Univerza *v Ljubljani*

Recent advances in Ring Imaging Čerenkov counters

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Why particle identification?

Ring Imaging CHerenkov counter – RICH

Some history

New concepts, photon detectors, radiators

Summary

Introduction: Why Particle ID?

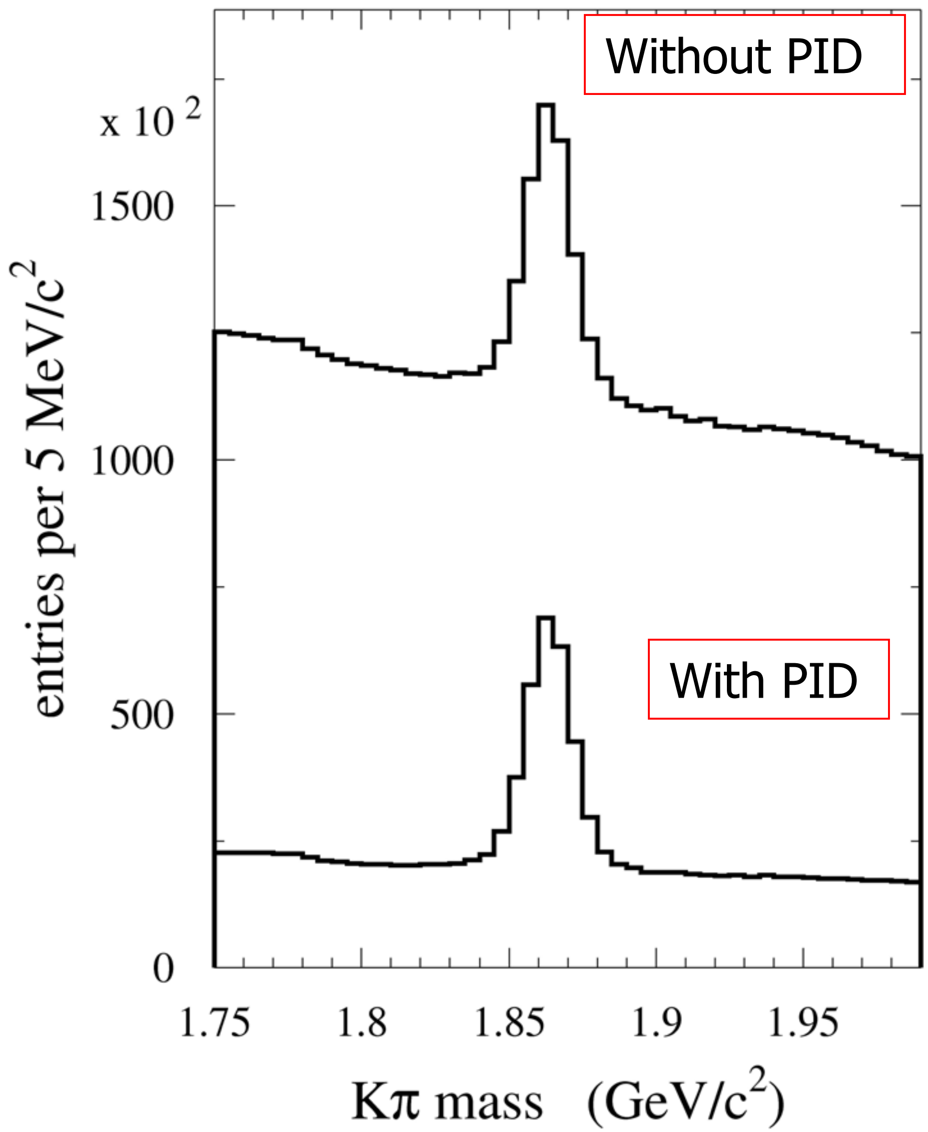
Particle identification is an important aspect of particle, nuclear and astroparticle physics experiments.

Some physical quantities in particle physics are only accessible with sophisticated particle identification (B-physics, CP violation, rare decays, search for exotic hadronic states).

Nuclear physics: final state identification in quark-gluon plasma searches

Astrophysics/astroparticle physics: identification of cosmic rays – separation between nuclei (isotopes), charged particles and high energy photons

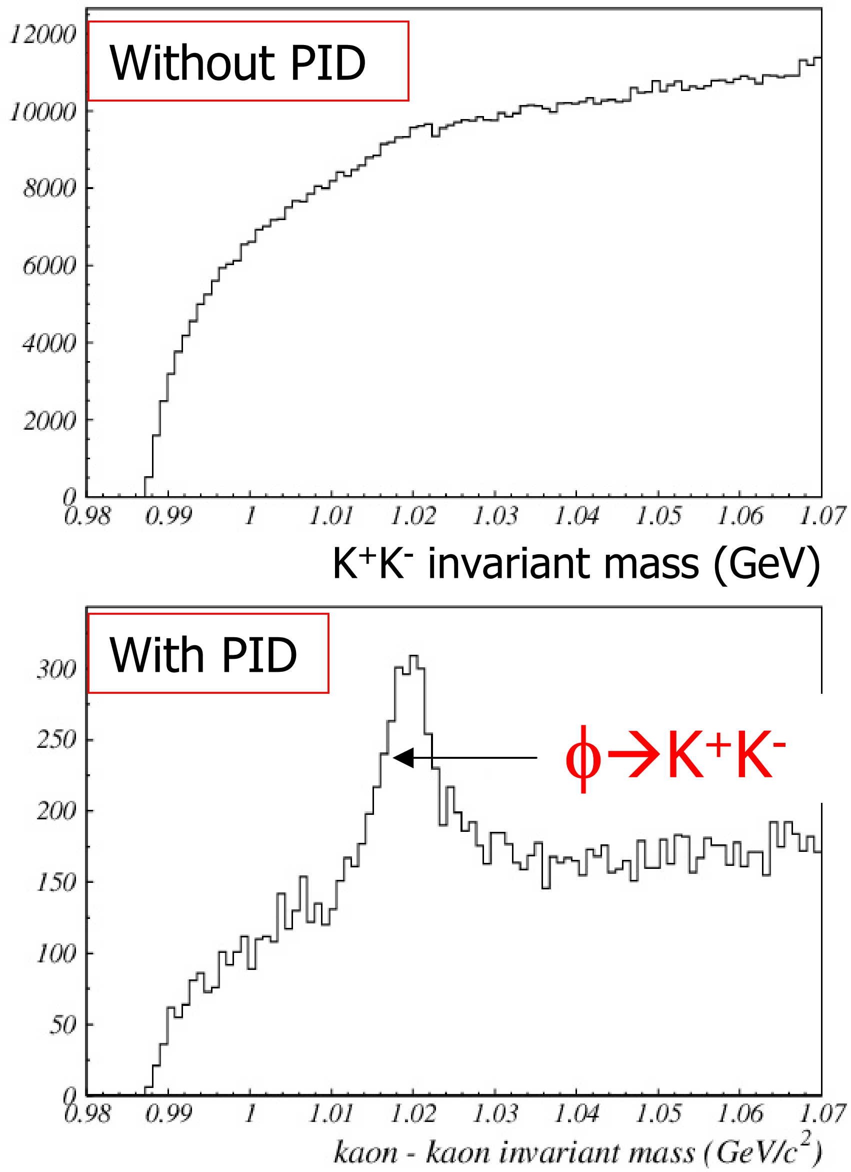
Introduction: Why particle ID?



Example 1: B factory

Particle identification reduces the fraction of wrong Kπ combinations (combinatorial background) by ~6x

Introduction: Why particle ID?



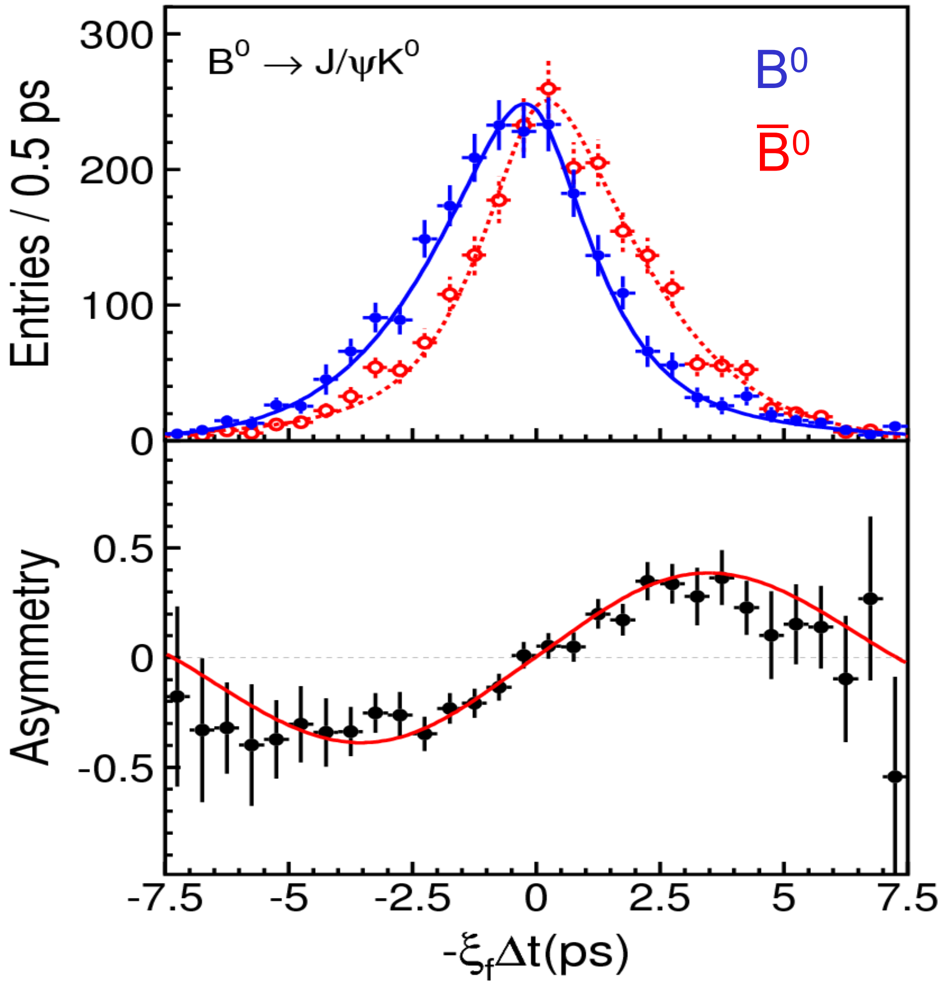
Example 2: HERA-B

K^+K^- invariant mass.

The inclusive $\phi \rightarrow K^+K^-$ decay only becomes visible after particle identification is taken into account.

Introduction: Why particle ID?

Particle identification at B factories (Belle and BaBar): was essential for the observation of CP violation in the B meson system.



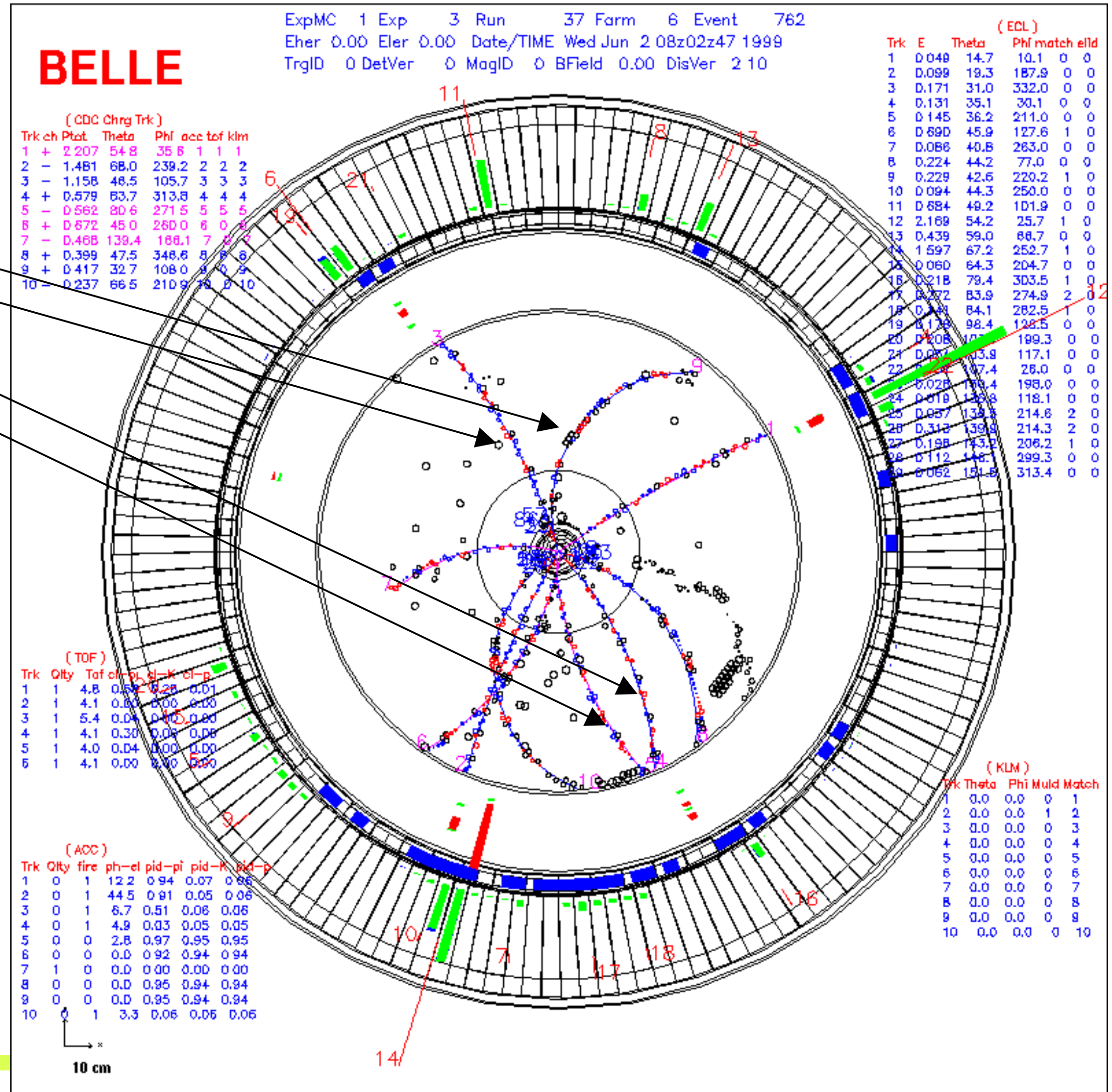
B^0 and its anti-particle decay diffently to the same final state $J/\psi\ K^0$

Was it a B or anti-B?

B^0 (or $\bar{B}^0$) → $K^0_S\, J/\psi$

$K^0_S \rightarrow \pi^- \pi^+$

$J/\psi \rightarrow \mu^- \mu^+$

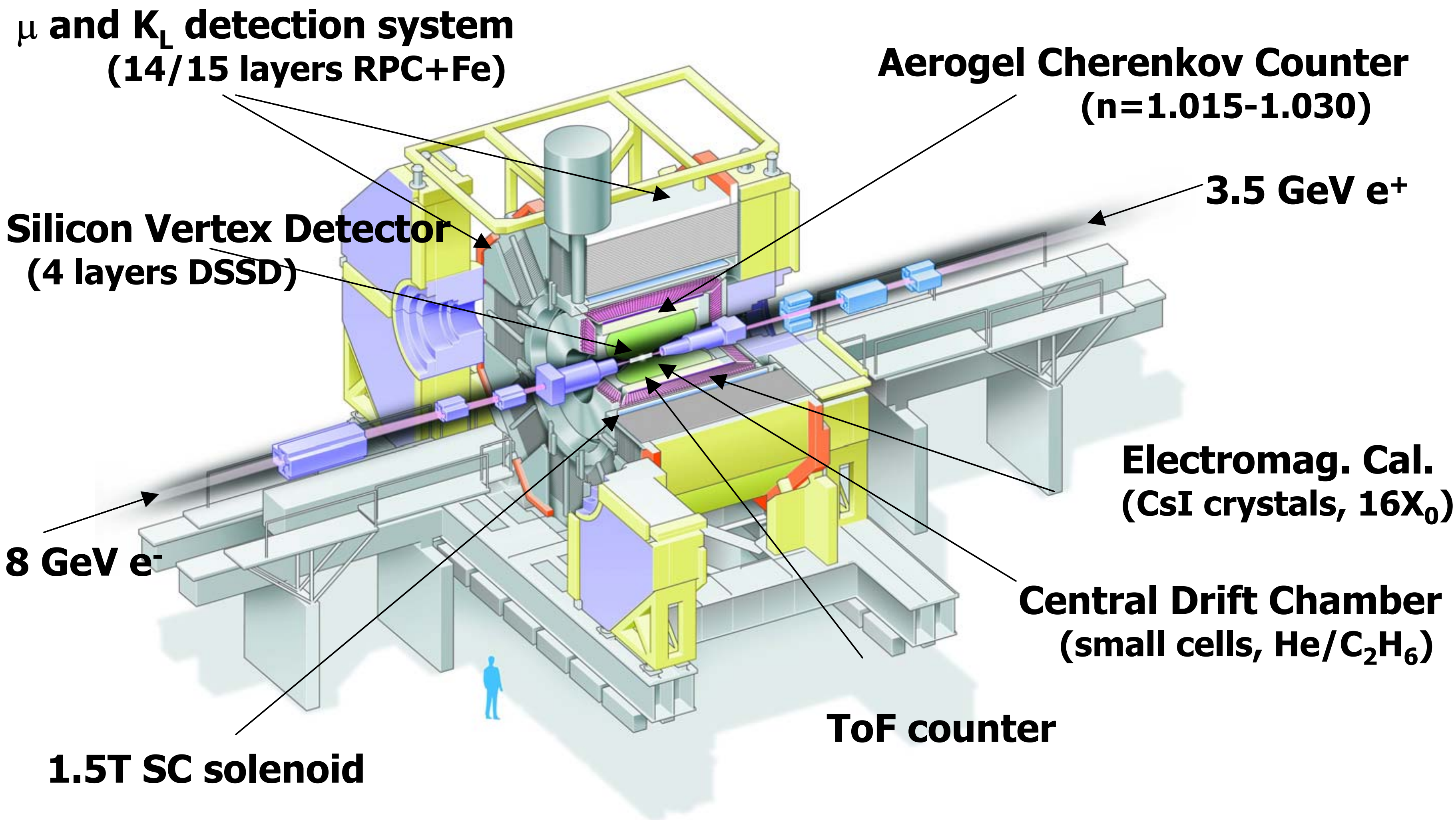


Flavour of the B: from decay products of the other B: charge of the kaon, electron, muon

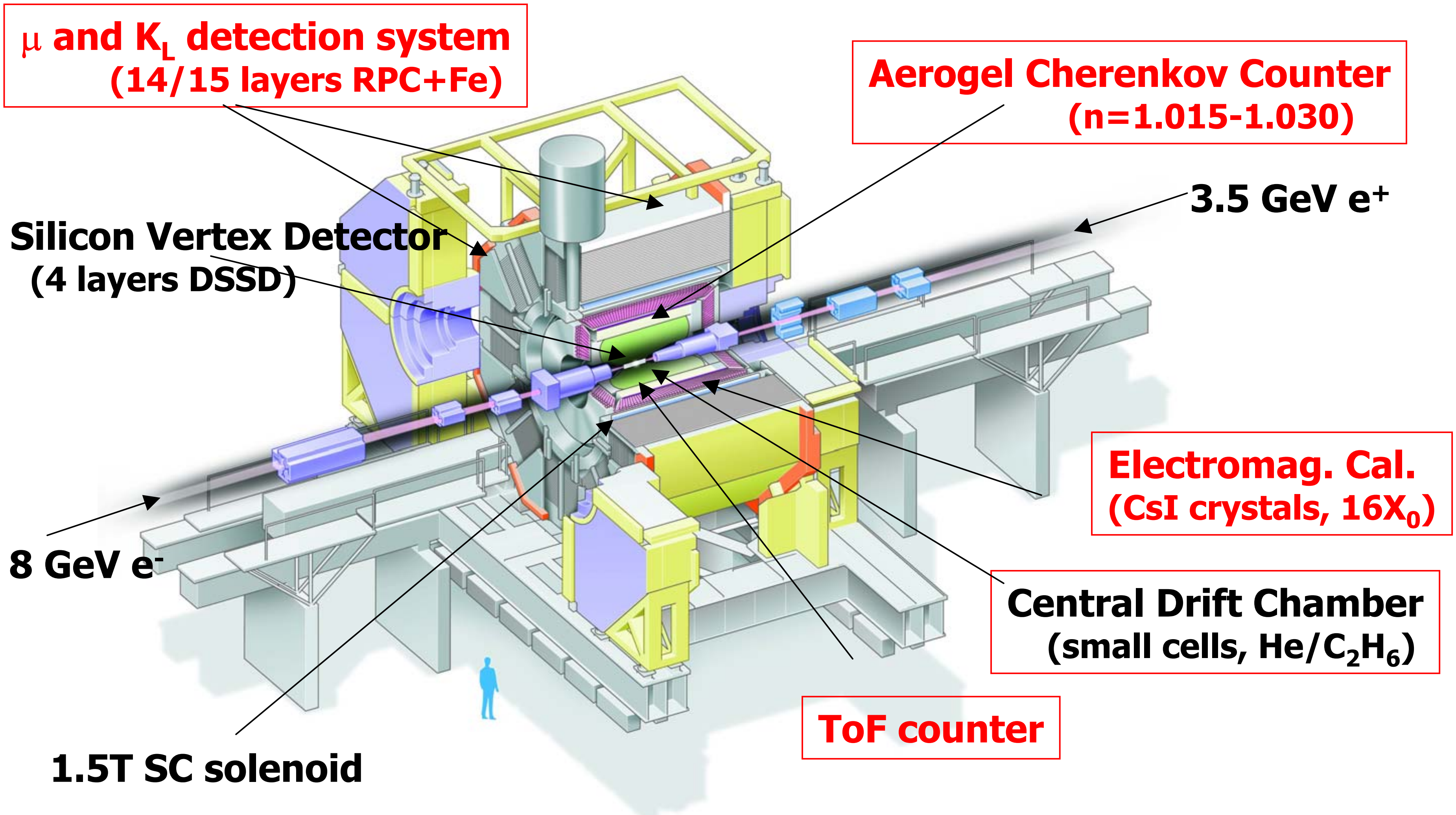
→need particle ID

Belle @ KEK-B in Tsukuba

Belle spectrometer



Particle identification systems in Belle



Identification of charged particles

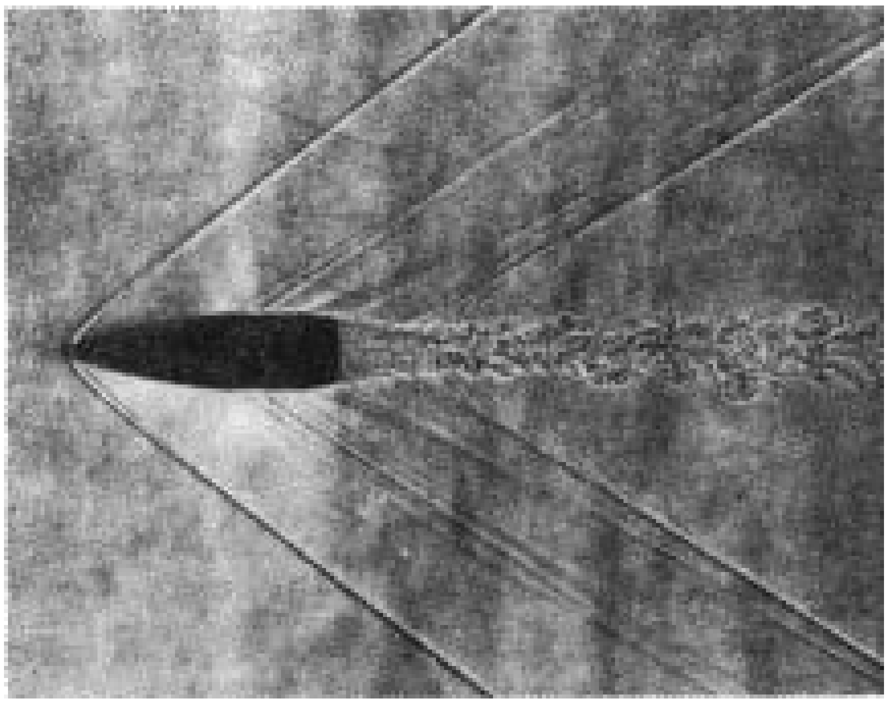
Particles are identified by their mass.

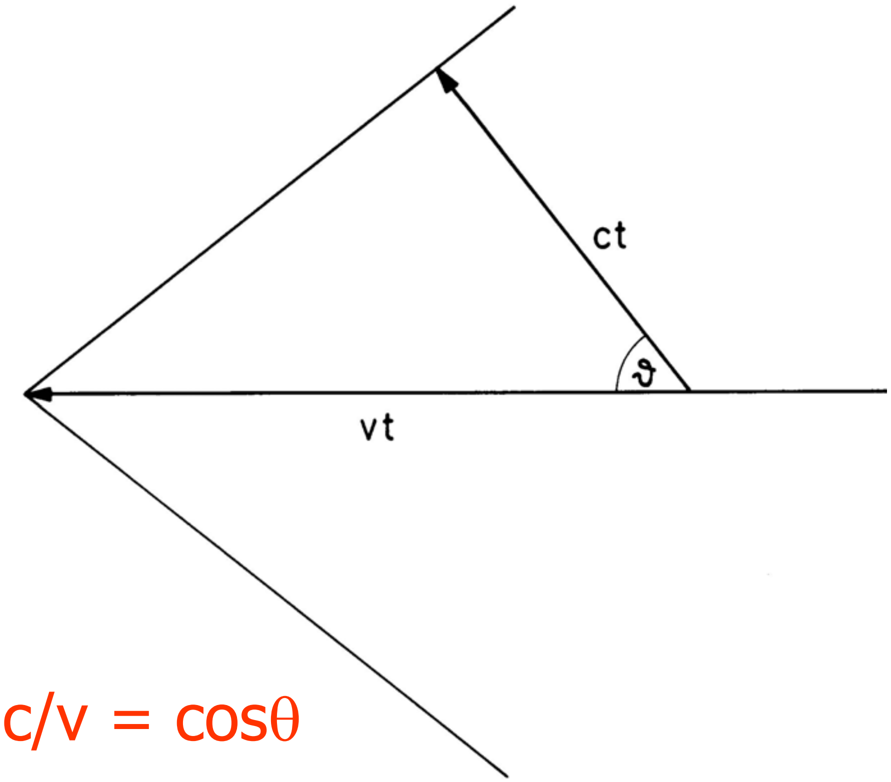
Determination of mass: from the relation between momentum and velocity, $p=\gamma mv$.

- Momentum known (radius of curvature in magnetic field)
- Measure velocity:
  - time of flight
  - ionisation losses dE/dx
  - Čerenkov angle

Velocity of a bullet

Determine the velocity of a bullet





$c/v = \cos\theta$

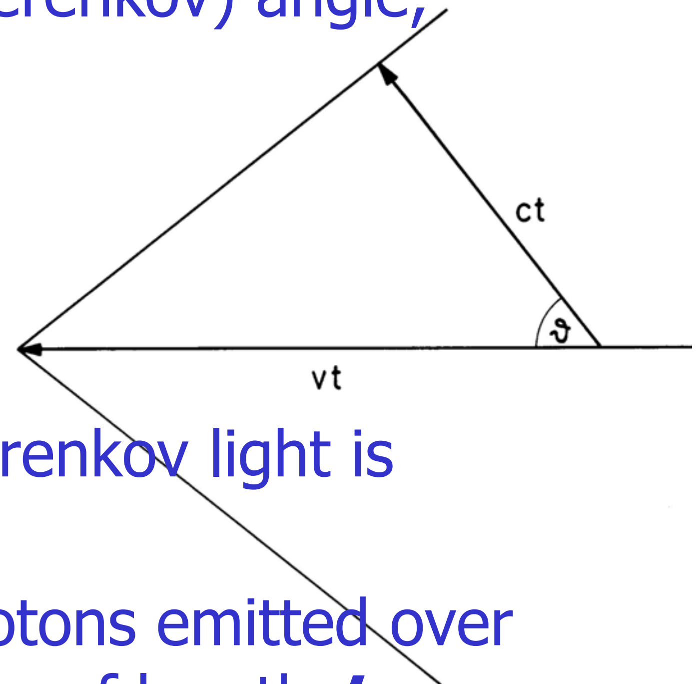
From the photograph:

angle 52°, $v = c/\cos\theta = 340\text{m/s} / \cos 52° = 552\text{m/s}$

Čerenkov radiation

A charged track with velocity v=βc exceeding the speed of light c/n in a medium with refractive index n emits polarized light at a characteristic (Čerenkov) angle,

cosθ = c/nv = 1/βn



Two cases:

1) $\beta < \beta_t$ = 1/n: below threshold no Čerenkov light is emitted.

2) $\beta > \beta_t$: the number of Čerenkov photons emitted over unit photon energy E=hν in a radiator of length ***L***:

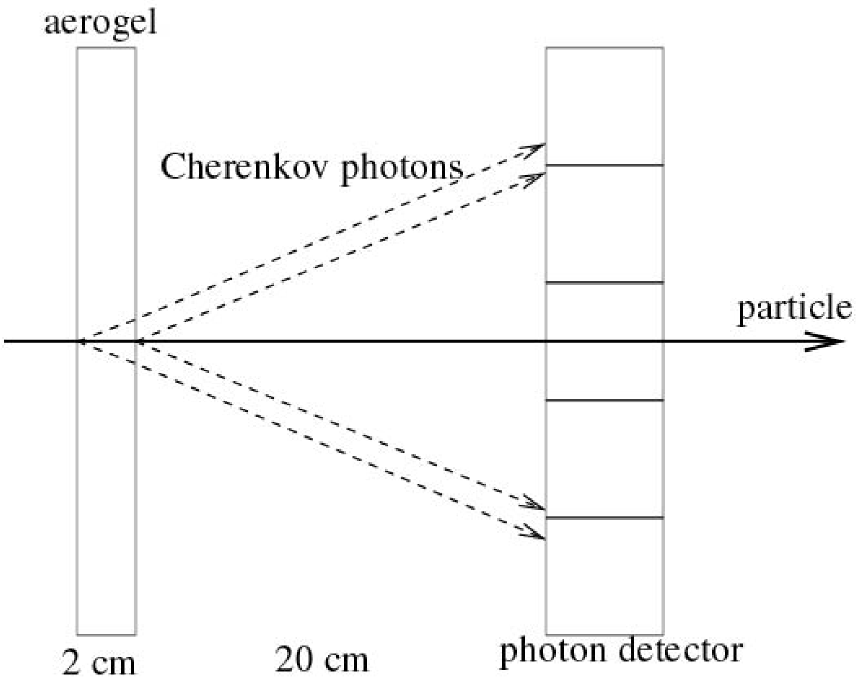
$$\frac{dN}{dE} = \frac{\alpha}{\hbar c} L \sin^2\theta = 370 (cm)^{-1} (eV)^{-1} L \sin^2\theta$$

Measuring Čerenkov angle

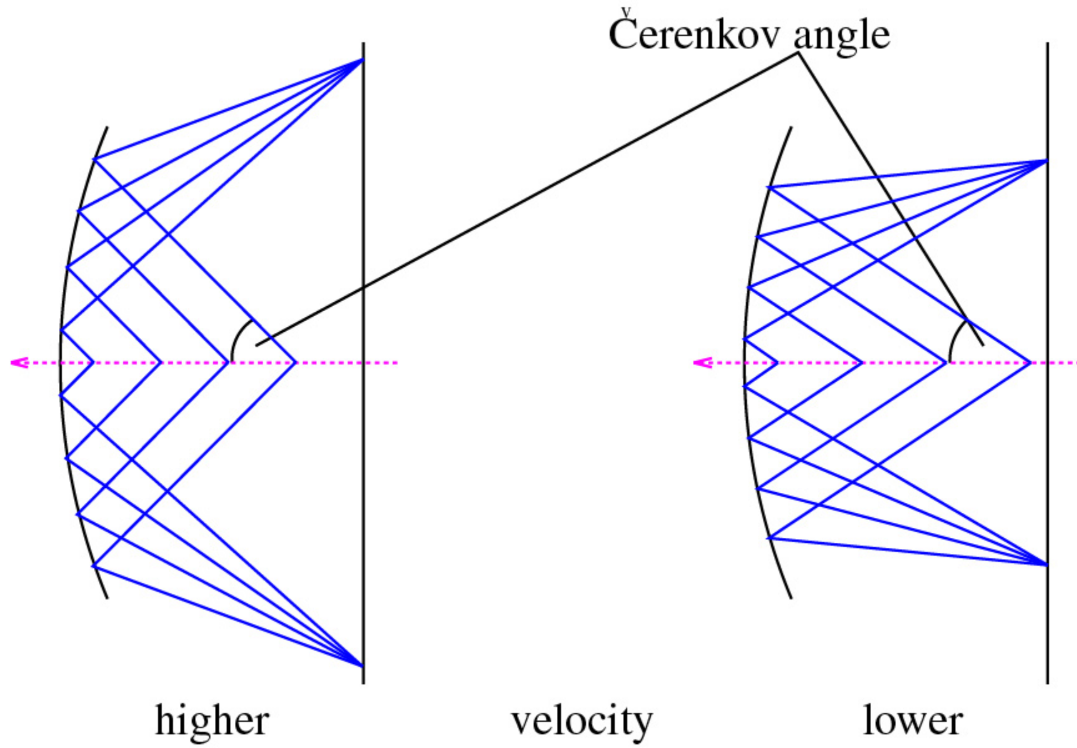
Idea: transform the direction into a coordinate →

ring on the detection plane

→ Ring Imaging CHerenkov



Proximity focusing RICH



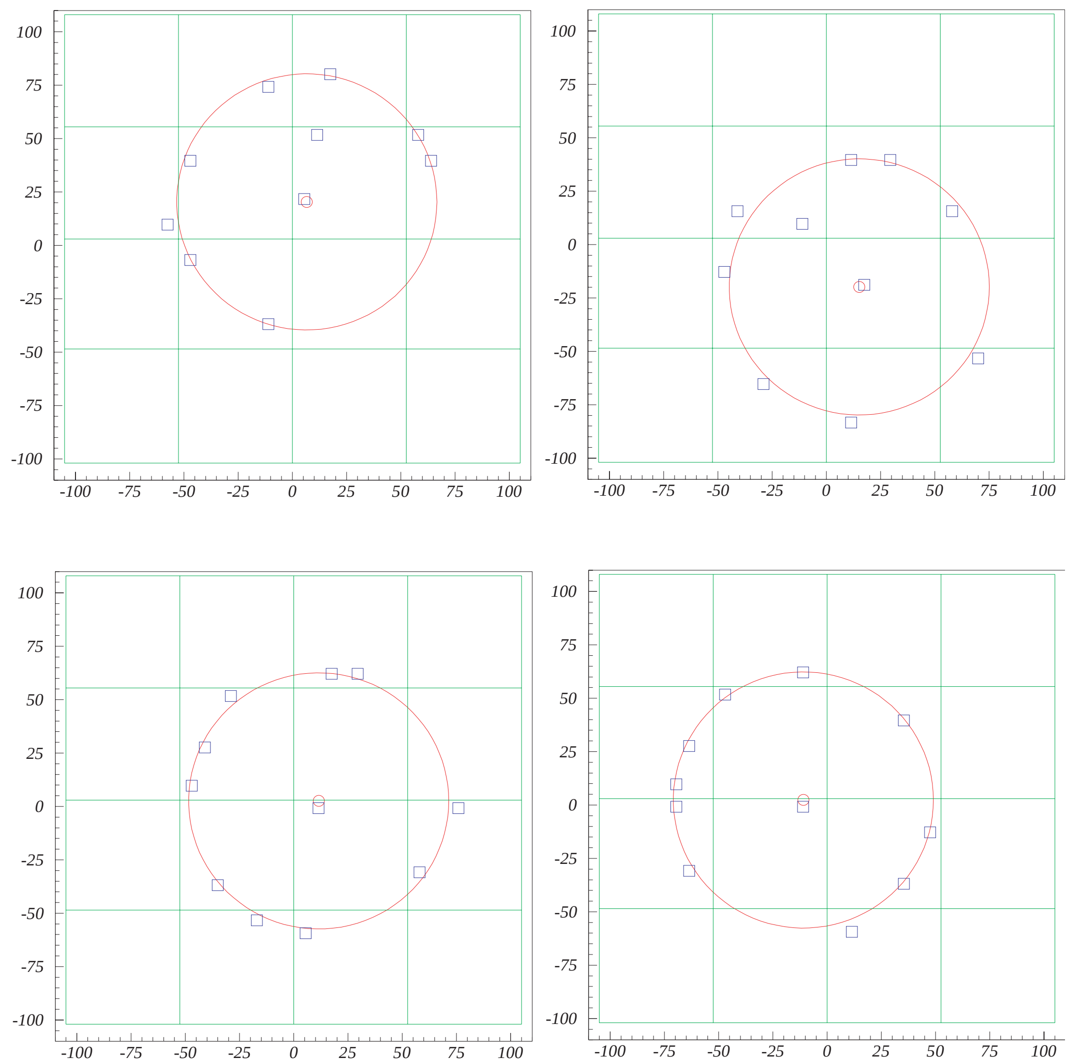
RICH with a focusing mirror

Measuring Čerenkov angle

From hits of individual photons → measure the angle.

Few photons detected

→Important to have a low noise detector



Number of detected photons

Example: in 1m of air (n=1.00027) a track with β=1 emits N=41 photons in the spectral range of visible light (ΔE ~ 2 eV).

If Čerenkov photons were detected with an average detection efficiency of ε=0.1 over this interval, N=4 photons would be measured.

In general: number of detected photons can be parametrized as **$N = N_0 L \sin^2\theta$**

where N_0 is the figure of merit,

$$N_0 = \frac{\alpha}{\hbar c} \int Q(E) T(E) R(E) dE$$

and Q T R is the product of photon detection efficiency, transmission of the radiator and windows and reflectivity of mirrors (as a function of photon energy E).

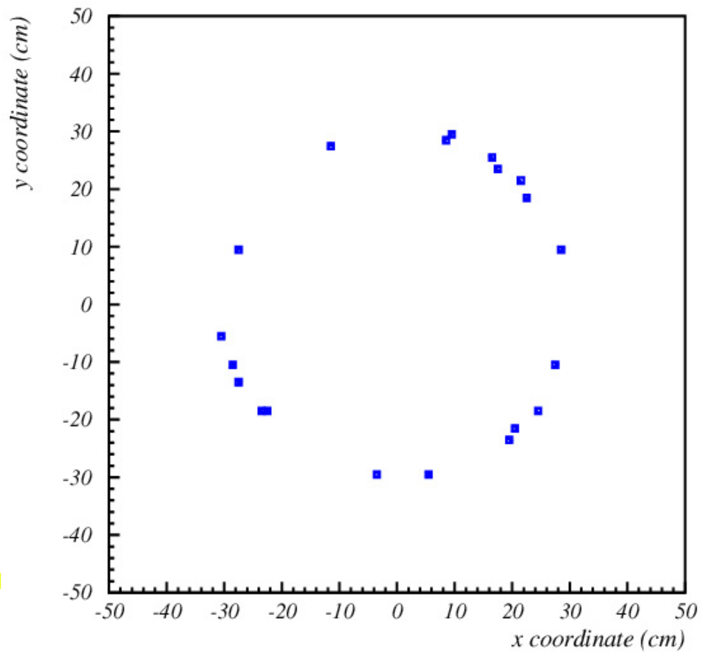
Typically: N_0 = 50 - 100/cm

Photon detection in RICH counters: fundamental requirements

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
- over a large area (square meters)



Photon detection in RICH counters: special requirements

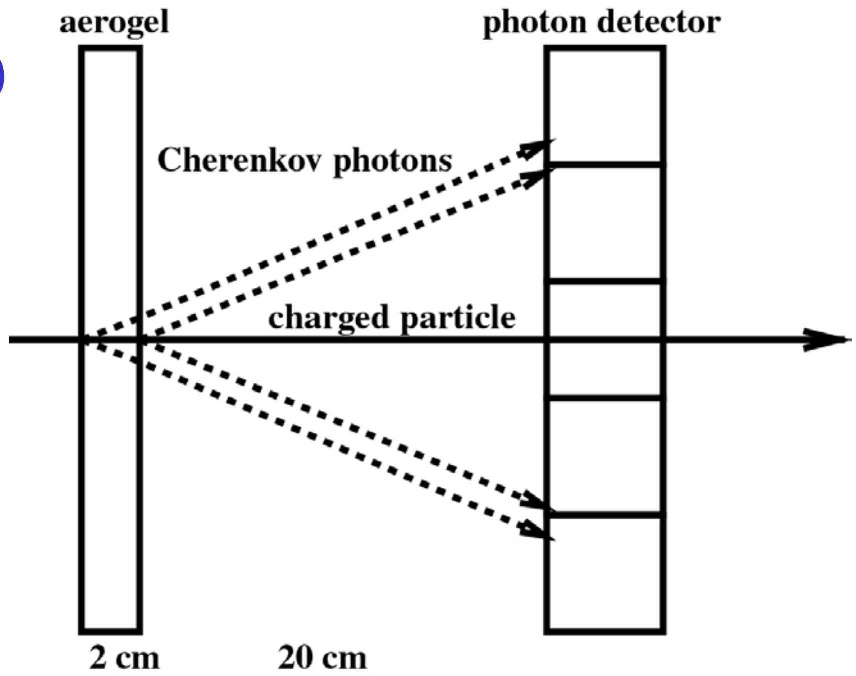
Special requirements depend on the specific features of individual RICH counter:

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

Resolution of a RICH counter

Determined by:

- Photon impact point resolution (~photon detector granularity)
- Emission point uncertainty
- Dispersion: $n=n(\lambda)$ in $1/\beta = n \cos\theta$
- Errors of the optical system
- Uncertainty in track parameters

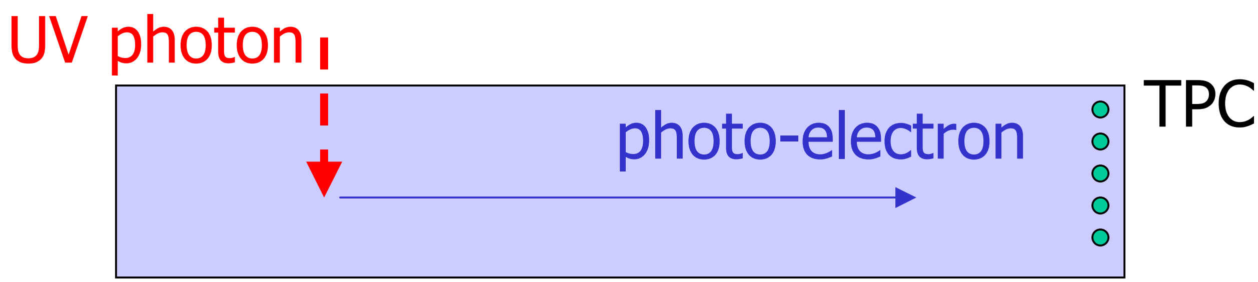


Short historical excursion

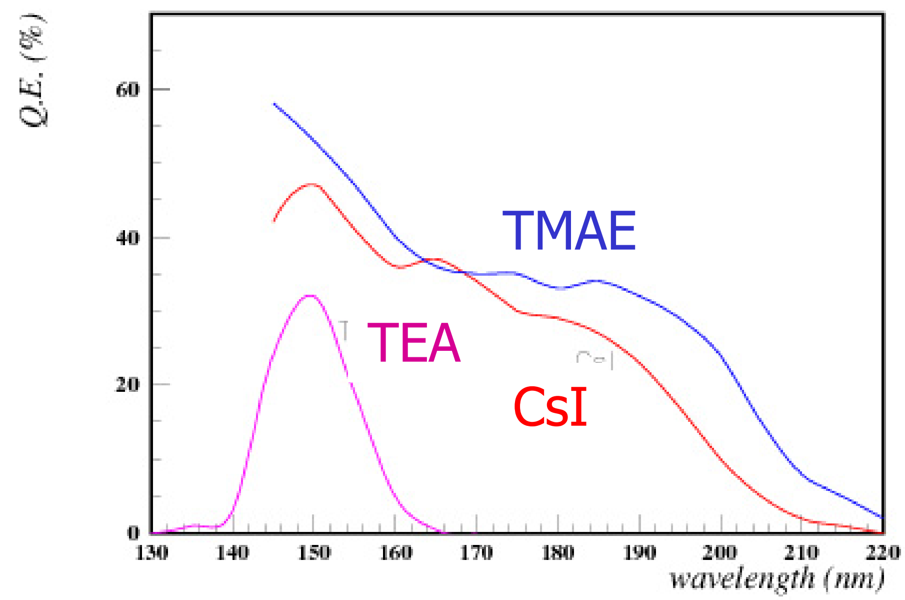
- 1934 Čerenkov characterizes the radiation
- 1938 Frank, Tamm give the theoretical explanation
- 50-ties - 70-ties Čerenkov counters are developed and are being used in nuclear and particle physics experiments, as differential and threshold counters
- 1977 Ypsilantis, Seguinot introduce the idea of a RICH counter with a large area wire chamber based photon detector
- 1981-83 first use of a RICH counter in a particle physics experiment (E605)
- 1992→ first results from the DELPHI RICH, SLD CRID, OMEGA RICH

First generation of RICH counters

DELPHI, SLD, OMEGA RICH counters: all employed wire chamber based photon detectors (UV photon → photo-electron → detection of a single electron in a TPC)

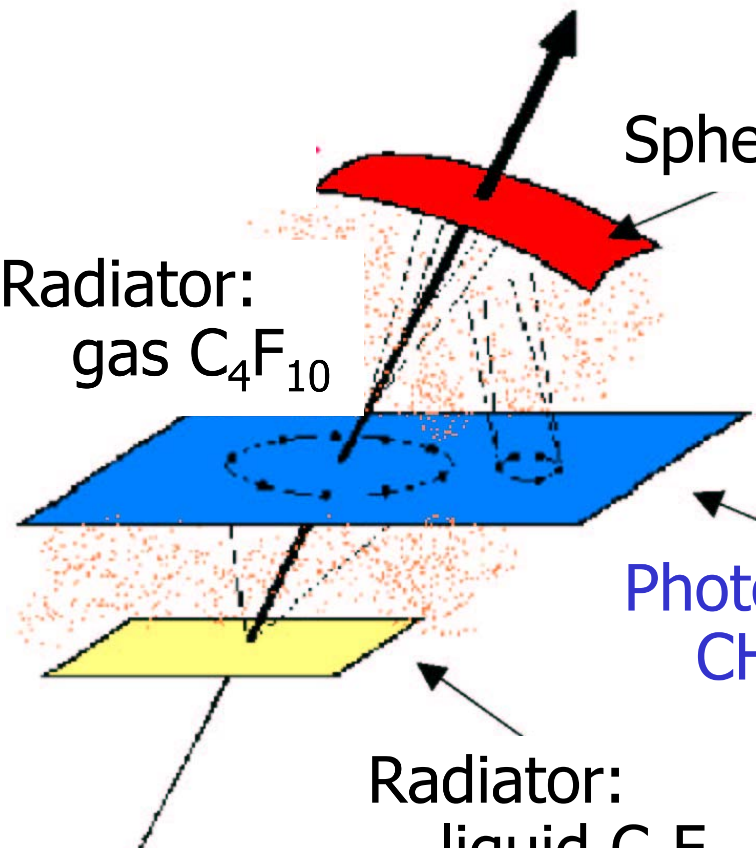


Photosensitive component: TMAE added to the gas mixture



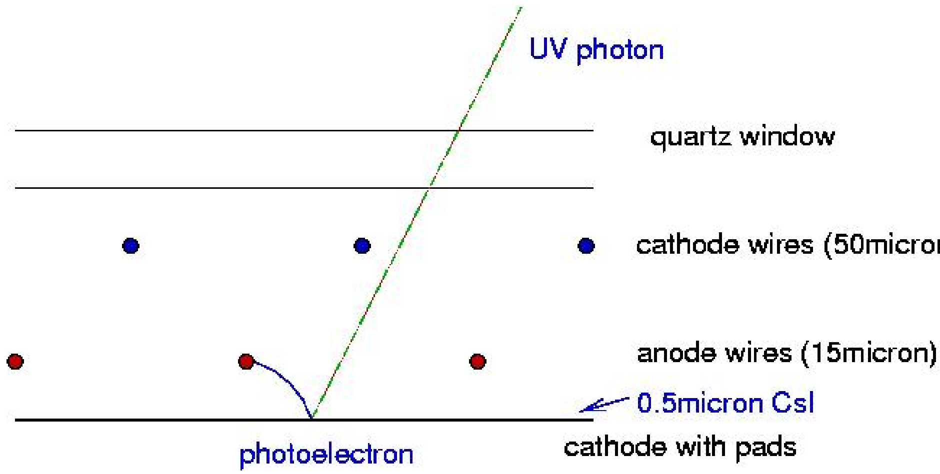
First generation of RICH counters

Inside the DELPHI RICH: segmented spherical mirror



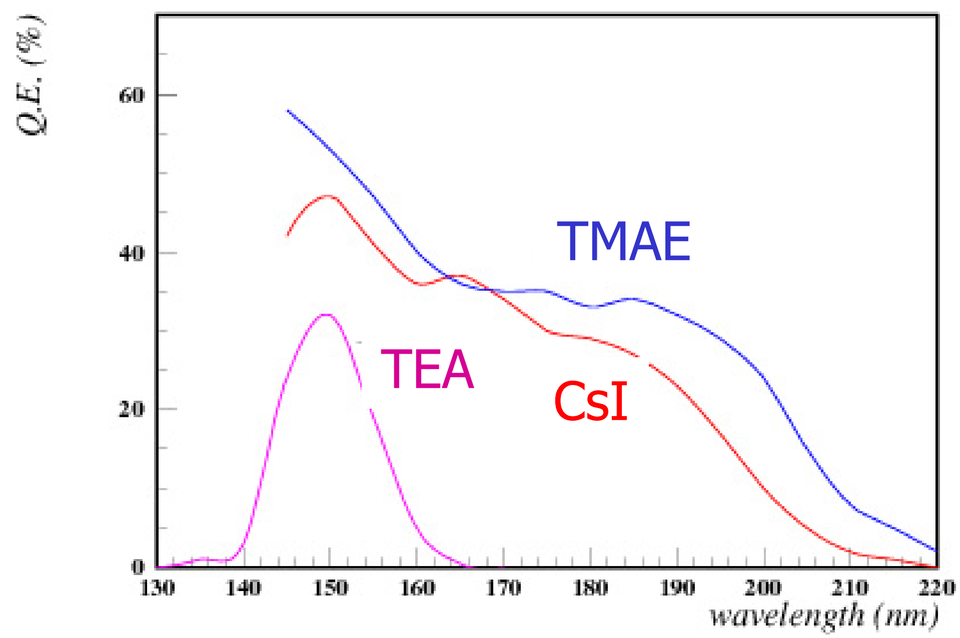
Fast RICH counters with wire chambers

Multiwire chamber with pad read-out: → short drift distances, fast detector



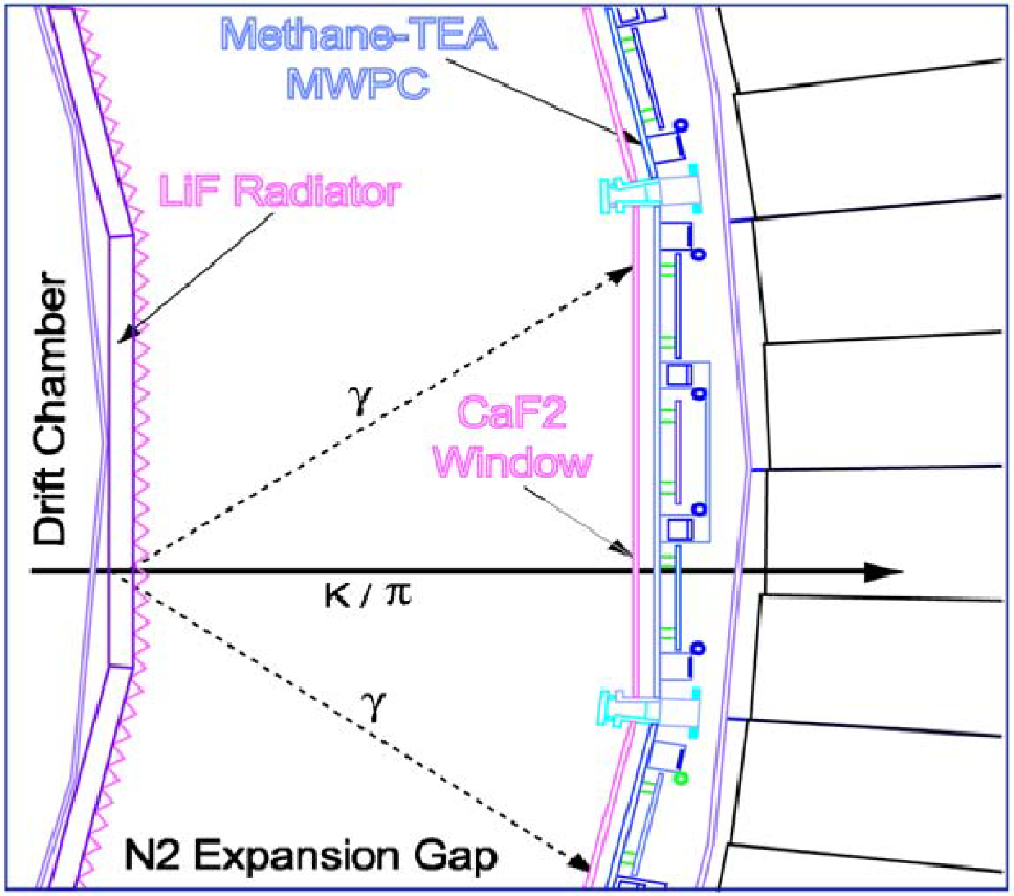
Photosensitive component:

- in the gas mixture (TEA)
- or a layer on one of the cathodes (CsI on the printed circuit pad cathode)



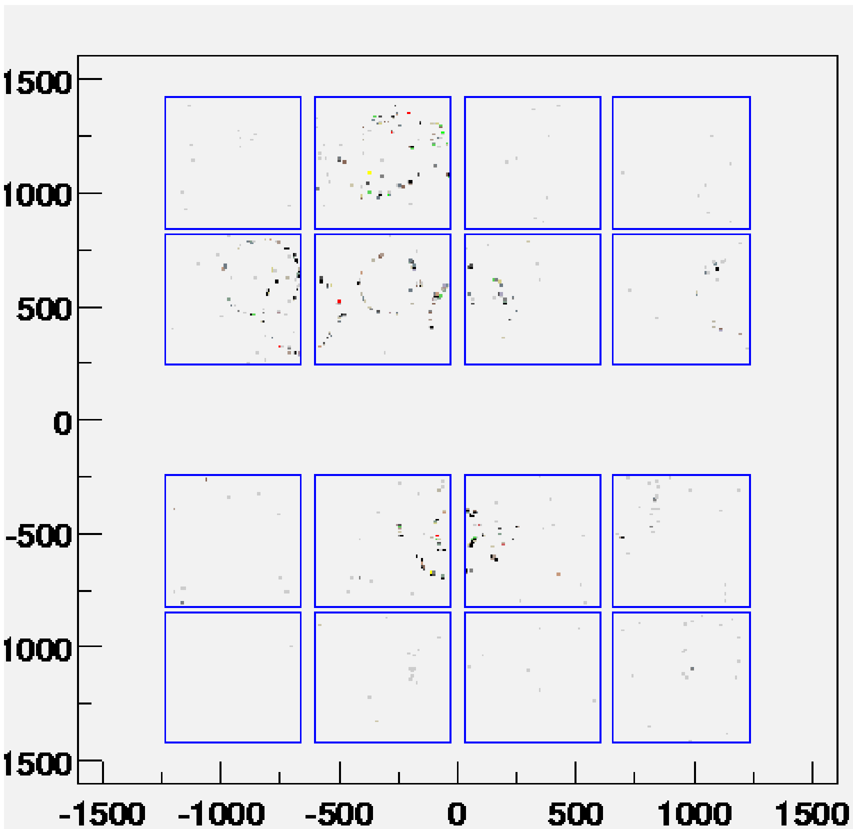
CLEOIII RICH

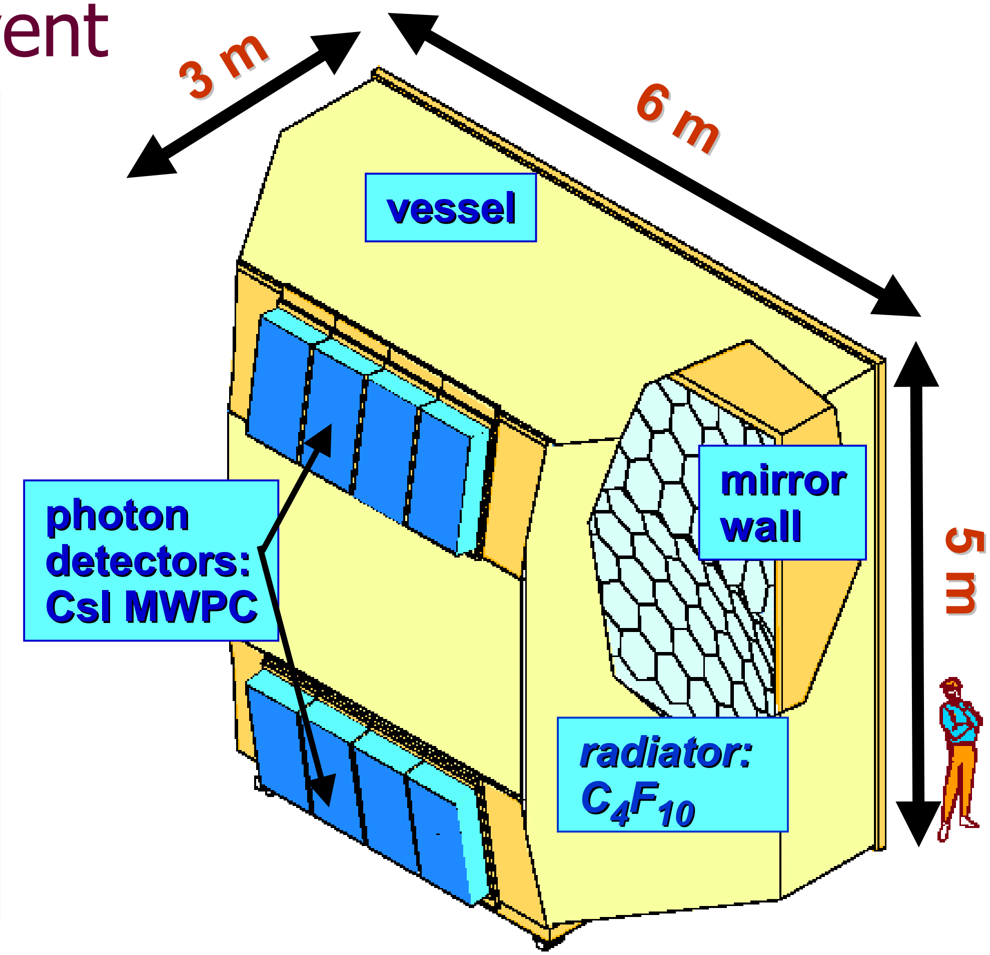
Photon detection in a wire chamber with a methane+TEA.



CsI based RICH counters: HADES, COMPASS, ALICE

COMPASS: calibration event





Early nineties: a new boost

The main motivation came from the planning of experiments to measure CP violation in the B meson system.

Kaon identification: one of the essential features.

Several proposals in Europe, US, Japan → several RICH designs and R+D programs.

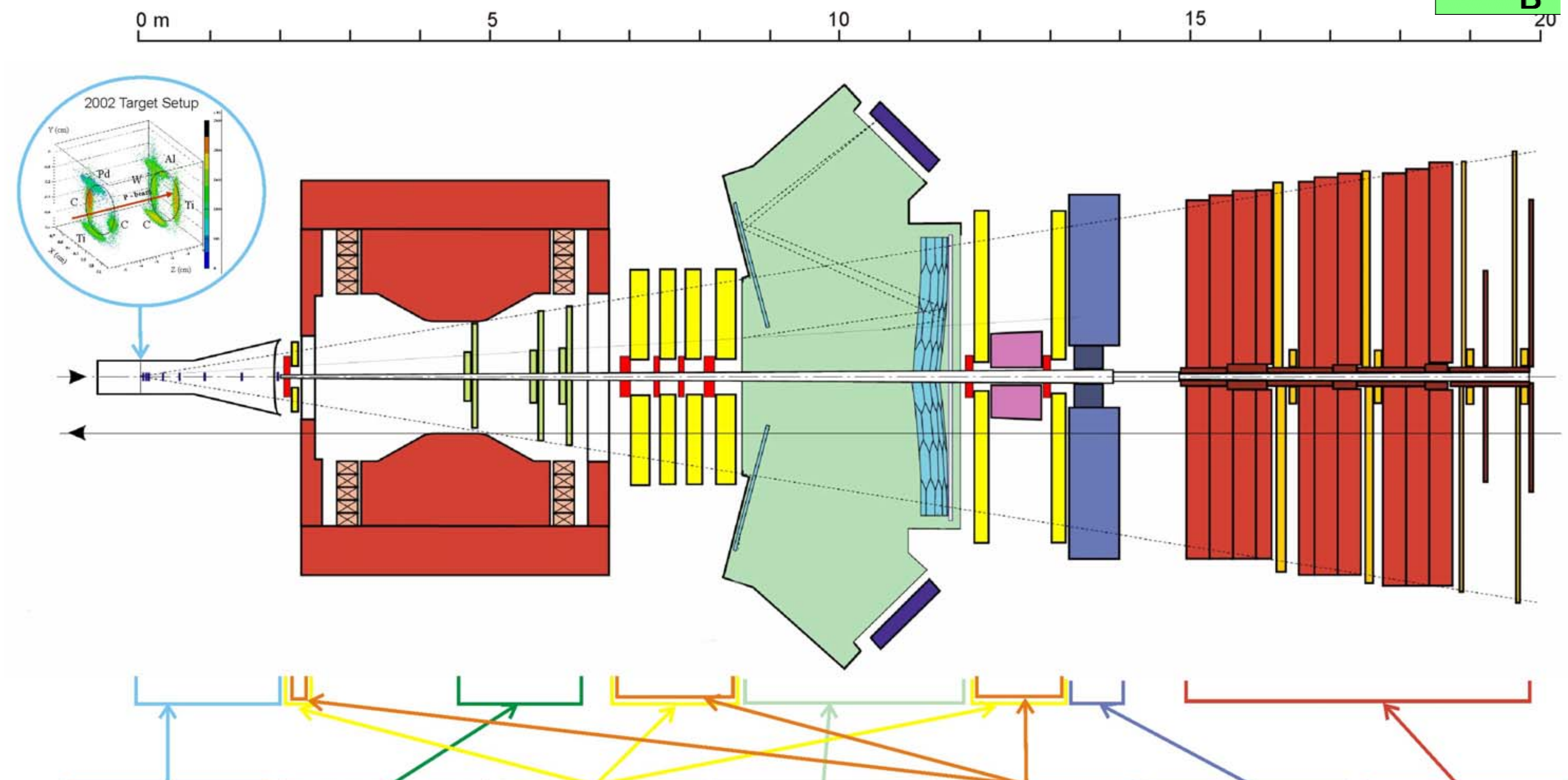
Wire chamber based photon detectors were found to be unsuitable (problems in high rate operation, ageing, only UV photons, difficult handling)

Second generation of RICH counters

Two important developments pioneered at DESY:

- Multianode PMTs as photon detectors (HERA-B)
- Aerogel as radiator (HERMES)

HERA-B side view



Target & Vertex
8 layers of double-sided Si-microstrips, movable on Roman-Pots; 8 wire-target (see above)

High p_T
3 superlayers gas, pixel and pad chambers; pre-trigger for high p_T tracks

Outer Tracker
7 superlayers of honeycomb drift chambers, 5 and 10mm cells

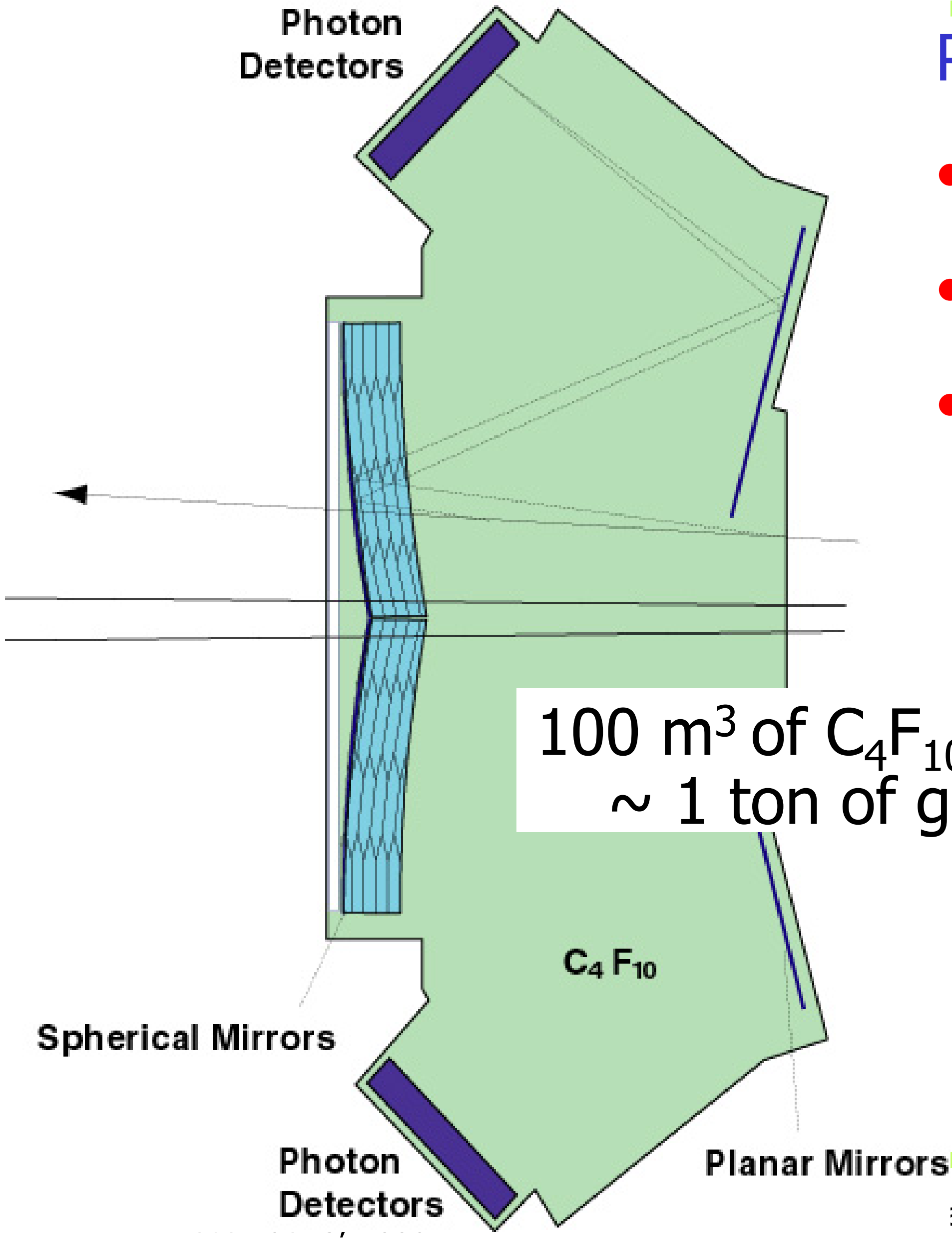
RICH
Spherical mirror inside C_4F_{10} radiator, Lens-enhanced multianode PMT focal plane.

Inner Tracker
7 superlayers of Micro Strip Gas Chambers with GEM-foil

Electromagnetic Calorimeter
W/Pb scintillator sandwich, shashlik WLS readout with PMTs; energy-cluster pre-trigger

Muon System
4 superlayers of gas-pixel, tube & pad chambers; pad-coincidence pre-trigger

HERA-B RICH



100 m^3 of C_4F_{10}
~ 1 ton of gas

Photon detector requirements:

- High QE over ~3m^2
- Rates ~1MHz
- Long term stability

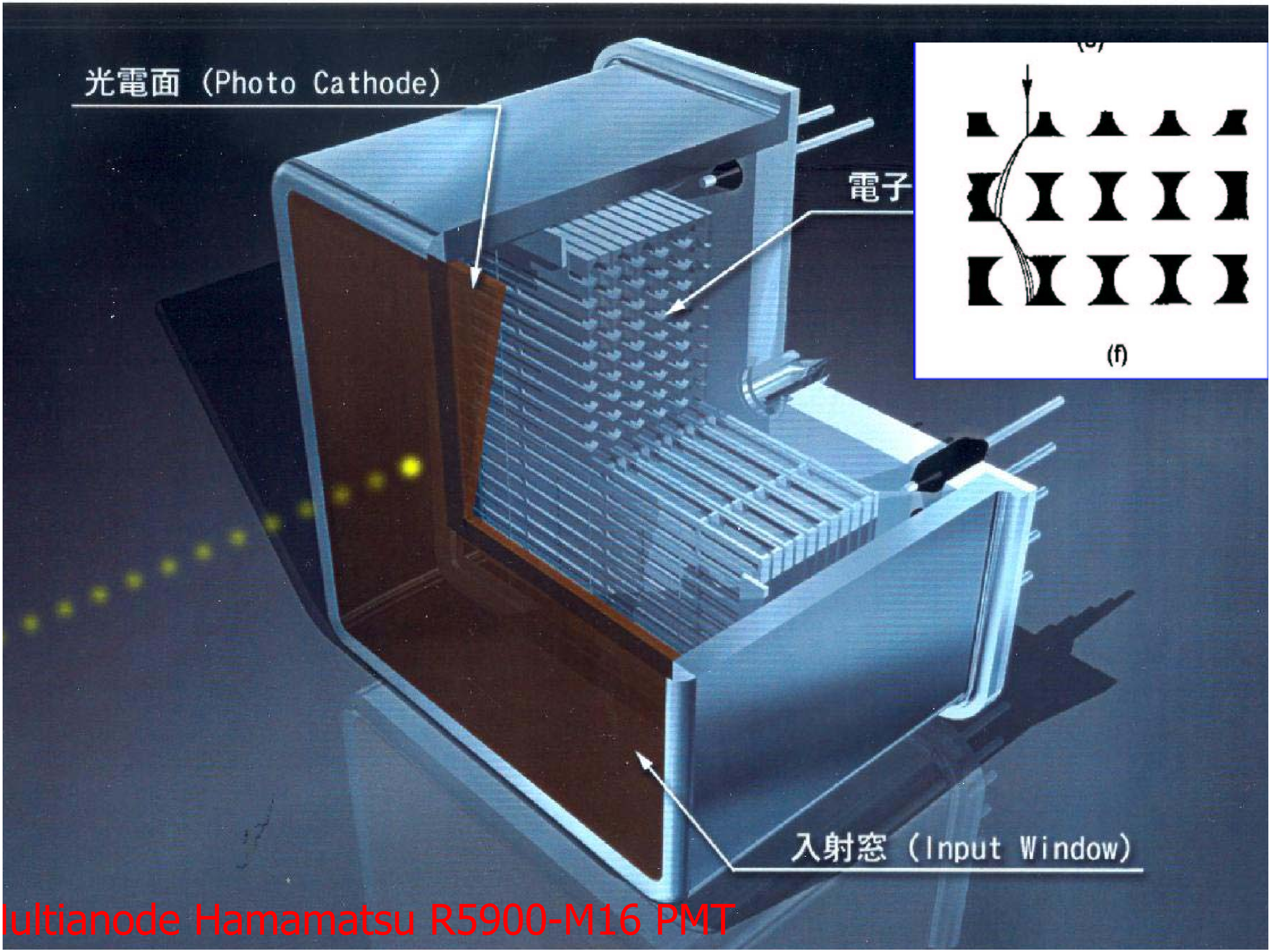
HERA-B RICH photon detector

Originaly considered: wire chambers with either TMAE or CsI. Tests: very good performance in test beams, but serious problems in long term operation at very high rates.

Hamamatsu just came out with the metail foil multianode PMTs of the R5900 series: first multianode PMTs with very little cross-talk

Tested on the bench and in the beam: excellent performance →easy decision

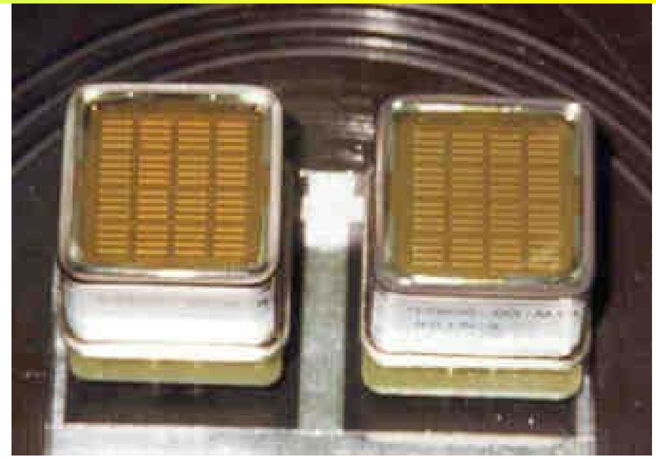
→ NIM A394 (1997) 27

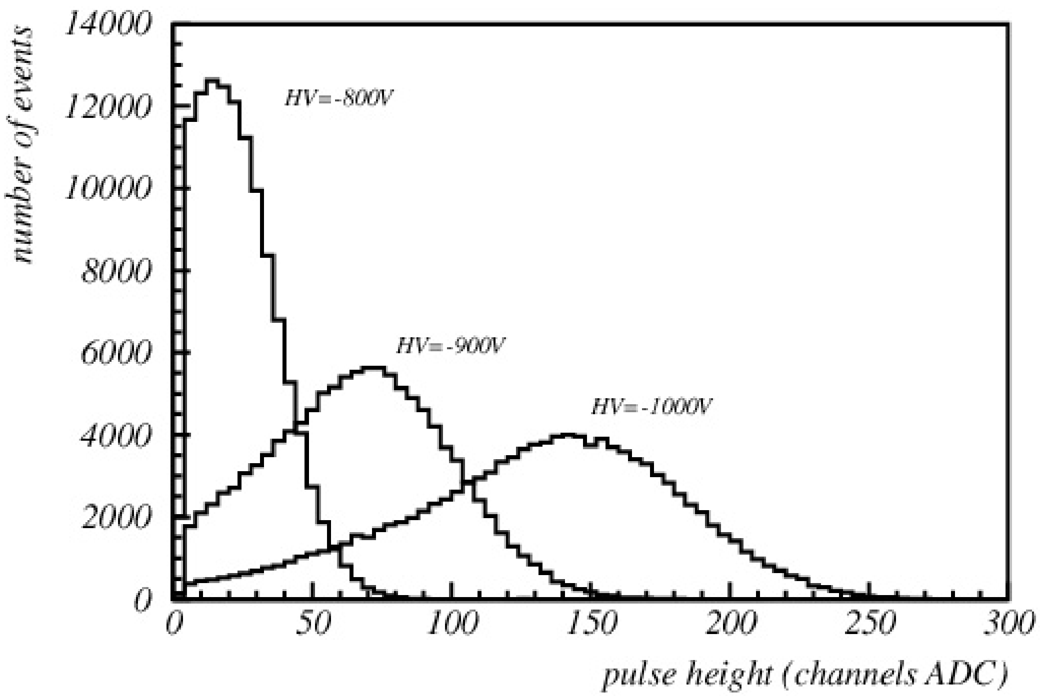


Iultianode Hamamatsu R5900-M16 PMT

Multianode PMTs

R5900-M16 (4x4 channels)
R5900-M4 (2x2 channels)





single photon pulse height

Key features:

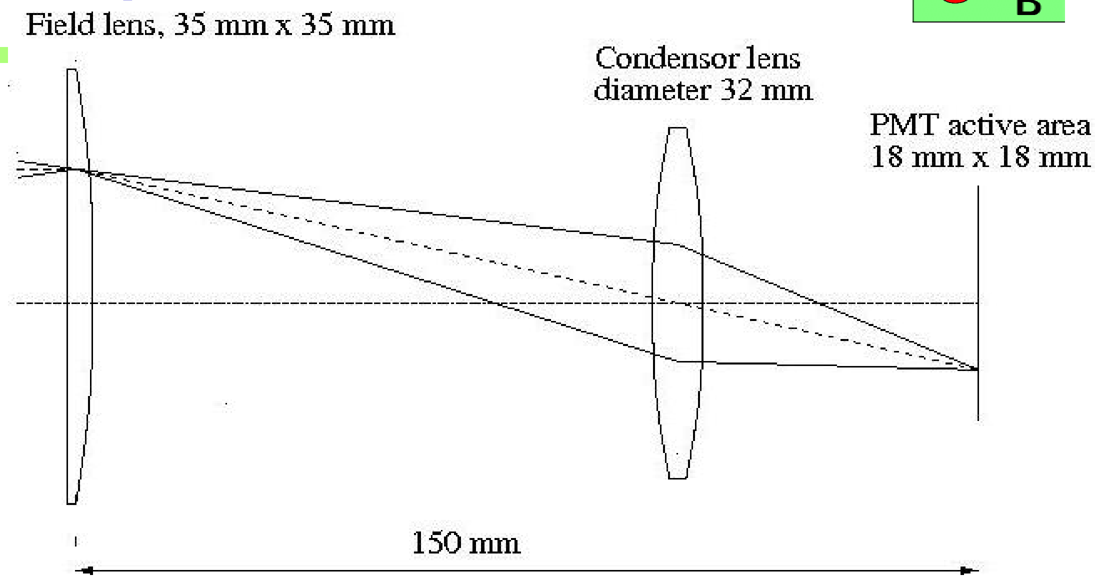
- Excellent single photon pulse height spectrum
- Low noise (few Hz/ch)
- Low cross-talk (<1%)

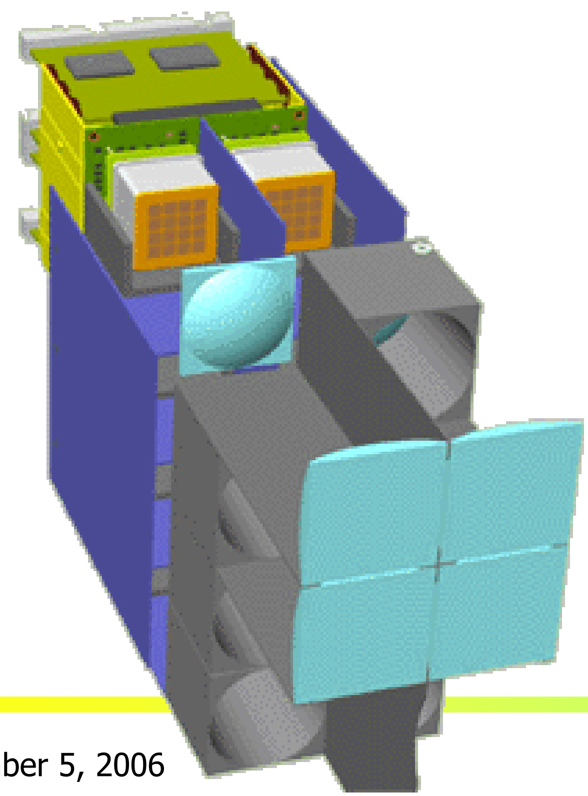
HERA-B RICH photon detector

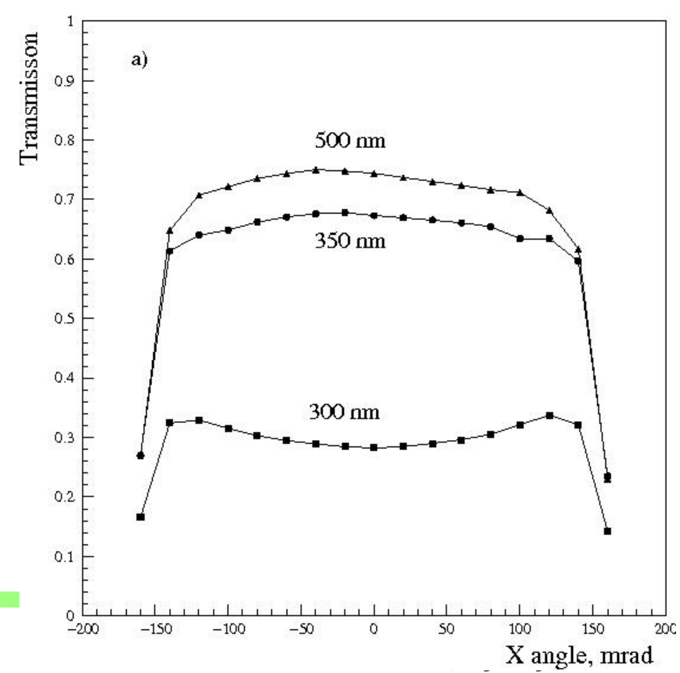
Light collection system (imaging!) to:

-Eliminate dead areas

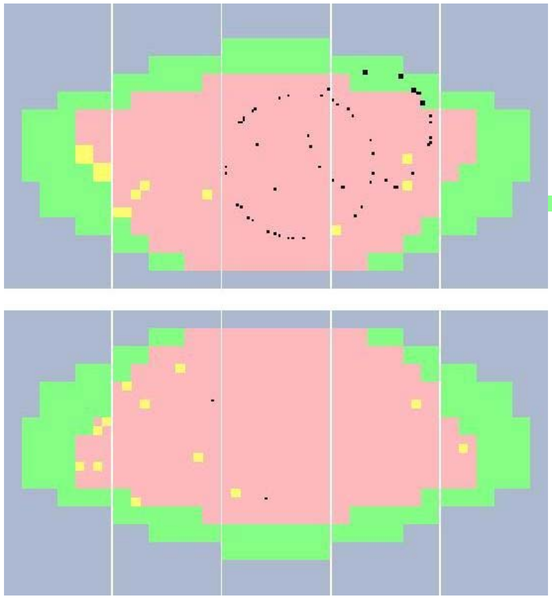
-Adapt the pad size





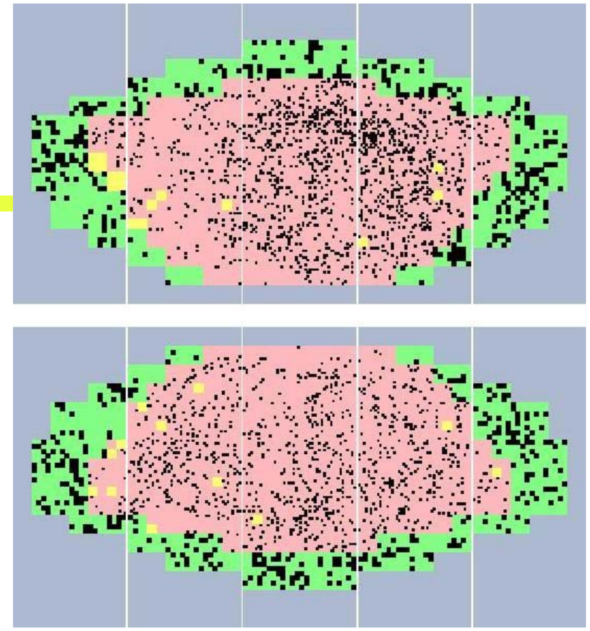


HERA-B RICH



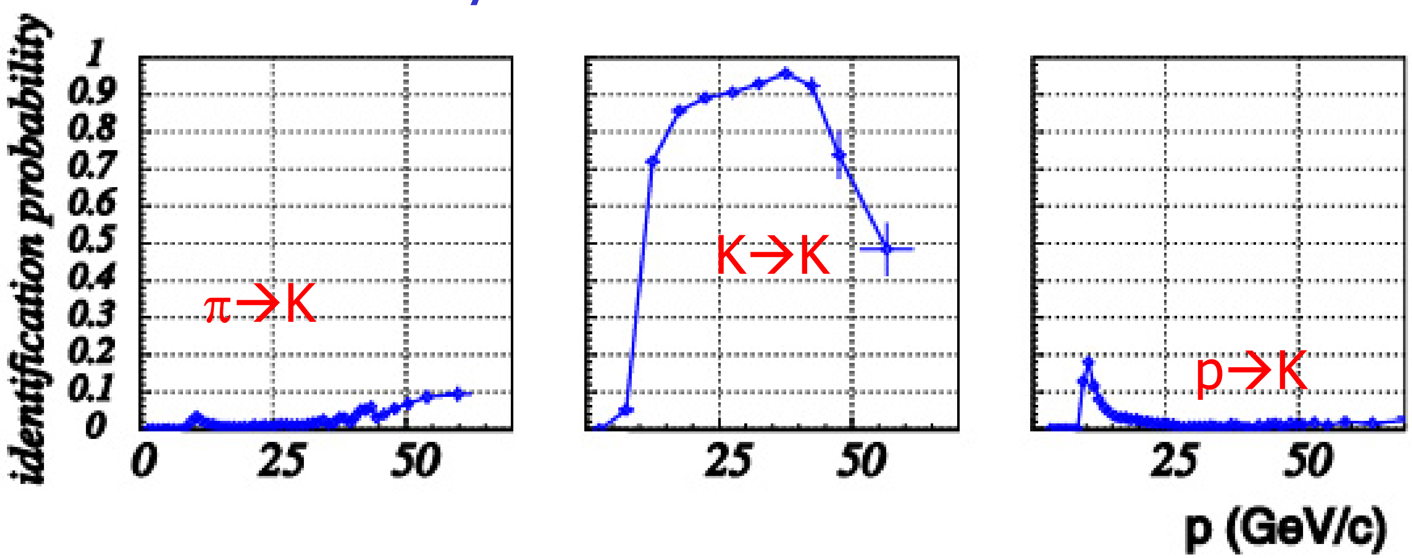
← Little noise, ~30 photons per ring

Typical event →

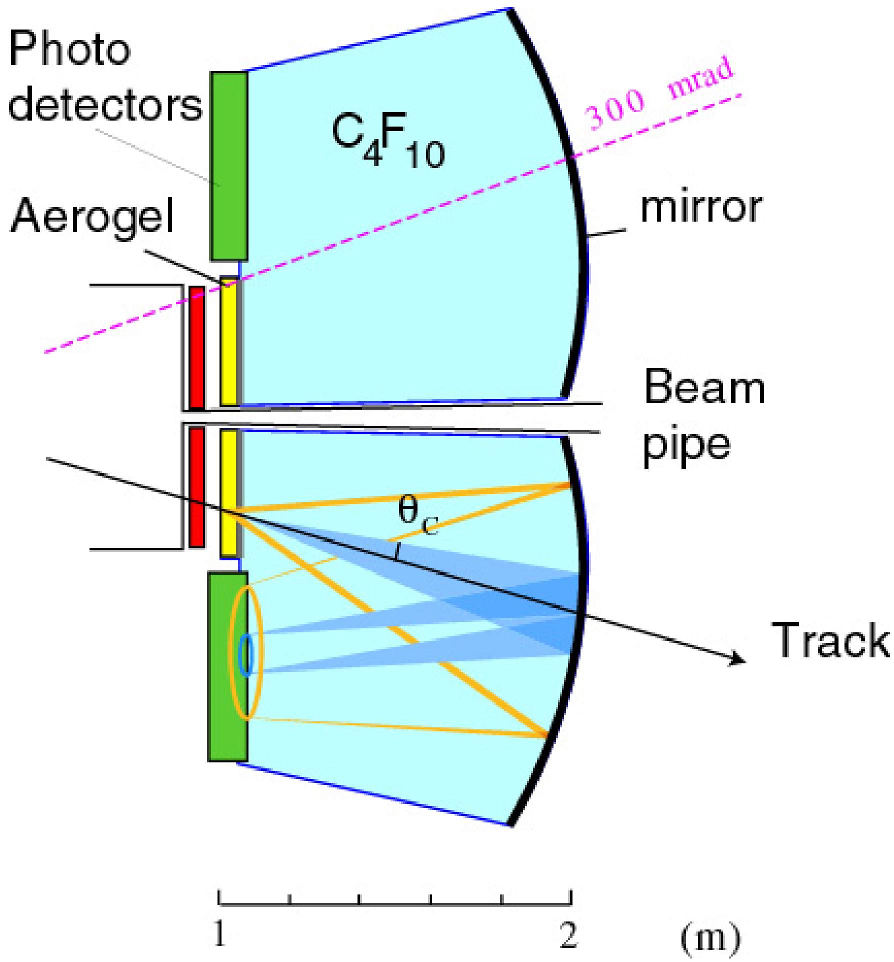


Worked very well!

Kaon efficiency and pion, proton fake probability



LHCb RICHes: similar geometry



RICH 1

Need:

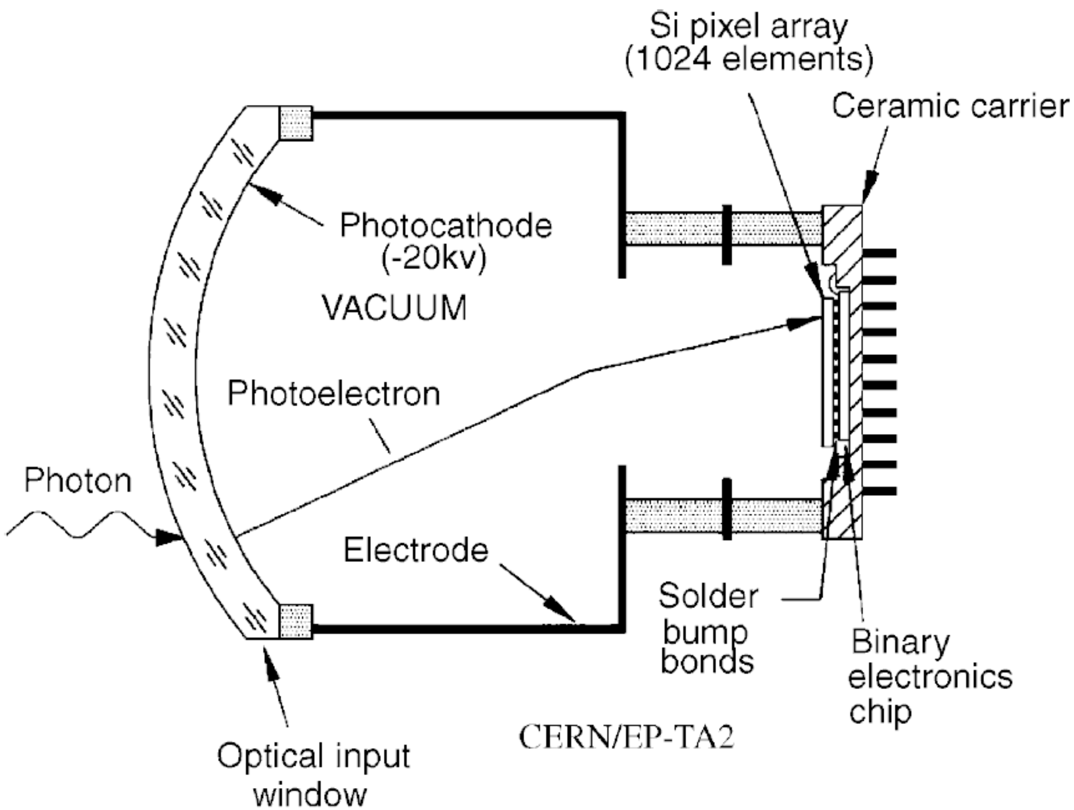
- Granularity 2.5x2.5mm^2
- Large area (2.8m^2) with high active area fraction
- Fast compared to the 25ns bunch crossing time
- Have to operate in a small magnetic field

R+D: study two types of hybrid photon detectors and MAPMT with a lens

LHCb RICHes

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

Hybrid PMT: accelerate photoelectrons in electric field (~10kV), detect it in a pixelated silicon detector.



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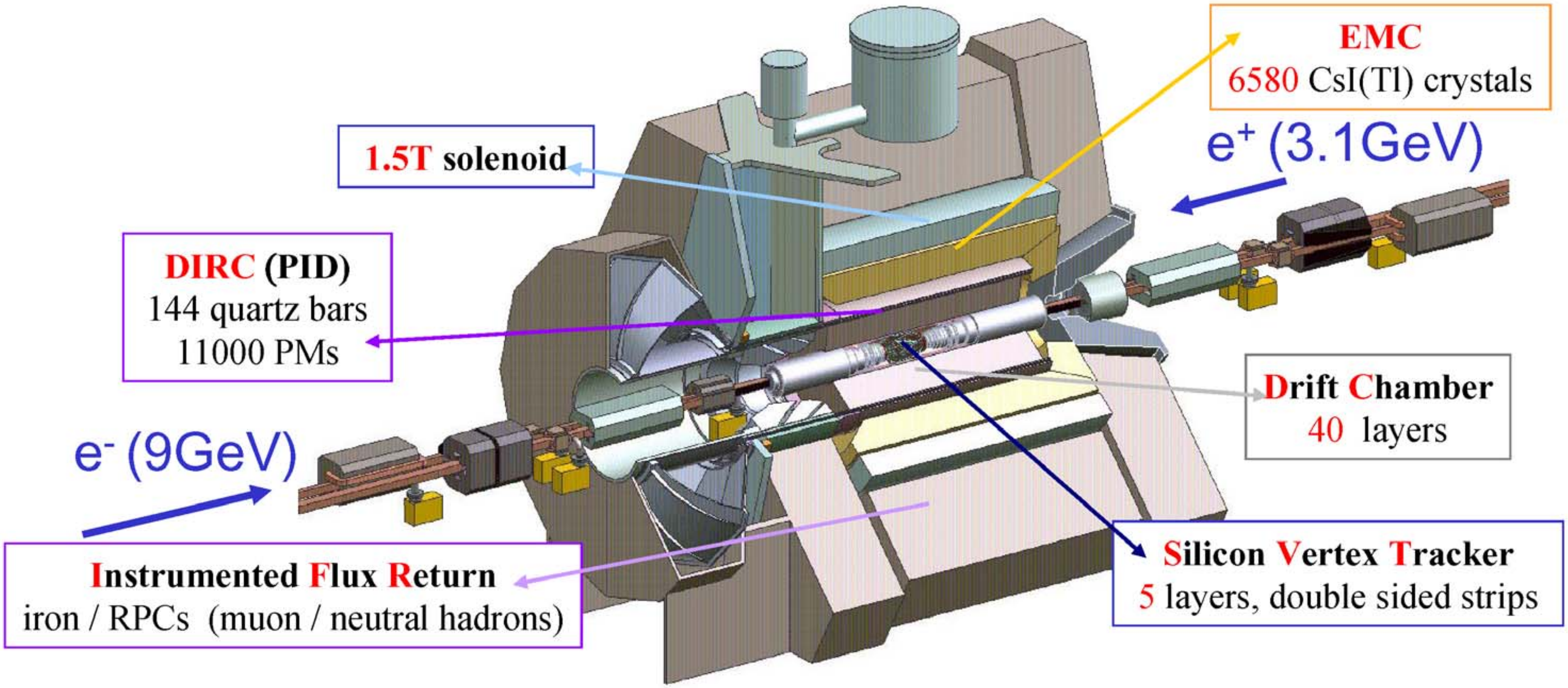
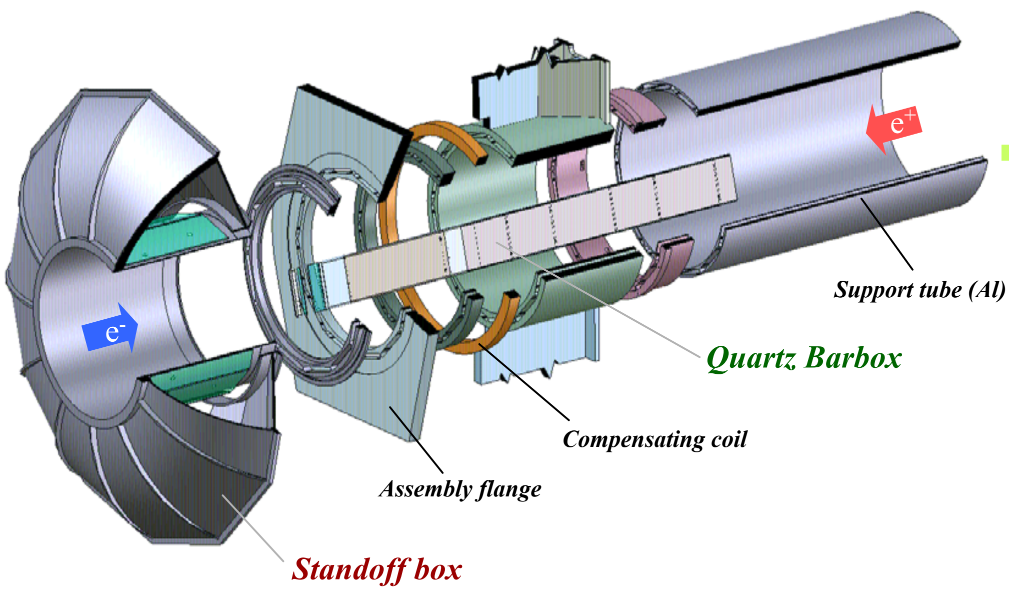
BaBar spectrometer at PEP-II

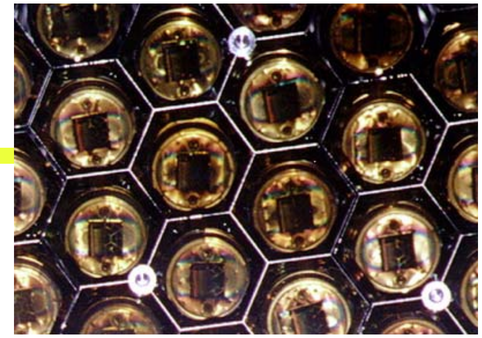


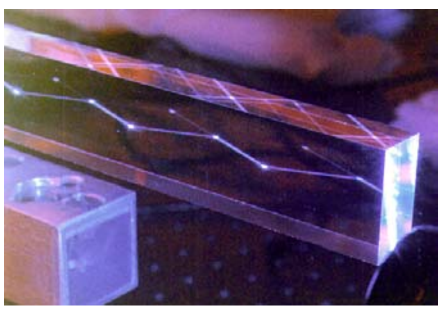
DIRC - detector of internally reflected Cherenkov light

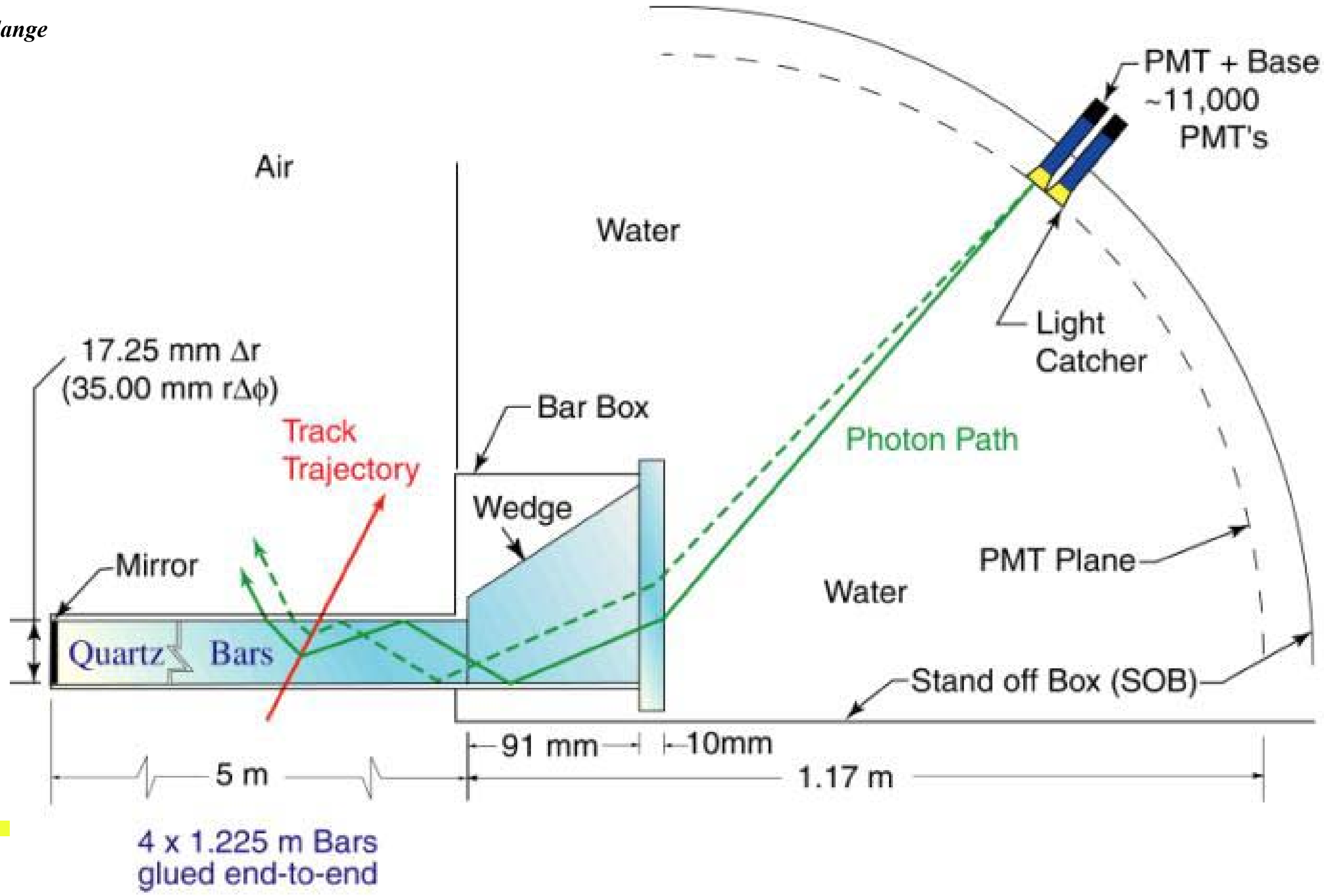
DIRC



e-
e+
Support tube (Al)
Quartz Barbox
Compensating coil
Assembly flange
Standoff box

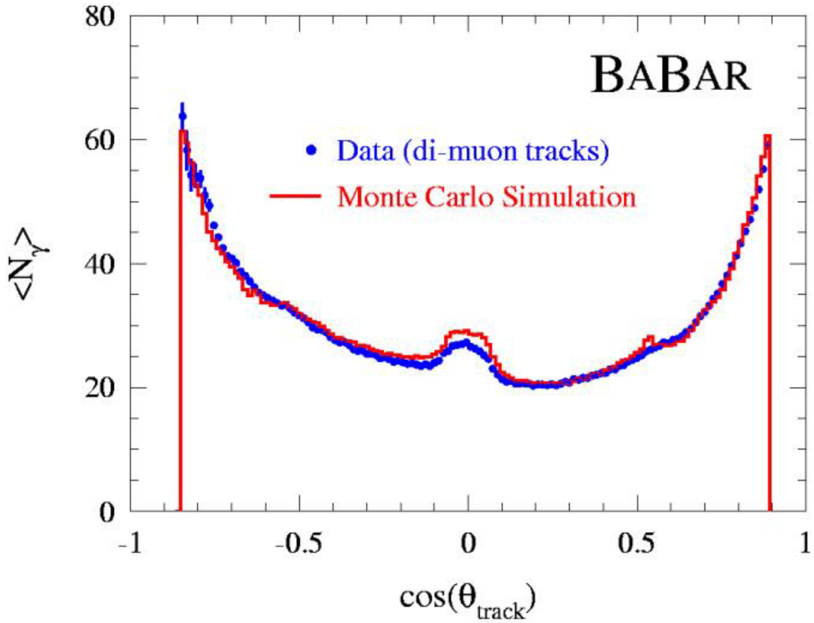






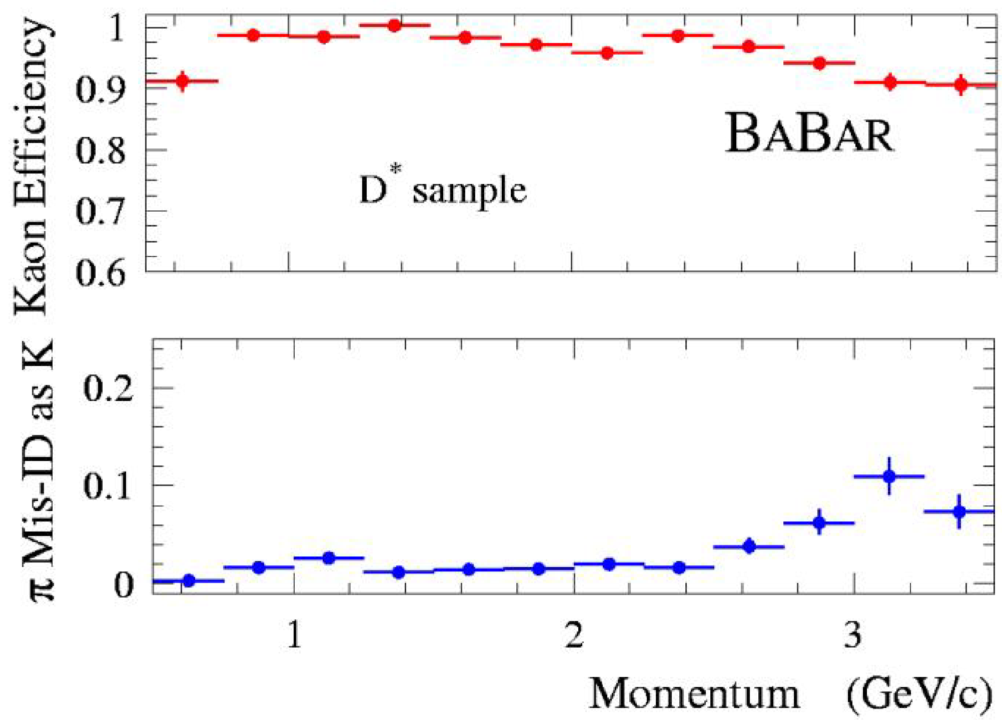
PMT + Base
~11,000
PMT's
Air
Water
Light
Catcher
17.25 mm Δr
(35.00 mm rΔϕ)
Bar Box
Photon Path
Track
Trajectory
Wedge
Mirror
PMT Plane
Water
Quartz
Bars
Stand off Box (SOB)
91 mm
10mm
5 m
1.17 m
4 x 1.225 m Bars
glued end-to-end

DIRC performance



← Lots of photons!

Excellent π/K separation



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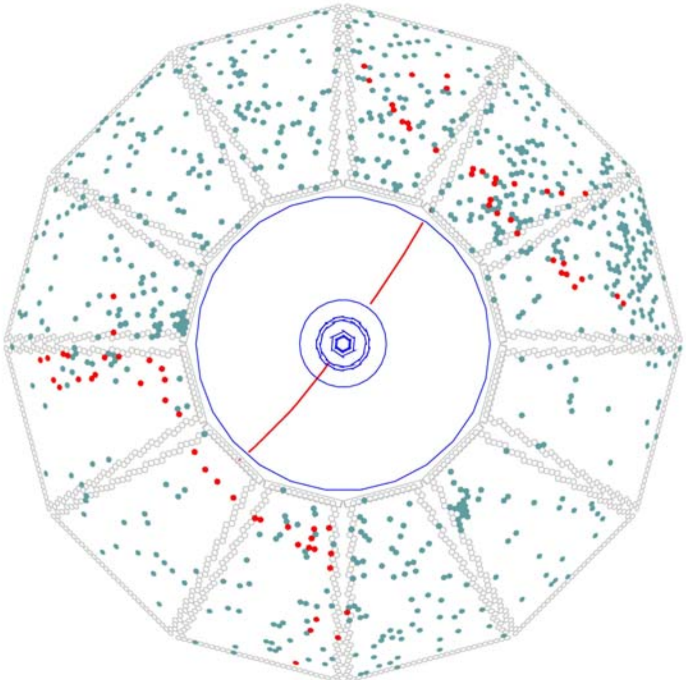
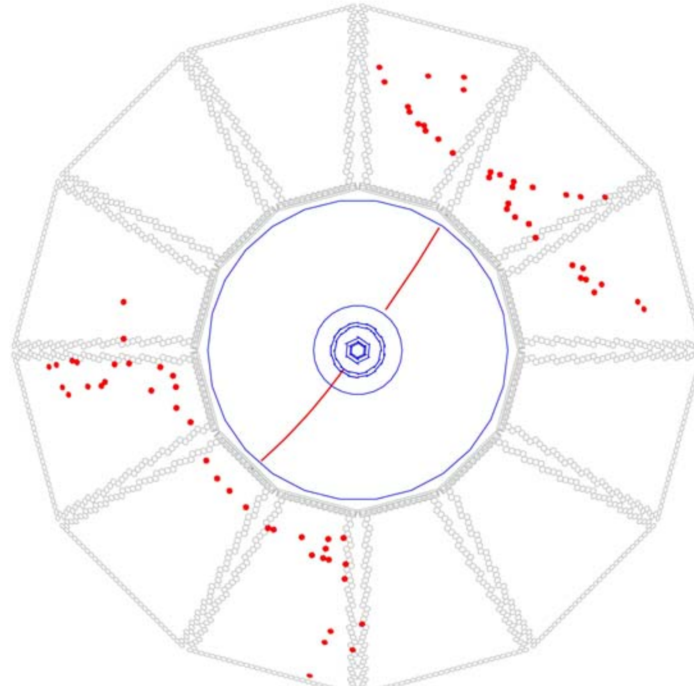
DIRC

BaBar DIRC: a Bhabha event $e^+ e^- \to e^+ e^-$





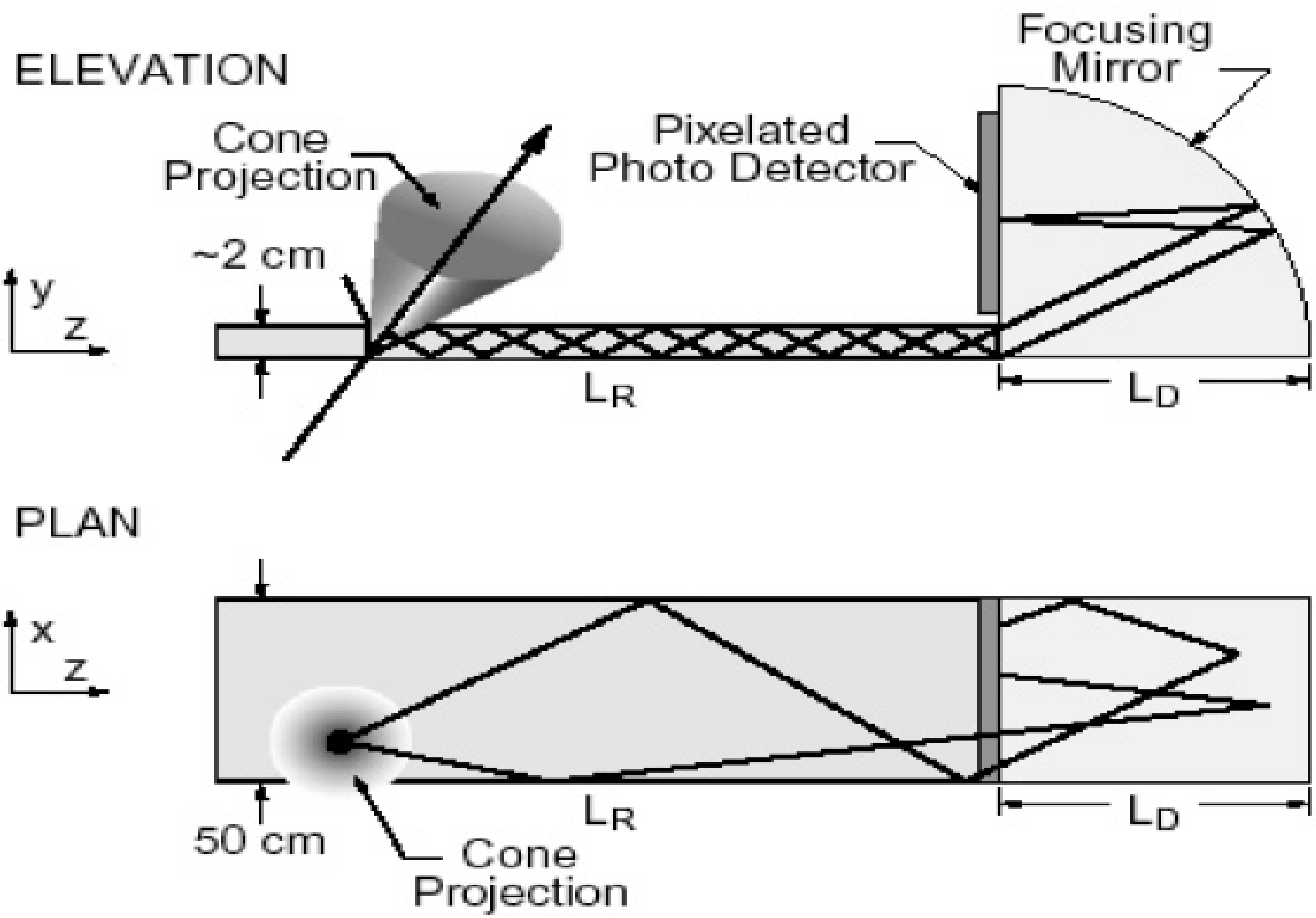
No time cut on the hits

With a +-4ns time cut

Timing information is essential for background reduction

Focusing DIRC

Upgrade: step further, remove the stand-off box -> focusing DIRC



Focusing DIRC

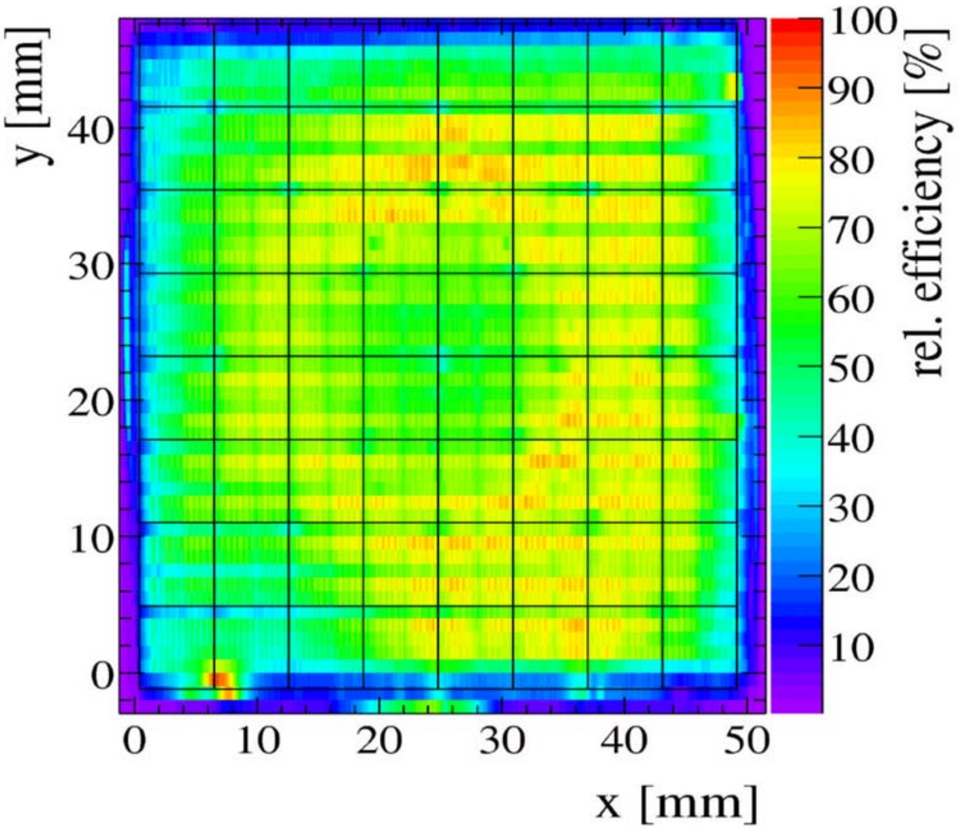
Idea: measure two coordinates with good precision, use precise timing information to correct for the dispersion (group and phase velocity depend on the wavelength)

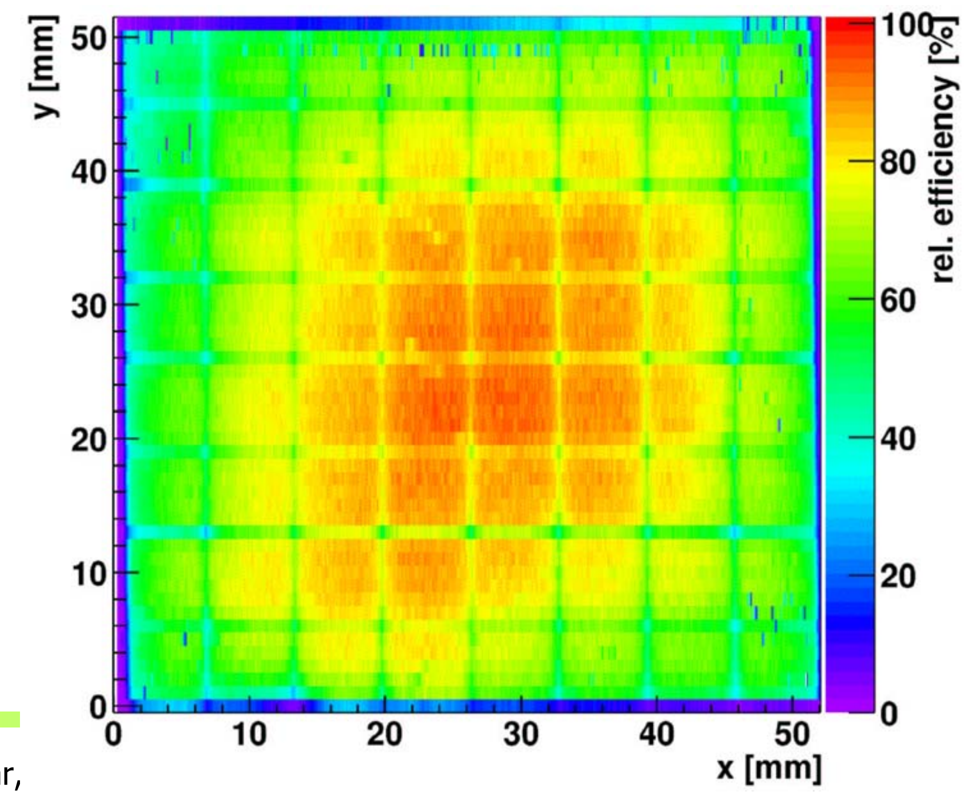
Photon detector requirements:

- Pad size ~5mm
- Time resolution ~50-100ps

Focusing DIRC photon detectors: relative efficiency

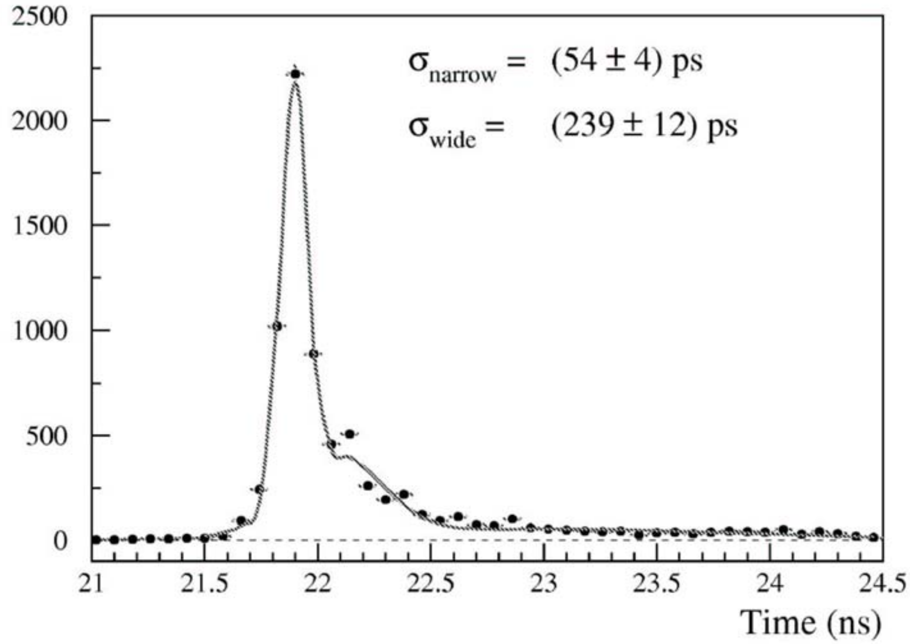
Hamamatsu H8500 (flat pannel)



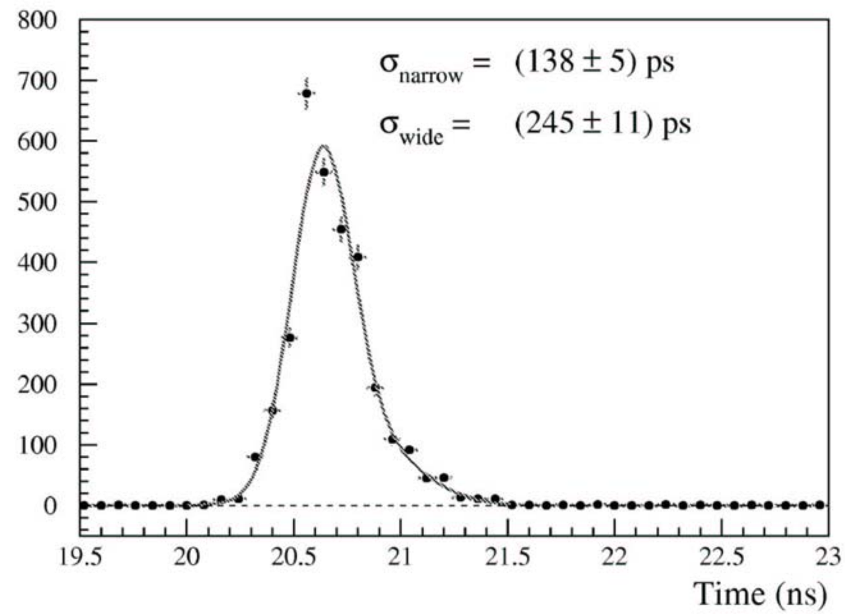


Burle 85011 MCP-PMT

Focusing DIRC photon detectors: time resolution



Burle 85011 MCP-PMT



Hamamatsu H8500 (flat pannel)

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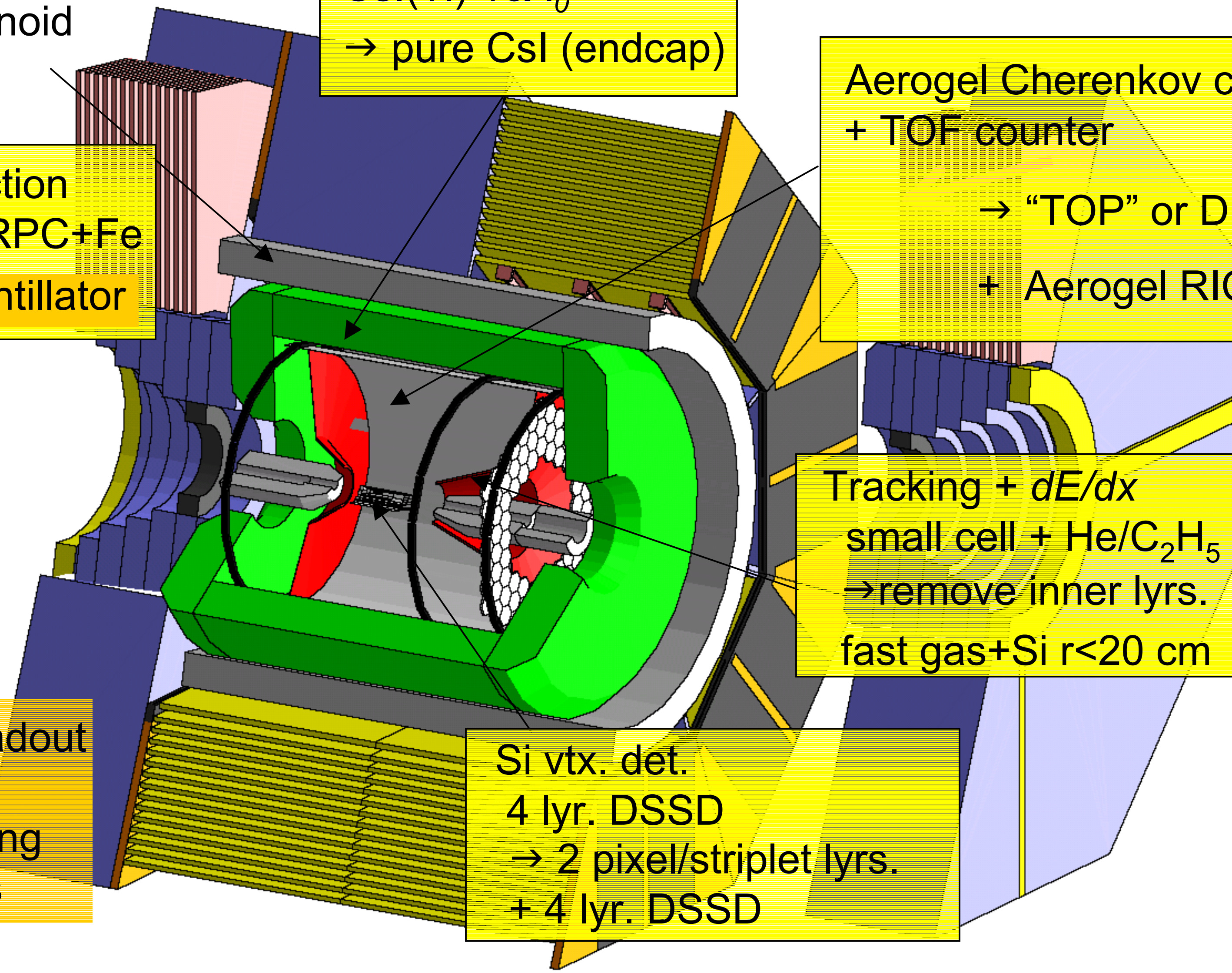
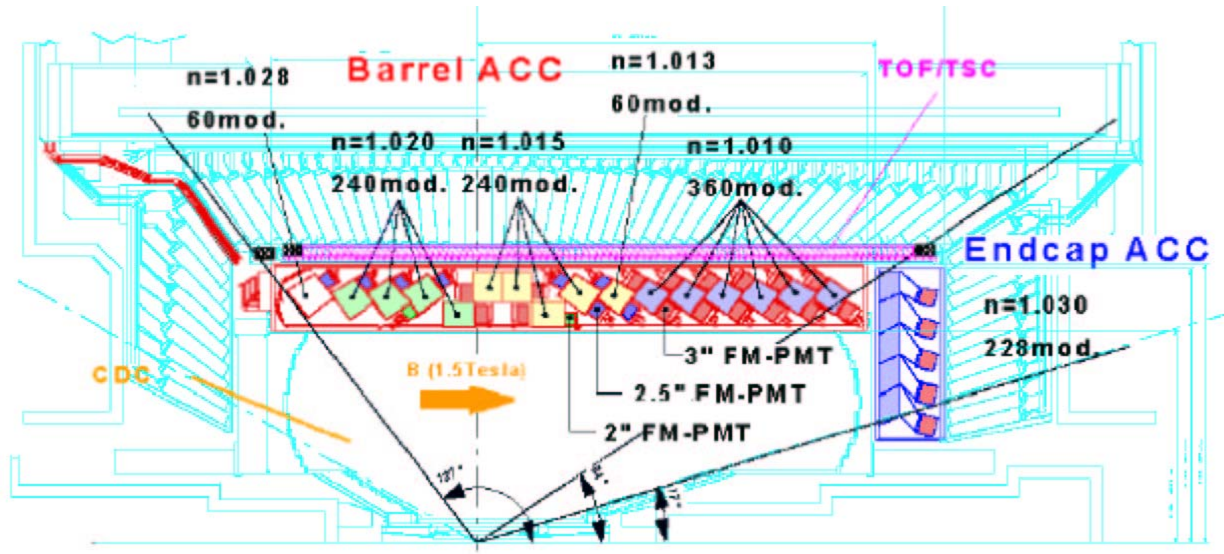
Belle Upgrade for Super-B

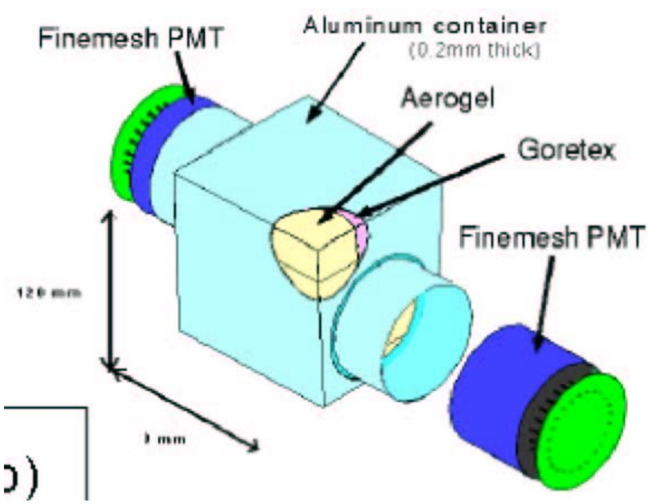


Present Belle: threshold Čerenkov counter ACC (aerogel Cherenkov counter)

K (below threshold) vs. π (above) by properly choosing n for a given kinematic region (more energetic particles fly in the 'forward region')

Detector unit: a block of aerogel and two fine-mesh PMTs

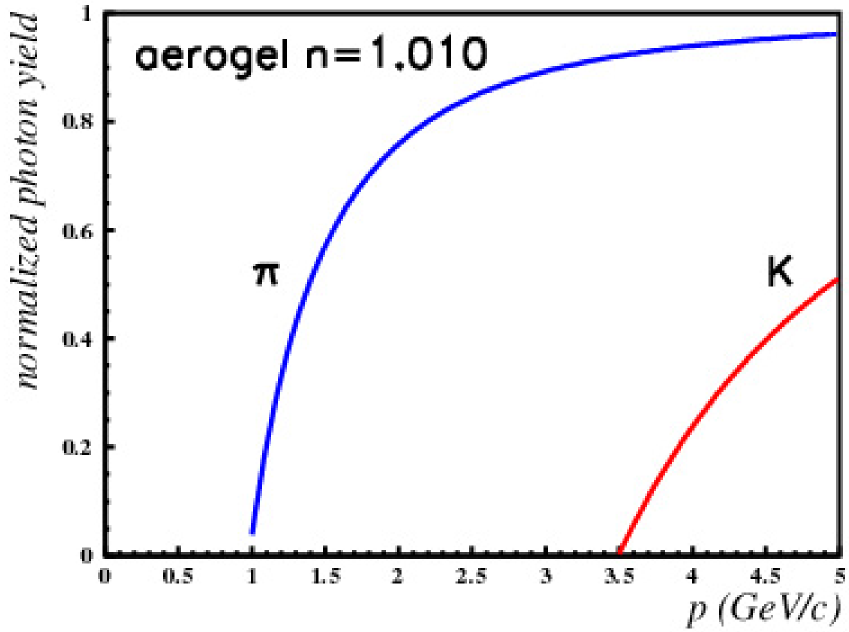




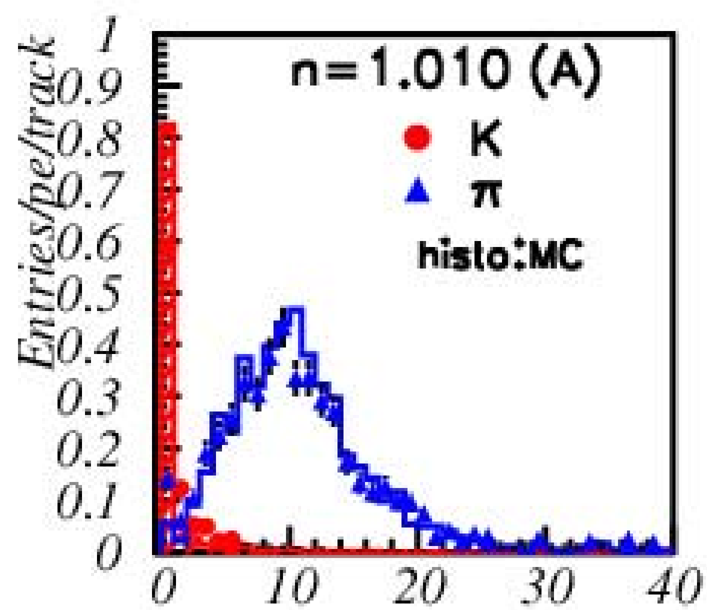
Fine-mesh PMT: works in high B fields

Belle ACC : threshold Čerenkov counter

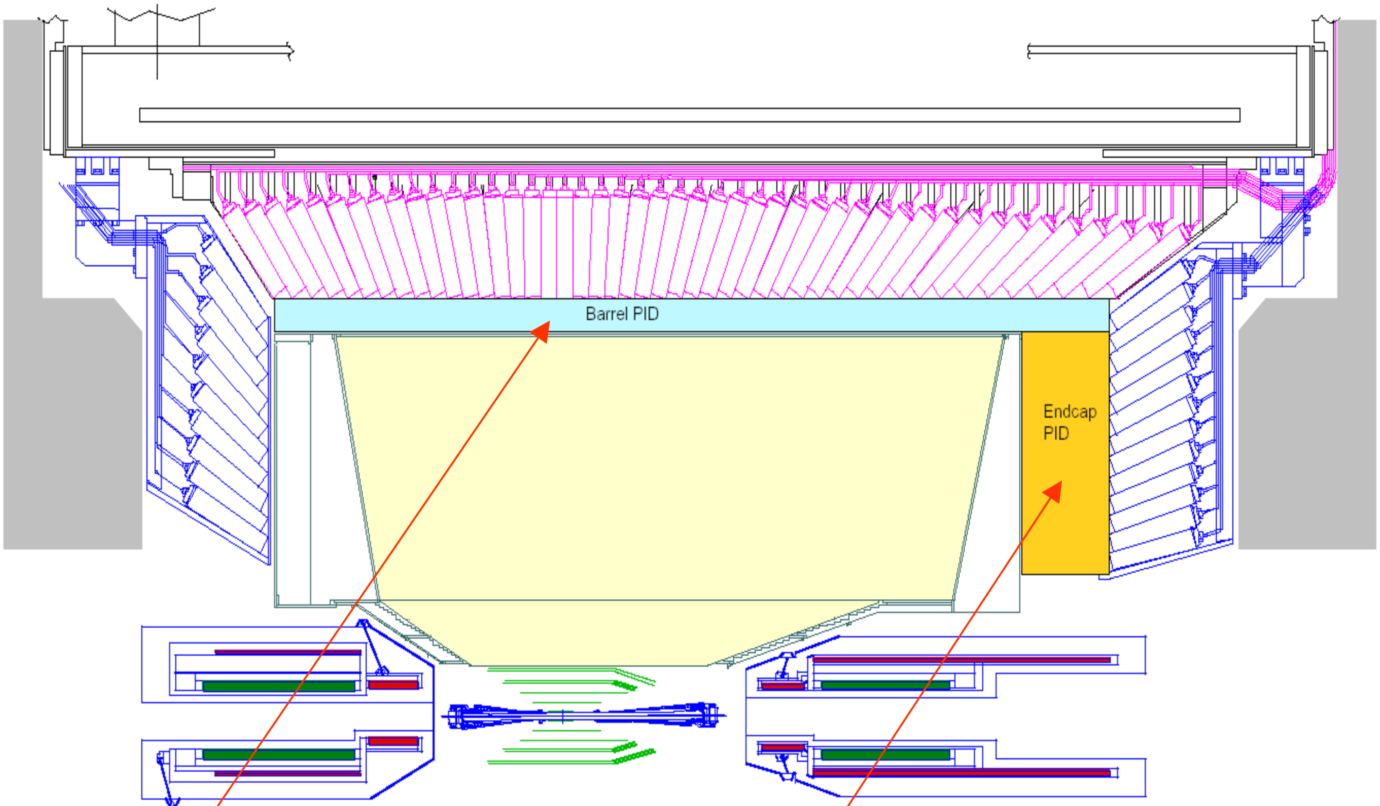
expected yield vs p



yield for 2GeV<p<3.5GeV: expected and measured number of hits



Belle upgrade – side view

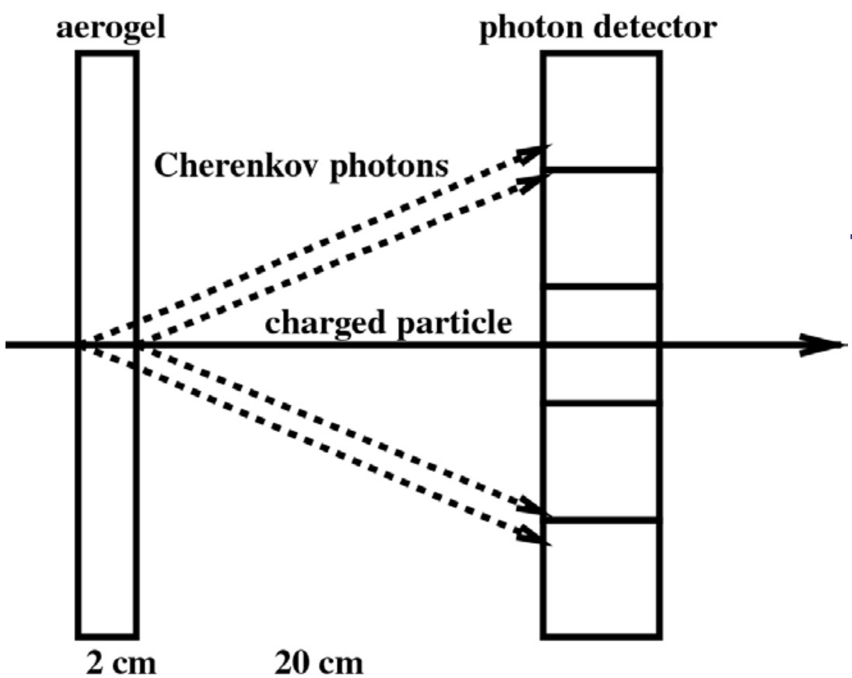


Two new particle ID devices, both RICHes:

Barrel: TOP or focusing DIRC

Endcap: proximity focusing RICH

Endcap: Proximity focusing RICH



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

For single photons: $\delta\theta_c(\text{meas.}) = \sigma_0 \sim 14$ mrad,
typical value for a 20mm thick radiator and 6mm PMT pad size

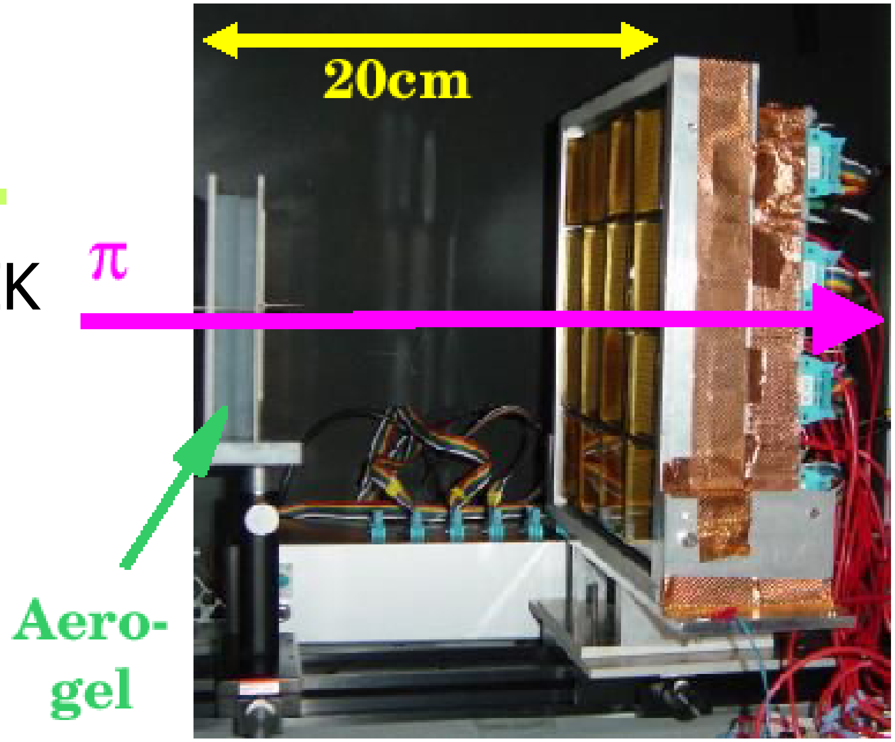
Per track: $$\sigma_{track} = \frac{\sigma_0}{\sqrt{N_{pe}}}$$

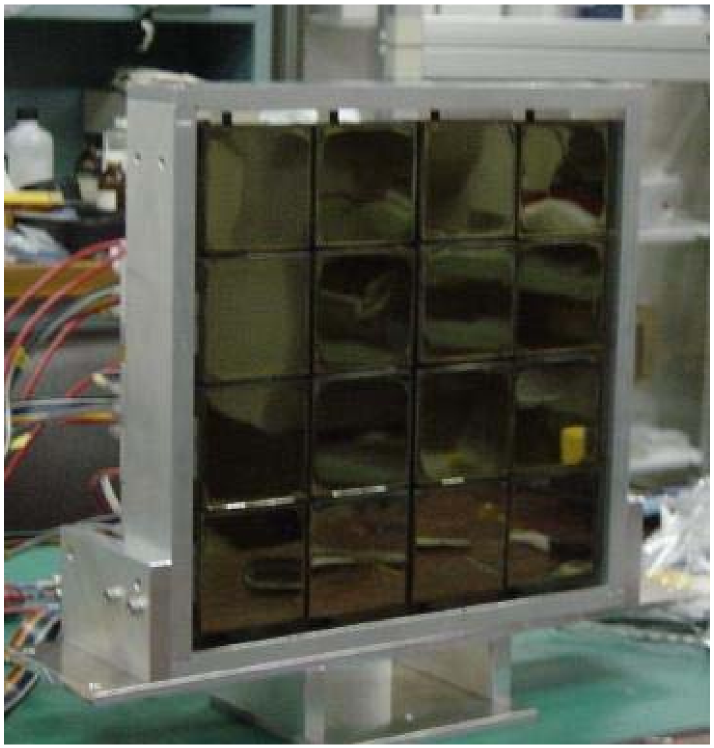
Separation: $[\theta_c(\pi) - \theta_c(K)]/\sigma_{track}$

→ 5σ separation with $N_{pe} \sim 10$

Beam tests

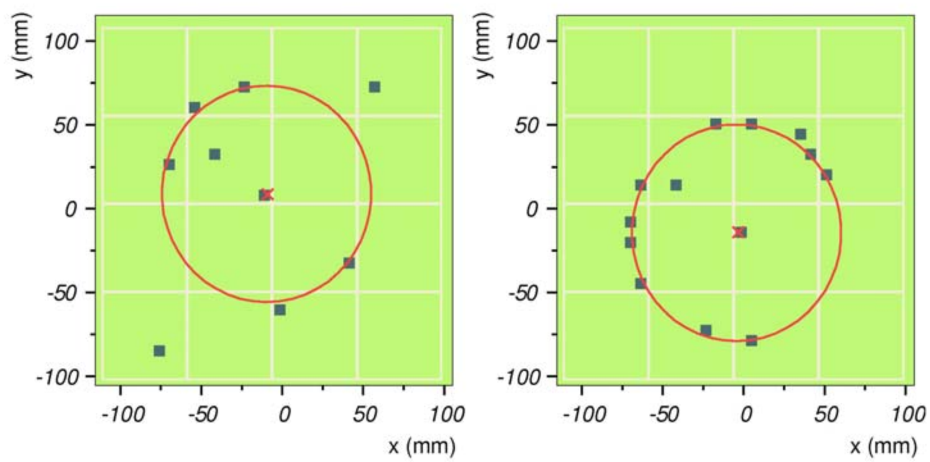
pion beam (π2) at KEK





Photon detector: array of 16 H8500 PMTs

Clear rings, little background

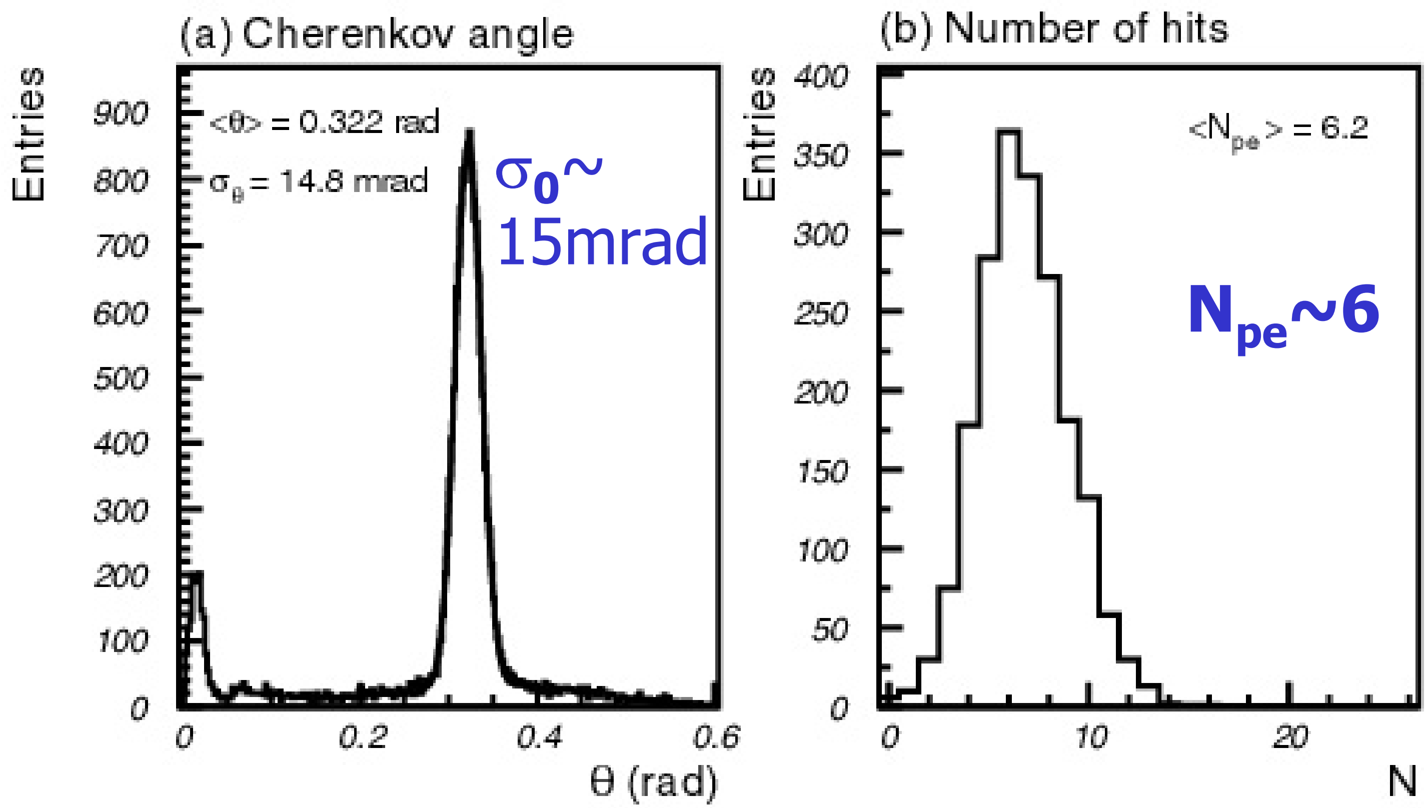


Beam test: Cherenkov angle resolution and number of photons

NIM A521(2004)367; NIM A553(2005)58

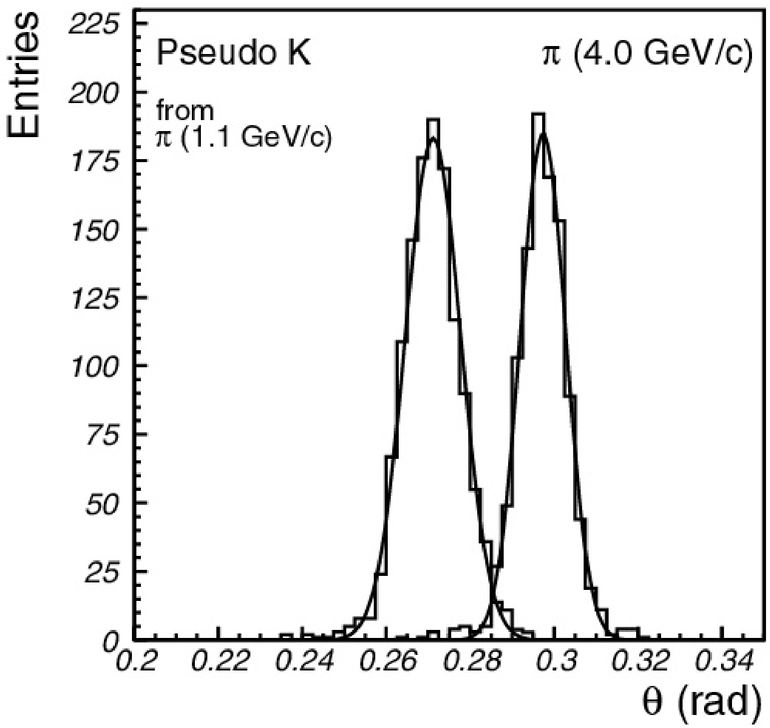
Beam test results with 2cm thick aerogel tiles:

>4σ K/π separation



→ Number of photons has to be increased.

PID capability on test beam data

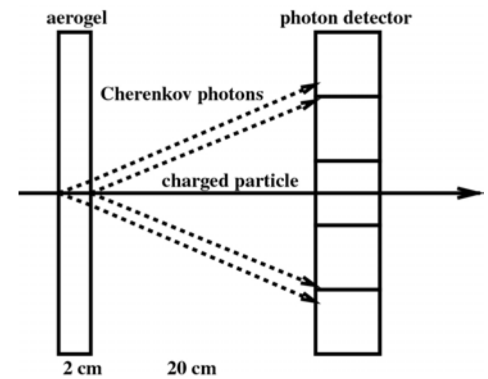


From typical values (single photon resolution 15mrad and 6 detected photons) we can estimate the Cherenkov resolution per track: 5.3mrad;

→ ~4σ π/K separation at 4GeV/c.

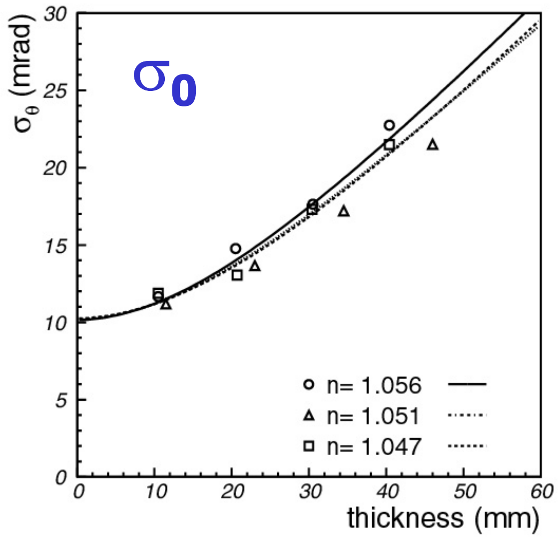
Illustration of PID performance: Cherenkov angle distribution for pions at 4GeV/c and 'kaons' (pions at 1.1GeV/c with the same Cherenkov angle as kaons at 4GeV/c).

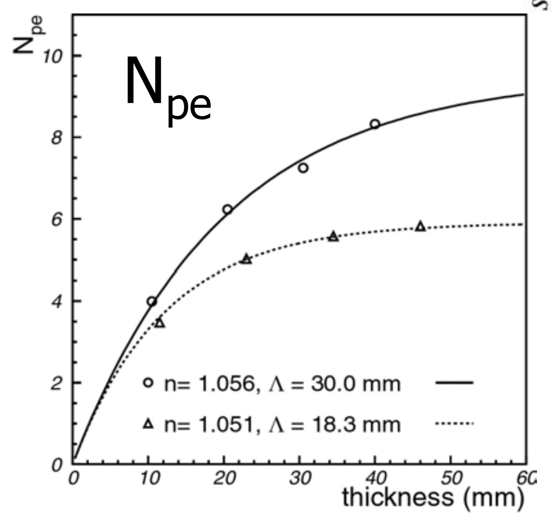
How to increase the number of photons?

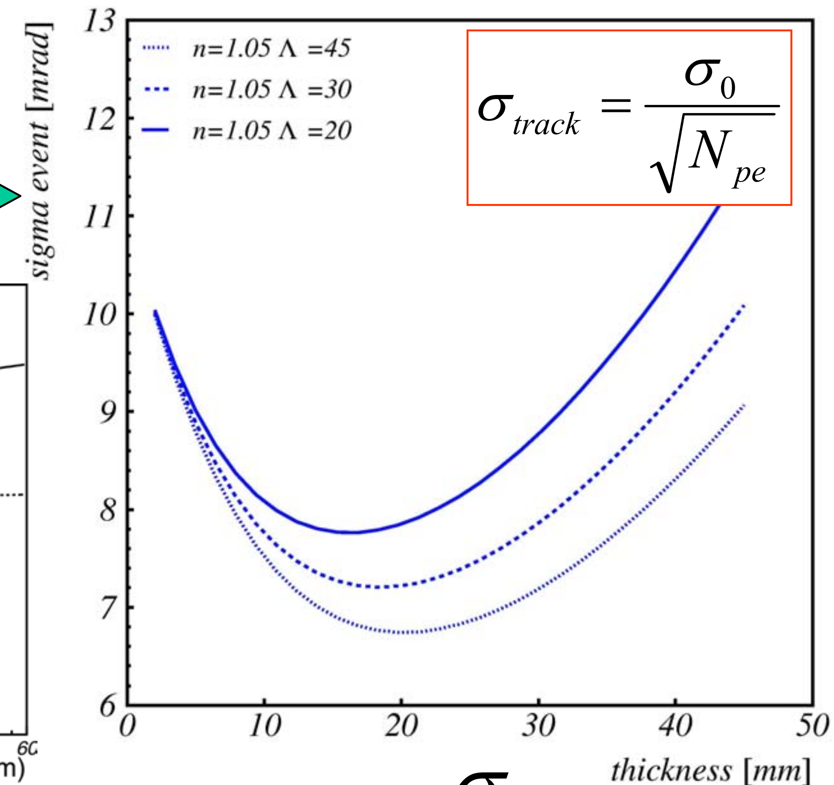


What is the optimal radiator thickness?

Use beam test data on σ_0 and N_{pe}







Minimize the error per track: $$\sigma_{track} = \frac{\sigma_0}{\sqrt{N_{pe}}}$$

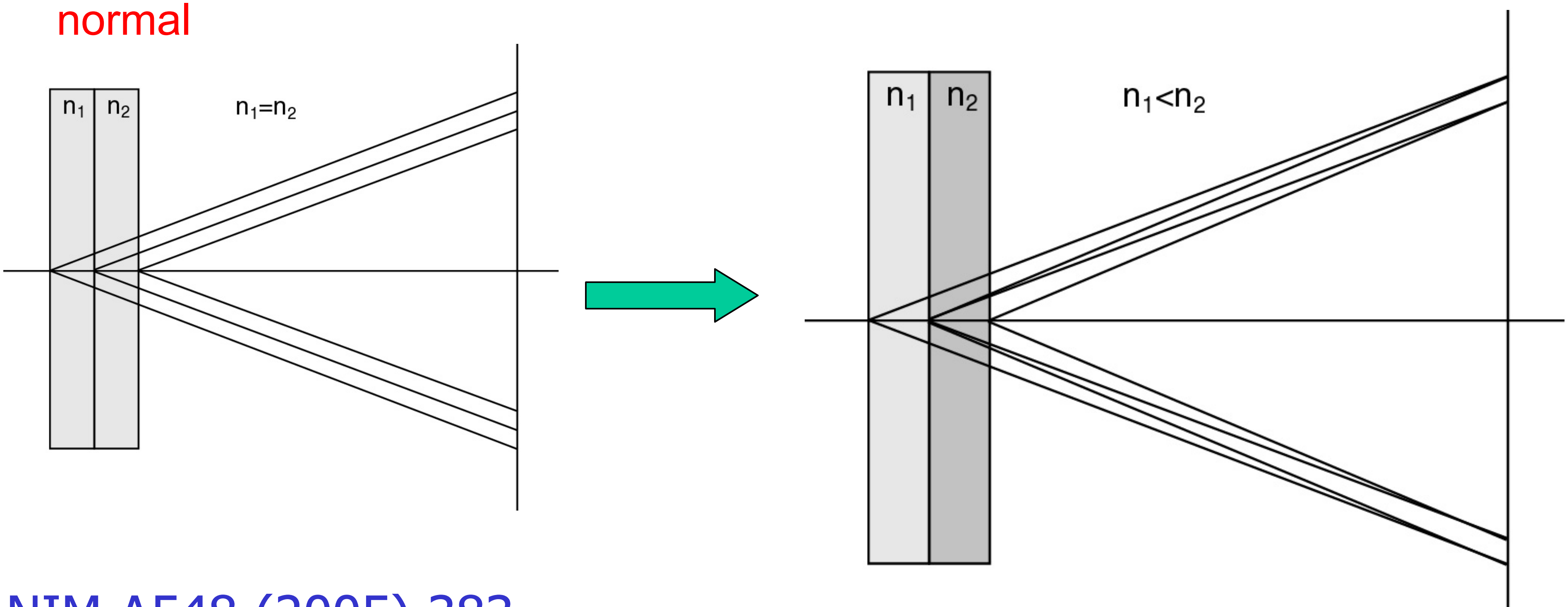
Optimum is close to 2 cm

Radiator with multiple refractive indices

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

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

normal

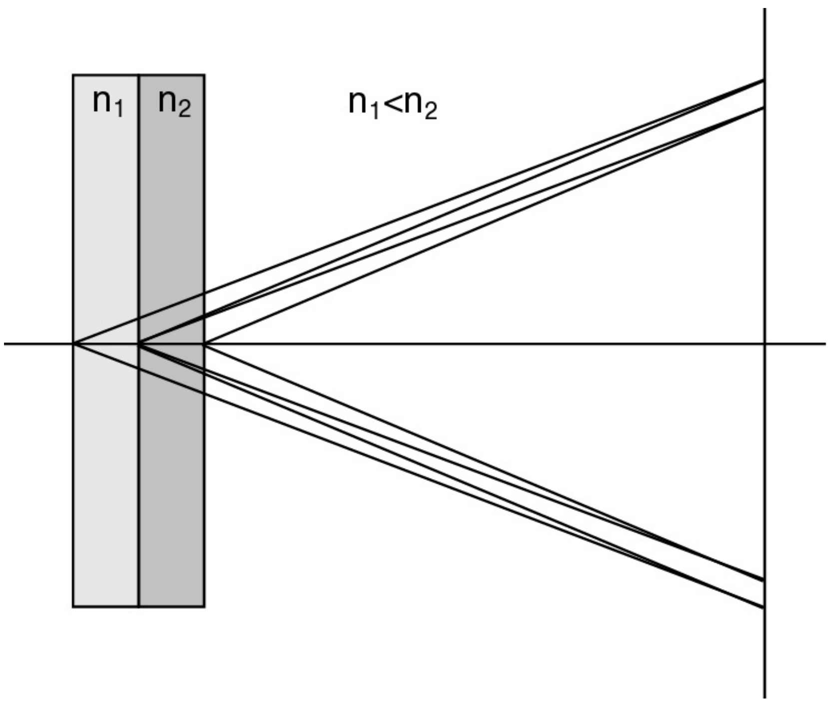


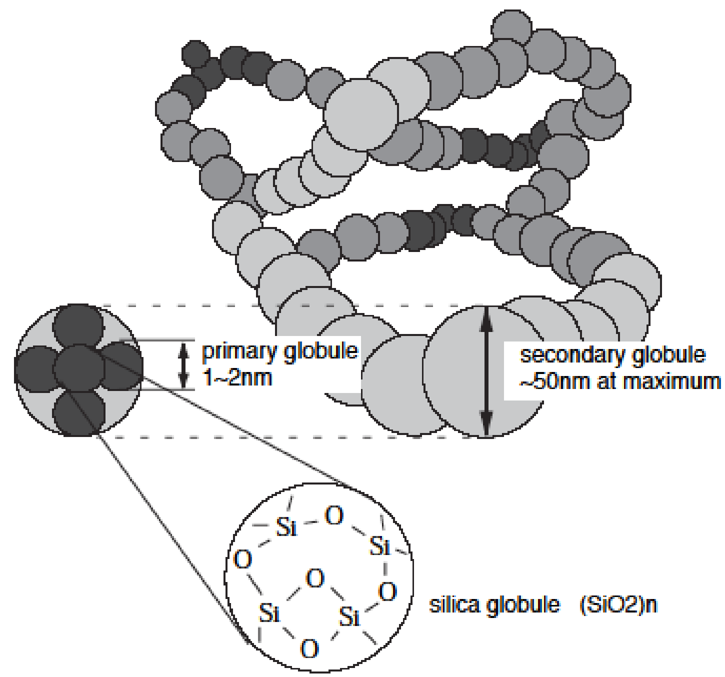
NIM A548 (2005) 383

→ focusing radiator

Radiator with multiple refractive indices 2

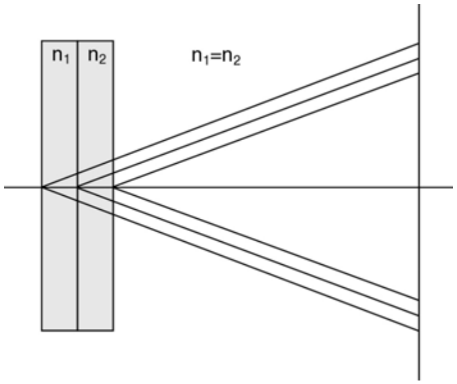
Such a configuration is only possible with aerogel (a form of Si_xO_y) – material with a tunable refractive index between 1.01 and 1.07.

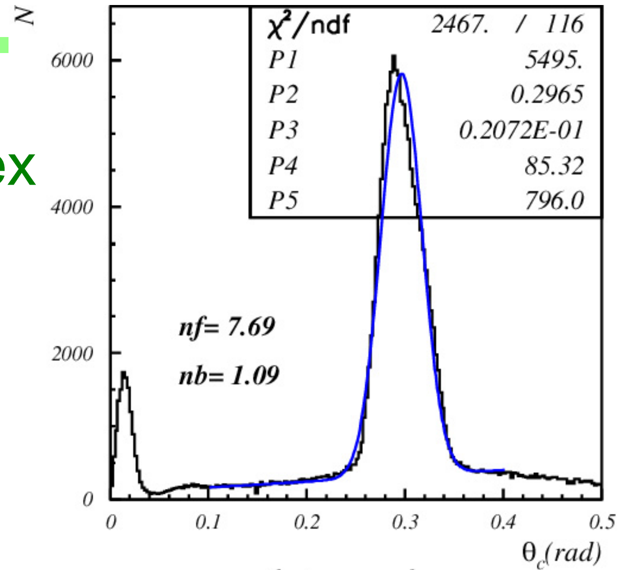




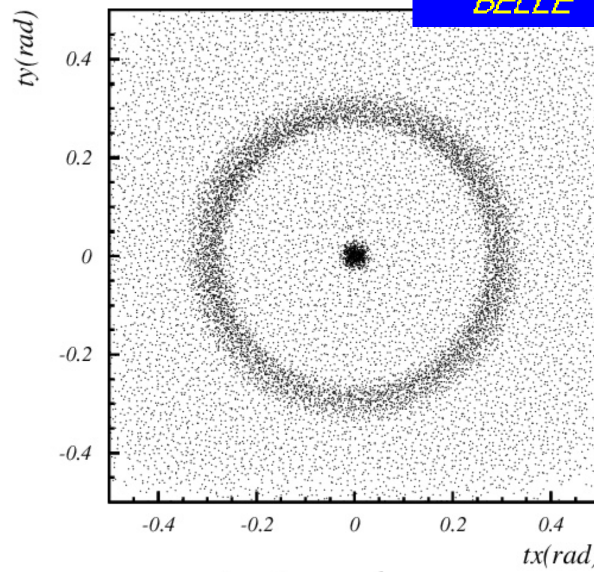
Focusing configuration – data

4cm aerogel single index



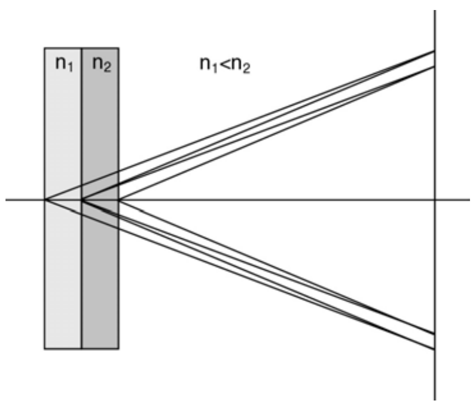


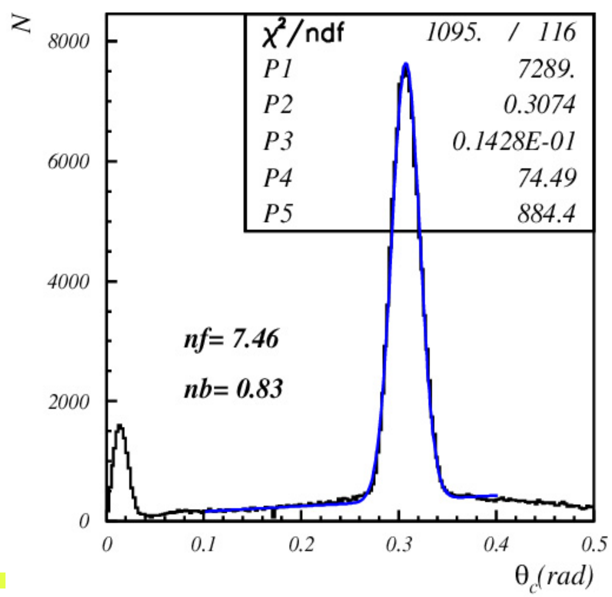
theta cerenkov

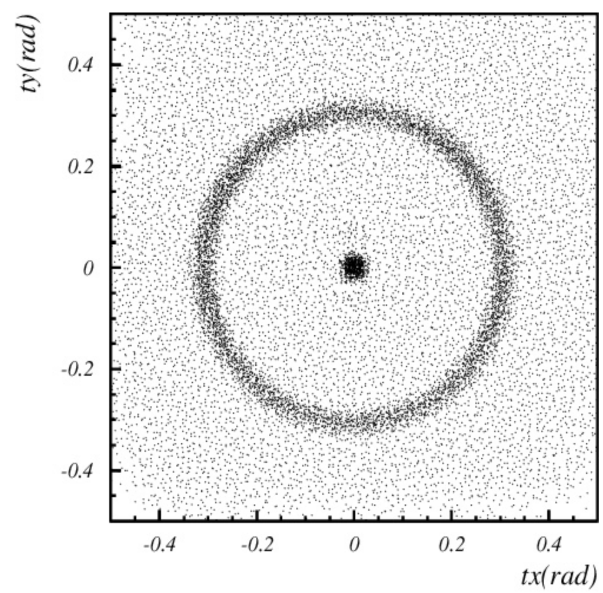


ring in cerenkov space

2+2cm aerogel

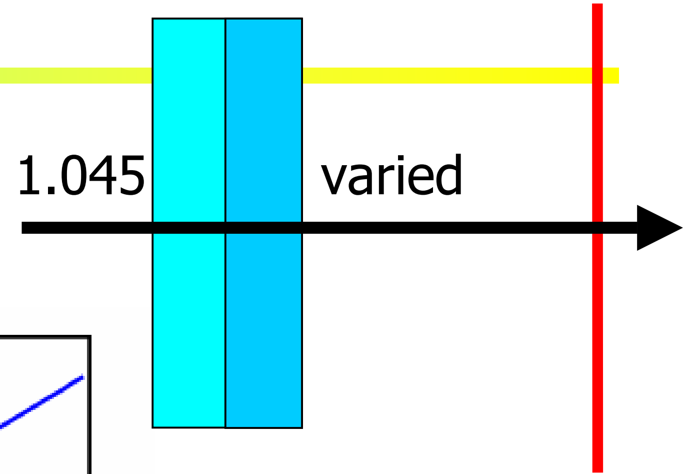


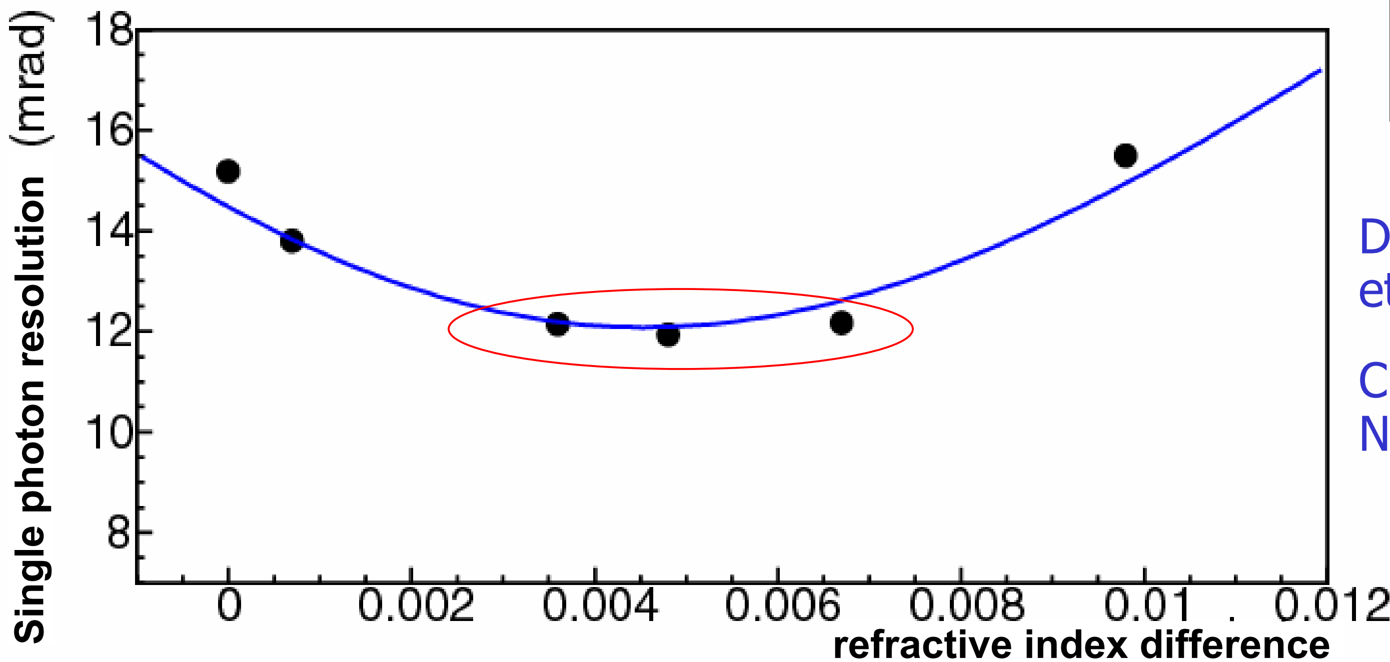




Focusing configuration – vary n_2-n_1

- upstream aerogel: d=11mm, n=1.045
- downstream layer: vary refractive index



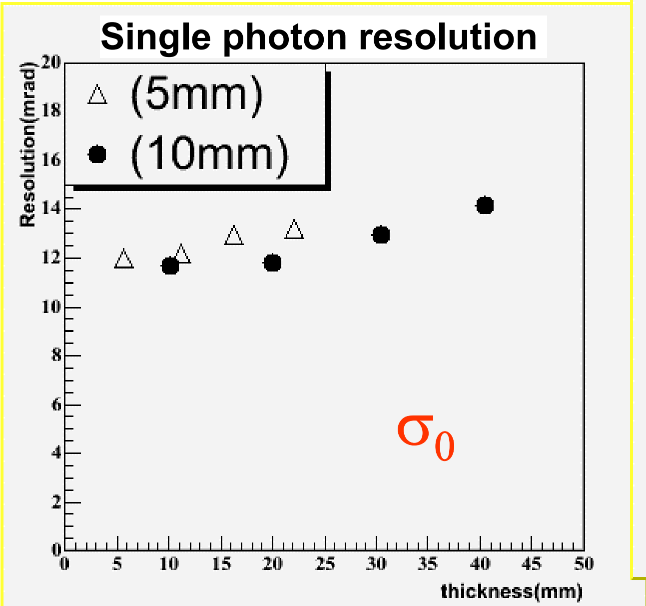


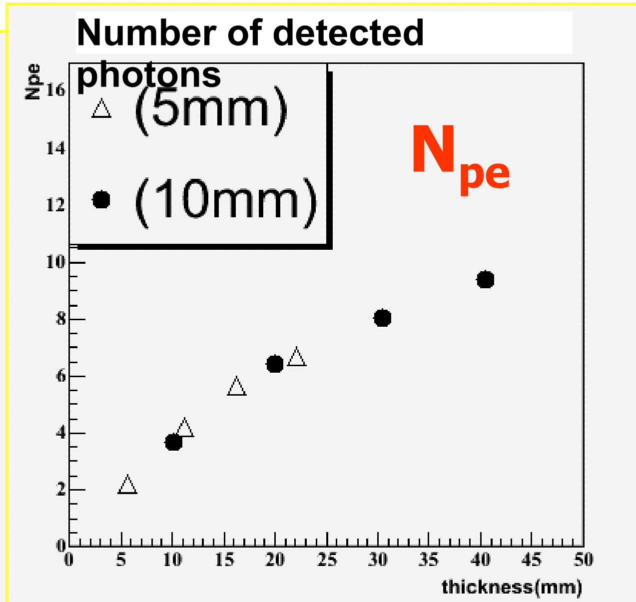
Data points: S. Korpar et al, Pisa meeting 2006.

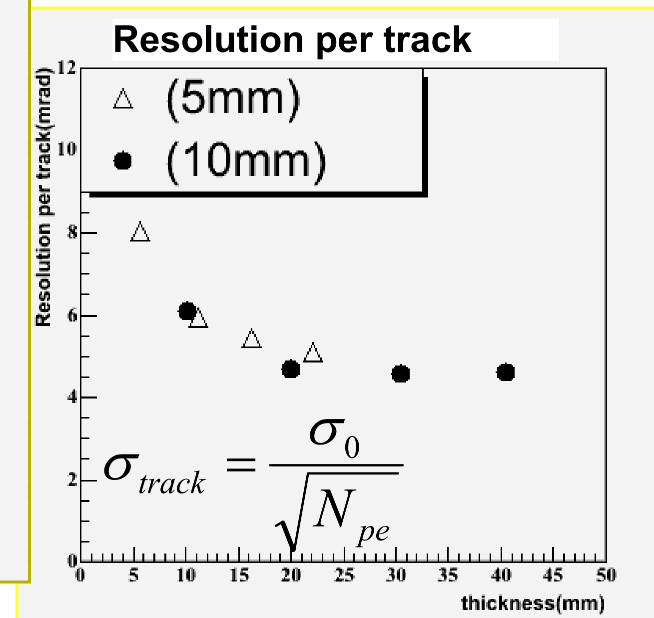
Curve: optimisation study NIM A565 (2006) 457

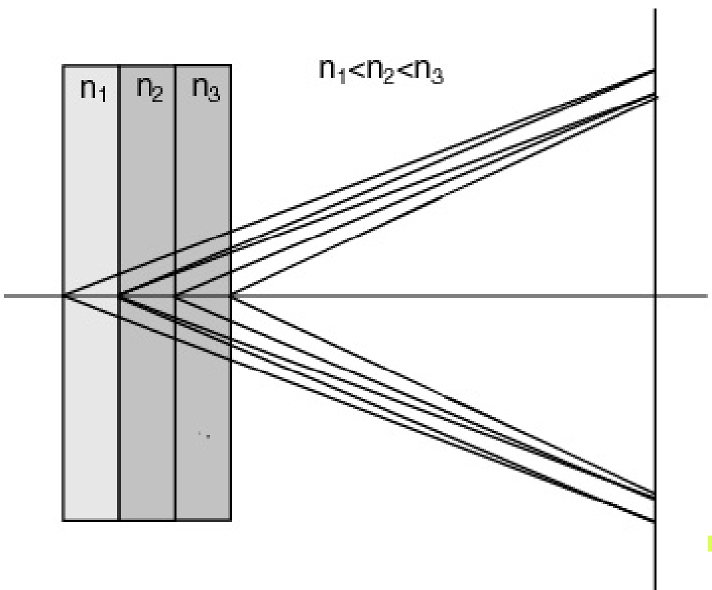
- measured resolution in good agreement with prediction
- a wide minimum allows for some tolerance in aerogel production

Multilayer extensions









Multiple layer radiators combined from 5mm and 10mm tiles

Cherenkov angle resolution per track: around 4.3 mrad

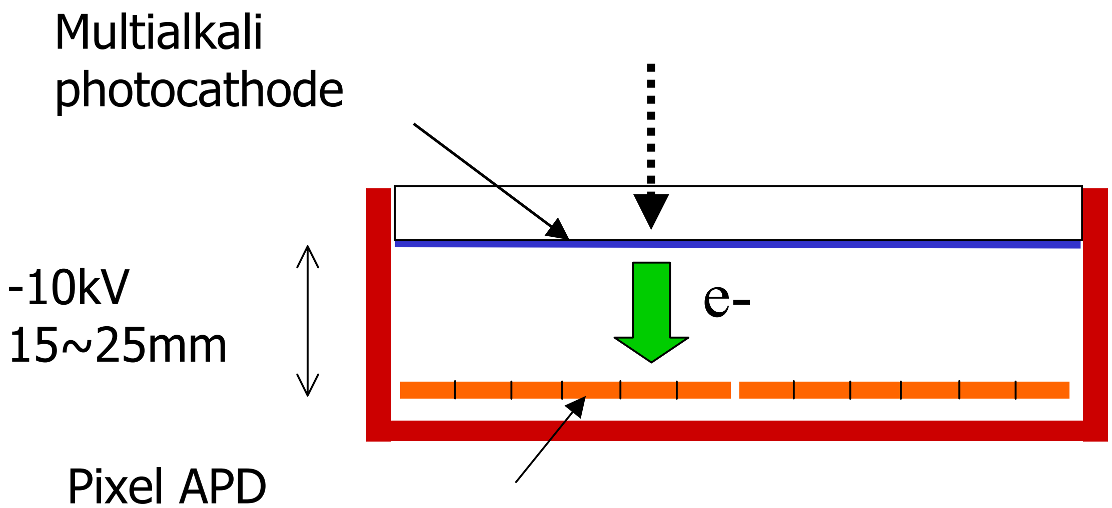
→ π/K separation at 4 GeV: >5σ

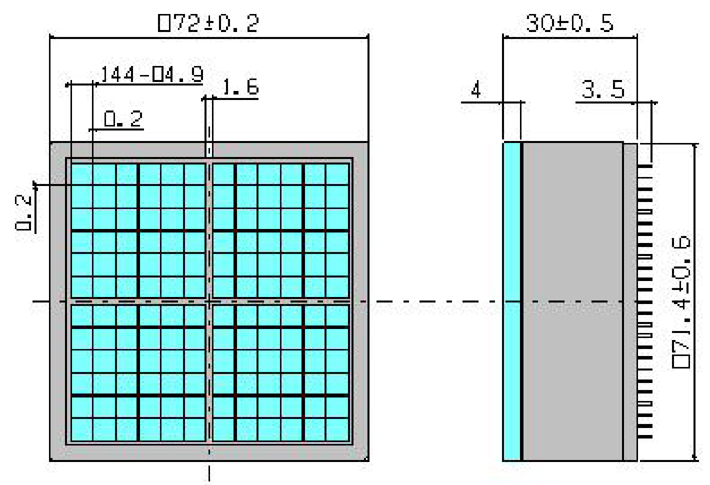
Photon detectors for the aerogel RICH requirements and candidates

Need: Operation in a high magnetic field (1.5 T)
Pad size ~5-6mm

Candidates:

- MCP PMT (Burle 85011)
- large active area HAPD of the proximity focusing type



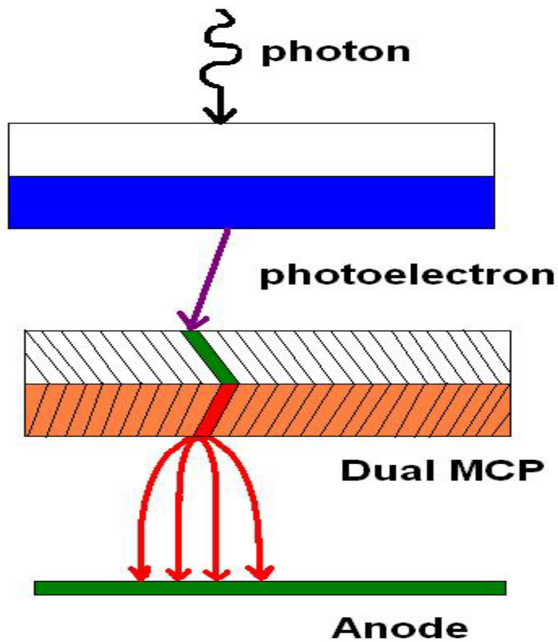


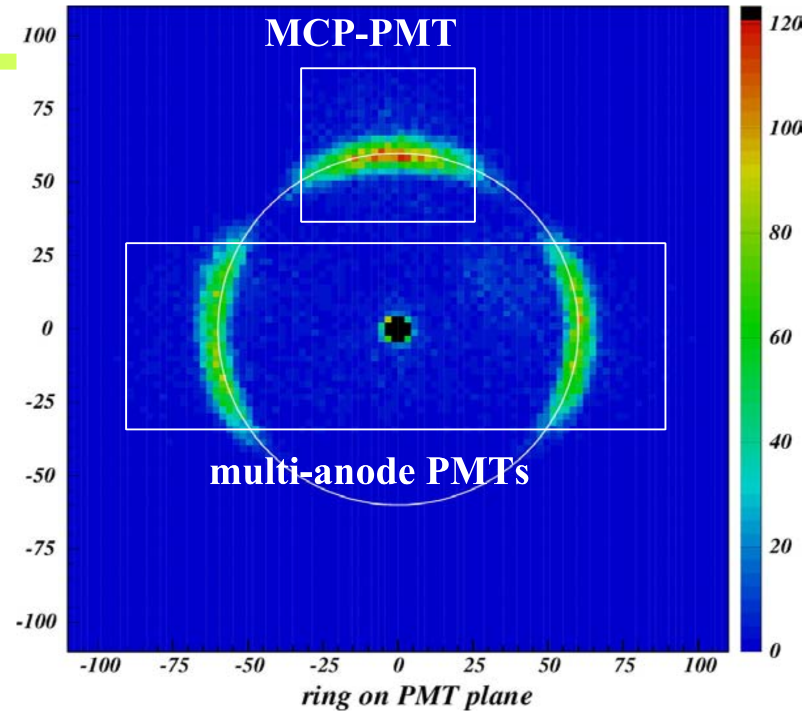
HAPD R&D project in collaboration with HPK.

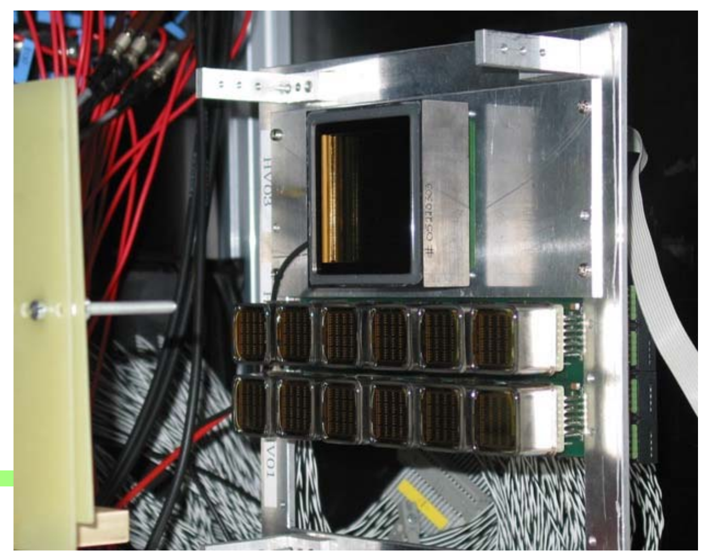
Problems: sealing the tube at the window-ceramic box interface, photocathode activation changes the properties of APD.

Photon detector candidate: MCP-PMT

BURLE 85011 microchannel plate (MCP) PMT: multi-anode PMT with two MCP steps





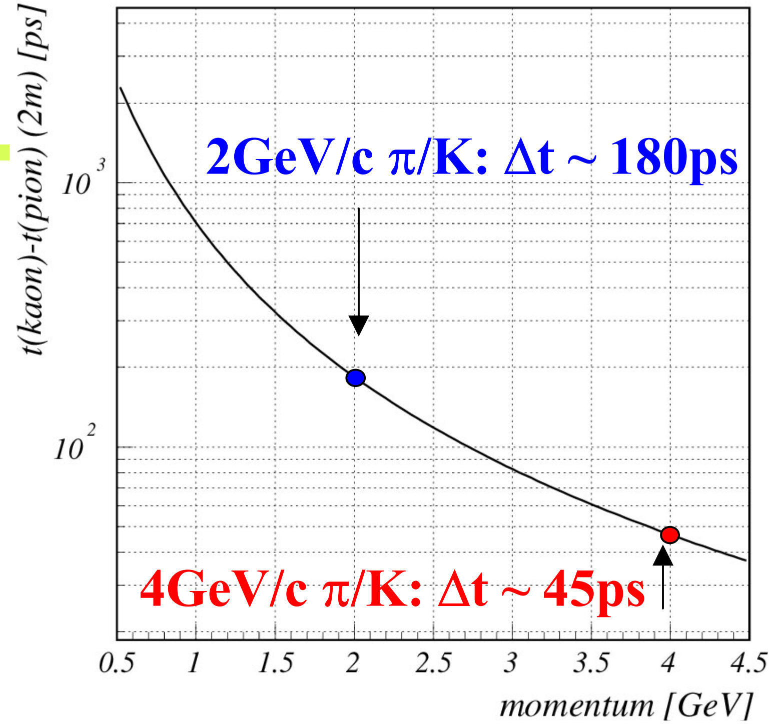


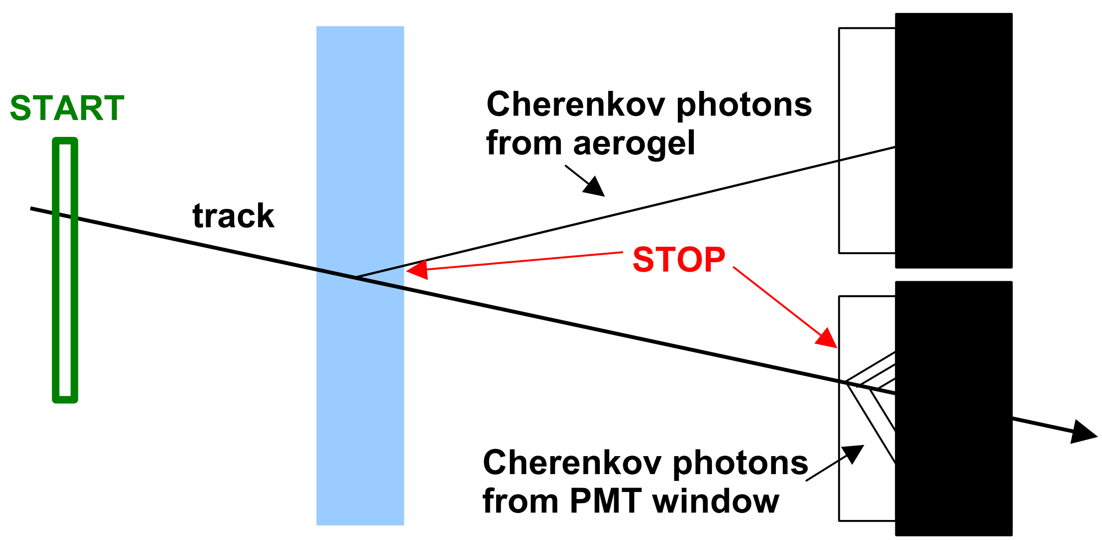
→good performance in beam and bench tests
→ very fast
→ R+D: ageing

TOF capability

With a fast photon detector, a proximity focusing RICH counter can be used also as a time-of-flight counter.

Time difference between π and K →





Cherenkov photons from two sources can be used:

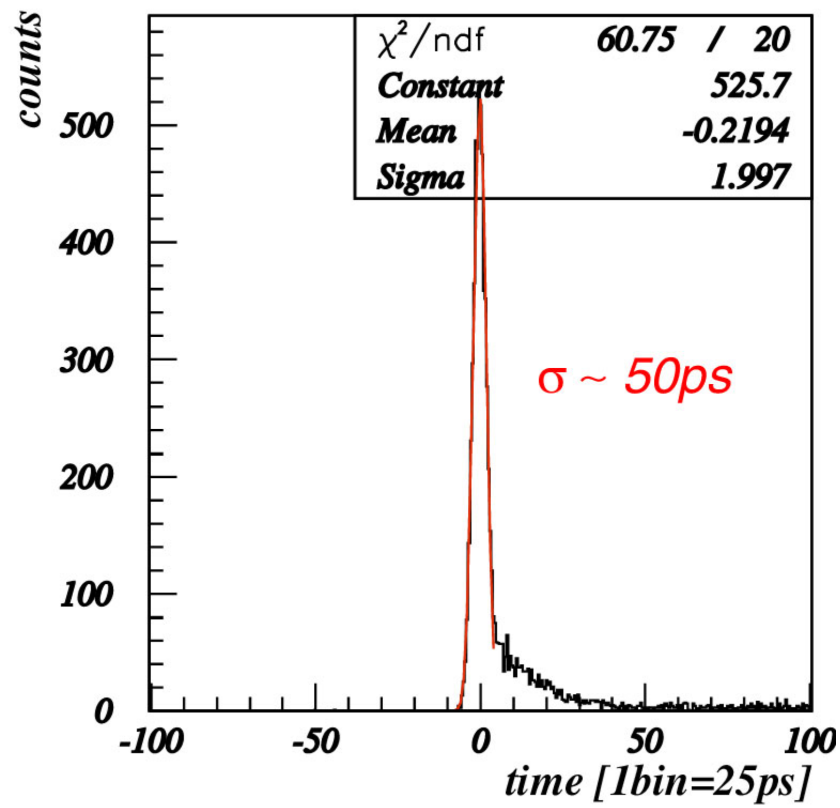
- photons emitted in the aerogel radiator
- photons emitted in the PMT window

TOF capability: photons from the ring

Beam tests: study timing properties of such a counter.

Time resolution for Cherenkov photons from the aerogel radiator: 50ps
→agrees well with the value from the bench tests

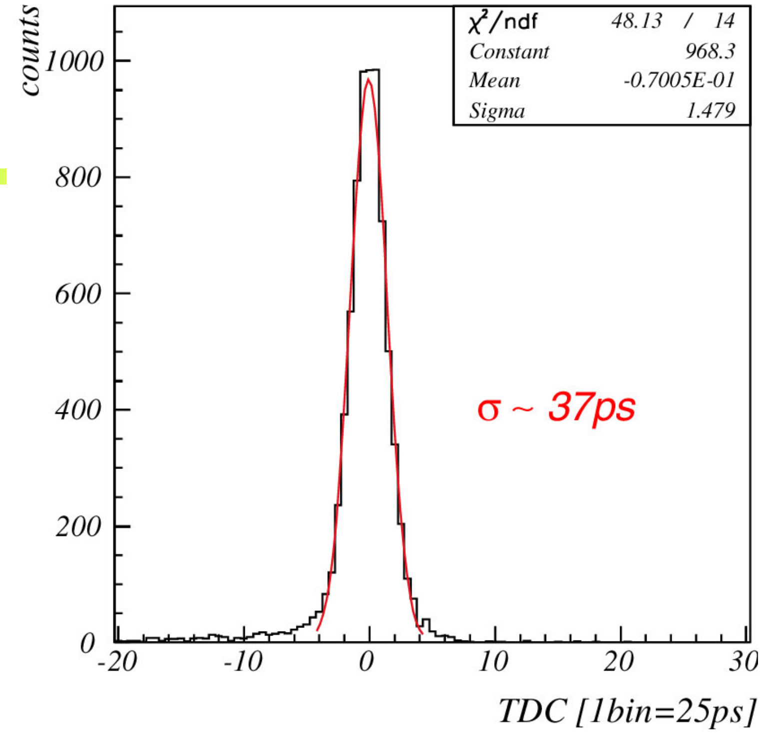
Resolution for full ring (~10 photons) would be around 20ps

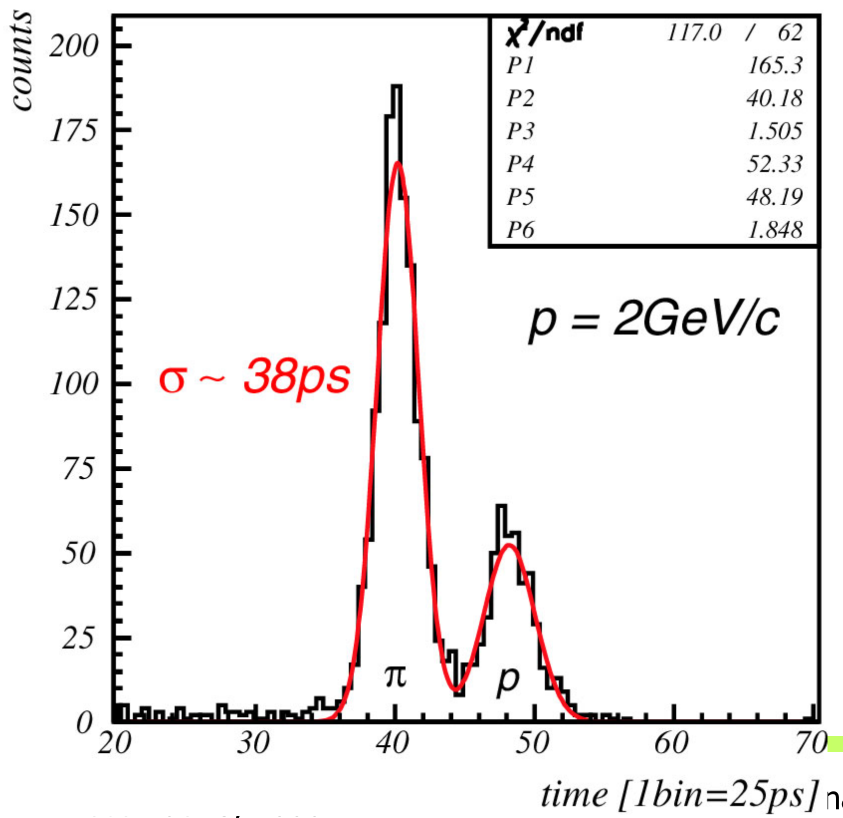


TOF capability: window photons

Expected number of detected Cherenkov photons emitted in the PMT window (2mm) is ~15

Expected resolution ~35 ps →





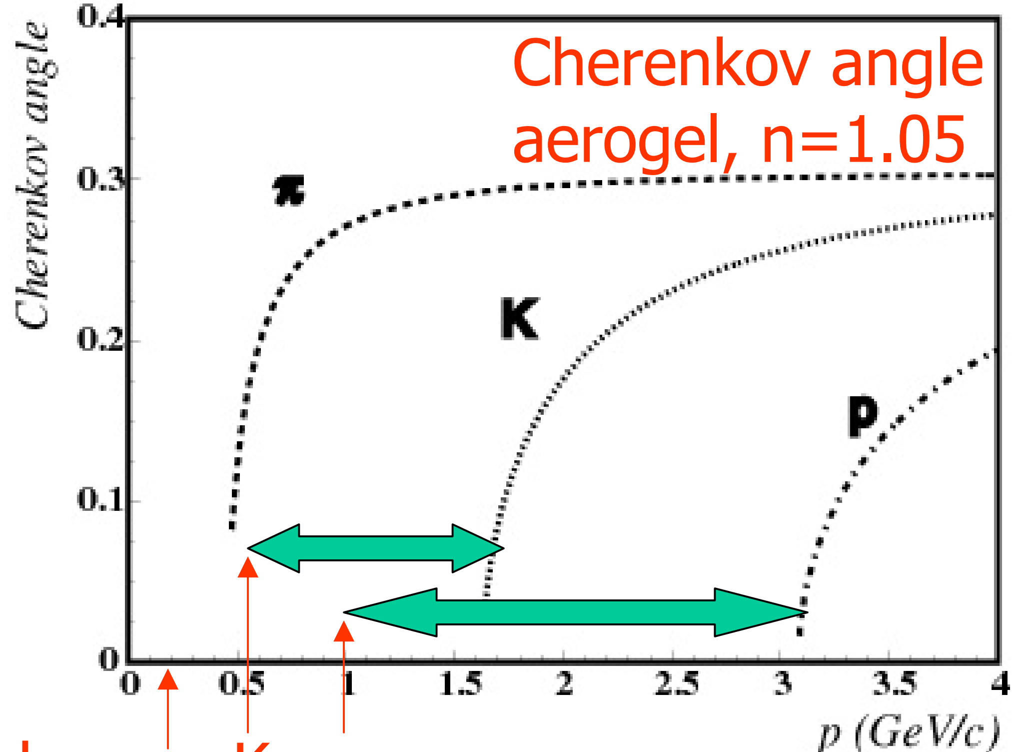
TOF test with pions and protons at 2 GeV/c.

Distance between start counter and MCP-PMT is 65cm

Time-of-flight with photons from the PMT window

Benefits: Čerenkov threshold in glass (or quartz) is much lower than in aerogel.

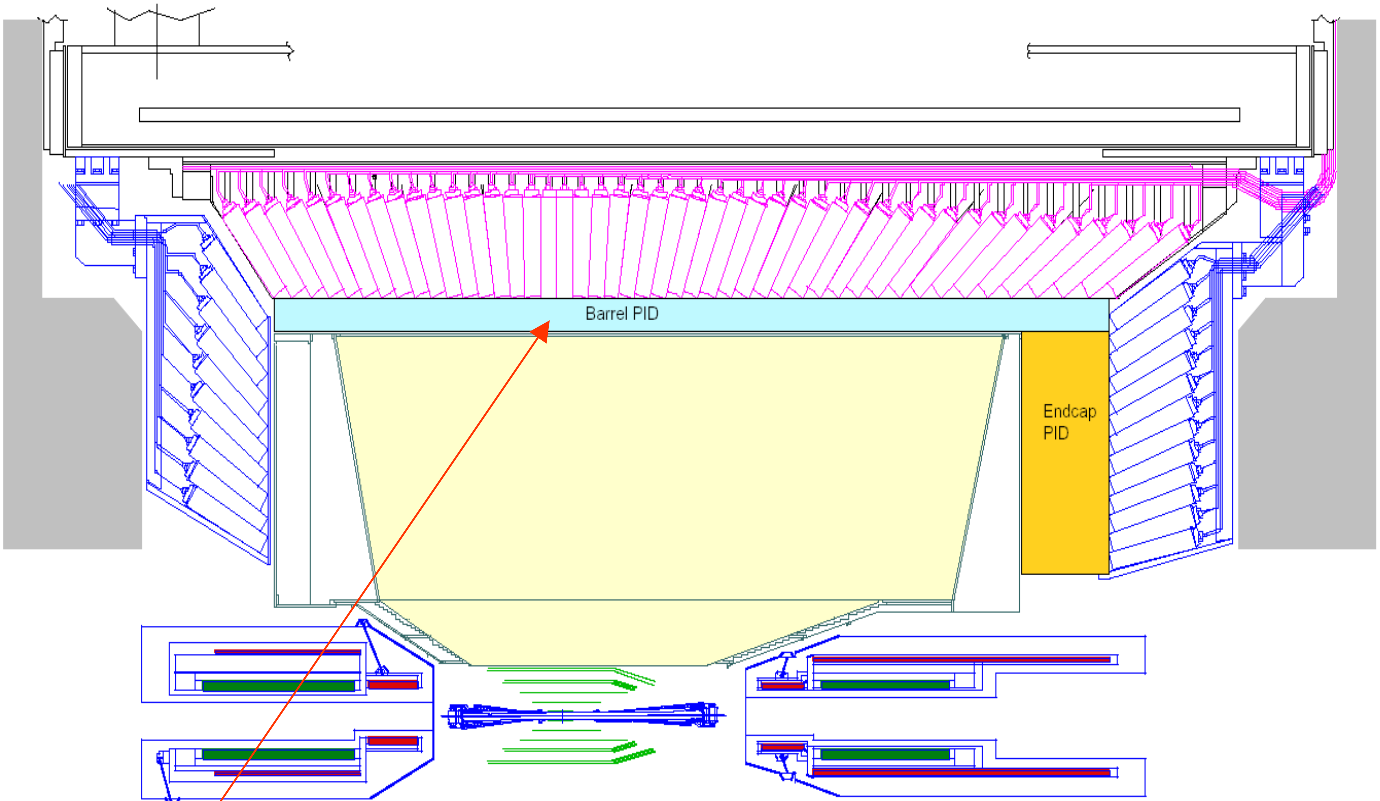
Aerogel: kaons (protons) have no signal below 1.6 GeV (3.1 GeV): identification in the veto mode.



Threshold in the window: π K p

Window: threshold for kaons (protons) is at ~0.5 GeV (~0.9 GeV): → positive identification possible.

Belle upgrade – side view

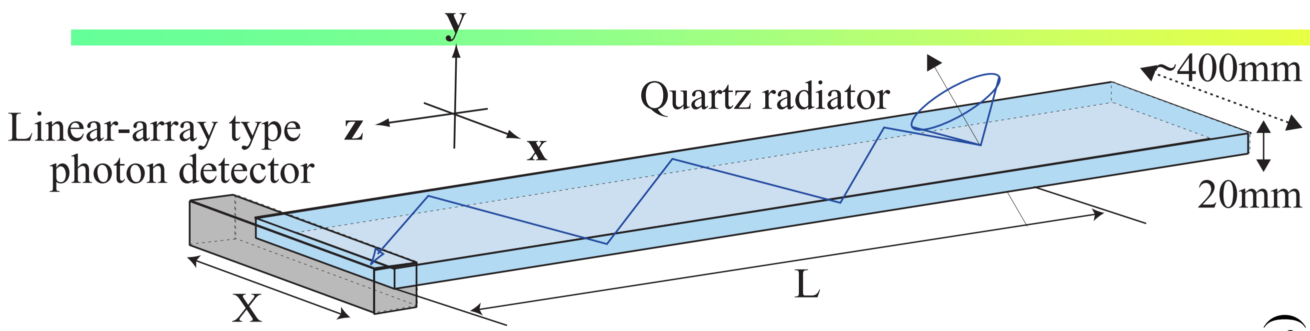


Two new particle ID devices, both RICHes:

Barrel: TOP or focusing DIRC

Endcap: proximity focusing RICH

Belle barrel upgrade: TOP counter

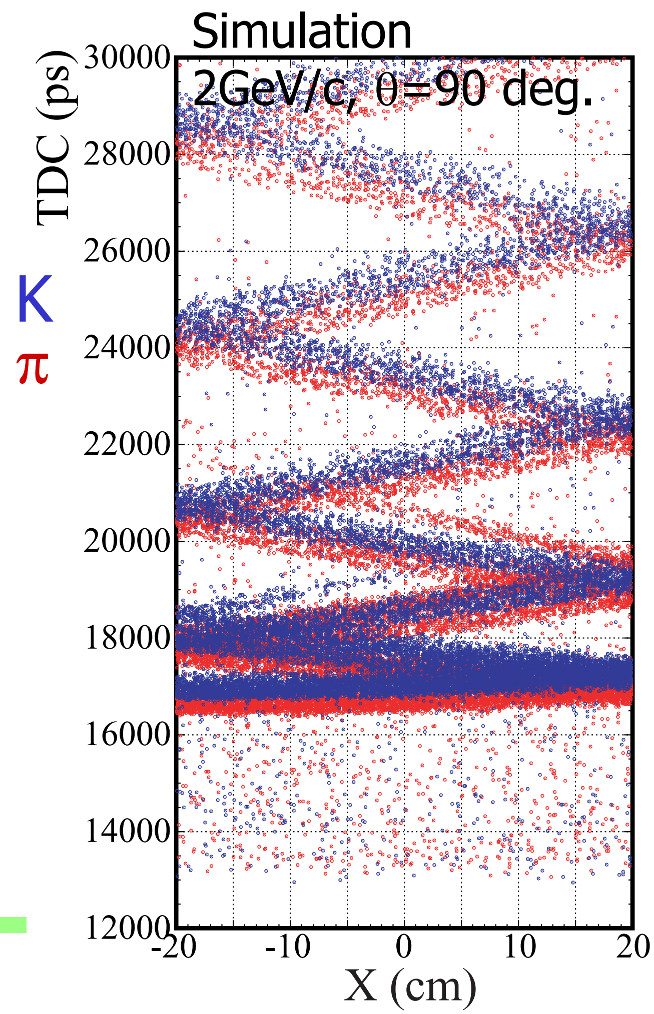


Time-of-Propagation counter:

Measurement of

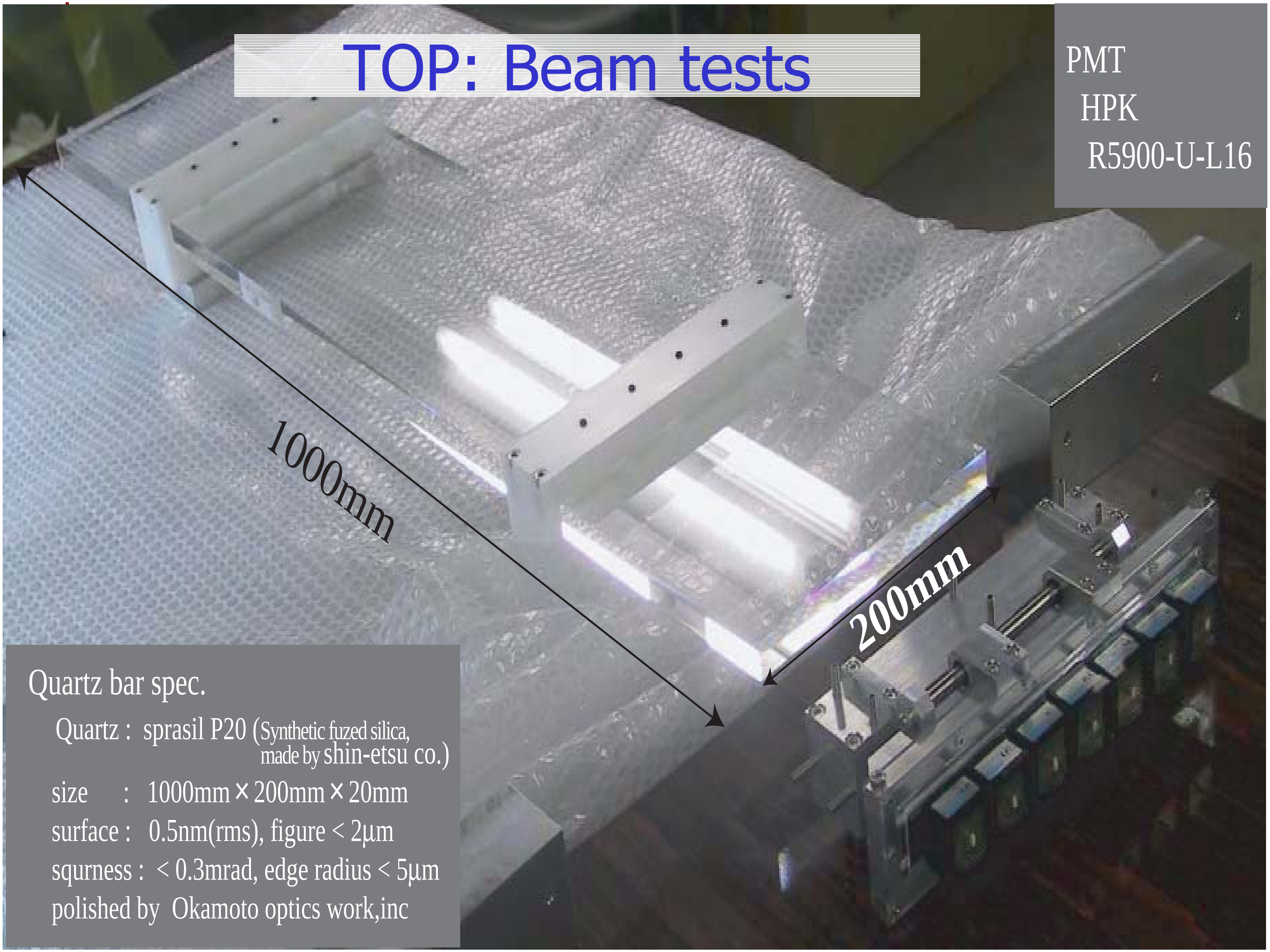
- One (or two coordinates) with a few mm precision
- Time-of-arrival

Excellent time resolution < ~40ps required for single photons at 1.5T



TOP: Beam tests

PMT
HPK
R5900-U-L16



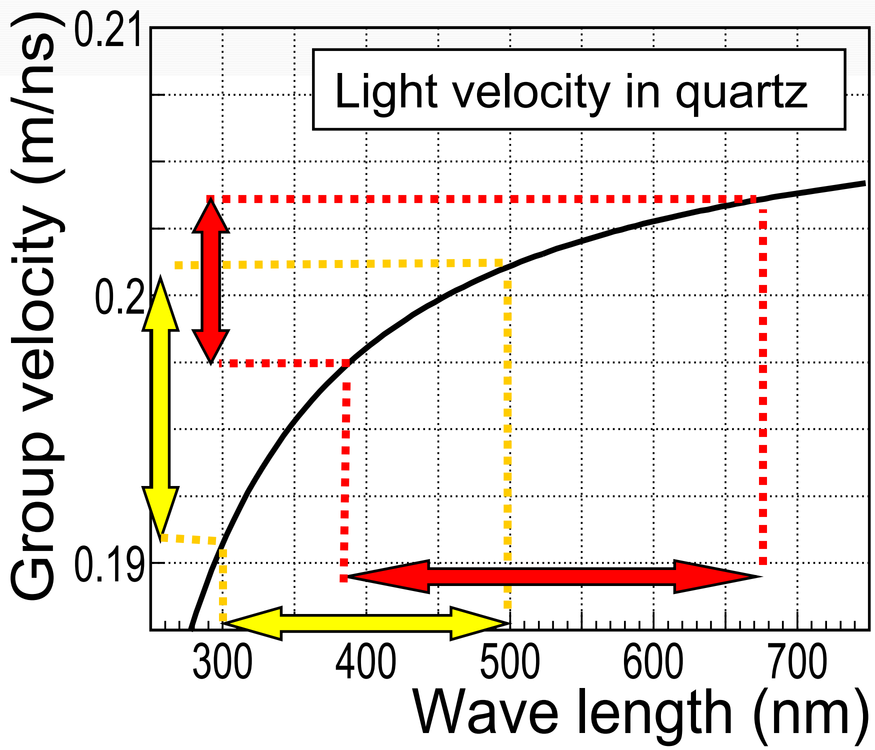
Quartz bar spec.

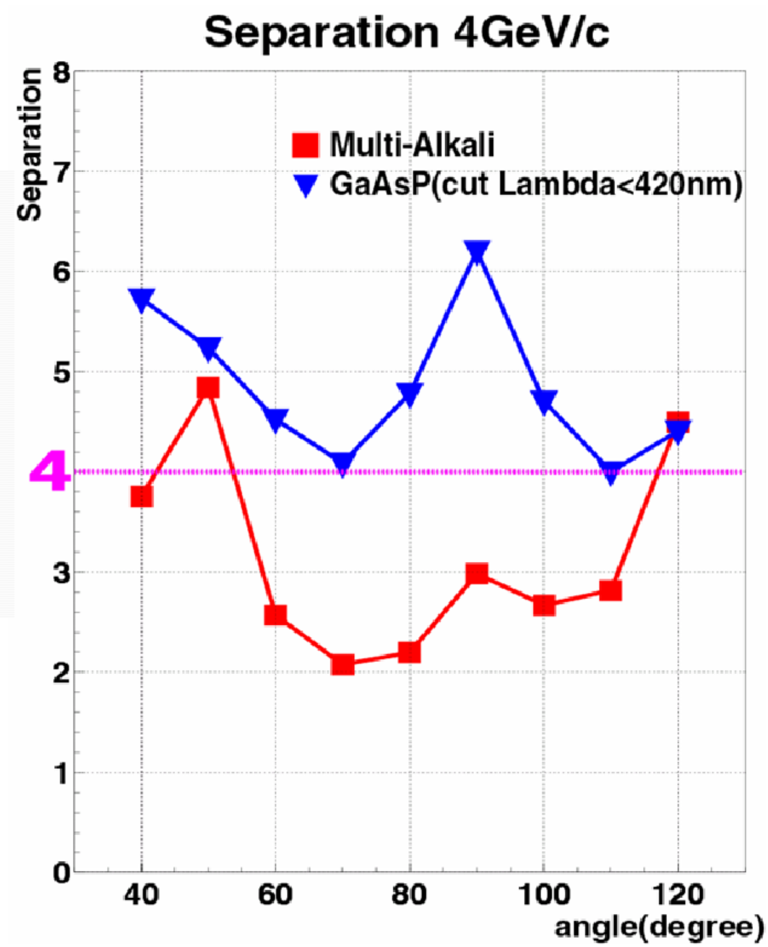
- Quartz : sprasil P20 (Synthetic fuzed silica, made by shin-etsu co.)
- size : 1000mm × 200mm × 20mm
- surface : 0.5nm(rms), figure < 2μm
- squrness : < 0.3mrad, edge radius < 5μm
- polished by Okamoto optics work,inc

TOP counter MC

Expected performance with:

bi-alkali photocathode: <4σ π/K separation at 4GeV/c (← chromatic dispersion)



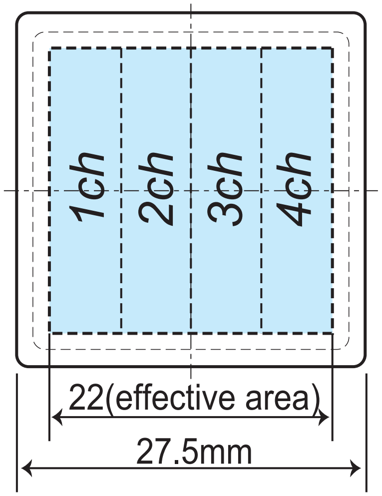


with GaAsP photocathode: >4σ π/K separation at 4GeV/c

GaAsP MCP-PMT with pads

- Square-shape MCP-PMT with GaAsP photo-cathode
- First prototype
  - 2 MCP layers
    - □ ϕ10μm holes
  - 4ch anodes
  - Slightly larger structure
    - Less active area

Target structure



- Enough gain to detect single photo-electron
- Good time resolution (TTS=42ps) for single p.e.
  - Slightly worse than single anode MCP-PMT (TTS=32ps)
- Next: increase active area frac., study ageing

Summary

RICH counters have evolved from the problem children ("RICH will come as the last component, if at all") to a standard and reliable tool in experimental particle physics.

They will play an essential role in the next generation of B physics experiments at the LHC and SuperB factories.

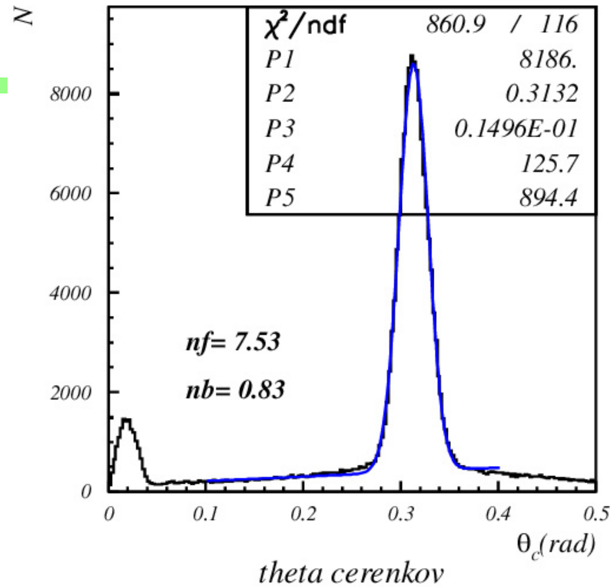
New concepts (focusing radiator, combination with time of flight) are being developed.

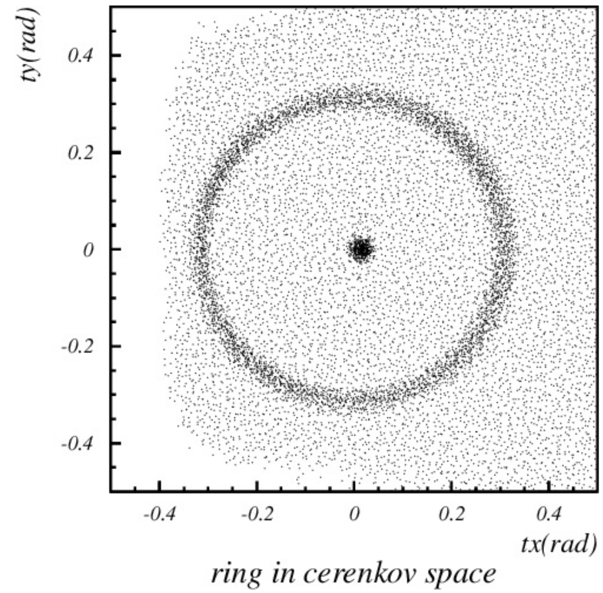
Working with them is real fun...

Back-up slides

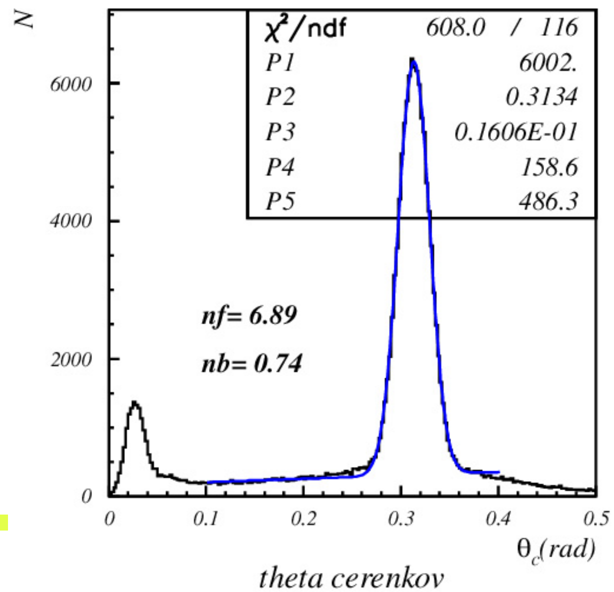
Focusing configuration - inclined tracks

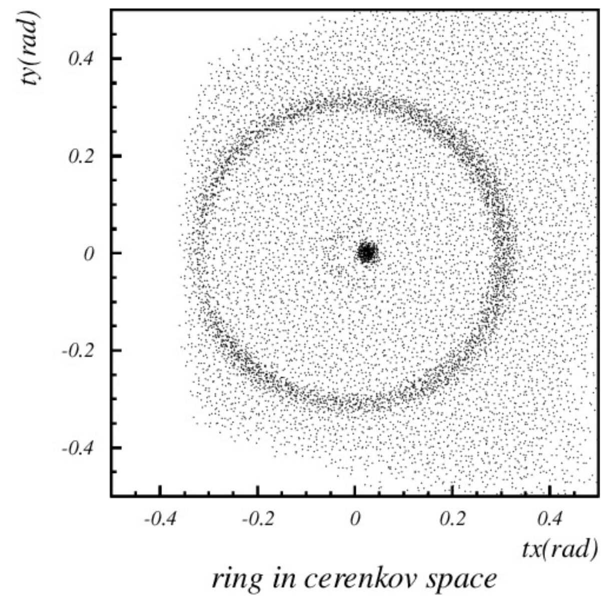
- 2+2cm aerogel
- angle 20°





- 2+2cm aerogel
- angle 30°

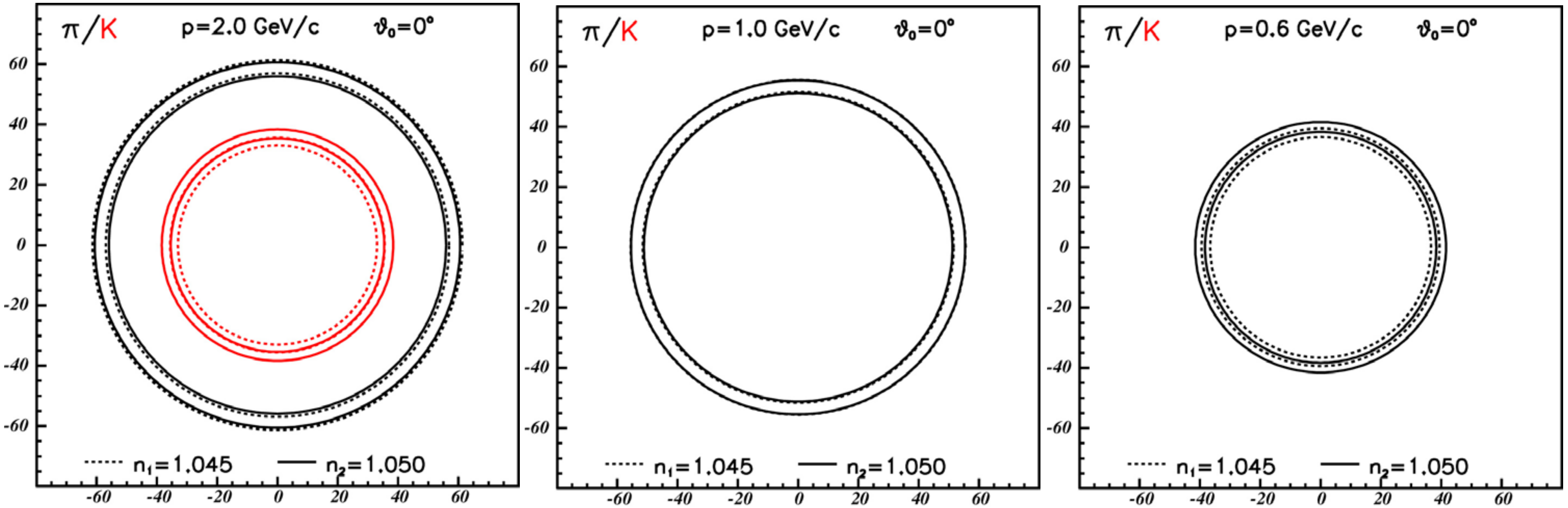




Works as well!

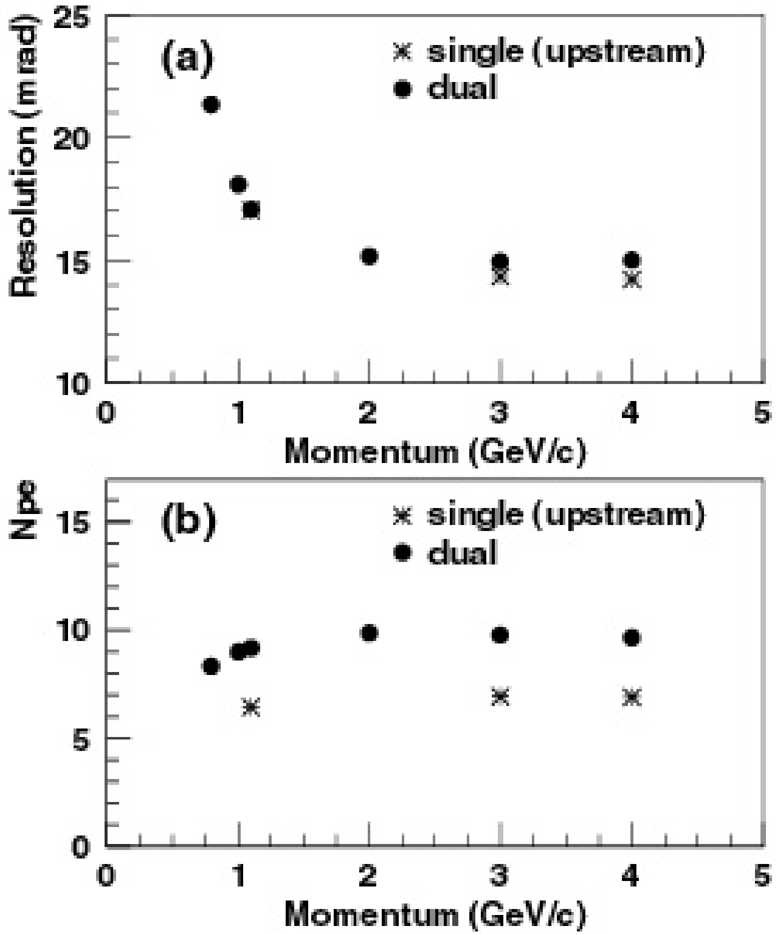
Focusing configuration – low momentum

- Matching of indices: done for high momentum tracks (4GeV/c)
- How is the overlapping of rings at lower momenta?



Good overlapping down to 0.6 GeV/c

Focusing configuration – momentum scan



- single photon resolution: dual radiator ~same as single (of half the thickness) for the full momentum range

- number of detected hits: dual radiator has a clear advantage

Overlapp optimized at 4GeV/c→ OK at low momenta as well

Burle MCP PMT beam test

- **BURLE MCP-PMT** mounted together with an array of 12(6x2) **Hamamatsu R5900-M16 PMTs** at 30mm pitch (reference counter)