Belle II upgrade

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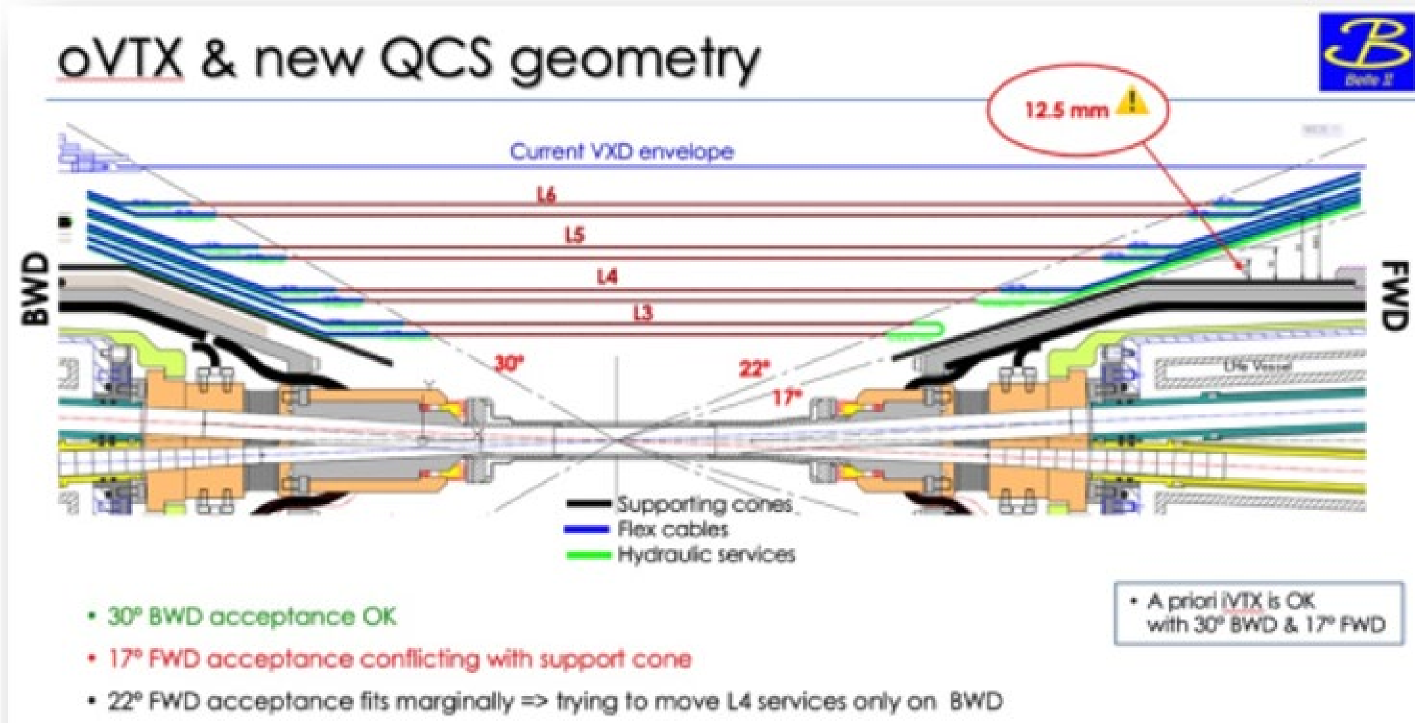
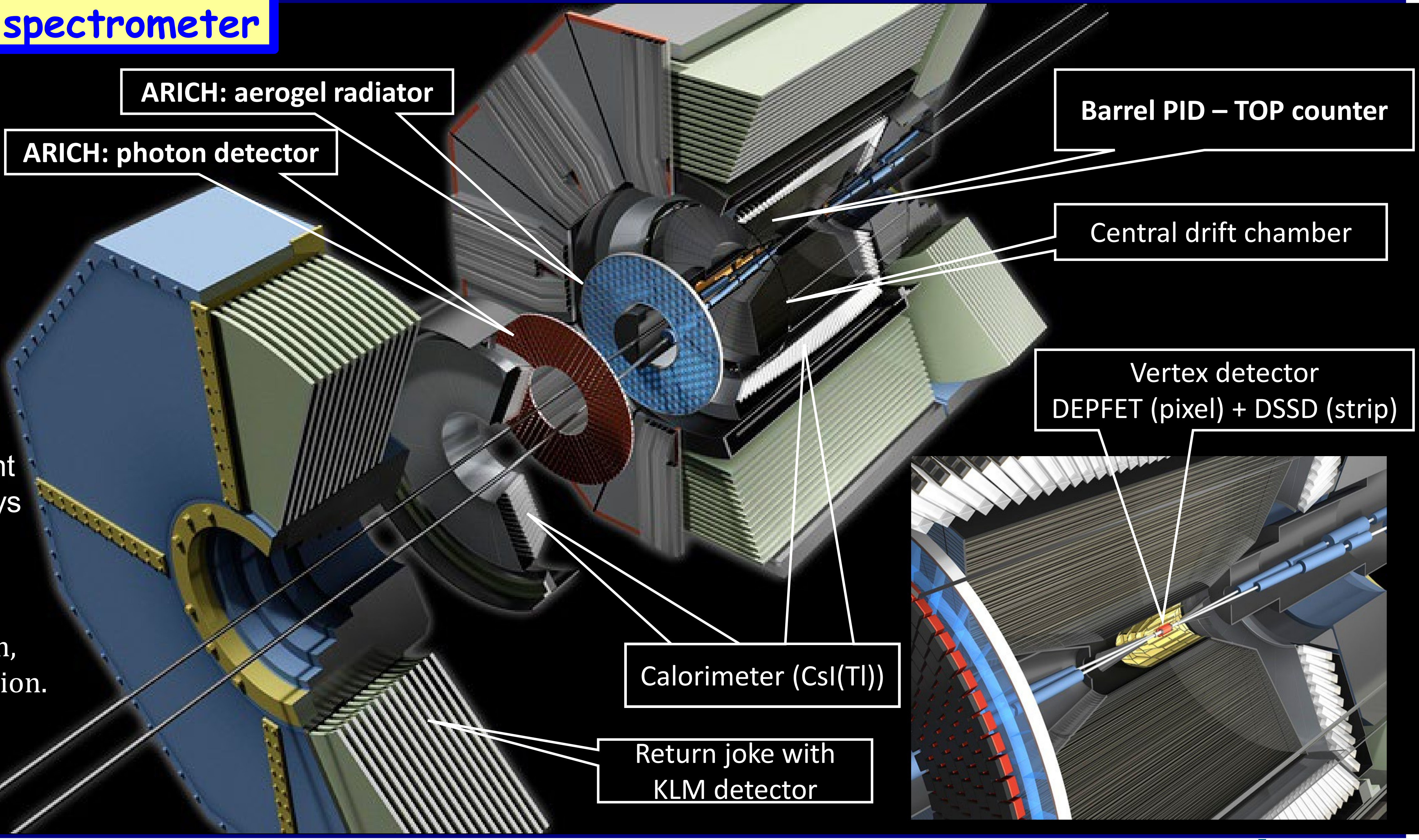
Outline:

- Belle II, Super-KEKB
- LS2 upgrade
  - Luminosity projections
  - Timeline
  - Super-KEKB upgrade
- ARICH ToDo list



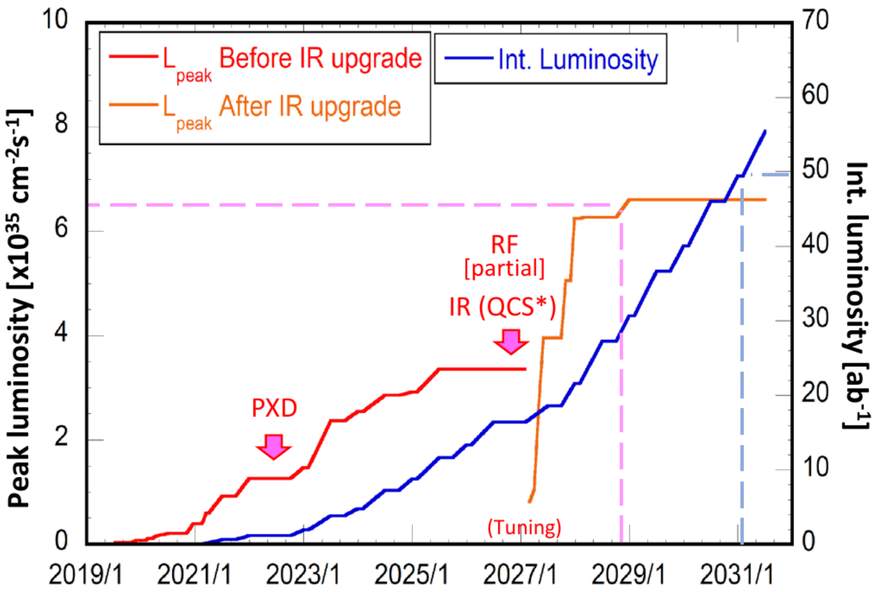
Belle II spectrometer

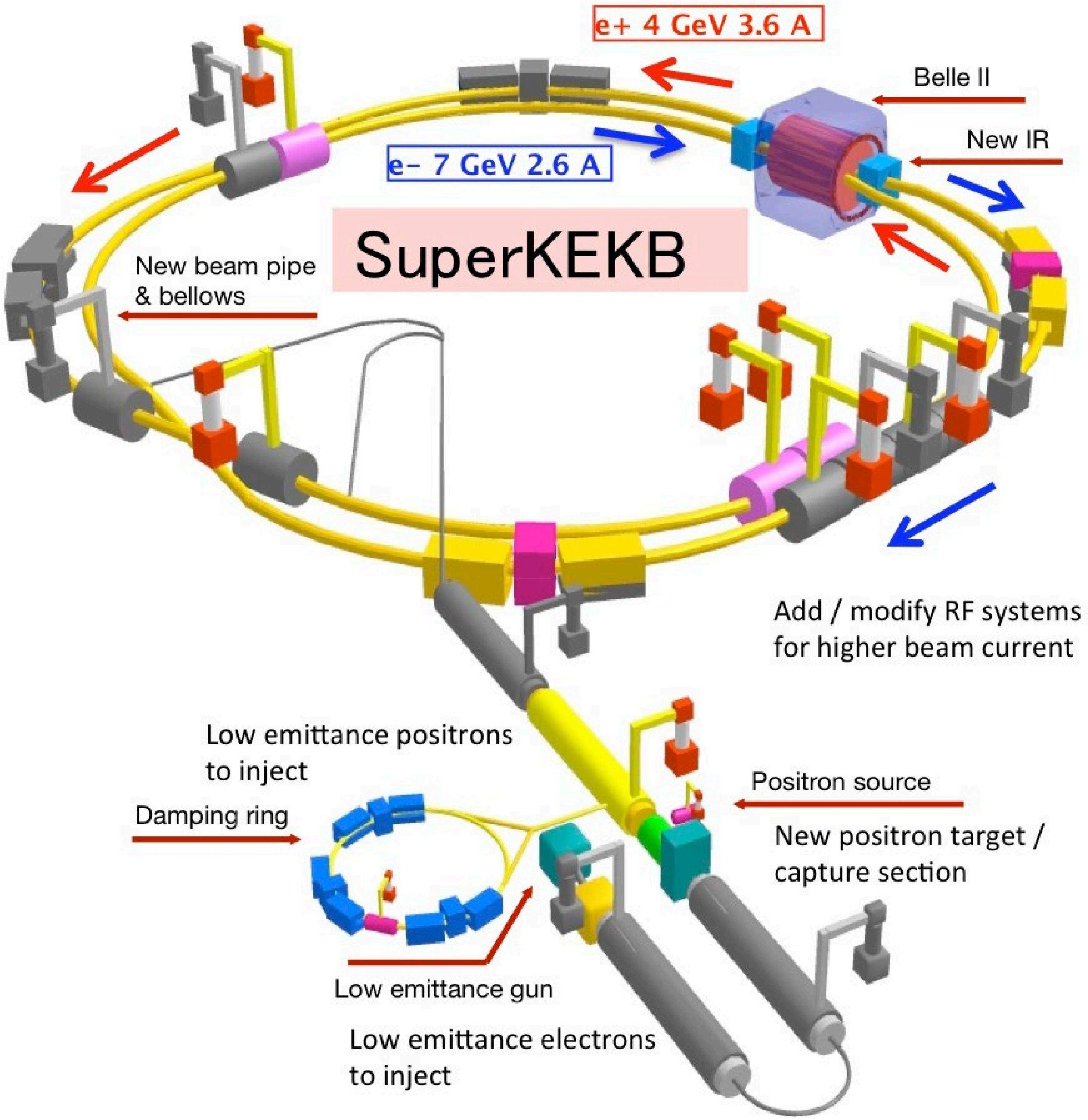
The aim is precise measurement of rare decays of B and D mesons, τ leptons, dark matter search, and CP violation.



Belle II eksperiment @ SuperKEKB

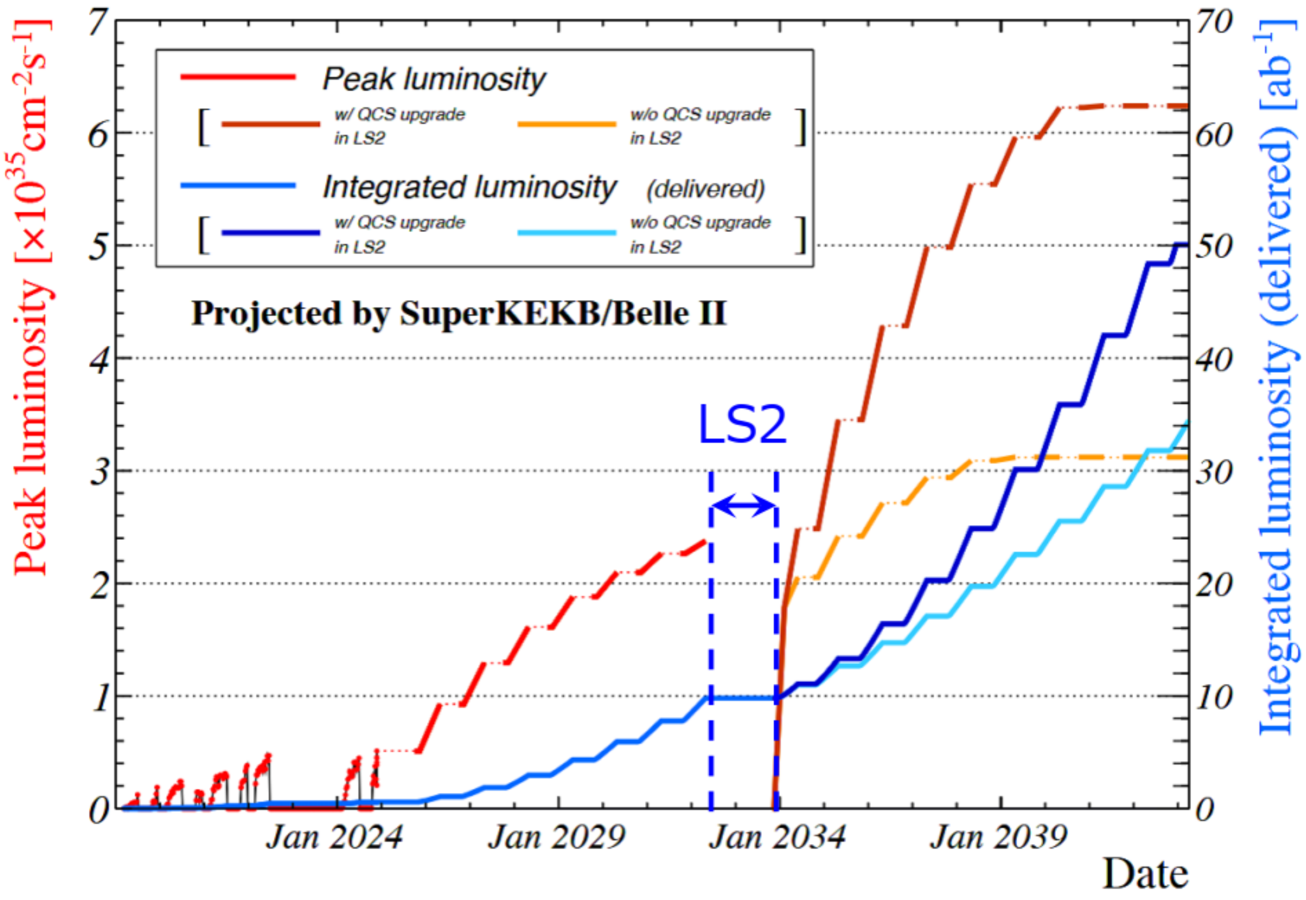
- Belle II spectrometer sits at the interaction point of SuperKEKB collider - upgraded KEKB
- $7\ \mathrm{GeV}$ electrons and $4\ \mathrm{GeV}$ positrons collide with a centre of mass energy of Υ_{4S} resonance mass.
- Target is to reach integrated luminosity $50\ \mathrm{ab}^{-1}$ by 2031, by 30x higher peak luminosity.
- More challenging for detectors:
  - $30\ \mathrm{kHz}$ trigger rate
  - higher background
  - radiation tolerance.





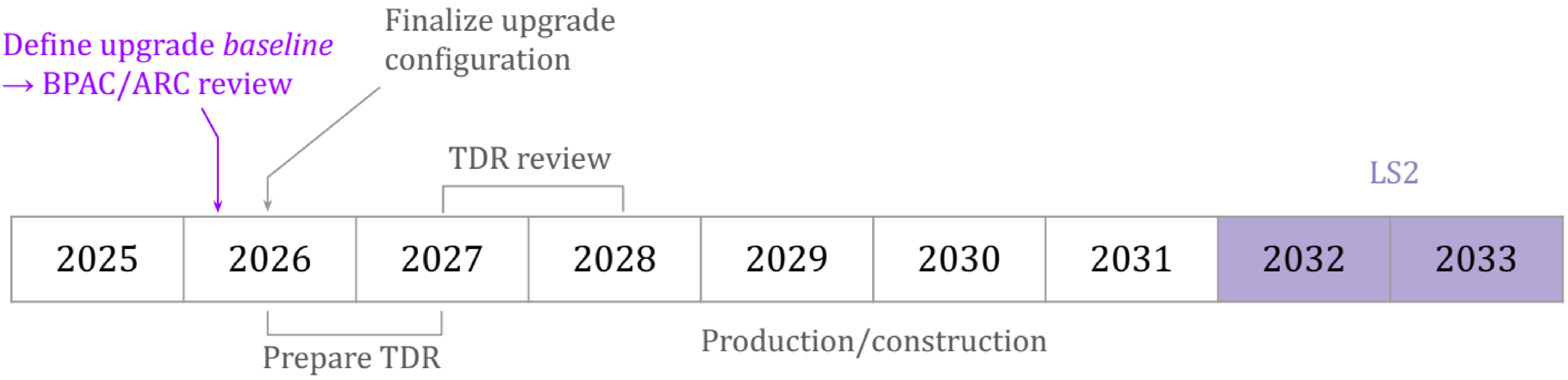
Luminosity projections

Long-term plan intended by SuperKEKB/Belle II



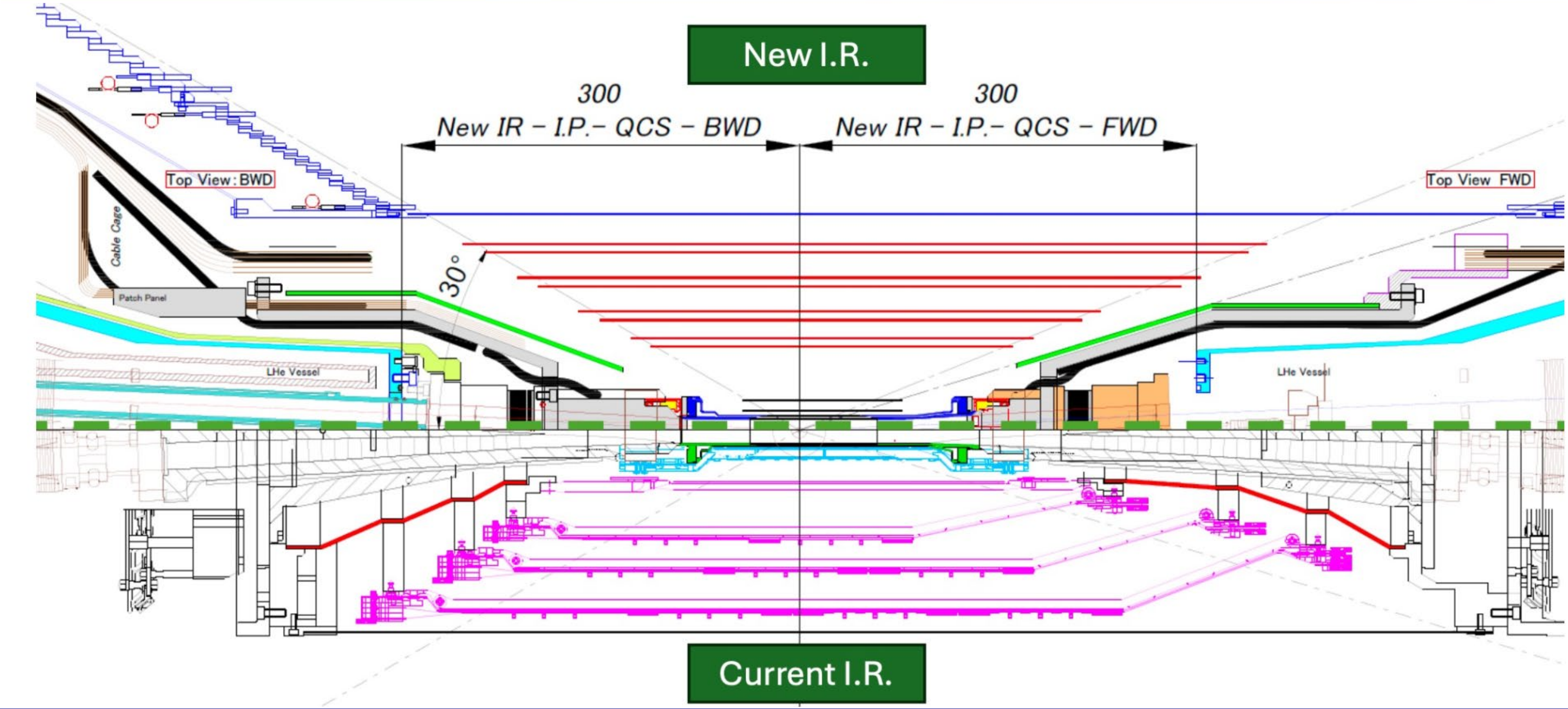
- During the 2032 long-term shutdown (LS2), major upgrades are planned for both SuperKEKB and Belle II.

LS2 upgrade project timeline



Belle II I.R. upgrade

- Instalation of new QCS magnets closer to interaction point
- Reduced forward acceptance: 17° to 22°



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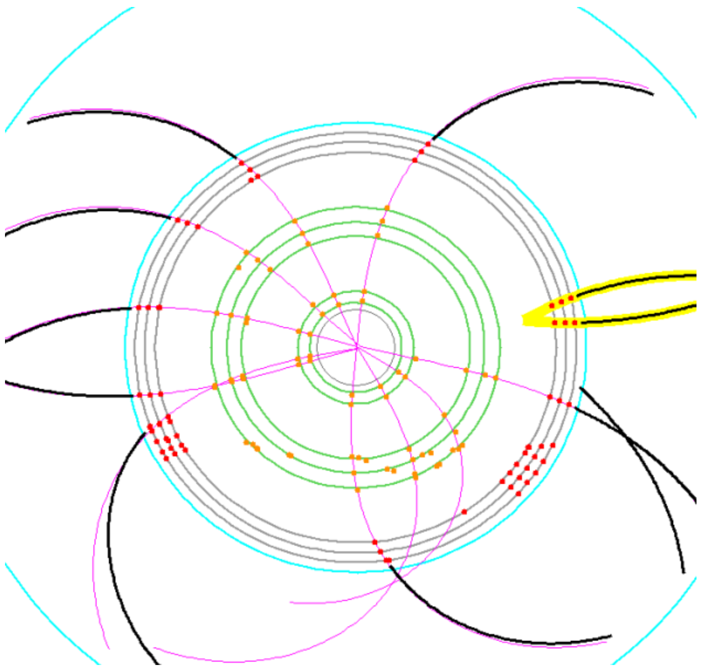
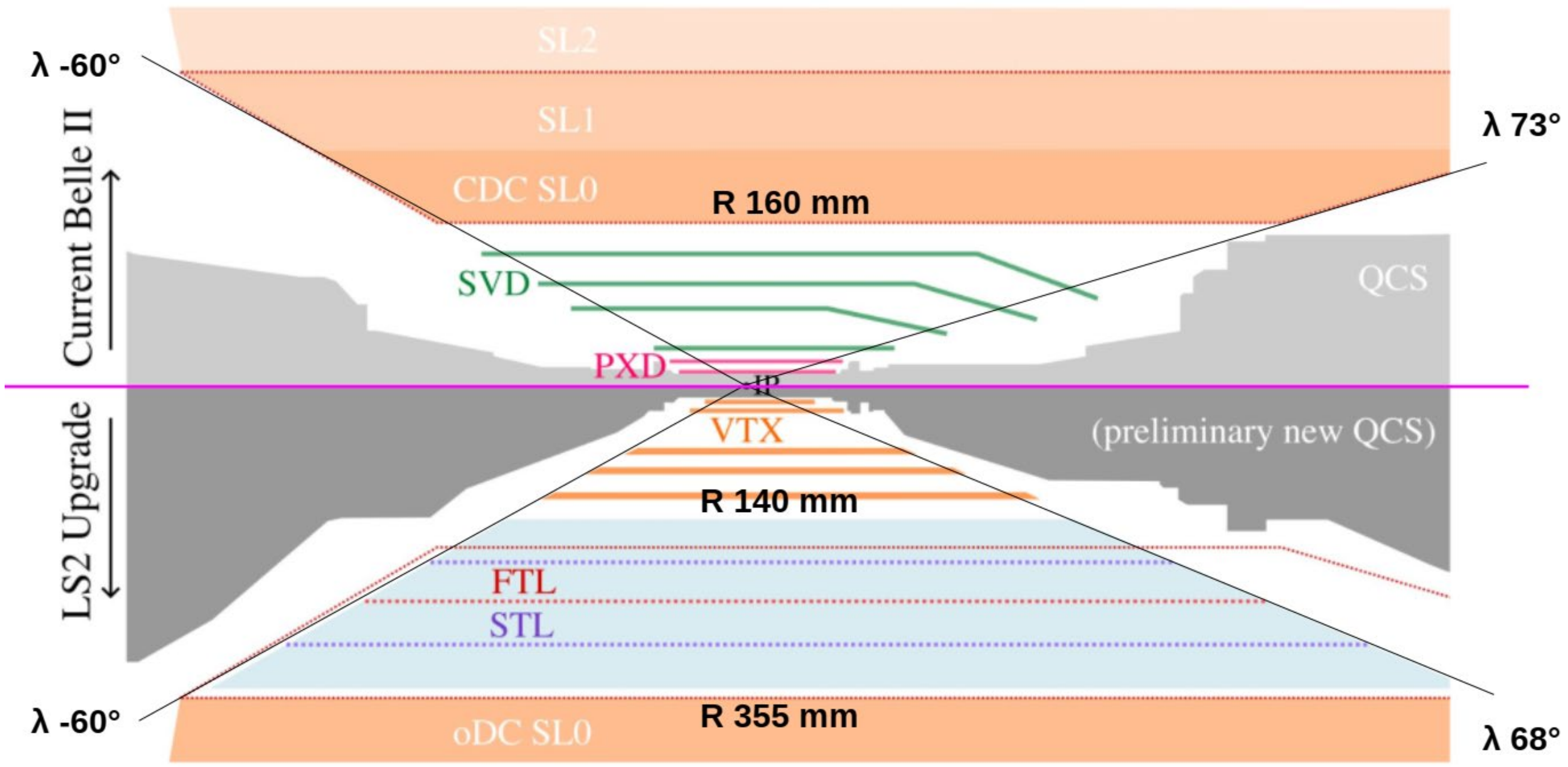
Tracking upgrade

- VTX – vertex detector (5 layer)
- FTL – fast timing layer (LGADs)
- STL – silicon transition layer (CMOS strips)
- oDC – outer drift chamber



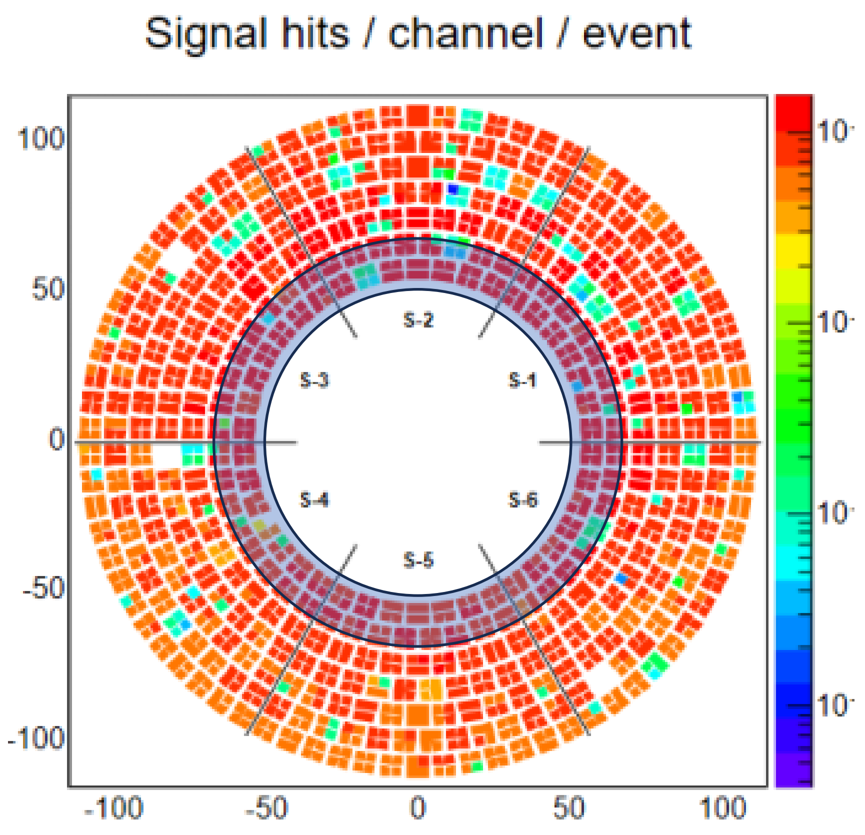


ARICH ToDo list

- HAPD modules repair and rearrangement:
    - Rearangement of HAPD modules for reduced acceptance
    - Cut damaged channels – high leakage current
    - Fix HV problems
    - Fix merger-FEB connection problems
    - Fix
- Firmware upgrade:
    - High-rate operation
    - Firmware repair on-the-fly
    - SEU resistance - redundancy
- Possible aerogel upgrade??

- Open software tsks:
    - Offset-threshold calibration
    - HV/LV slow control
    - Aerogel optimisation studies – refractive indices, hexagon tiles, outer region disagreement
    - …

- Hardware development:
    - LAPPD, HRPPD, 2” MCP-PMTs
    - SiPMs – keep an eye on progress in radiation hardness



BACKUP SLIDES

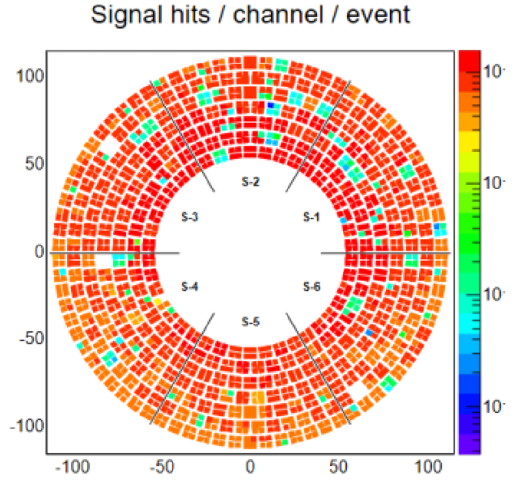
HAPD modules status

HV channel status

- 4 bias channels newly masked (or set to guard voltage)
- Total number of masked APDs: 117 (7.0%)

	2019	2020	2021	2022	2023	2024	2025	2026
Ratio	4.8%	5.6%	6.0%	6.5%	5.4%	6.6%	6.7%	**7.0%**

2026b (exp 42 / run 1930)



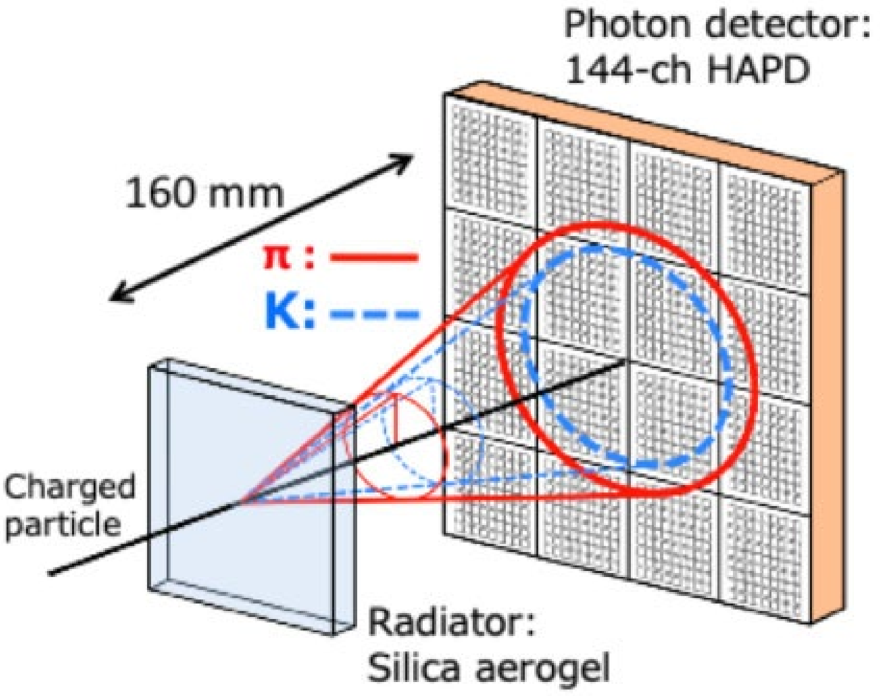
HV state stuck

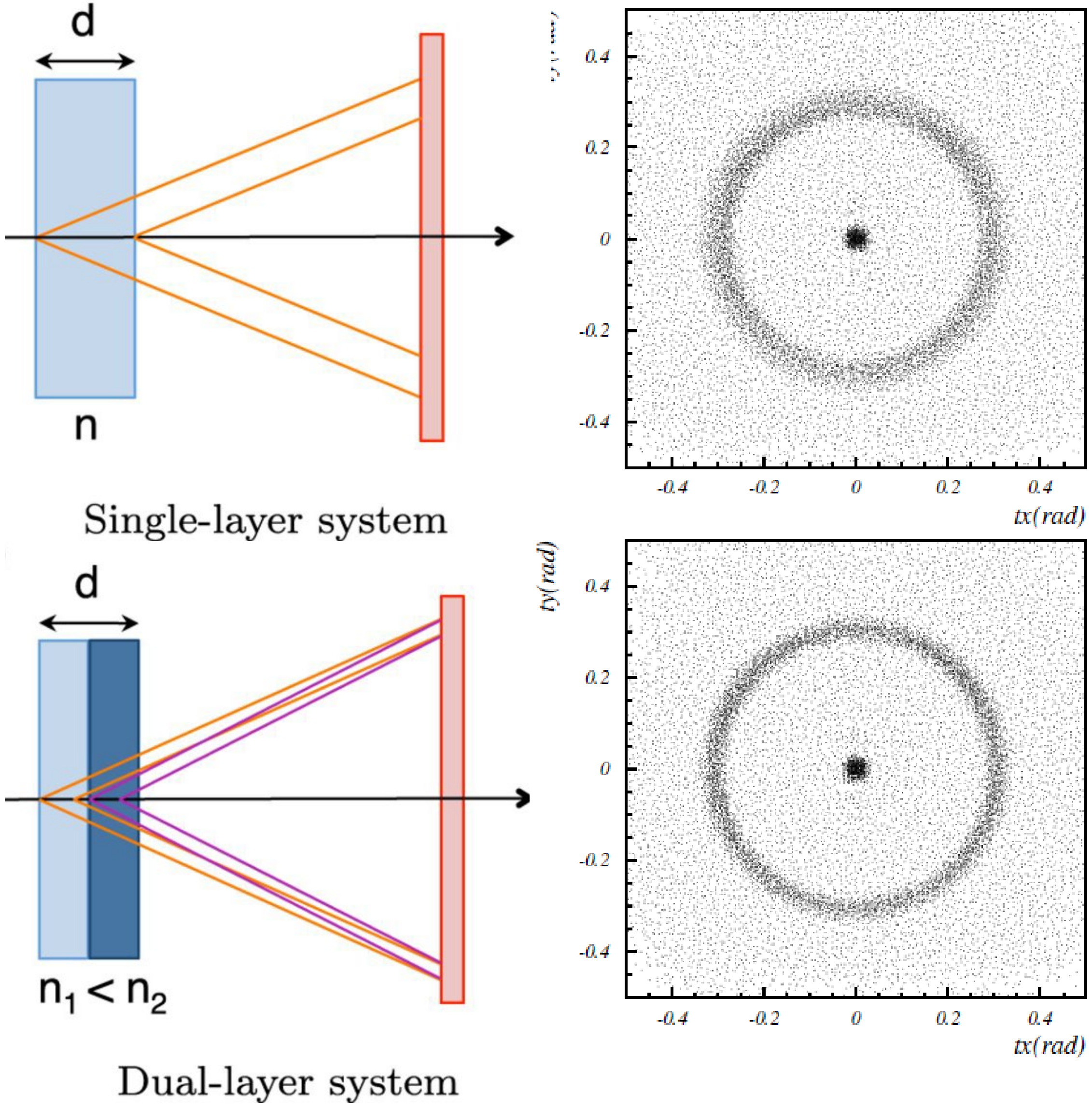
- SKB kicker interlock signal issued at 22:46 Apr 15 → ARICH HV stayed OFF.
- When turning on HV at the start of physics run around 15:40 Apr 16, ARICH HV status was stuck in TURNING ON.
  - It seems that communication was lost for some channels. As a result, the daemon couldn't judge whether the guard channels were turned on properly.
  - Restarting daemon fixed the trouble (by Uno-san), took ~10mins
- More investigation on HV daemon is necessary after 2026b.

ARICH - basics

Proximity focusing Aerogel Ring Imaging CHerenkov detector (ARICH) components:

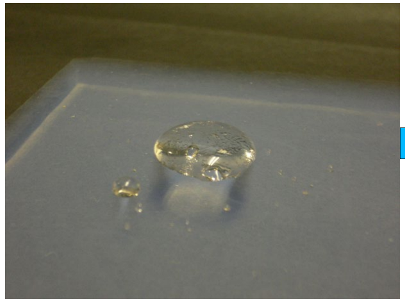
- double layer focusing aerogel radiator (20 mm + 20 mm)
- 160 mm expansion gap
- photon detector based on 420 Hybrid Avalanche Photo Detectors (HAPD)
- front-end electronics with dedicated ASICs and FPGAs

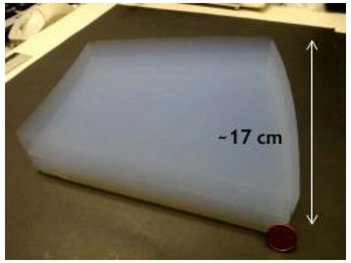


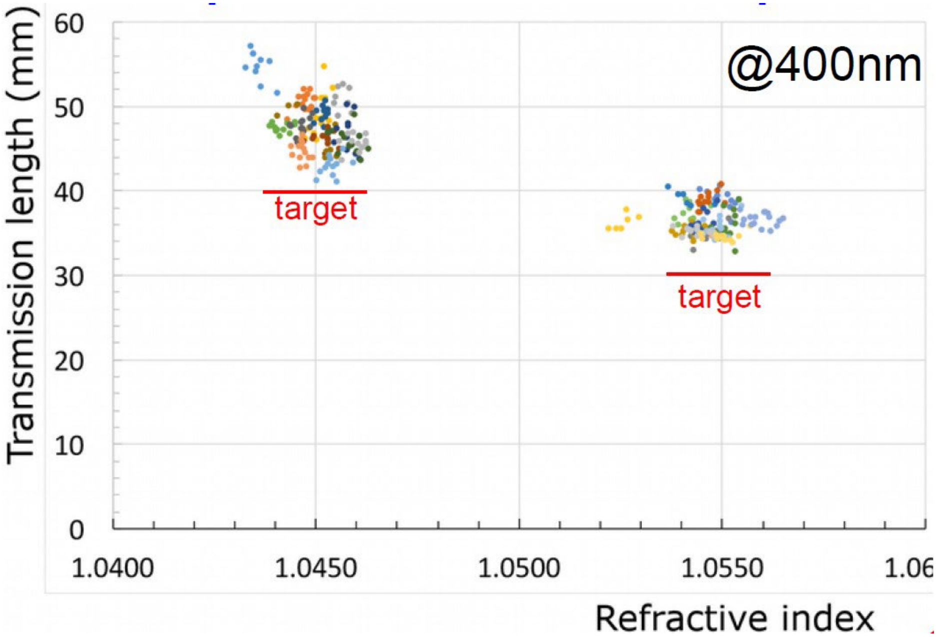


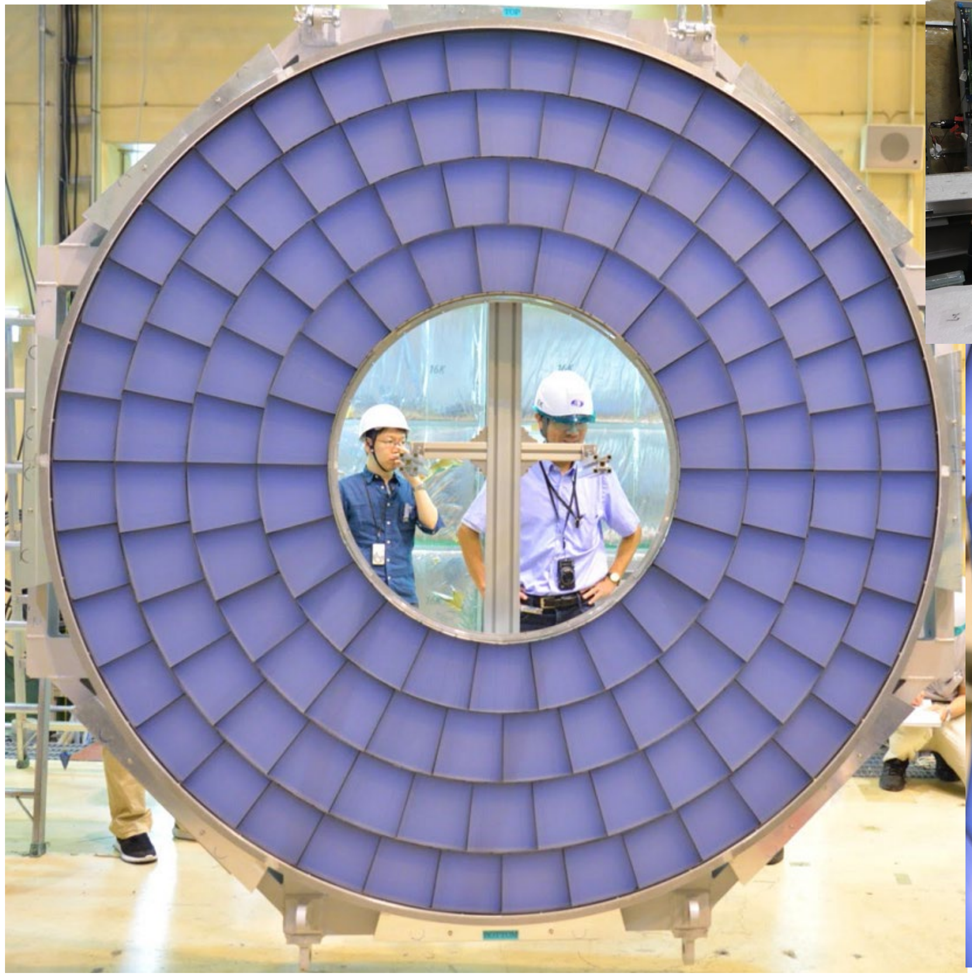
Aerogel radiator

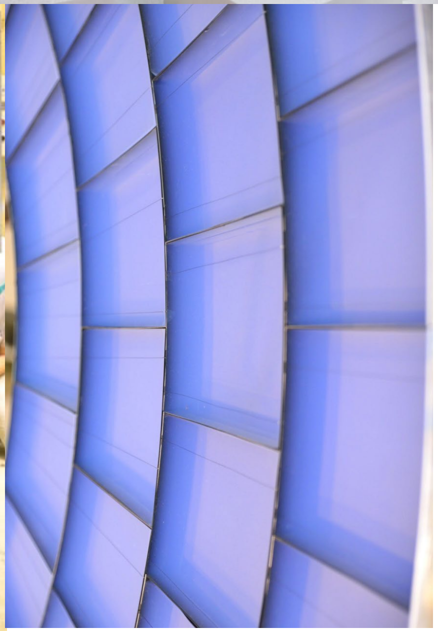
- two layers of $20\ mm$ thick hydrophobic aerogel :
  - upstream, $\mathrm{n} \approx 1.045, \lambda_{400\ nm} \approx 47\ \mathrm{mm}$
  - downstream, $n = 1.055\ , \lambda_{400nm} \approx 37\ \mathrm{mm}$
- 4 segmented rings, 2×124 tiles
- all but exit surface of each pair covered by black paper
- each pair fixed by two black strings running radially
- completed in December 2016



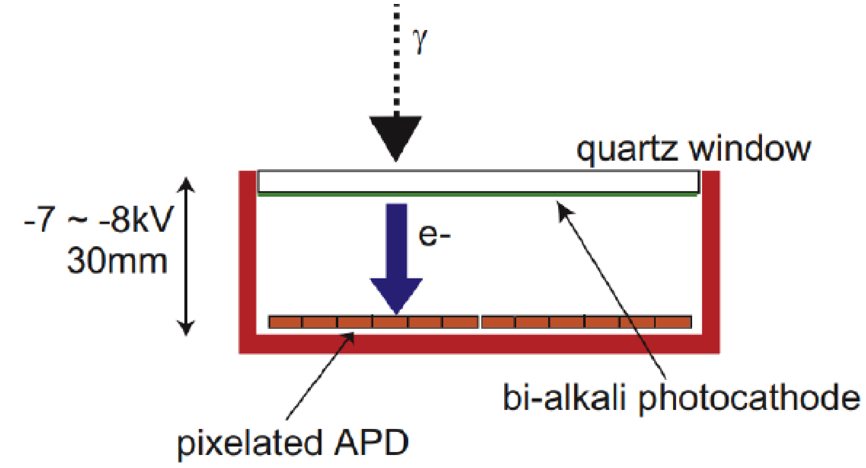


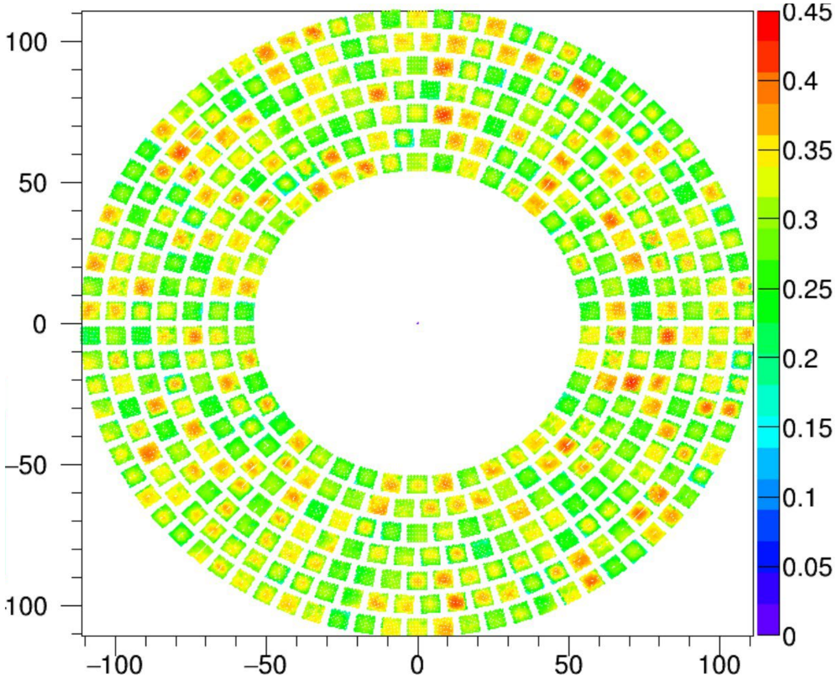






Photon detector - HAPD

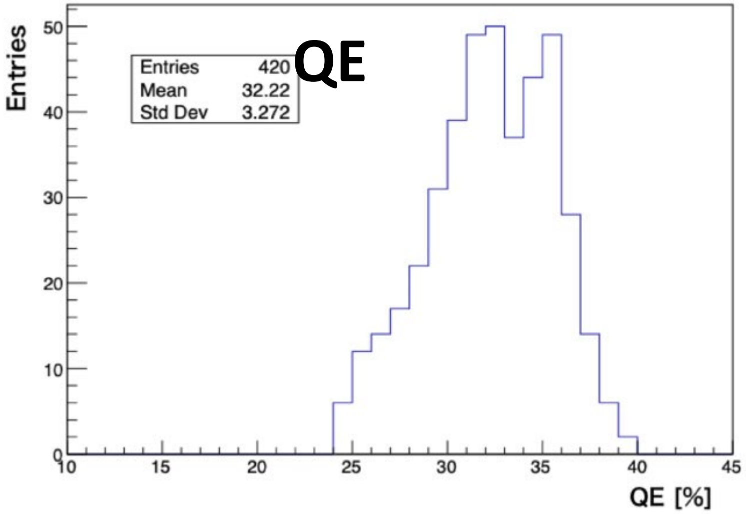


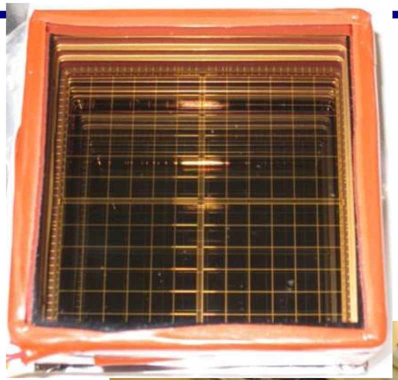


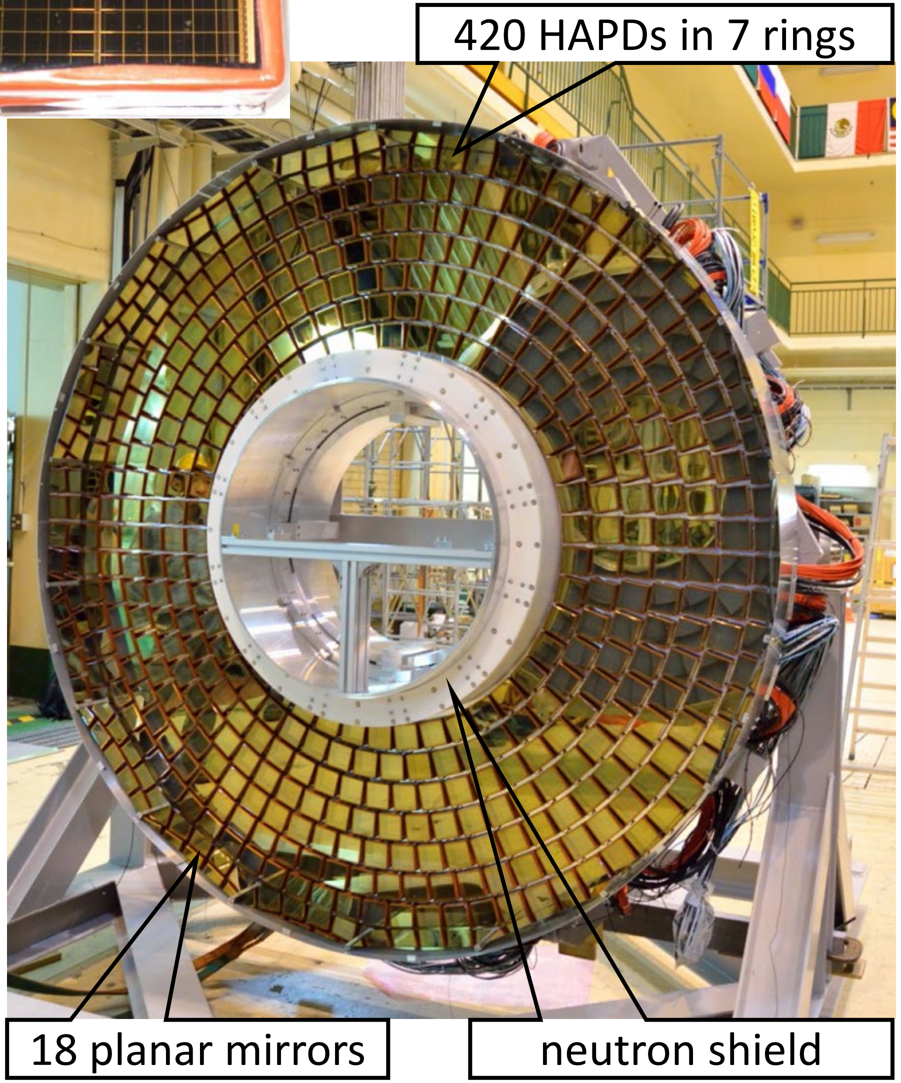
Photon detector is constructed from 420 HAPD modules.

HAPD properties:

- size: $73 \times 73 \times 28\ \mathrm{mm}^3$
- 2×2 APDS with 6×6 channels, $4.9 \times 4.9\ \mathrm{mm}^2$ @ 5.1mm pitch
- $< QE_{400nm} > \approx 32\ \%$
- combined gain $\approx 70\mathrm{k}$
- channel capacitance $80\ \mathrm{pF}$
- operation in $\mathrm{B} = 1.5\ \mathrm{T}$
- radiation tolerance $\approx 10^{12}\ \frac{n_{1MeV}}{\mathrm{cm}^2}$



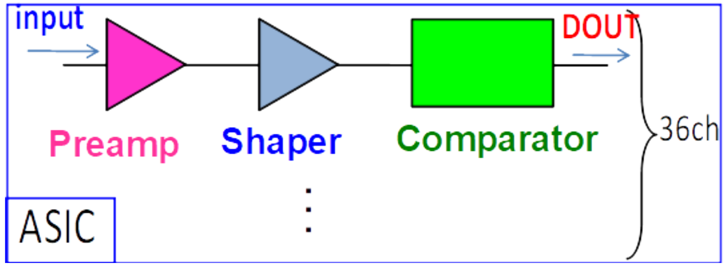


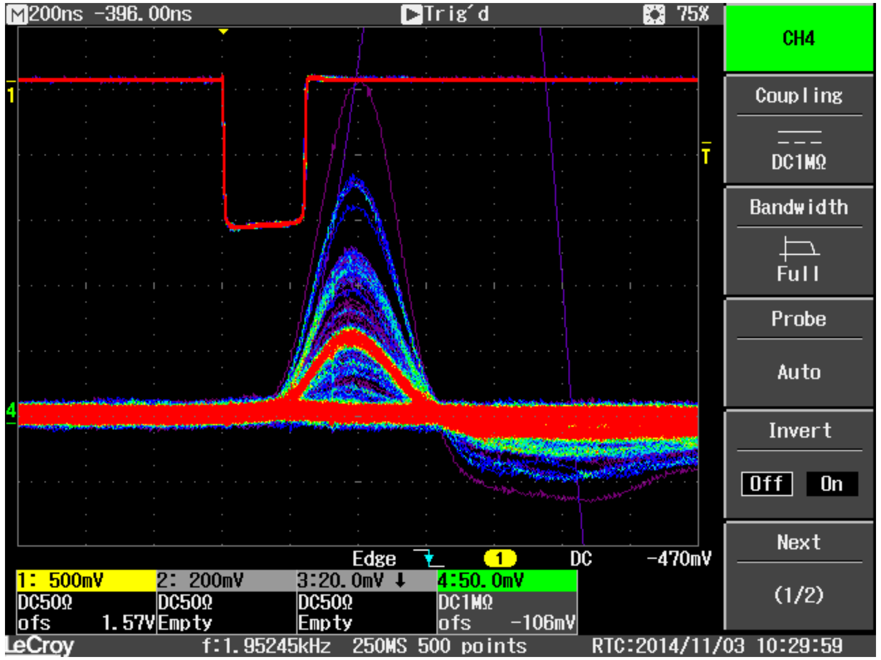


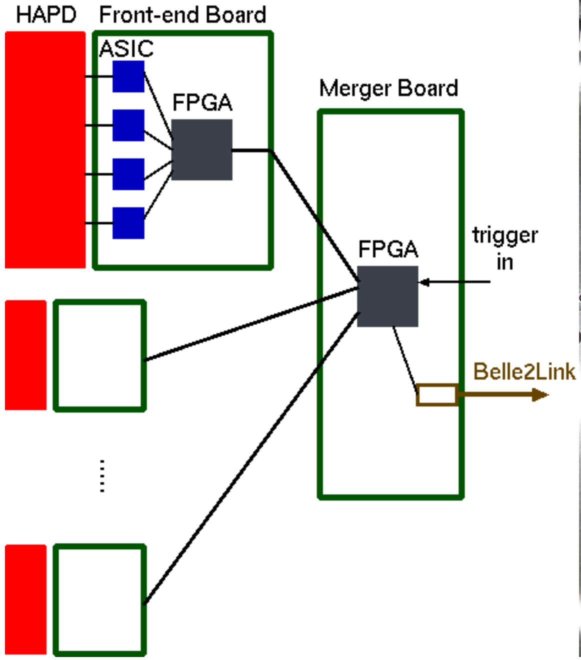
Front-end electronics

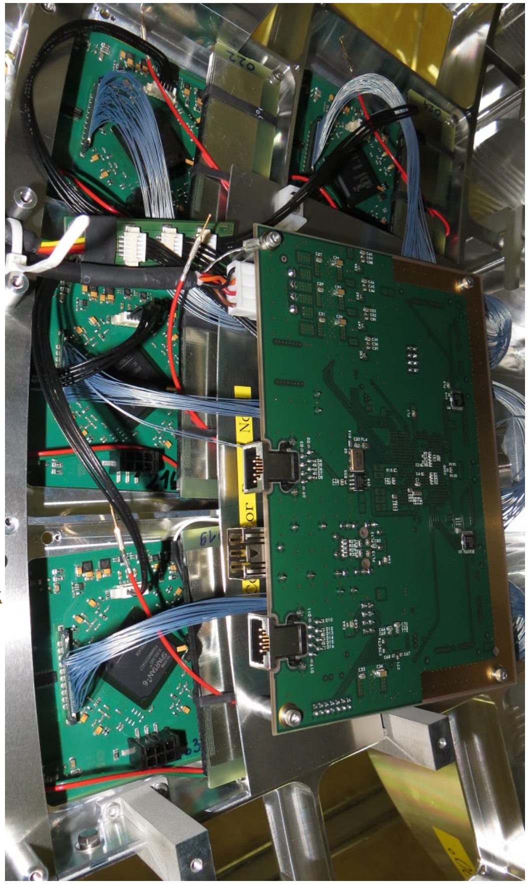
Front-end electronics is organized in units of one merger board (MB) controling 6 (or 5) front-end boards (FEB)

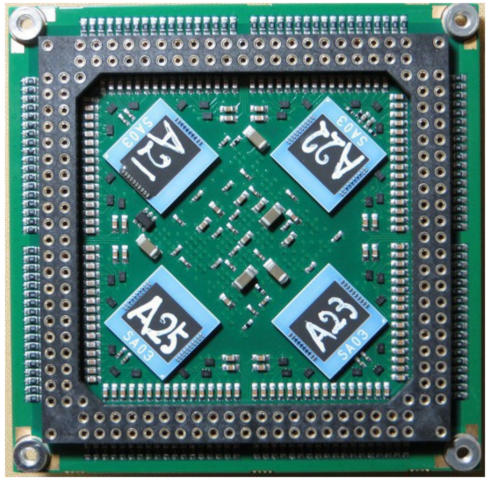
- FEB is based on 4 36 ch. ASICs each covering one APD, and Spartan-6 FPGA
- MB controls FEB slow control parameters, and collects and transfers data to back-end DAQ

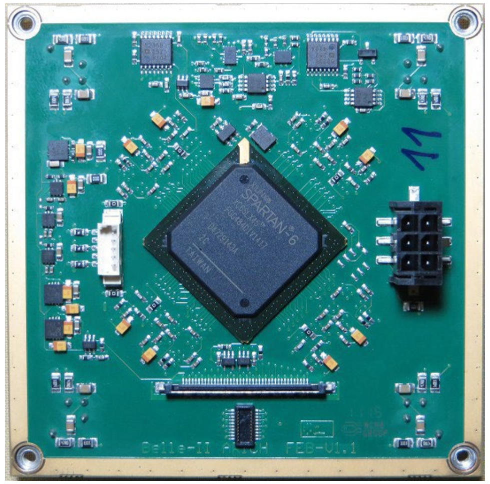






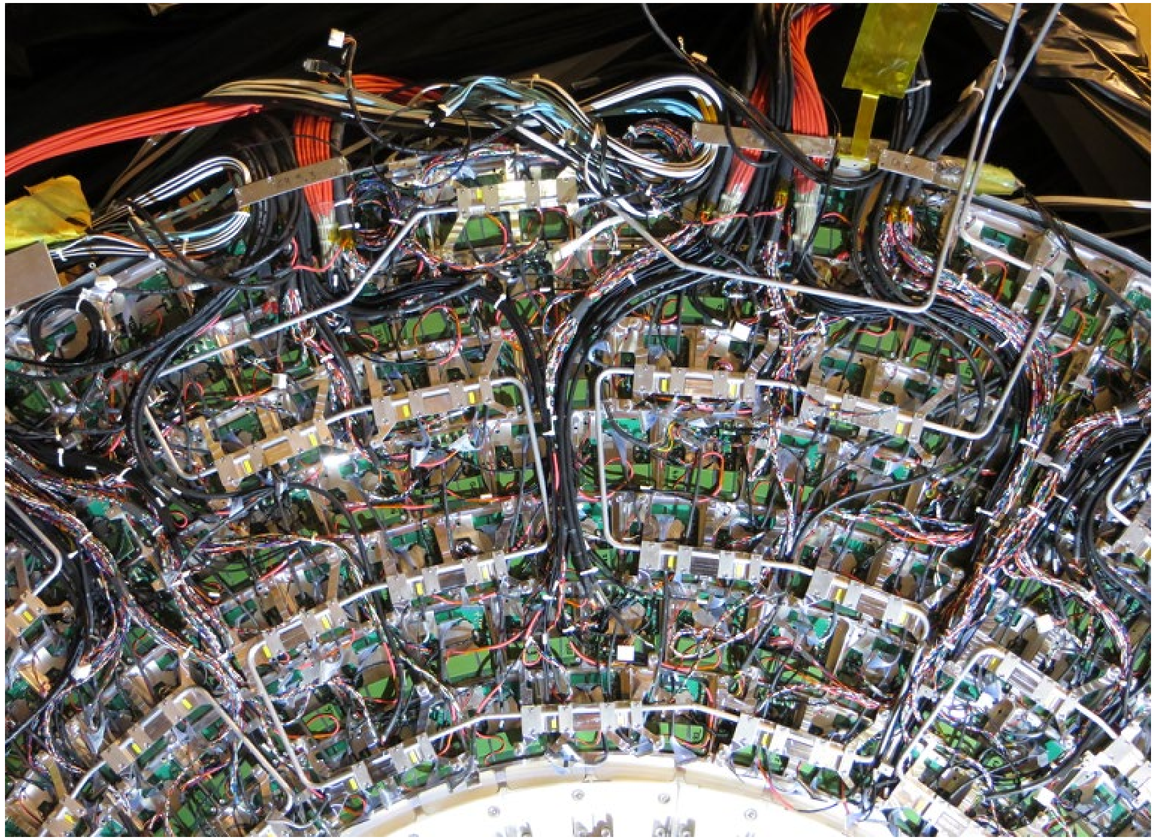


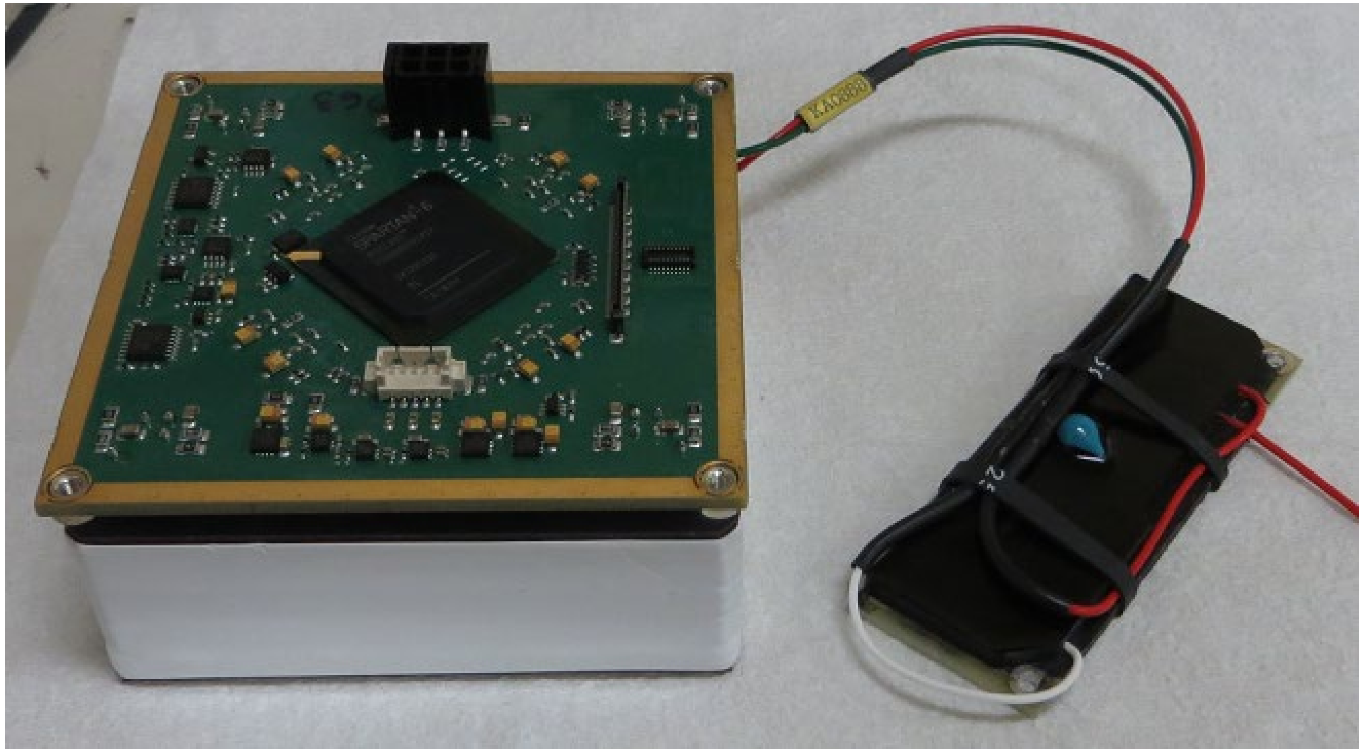


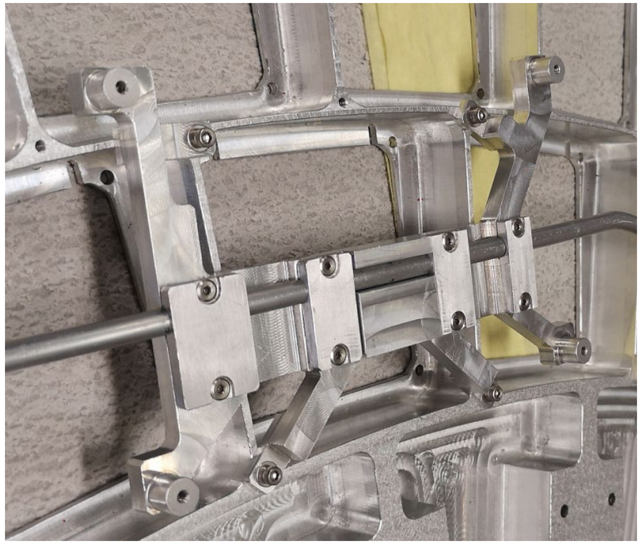


HAPD module assembly, cooling

HAPD module: HAPD + FEB + HV divider board





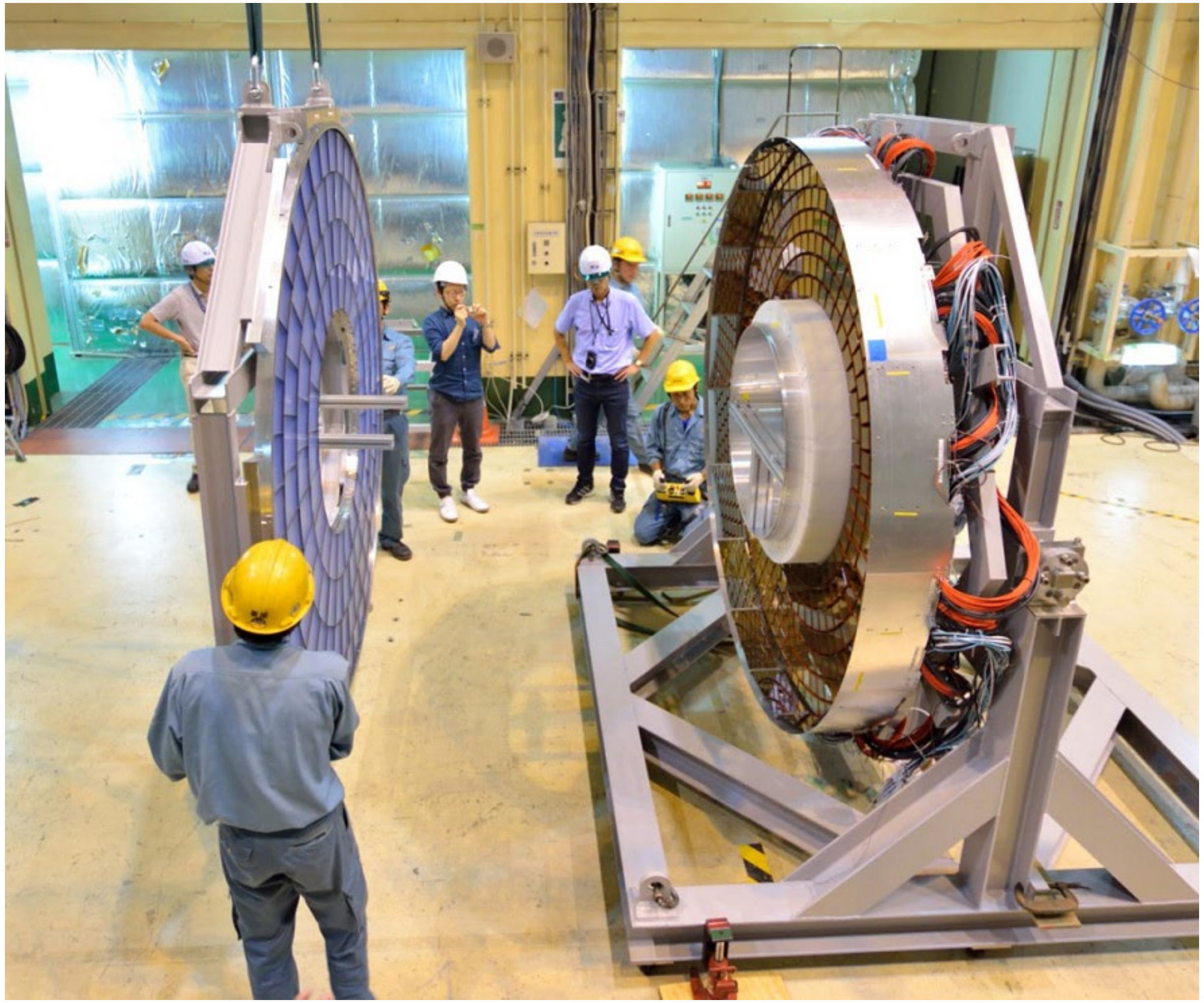


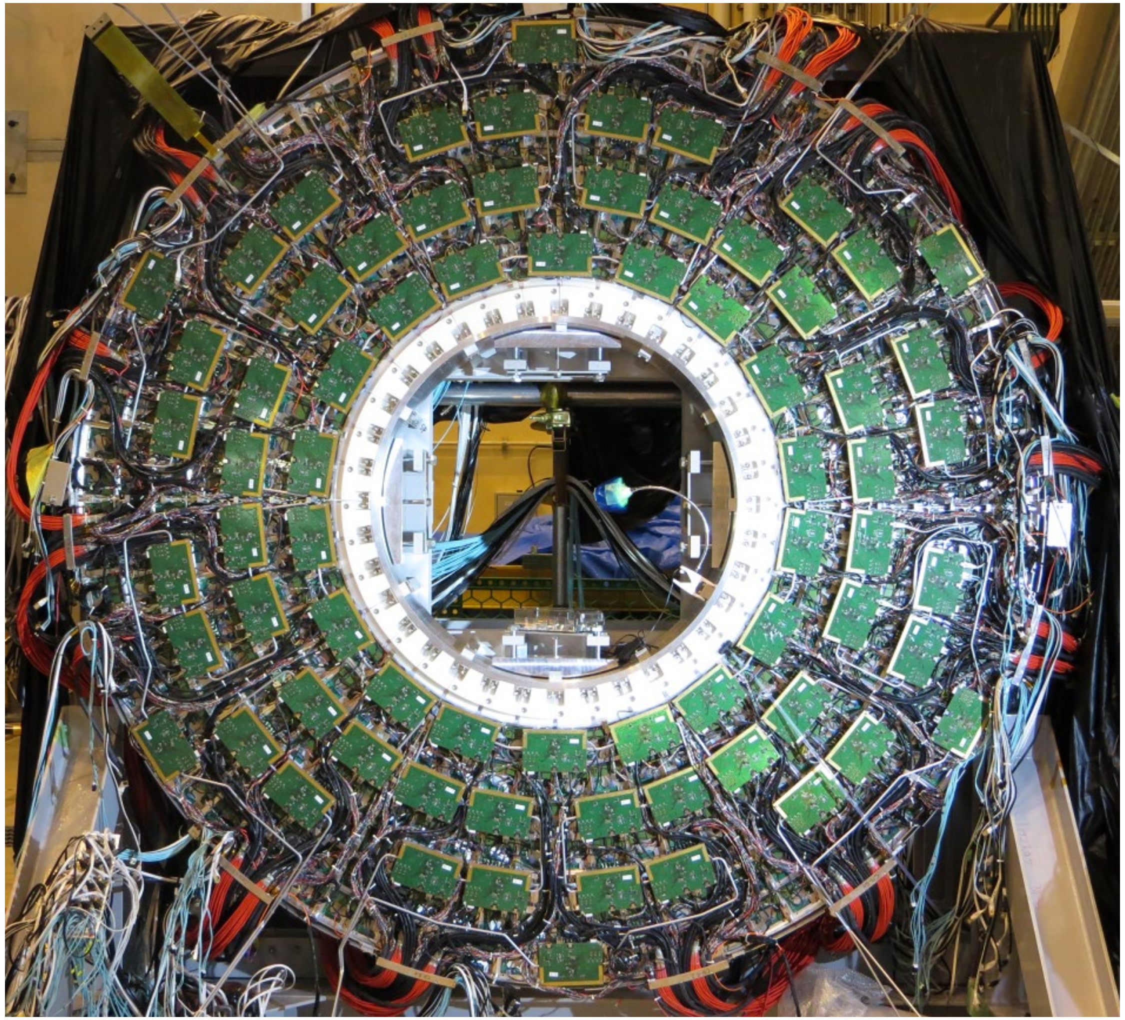
Cooling system was designed and installed in 2018

ARICH integration

Joining radiator and photon detector parts in 2017.

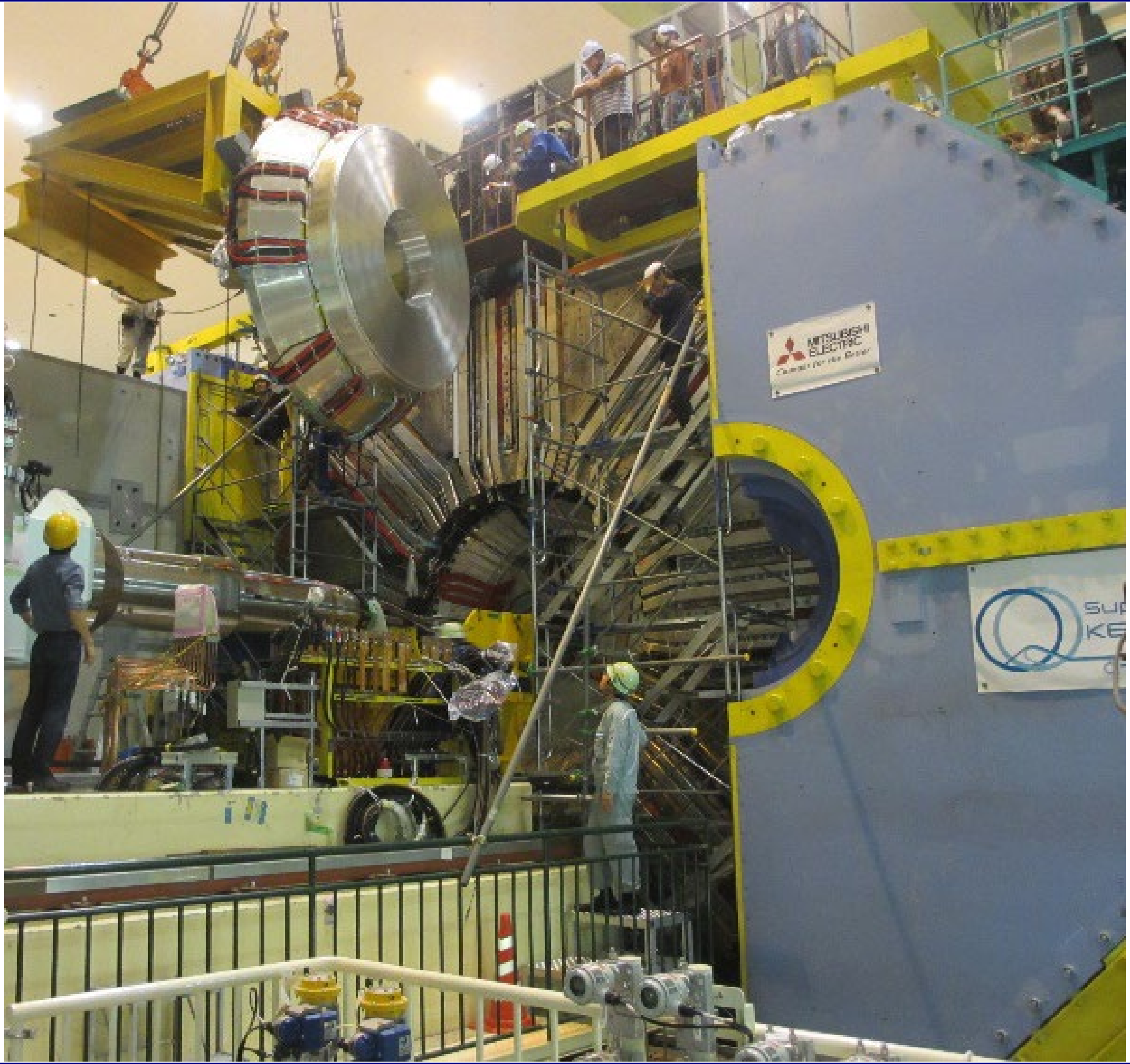
Back side view of ARICH with FE boards, cooling system, cabling and merger boards on top.





ARICH installation

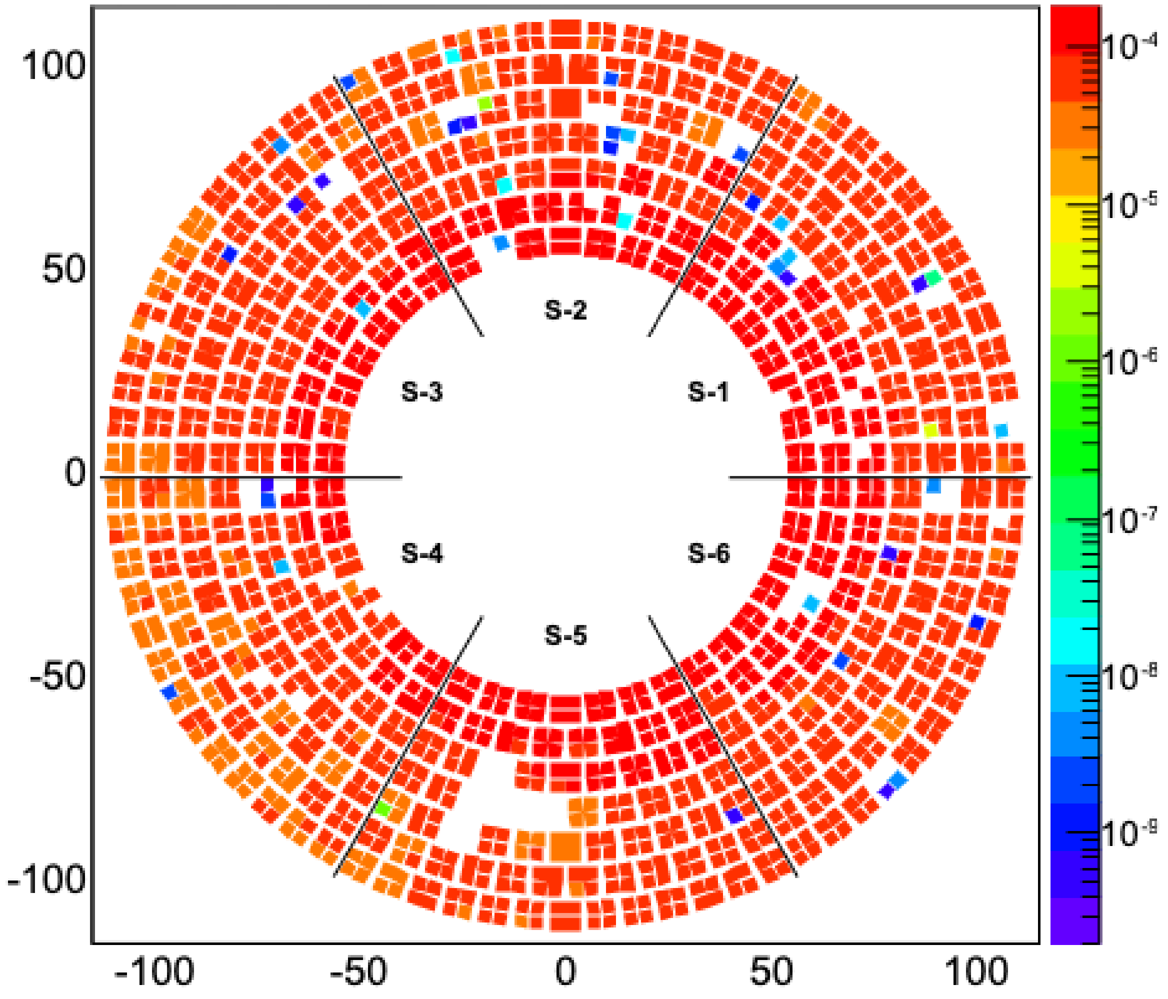
- Transfer of the forward end-cap to final position in 2017, first beam operation of Belle II April – June 2018
- Extracted and reinstalled during 2018 shutdown for cooling system upgrade before the beam operation start in 2019
- Extracted again in summer 2022 for installation of vertex detectors during LS1. LV cables repaired.



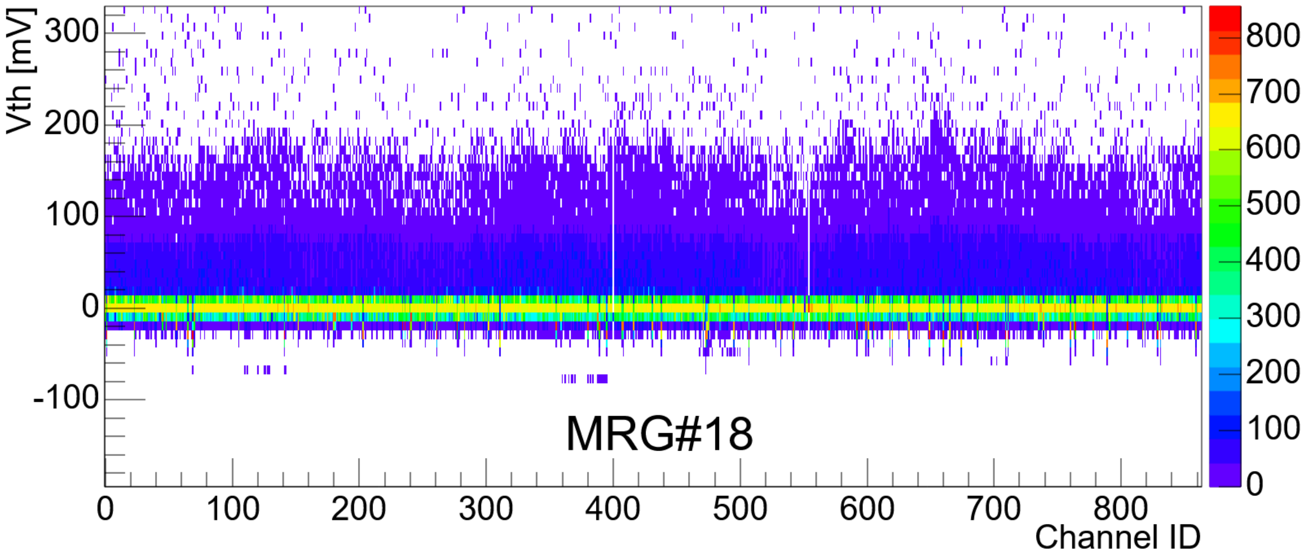
ARICH operation status

Since March 2019 ARICH is fully operational.

- Current status:
  - $\approx 94\ \%$ of ARICH channels operational
  - $\approx 1\ \%$, 1 merger group with 5 HAPD modules, off due to LV cable problem
  - $\approx 5\ \%$, off due to HV or bias problems – different reasons under study
- Electronics efficiency for single photon signals well above 90% – threshold set at $50\ \mathrm{mV}$.



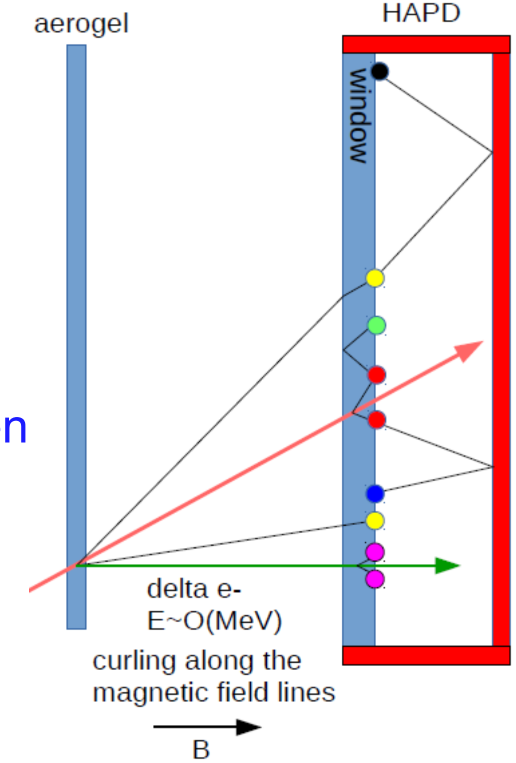
- Average hits per APD per event – white, blue, green are inactive APDs

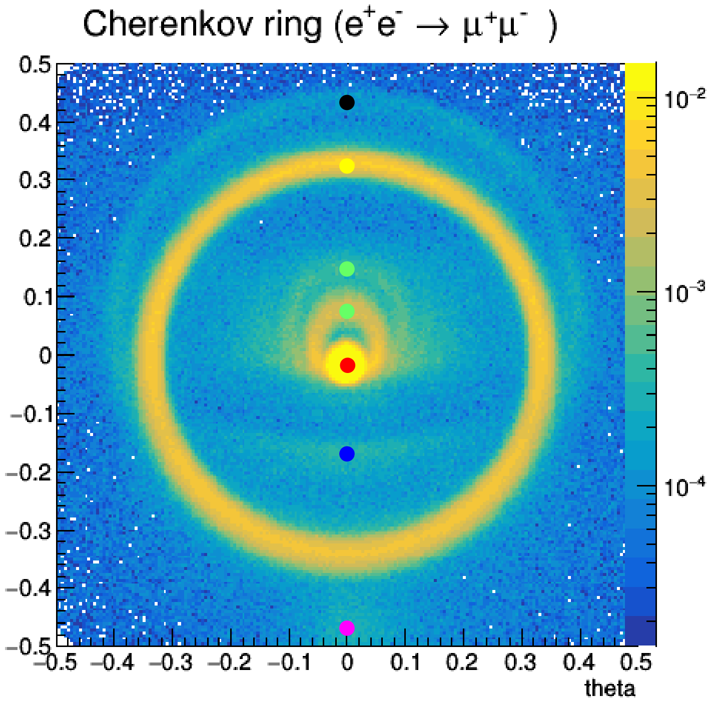


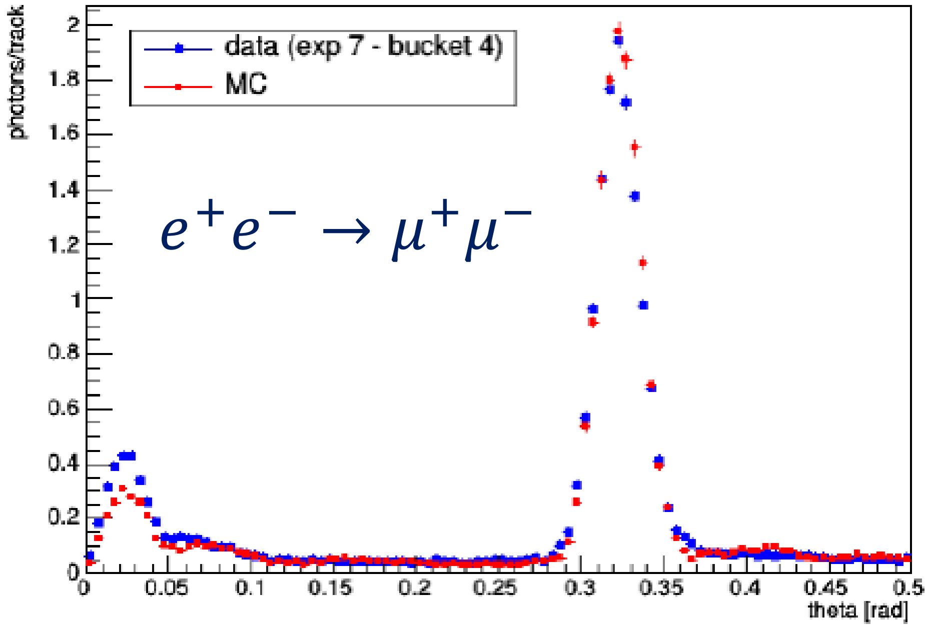
- Thershold scan for all the channels connected to merger 18 - LED illumination

ARICH calibration and alignment ($e^+e^- \to \mu^+\mu^-$)

- First, detector efficiency is calibrated by identifying and removing hot and dead channels.
- ARICH is aligned by maximising the agreement between expected and measured photon distributions and includes:
  - global alignment to tracking system
  - internal alignment of positions and rotations of mirrors and aerogel tiles
- After alignment, a very good agreement is achieved between expected and measured Cherenkov angle distributions.







Photon distribution components:
- **Cherenkov photons from aerogel – direct** and scattered
- Cherenkov photons produced in HAPD window:
  - by primary particle
  - by delta electrons from aerogel
- Cherenkov photons from air gap
- All above can undergo further reflections inside HAPD

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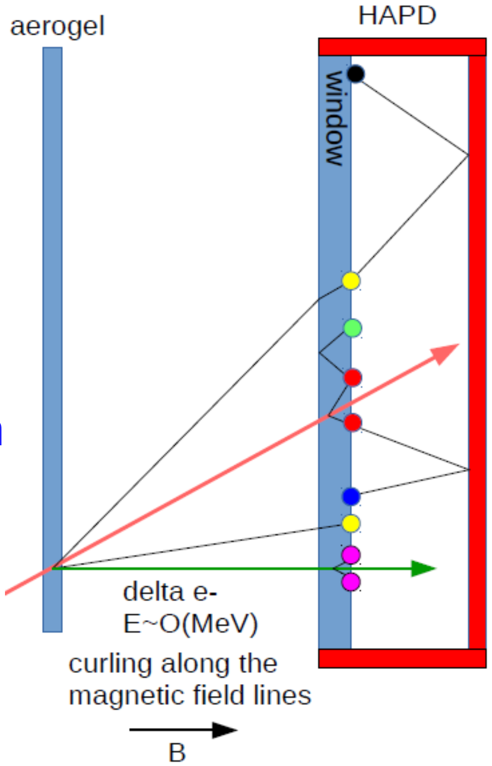

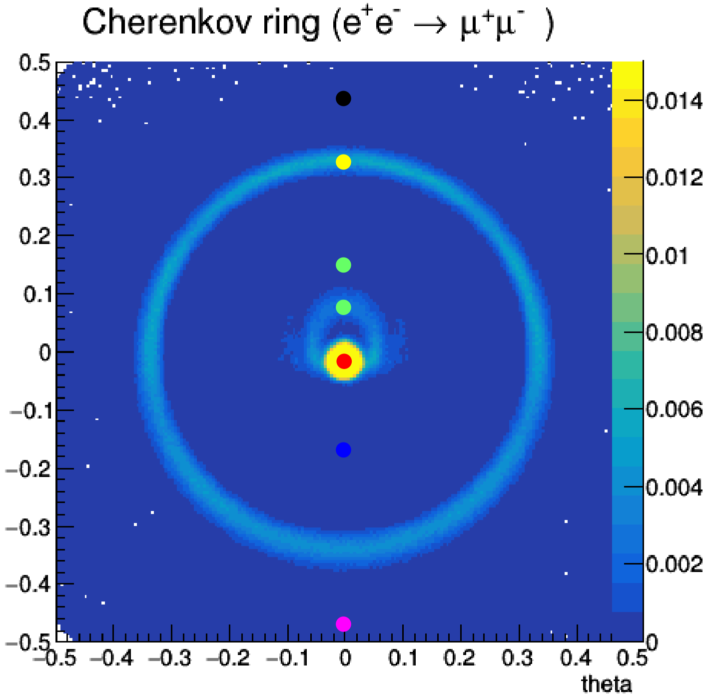

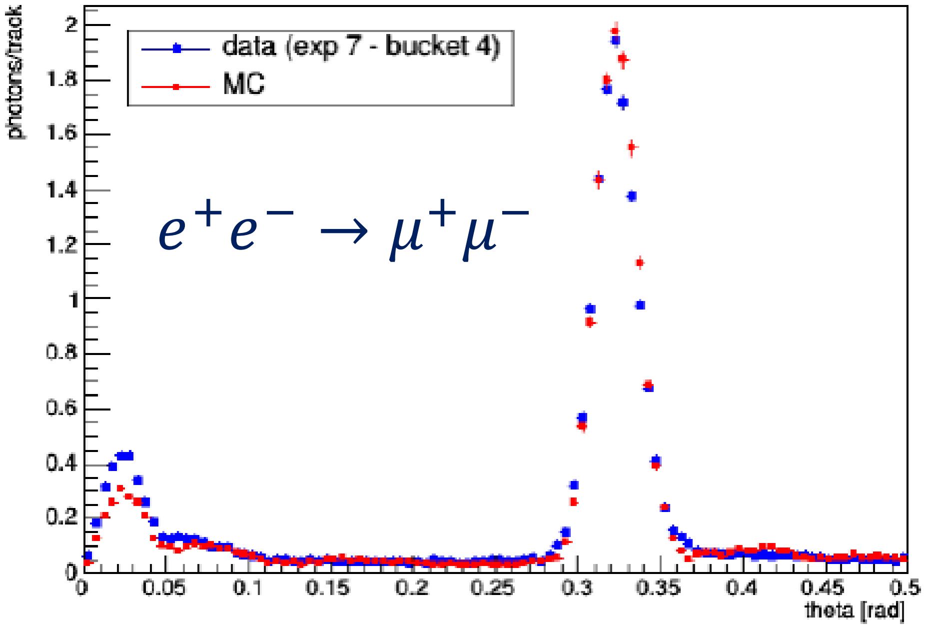

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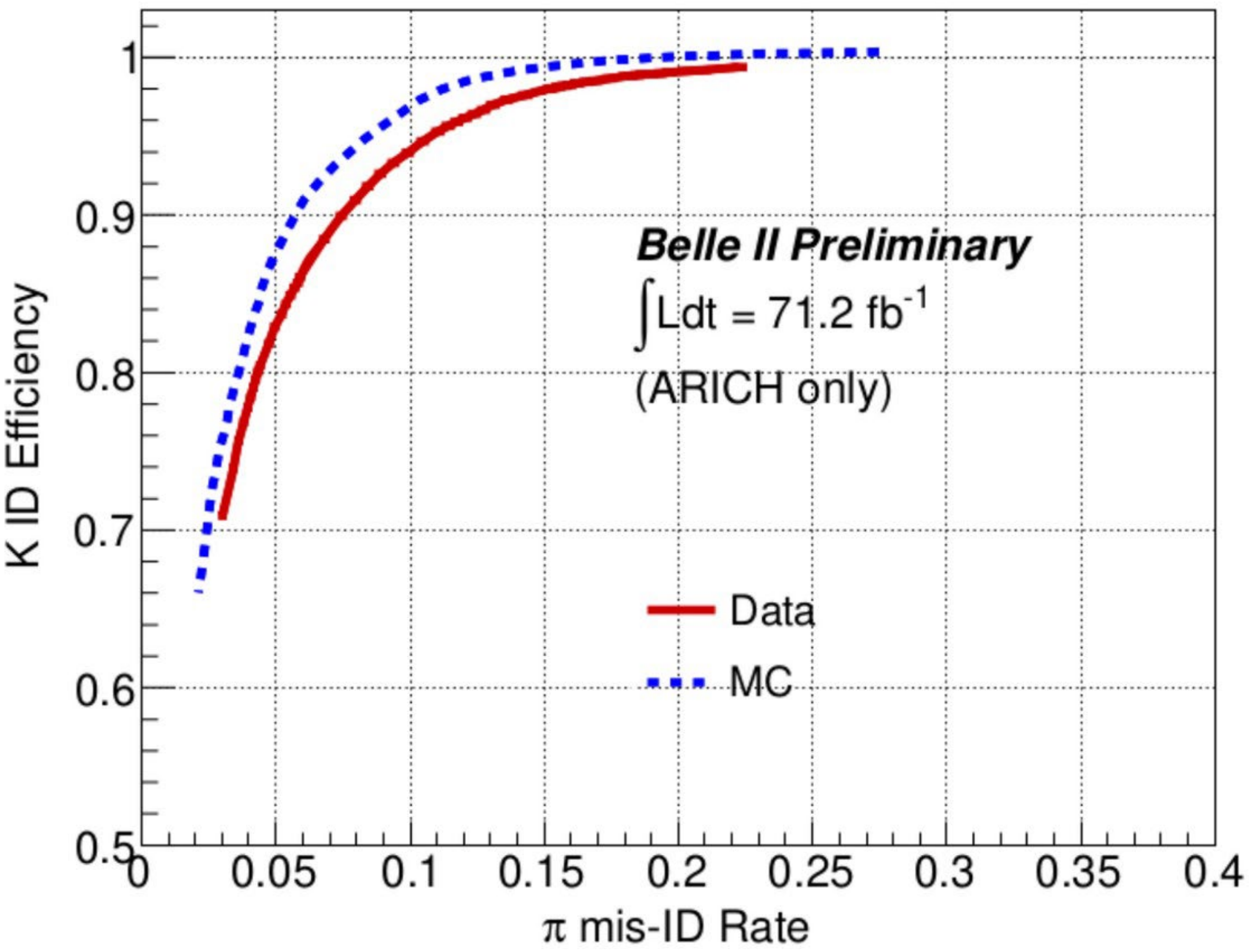
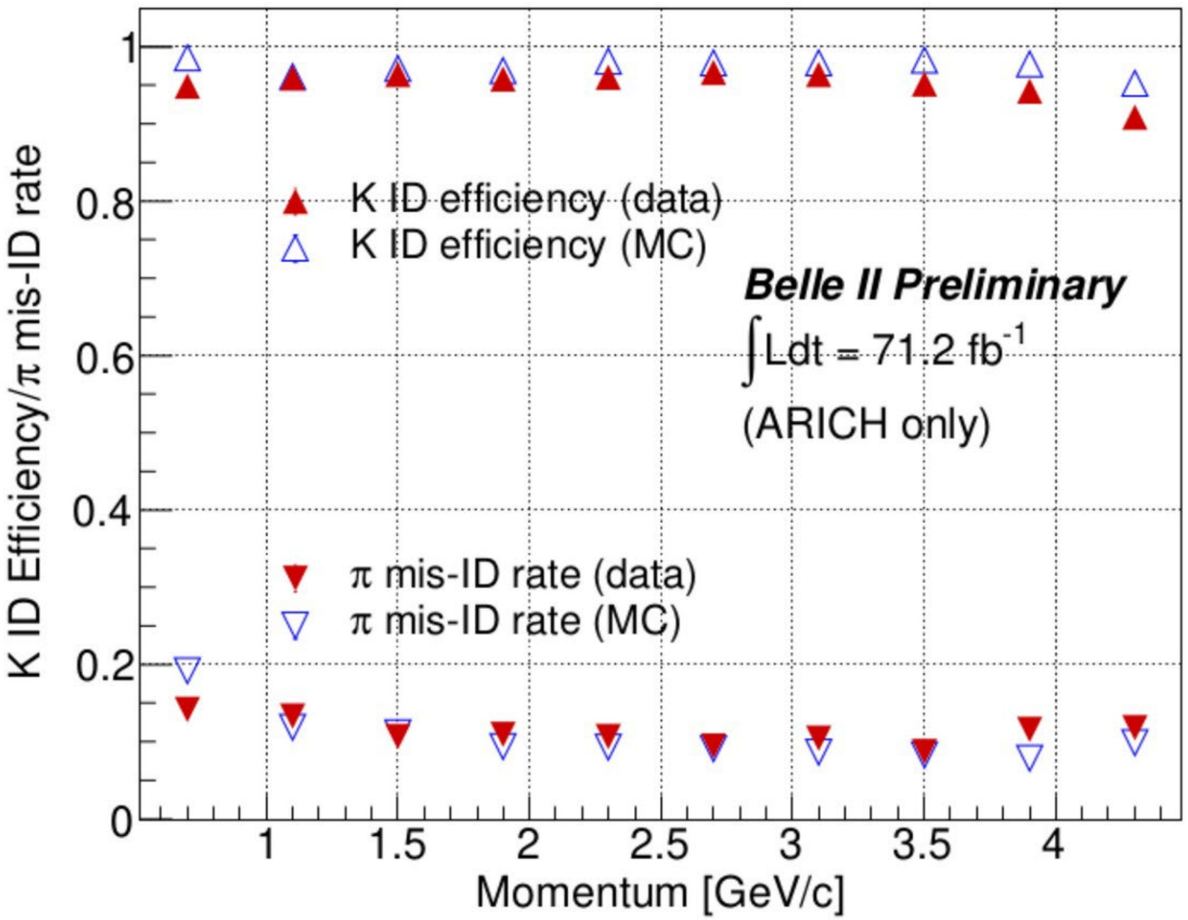
ARICH PID performance

- ARICH K efficiency vs. π misidentification probability



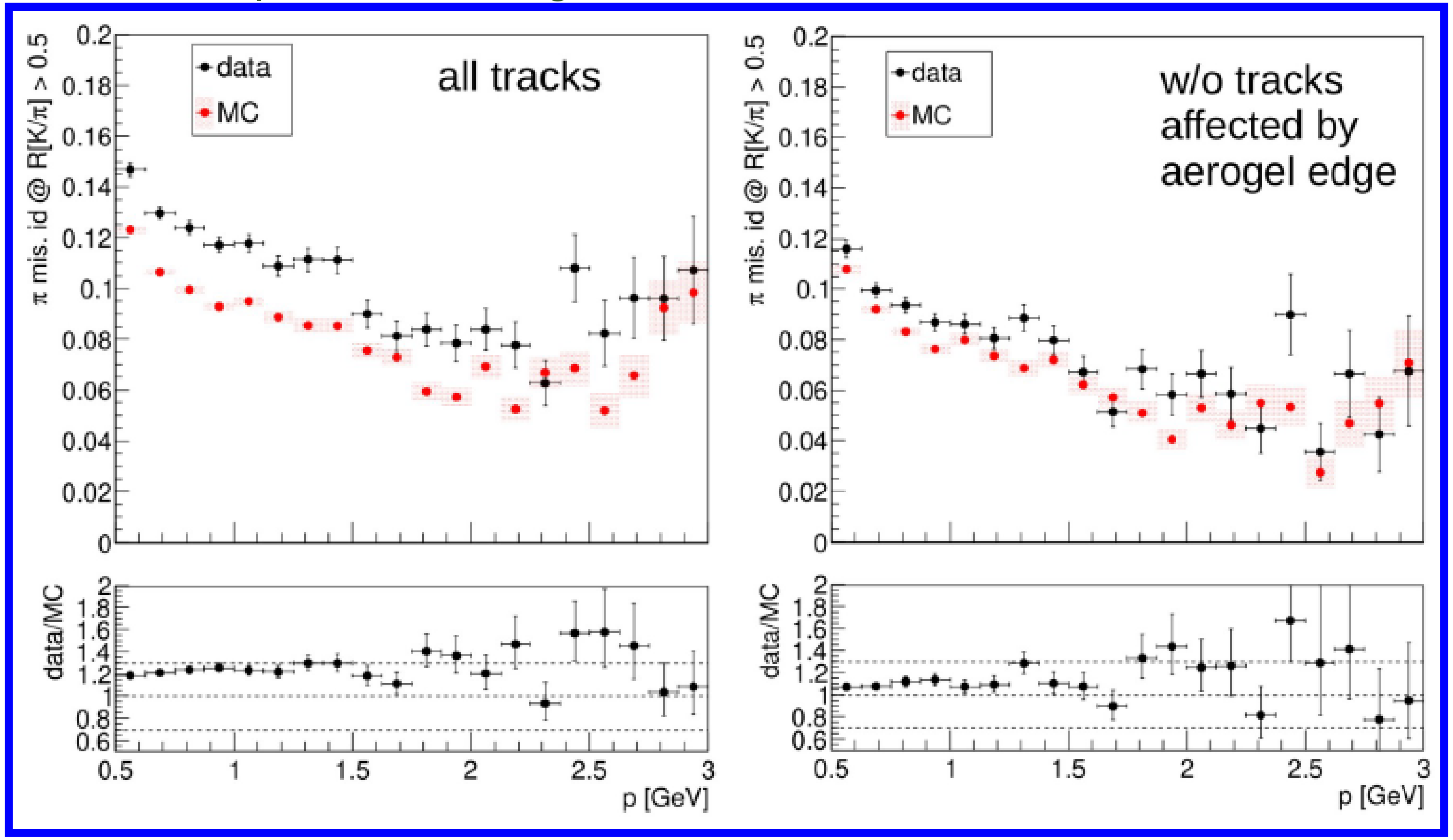
- Momentum dependence of ARICH K efficiency and π misidentification probability

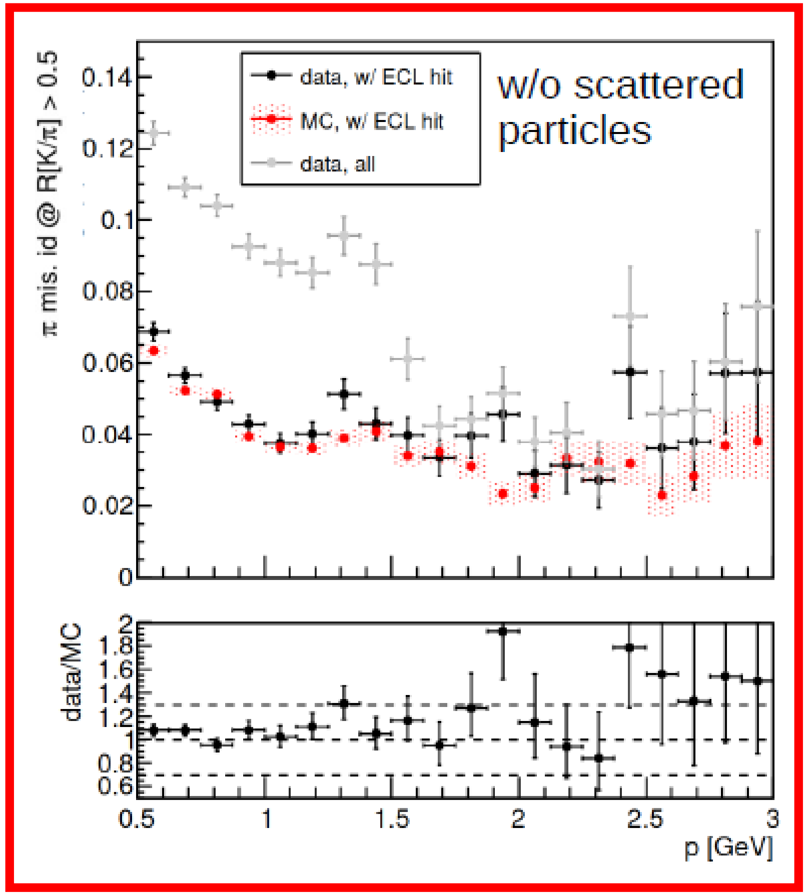


ARICH PID performance

Possible sources of MC/data discrepancy:

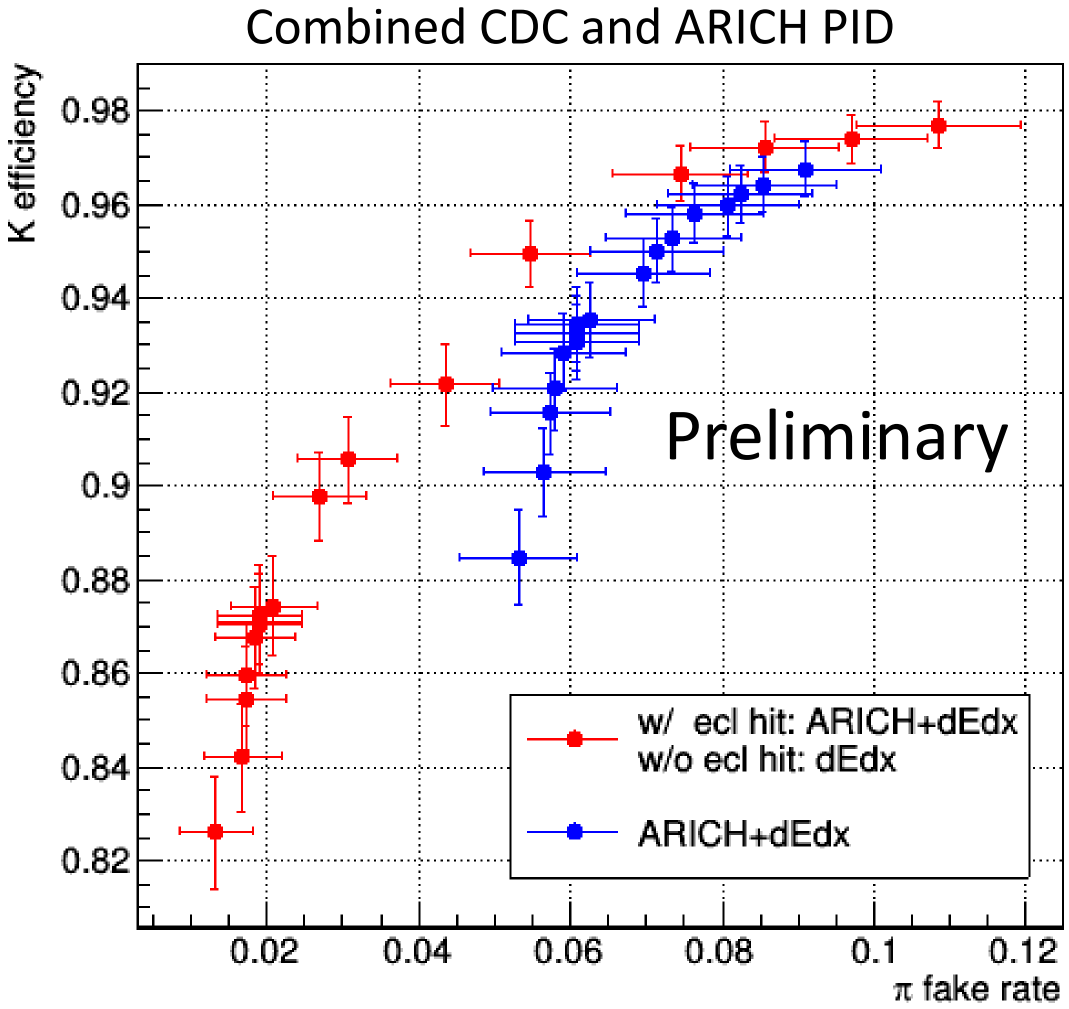
- Imperfect description of aerogel gaps
- Misalignment of aerogel tiles
- Possible underestimate of material budget in front of ARICH – particle decay and scattering
- Other possible misalignment sources



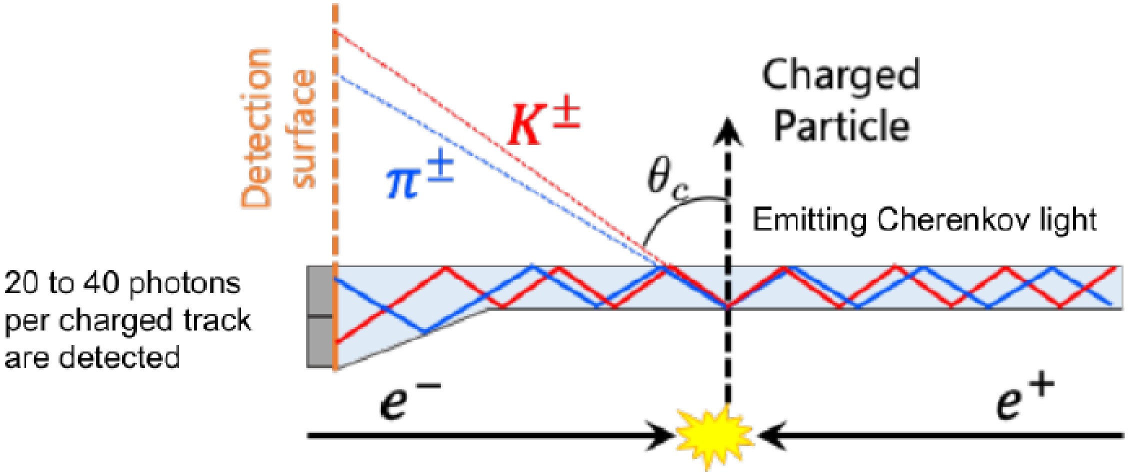


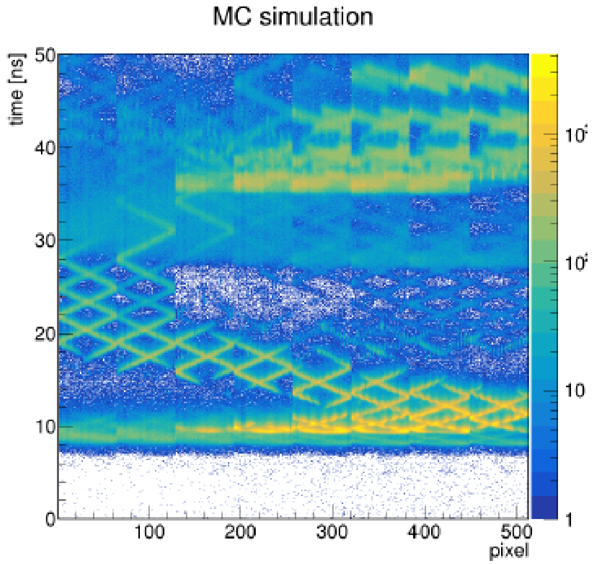
Combined PID – strong scattering/decay

- Large fraction of misidentified pions, especially at low momenta, are due to pions that are strongly scattered or decay on their way to ARICH detector.
- Due to missing photos around extrapolated track position such tracks are likely to be identified as kaons.
- Such tracks can be identified by missing ECL cluster and/or missing signal in case of tracks hit in HAPD window.



TOP - basics



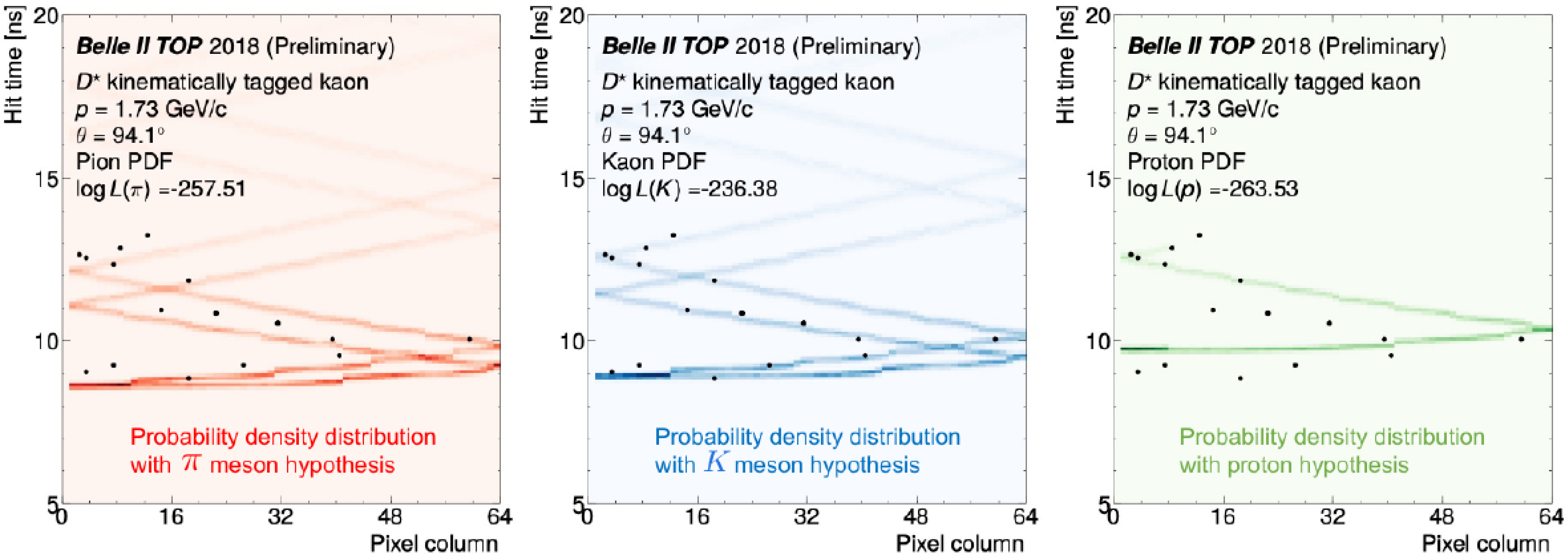


- Cherenkov photons transported to the photon sensors by means of total internal reflections (DIRC)
- Two dimensional information about the Cherenkov ring by measuring the time-of-arrival and the position of photons at photon sensors.
- Time-of-arrival is measured relative to the e^+e^- collision time $\rightarrow$ includes time-of-flight of the particle.

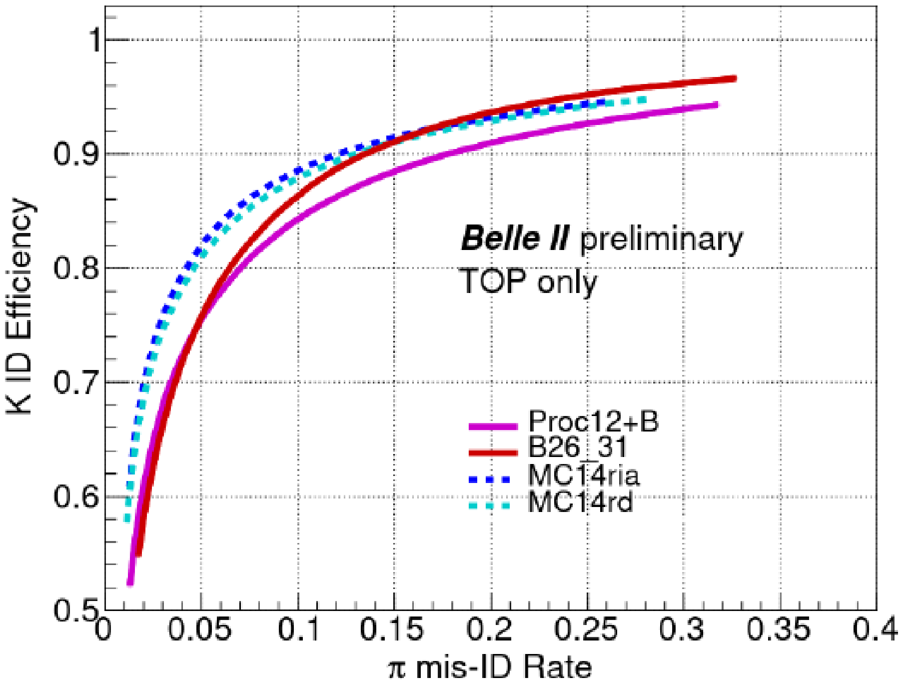
time-of-flight measurement combined with Cherenkov ring imaging

TOP – event example

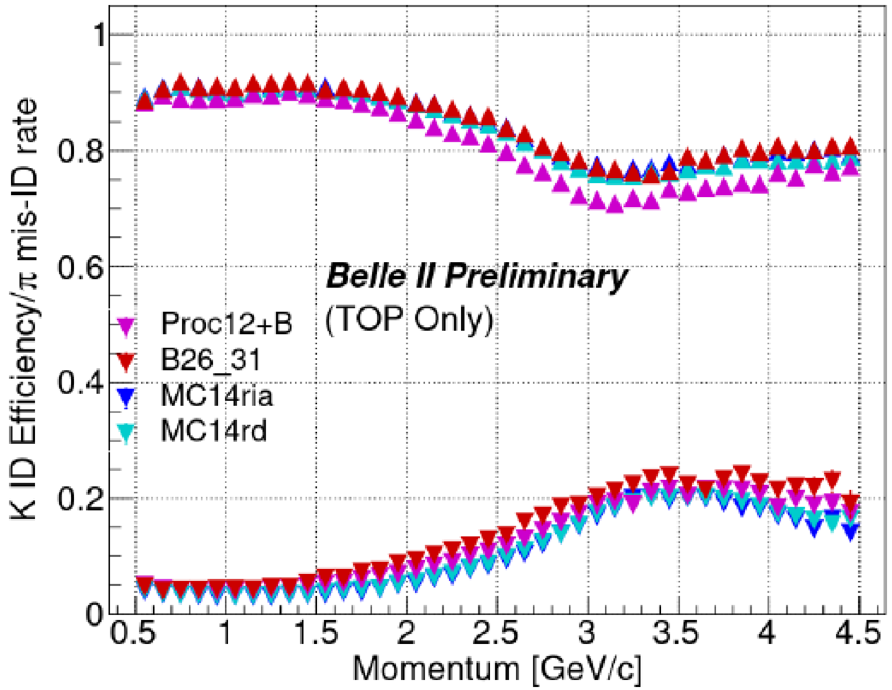
- Kinematically tagged kaon from $D^{*+} \to D^0(\to K^-\pi^+)\pi^+$ decay



TOP – PID performance: $D^{*+} \to D^0(\to K^-\pi^+)\pi^+$

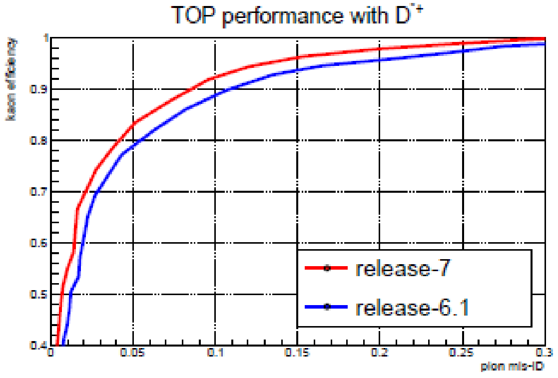


$\mathcal{L}_K > \mathcal{L}_\pi$

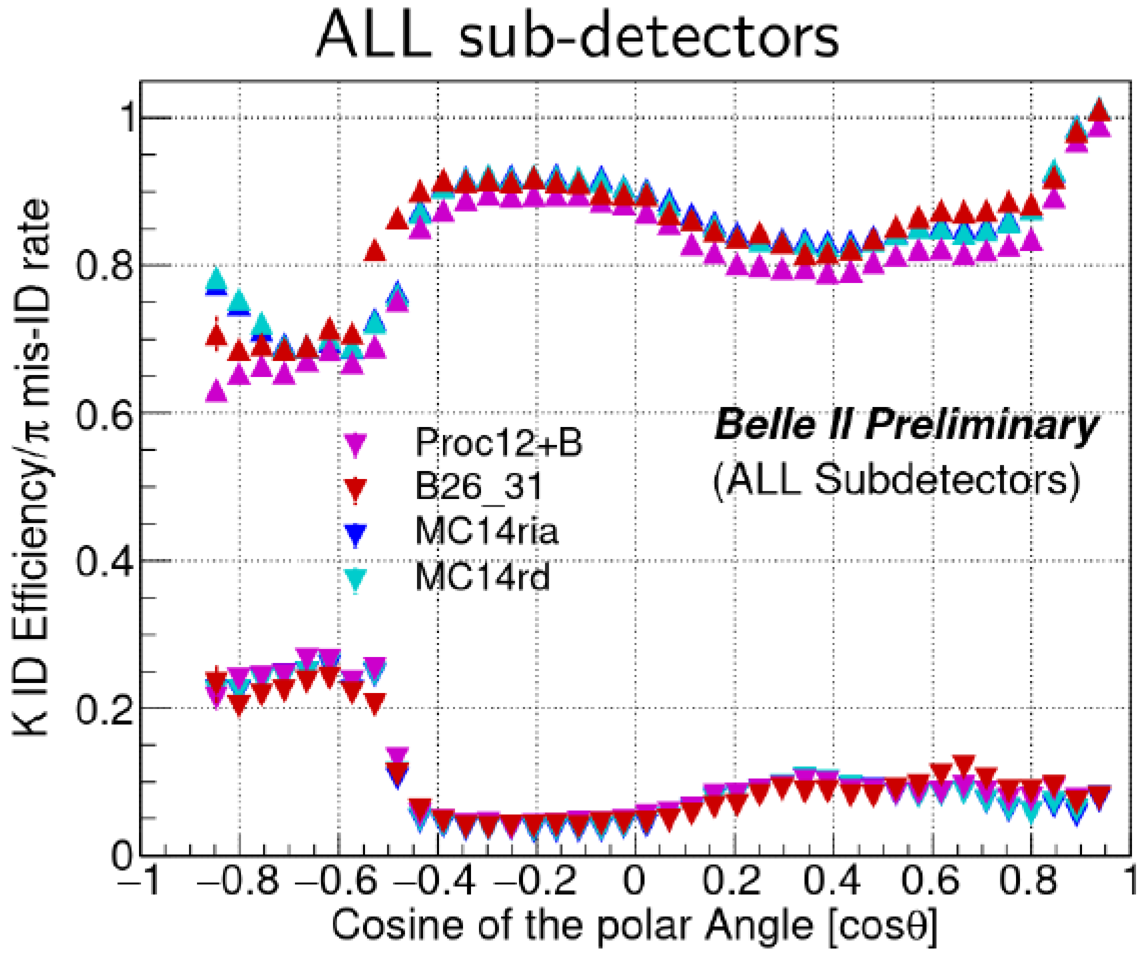


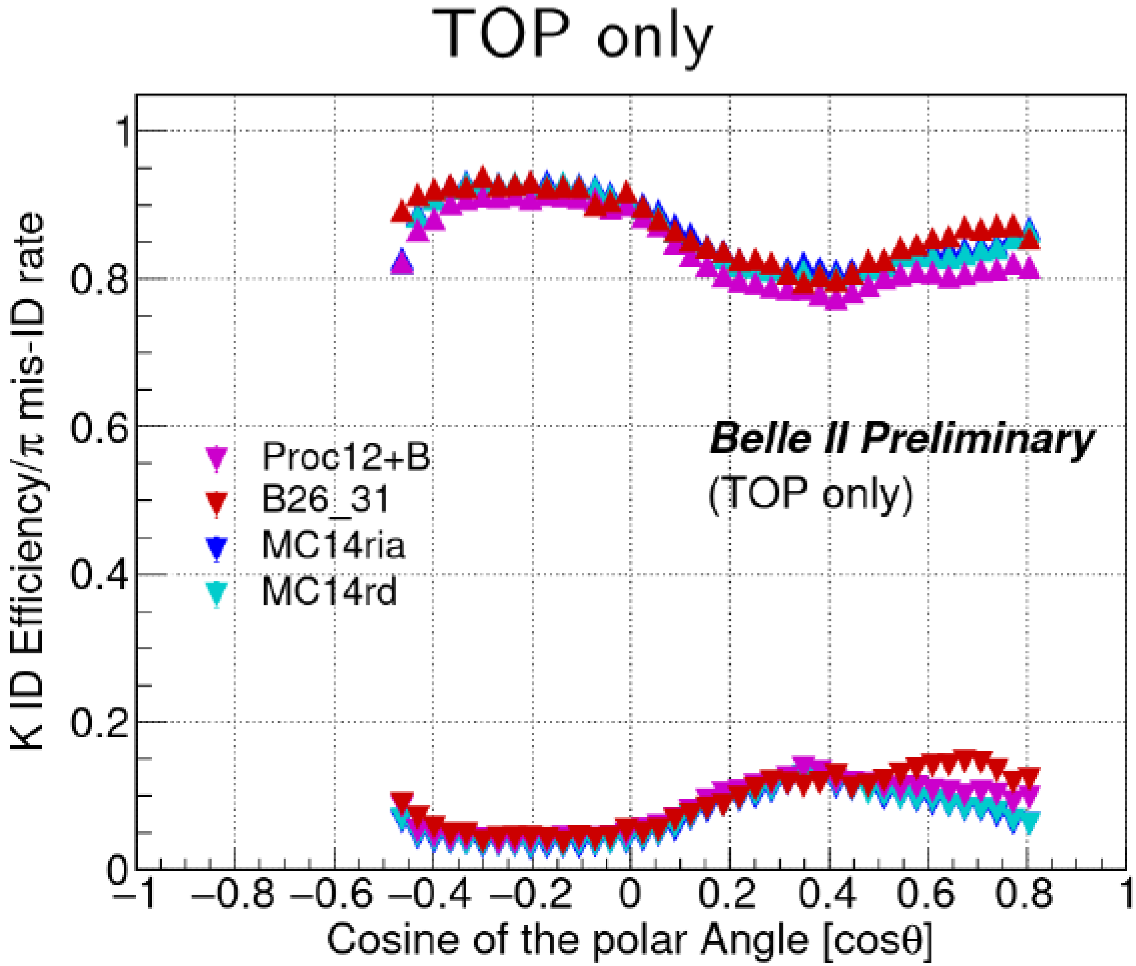
reprocessing	year	K effi at 10% π fake
proc9	2019	80%
proc10	2020	82%
proc11/12	2021	84%
proc13	2022	86%
(proc14)	(2023)	$\sim$90%

test on small dataset



PID vs. polar angle

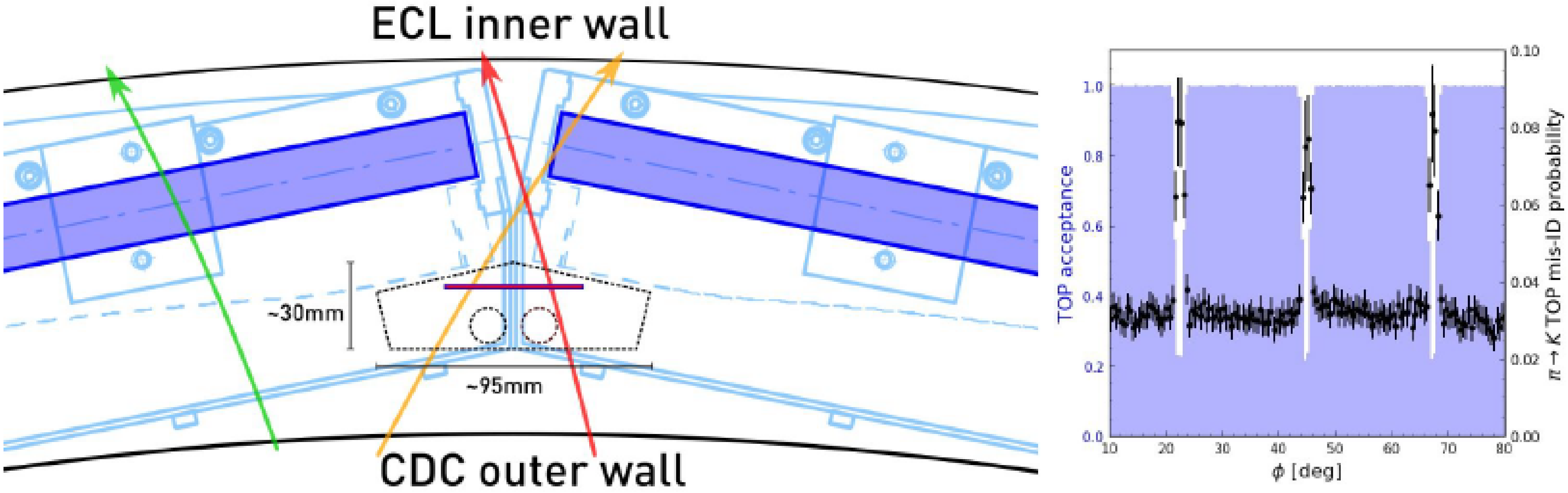




Proc12+B: software release-5 (2020)
B26_31: software release-6 (2021)

STOPGAP- A ToF for Belle II as Fast MAPS Demonstrator

The Belle II Barrel PID has holes...



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Summary & plan