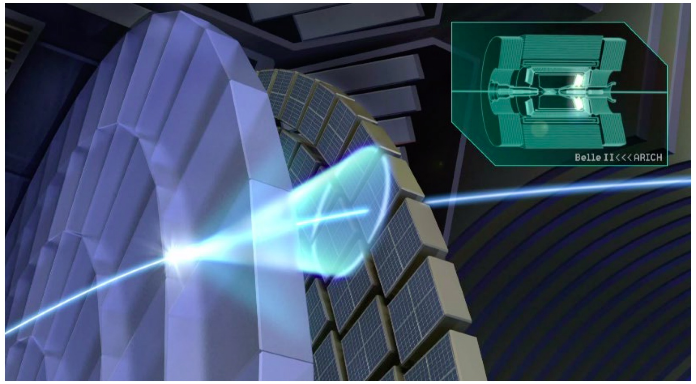
Institut "Jožef Stefan", Ljubljana, Slovenija

# ARICH at Belle II



Rok Pestotnik

Jožef Stefan Institute, Ljubljana, Slovenia

Contents:

- Belle II
- ARICH design
- Current operation & performance
- Upgrade plans

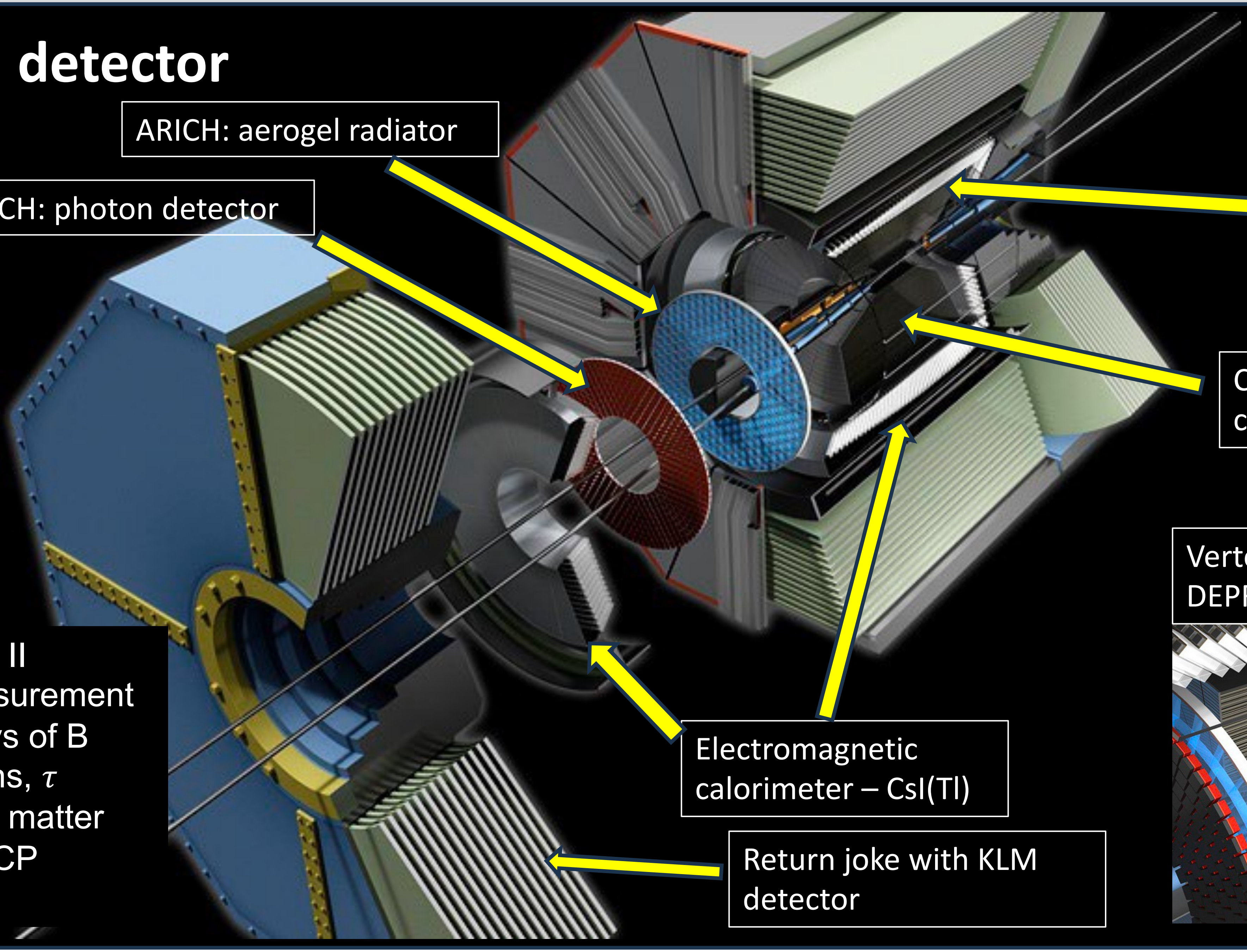
# Contributors

Institut "Jožef Stefan", Ljubljana, Slovenija

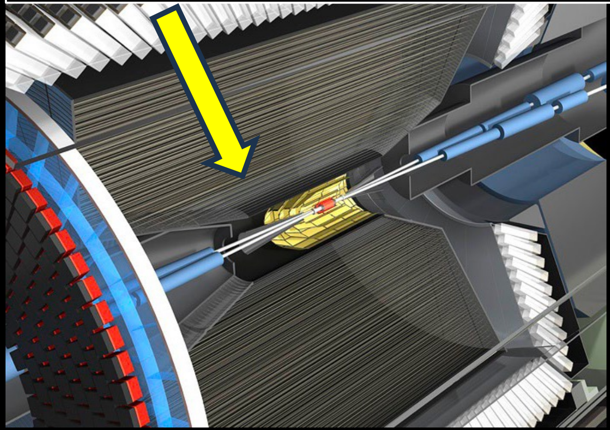

R. Pestotnik[a,*], I. Adachi[b,c], K. Adamczyk[a], L. Burmistrov[d], R. Dolenec[n,a], K. Furui[e], T. Iijima[f], S. Iwaki[h], S. Iwata[g,h], G. Ghevondyan[j], R. Giordano[i], H. Kakuno[h], G. Karyan[j], H. Kawai[k], T. Kawasaki[l], H. Kindo[c], T. Kohriki[b], T. Konno[l,h], S. Korpar[m,a], P. Križan[n,a], T. Kumita[h], Y. Lai[o], A. Lozar[a], K. Matsuoka[b,c,f], K. Motohashi[h], G. Nazaryan[j], S. Nishida[b,c], M. Nishimura[b], K. Ogawa[p], S. Ogawa[q], T. Park[h], L. Šantelj[n,a], Y. Seino[p], A. Seljak[a], L. Senekovič[a], M. Shoji[b], T. Sumiyoshi[h], M. Tabata[k], M. Tsurufuji[h], K. Uno[p], E. Waheed[b], K. Watanabe[h], M. Yonenaga[h], Y. Yusa[p]

[a] *Jožef Stefan Institute, Ljubljana, Slovenia*
[b] *High Energy Accelerator Research Organization (KEK), Tsukuba, Japan*
[c] *SOKENDAI (The Graduate University of Advanced Studies), Tsukuba, Japan*
[d] *Laboratoire de l'accélerateur Linéaire (LAL), Orsay, France*
[e] *University of Tokyo, Tokyo, Japan*
[f] *Nagoya University, Nagoya, Japan*
[g] *Tokyo Metropolitan College of Industrial Technoligy, Tokyo, Japan*
[h] *Tokyo Metropolitan University, Hachioji, Japan*
[i] *Università di Napoli "Federico II" and Istituto Nazionale di Fisica Nucleare, Napoli, Italy*
[j] *Alikhanyan National Science Laboratory, Yerevan, Armenia*
[k] *Chiba University, Chiba, Japan*
[l] *Kitasato University, Sagamihara, Japan*
[m] *University of Maribor, Slovenia*
[n] *University of Ljubljana, Slovenia*
[o] *Kavlil Institute for the Physics and Mathematics of the Universe, Japan*
[p] *Niigata University, Niigata, Japan*
[q] *Toho University, Funabashi, Japan*

# Belle II detector




Vertex detector
DEPFET (pixel) + DSSD (strip)



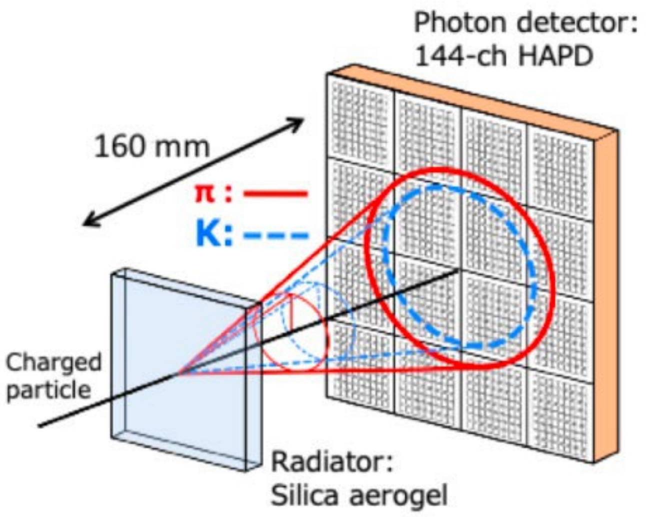
Goal of Belle II
Precise measurement of rare decays of B and D mesons, $\tau$ leptons, dark matter search, and CP violation.

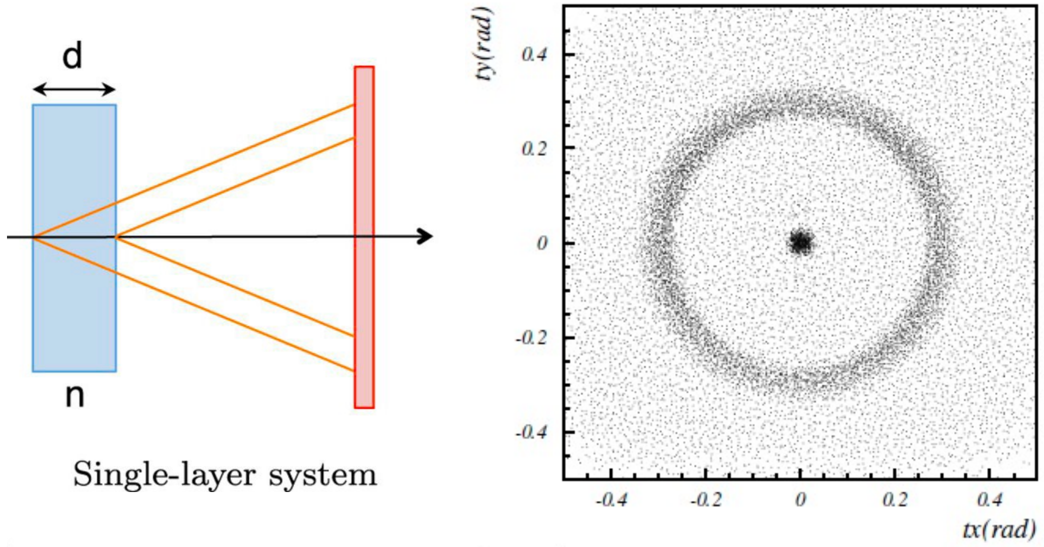
# ARICH - RICH with an aerogel radiator



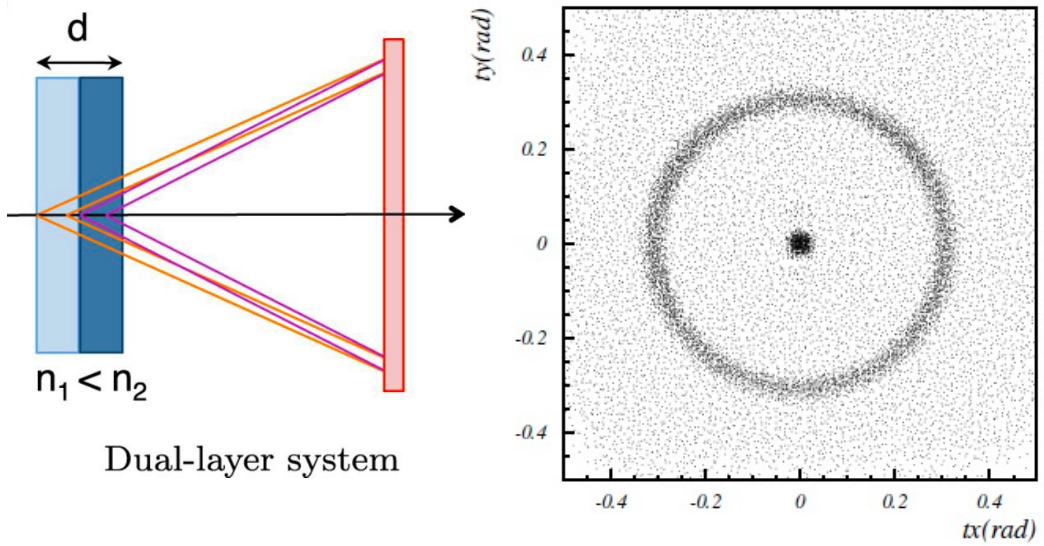
Proximity focusing Aerogel Ring Imaging Cherenkov detector (ARICH) components:

- double layer focusing aerogel radiator ( 20+20 mm) to increase the number of photons without degrading the resolution
- 160 mm expansion gap
- photon detector based on 420 Hybrid Avalanche Photo Detectors (HAPD)
- front-end electronics with dedicated ASICs. and FPGAs




Single-layer system




Dual-layer system

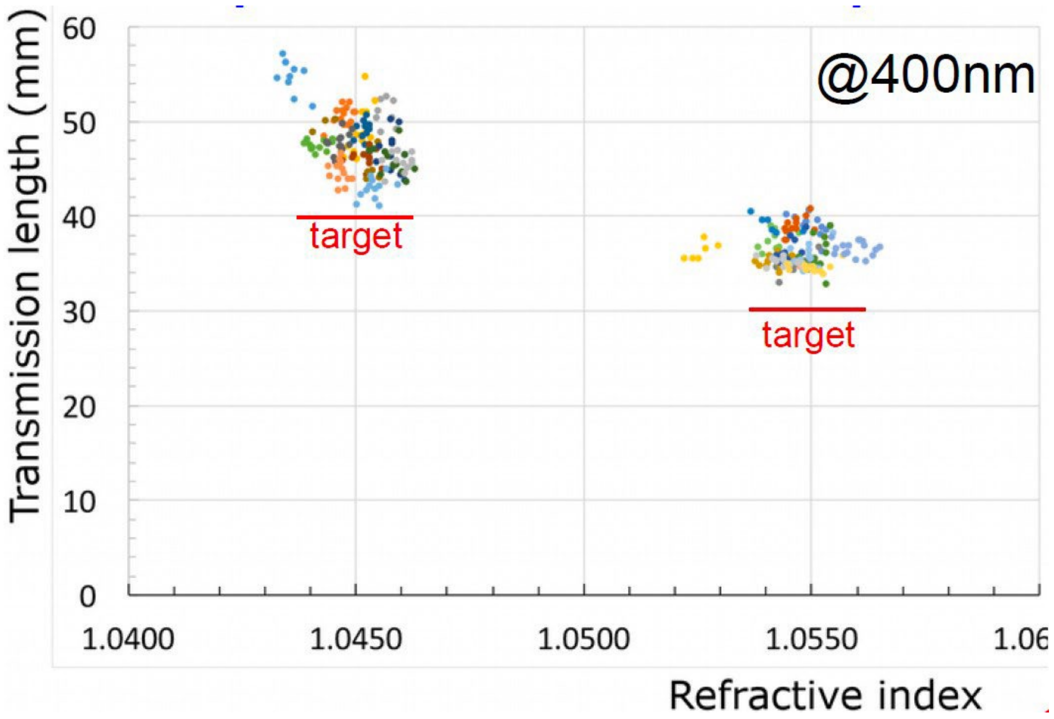
# Aerogel radiator

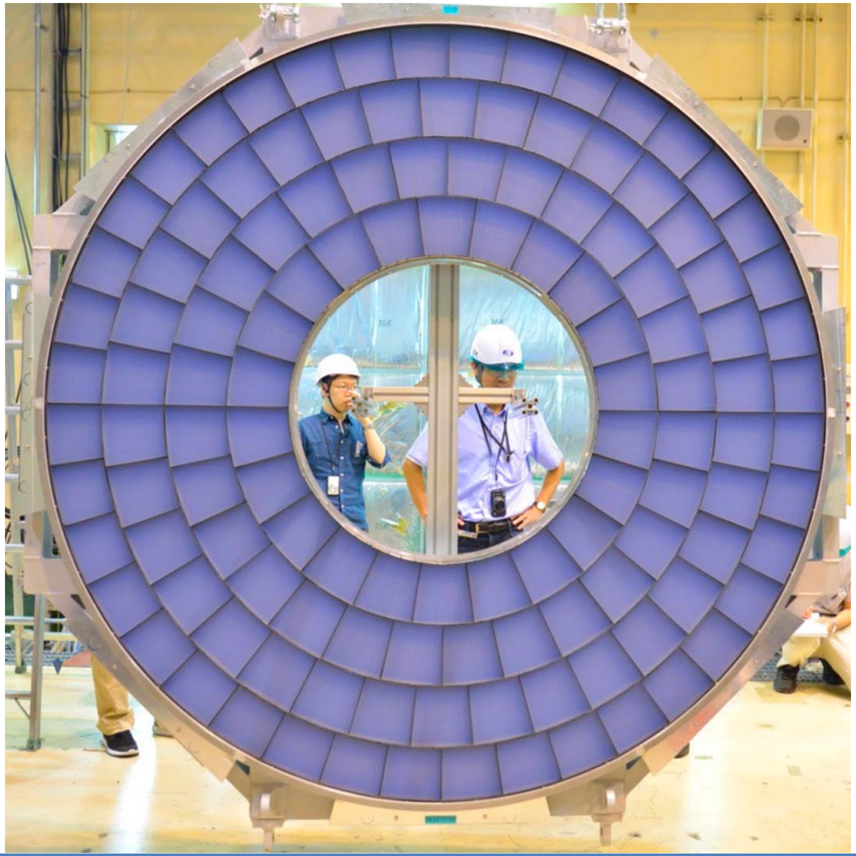


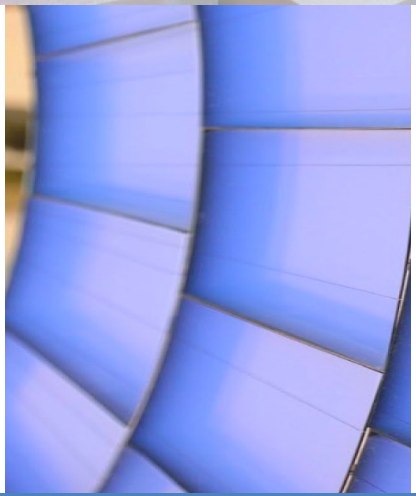
Two layers of 20 mm thick hydrophobic aerogel:

- upstream, $n \approx 1.045$, TL@$\lambda_{400nm} \approx 45$mm
- downstream, $n = 1.055$, TL@ $\lambda_{400nm} \approx 35$mm

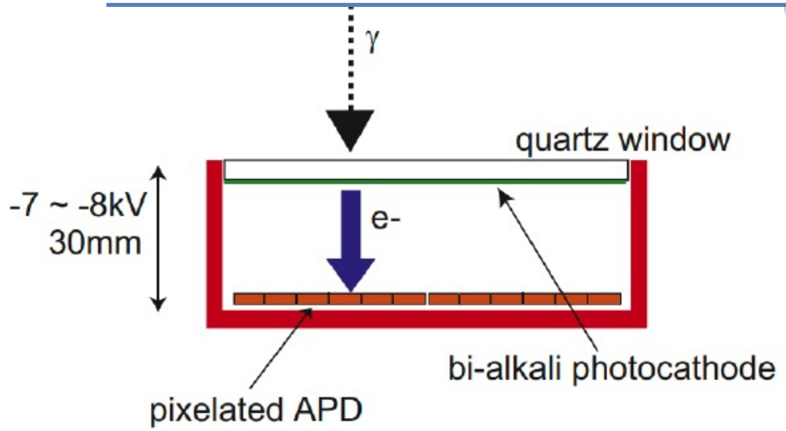
- 4 segmented rings, $2 \times 124$ tiles
- all but exit surface of each pair covered by a black paper
- each pair fixed by two black strings running radially
- completed in December 2016



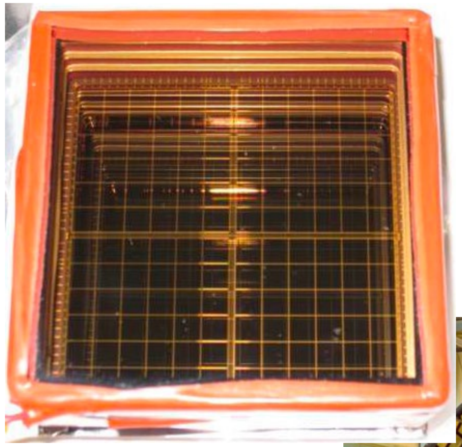
# Photon detector with HAPD

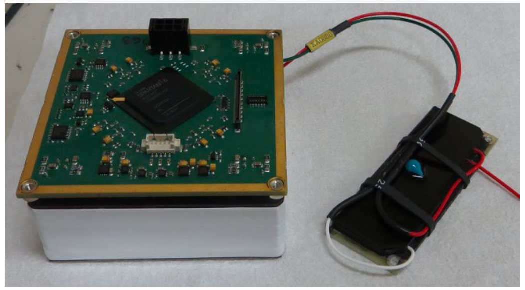



constructed from 420 HAPD modules.

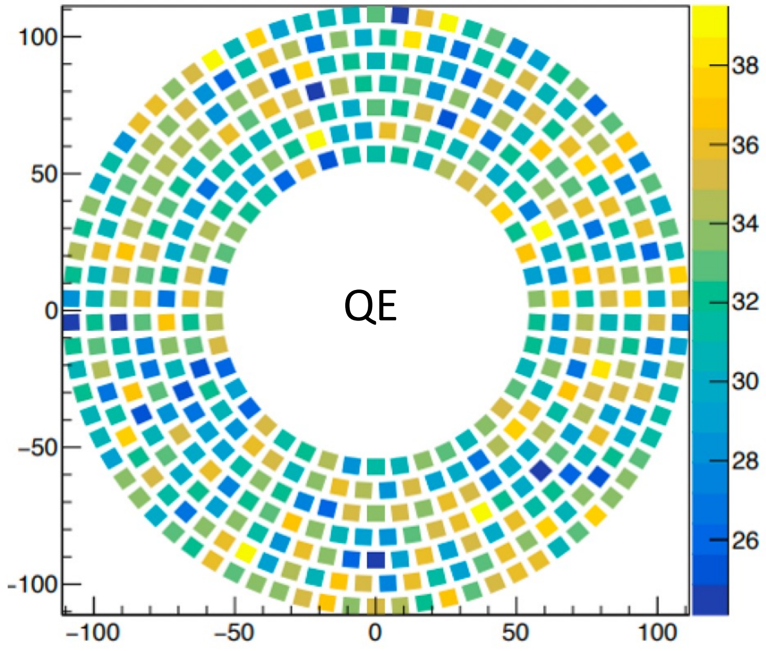
HAPD properties:

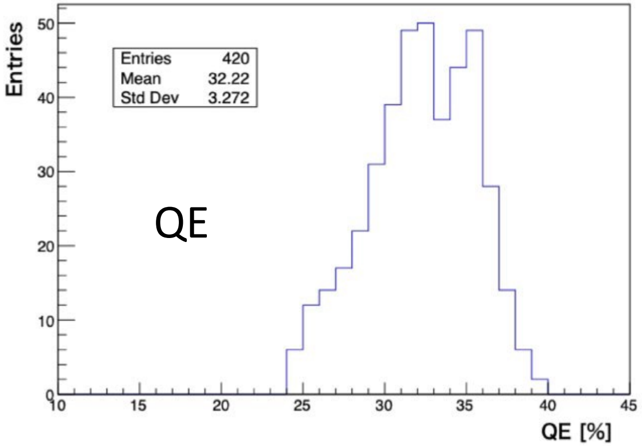
- size: $73\times73\times28$ mm$^3$
- $2\times2$ APDs with $6\times6$ channels, $4.9\times4.9$mm2@ 5.1mm pitch
- avg. $QE@400\mathrm{nm} \approx 32\%$
- combined gain $\approx$70k
- channel capacitance 80pF
- operation in B=1.5T
- radiation tolerance $\approx 10^{12}$ $n$.e./cm$^2$

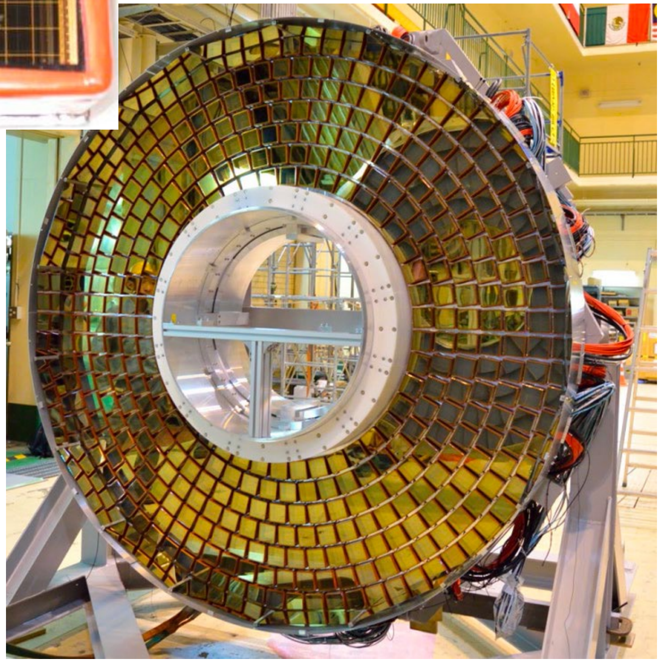




420 HAPDs in 7 rings

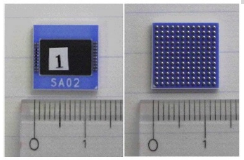


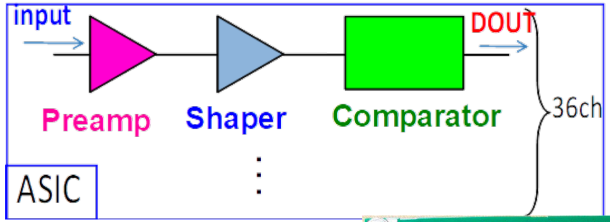
18 planar mirrors Neutron shield

# Front-end electronics



SA02 (36ch)

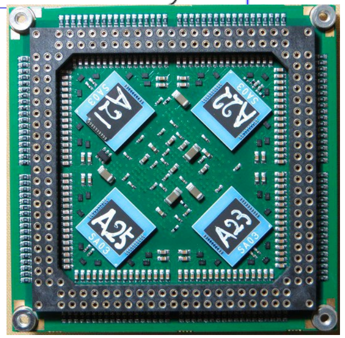
Institut "Jožef Stefan", Ljubljana, Slovenija

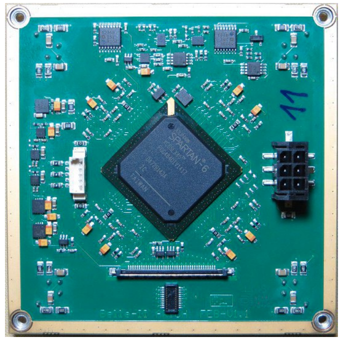


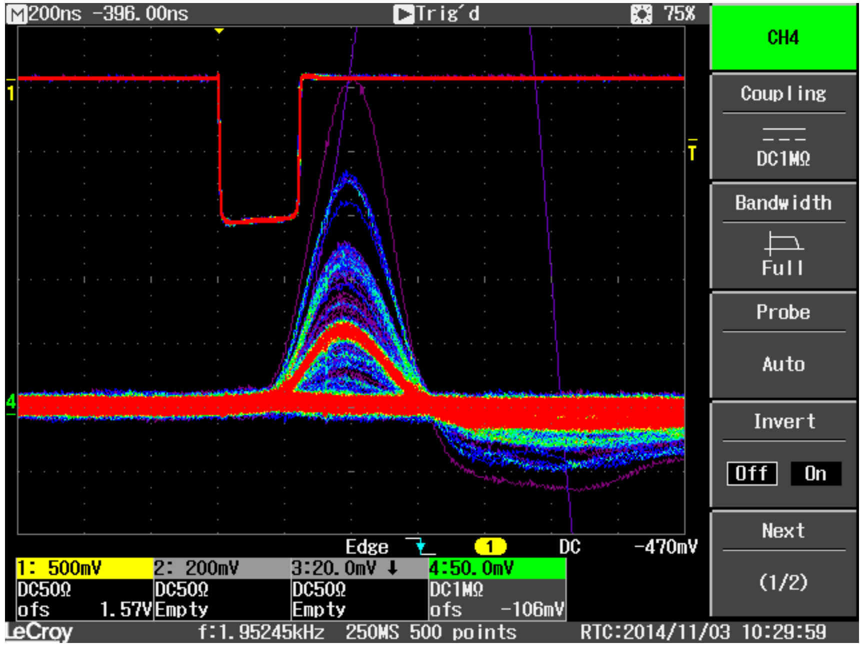


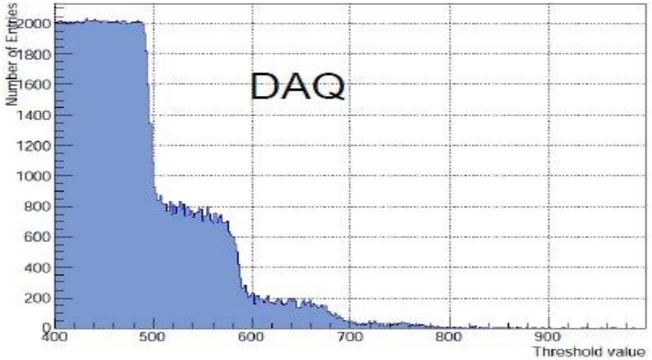
Front-end electronics is organized in units of one merger board (MB) controling6 (or 5) front-end boards (FEB)

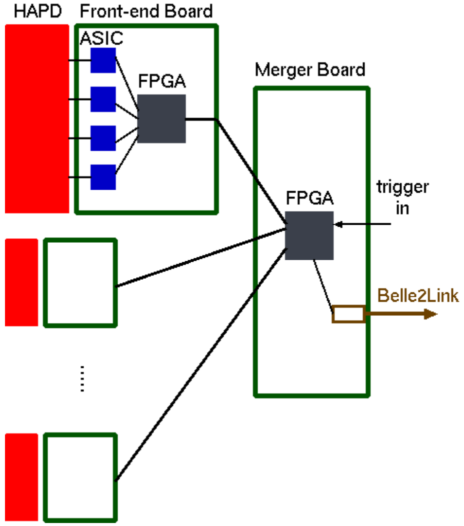
- FEB is based on 4 36 ch. ASICs each covering one APD, and Spartan-6 FPGA
- MB controls FEB slow control parameters, and collects and transfers data to back-end DAQ

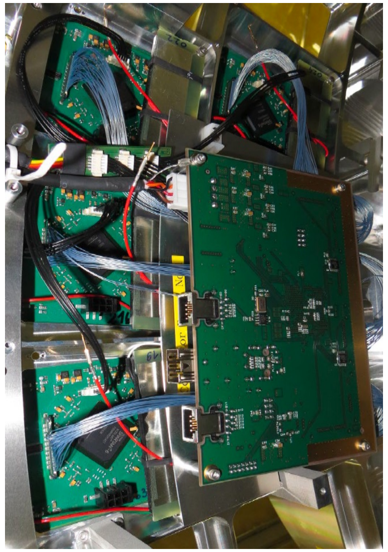






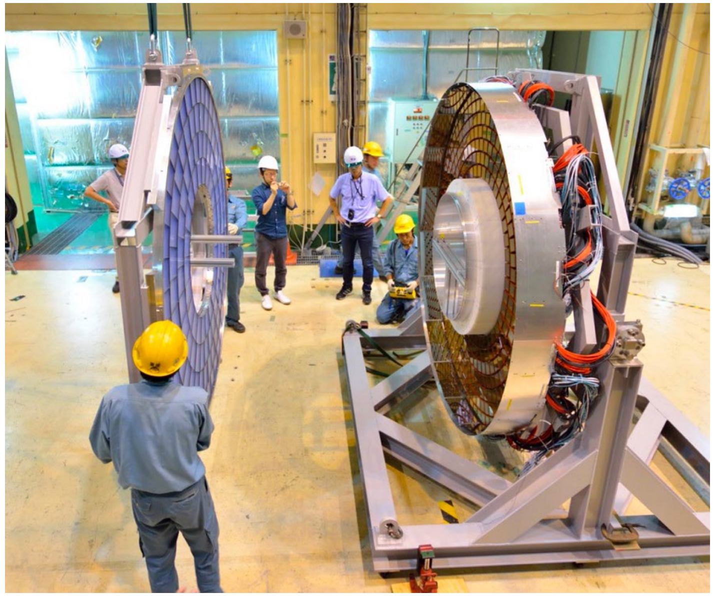



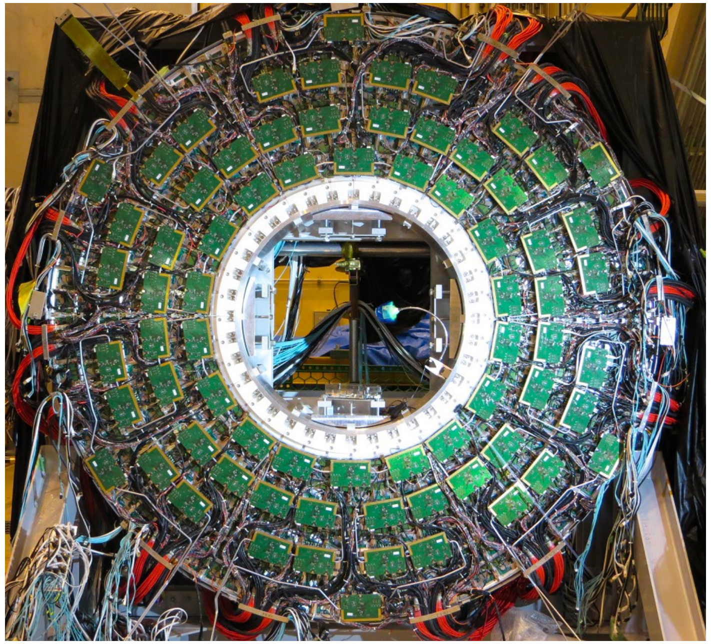
# Integration and installation

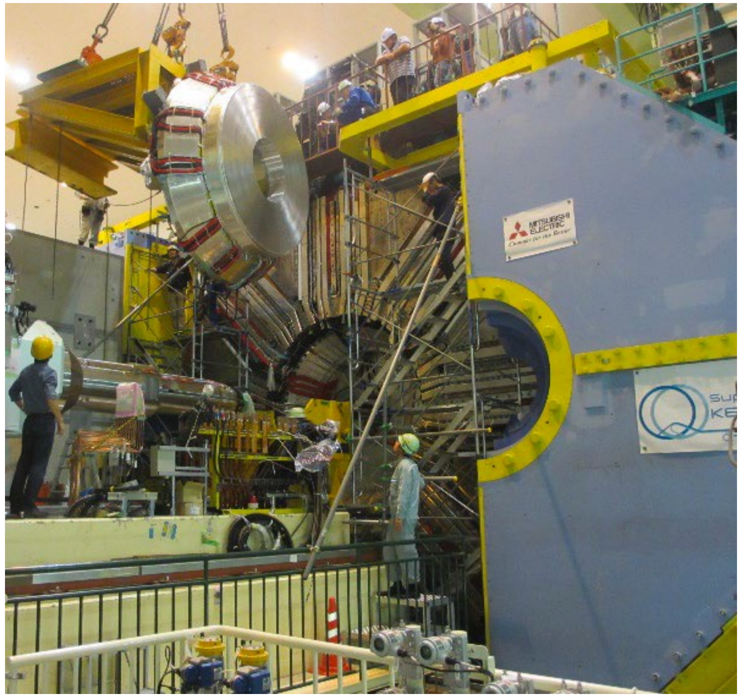


Joining radiator and photon detector parts in 2017.



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





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

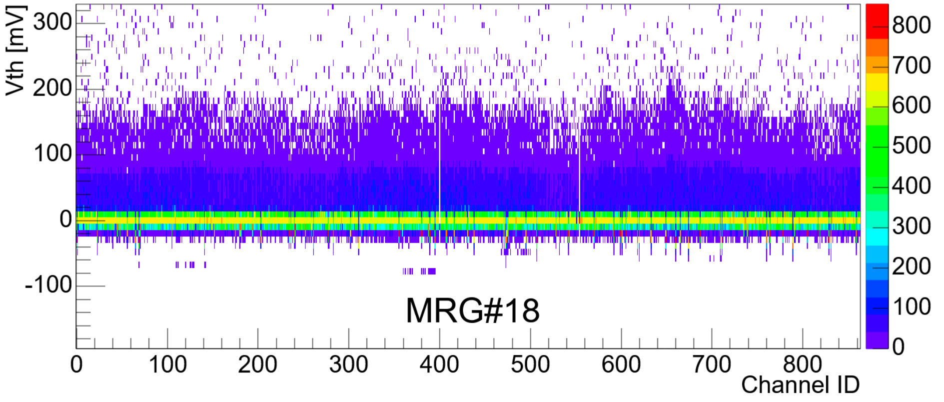
# Operation status

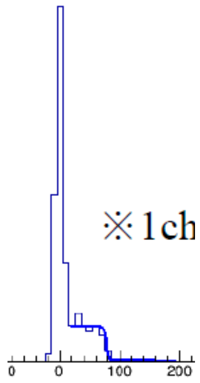
Since March 2019 ARICH is fully operational.

Current status:

- 94% of ARICH channels operational
- 1% 1 merger group with 5 HAPD modules, off due to LV cable problem
- 5% off due to HV or bias problems – different reasons under study

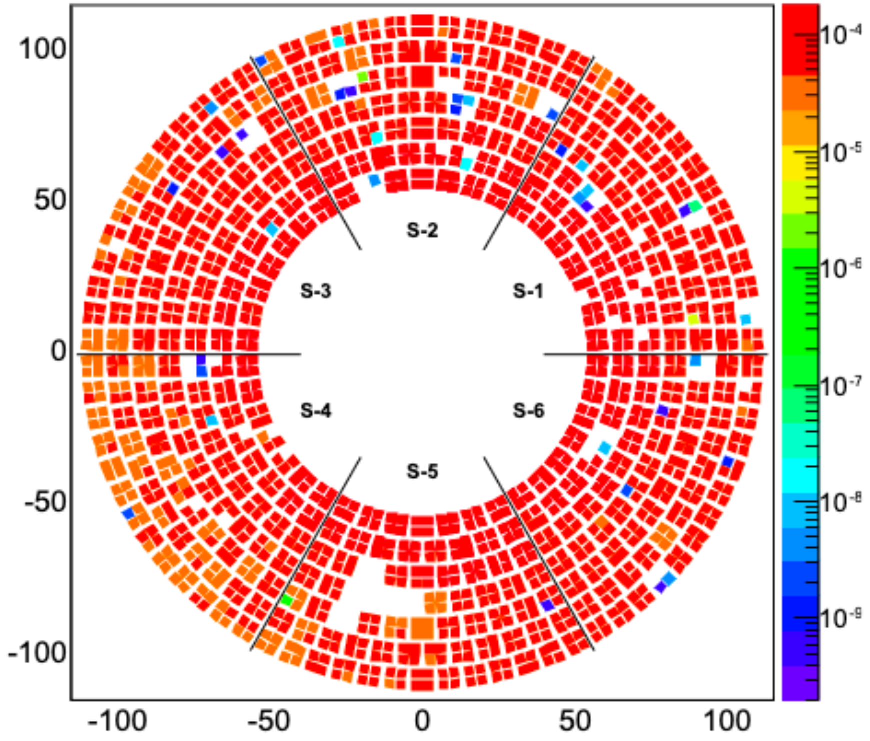
- Electronics efficiency for single photon signals well above 90% – threshold set at 50mV.




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

Signal hits / channel / event



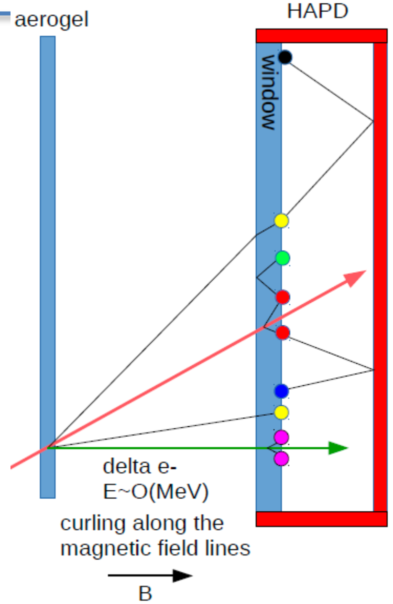

Average hits per APD per event – white, blue, green are inactive APDs

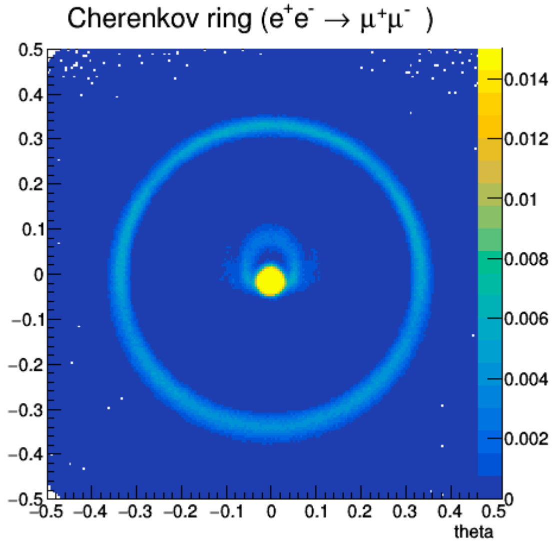
# Calibration and alignment ($e+e- \to \mu+\mu-$)

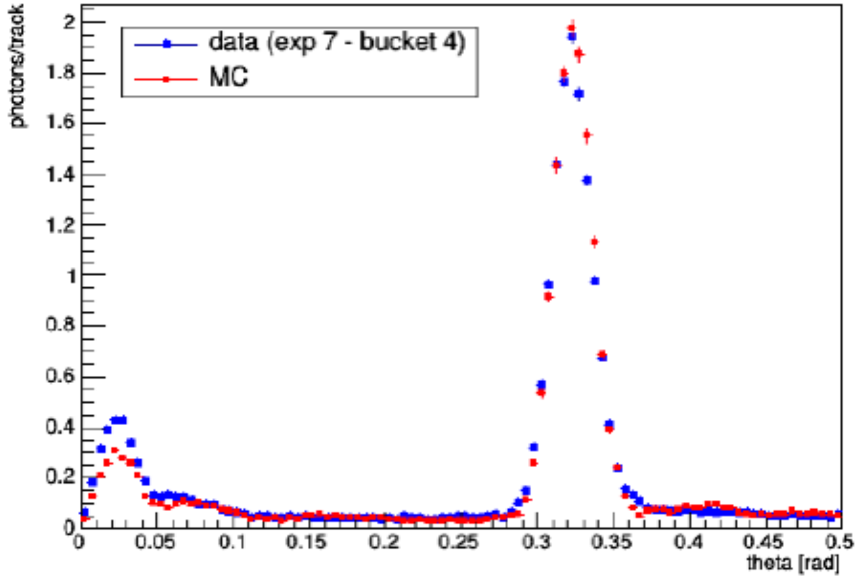
Institut "Jožef Stefan", Ljubljana, Slovenija

- Identify and remove hot and dead channels.
- Align the system by maximizing the agreement between expected and measured photon distributions:
  - Global alignment to a tracking system
  - Internal alignment of positions and rotations of mirrors and aerogel tiles

✋ Very good agreement is achieved between expected and measured Cherenkov angle distributions



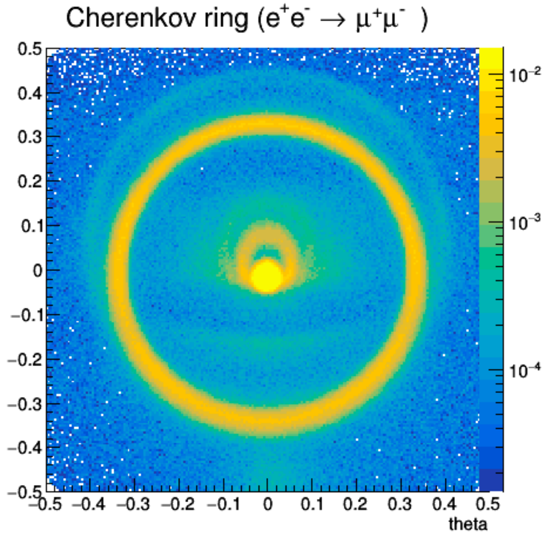




Photon distribution components:

- **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



# Likelihood function and PDF construction

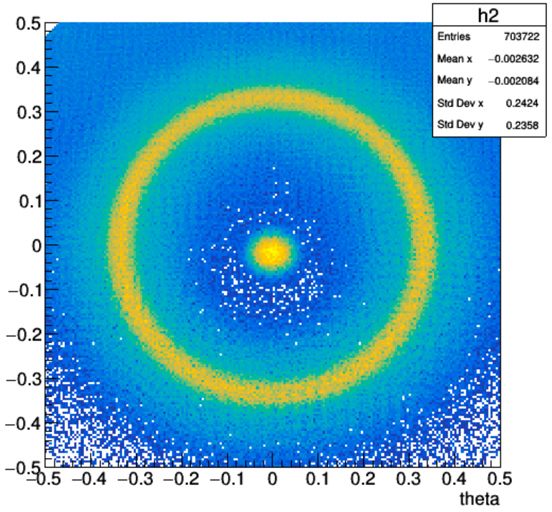
Institut "Jožef Stefan", Ljubljana, Slovenija

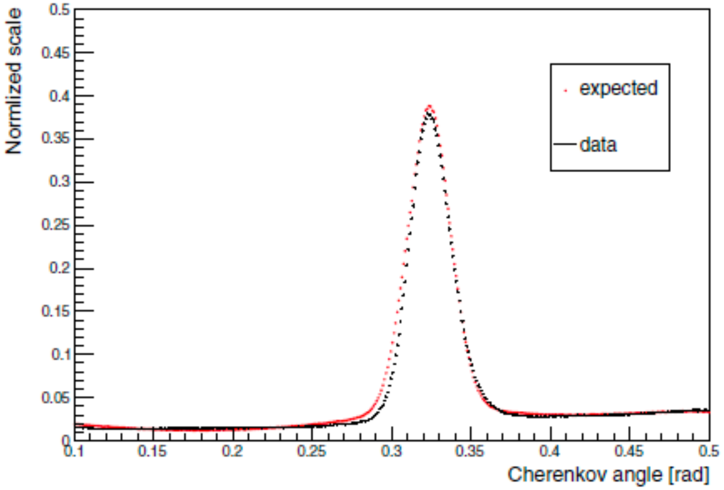
Particle identification is based on a maximum likelihood function – comparing measured with expected hit distribution for different particle hypothesis

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

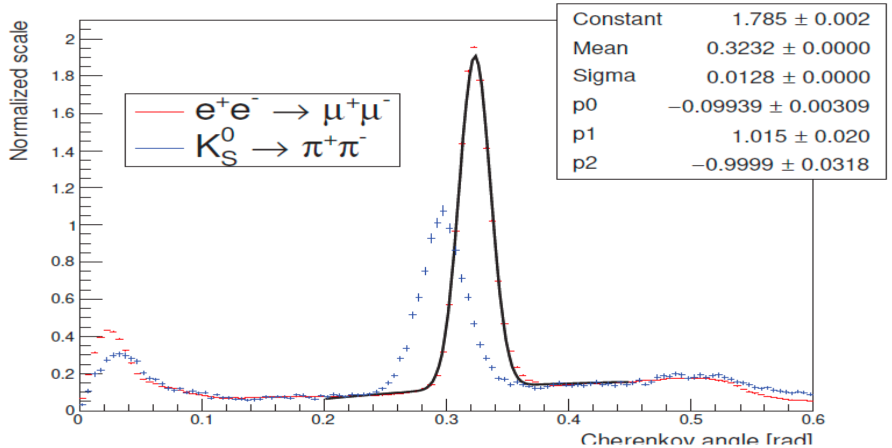
$n_{h,i}$ … expected number of hits detected by pixel $i$ for hypothesis $h$ - integral of PDF over pixel area,
and $N_h = \Sigma\, n_{h,i}$

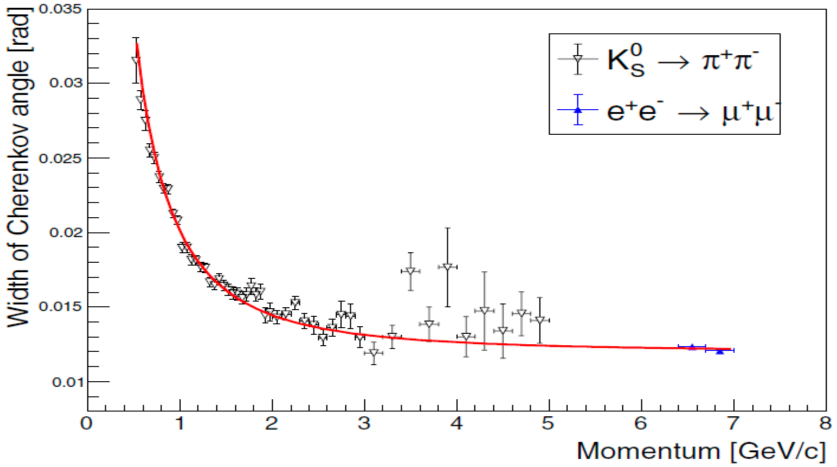
Main PDF components: direct and scattered Ch. photons from aerogel, correlated and uncorrelated background




PDF parameters calibrated by $K_S{}^0 \rightarrow \pi^+\pi^-$ decays for low momentum and $e^+e^- \rightarrow \mu^+\mu^-$ for high momentum

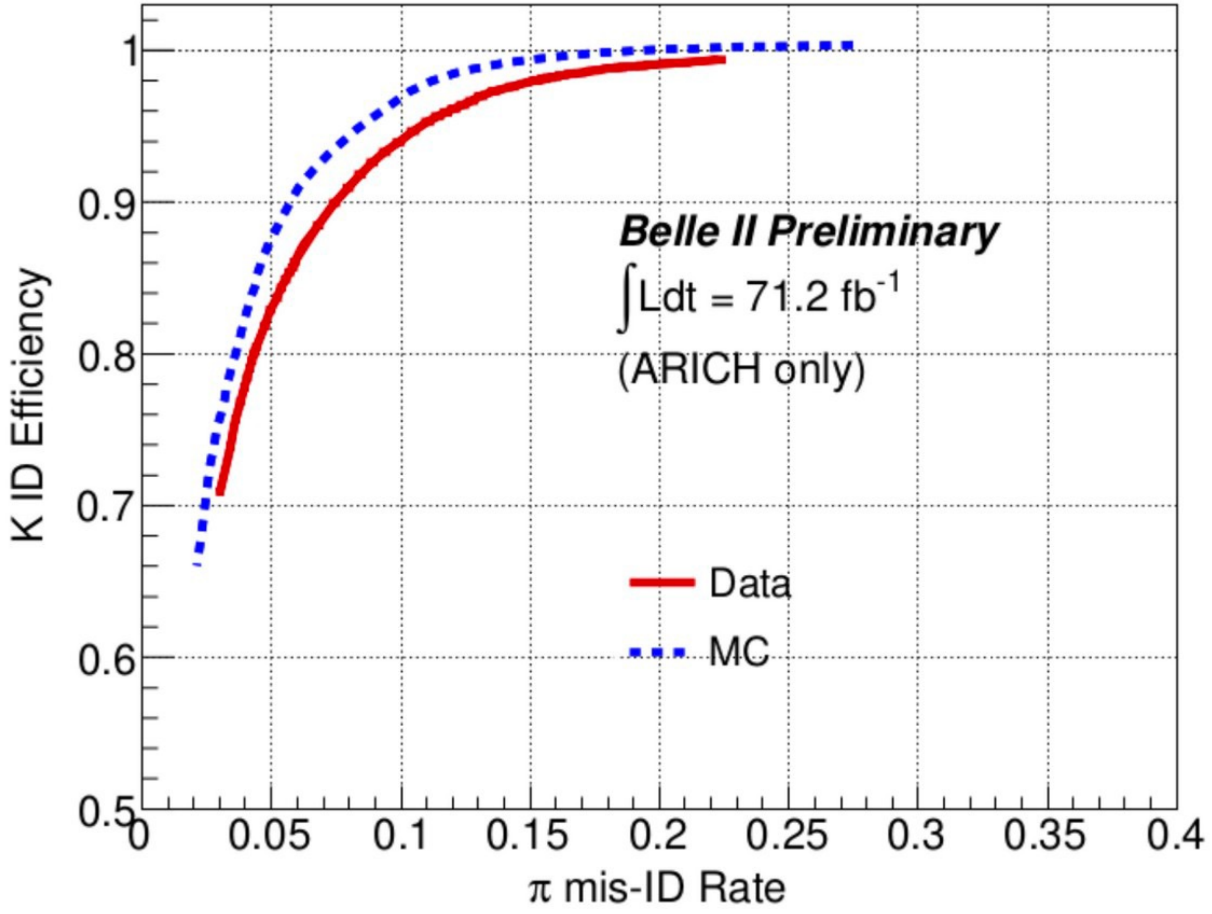


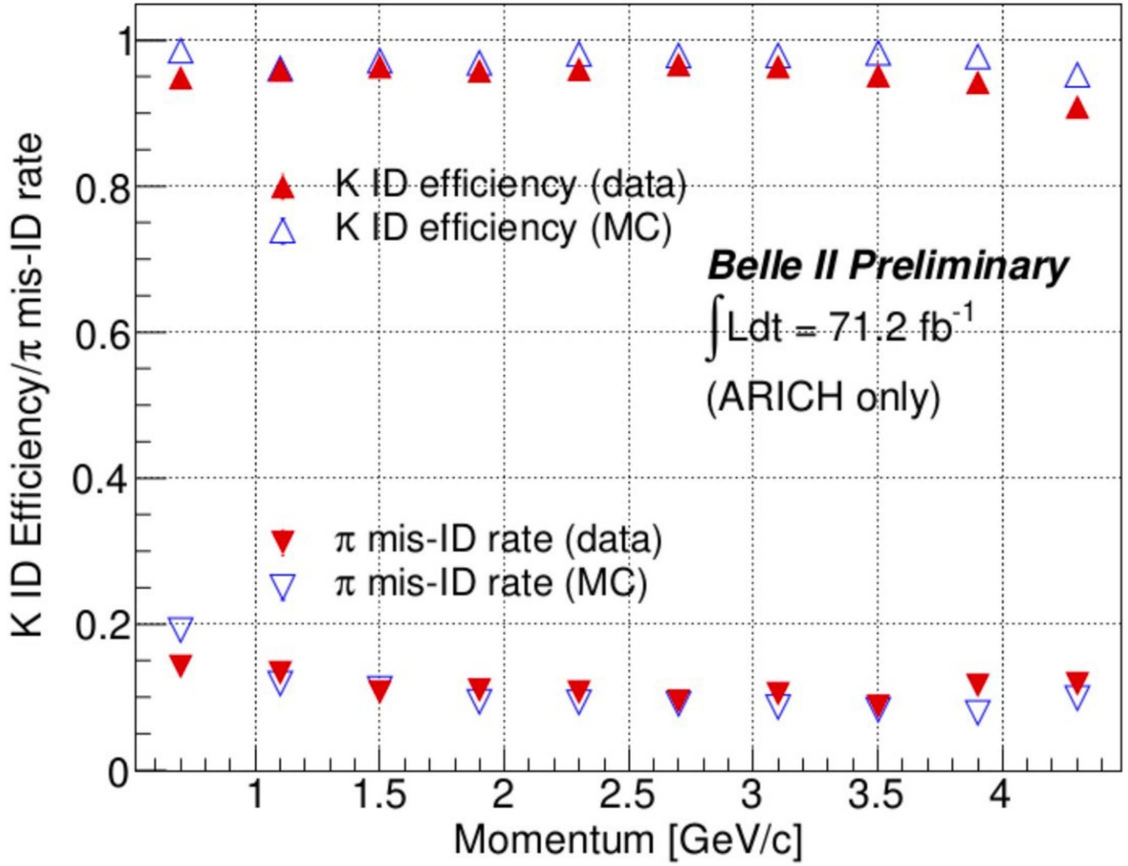
# Achieved ARICH performance



ARICH K efficiency vs. $\pi$ misidentification probability




Momentum dependence of ARICH K efficiency and $\pi$ misidentification probability



# Challenges: Decayed & scattered tracks

- *According to MC ~10% of particles with extrapolated track in the ARICH don't reach the detector*

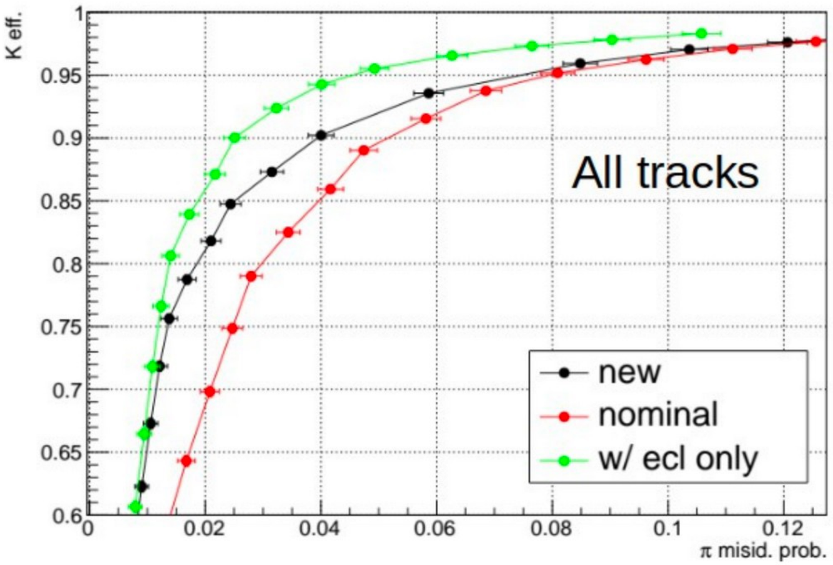
*→ decay in flight + inelastic hadronic scattering in the material*

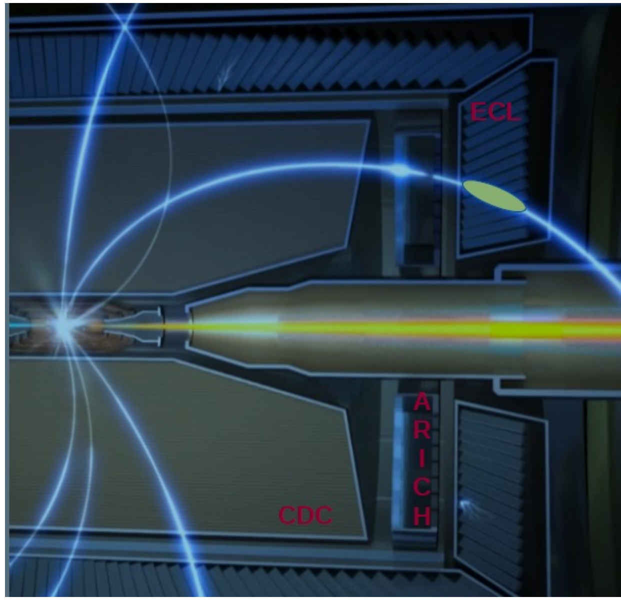
- *significant contribution to the misidentification rates (e.g. scattered pion → strongly id. as kaon)*

*Recognizing decayed/scattered particles improves Belle II global PID*

- *search for a track associated cluster in the electromagnetic calorimeter (ECL)*
- *~75% of decayed/scattered particles are contained in a sub-sample*

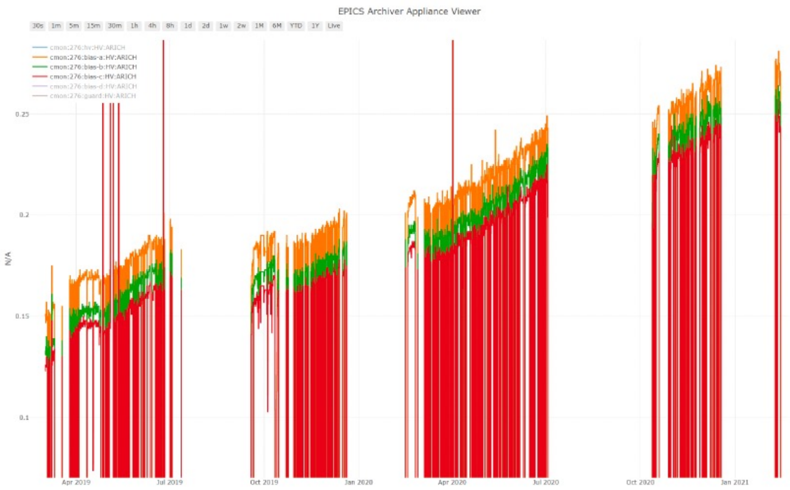
*MC:*

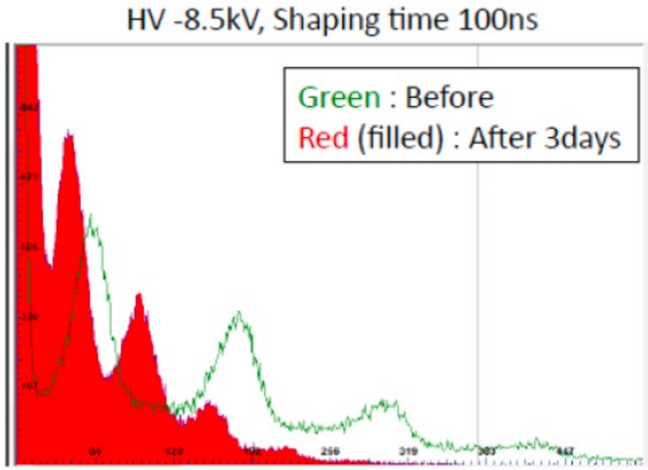


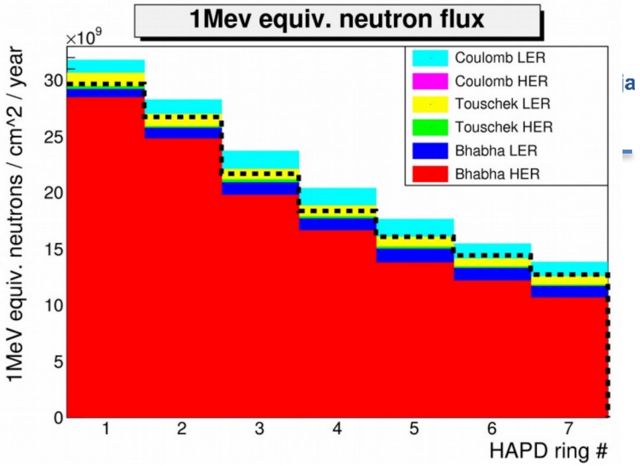
# Outlook

- Increase of dark current due to a neutron damage:
- neutron fluence (@$L_{design}$ $=8x\ 10^{35}\ /cm^2\ s$ ) $= 2.4x\ 10^{11} neq/cm^2$
  - The expected radiation dose (20Gy) is 25 lower than the maximal value used during sensor R&D.
- Time dependence of measured APD diode currents (in uA) for a module with a typical behavior:

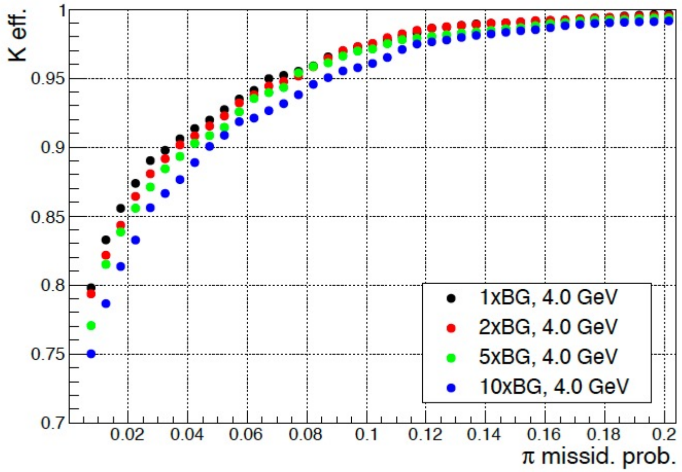



Mitigation: adjust gain and shaping time in the electronics




K identification efficiency for different nominal background levels




Reliable operation expected until the designed luminosity is reached.

# Beyond BelleII

Upgrade of Belle II to increase the luminosity by a factor of 5

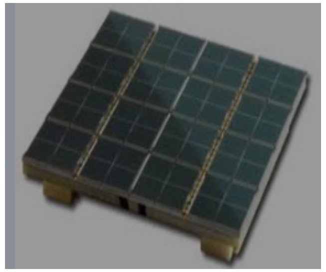
- ❑ HAPD will not be able to operate any more.

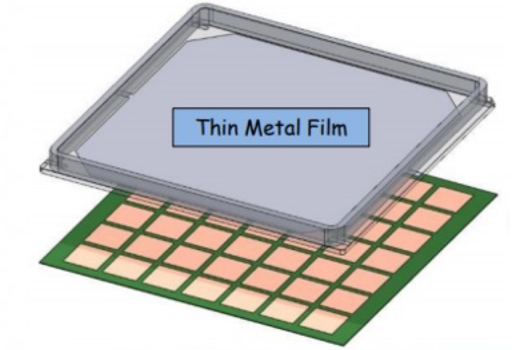
Replacement candidates under evaluation:

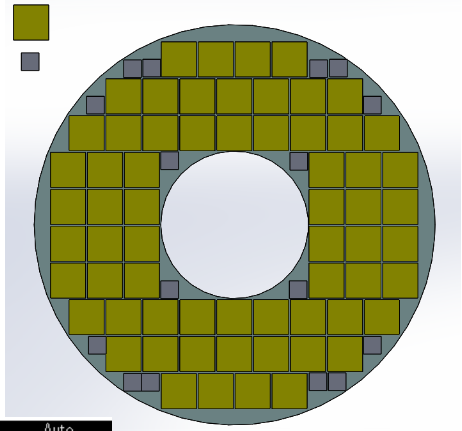
- Silicon photomultipliers working at low temperatures
- LAPPD by INCOM USA (20x20xm+10x10cm)

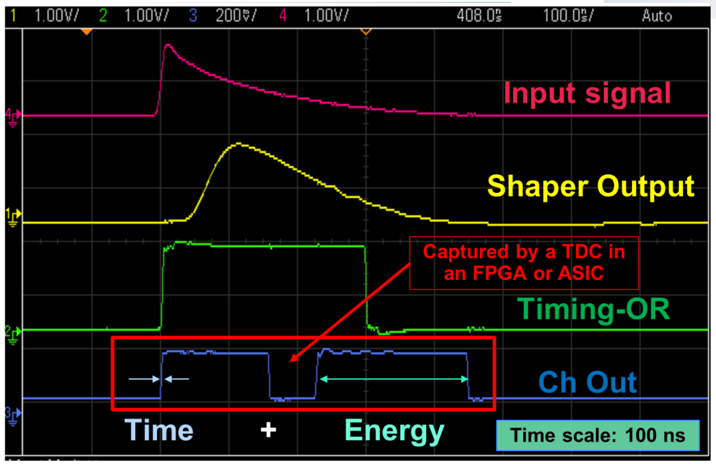
Readout based on the novel FastIC chip - configurable multi-channel ASIC for fast-timing applications – 65nm CMOS (collaboration of CERN and Uni Barcelona):

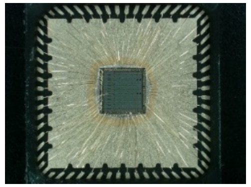
- Time: 10 - 100 ps + Energy: linear (< 3%) for 1000s p.e. range (~10 bit) -> Precise time-walk correction
- 10 mW/ ch
- 1USD/ ch. / volume production







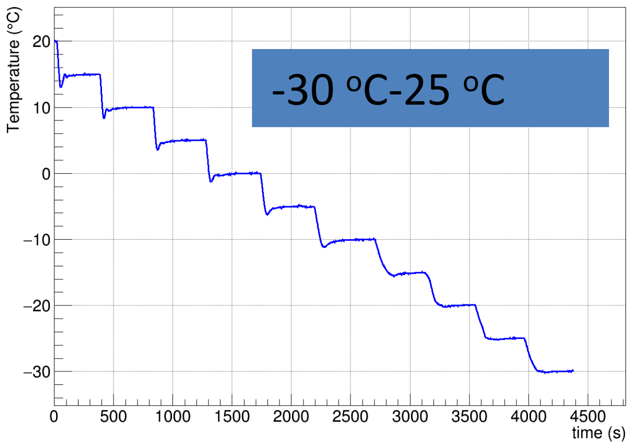



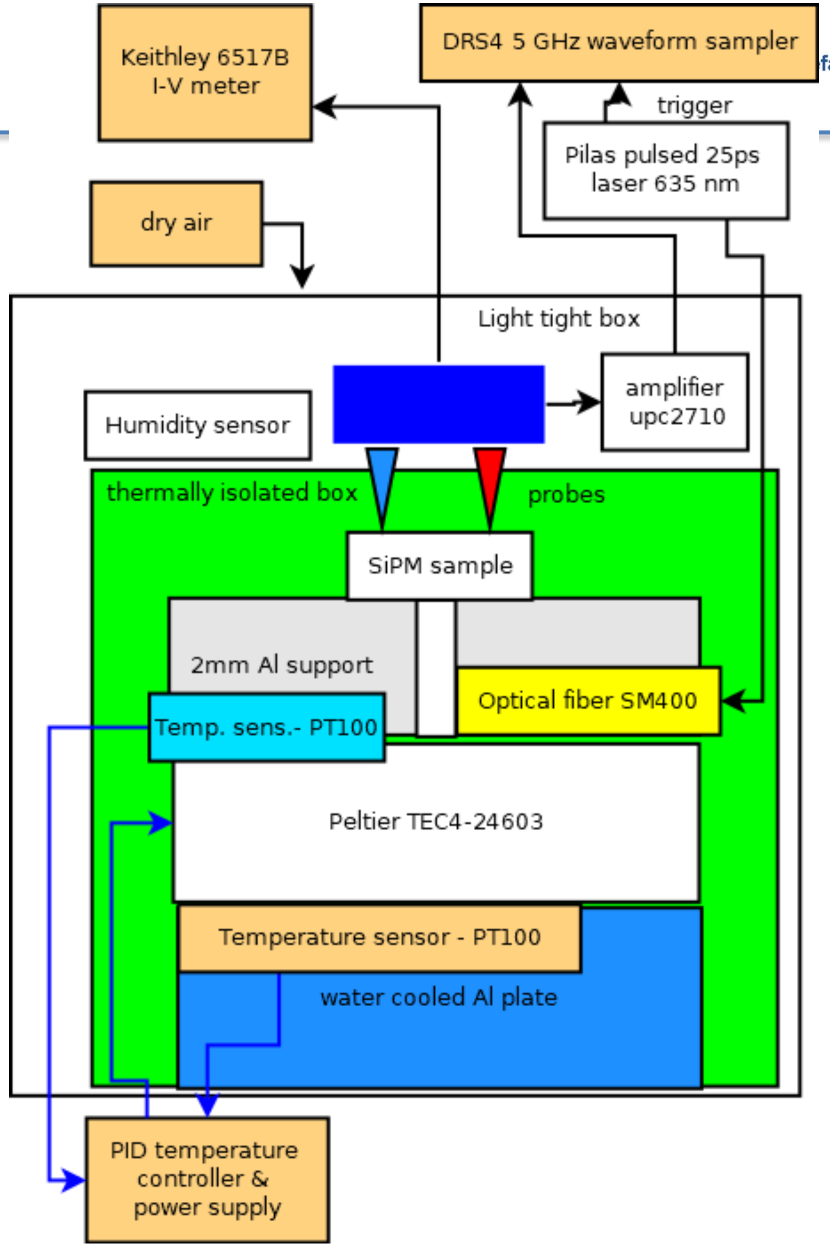
# SiPM characterization

Experimental setup:
Probe station to measure:

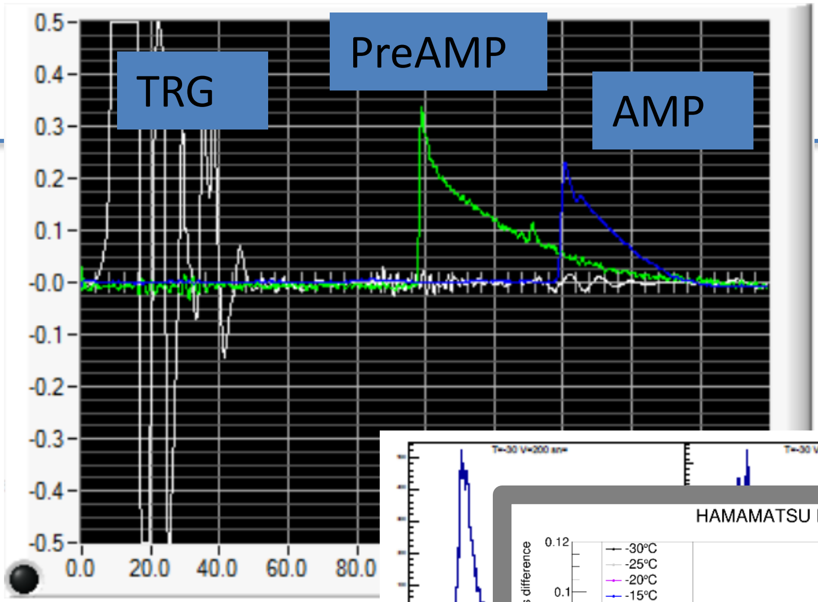
- IV curves
- Waveform acquisition with DRS4
- DCR with NIM counter

Temperature controlled sample:
Peltier with water cooling



# Waveform analysis

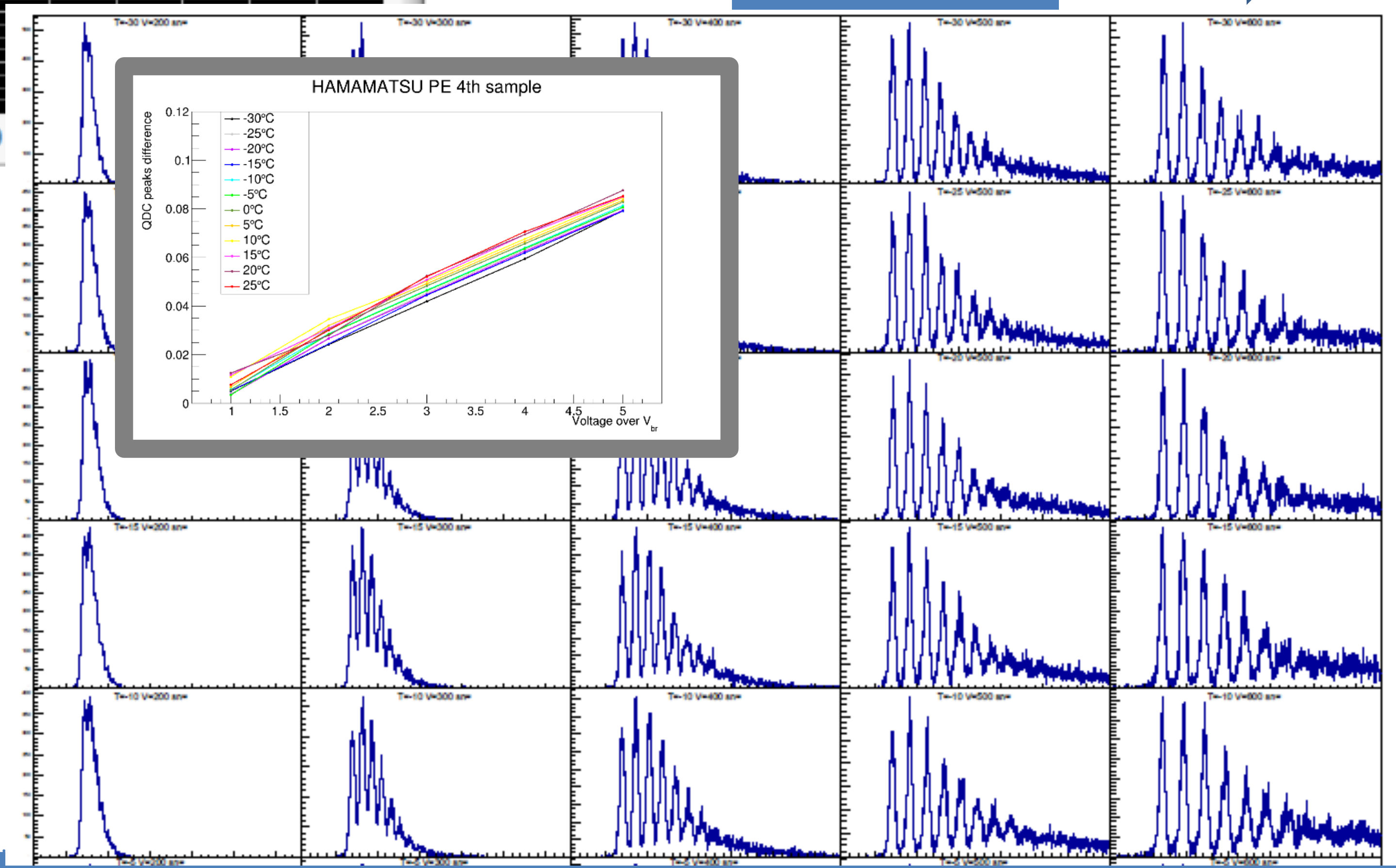



Accumulated charge distributions:

**Clear separation of single photon signals in all samples**

OverVoltage

Temperature



# Irradiated samples

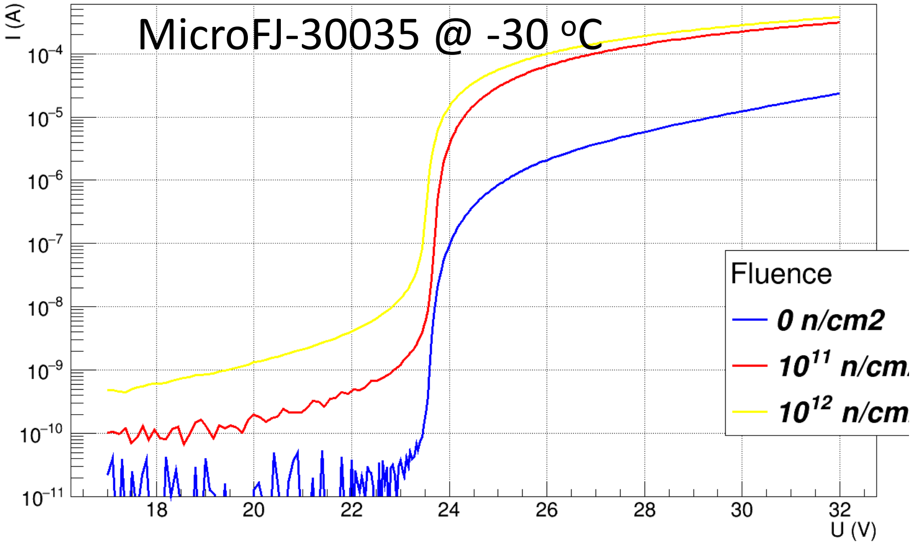
Institut "Jožef Stefan", Ljubljana, Slovenija

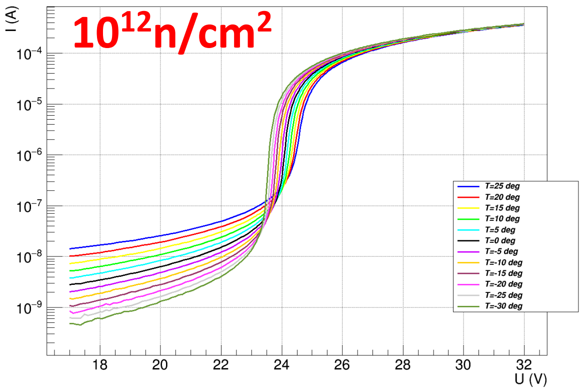
Irradiation @ TRIGA nuclear reactor at Jožef Stefan Institute, Ljubljana

Fluence

$10^{11}$ n/cm$^2$
$10^{12}$ n/cm$^2$

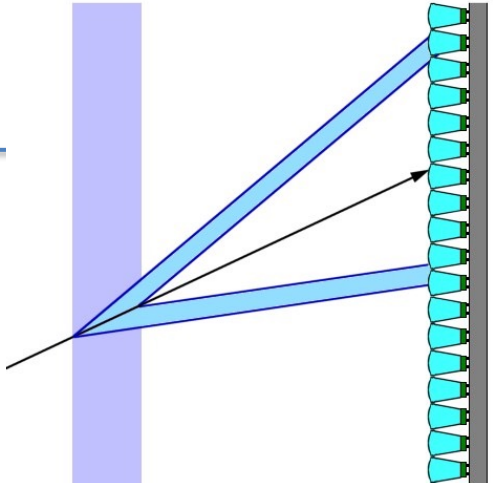
No single photo electron signals observed due to high DCR and baseline shift




How to mitigate the radiation? Lower temperature ->
Hard to design the cooling system in front of the calorimeter.
Change of internal structure of SiPMs – bulk damage in the Silicon – more ore less same effects

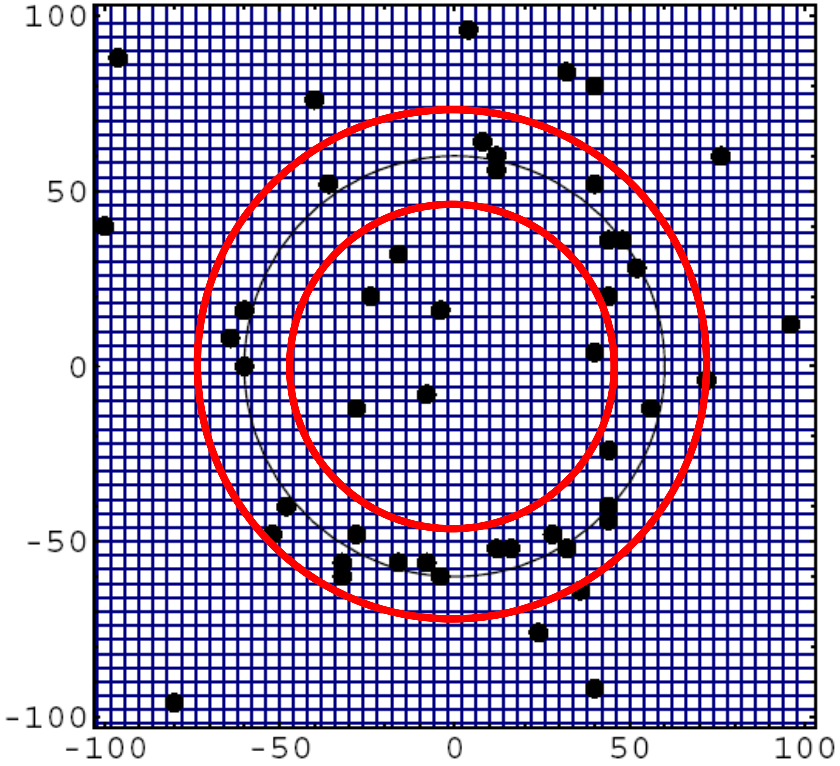
# Signal to noise



Expected number of background hits depends on:

- ring area ~ 2000 mm$^2$
- dark count rate ~ 600kHz/mm$^2$
- coincidence window ~ 5ns

$$N_{dark} \sim 6 \quad \rightarrow \quad N_{ph}/N_{dark} \sim 3.3$$




**Ratio can be increased by:**

- **smaller ring image area**
- **narrower time window**
- **use of light collection system (light guides) to increase effective area of the sensor**

# Summary

- ARICH of Belle II consists of an double layer aerogel plane and photon detector
  - 420 HAPD and 128 aerogel tiles
  - HAPD operate in a 1.5 T magnetic field
- Installed in 2016
- Commisioned until 2019
- Fully operational
- Provides high K identification efficiency
- Reliable operation, almost no loss of efficiency
- With the increase of luminosity, the noise of sensors will increase
- No problems expected by the time the designed luminosity will ber reached