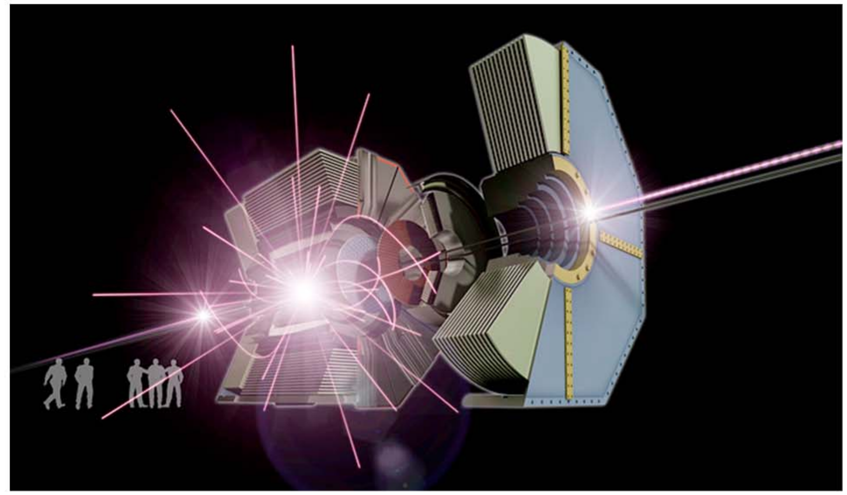
ANIMMA
Portorož Slovenia 17 – 21 June 2019

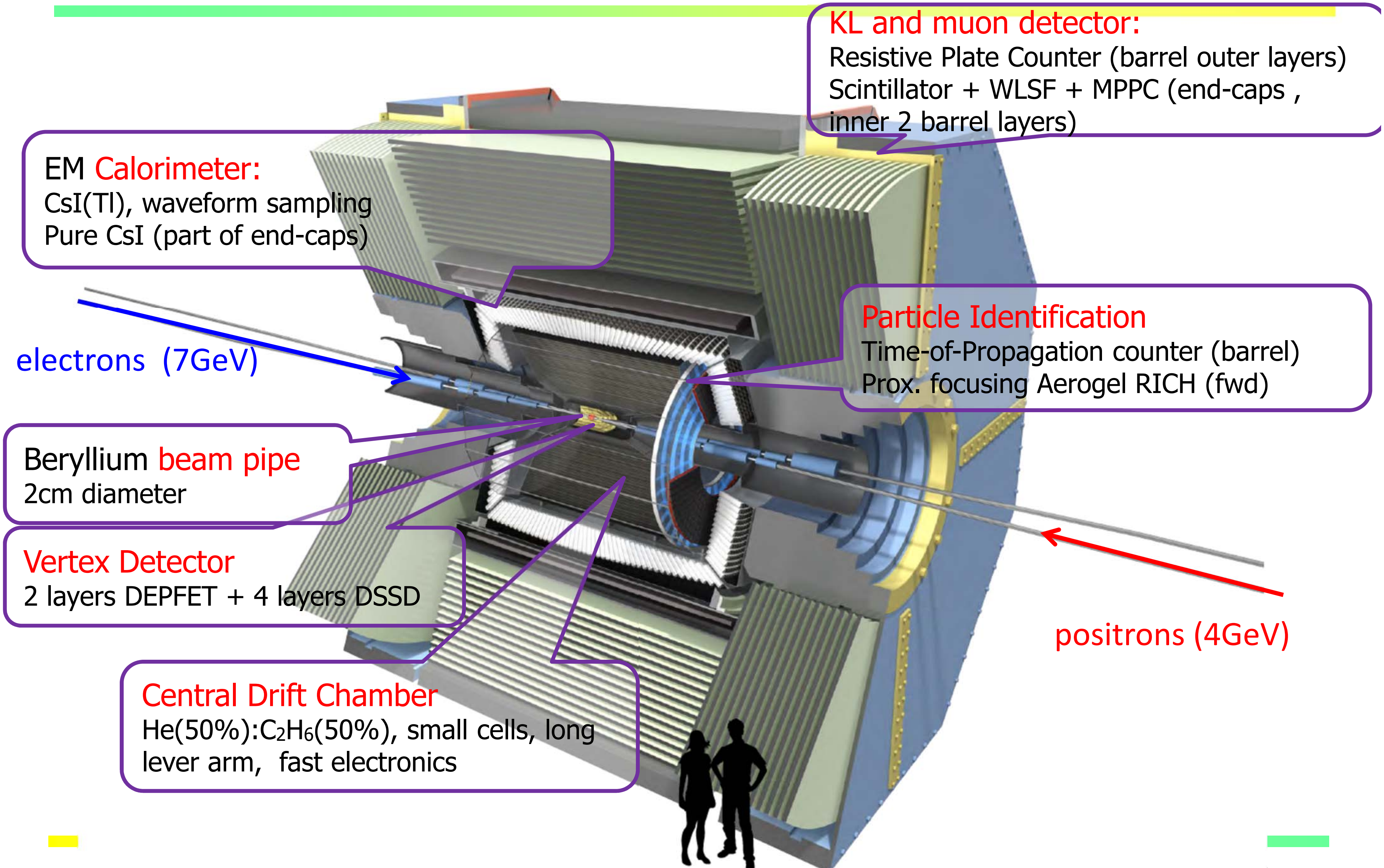


Recent advances in detectors for particle physics

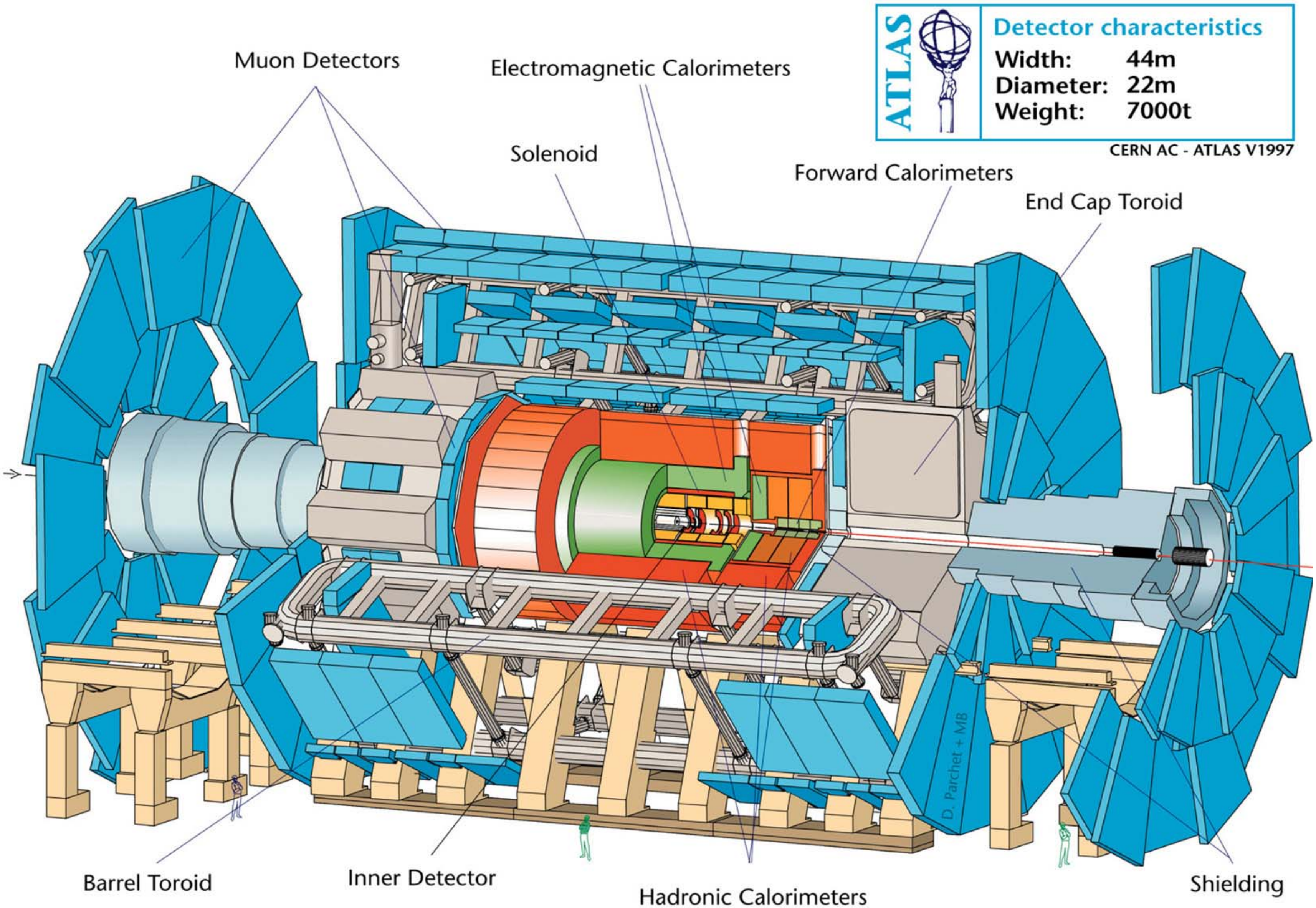
Peter Križan

University of Ljubljana and J. Stefan Institute

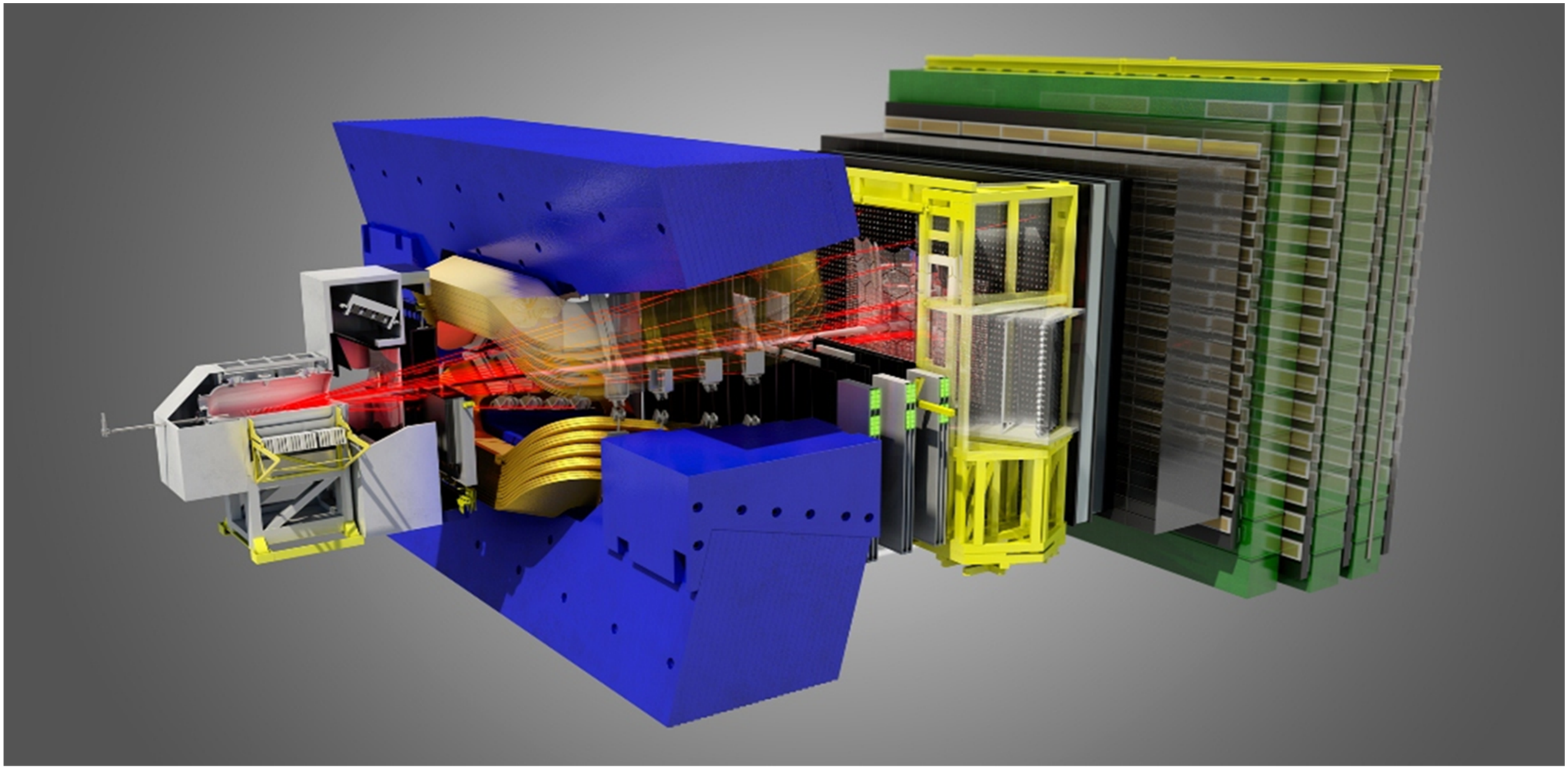
A ‘typical‘ particle physics experiment 1: Belle II



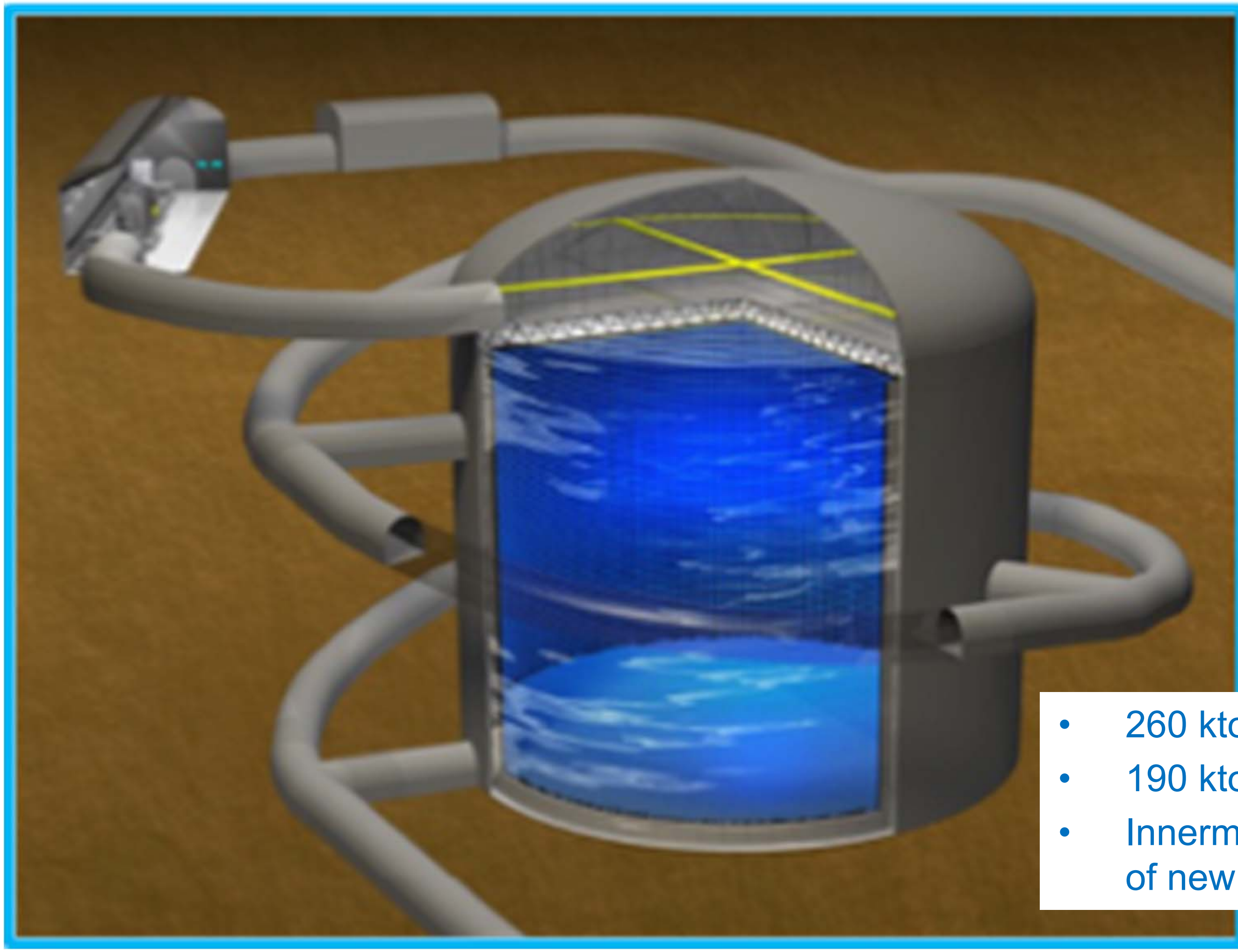
A ‘typical‘ particle physics experiment 2: ATLAS



A ‘typical‘ particle physics experiment 3: LHCb



A ‘typical‘ particle physics experiment 4



- 260 kton ultrapure water
- 190 kton fiducial mass: 10×SK
- Innermost volume viewed by 40,000 of new 50 cm PMT

Contents

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

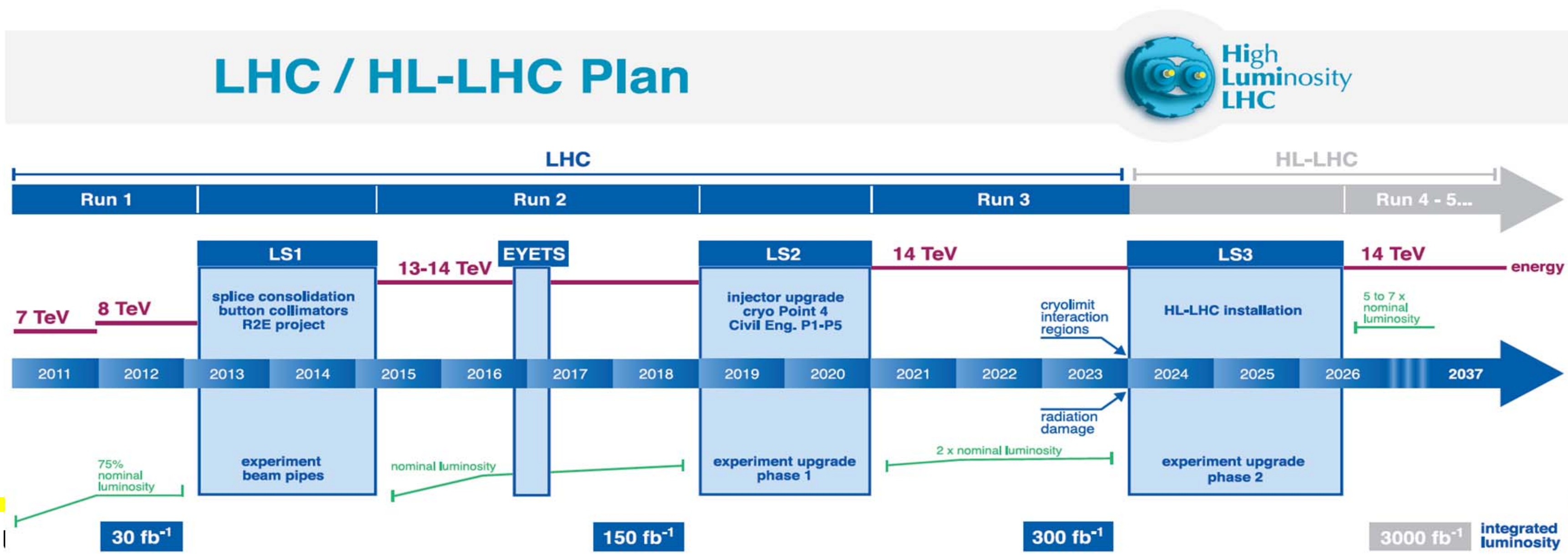
Where are we?

Intensity frontier:

- Belle II just started taking data
- LHCb is being upgraded

Energy frontier:

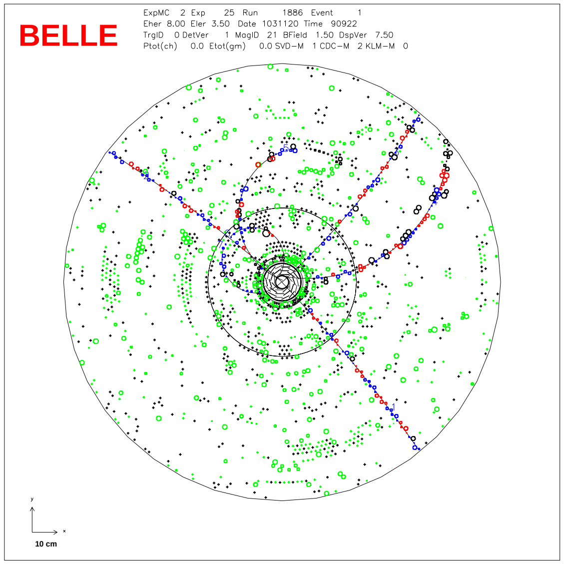
- ATLAS and CMS are getting ready for a major upgrade in the next long shut-down
- ALICE is being upgraded

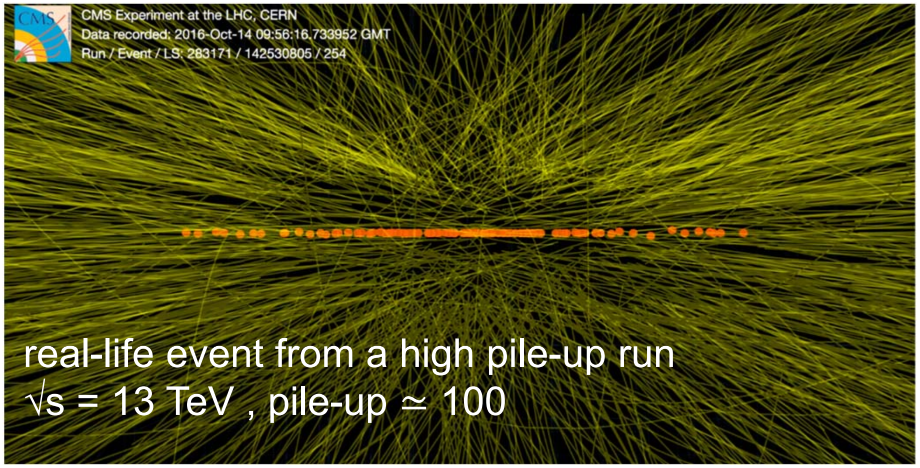


Tracking (and vertexing)

Various needs:

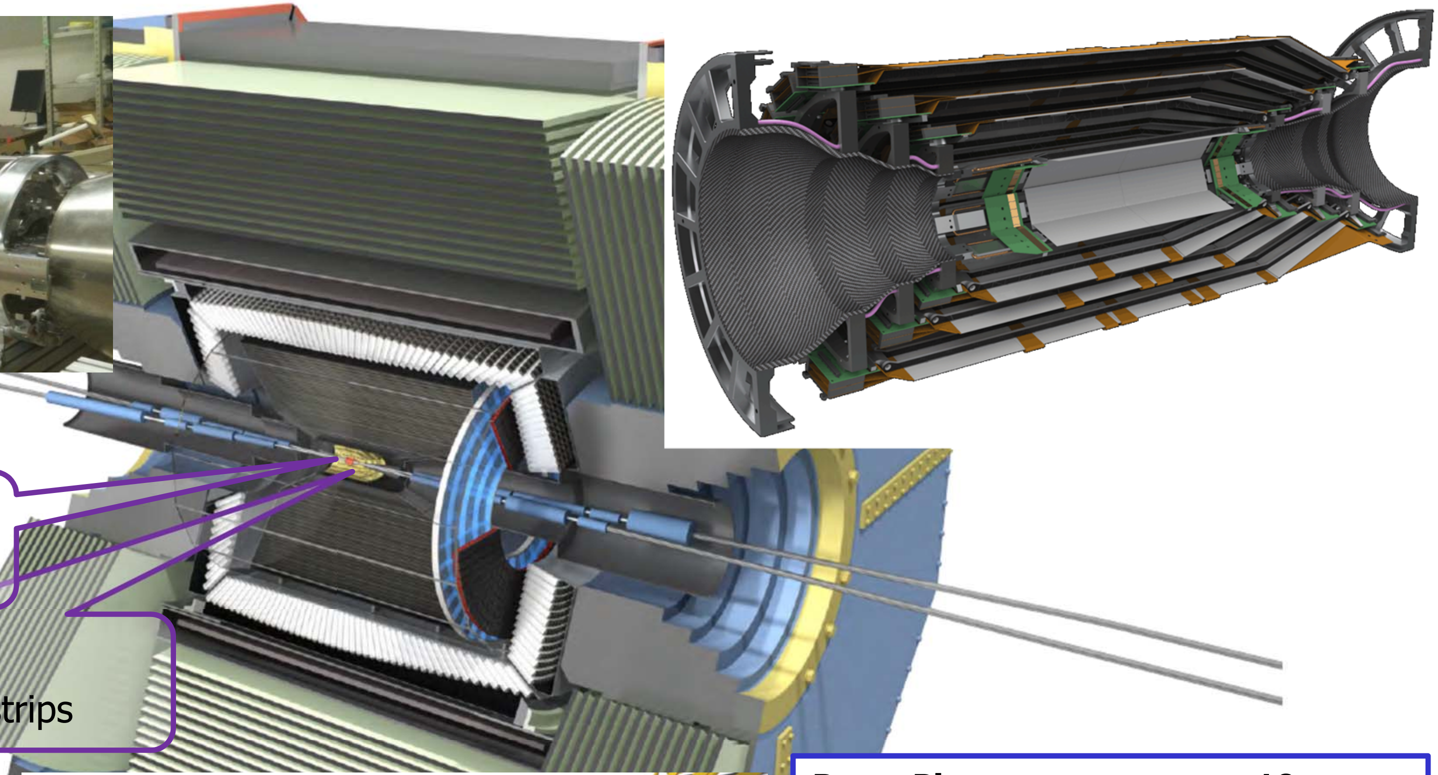
- Lower energies (Belle II): precision tracking and minimal multiple scattering, few particles in the final state, no event overlap
- LHC: precision with a high density of particles, multiple overlayed interactions within the same event, high radiation load





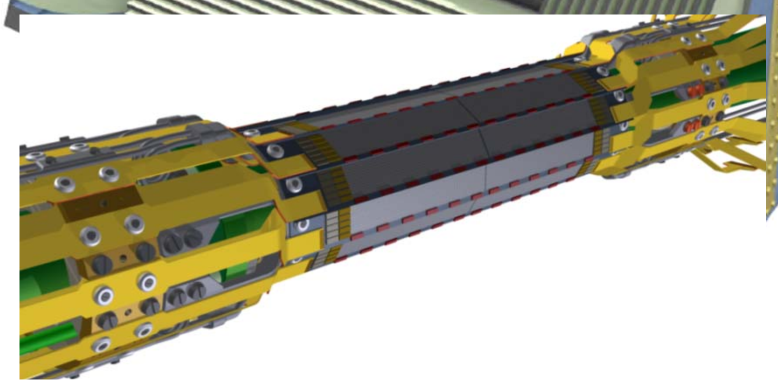
Vertexing at Belle II:

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

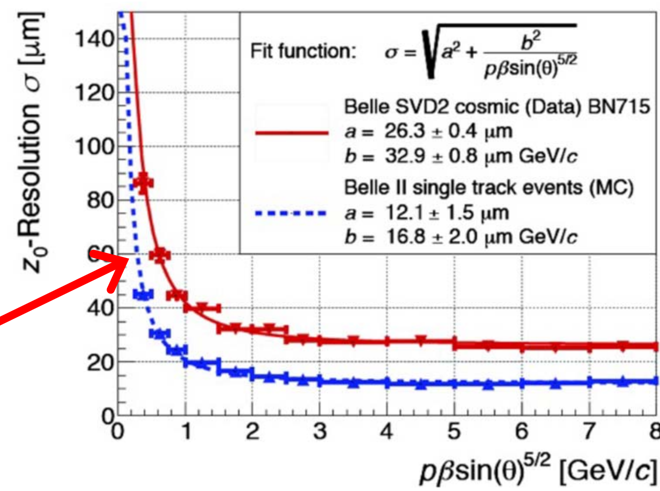


Beam Pipe		**r = 10mm**
DEPFET pixels		
	Layer 1	**r = 14mm**
	Layer 2	**r = 22mm**
DSSD silicon strips		
	Layer 3	**r = 39mm**
	Layer 4	**r = 80mm**
	Layer 5	**r = 104mm**
	Layer 6	**r = 135mm**

Expected performance

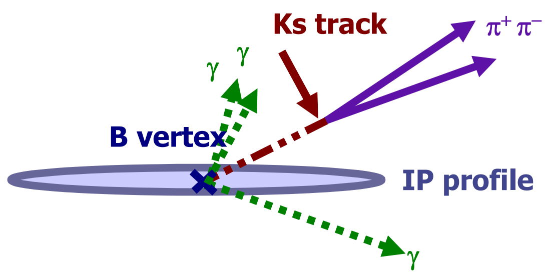
Significant improvement in vertex resolution vs Belle!

Less Coulomb scattering

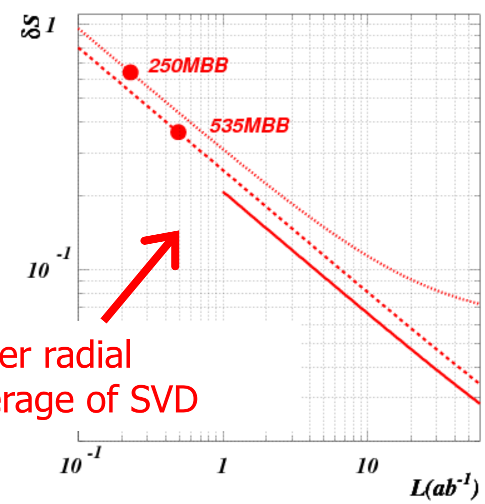


Pixel detector close to the beam pipe

Significant improvement in $\delta S(K_S\pi^0\gamma)$



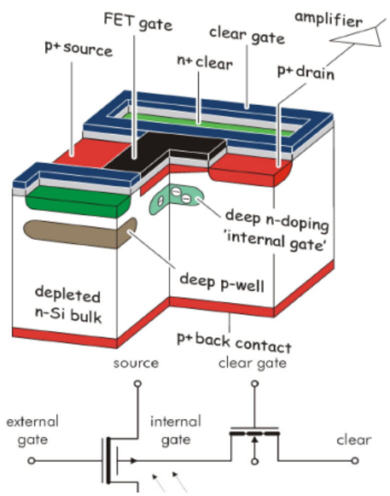
B decay point reconstruction with K_S trajectory



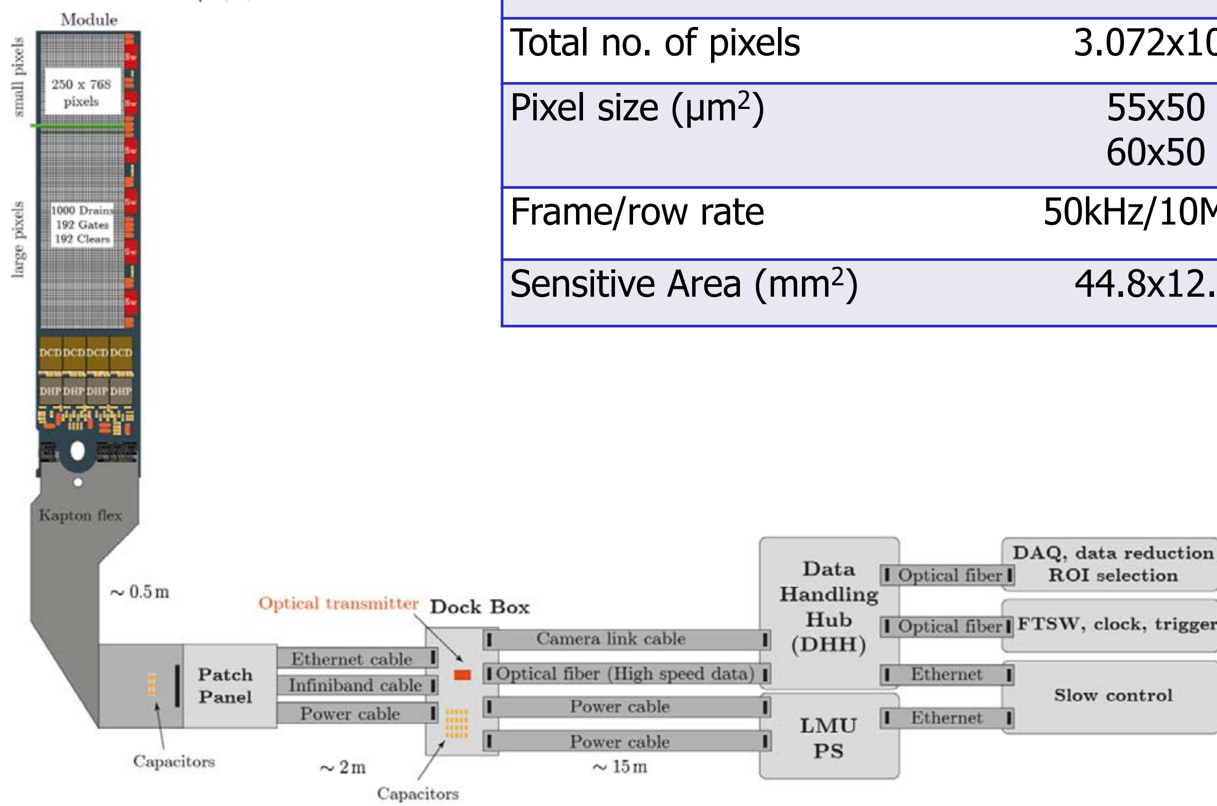
Larger radial coverage of SVD

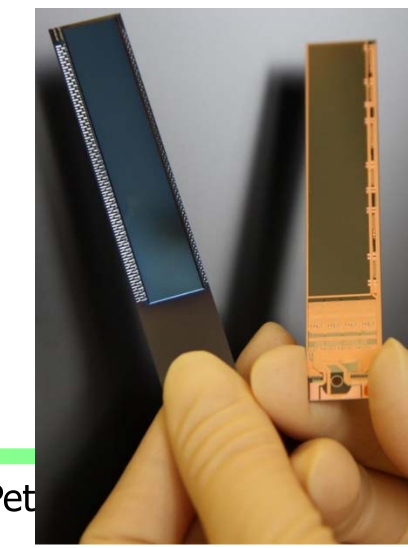
Pixel detector: 2 layers of DEPFET sensors

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

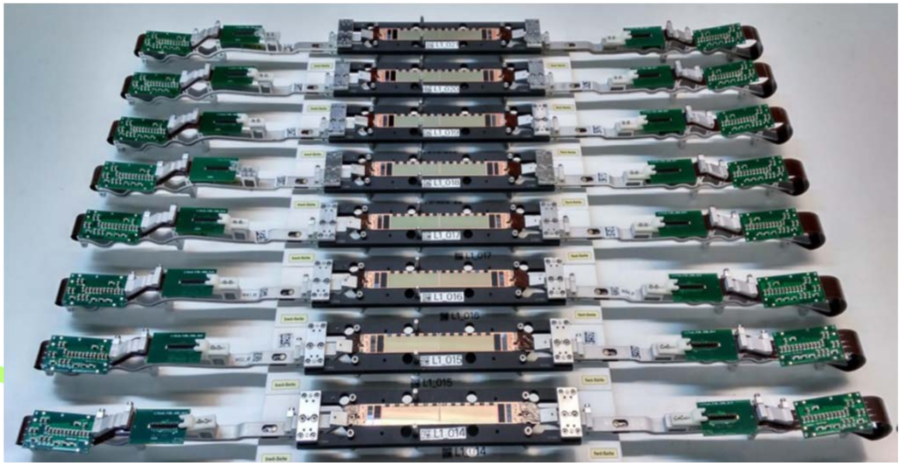




Pet

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 → CO2 cooling



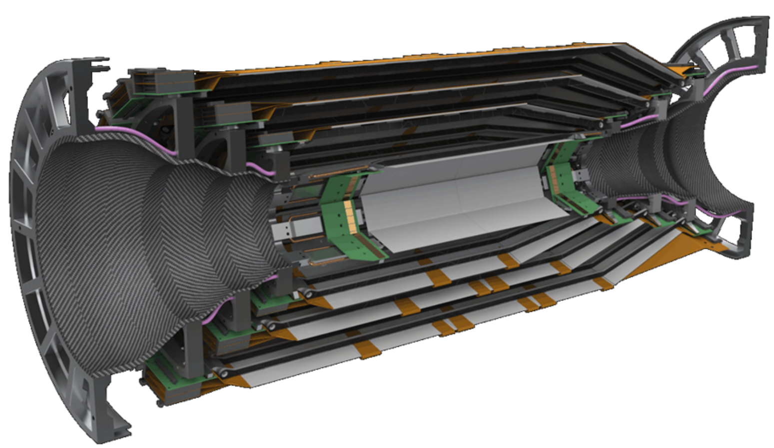
SVD: four layers of double sided silicon strip detectors.

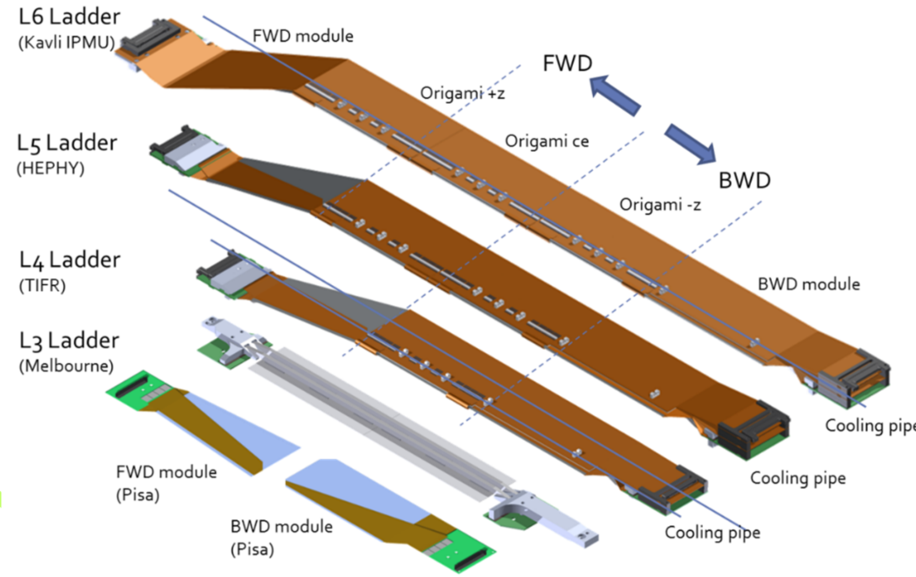
Main R+D areas:

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

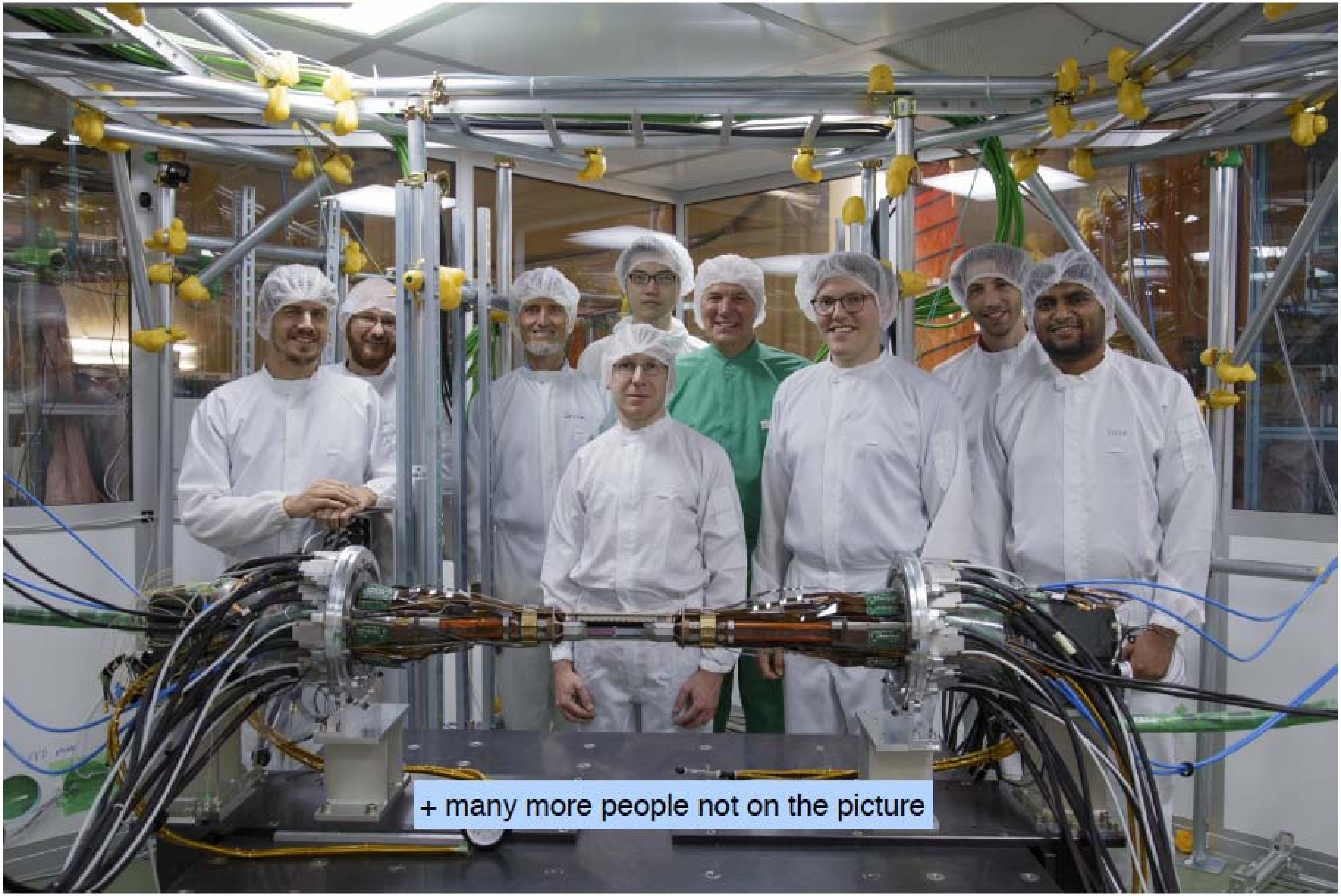
Excellent time resolution (~4ns) thanks to multiple recorded samples and waveform fitting

CO_2 dual-phase cooling



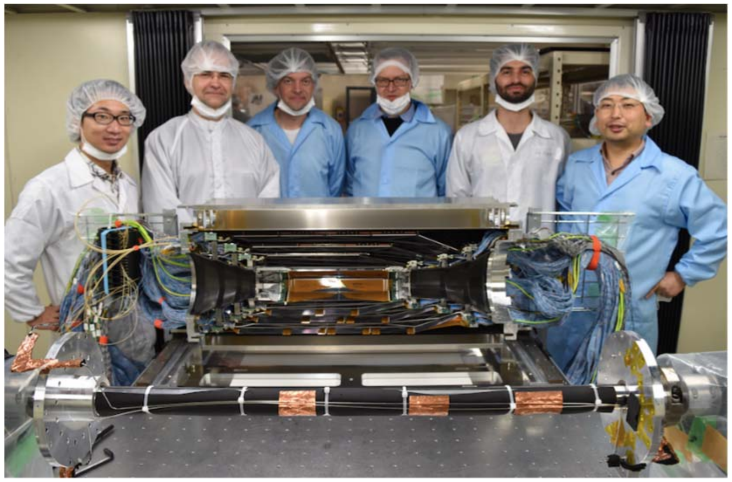


Both PXD Halfs assembled on Beam Pipe

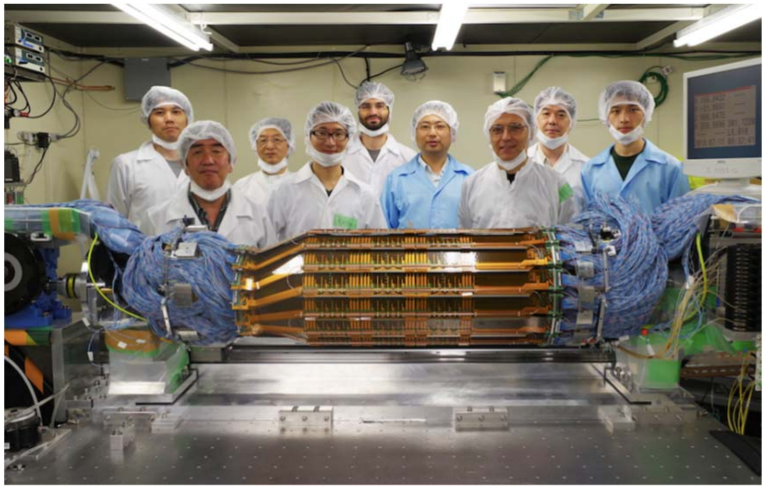


SVD construction steps

SVD +X completion (Feb 2018)

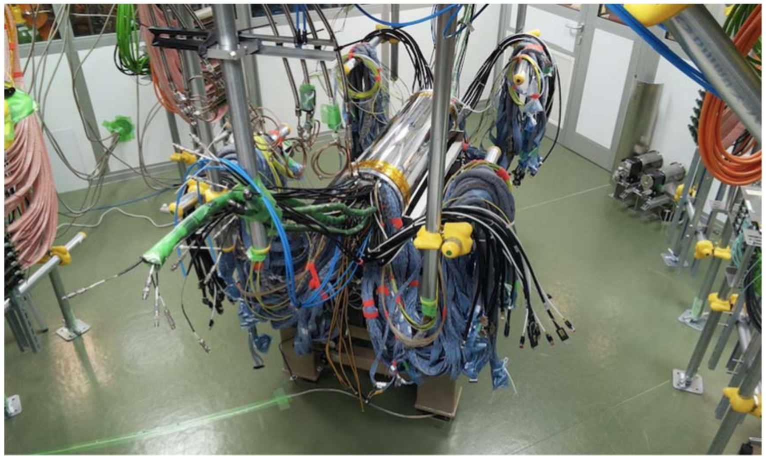


SVD -X completion (Jul 2018)

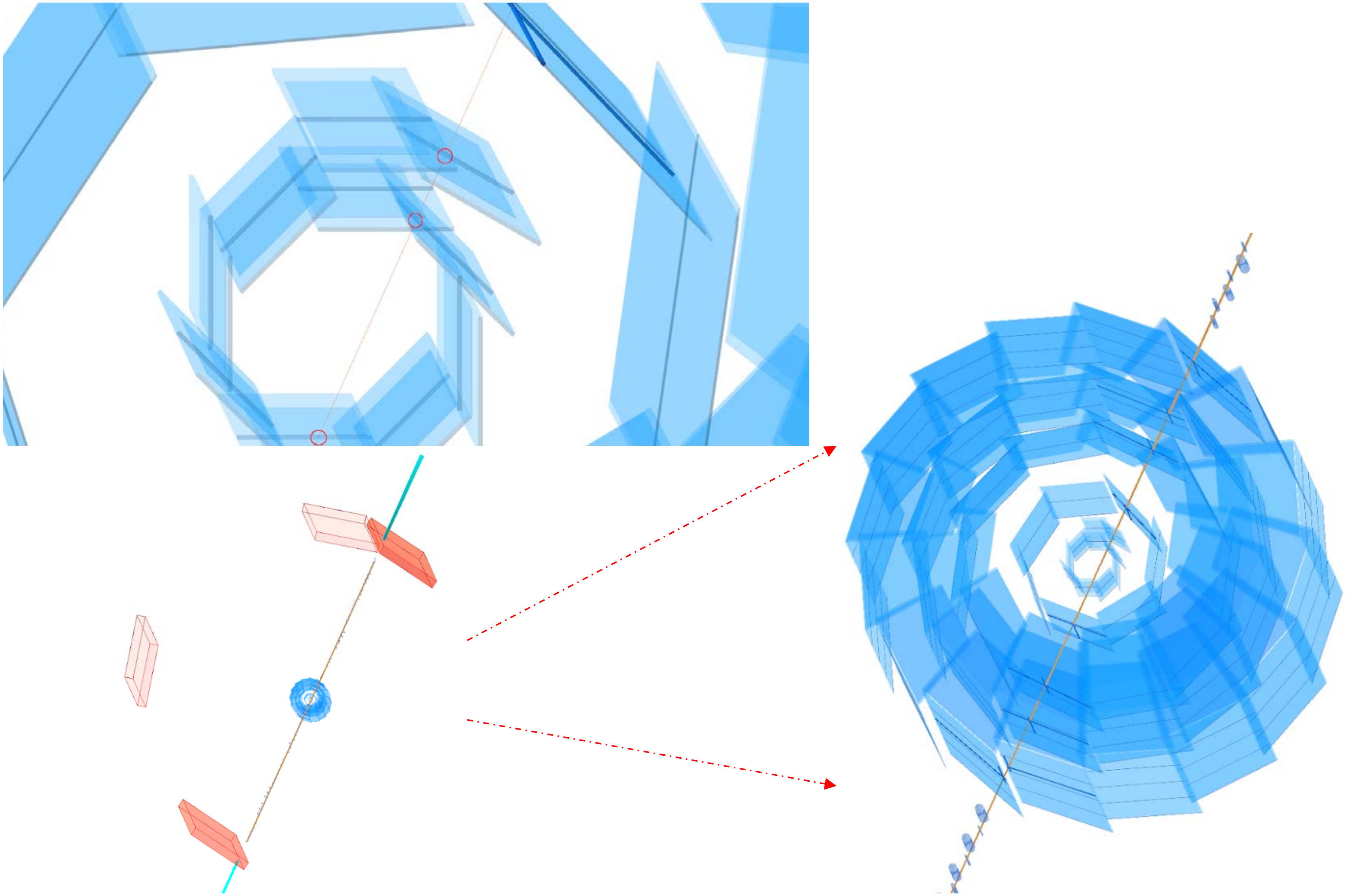


+X mount on PXD (Oct 3, 2018)

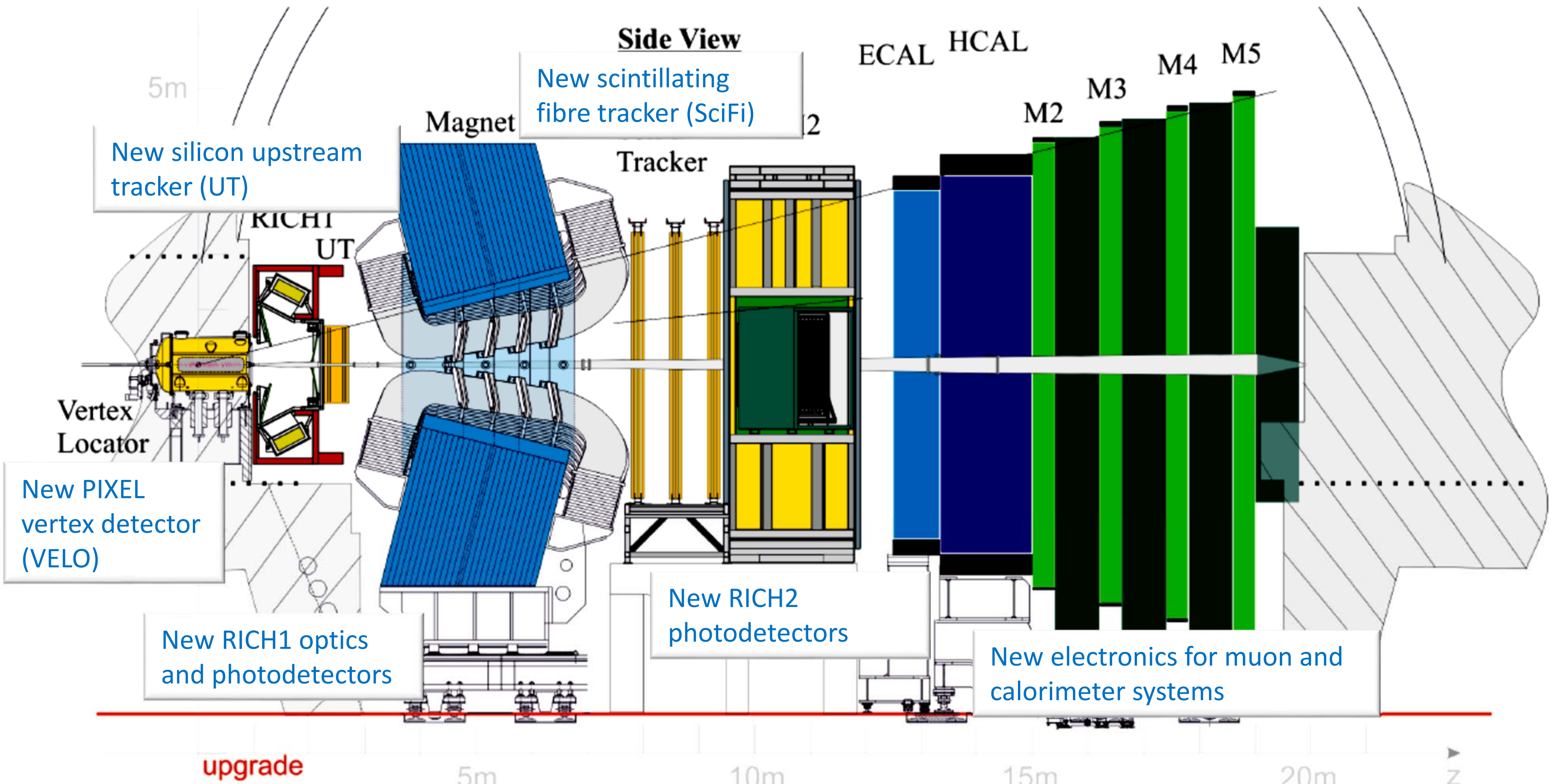
And completed… (Oct 4, 2018)



Belle II vertex detector in action



LHCb Upgrade: in progress



- $50\,fb^{-1}$, $2{\times}10^{33}\,cm^{-2}\,s^{-1}$
- All front-end electronics read out at 40 MHz
- 30 MHz avg. input to a full software trigger

LHCb Vertex LOcator upgrade

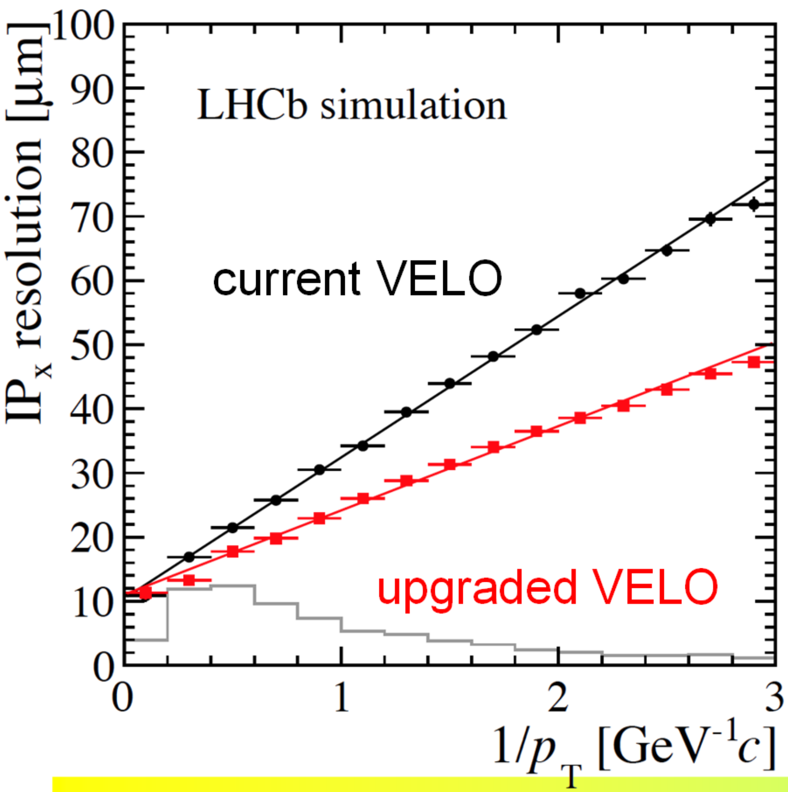
The upgraded VELO will be installed in the 2019-2020 shutdown to take data in Run III

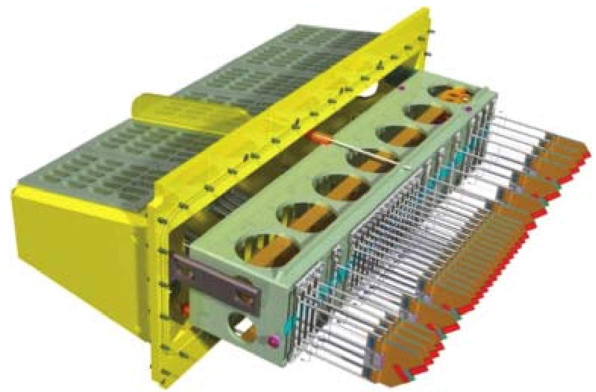
Operation @ 40 MHz and $2x10^{33}$ $cm^{-2}s^{-1}$ and

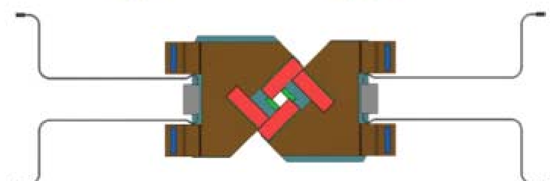
at 3.5 mm from the beams

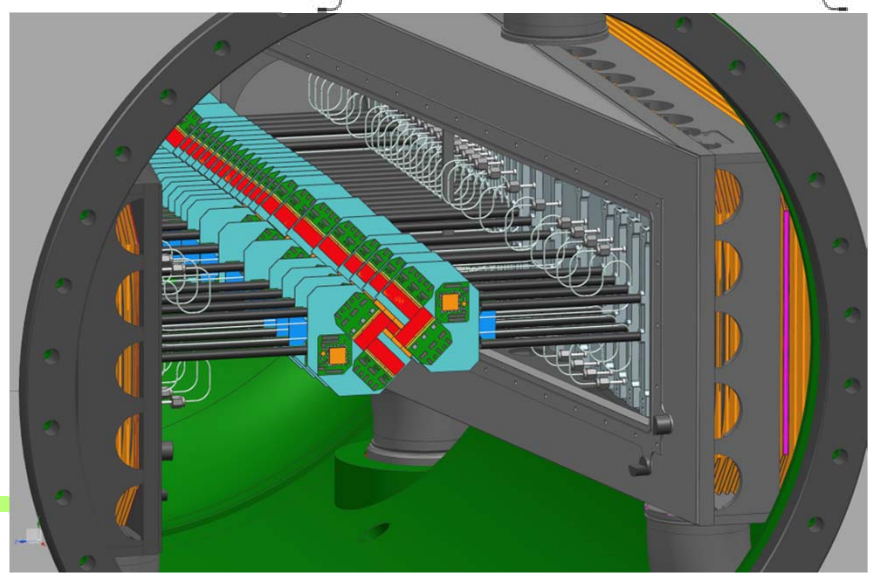
2.8 Tb/s data rates

8×10^{15} 1 MeV n_{eq} cm^{-2} max fluence

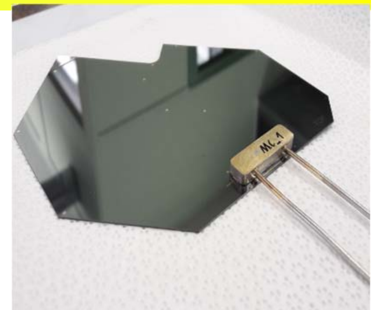






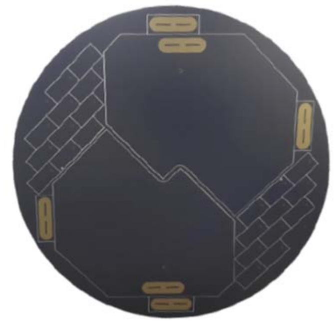


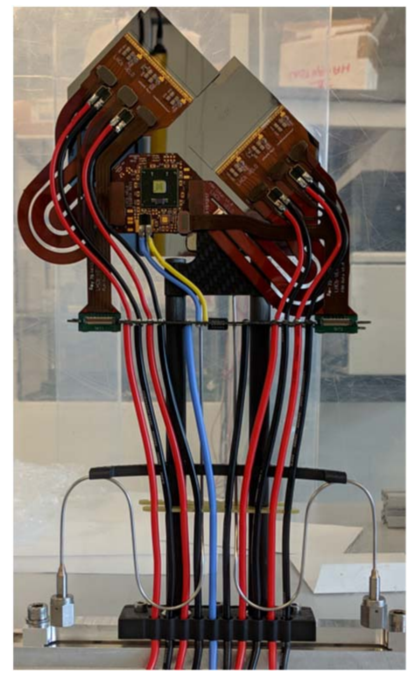
LHCb Vertex LOcator upgrade

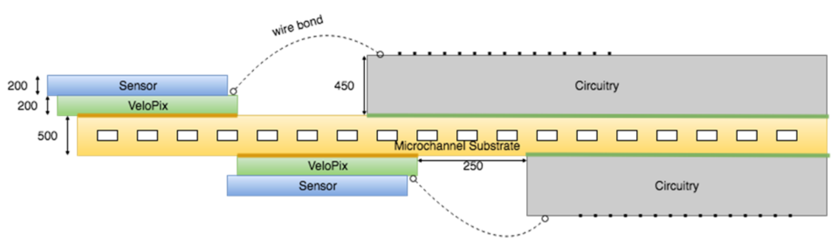


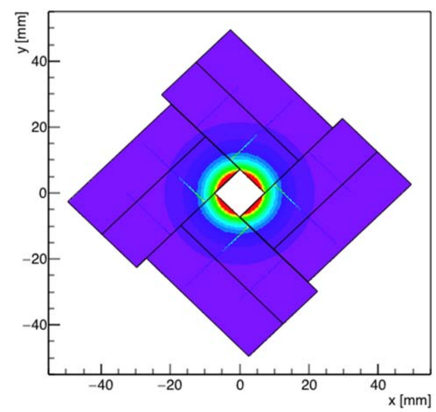
Micro-channel cooling

- 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





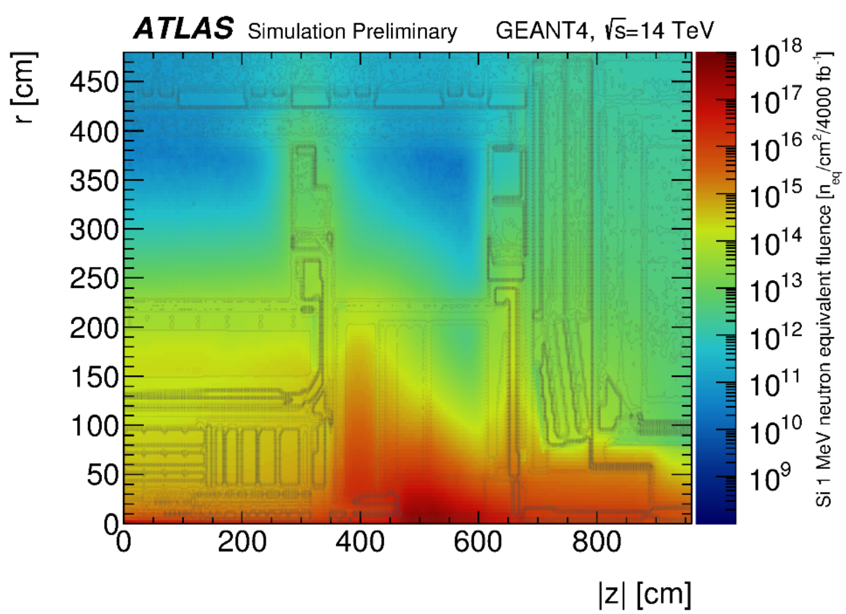


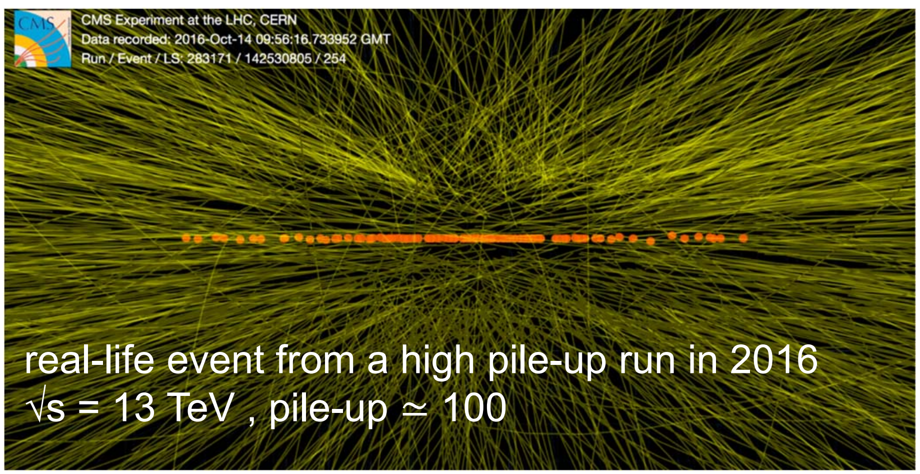


The HL-LHC environment

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





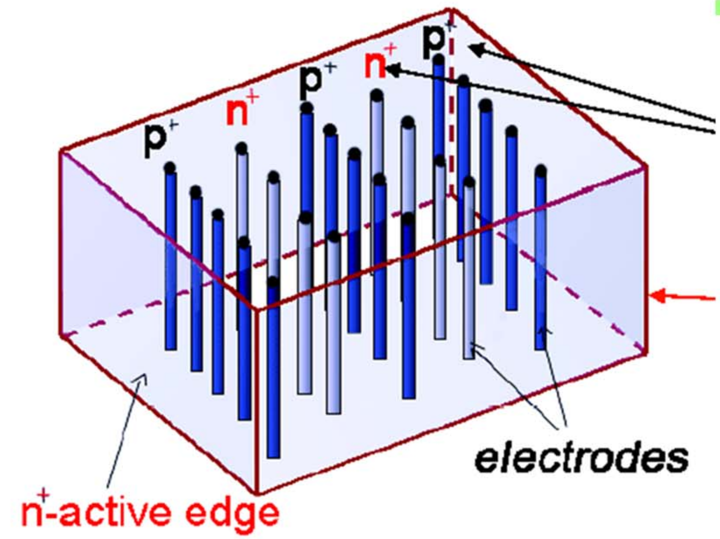
Silicon particle detectors: directions for the future

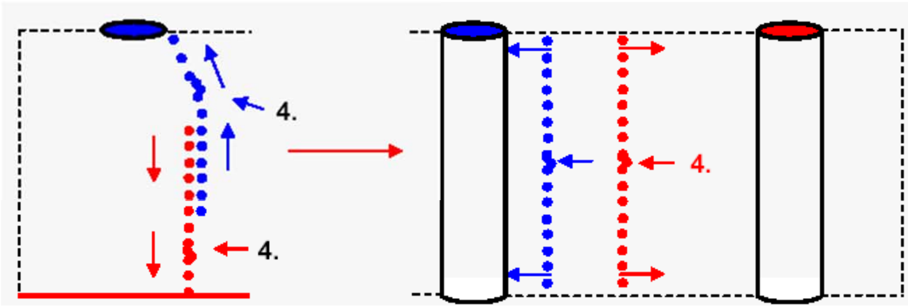
- Extreme radiation hardness – 3D detectors (hybrid technology – possibly also developments into monolitic)

- 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





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

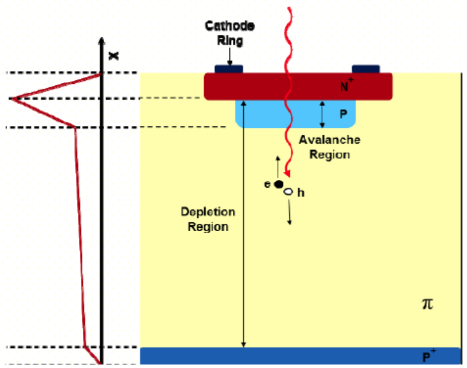
Limitations

- 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

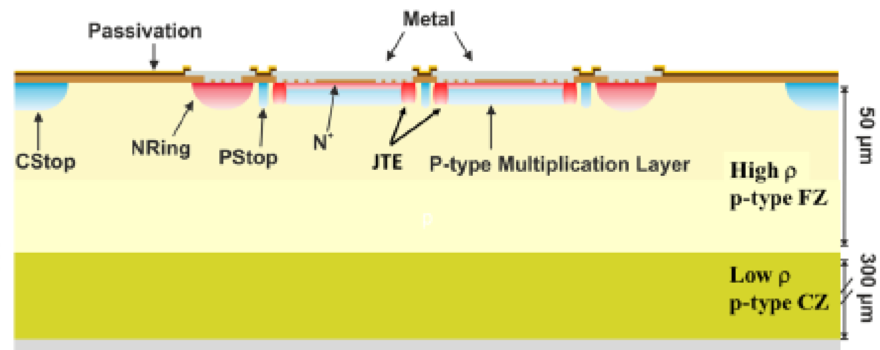
Low Gain Avalanche Detectors (LGAD)

- 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

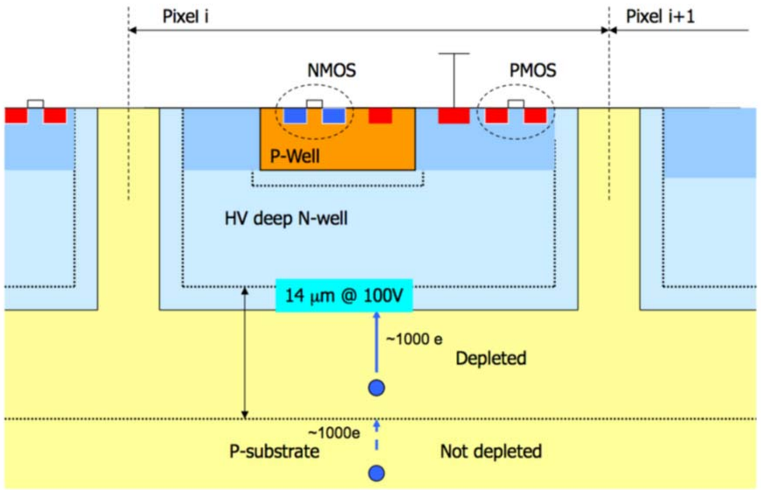
- Gain very sensitive to p+ layer doping and process parameters (~1e16 cm^{-3}, ~2 mm deep)
- Gains of up to 100 achieved giving excellent timing resolution of 26 ps for thin LGADs
- Currently the best technology for achieving excellent timing measurement for MIP – will be employed at ATLAS and CMS experiments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

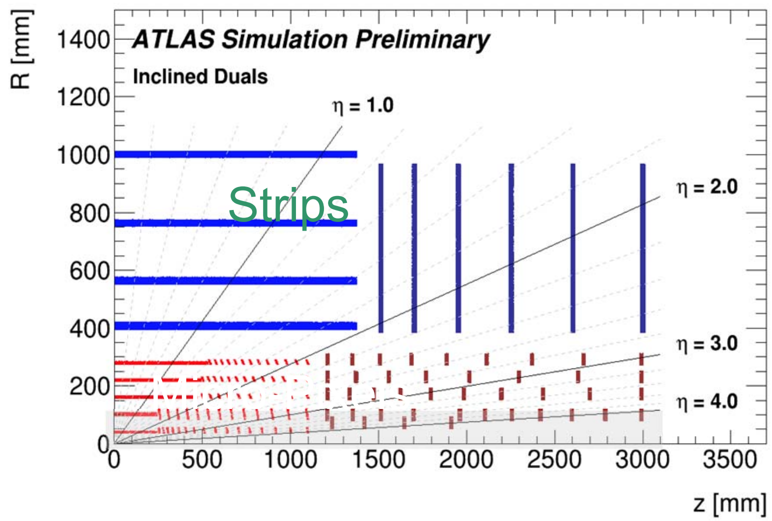
- Different substrates often limited by vendor – up to full depletion of 300 mm
- Excellent position resolution

Limitations:

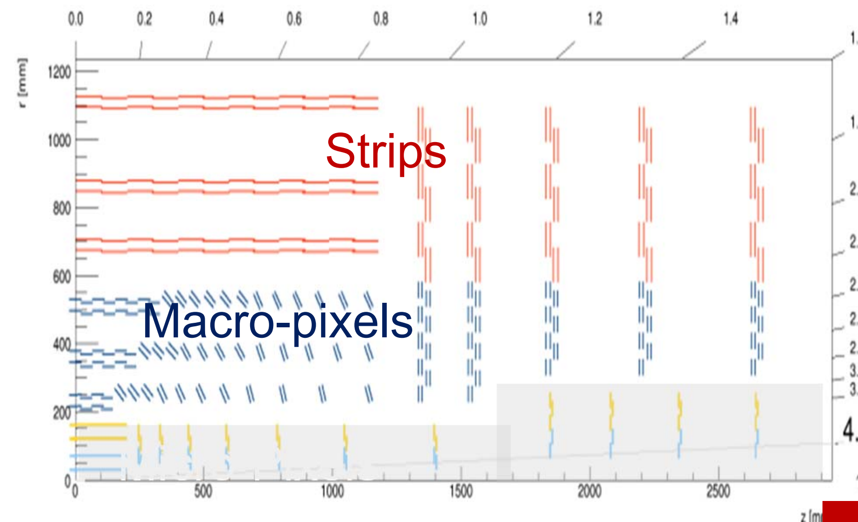
- Radiation hardness – problem of acceptor removal which changes detector performance
- Speed – for timing applications is not yet optimal
- SOI substrates or different other designs/processes including “Shallow Trench Isolation” affect charge collection

HL-LHC

Doublet layers: 2Strip, Pixel-Strip to provide trigger information at L1

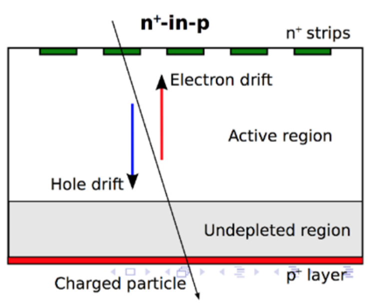


η<4

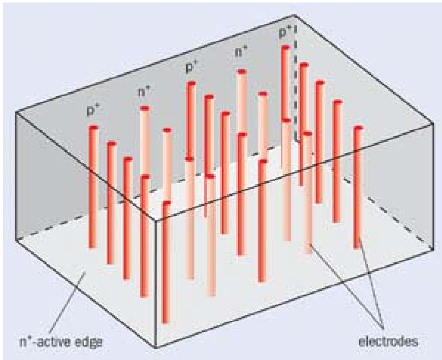


η<4

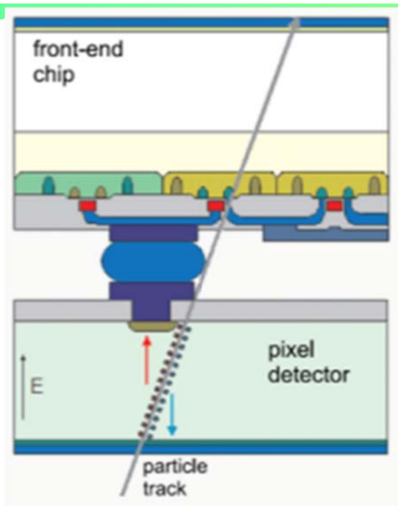
- Easy Extraction
- Inclined layers
- All n-in-p sensors with different thickness



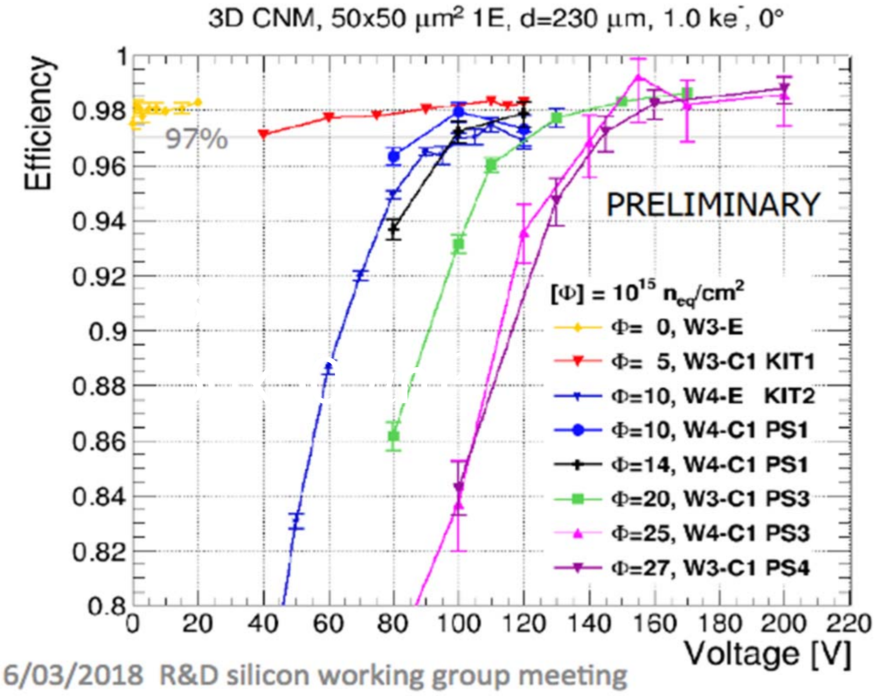
3D sensors in the innermost layers



Hybrid detectors

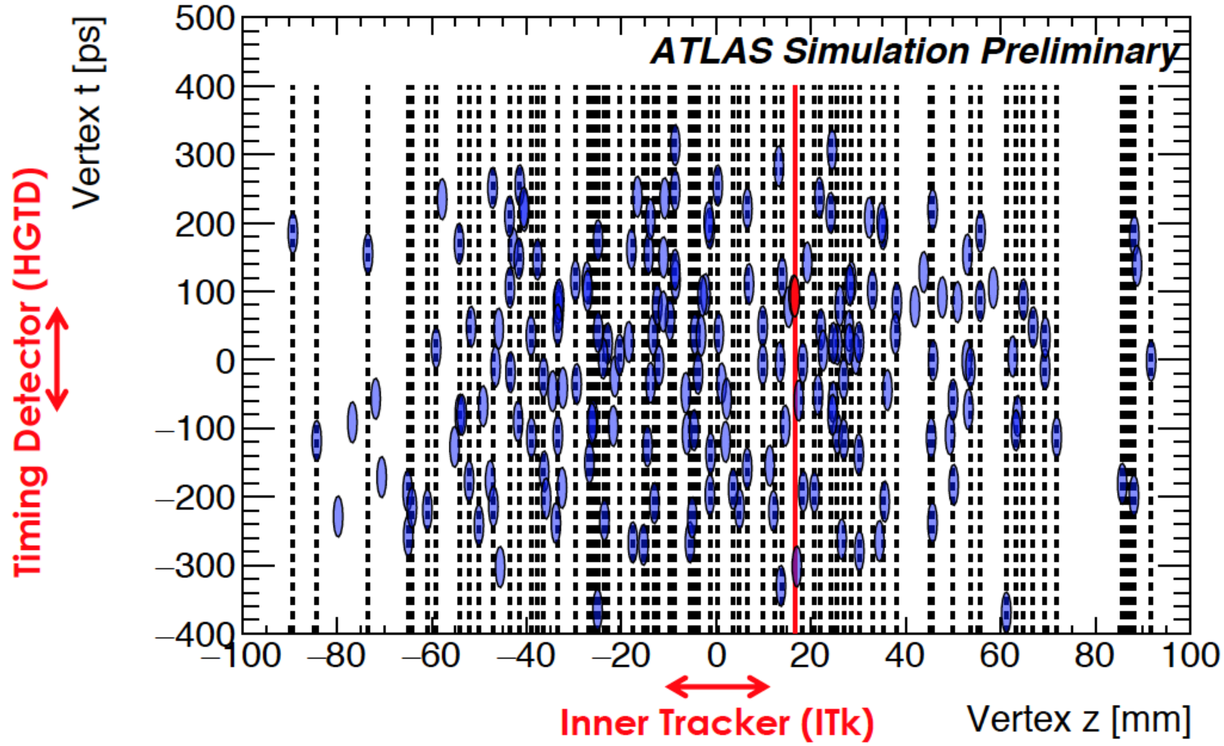


Over 98% efficiency up to 2.7 x 10^{16} n_{eq}/cm^2 with a bias voltage of 150 V



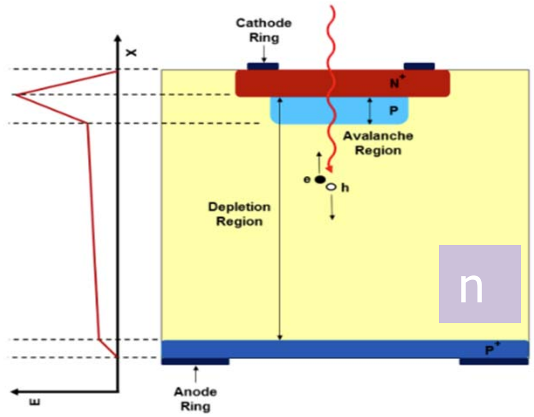
- 3D and Planar sensors can reach a radiation hardness of >10^{16} n_{eq}/cm^2
- Further development needed to achieve better lithography for smaller (25×100μm²) 3D sensors
- Joint CERN RD53 development of readout chip with 65 nm CMOS technology between ATLAS and CMS

Timing

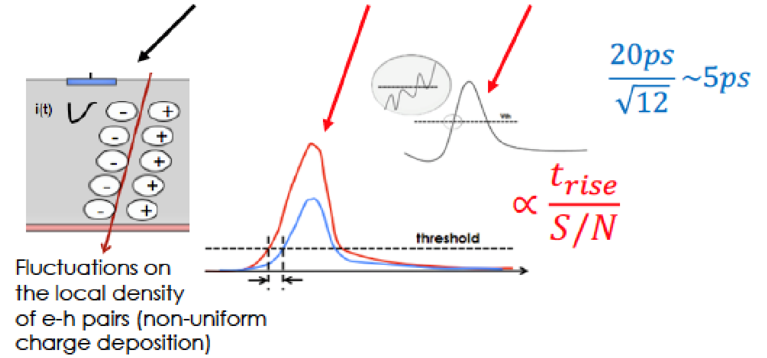


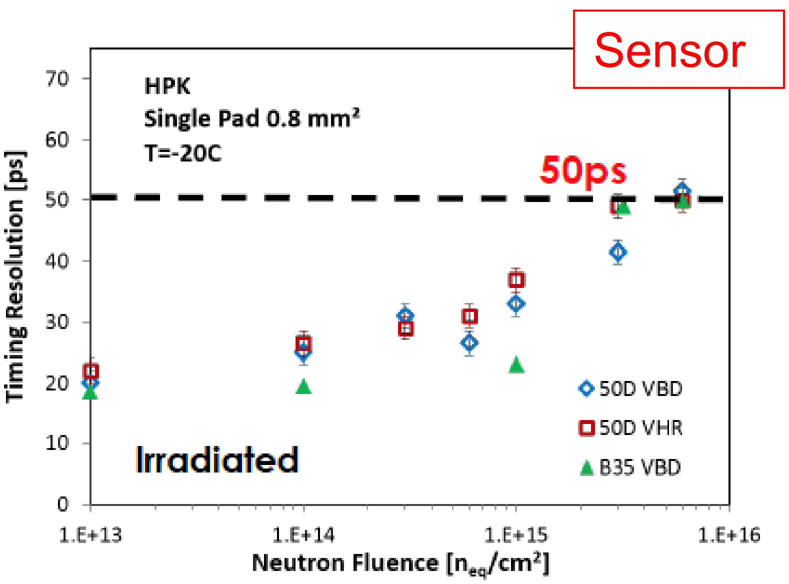
Exploit the time spread of collisions to reduce the pileup contamination

LGAD

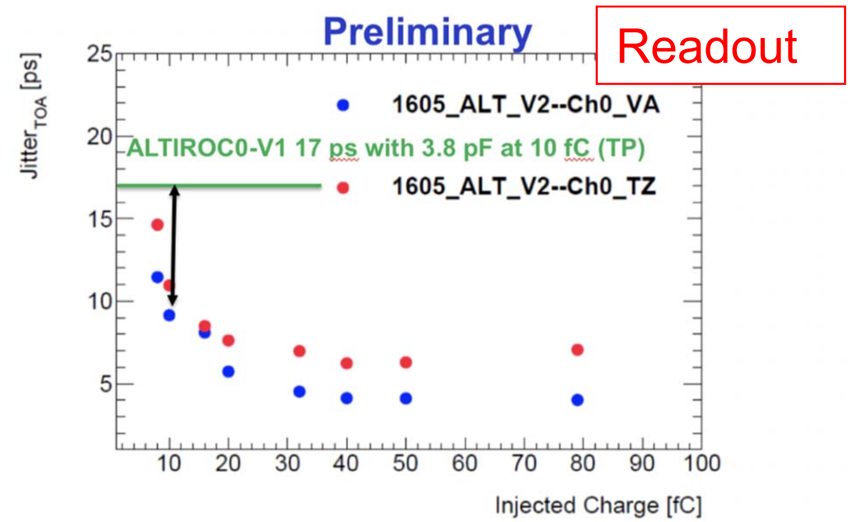


$$\sigma_t^2 = \sigma_{Landau}^2 + \sigma_{time-walk}^2 + \sigma_{jitter}^2 + \sigma_{TDC}^2 + \sigma_{clock}^2$$





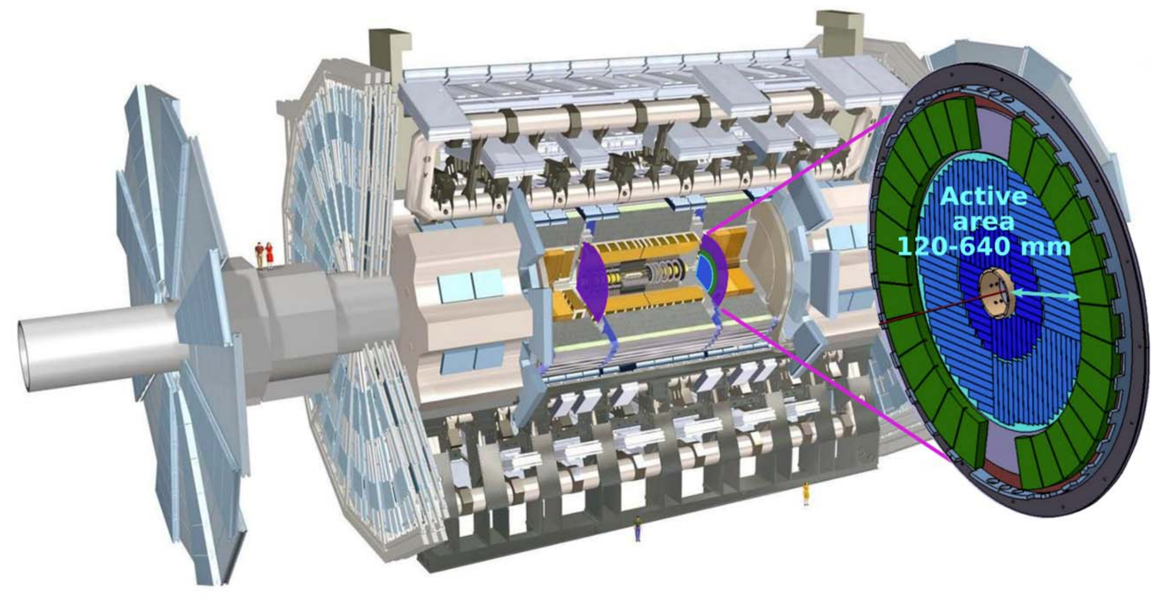
σ(t) < 50 ps @ 5 x 10^{15} n_{eq}/cm^2



Still need to check that input parasitic capacitance on PCB is similar for V2 and V1

ALTIROC0-V1 17 ps with 3.8 pF at 10 fC

Timing layers in ATLAS



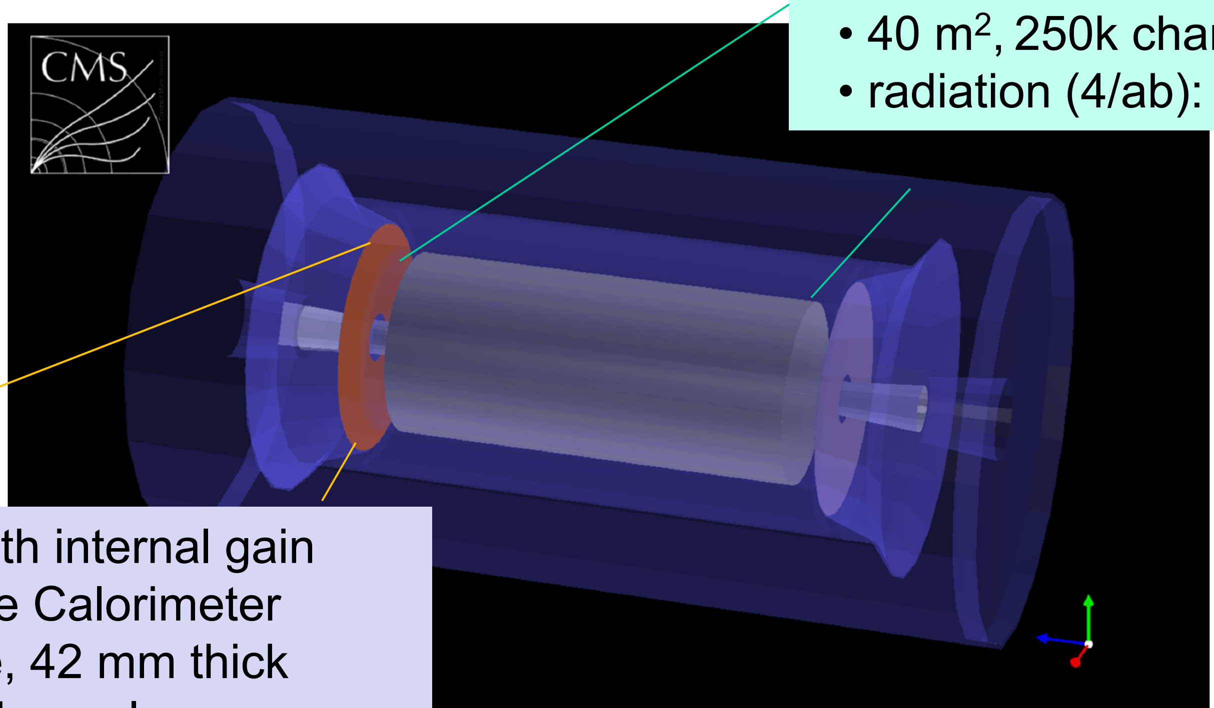
- Low Gain Avalanche Detector (LGADs) pixel size: 1.3x1.3 mm^2
- Excellent time resolution (30ps/track), flat in η
- radiation-hard (up to $3.7x10^{15}$ n_{eq}/cm^2 and 4.1MGy)
- Occupancy< 10%

- 2 double planar layers per endcap providing an average number of hits per track of 2-3
- Pseudorapidity coverage: $2.4<|\eta|<4.0$
- Radial extension: 12 cm < R < 64 cm
- z position: 3.5 m
- Thickness in z: 7.5cm

Timing layer at CMS

- Thin layer between the tracker and the calorimeters
- ~30 ps resolution for charged tracks (above 0.7 GeV)
- Hermetic coverage for |η| < 3.0

Barrel: LYSO tiles + SiPM readout at tracker-ECAL interface, 25 mm thick
- 40 m^2, 250k channels
- radiation (4/ab): 2×10^{14} n_{eq}/cm^2

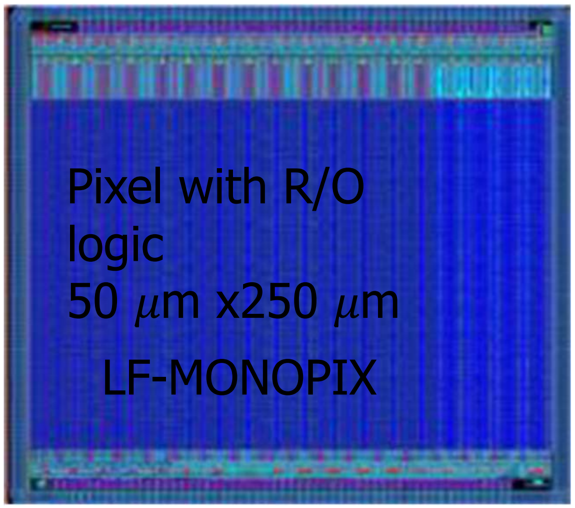


Endcap: Si with internal gain (LGAD) on the Calorimeter Endcap nose, 42 mm thick
- 12 m^2, 4M channels
- radiation (4/ab): ~10^{15} n_{eq}/cm^2

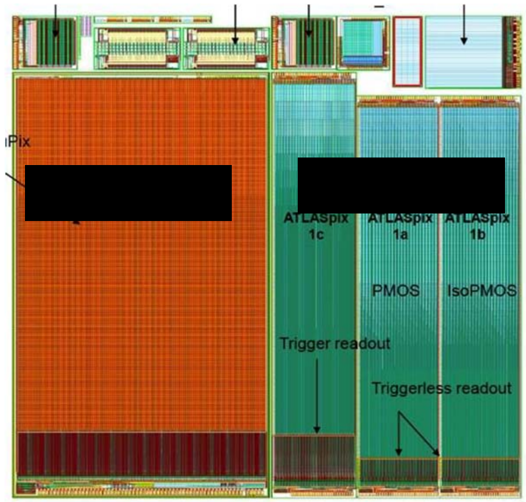
ATLAS CMOS demonstrator program

WITH SEVERAL FOUNDRIES

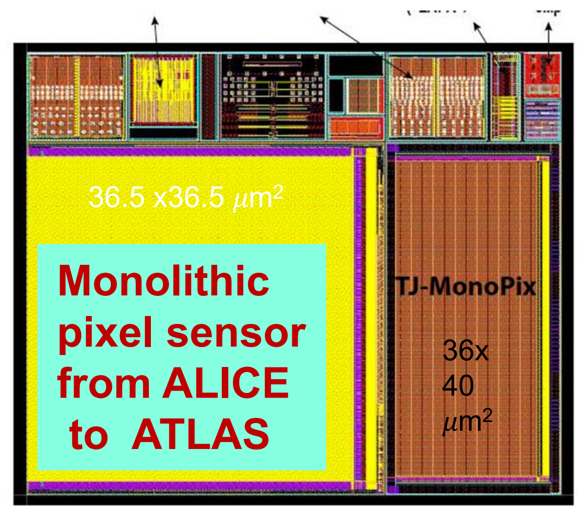
LFOUNDRY



ams



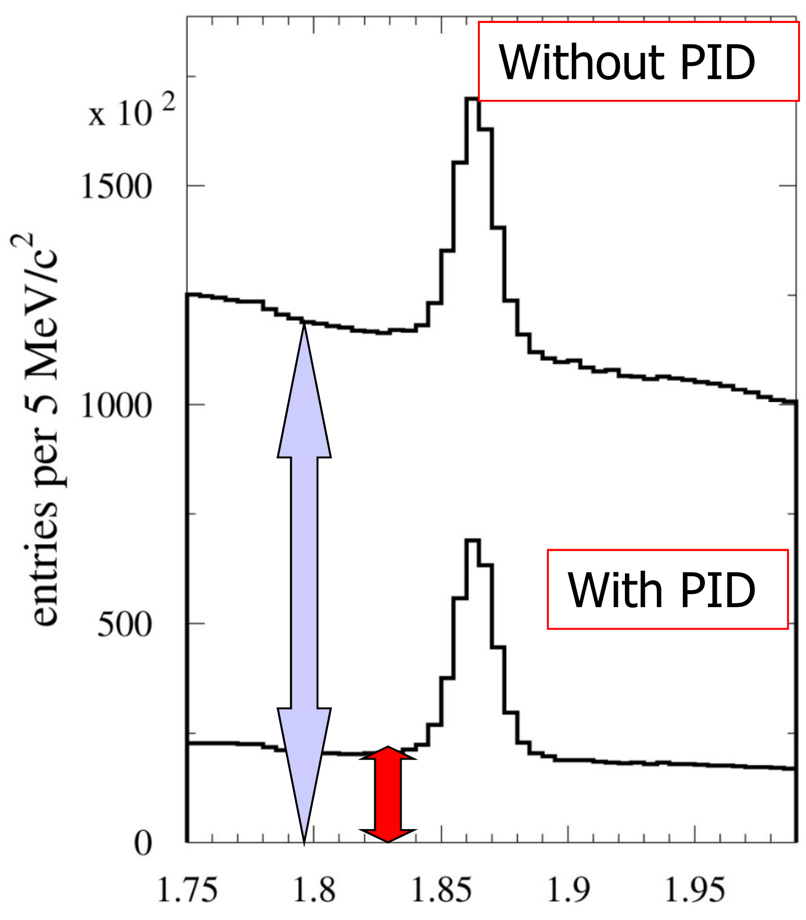
TOWERJAZZ

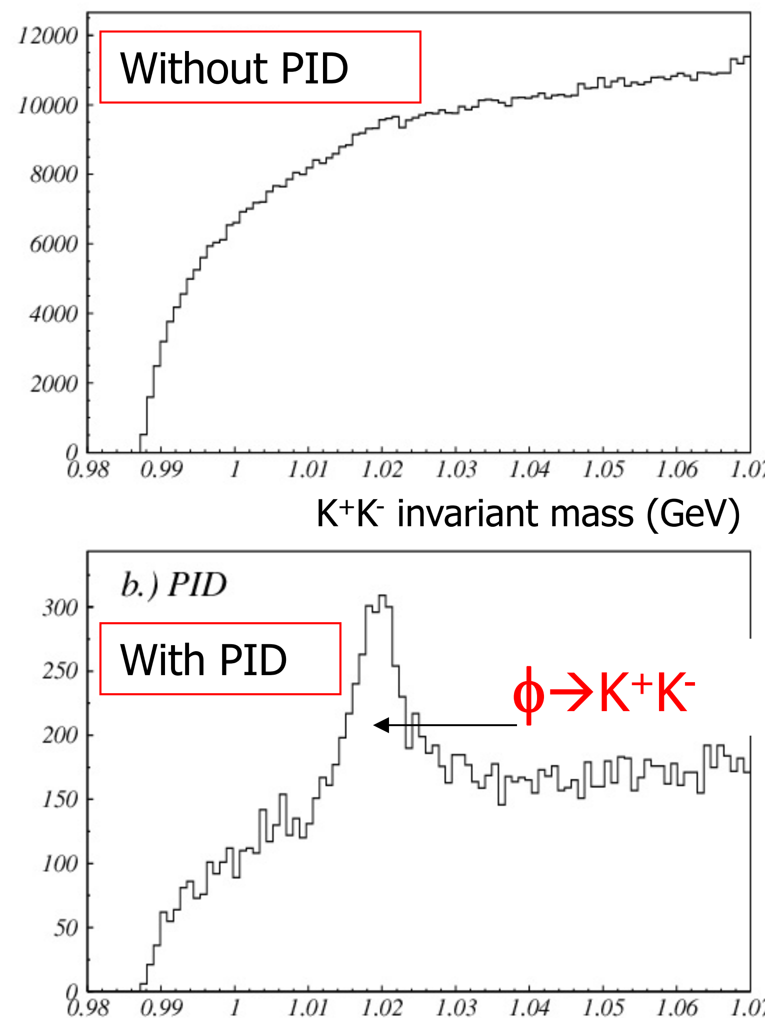


Depleted CMOS did not make it for the next upgrade, but remains extremely important for further LHC upgrades, CepC, CLIC, ILC, FCCee and FCChh

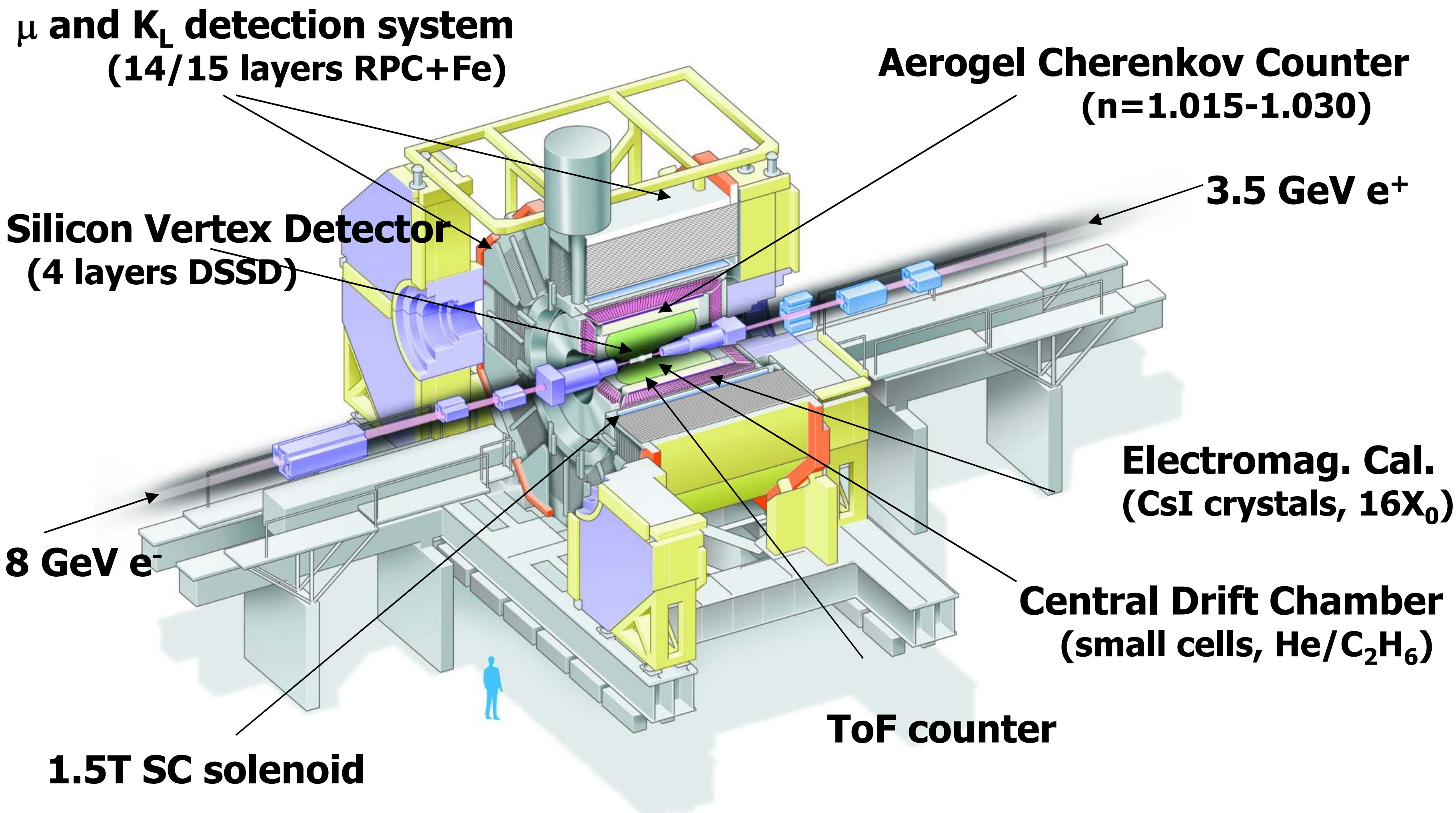
Particle identification

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

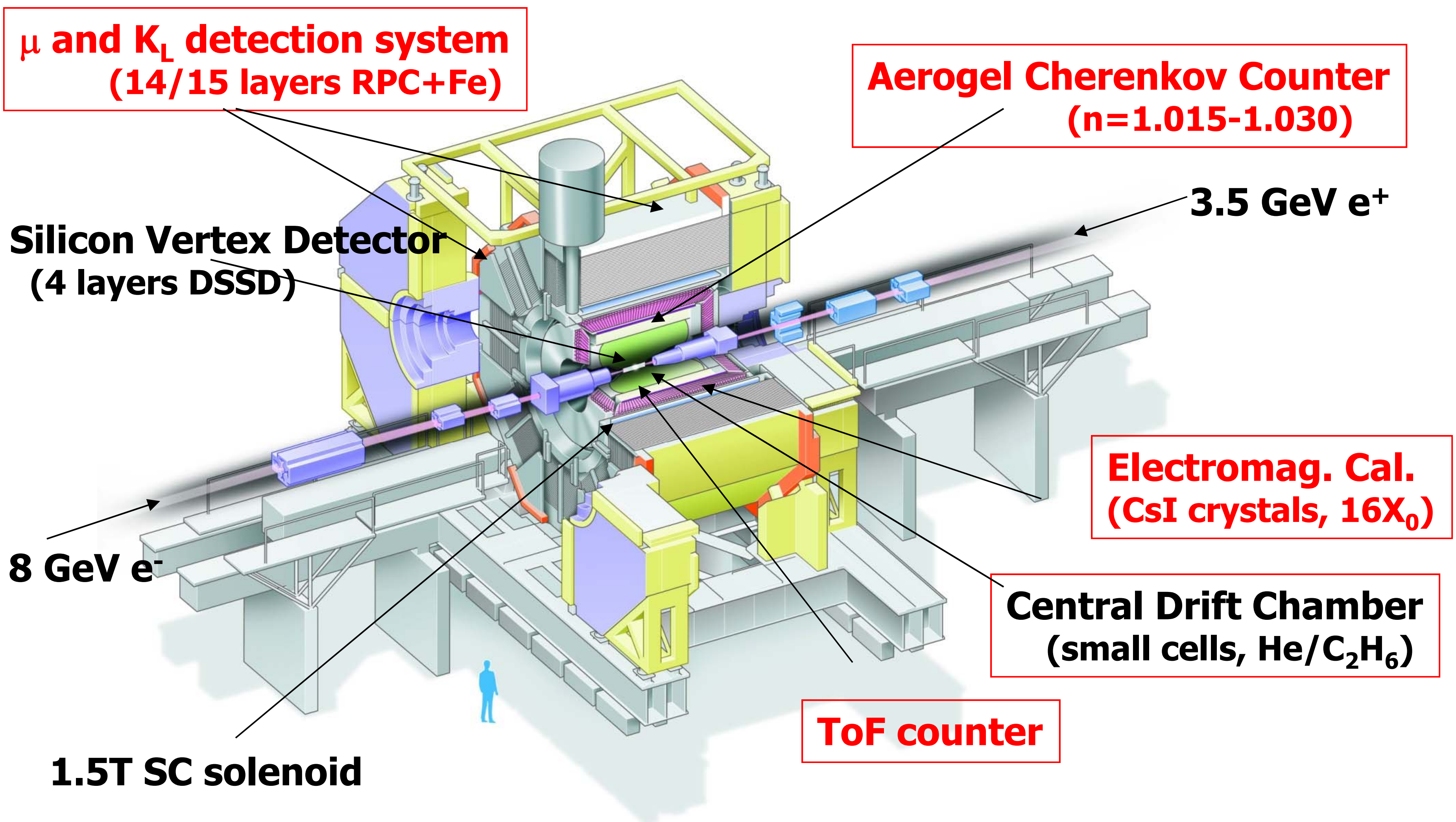




Example: Belle



Particle identification systems in Belle



Identification of charged particles

Particles (e, μ, π, K, p) in the final state are identified by their mass or by the way they interact.

Determination of mass: from the relation between momentum and velocity, $p=\gamma mv$ (p is known - radius of curvature in magnetic field)

→Measure velocity by:

- time of flight
- ionisation losses dE/dx
- Cherenkov photon angle (and/or yield)
- transition radiation

Mainly used for the identification of hadrons.

Identification through interaction: electrons and muons

- muon systems
- calorimeters

Identification of charged particles

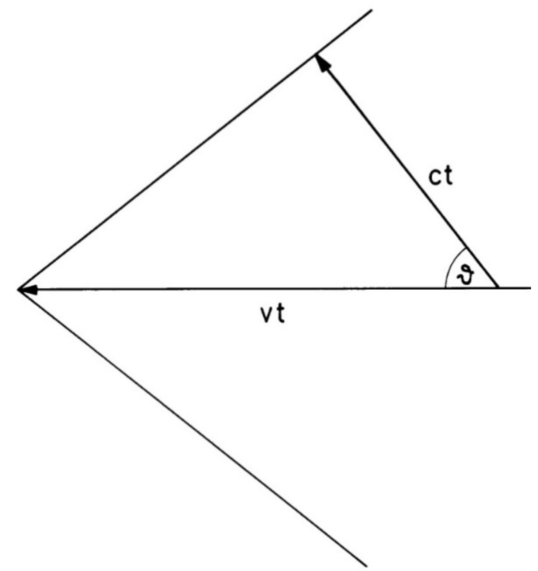
Particles (e, μ, π, K, p) in the final state are identified by their mass or by the way they interact.

Determination of mass: from the relation between momentum and velocity, $p=\gamma mv$ (p is known - radius of curvature in magnetic field)

→Measure velocity by:

- time of flight
- ionisation losses dE/dx
- Cherenkov photon angle (and/or yield)
- transition radiation

Mainly used for the identification of hadrons.



Identification through interaction: electrons and muons

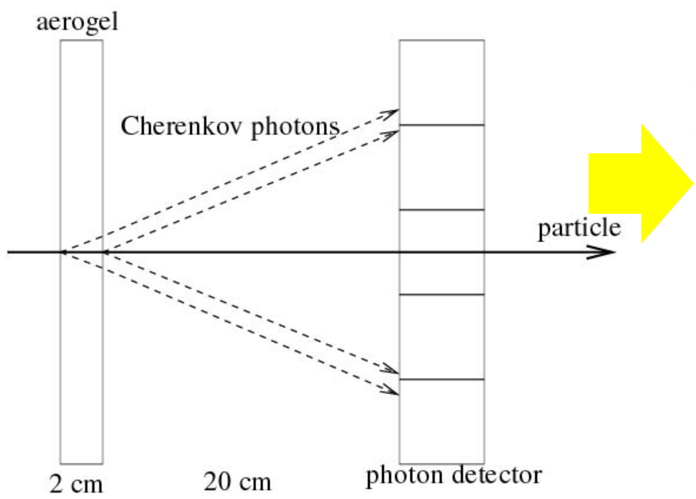
- muon systems
- calorimeters

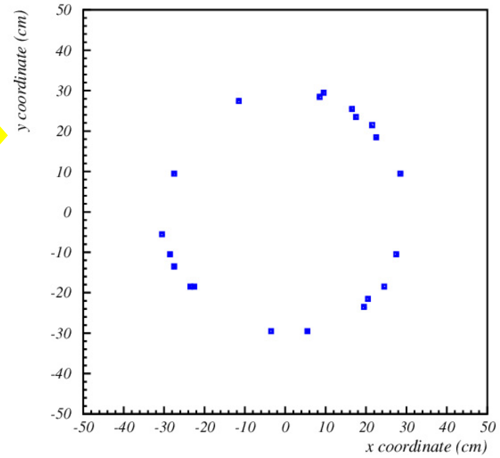
Measuring the Cherenkov angle

$\cos\theta = c/nv = 1/\beta n$

Idea: transform the direction into a coordinate → ring on the detection plane

→ Ring Imaging Cherenkov (RICH) counter

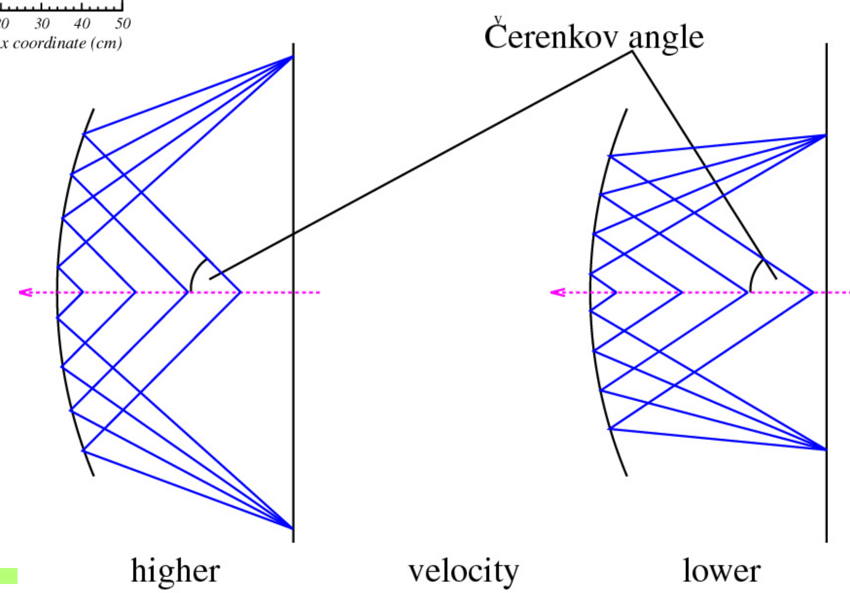




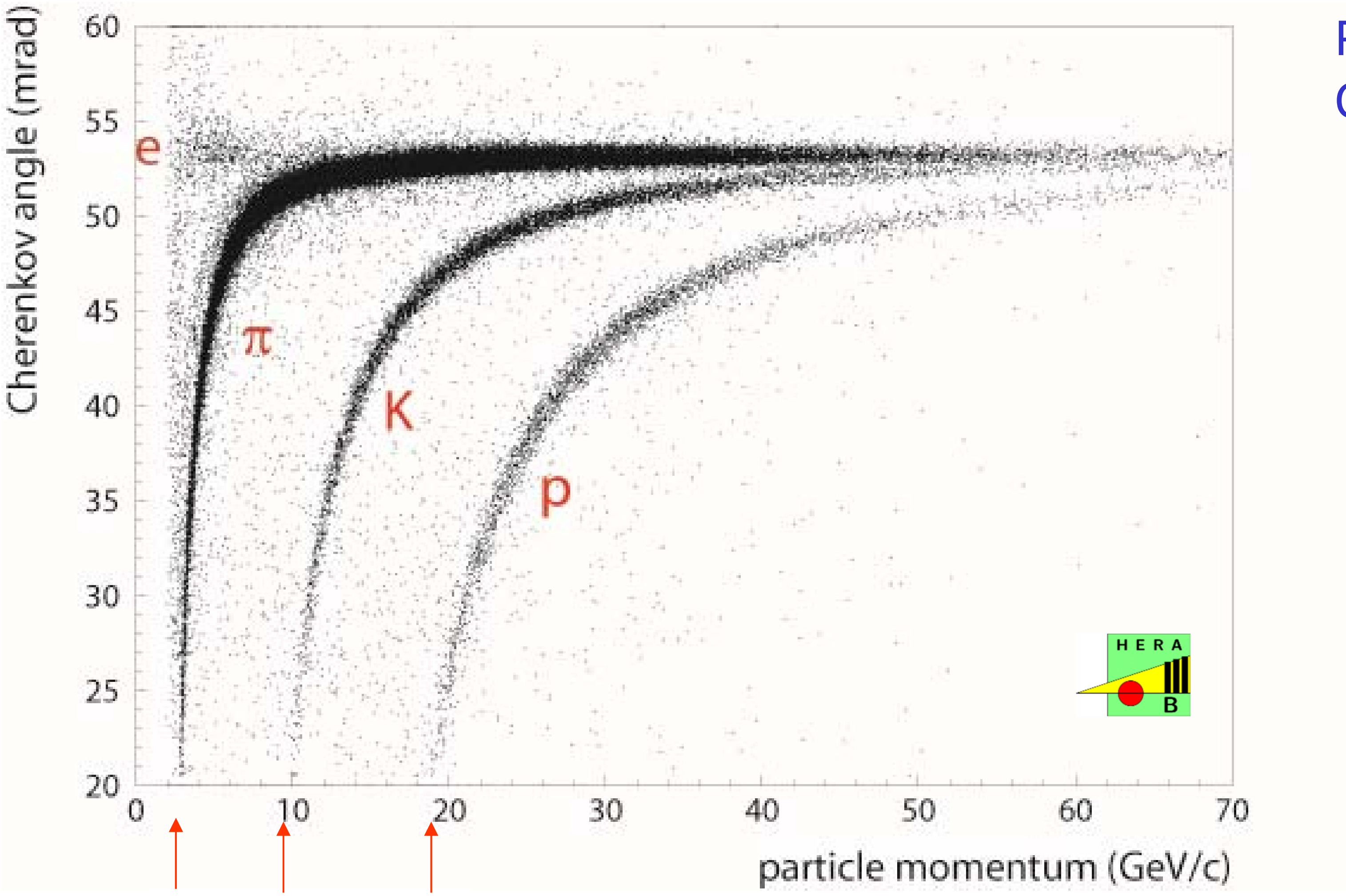
Proximity focusing RICH

RICH with a

focusing mirror



Measuring Cherenkov angle



Radiator: C_4F_{10} gas

π K p

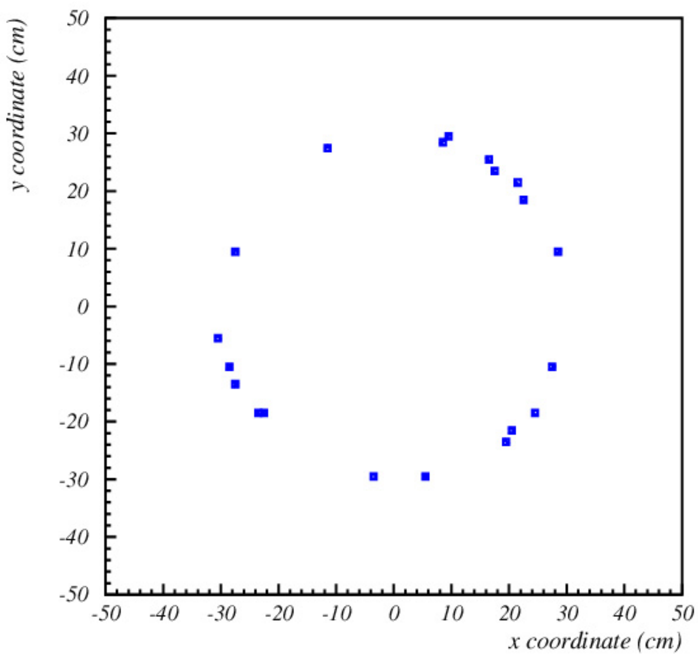
thresholds

Photon detection in RICH counters

RICH counter: measure photon impact point on the photon detector surface

→ detection of single photons with

- sufficient spatial resolution
- high efficiency and good signal-to-noise ratio (few photons!)
- over a large area (square meters)

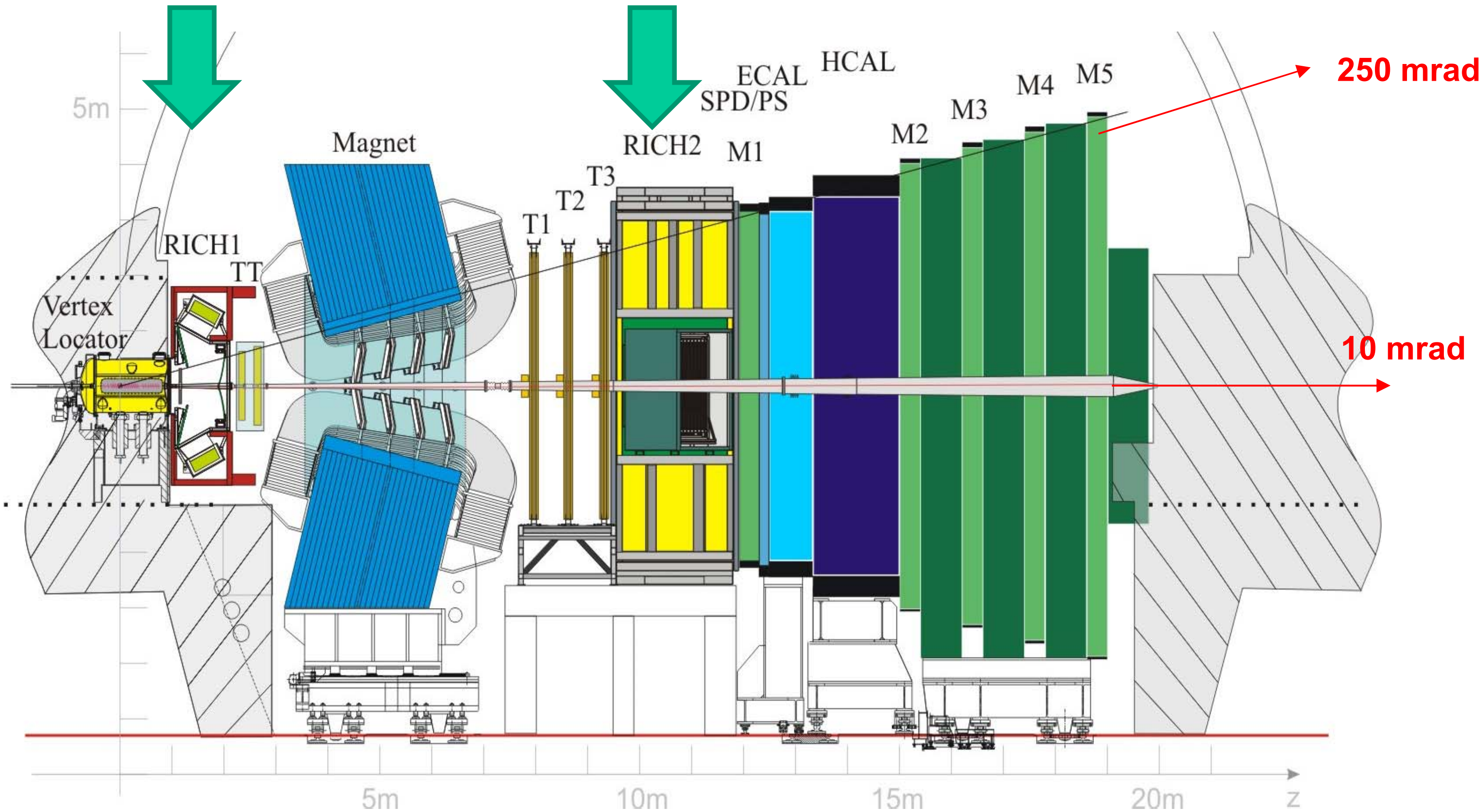


Special requirements:

- Operation in magnetic field
- High rate capability
- Very high spatial resolution
- Excellent timing (time-of-arrival information)

Photon detector is the most crucial element of a RICH counter

The LHCb RICH counters



Vertex reconstruction:
VELO

Trigger:
Muon Chambers
Calorimeters
Tracker

PID:
RICHes
Calorimeters
Muon Chambers

Kinematics:
Magnet
Tracker
Calorimeters

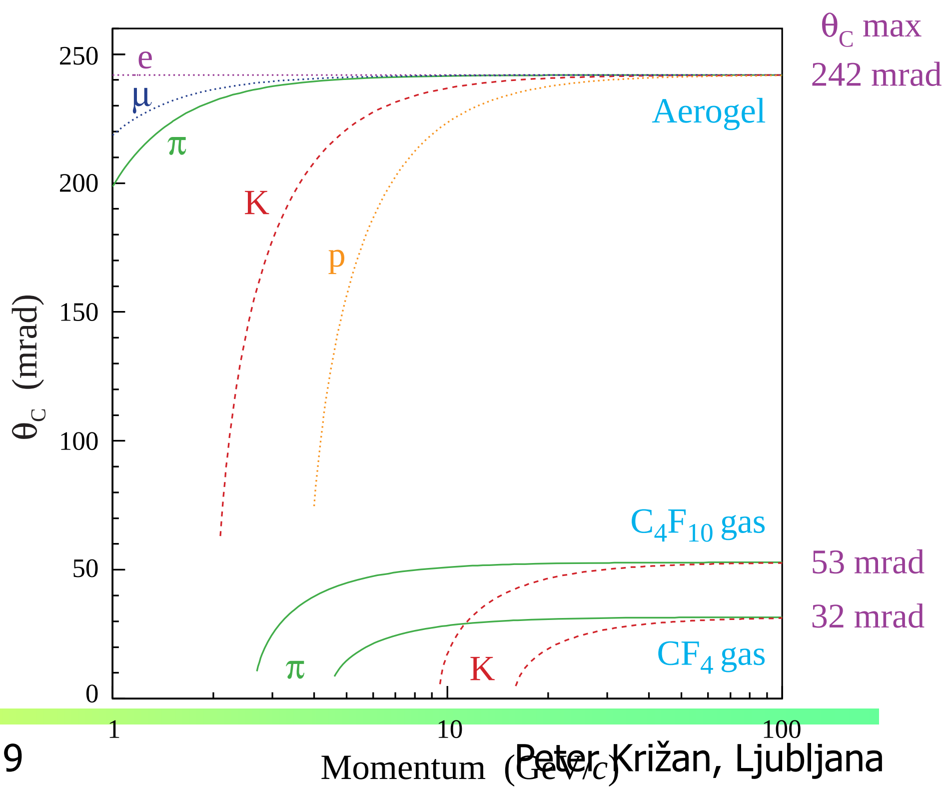
LHCb RICHes

Need:

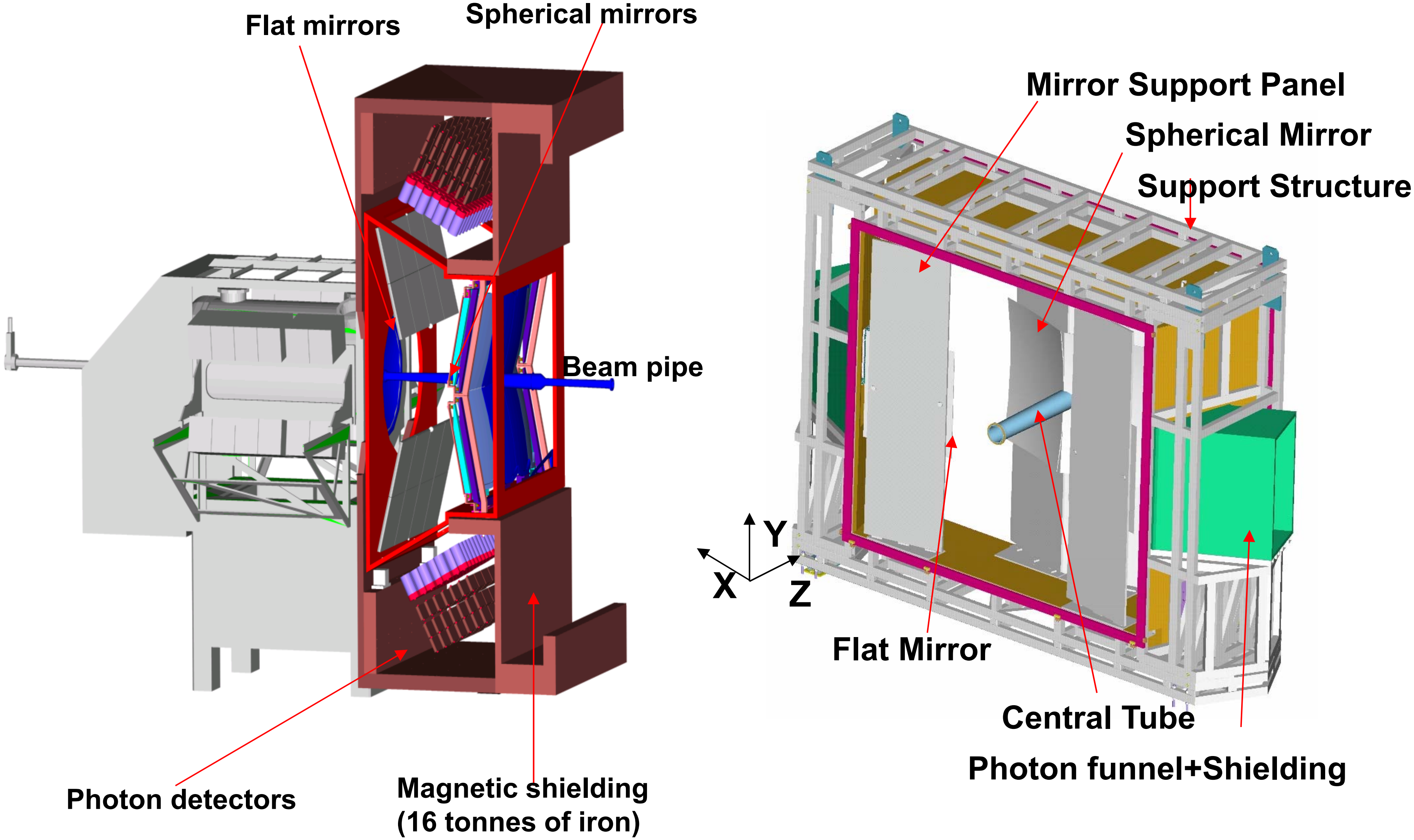
- Particle identification for momentum range ~2-100 GeV/c
- Granularity 2.5x2.5mm^2
- Large area (2.8m^2) with high active area fraction
- Fast compared to the 25ns bunch crossing time
- Have to operate in a small B field

→3 radiators

- Aerogel
- C_4F_{10} gas
- CF_4 gas



LHCb RICHes

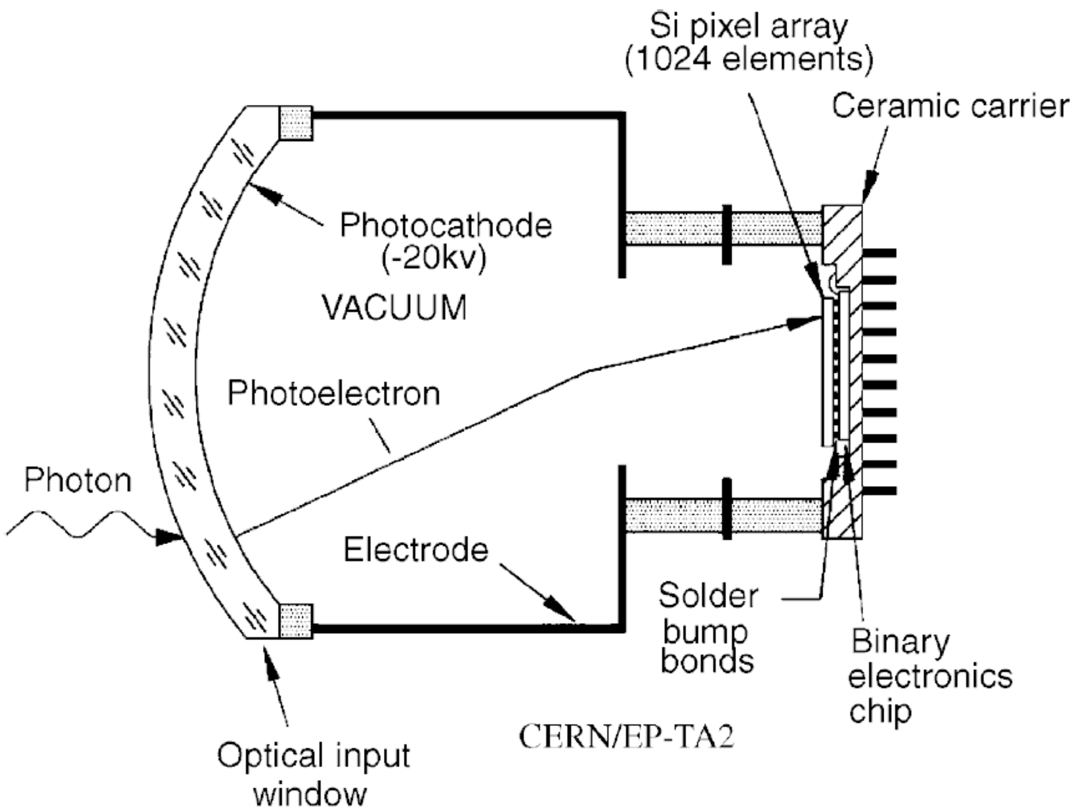


Flat mirrors
Spherical mirrors
Beam pipe
Photon detectors
Magnetic shielding
(16 tonnes of iron)
Mirror Support Panel
Spherical Mirror
Support Structure
Y
X
Z
Flat Mirror
Central Tube
Photon funnel+Shielding

LHCb RICHes

Photon detector: hybrid PMT (R+D with DEP) with 5x demagnification (electrostatic focusing).

Hybrid PMT: accelerate photoelectrons in electric field (~20kV), detect it in a pixelated silicon detector.



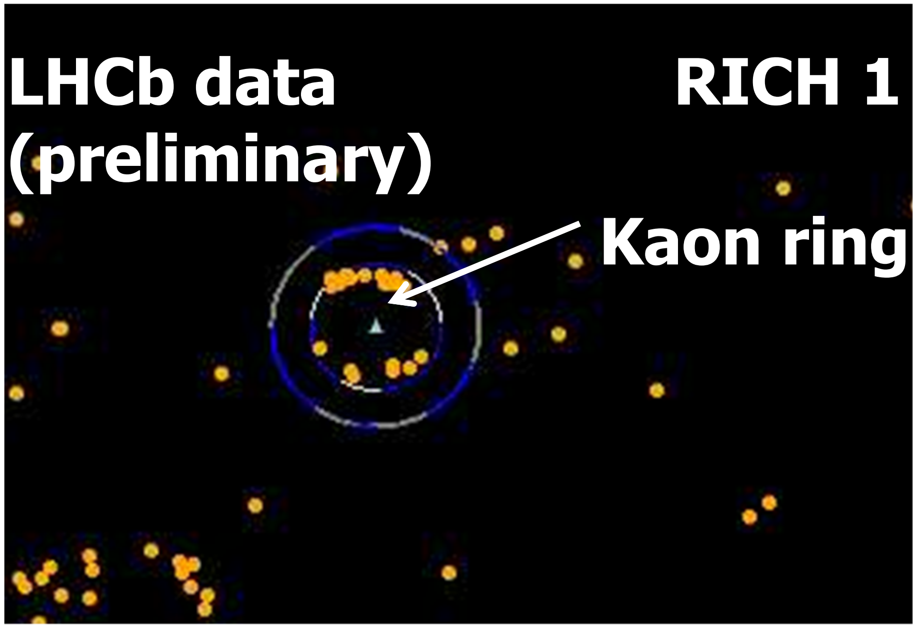
NIM A553 (2005) 333

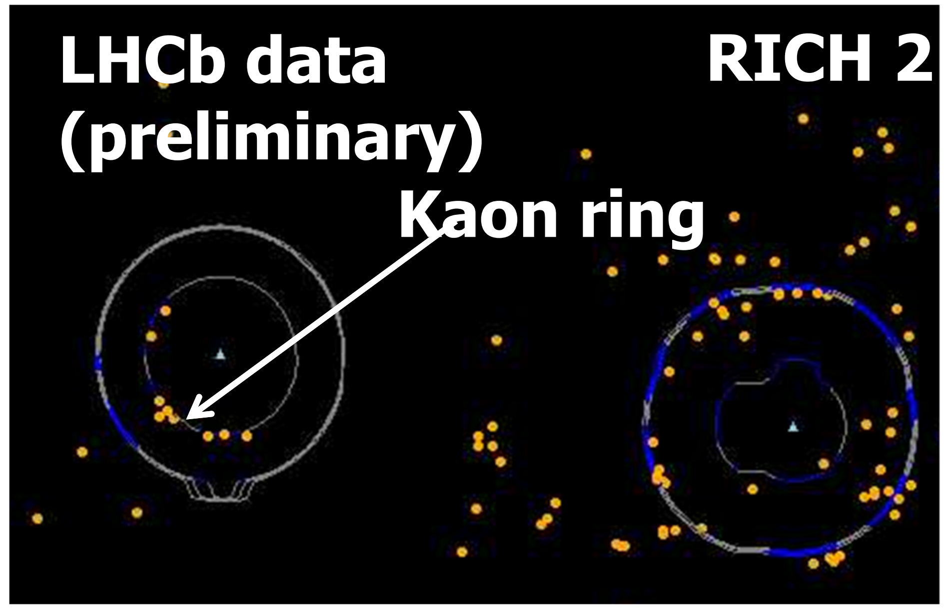
LHCb Event Display

RICH1

Early data, Nov/Dec 2009
LHC beams √s = 900 GeV

RICH2

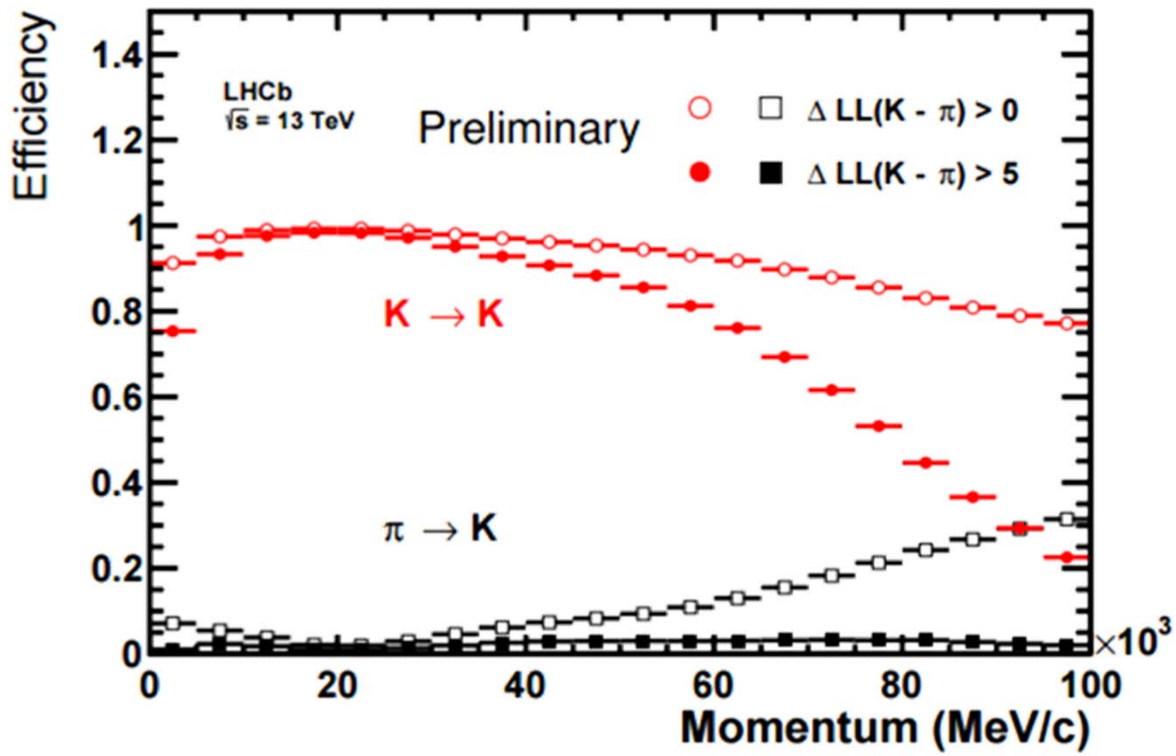




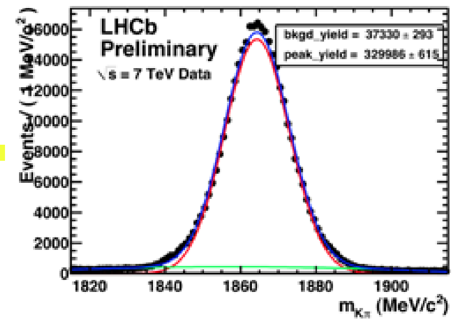
- Orange points → photon hits
- Continuous lines → expected distribution for each particle hypothesis

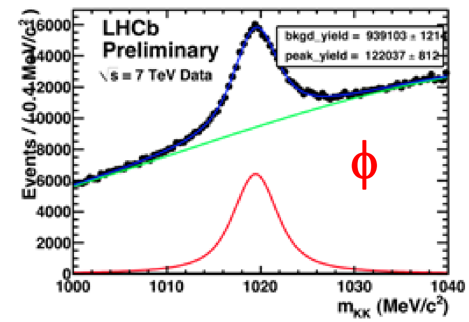
F. Muheim, RICH 2010

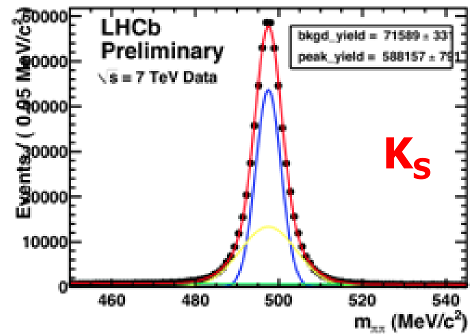
LHCb RICHes: performance

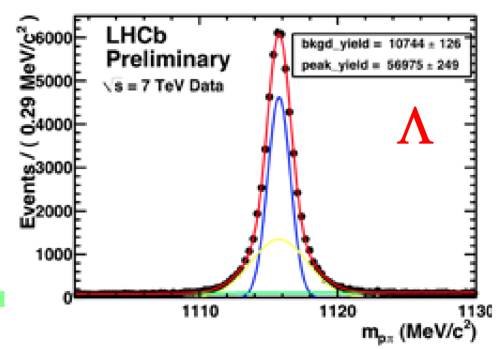


D from D*







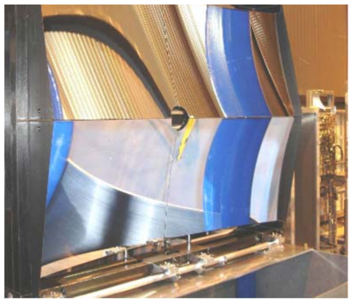


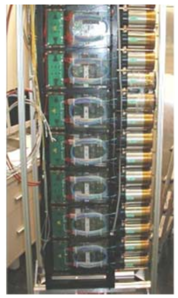
Efficiency and purity from data → excellent agreement with MC

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

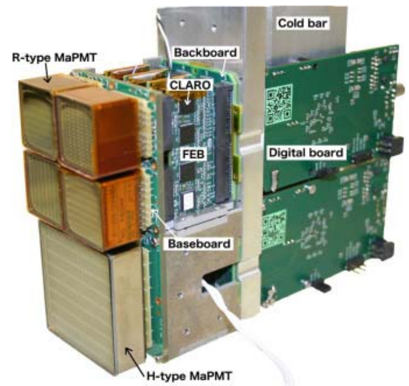
LHCb particle identification upgrade(s)

RICH Upgrade





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

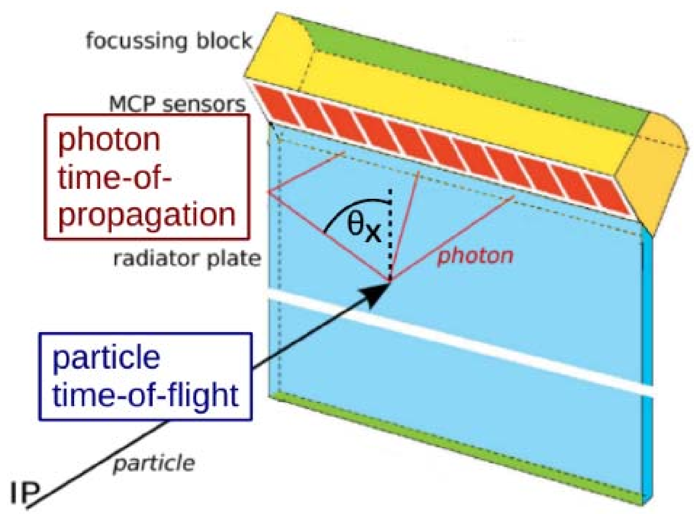


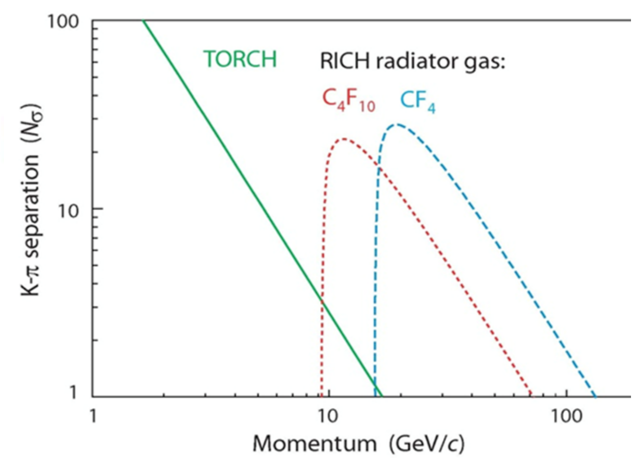
MaPMTs from Hamamatsu

Upgrade IA: New optics, photo detectors, new electronics

LS3

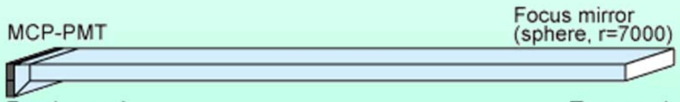
TORCH (Time Of internally Reflected CHerenkov light) ToF resolution ~10-15 ps (per track) using micro channel plate PMTs





Particle Identification Devices

Barrel PID: Time of Propagation Counter (TOP)



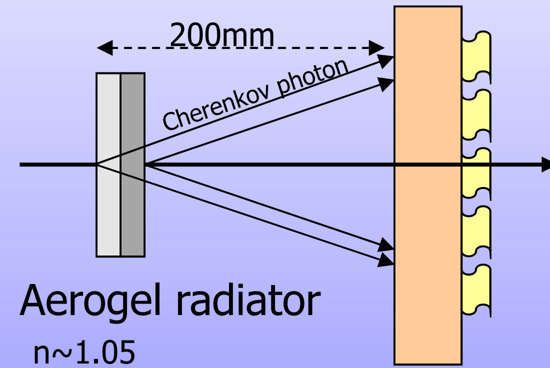
Quartz radiator

Focusing mirror

Small expansion block

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

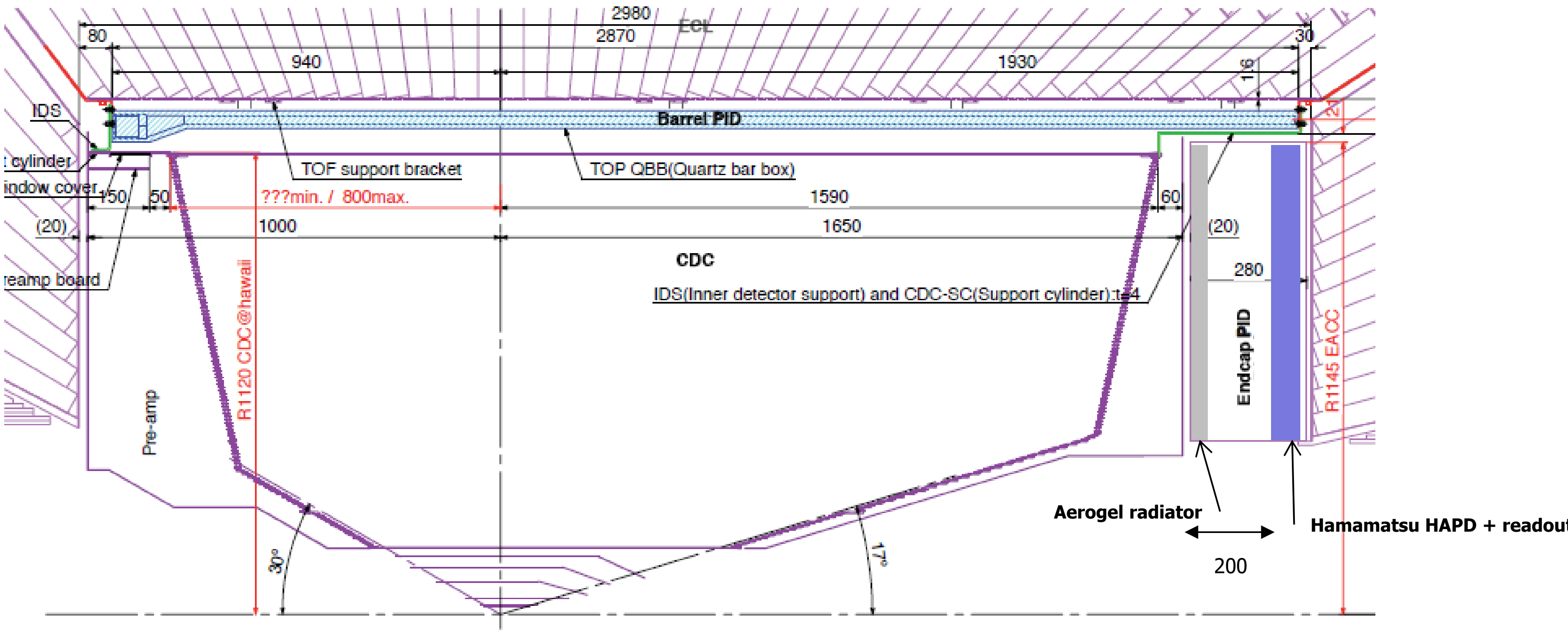
Endcap PID: Aerogel RICH (ARICH)



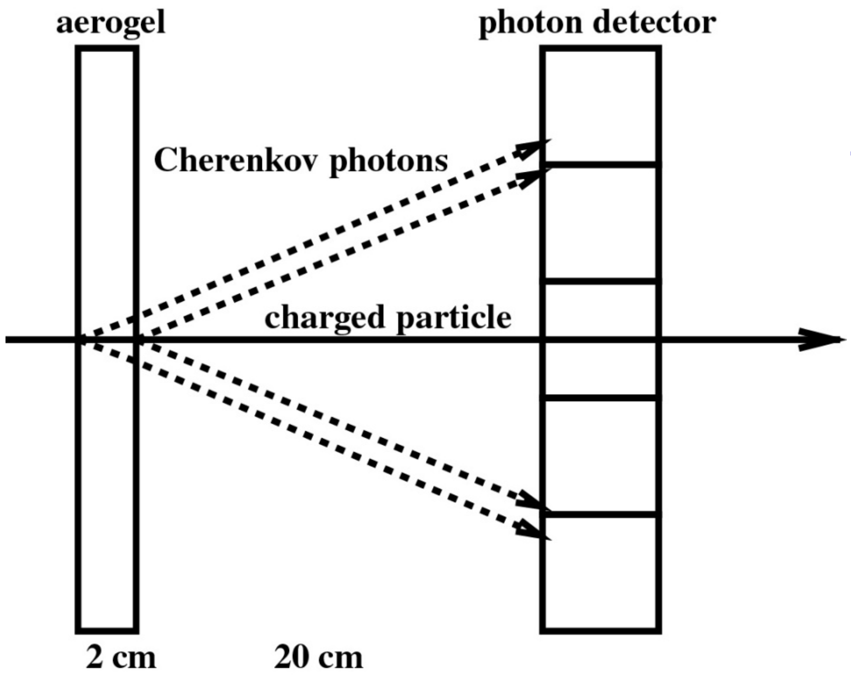
Aerogel radiator

n~1.05

Hamamatsu HAPD



Endcap: Proximity focusing RICH



K/π separation at 4 GeV/c:
$\theta_c(\pi)$ ~ 308 mrad (n = 1.05)
$\theta_c(\pi) - \theta_c(K)$ ~ 23 mrad

For single photons: $\delta\theta_c$(meas.)=σ_0 ~ 14 mrad,
typical value for a 20mm thick radiator and 6mm PMT pad size

Per track:

$$\sigma_{track} = \frac{\sigma_0}{\sqrt{N_{pe}}}$$

Separation: $[\theta_c(\pi) - \theta_c(K)]/\sigma_{track}$

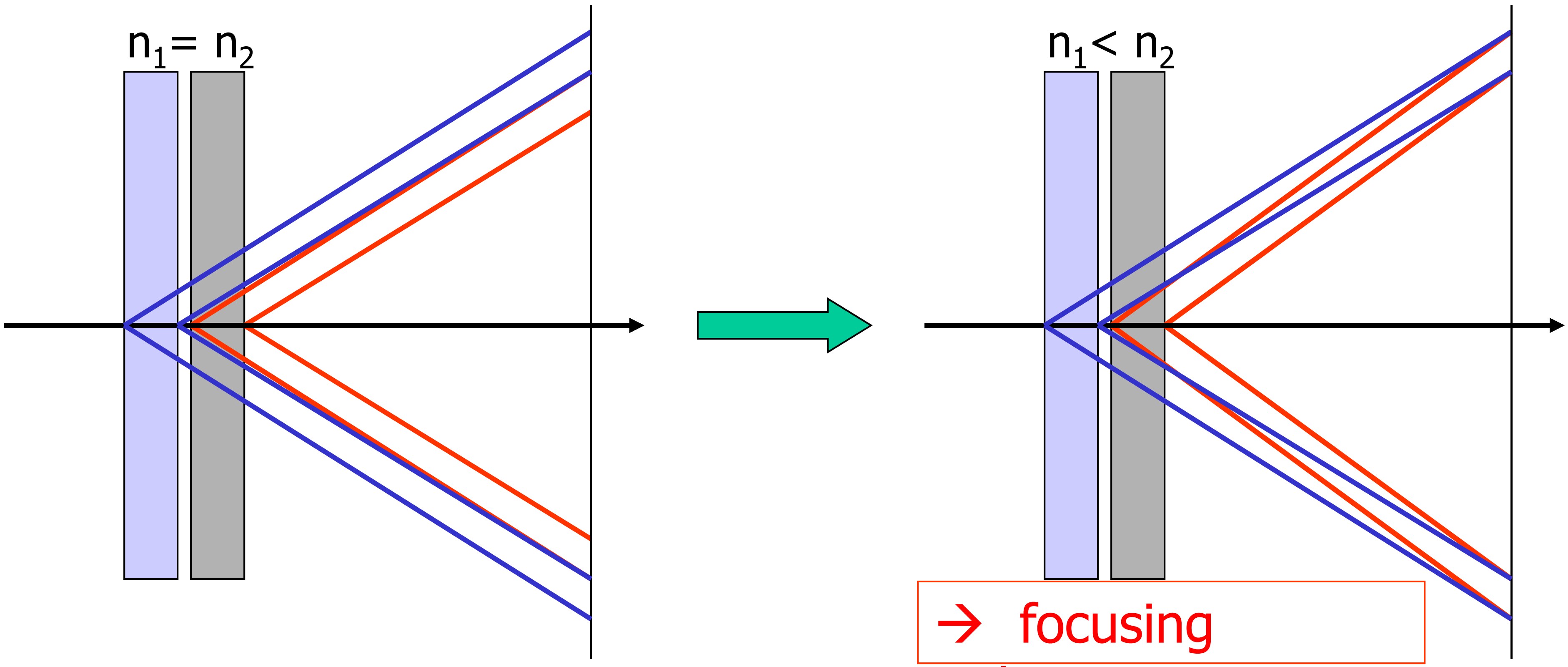
→ 5σ separation with N_{pe}~10

Radiator with multiple refractive indices

How to increase the number of photons without degrading the resolution?

normal

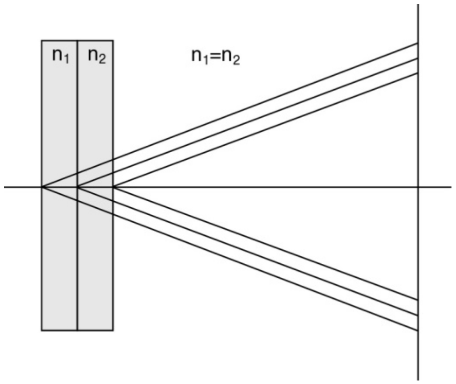
→ stack two tiles with different refractive indices: “focusing” configuration

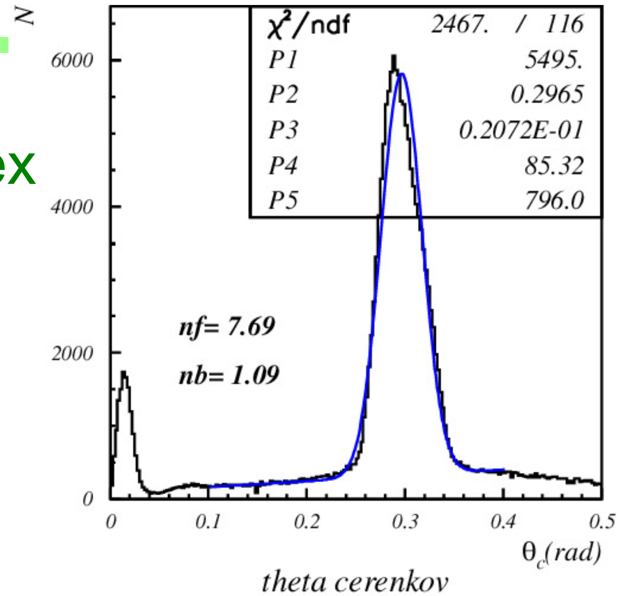


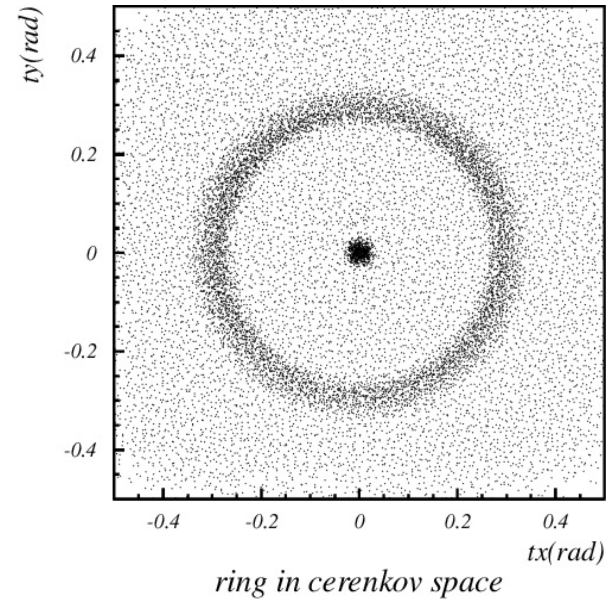
Such a configuration is only possible with aerogel (a form of Si_xO_y) – material with a tunable refractive index between 1.01 and 1.13.

Focusing configuration – data

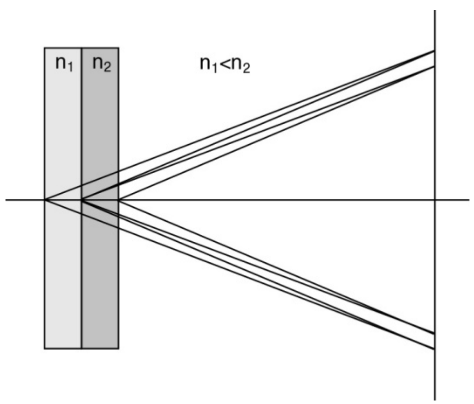
4cm aerogel single index

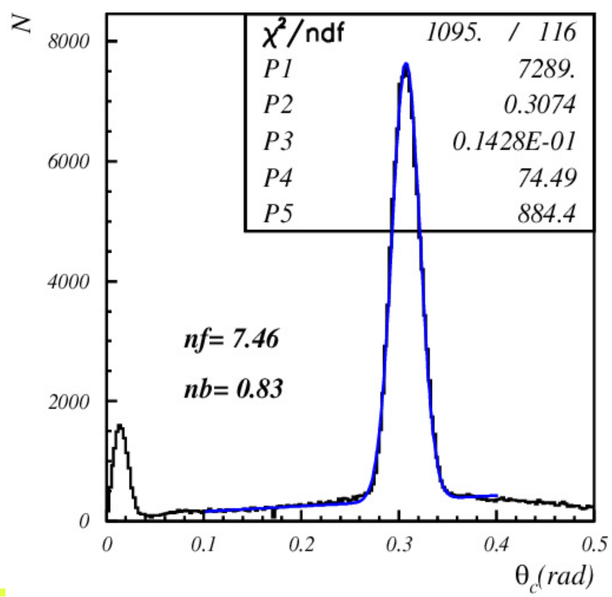


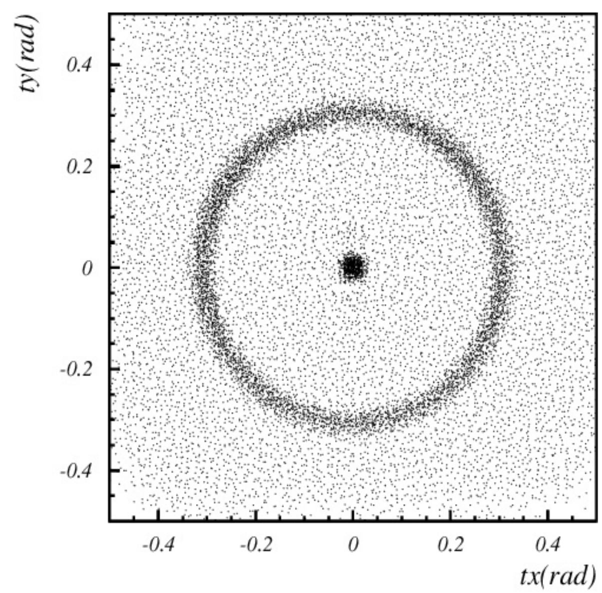




2+2cm aerogel







→NIM A548 (2005) 383, NIMA 565 (2006) 457

4x4 array of flat pannel MAPMTs

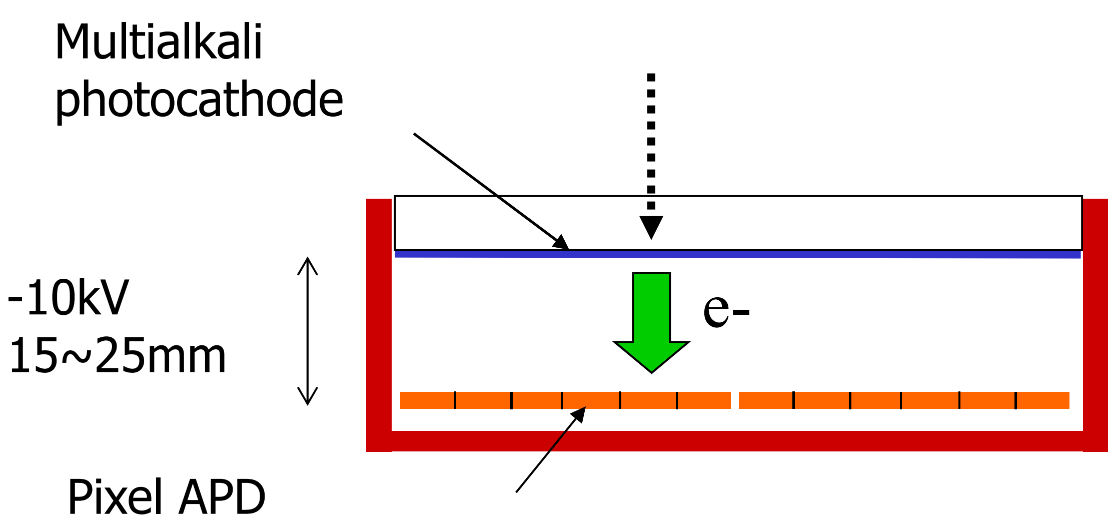
Photon detectors for the aerogel RICH requirements and candidates

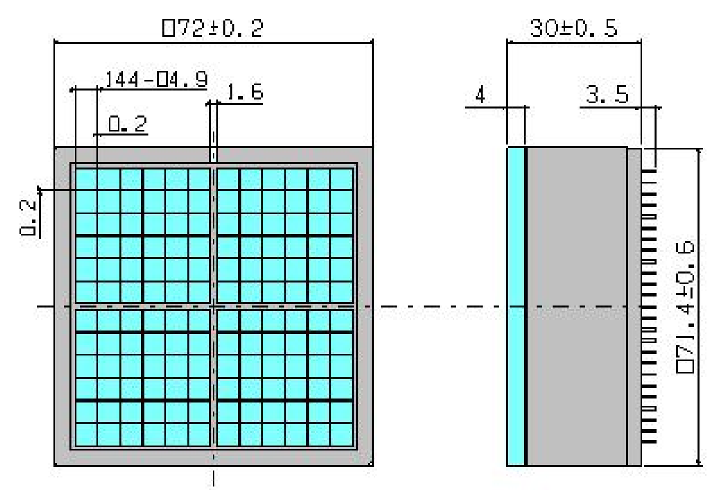
Need: Operation in a high magnetic field (1.5 T)

Pad size ~5-6mm

Final choice: large active area HAPD of the proximity focusing type

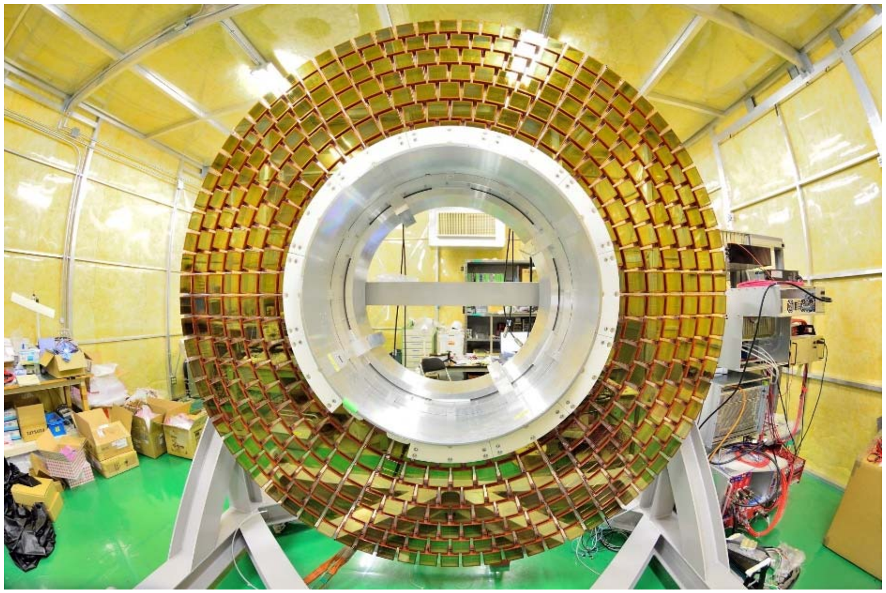
Candidates: MCP PMT (Photonis/Burle 85011, SiPMs)

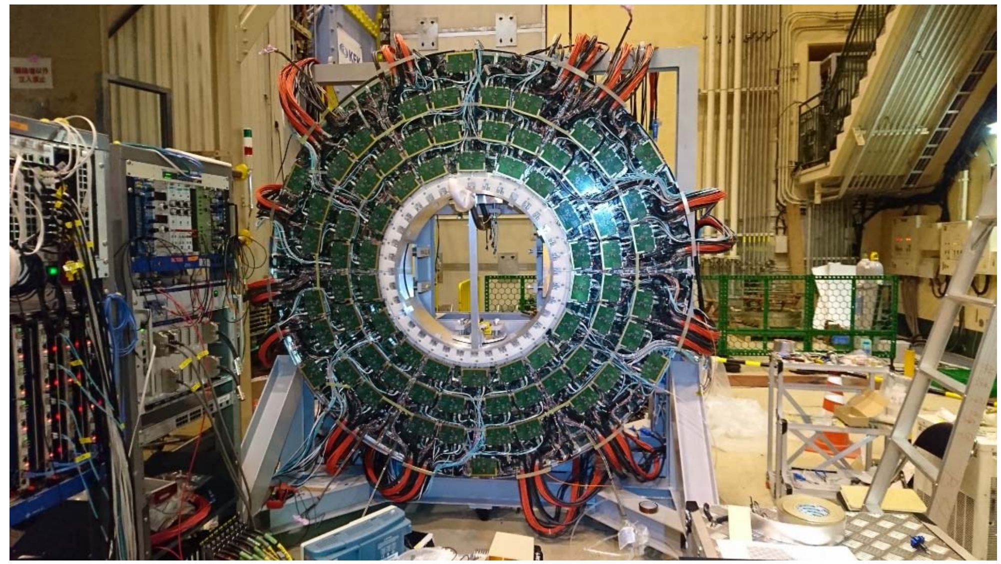


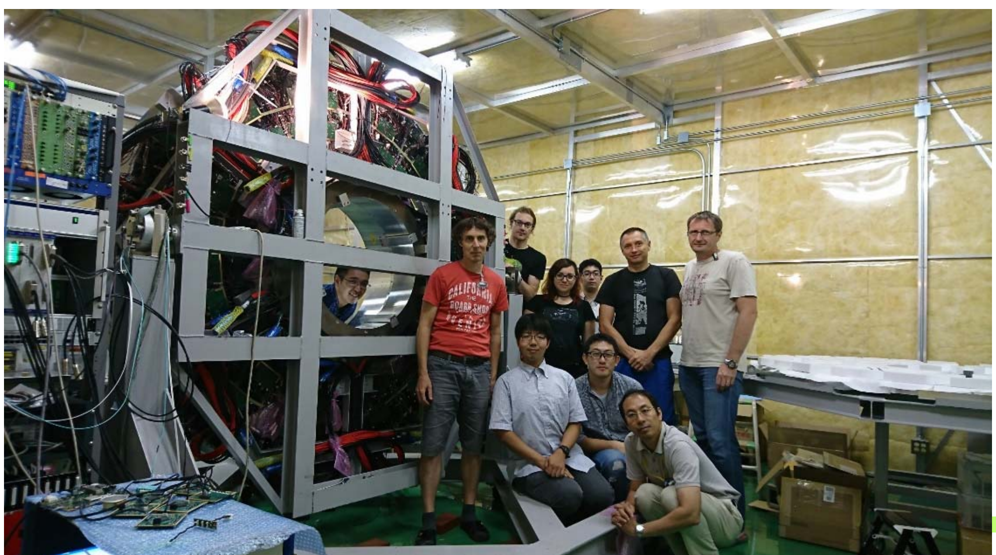


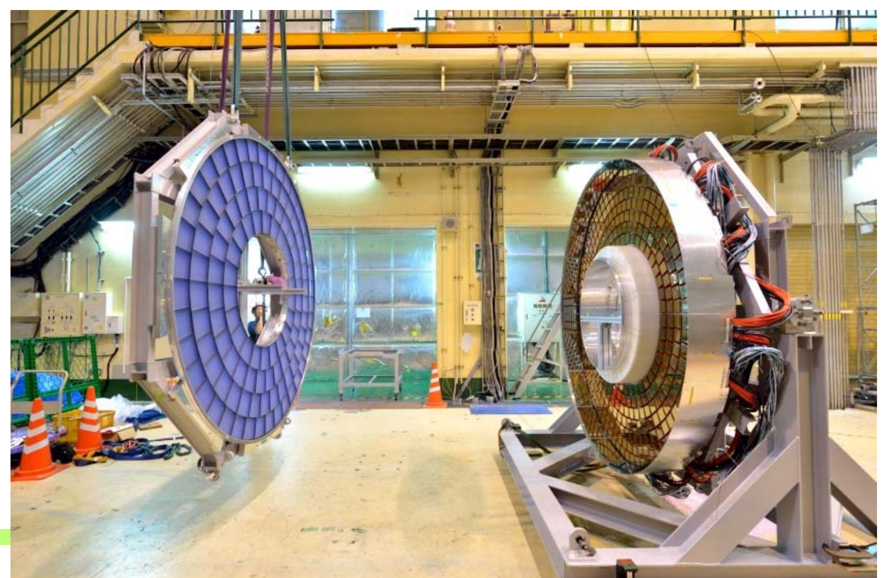
HAPD R&D project in collaboration with HPK.

The big eye of ARICH

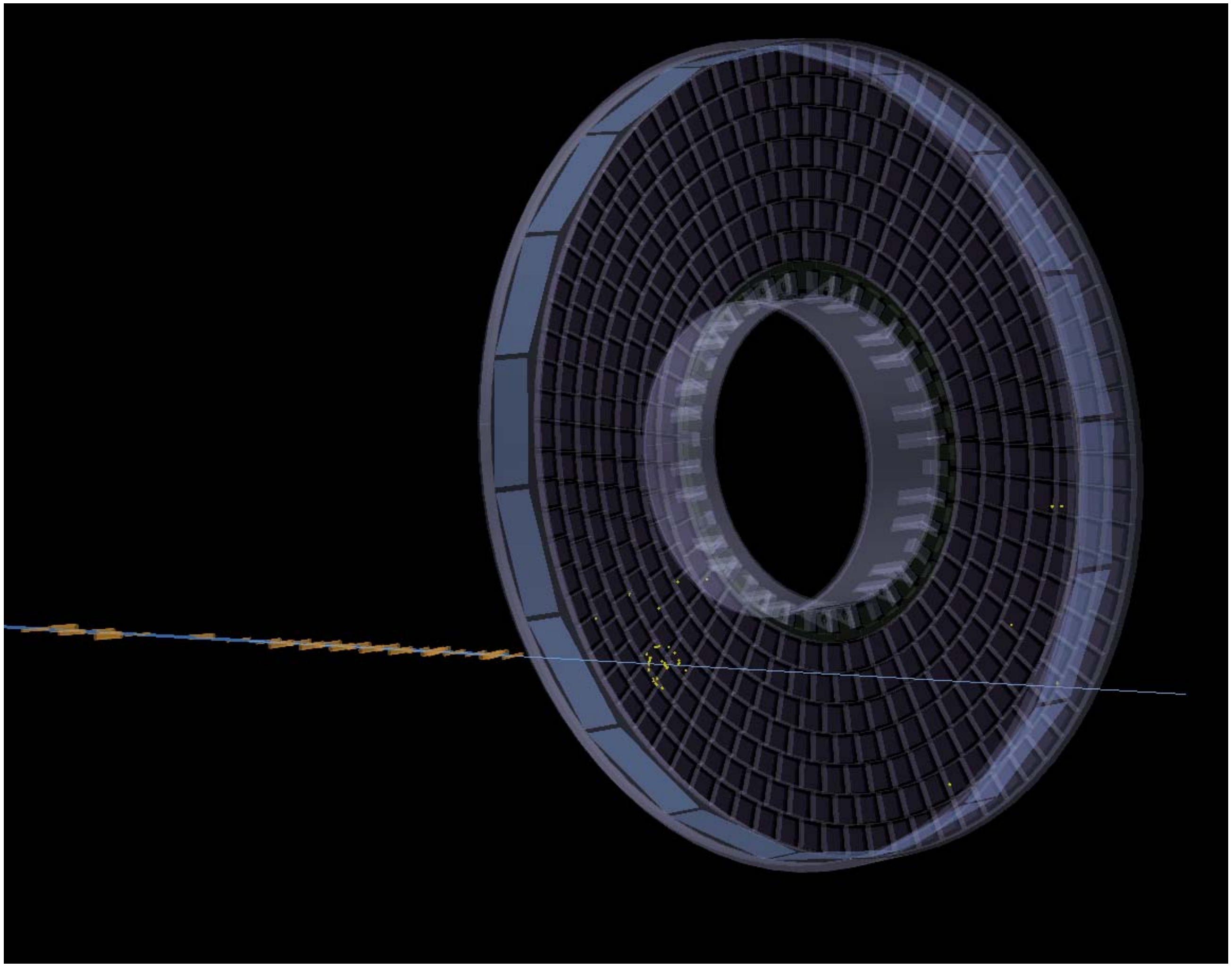








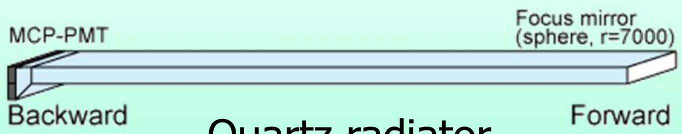
ARICH: Rings from cosmic ray muons



First events recorded in the fully instrumented ARICH.

Belle II PID systems

Barrel PID: Time of Propagation Counter (TOP)



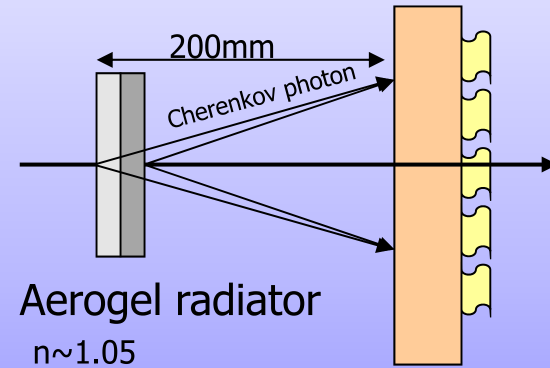
Quartz radiator

Focusing mirror

Small expansion block

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

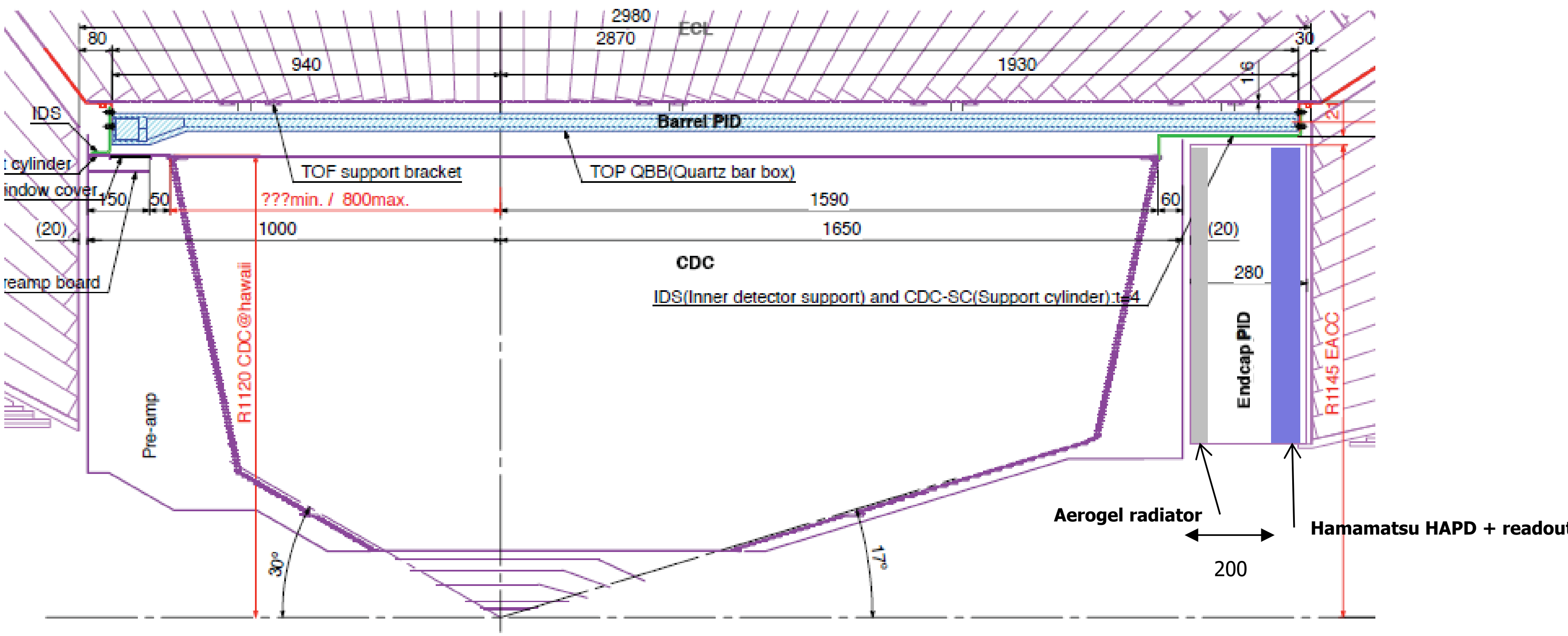
Endcap PID: Aerogel RICH (ARICH)



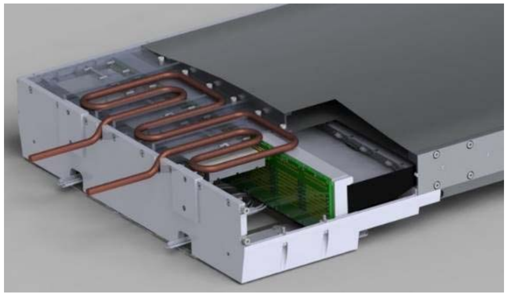
Aerogel radiator

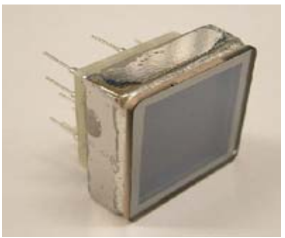
n~1.05

Hamamatsu HAPD
+ new ASIC

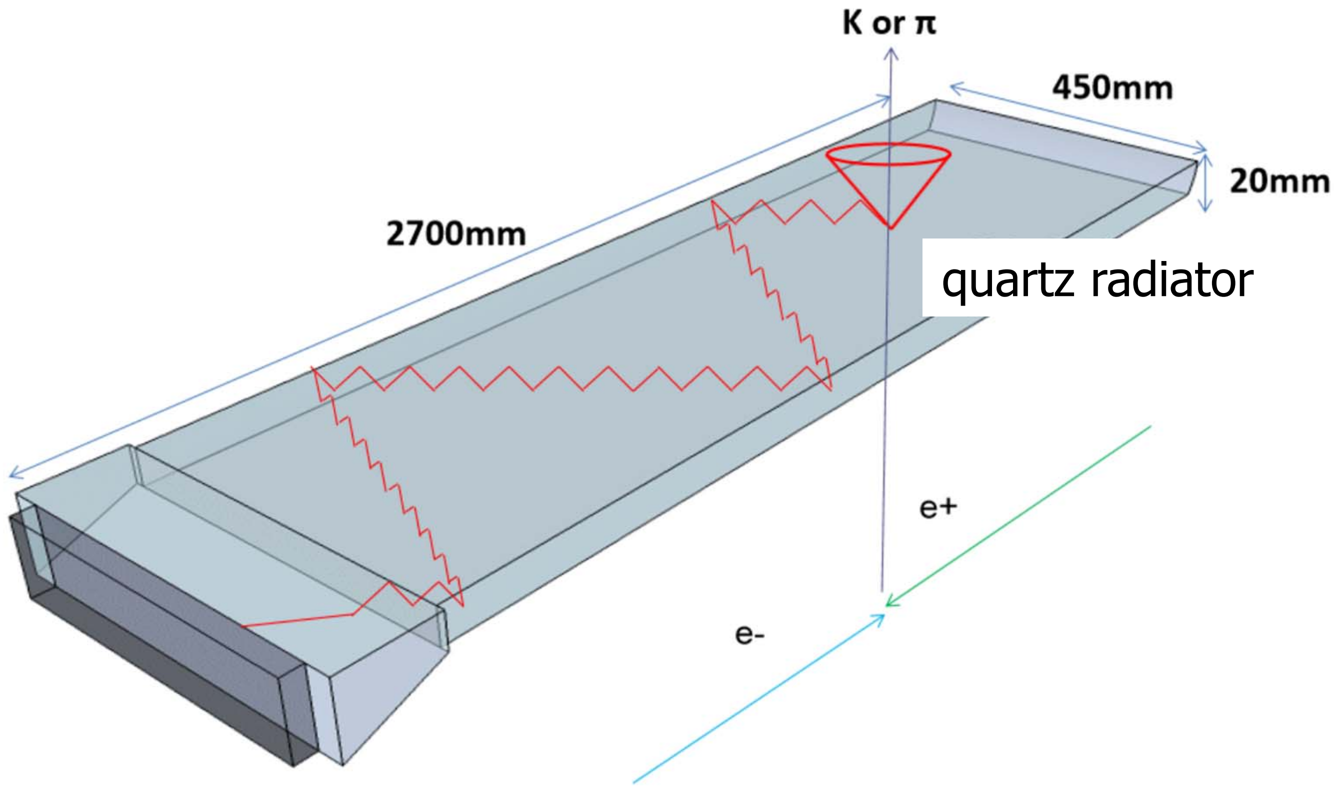


Barrel PID: Time of propagation (TOP) counter



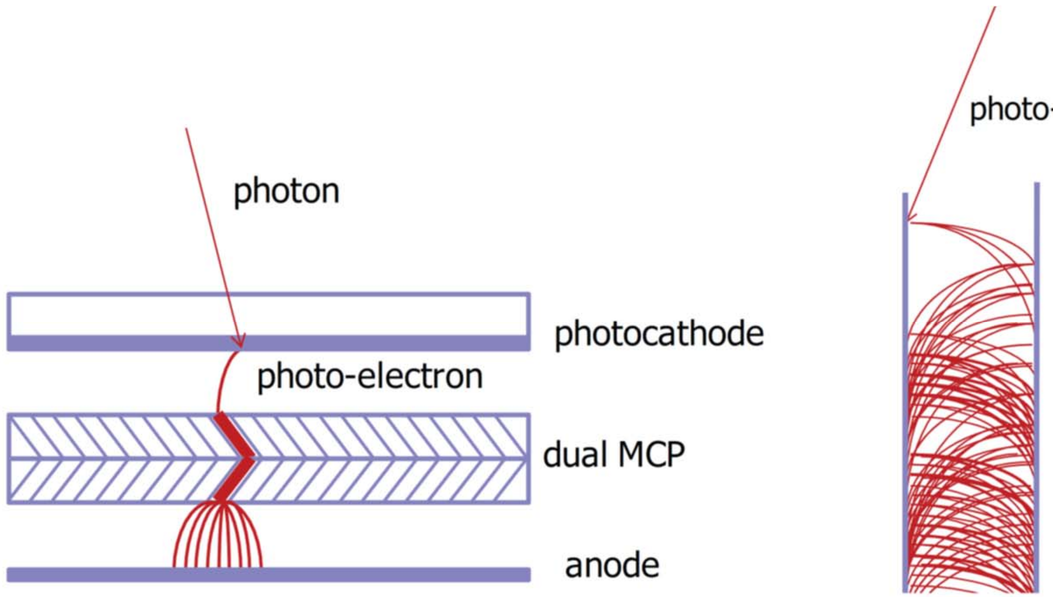


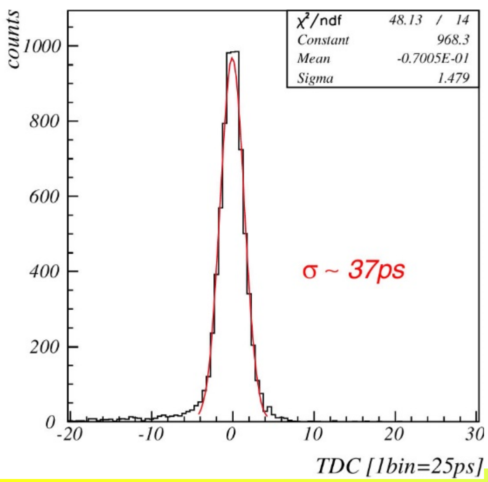
Photon detector:
Hamamatsu SL10
MCP-PMT
Readout: waveform
sampling



- 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

MCP PMTs for a very fast timing

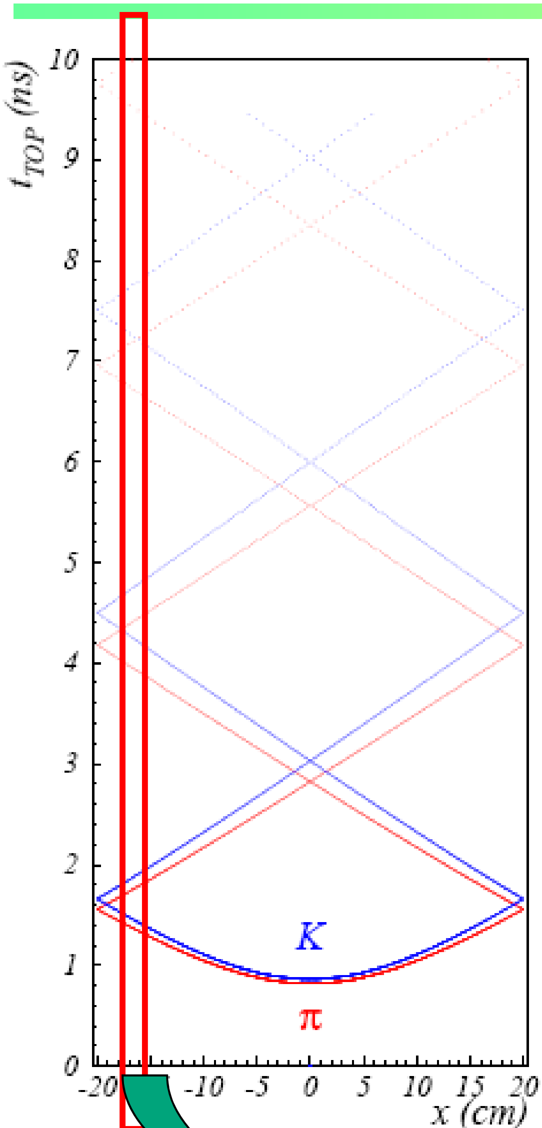




Micro-channel plate PMTs:

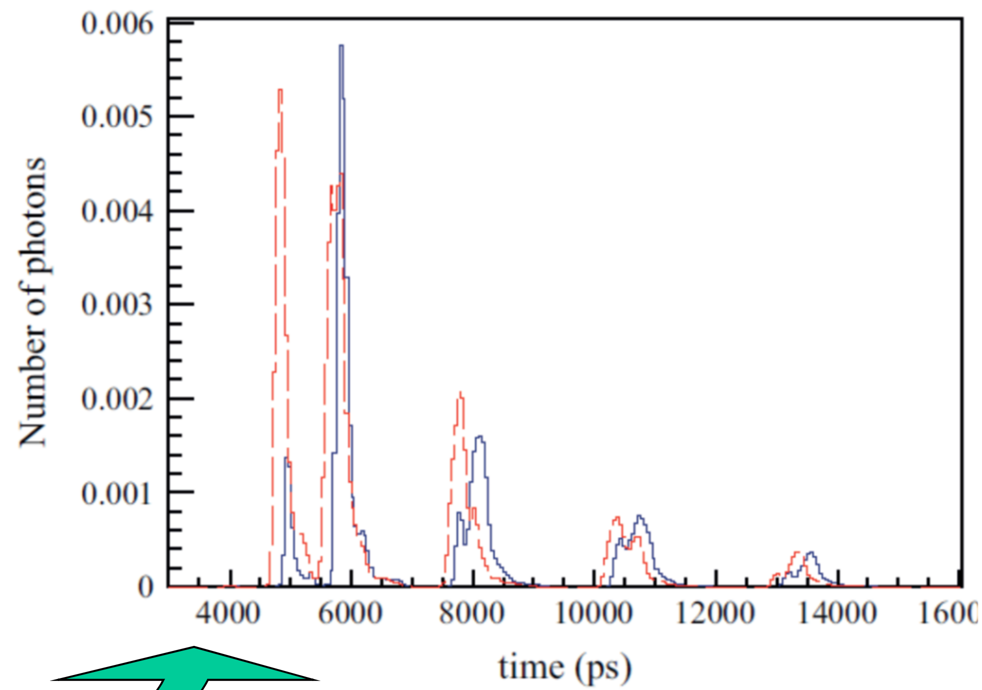
Single photon resolution: typically 20ps – 40ps

TOP image

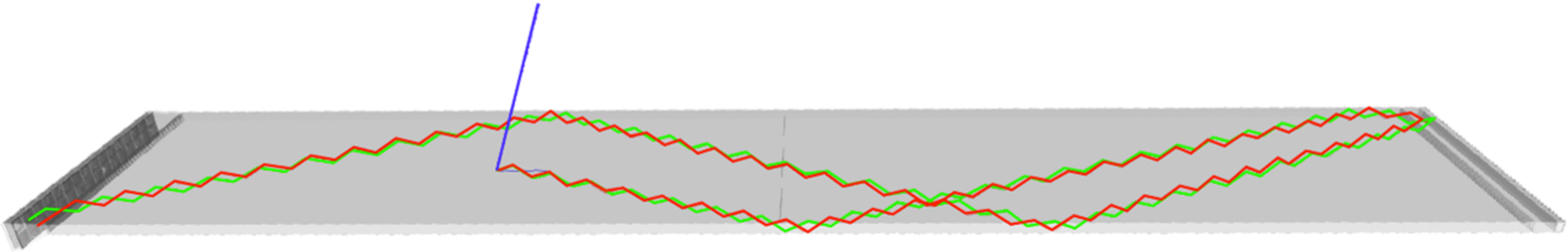


Pattern in the coordinate-time space ('ring') of a pion hitting a quartz bar with 512 MCP PMT channels

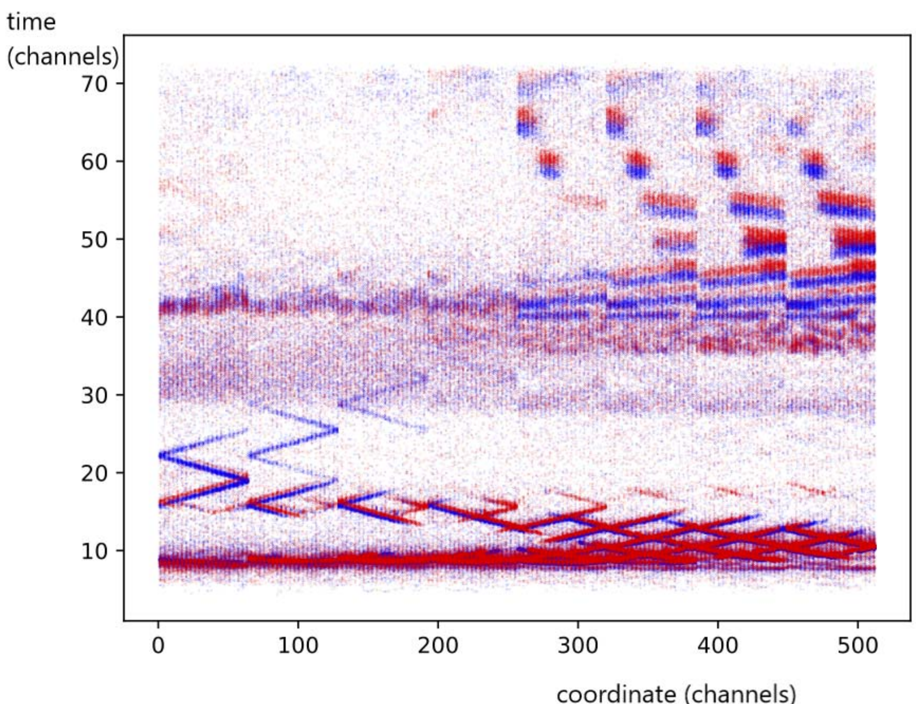
Time distribution of signals recorded by one of the PMT channels: different for π and K



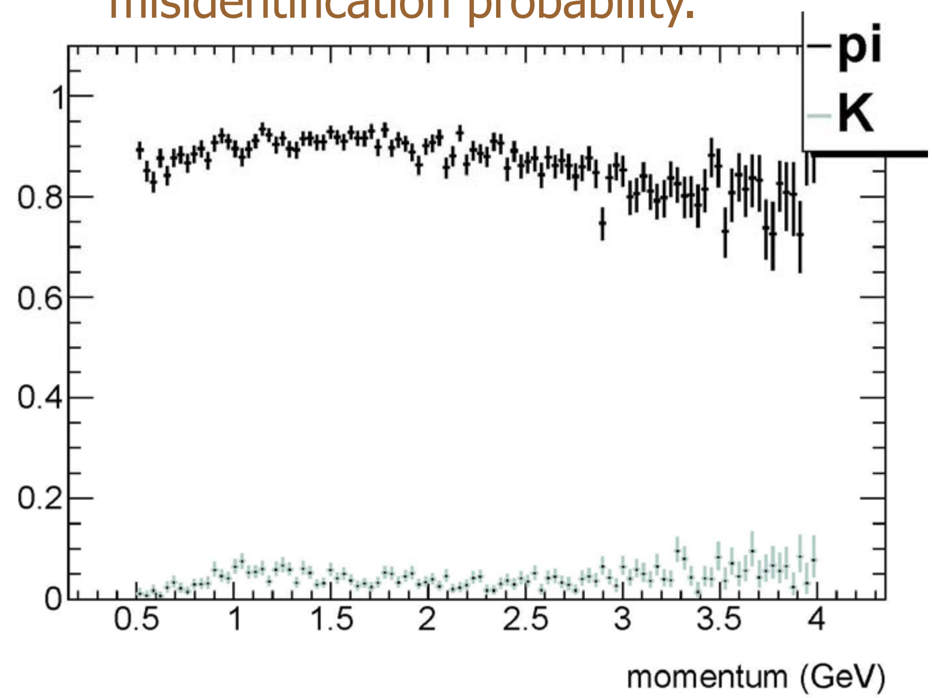
Separation of kaons and pions



Pions vs kaons in TOP:
different patterns in the time vs PMT impact point coordinate

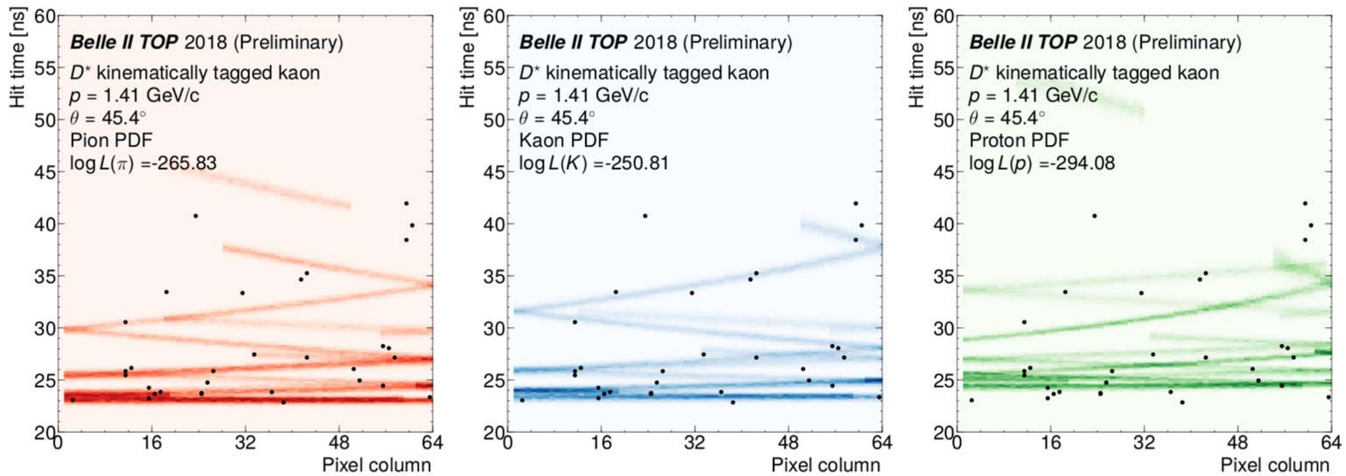


Pions vs kaons:
Expected PID efficiency and misidentification probability.



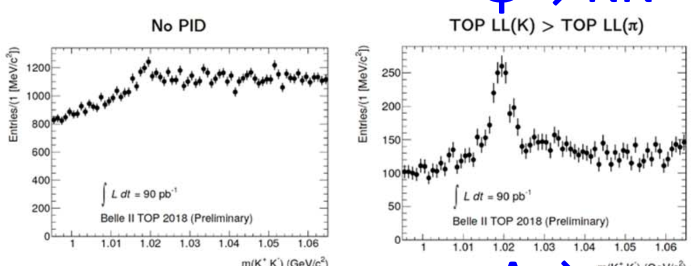
TOP first events

The early data demonstrated that the TOP principle is working



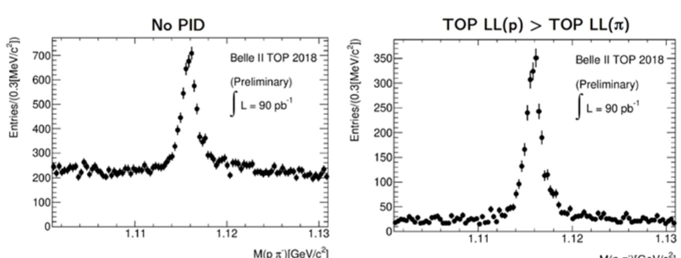
φ → K⁺K⁻ with both the tracks in the TOP acceptance

φ→KK

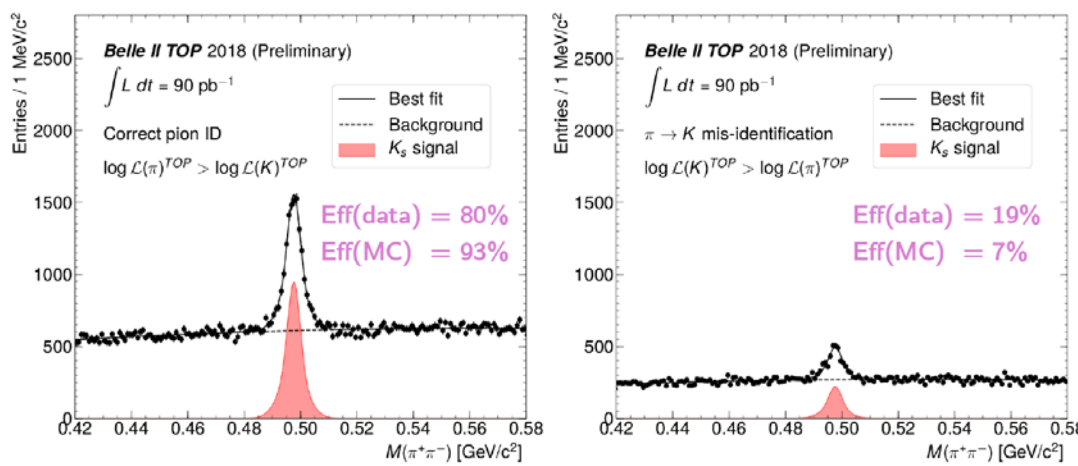


Λ → pπ with the **proton candidate** in the TOP acceptance

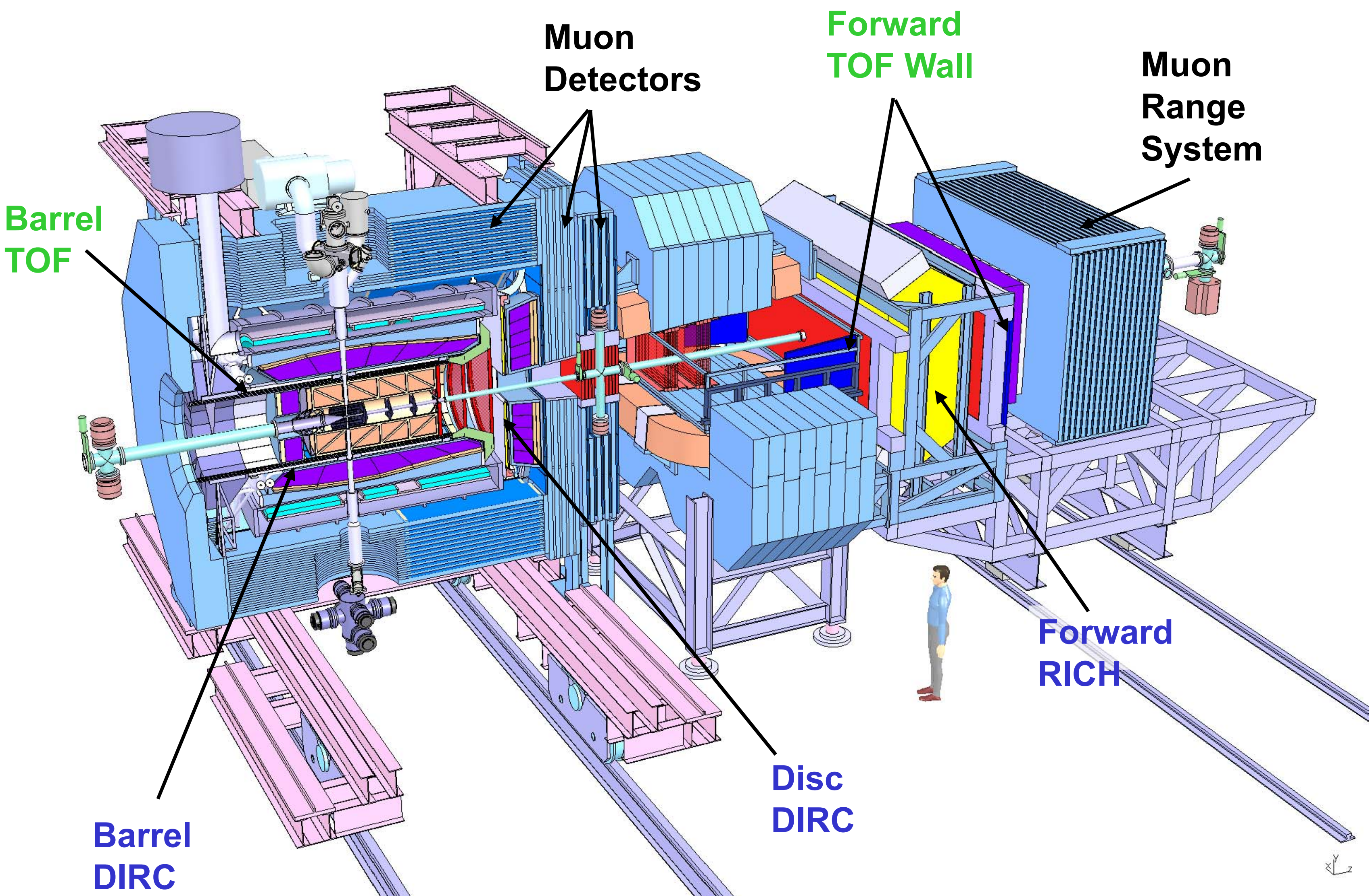
Λ→pπ



$K_s \to \pi\pi$



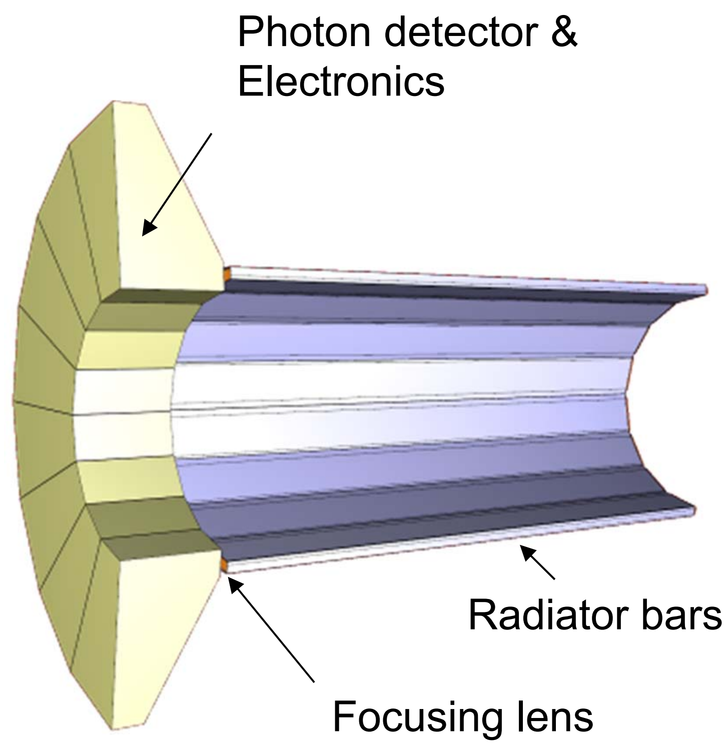
PID for PANDA



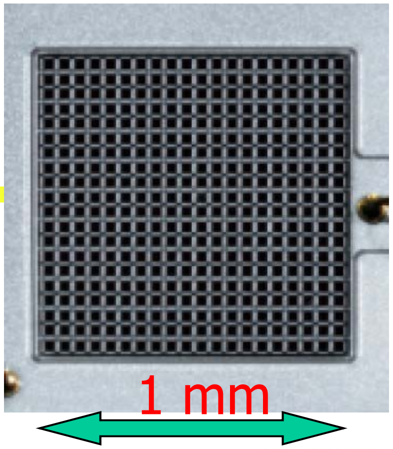
Barrel DIRC

- Similar to BaBar DIRC
- π/K separation 0.5 < *p* < 4 GeV/c
- Inner radius: 48 cm
- Radiator: 96 bars, fused silica (n=1.47), size: 17mm (T) x 33mm(W) x 2500mm (L)
- Compact photon detector: array of MCP-PMT (Photonis) in magnetic field 0.5-1 T

  total 7000-10000 channels
- Time of propagation → dispersion corrections (3D-DIRC concept – *x,y,t*)
- Focusing optics



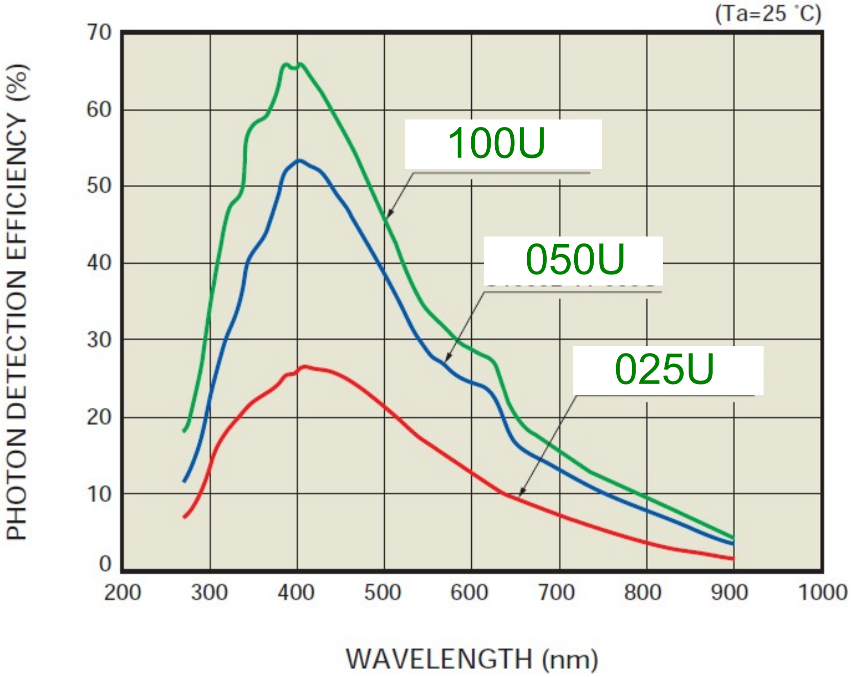
SiPMs as photon detectors for RICH detectors?



SiPM is an array of APDs operating in 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!

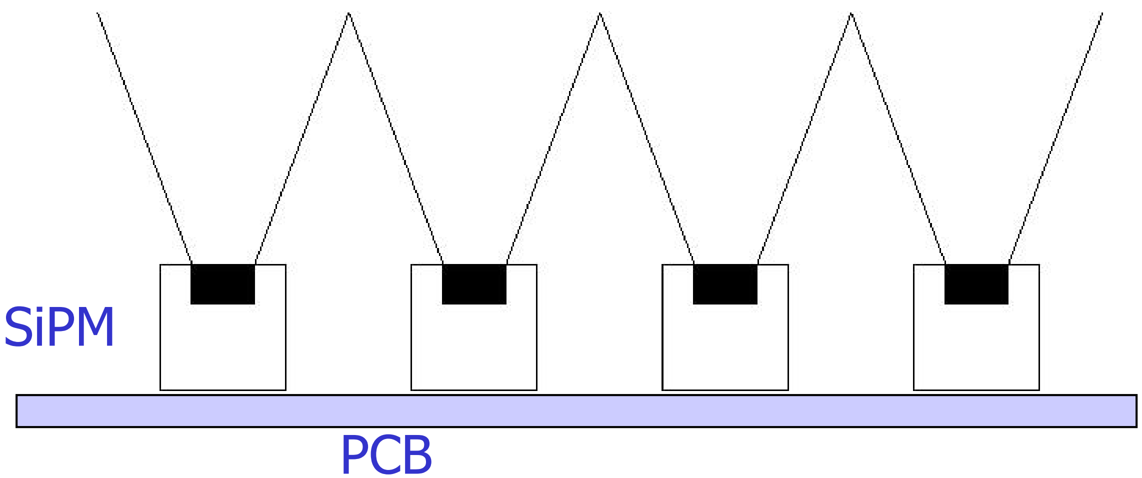
Dark counts have single photon pulse heights (rate 0.1-1 MHz)

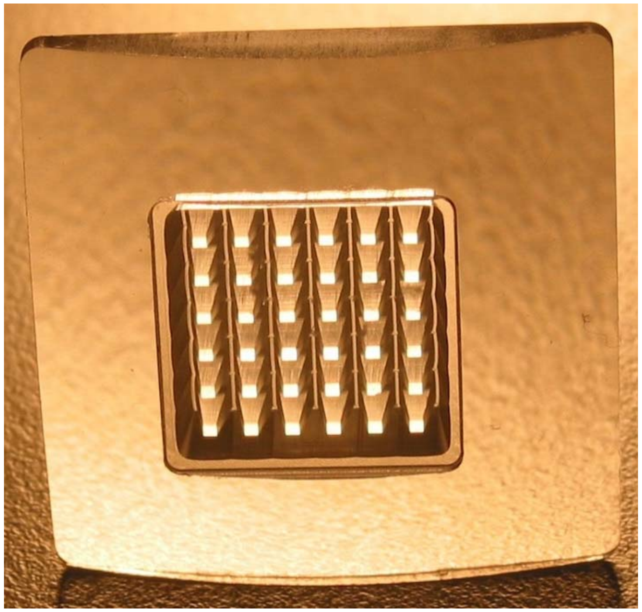
SiPM as photosensor for a RICH counter

Improve the signal to noise ratio:

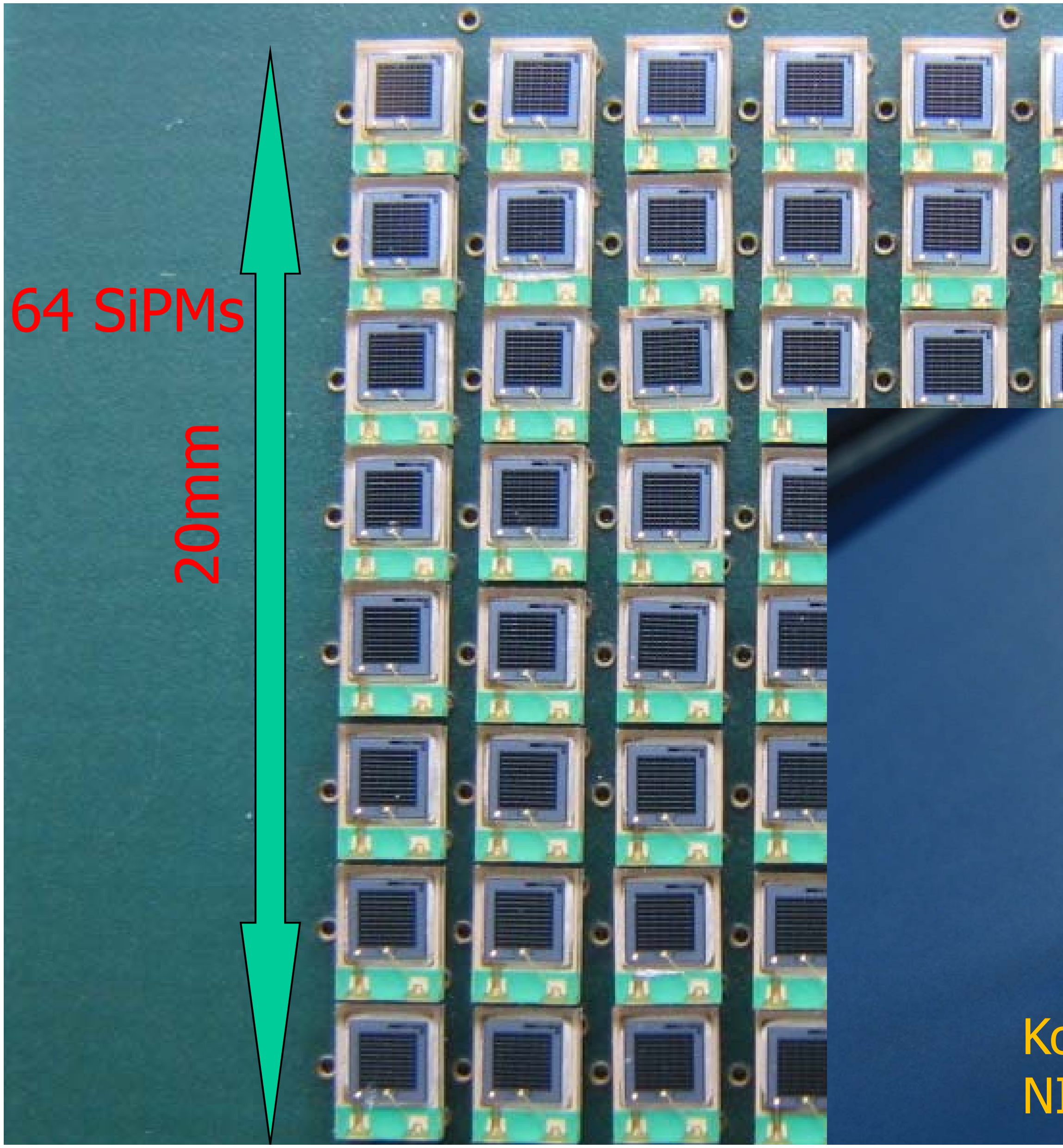
- Reduce the noise by a narrow (<10ns) time window (Cherenkov light is prompt!)
- Increase the number of signal hits per single sensor by using light collectors

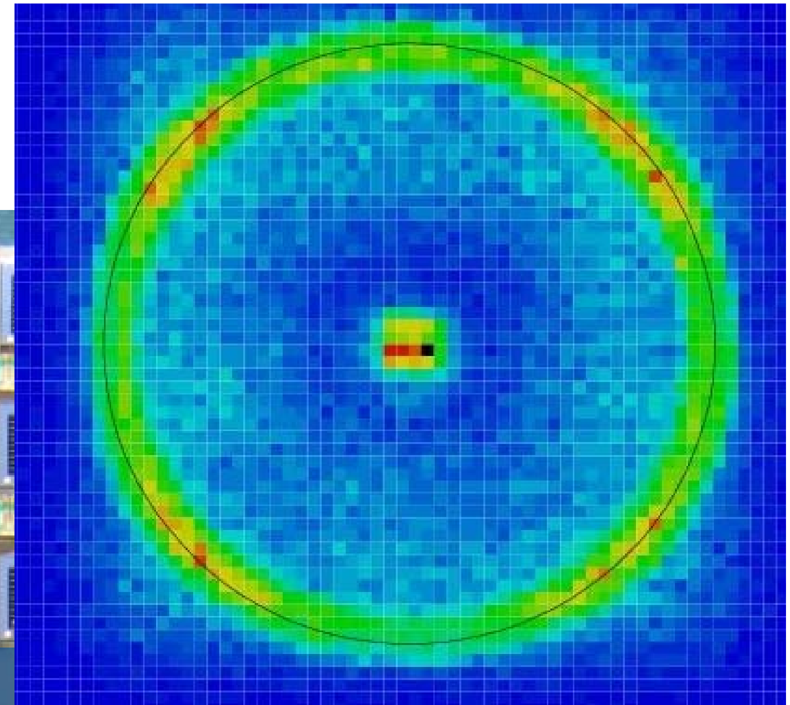
E.g. light collector with reflective walls or plastic light guide

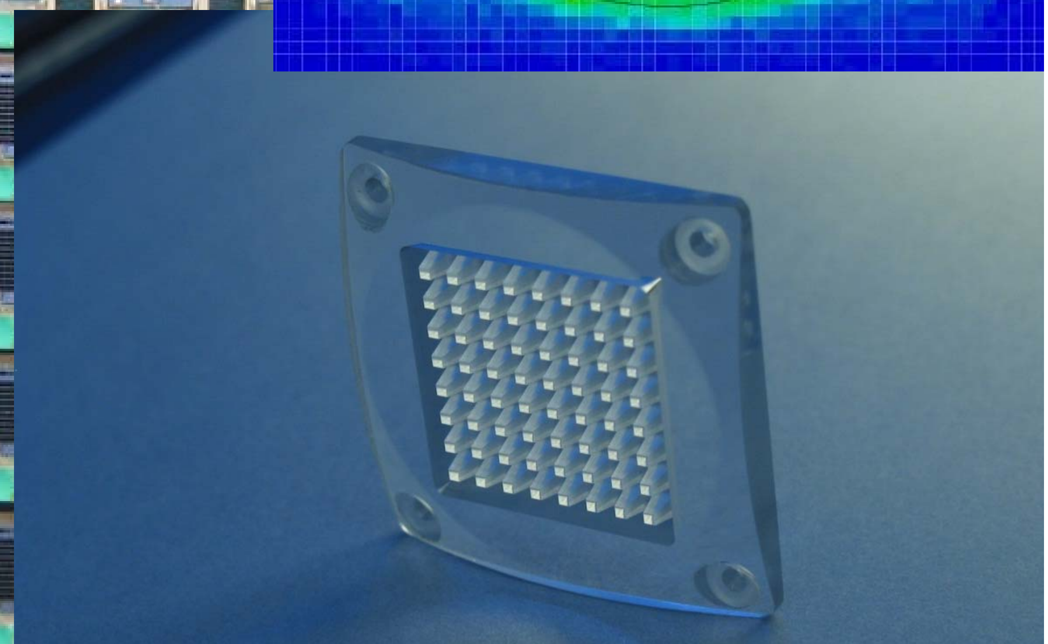




Photon detector with SiPMs and light guides





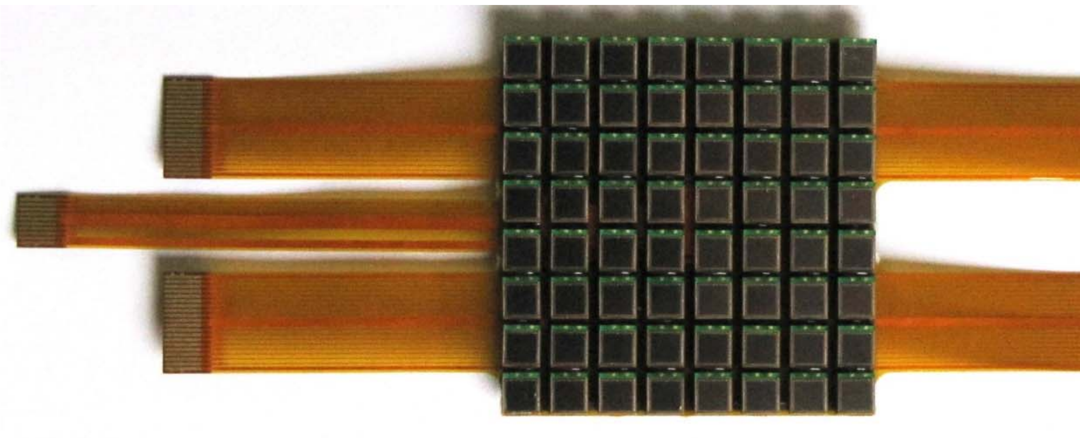


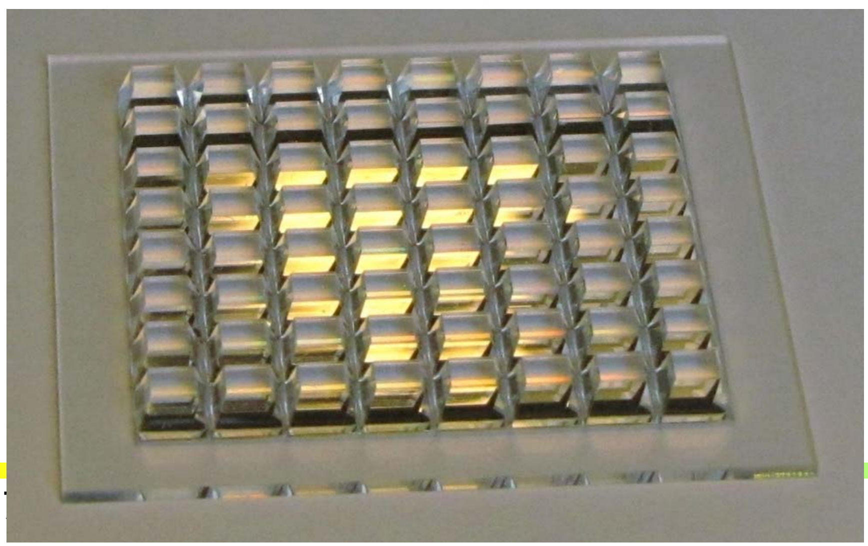
Korpar et al., NIM A594 (2008) 13;
NIM A613 (2010) 195

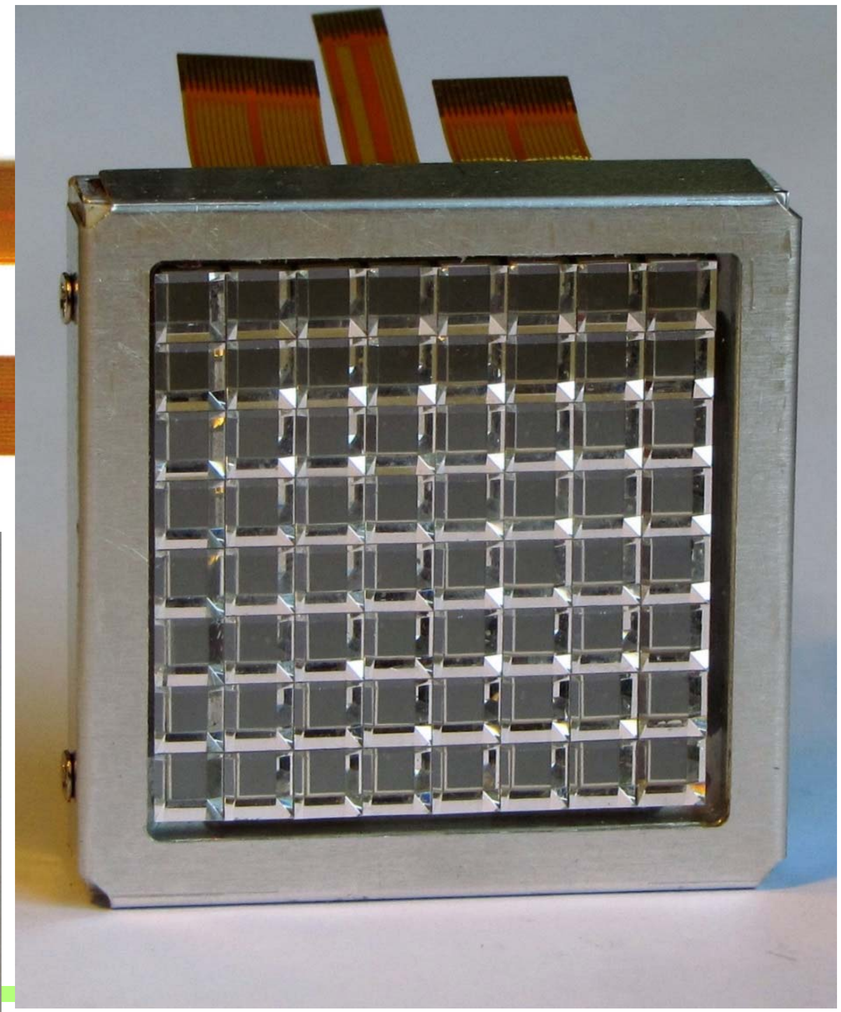
Next step: use arrays of SiPMs

Example: Hamamatsu MPPC S11834-3388DF

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



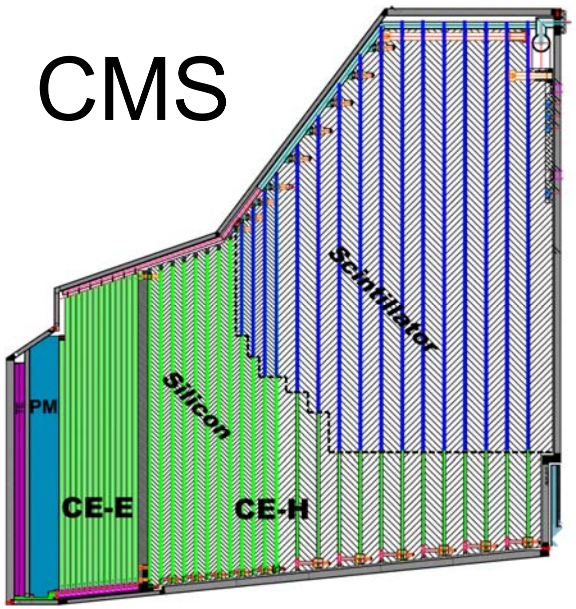




Calorimetry: Particle flow calorimetry at CMS

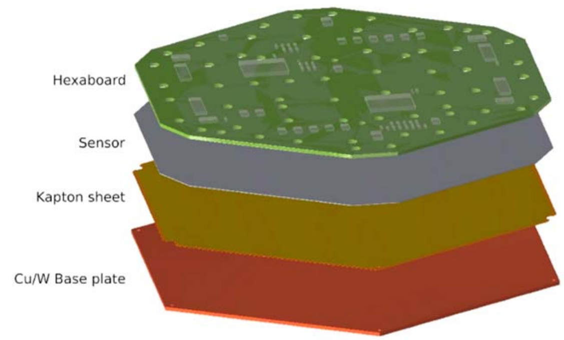
High Granularity calorimetry

CMS



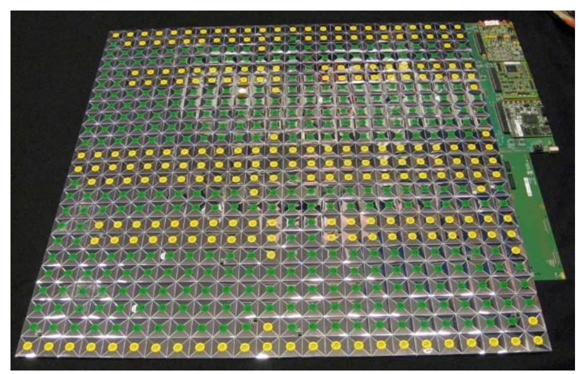
- Silicon: 600 m^2
- Scintillator: 500 m^2
- 6 M Channels

Silicon sampling calorimeter



FE- ROC providing Time-of-arrival (TOA) with a precision of 20ps

Scintillator tiles with on-tile SiPM readout

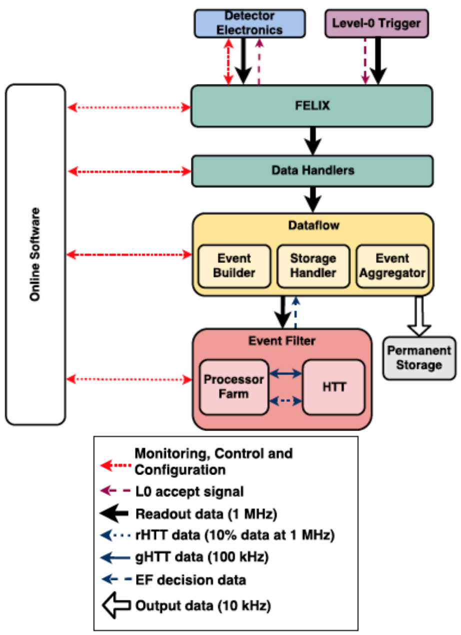


Trigger data from ASICs (300 TB/s) fed through concentrators to the back-end system (2 TB/s)

Successfully tested in a test beam at DESY

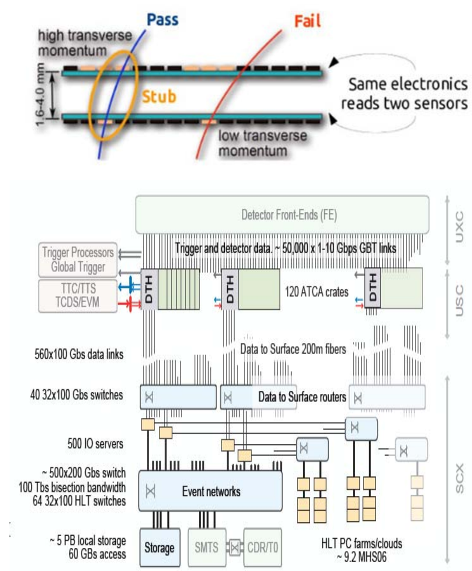
Trigger development

ATLAS



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

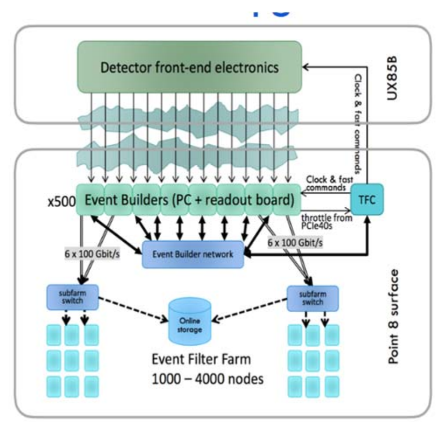
CMS



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

LHCb

40 MHz trigger-less DAQ



Massive use of data links

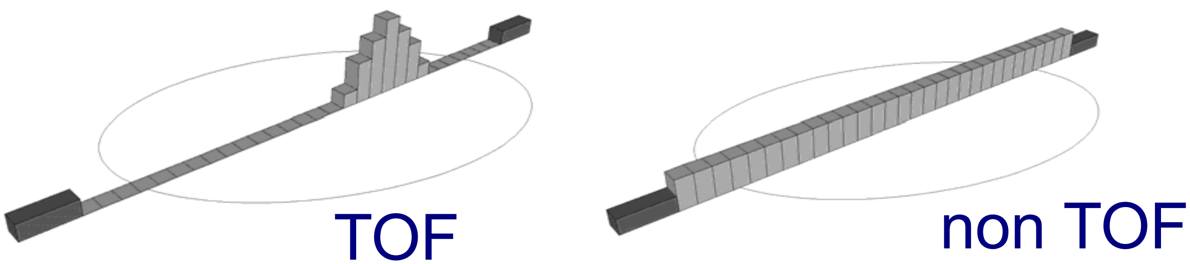
Applications in medical imaging: advances in TOF-PET

Time-of-Flight difference of annihilation gammas is used to improve the contrast of images obtained with PET

Localization of source position along the line of response:

$\Delta t \sim 66\text{ps} \rightarrow \Delta x = c_0 \Delta t/2 \sim 1\text{cm}$

Δt = coincidence resolving time, CRT



However, PET systems based on SiPM readout are reaching CRT of ~300 ps, and only with small crystals ~3x3x3 mm^3 CRT<100 ps

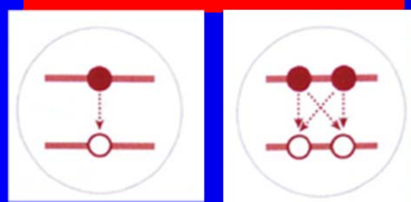
Novel photon detectors – MCP-PMTs and SiPMs – have excellent timing resolution
→ TOF resolution limited by the spread in photon emission and arrival time

Faster annihilation gamma detection method → a faster light emission mechanism

Possible sources of prompt photons (< 1ns)

Ce^{3+} Activator: 5d-4f
Ca^{2+} & Mg^{2+} co-doping
τ_r ~ 20 ps τ_d ~ 16 ns

Excitons/Bi-exciton stable at 300 K



Hot Intraband Luminescence
0.1 - 10 ps

$$\frac{1}{\tau} = \frac{4e^2}{3\hbar c^3}\omega_{21}^3 \left|\vec{r}_{21}\right|^2$$

Cross Luminescence
<1ns
<300 nm – low LY

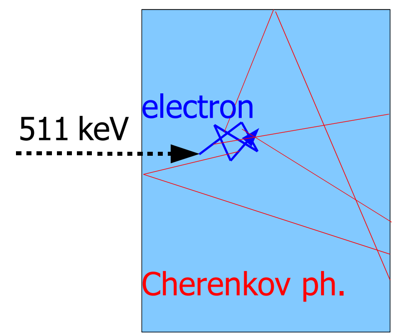
Cerenkov
τ ~ 5-10 ps

High donor band semiconductors
<1ns
quenched at room temperature

Annihilation gamma detection with Cherenkov light

Cherenkov light is promptly produced by a charge particle traveling through the medium with velocity higher than the speed of light c_0/n. Photoelectron emits Cherenkov light in ~1ps.

Disadvantage of Cherenkov light is the small number of Cherenkov photons produced per interaction



$$N \approx \frac{370}{eV\,cm}\, l\, \Delta E\, \sin^2_C\vartheta \approx 370\times0.01\times2\times0.75 \approx 8$$

→ detection at a single photon level!

Cherenkov radiator: PbF_2 an excellent candidate

- high gamma stopping power
- high fraction of gamma interactions via photoeffect → electrons with maximal kinetic energy → more Cherenkov photons

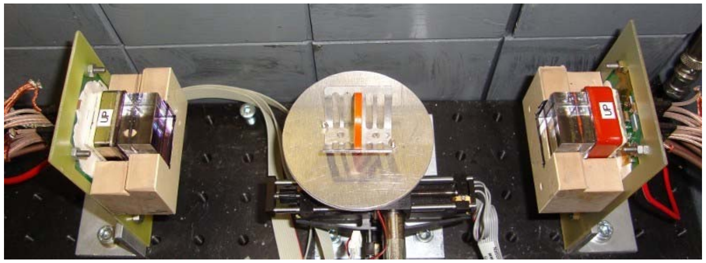
	ρ (g/cm³)	n	e⁻ Cherenkov threshold (keV)	Cutoff wavelength (nm)	Attenuation length (cm)	Photofraction
PbF_2	**7.77**	**1.82**	**101**	**250**	**0.91**	**46%**
LYSO	7.4				1.14	32%
$LaBr_3$	5.1				2.23	15%

+ high transmission in visible and near UV

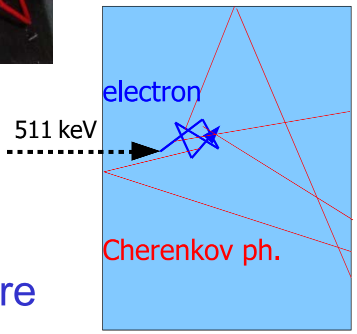
Excellent TOF PET timing with MCP PMTs

Pioneering experiment, two detectors in a back-to-back configuration:
PbF_2 25x25x15 mm^3 with MCP-PMT as photodetectors

- single photon timing ~ 50 ps FWHM
- active surface 22.5x22.5 mm^2

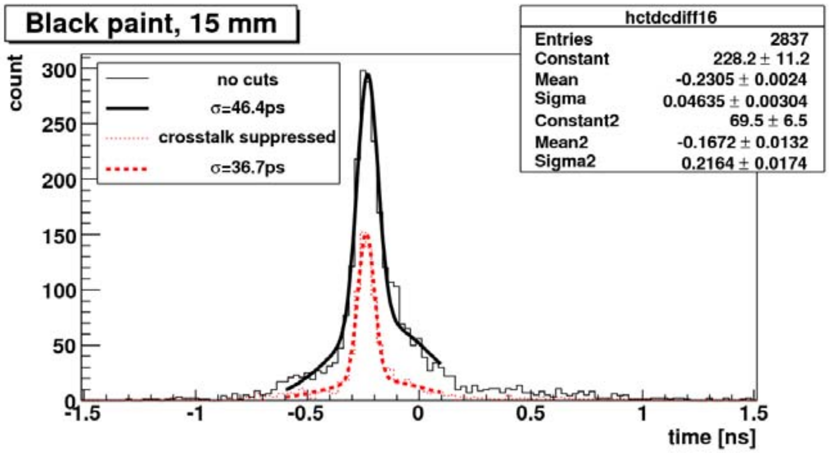


black painted, Teflon wraped, bare



Timing resolution (black painted):
~ 70 ps FWHM, 5mm crystal
~100 ps FWHM 15mm crystal

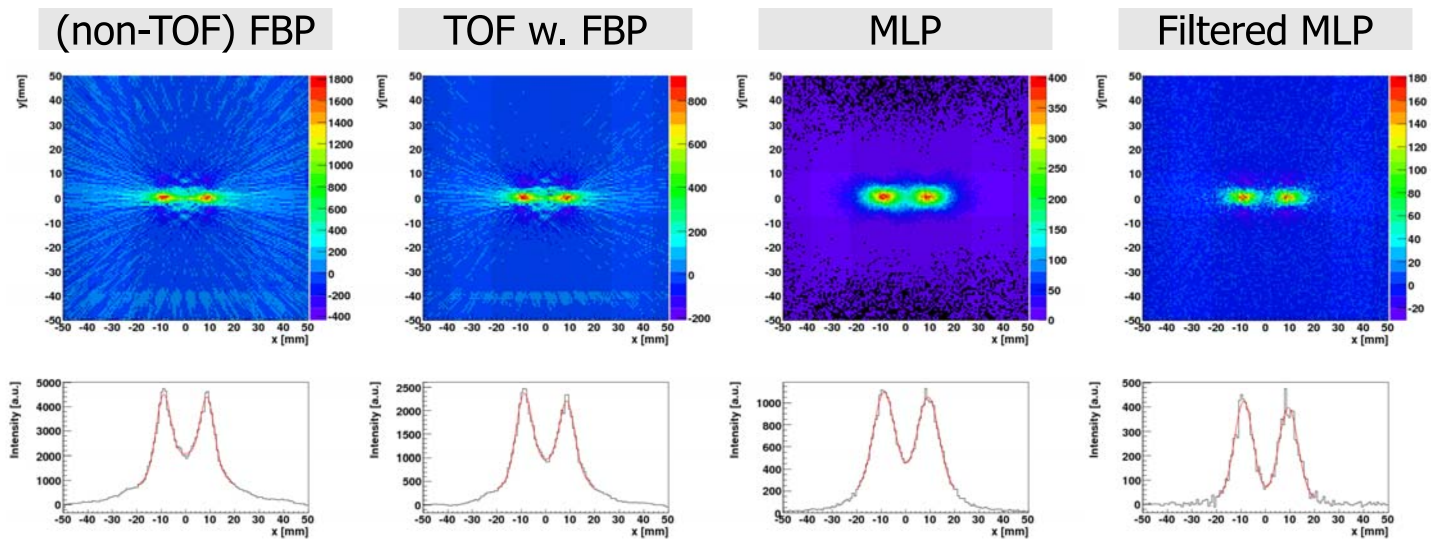
Efficiency (Teflon wrapped):
~ 6%, single side
(typically ~ 30% for LSO)



NIM A654(2011)532

Reconstruction - experiment

Two ^{22}Na point sources at +10 mm and -10 mm 4x4 segmented, black painted PbF_2 radiators



→ A simple, very fast Most-likely-point (MLP) method (~histograming of points) already gives a reasonable image

→ NIM A732 (2013) 595

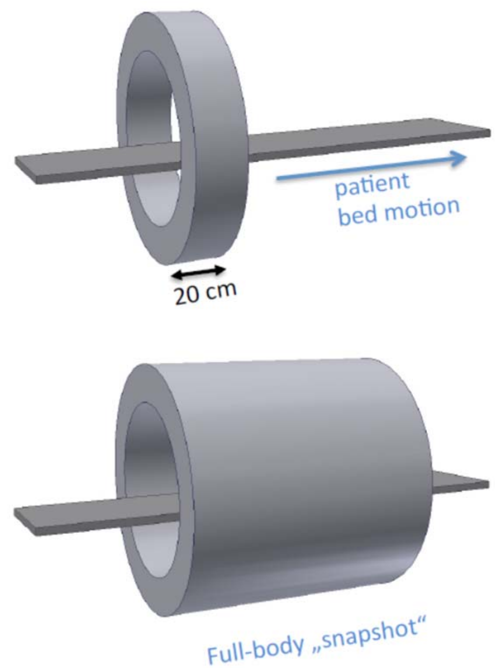
Cherenkov based PET scanner?

PbF_2 not a scintillator → considerably cheaper!

Smaller attenuation length than LYSO – small parallax error

→ Cheaper normal scanner or

→ Total/half body device



Extending axial FOV 20 cm → 200 cm:
estimated 6-fold increase in SNR →

- Better image quality
- OR Shorter scanning time
- OR Less injected activity: 8 mSv → 0.2 mSv

SiPMs for Cherenkov TOF PET?

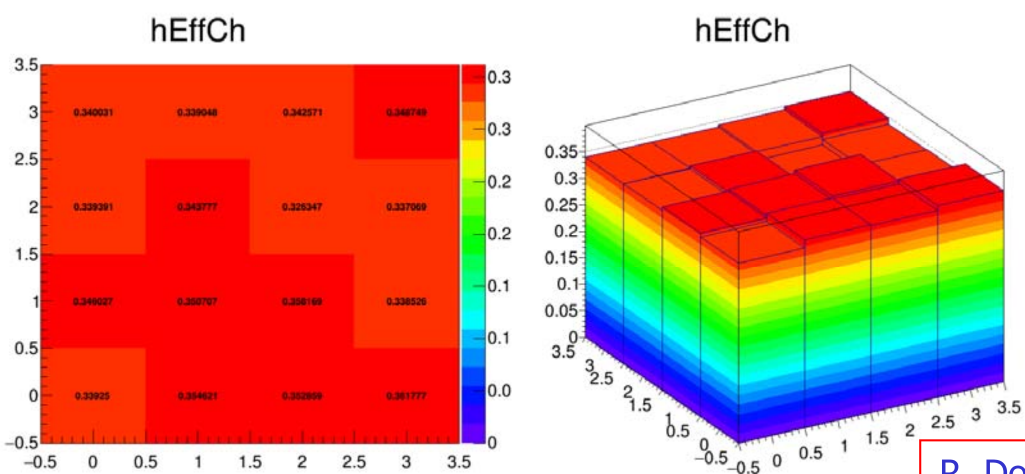
Advantages:

- high PDE – more than 50%
- flexible granularity
- low operation voltage
- operation in magnetic field
- affordable price (potentially)

Disadvantages:

- high dark count rate ~ 100kHz/mm^2 (→cooling)
- single photon timing - resolution not yet below 100 ps FWHM (specially for large area devices)

→ Explore new devices and test them!



Efficiency: ~35%

Uniform over the 4x4 module

R. Dolenec et al., @RICH2018, to be published in NIMA

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