VCI VIENNA CONFERENCE ON INSTRUMENTATION
15TH VIENNA CONFERENCE ON INSTRUMENTATION

Belle II aerogel RICH detector

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Outline

Introduction

1. Flavour physics, SuperKEKB accelerator and BELLE II experiment

    1.1 One word about the physics

    1.2 The accelerator

    1.3 The detector

ARICH

2. Aerogel RICH : Particle identification detector in forward region of BELLE II

    2.1 Aerogel Ring Imaging CHerenkov counter (ARICH) : concept

    2.2 The aerogel radiator

    2.2 The photon detector : HAPD

Performance

3. Measured performance of the ARICH detector with BhaBha electrons.

4. Backup slides, appendix, ...

One word about the physics

- An ultimate goal of modern particle physics experiments is a **search of a new physics**.
- Quark flavor mixing and CP - violation are described by the Cabibbo-Kobayashi-Maskawa matrix (3 x 3).
- The matrix is unitary and therefore can be graphically resented as triangle (unitary) in a complex plane.

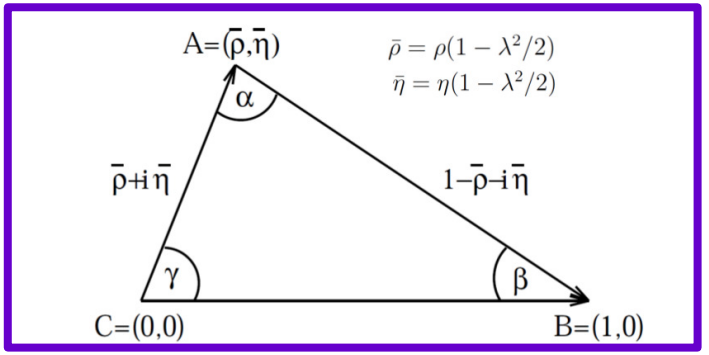
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = V_{\rm CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Weak eigenstates

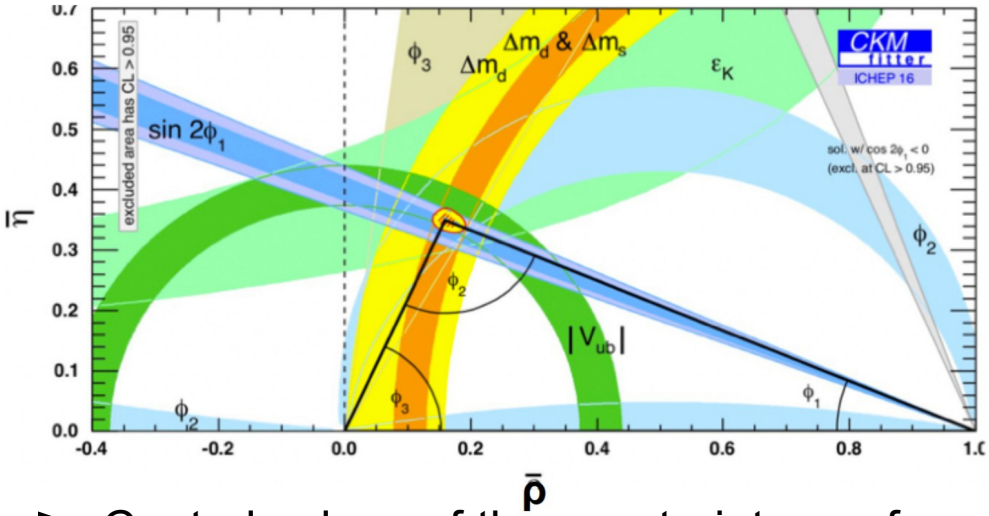
Mass eigenstates

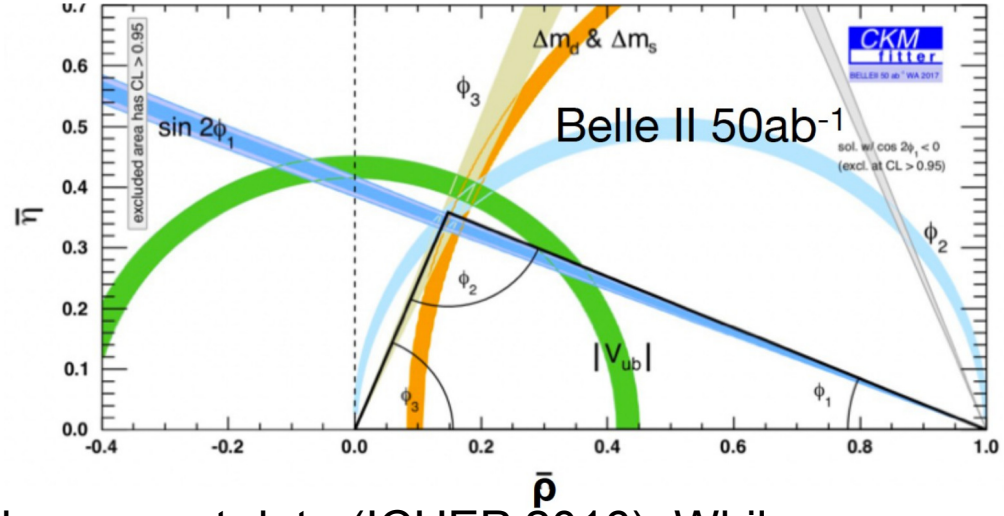
Cabibbo-Kobayashi-Maskawa unitary matrix

$$V_{\rm CKM} V_{\rm CKM}^{\dagger} = 1$$



- B physics plays an important role in constraining the angles and the sides of the Unitary Triangle (UT).
- At present knowledge the UT apex determined within statistical errors.





- Central values of the constraints are from the present data (ICHEP 2016). While errors are those expected to be with Belle II data.
- **In case the measurements will not sum – up to a close triangle → New Physics !!!**

Time line of the Belle II experiment

Phase 1

- 2017
- Accelerator study
- Test of the the nano-beam scheme
- Beam background study

Phase 2

- April 2018
- First collision and Belle II detector data taking
- Background study
- Calibration of the Belle II detector subsystems

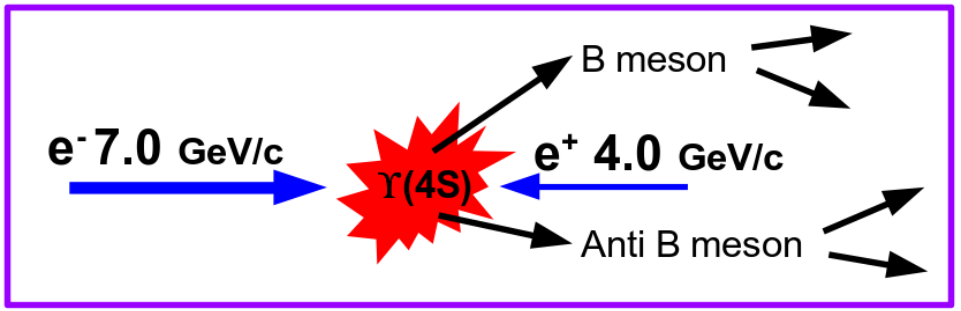
- Upgrade and bug removals
  - **ARICH cooling system upgrade**
  - ARICH daq bug fixing, H.V. bug fixing ...

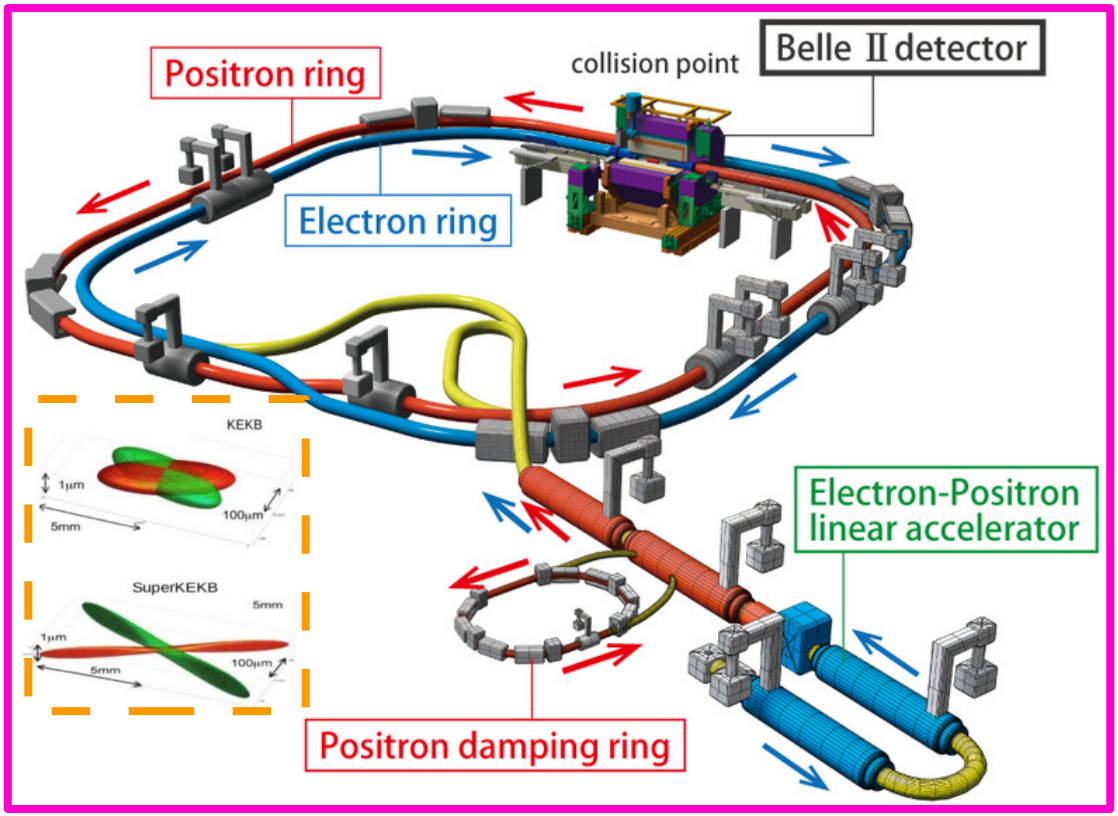
Phase 3

- Machine dedicated runs : march 2019
- Data taking campaign : Beginning of April 2019 – End of June

SuperKEKB machine

- Located at Japan (Tsukuba)
- Upgrade of existing KEKB machine
- Luminosity frontier
- Electron positron asymmetric collider.
- Energy in the center of mass is 10.58 GeV, corresponding to the mass of the $\Upsilon(4S)$ resonance.





- The design of SuperKEKB is based on the new concept of the nano-beam scheme.

Table 8: Machine parameters for HER and LER.

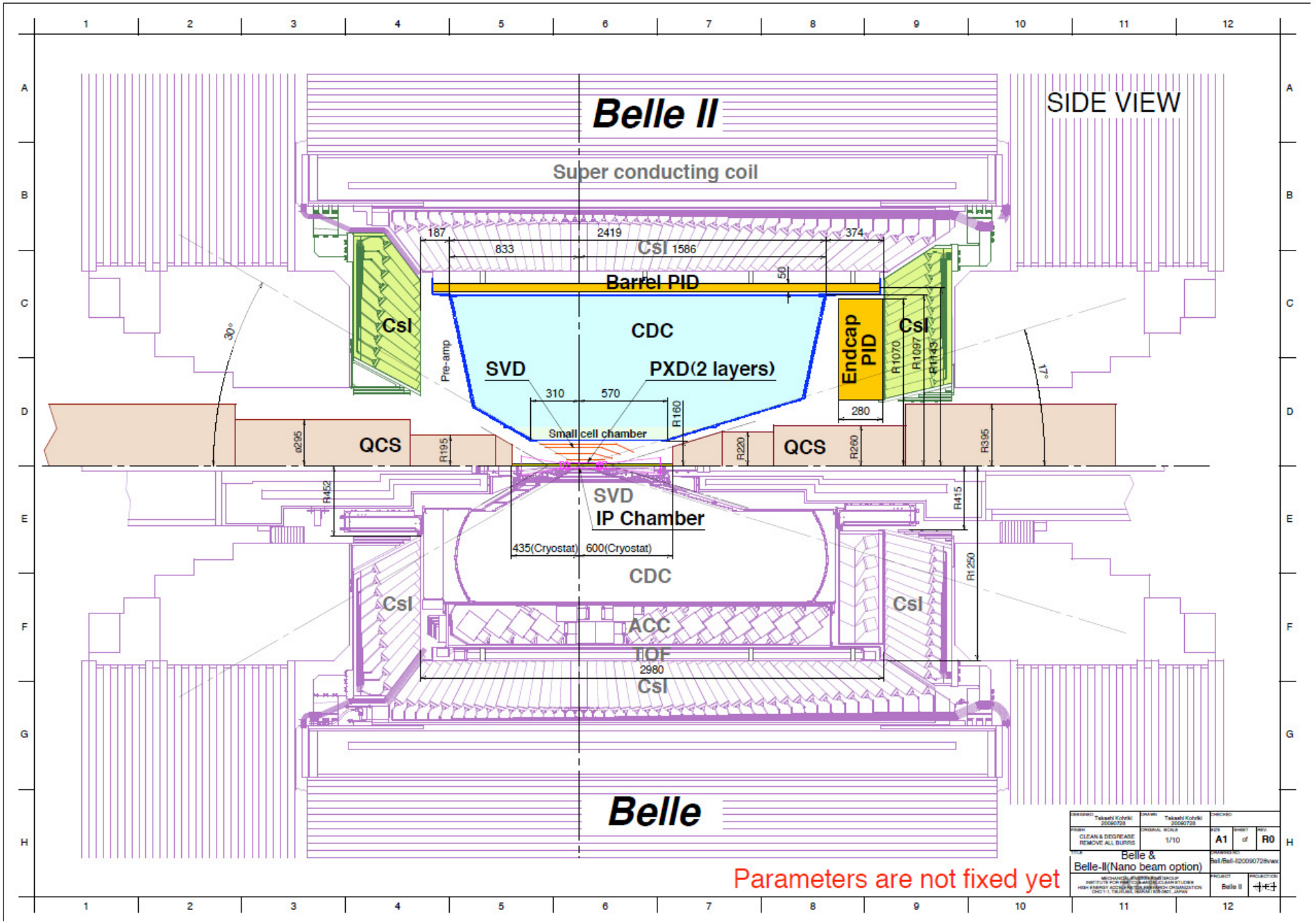
Parameter	LER	HER	Unit
E	4.000	7.007	GeV
I	3.6	2.6	A
β_x^*	32	25	mm
β_y^*	270	300	μm
σ_z	6	5	mm

* indicates values at the IP

Table 9: Machine parameters.

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



ARICH detector located in forward endcap (PID) two meters from interaction point.

Target performance : K/pi separation at > 4σ C.L. @ 0.5 < p < 4 GeV/c.

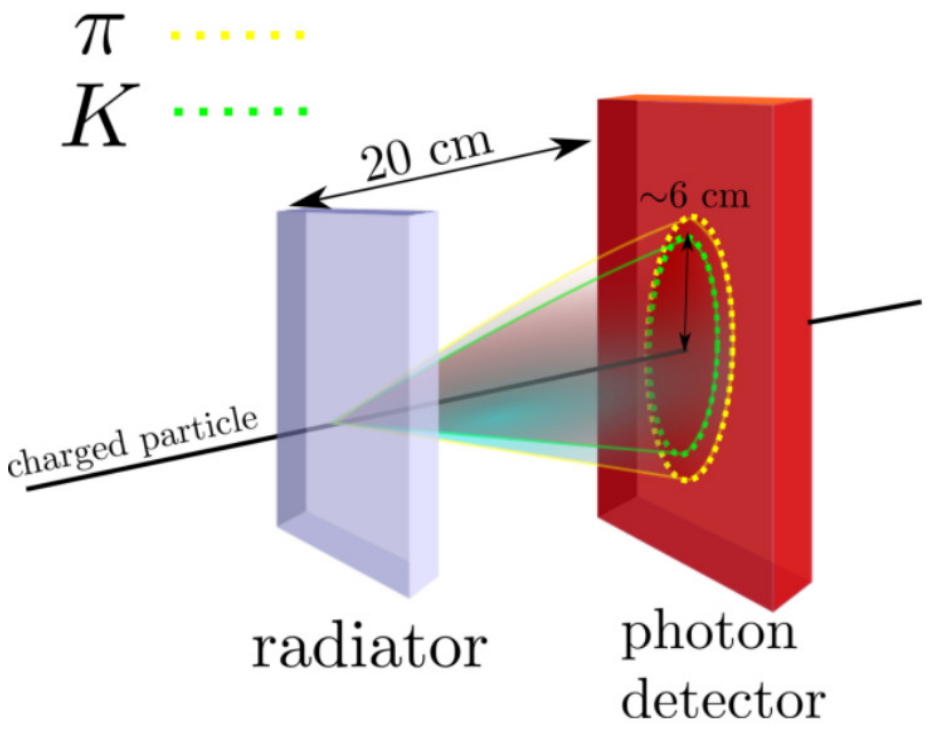
ARICH covers [15° -32°] polar angle.

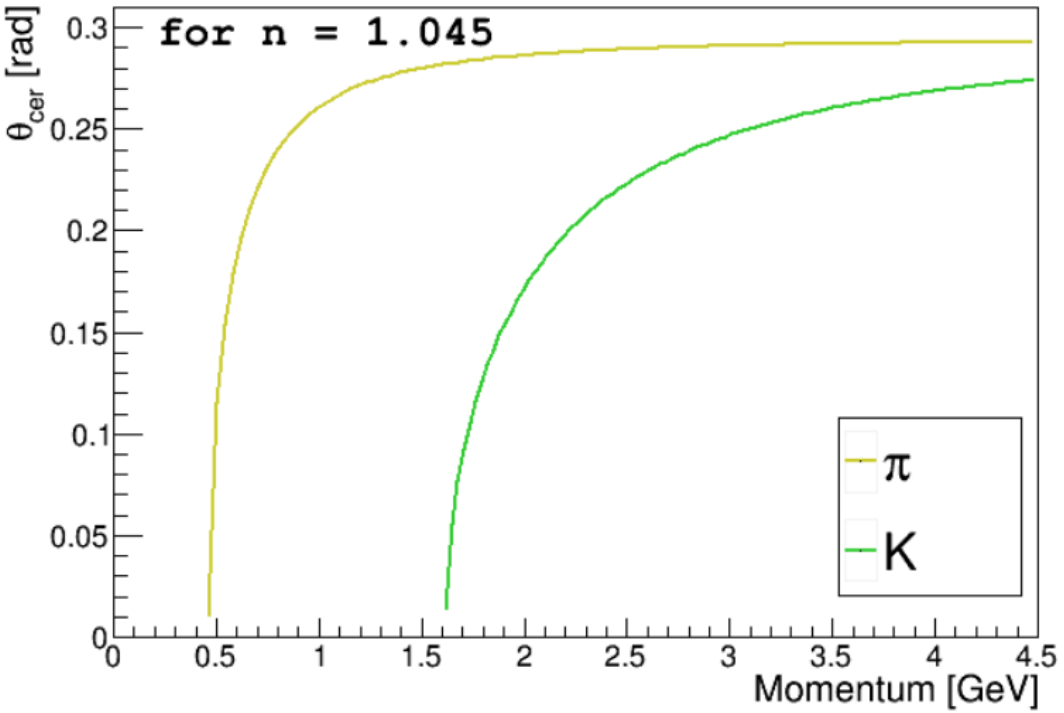
Aerogel Ring Imaging CHerenkov counter (ARICH) : concept

$$\cos\theta_c = \frac{1}{n\beta} \qquad \beta = v/c \qquad \frac{\partial^2 N}{\partial x \partial \lambda} = \frac{2\pi\alpha z^2}{\lambda^2}\left(1 - \frac{1}{(n(\lambda))^2\beta^2}\right) \sim 1/\lambda^2$$

Particle mass $\leftarrow m = \frac{p}{c}\sqrt{n^2\cos^2\theta_c - 1}$

- p: Particle momentum
- θ_c: Particle Cherenkov angle
- n: Aerogel refractive index





Why we choose aerogel radiator? Why double layer ?

$$\beta = \frac{1}{n\cos(\theta)} \rightarrow \frac{\sigma_\beta}{\beta} = \sigma_\theta \tan(\theta) \rightarrow \frac{\sigma_\beta}{\beta} \rightarrow 0 \quad \theta \rightarrow 0 \quad \boxed{n \rightarrow 1}$$

$$N_{Cherenkov\ light} \sim \left(1 - \frac{1}{n^2\beta^2}\right) L \rightarrow$$ **As a consequence we need to use thicker radiator**

Fine adjustment of n for aerogel : $n(\lambda) = p_{\mathrm{Intercept}} + k(\lambda)\rho$

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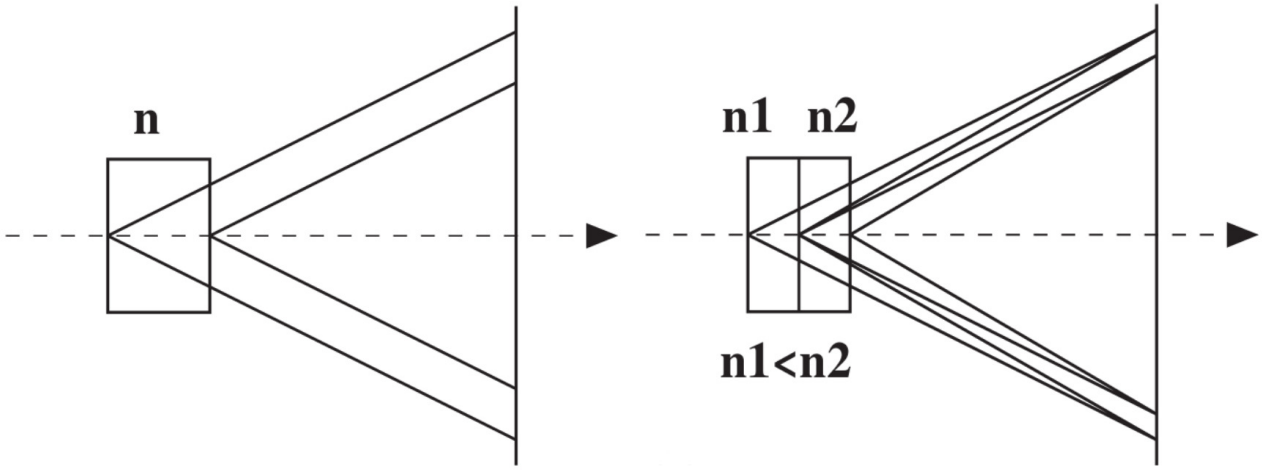
Single thick radiator

Double layer radiator



Focusing configuration

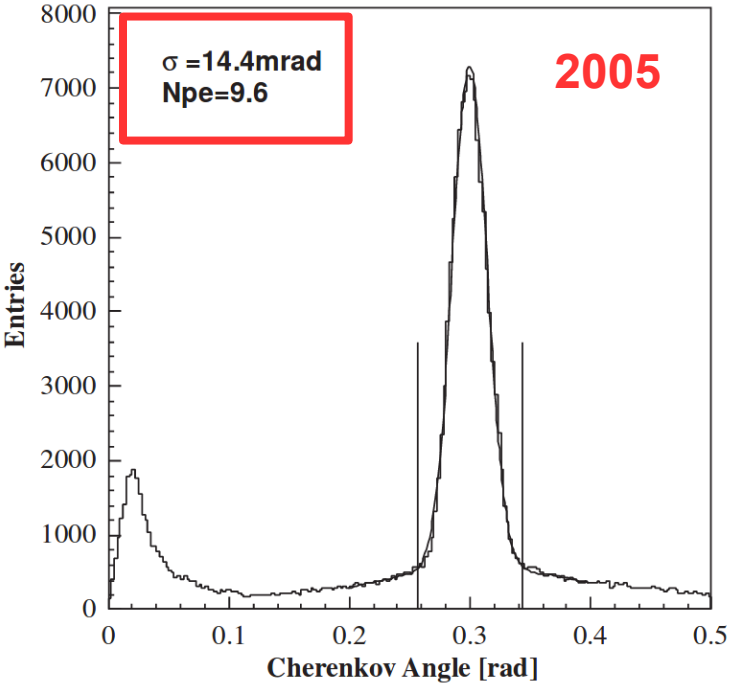
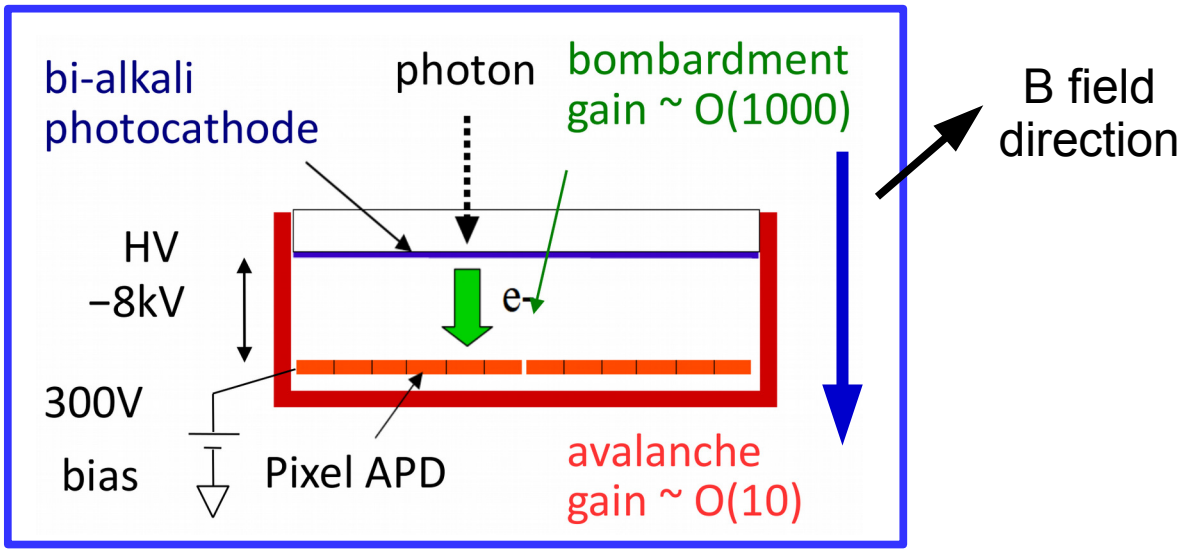
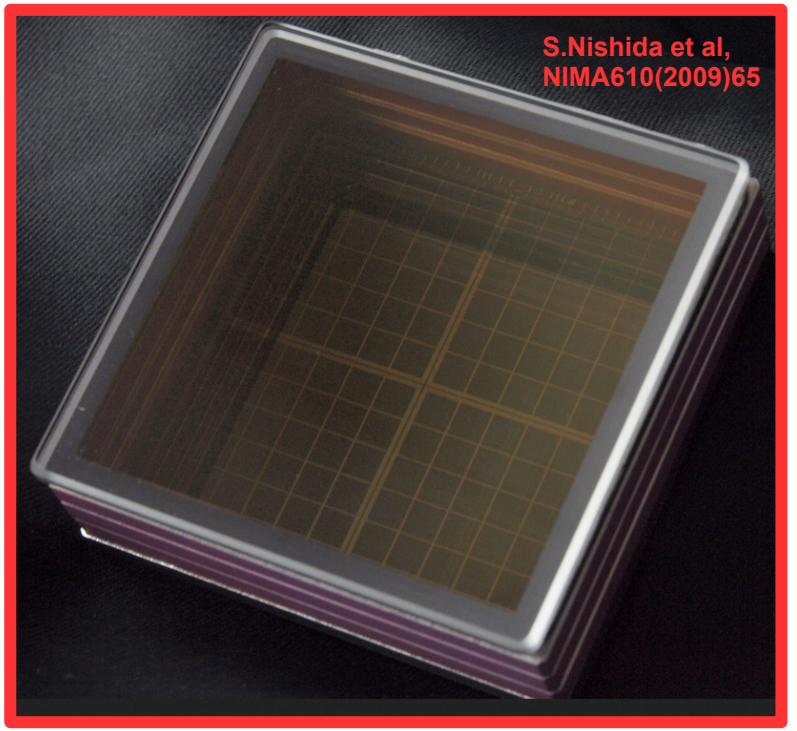


Fig. 7. Distribution of the Cherenkov angle for accumulated single photons from 4 GeV/c pions in the case of a focusing dual radiator combination with 20 mm thick radiators ($n = 1.047$ and $n = 1.057$).

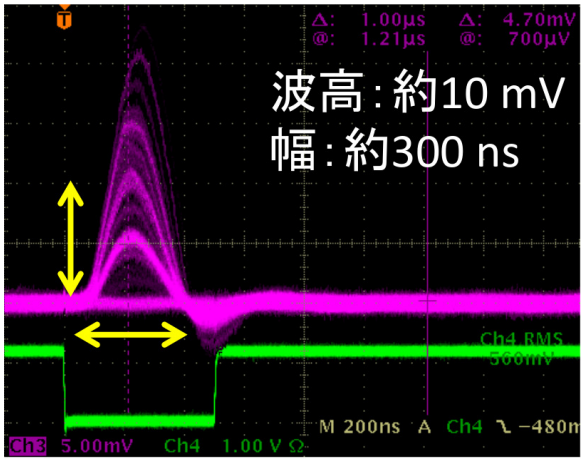
The photon detector : HAPD

- Hybrid Avalanche Photo Detector (HAPD).
- 144 pixelated APDs : 4.9 x 4.9 mm^2 channel size. Effective area : 63 mm×63 mm.
- Signal gain > $4x10^4$ by Hybrid amplification process.
- Operation in 1.5 T magnetic field.

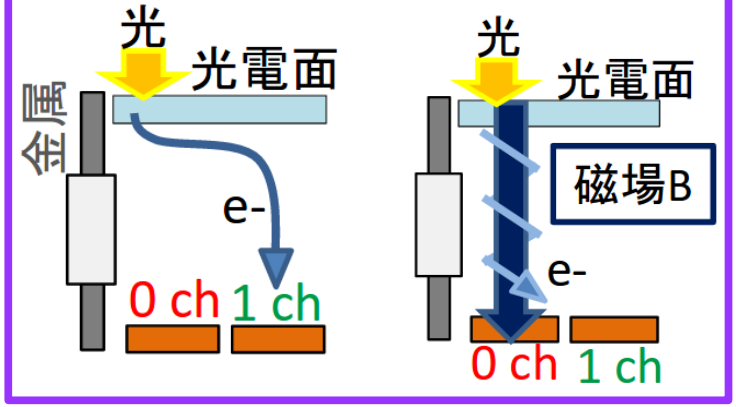


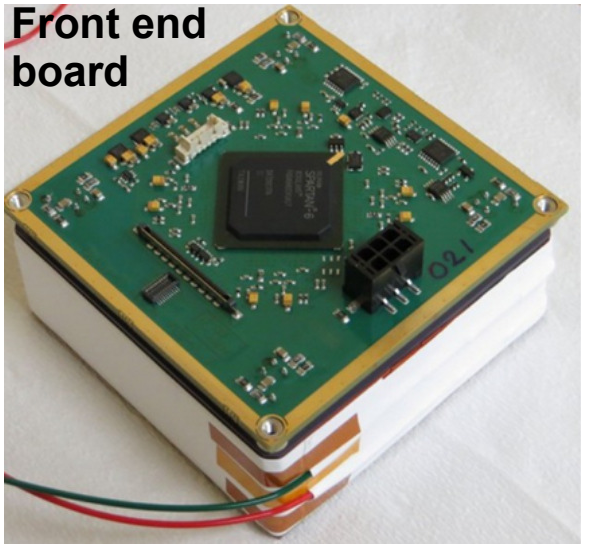


Separate 1 – 2 – 3 p.e.



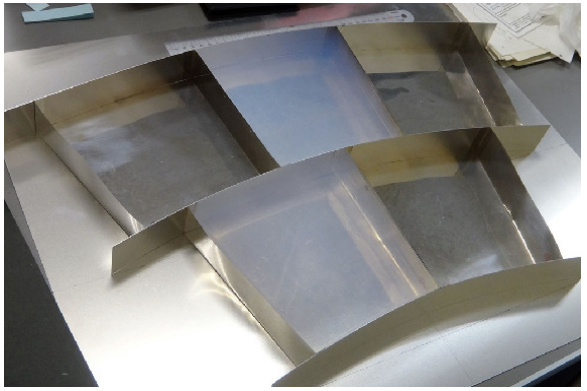
Enhancement in the magnetic field



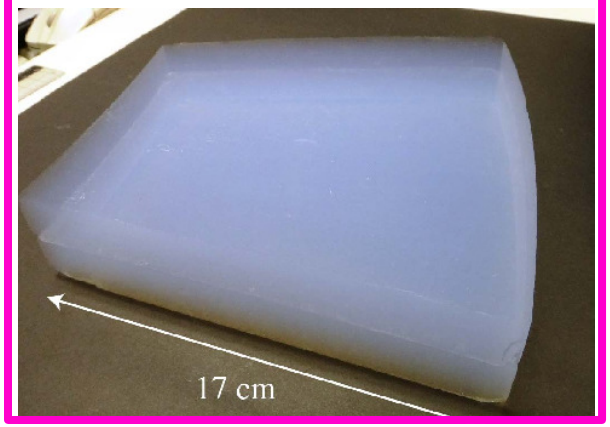


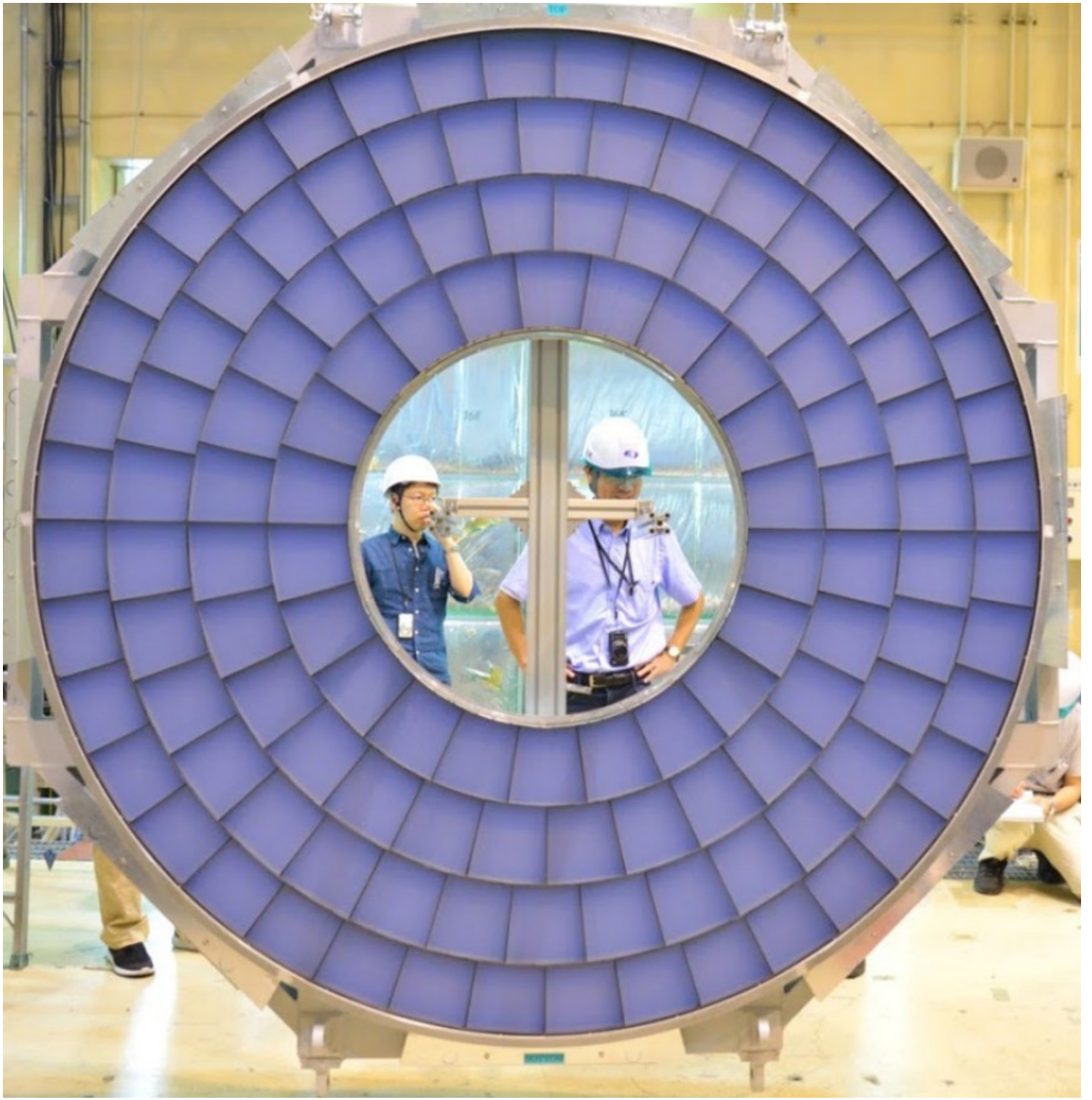
ARICH aerogel plane

- Two aerogel layers
- 124 aerogel tiles per layer
- 248 aerogel tiles in total



Two layers of wedge-shaped aerogel single tiles of size : 17 x 17 x 4 cm^3

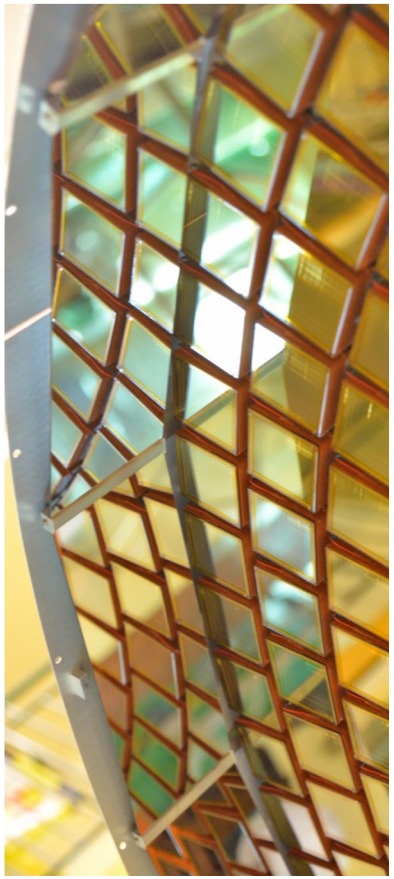


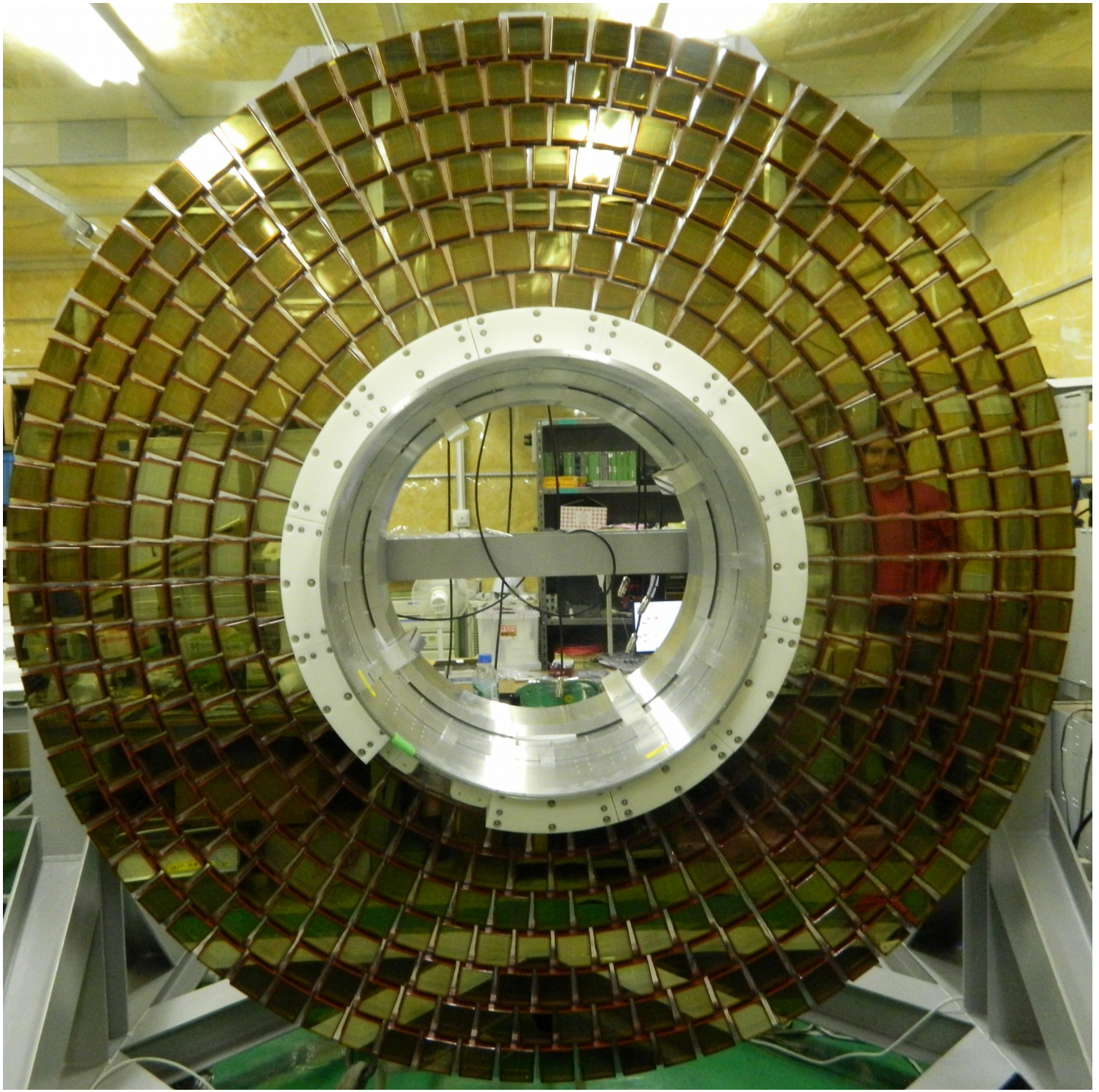


ARICH photon detector

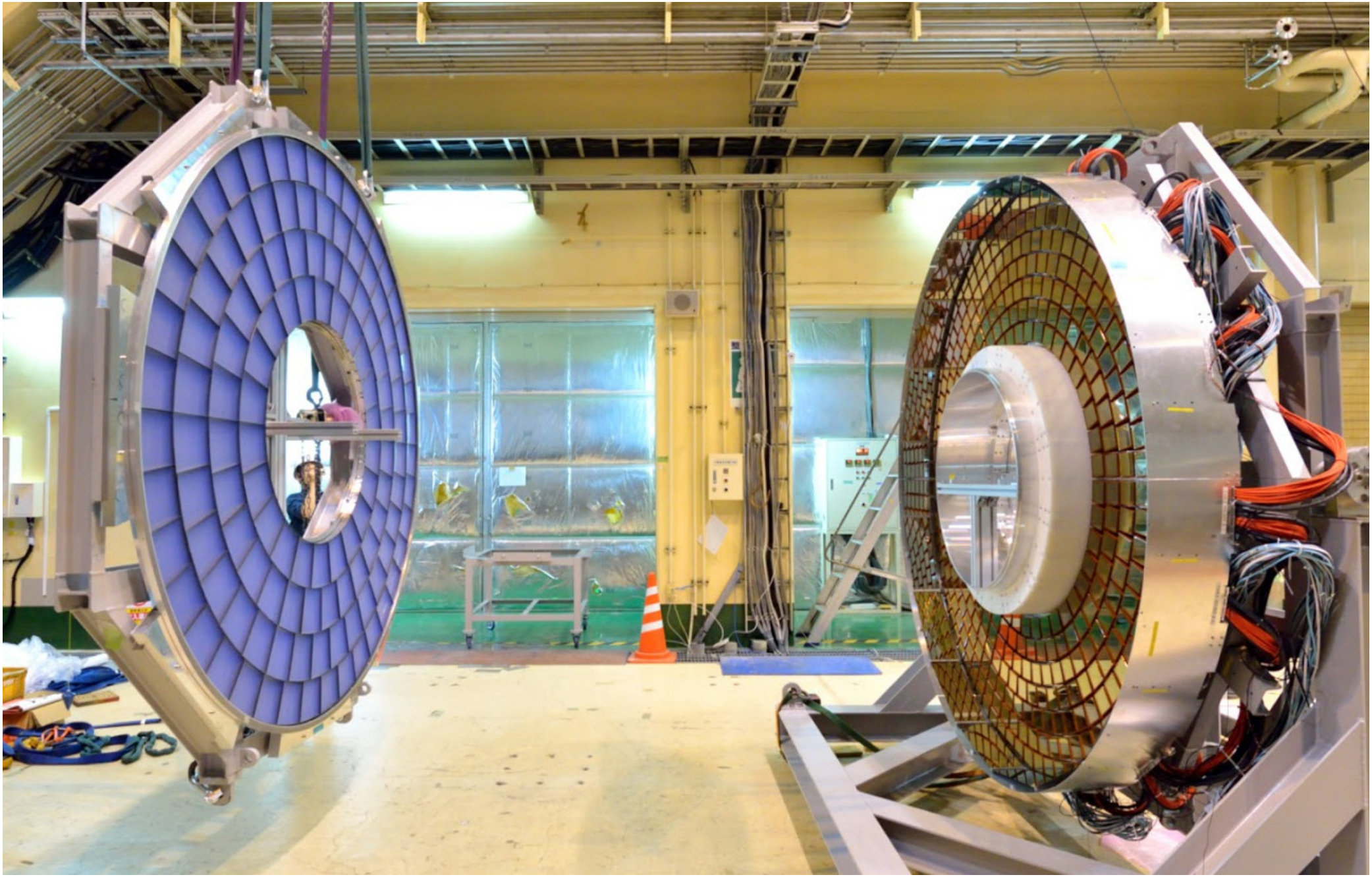
- 420 HAPD modules with
- 60480 redout channels
- 18 planar mirror plates

Mirrors from the edge



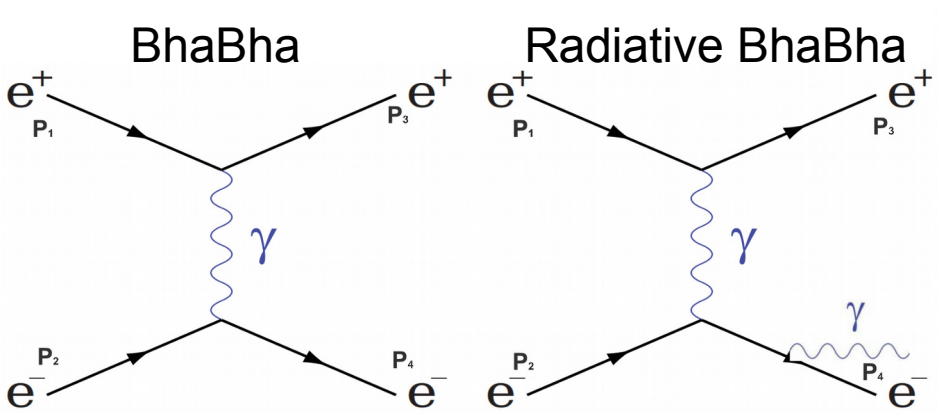


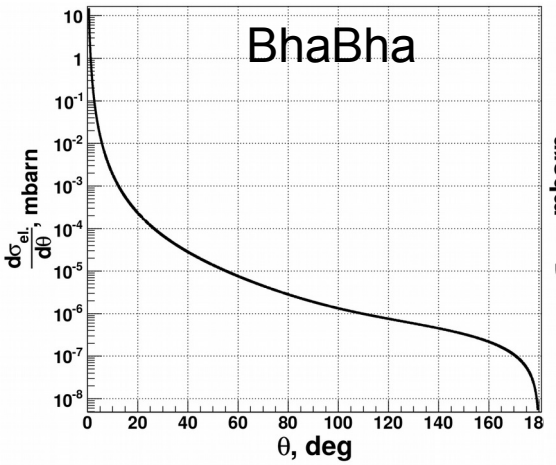
ARICH assembly – October 2017

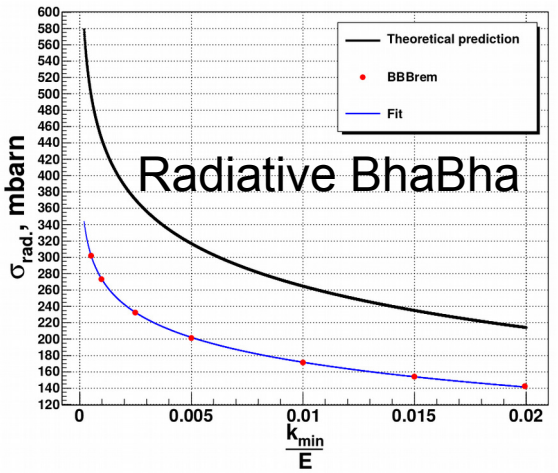


ARICH performance estimation with BhaBha and radiative BhaBha events.

→ The first collisions at SuperKEKB took place on 26 of April in 2018.







Track selection criterion :

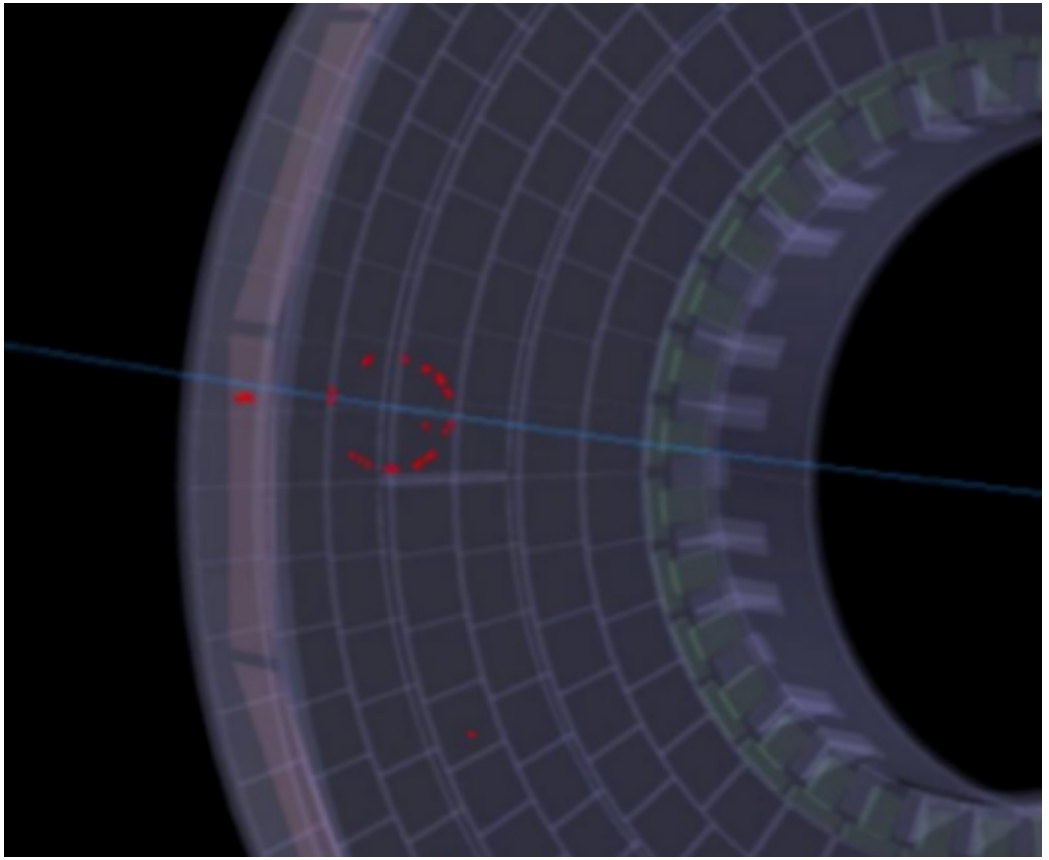
- → Charged track
- → BhaBha triggered events : back to back isolated tracks with ECL energy deposition.
- → Kinematics cuts :
  - → Momentum > 6 GeV/c
  - → z_0 from IP within 1 cm
  - → Impact parameter from IP less then 1 cm

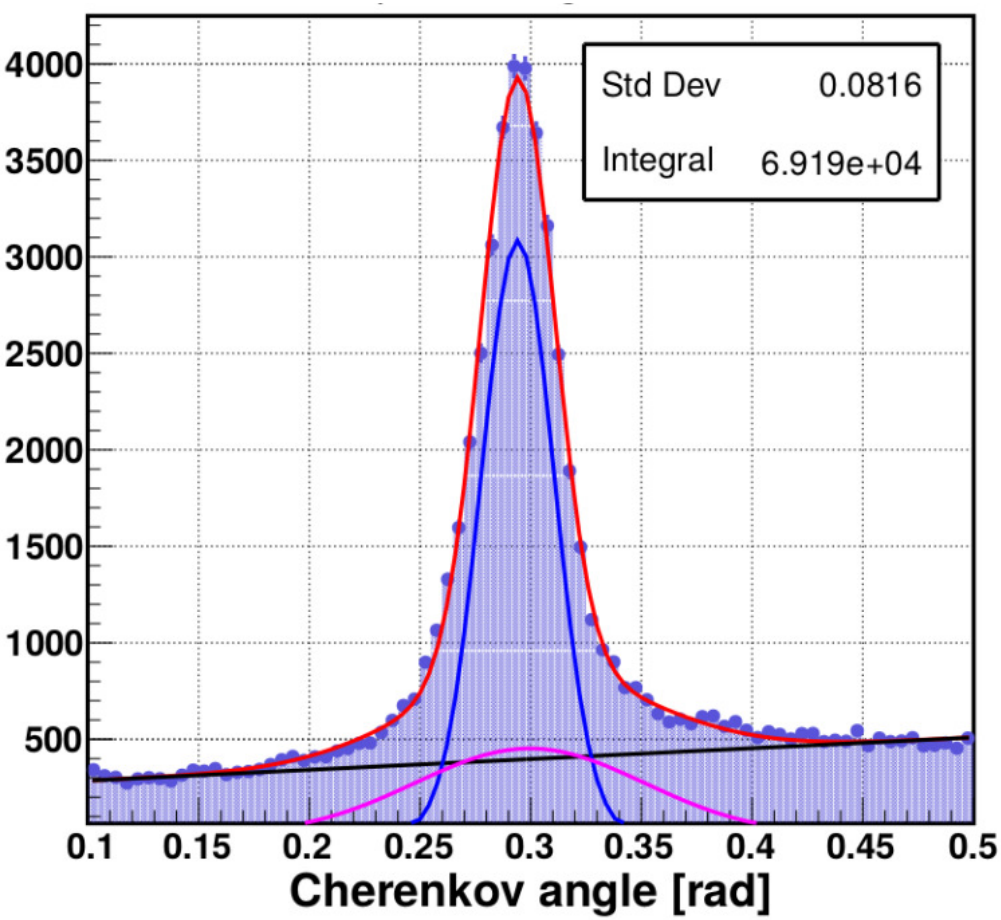
Other considerations :

- → Excluding dead or masked channels/regions
- → Including central drift chamber and ARICH alignment.

Single Cherenkov photon angle resolution.

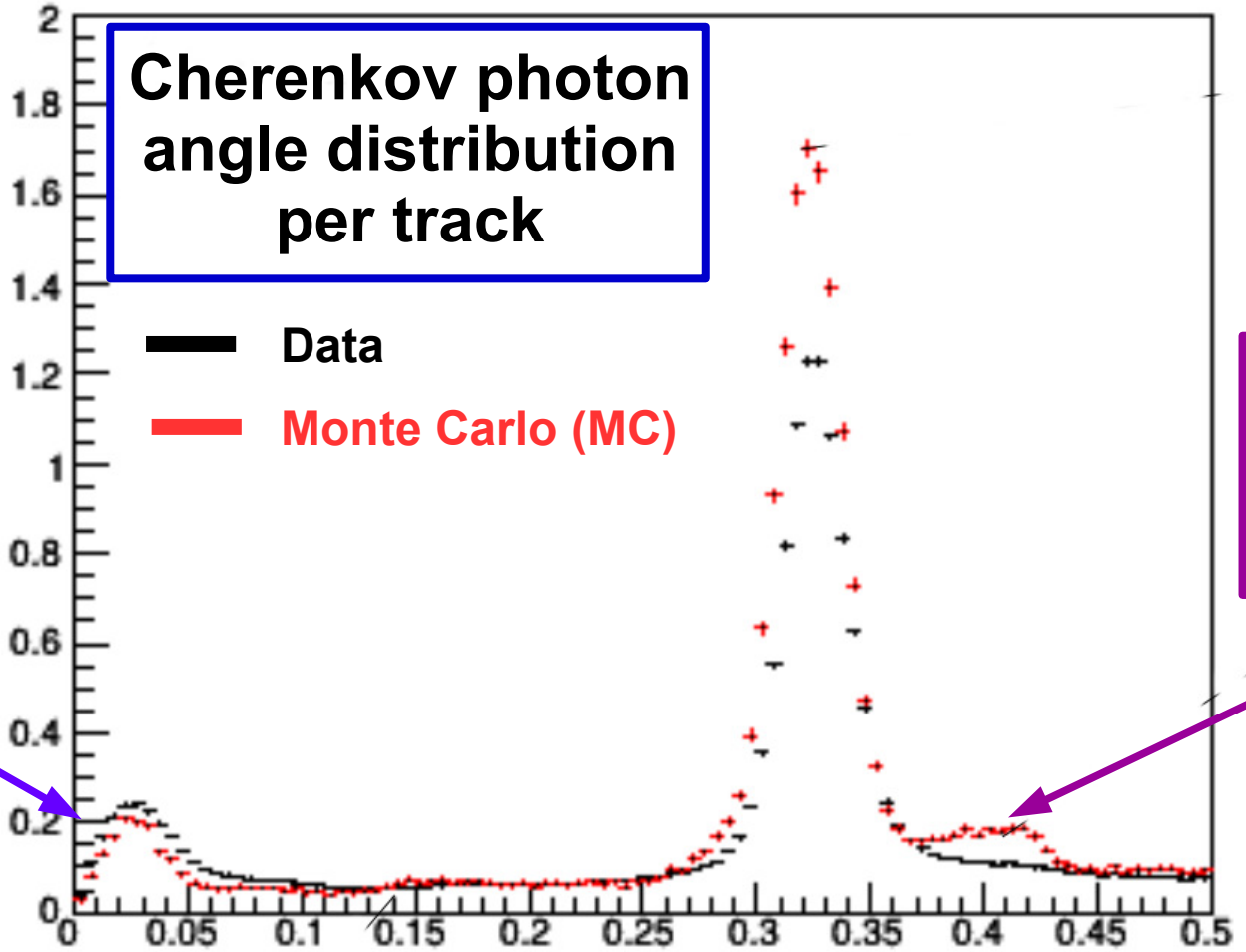
Reconstructed Cherenkov ring visualized with event display.





- Black line - non correlated background (electronics, beam background ...)
- Magenta line - correlated background (Rayleigh scattered photons, reflection from APD ...)
- Blue line – signal photons. Single photon resolution ~14 mrad.

Data vs Monte Carlo (without any tuning)



Photons from HAPD window

Number of reflected photons from APD is too high in MC

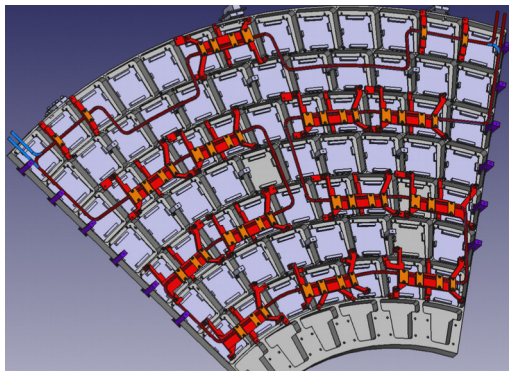
→ Number of signal photons is ~20% less with respect to the simulation.

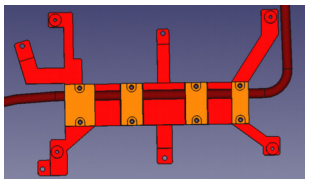
→ The signal threshold is same for all the HAPD's. However the gain and single photon amplitude is different for a given HAPD.

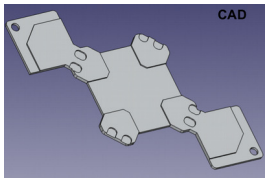
→ The masking of the dead and not working channels is not fully implemented.

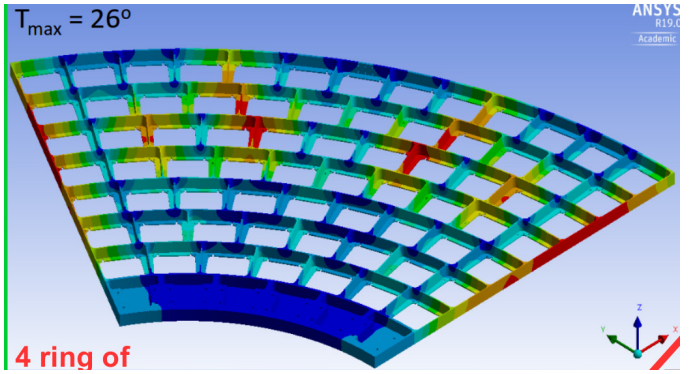
ARICH cooling system upgrade

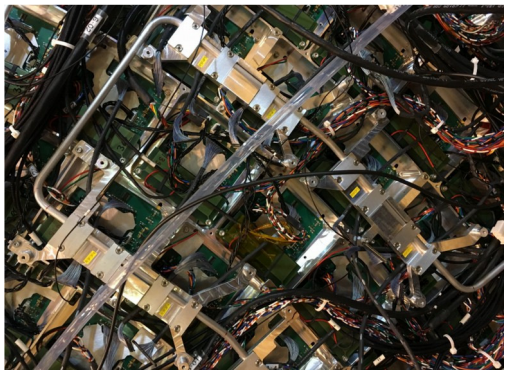
- Baseline cooling system* - was not sufficient to cool down the full detector.
- New cooling system has been designed, simulated, fabricated, installed and tested after phase 2.



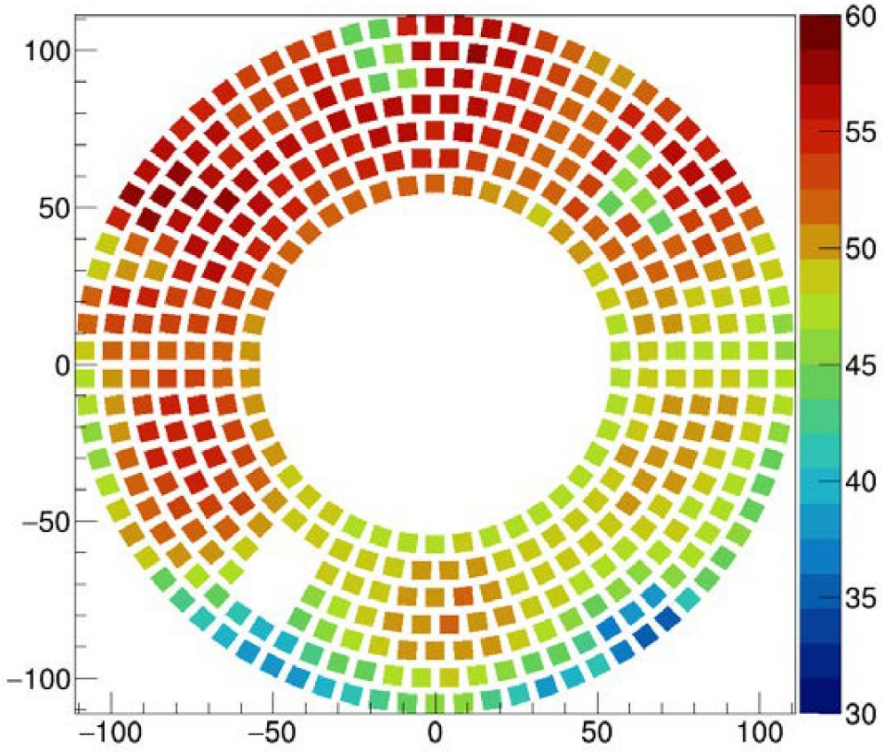




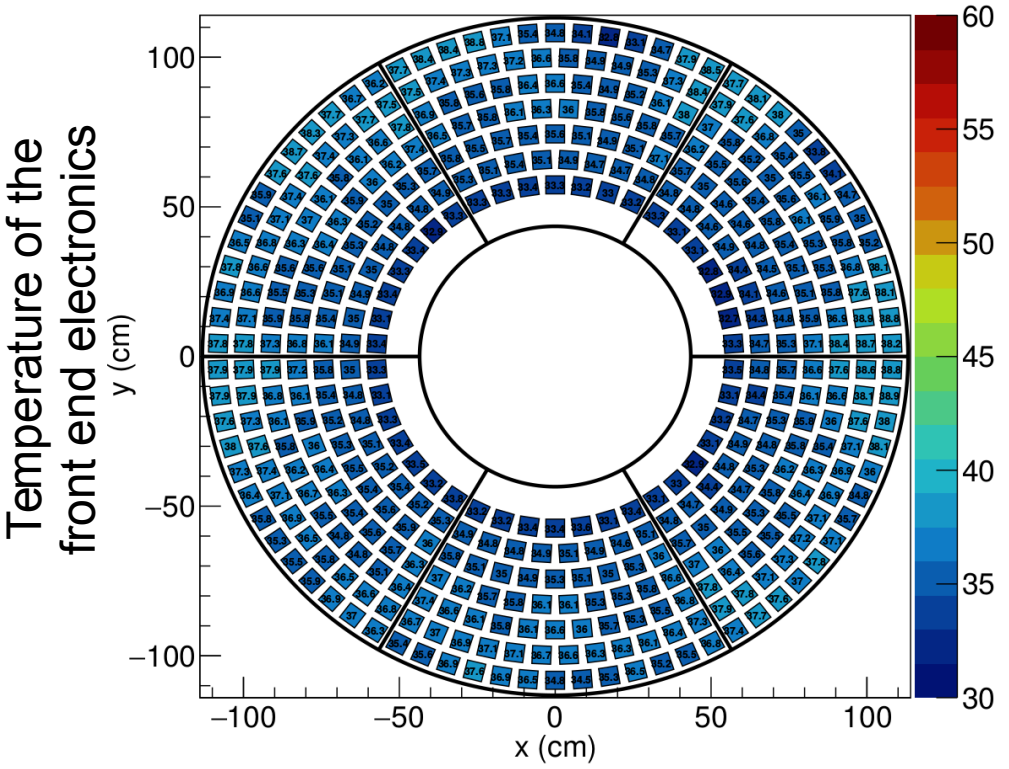




180209-085553 Phase 2



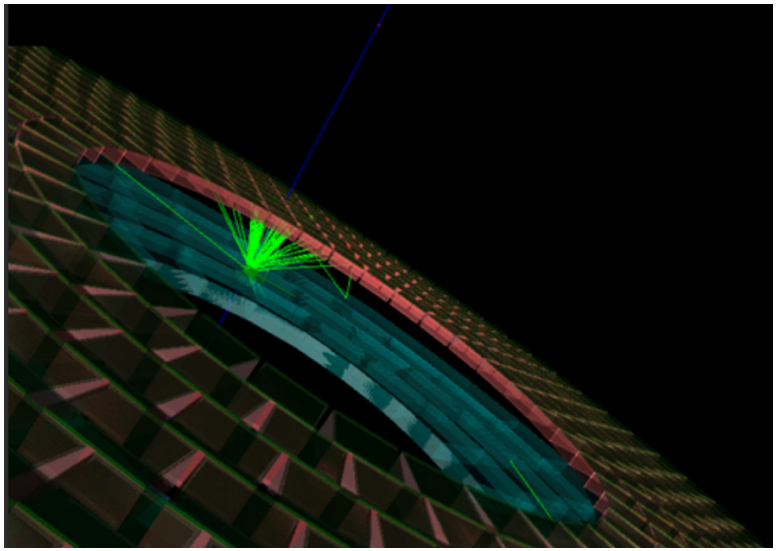
feb_t1 2019.2.14 1:21:1 **After phase 2**

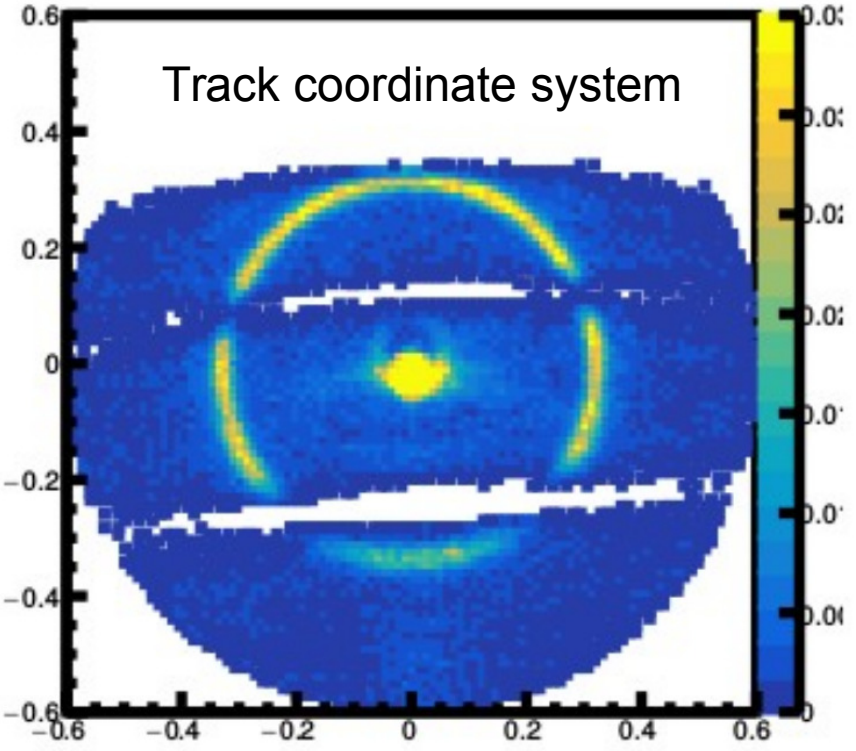


* Designed and installed by the external company.

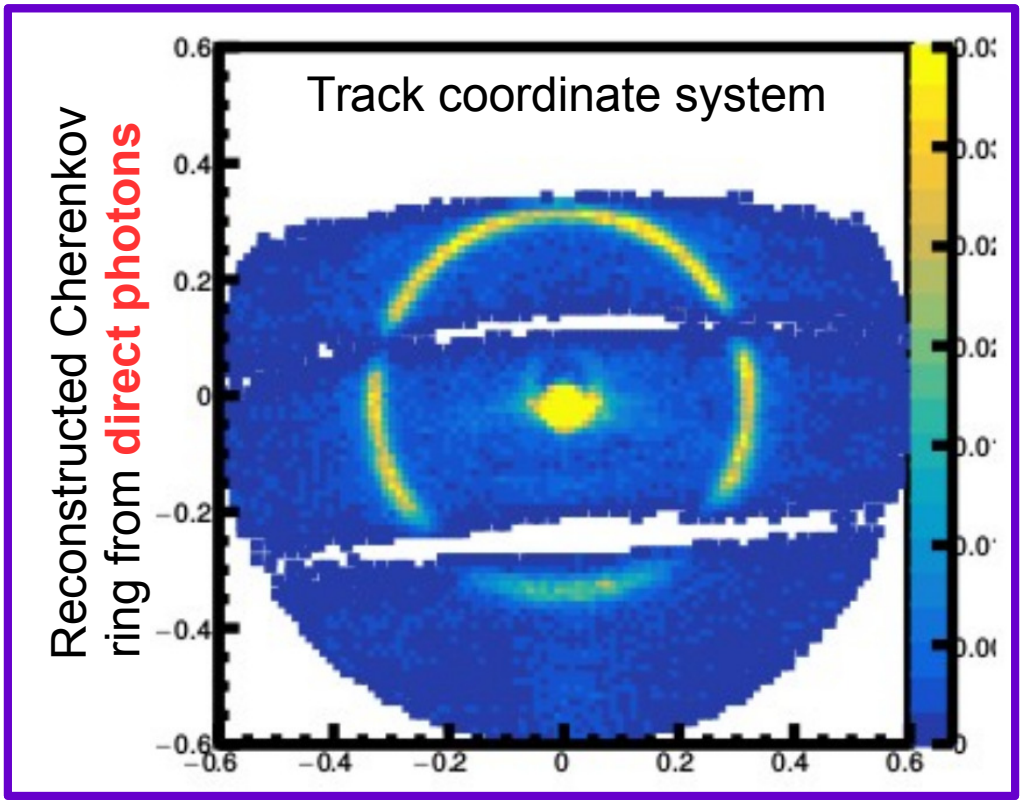
Conclusions

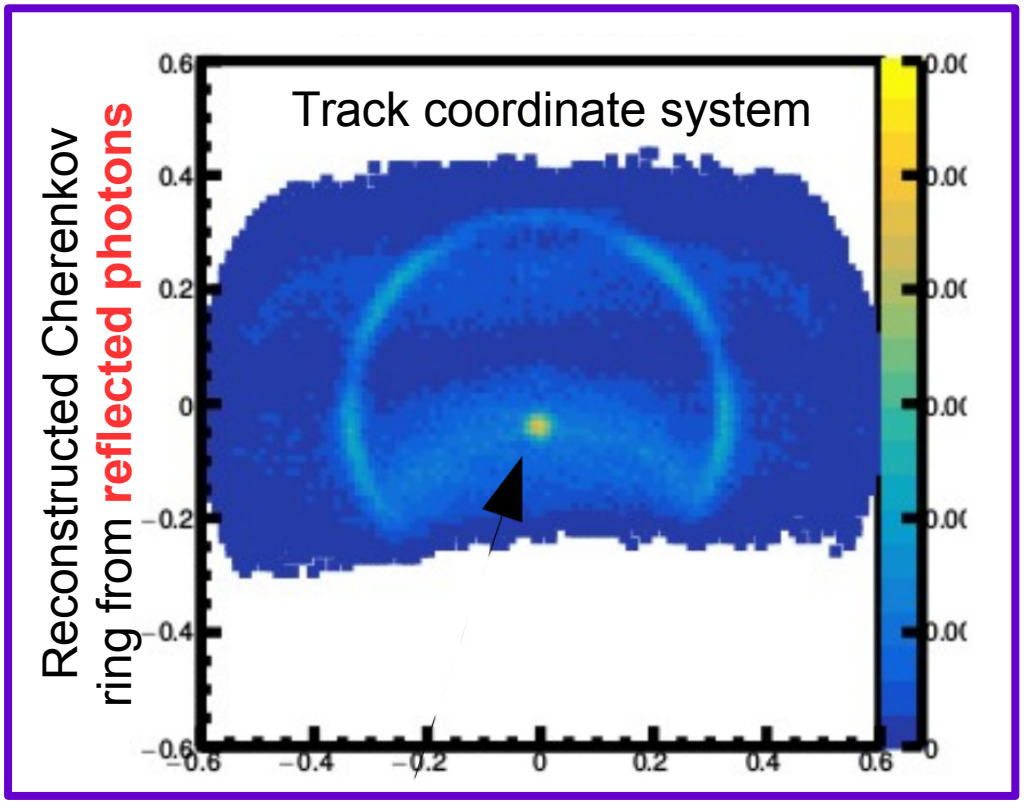
- BELLE II detector had take first collision data (started 26 of April 2018)
- Estimation of the ARICH detector performance have been done with BhaBha electrons.
- Single photon resolution measured to be ~14 mrad (in agreement with simulation within 10 %).
- Number of signal photons is ~20% less with respect to the simulation.
- It corresponds to ~4 σ K/pi separation for tracks with 4 GeV/c momentum.
- Monte Carlo tuning in ongoing.
- Upgrade of the ARICH cooling system have been done.





Backup slides, appendix, ...


Reconstructed Cherenkov ring from direct photons
Track coordinate system


Reconstructed Cherenkov ring from reflected photons
Track coordinate system

RICH reconstruction. PID.

- “Simple” ring fit and Cherenkov angle reconstruction provide PID information but less precise then logarithm likelihood analysis.
- PID with ARICH detector based on logarithm likelihood analysis.

$$lnL = -N + \sum_{\text{hit } i} n_i + ln\left(1 - e^{-n_i}\right)$$

Expected number of detected photons

Number of detected photons

Probabilities for a HAPD pad to be hit.

Hit probability

$$n_i = n_s^i + n_b^i$$

Signal

Background

Detection efficiency

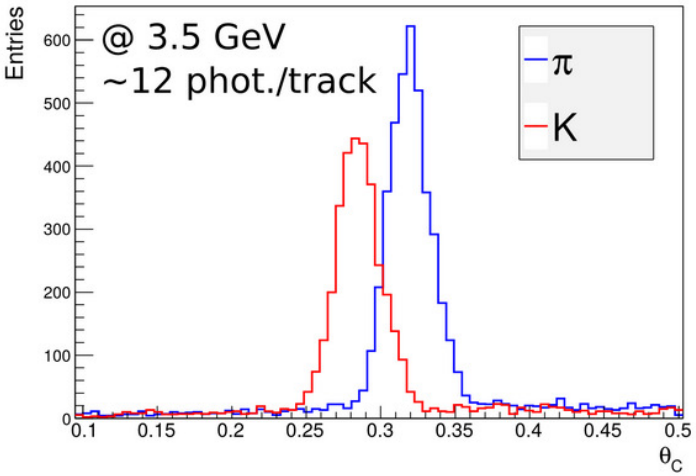
$$n_{s,r}^i = \varepsilon_i n_{t,r} \int_{\Omega_i} S_r(\theta_r, \phi_r) d\theta_r d\phi_r$$

Radiator

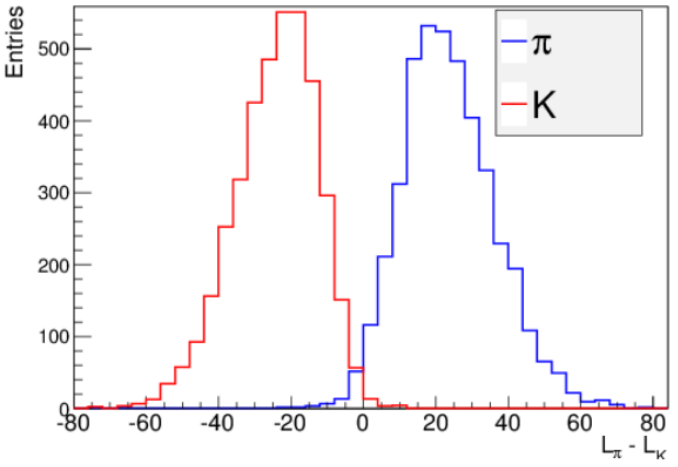
Total number of photons emitted in the radiator of type r

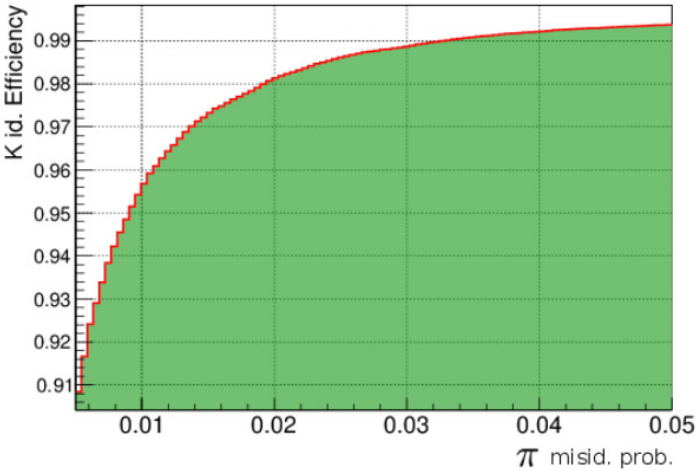
Is the probability for a Cherenkov photon being emitted by particle.

PID with Cherenkov angle reconstruction



PID with likelihood analysis





CKM unitary matrix and Wolfenstein parametrization

Weak eigenstates (*d′, s′, b′*) are linear combinations of the mass eigenstates (*d, s, b*)

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix} = V_{\rm CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

The non – diagonal elements of the CKM matrix allow for the transitions between quarks of different families

---

Wolfenstein parametrization of the CKM matrix is shown below:

$$V_{\rm CKM} = \begin{pmatrix} 1 - \frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

3 real parameters (λ, ρ, A) and 1 CP – violating complex phase (η)

Weak eigenstates (*d′, s′, b′*) are linear combinations of the mass eigenstates (*d, s, b*)

Quark flavour mixing and CP-violation are described by the Cabibbo-Kobayashi-Maskawa (CKM) unitary (3 x 3)matrix

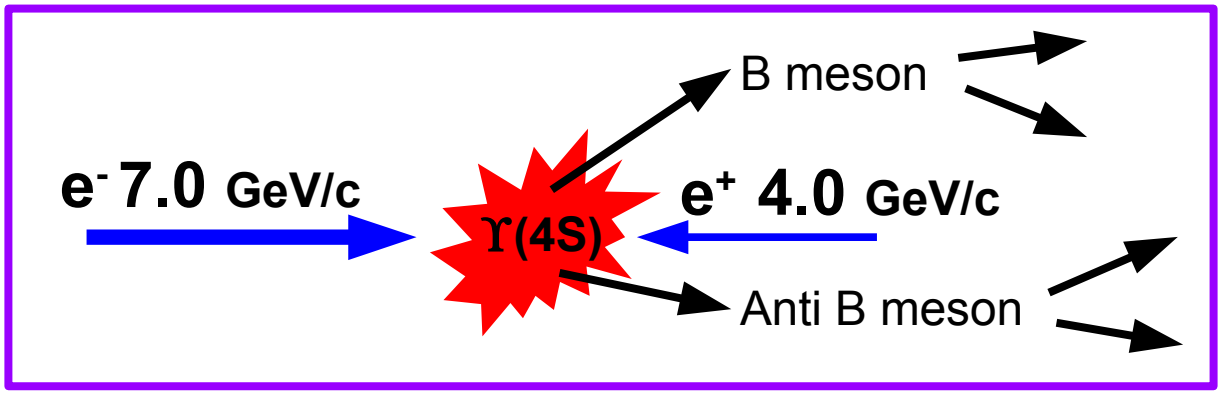
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = V_{\mathrm{CKM}} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

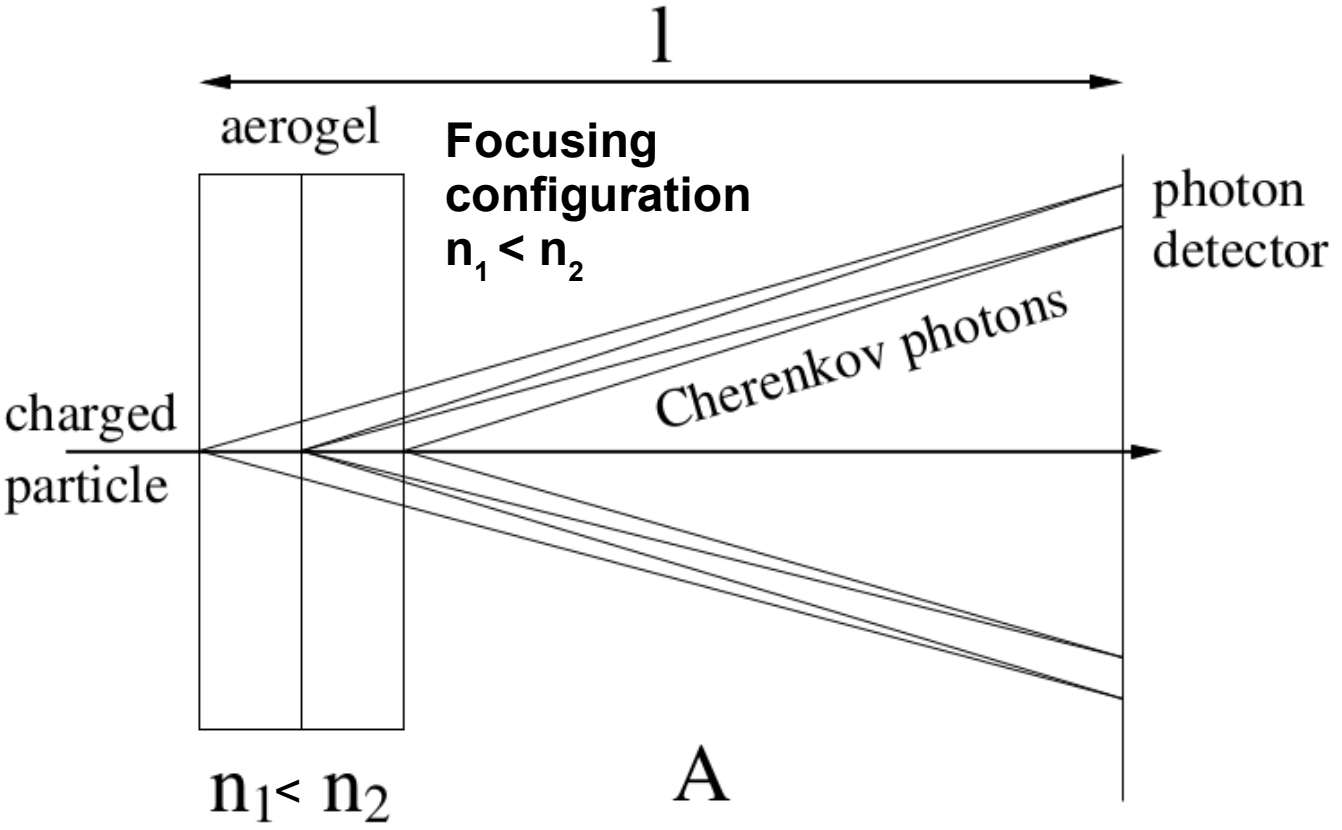
Weak eigenstates

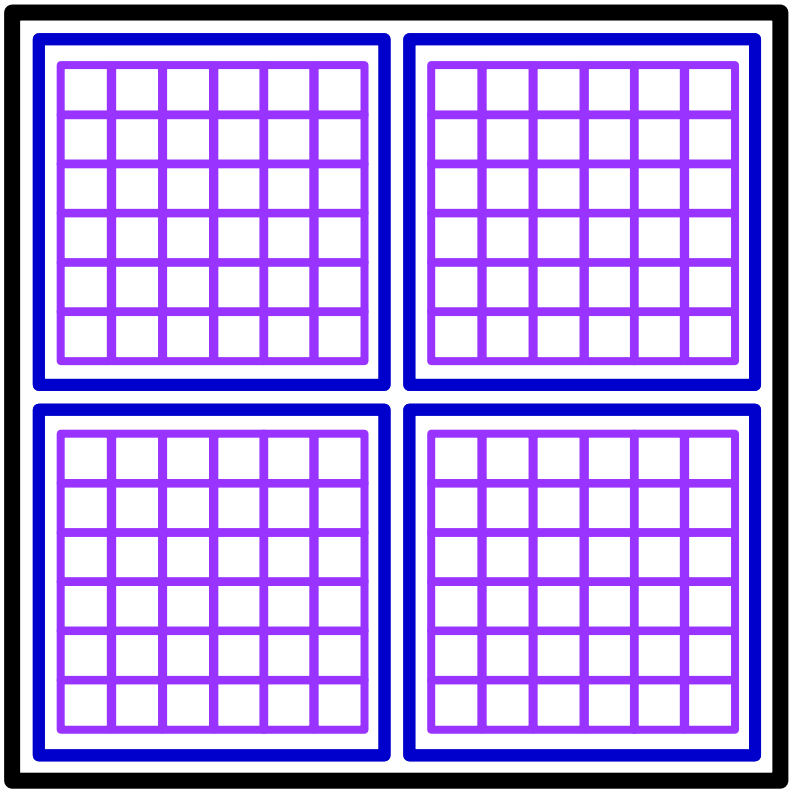
Mass eigenstates

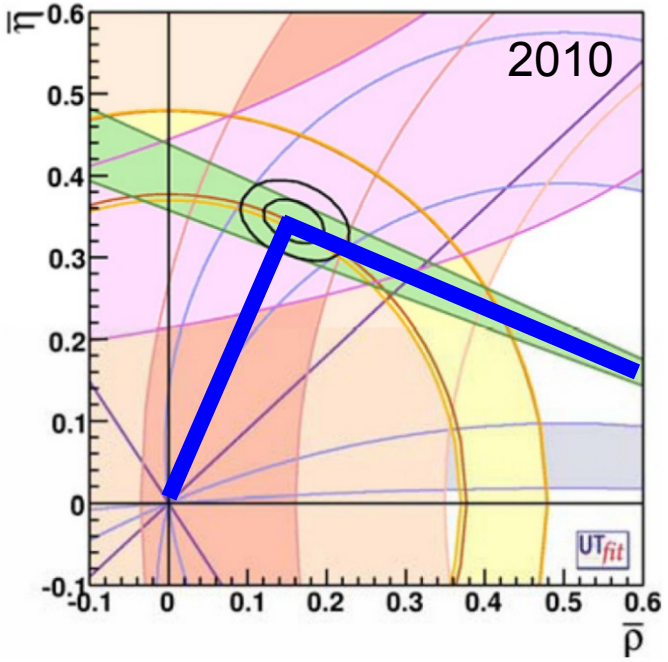
Cabibbo-Kobayashi-Maskawa unitary matrix

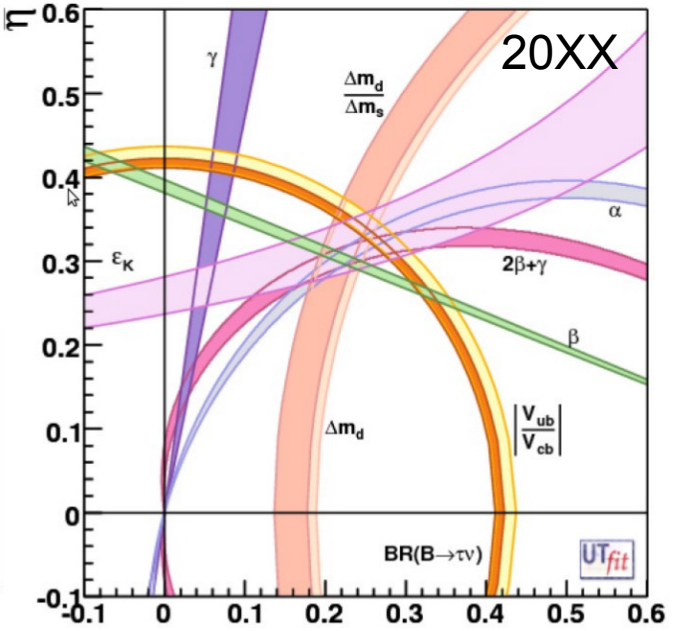
$$V_{\mathrm{CKM}} V_{\mathrm{CKM}}^{\dagger} = 1$$


B meson
e- 7.0 GeV/c
e+ 4.0 GeV/c
ϒ(4S)
Anti B meson


l
aerogel
Focusing
configuration
$n_1 < n_2$
photon
detector
Cherenkov photons
charged
particle
$n_1 < n_2$
A







Central values of the constraints are from the present data (2010). While errors are those expected to be 10 time less with Belle II data.

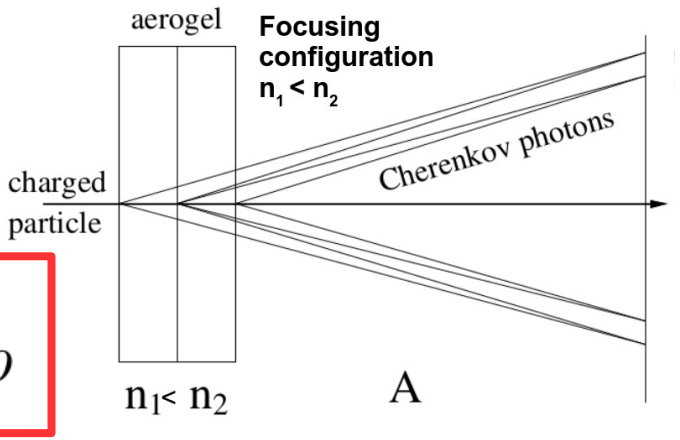
In case the measurements will not sum – up to a close triangle → New Physics !!!

Why we choose aerogel radiator? Aerogel parameters.

$$\beta = \frac{1}{n\cos(\theta)} \rightarrow \frac{\sigma_\beta}{\beta} = \sigma_\theta \tan(\theta) \rightarrow \frac{\sigma_\beta}{\beta} \rightarrow 0 \quad \theta \rightarrow 0 \quad \boxed{n \rightarrow 1}$$

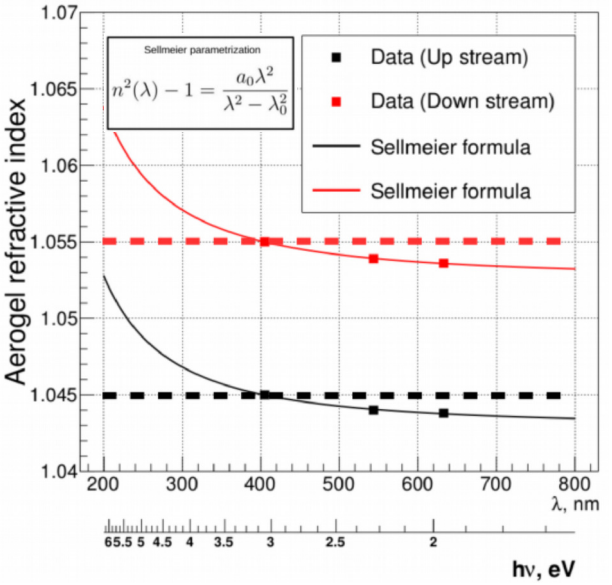
$$N_{Cherenkov\ light} \sim \left(1 - \frac{1}{n^2\beta^2}\right) L$$

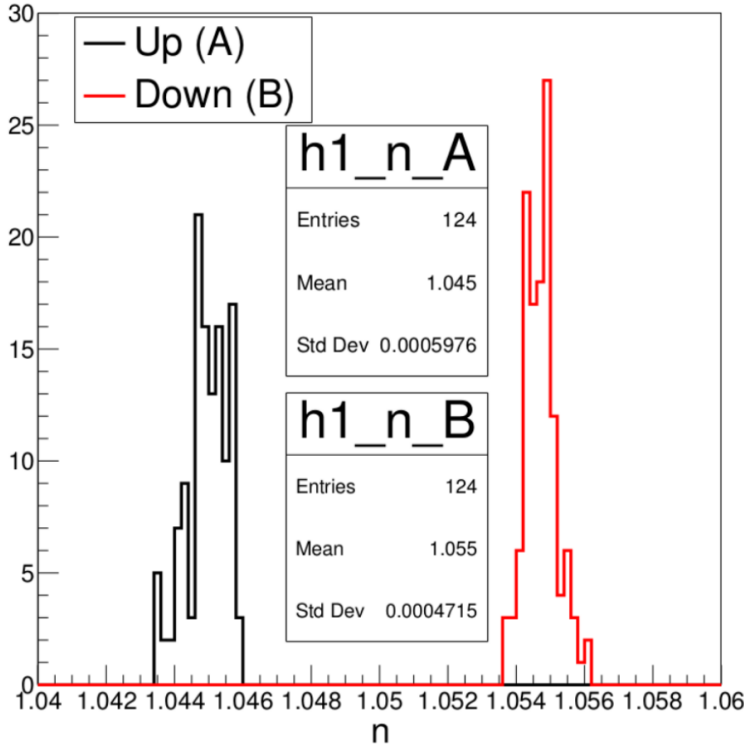
As a consequence we need to use thicker radiator



Fine adjustment of n

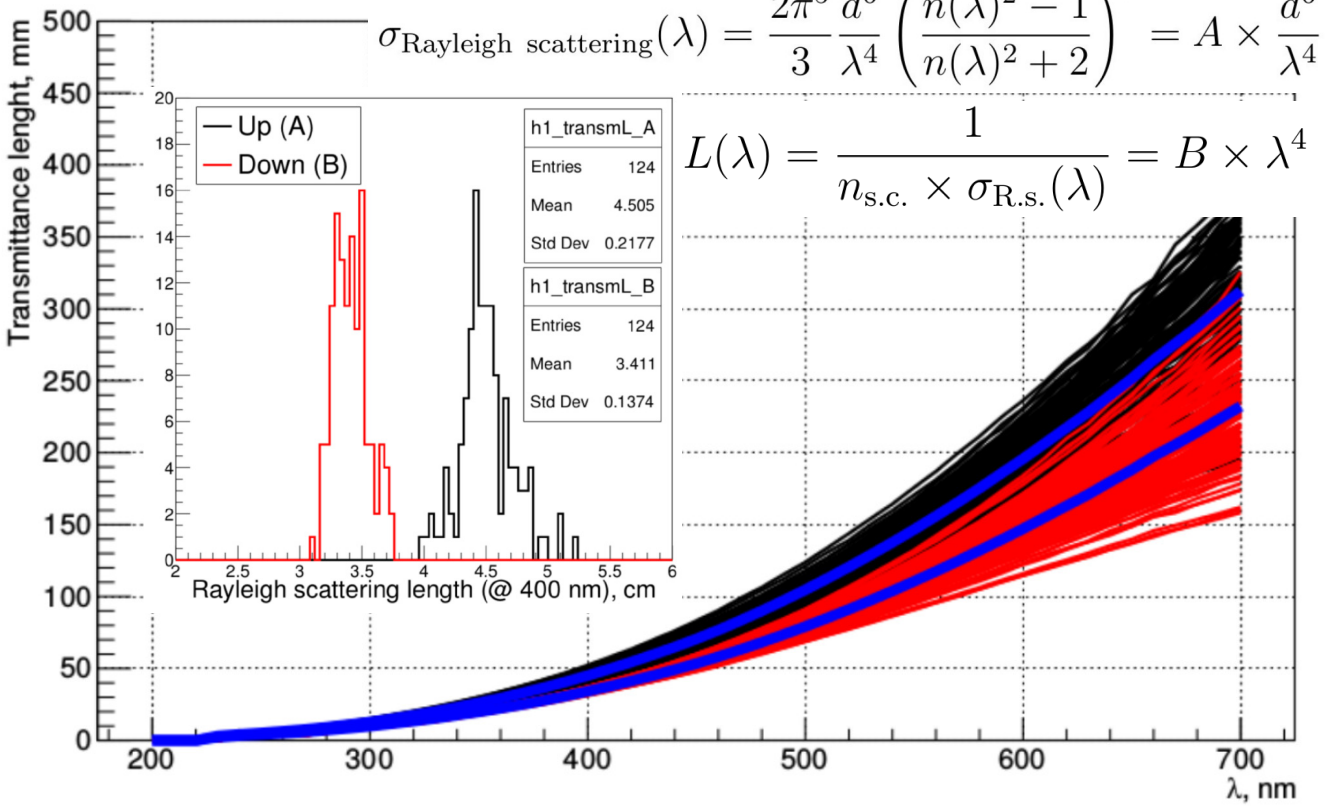
$$n(\lambda) = p_{\text{Intercept}} + k(\lambda)\rho$$





$$\sigma_{\text{Rayleigh scattering}}(\lambda) = \frac{2\pi^5}{3}\frac{d^6}{\lambda^4}\left(\frac{n(\lambda)^2 - 1}{n(\lambda)^2 + 2}\right)^2 = A \times \frac{d^6}{\lambda^4}$$

$$L(\lambda) = \frac{1}{n_{\text{s.c.}} \times \sigma_{\text{R.s.}}(\lambda)} = B \times \lambda^4$$



Aerogel Ring Imaging CHerenkov counter (ARICH) : concept

- Cherenkov radiation is electromagnetic radiation emitted when a charged particle passes through a dielectric medium of refractive index n with a velocity v greater than the speed of light (c/n) in that medium.
- First observation in 1934 by **Pavel Cherenkov**.
  (During the experiments on luminescence of liquids under gamma rays)
- Theoretical explanation has been given by **Ilya Frank** and **Igor Tamm** in 1937. (Based on classical electrodynamics)
- Nobel Price (by P. Cherenkov, I. Frank, I.Tamm) in 1958

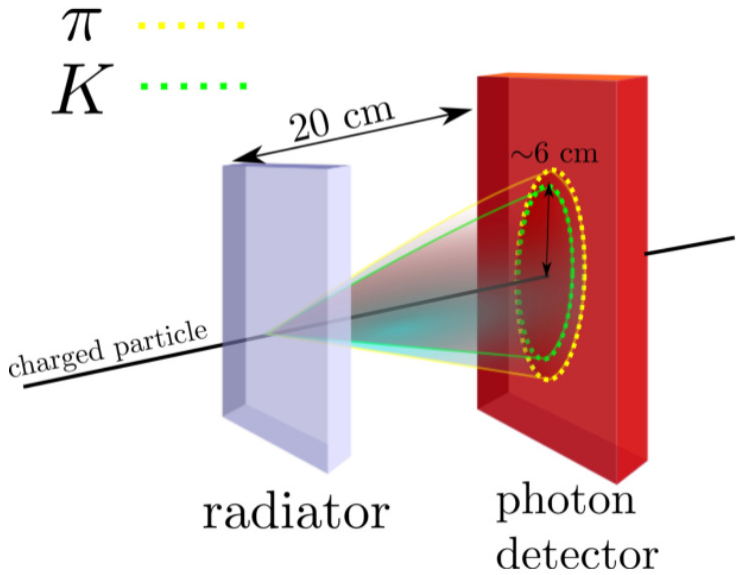
$$\cos\theta_c = \frac{1}{n\beta}$$

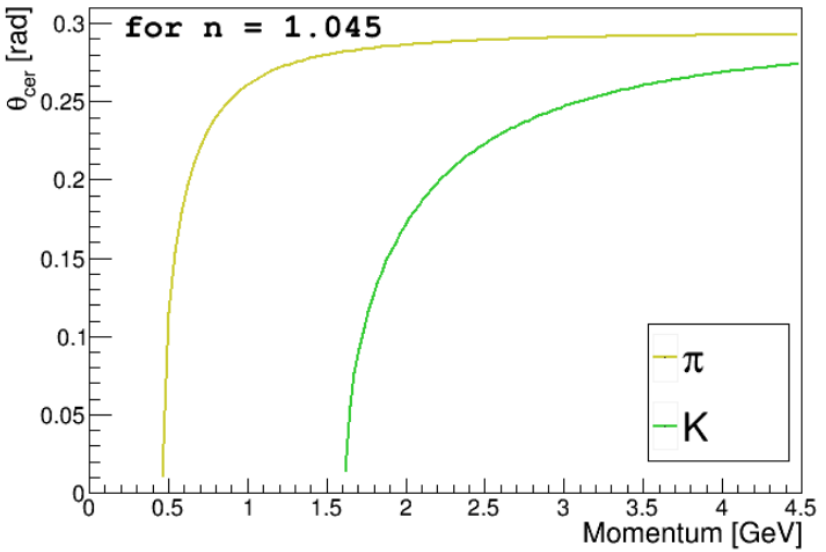
$$\beta = v/c$$

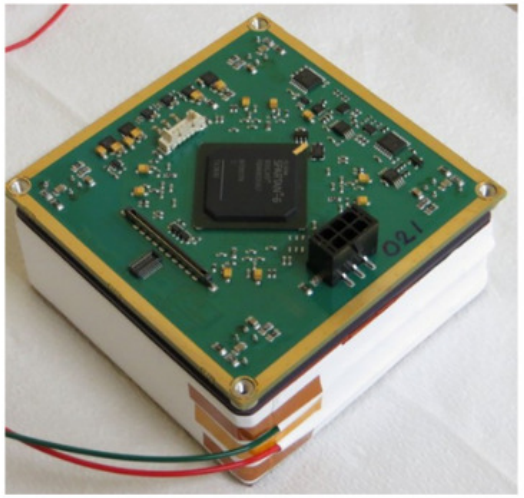
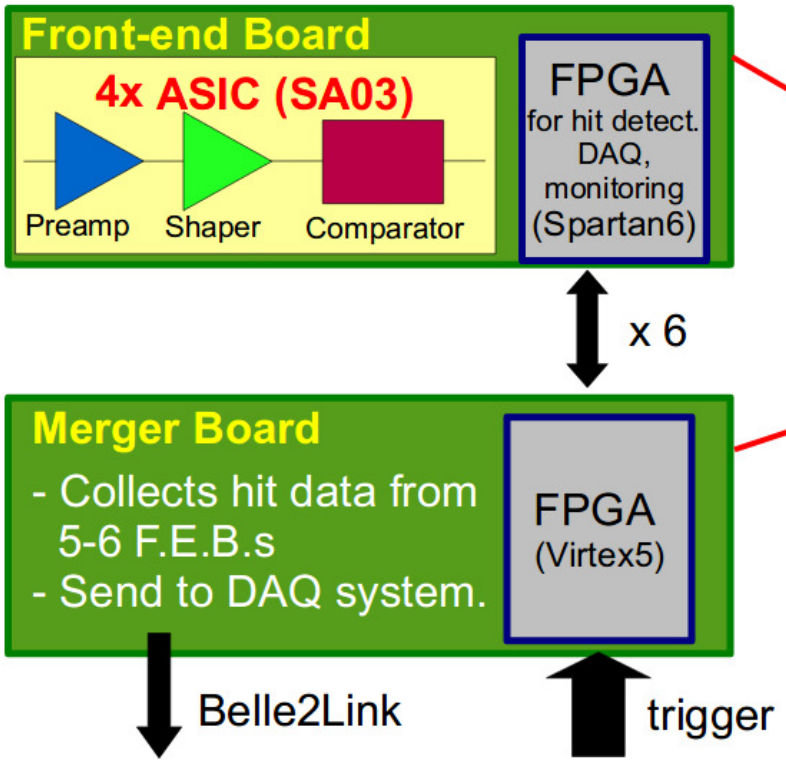
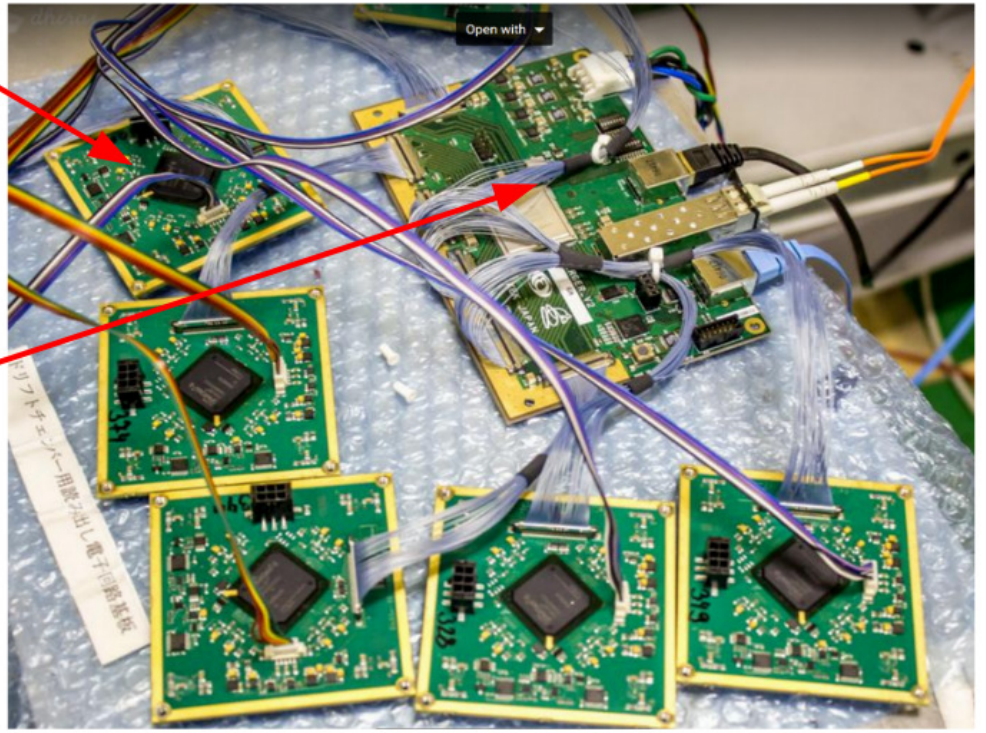
$$\frac{\partial^2 N}{\partial x \partial \lambda} = \frac{2\pi\alpha z^2}{\lambda^2}\left(1 - \frac{1}{(n(\lambda))^2\beta^2}\right) \sim 1/\lambda^2$$

Particle mass $\leftarrow m = \frac{p}{c}\sqrt{n^2\cos^2\theta_c - 1}$

- p: Particle momentum
- θ_c: Particle Cherenkov angle
- n: Aerogel refractive index





DAQ

- in total 60.000 channels.
- limited space of 5 cm behind array of HAPDs.
- ASIC SA03 (36 ch/chip → 4 ASICS / HAPD).
- Variable gain (3.1-12.5 V/pC) and shaping time (100-200 ns)
  → optimization for increasing noise levels (neutron radiation)
- mass production completed.