RICH 2018, 29.7.- 4.8.2018, Moscow, Russia

Calibration of the Belle II Aerogel Ring Imaging detector

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on behalf of the Belle II ARICH group:

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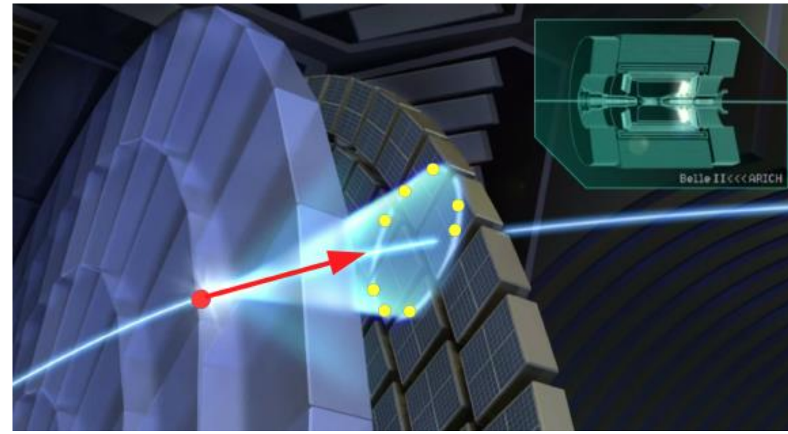
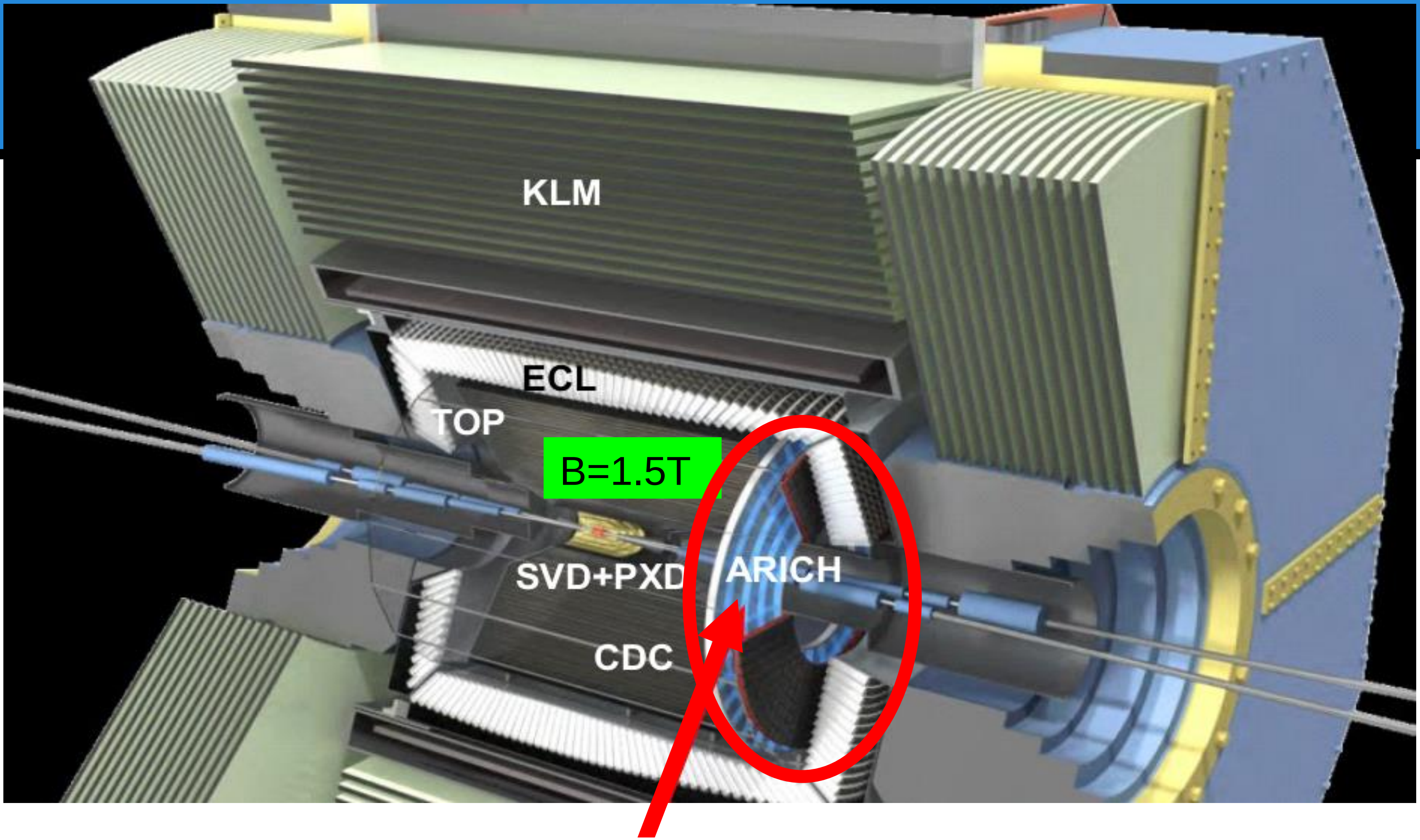
Outline

- ❑ Introduction
- ❑ Particle identification with aerogel RICH
- ❑ Calibration of the detector
- • Before the installation
- • With the collision data
- • Particle identification efficiency determination
- ❑ Summary



Particle identification in Belle II



Two dedicated particle ID devices - both RICHes – designed to fit into available space:

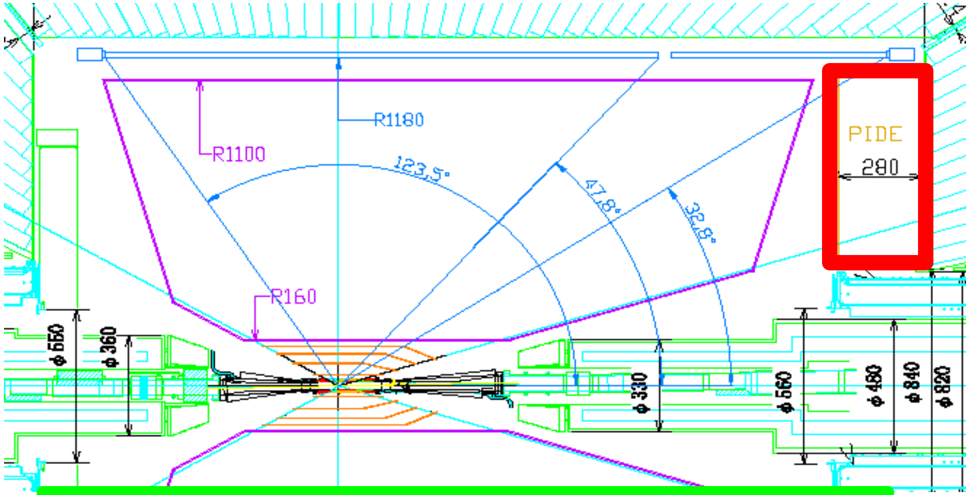
- Barrel: imaging Time-Of-Propagation (TOP) Talk by Umberto Tamponi – Monday
- End-cap: **Proximity focusing Aerogel RICH (ARICH)**

Talk by H. Kindo – Monday

Proximity focusing Aerogel RICH design

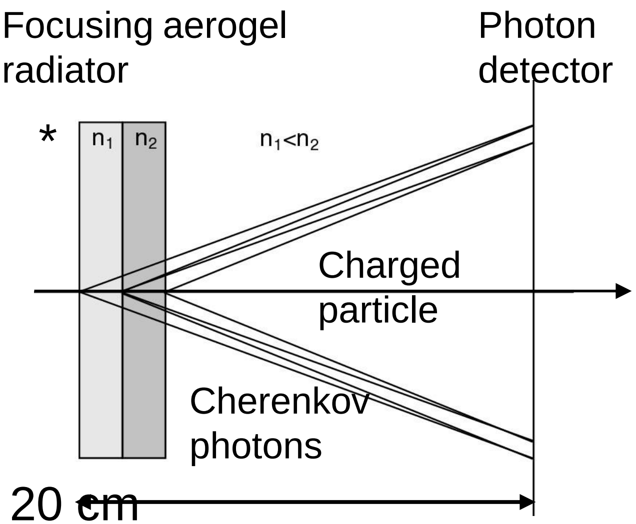
Goals and constraints:

- > 4 σ K/π separation @ 1-3.5 GeV/c
- operation in magnetic field 1.5T
- limited available space ~280 mm
- radiation tolerance (n,γ)



Selected type:

proximity focusing aerogel RICH



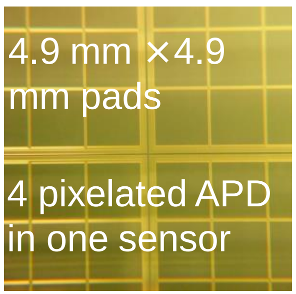
T.Iijima, S.Korpar et al. NIMA548 (2005) 383

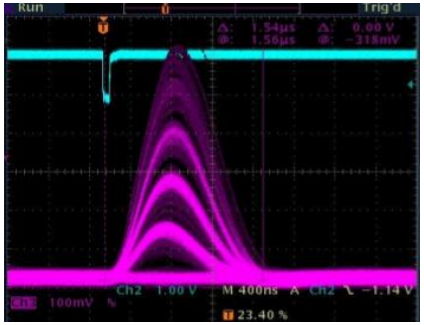
- <n> ~ 1.05
- $\theta_c(\pi) \approx 307$ mrad @ 3.5 GeV/c
- $\theta_c(\pi) - \theta_c(K) = 30$ mrad @ 3.5 GeV/c
  - pion threshold 0.44 GeV/c,
  - kaon threshold 1.54 GeV/c
- neutron fluence: up to ~10^{12} n/cm2
- radiation dose: up to ~1000 Gy

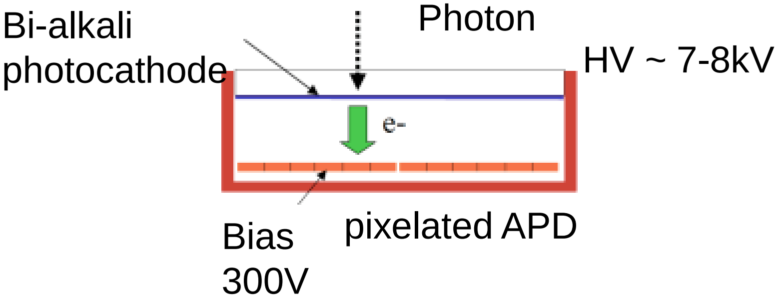
* to increase the number of photons without degrading the resolution

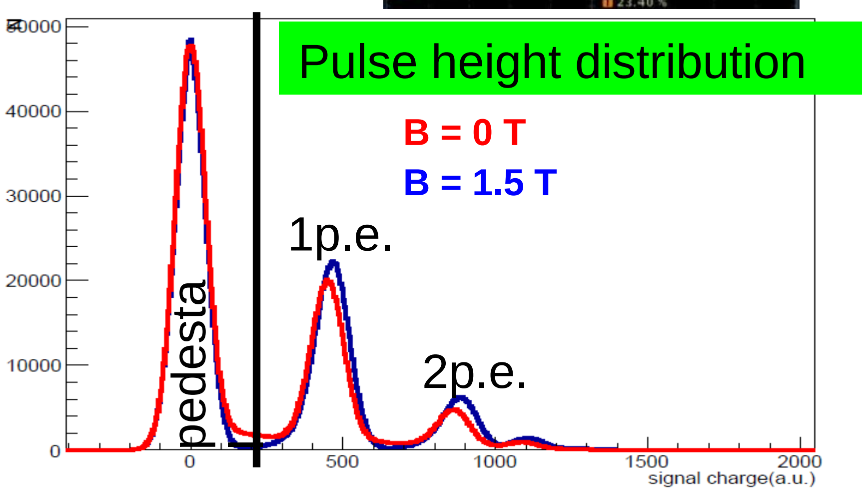
Hybrid Avalanche Photo-Detector

- 144 ch. HAPD developed with the Hamamatsu Photonics
- Excellent separation of single photoelectrons
- Works in a magnetic field of 1.5T









Talk by M.Yonenaga, Tuesday

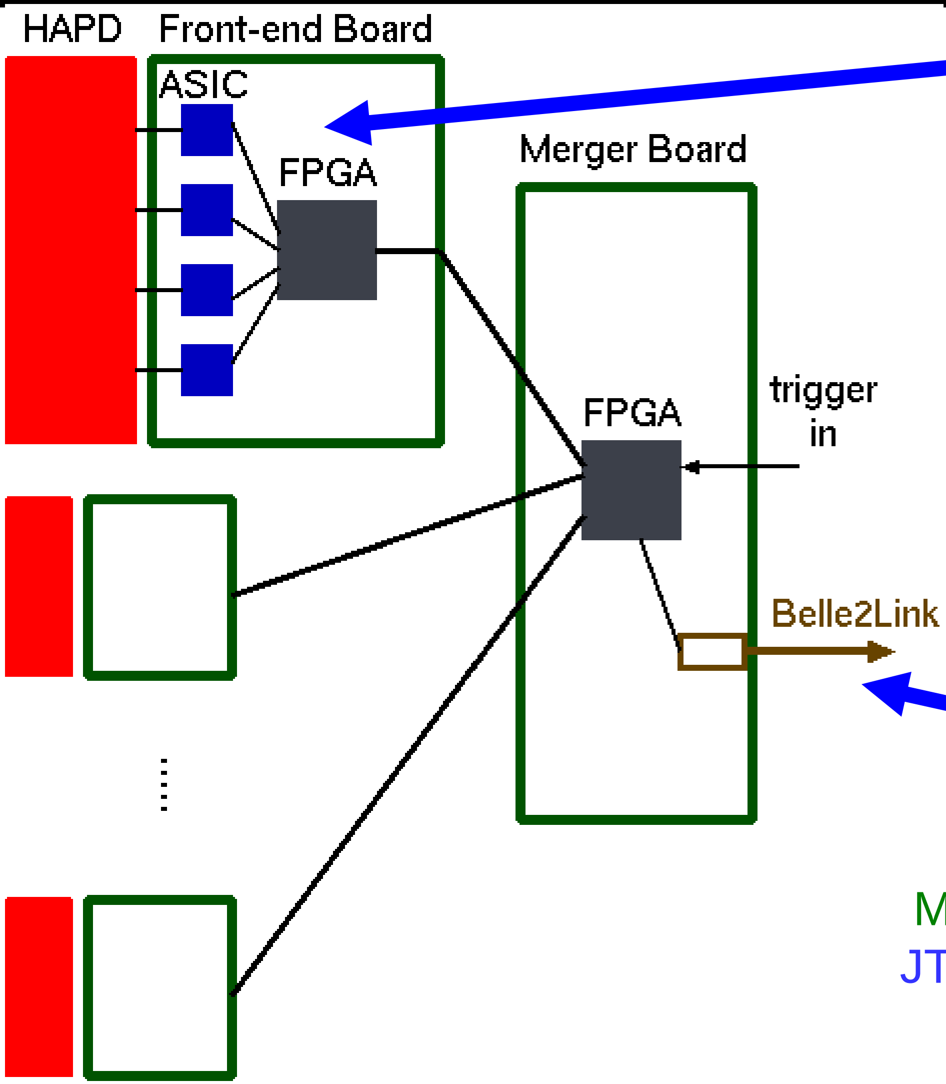
Specifications

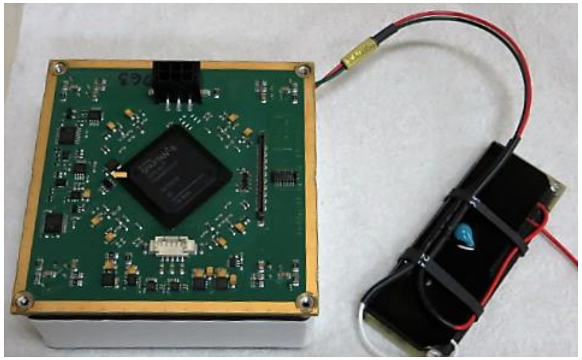
Package	73×73mm2
sensitive area	64%
# of pixels	144(36×4chips)
capacitance	80pF
weight	220g
peak QE	28%
bombardment gain	1500
avalanche gain	~30
total gain	~45000

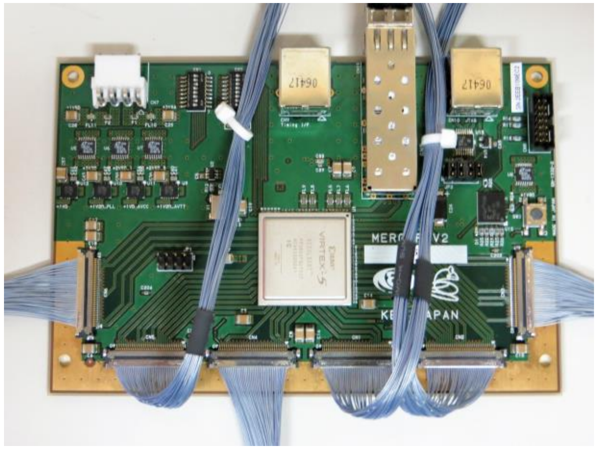
Readout electronics

Front-end board with 4 ASICs and Spartan6 FPGA

limited space (~5cm) behind the HAPD

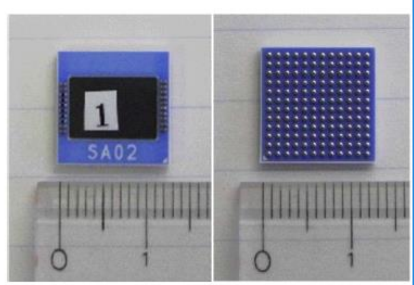




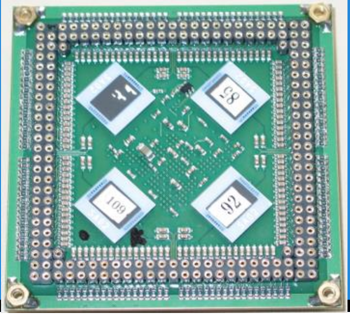


Merger board prototype with Virtex5 FPGA:
JTAG, optical link, trigger in, front-end conn.

Front end Readout Board



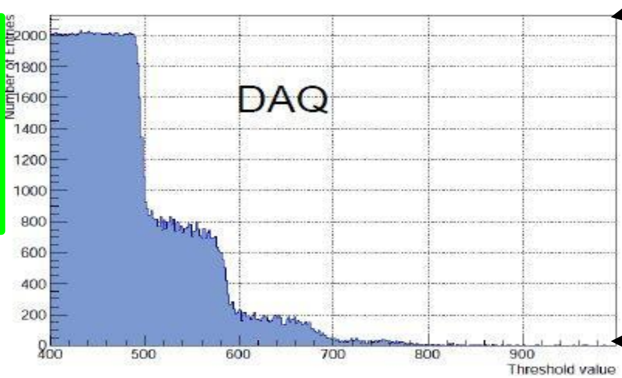
SA02 (36ch)

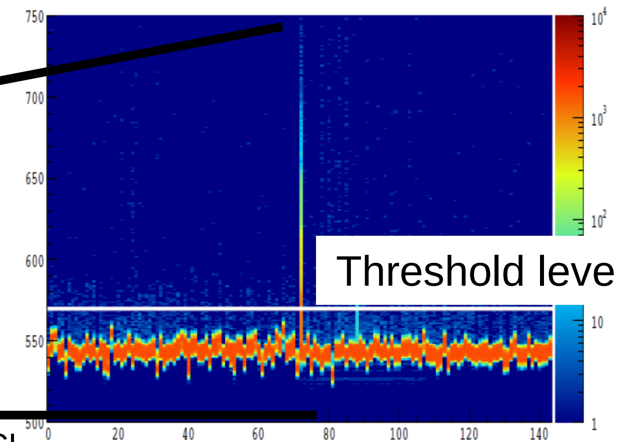


- 36 channel ASIC (preamp., shaper and comparator) provides hit information.
  - settings: 4 step gain, 4 step peaking time, offset level
  - peaking time >100 ns
- FPGA (Xilinx Spartan6):
  - hit detection and data transfer
  - coarse time-over-threshold measurement to discriminate between single Cherenkov photons from aerogel and the Cherenkov photons produced in the HAPD window
  - monitoring of supply voltages and temperature

Poster R. Pestotnik et al. **Front end electronics of the Belle II ARICH**

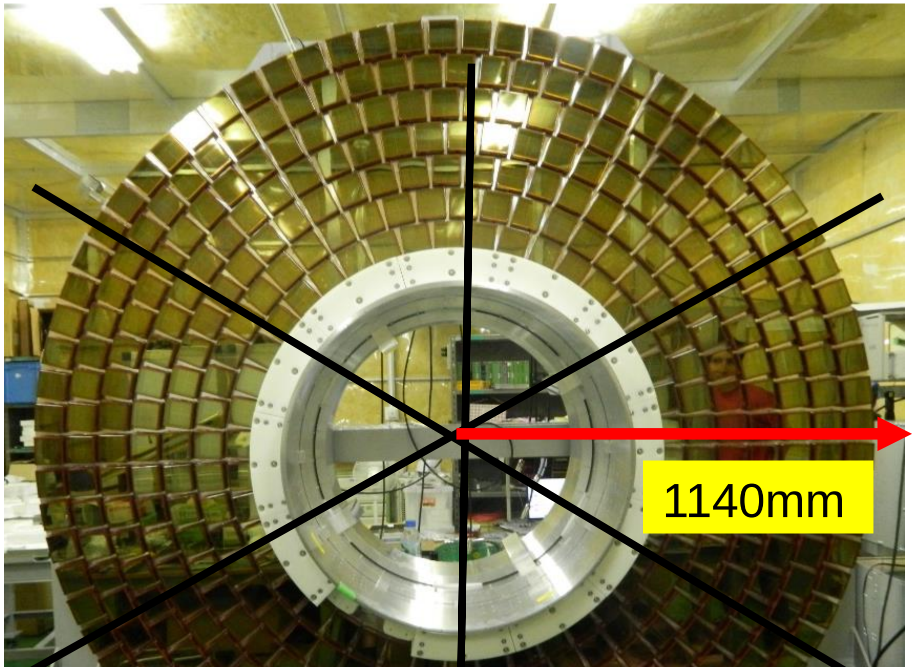
Threshold scan
Response to
single photons from laser – one channel is illuminated





Putting everything together

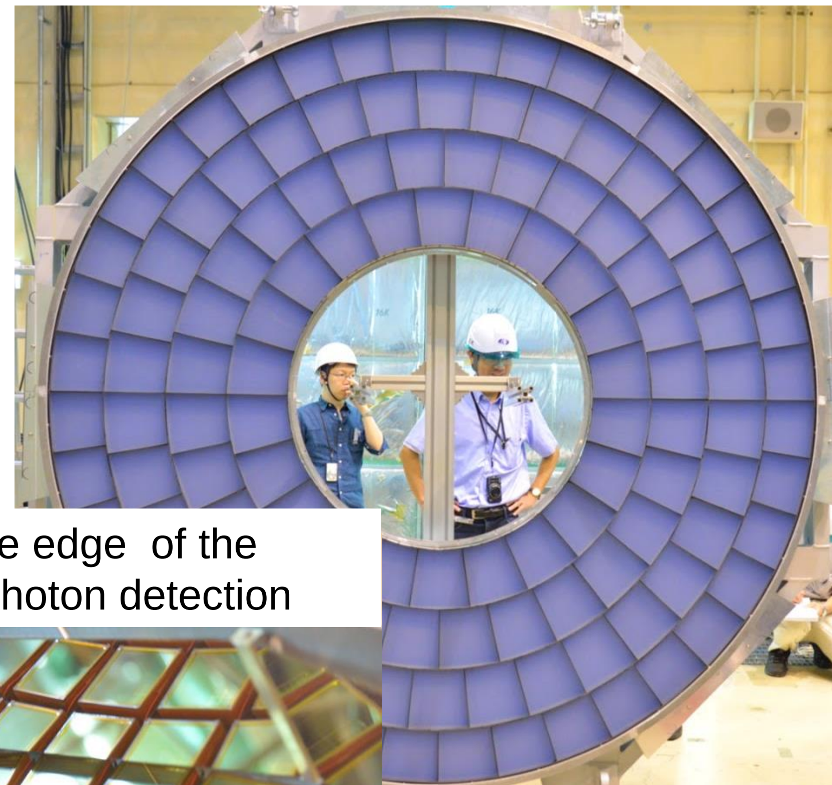
420 HAPD modules in 7 rings

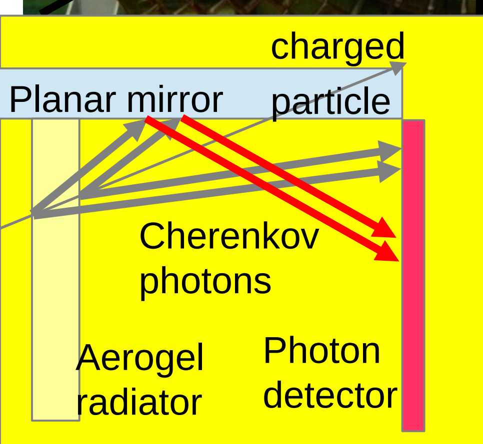


Aerogel : 124x2 pieces n=1.045 and 1.055
-wedge shape, each layer 20mm thick

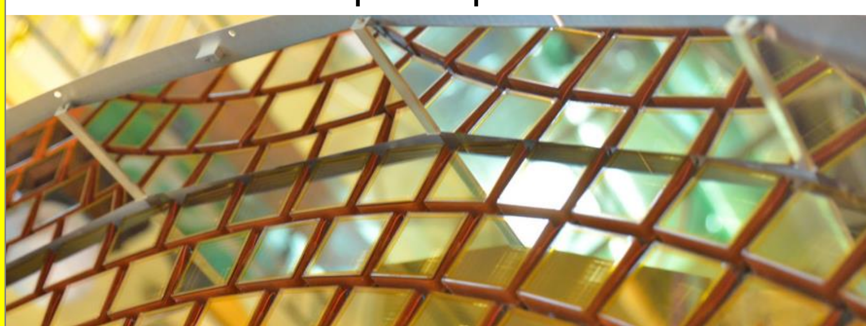
- 4 types depending on radius
- Cut out from square tile ~175 mm in side

Poster by M. Tabata



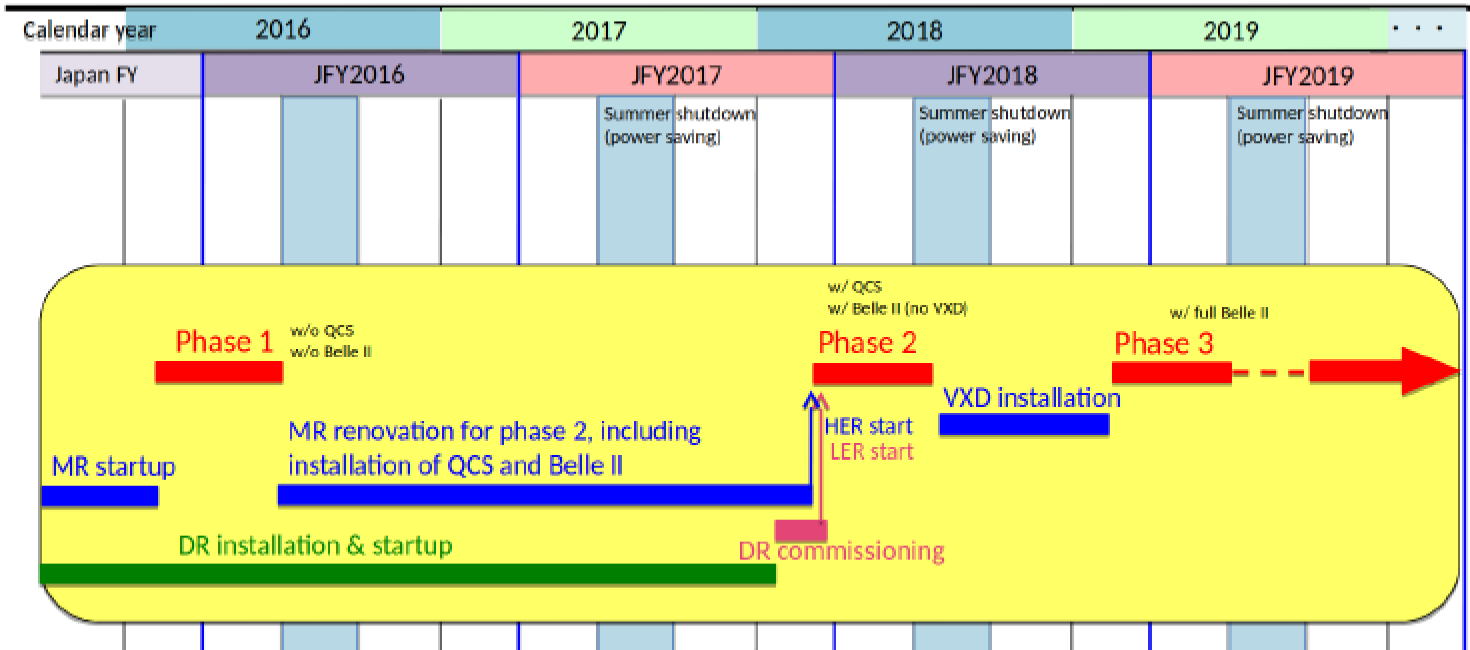


Planar mirrors on the edge of the detector to improve photon detection



Timeline

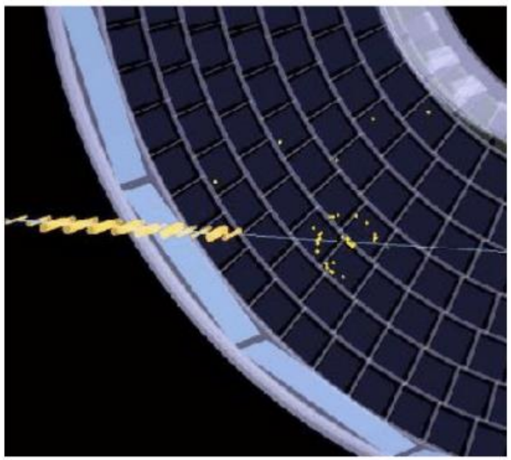
Sept. 2017 : ARICH installed in the Belle II spectrometer
Sept.-Dec. 2017: connection of the power supplies and tests of the electronics
Winter 2018 : Cosmic ray tests
Apr.- Jul. 2018 : Phase II run (Belle II detector w/o pixel detector)
Autumn 2018 : Access to the detector – tests of several components, upgrade of the cooling system.



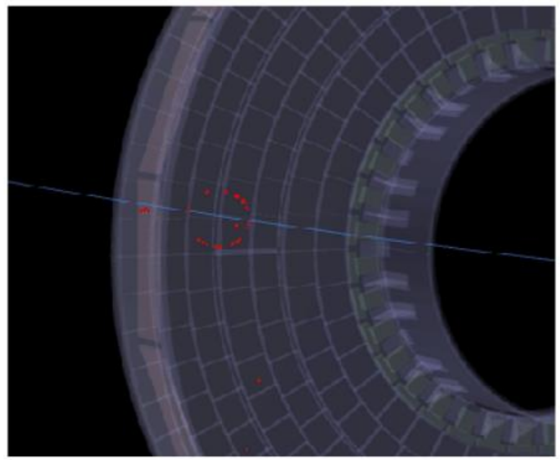
First data

Important milestone achieved: Observation of

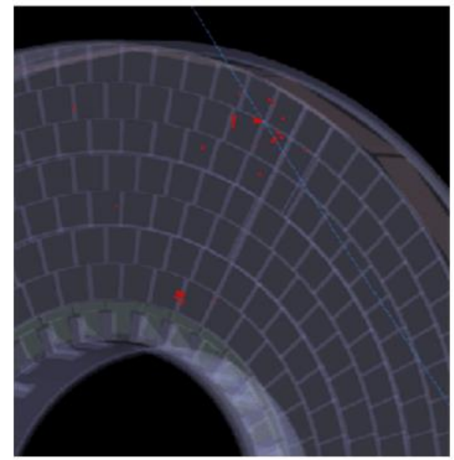
Cherenkov rings during the Cosmic and Beam runs



Cosmic



Beam

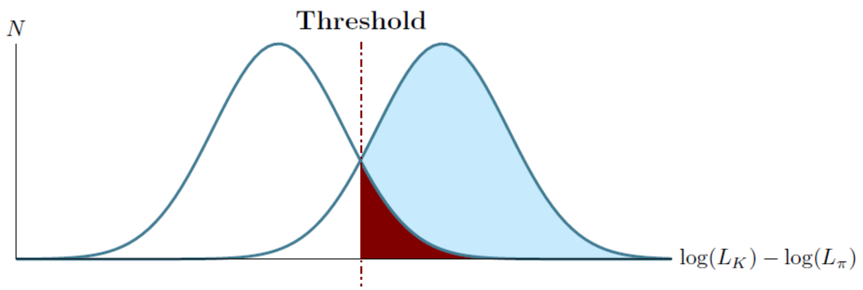


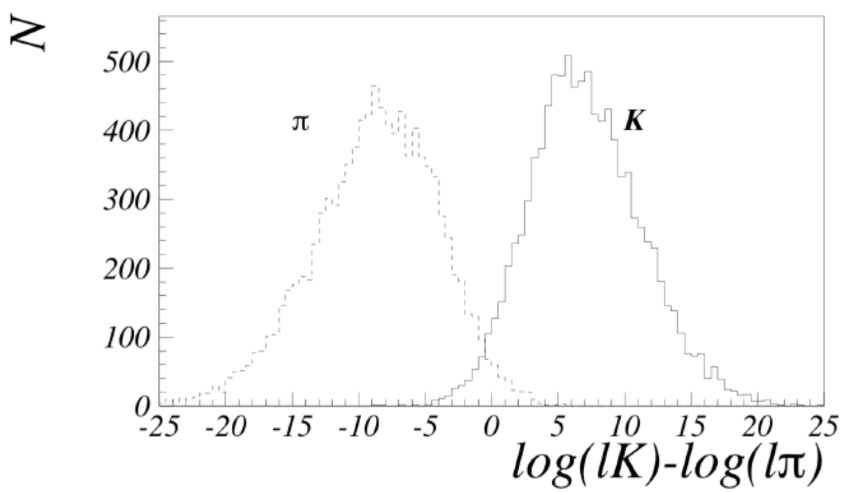
Beam

This pictures are of course not enough to identify particles

Particle identification in the aerogel RICH

- For each particle hypothesis (e,mu,pi,K,p) evaluate a likelihood function
- Determine momentum dependent threshold based on the sample of independently identified particles
- Determine the identity
- How do we construct the likelihood function?





Likelihood construction

Small number of tracks, overlap of rings from different particles not very likely

p_i – probability that a a pixel i was hit distributed binomially
n_i - expected i.e. calculated average number of hits on the particular pixel
m_i – measured number of photons in the particular pixel

$$p_i = \frac{e^{-n_i} {n_i}^{m_i}}{m_i!}$$

$$p_i = \begin{cases} e^{-n_i} & \text{for } m_i = 0 \text{ non hit pixels,} \\ 1 - e^{-n_i} & \text{for } m_i > 0 \text{ hit pixels.} \end{cases}$$

$$L = \prod_{\text{all pixels}} p_i = \prod_{\text{not hit i}} p_i \prod_{\text{hit i}} p_i = \prod_{\text{not hit i}} e^{-n_i} \prod_{\text{hit } i} (e^{n_i} - 1)$$

$$lnL = - \sum_{\text{not hit i}} n_i - \sum_{\text{hit i}} n_i + \sum_{\text{hit i}} n_i + \sum_{\text{hit } i} ln\,(e^{n_i} - 1)$$

For a given hypothesis:
N number of expected hits = sum of expected average number of hits on the detector

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

* Follows P. Baillon and R. Forty

Likelihood construction II

Advantage of this procedure:
one now has to calculate the average number of hits n_i only for the hit pixels.

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

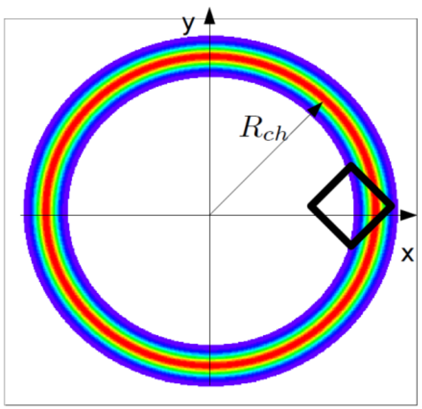
n_i is a sum of a signal and background contribution $$n_i = n_s^i + n_b^i$$

Signal contributions from different radiators $$n_s^i = \sum_r n_{s,r}^i$$

$$n_{s,r}^i = \varepsilon_i n_{t,r} \int_{\Omega_i} S_r(\theta_r, \phi_r) d\theta_r d\phi_r \qquad S_r(\theta_r, \phi_r) = \frac{1}{2\pi} \frac{1}{\sqrt{2\pi}\sigma_{\theta_r}} e^{-\frac{(\theta_r - \theta_r^h)^2}{2\sigma_{\theta_r}^2}}$$

Ω_i Solid angle of a single pad

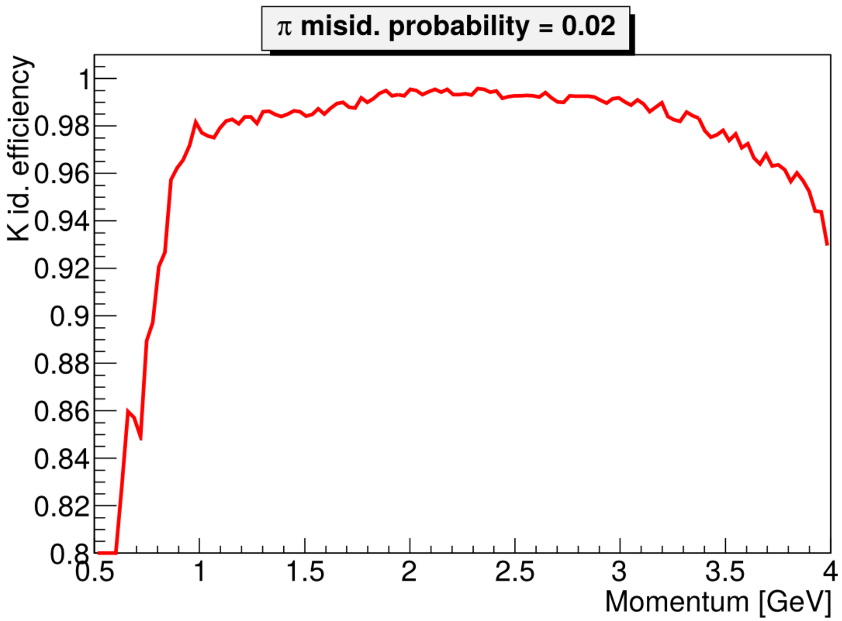
σ_{θ_r} Single photon resolution without pad size uncertainty

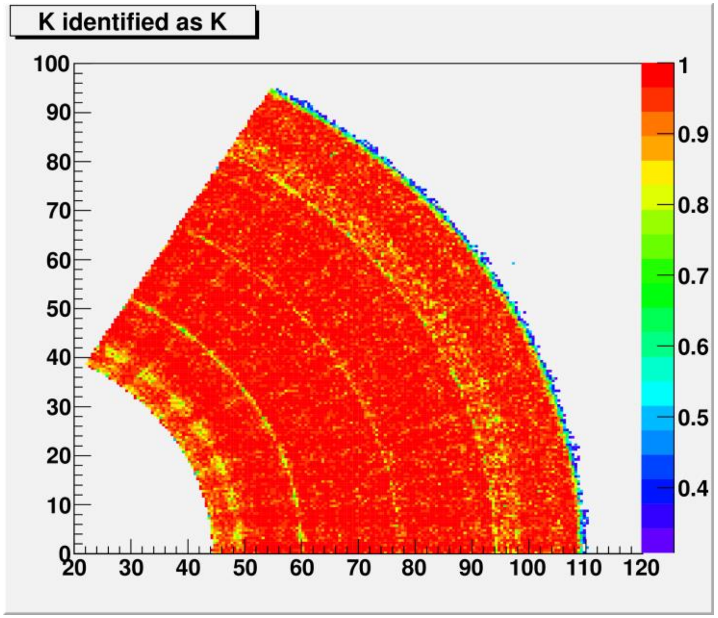


can be calculated analytically

Monte Carlo performance

Detailed simulation performed in the Belle II software framework - BASF2





K id. Eff. for p=3-4 GeV/c 1% pion fake

Excellent PID efficiency over wide momentum range.

Homogeneous response over the sensitive area of the detector (1 sextant is shown)

Calibration of the detector

Why? **Impact of a calibration on separation capabilities**

Quantities from the likelihood function:

$$n_i = n_s^i + n_b^i \qquad n_s^i = \sum_r n_{s,r}^i \qquad S_r(\theta_r, \phi_r) = \frac{1}{2\pi}\frac{1}{\sqrt{2\pi}\sigma_{\theta_r}} e^{-\frac{(\theta_r - \theta_r^h)^2}{2\sigma_{\theta_r}^2}}$$

Non calibrated detector:

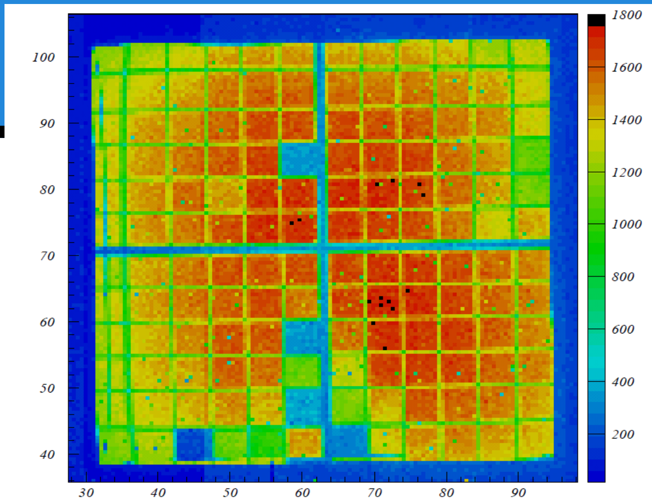
- number of signal photons: not well known &smaller
- Backgrounds : not well known & higher
- Width of the PDF : not well known & larger

➡ Lower identification efficiencies , higher misidentification probabilities

Three stages of calibration:

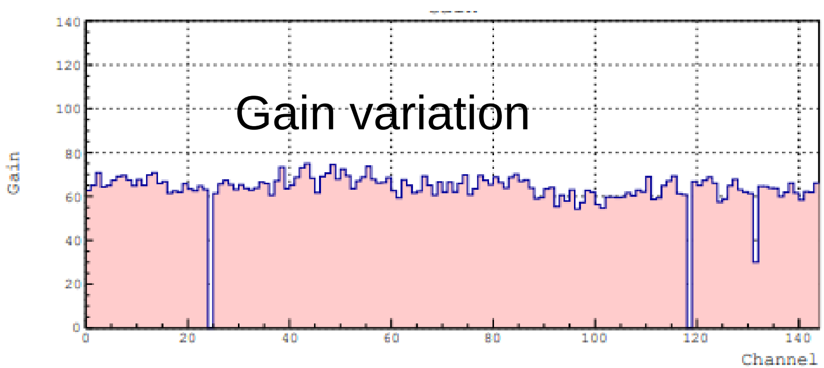
- I. Calibration of operational parameters before the installation
- II. Calibration of the detector with the detector data: Online/Offline
- III. Determination of the efficiency and misidentification probabilities by using particles unambiguously identified without RICH

I. Calibration of parameters before the installation

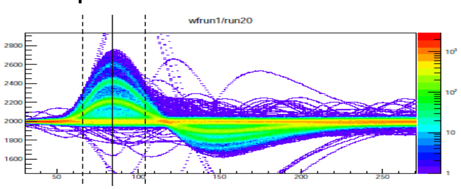


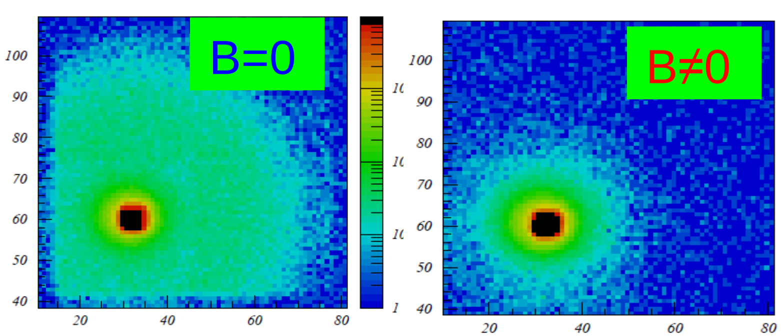
Measurements for each sensor:

- Operation parameters (HV, APD bias Voltage)
- Position dependence of QE, PDE and gain
- Response in the magnetic field

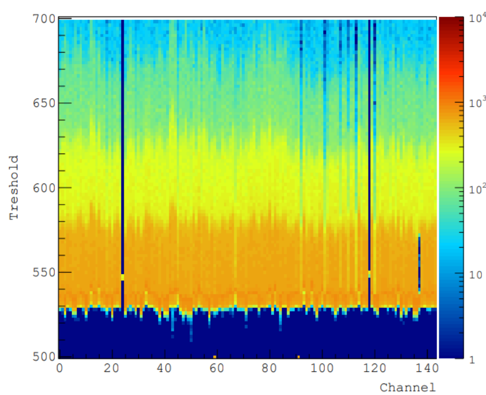


Monitor output of an individual channel

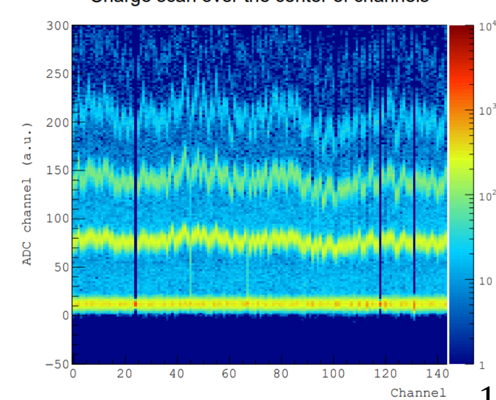




Treshold scan over the center of channels

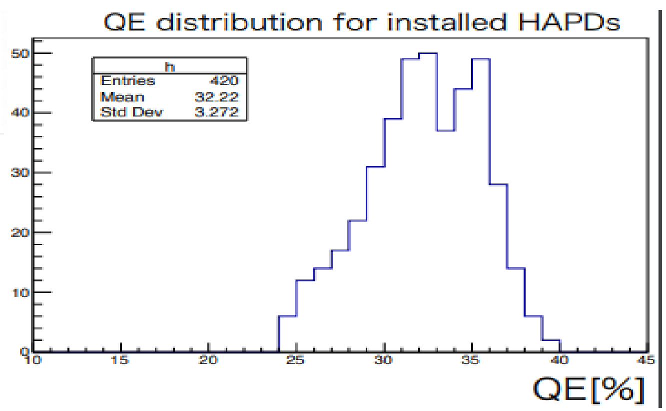


Charge scan over the center of channels

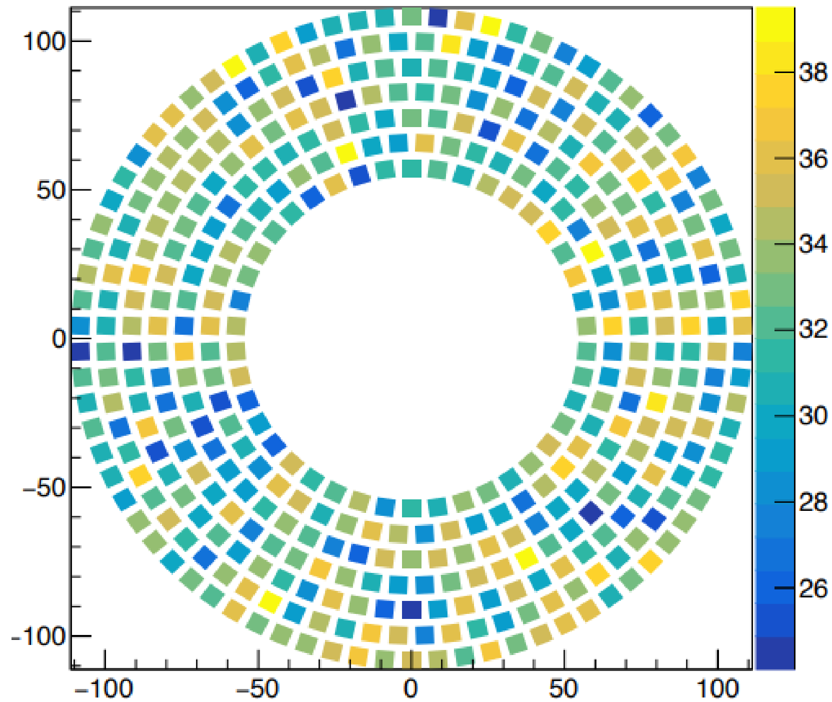


All the measurements are stored in the **Belle II database** and some are used during the reconstruction:

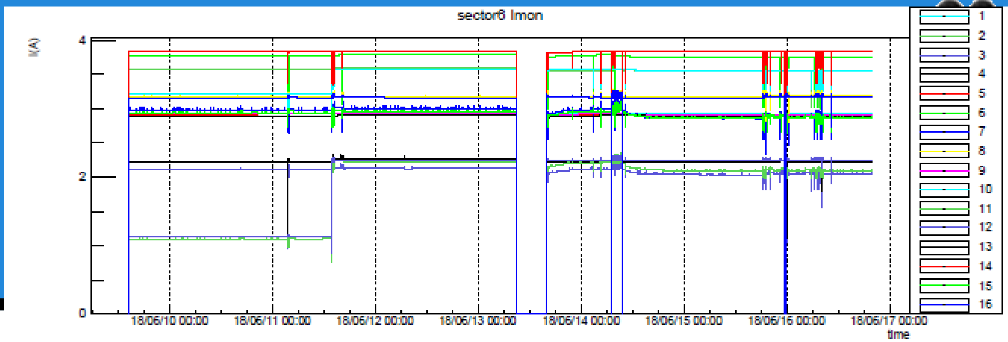
- PDE,
- hot and dead channels



Average QE on the detector

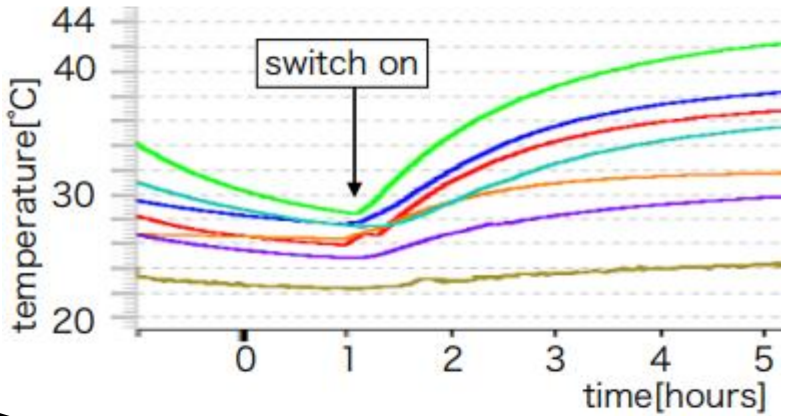


Calibration with the data

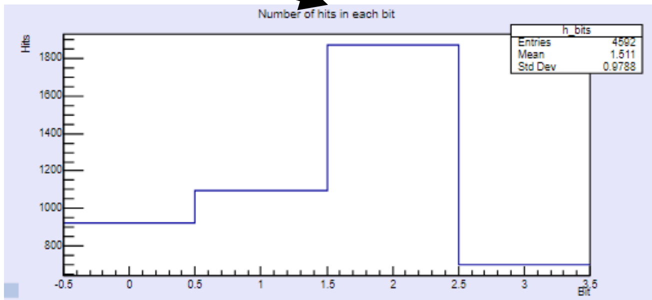


Constant monitoring and update of run operation parameters:

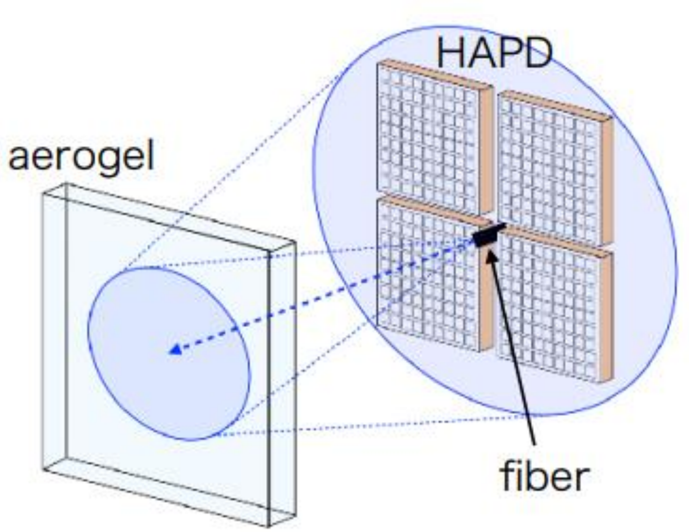
- HAPD: HV and bias
- Electronics: Power supply and temperatures
  - FPGA:
    - sampling frequency,
    - delay relative to trigger signal,
    - SEU detection and repair (due to neutron backgrounds)
  - ASIC: Gain, Channel offsets, Threshold



Special calibration runs will be performed regularly once per day/week.



Calibration with special runs with LED illumination

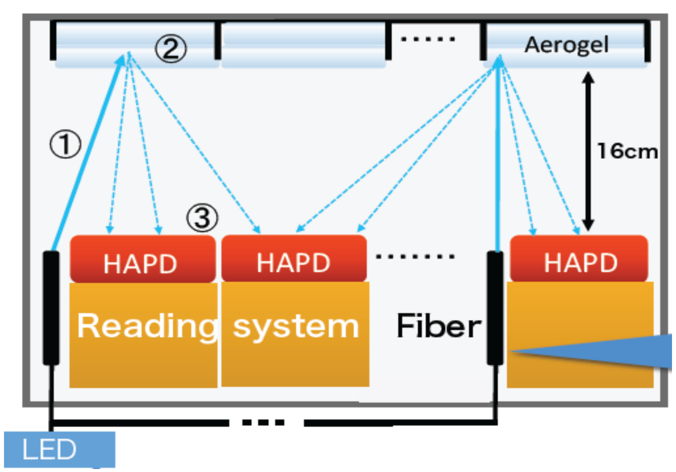


During the calibration run the surface of the aerogel plane is illuminated by LED light (λ=470nm) distributed by optical fibers to several points on the detector.

The reflected light is registered by the HAPD sensors and allows calibration before physics data taking:

- Determine hot and dead channels
- By measuring the response for different thresholds:
  - Relative sensitivity, gain and offset for each channel can be determined

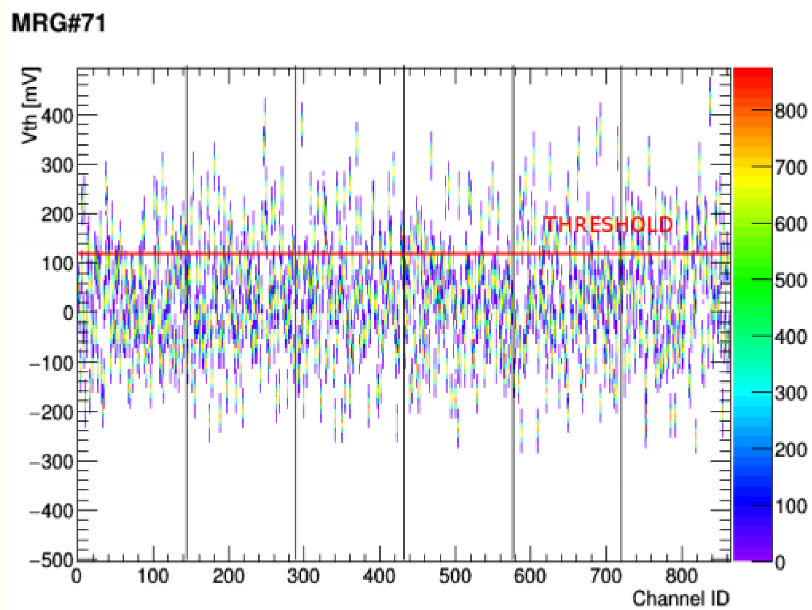
New set of configuration parameters can be uploaded through the DAQ to the ASICs/FPGAs on the front end boards.

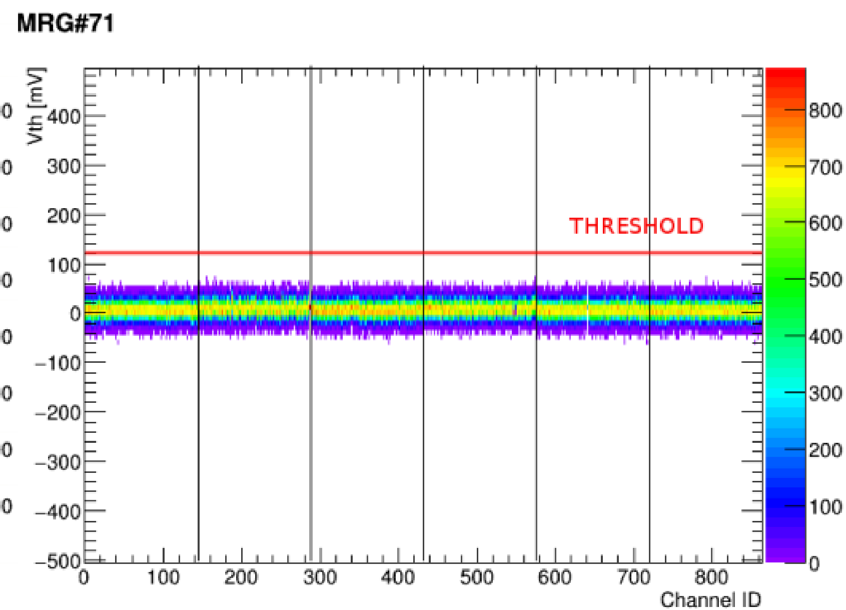


Talk by M.Yonenaga, Tuesday

Channel Calibration

Adjusting offsets for 6 FEB
(controlled by one of the 72 merger boards)

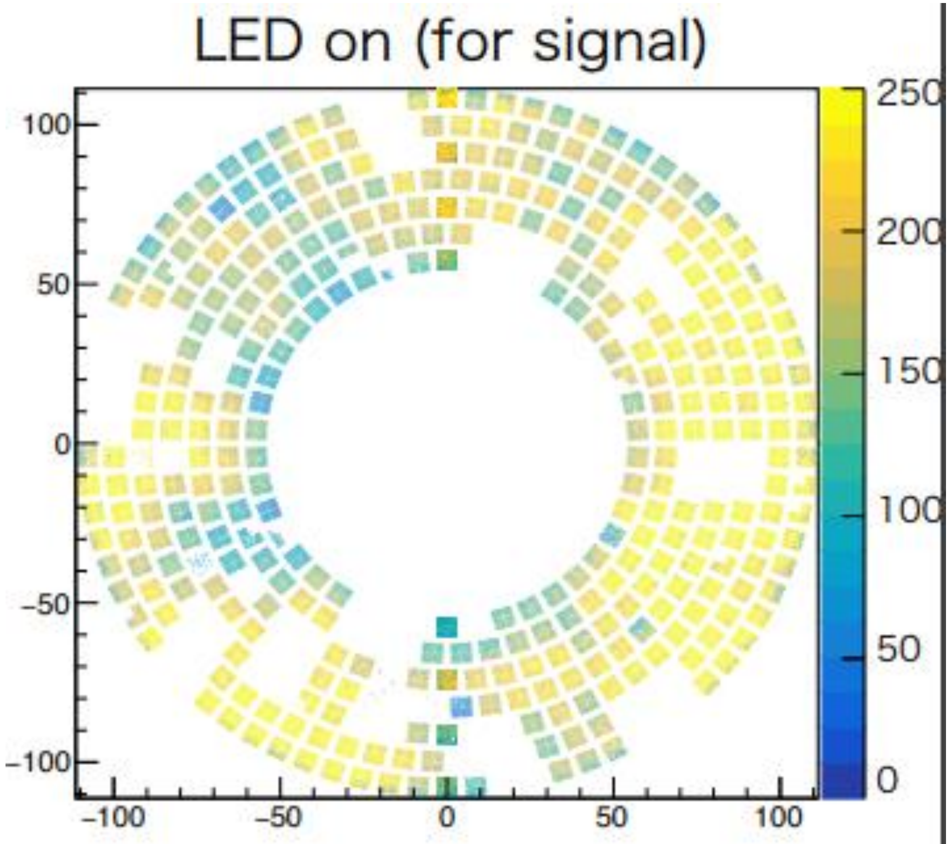




Non aligned

Aligned - the offset settings adjusted

After offsets are adjusted and threshold set:
determine hot and dead channels



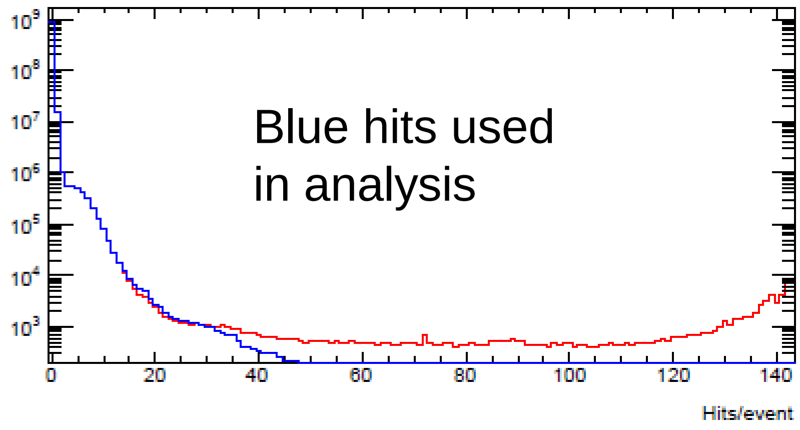
Still many dead areas due to
problems with individual merger boards
to be repaired during shutdown

Calibration with the data

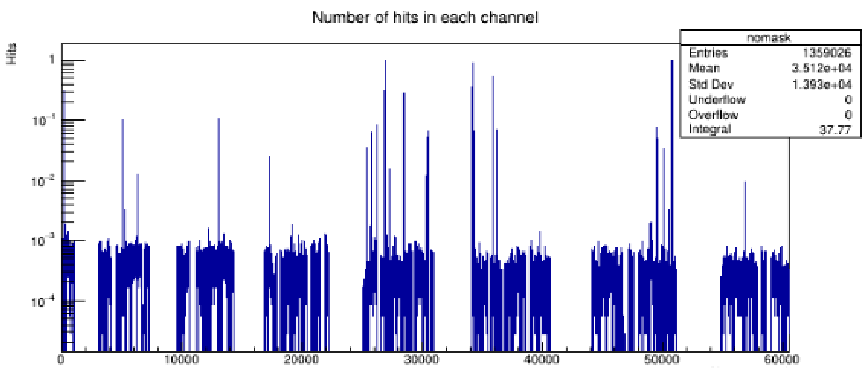
During the normal data taking the data are monitored constantly:

- On event by event basis :
  - HAPDs with too many hits are not used in the identification algorithm
  - If the readout module stops responding it is also masked out (SEU not correctable events) until the next firmware reset)

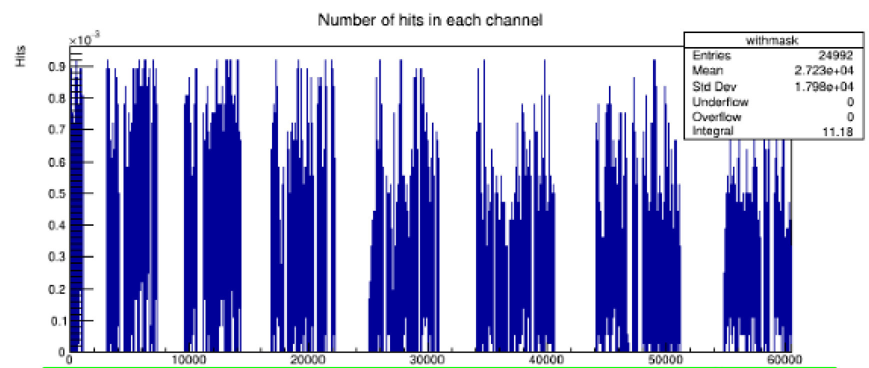
- For every run: Dead and hot channel masks are calculated and used in the reprocessing (we do not expect the number of dead and hot channels will be changing significantly)



Hot and dead channels

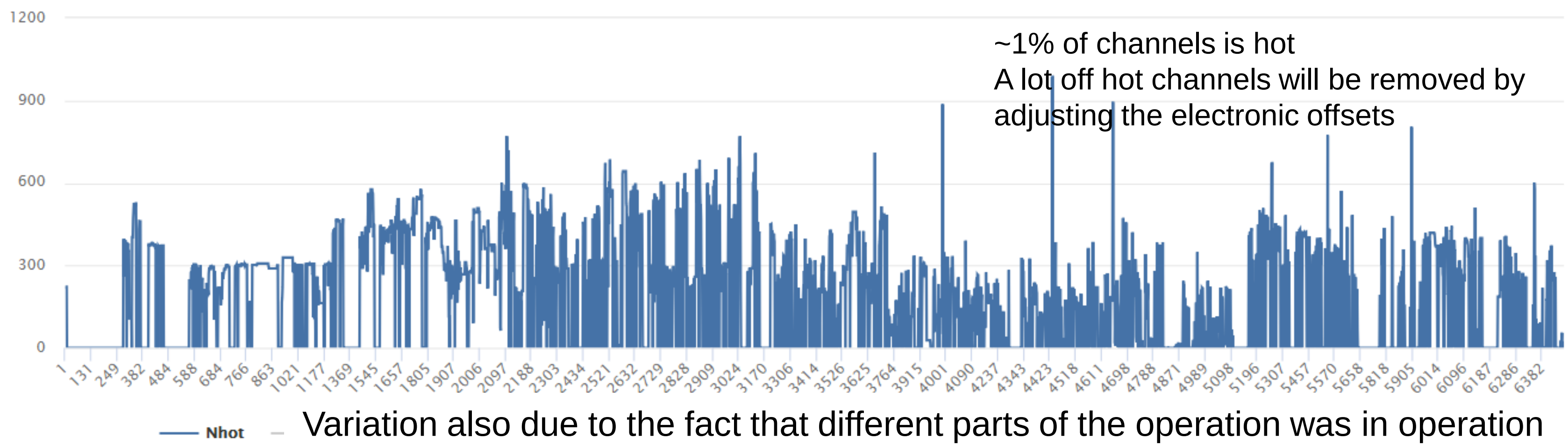


All channels – log scale



Hot channels removed – linear scale

Run dependence of the number of hot channels

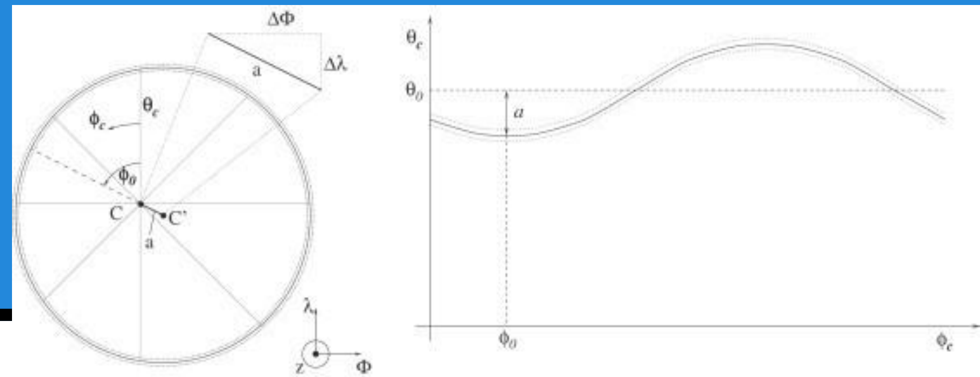


~1% of channels is hot

A lot off hot channels will be removed by adjusting the electronic offsets

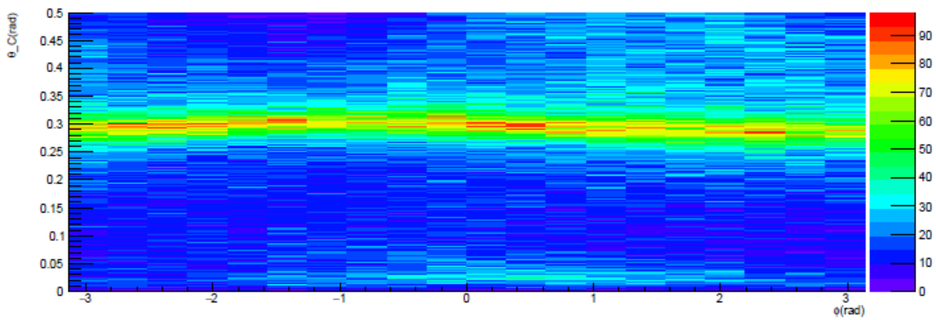
Variation also due to the fact that different parts of the operation was in operation

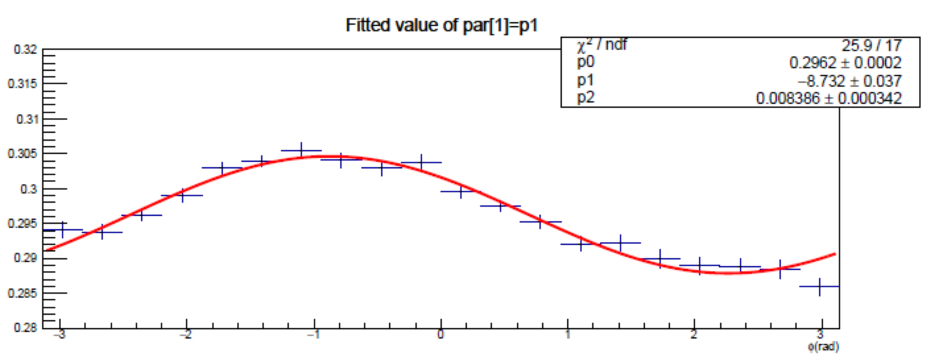
Alignment of mirrors and sensors



Due to misalignment the azimuthal dependence of the Cherenkov angle distribution is not constant

$$\theta_c = p0 + p2\sin(\phi_c - p1)$$





Global alignment:

- determine shifts wrt tracking

Local alignment:

By limiting the track impact position to different regions, we will determine

- displacements of
  - mirrors,
  - sensors
- distortions due to magnetic fields

Preliminary results for segmenting detector to several parts

- shifts are bellow 1 mm

Poster S. Tamechika et al. →
Alignment algorithm of Belle II ARICH

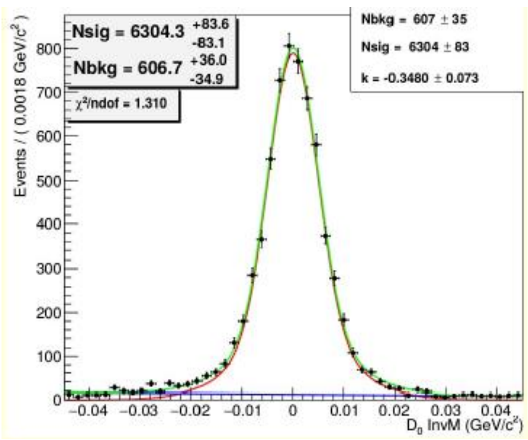
Efficiency determination

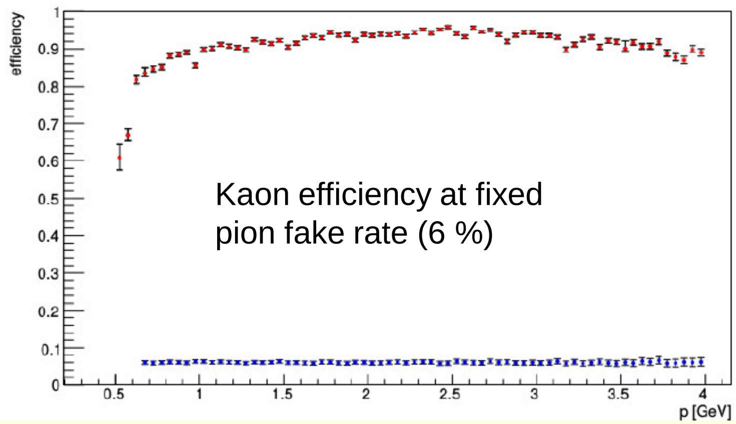
use the decays where we can identify the decay products independently from RICH:
e.g.. $D^{+*} \to D^0 \pi_s^+$ + charge conjugated mode

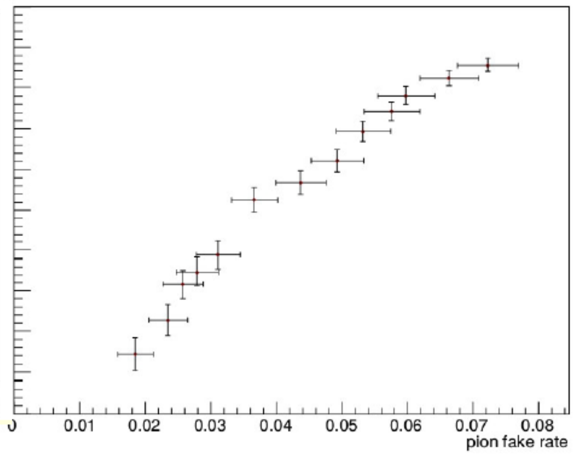
$$D^0 \to K^- \pi^+$$

- The charge of the slow pion determines the identity of the particles from the D^0 meson decay.

Efficiency determination by fitting the D^0 invariant mass before and after the PID cut (tested on MC events)

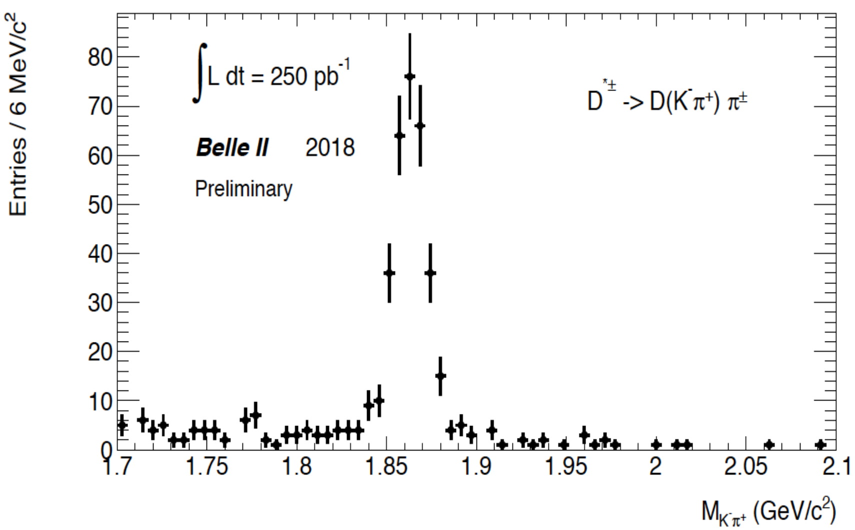


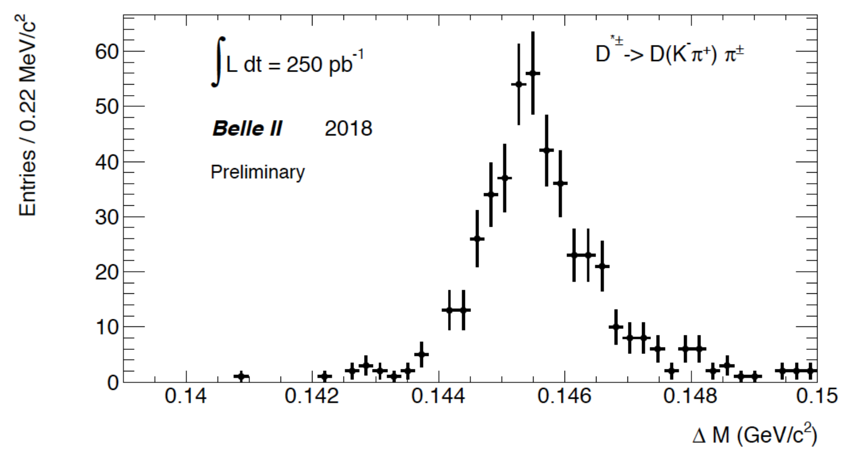




Efficiency determination from data

The measured D^0 mass from first reconstructed D* decays from beam collisions





We expect to get preliminary results after data reprocessing

Summary

- Proximity focusing RICH with aerogel as the radiator installed in the Belle II spectrometer for efficient particle identification in the forward end-cap of the Belle II spectrometer

- For an efficient PID, the detector requires a calibration in order to:
  - Determine and minimize the Cherenkov angle resolution
  - Determine and minimize the background
  - Determine and maximize the number of detected Cherenkov photons

  quantities that directly impact the identification algorithms

- After the calibration we expect to meet the expectations from beam tests and Monte Carlo studies and an excellent kaon identification efficiency of more than 90% over a wide range of momenta at a rather low pion misidentification probability of 2% .

- Based on the experiences with running the detector in the past 3 months we will establish the calibration procedures to ensure optimal operation of the detector in the next run, starting in February 2019