2/hr.
- We utilizes the scheme of real-time self-repair on FEB SEU.
  - By accessing icap interface, Majority vote redundant frame bits to detect damaged frame and repair it by partial re-configuration.
  - Application for ARICH: Scrubber is implemented in Merger. Configuration frame of FEB would be readout to Merger.
  - The design has been validated and has better performance then Xilinx Soft Error Mitigation (SEM) IPCore.

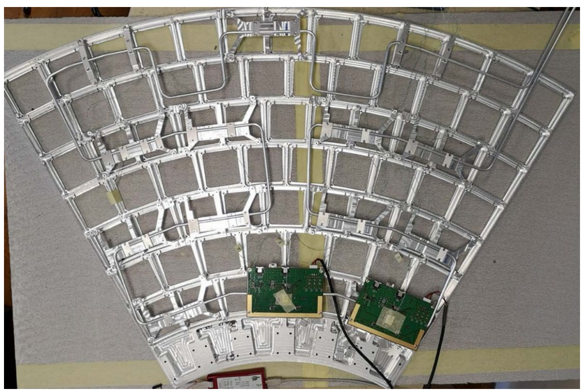


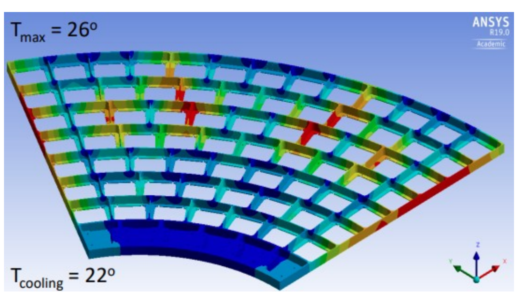


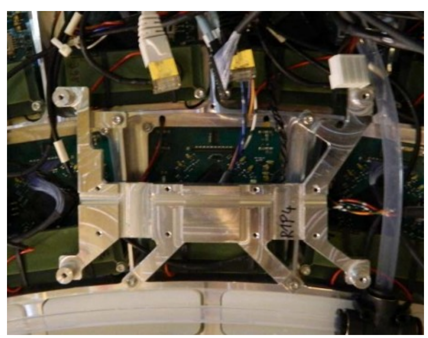
Different FPGA for Merger/FEB.
Modification in interface: icap → JTAG.

Cooling system

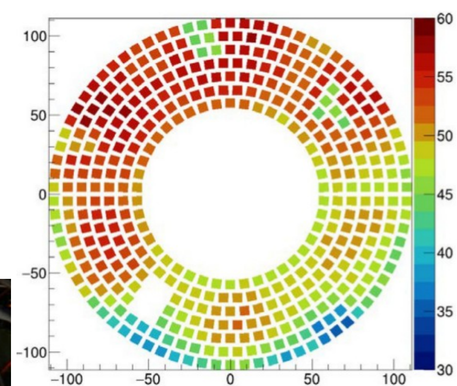
- Due to temperature problem, ARICH could operate only 2/3 of the electronics in most of Phase 2.
- New cooling system with additional metallic support and cooling pipes attached on FPGA cores. Ready in the end of 2018.
  In Phase 3, ARICH has full readout system operation.



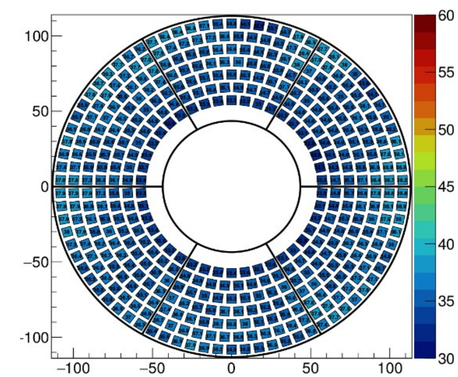




A special run in Phase 2 with full setup.



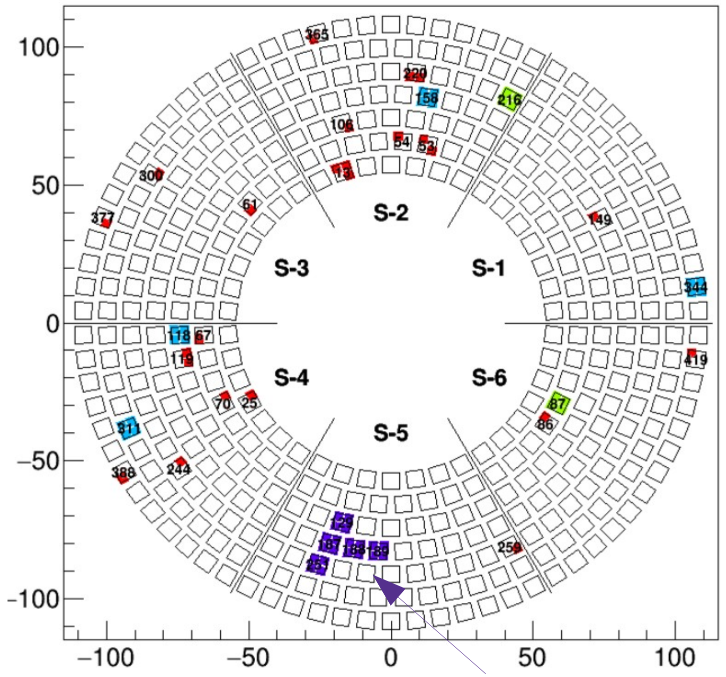
Phase 3

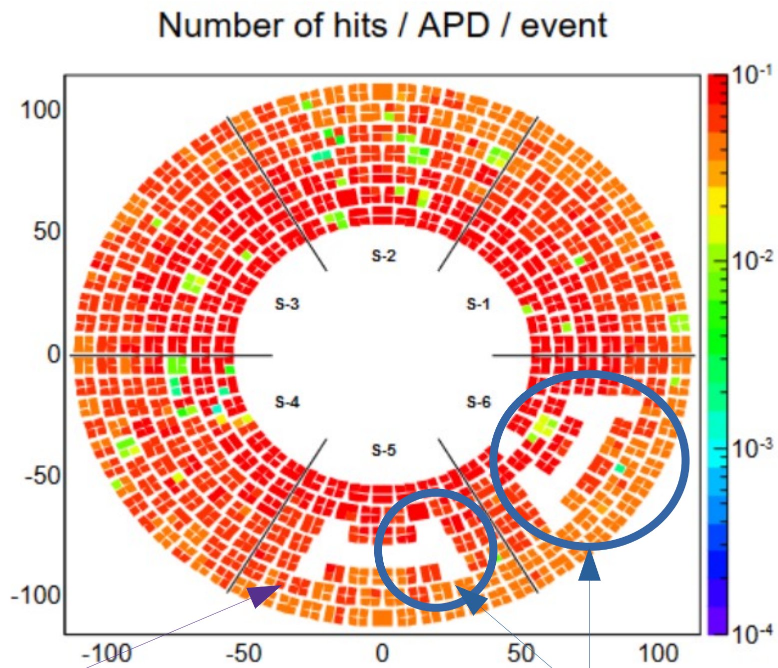


Temperature per FEB

Overall hardware status in Phase 3

- Malfunctioning APDs: 3%
  - Mainly due to problems in high voltage in HAPD.
- Malfunctioning electronic (readout channels): 1 Merger, 1.4%
  - Due to problem in power supply to electronics and in data link.





1 Merger (5 FEB) is constantly masked in Phase 3 due to voltage supply.

3 Mergers were sometimes excluded in Phase 3 due to unstable data link. To be fixed for 2020 runs.

PID likelihood

- PID is based on the comparison on the Cherenkov angle distribution between the observed pattern and the expected probability density functions (PDFs) of the charged particle hypothesis.

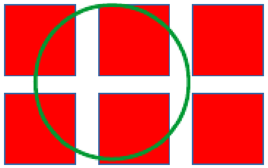
- Likelihood definition:

$$\ln \mathcal{L}_h = -\boxed{N_h} + \sum_{\text{hit } i} [\boxed{n_{h,i}} + \underline{\ln (1 - e^{-n_{h,i}})}]$$

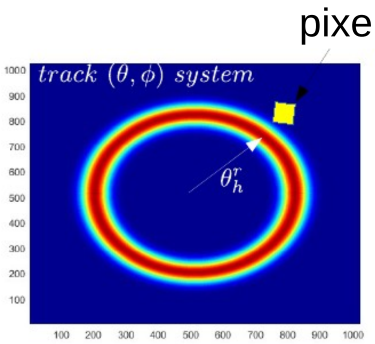
Probability of a pixel to get hit.

  - *h*: charge particle hypothesis.

- ***N_h***: Expected total number of hits.
Considering the factor such as scattering, absorption, acceptance, etc.



- ***$n_{h,i}$***: Expect number of hits on pixel i.
Obtained by integrating the PDF over the pixel *i*.



- Likelihood ratio is defined to separate *K* from *π*:

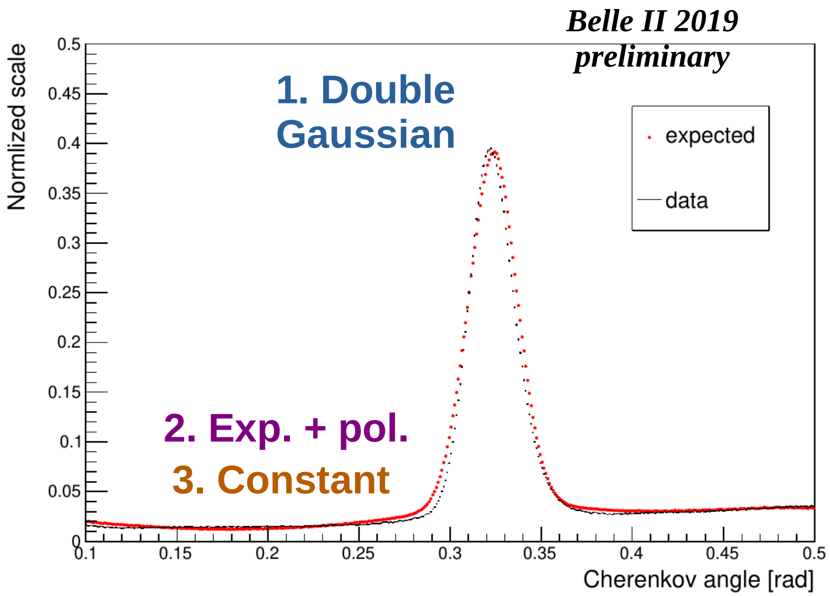
$$R_{K/\pi} = \frac{\mathcal{L}_K}{\mathcal{L}_K + \mathcal{L}_\pi}$$

$$R_{\pi/K} = \frac{\mathcal{L}_\pi}{\mathcal{L}_K + \mathcal{L}_\pi} = 1 - R_{K/\pi}$$

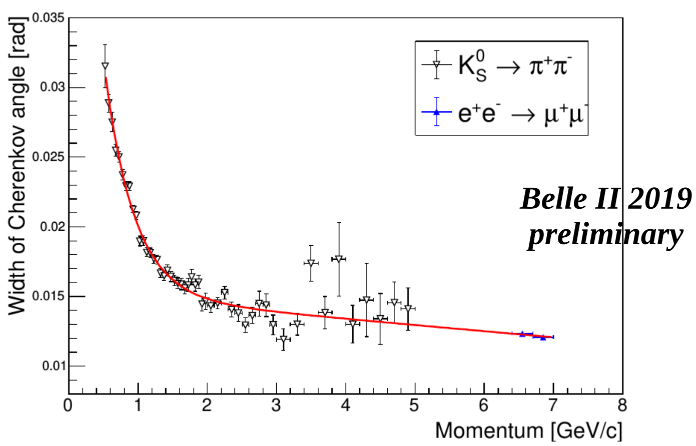
PDF calibration

- PDF is constructed by following components:
  - **1.** Cherenkov photons from aerogel.
  - **2.** Track assoicated background.
  - **3.** Random background.
    electronics noise,
    HAPD dark counts, etc.

- Calibration is performed with $ee \rightarrow \mu\mu$ (for p > 7 GeV/c) and $Ks \rightarrow \pi\pi$ (for p < 5 GeV/c) control samples.
  - Width of the Gaussian peak is calibrated as a function of momentum.
  - Random background: By using the hits in the time window sideband to obtain the the average number of hits per event for all channels.

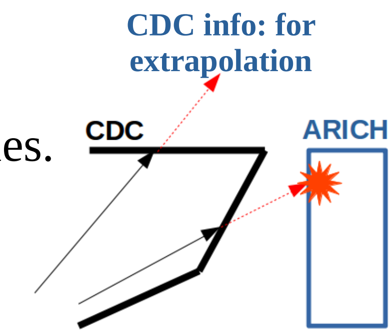


Comparision between early Phase3 data and PDF using ee → μμ sample.

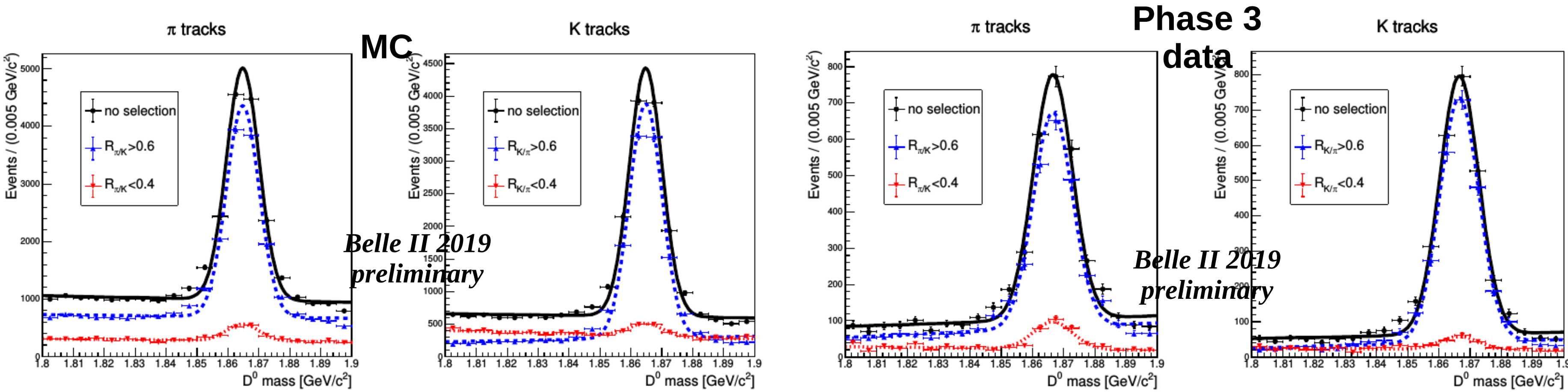


PID performance check

- The performance is checked by using $D^{*+} \to D^0\pi^+$ and $D^0 \to K^-\pi^+$ control sample with an early Phase 3 data of 5.15 fb^{-1} and MC samples.
  - 1 track from D^0 reaches ARICH, and it passes Drift Chamber.
  - $|M(D^{*})\text{-}M(D^0)\text{-}0.1454| < 0.0015$ GeV/c^2.



- Reconstructed D^0 mass:



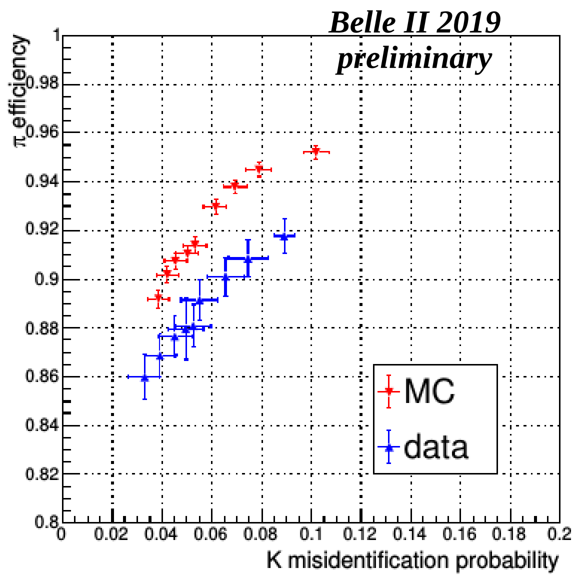
- Overall performance between data and MC with requiring $R > 0.6$ (< 0.4):
  - Basically consistent. 3% difference for pion.

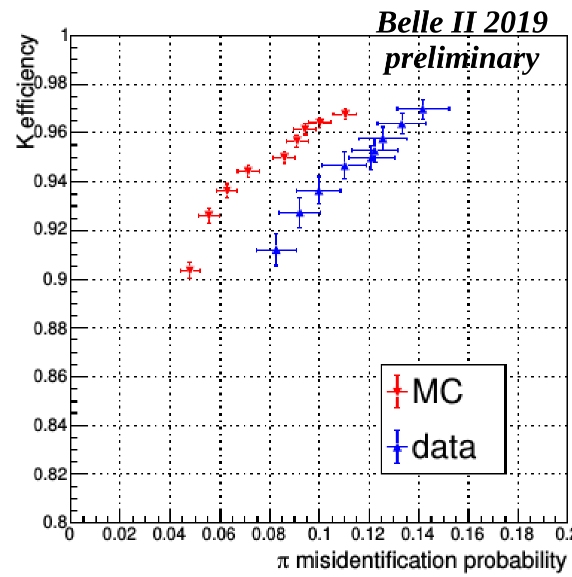
No selection
$R_{K/pi} > 0.6$
$R_{K/pi} < 0.4$

	K eff.	π mis.	π eff.	K mis.
data	$94.7 \pm 0.5\,\%$	$11.0 \pm 0.9\,\%$	$88.0 \pm 0.8\,\%$	$5.0 \pm 0.8\,\%$
MC	$94.4 \pm 0.3\,\%$	$7.1 \pm 0.4\,\%$	$91.1 \pm 0.3\,\%$	$5.0 \pm 0.4\,\%$

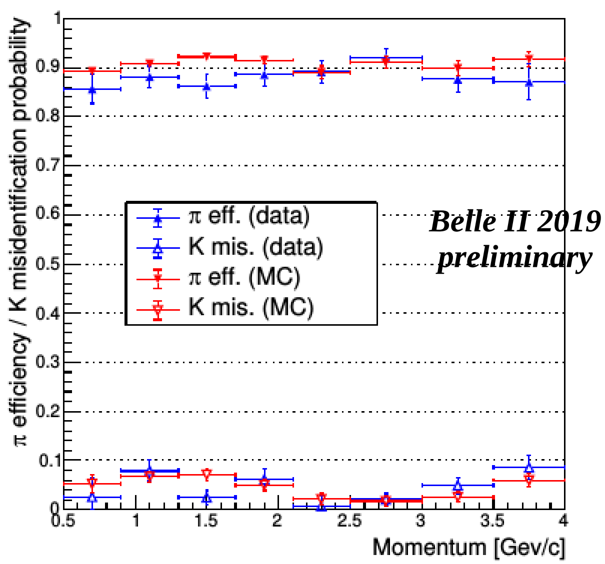
PID performance check (cont'd)

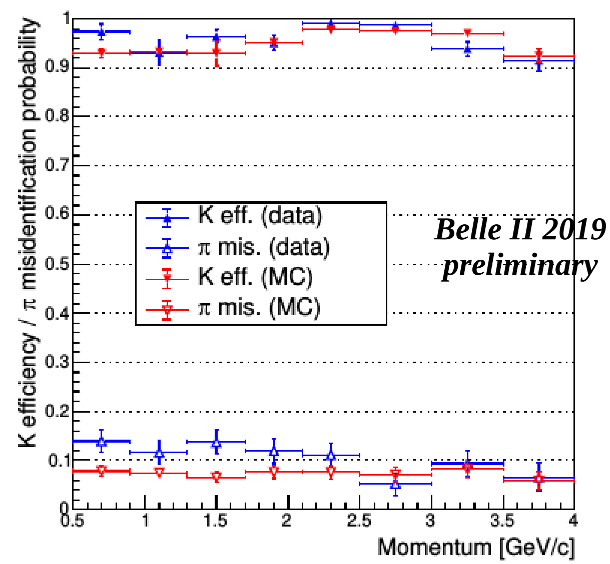
- K (π) eff. v.s. π (K) mis-ID probability:





- Eff. and mis-ID probability as function of momentum with requiring $R > 0.6$.
  - Consistent between data and MC.
  - No special tendency with momentum.





Summary

- ARICH detector is the PID device located in the forward endcap region of Belle II. Key to PID with ARICH is the radius of Cherenkov ring image.

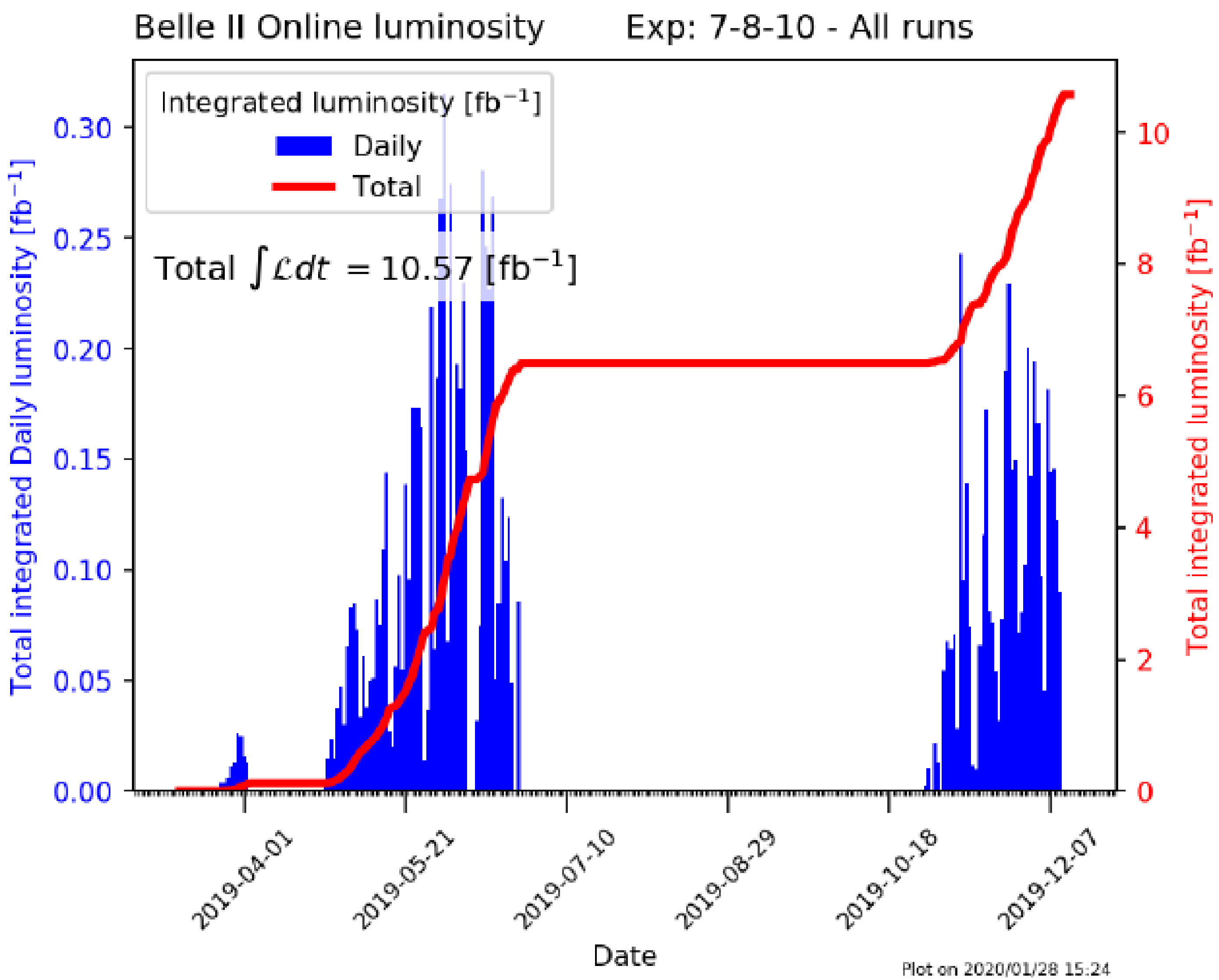
- The detector has been installed on Belle II in 2017 summer, and commissioning has been completed in Phase 2.

- The hardware system has been operating stably in Phase 3. New features are also introduced such as new cooling system and self-repair on FPGA SEU to enhance the stability in long-term operation.

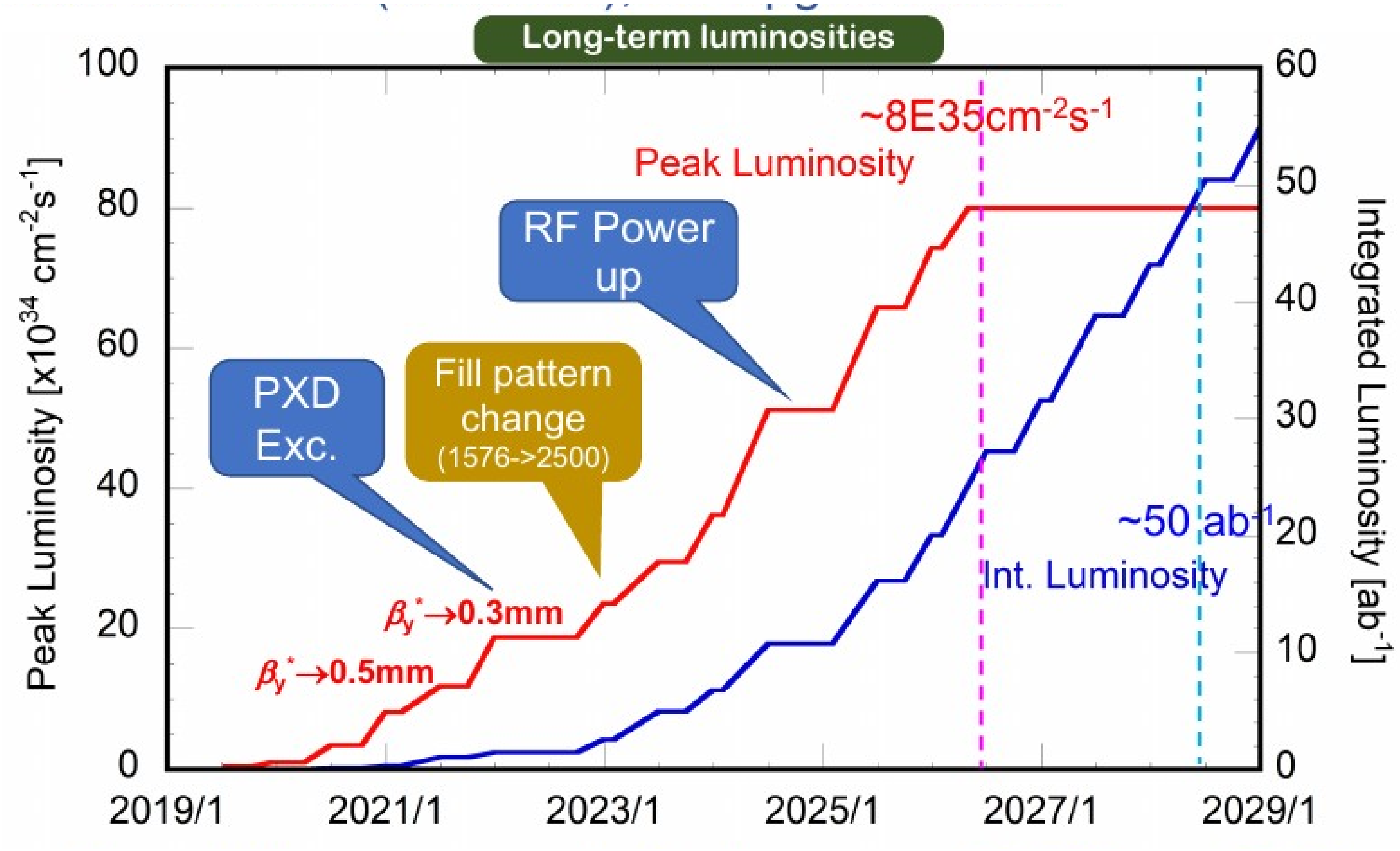
- The performance of PID with ARICH data has been also checked by using the data in Phase 3. It is close to expectation and the results are consistent between Phase 3 data and MC sample. The study will be published soon.

Backup

SuperKEKB luminosity



Operation plan and luminosuty projection



PID likelihood

- $$\mathcal{L}_h = \prod_{\text{all channel}} p_{h,i}(m_{h,i}) \qquad (p_{h,i}(m_{h,i}) = \frac{e^{-n_{h,i}} n_{h,i}^{m_{h,i}}}{m_{h,i}!}),$$

  Probability to have $m_{h,i}$ hit on pixel i.
  $n_{h,i}$: average hit

- $$p_{h,i}(\text{no hit}) \quad = \quad e^{-n_{h,i}}$$
  $$p_{h,i}(\text{hit}) \quad = \quad 1 - p_{h,i}(\text{no hit}) = 1 - e^{-n_{h,i}}$$
  - We consider just hit or not.

- With logarithm: $\ln \mathcal{L}_h = -N_h + \sum_{\text{hit } i} [n_{h,i} + \underline{\ln(1 - e^{-n_{h,i}})}]$

Expected total number of hits

Expected number of hits of pixel I.

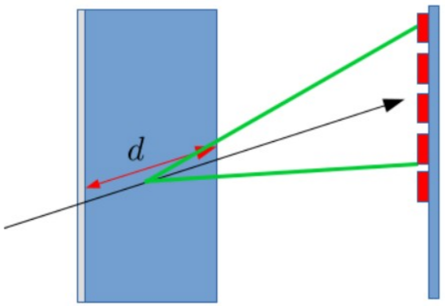
Probability of a pixel to get hit.

PID likelihood: *ni*, expected number of hits of pixel i

- $$n_i = n_i^1 + n_i^2 + n_i^b$$

  1st aeogel layer — 2nd — background

- $$N^r = \frac{dN_{ch}}{dx}\lambda_{abs}(1 - e^{-d/\lambda_{abs}})$$



  – Consider the loss on the edges and between aerogel tiles.

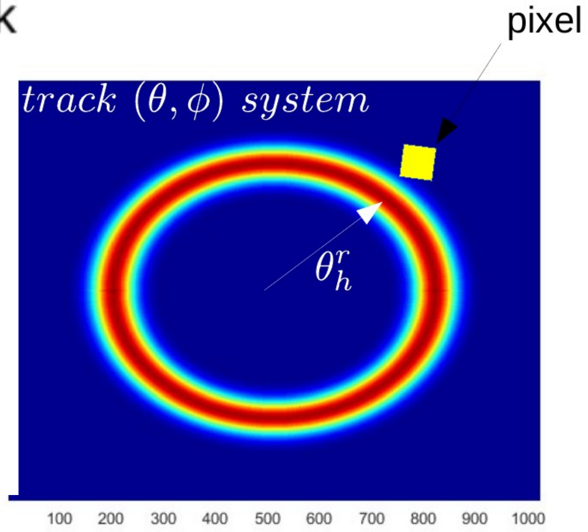
detection efficiency

Expected cherenkov peak for given hypothesis h

- $$n_i^r = \boxed{\epsilon_{det}}\boxed{N^r}\int_{\boxed{\Omega_i}}\frac{1}{2\pi}\boxed{G(\theta, \theta_h^r, \sigma_h^r)}d\theta d\phi$$

expected number of photons emitted from aerogel layer r (1,2)

Solid angle covered by I-th pixel



PID likelihood: N_h, expected total number of hits

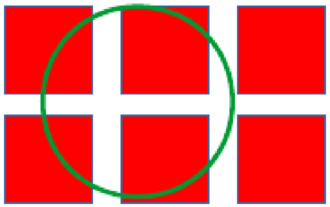
- $$N = \boxed{\epsilon_{acc}}\epsilon_{det}(N^1 + N^2) + N_b$$

Ring geometrical acceptance

emmited from 1st 2nd aerogel

background

- The expected number of emitted photons, considering the reductions due to:
  - Scattering and absorption in the silica aerogel.
  - Geometrical acceptance.
  - Detection efficiency.
  - Background hits.



K/π separation with Phase 2 data

- Mean = 293 ± 17 mrad
  Sigma = 16.68 ± 0.26 mrad

- By the number within 3σ,
  the number of photons per track ($N_{p.e.}$) is = 8.77

- Resolution of Cherenkov angle for single track:
  $$\sigma_{track} = \frac{\sigma_\theta}{\sqrt{N_{P.e.}}} = 5.63 \text{ mrad}$$

- *K/π* separation power:
  $$\frac{\Delta\theta(4\ GeV/c)}{\sigma_{track}} = 4.2\sigma \text{ at } 4 \text{ GeV}/c$$