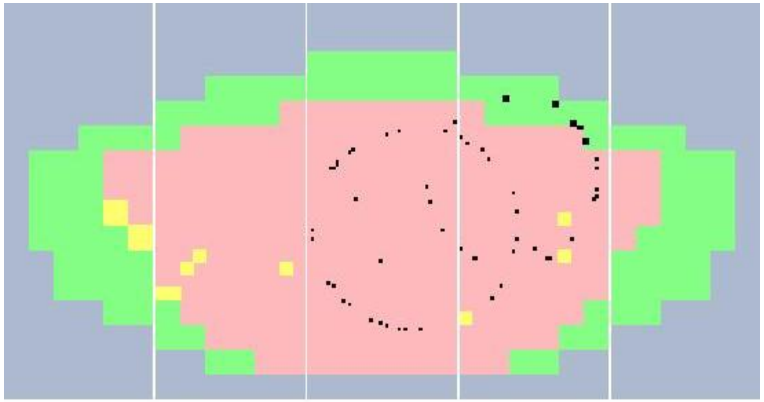
TRDs for the third Millennium

14-16 September 2011, Bari



Overview of particle identification techniques

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“Jožef Stefan” Institute

Contents

Why particle identification?

Ring Imaging CHerenkov counters

- New concepts, photon detectors, radiators

Time-of-flight measurement

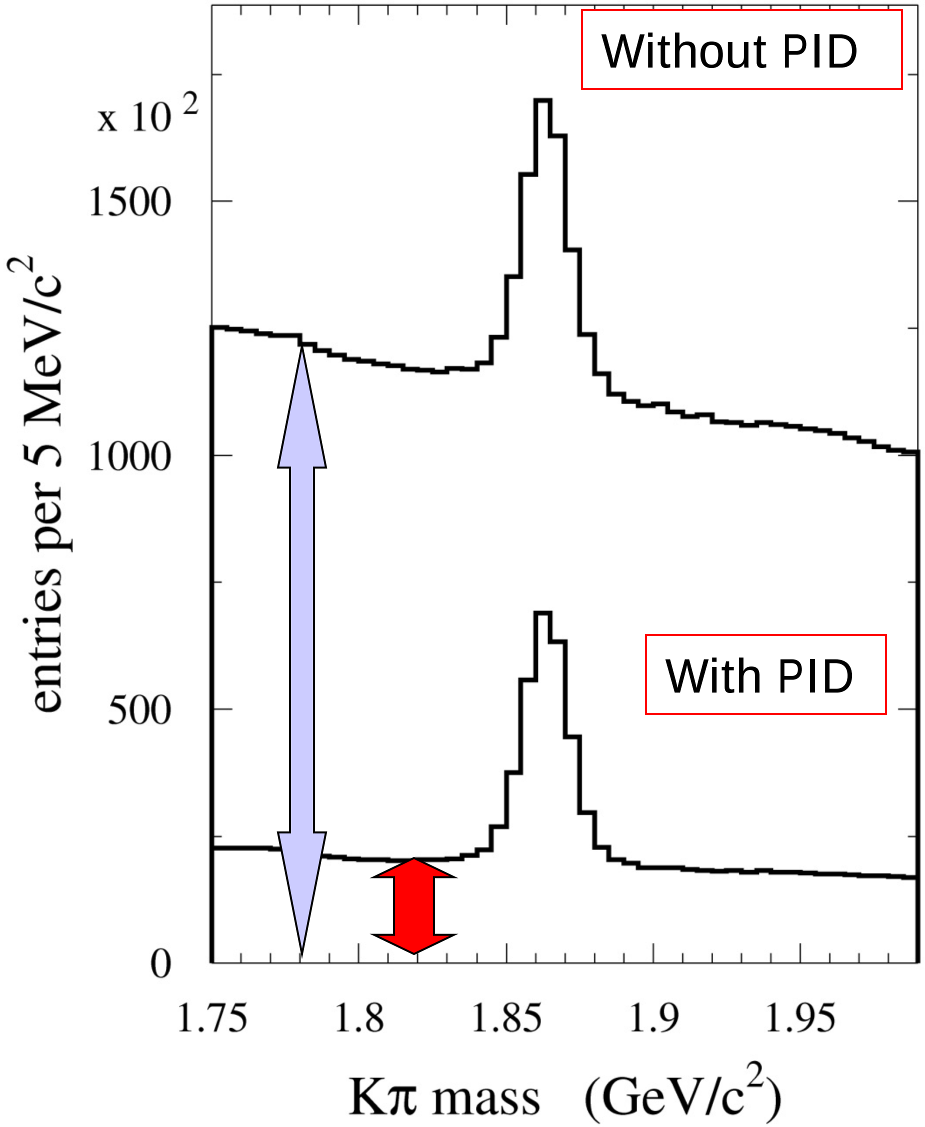
dE/dx

Transition radiation detectors

Summary

→write-up in a review paper: JINST 4:P11017,2009.

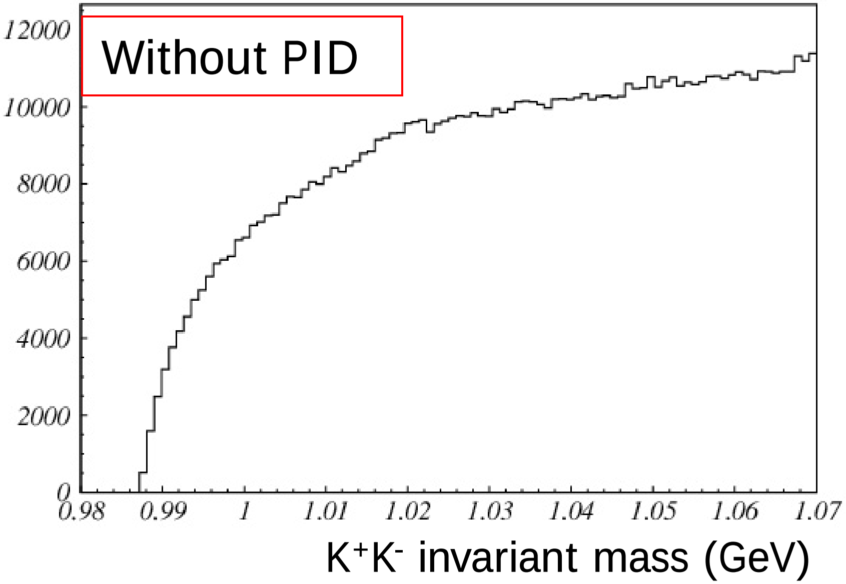
Why particle ID?

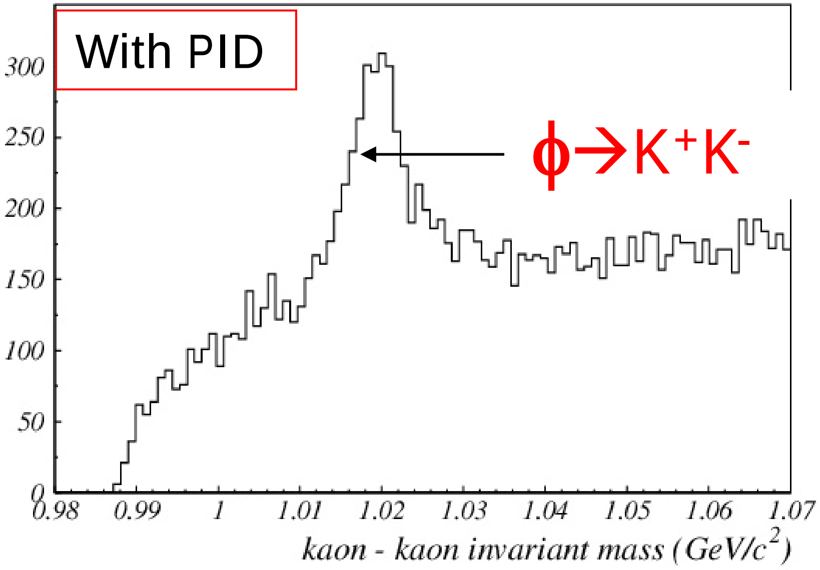


Example 1: B factory

Particle identification reduces the fraction of wrong Kπ combinations (combinatorial background) by ~5x

Why particle ID?



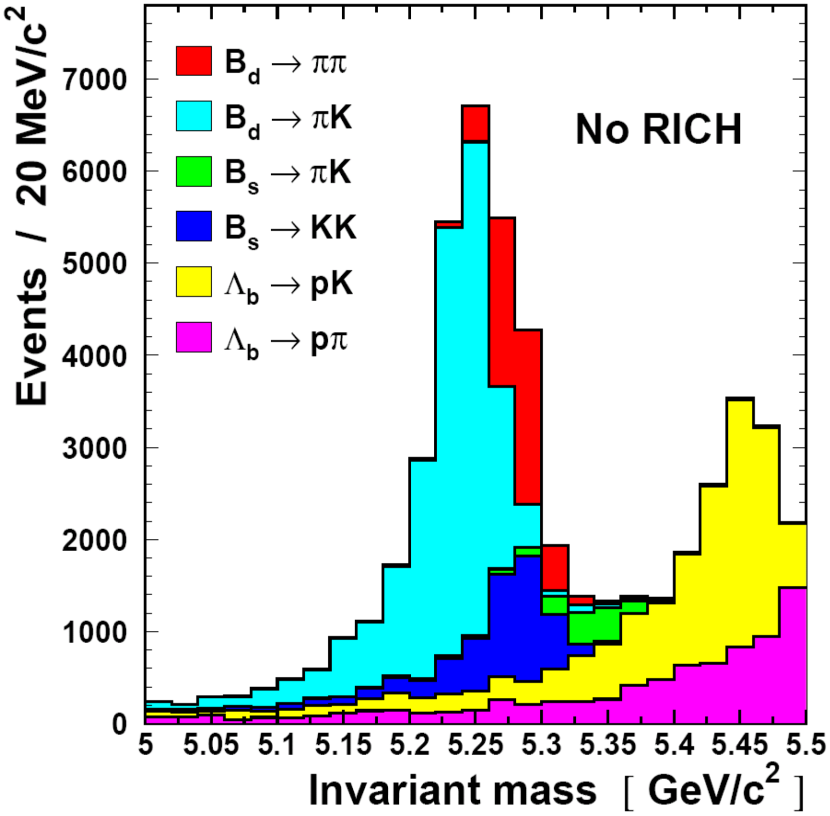


Example 2: HERA-B

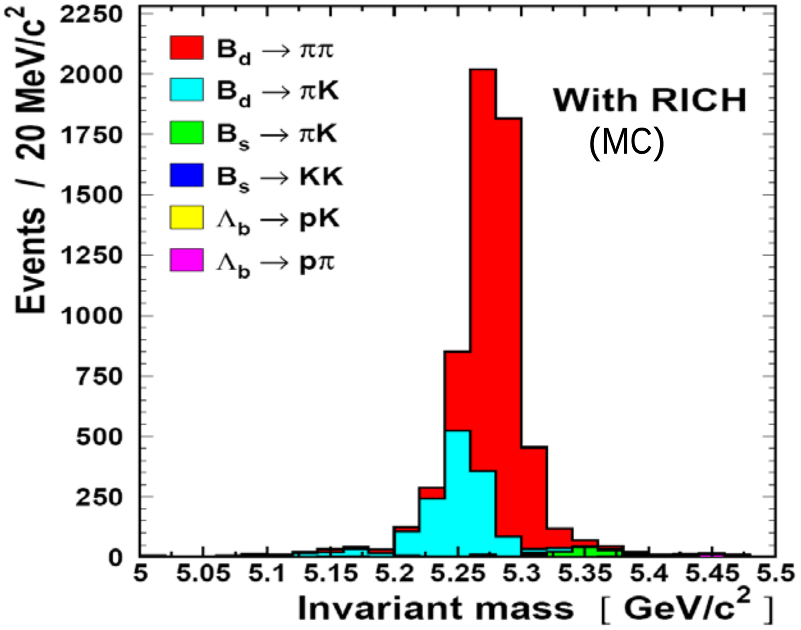
K^+K^- invariant mass.

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

Why particle ID?



Example 3: LHCb



Need to distinguish $B_d \rightarrow \pi\pi$ from other similar topology 2-body decays and to distinguish B from anti-B using K tag.

Why particle ID?

PID is also needed in:

- General purpose LHC experiments: final states with electrons and muons

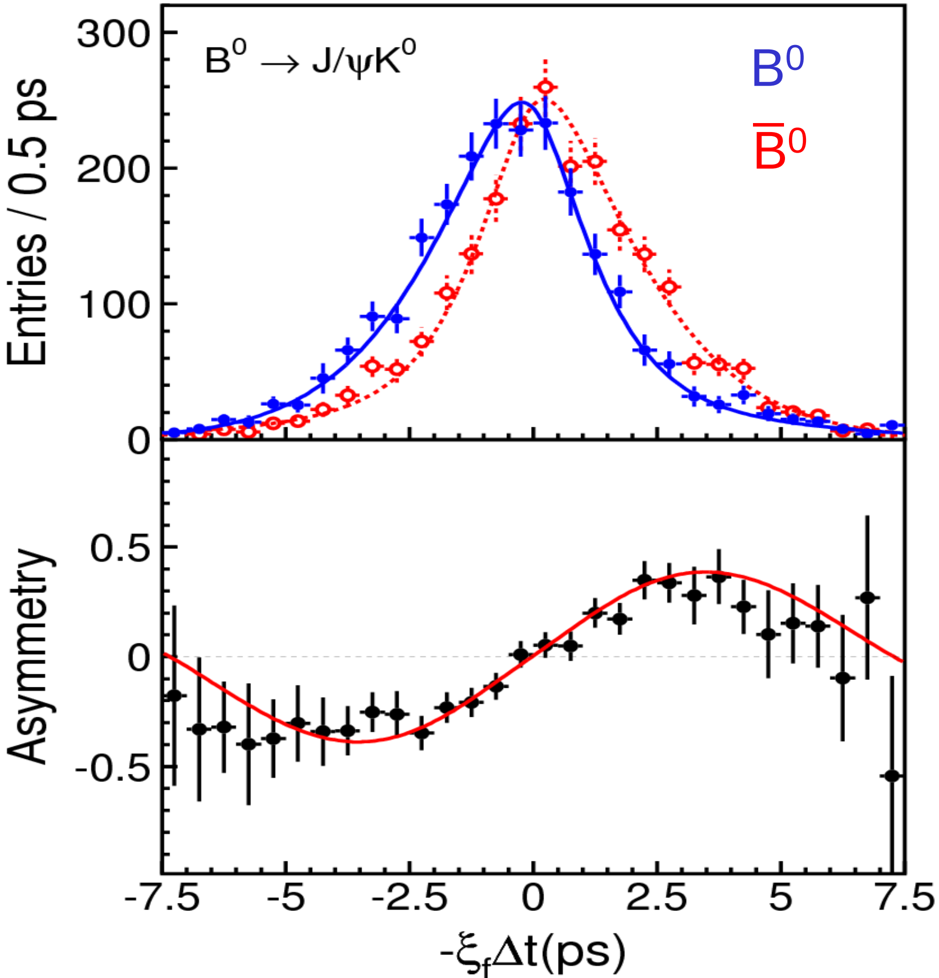
- Searches for exotic states of matter (quark-gluon plasma)

- Spectroscopy and searches for exotic hadronic states

- Studies of fragmentation functions

Why particle ID?

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

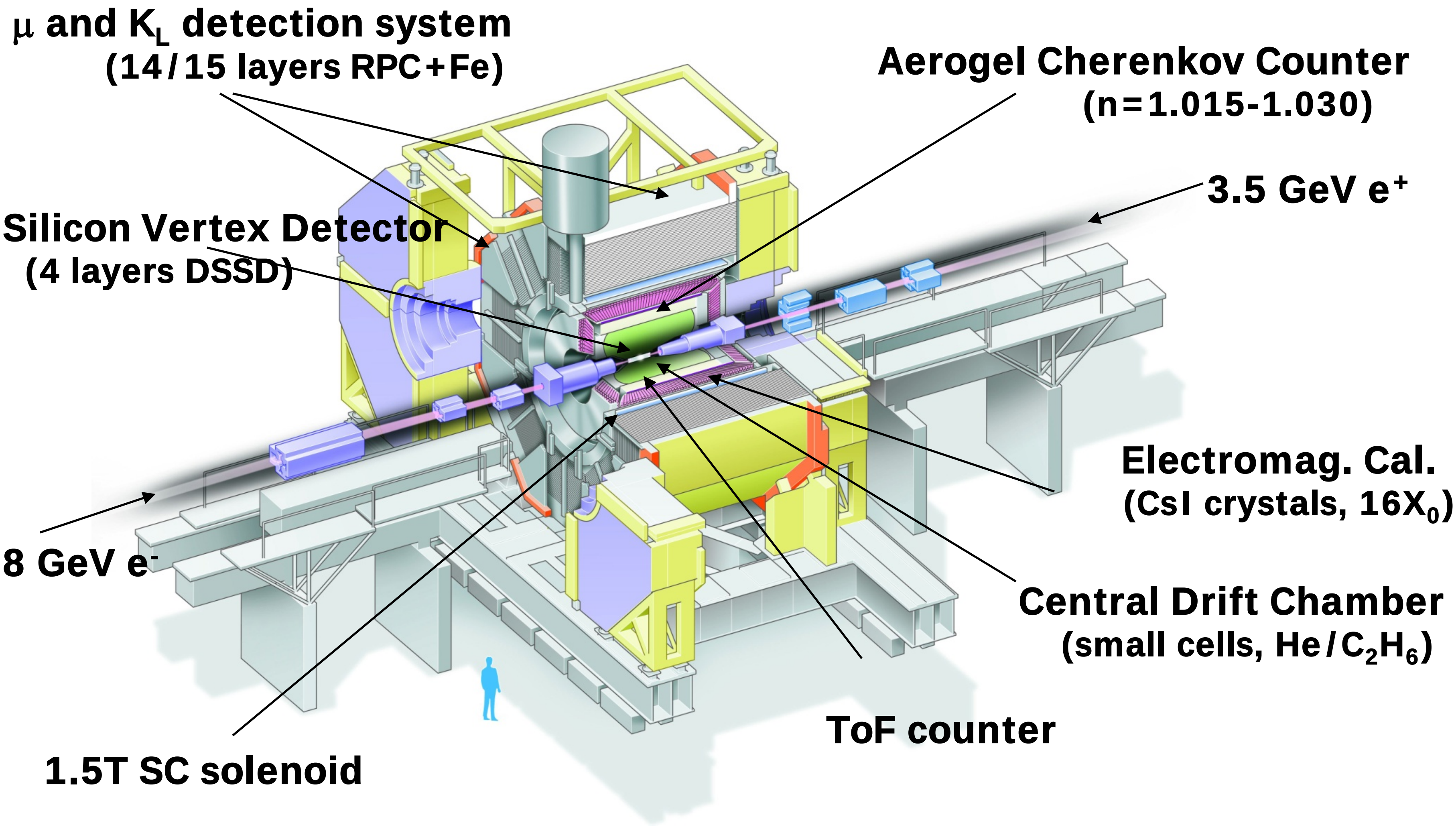


B^0 and its anti-particle decay differently to the same final state $J/\psi\ K^0$

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

→particle ID is compulsory

Example: Belle



μ and K_L detection system
(14/15 layers RPC+Fe)

Aerogel Cherenkov Counter
(n=1.015-1.030)

3.5 GeV e^+

Silicon Vertex Detector
(4 layers DSSD)

Electromag. Cal.
(CsI crystals, $16X_0$)

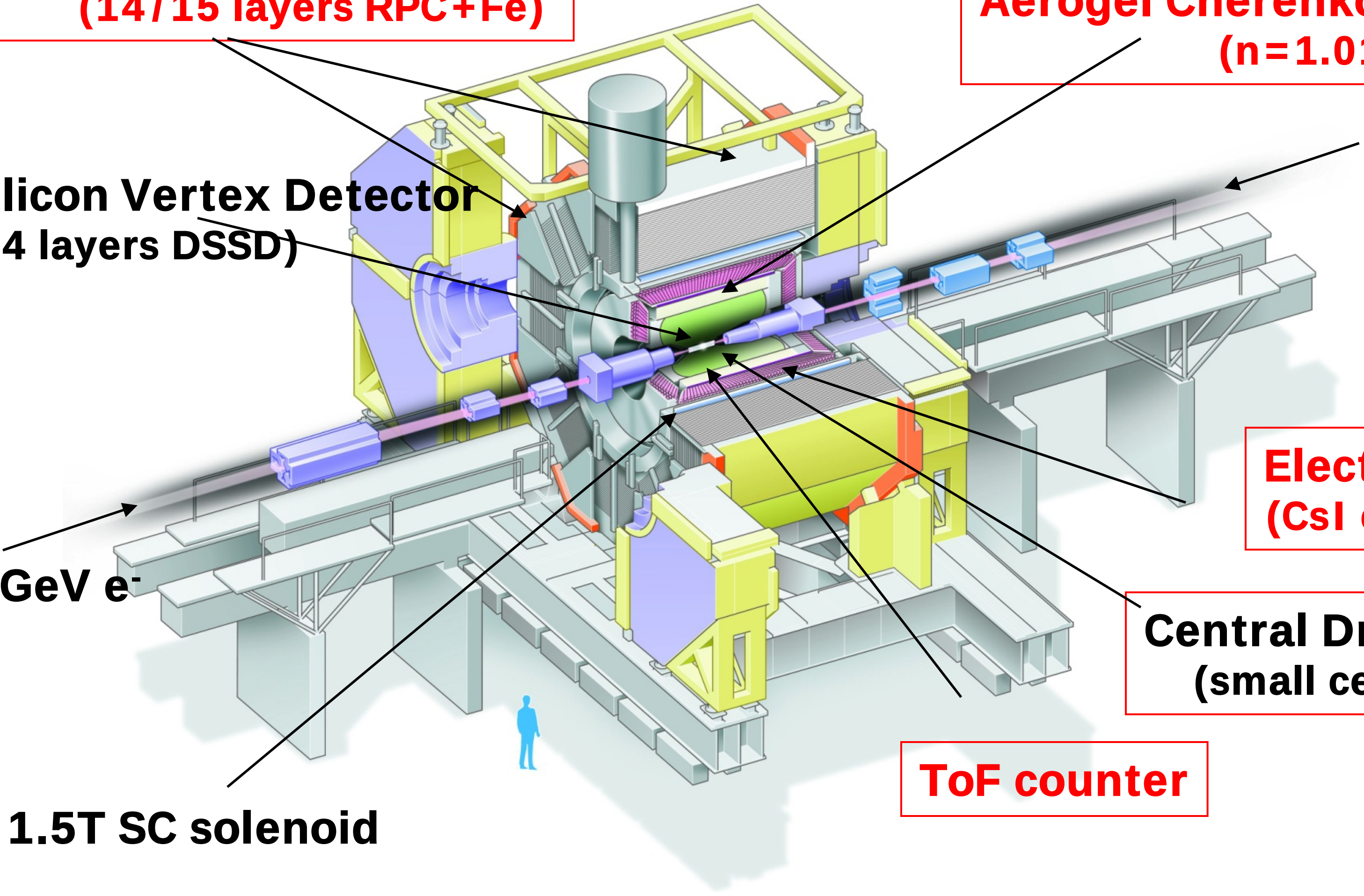
8 GeV e^-

Central Drift Chamber
(small cells, He/C_2H_6)

ToF counter

1.5T SC solenoid

Particle identification systems in Belle



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ToF counter

1.5T SC solenoid

Identification of charged particles

Particles 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.

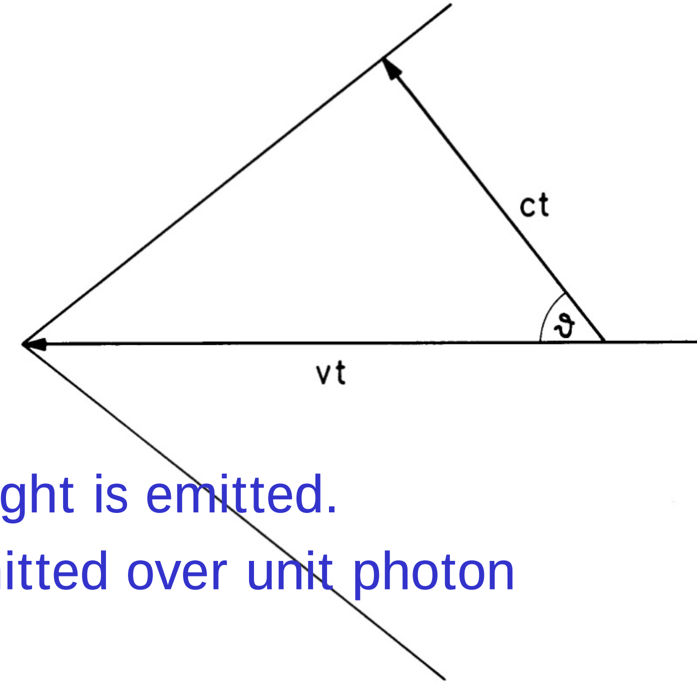
Identification through interaction: electrons and muons

→Calorimeters, Muon systems

Cherenkov 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 (Cherenkov) angle,

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



Two cases:

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

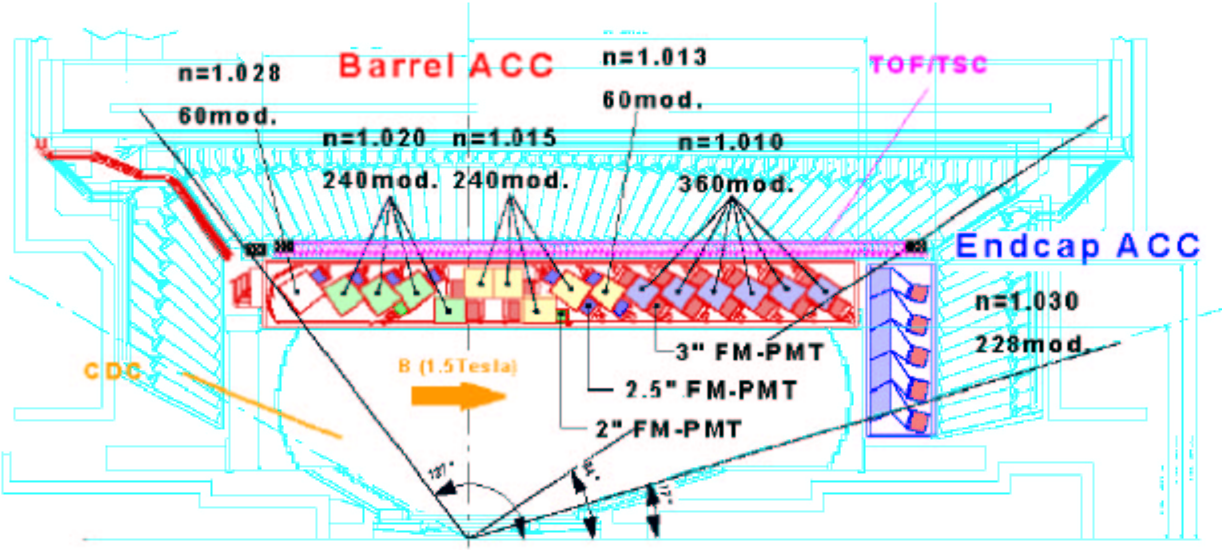
→ $\beta > \beta_t$: the number of Cherenkov photons emitted over unit photon energy E=hν in a radiator of length *L*:

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

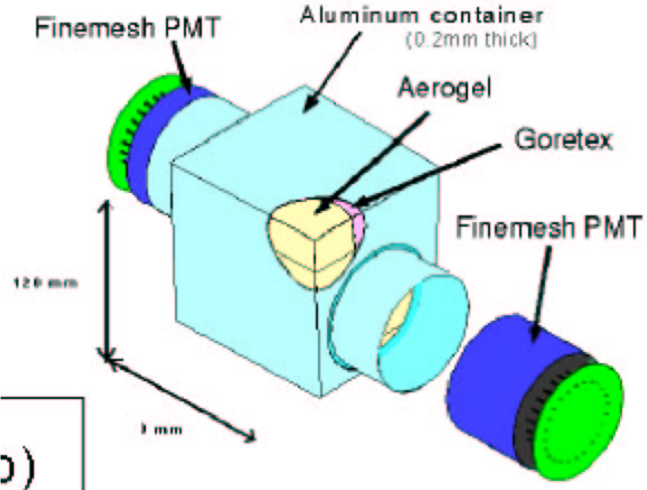
→Few detected photons

Belle: threshold Cherenkov 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')



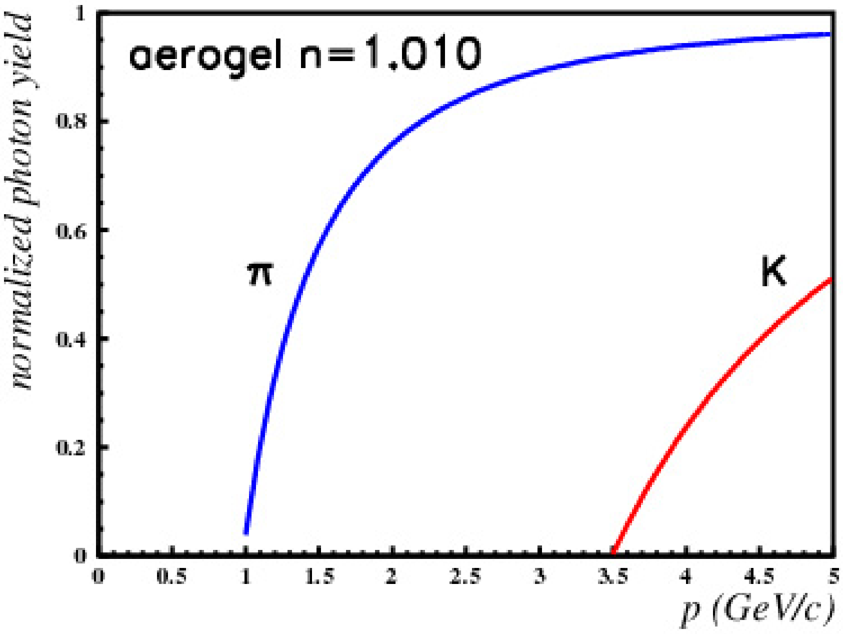
Detector unit: a block of aerogel and two fine-mesh PMTs



Fine-mesh PMT: works in high B fields (1.5 T)

Belle ACC : threshold Cherenkov counter

expected yield vs p



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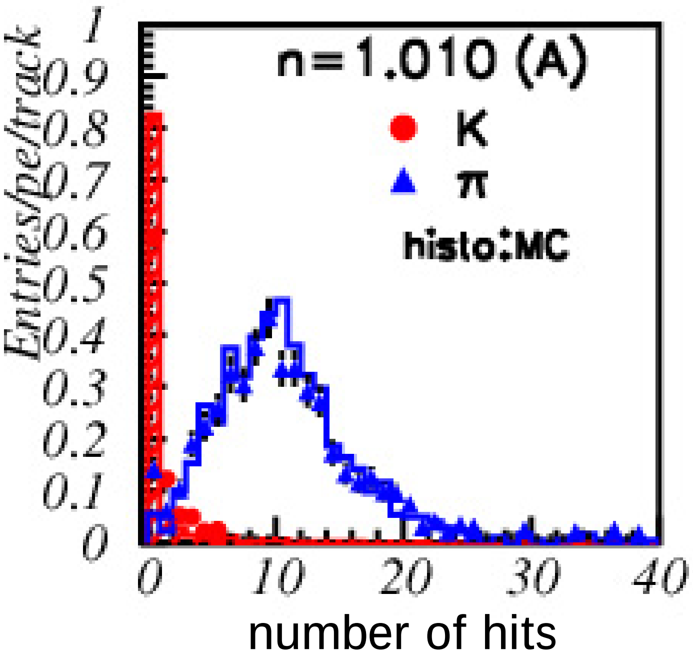
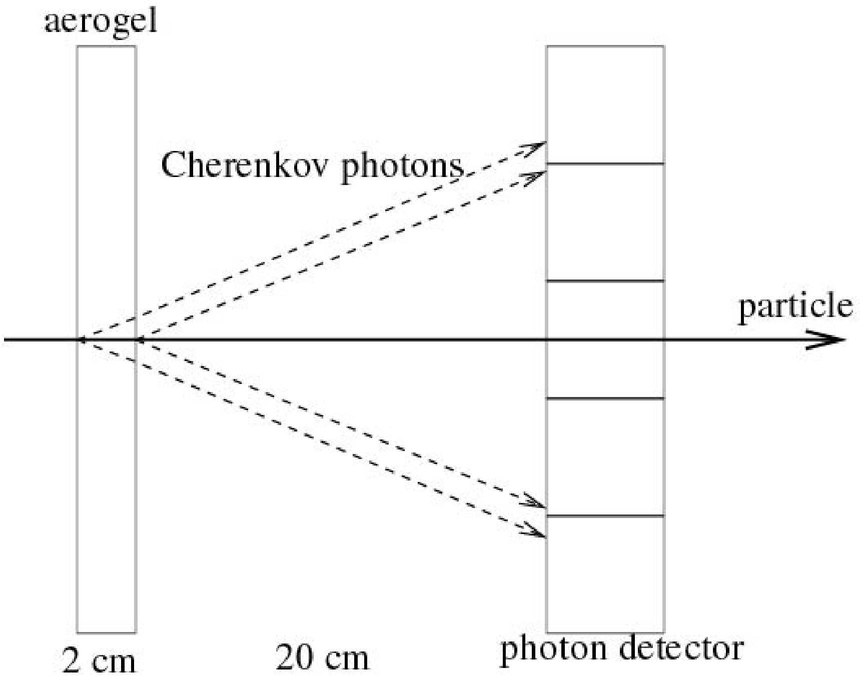
yield for 2GeV<p<3.5GeV:
expected and measured
number of hits



→ Good separation between pions (light) and kaons (no light) between ~1.5 GeV/c and 3.5 GeV/c

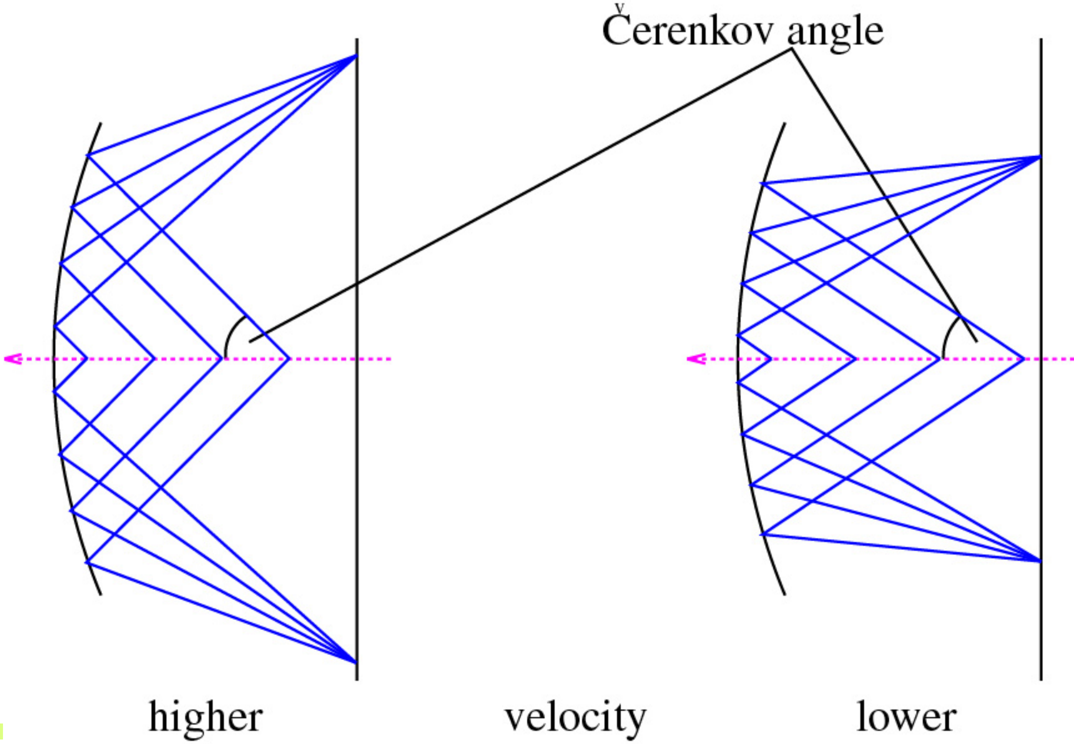
Measuring Cherenkov angle



Proximity focusing RICH

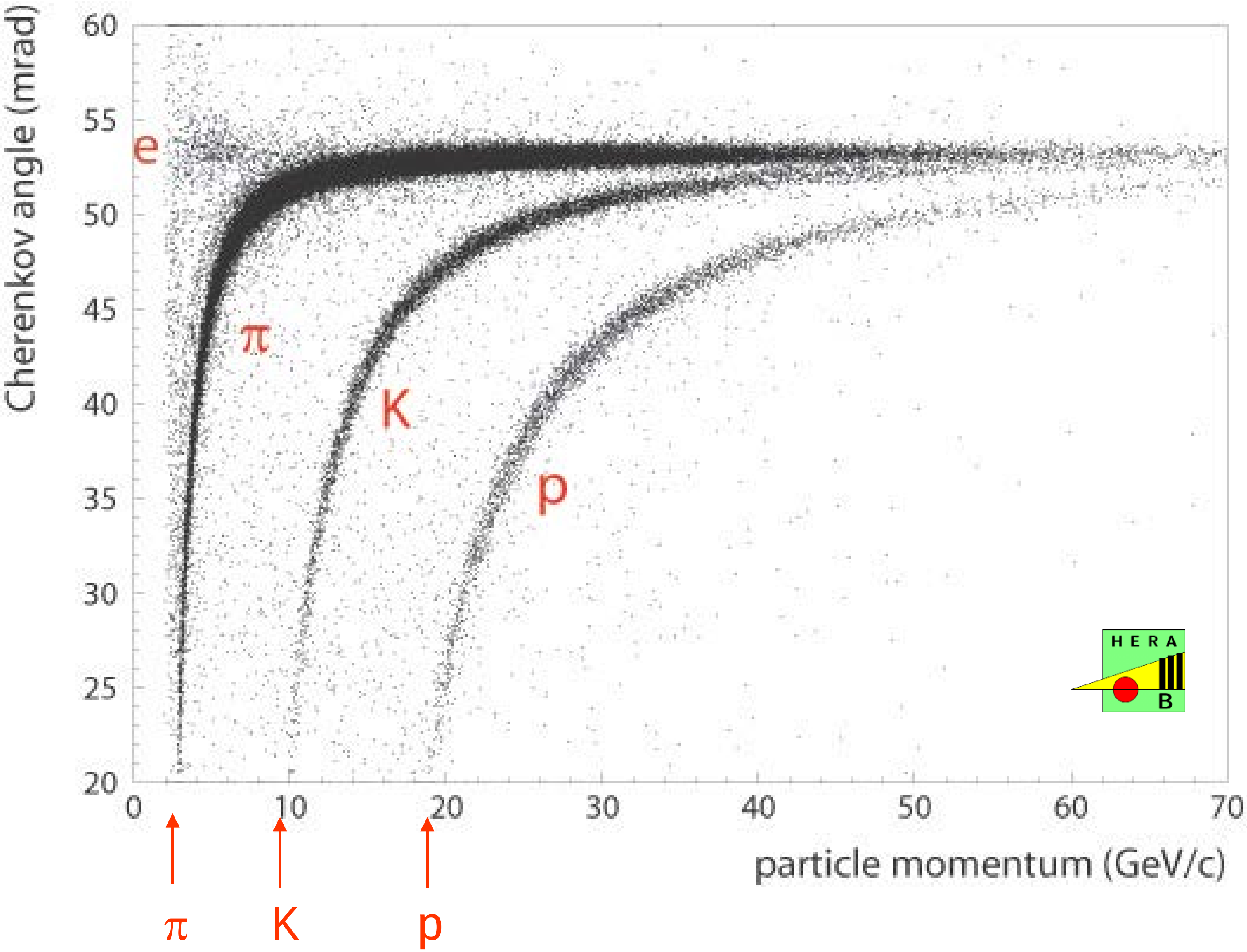
Idea: transform the direction into a coordinate → ring on the detection plane

→ Ring Imaging CHerenkov



RICH with a focusing mirror

Measuring Cherenkov angle



Radiator:
C_4F_{10} gas

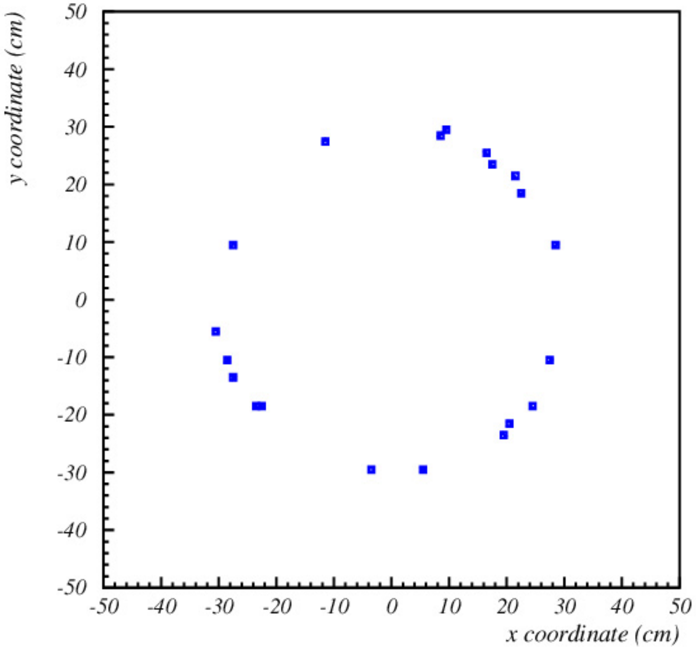
thresholds

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)



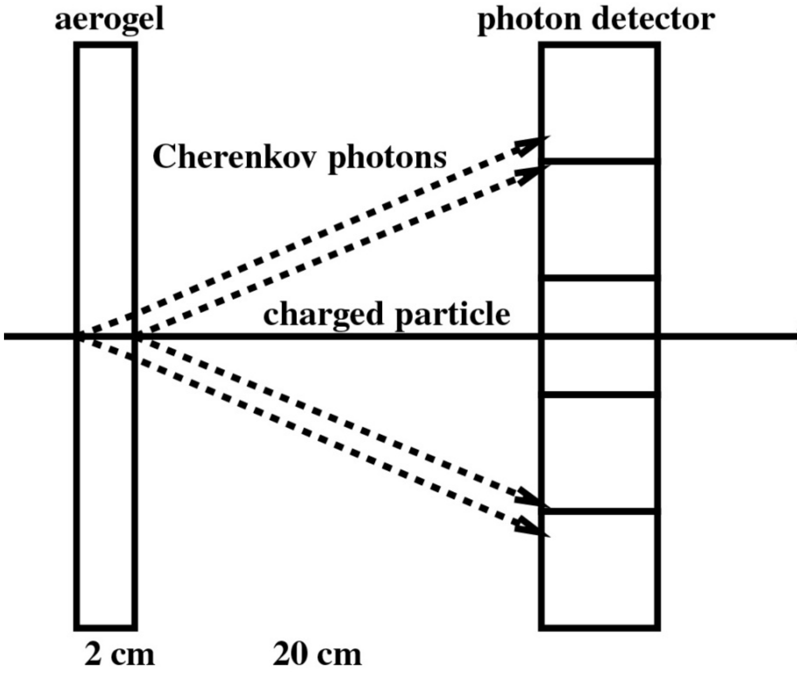
Special requirements:

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

Resolution of a RICH counter

Determined by:

- Photon impact point resolution (~photon detector granularity)
- Emission point uncertainty (not in a focusing RICH)
- Dispersion: $1/\beta = n(\lambda) \cos\theta$
- Errors of the optical system
- Uncertainty in track parameters



Resolution per track:

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

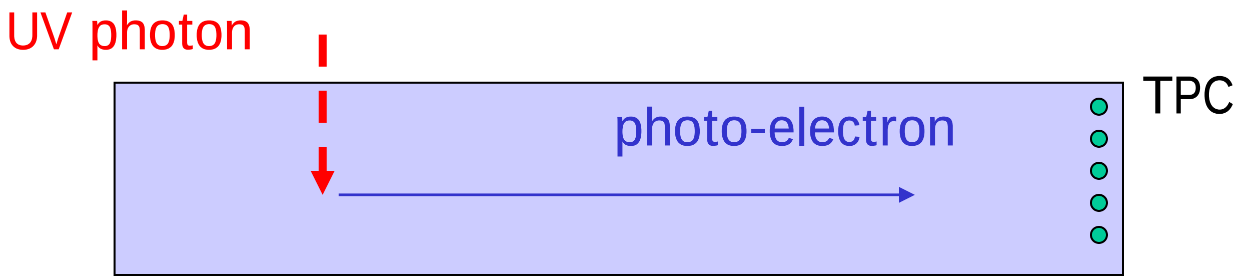
single photon resolution

# of detected photons

(in the case of low background)

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)

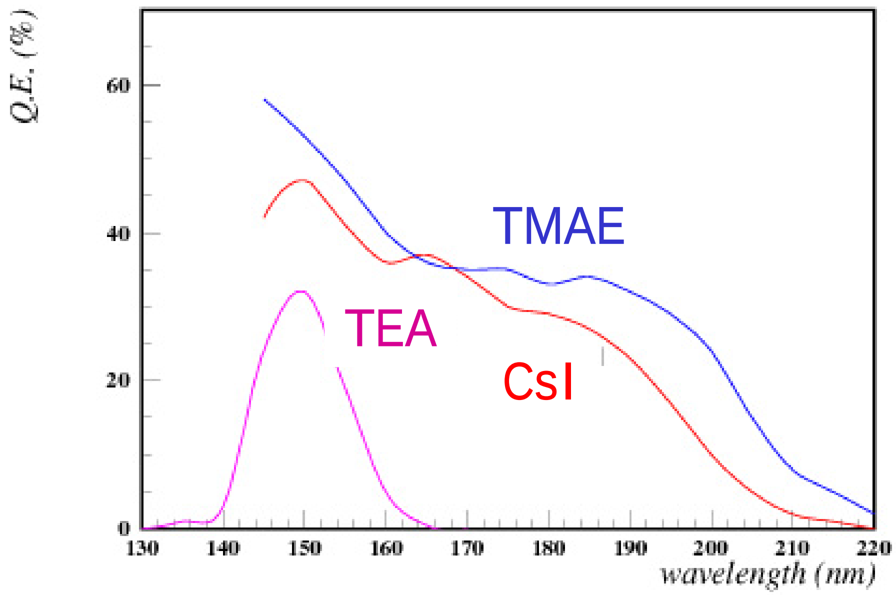


UV photon

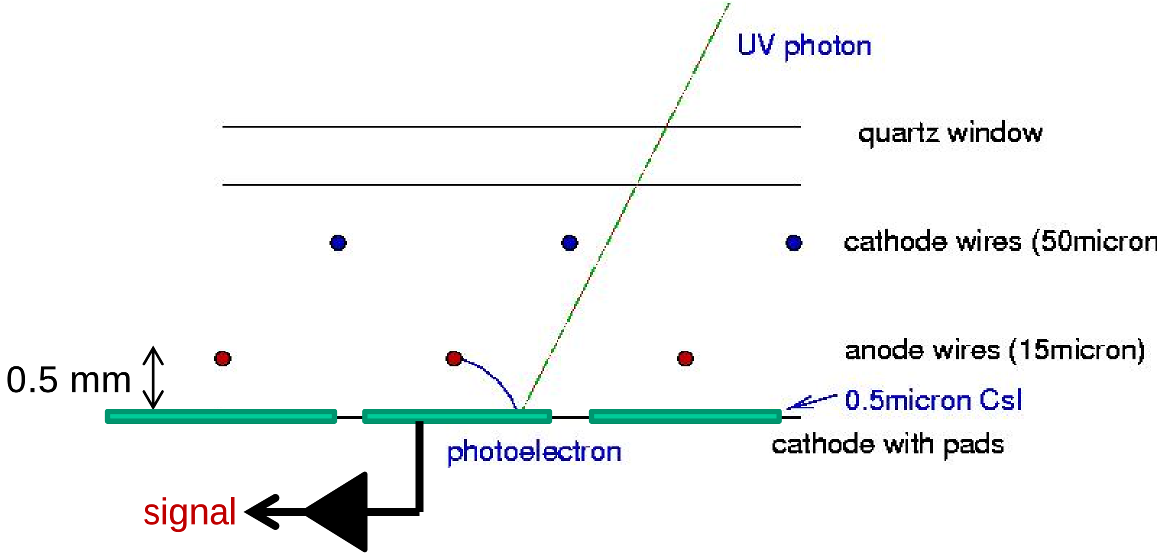
photo-electron

TPC

Photosensitive component:
TMAE added to the gas mixture



Fast RICH counters with wire chambers

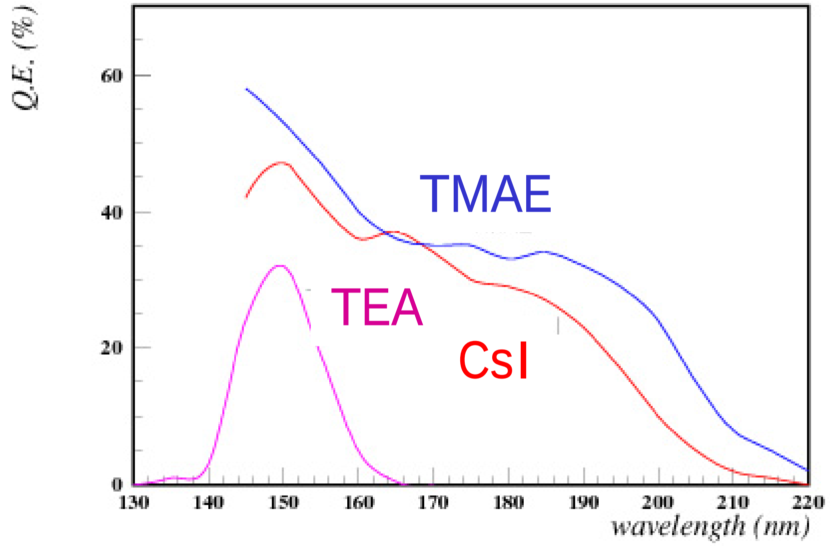


Multiwire chamber with
cathode pad read-out:
→ short drift distances,
fast detector

Photosensitive component:

- in the gas mixture (TEA):
CLEOIII RICH

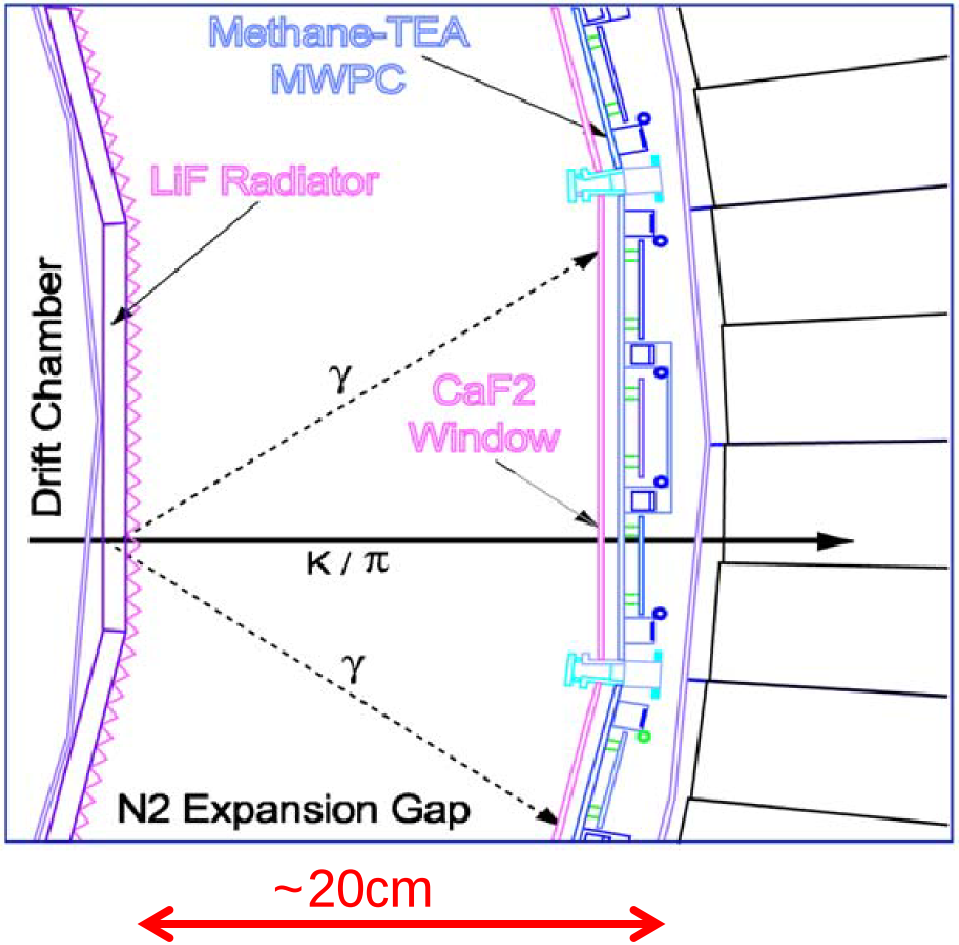
- or a layer on one of the cathodes (CsI on the printed circuit cathode with pads) →



Works in high magnetic field!

CLEOIII RICH

Photon detection in a wire chamber with a methane+TEA mixture.
Technique pioneered by T. Ypsilantis and J. Seguinot

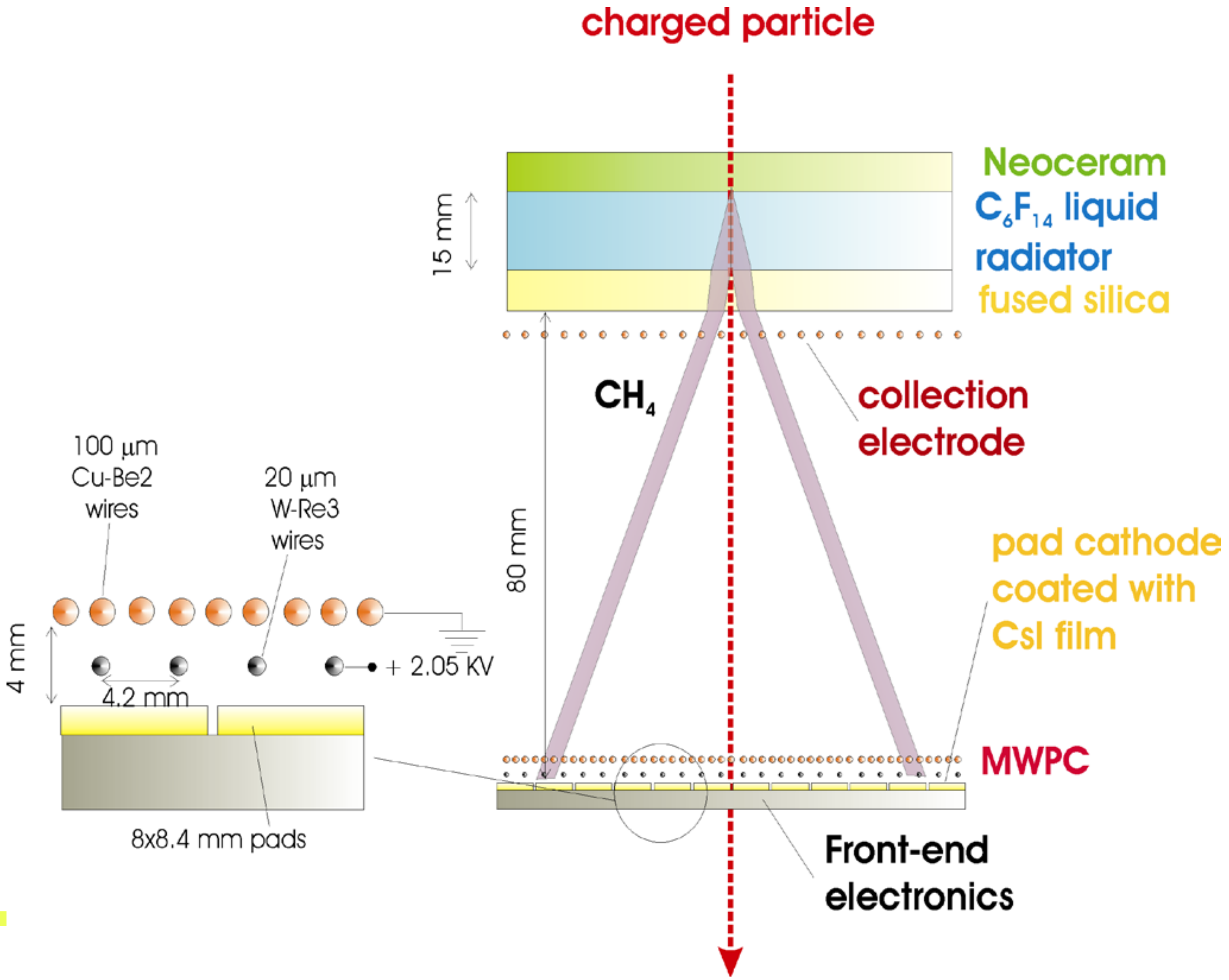


CsI based RICH counters: HADES, COMPASS, ALICE

HADES and COMPASS RICH: gas radiator + CsI photocathode → long term experience in operation

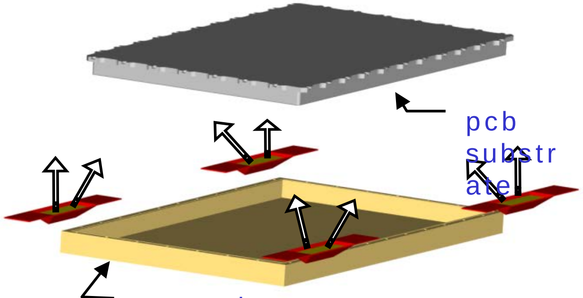
ALICE:

- liquid radiator
- proximity focusing



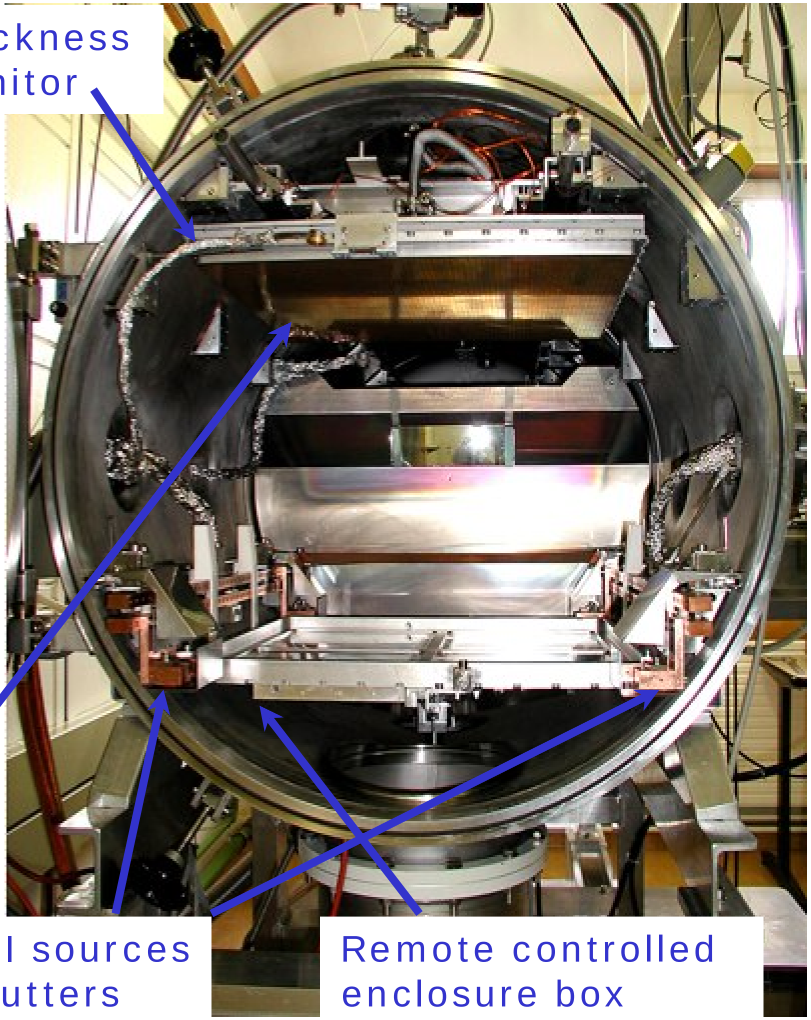
CERN CsI deposition plant

Photocathode produced with a well defined, several step procedure, with CsI vaccum deposition and subsequent heat conditioning



pcb substrate

protective box



Thickness monitor

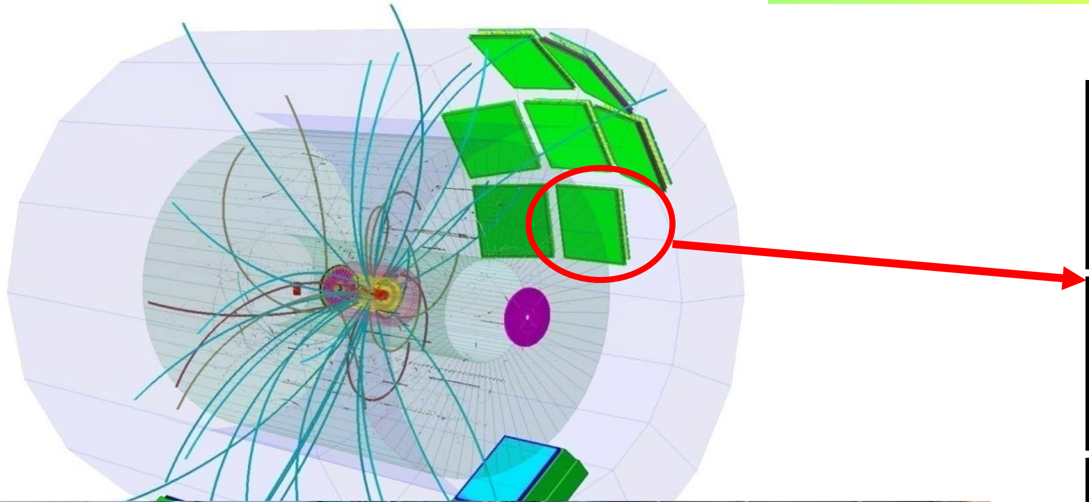
PC

4 CsI sources + shutters

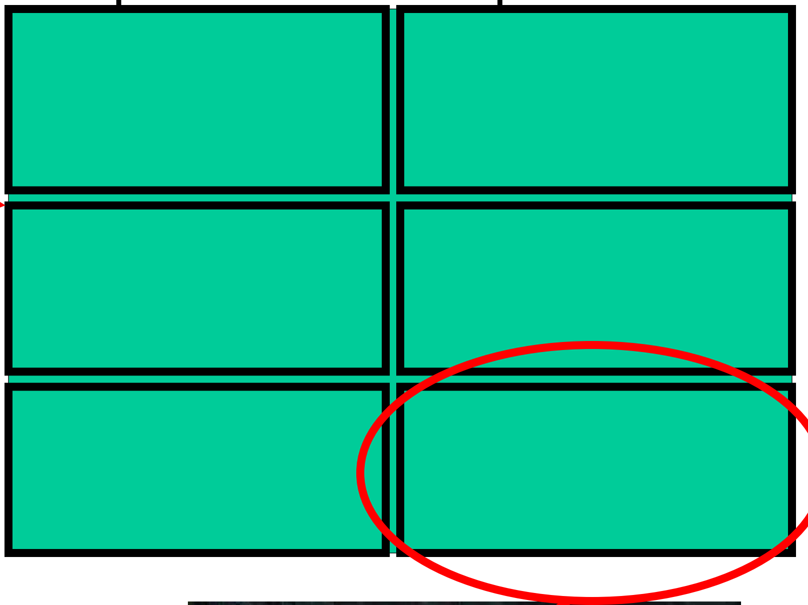
Remote controlled enclosure box

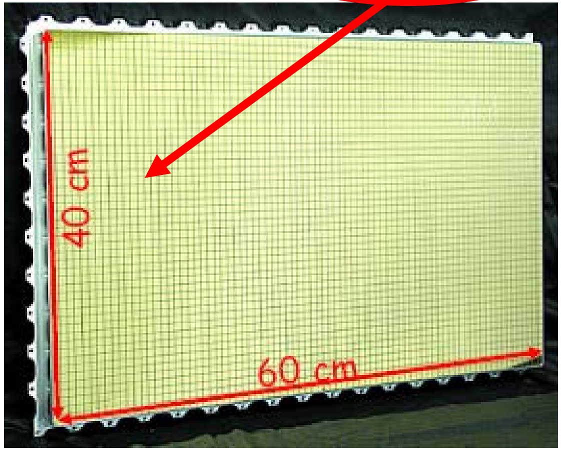
ALICE RICH = HMPID

The largest scale (11 m^2) application of CsI photo-cathodes in HEP!

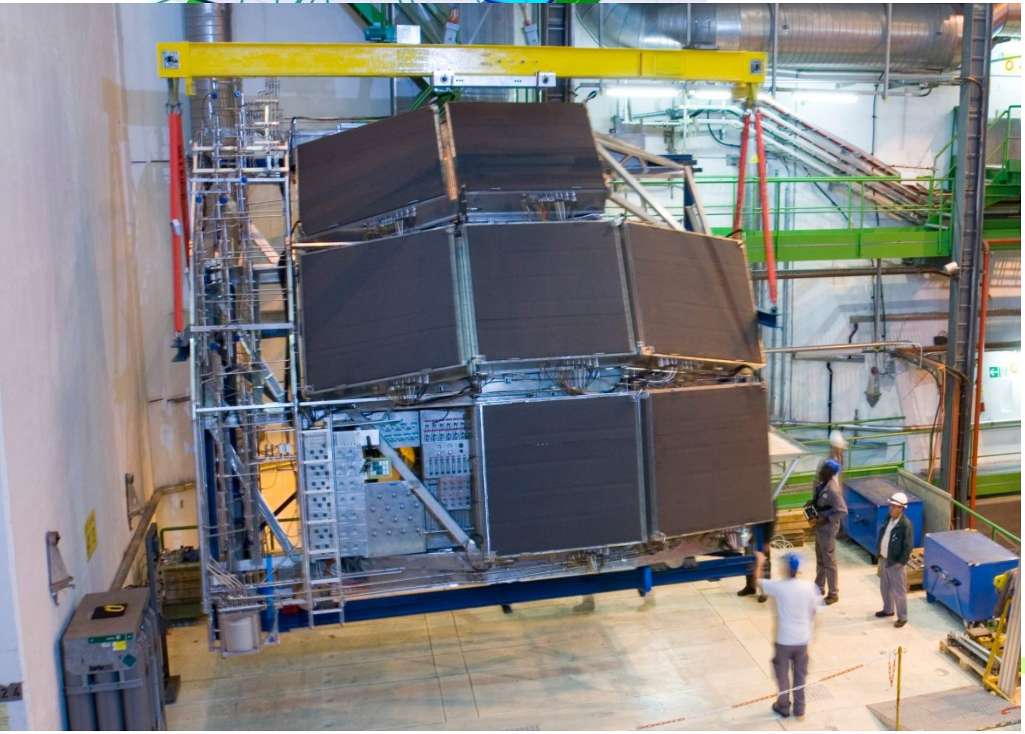


Six photo-cathodes per module

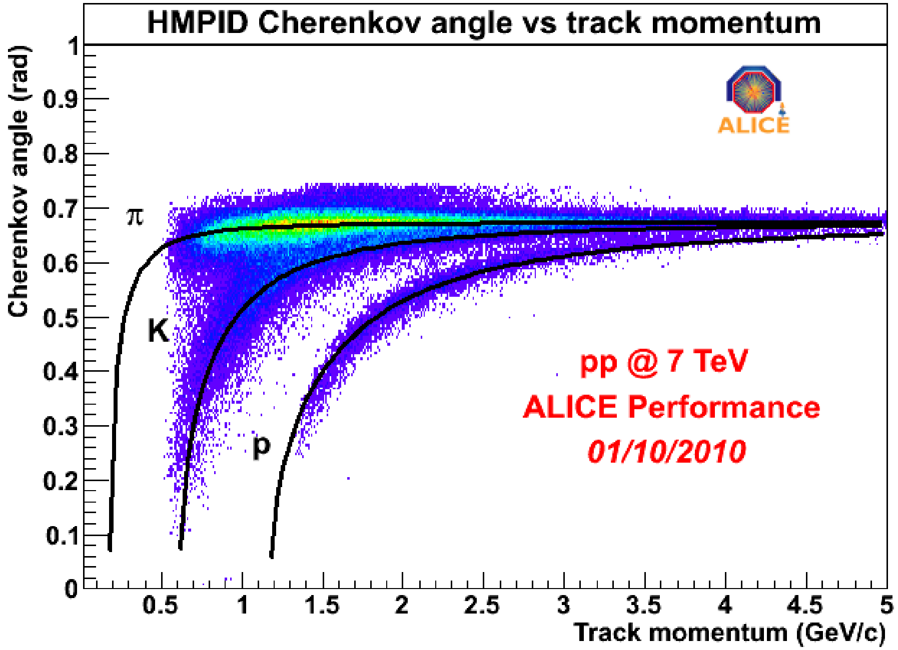


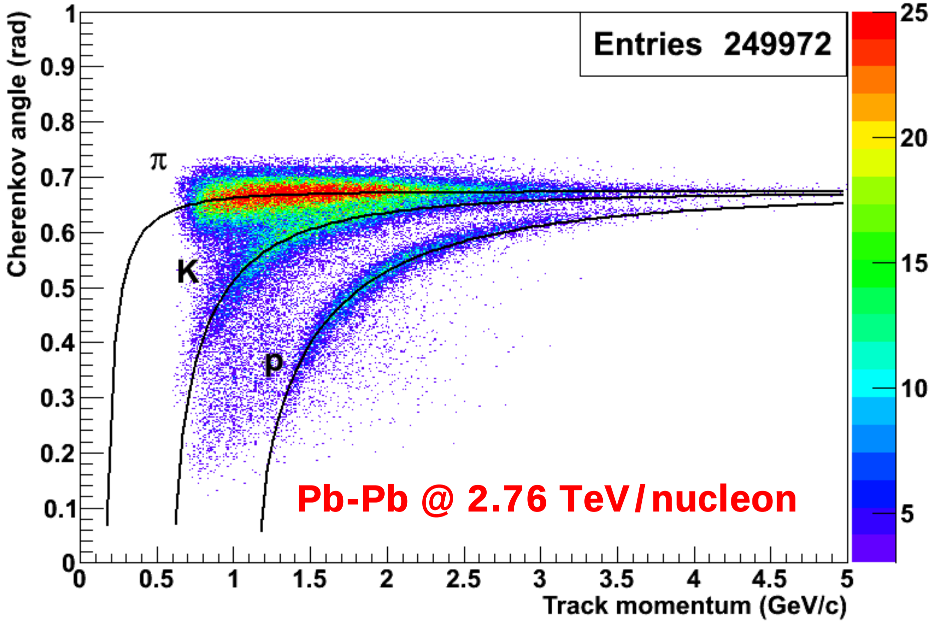


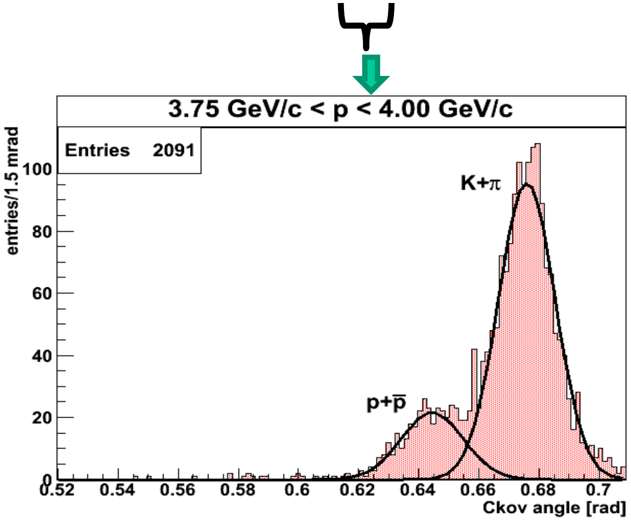
CsI photo-cathode is segmented in 0.8x0.84 cm pads



ALICE HMPID performance







→ Talk by D. DiBari

Cherenkov counters with vacuum based photodetectors

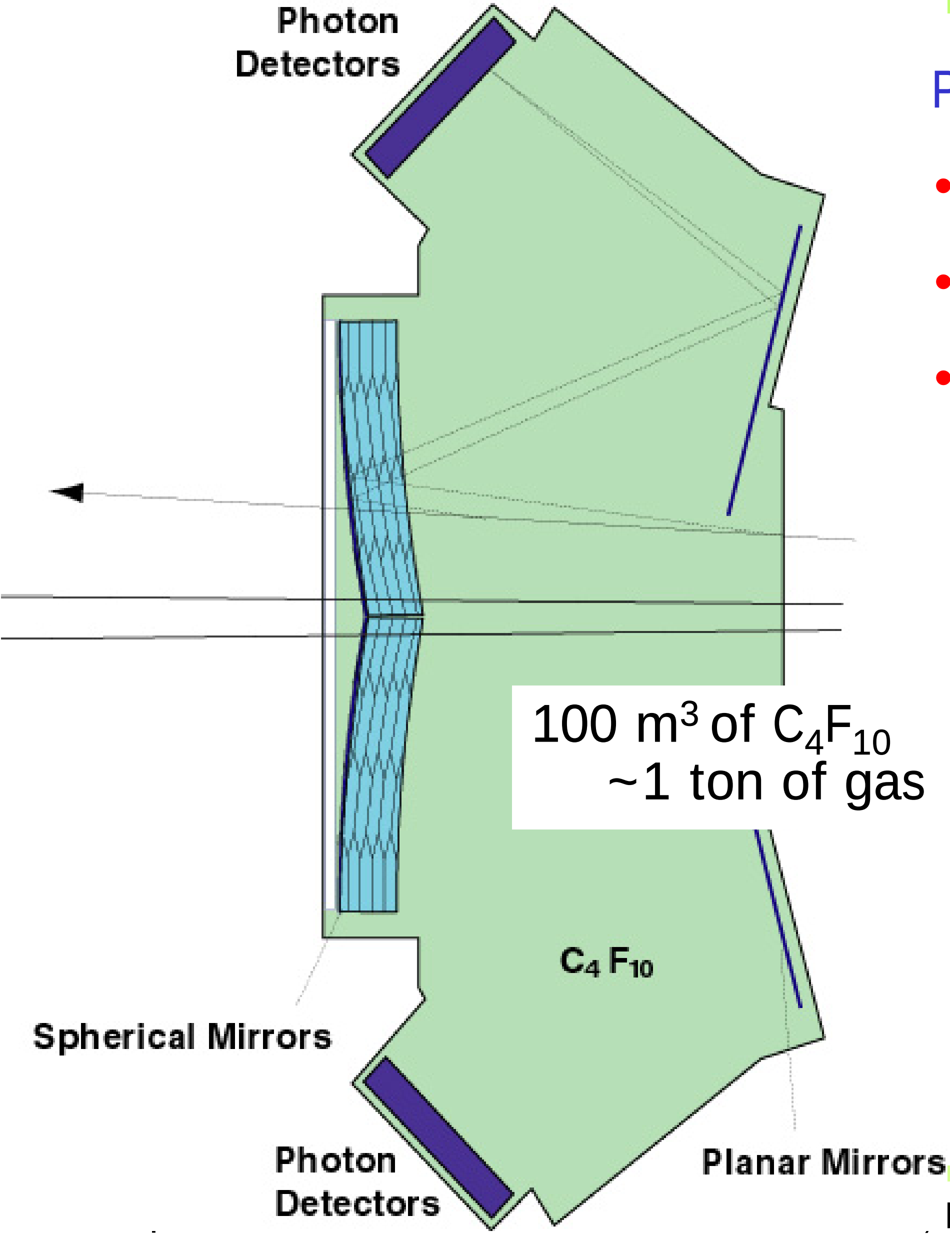
Operation at high rates over extended running periods (years) → wire chamber based photon detectors were found to be unsuitable (problems in high rate operation, ageing, only UV photons, difficult handling in 4π spectrometers)

→ Need vaccum based photon detectors (e.g. PMTs)

Good spacial resolution (pads with ~5 mm size)

→ Need multianode PMTs

HERA-B RICH

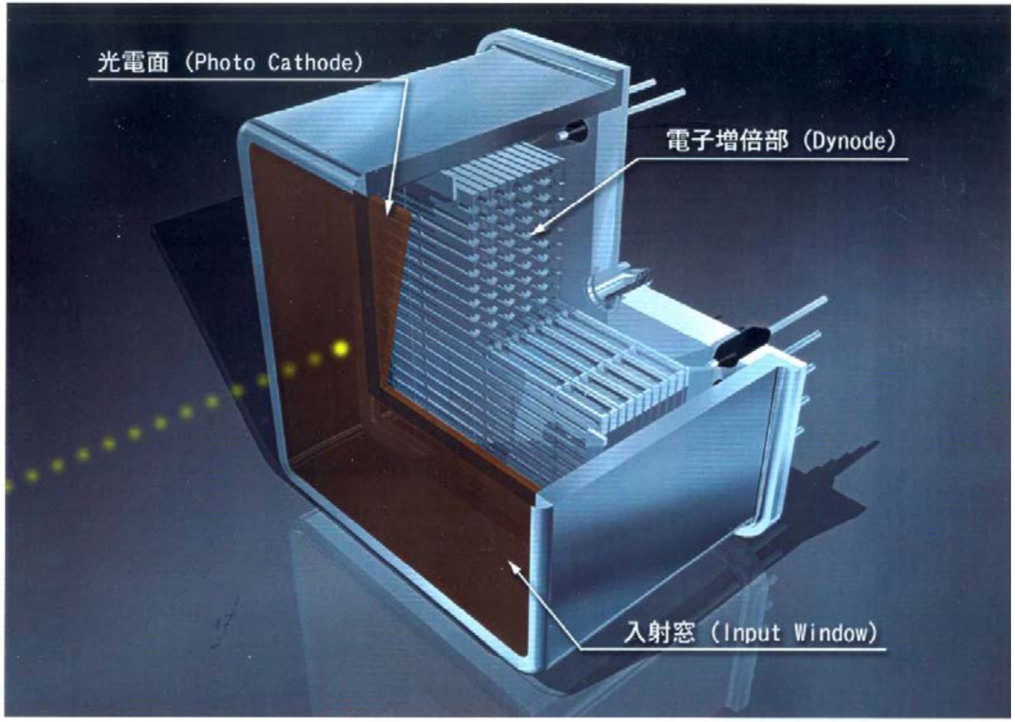


100 m^3 of C_4F_{10}
~1 ton of gas

Photon detector requirements:

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

Multianode PMTs



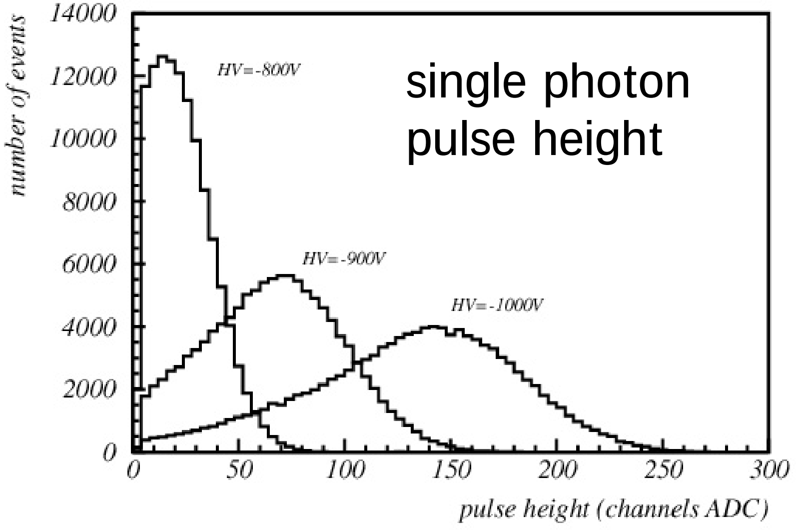
Multianode PMTs with metal foil dynodes and 2x2, 4x4 or 8x8 anodes Hamamatsu R5900 (and follow up types 7600, 8500)

→Excellent single photon pulse height spectrum

→Low noise (few Hz/ch)

→Low cross-talk (<1%)

→ NIM A394 (1997) 27

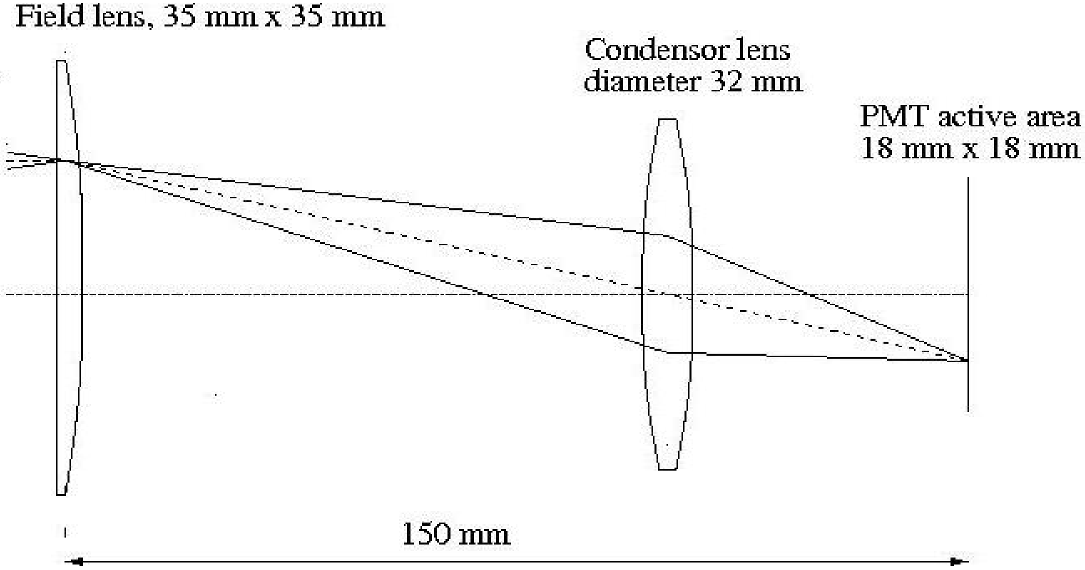


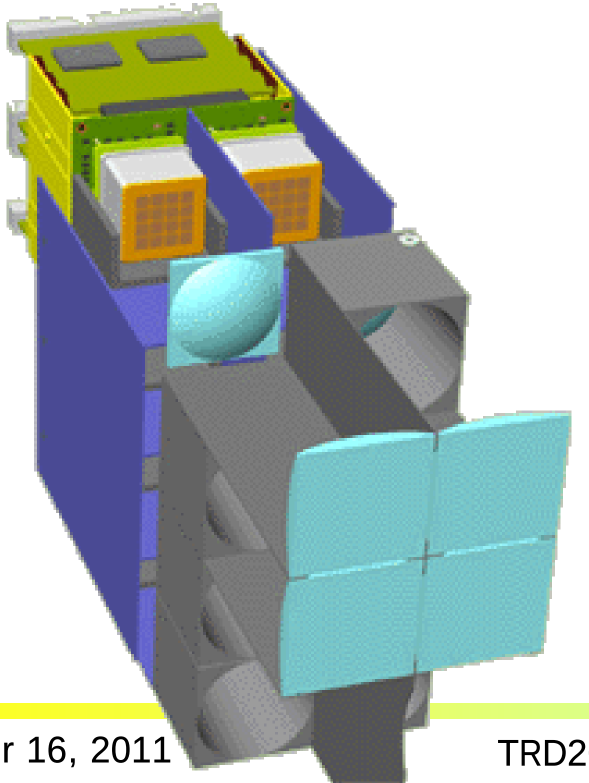
Photon detector with light collection

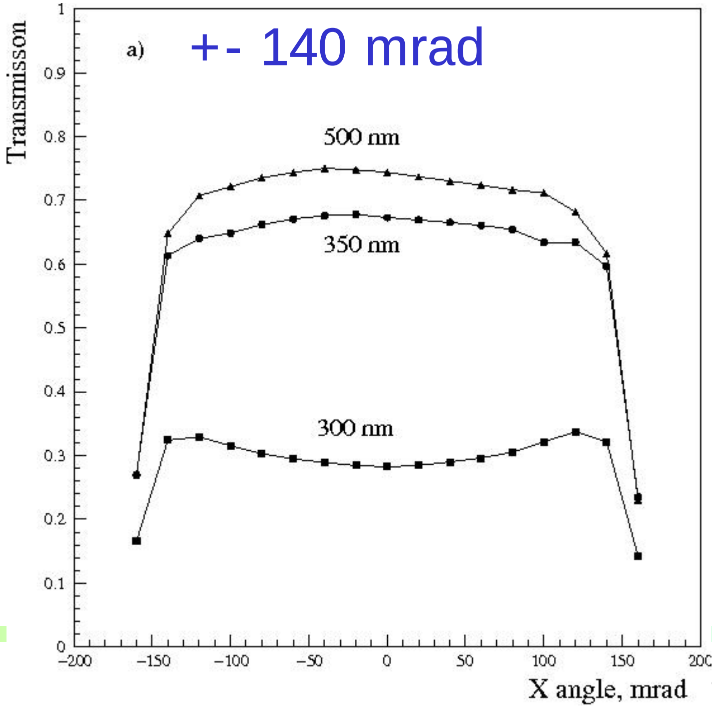
Light collection system (imaging!) to:

-Eliminate dead areas

-Adapt the pad size

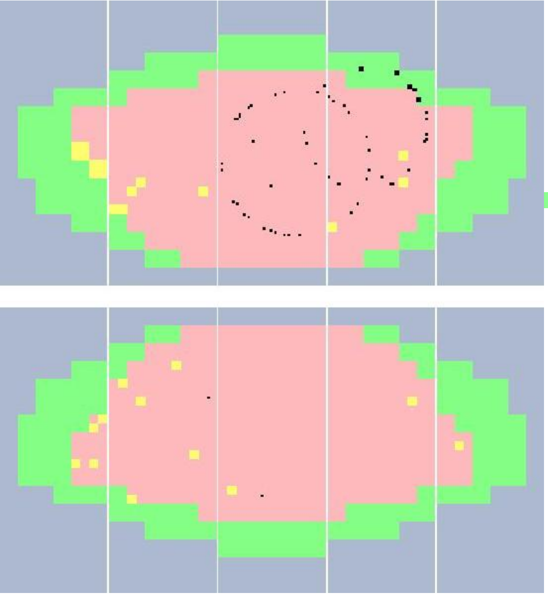






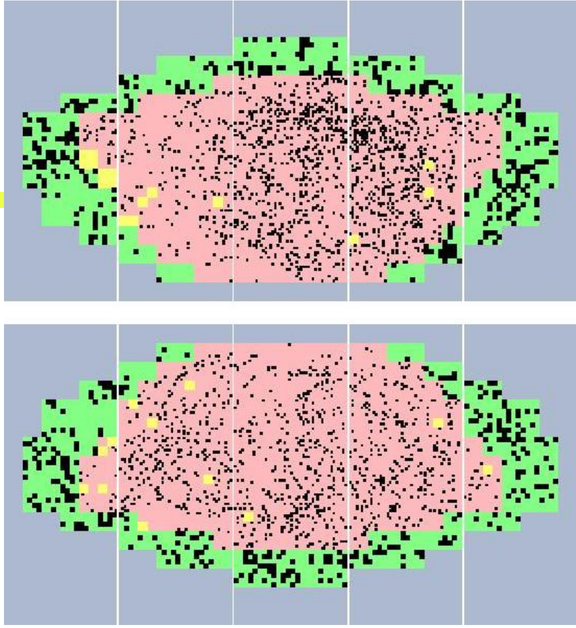
+- 140 mrad

HERA-B RICH

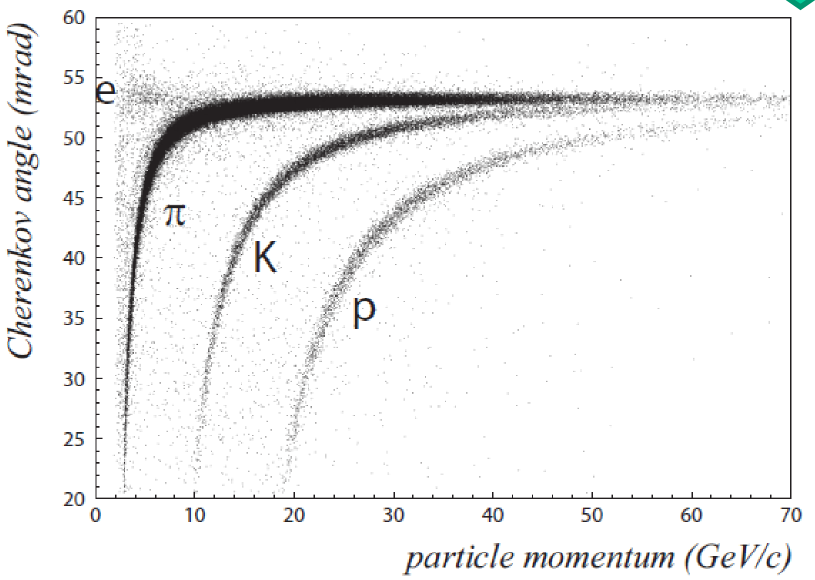


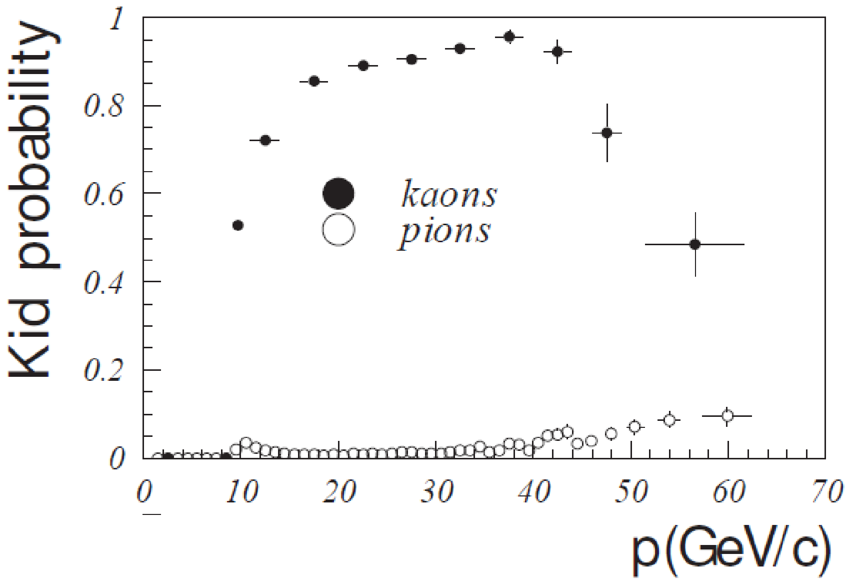
← Little noise, ~30 photons per ring

Typical event →



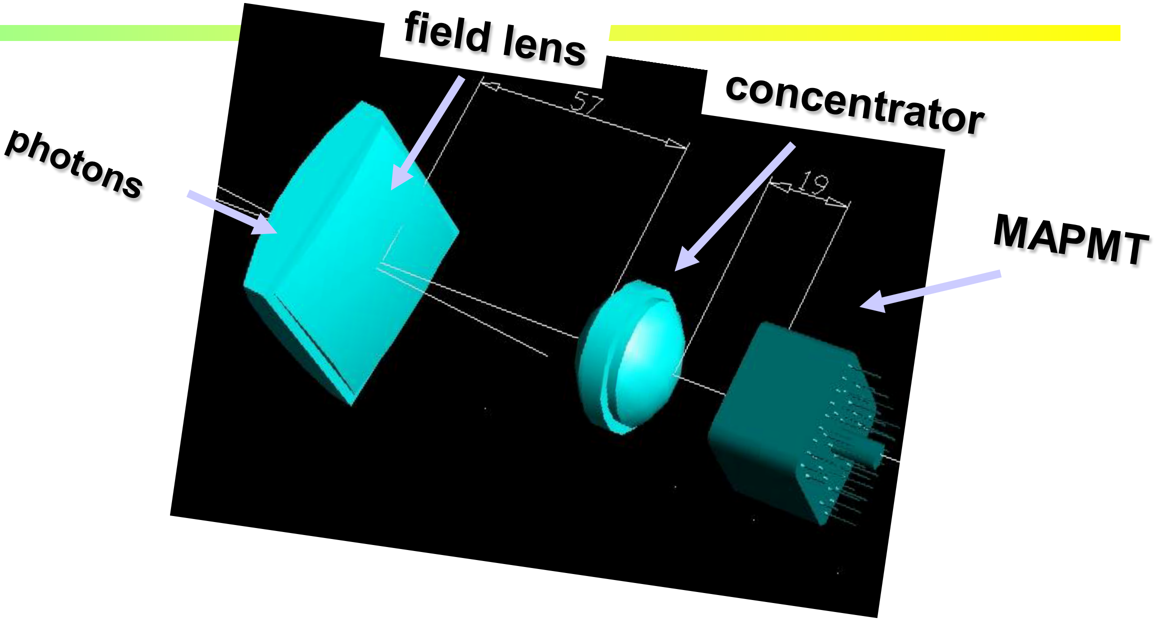
Worked very well!





Kaon efficiency and pion fake probability

Photon detector for the COMPASS RICH-1



Upgraded COMPASS RICH-1:
similar concept as in the
HERA-B RICH

New features:

- UV extended PMTs & lenses (down to 200 nm) → more photons
- surface ratio = (telescope entrance surface) / (photocathode surface) = 7
- fast electronics with <120 ps time resolution

COMPASS RICH-1 upgrade

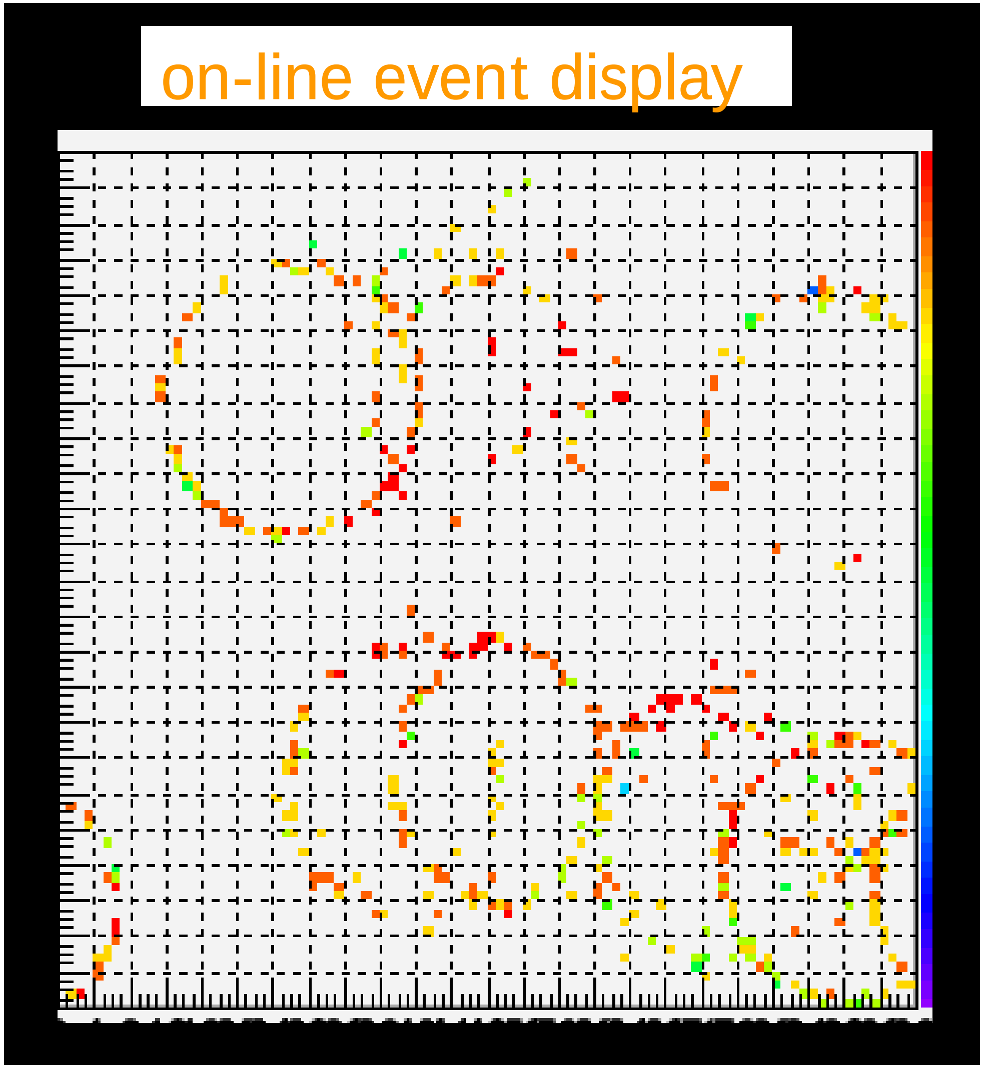
Performance:

~ 60 detected photons per ring at saturation ($\beta = 1$) → N_0 ~66 cm^{-1}

σ_θ ~ 0.3 mrad → 2 σ π-K separation at ~ 60 GeV/c

K-ID efficiency ($K^\pm$ from Φ decay) > 90%

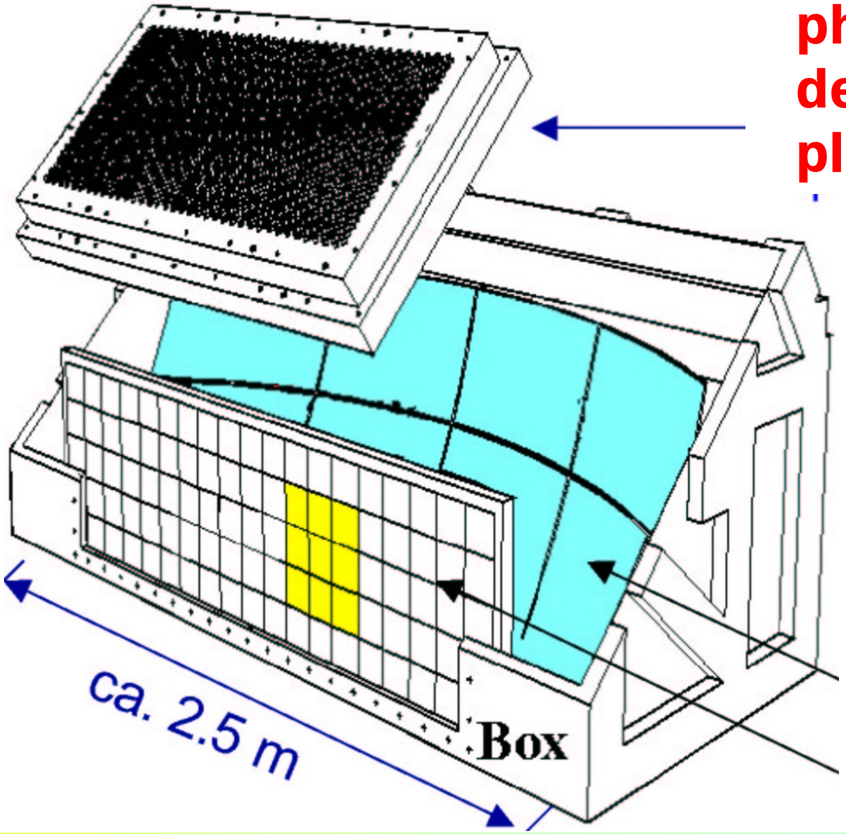
π → K misidentification ($\pi^\pm$ from K_s decay) ~ 1 %



RICHes with several radiators

Extending the kinematic range → need more than one radiator

- DELPHI, SLD (liquid +gas)
- HERMES (aerogel+gas)

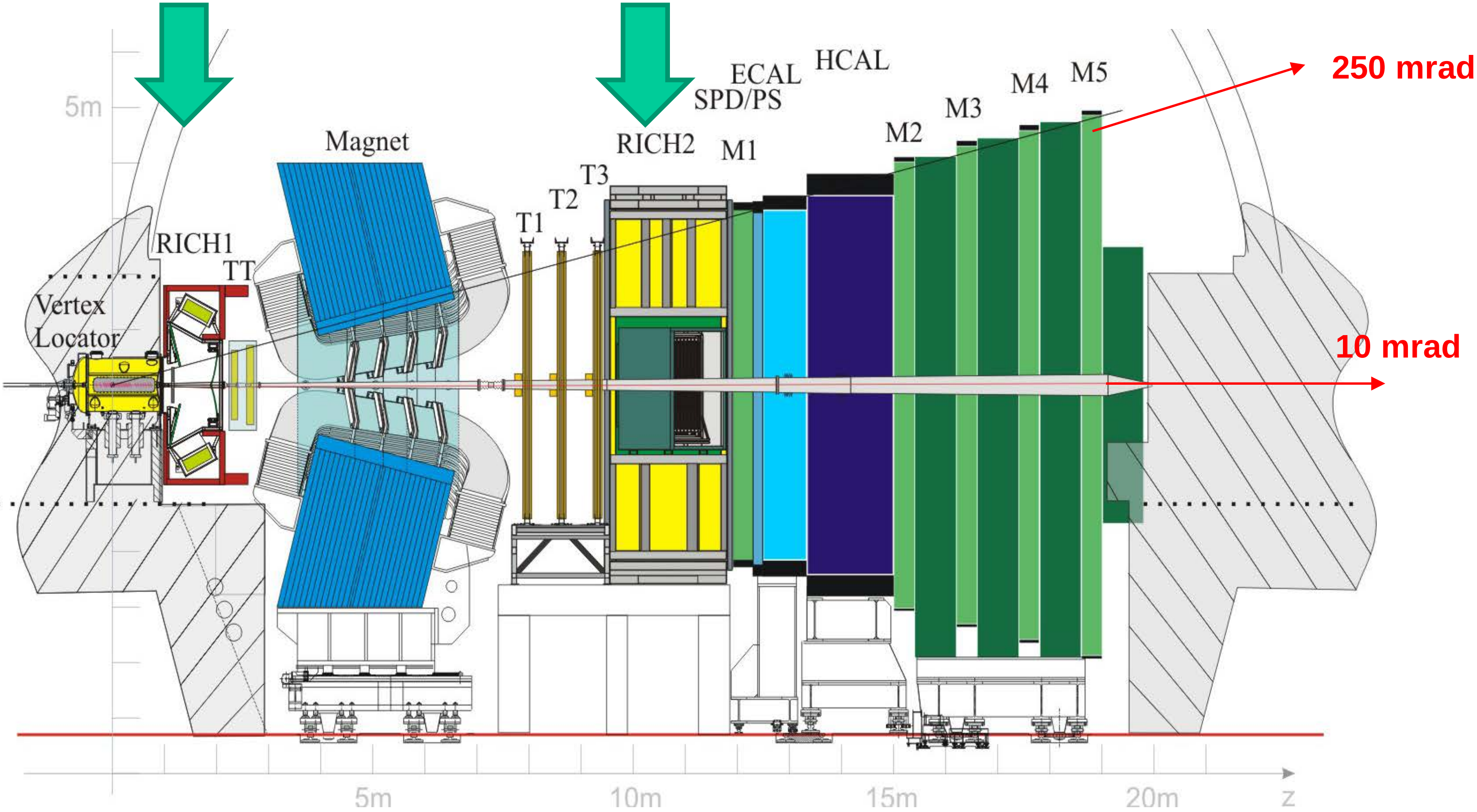


photon detector plane

C_4F_{10}

aerogel

The LHCb RICH counters



Vertex reconstruction:
VELO

Trigger:
Muon Chambers
Calorimeters
Tracker

PID:
RICHes
Calorimeters
Muon Chambers

Kinematics:
Magnet
Tracker
Calorimeters

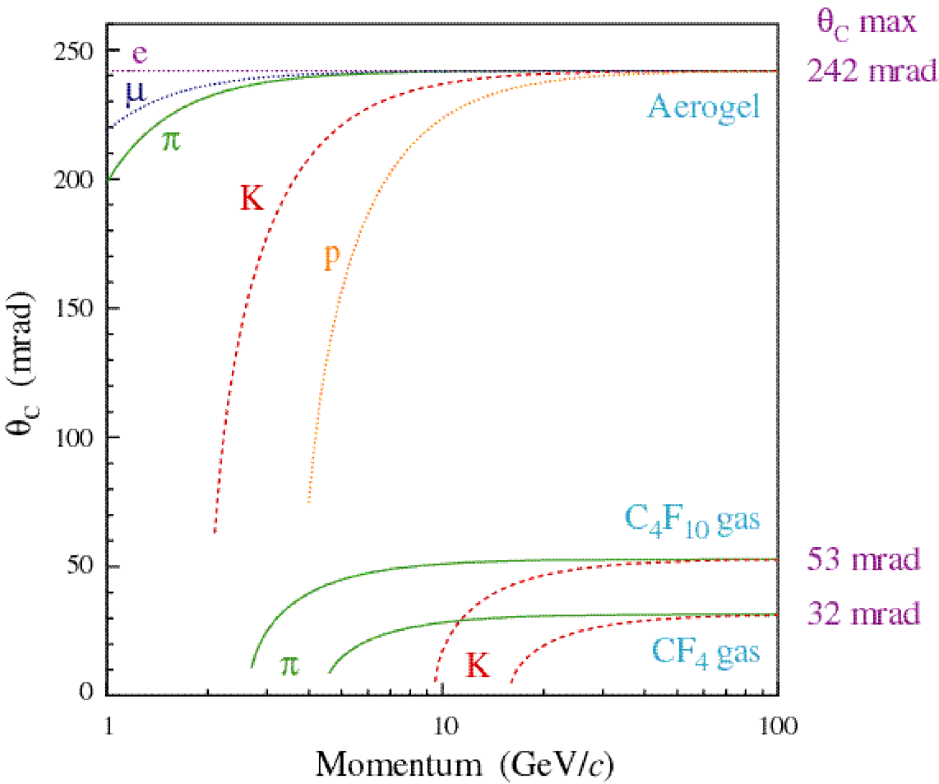
LHCb RICHes

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

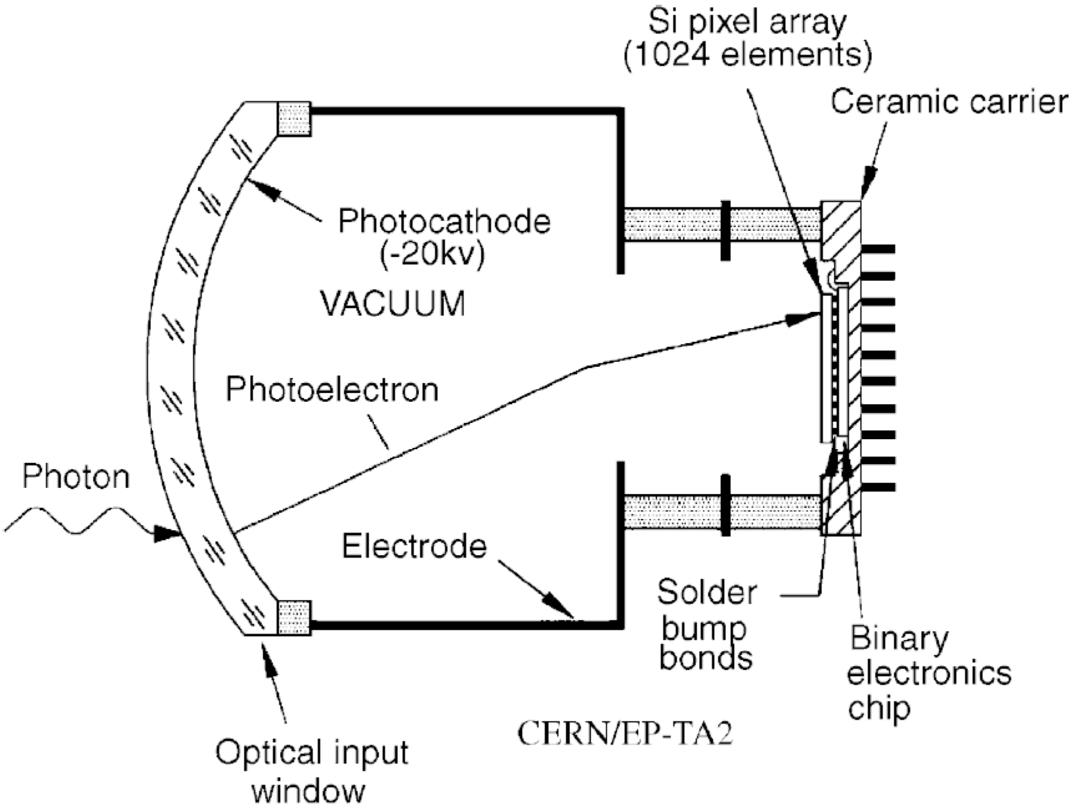
- Aerogel
- C_4F_{10}
- CF_4



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.



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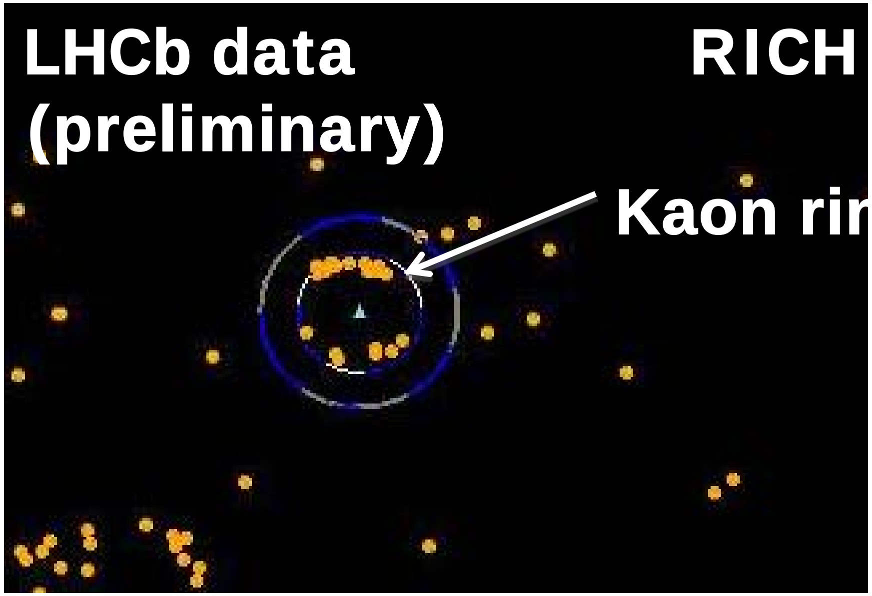
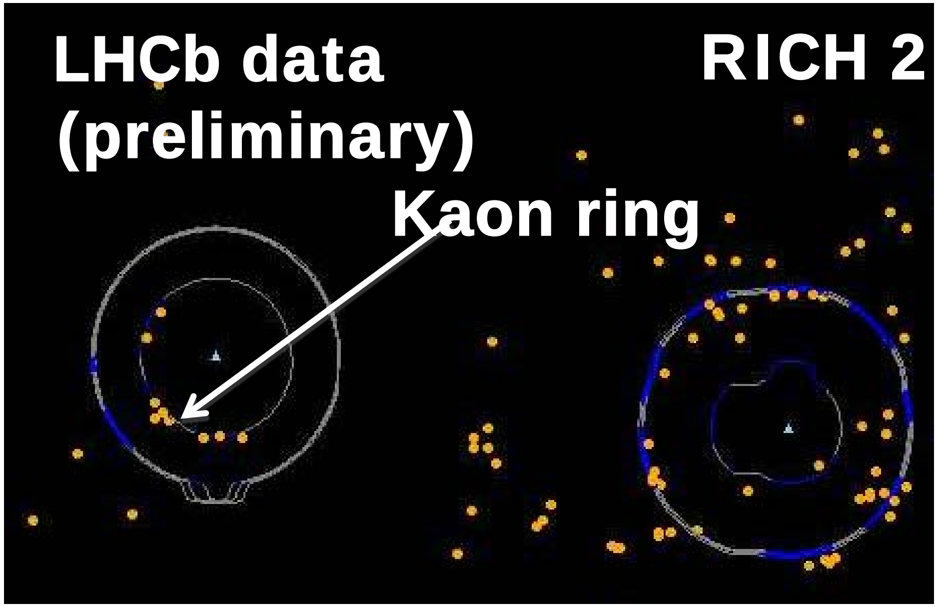
LHCb Event Display

RICH1

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

RICH2

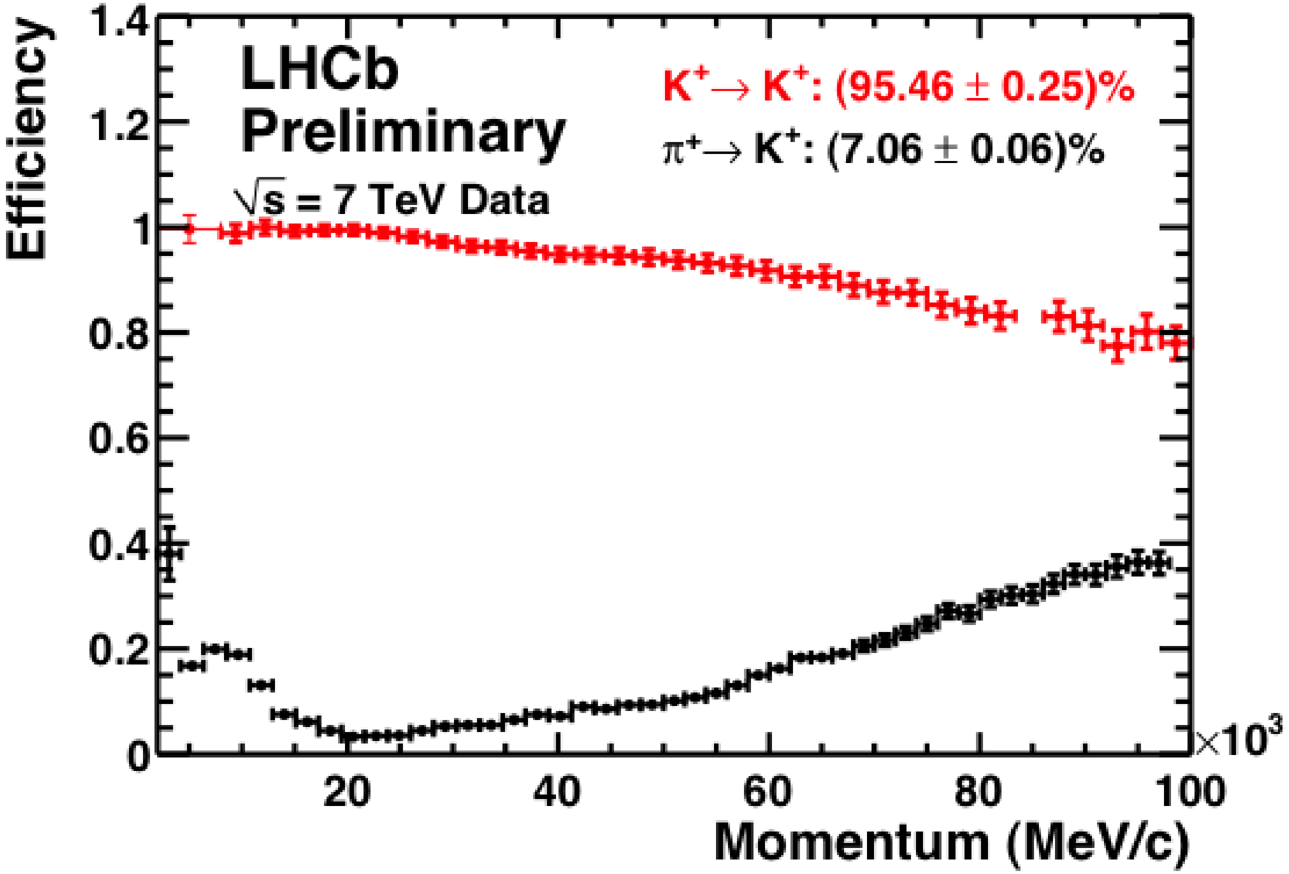


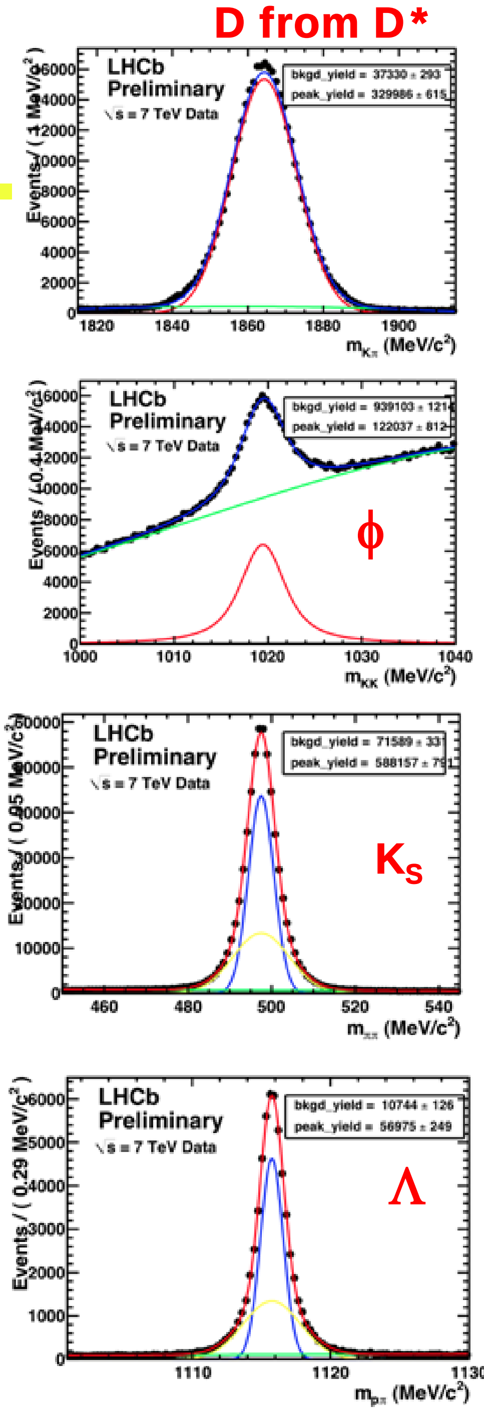


- Orange points → photon hits
- Continuous lines → expected distribution for each particle hypothesis

F. Muheim, RICH 2010

LHCb RICHes: performance

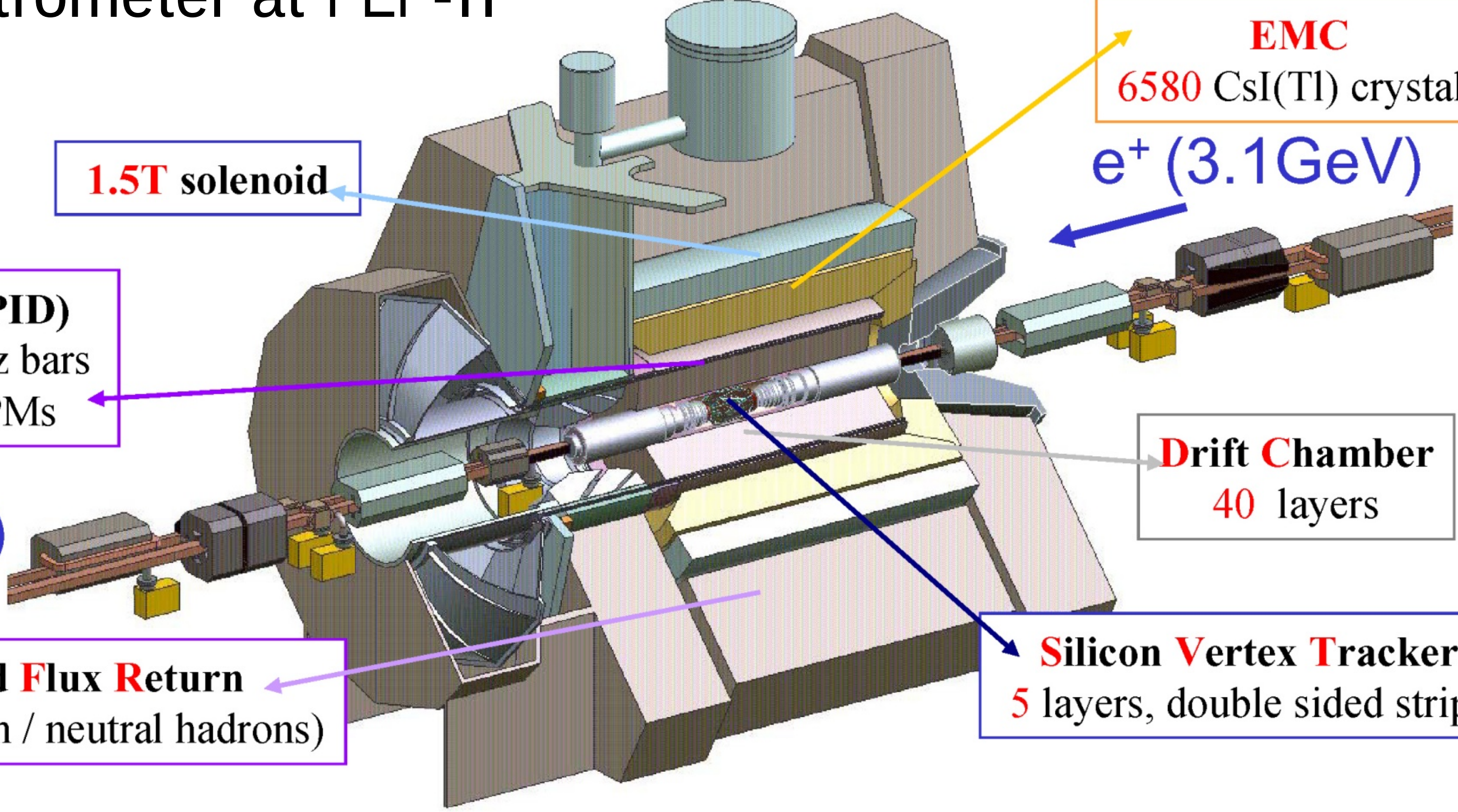




Efficiency and purity from data → excellent agreement with MC

DIRC - detector of internally reflected Cherenkov light

BaBar spectrometer at PEP-II



EMC
6580 CsI(Tl) crystals

e^+ (3.1GeV)

1.5T solenoid

DIRC (PID)
144 quartz bars
11000 PMs

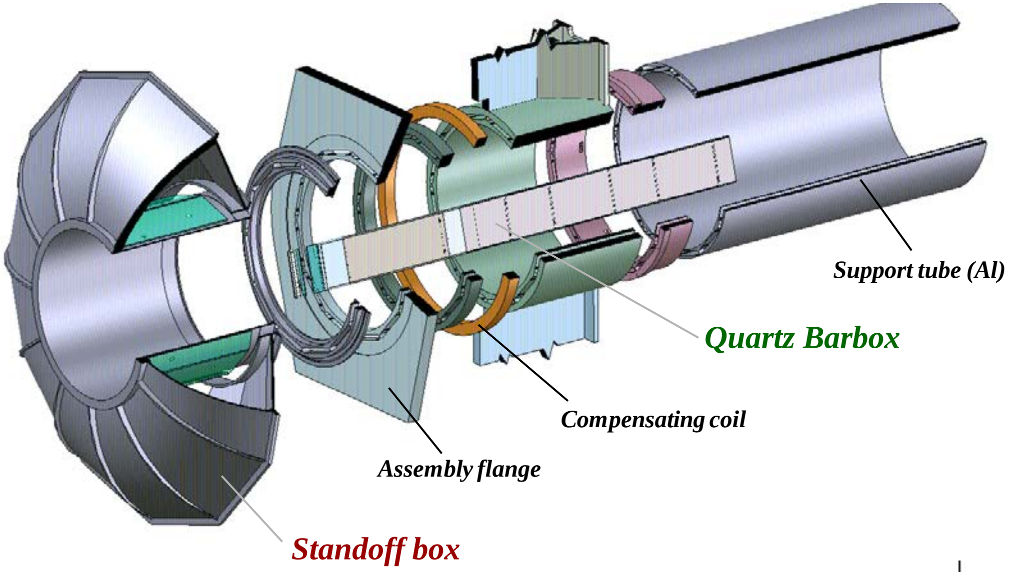
Drift Chamber
40 layers

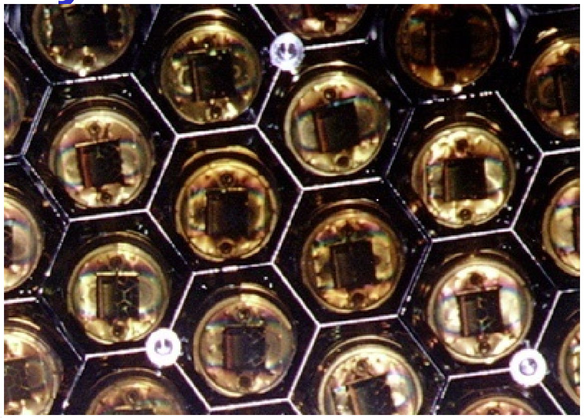
e^- (9GeV)

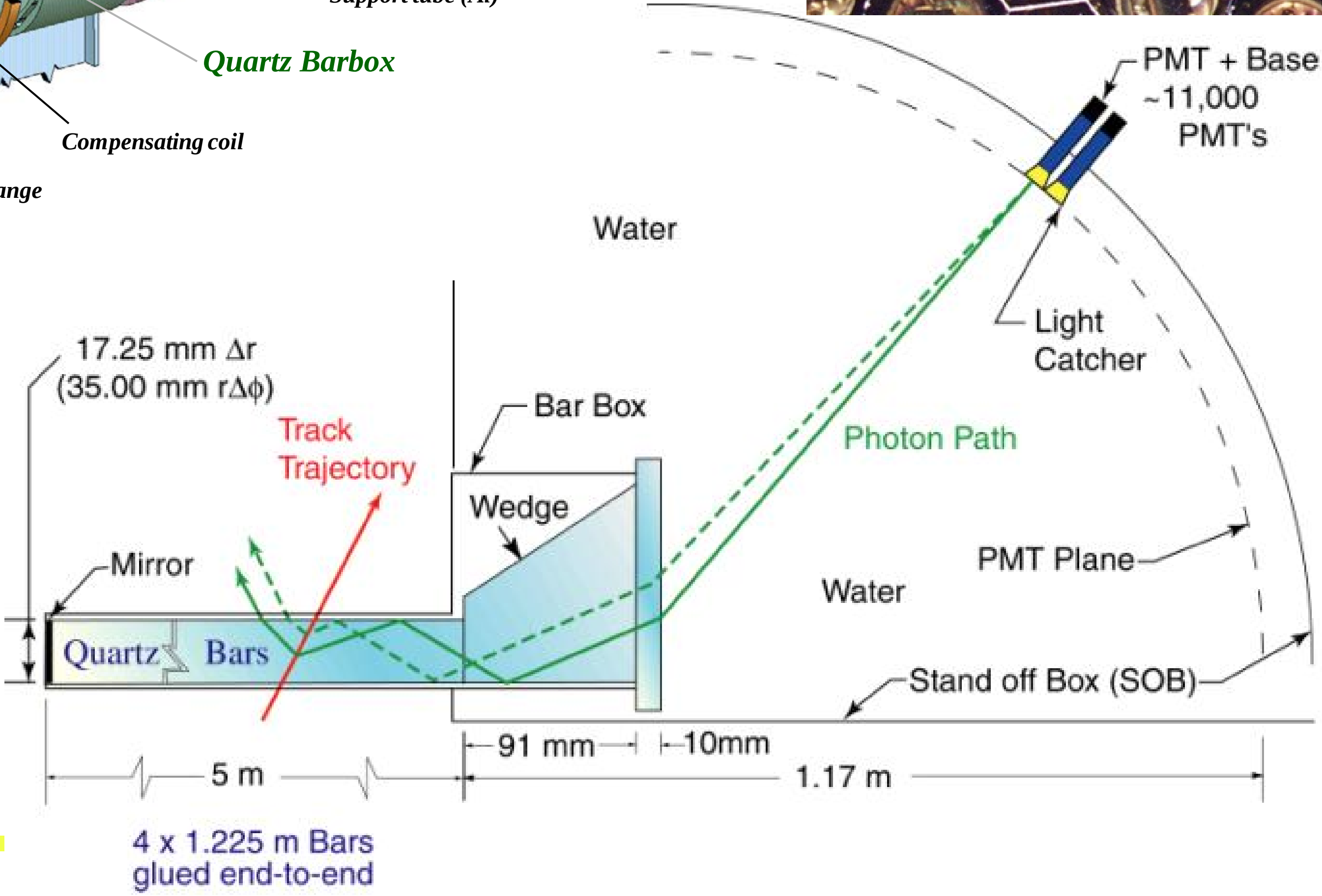
Silicon Vertex Tracker
5 layers, double sided strips

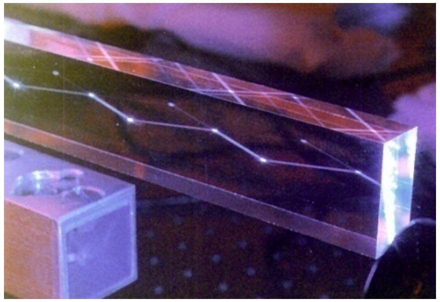
Instrumented Flux Return
iron / RPCs (muon / neutral hadrons)

DIRC (@BaBar) - detector of internally reflected Cherenkov light

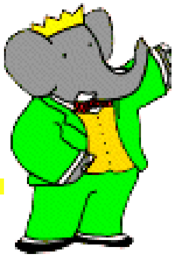


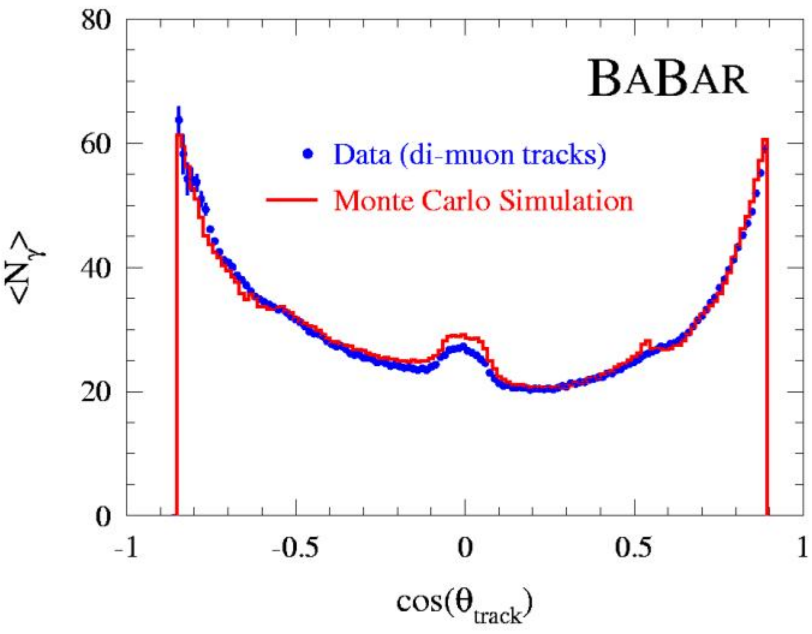






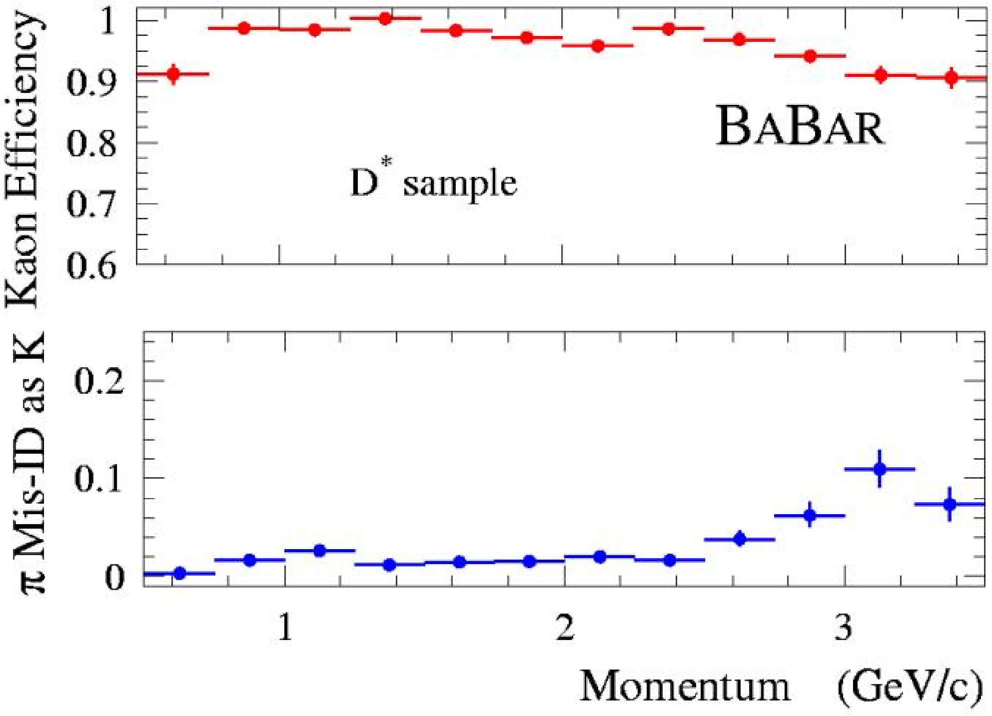
DIRC performance





← Lots of photons!

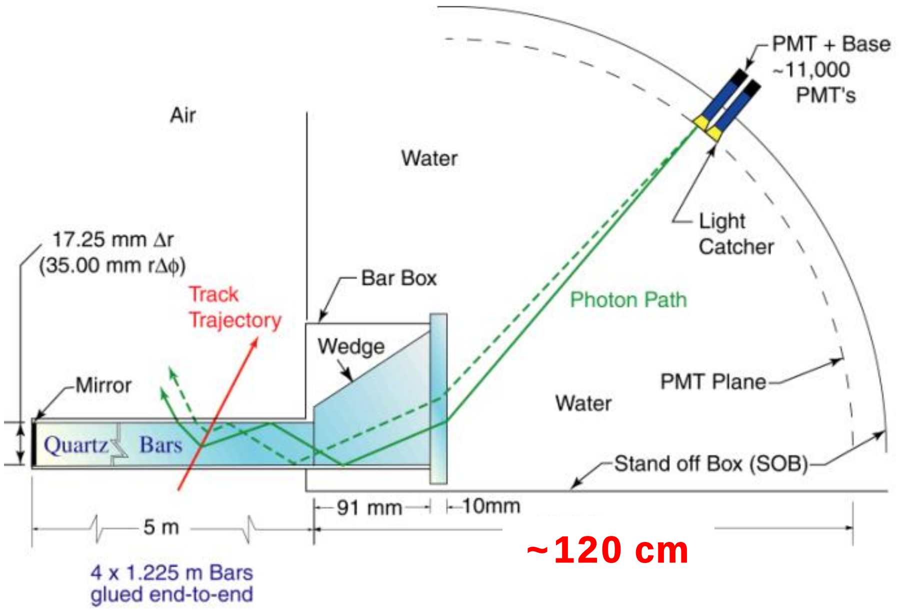
Excellent π/K separation

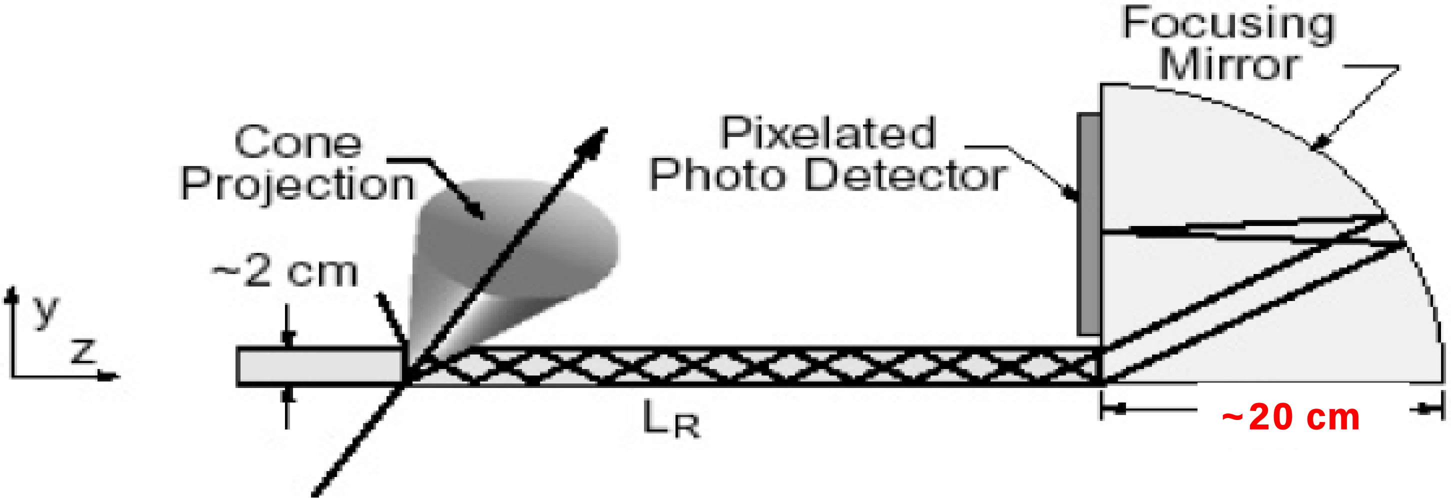


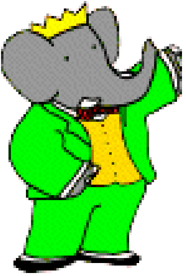
NIM A553 (2005) 317

Focusing DIRC

Upgrade: step further, remove the stand-off box →







Focusing DIRC

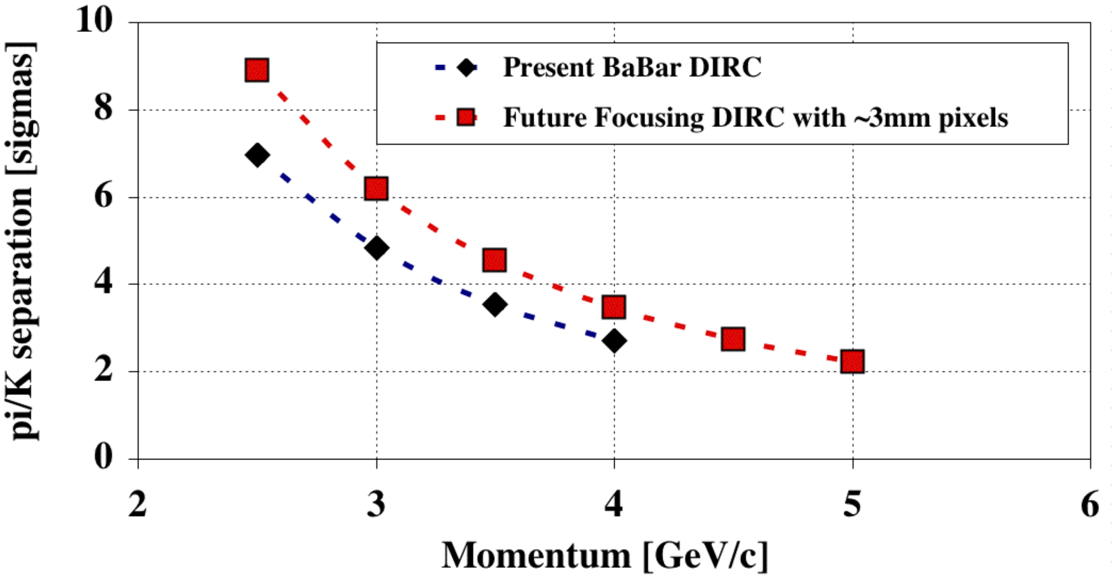
Super-B factory: 100x higher luminosity => DIRC needs to be smaller and faster

Focusing and smaller pixels can reduce the expansion volume by a factor of 7-10

Timing resolution improvement: σ ~1.7ns (BaBar DIRC) → σ ≤150-200ps (~10x better) allows a measurement of the photon group velocity $c_g(\lambda)$ to correct the chromatic error of θ_c.

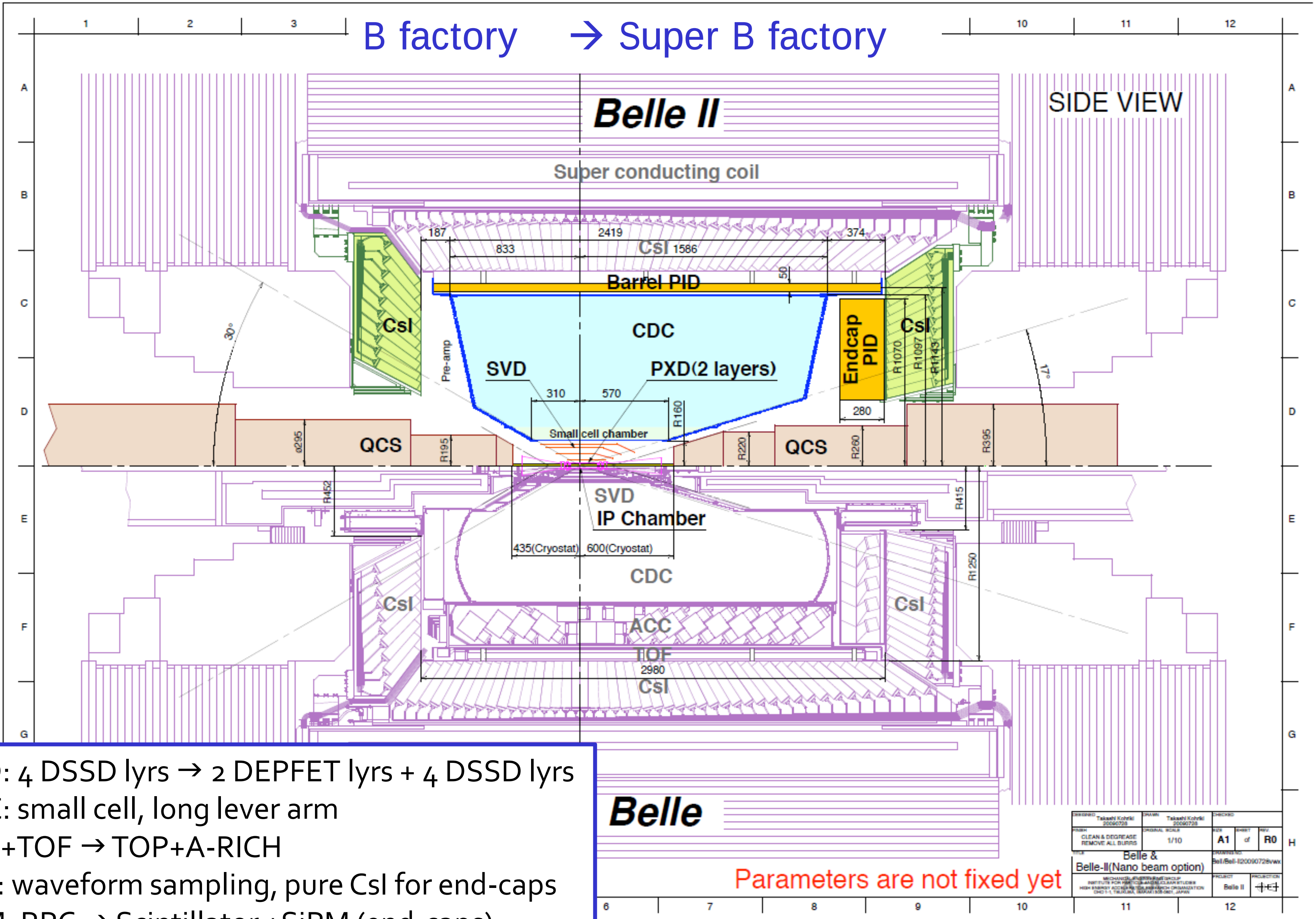
Photon detector:

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



Belle → Belle II

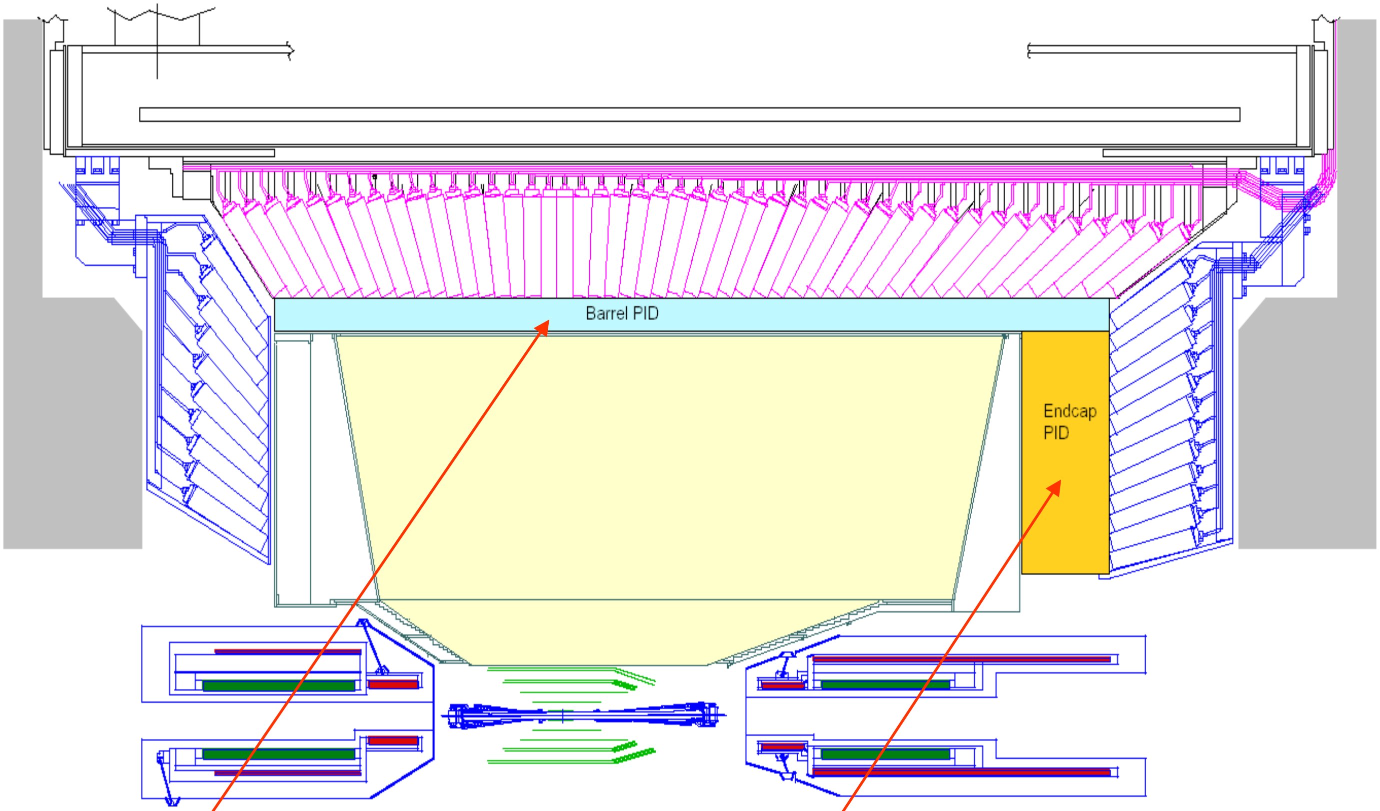
B factory → Super B factory



Parameters are not fixed yet

SVD: 4 DSSD lyrs → 2 DEPFET lyrs + 4 DSSD lyrs
CDC: small cell, long lever arm
ACC+TOF → TOP+A-RICH
ECL: waveform sampling, pure CsI for end-caps
KLM: RPC → Scintillator +SiPM (end-caps)

Belle II PID systems – side view

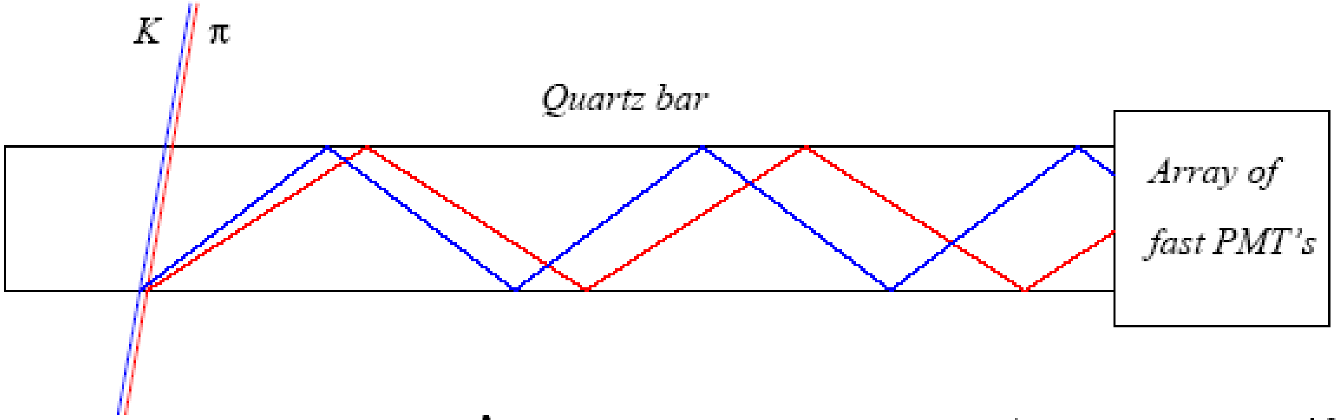


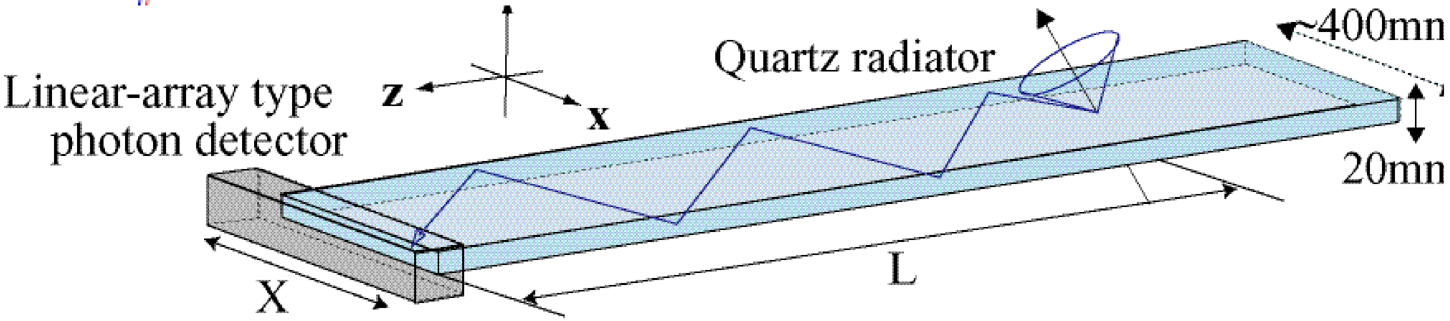
Two new particle ID devices, both RICHes:

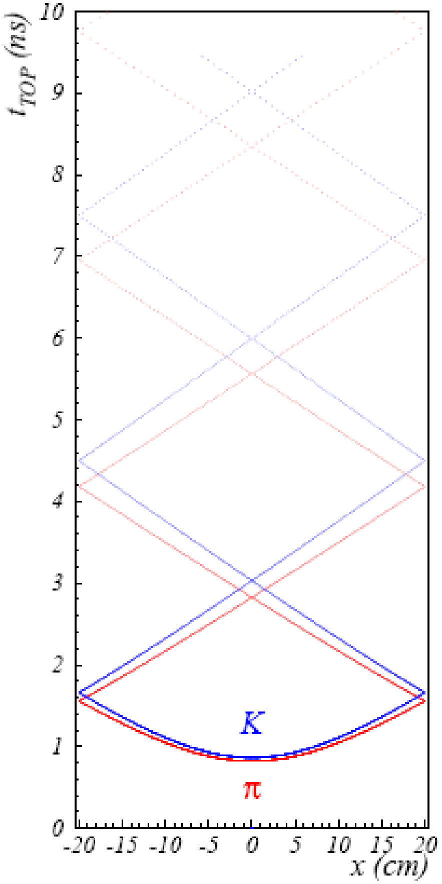
Barrel: time-of-propagation (TOP) counter

Endcap: proximity focusing RICH

Time-Of-Propagation (TOP) counter



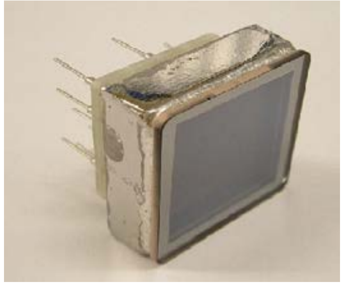




Similar to DIRC, but instead of two coordinates measure:

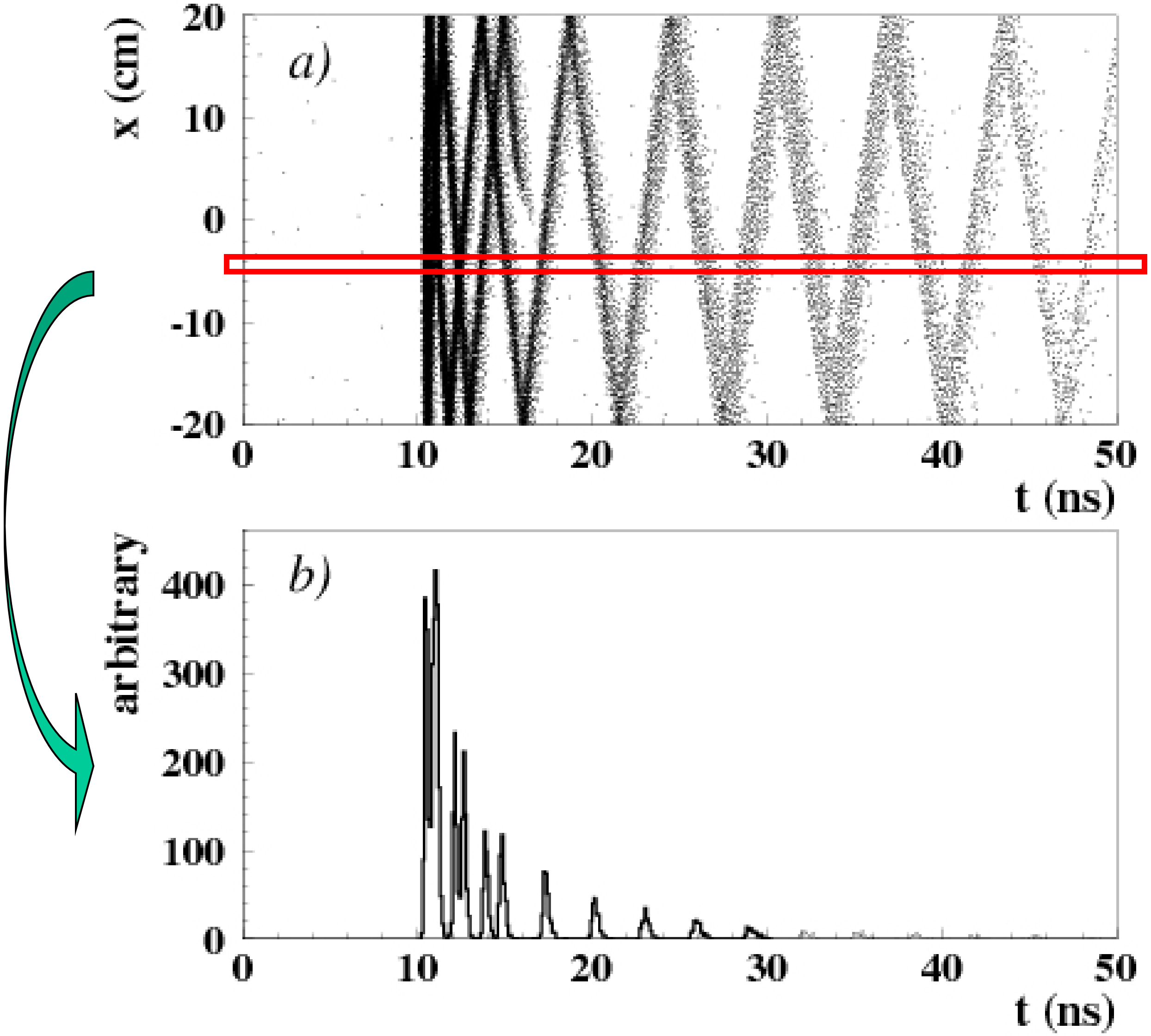
- One (or two coordinates) with a few mm precision
- Time-of-arrival

→ Excellent time resolution < ~40ps
required for single photons in 1.5T B field



Hamamatsu
SL10 MCP-PMT

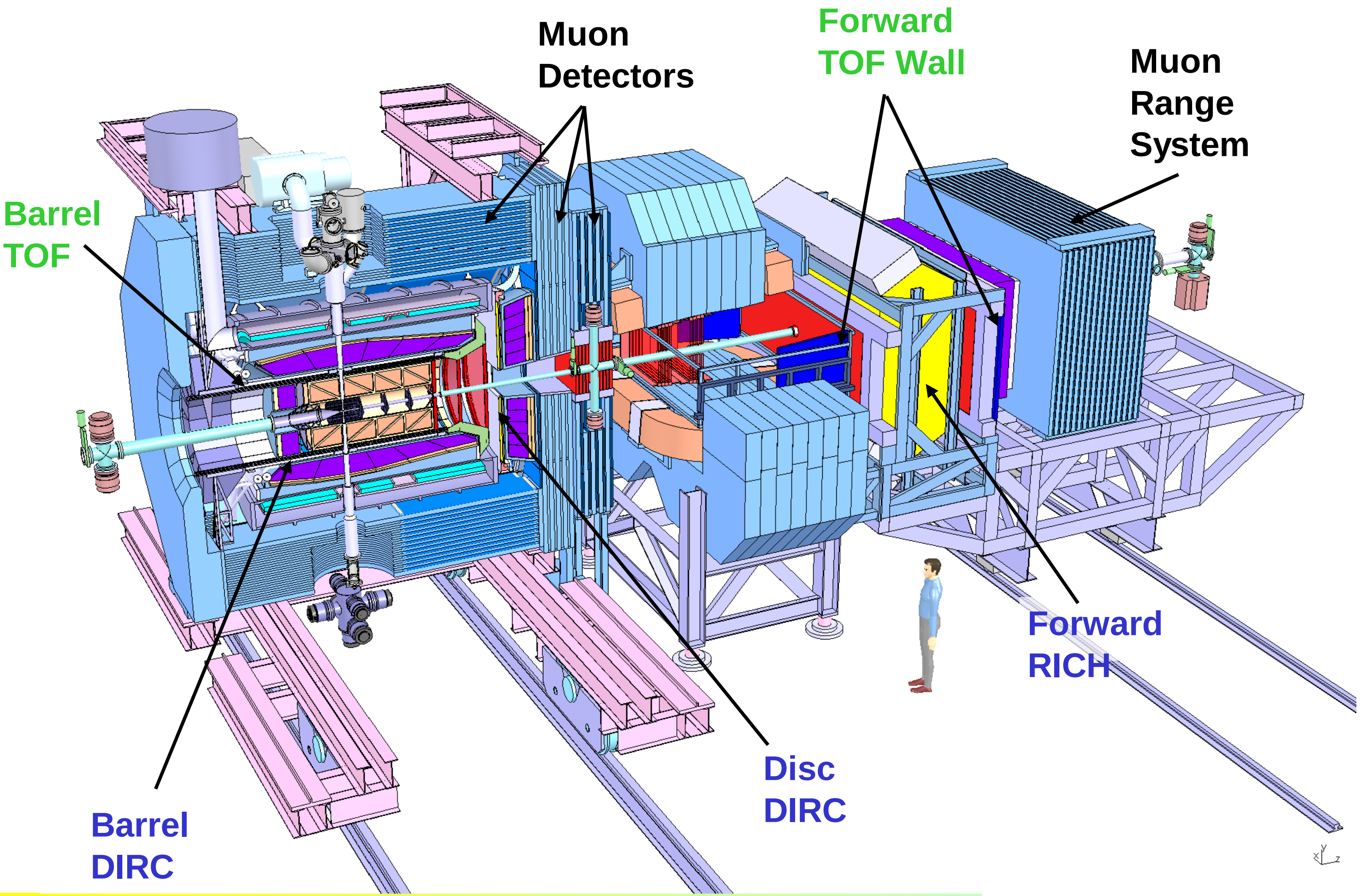
TOP image



Pattern in the coordinate-time space ('ring') of a pion hitting a quartz bar with ~80 MAPMT channels

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

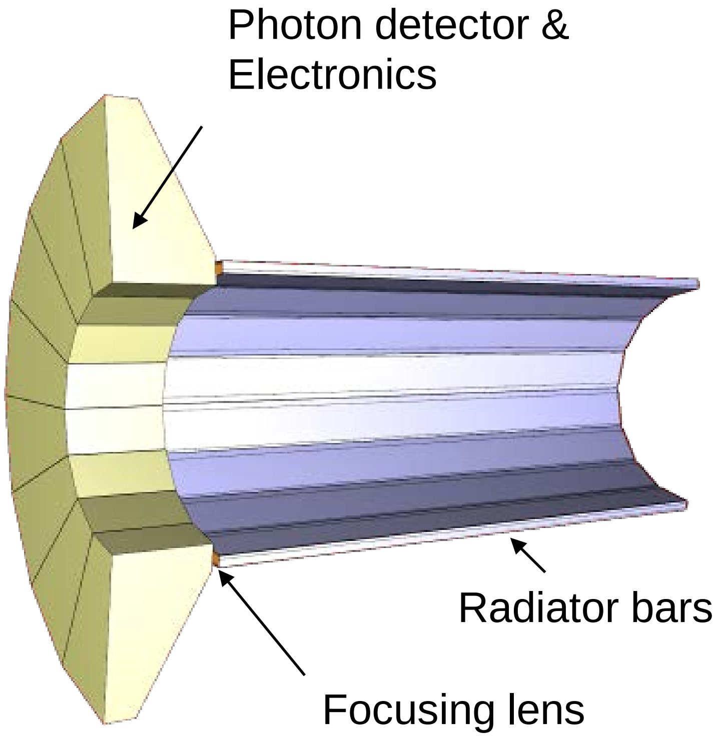
PID for PANDA



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 (Burle Planacon) in magnetic field 0.5 -1 T

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



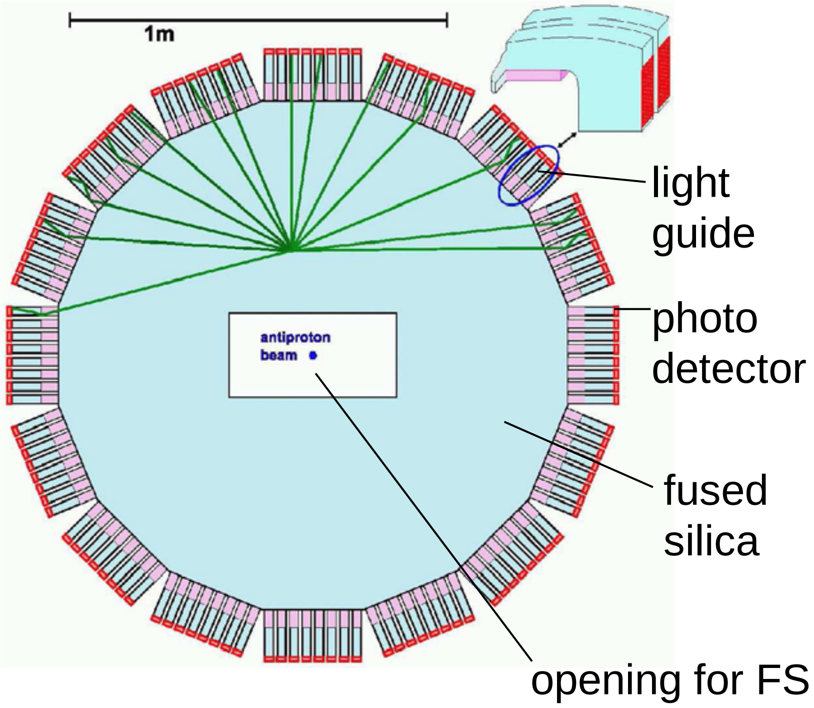
Disc DIRC

Radiator: fused silica 20 mm thick,
R =1m

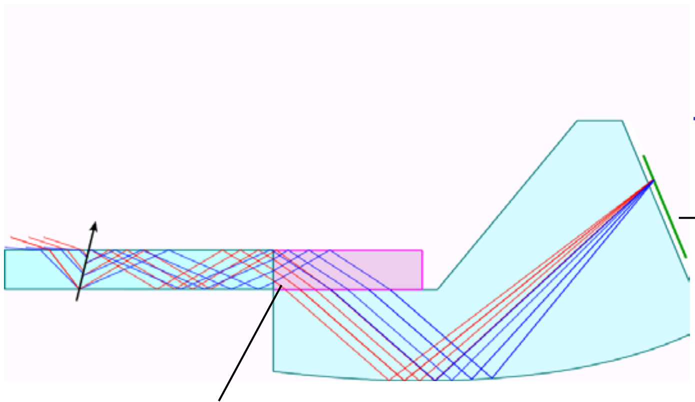
π/K separation up to 4 GeV/c

Focusing light guide

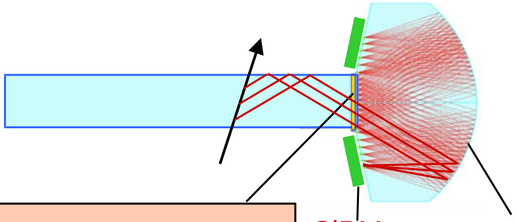
Photon detector in ~1T field
capable of rates 0.75 MHz/cm^2
(MCP-PMTs or dSiPMs)



Two options for light guides



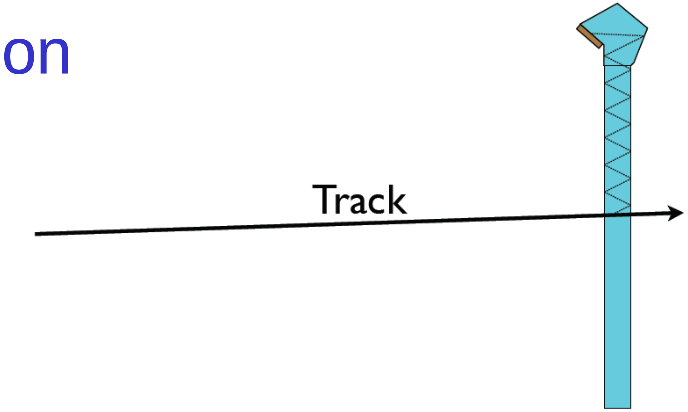
dispersion correction: LiF block

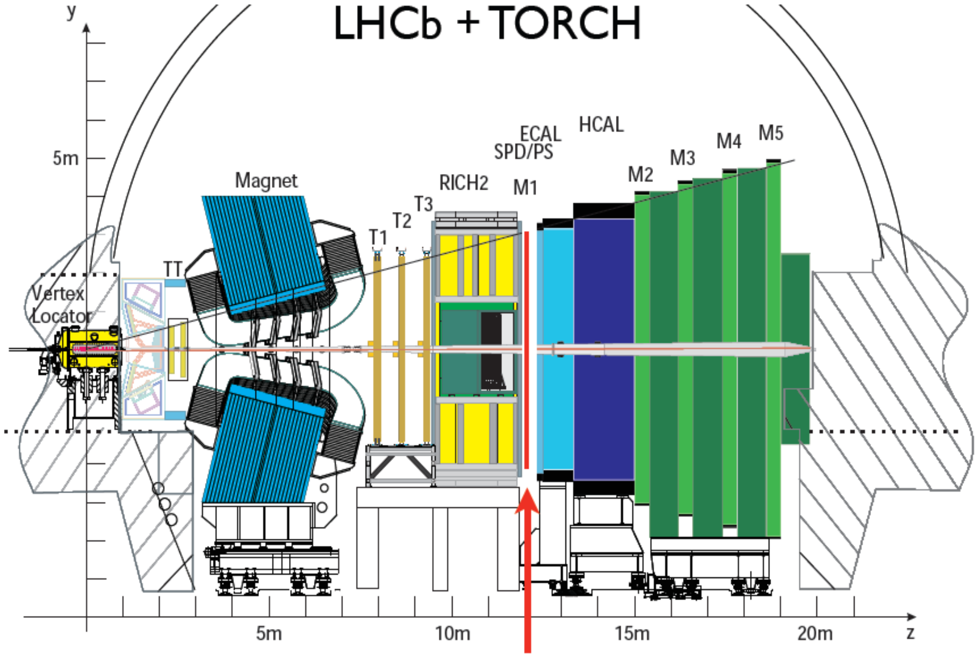


dispersion correction: dichroic mirror

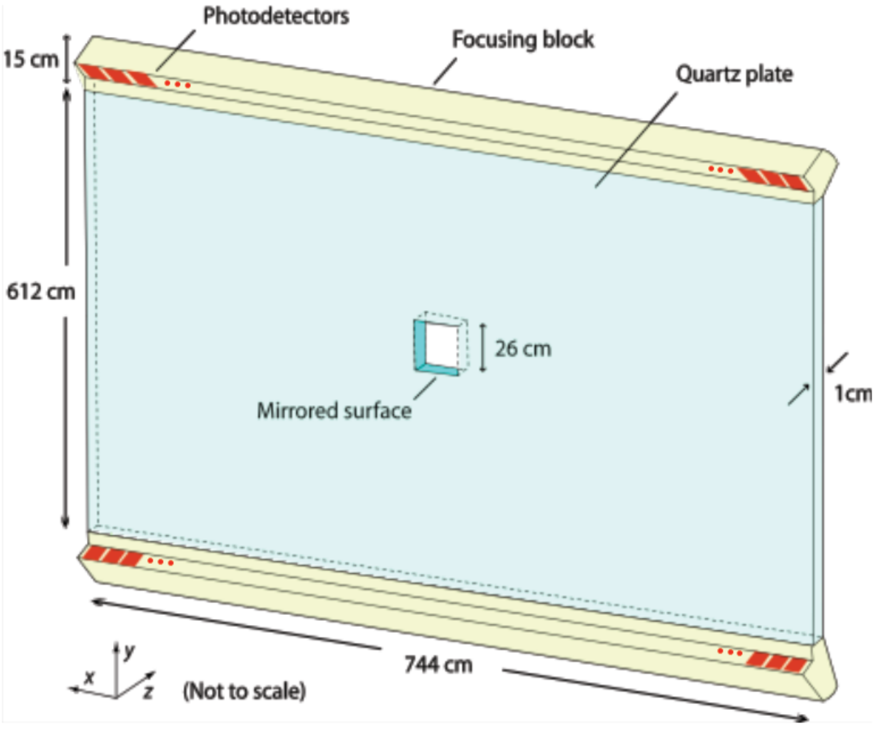
LHCb PID upgrade: TORCH

A special type of Time-of-Propagation counter for the LHCb upgrade



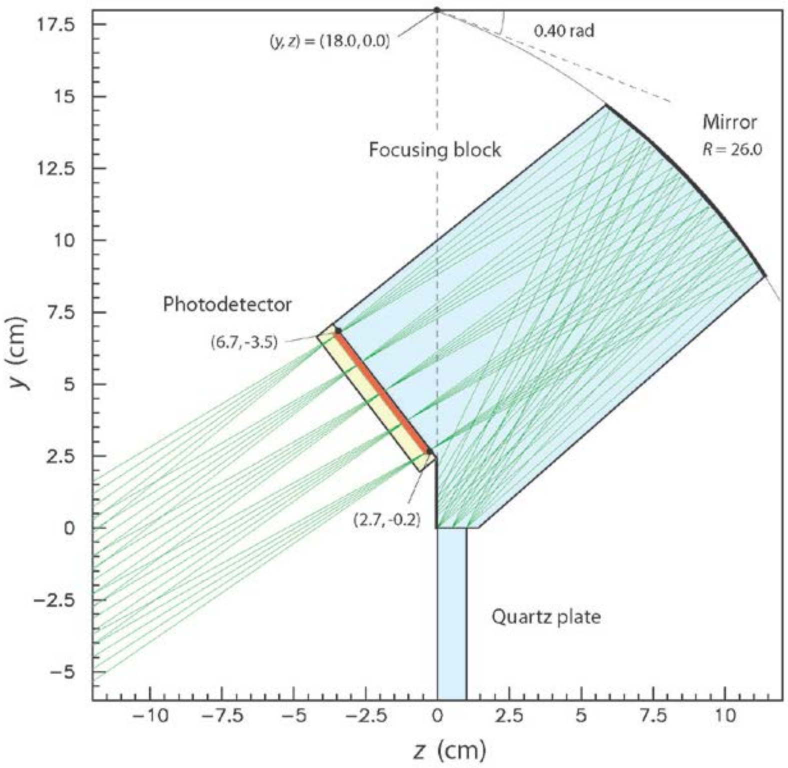


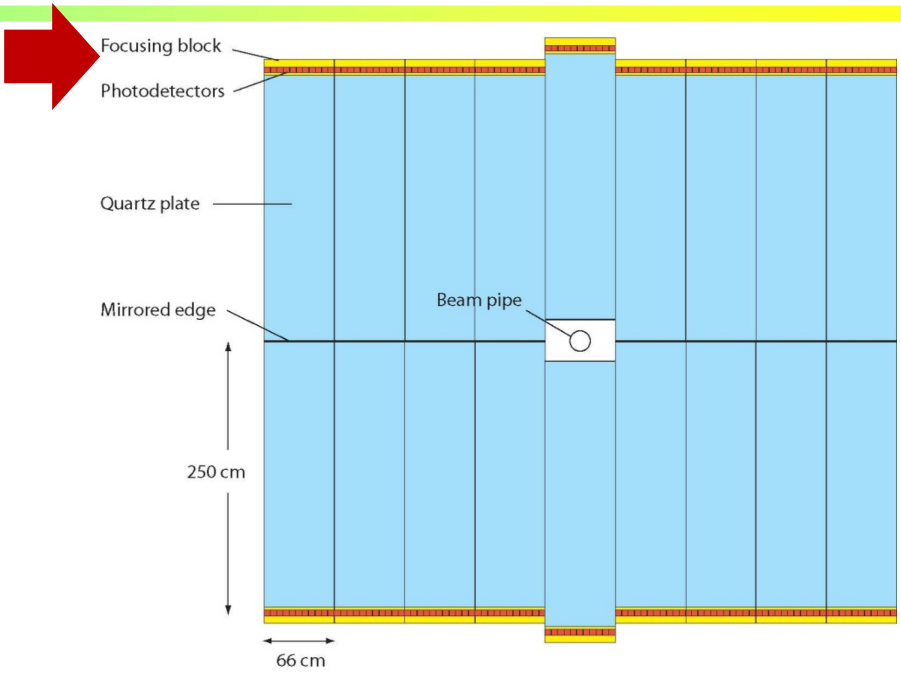
1cm-thick quartz plate at z=12m

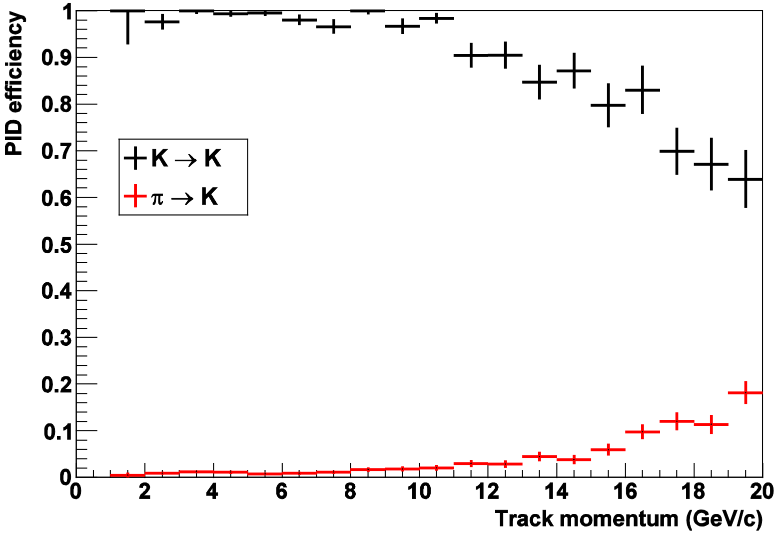


Sides are instrumented too (not shown)

LHCb PID upgrade: TORCH

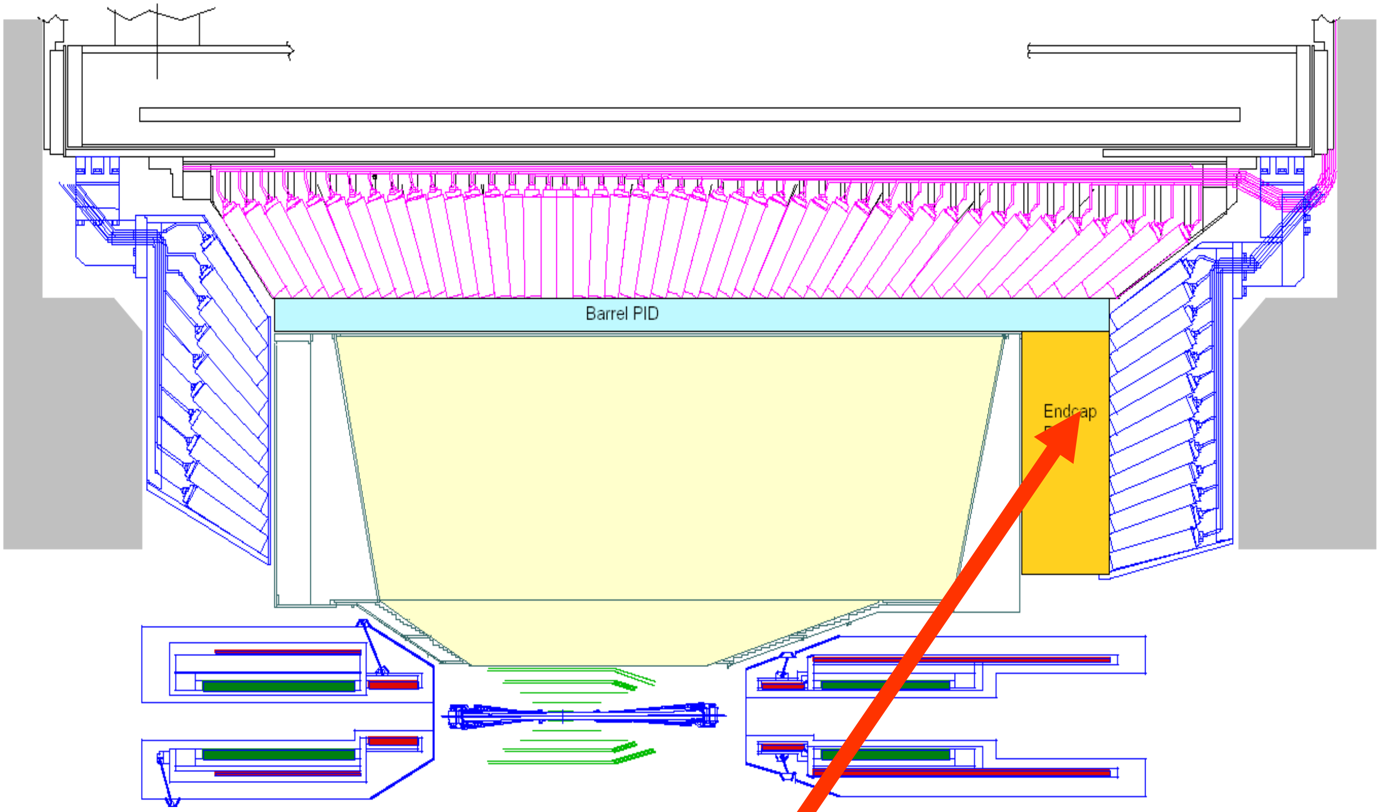






Expected performance with Photonis Planacon MCP PMTs

Belle II PID system

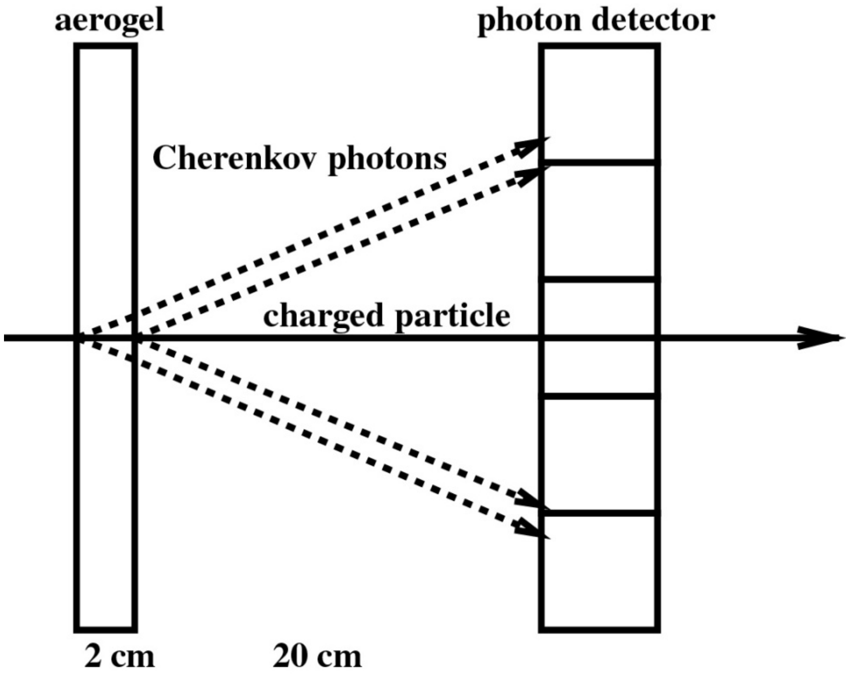


Two new particle ID devices, both RICHes:

Barrel: Time-of-propagation counter (TOP) counter

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

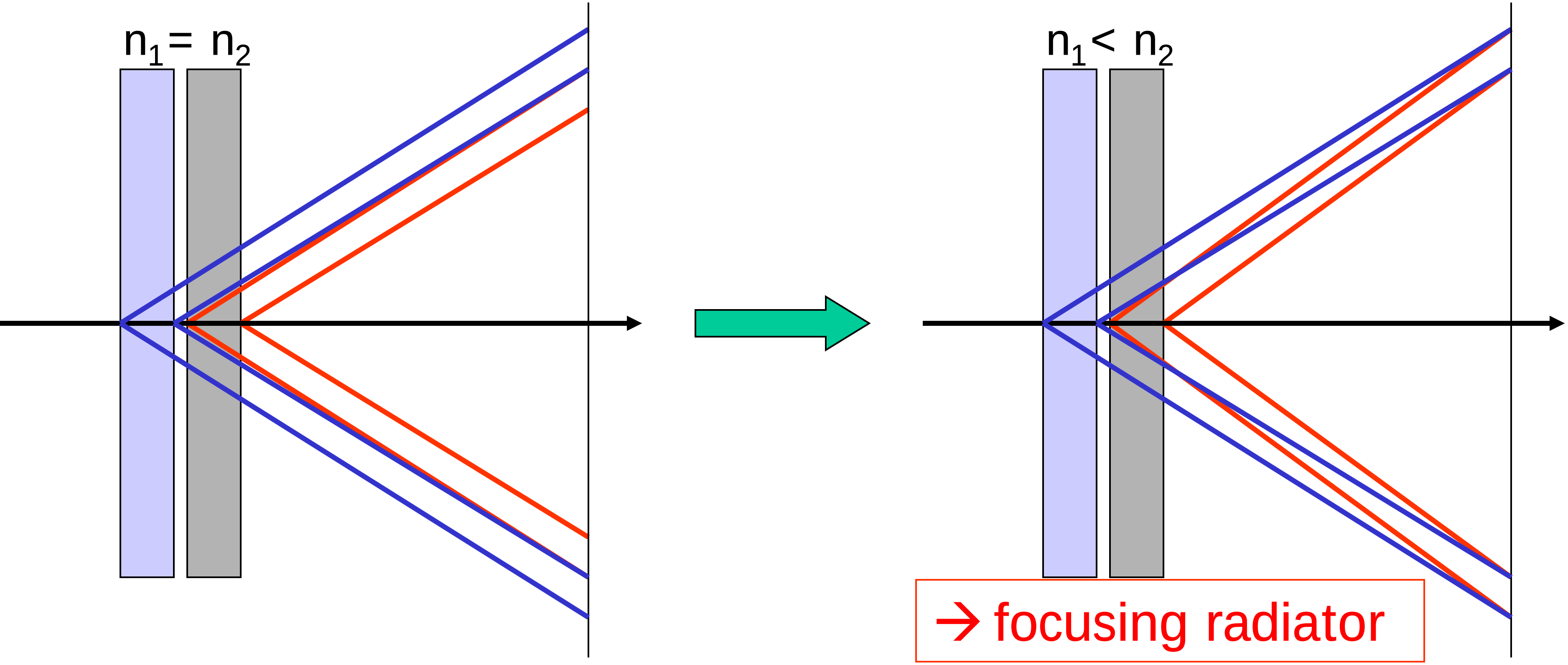
→ 5σ separation with $N_{pe} \sim 10$

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

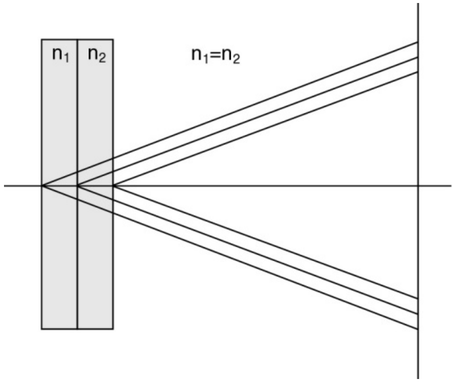


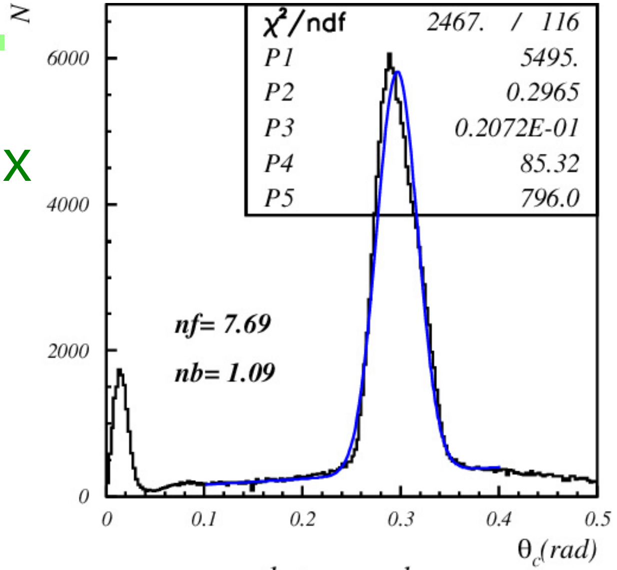
→ focusing radiator

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.

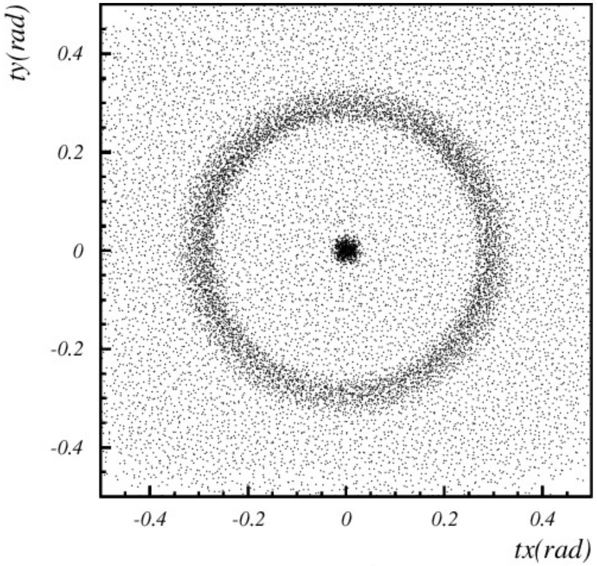
Focusing configuration – data

4cm aerogel single index



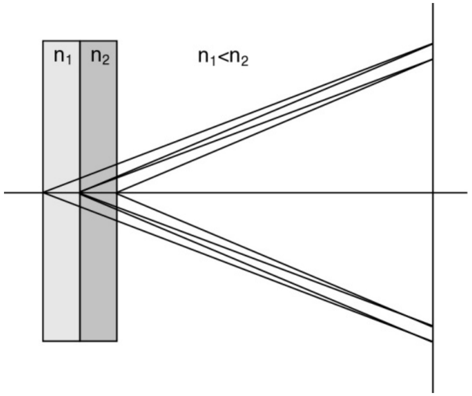


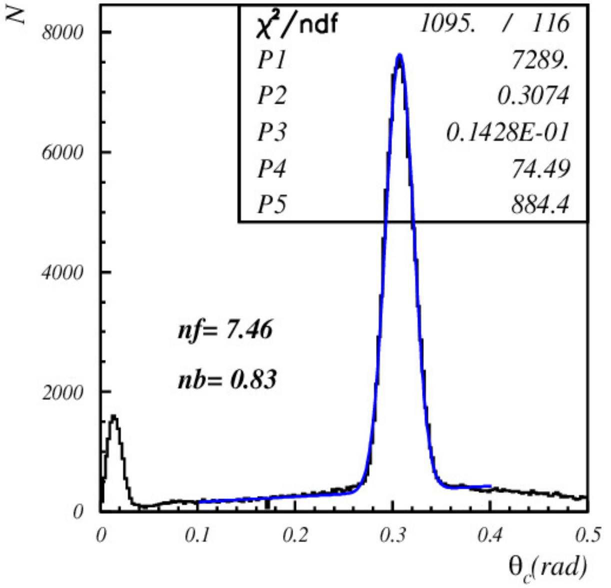
theta cerenkov

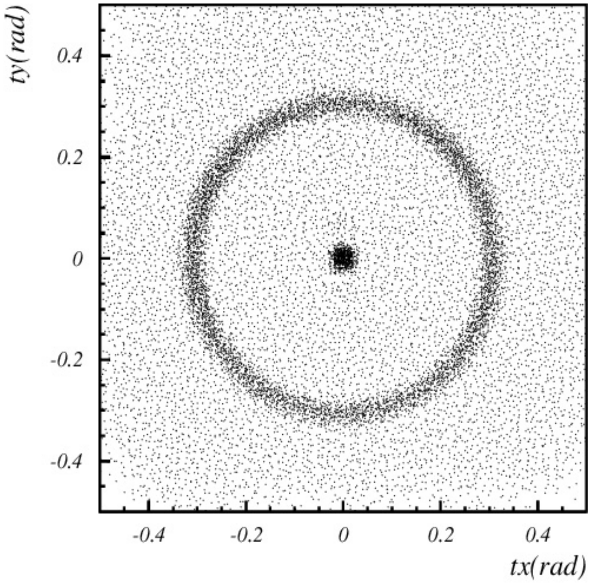


ring in cerenkov space

2+2cm aerogel





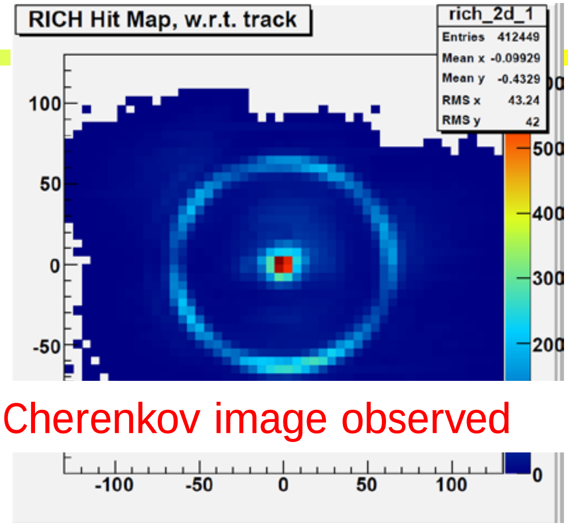


→NIM A548 (2005) 383, NIMA 565 (2006) 457

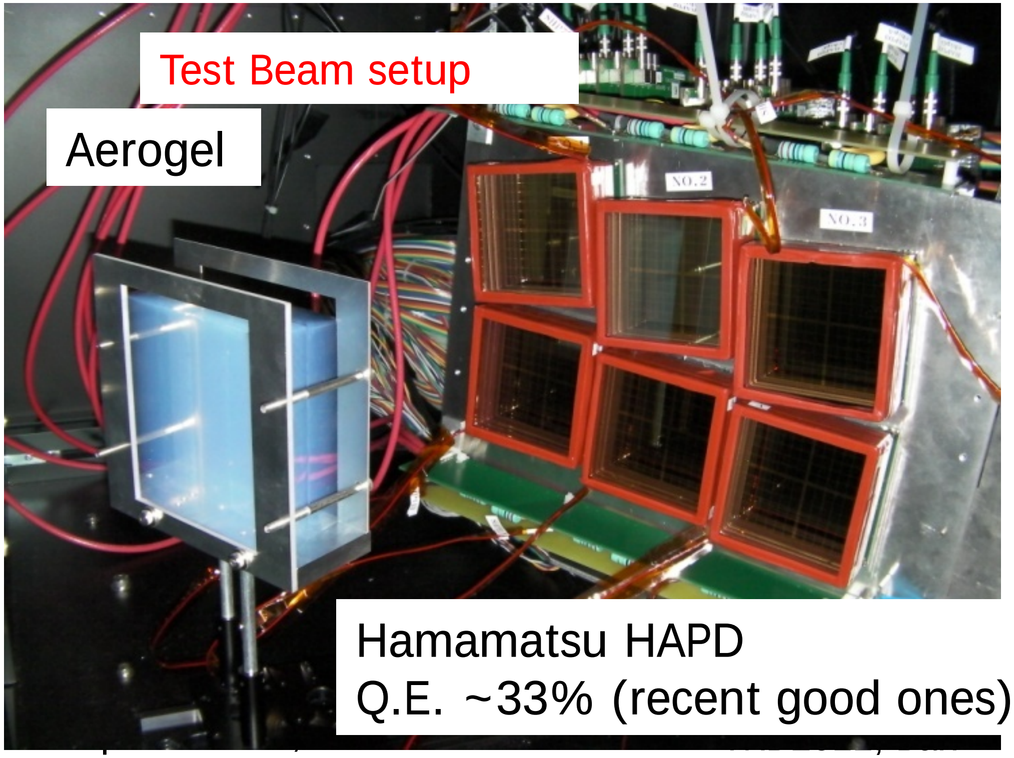
Aerogel RICH photon detectors

Need:
Operation in 1.5 T magnetic field
Pad size ~5-6mm

Baseline option: large active area HAPD of the proximity focusing type



Clear Cherenkov image observed

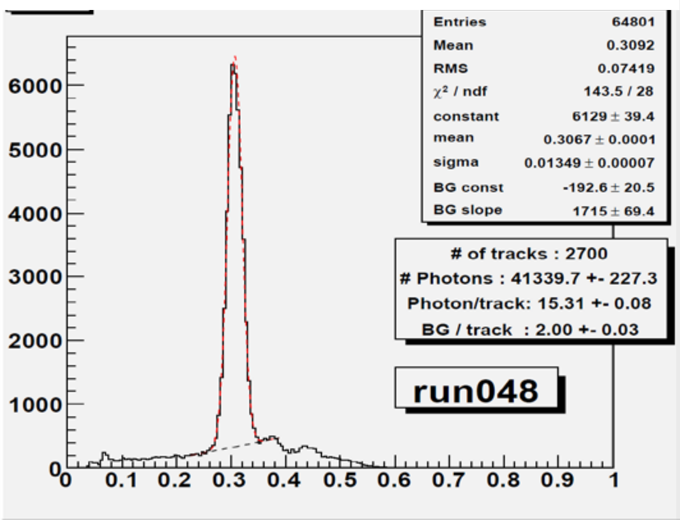


Test Beam setup

Aerogel

Hamamatsu HAPD
Q.E. ~33% (recent good ones)

Cherenkov angle distribution

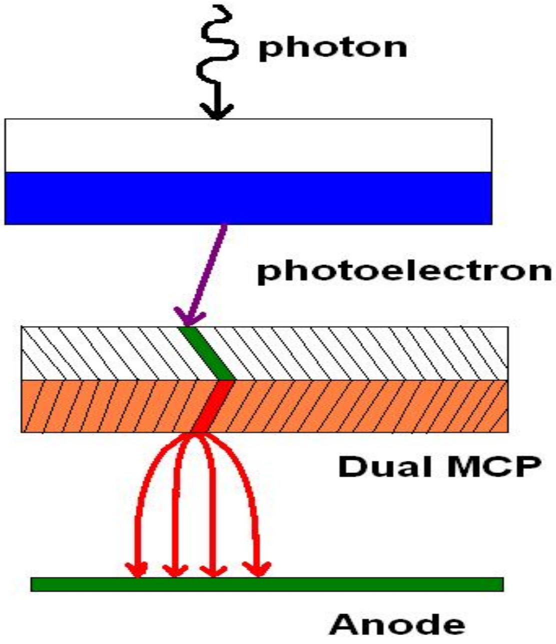


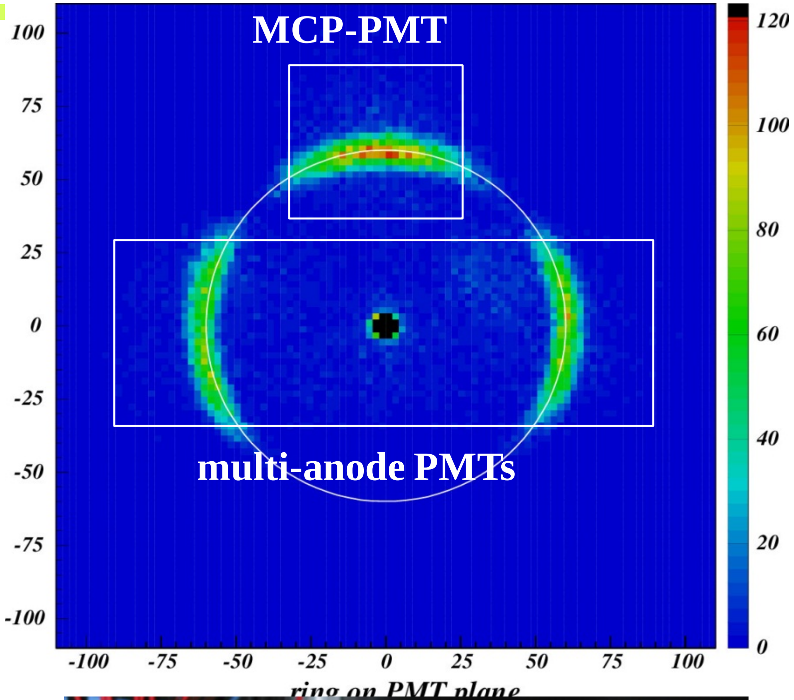
6.6 σ p / K at 4GeV / c !

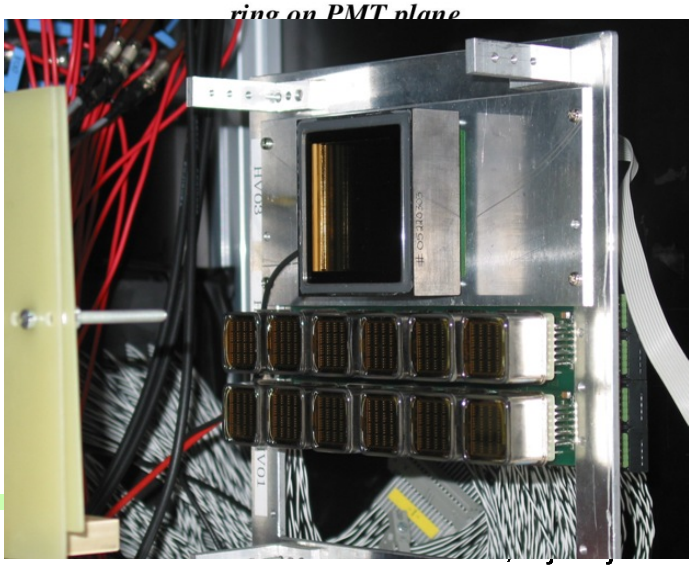
→ NIM A595 (2008) 180

Fallback solution: BURLE/Photonis Planacon MCP-PMT

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



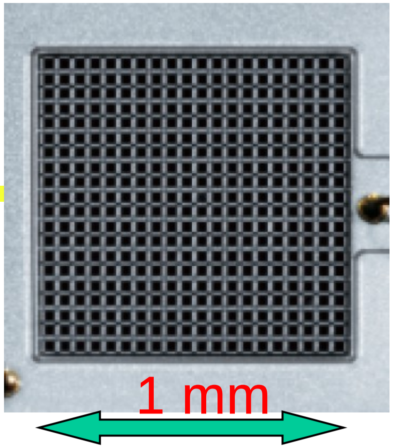




→good performance in beam and bench tests, NIMA567 (2006) 124

→ very fast (σ_t < 40 ps)

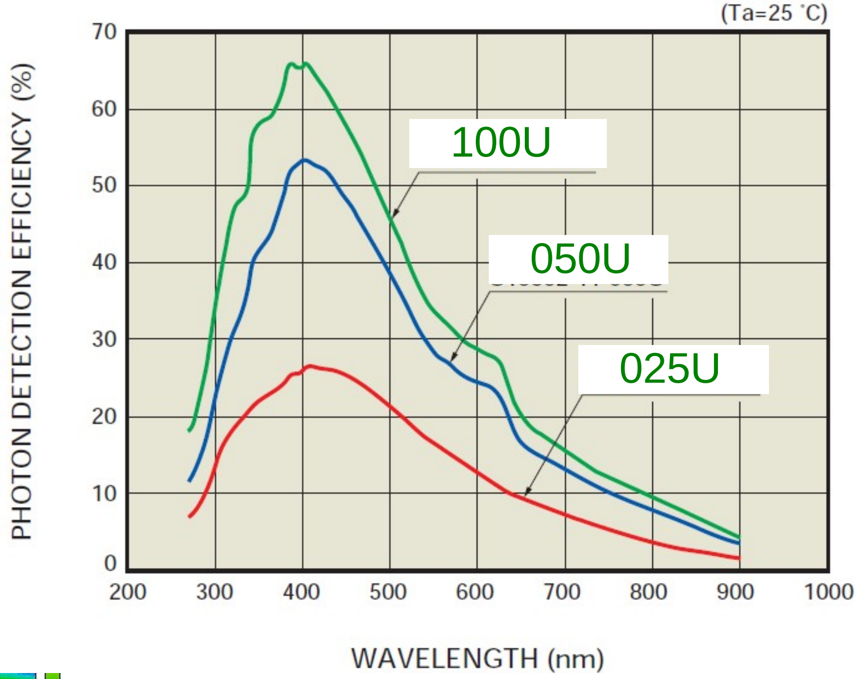
SiPMs as photon detectors?

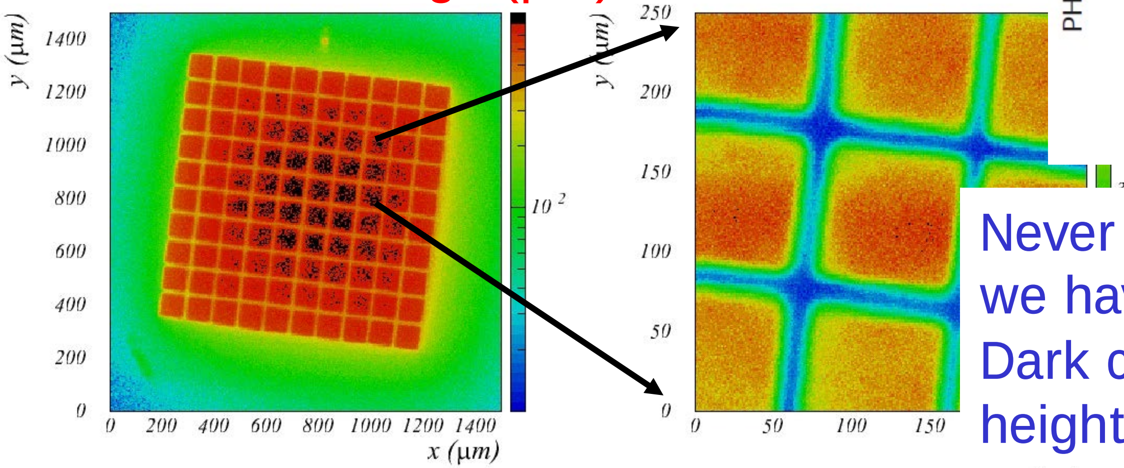


SiPM is an array of APDs operating in Geiger mode. Characteristics:

- 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)





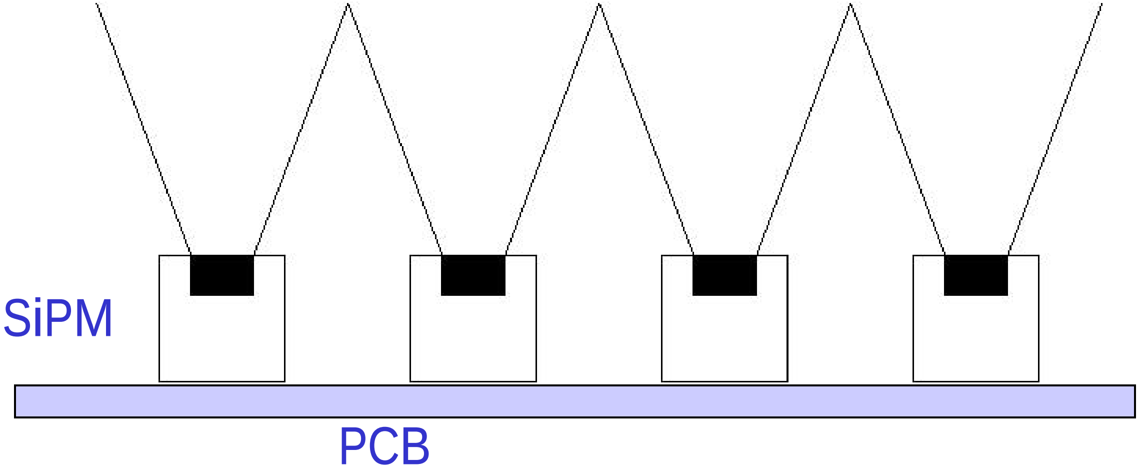
Never before tested in a RICH where we have to detect single photons. ← Dark counts have single photon pulse heights (rate 0.1-1 MHz)

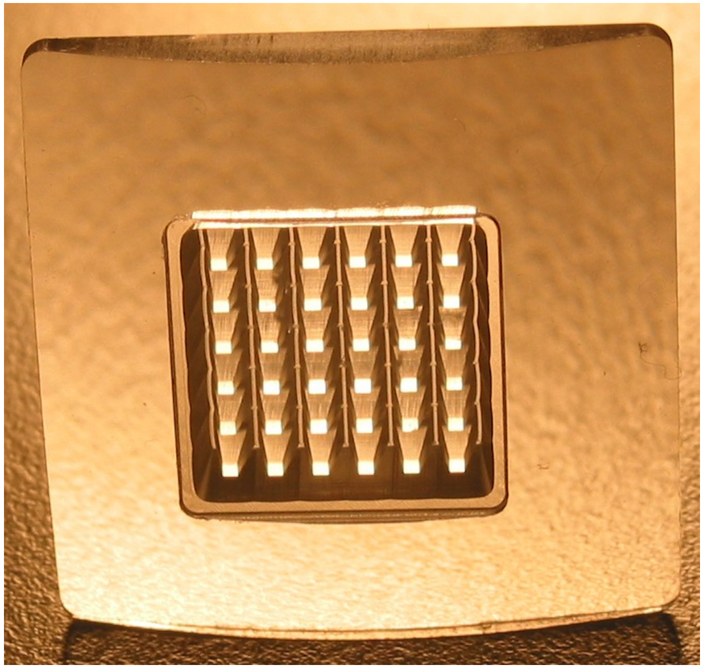
Can such a detector work?

Improve the signal to noise ratio:

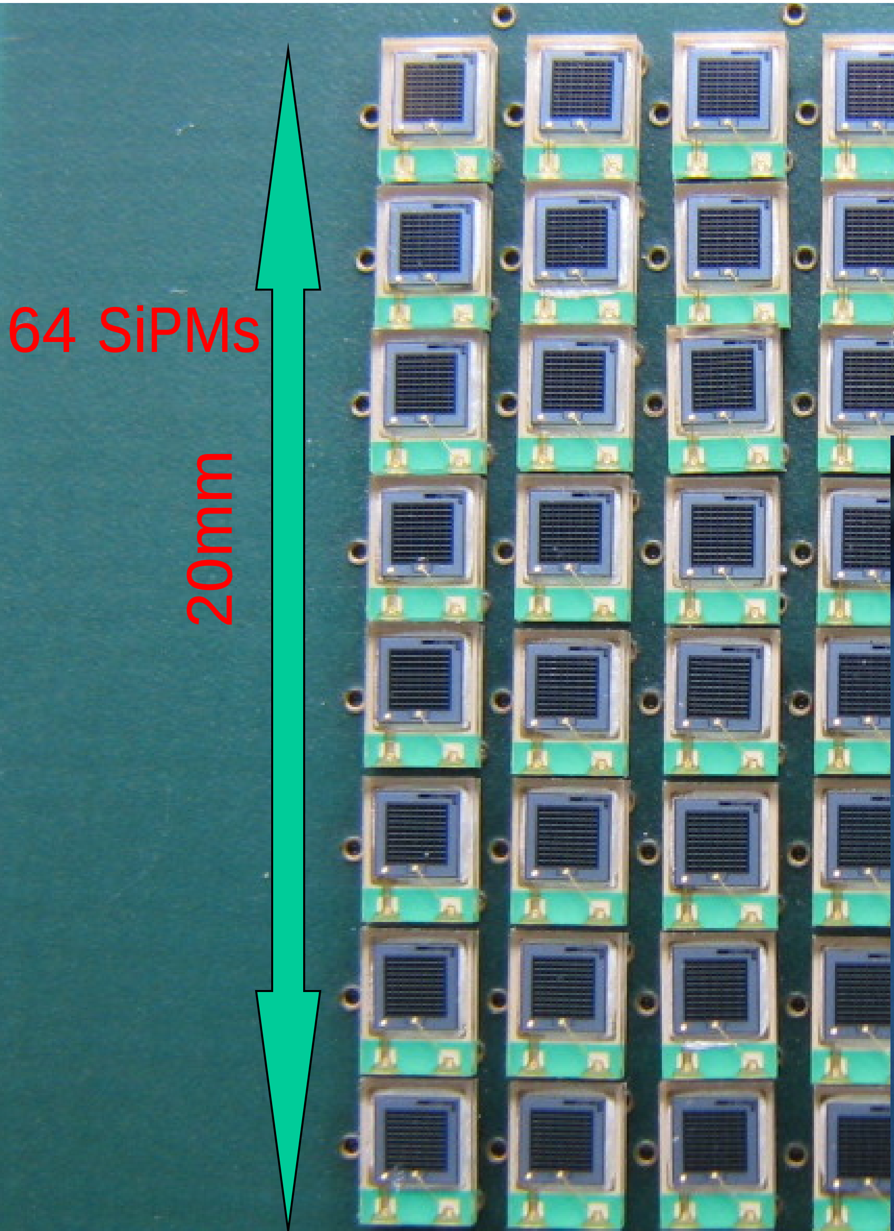
- Reduce the noise by a narrow (<10ns) time window
- Increase the number of signal hits per single sensor by using light collectors and by adjusting the pad size to the ring thickness

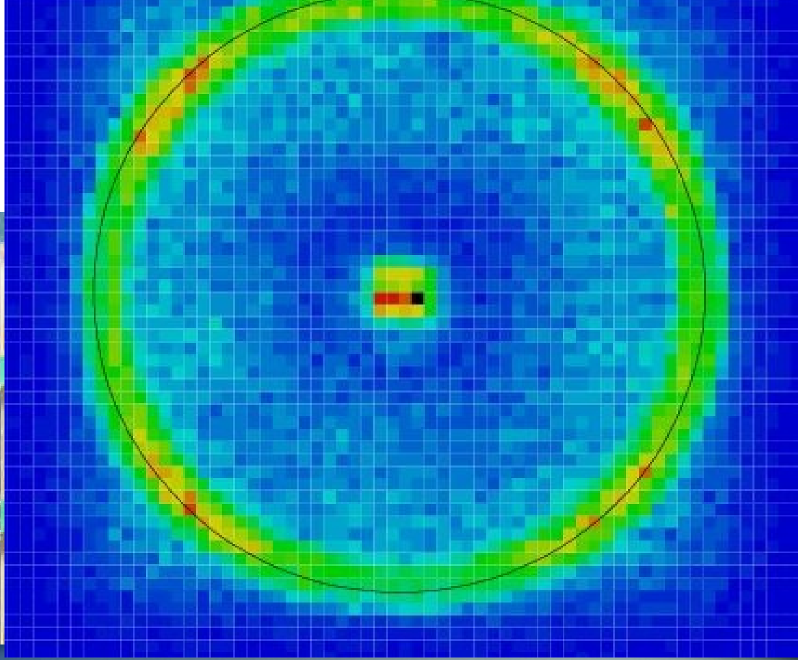
E.g. light collector with reflective walls or plastic light guide

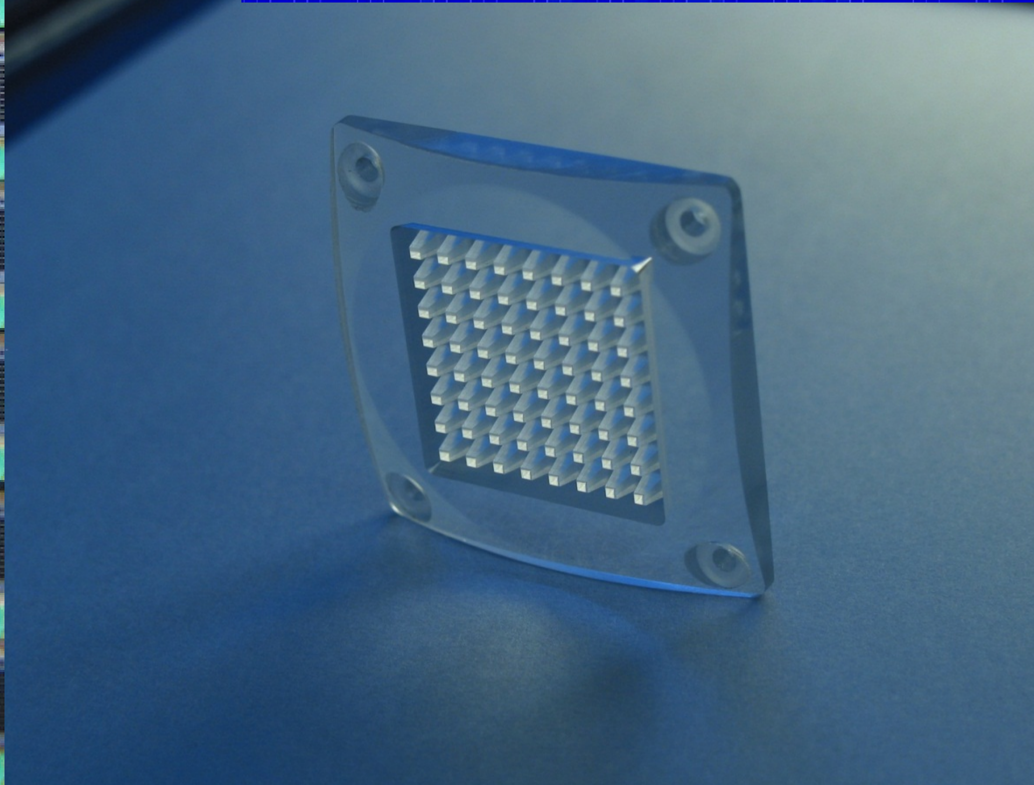




Photon detector with SiPMs and light guides







Time-of-Flight (TOF) counters

Measure velocity by measuring the time between the interaction and the passing of the particle through the TOF counter.

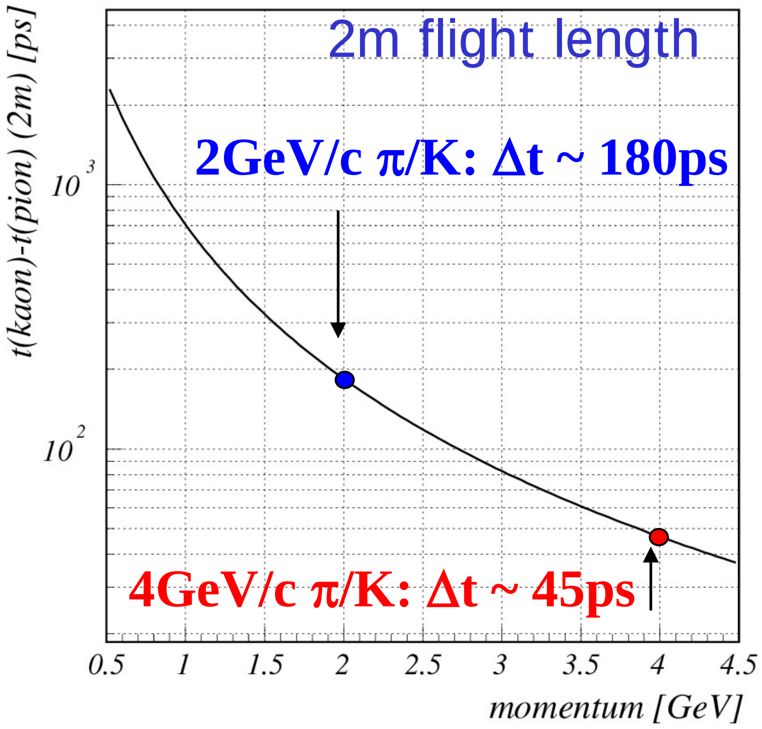
Traditionally: plastic scintillator + PMTs

Typical resolution: ~100 ps →pi/K sepration up to ~1GeV.

To go beyond that: need faster detectors:
→use Cherenkov light (prompt) instead of scintillations
→use a fast gas detector (Multi gap RPC)

However: make sure you also know the interaction time very precisely...

Time difference between π and K:



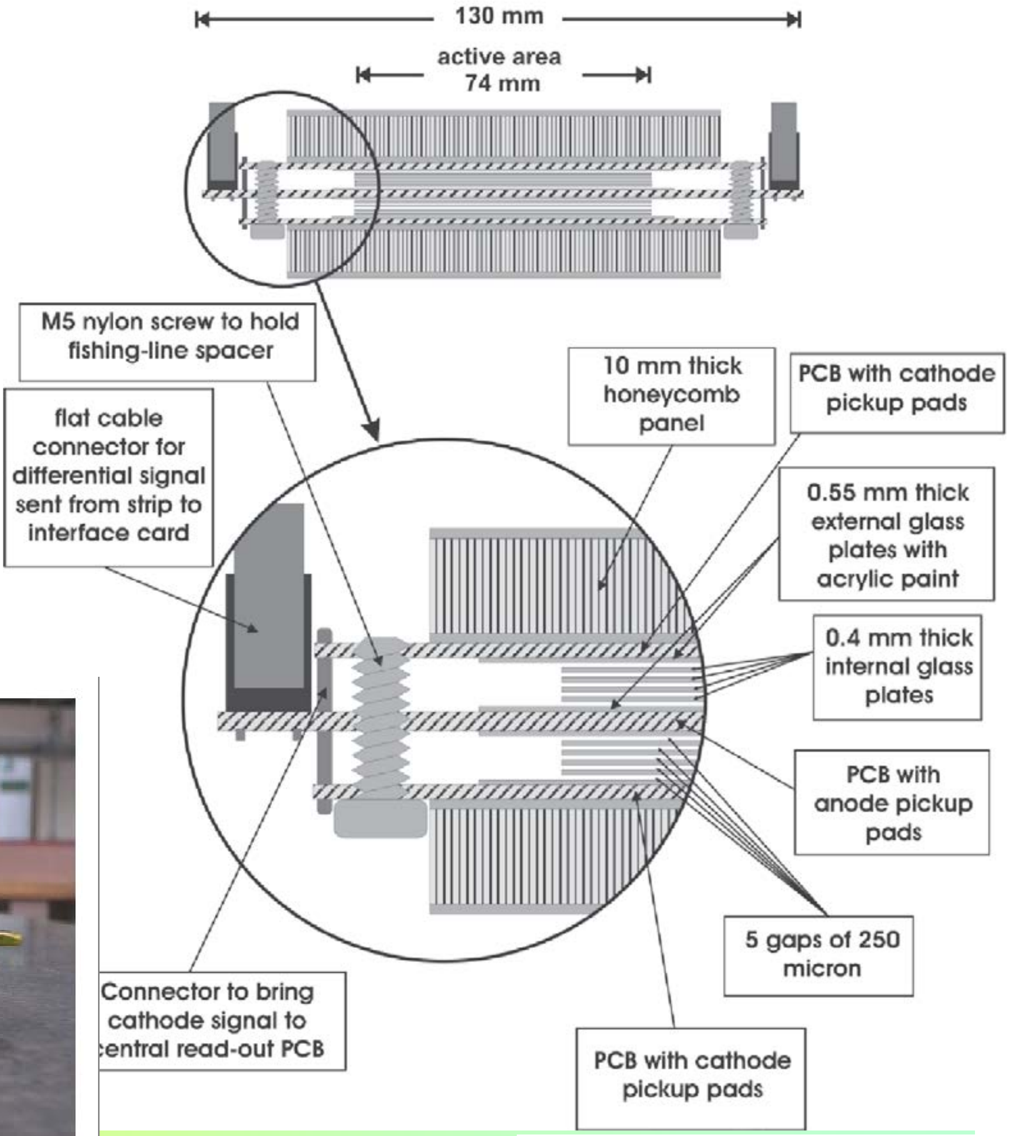
ALICE TOF

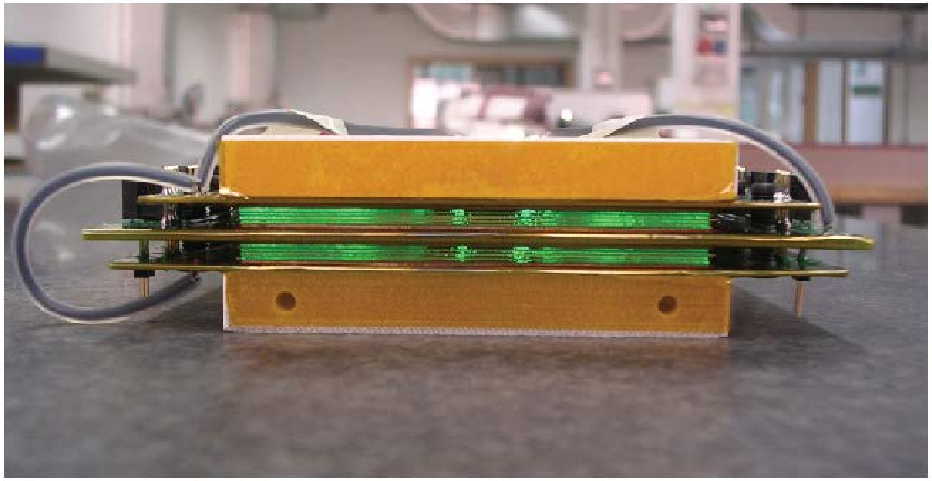
Very fast large area (140m^2) particle detector:

→ MRPC, multi-gap RPC

σ=50ps (incl. read-out)

π/K separation (3σ) up to 2.5 GeV/c at large track densities



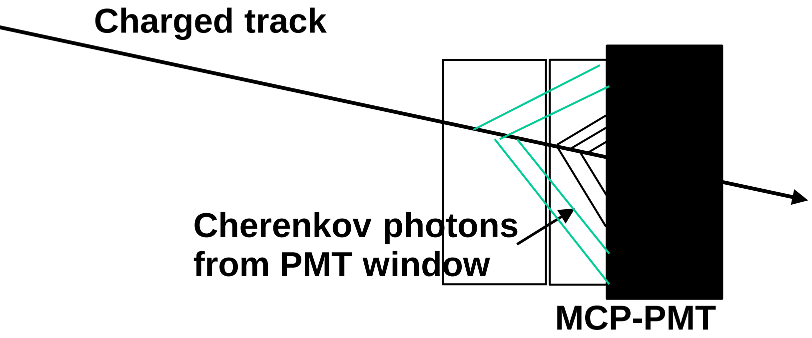


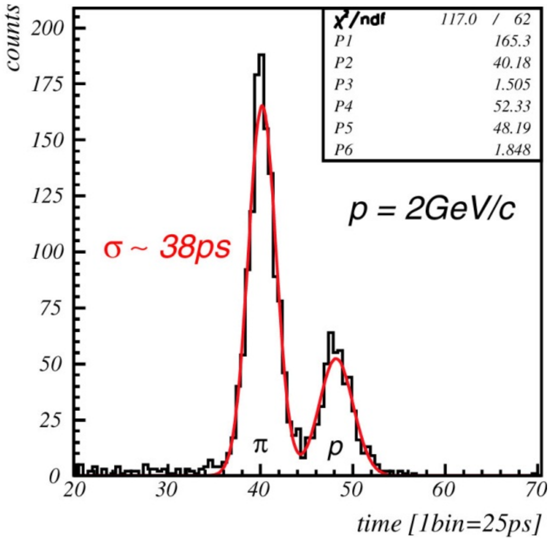
→ Talk by A. Alici

TOF with Cherenkov light

Idea: detect Cherenkov light with a very fast photon detector (MCP PMT).

Cherenkov light is produced in a quartz plate in front of the MCP PMT and in the PMT window.



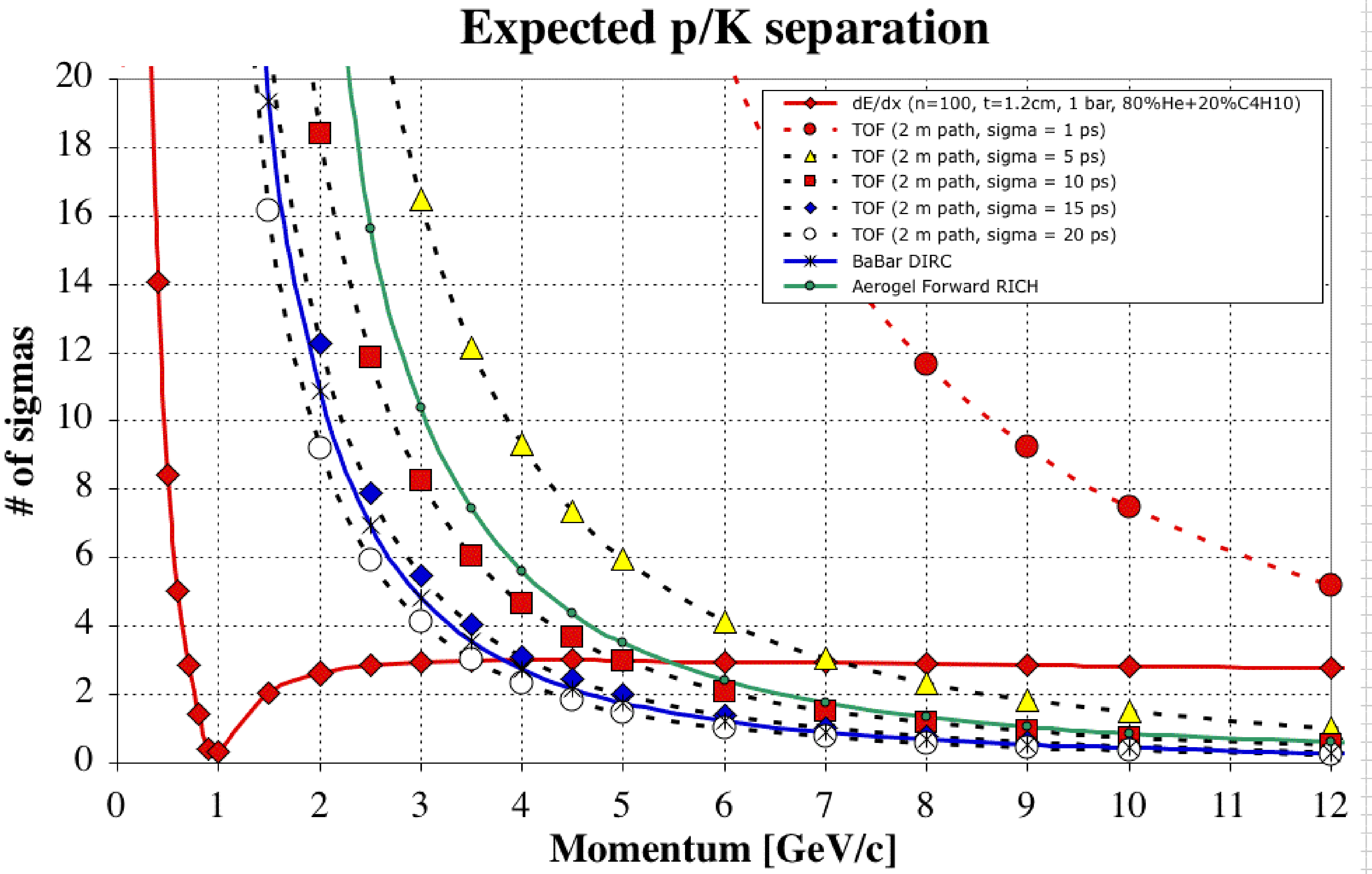


Proof of principle: beamt test with pions and protons at 2 GeV/c.

Only photons from the window

Distance between start counter and MCP-PMT was only 65cm

Time-of-flight with fast photon detectors



J. Va’vra, slides shown at RICH07

Time-of-flight with fast photon detectors

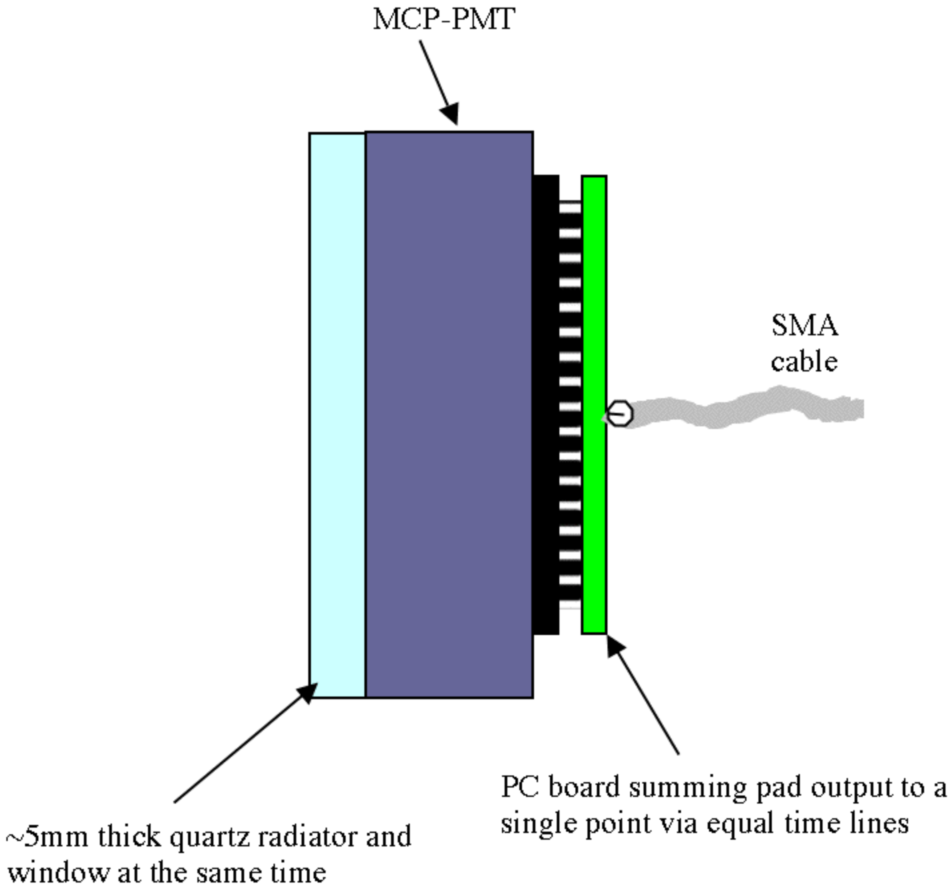
Recent results:

→resolution ~5ps measured

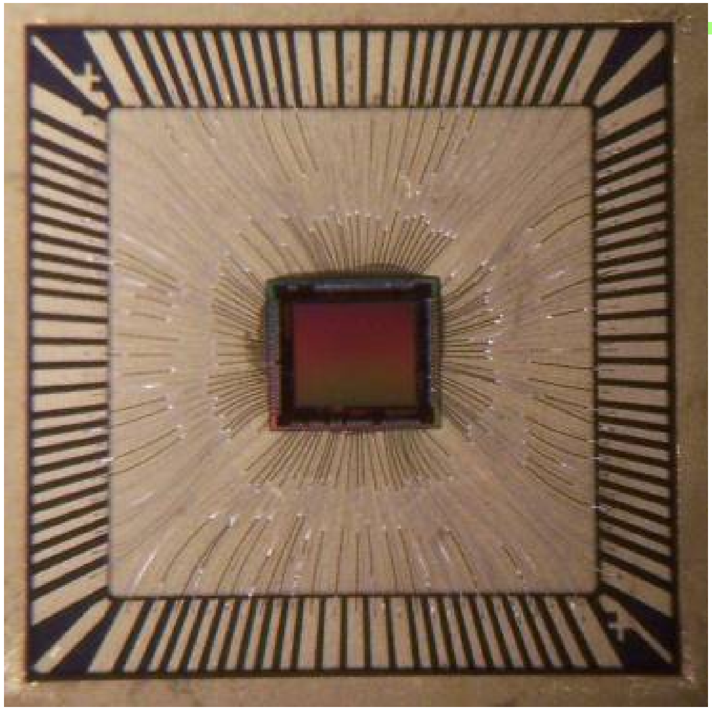
- K. Inami NIMA 560 (2006) 303
- J. Va'vra NIMA 595 (2008) 270

Open issues:

- read-out
- start time



Read out: Buffered LABRADOR (BLAB1) ASIC



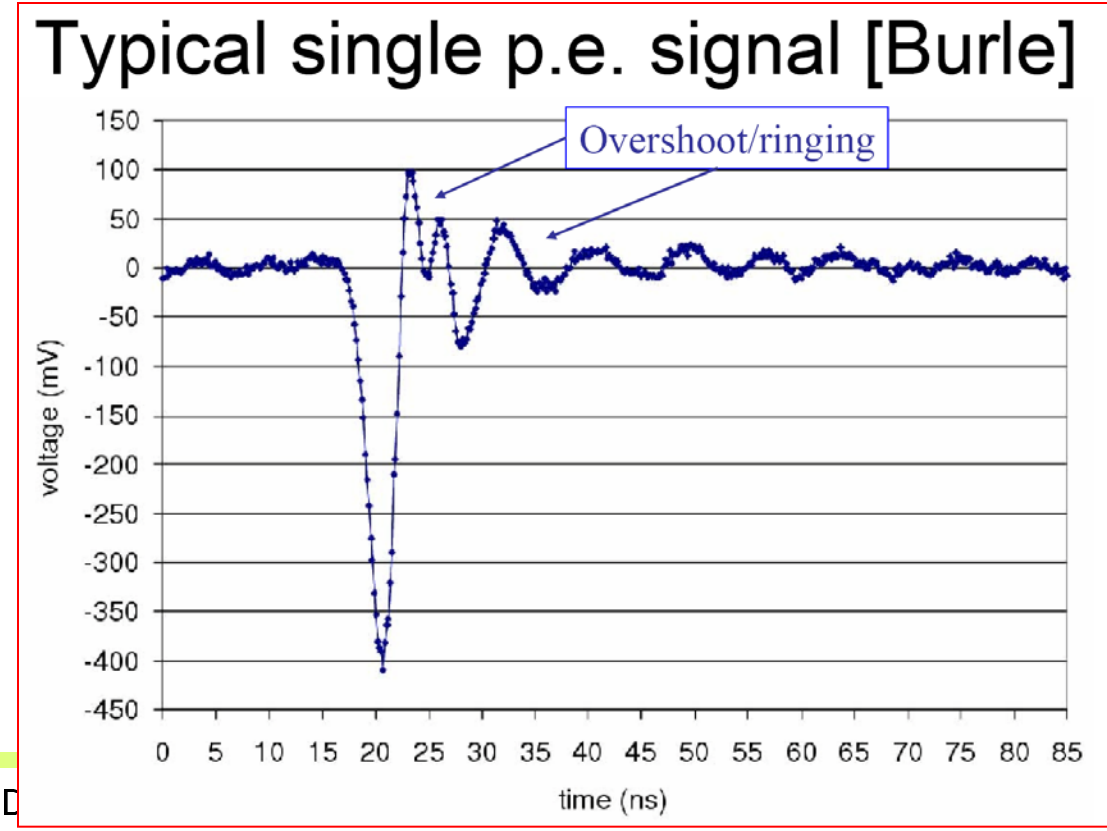
Gary Varner (Hawaii)

Variant of the LABRADOR 3

Successfully flew on ANITA in Dec 06/Jan 07 (<= 50ps timing)

3mm x 2.8mm, TSMC 0.25um

- 64k samples deep
- Multi-MSa/s to Multi-GSa/s

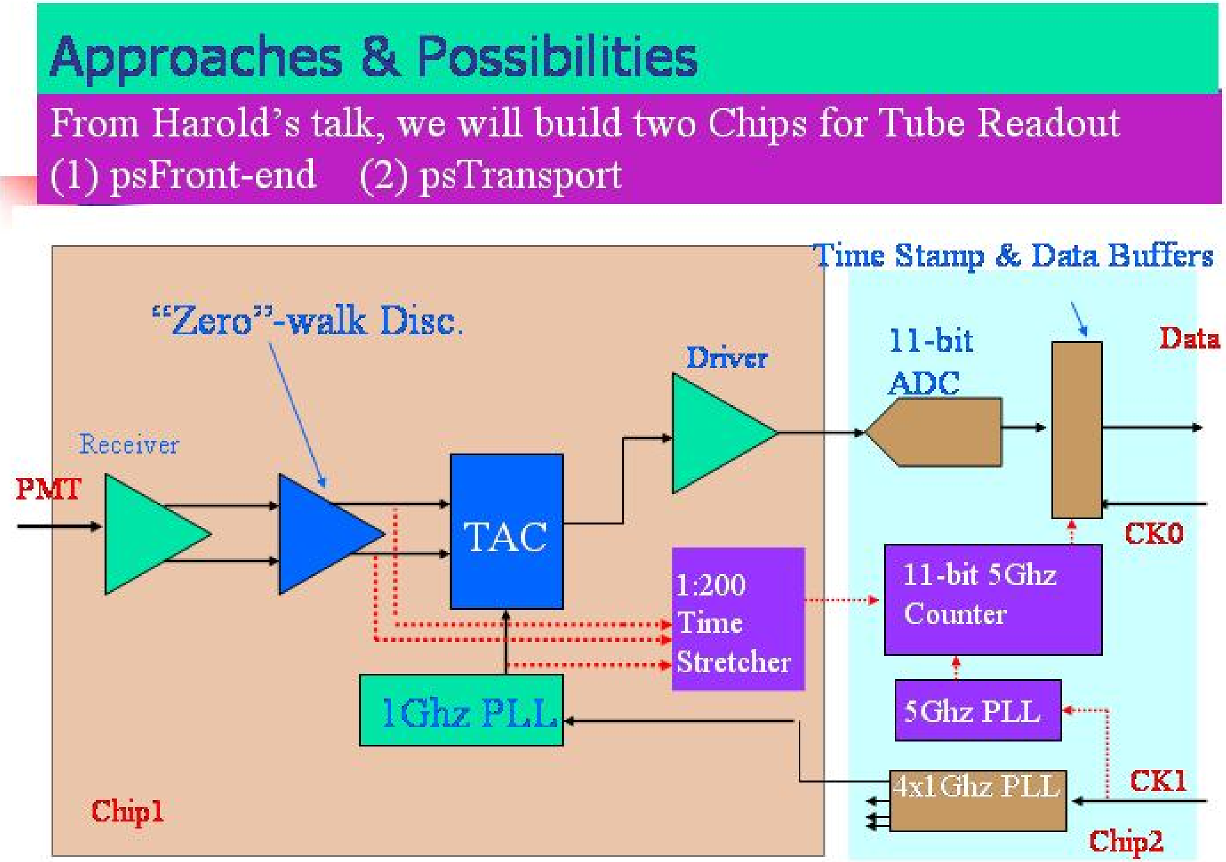


Typical single p.e. signal [Burle]

Overshoot/ringing

Effort to develop ps TOF counter

H. Frisch & H. Sanders, Univ. of Chicago, K. Byrum, G. Drake, Argonne lab

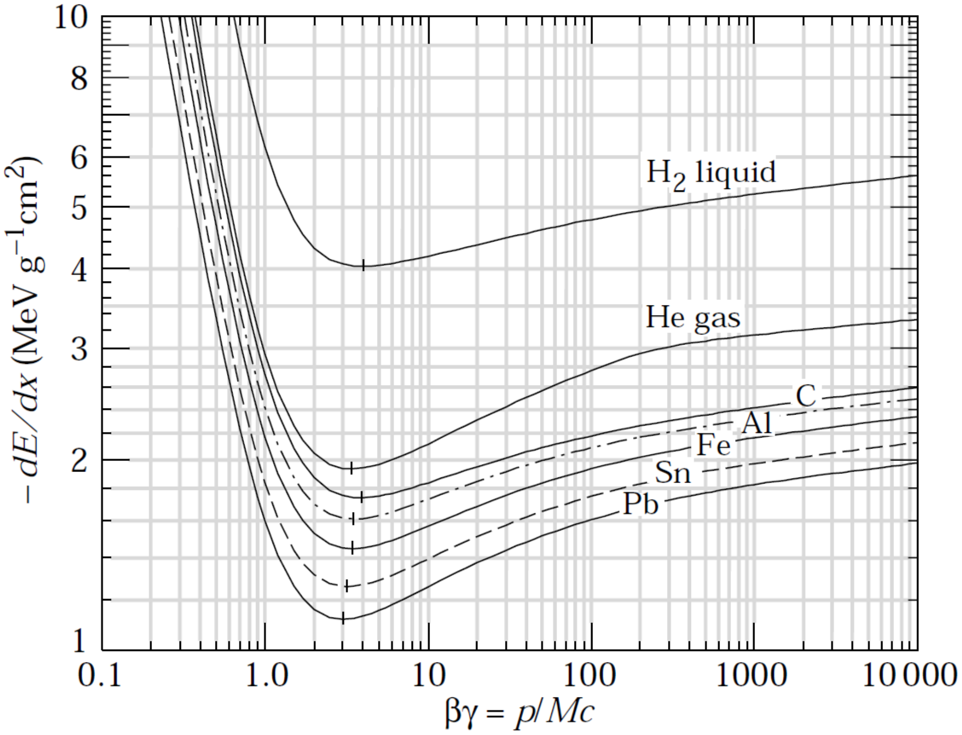


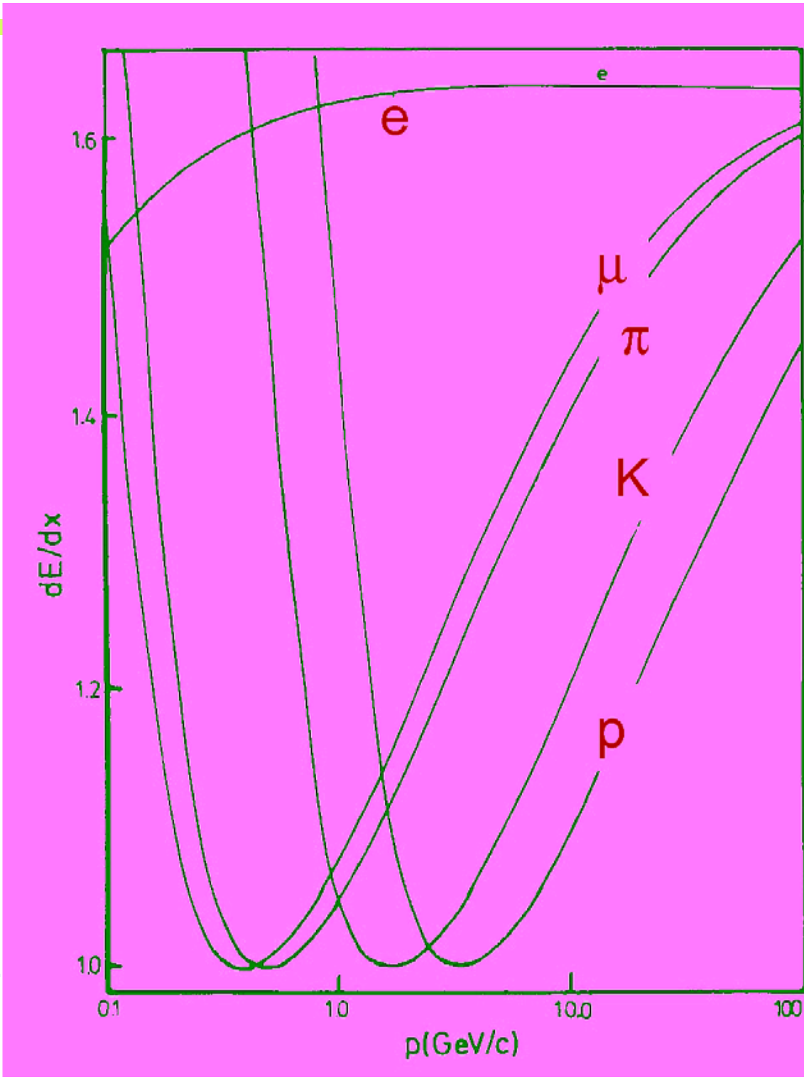
Approaches & Possibilities

From Harold's talk, we will build two Chips for Tube Readout
(1) psFront-end (2) psTransport

- ASIC-based technology for a new CFD & TDC

Identification with the dE/dx measurement





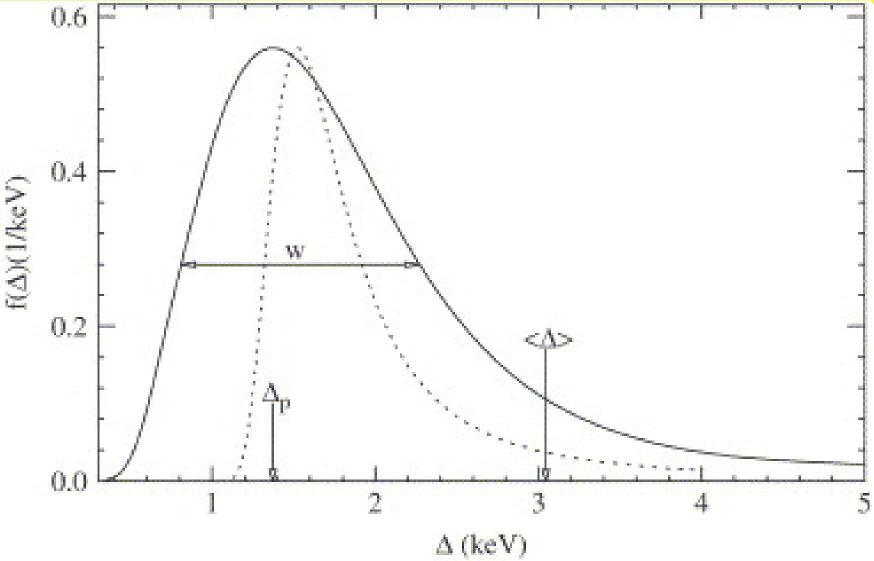
dE/dx is a function of velocity β

For particles with different mass, the Bethe-Bloch curve gets displaced if plotted as a function of p

For good separation: resolution should be ~5%

Identification with dE/dx measurement

Problem: long tails (not Gaussian!)



Energy loss distribution for particles with $\beta\gamma=3.6$ traversing 1.2 cm of Ar gas (solid line).

Parameters describing $f(\Delta)$ are the most probable energy loss $\Delta_p(x;\beta\gamma)$ = the position of the maximum at 1371 eV, and ***w***, the full-width-at-half-maximum (FWHM) of 1463 eV. The mean energy loss is 3044 eV. Dotted line: the original Landau function.

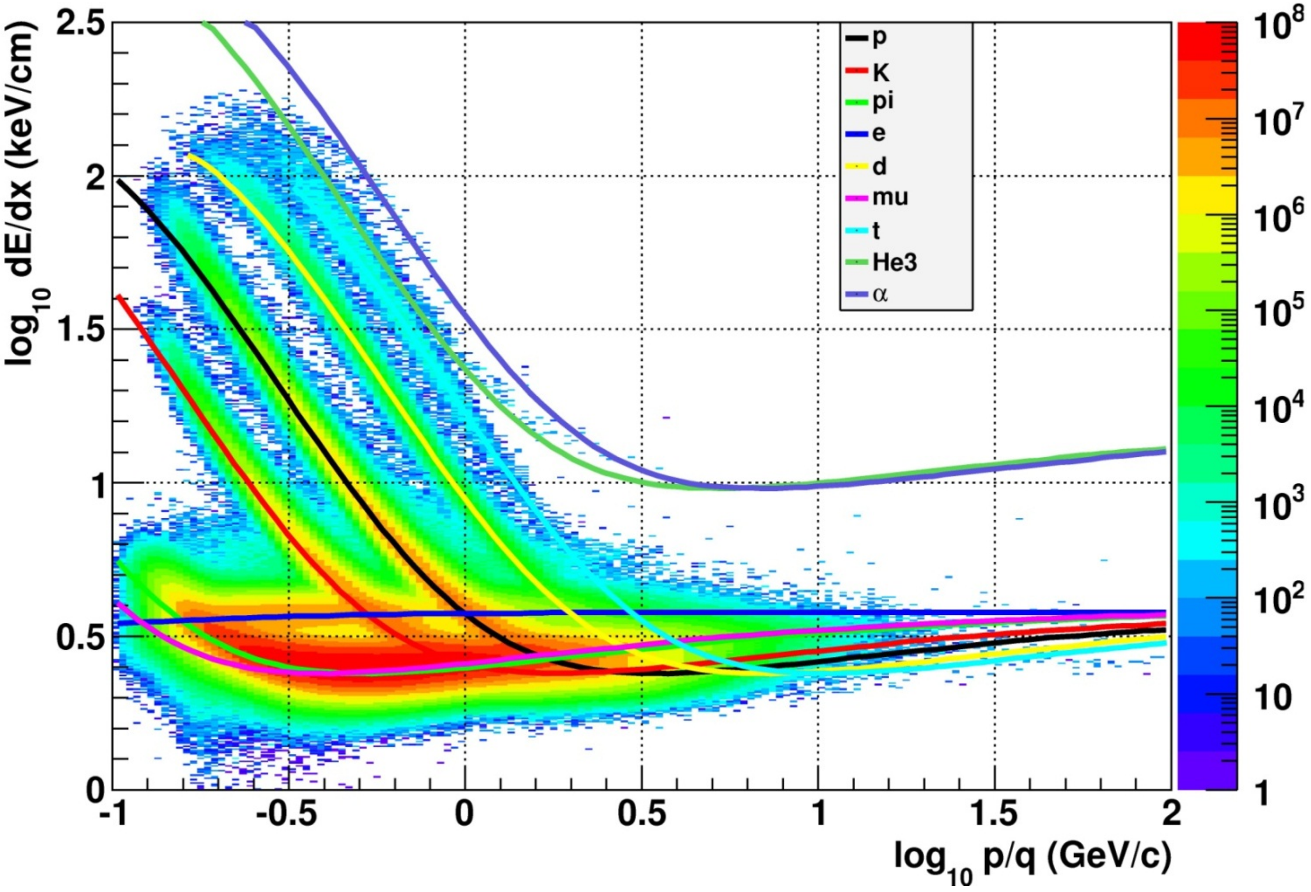
→Many samples along the track (~100 in ALICE TPC), remove the largest ~40% values (reduce the influence of the long tail) → truncated mean

→ Hans Bichsel: A method to improve tracking and particle identification in TPCs and silicon detectors, NIM A562 (2006) 154

Identification with dE/dx measurement

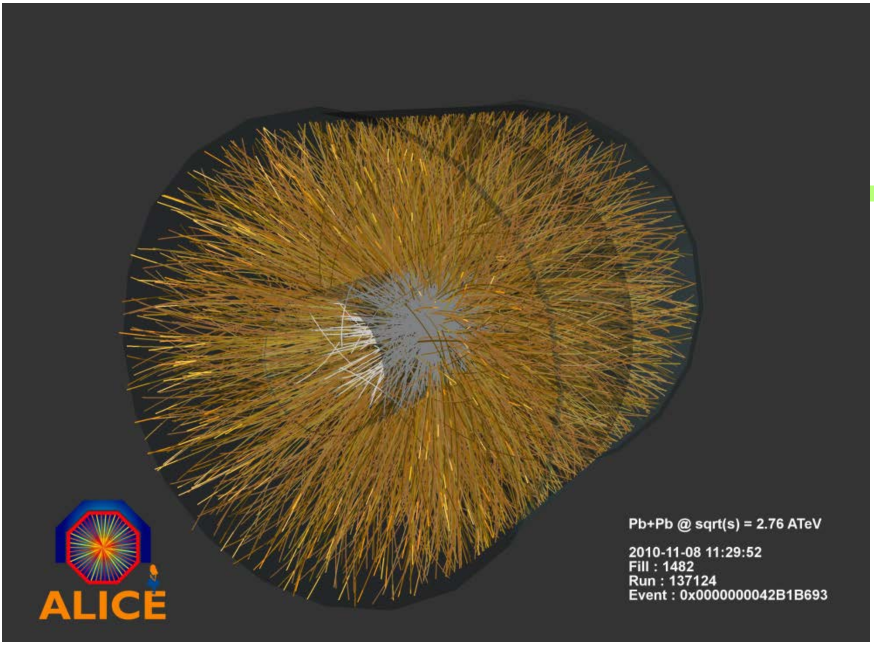
dE/dx performance in the STAR TPC

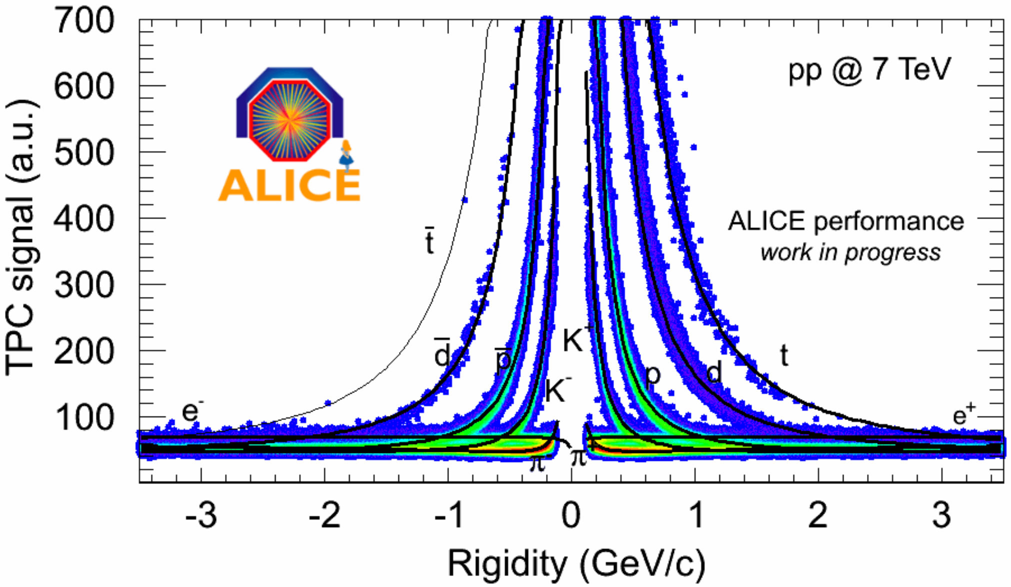
gold-gold collisions

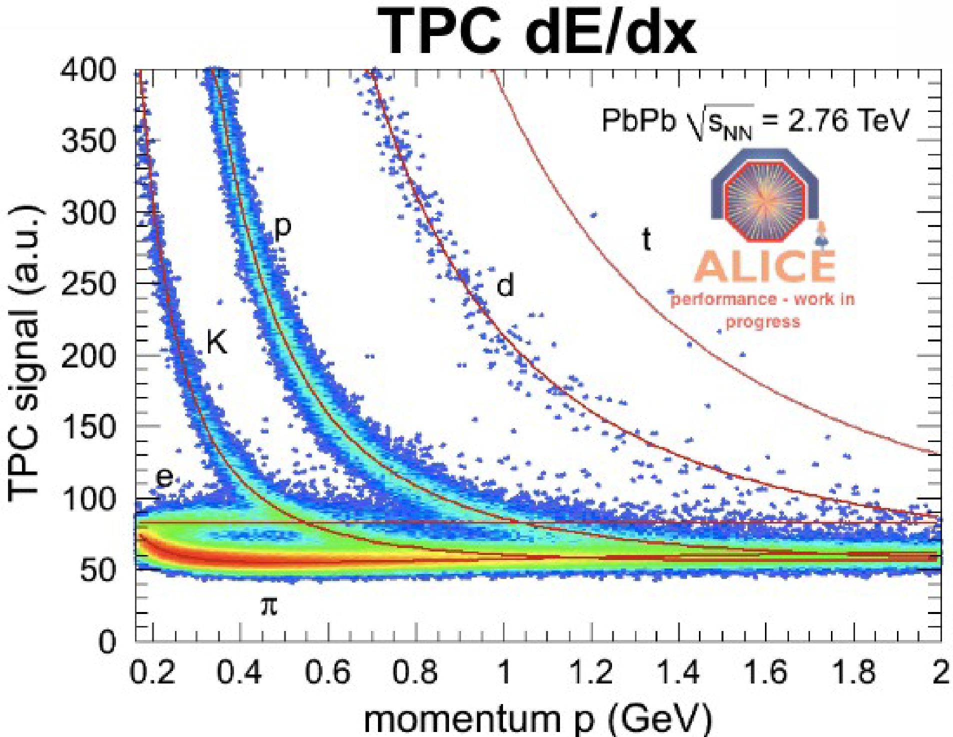


Energy loss in the STAR TPC: truncated mean as a function of momentum. The curves are Bichsel model predictions.

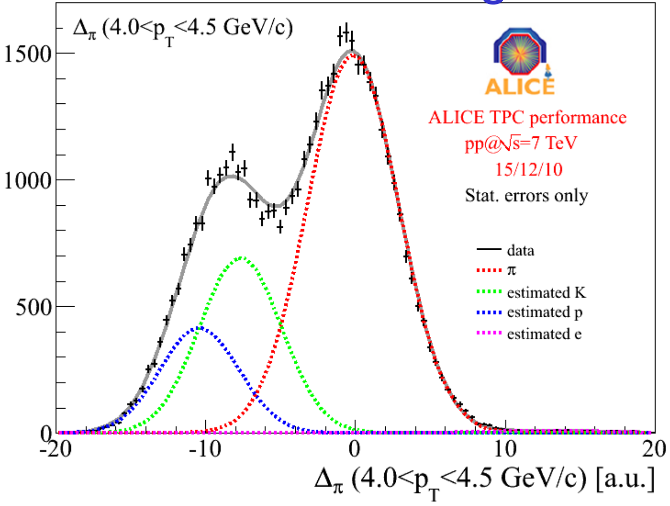
dE/dx in ALICE







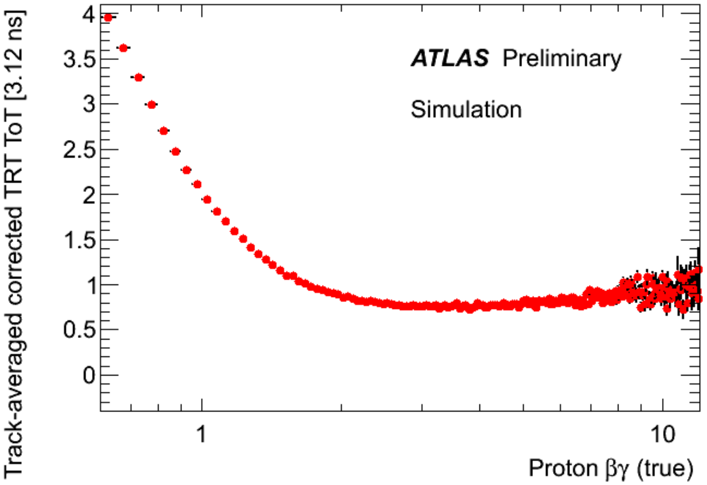
relativistic rise region



ari

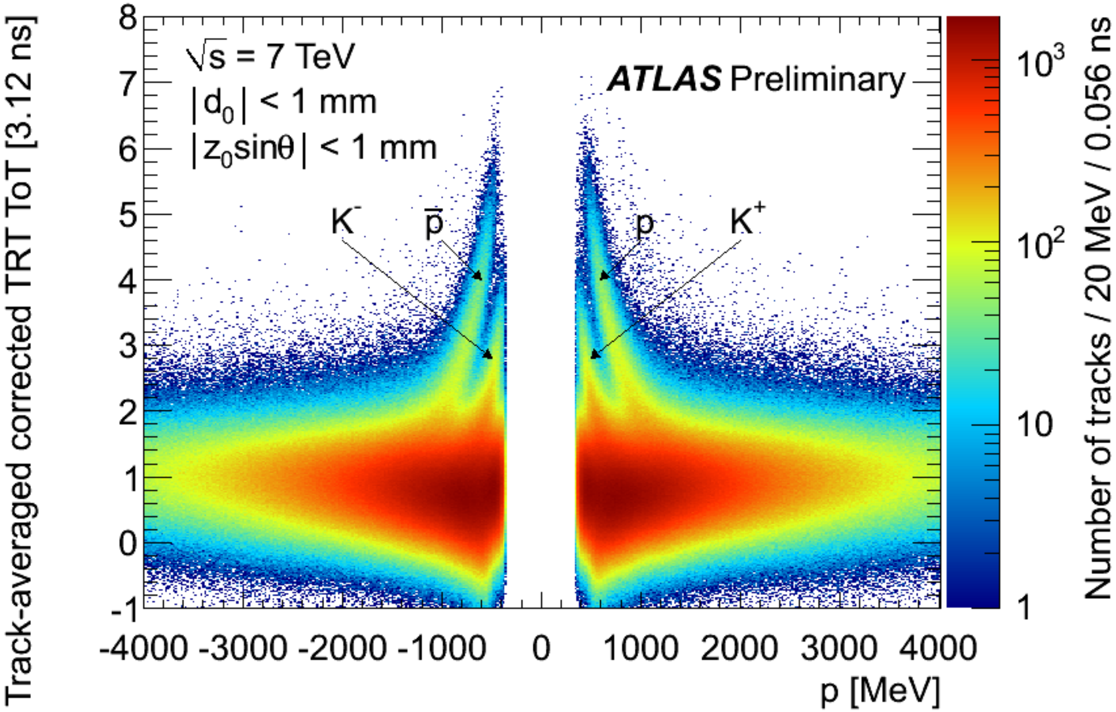
→ Talk by Weilin Wu

Time-over-Threshold (ToT): ATLAS TRT



The relation between the track ToT measurement and the track βγ, obtained from MC studies.

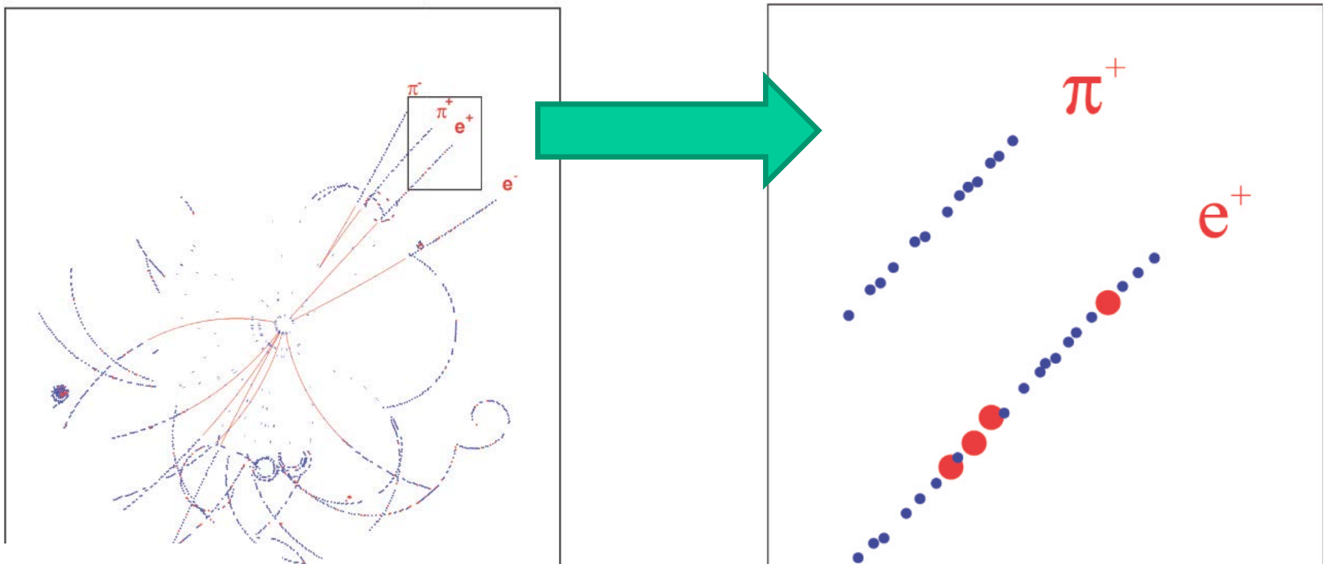
2010 data: The track-averaged ToT distribution as a function of the track momentum.

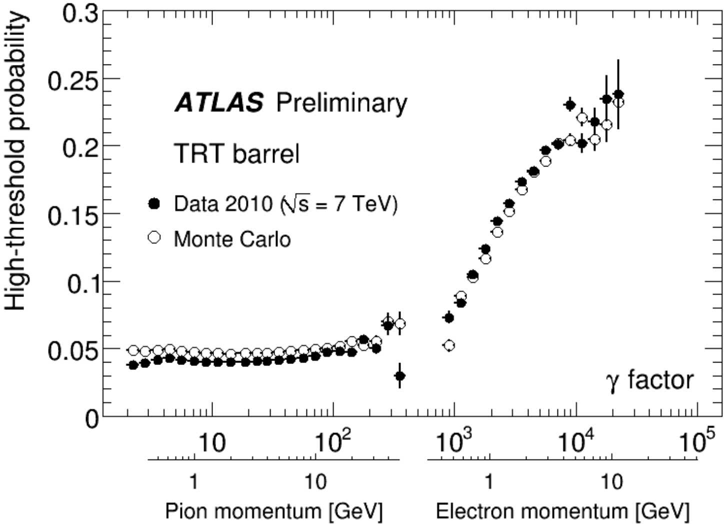


→ Talk by J.-F. Marchand

Transition radiation

pion-electron separation in the ATLAS TRT





Main topic of this conference, so I stop here.

I do not want to teach the experts...

Summary

Particle identification is an essential part of most experiments in particle physics, and has contributed substantially to our present understanding of elementary particles and their interactions. It will continue to have an important impact in searches for new physics.

A large variety of techniques has been developed for different kinematic regions and different particles, based on Cherenkov radiation, TOF, dE/dx and TR.

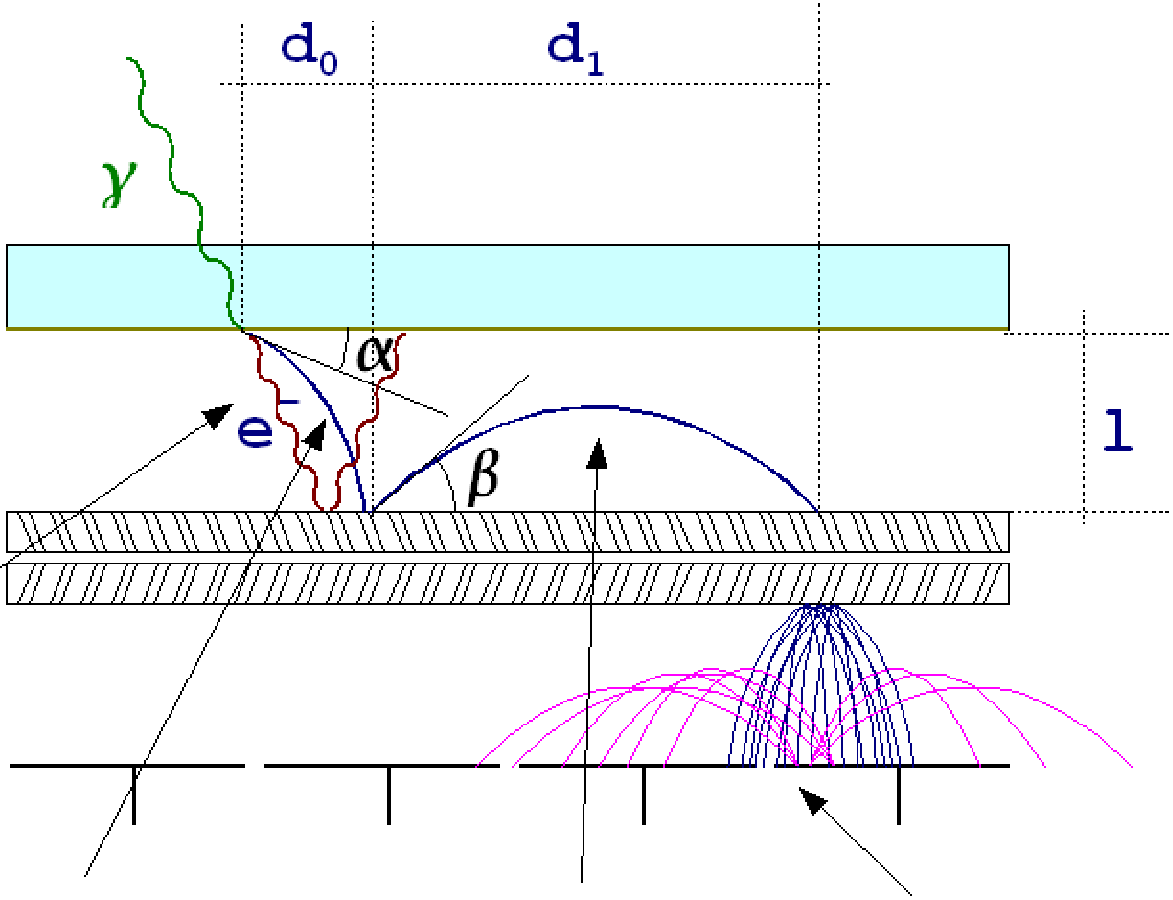
New concepts and detectors are being studied → this is a very active area of detector R+D.

Back-up slides

MCP PMT: processes involved in photon detection

Parameters used:

- $U = 200$ V
- $l = 6$ mm (K-MCP)
- $E_0 = 1$ eV
- $m_e = 511$ keV/c^2
- $e_0 = 1.6\ 10^{-19}$ As



Internal-reflection

Photo-electron:

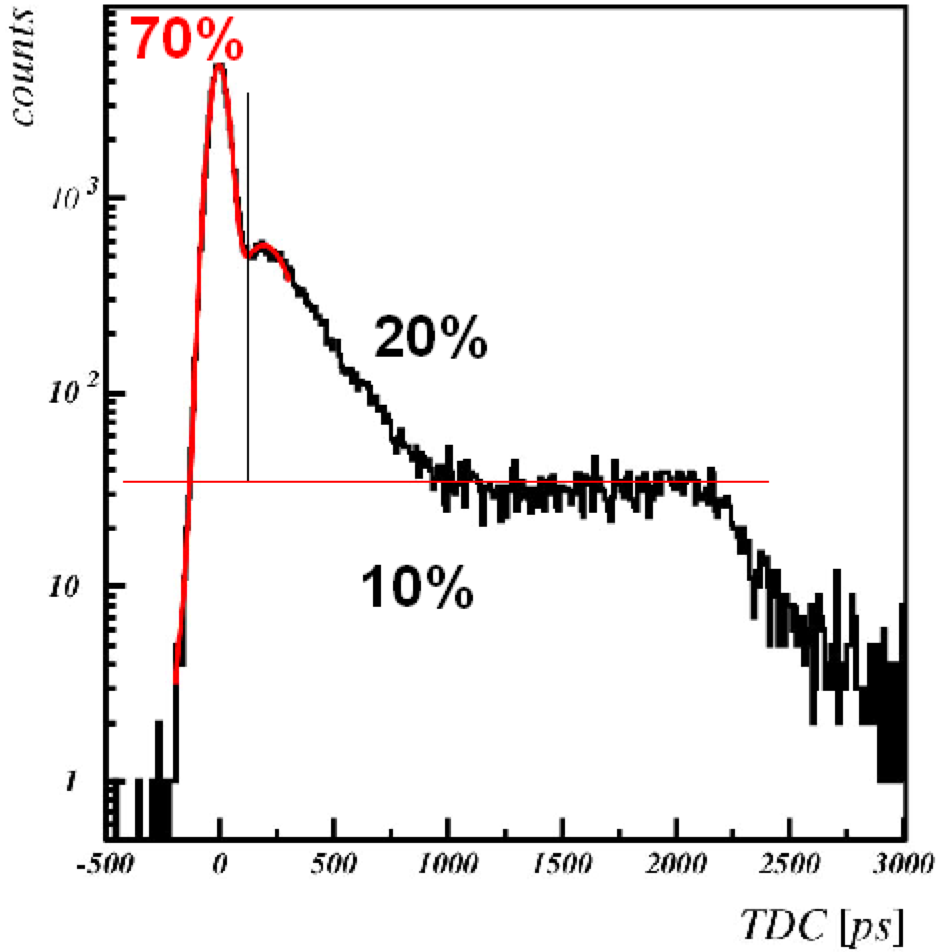
- $d_{0,max} \sim 0.8$ mm
- $t_0 \sim 1.4$ ns
- $\Delta t_0 \sim 100$ ps

Backscattering:

- $d_{1,max} \sim 12$ mm
- $t_{1,max} \sim 2.8$ ns

Charge sharing

MCP PMT timing

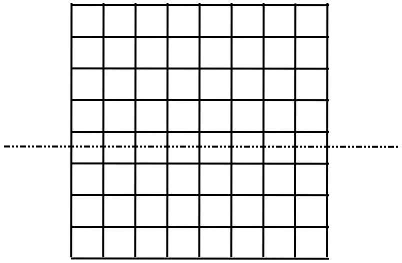


Tails understood (scattering of photoelectrons off the MCP), can be significantly reduced by:

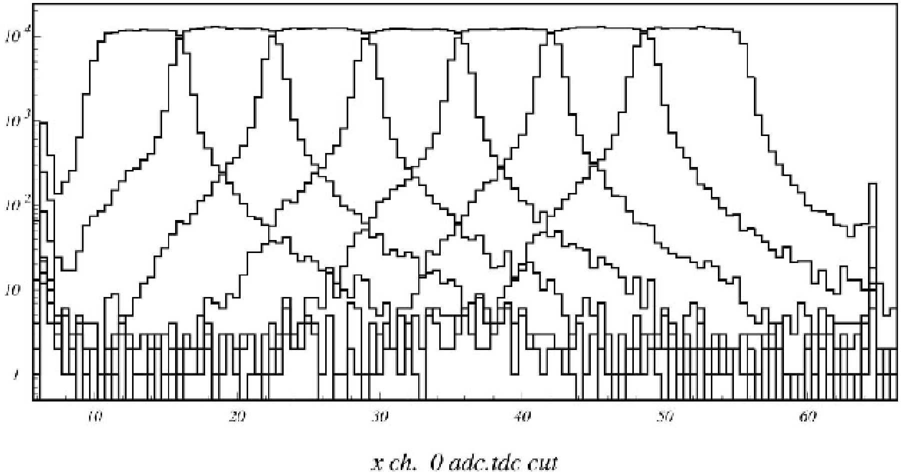
- decreased photocathode-MCP distance and
- increased voltage difference

- prompt signal ~ 70%
- short delay ~ 20%
- ~ 10% uniform distribution

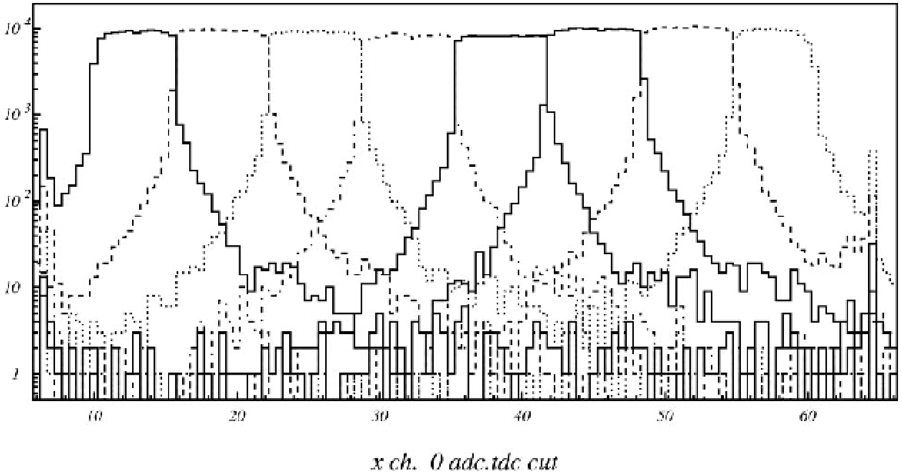
MCP PMT: sensitivity



Number of detected hits on individual channels as a function of light spot position.



B = 0 T,
HV = 2400 V



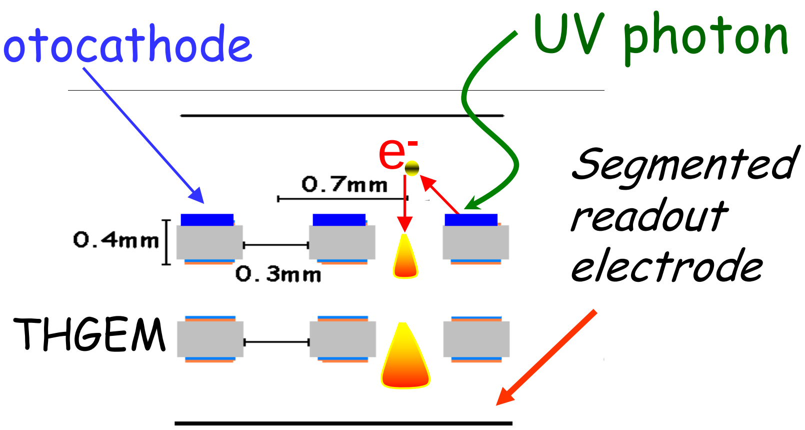
B = 1.5 T,
HV = 2500 V

In the presence of magnetic field, charge sharing and cross talk due to long range photoelectron back-scattering are considerably reduced.

Wire chamber based photon detectors: recent developments

Instead of MWPC:

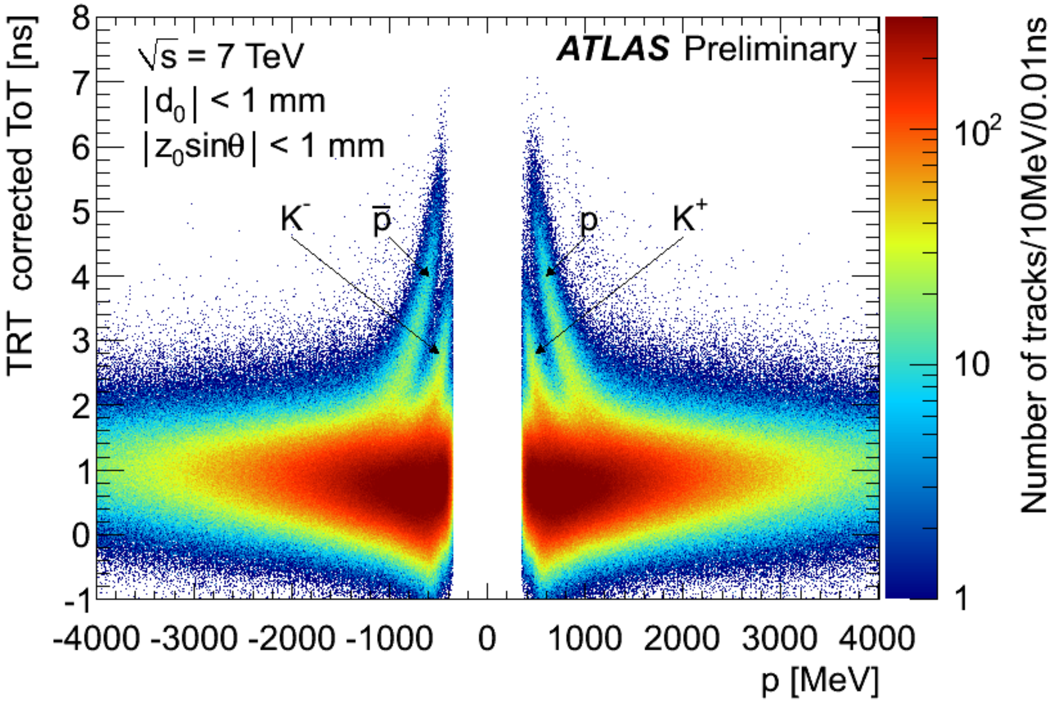
- Use multiple GEM with semitransparent or reflective photocathode → PHENIX RICH
- Use chambers with multiple thick GEM (THGEM) with transm. or refl. photocathode (considered for the COMPASS RICH)

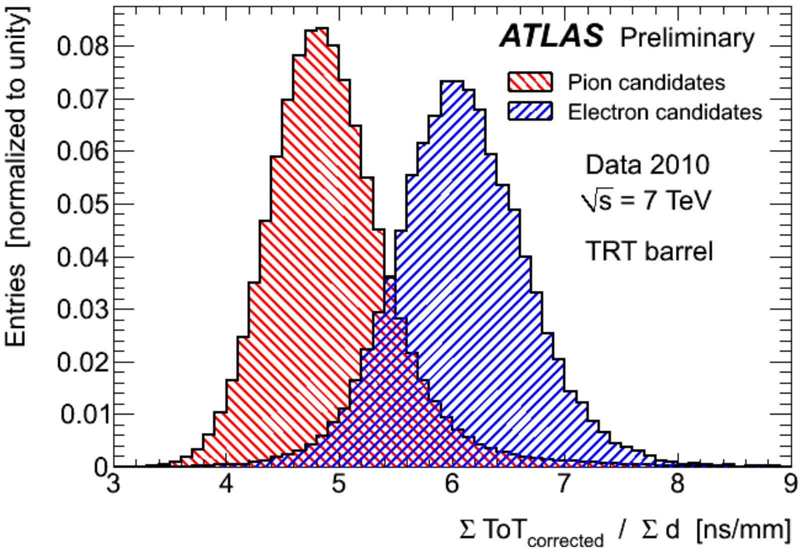


Ion damage of the photocathode: ions can be blocked

TRT performance in 2010 data 2

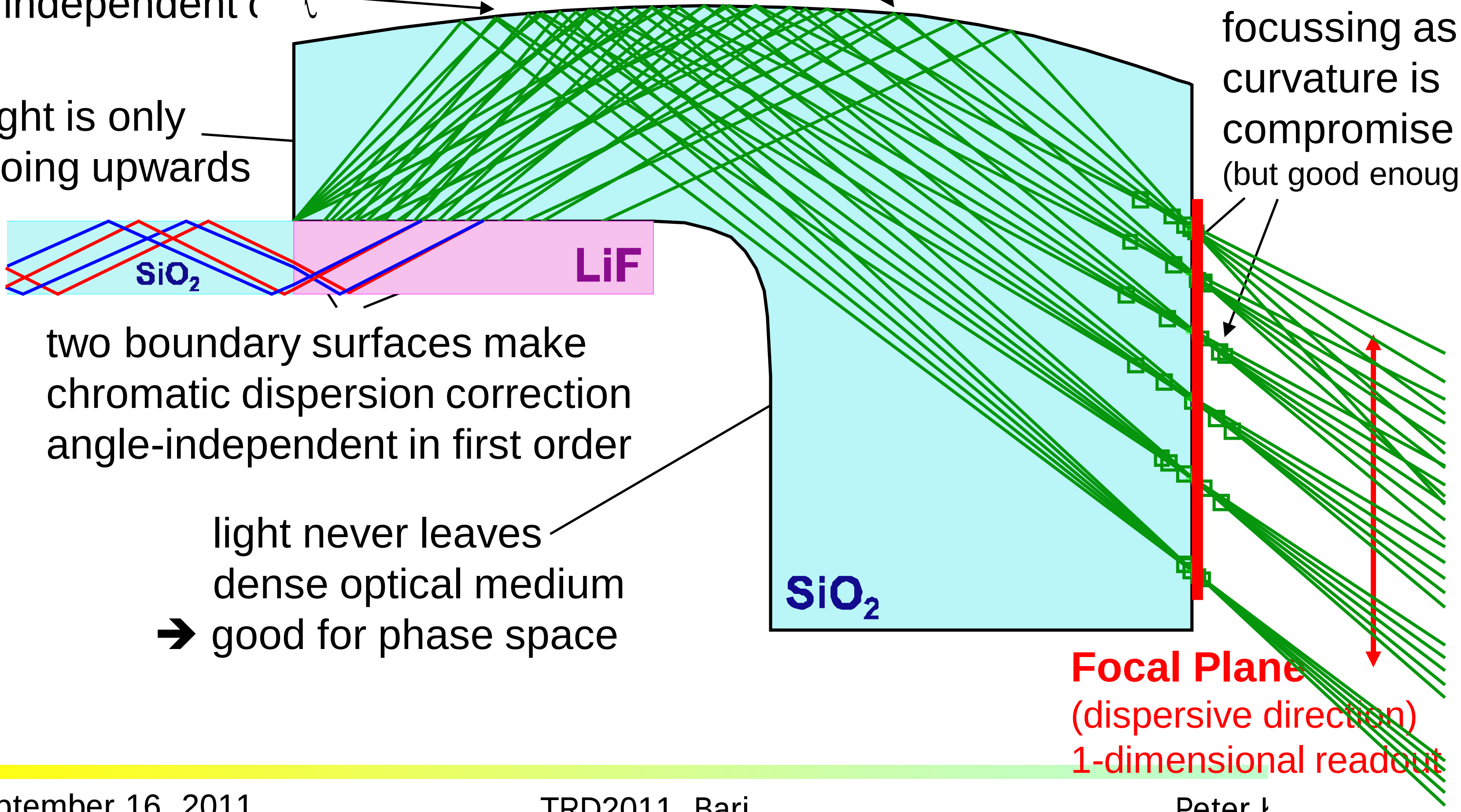
dE/dx performance:
time-over-threshold





Additional e/pion separation in
time-over-threshold

PANDA endcap DIRC
focussing & chromatic correction



total internal reflection
angle independent of λ

no mirror coating

1-dim aspheric surface

not-perfect
focussing as
curvature is
compromise
(but good enough)

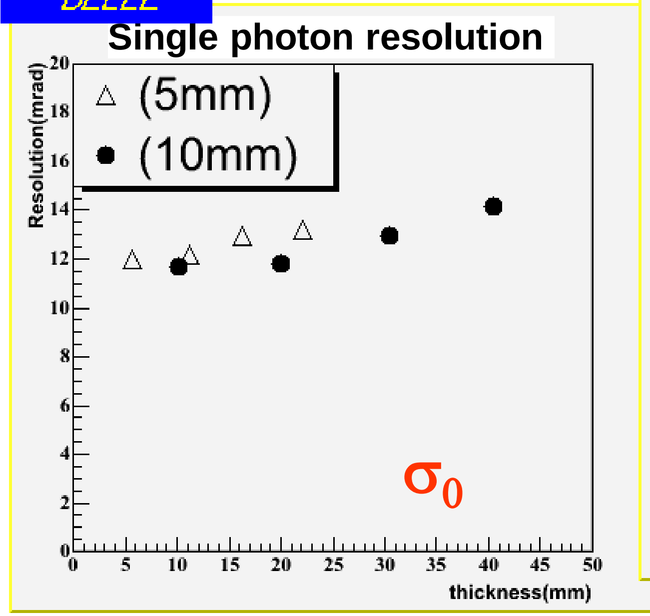
light is only
going upwards

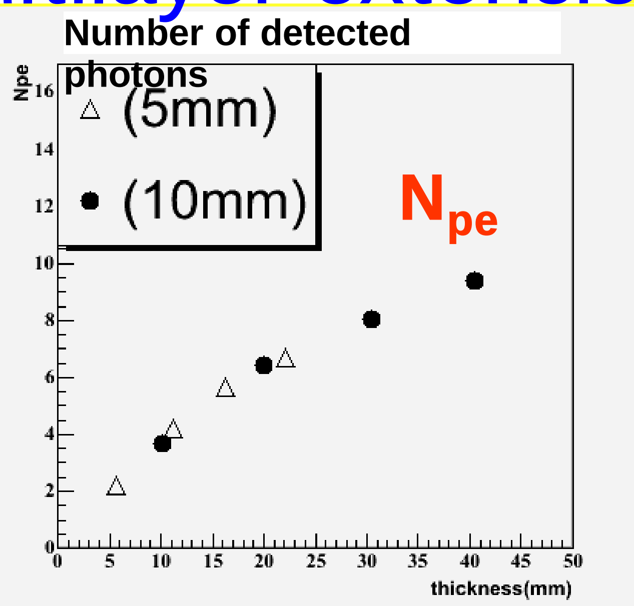
two boundary surfaces make
chromatic dispersion correction
angle-independent in first order

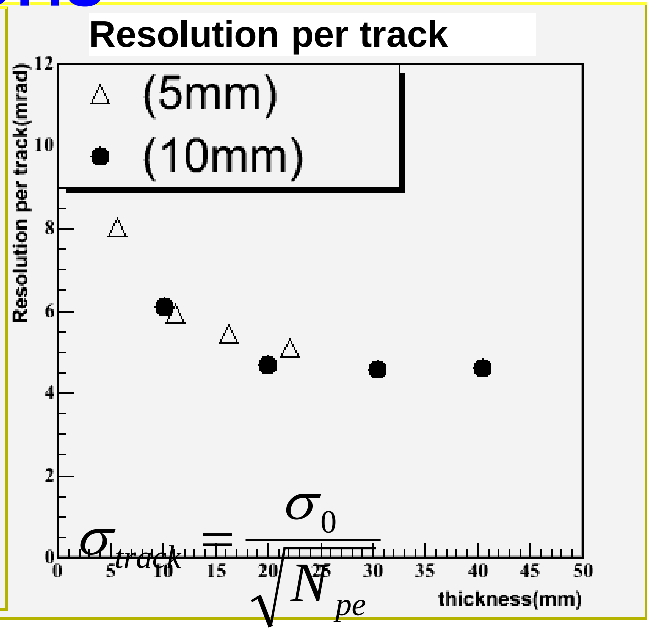
light never leaves
dense optical medium
➔ good for phase space

Focal Plane
(dispersive direction)
1-dimensional readout

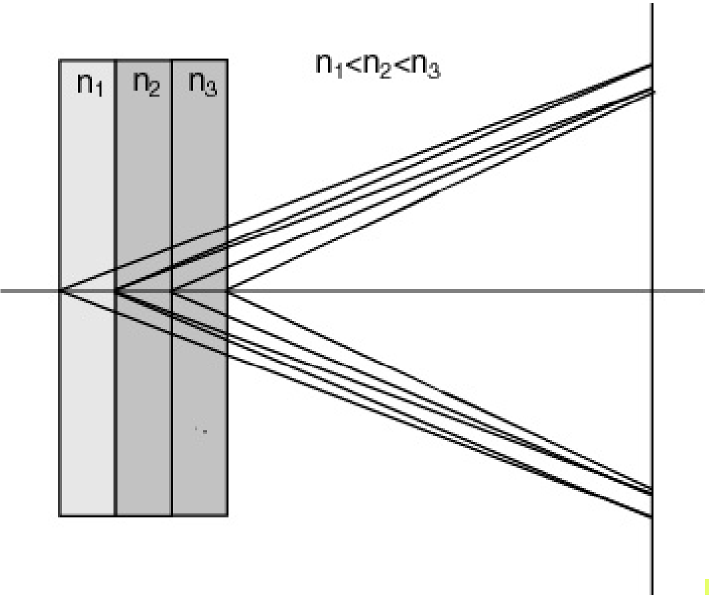
Multilayer extensions


Single photon resolution


Number of detected photons


Resolution per track

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



Cherenkov angle resolution per track: around 4.3 mrad

→ π/K separation at 4 GeV: >5σ

Several optimisation studies:

Križan et al NIMA 565 (2006) 457

Barnyakov et al NIMA 553 (2005) 70