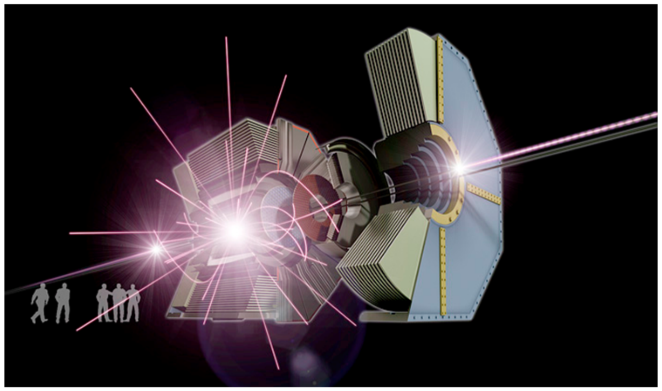
IWHSS 2020



Recent advances in detectors

Peter Križan

University of Ljubljana and J. Stefan Institute

Contents

Introduction

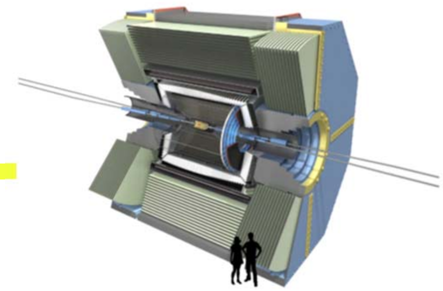
New sensors for tracking (and vertexing)

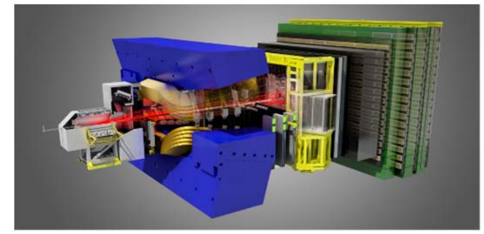
Particle identification

Low level light sensors

A very broad topic for a single talk – very hard to cover all interesting developments → Some subsample, also partly reflecting my own interests, hopefully broad enough to be interesting for everybody

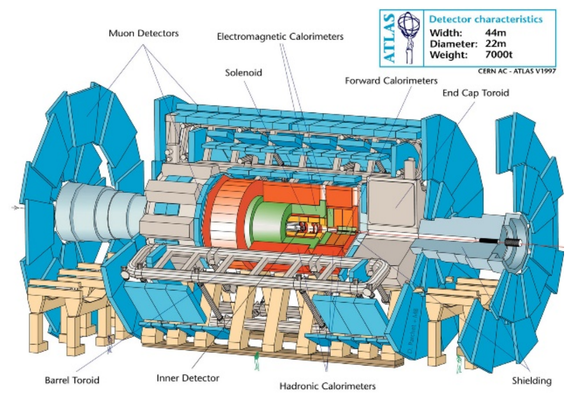
Where are we?





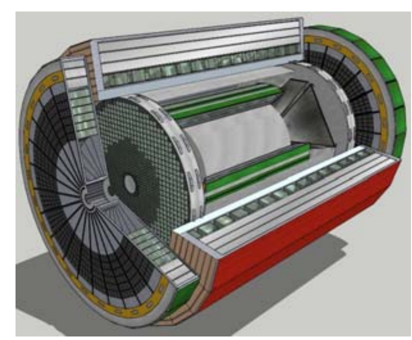
Intensity frontier:

- Belle II started taking data
- LHCb is being upgraded



Energy frontier:

- ATLAS and CMS are getting ready for a major upgrade in the next long shut-down
- ALICE is being upgraded



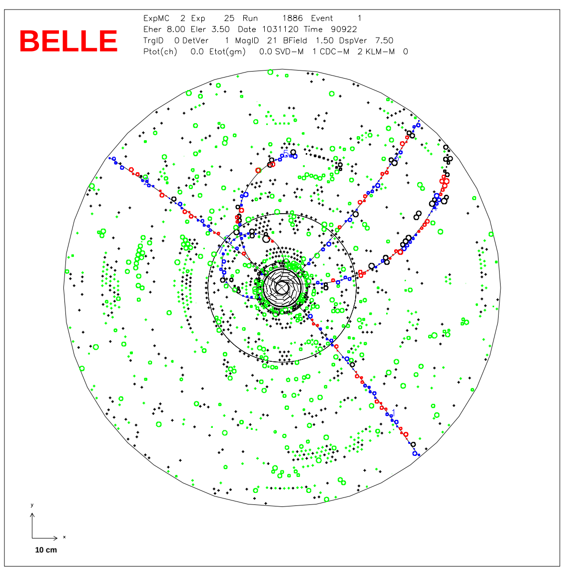
Electron-ion collider experiments:

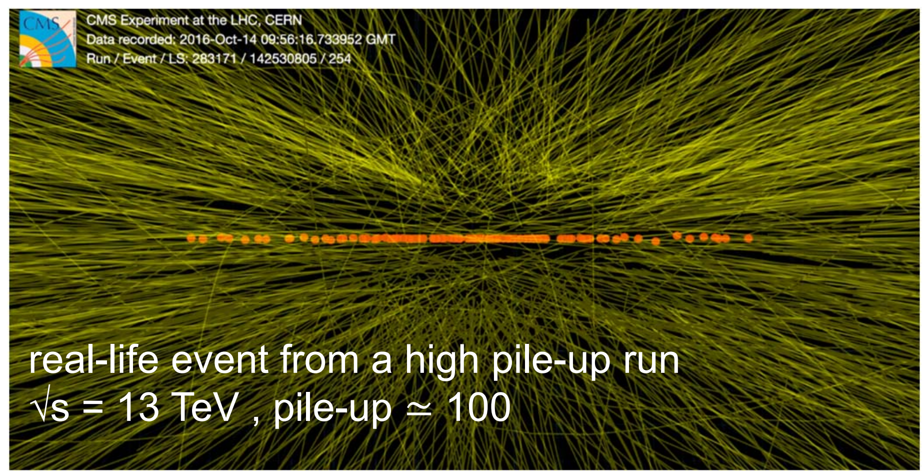
- Preparation with a very tight schedule

Tracking (and vertexing)

Various needs:

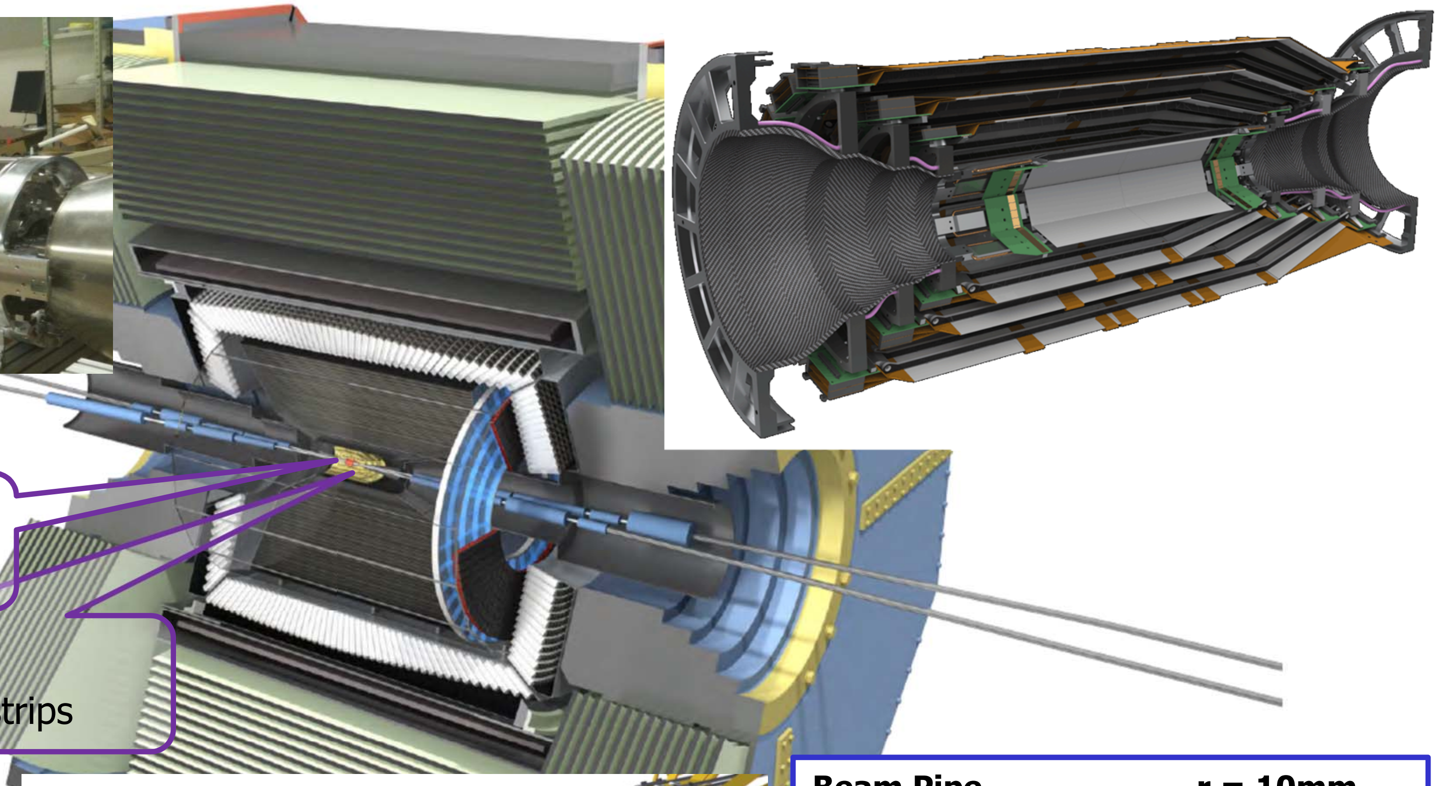
- Lower energies (Belle II): precision tracking and minimal multiple scattering, few particles in the final state, no event overlap
- LHC: precision with a high density of particles, multiple overlayed interactions within the same event, high radiation load





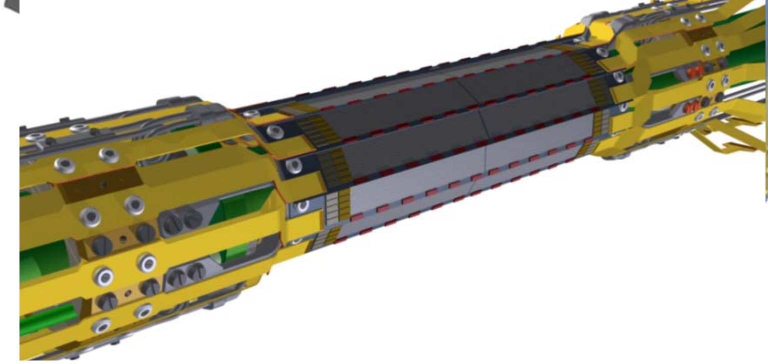
Vertexing at Belle II:

Momenta of charged particles from B meson decays: p < 4 GeV/c



Beryllium beam pipe
2cm diameter

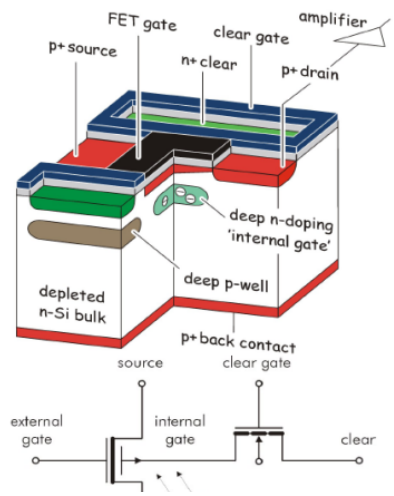
Vertex Detector
2 layers pixels + 4 layers strips



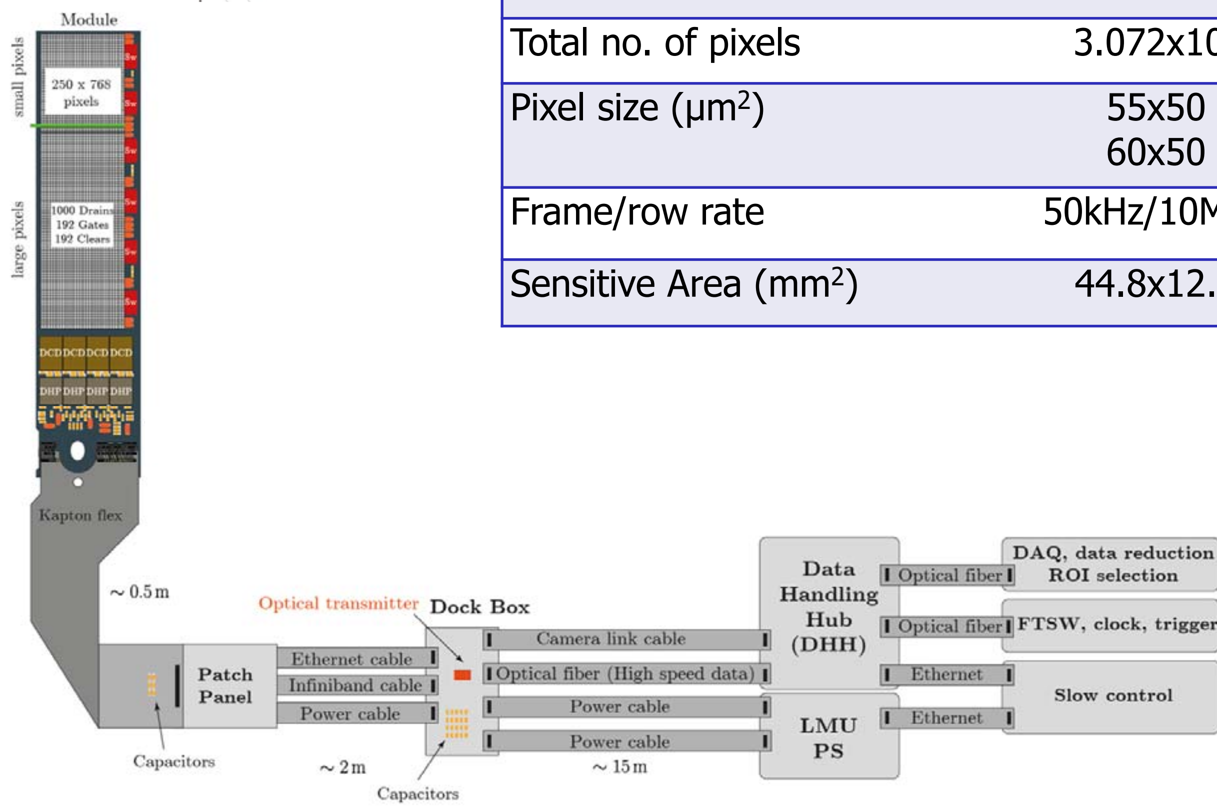
Beam Pipe		**r = 10mm**
DEPFET pixels		
	Layer 1	**r = 14mm**
	Layer 2	**r = 22mm**
DSSD silicon strips		
	Layer 3	**r = 39mm**
	Layer 4	**r = 80mm**
	Layer 5	**r = 104mm**
	Layer 6	**r = 135mm**

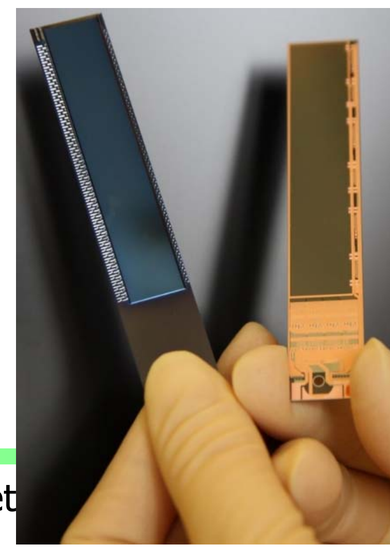
Pixel detector: 2 layers of DEPFET sensors

DEpleted P-channel FET



	L1	L2
# ladders (modules)	8 (16)	12 (24)
Distance from IP (cm)	1.4	2.2
Thickness (µm)	75	75
#pixels/module	768x250	768x250
#of address and r/o lines	192x1000	192x1000
Total no. of pixels	3.072×10^6	4.608×10^6
Pixel size (µm^2)	55x50 60x50	70x50 85x50
Frame/row rate	50kHz/10MHz	50kHz/10MHz
Sensitive Area (mm^2)	44.8x12.5	61.44x12.5





Pet

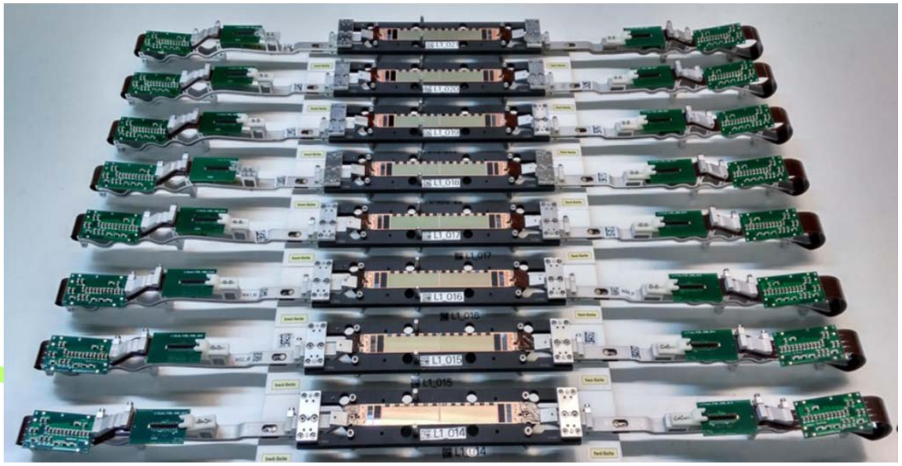
Key R&D aspects for Belle II PXD

- Low-mass modules
  - Unique all-silicon module, self-supporting 75 µm thin silicon → 0.2% X_0
  - Active pixel sensor → amplification of signal from thin silicon
  - Low power dissipation in sensitive area

- Dedicated read-out ASICs
  - Three types of ASICs (DCD, DHP, Switcher)
  - Fast front-end ASIC allowing fast read-out for acceptable occupancy
  - On-module data reduction

- Module assembly procedure
  - All assembly steps compatible with low-mass modules

- Low-mass support structures within the sensitive volume and efficient thermal management → CO_2 cooling



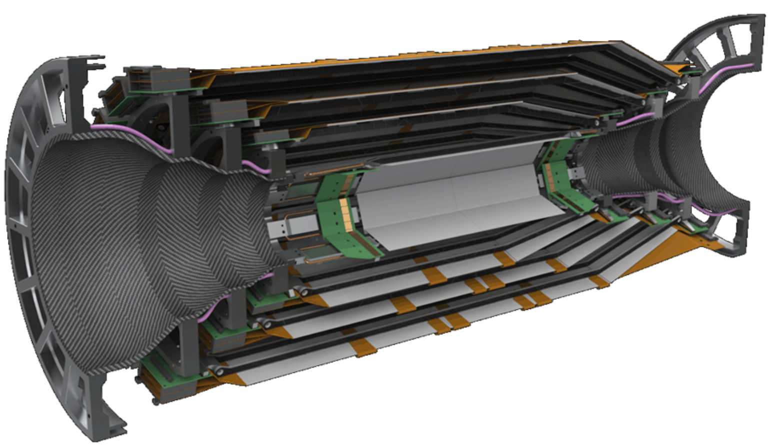
SVD: four layers of double sided silicon strip detectors.

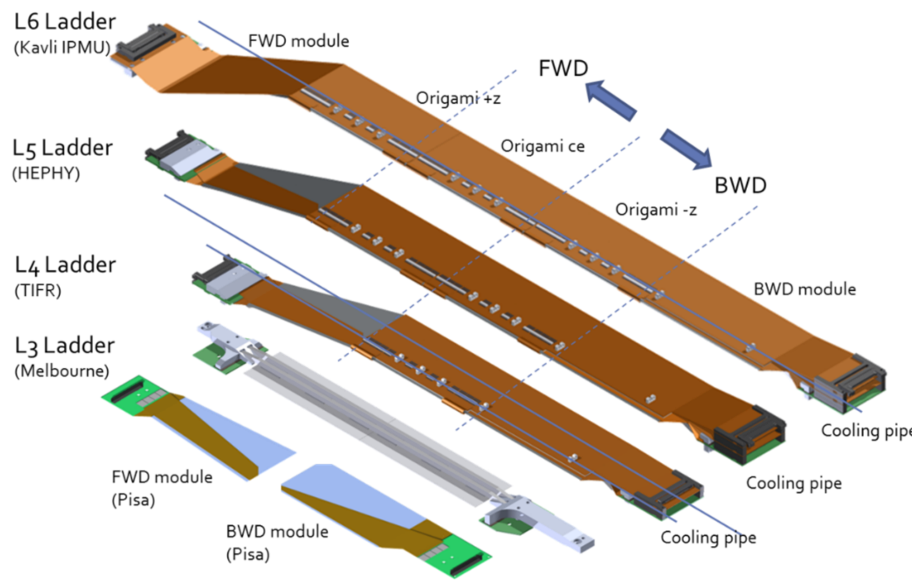
Main R+D areas:

Origami chip-on-sensor concept (readout chips on top of the sensors with flex pitch adapters bent around the edge to reach the bottom sensor side) for good S/N with fast readout and moderate material budget

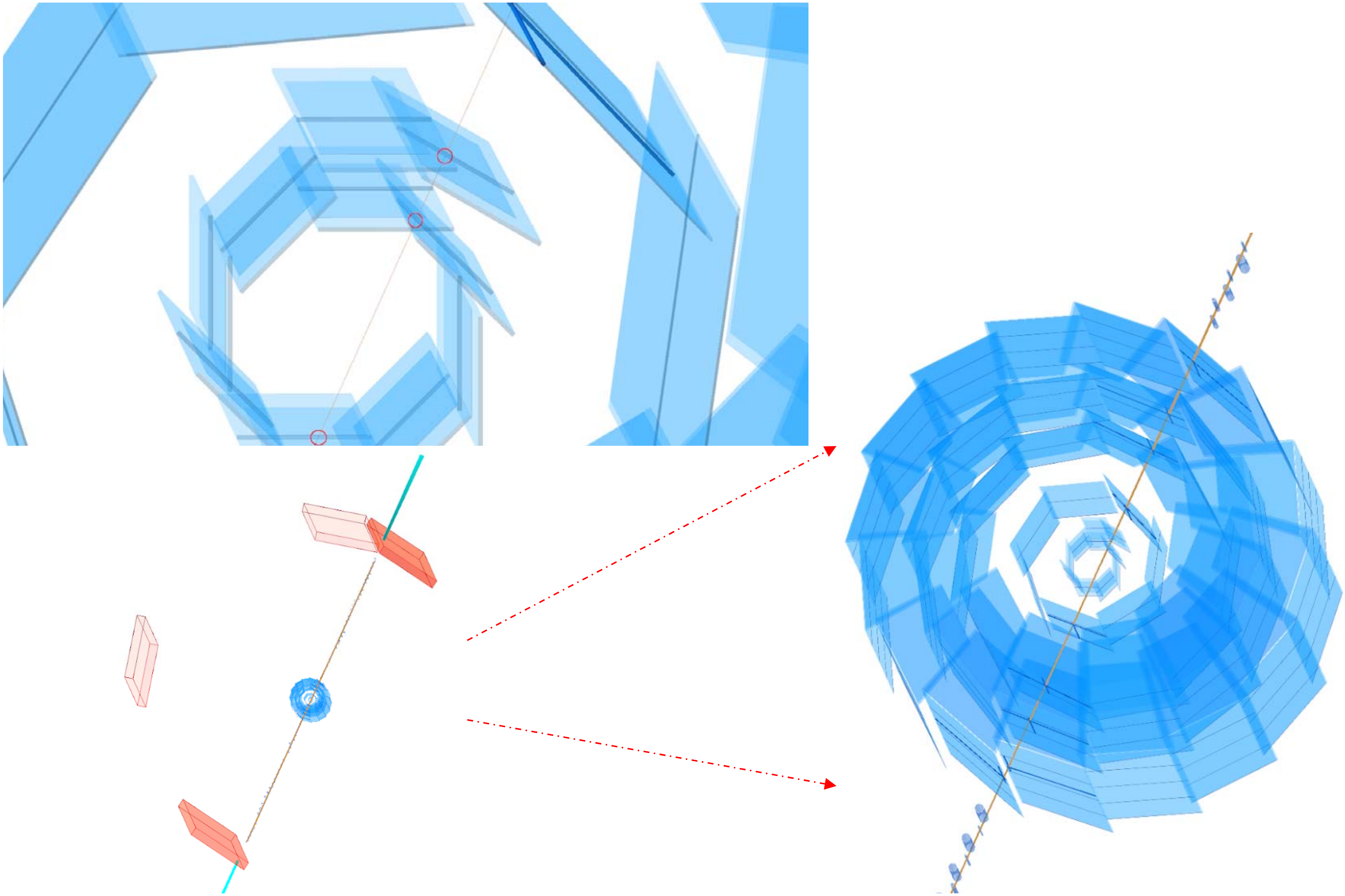
Excellent time resolution (~4ns) thanks to multiple recorded samples and waveform fitting

CO_2 dual-phase cooling

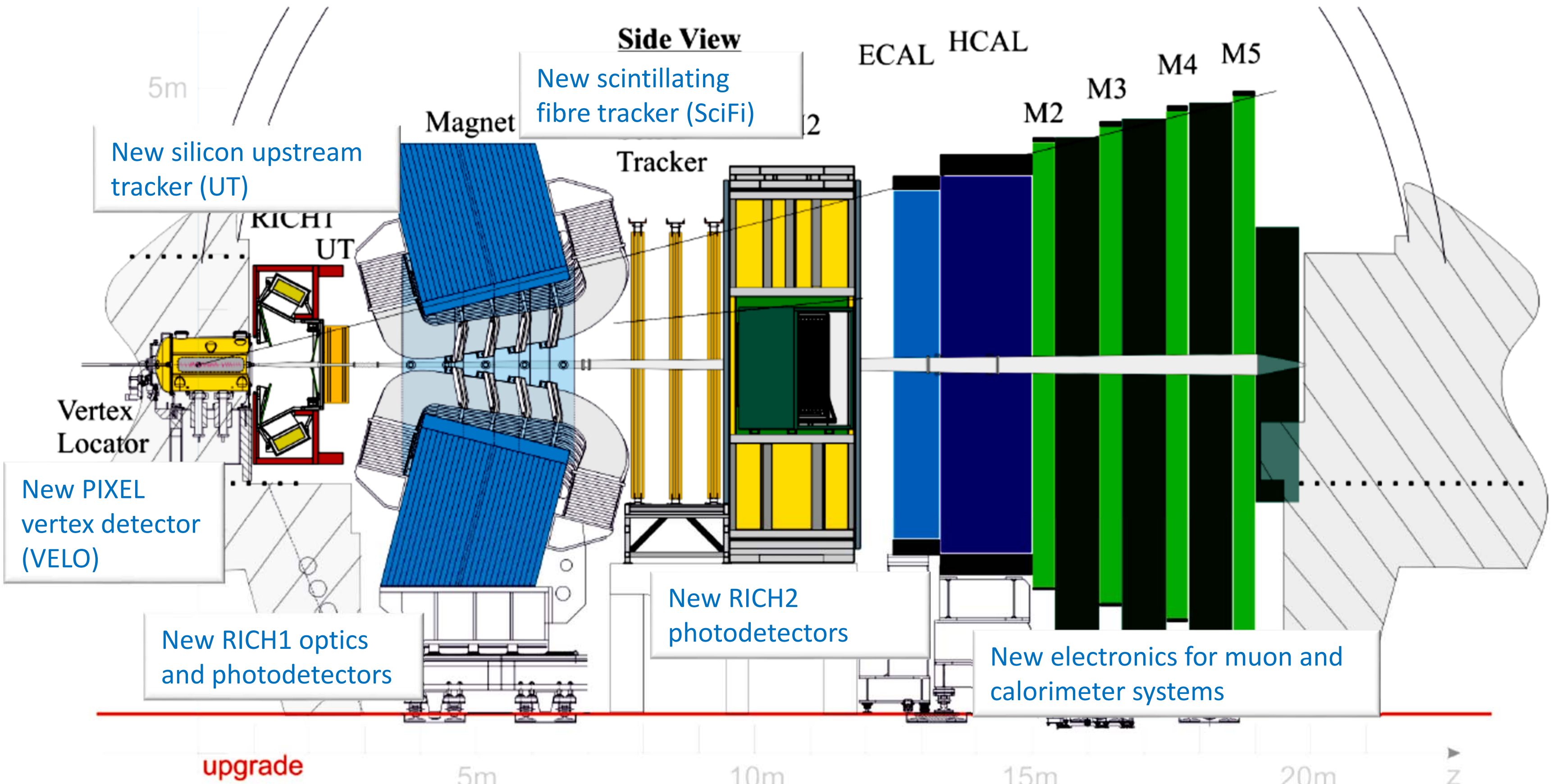




Belle II vertex detector in action



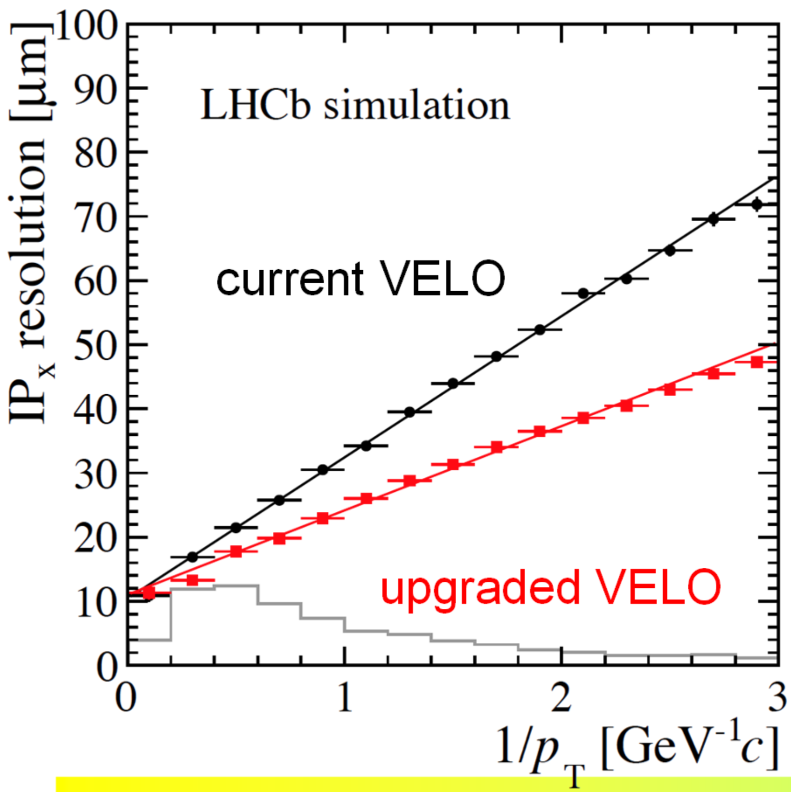
LHCb Upgrade: in progress

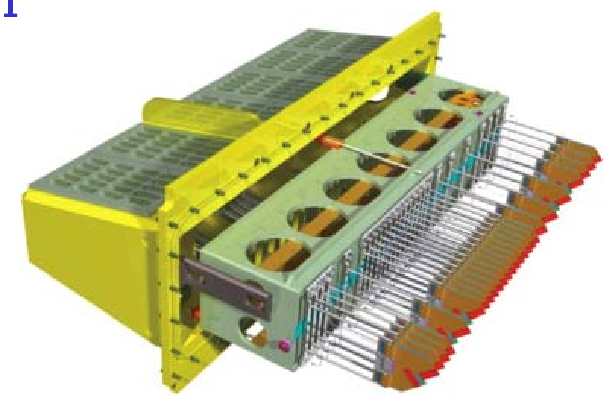


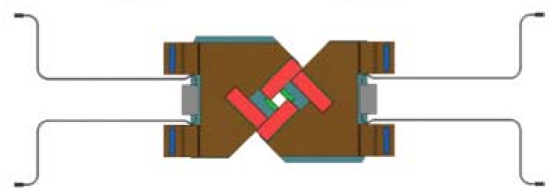
- 50 fb^{-1}, $2\times10^{33}\ cm^{-2}\ s^{-1}$
- All front-end electronics read out at 40 MHz
- 30 MHz avg. input to a full software trigger

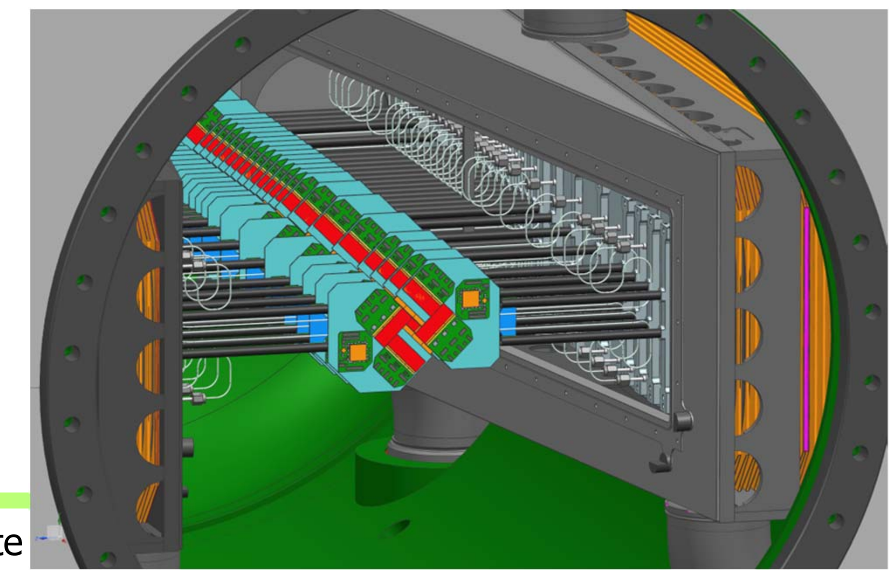
LHCb Vertex LOcator upgrade

The upgraded VELO is being installed to take data in Run III
Operation @ 40 MHz and 2×10^{33} $cm^{-2}s^{-1}$ and at 3.5 mm from the beams, 2.8 Tb/s data rates,
8×10^{15} 1 MeV n_{eq} cm^{-2} max fluence





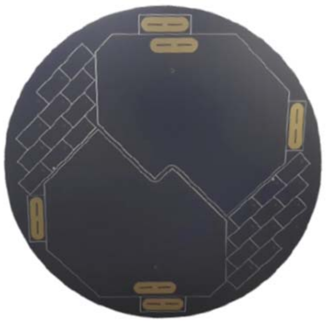


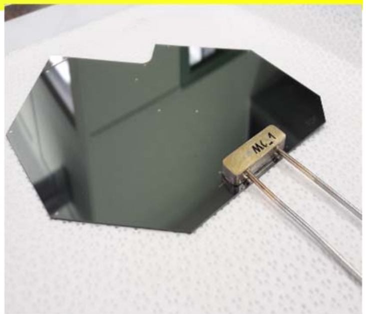


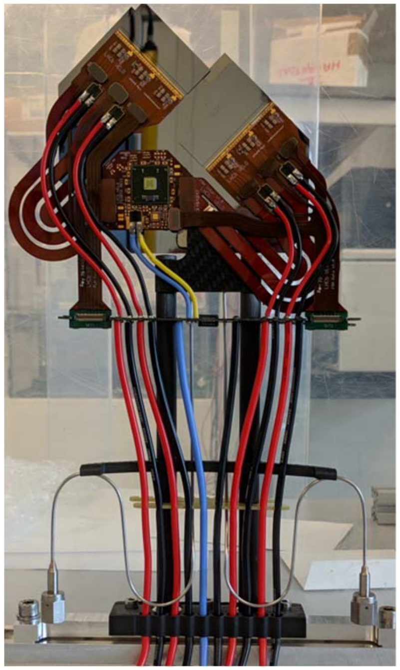
LHCb Vertex LOcator upgrade

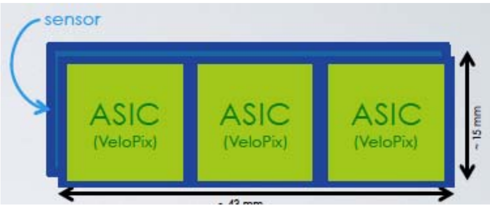
Micro-channel cooling

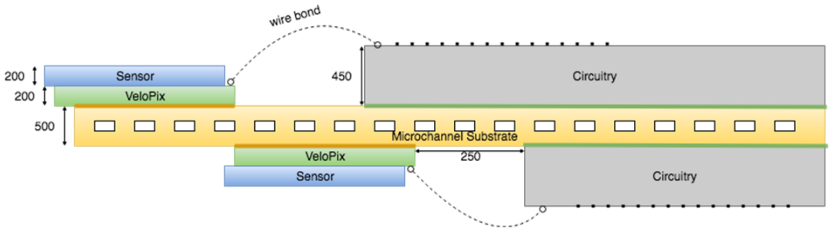
- 500 µm thick silicon substrate with integrated micro channels (70 μm x 200 μm) :
  - same thermal expansion as sensors
  - low material
  - high thermal efficiency
  - cooling power ~50 W
- pressure: 14 bar @ -30 ^{o}C, 60 bar @ 22 ^{o}C

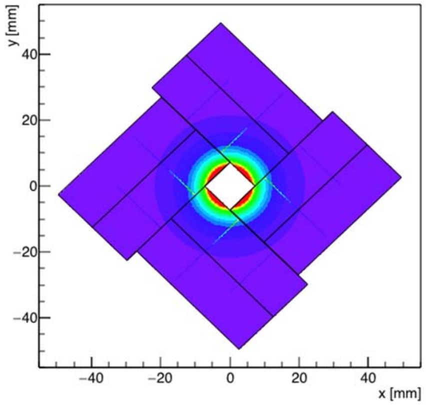








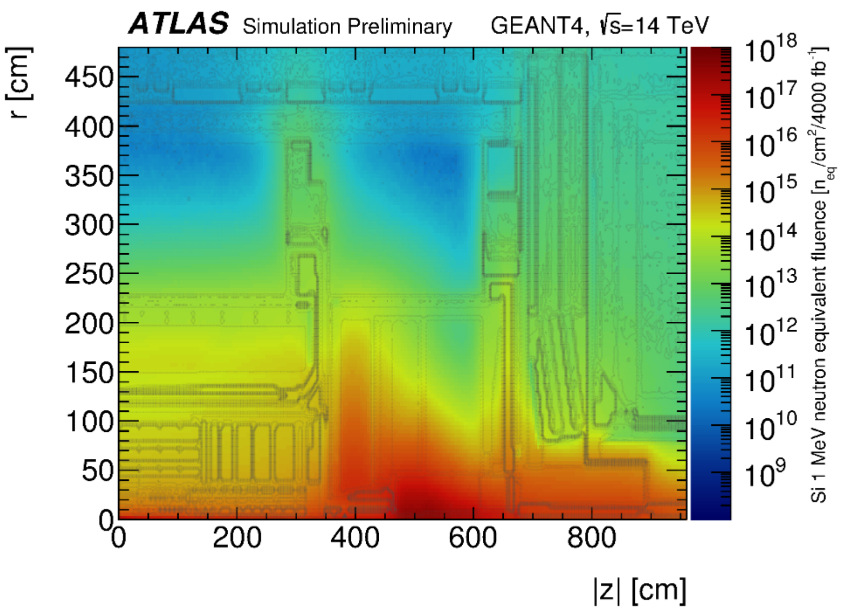


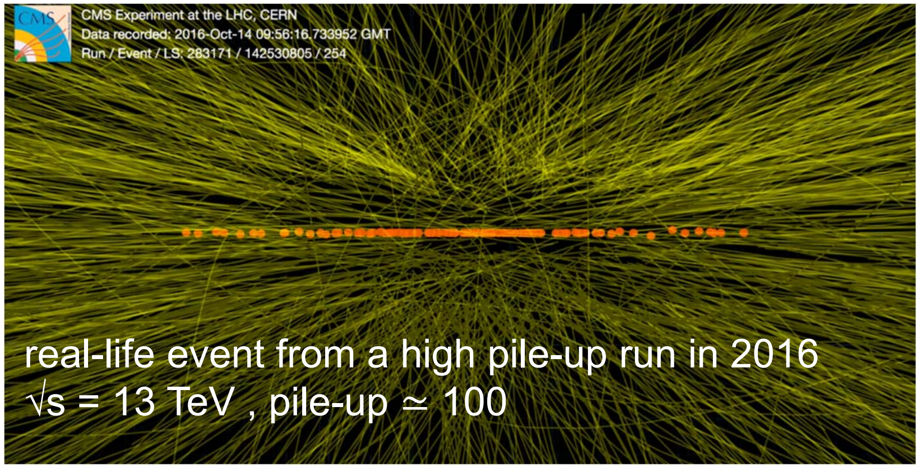


The HL-LHC environment

Radiation levels up to:

- Fluence of 2×10^{16} 1 MeV n_{eq}/cm^2
- Total Ionizing Dose (TID) ~ 1 Grad
- Pileup up to 240

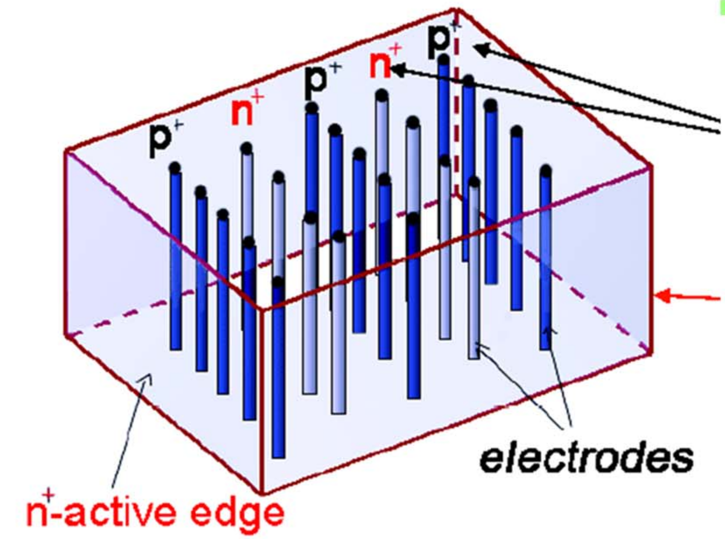




Silicon particle detectors: directions for the future

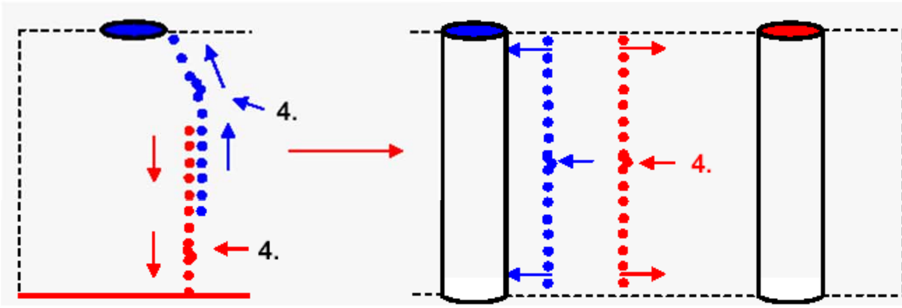
- Extreme radiation hardness – 3D detectors (hybrid technology – possibly also developments into monolitic)
- Large area coverage for position resolution (mass production) – depleted CMOS sensors (fully monolitic or hybrid ASIC)
- Timing detectors – LGAD with a possible application of 3D (hybrid technology)

3D detectors



Both electrode types are processed inside the detector bulk instead of being implanted on the wafer's surface.

The edge is an electrode. Dead volume at the edge < 5 μm!



Key advantages

- Better charge collection efficiency over the large fluence range (up to 3e16 cm^{-2} – close to 100%)
- Faster charge collection (depends on inter-column spacing) – very promising for timing applications
- Reduced full depletion voltage and by that the power
- Larger freedom for choosing electrode configuration
- Recent progress allowing also single sided processing

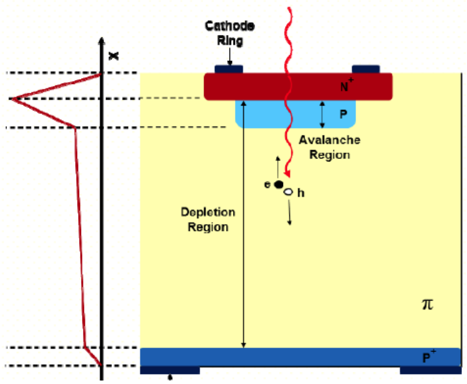
Limitations

- Columns are a dead area (aspect ratio ~30:1) - but most of the tracks are anyway inclined
- Much higher inter-electrode capacitance (hence noise), particularly if small spacing is desired
- Availability on a large scale
- Time-scale and cost

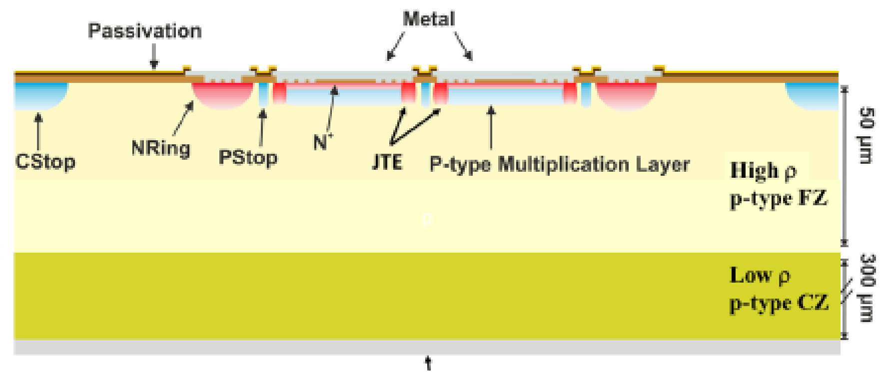
Low Gain Avalanche Detectors (LGAD)

- APD like devices which allow segmentation and high voltage operation close to breakdown
- Pioneered by RD50 and getting more and more attention worldwide (HPK, FBK, Micron)

Schematic view of device



ATLAS High Granularity Timing Detector Test Prototype (2x2 array)



Key properties

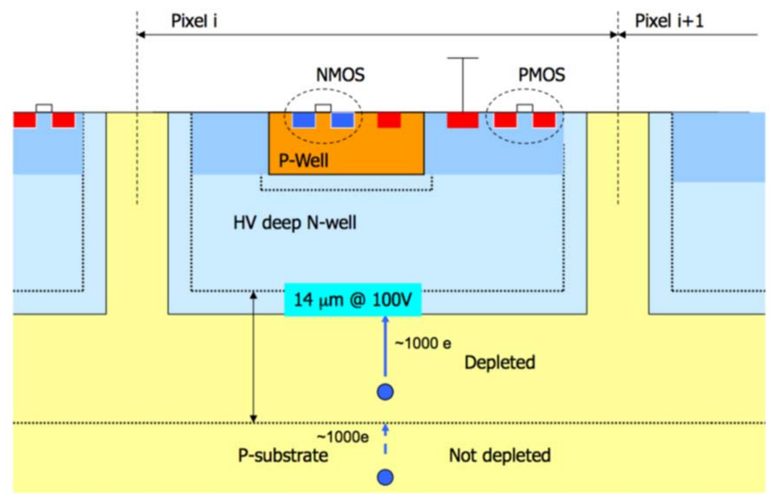
- Gain very sensitive to p+ layer doping and process parameters (~1e16 - 1e17 cm^{-3}, ~2 μm deep)
- Gains of up to 100 achieved giving excellent timing resolution of 26 ps for thin LGADs
- Currently the best technology for achieving excellent timing measurement for MIP – will be employed at ATLAS and CMS experiments after the upgrade

Limitations:

- Radiation hardness – problem of acceptor removal which decreases the gain with fluence (intensive search for solution: carbon coimplantation and understanding removal mechanism)
- Regions around the electrodes do not have gain – fill factor improvement

Depleted-CMOS detectors

- HV-CMOS process which allows monolithic detectors with application of external HV depletion
- First devices produced showing huge potential in all respects: scalability (12” wafers), cost and integration (everything integrated on chip electronics + detector)



Key properties

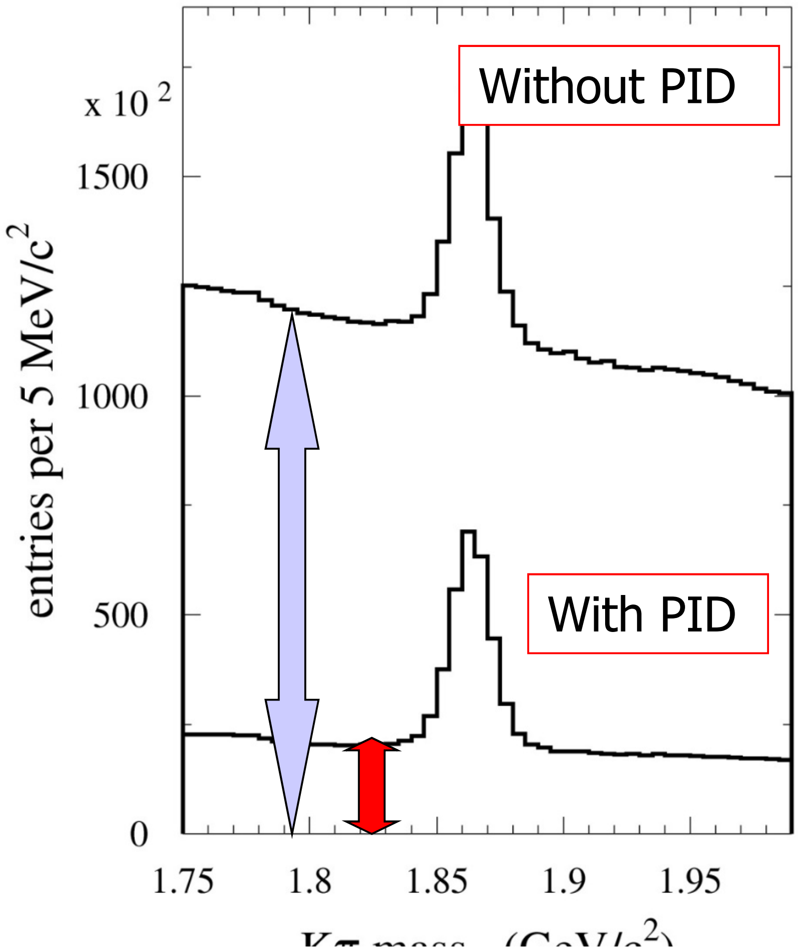
- Different substrates often limited by vendor – up to full depletion of 300 μm
- Excellent position resolution

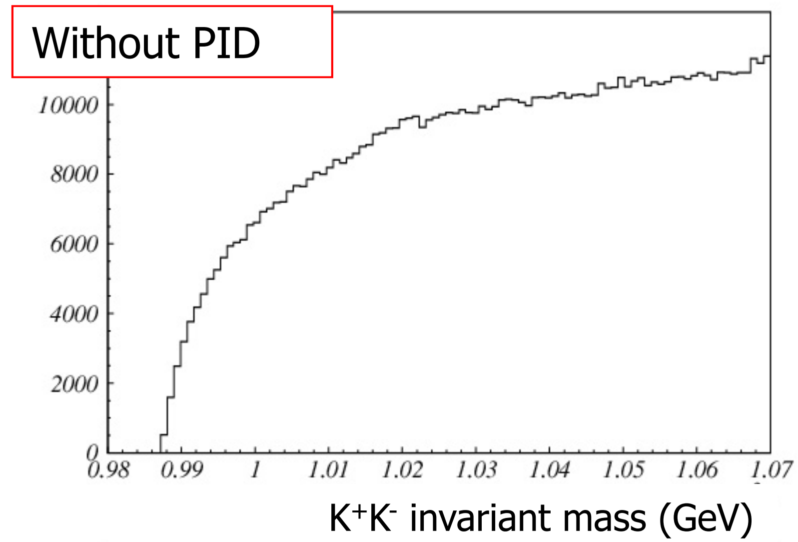
Limitations:

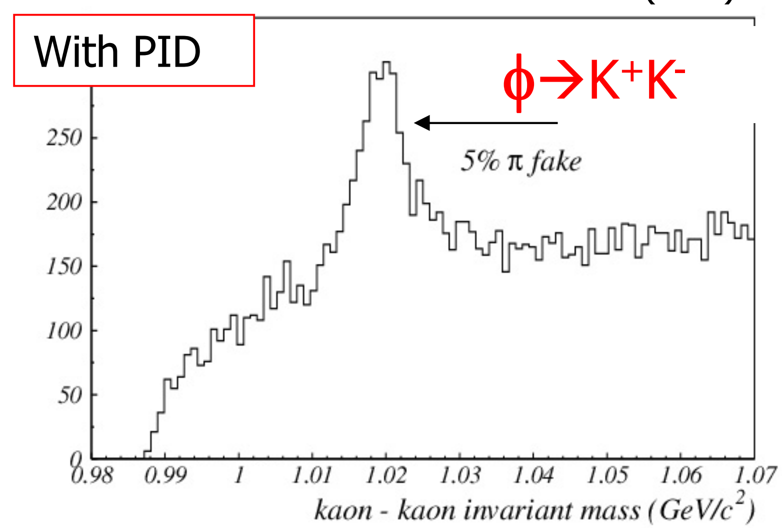
- Radiation hardness – problem of acceptor removal which changes detector performance
- Speed – for timing applications is not yet optimal
- SOI substrates or different other designs/processes including “Shallow Trench Isolation” affect charge collection

Particle identification

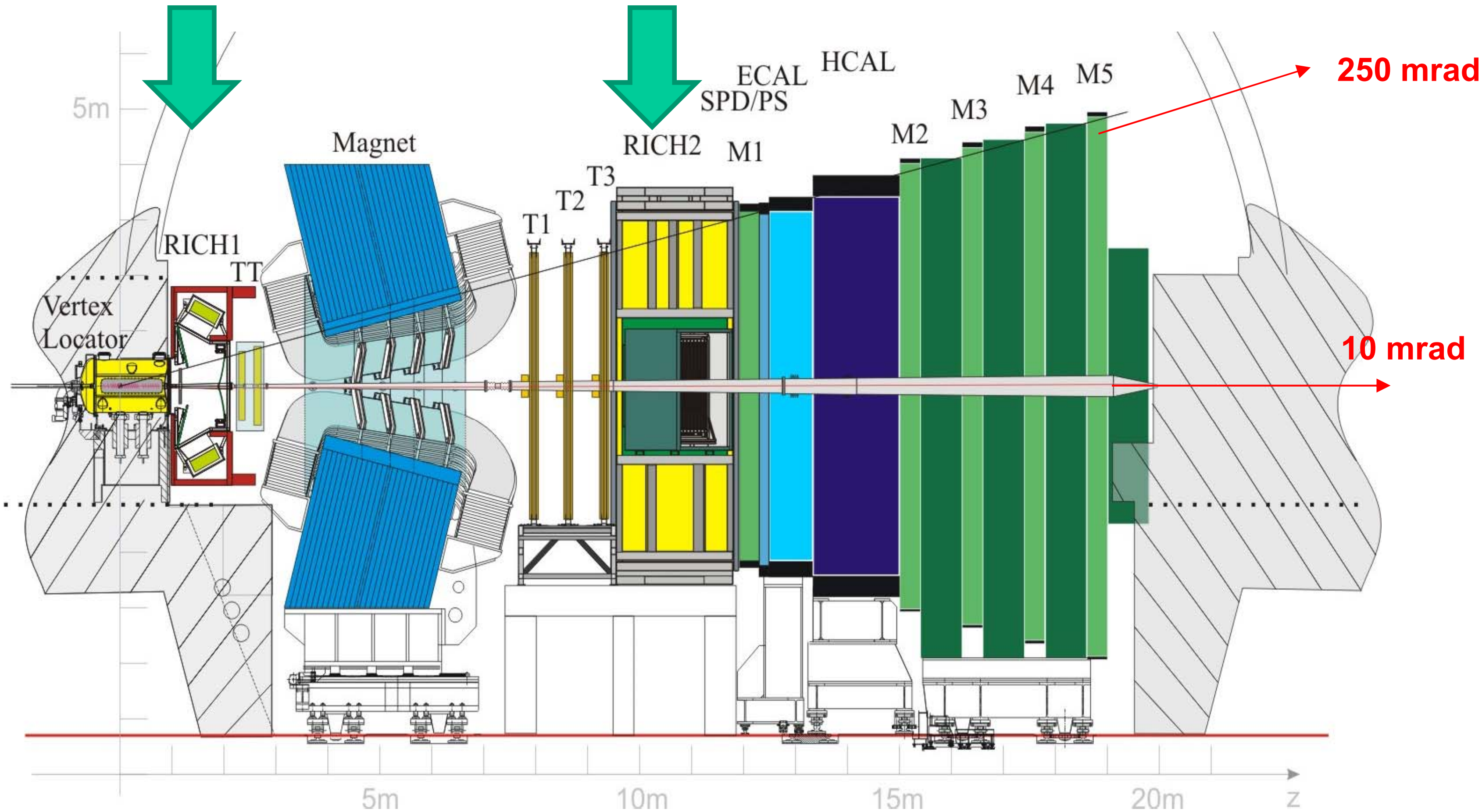
Essential: reduces the combinatorial background and allows to tag the flavour of decaying particles.







The LHCb RICH counters



Vertex reconstruction:
VELO

Trigger:
Muon Chambers
Calorimeters
Tracker

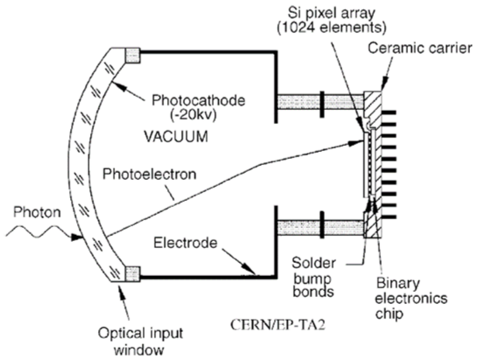
PID:
RICHes
Calorimeters
Muon Chambers

Kinematics:
Magnet
Tracker
Calorimeters

LHCb RICHes

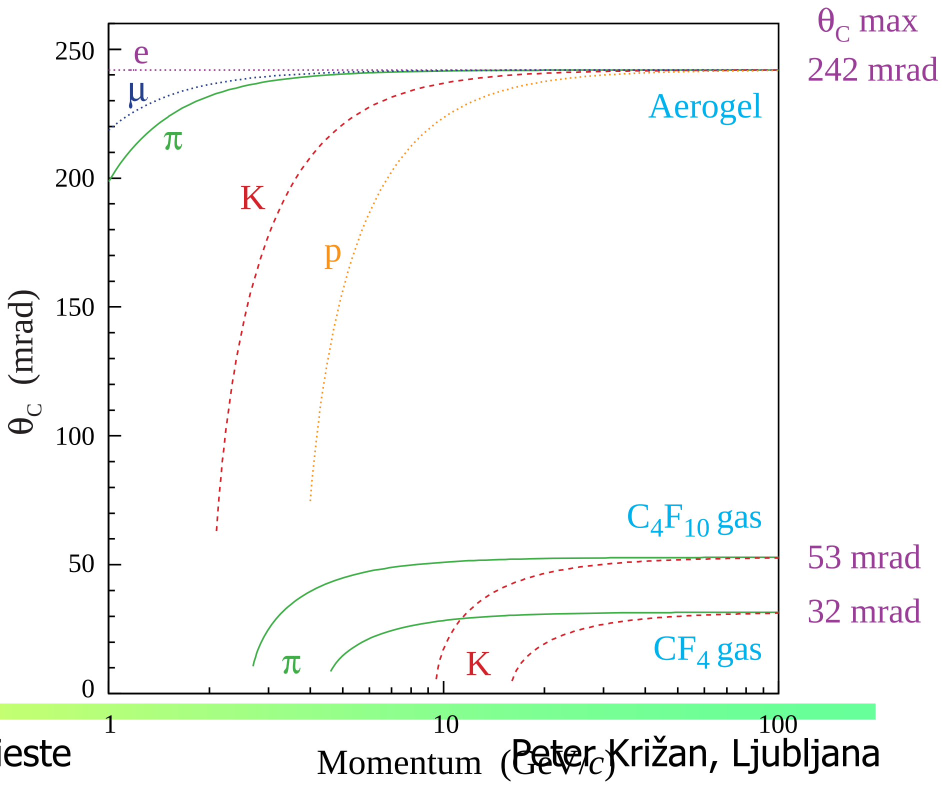
Need:

- Particle identification for momentum range ~2-100 GeV
- Photosensor granularity 2.5x2.5mm^2
- Large area (2.8m^2) with high active area fraction
- Fast compared to the 25ns bunch crossing time
- Have to operate in a small B field

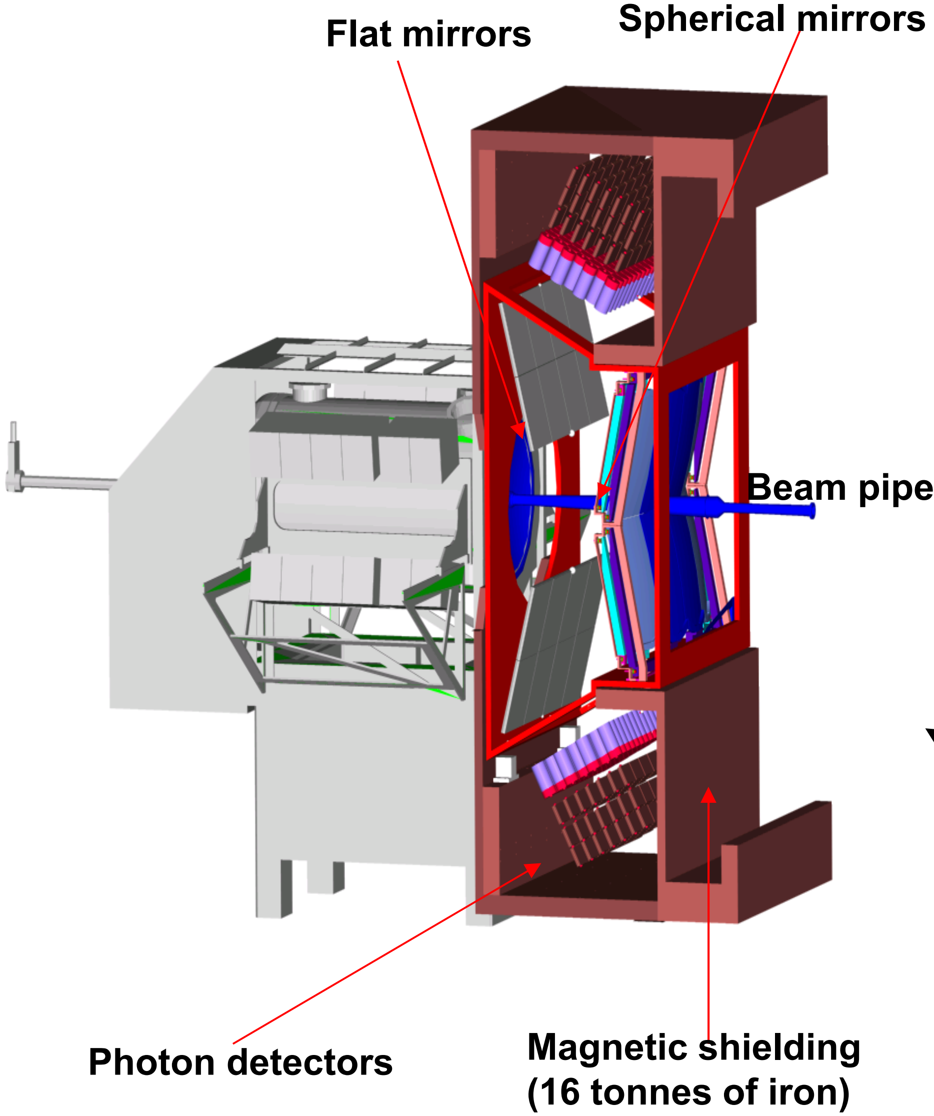


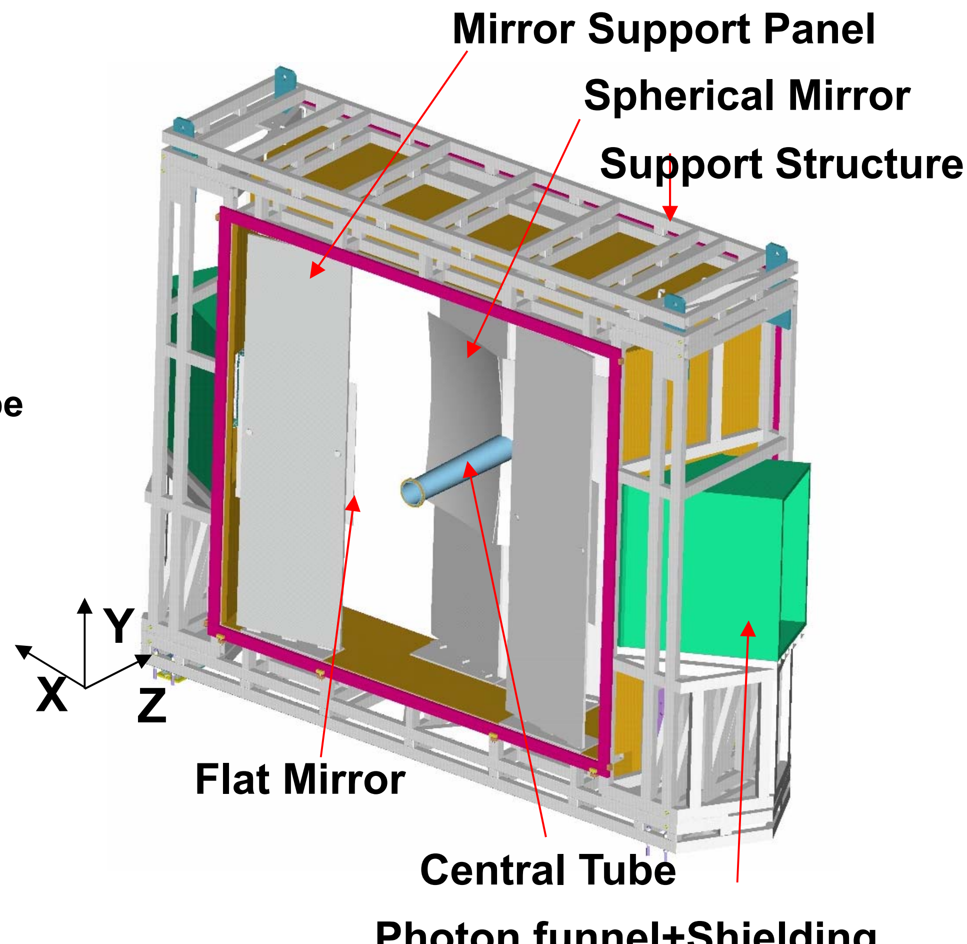
→3 radiators (originally)

- Aerogel
- C_4F_{10} gas
- CF_4 gas

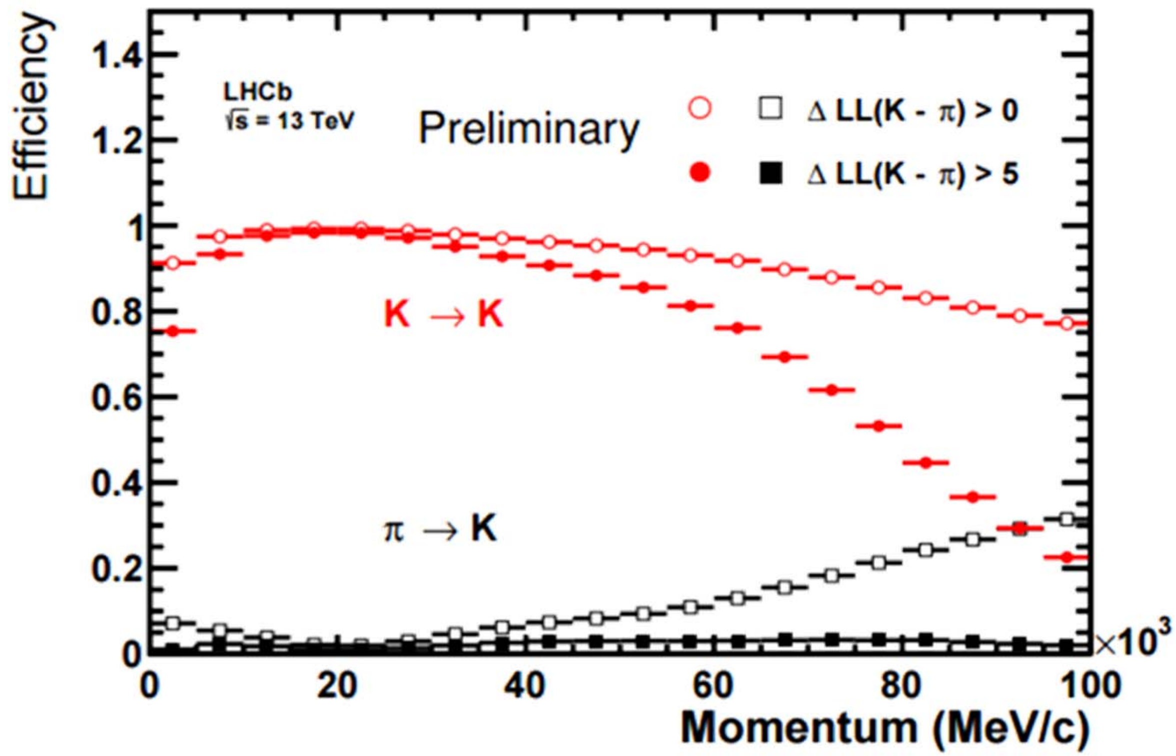


LHCb RICHes

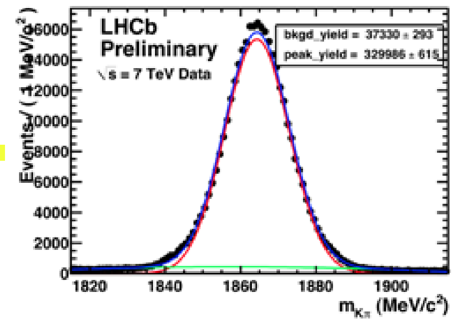

Flat mirrors
Spherical mirrors
Beam pipe
Photon detectors
Magnetic shielding
(16 tonnes of iron)

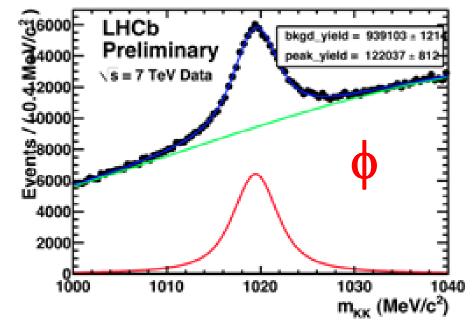

Mirror Support Panel
Spherical Mirror
Support Structure
Y
X
Z
Flat Mirror
Central Tube
Photon funnel+Shielding

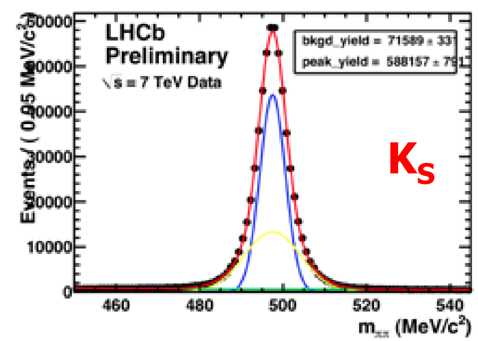
LHCb RICHes: performance

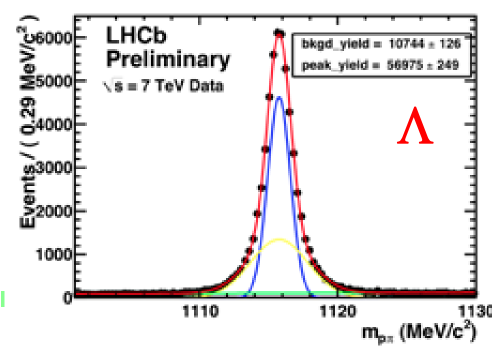


D from D*







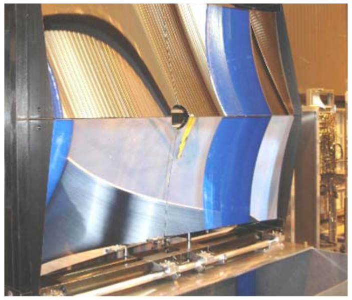


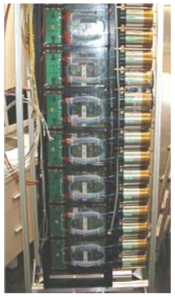
Efficiency and purity from data → excellent agreement with MC

Performance of the two RICHes essential for the big success of the LHCb experiment

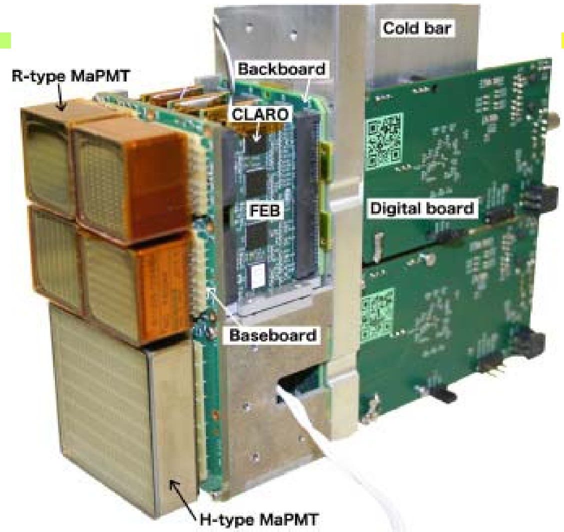
LHCb particle identification upgrade(s)

RICH Upgrade





Photosensor: Hybrid Photon Detector with 1 MHz max. readout rate

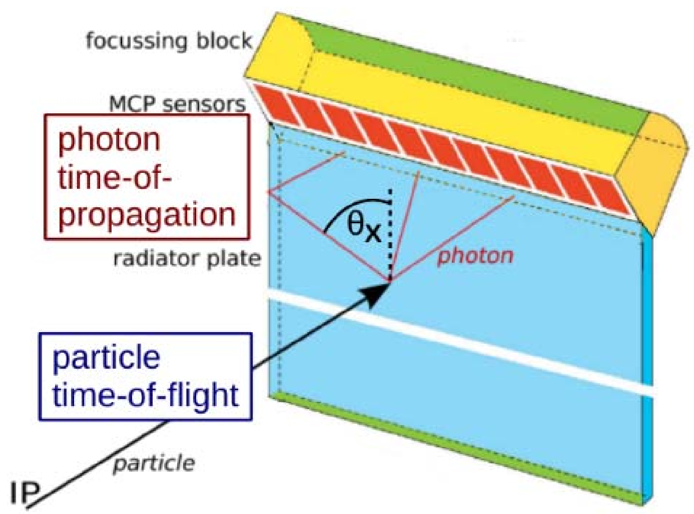


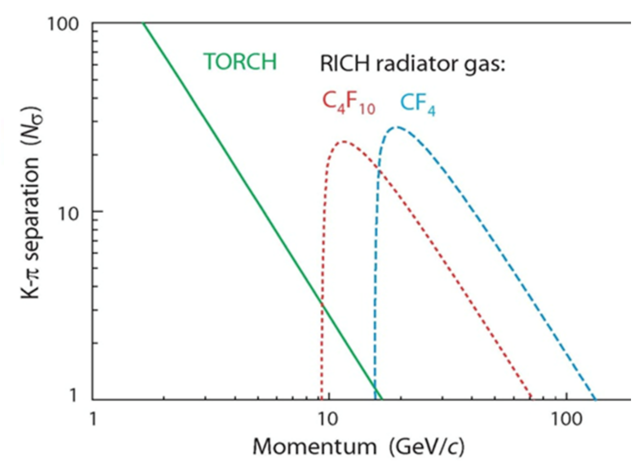
MaPMTs from Hamamatsu

Upgrade IA: New optics, photo detectors, new electronics

LS3

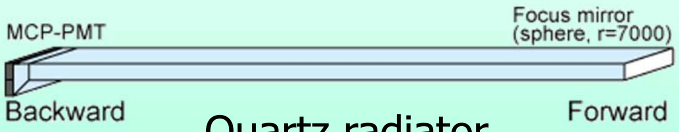
TORCH (Time Of internally Reflected CHerenkov light) ToF resolution ~10-15 ps (per track) using micro channel plate PMTs





Belle II PID systems

Barrel PID: Time of Propagation Counter (TOP)



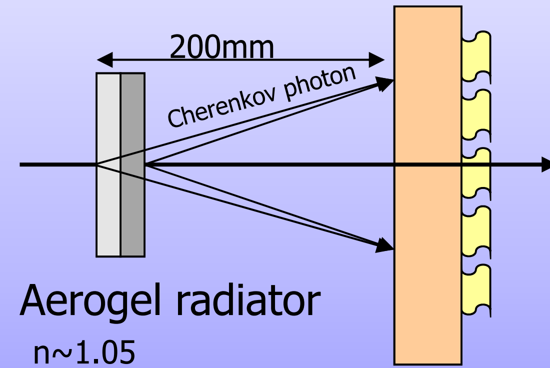
Quartz radiator

Focusing mirror

Small expansion block

Hamamatsu MCP-PMT (measure t, x and y)

Endcap PID: Aerogel RICH (ARICH)

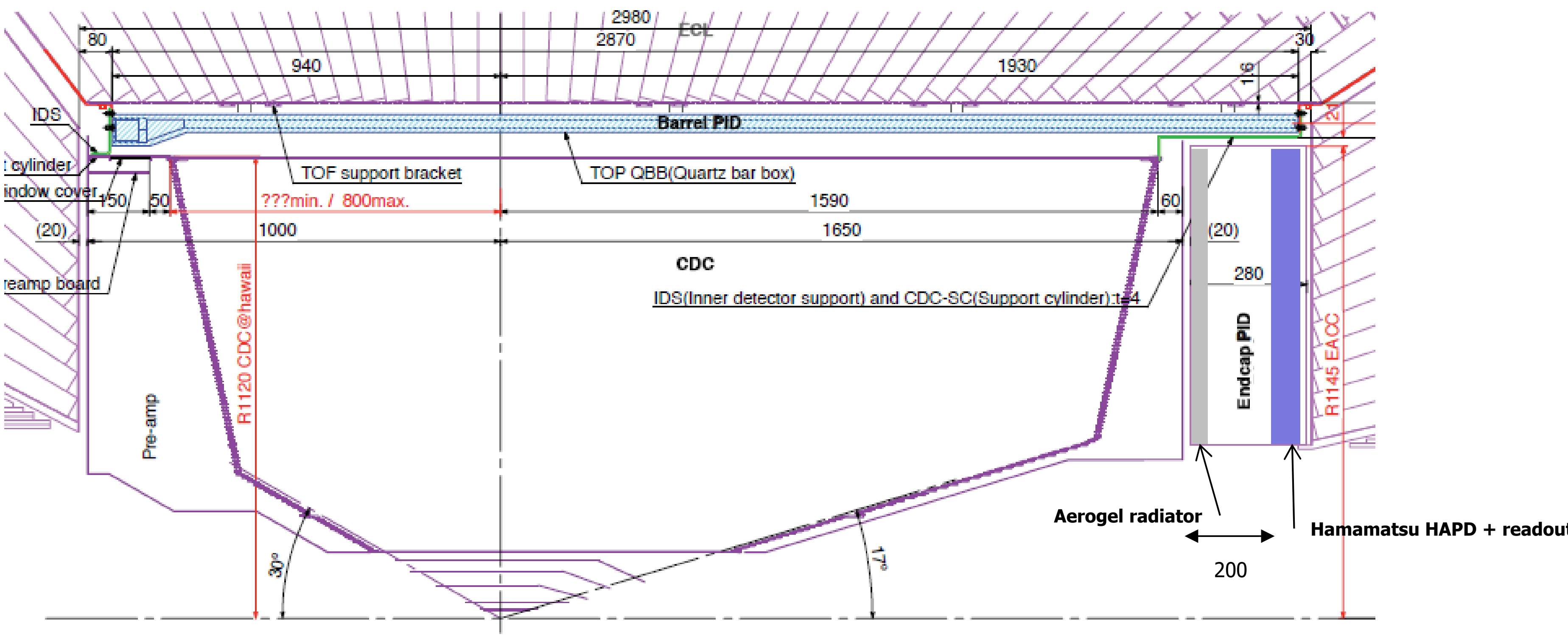


Aerogel radiator

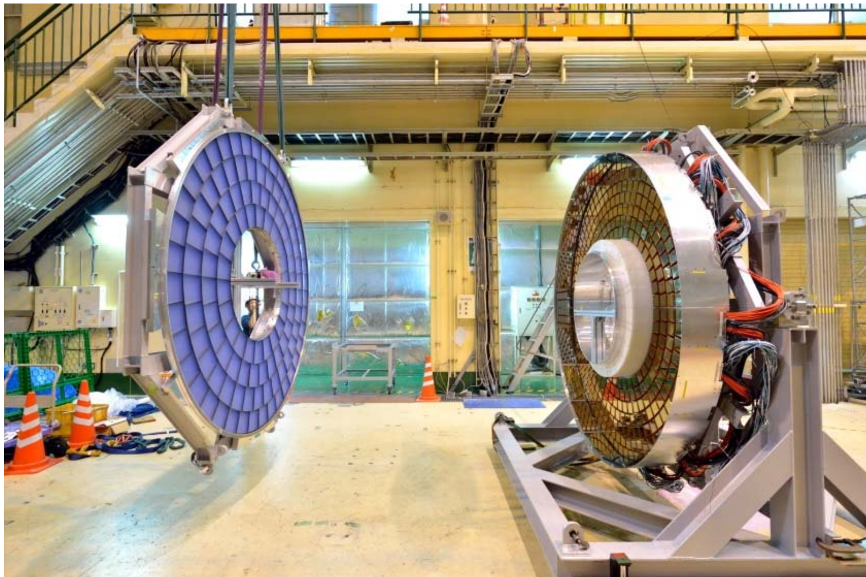
n~1.05

Hamamatsu HAPD

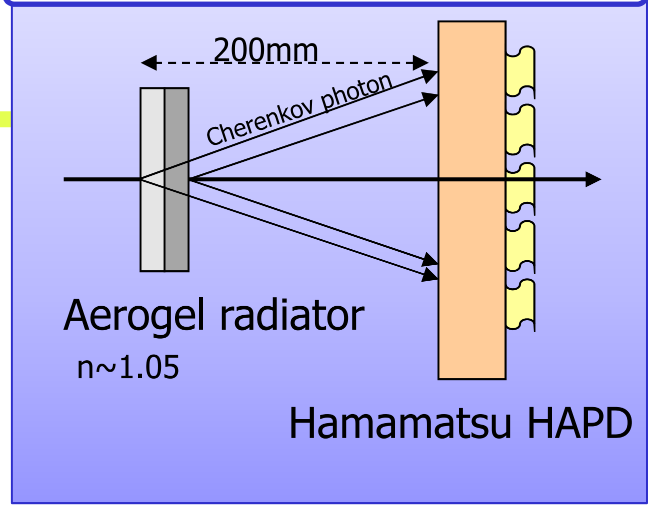
+ new ASIC

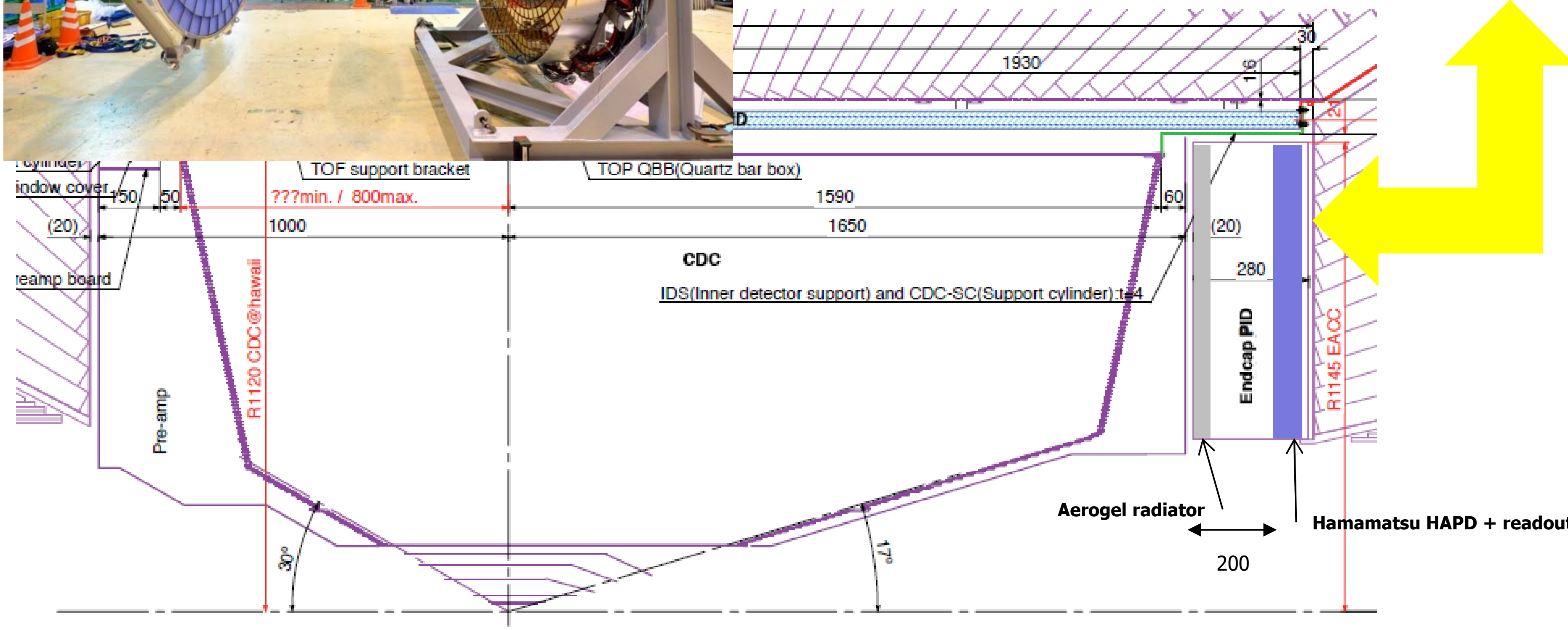


PID Devices: ARICH



Endcap PID: Aerogel RICH (ARICH)





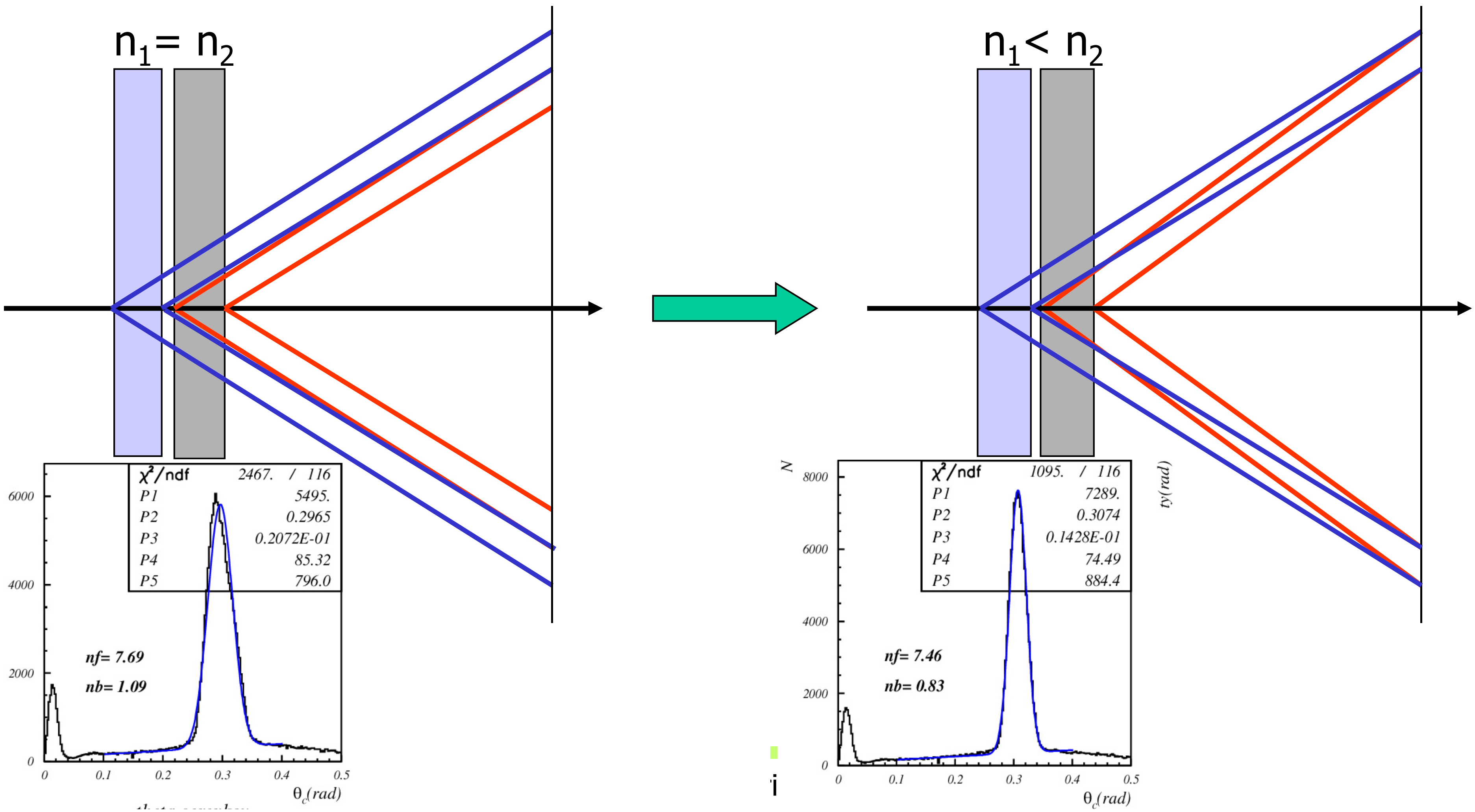
Radiator with multiple refractive indices

Small number of photons from aerogel → need a thick layer of aerogel.

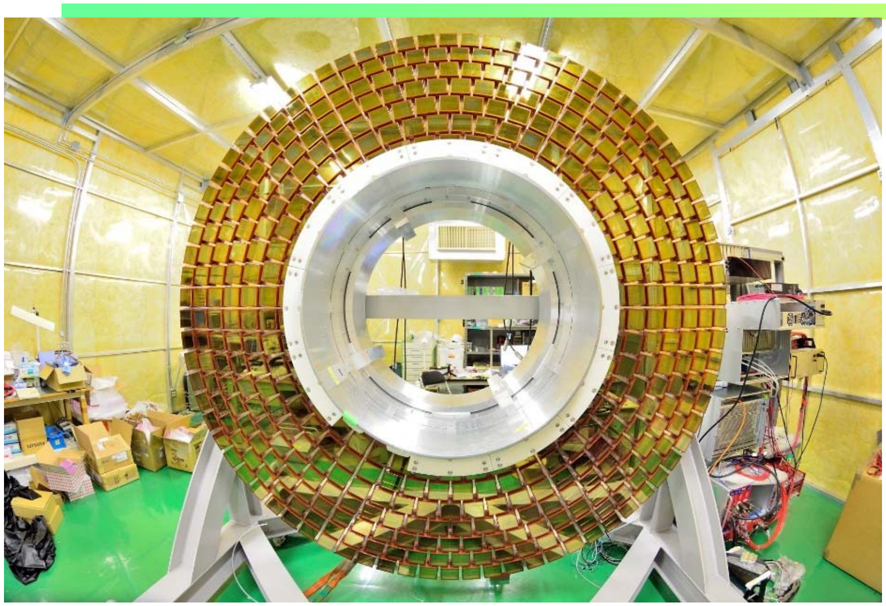
How to improve the resolution by keeping the same number of photons?

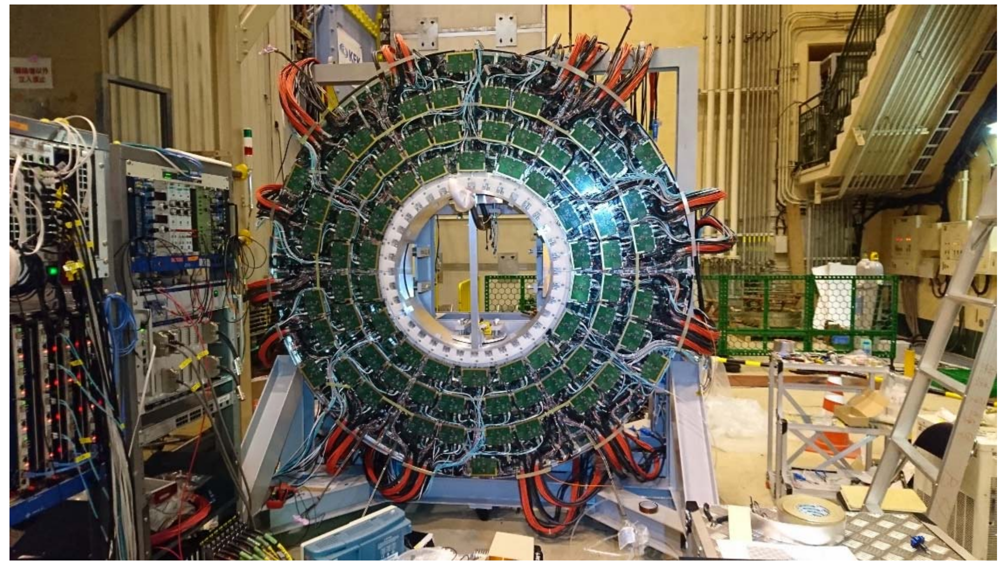
→ stack two tiles with different refractive indices:
"focusing" configuration → "focusing radiator"

normal



The big eye of ARICH





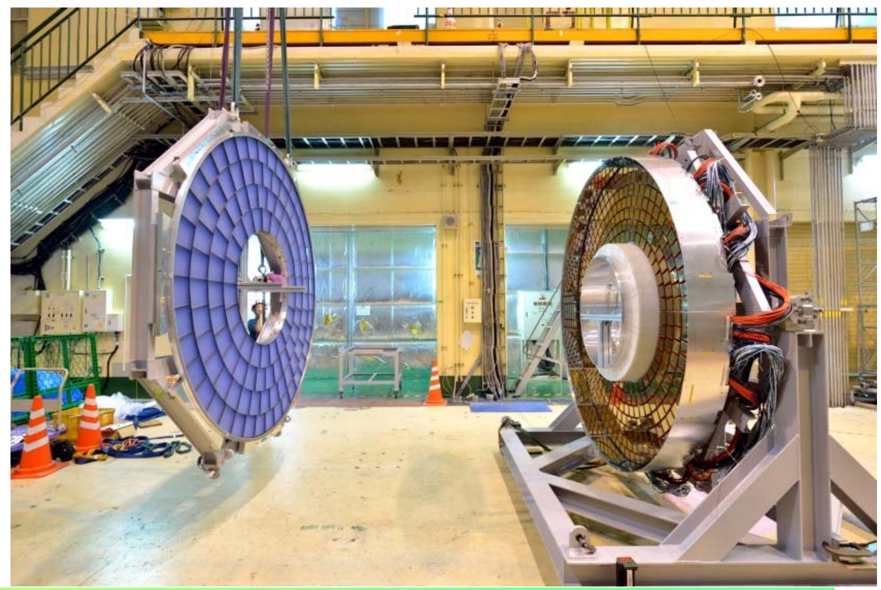
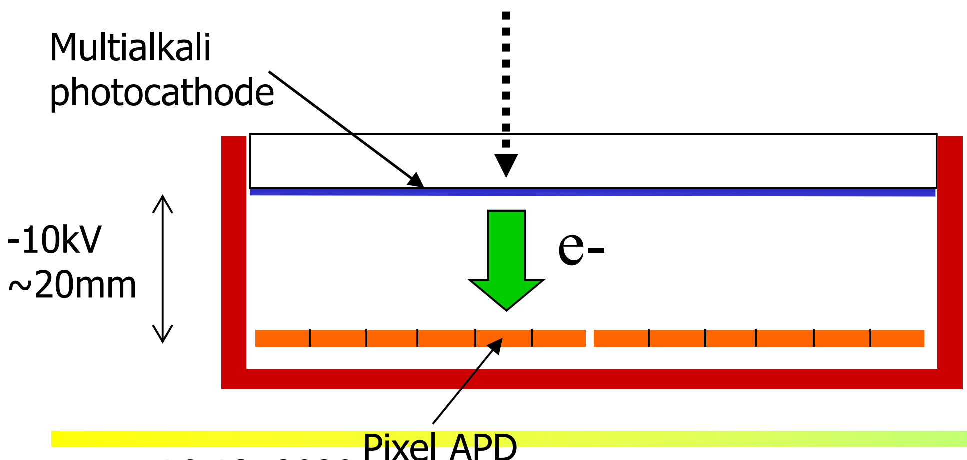
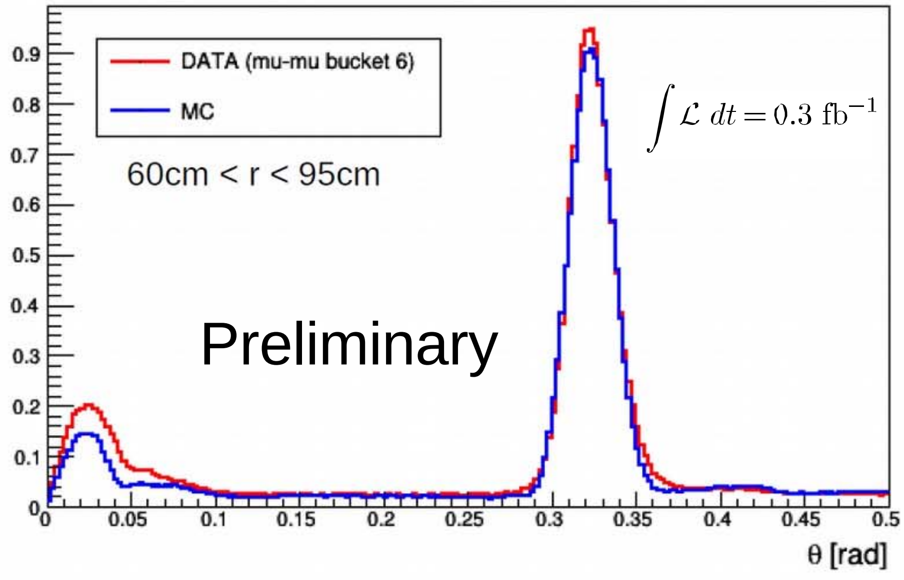


Photo-sensors: 420 HAPDs



Performance in the early Belle II data

Cherenkov angle distribution in $e^+e^- \to \mu^+\mu^-$



Overall a very good DATA/MC agreement !

DATA

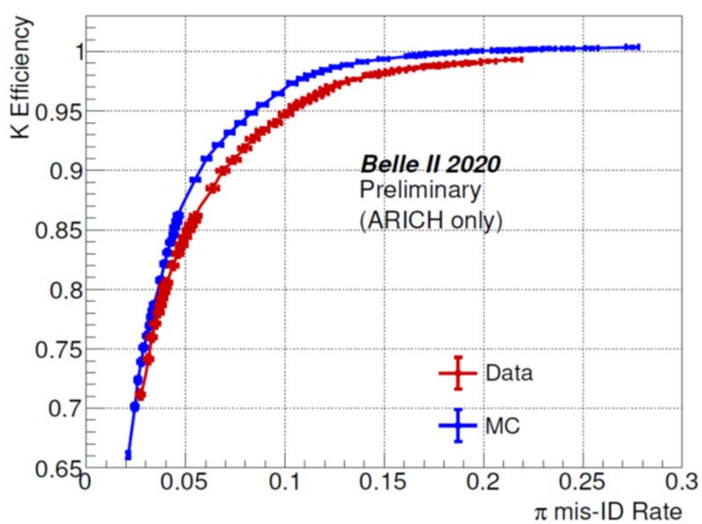
$N_{sig} = 11.38/\mathrm{track}$

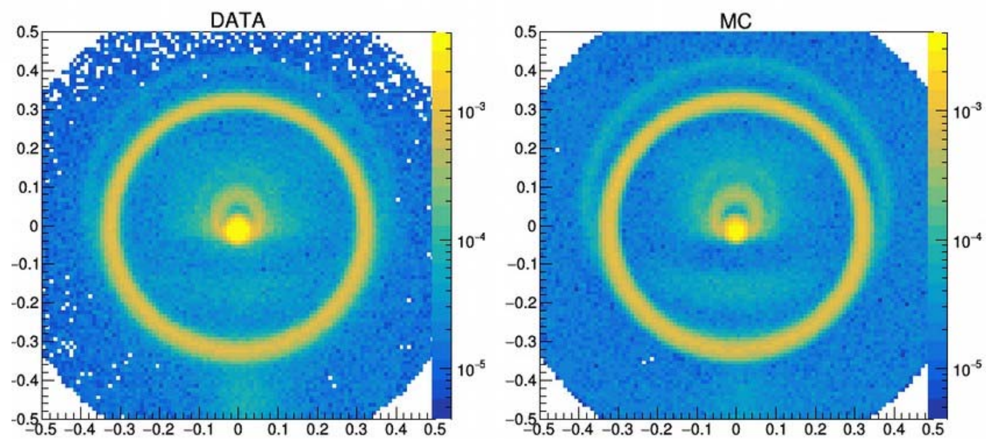
$\sigma_c = 12.7$ mrad

MC

$N_{sig} = 11.27/\mathrm{track}$

$\sigma_c = 12.75$ mrad



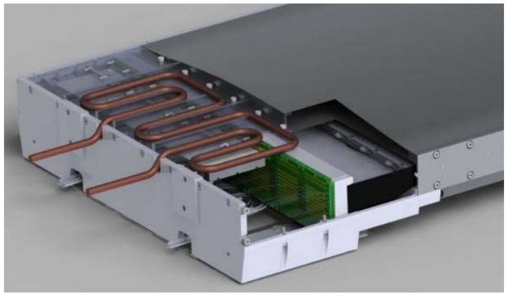


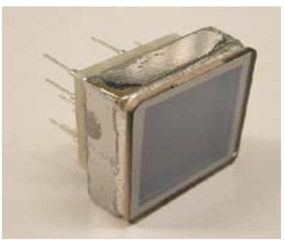
Chrenkov ring (accumulated)

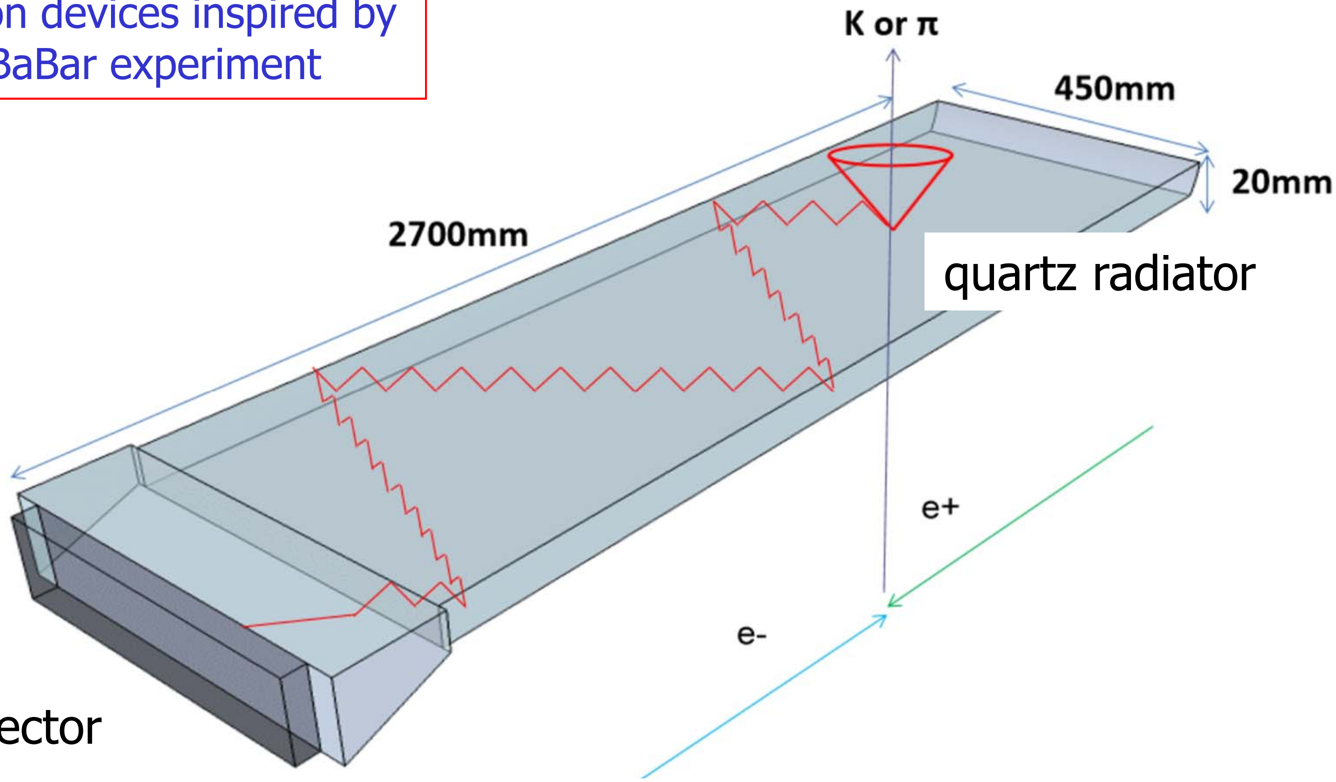
Refinements of PDFs are underway, further improvements of performance expected

Barrel PID: Time of propagation (TOP) counter

One of the new generation devices inspired by the DIRC counter of the BaBar experiment



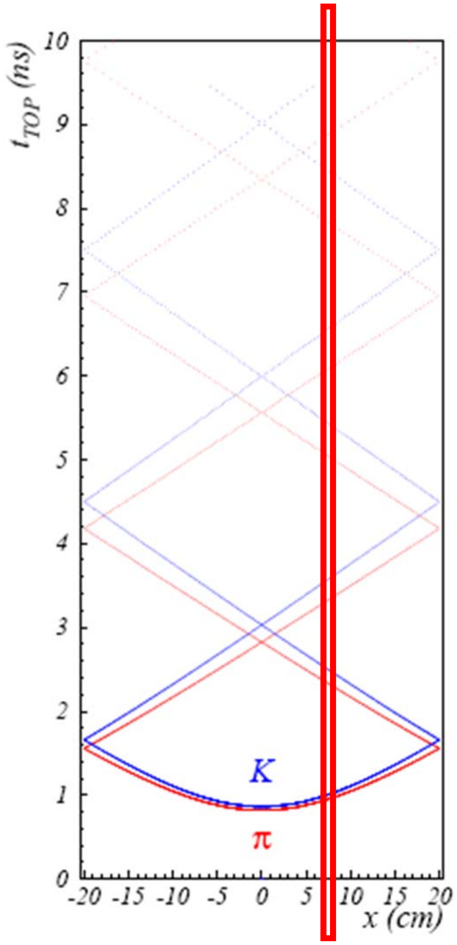




Photon detector

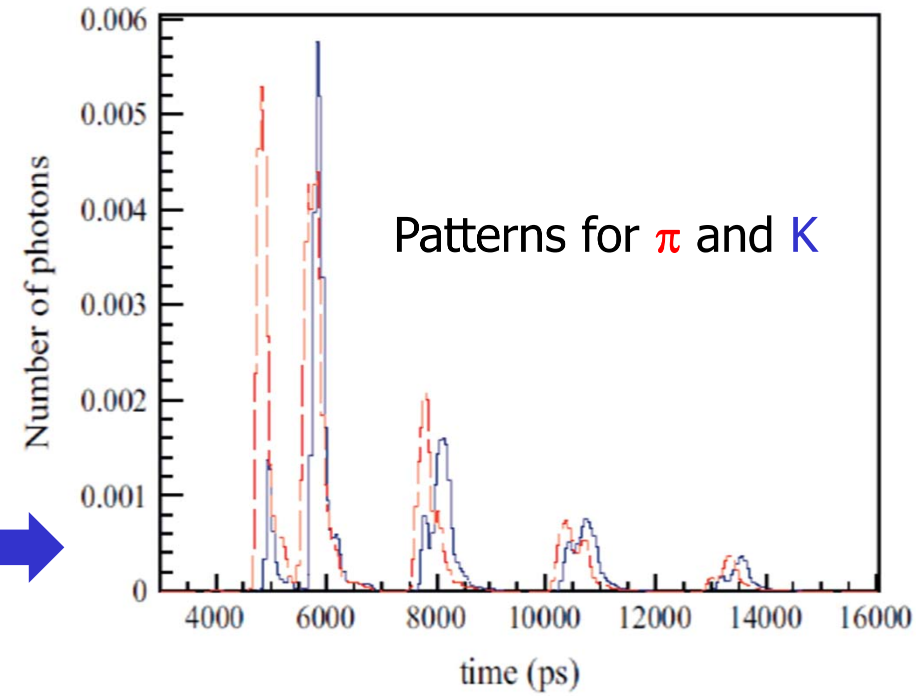
- Cherenkov ring imaging with precise time measurement.
- Reconstruct Cherenkov angle from two hit coordinates and the time of propagation of the photon
  - Quartz radiator (2cm thick)
  - Photon detector (MCP-PMT)
    - Excellent time resolution ~ 40 ps
    - Single photon sensitivity in 1.5 T

TOP image reconstruction



Pattern in the coordinate-time space ('ring') of a pion and kaon hitting a quartz bar

Time distribution of signals recorded by one of the PMT channels (slice in x): different for π and K (~shifted in time)

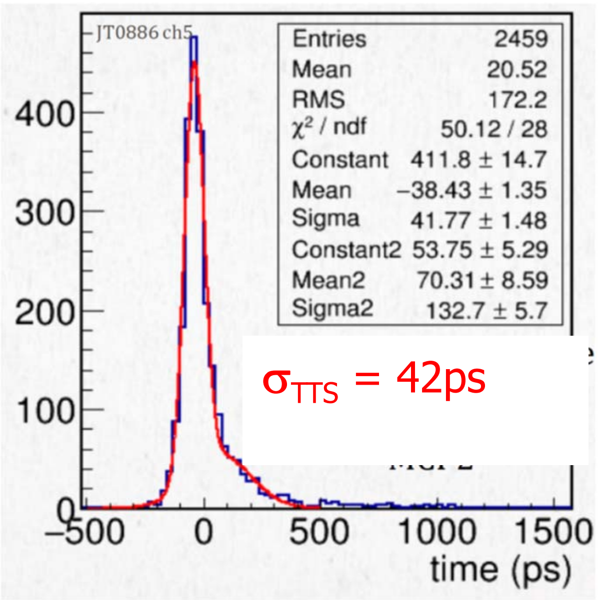


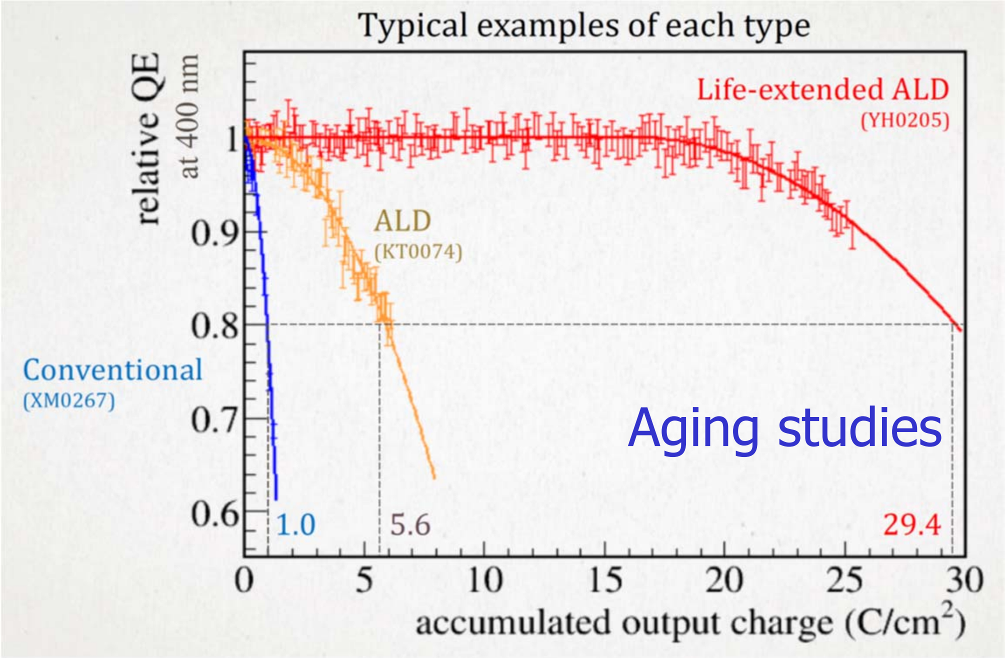
The name of the game: analytic expressions for the 2D likelihood functions

→NIMA A595 (2008) 252-255

TOP R+D areas

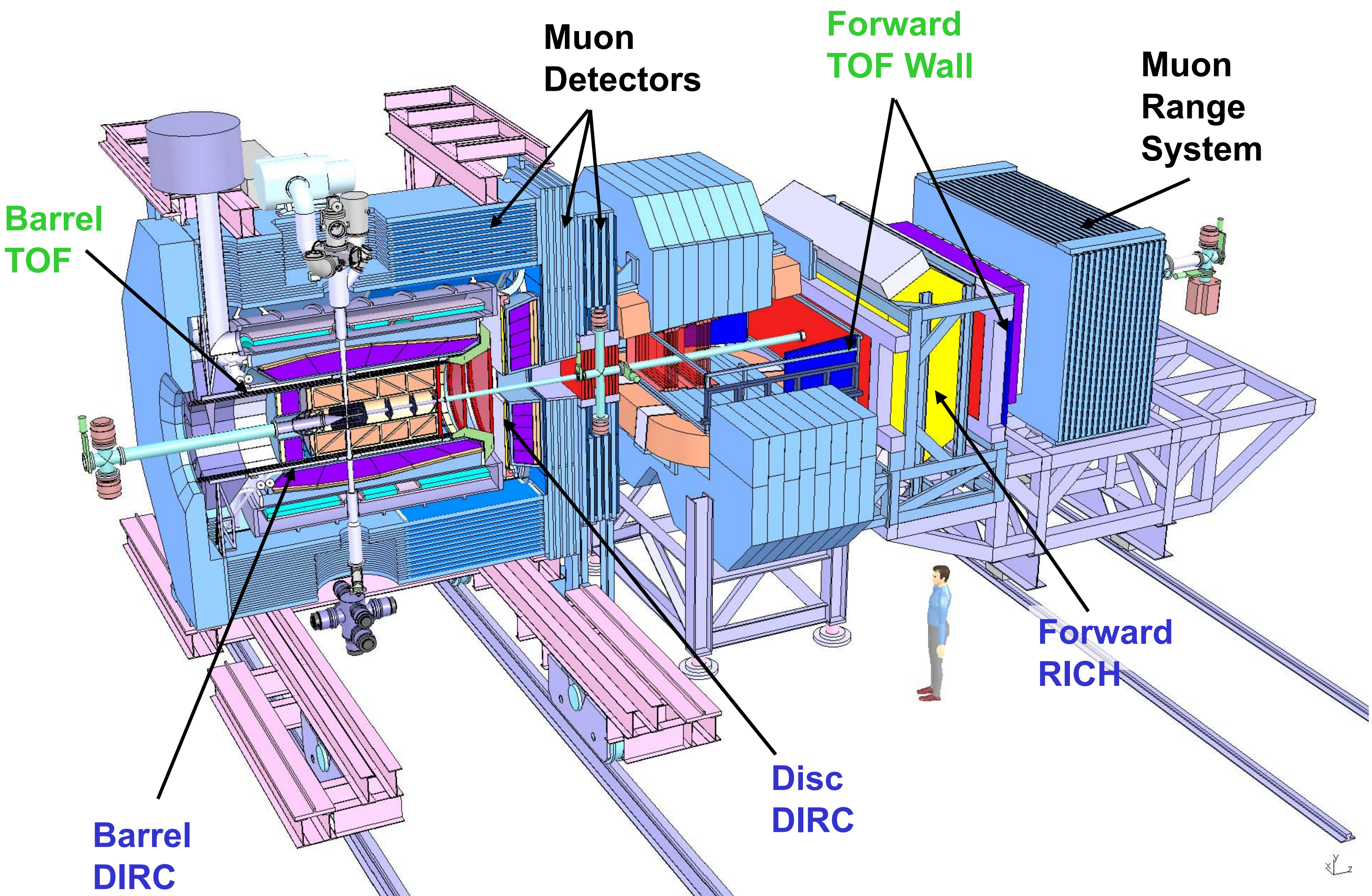
- Very fast photosensors for operation in 1.5 T field (MCP PMTs)
- R+D to mitigate aging of photocathodes in MCP PMTs (ALD)





- Very fast and compact readout electronics with waveform sampling for a precise time measurement
- Production of large quartz pieces, construction of modules, mechanics and installation methods
- Analytic expressions for the very complex 2D likelihood functions.

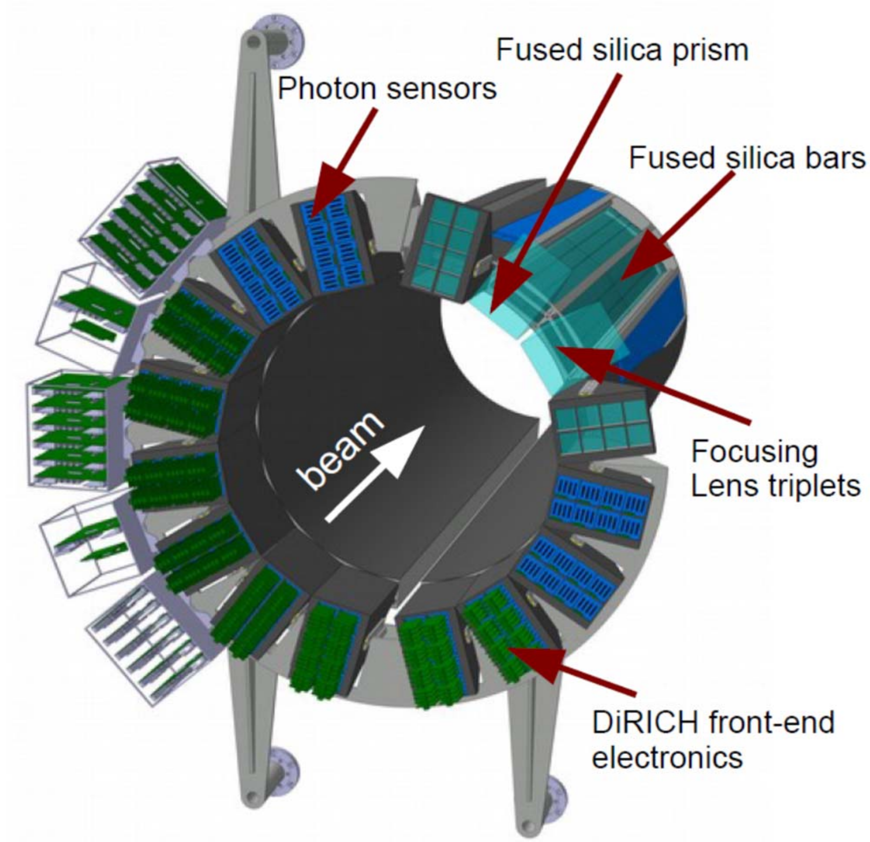
PID for PANDA



Barrel DIRC

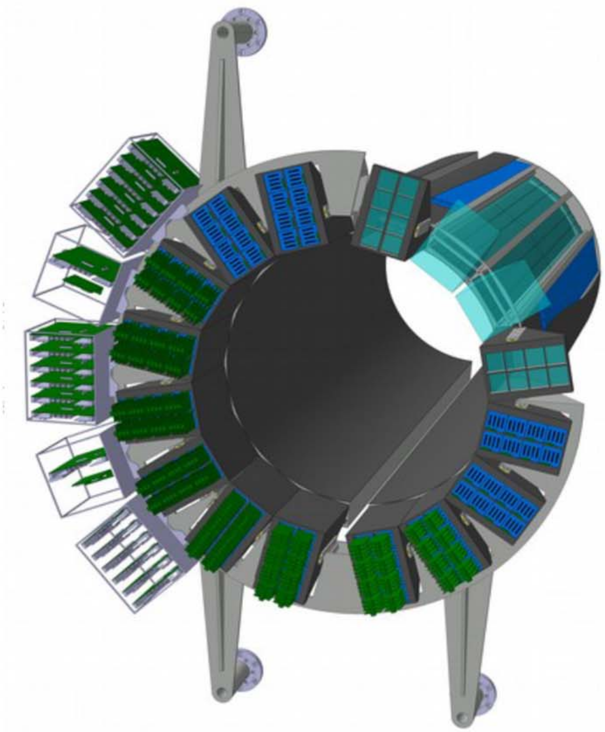
Based on BABAR DIRC and SuperB FDIRC with key improvements

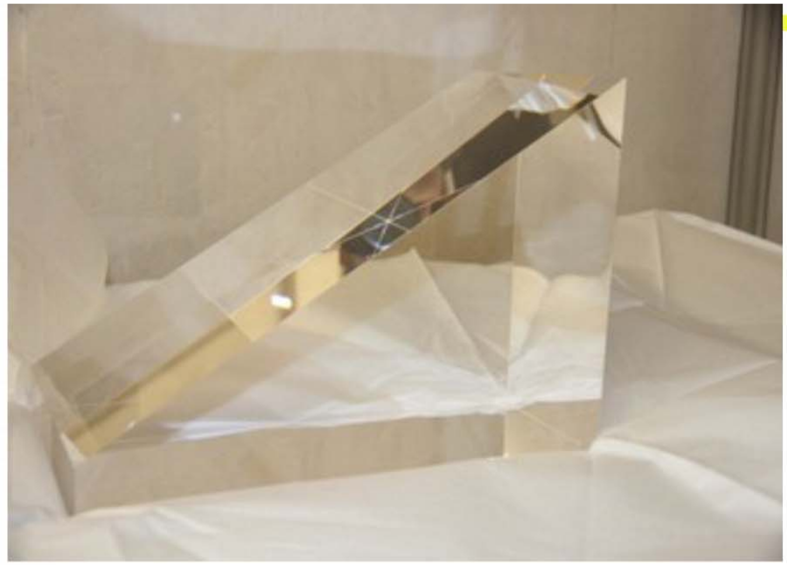
- Barrel radius ~48 cm; expansion volume depth: 30 cm.
- 48 narrow radiator bars, synthetic fused silica 17mm (T) x 53mm (W) x 2400mm (L)
- Compact photon detector:
  30 cm fused silica expansion volume
  8192 channels of MCP-PMTs in ~1T B field
- Focusing optics: spherical lens system
- Fast photon detection:
  fast electronics → 100-200 ps timing

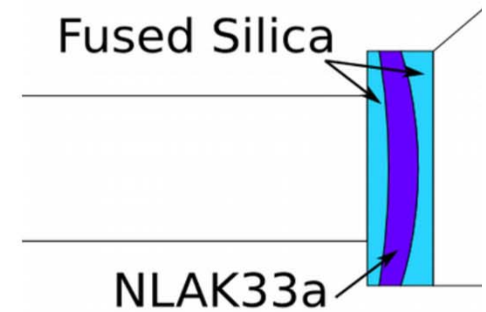


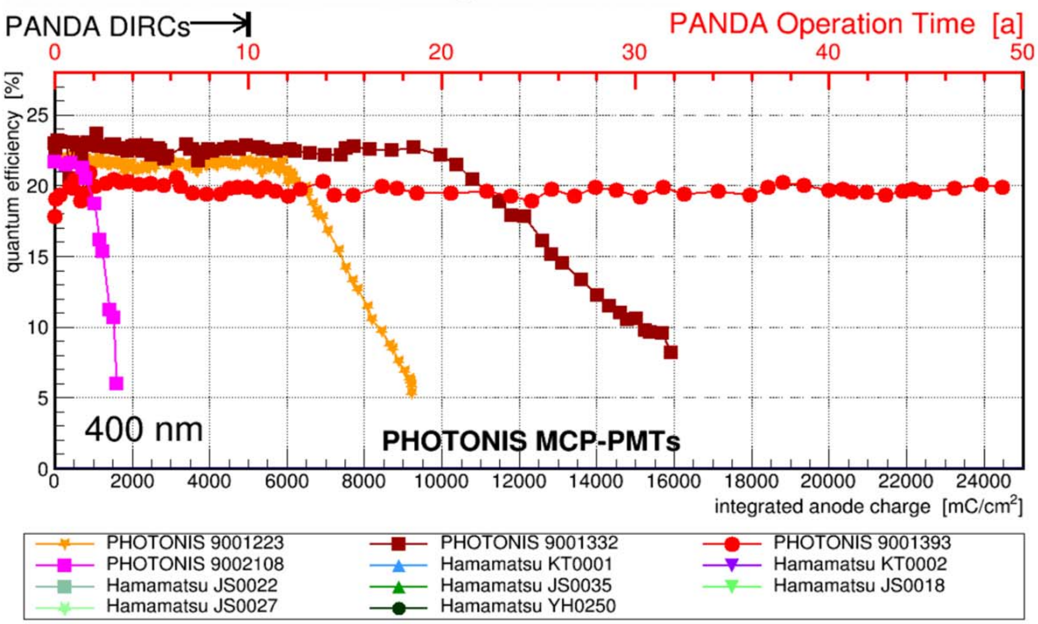
- A similar detector is also considered for the barrel region of the EIC detector

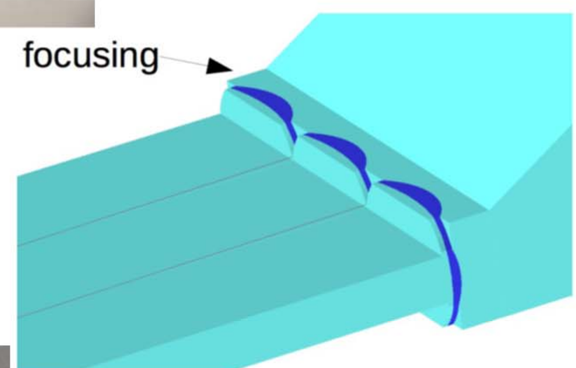
PANDA Barrel DIRC





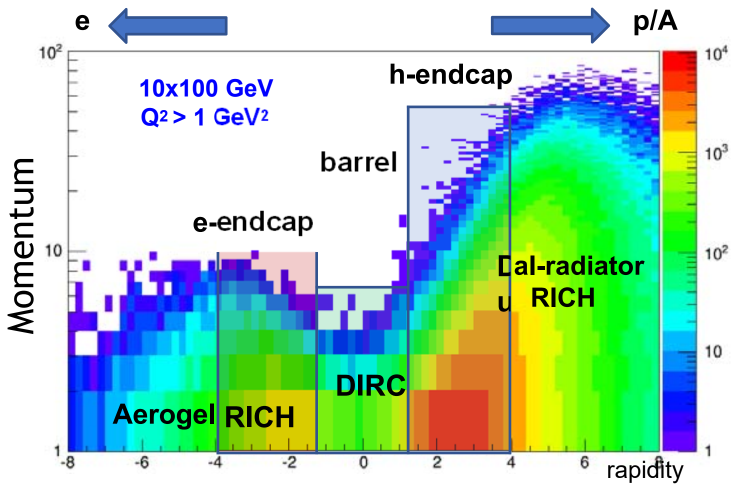


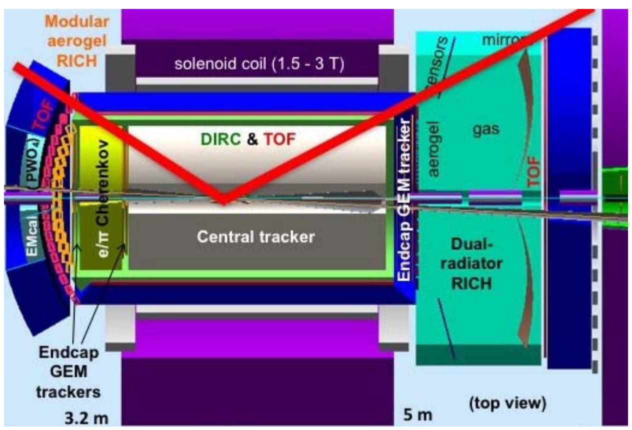




- A similar detector is also considered for the barrel region of the EIC detector

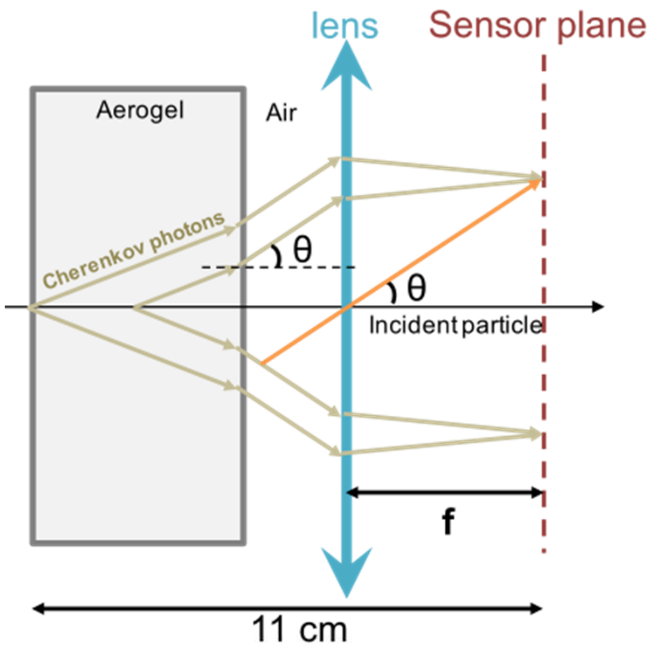
PID devices for the Electron Ion Collider

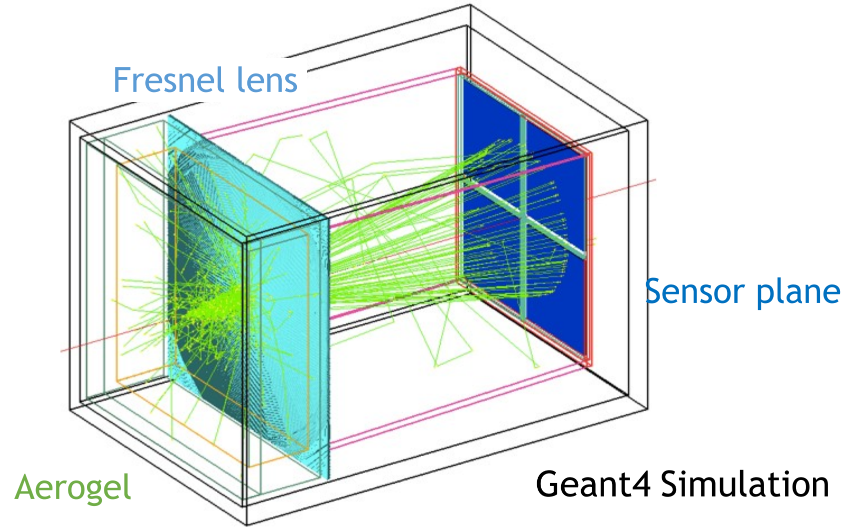


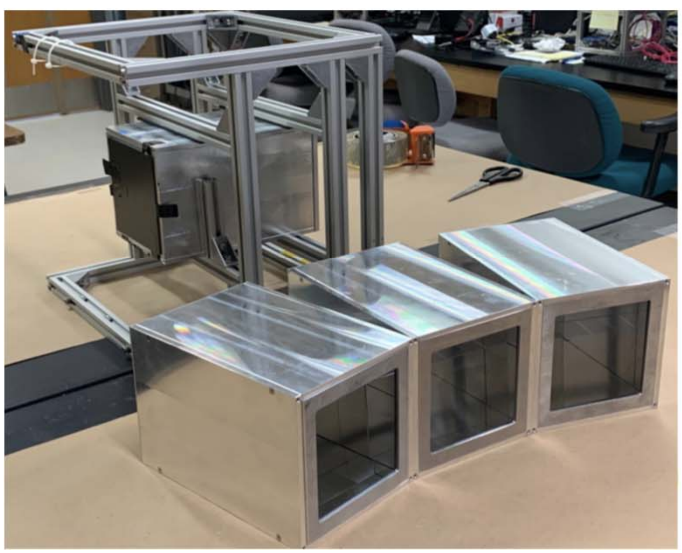


- **h-endcap**: A RICH with two radiators (gas + aerogel) is needed for
  π/K separation up to ~50 GeV/c **dRICH**
- **e-endcap**: A compact aerogel RICH which can be projective
  π/K separation up to ~10 GeV/c **mRICH**
- **barrel**: A high-performance DIRC provides a compact and cost-effective way to cover the area.
  π/K separation up to ~6-7 GeV/c **DIRC**
- **TOF (and/or dE/dx in TPC)**: can cover lower momenta.

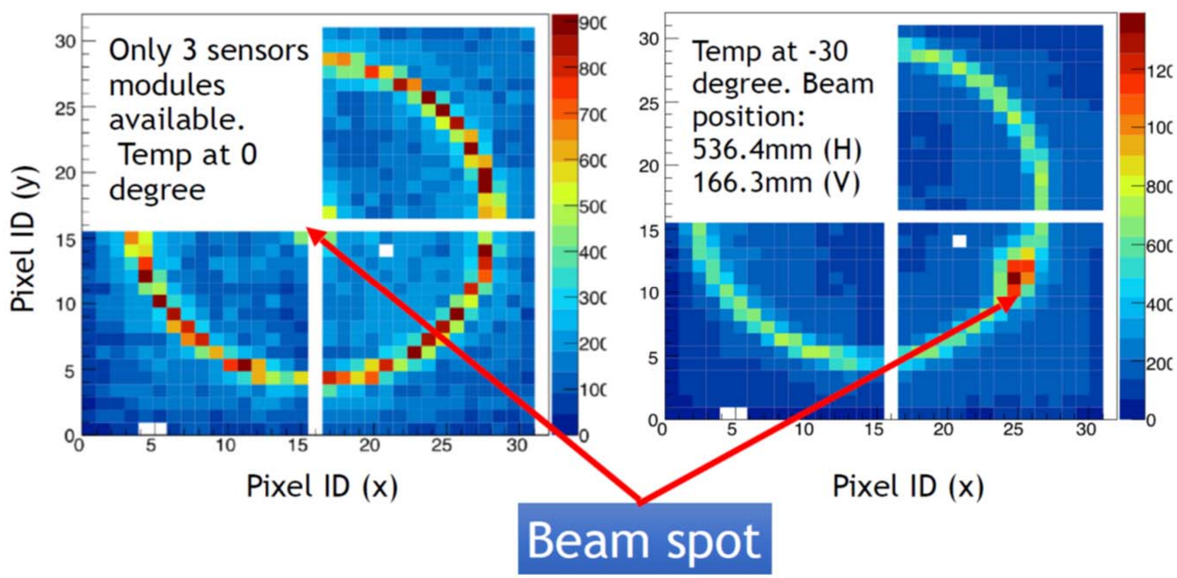
EIC detector PID: mRICH



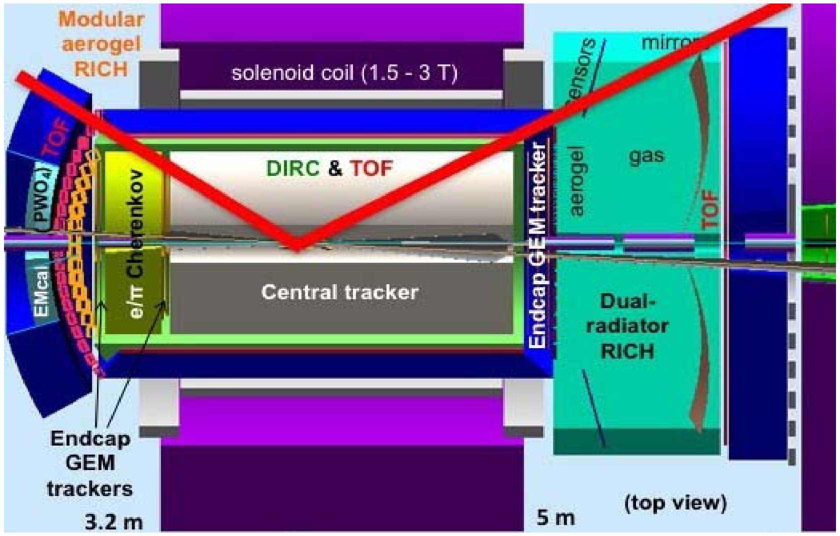




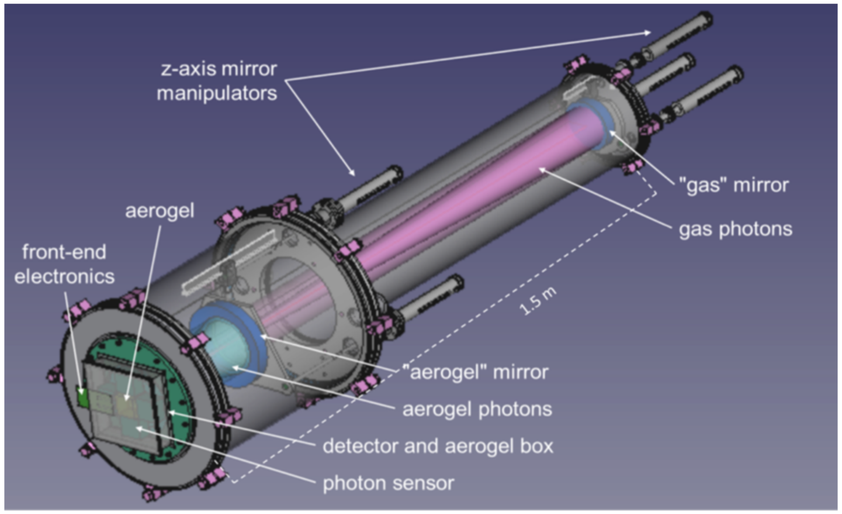
Beam test with SiPMs as sensors



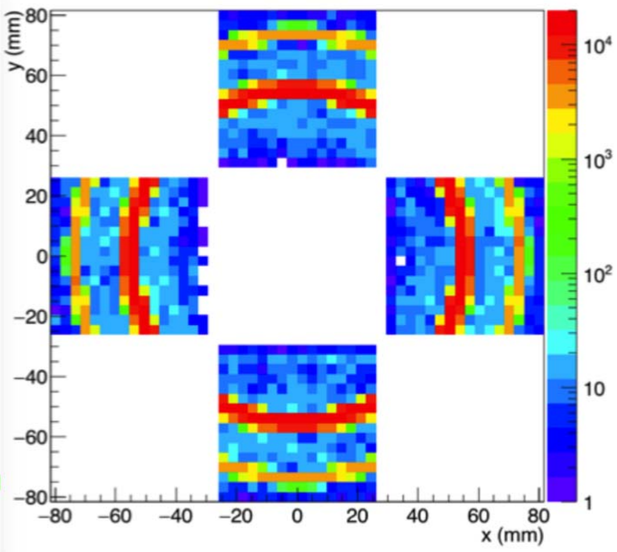
EIC detector PID: dRICH



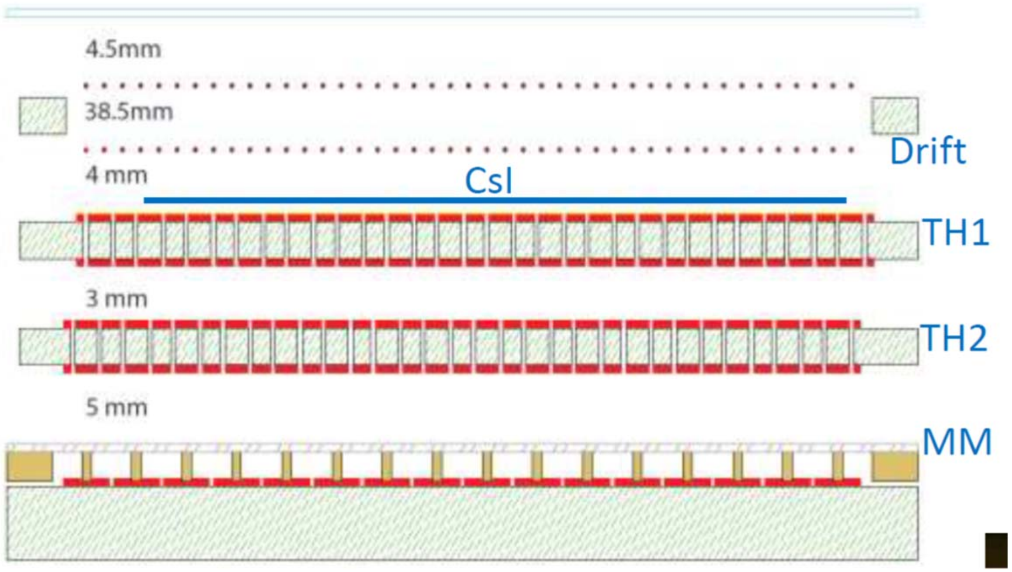
Dual radiator RICH: aerogel and gas



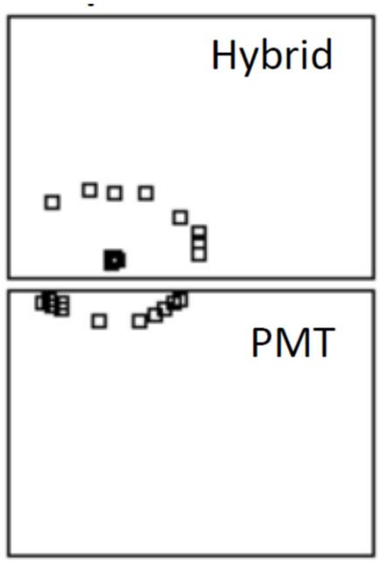
Beam test, apparatus and results



Gas based photo-sensor: THGEM + micromegas



Developed for COMPASS with CsI as the phosensitive substance.



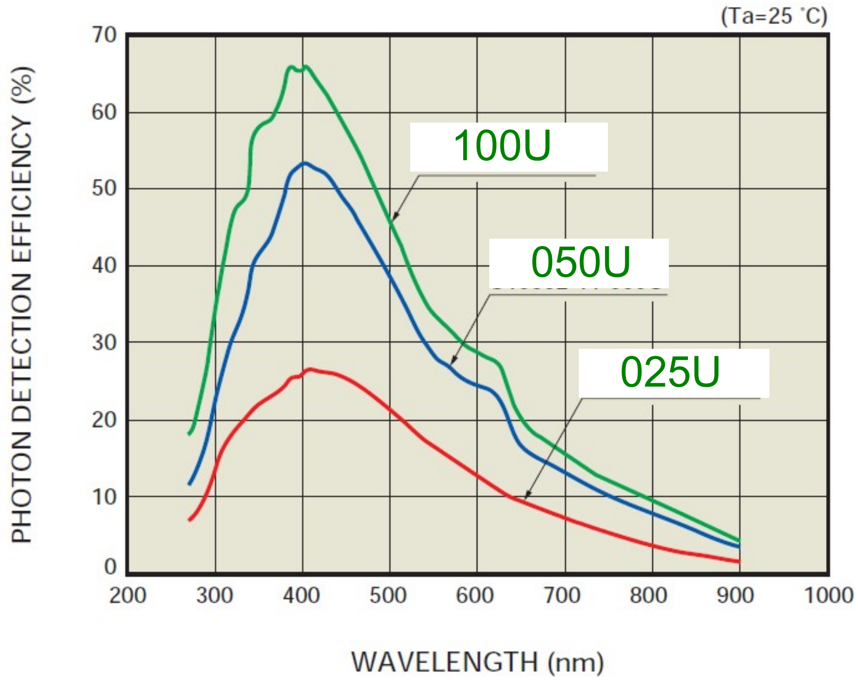
RICH for EIC: to increase the number of photons in the far UV, remove the window. → CsI might not be robust enough (humidity, ion bombardment).

Looking for alternatives: nano diamond photocathodes – interesting, but still some way to go

SiPMs as photon detectors for RICH detectors

SiPM: array of APDs operating in the Geiger mode.
Characteristics:

- low operation voltage ~ 10-100 V
- gain ~ 10^6
- peak PDE up to 65%(@400nm)
  PDE = QE x ε_{geiger} x ε_{geo} (up to 5x PMT!)
- ε_{geo} – dead space between the cells
- time resolution ~ 100 ps
- works in high magnetic field
- dark counts ~ few 100 kHz/mm^2
- radiation damage (p,n)



Not trivial to use in a RICH where we have to detect single photons!

Dark counts have single photon pulse heights (rate 0.1-1 MHz) – and this gets worse with n irradiation…

SiPM as photosensor for a RICH counter

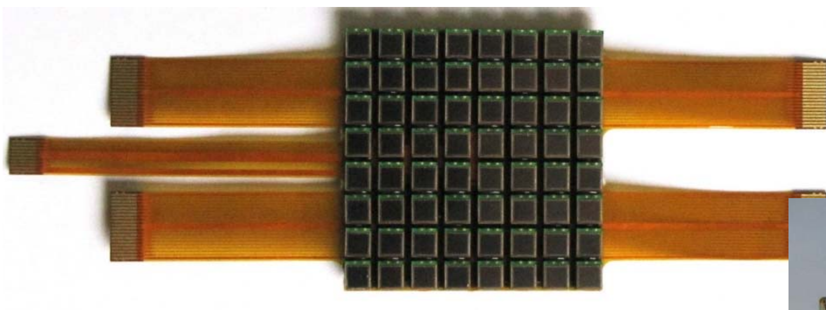
Improve the signal to noise ratio:

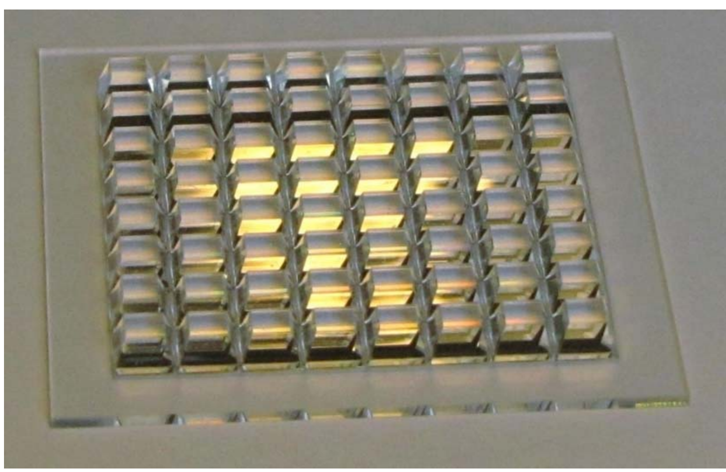
•Reduce the noise by a narrow (<10ns) time window (Cherenkov light is prompt!)

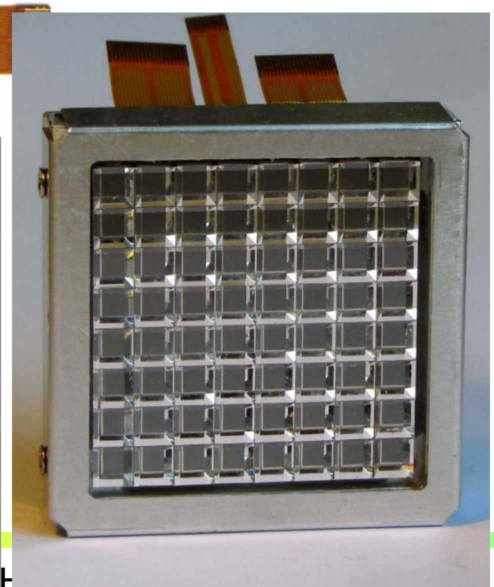
•Increase the number of signal hits per single sensor by using light collectors

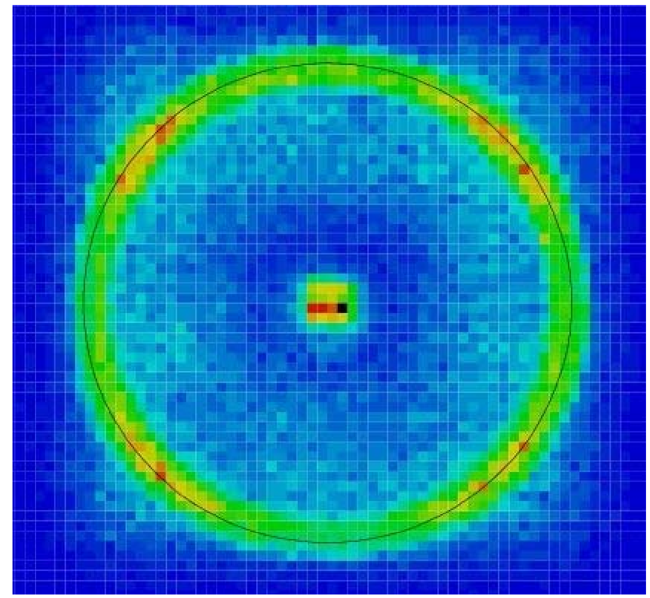
Example: Hamamatsu MPPC S11834-3388DF

- 8x8 SiPM array, with 5x5 mm^2 SiPM channels
- Active area 3x3 mm^2





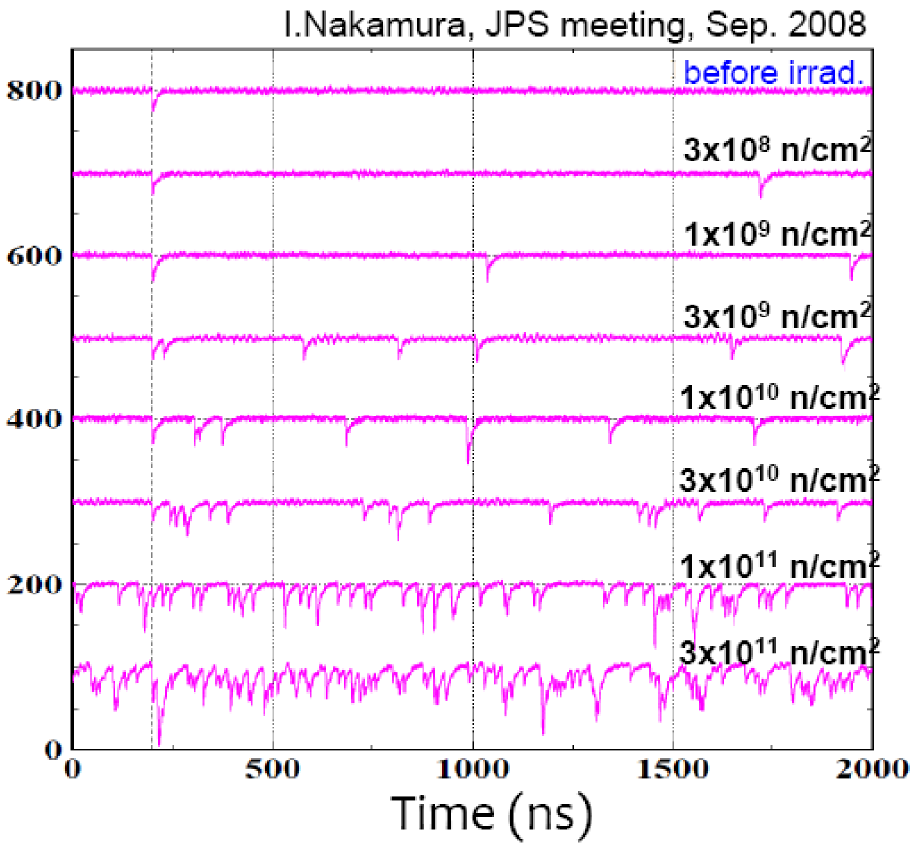




First rings with SiPMs

→ NIM A594 (2008) 13; NIM A613 (2010) 195

SiPMs: Radiation damage



Expected fluence at 50/ab at Belle II:
$20\ 10^{11}$ n cm^{-2}

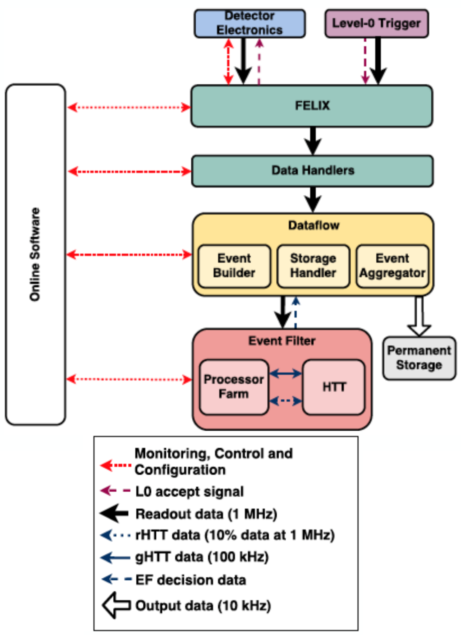
→ Worst than the lowest line

→Need cooling of sensors with wave-form sampling readout electronics, and preferably also some annealing method

Considered for RICHes in the EIC detector, the next LHCb upgrade and for the Belle II upgrade by the end of the decade

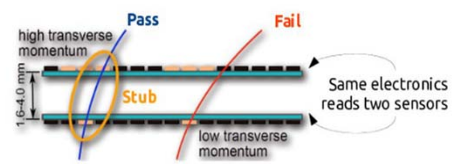
Trigger development

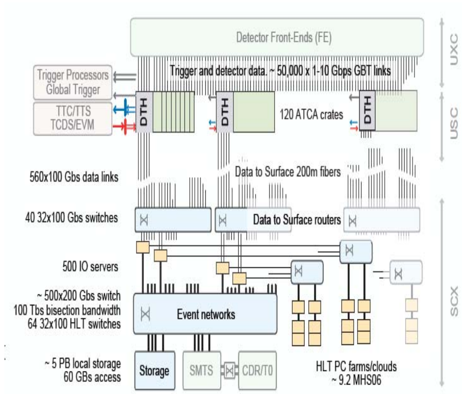
ATLAS



Minimize data flow bandwidth by using multiple trigger levels and regional readout (RoI)

CMS

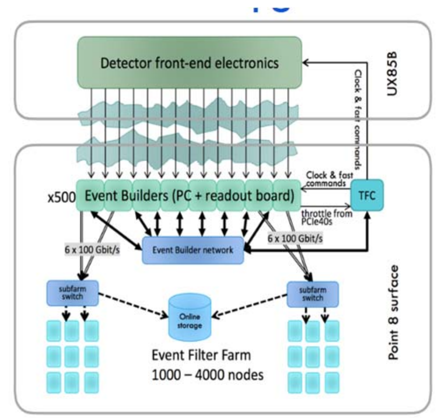




Allow large data flow bandwidth. Invest in scalable commercial network and processing systems

LHCb

40 MHz trigger-less DAQ



Massive use of data links

Summary

Detectors for particle physics experiments are our discovery tools – well designed and well functioning devices have been essential for our present understanding of elementary particles and their interactions.

A very vibrant research area: a large variety of new methods and techniques has either been developed recently, or is under commissioning or early data taking.

New challenges are waiting for us when planning the next generation of experiments