Recent advances in Ring Imaging Čerenkov counters

Peter Križan

University of Ljubljana and J. Stefan Institute

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Why particle identification?

Ring Imaging CHerenkov counter - RICH

New concepts, photon detectors, radiators

Summary

Introduction: Why Particle ID?

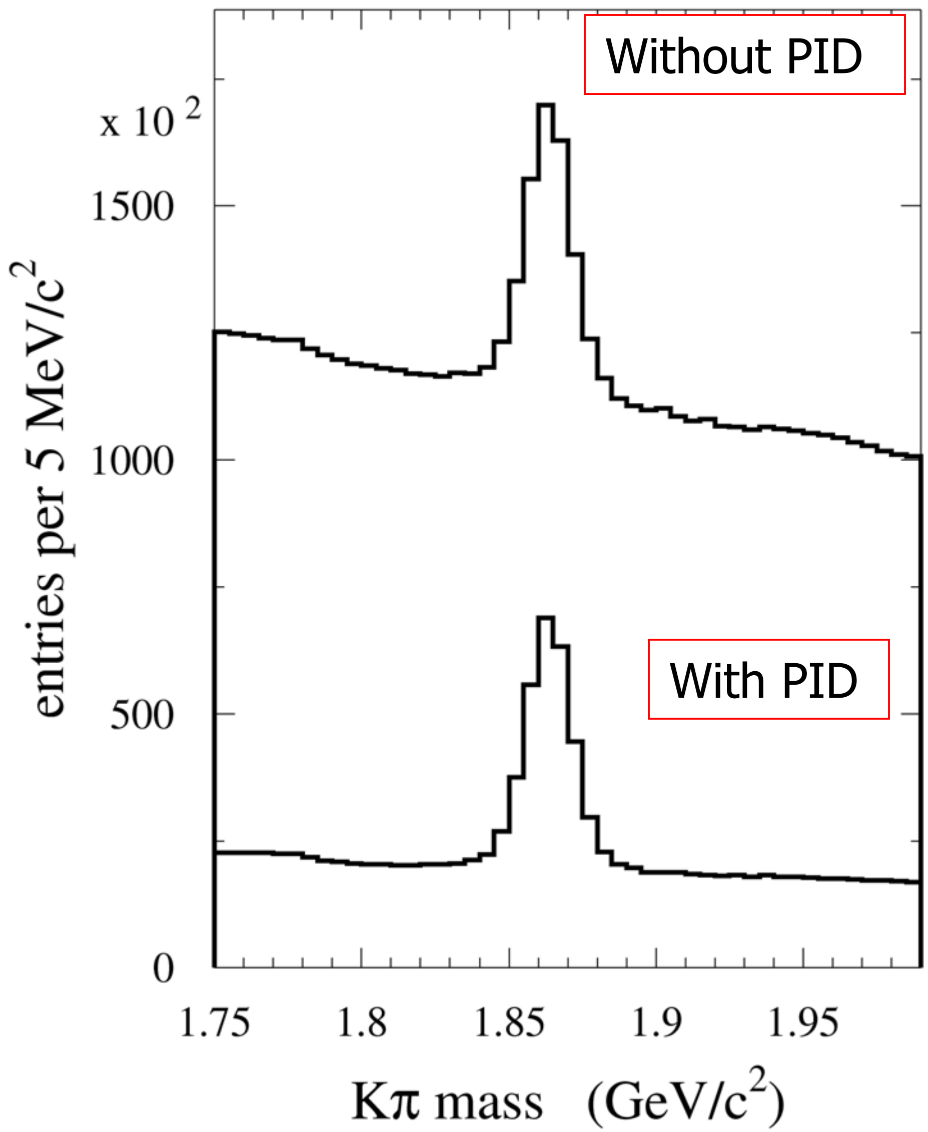
Particle identification is an important aspect of particle, nuclear astroparticle physics experiments.

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

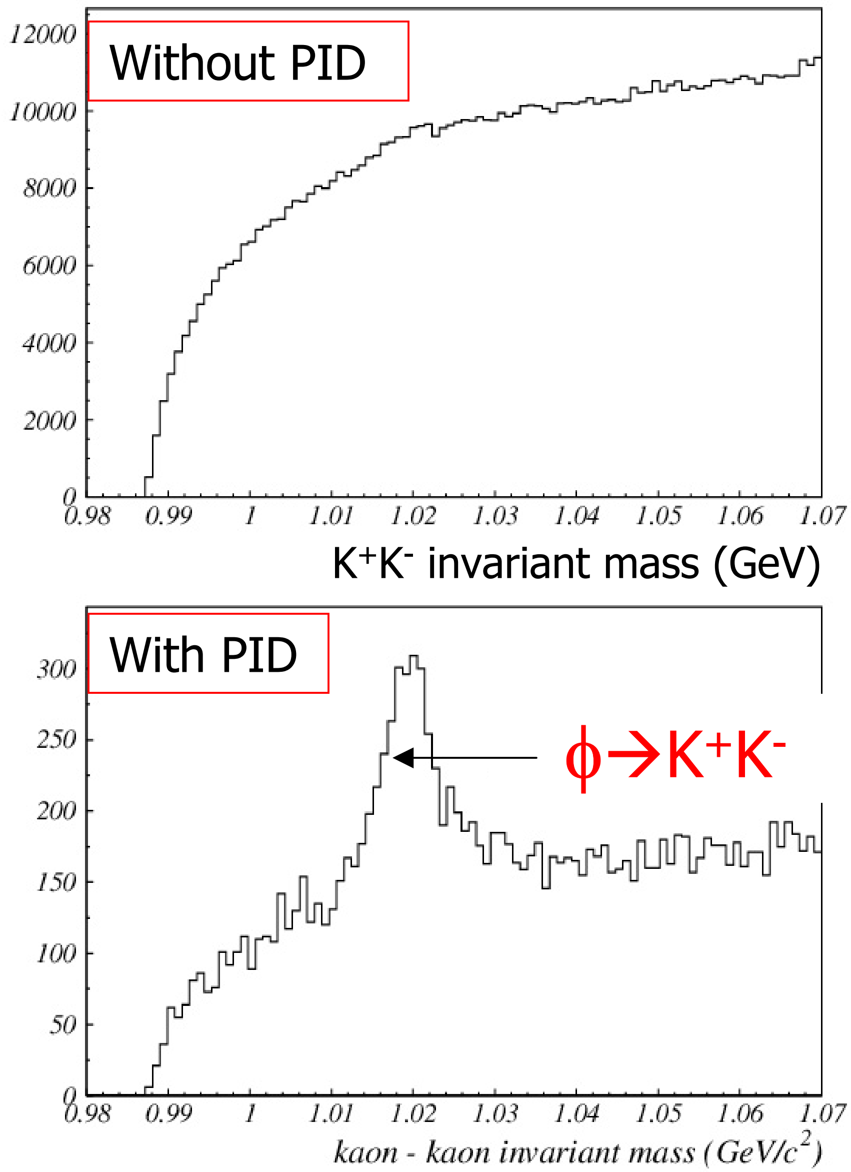
Introduction: Why Particle ID?



Example 1: B factory

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

Introduction: Why Particle ID?



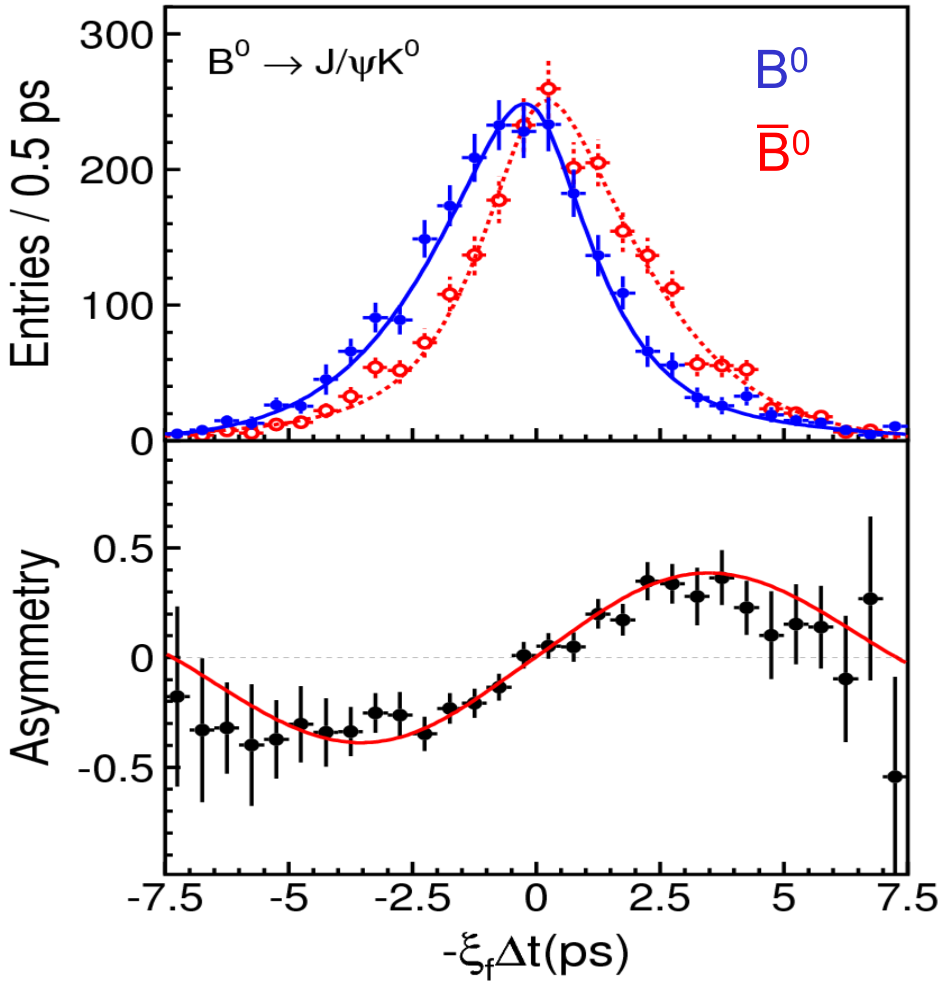
Example 2: HERA-B

K^+K^- invariant mass.

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

Introduction: Why Particle ID?

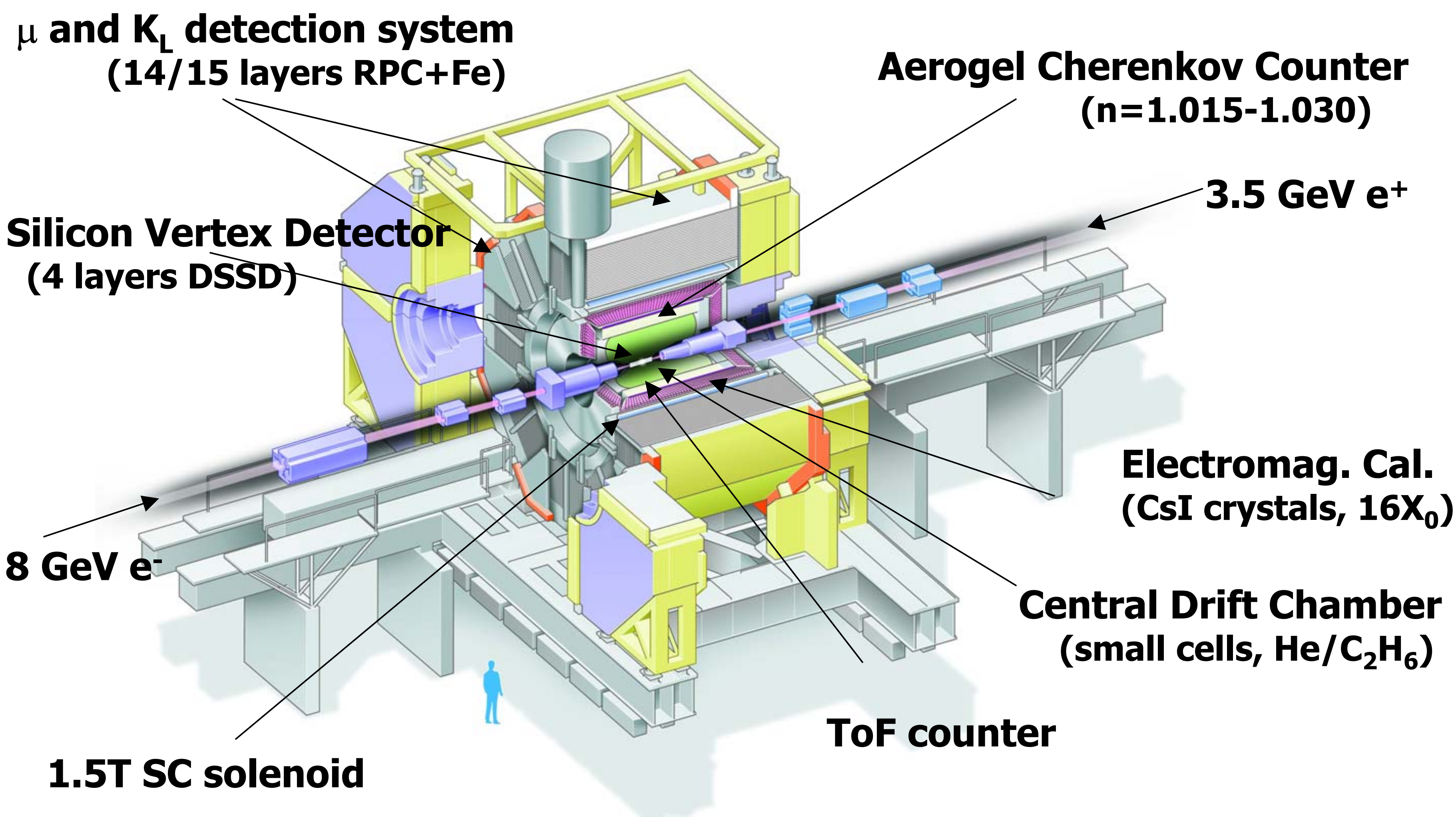
Particle identification at B factories (Belle and BaBar): was essential for the observation of CP violation in the B meson system.



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

Belle @ KEK-B in Tsukuba

Belle spectrometer at KEK-B



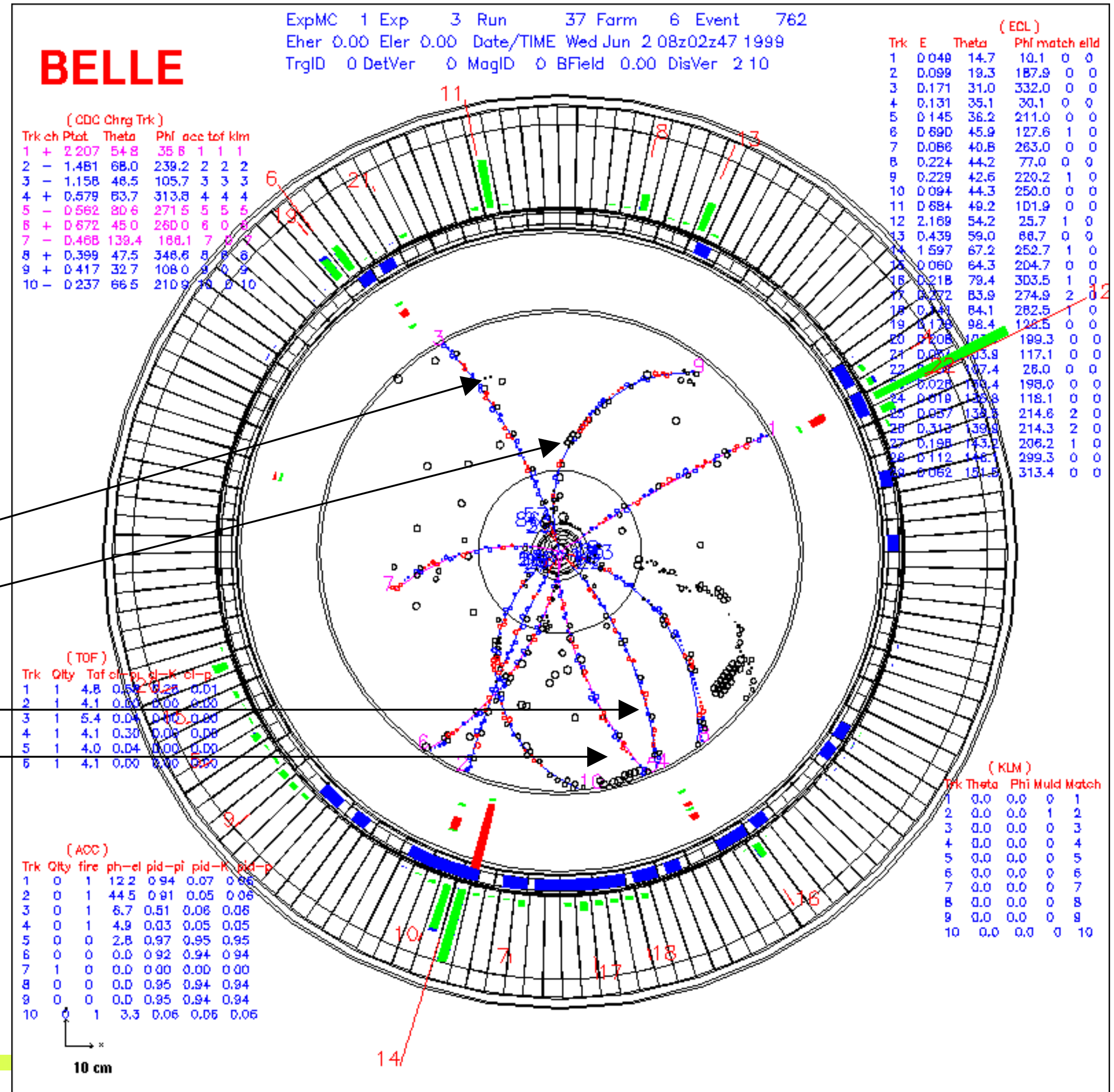
What do we measure?

- Charged particle tracks in magnetic field (radius of curvature → momentum)
- Identity of particles

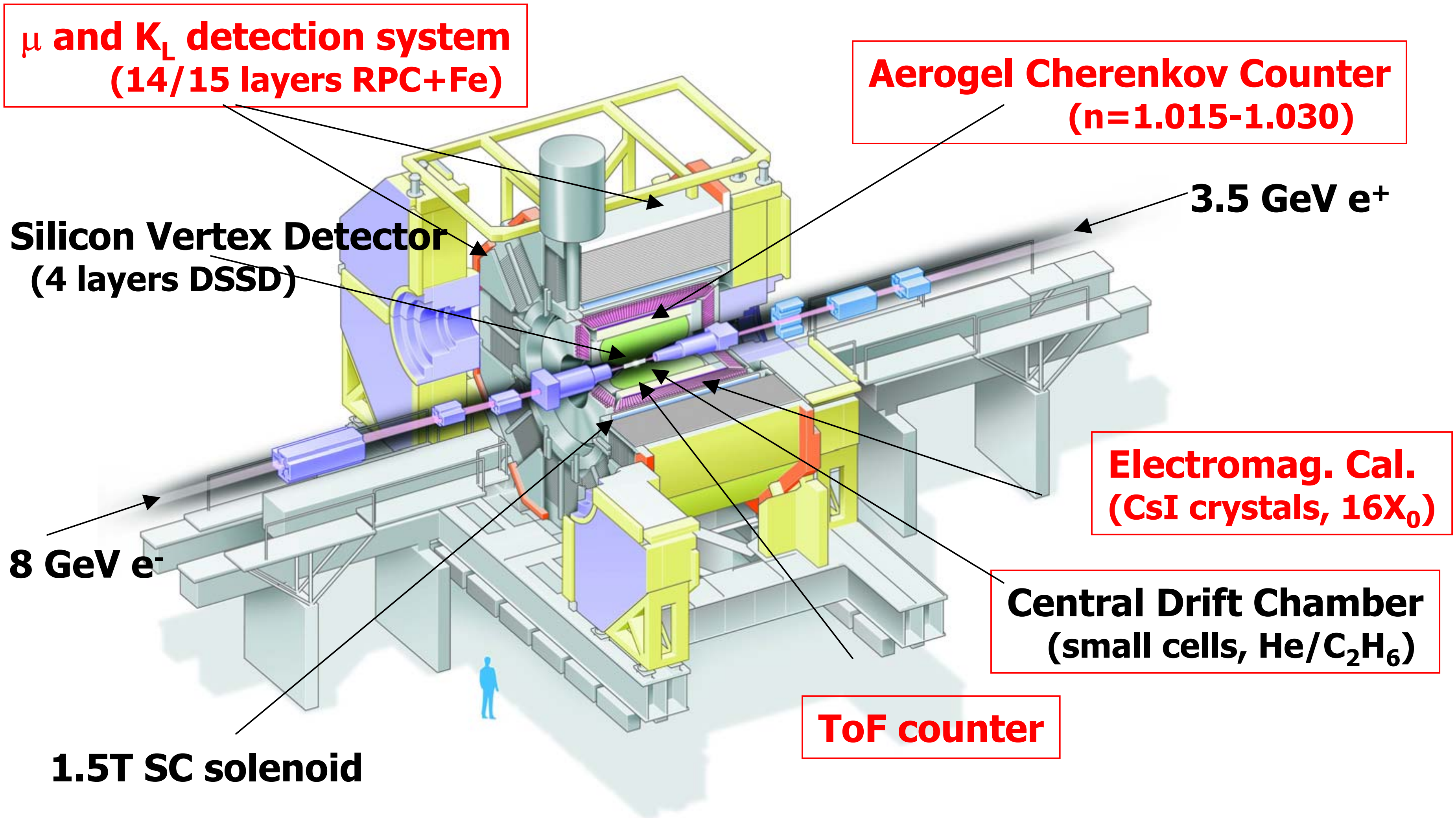
$B^0 \rightarrow K^0_S J/\psi$

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

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



Particle identification systems in Belle



Identification of charged particles

Particles are identified by their mass.

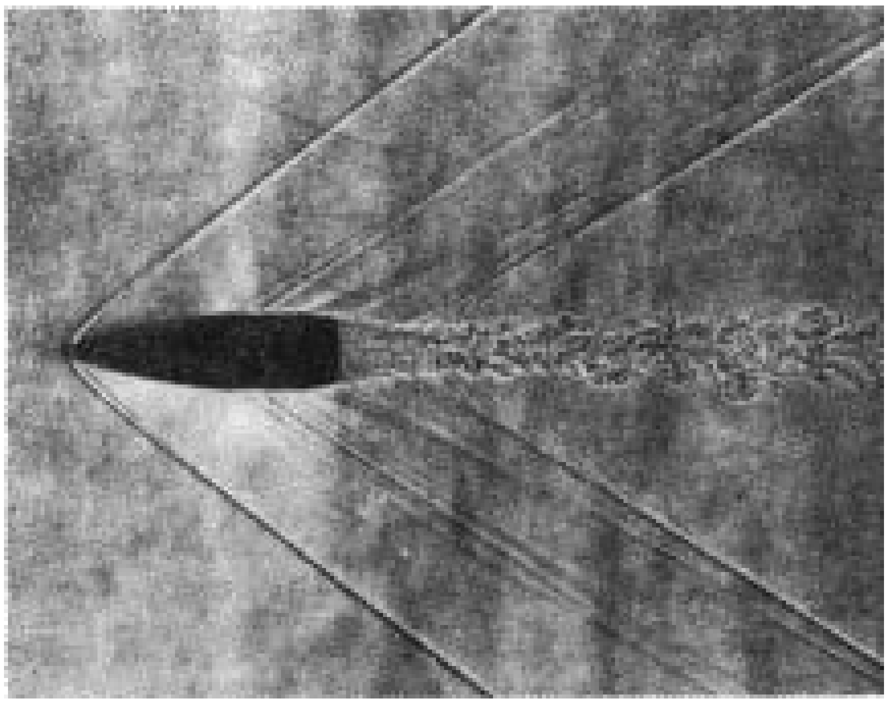
Determination of mass: from the relation between momentum and velocity, $p=\gamma mv$

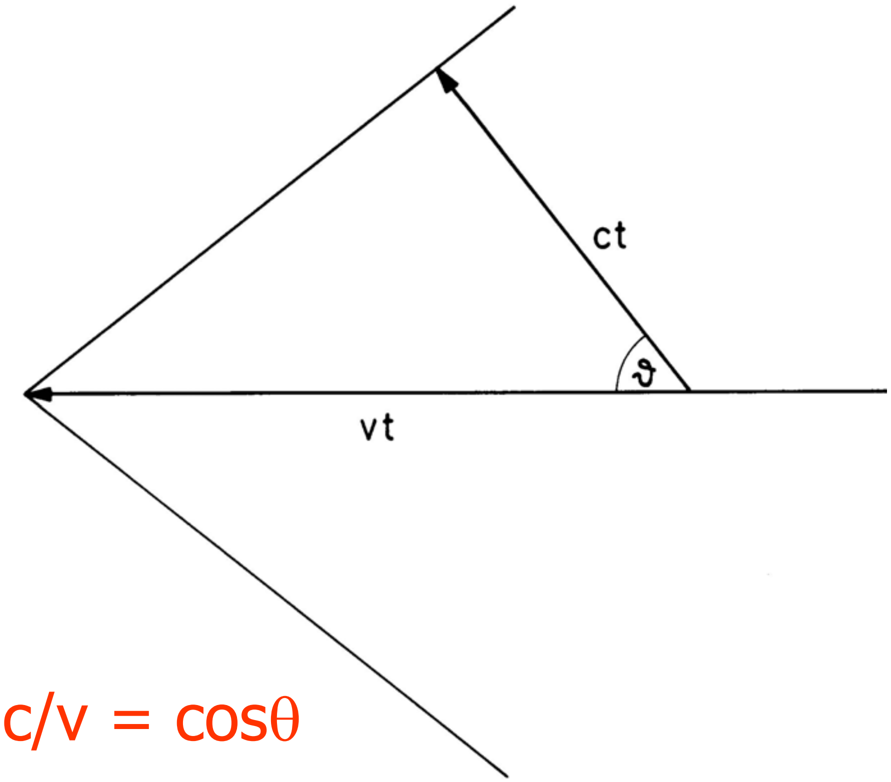
Measure independently:

- momentum p (radius of curvature in magnetic field)
- velocity v
  - time of flight
  - ionisation losses dE/dx (depend on velocity)
  - Čerenkov angle

Velocity of a bullet

Determine the velocity of the bullet





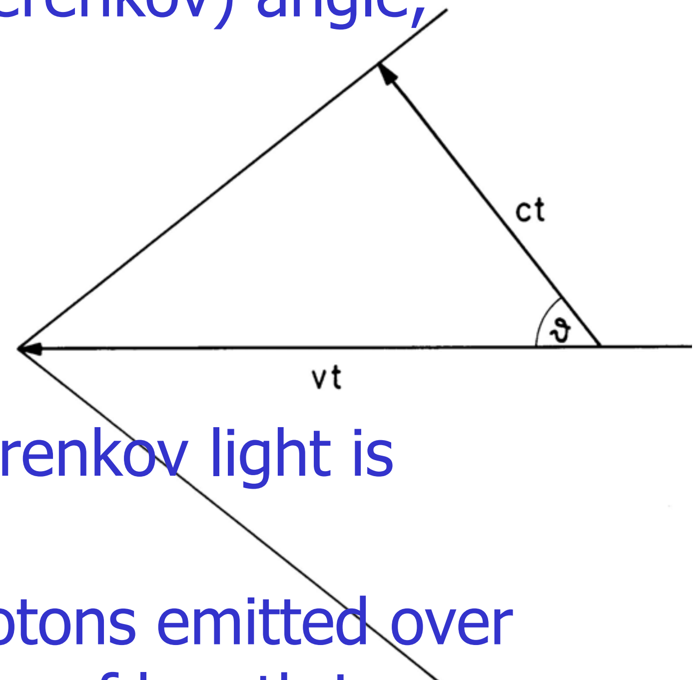
$c/v = \cos\theta$

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,

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



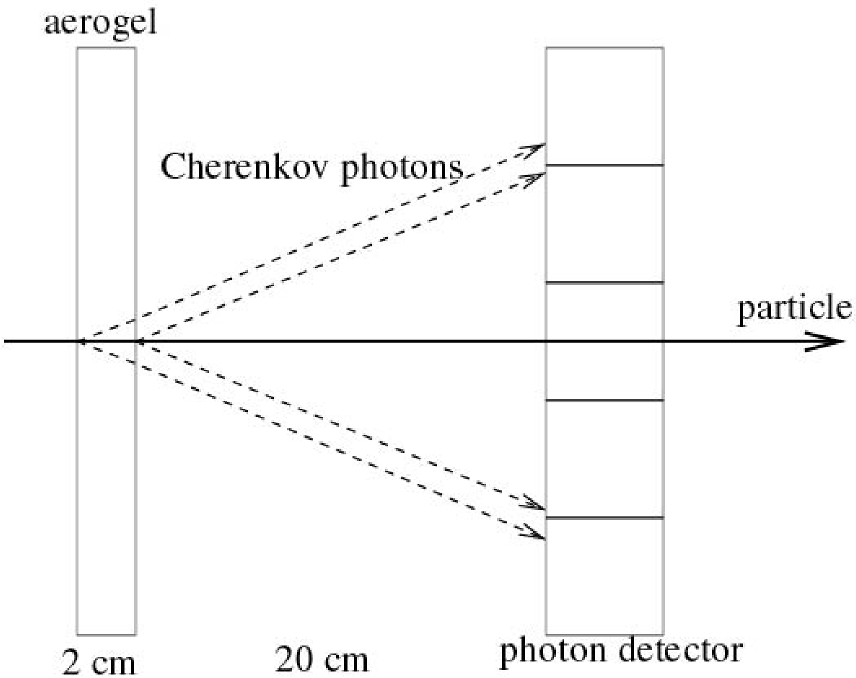
Two cases:

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:

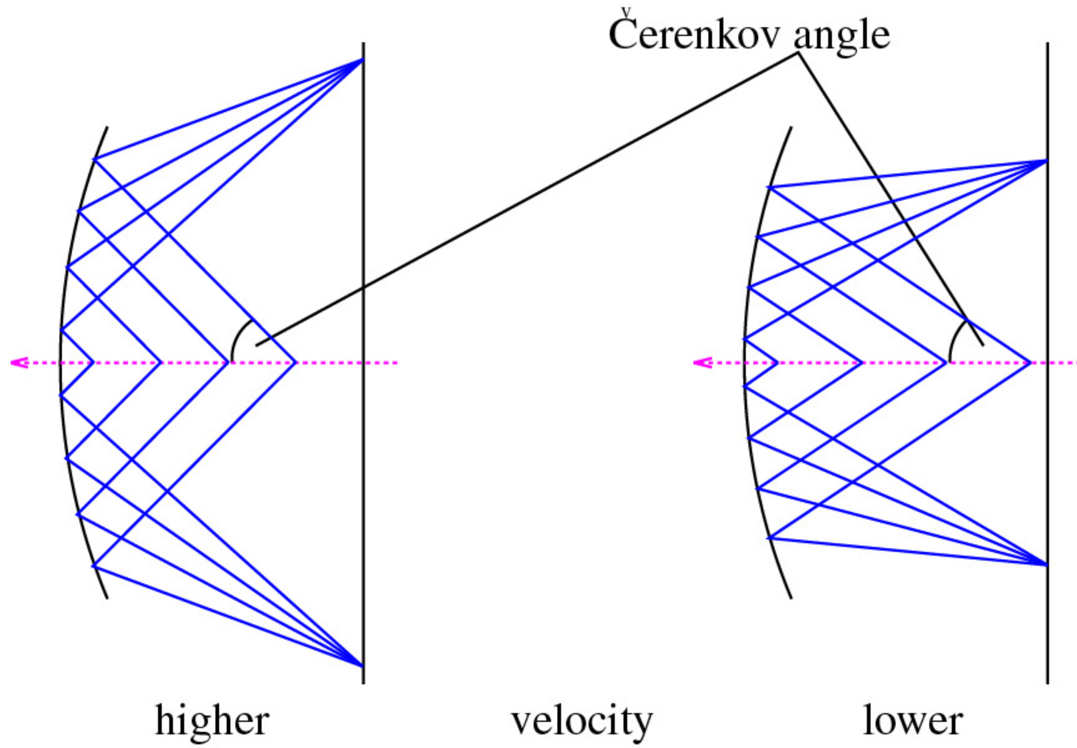
$$\frac{dN}{dE} = n_e L \frac{d\sigma}{dE} = n_e L \frac{\alpha}{\hbar c} \sin^2\theta = 370 (cm)^{-1} (eV)^{-1}$$

Measuring Čerenkov angle



Proximity focusing RICH

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



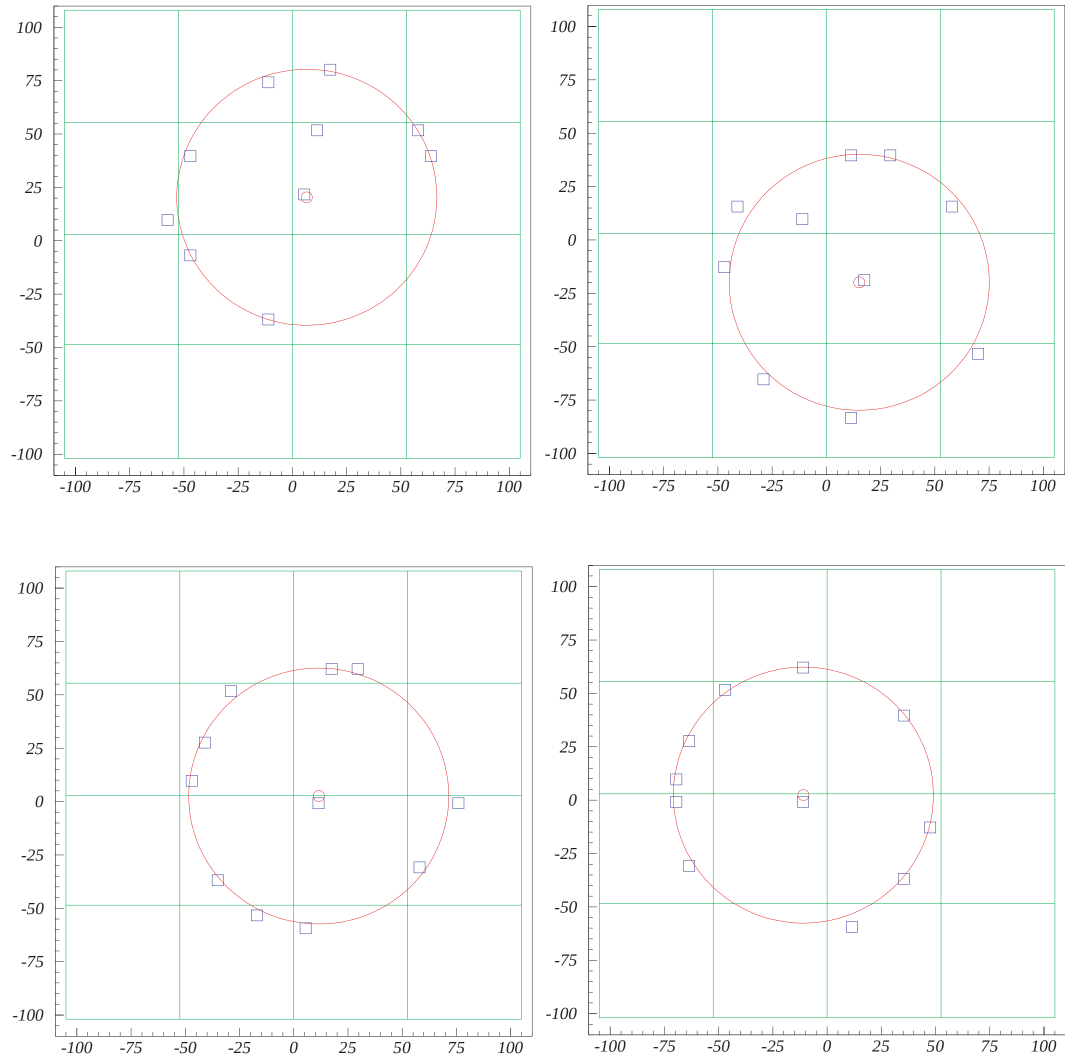
RICH with a focusing mirror

Measuring Čerenkov angle

From hits of individual photons → measure 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 ($\Delta E \sim 2$ 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.

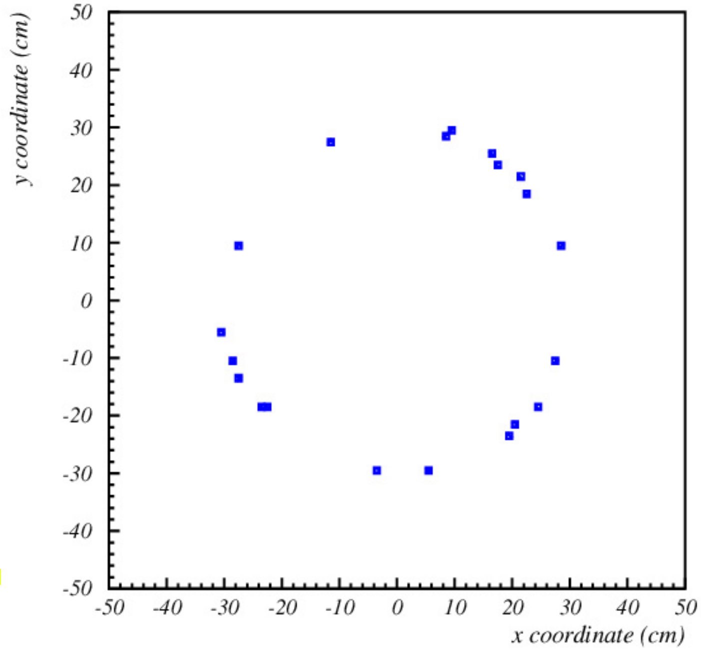
Typically: N_0 = 50 - 100/cm

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:

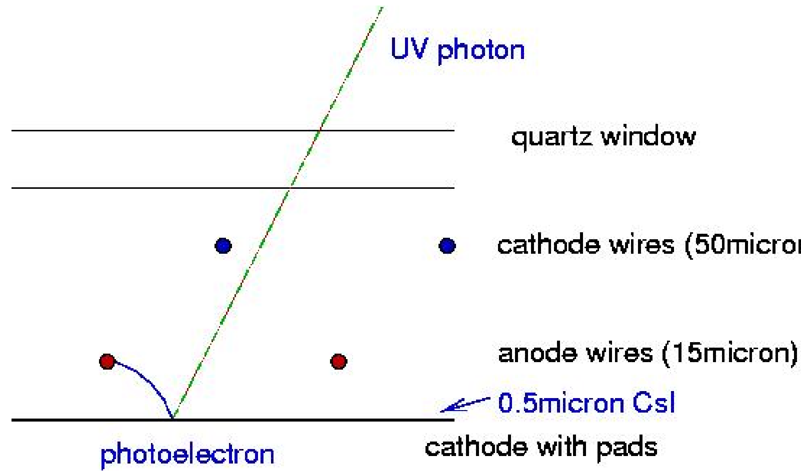
- Operation in (high) magnetic field
- High rate capability
- Very high spatial resolution
- Excellent timing (time-of-arrival information)

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
- 1958: Nobel prize for Čerenkov
- 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

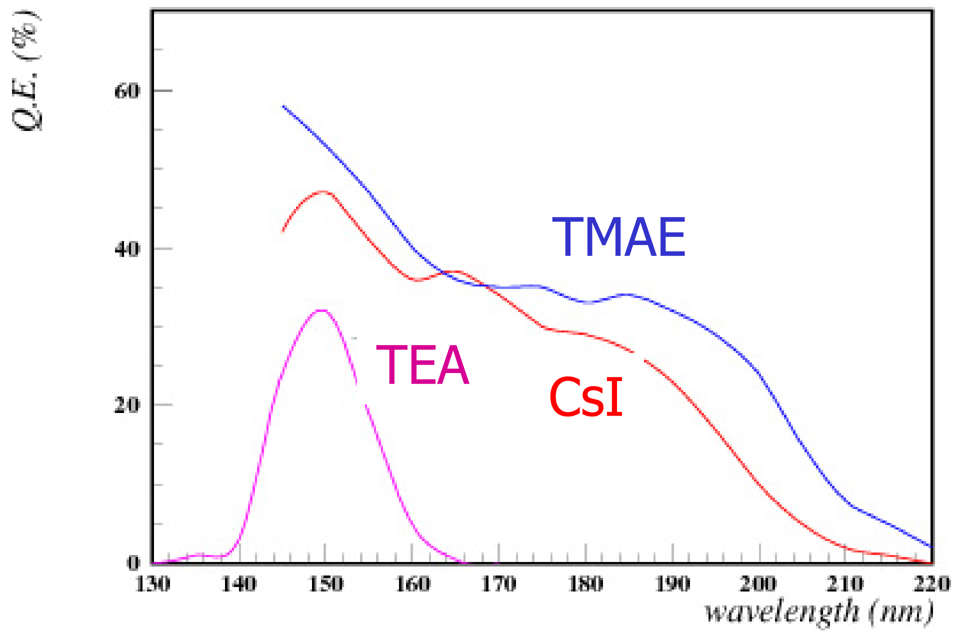
DELPHI, SLD, OMEGA RICHes: all employed wire chamber based photon detectors (UV photon → photoelectron → detection of a single electron in a wire chamber)



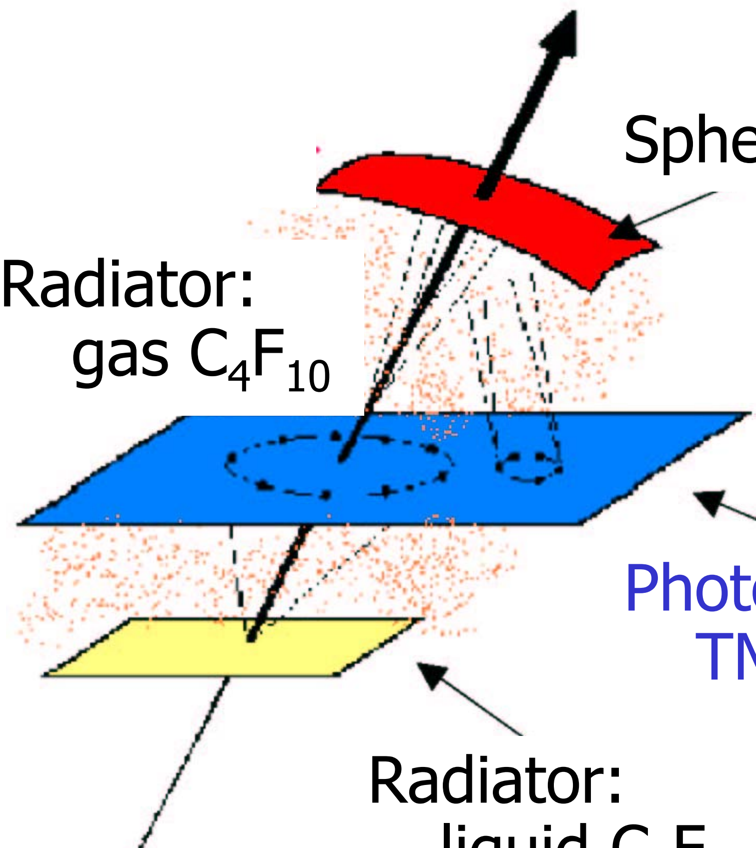
Photosensitive component:

•added to the gas mixture (TMAE, TEA)

•layer on one of the cathodes (CsI on the printed circuit pad cathode)



First generation of RICH counters



Inside the DELPHI RICH:
segmented spherical mirror

Early nineties: a new boost

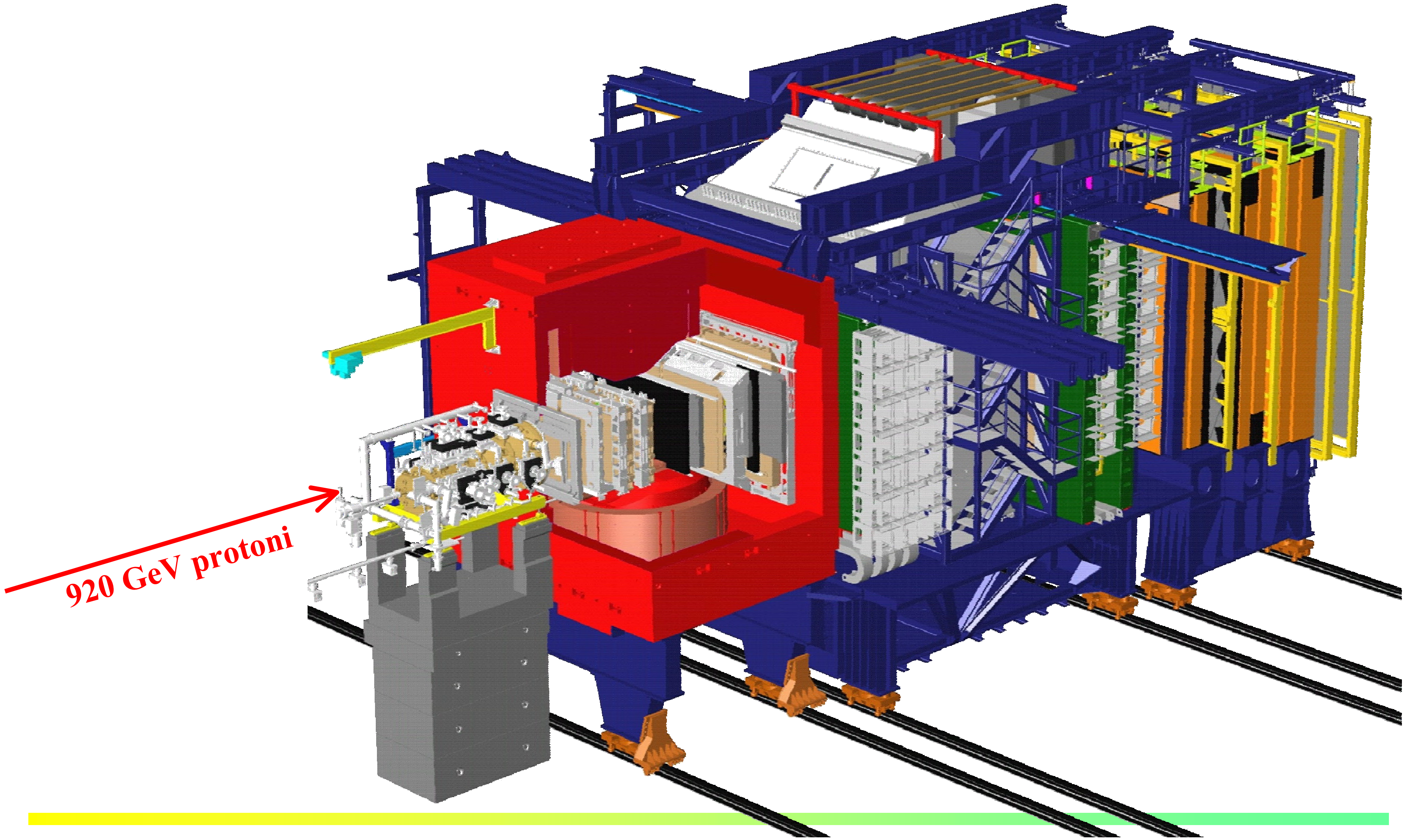
The main motivation came from the planning of experiments to measure CP violation in the B meson system.

Kaon identification: one of the essential features.

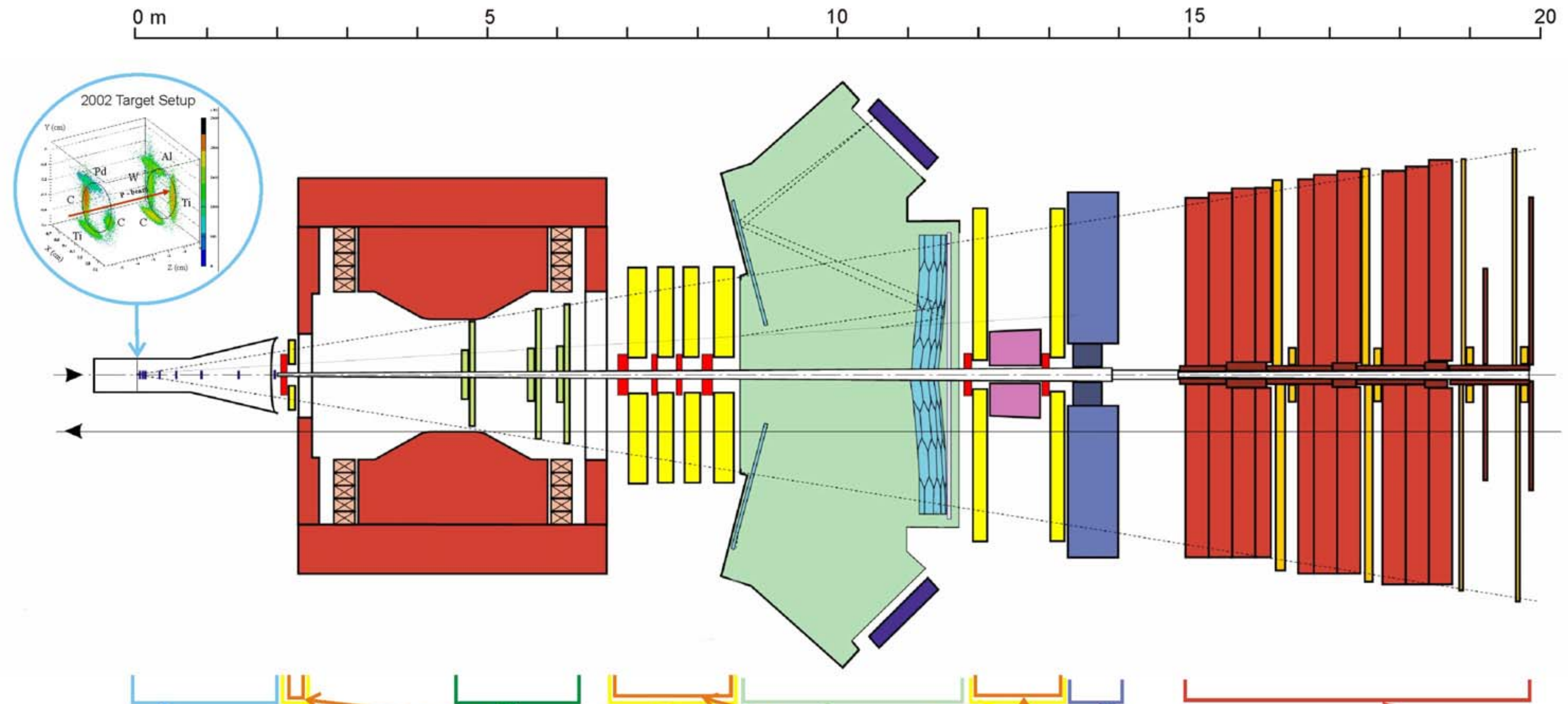
Several proposals in Europe, US, Japan → several RICH designs and R+D programs.

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

HERA-B: a fixed target experiment



HERA-B: a fixed target experiment



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

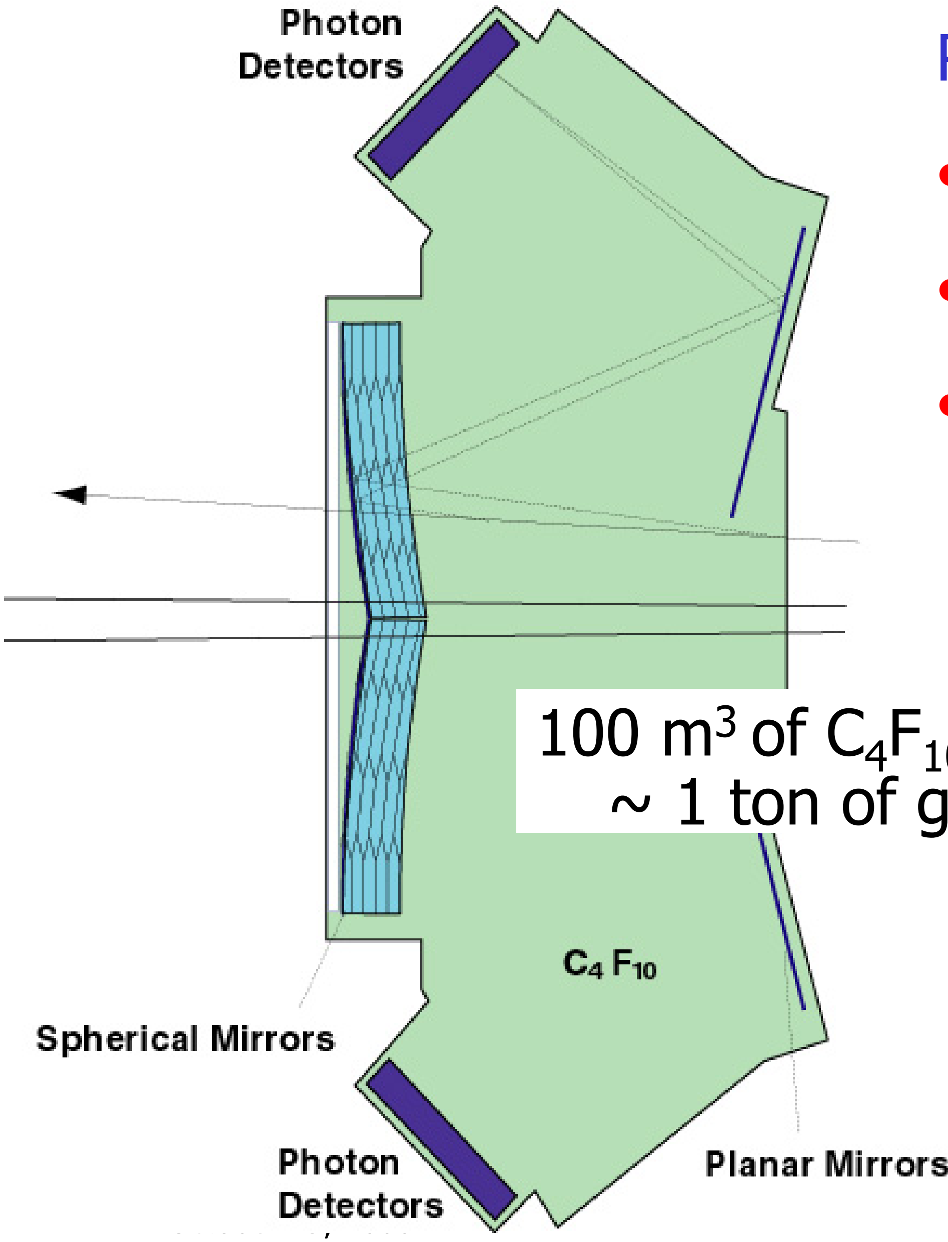
RICH
Spherical mirror inside C_4F_{10} radiator, Lens-enhanced multianode PMT focal plane.

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

Electromagnetic Calorimeter
W/Pb scintillator sandwich, shash-lik 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

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

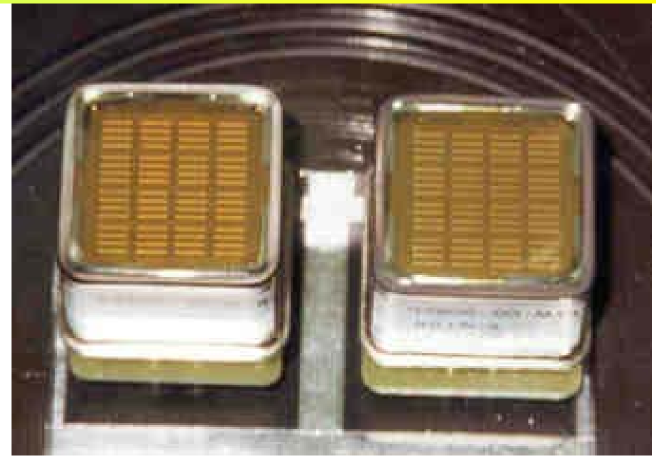
Tested on the bench and in the beam: excellent performance →easy decision

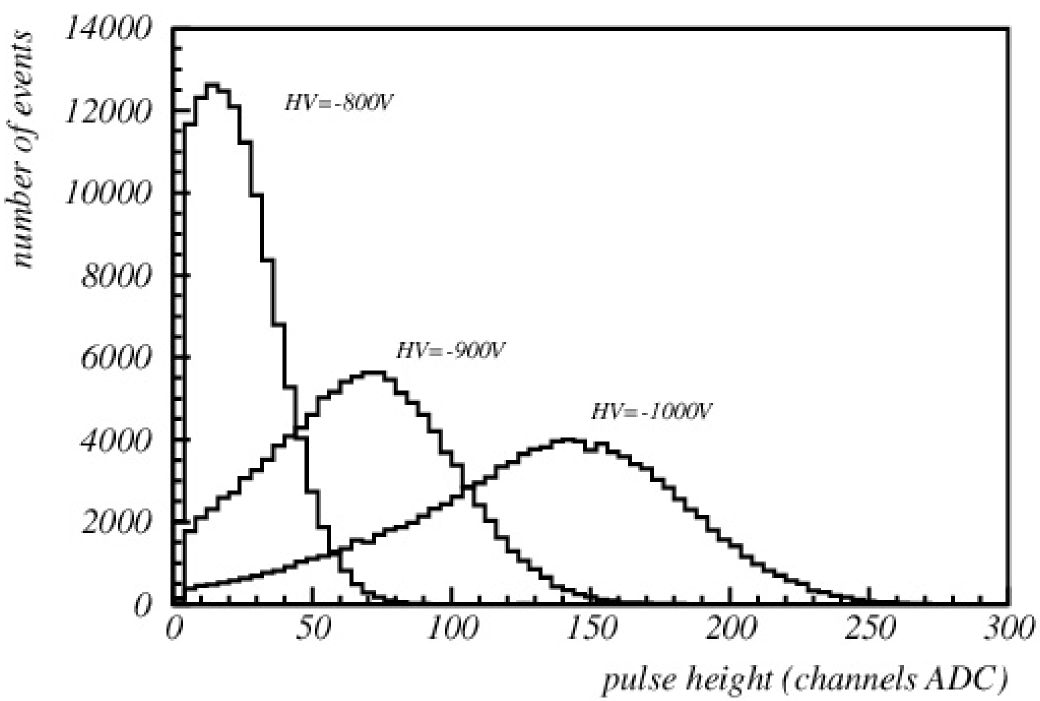
→ NIM A394 (1997) 27

lultianode Hamamatsu R5900-M16 PMT

Multianode PMTs

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





Key features:

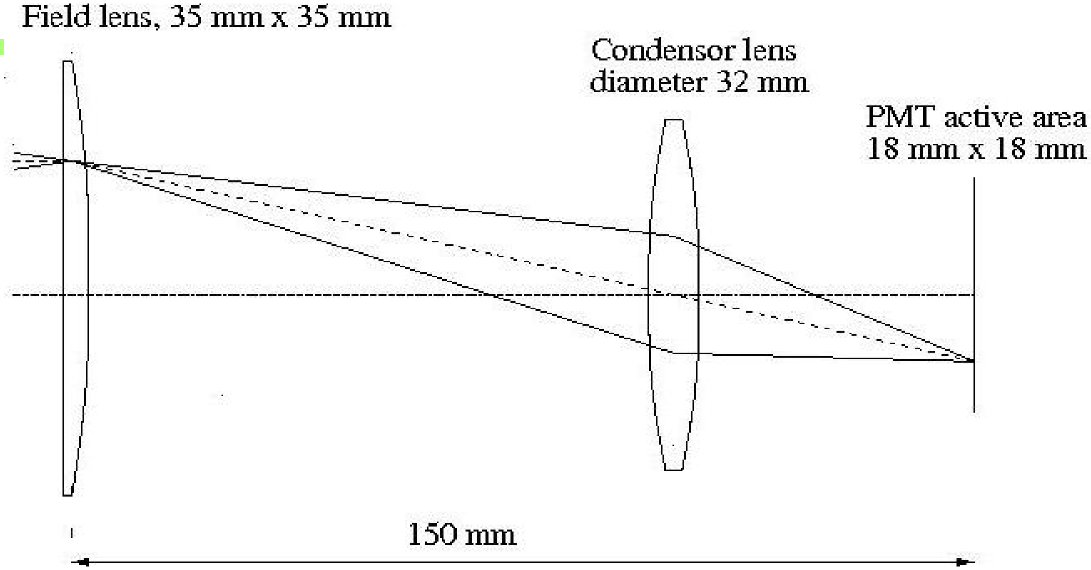
- Excellent single photon pulse height spectrum
- Low noise
- Low cross-talk

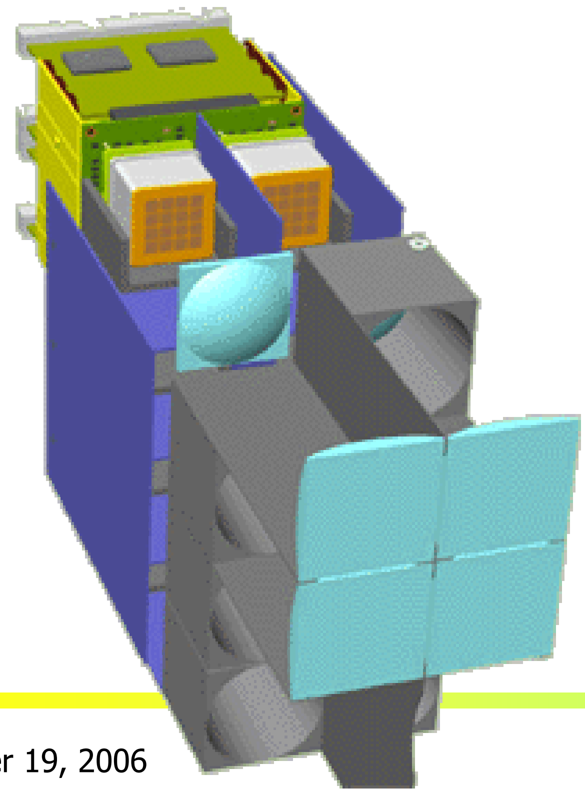
HERA-B RICH photon detector

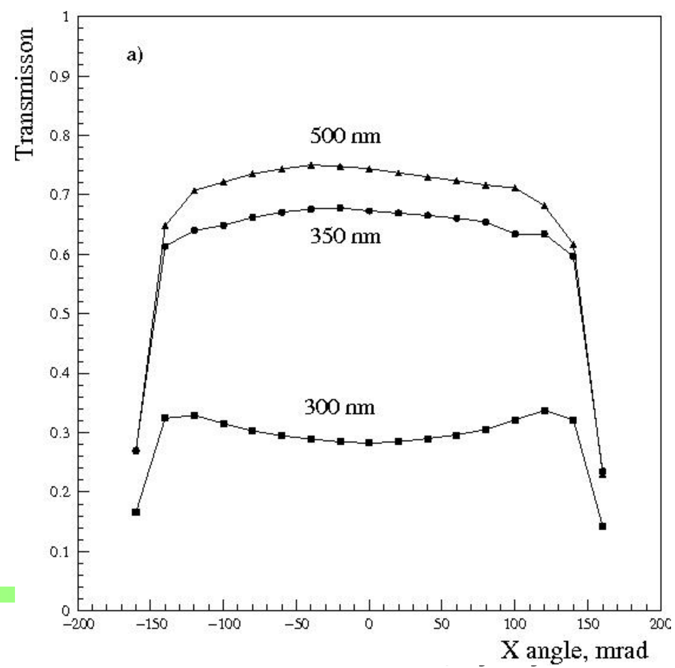
Light collection system (imaging!) to:

-Adapt the pad size

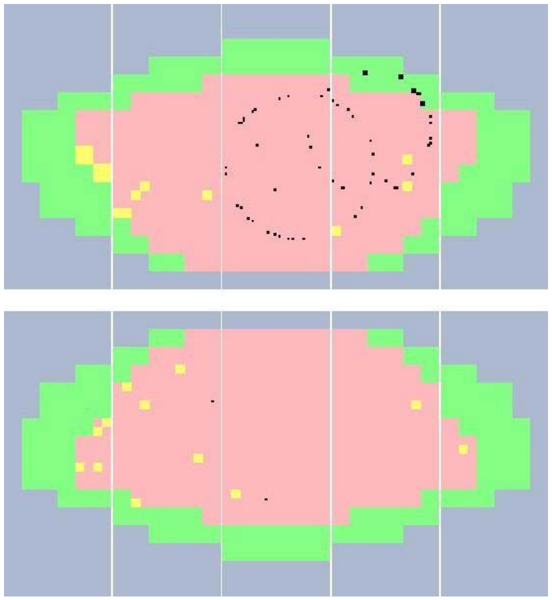
-Eliminate dead areas





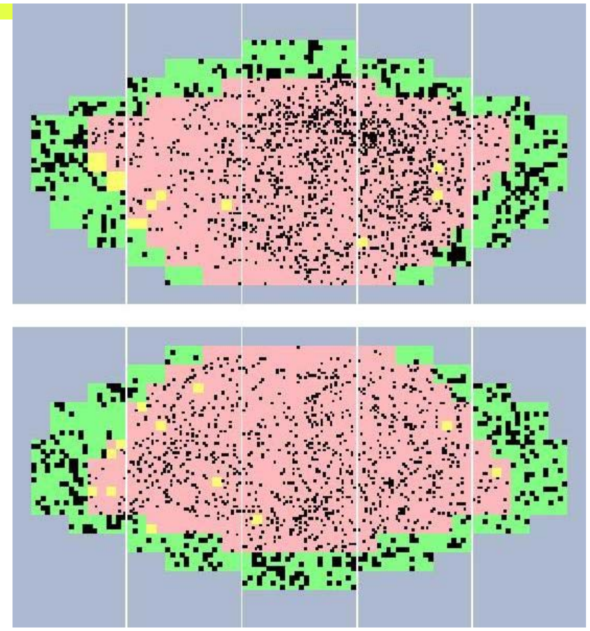


HERA-B RICH

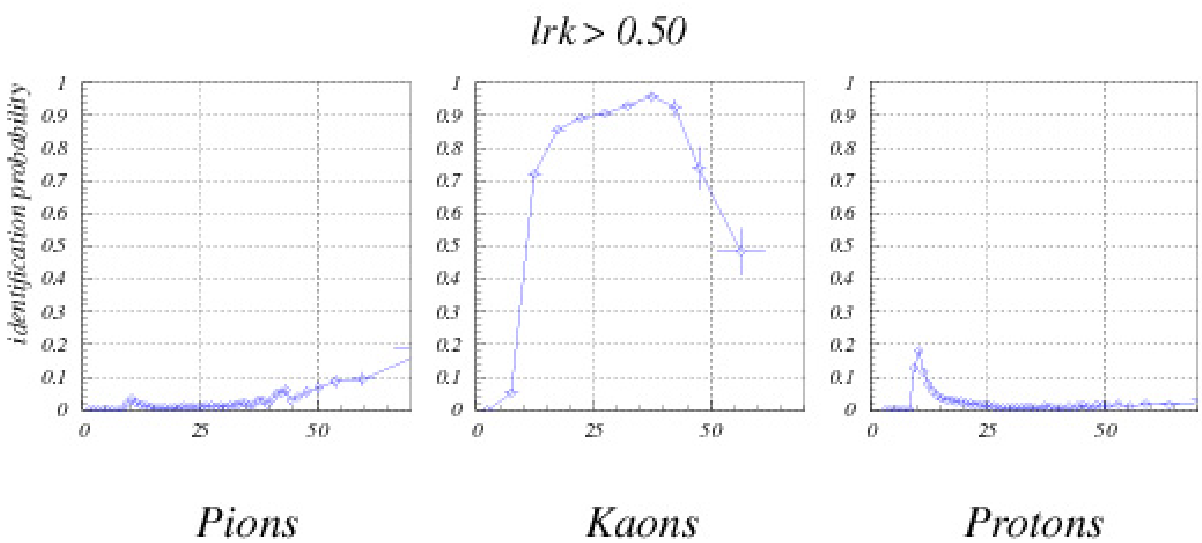


Little noise, very clear rings
←

Typical event →

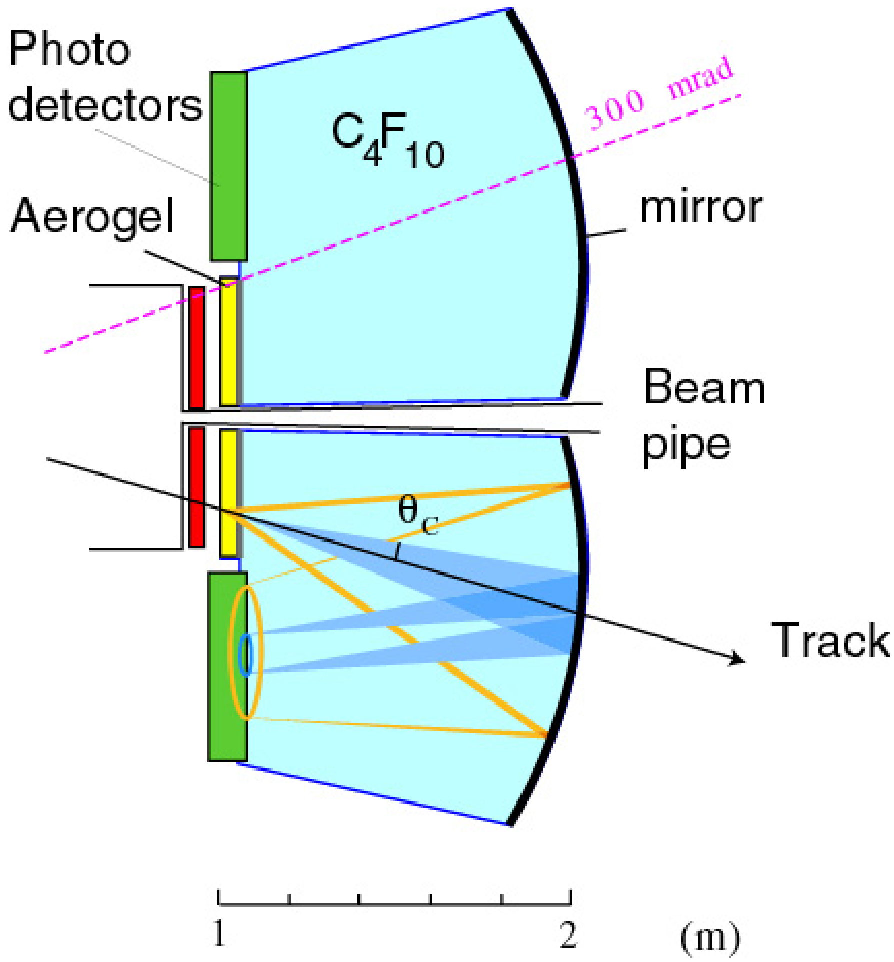


Still: it works very well!



Kaon efficiency and pion, proton fake probability

LHCb RICHes: similar geometry



RICH 1

Need:

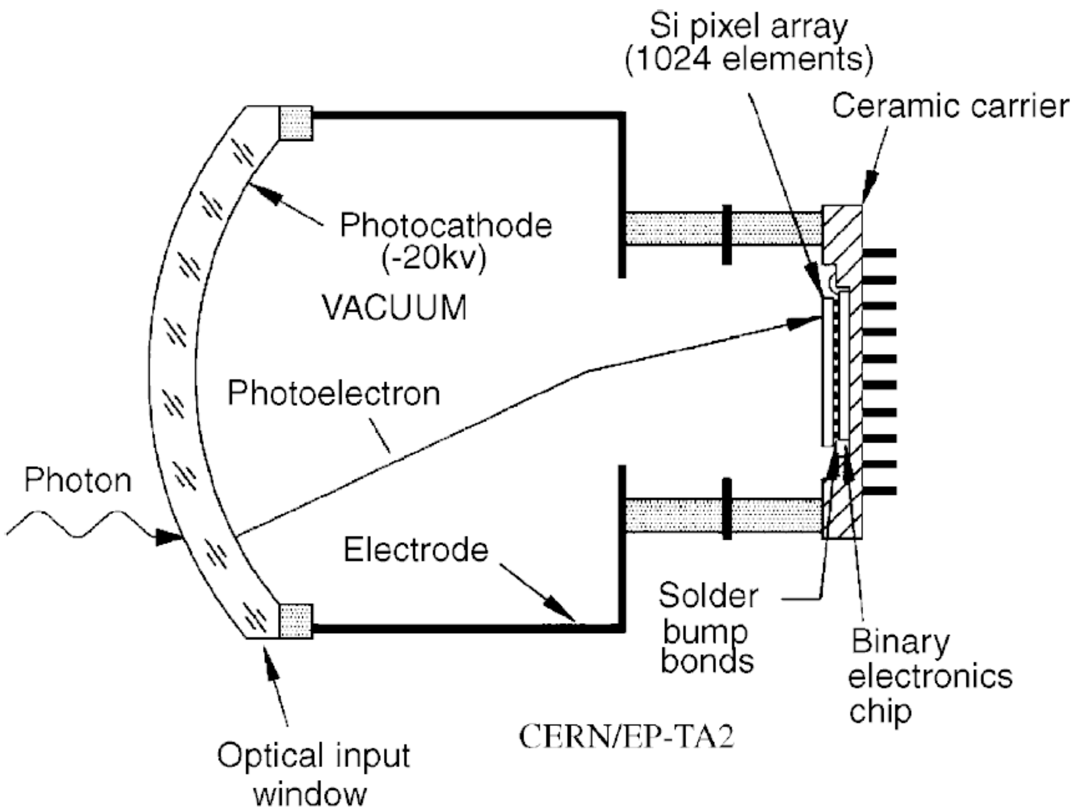
- Granularity 2.5x2.5mm^2
- Large area (2.8m^2) with high active area fraction
- Fast compared to the 25ns bunch crossing time
- Have to operate in a small magnetic field

R+D: two types of hybrid photon detectors, focusing type + 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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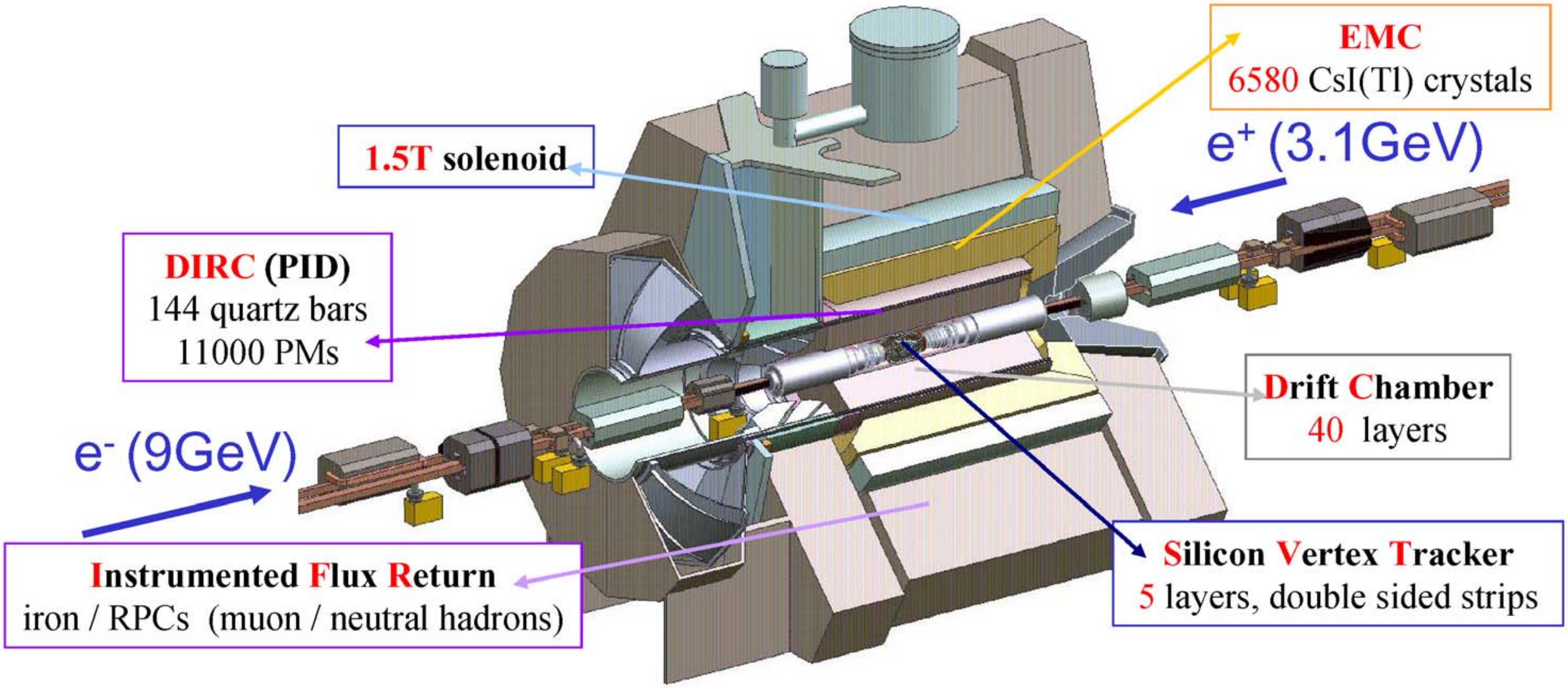
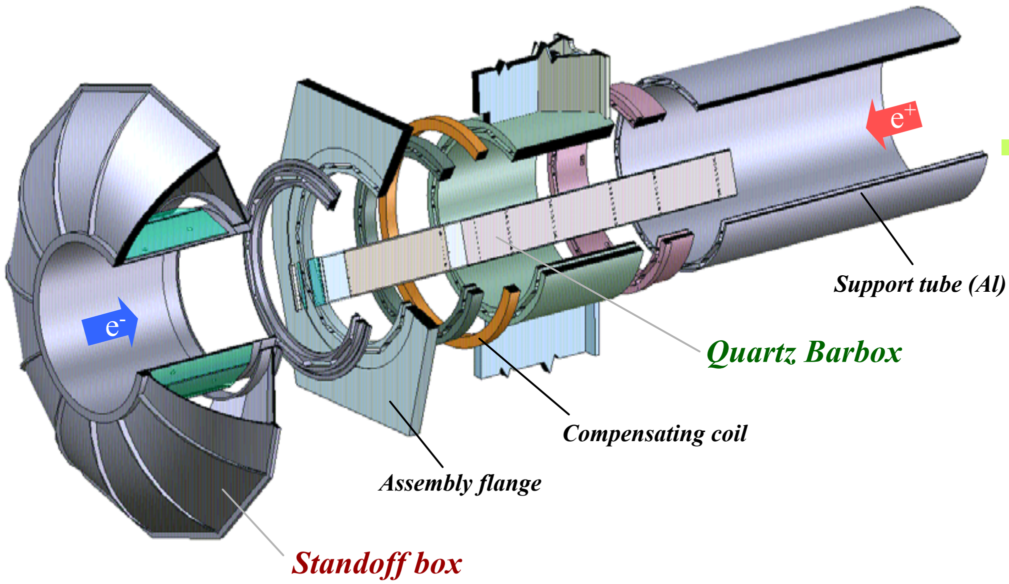
BaBar spectrometer at PEP-II

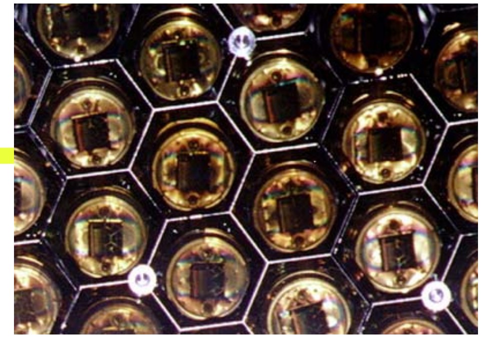


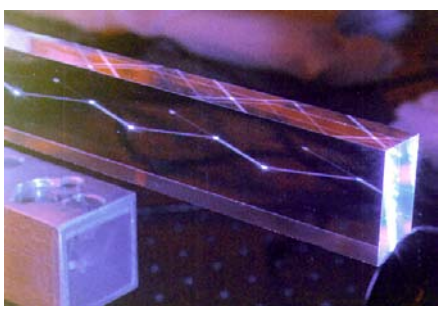
DIRC - detector of internally reflected Cherenkov light

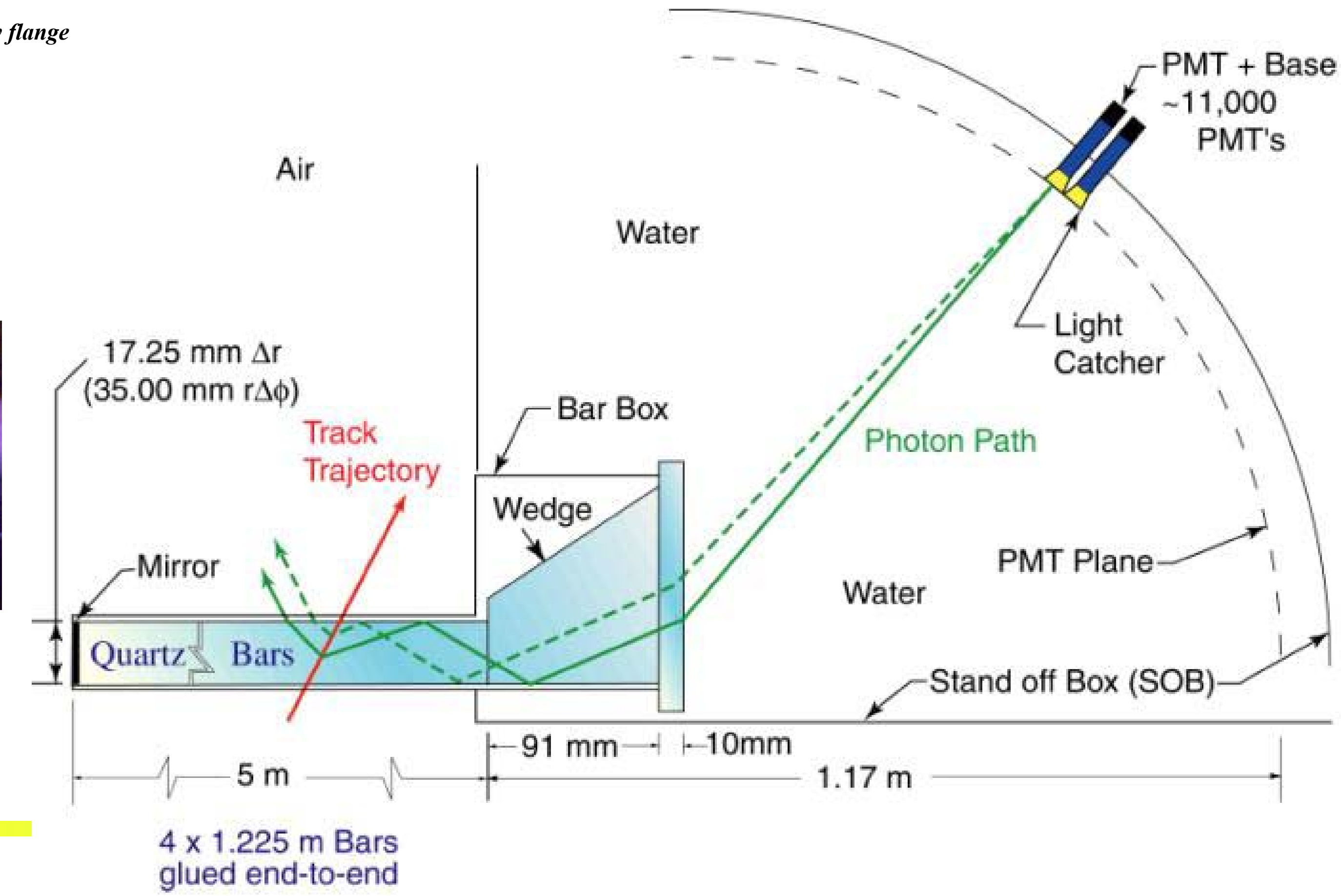
DIRC



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

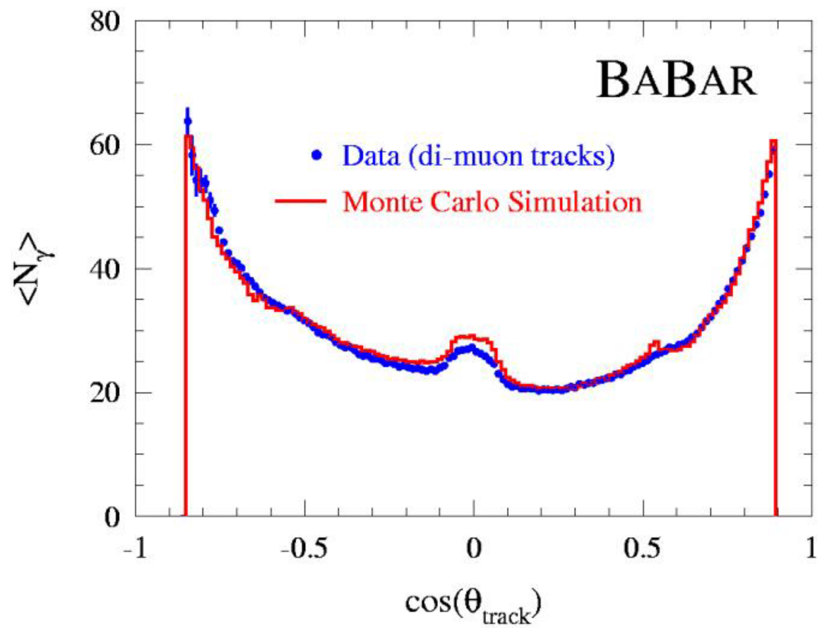






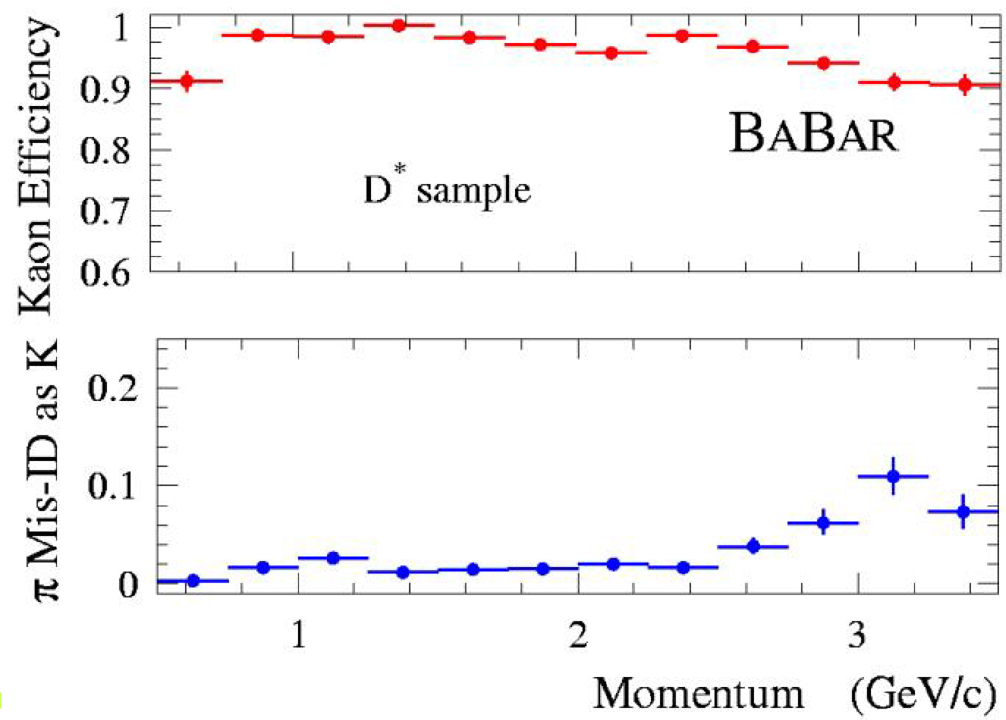
PMT + Base
~11,000
PMT's
Air
Water
Light
Catcher
17.25 mm Δr
(35.00 mm rΔϕ)
Track
Trajectory
Bar Box
Photon Path
Wedge
Mirror
PMT Plane
Water
Quartz
Bars
Stand off Box (SOB)
91 mm
10mm
5 m
1.17 m
4 x 1.225 m Bars
glued end-to-end

DIRC performance



← Lots of photons!

Excellent π/K separation



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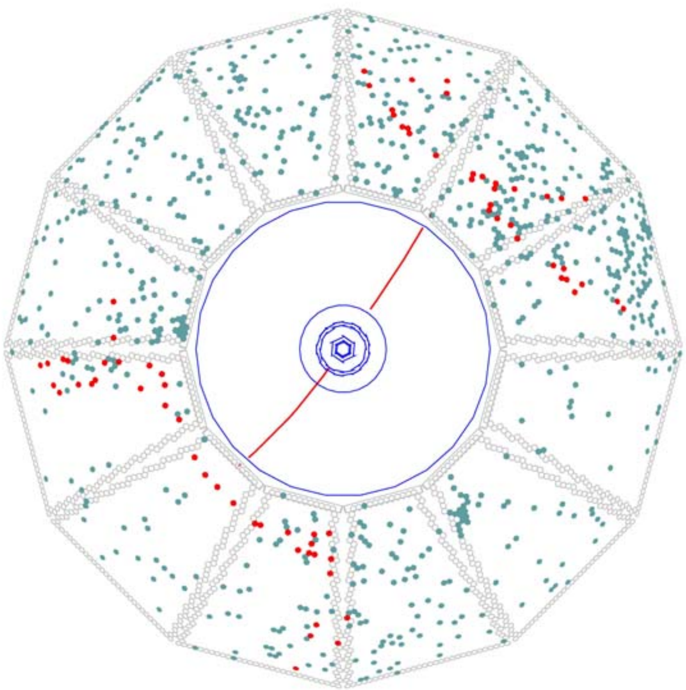
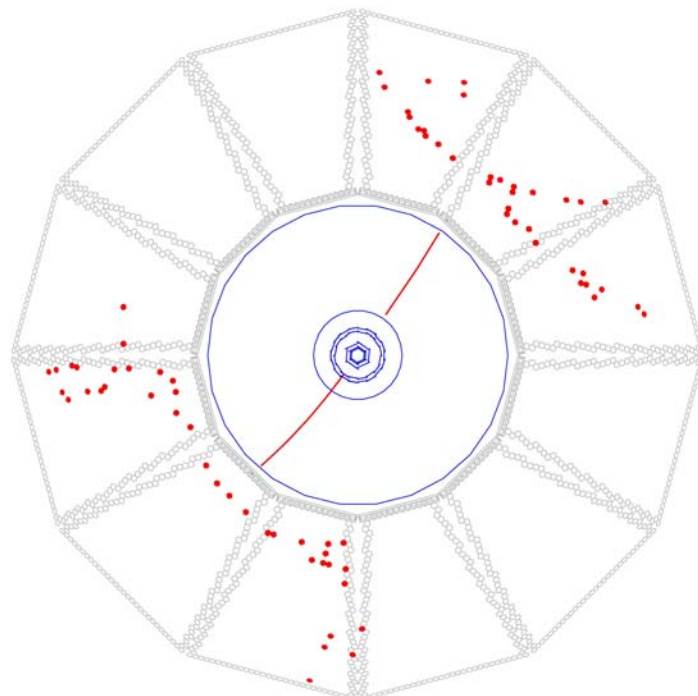
DIRC

Babar DIRC: a Bhabha event $e^+ e^- \rightarrow e^+ e^-$



No time cut on the hits

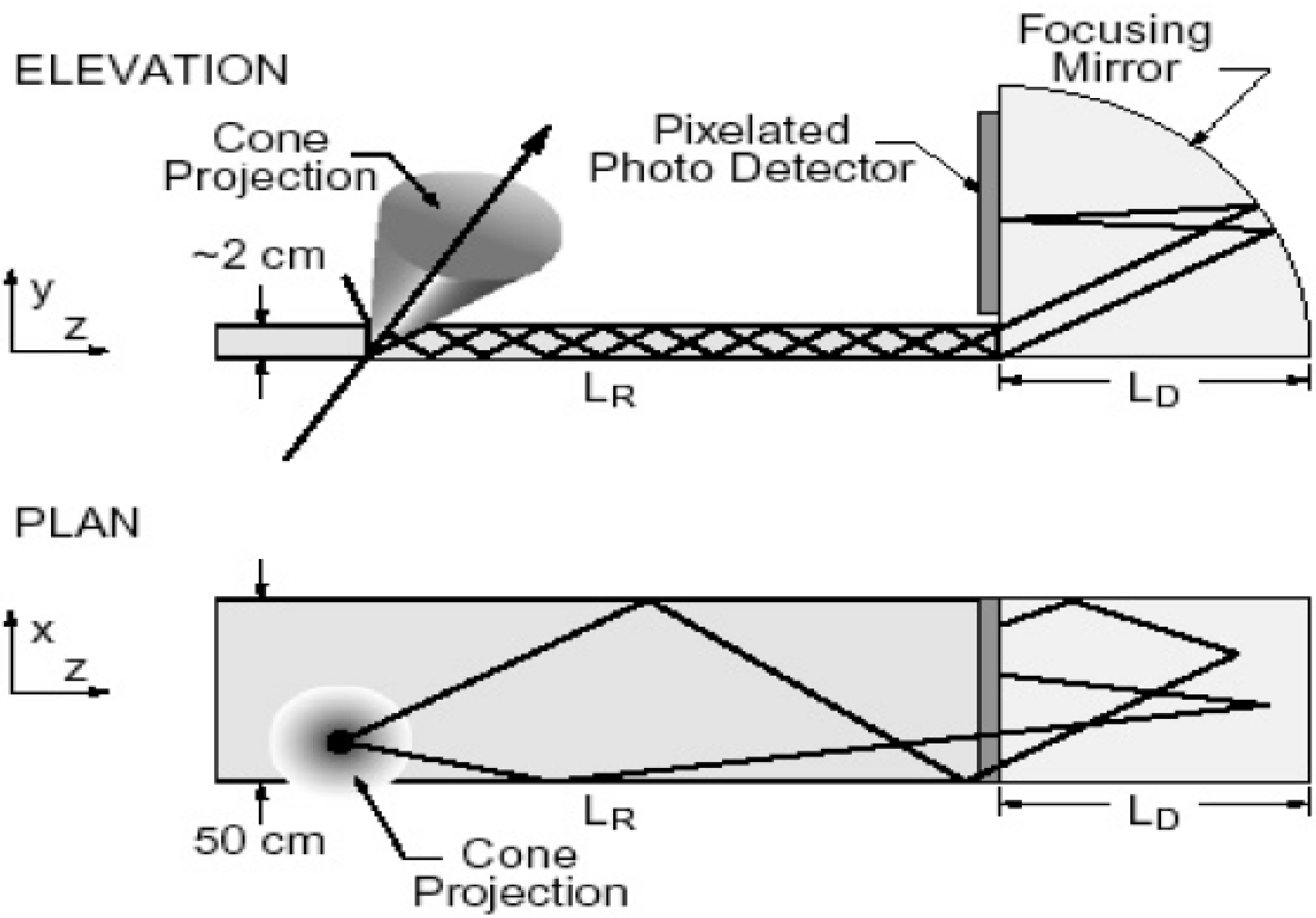


With a +-4ns time cut

Timing information is essential for background reduction

Focusing DIRC

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



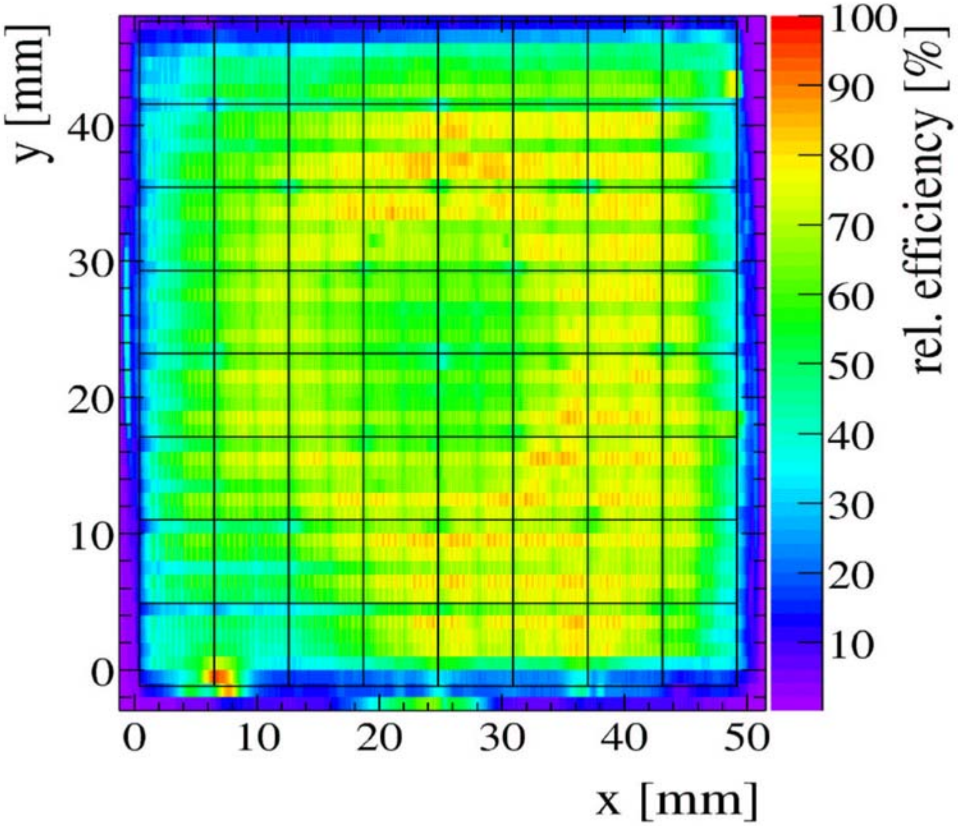
Focusing DIRC

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

Photon detector requirements:

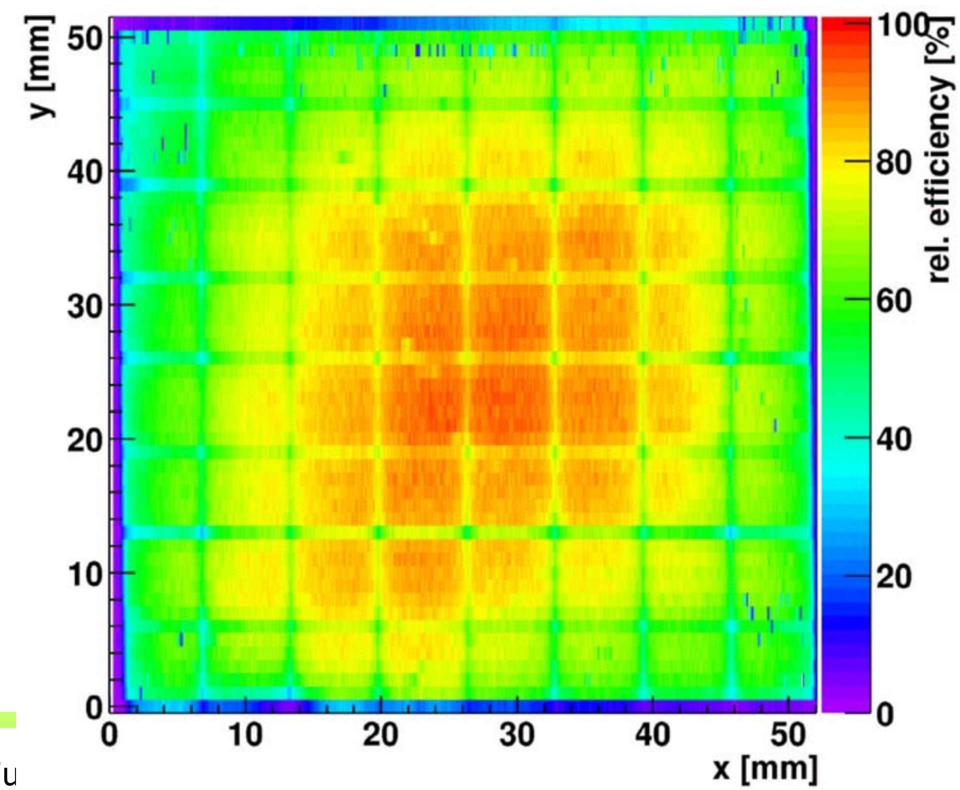
- Pad size ~5mm
- Time resolution ~50-100ps

Focusing DIRC photon detectors: relative efficiency

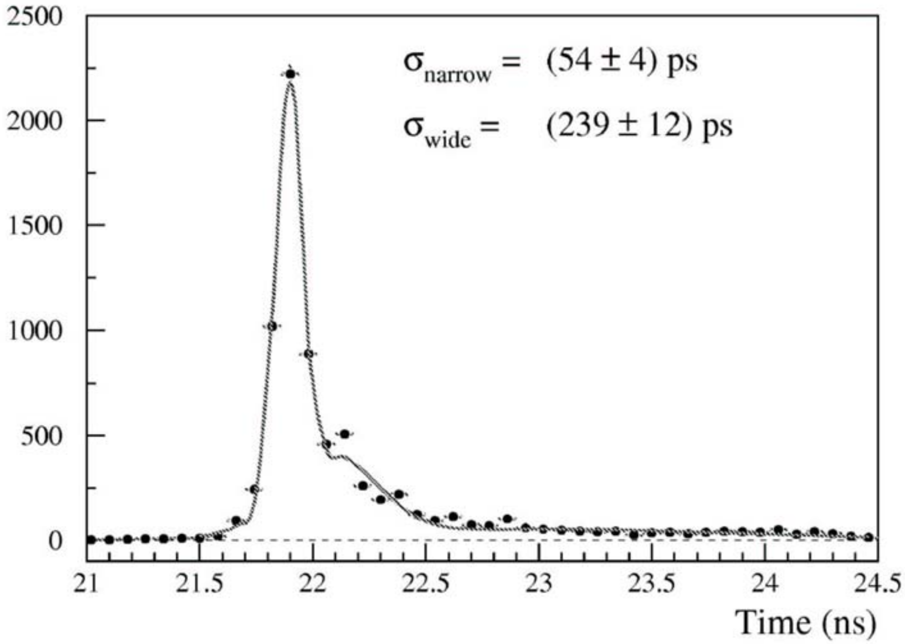


Burle 85011 MCP-PMT

Hamamatsu H8500 (flat pannel)

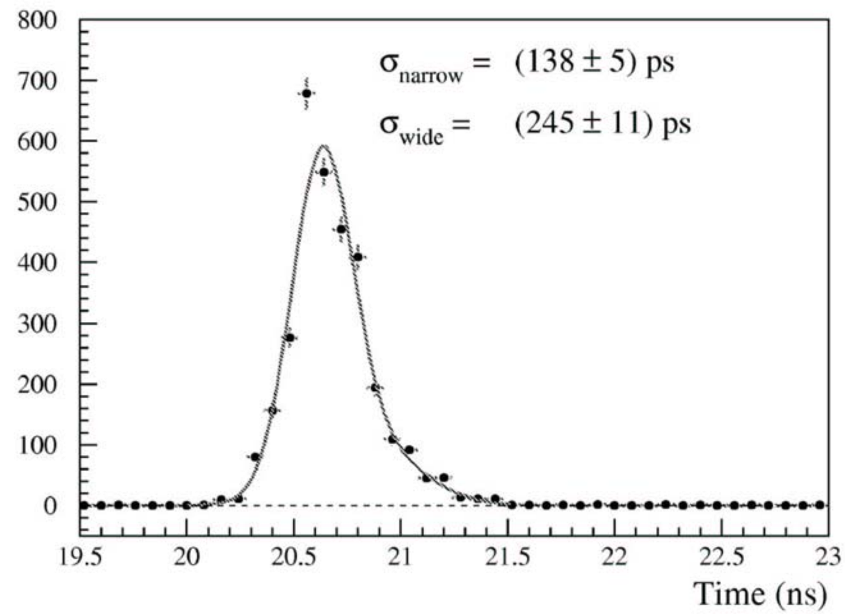


Focusing DIRC photon detectors: time resolution



Hamamatsu H8500 (flat pannel)

Burle 85011 MCP-PMT



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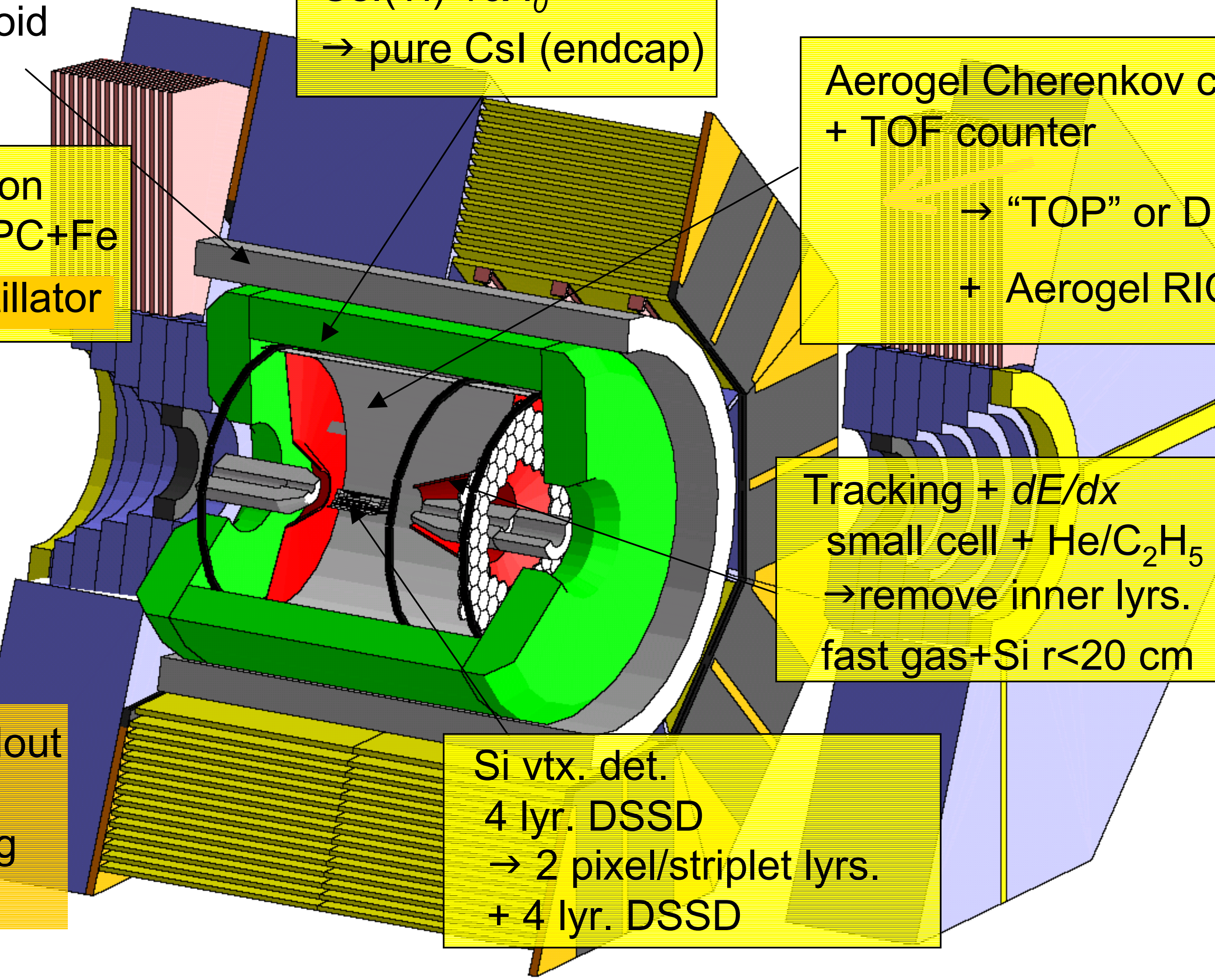
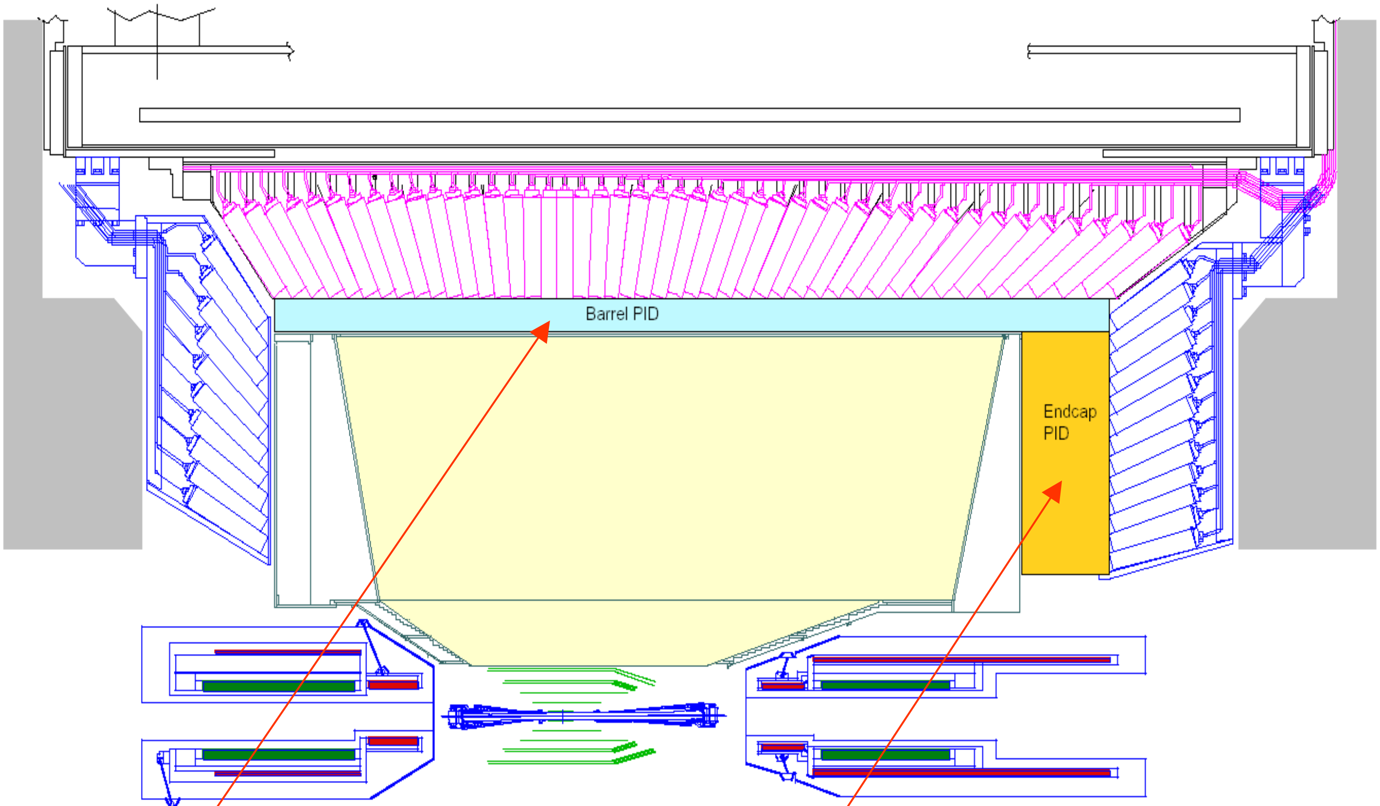
Belle Upgrade for Super-B



Belle upgrade – side view

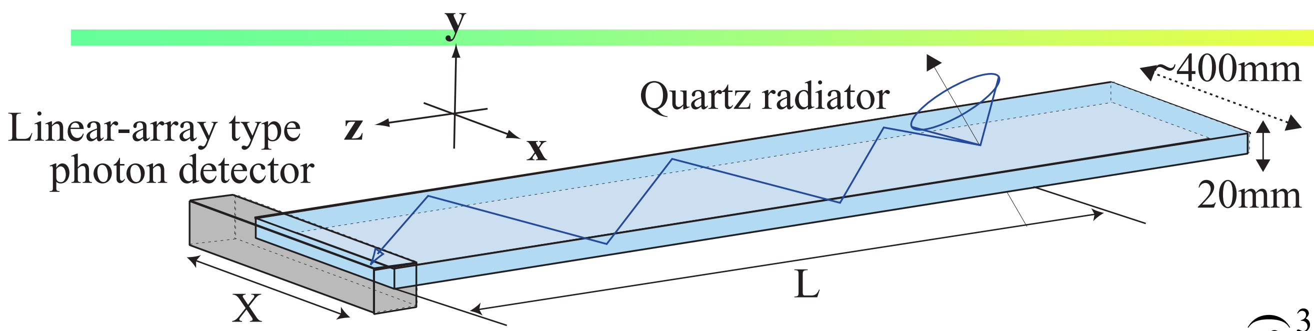


Two new particle ID devices, both RICHes:

Barrel: TOP or focusing DIRC

Endcap: proximity focusing RICH

Belle barrel upgrade: TOP counter

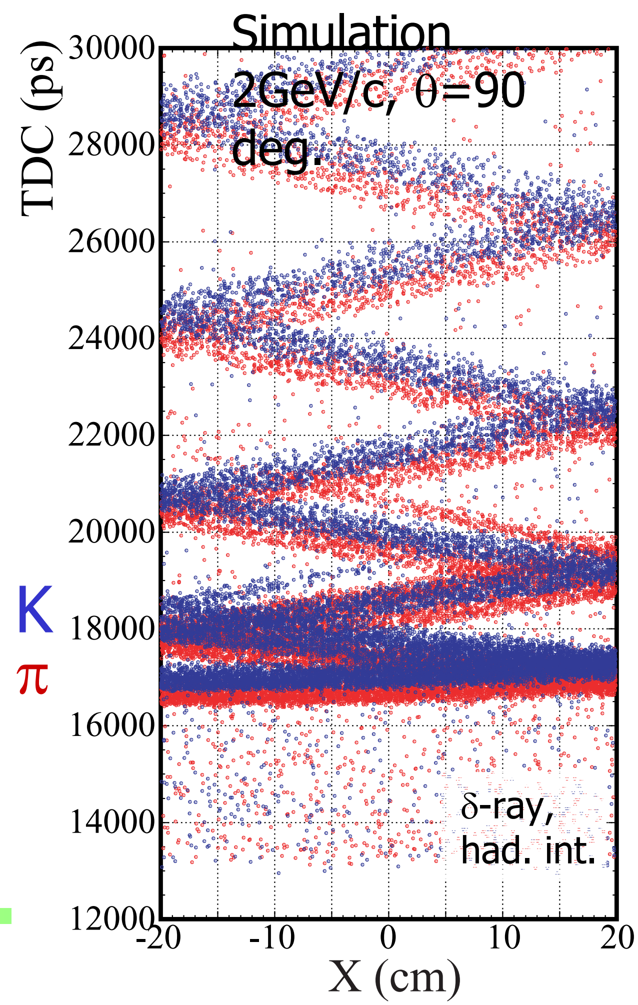


Time-of-Propagation counter:

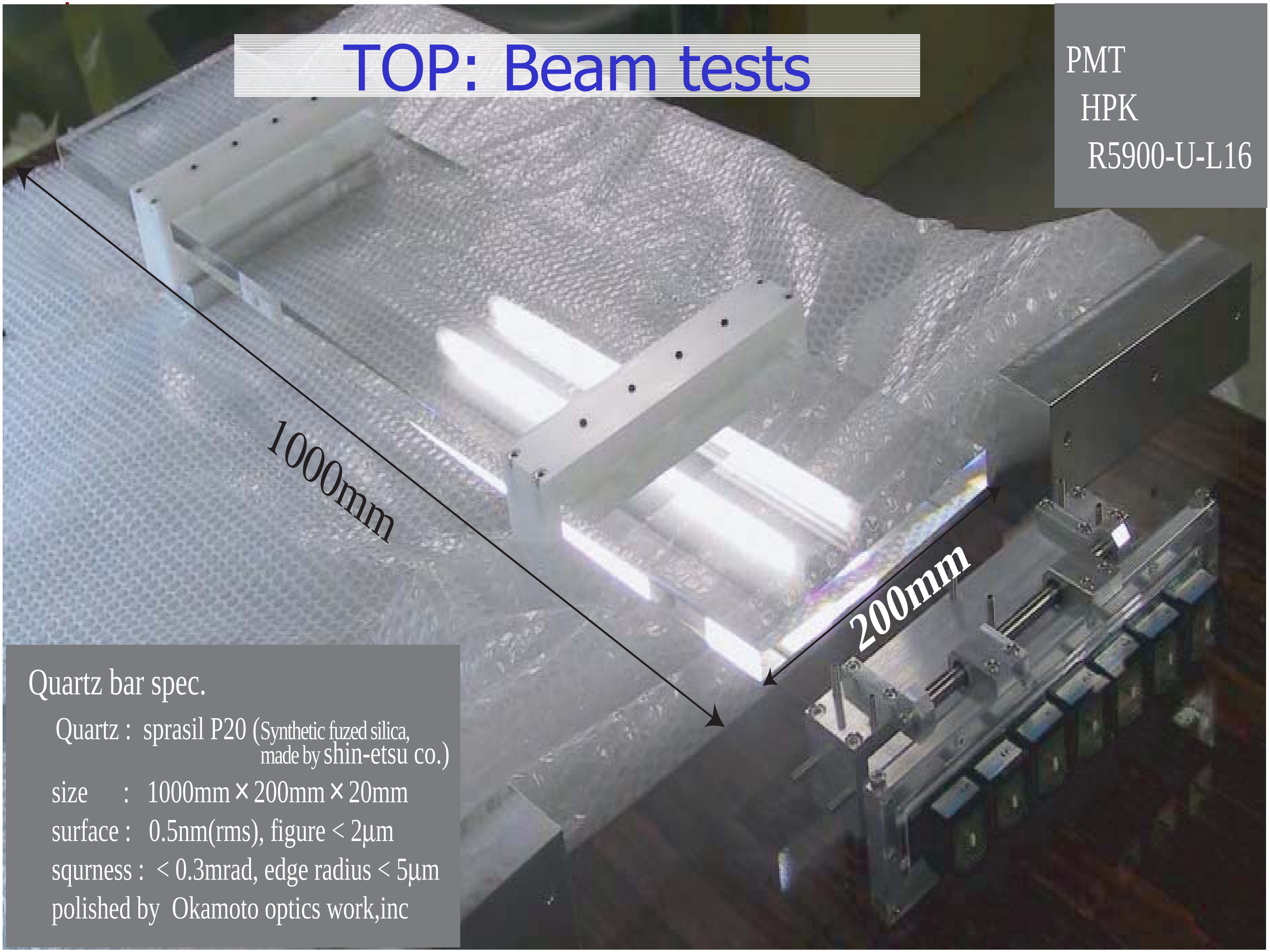
Measurement of

- 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.)

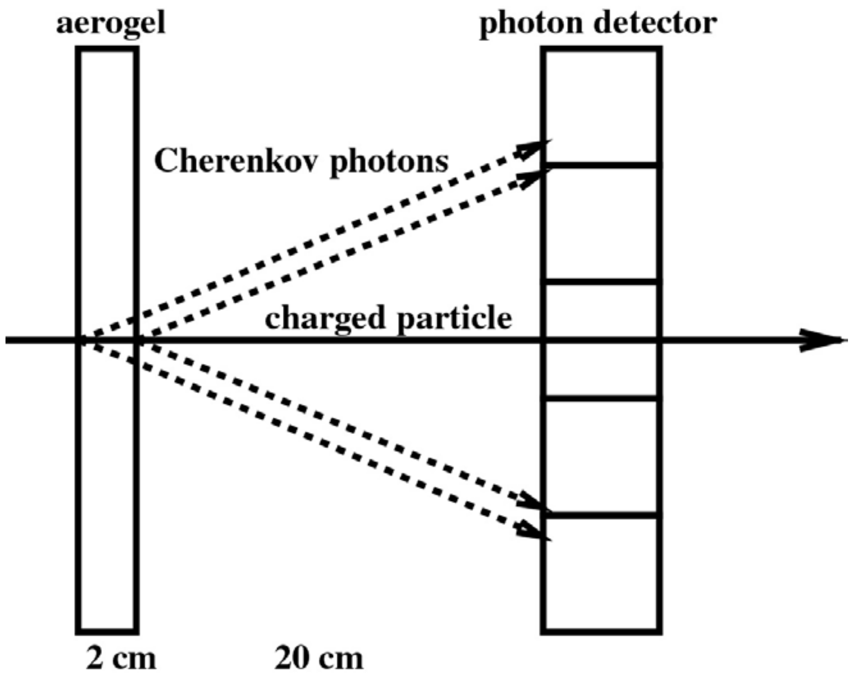
size : 1000mm × 200mm × 20mm

surface : 0.5nm(rms), figure < 2μm

squrness : < 0.3mrad, edge radius < 5μm

polished by Okamoto optics work,inc

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

$\delta\theta_c$(meas.) = $\sigma_0 \sim 14$ mrad,

typical value for a 20mm thick radiator and 6mm PMT pad size

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

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

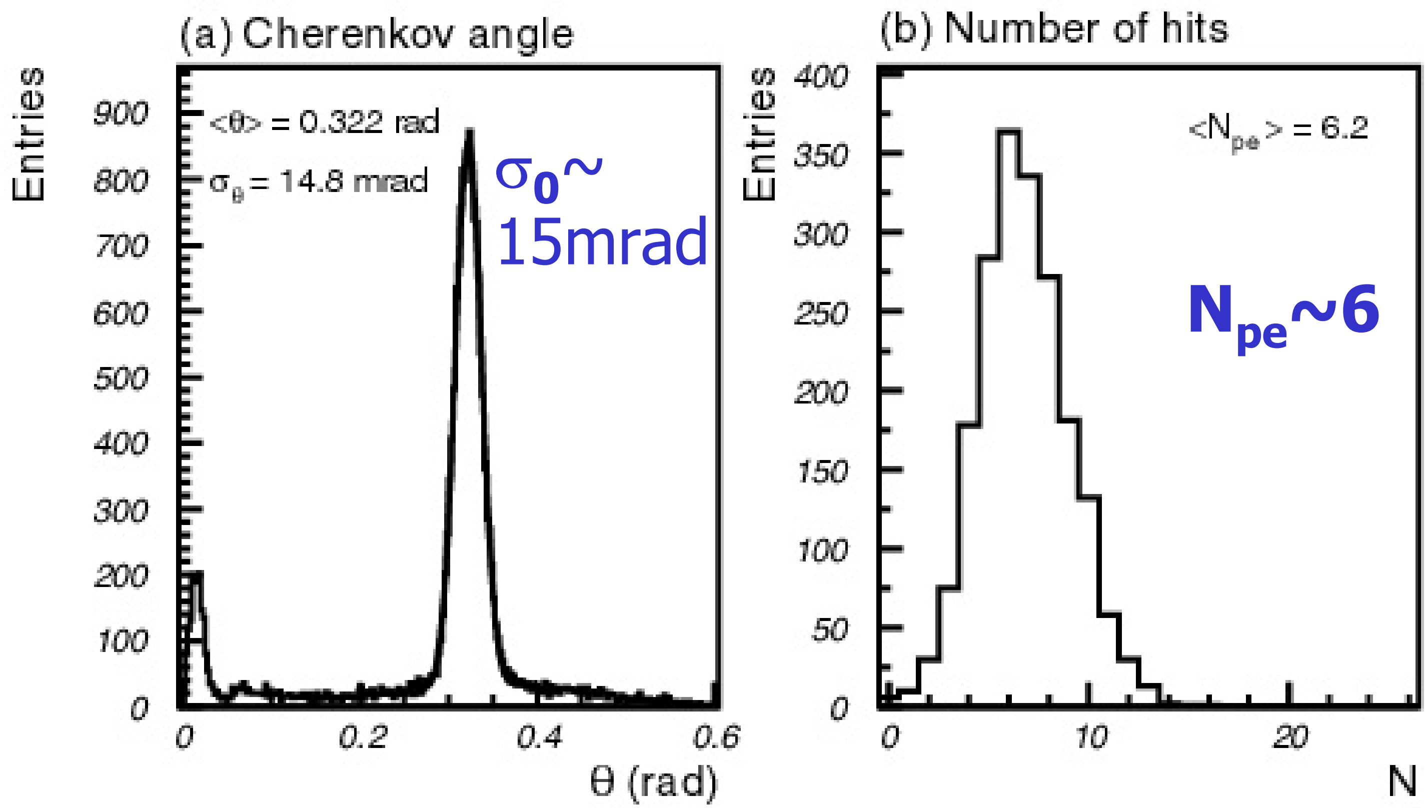
→ 5σ separation with $N_{pe} \sim 10$

Beam test: Cherenkov angle resolution and number of photons

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

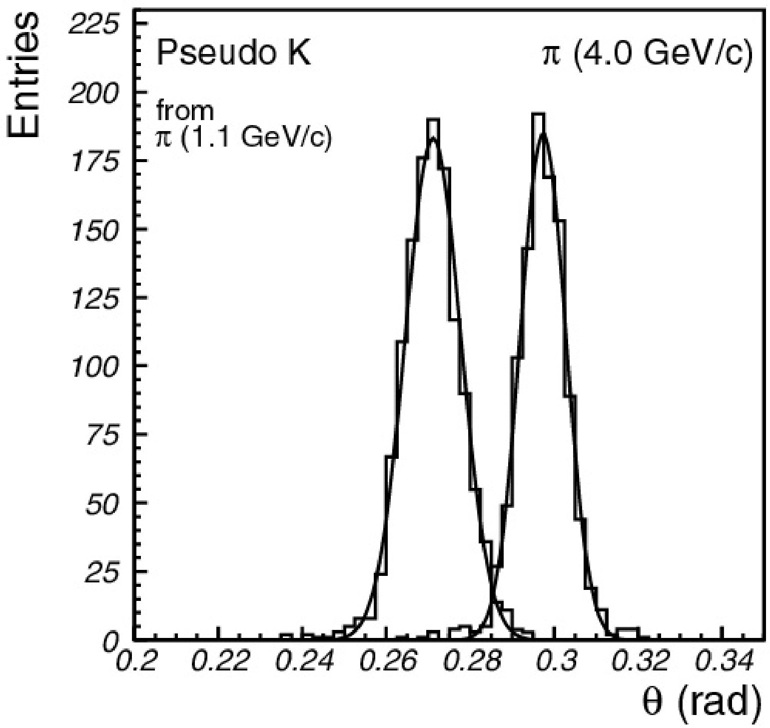
Beam test results with 2cm thick aerogel tiles:

>4σ K/π separation



→ Number of photons has to be increased.

PID capability on test beam data

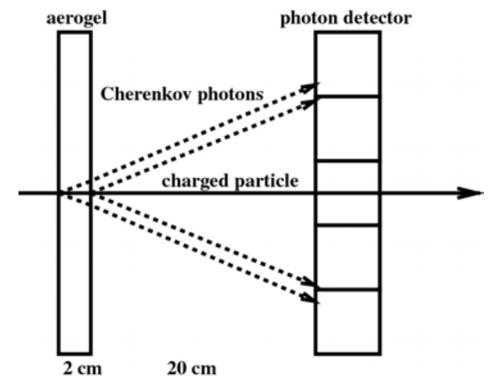


From typical values (single photon resolution 15mrad and 6 detected photons) we can estimate the Cherenkov resolution per track: 5.3mrad;

→ ~4σ π/K separation at 4GeV/c.

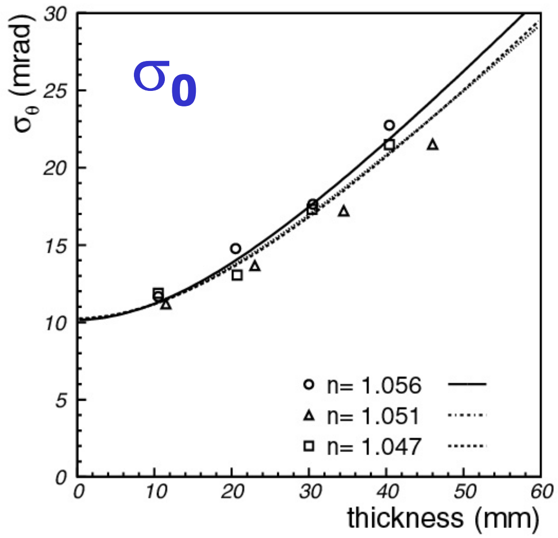
Illustration of PID performance: Cherenkov angle distribution for pions at 4GeV/c and 'kaons' (pions at 1.1GeV/c with the same Cherenkov angle as kaons at 4GeV/c).

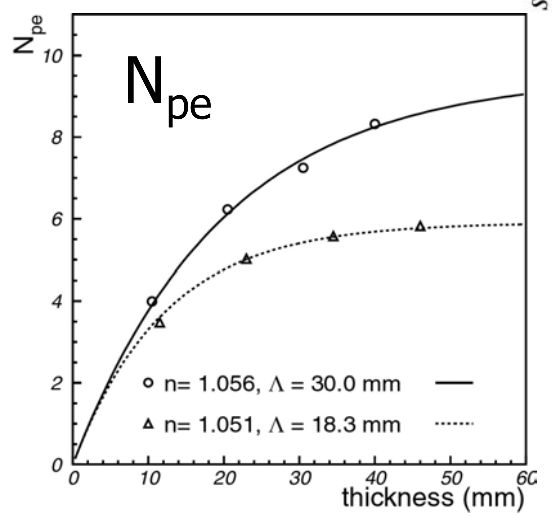
How to increase the number of photons?

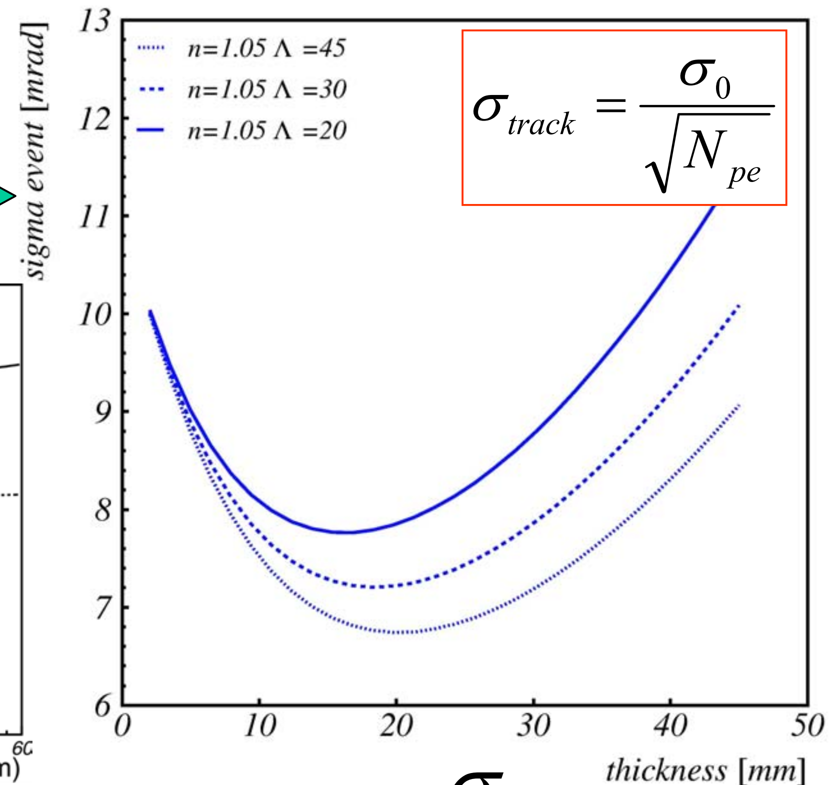


What is the optimal radiator thickness?

Use beam test data on σ_0 and N_{pe}







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

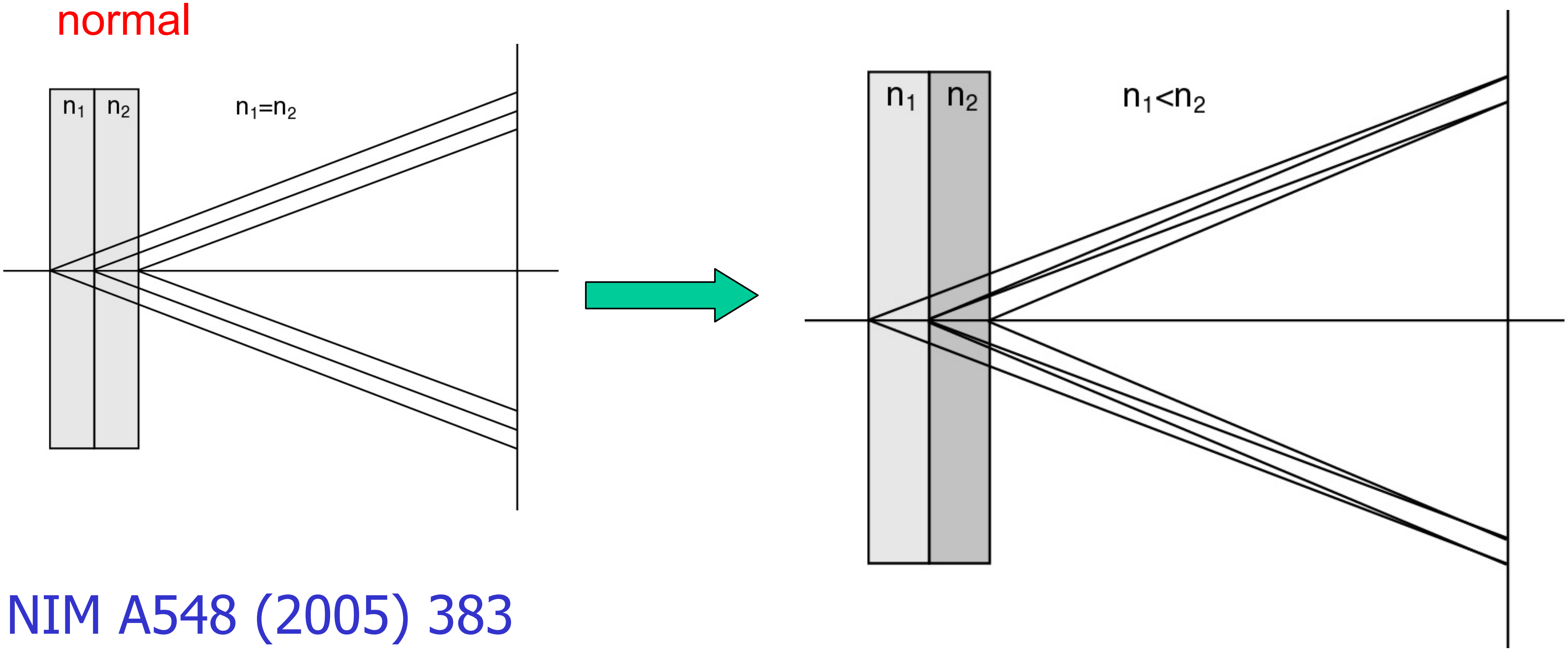
Optimum is close to 2 cm

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



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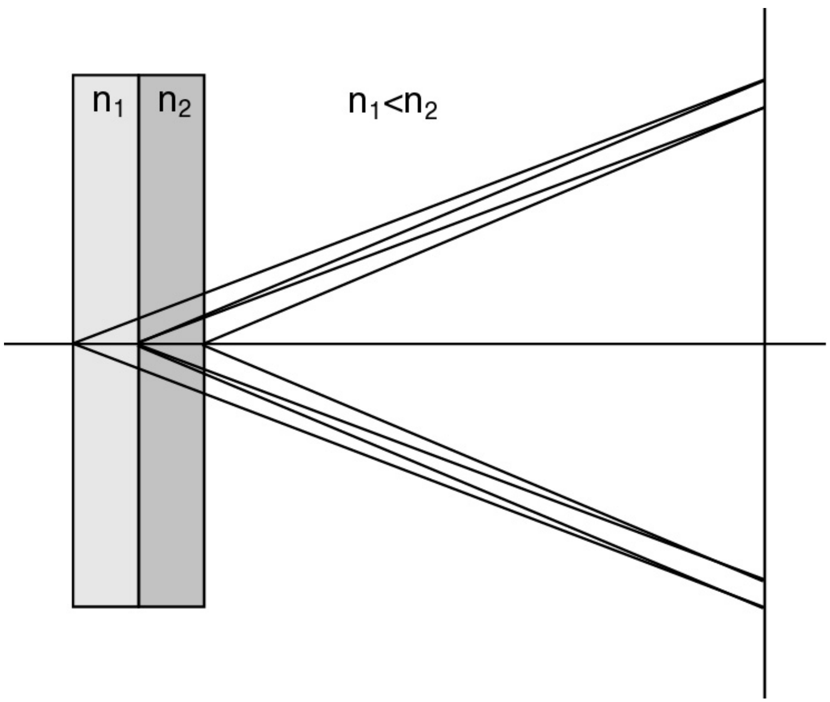
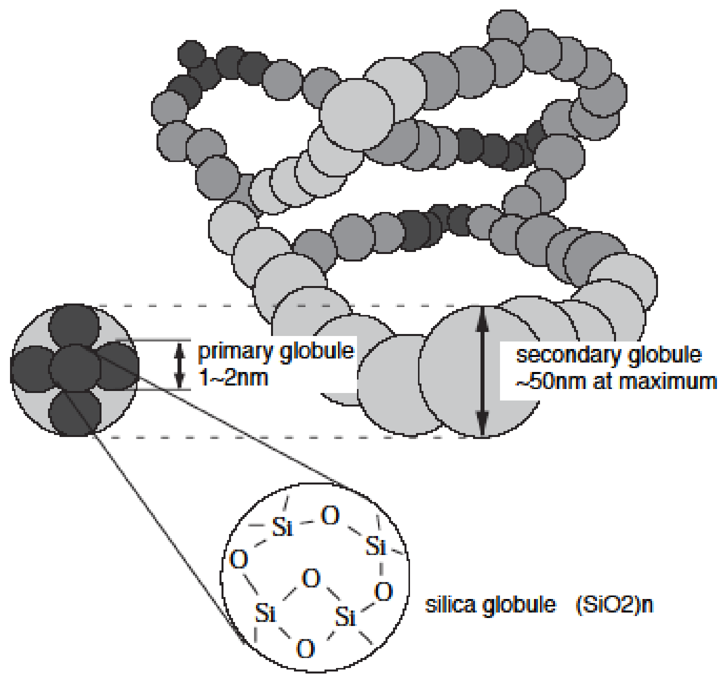
Radiator with multiple refractive indices 2

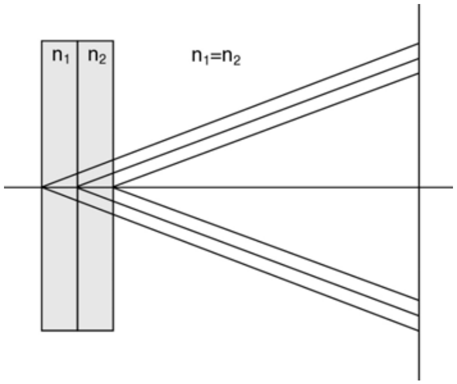
Such a configuration is only possible with aerogel (a form of Si_xO_y) – material with a tunable refractive index between 1.01 and 1.07.

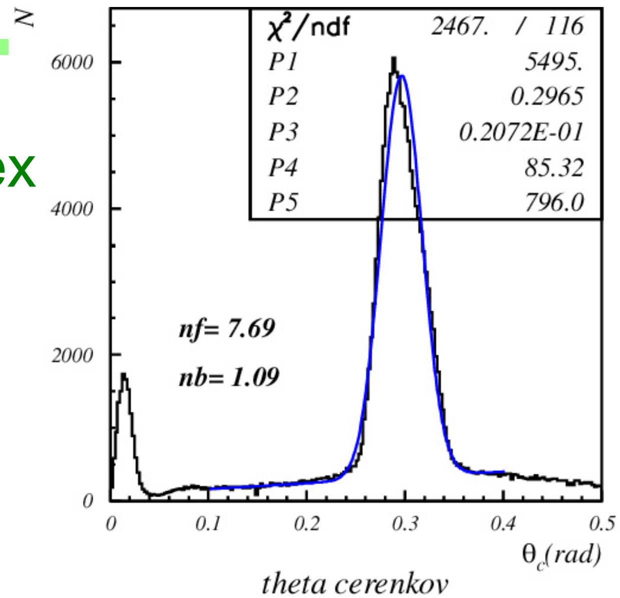


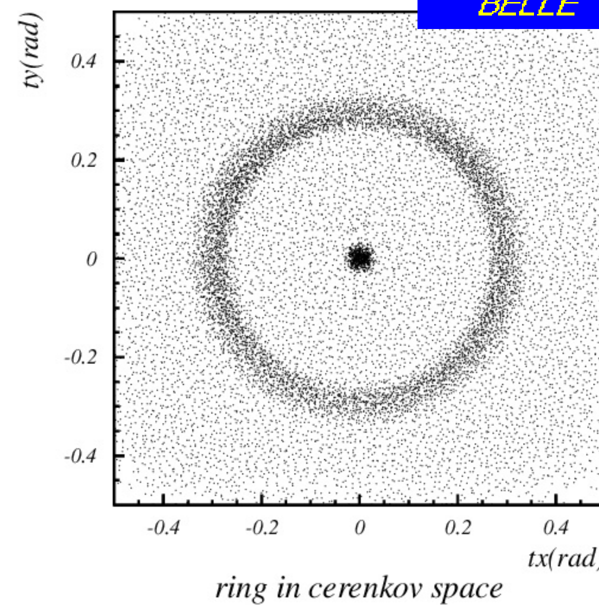


Focusing configuration – data

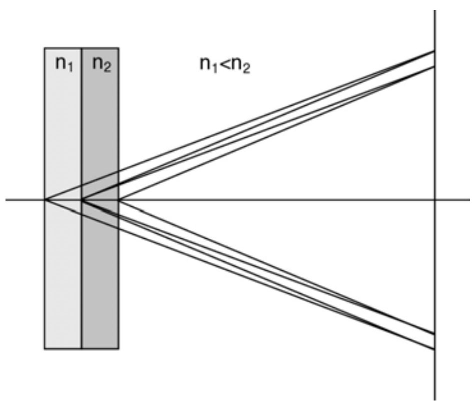
4cm aerogel single index

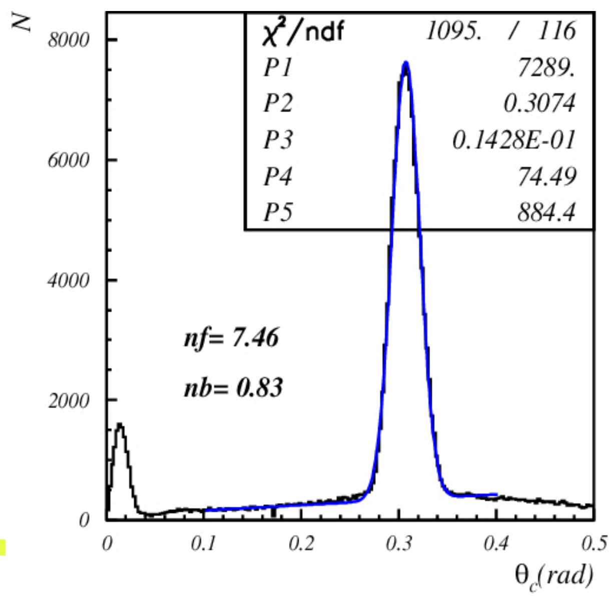


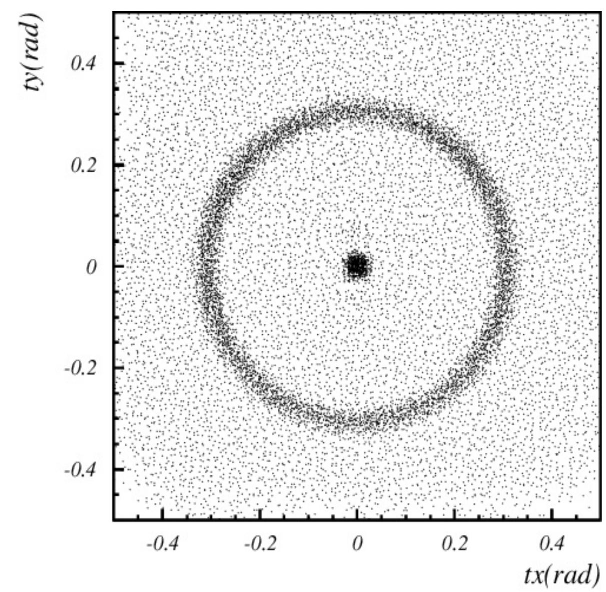




2+2cm aerogel







Focusing configuration – n_2-n_1 variation

- upstream aerogel: d=11mm, n=1.045
- downstream aerogel layer: vary refractive index
- measured resolution in good agreement with prediction
- a wide minimum allows for some tolerance in aerogel production

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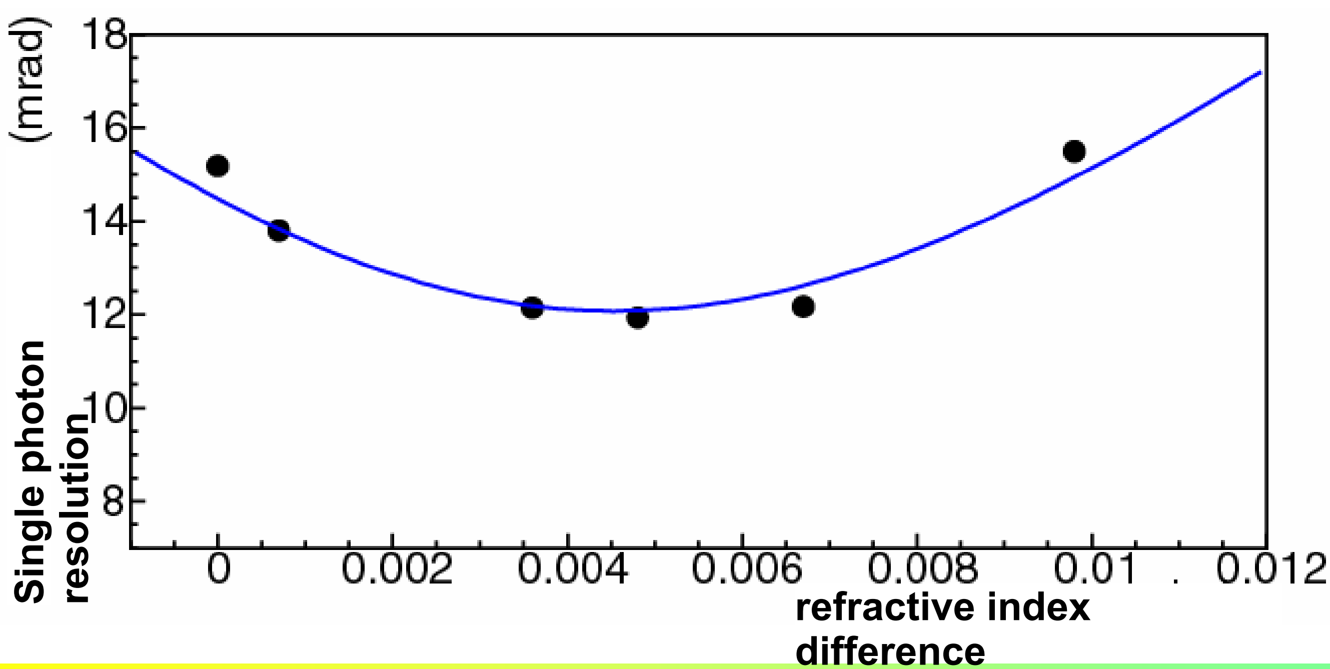
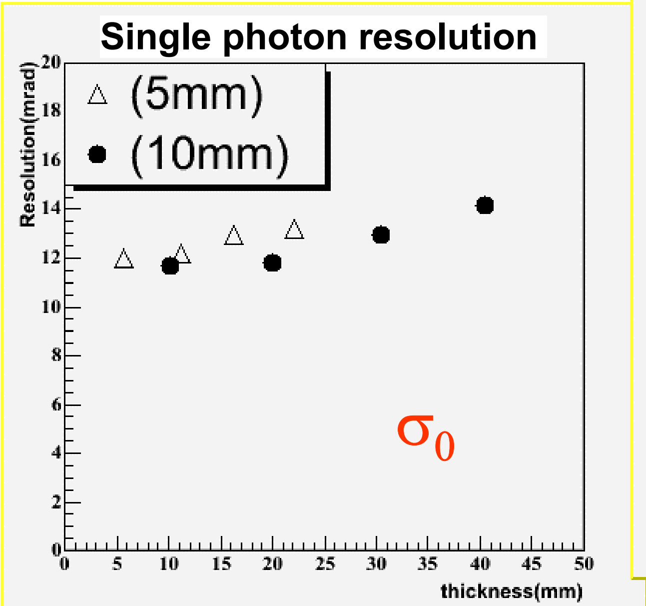
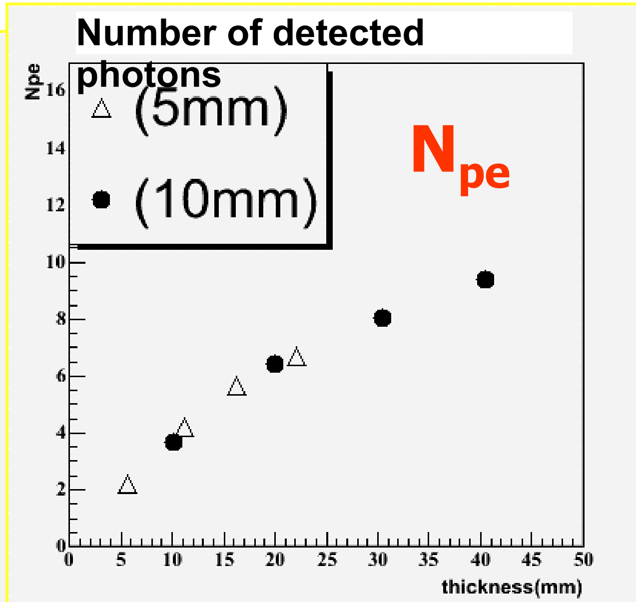
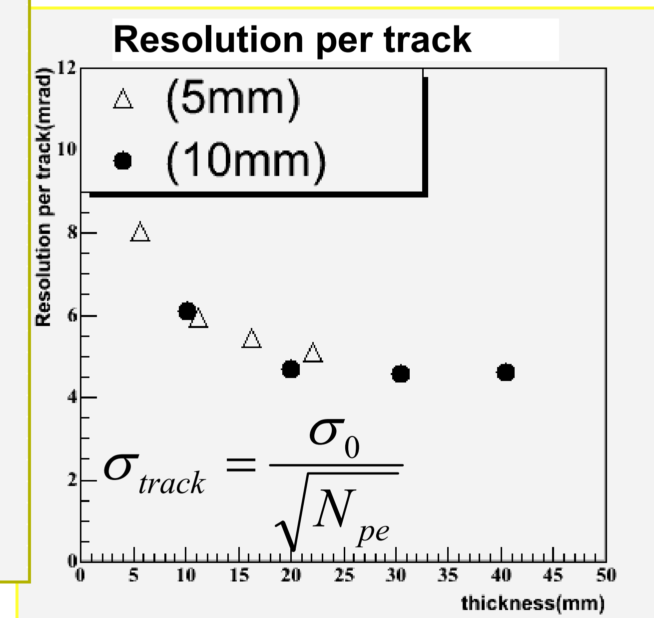
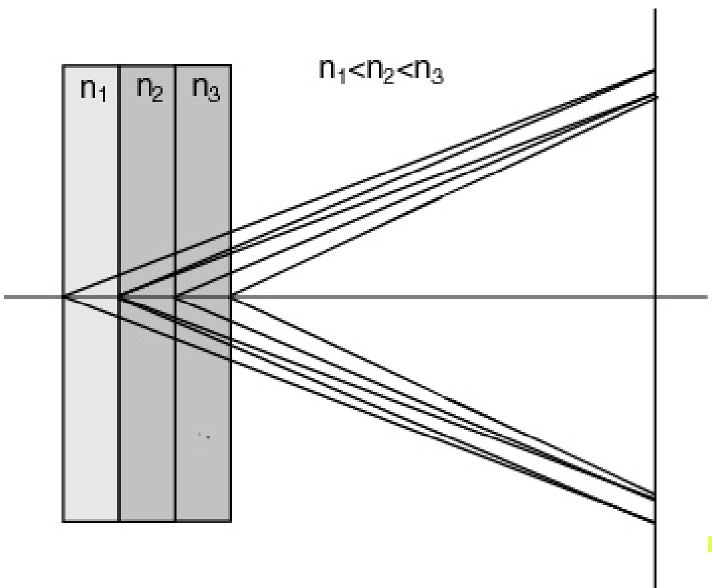


Multilayer extensions









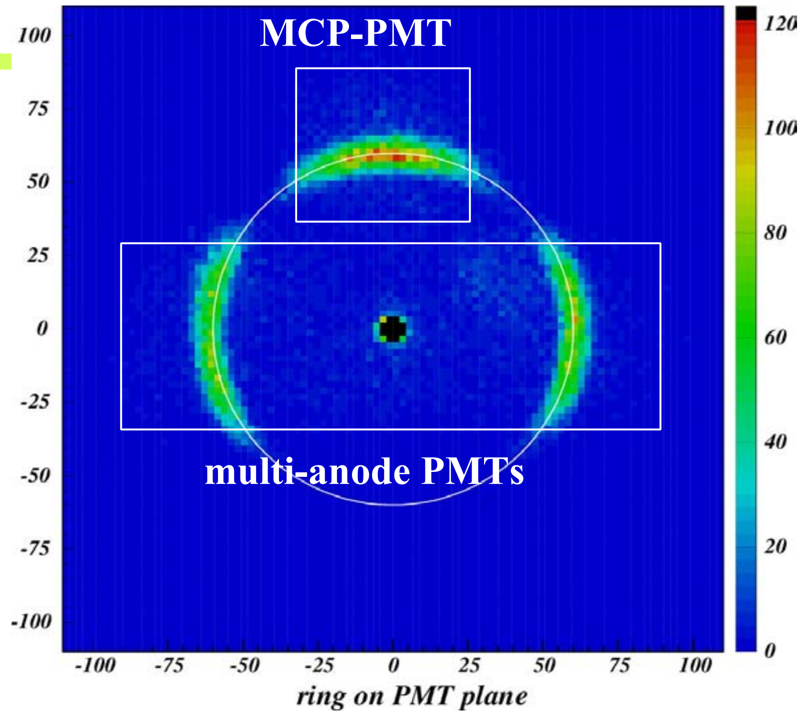
Multiple layer radiators combined from 5mm and 10mm tiles

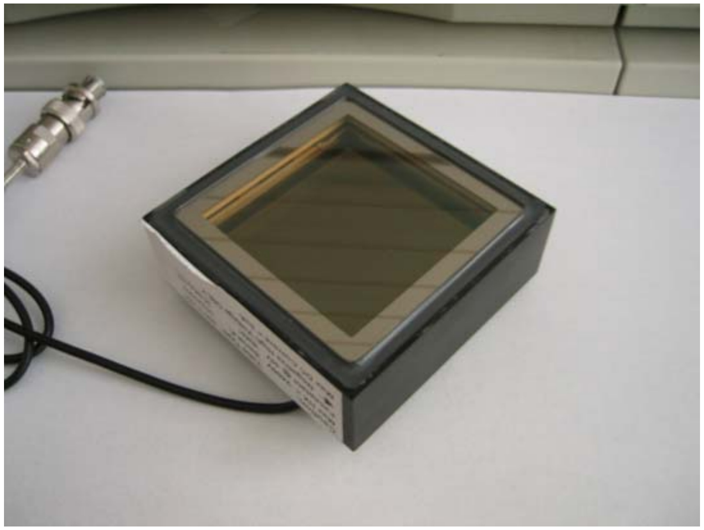
Cherenkov angle resolution per track: around 4.3 mrad

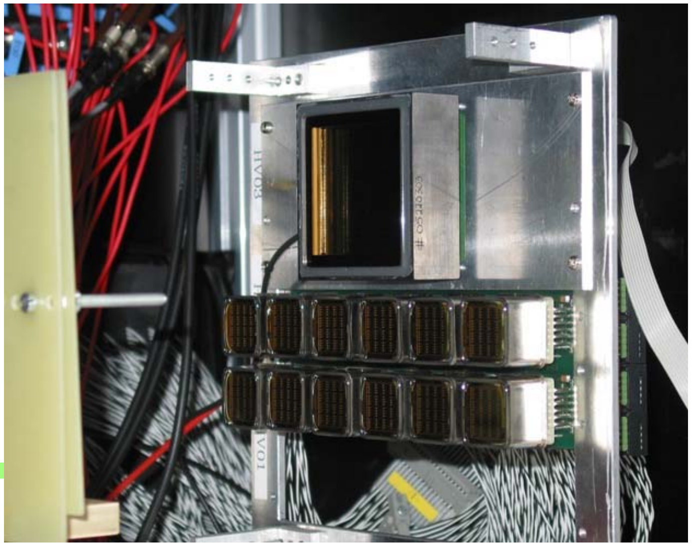
→ π/K separation at 4 GeV: >5σ

Photon detector candidate: MCP-PMT

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



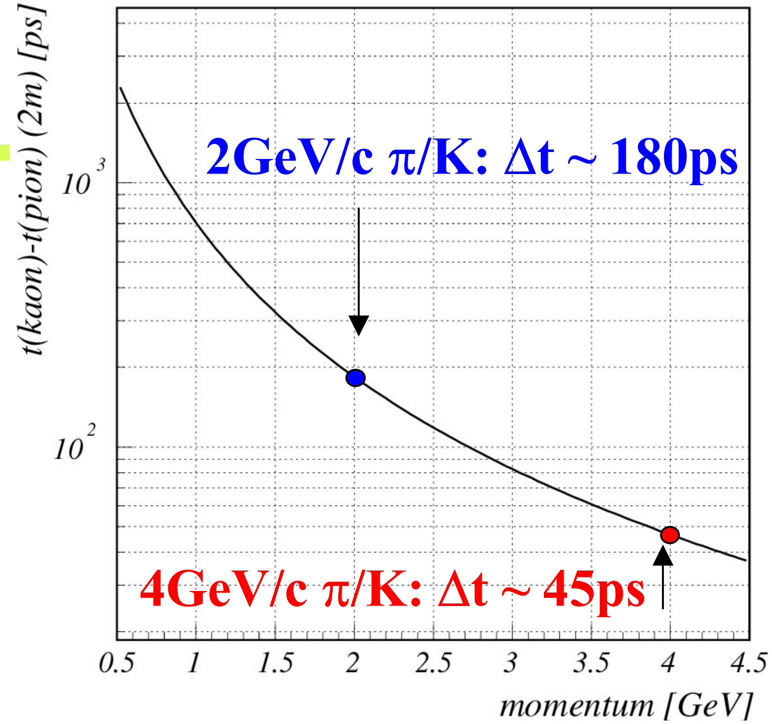


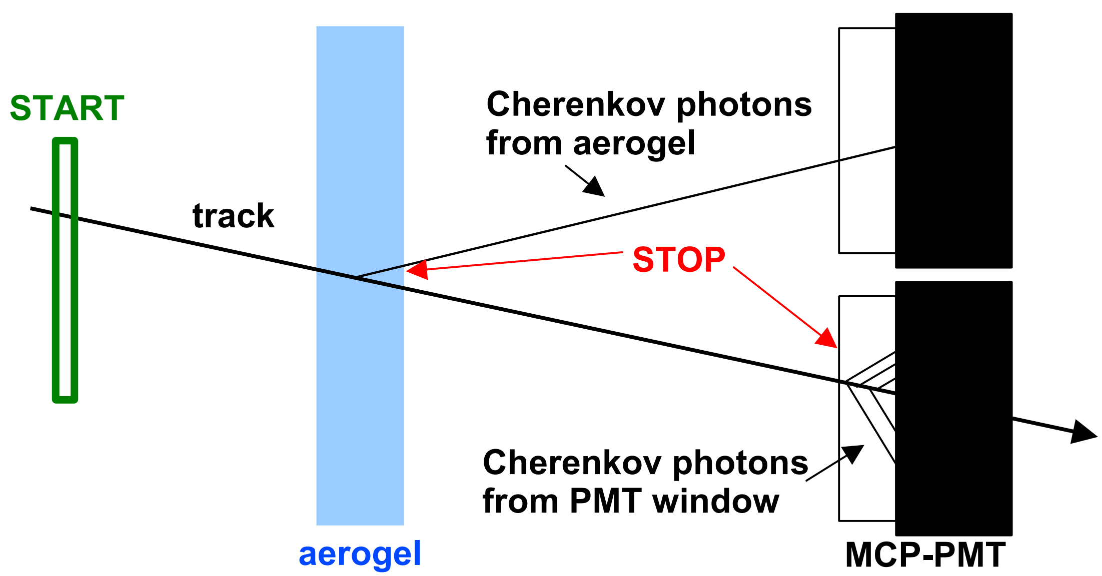


TOF capability

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:

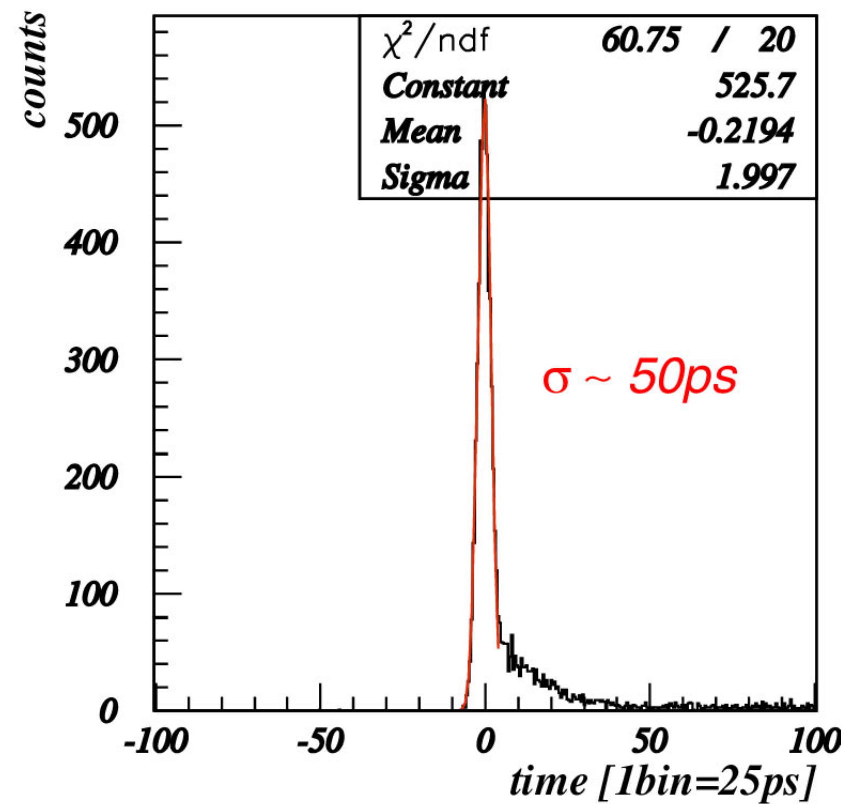
- photons emitted in the aerogel radiator
- photons emitted in the PMT window

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

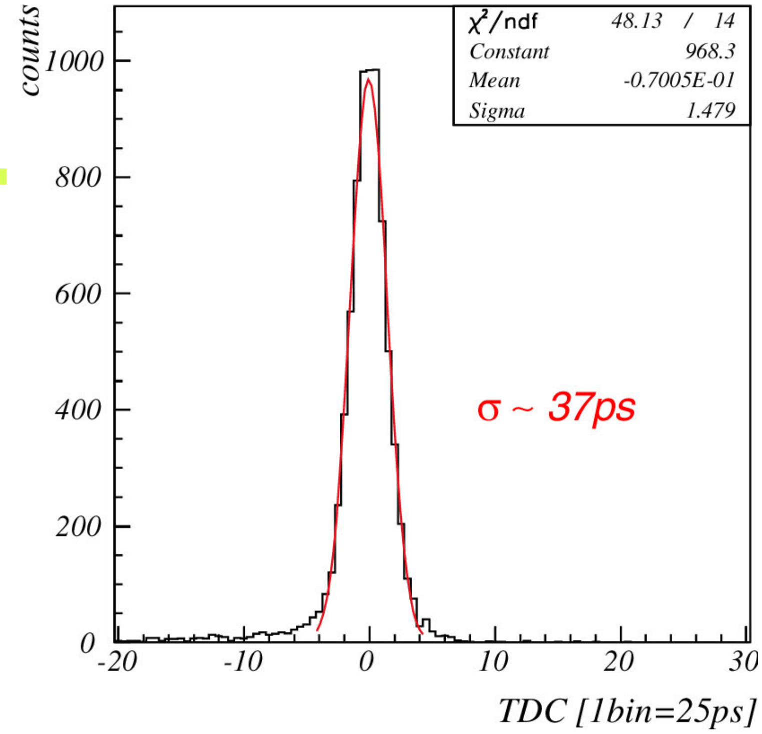
Resolution for full ring (~10 photons) would be around 20ps

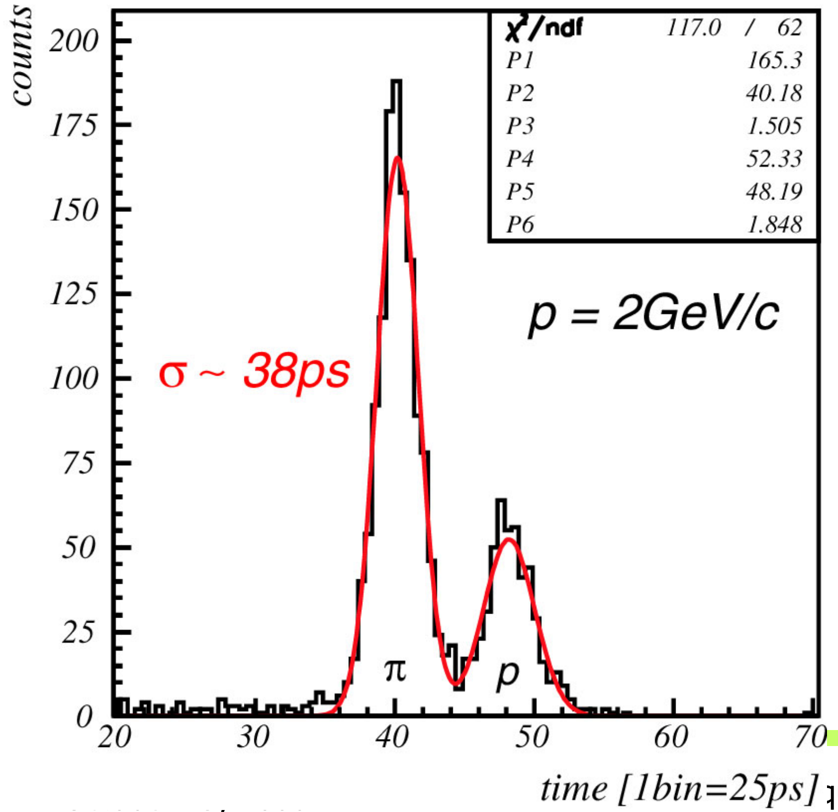


TOF capability: window photons

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

Expected resolution ~35 ps →





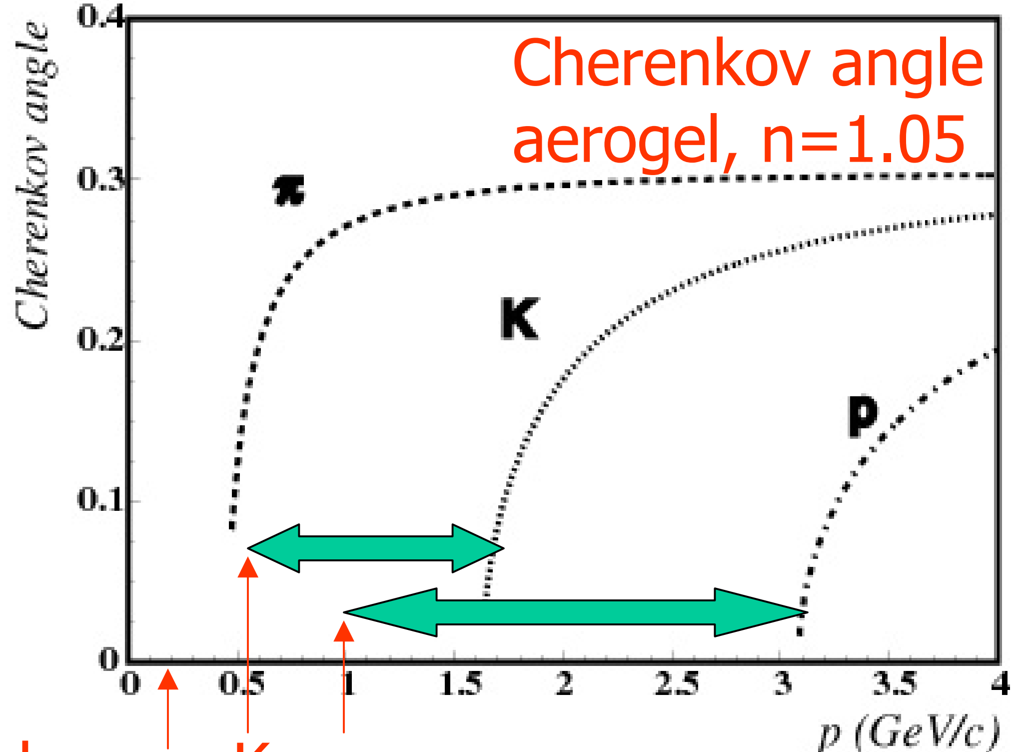
TOF test with pions and protons at 2 GeV/c.

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.

Summary

RICH counters have evolved from the problem childs ("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 SuperB factories.

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

Working with them is real fun...