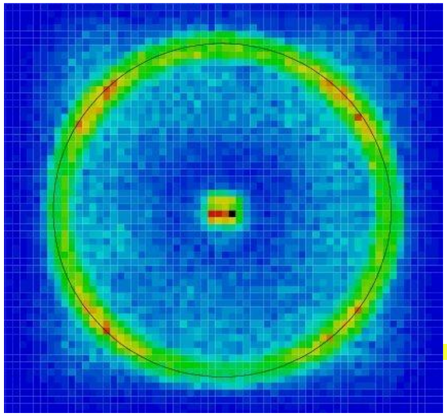
Univerza v Ljubljani

Application and detection of Cherenkov radiation

Peter Križan

University of Ljubljana and J. Stefan Institute



Workshop on fast Cherenkov detectors, Giessen,
May 11-13, 2009

JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

Contents

Applications of Cherenkov radiation in particle physics

Particle identification

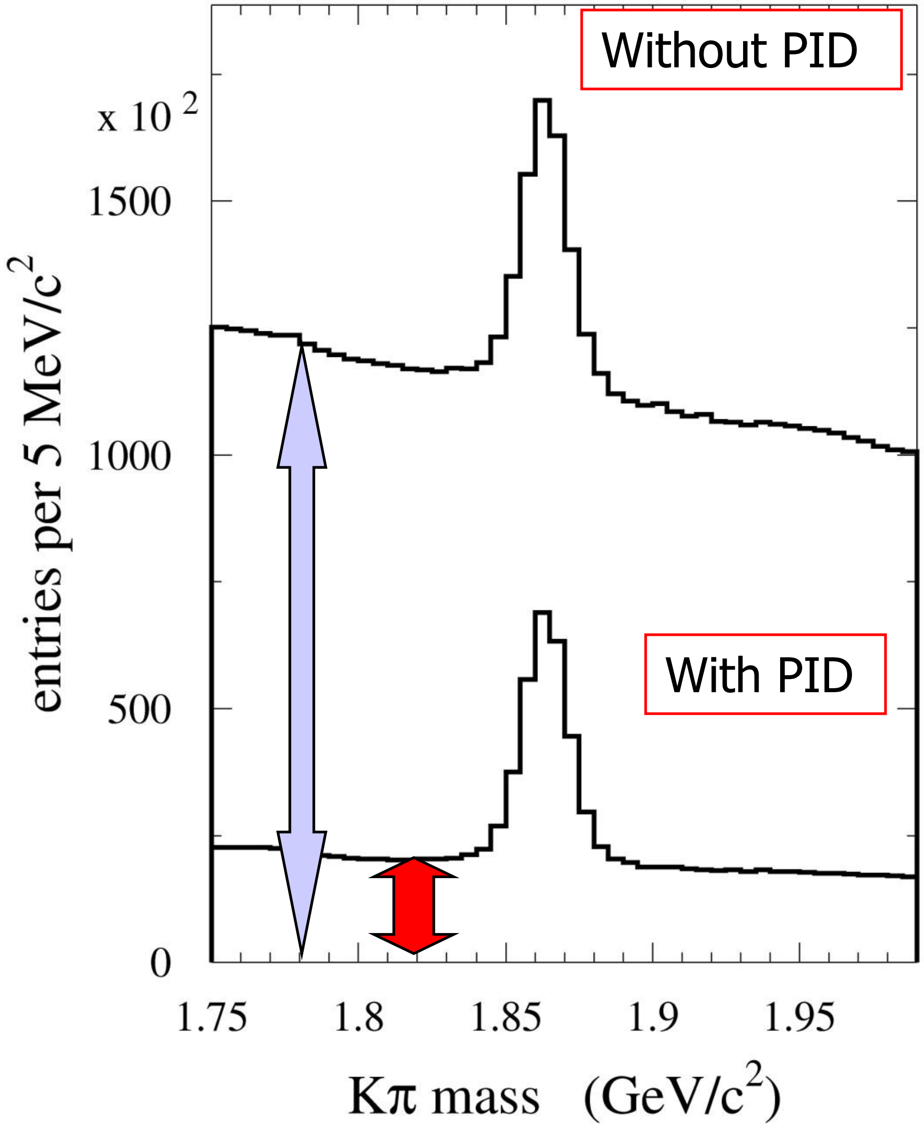
- threshold Cherenkov counters
- Ring Imaging CHerenkov counters
- Time-of-flight measurement with Cherenkov photons

Calorimetry

Tracking

This talk: applications in particle identification

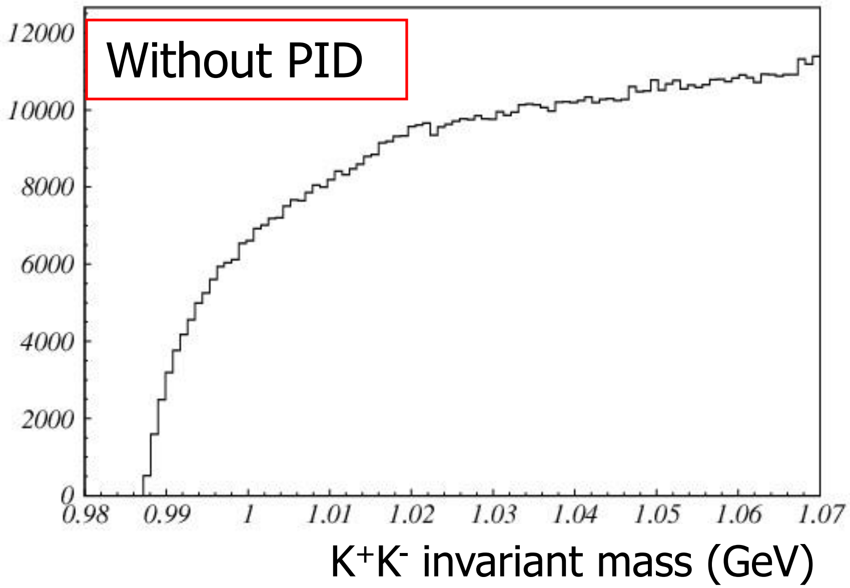
Why particle ID?

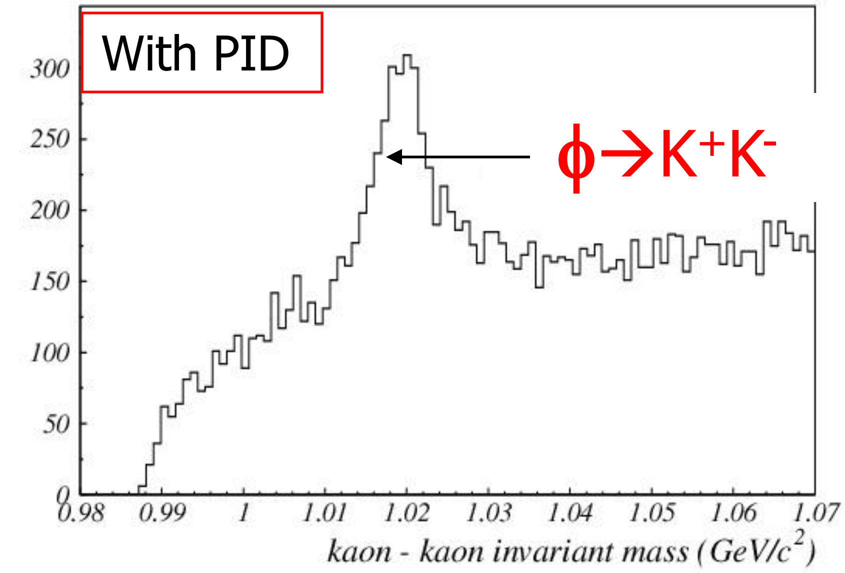


Example 1: B factory

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

Why particle ID?



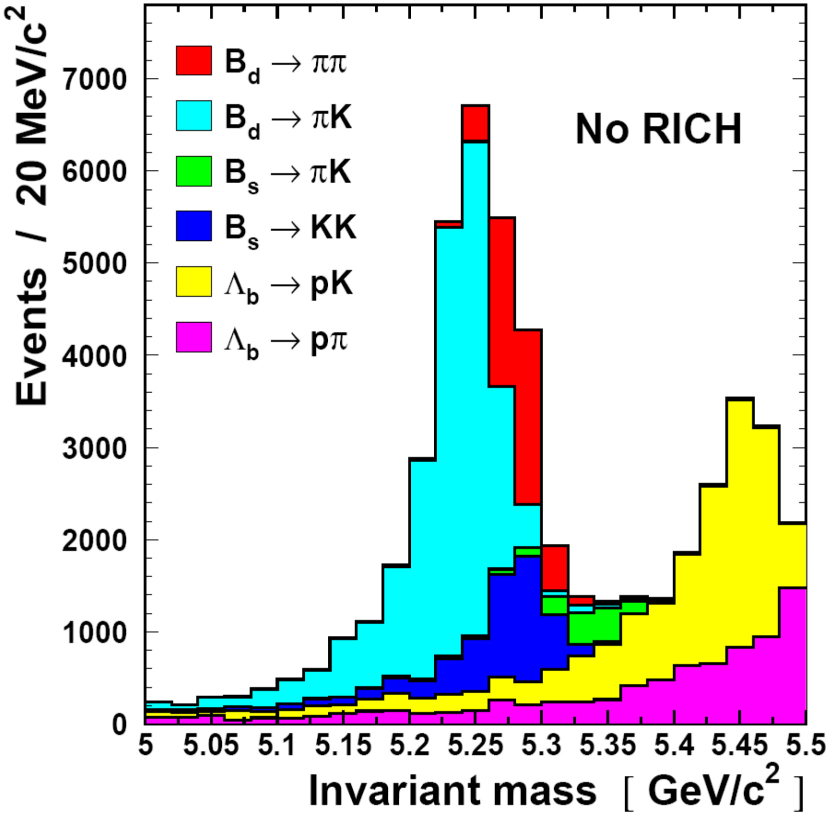


Example 2: HERA-B

K^+K^- invariant mass.

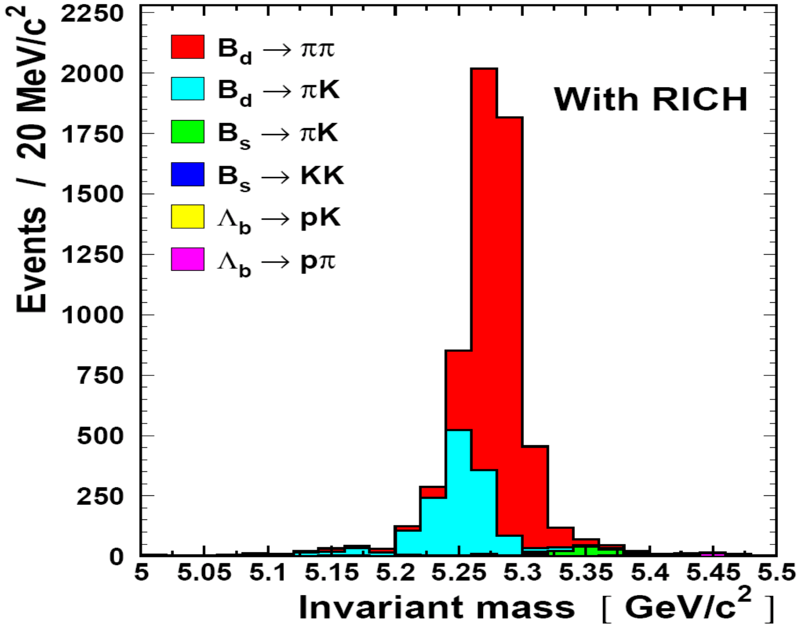
The inclusive $\phi \rightarrow K^+K^-$ decay only becomes visible after particle identification is taken into account.

Why particle ID?



Example 3: LHCb

(MC prediction)



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.

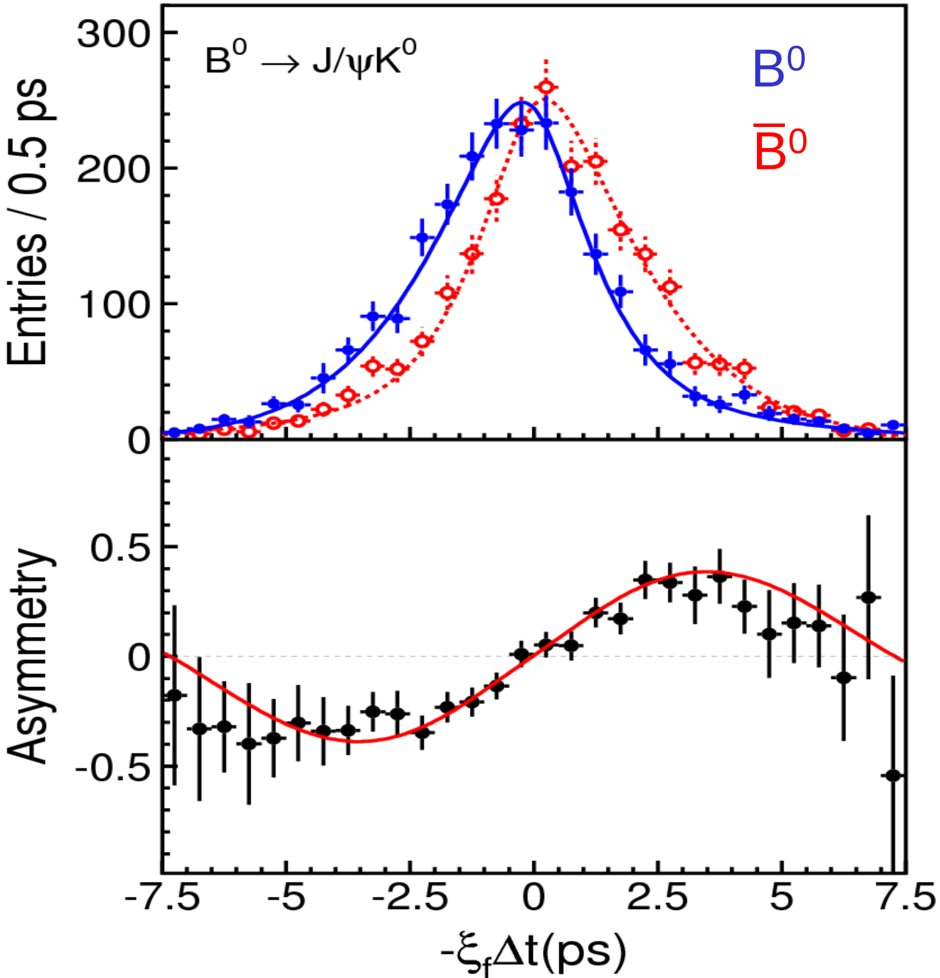
Why particle ID?

PID is also needed in:

- Spectroscopy of charmonium and charmonioum like states
- Spectroscopy of charmed hadrons
- Searches for exotic hadronic states
- Searches for exotic states of matter (quark-gluon plasma)

Why particle ID?

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

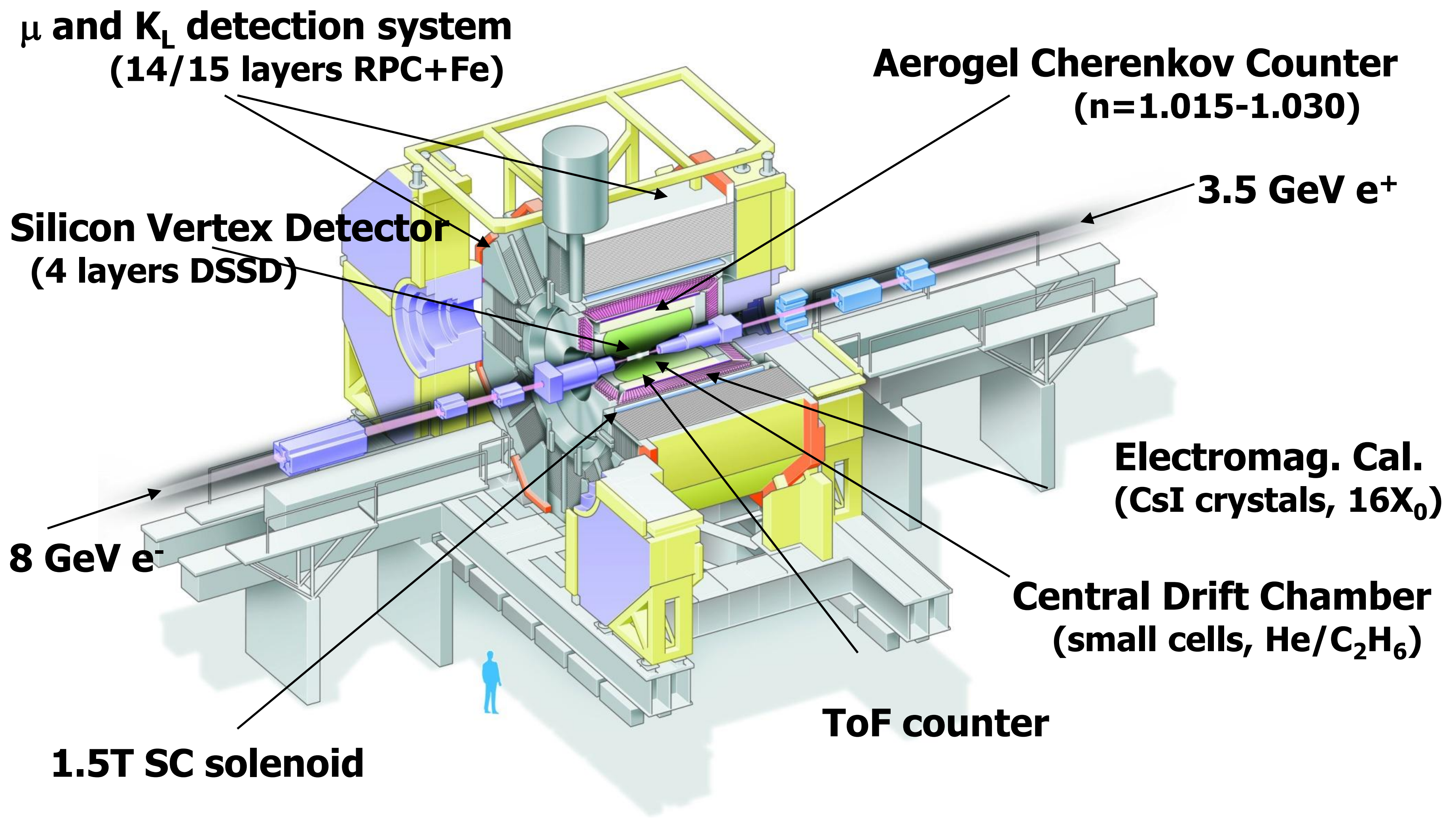


B^0 and its anti-particle decay differently to the same final state $J/\psi\ K^0$

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, $16X_0$)

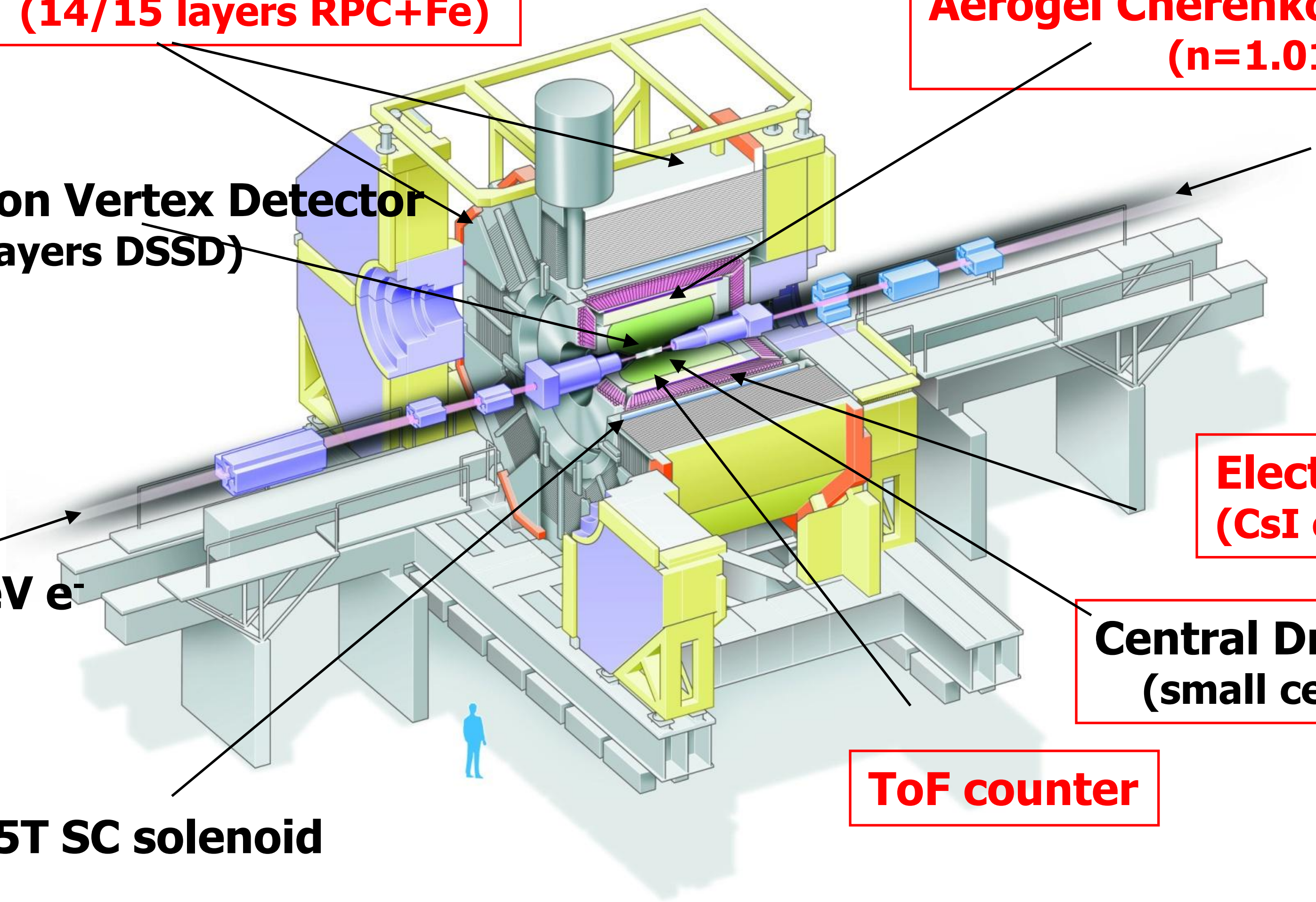
8 GeV e^-

Central Drift Chamber (small cells, He/C_2H_6)

ToF counter

1.5T SC solenoid

Particle identification systems in Belle



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

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, $p=\gamma mv$. Momentum known (radius of curvature in magnetic field)

→Measure velocity:

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

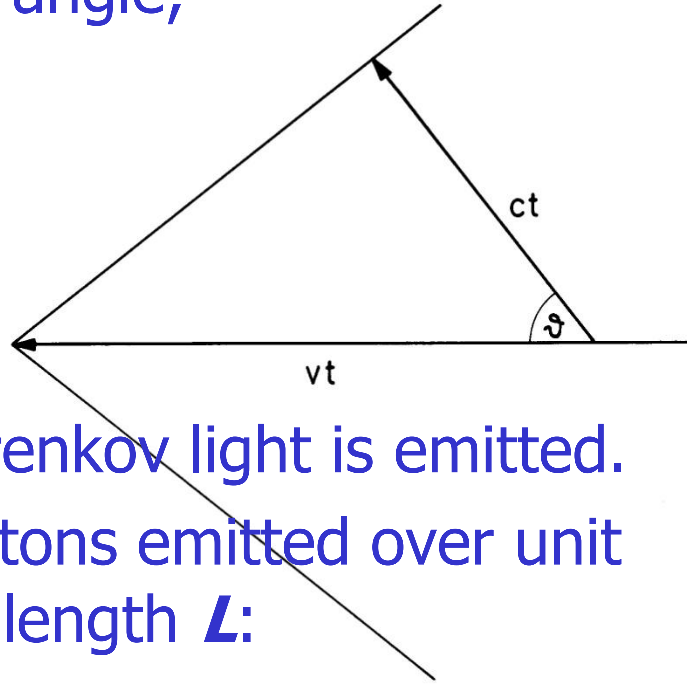
Mainly used for the identification of hadrons.

Identification through interaction: electrons and muons

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:

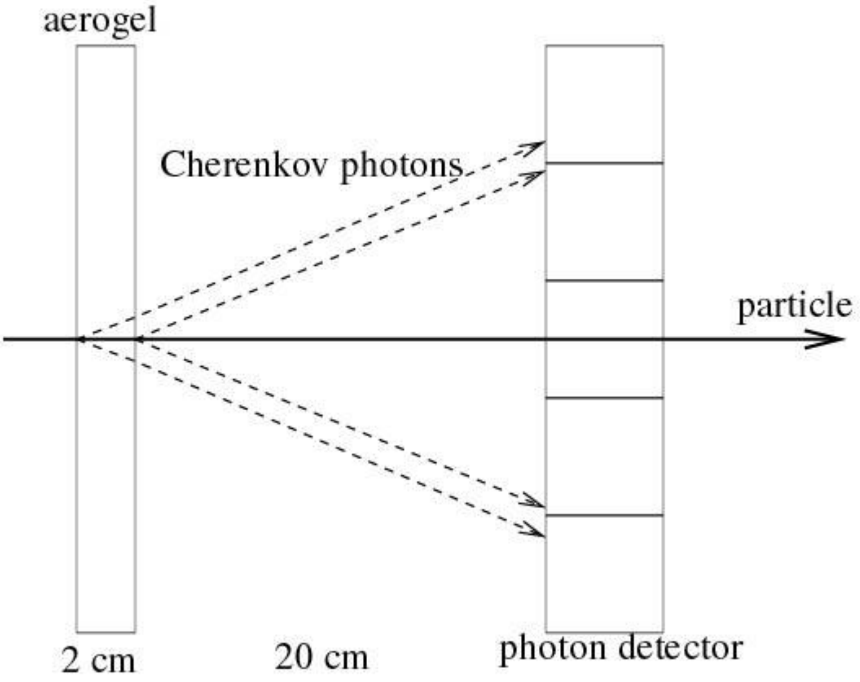
→ $\beta < \beta_t = 1/n$: below threshold no Cherenkov light is emitted.

→ $\beta > \beta_t$: 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

Measuring Cherenkov angle

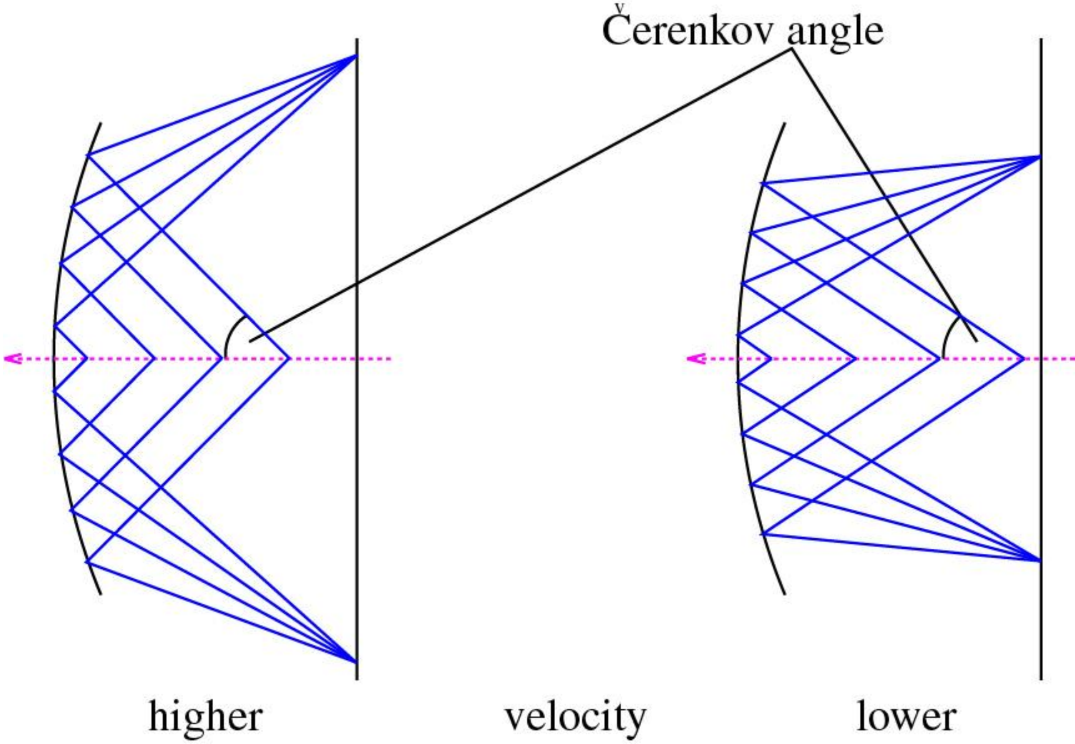


Proximity focusing RICH

Idea: transform the direction into a coordinate →

ring on the detection plane

→ Ring Imaging CHerenkov



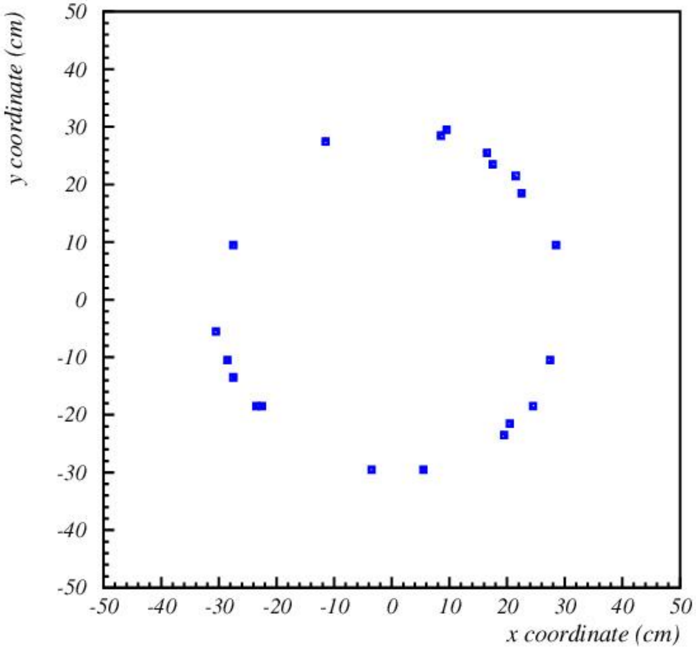
RICH with a focusing mirror

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
- over a large area (square meters)



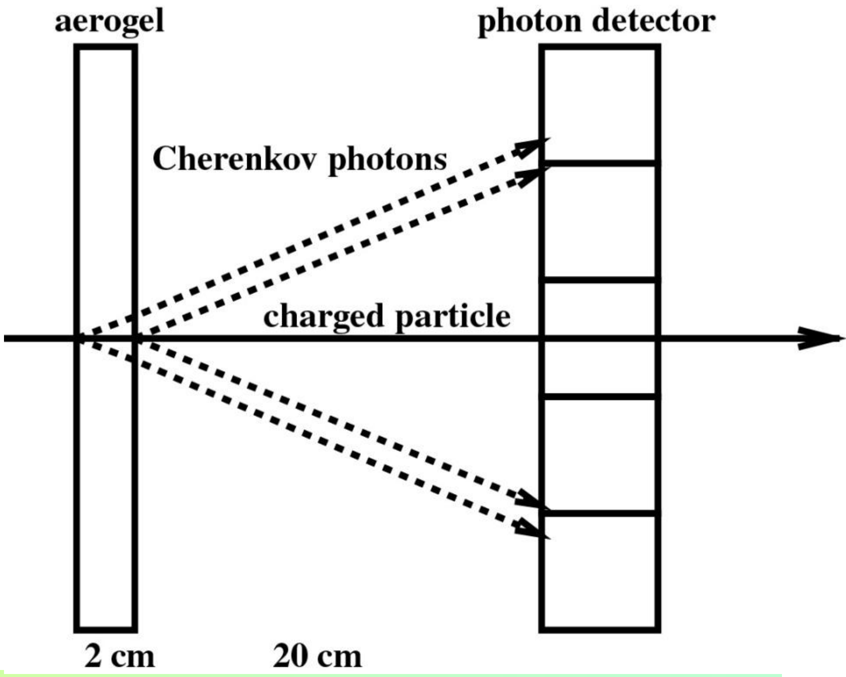
Special requirements:

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

Resolution of a RICH counter

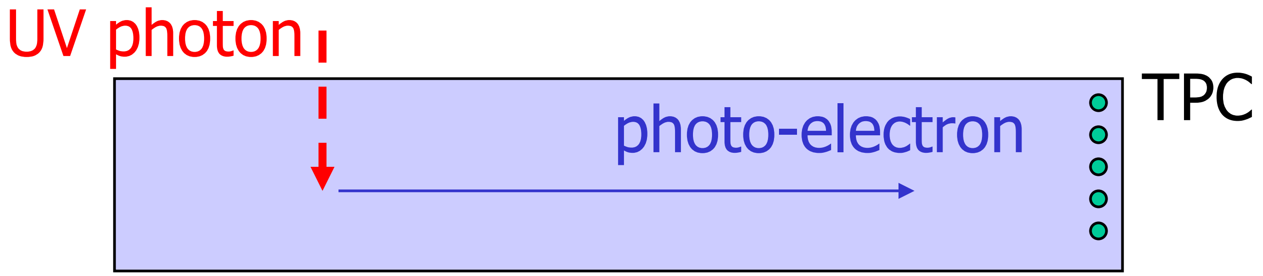
Determined by:

- 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

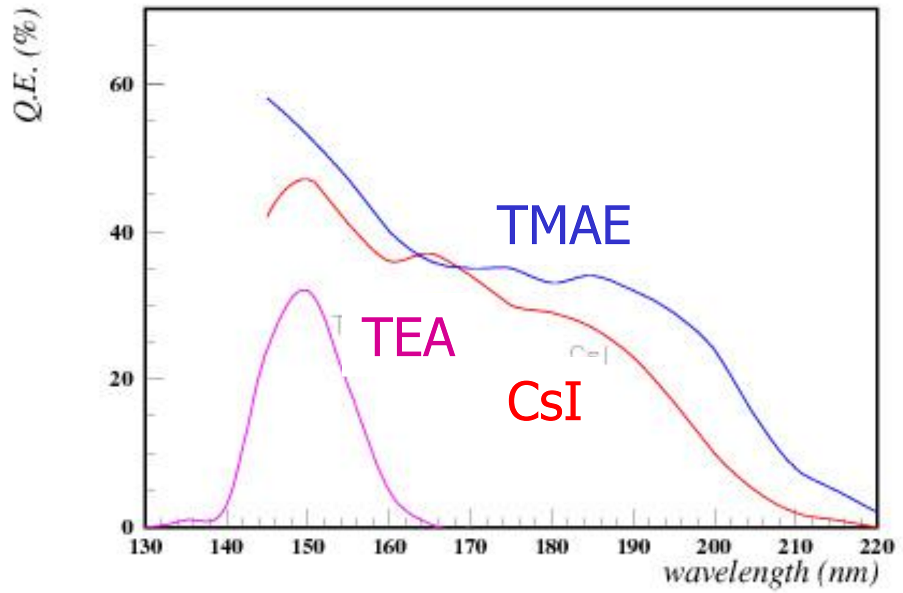


First generation of RICH counters

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

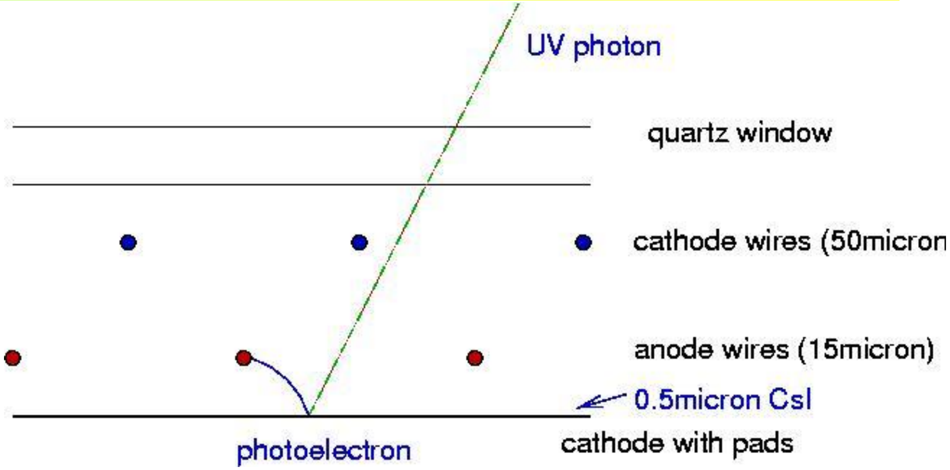


Photosensitive component:
TMAE added to the gas mixture



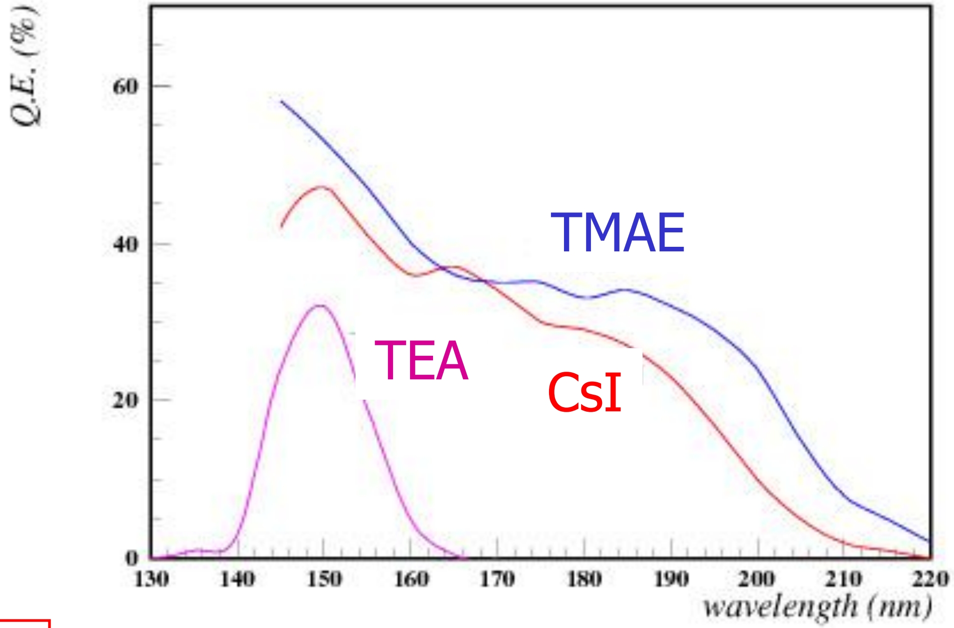
Fast RICH counters with wire chambers

Multiwire chamber with 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 pad cathode) →



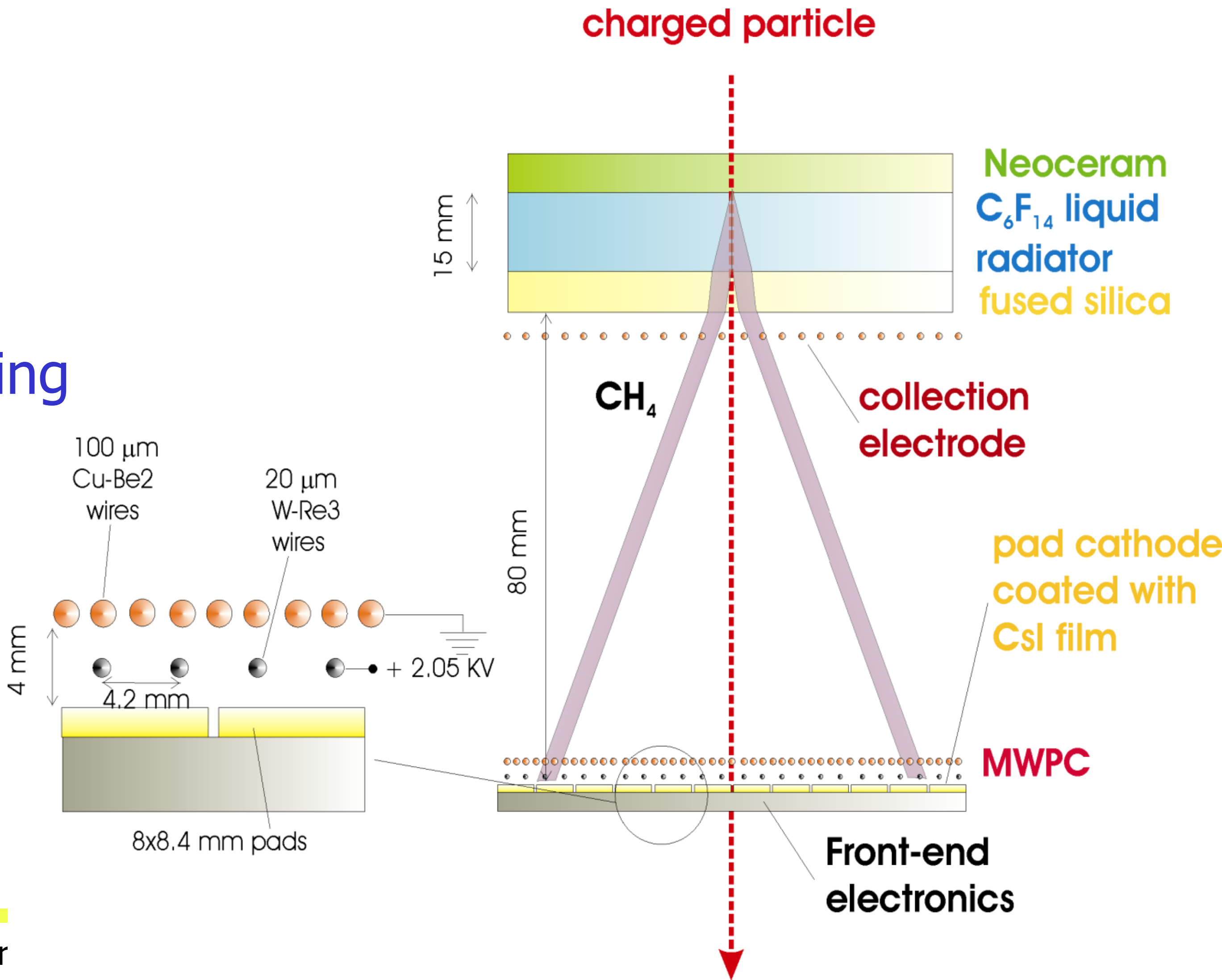
Works in high magnetic field!

CsI based RICH counters: HADES, COMPASS, ALICE

HADES and COMPASS RICH: have been running for several years

ALICE:

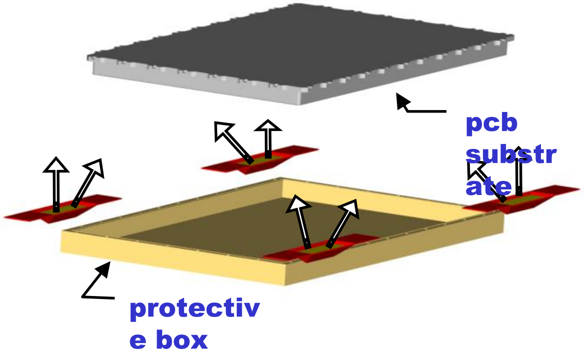
- liquid radiator
- proximity focusing

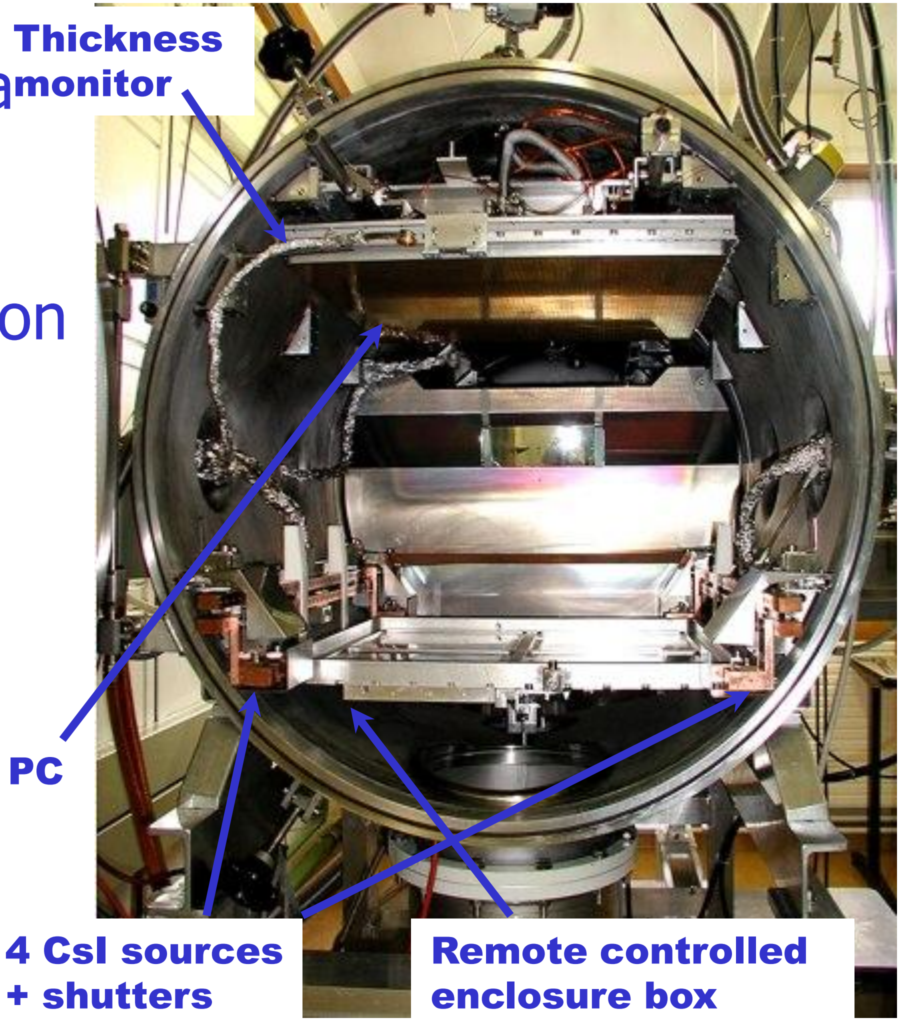


CERN CsI deposition plant

Photocathode produced with a well defined, several step procedure, including heat conditioning after CsI deposition

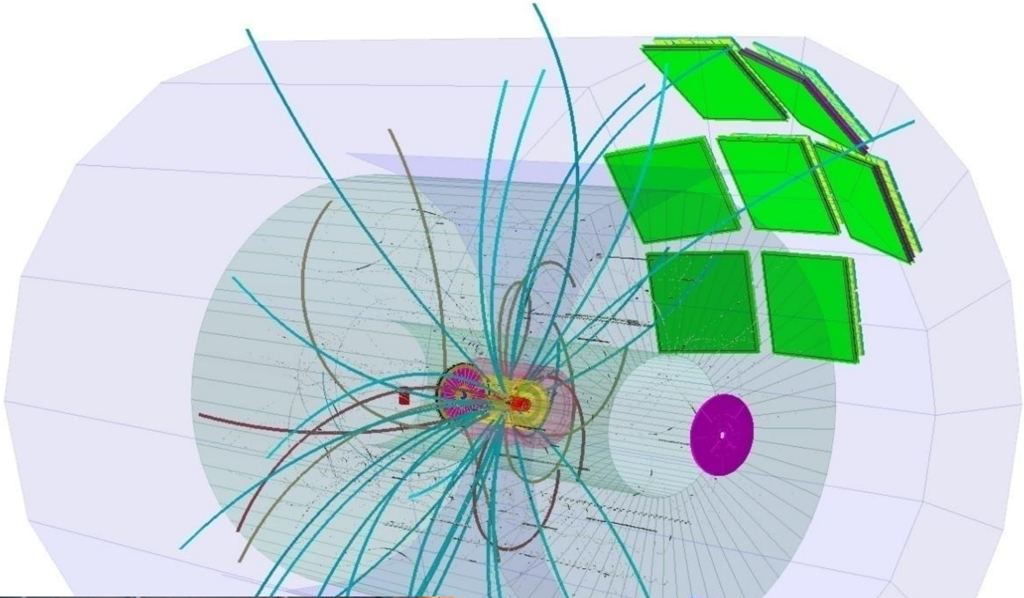
In situ quality control





ALICE RICH

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

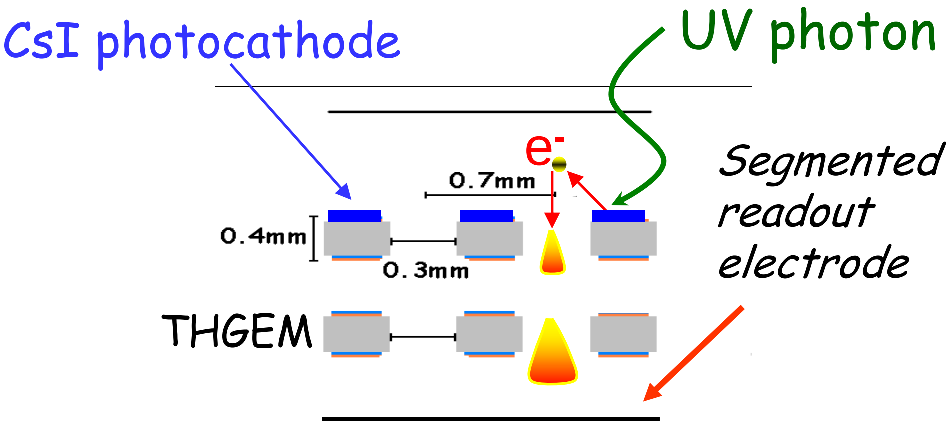


Wire chamber based photon detectors: recent developments

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

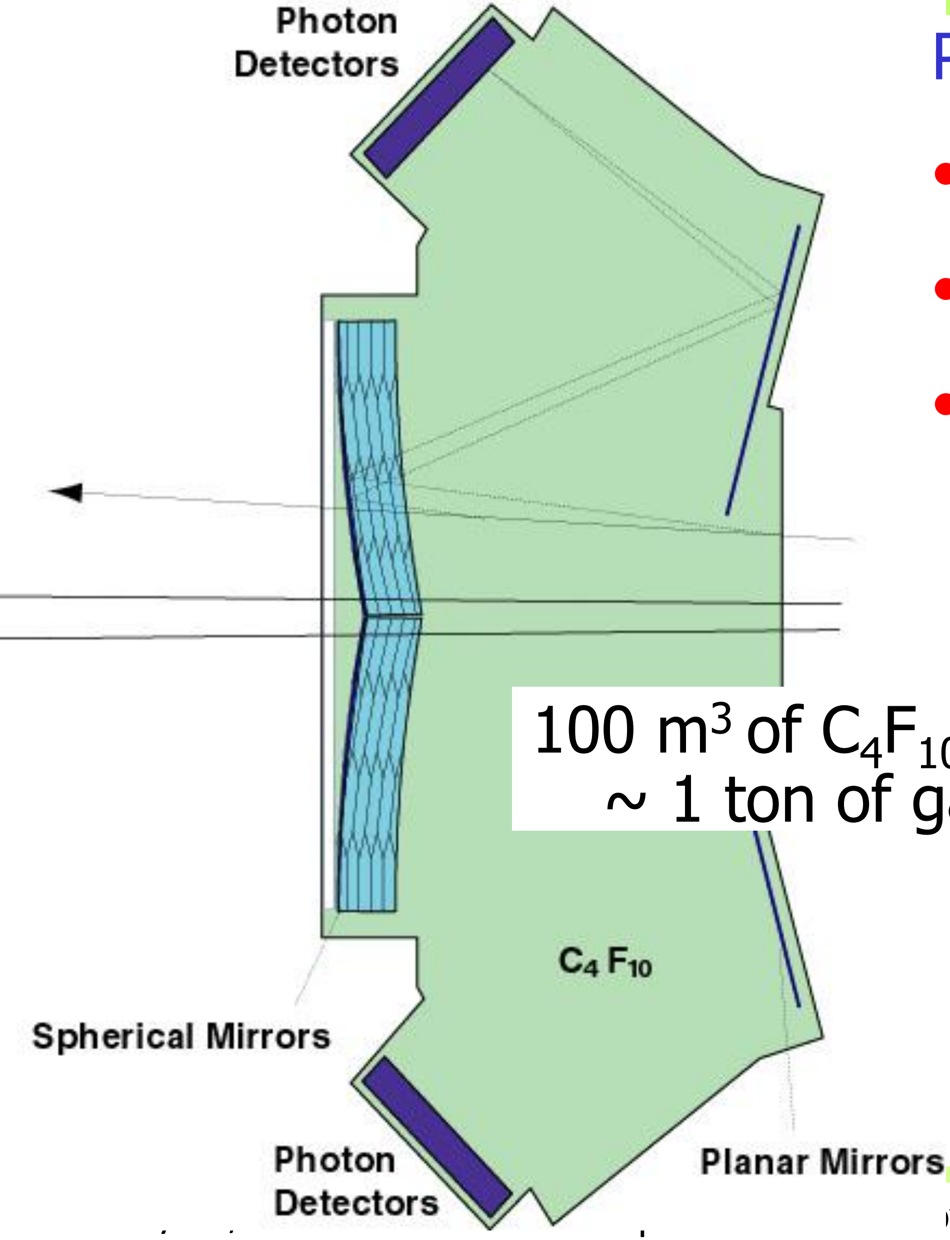


Ion damage of the photocathode: ions can be blocked

Cherenkov counters with vacuum based photodetectors

Some applications: 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)

HERA-B RICH



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

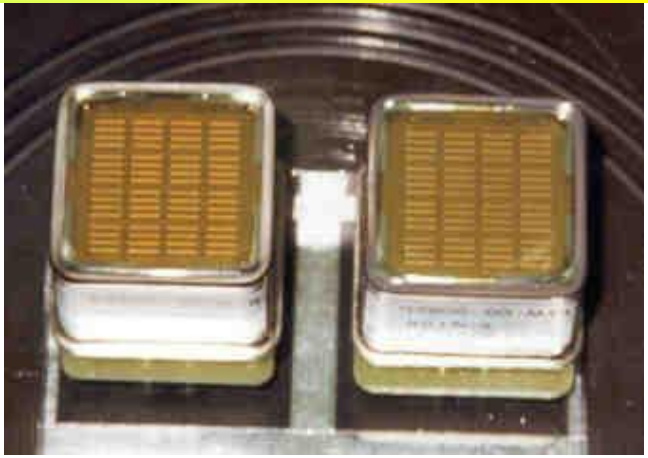
Photon detector requirements:

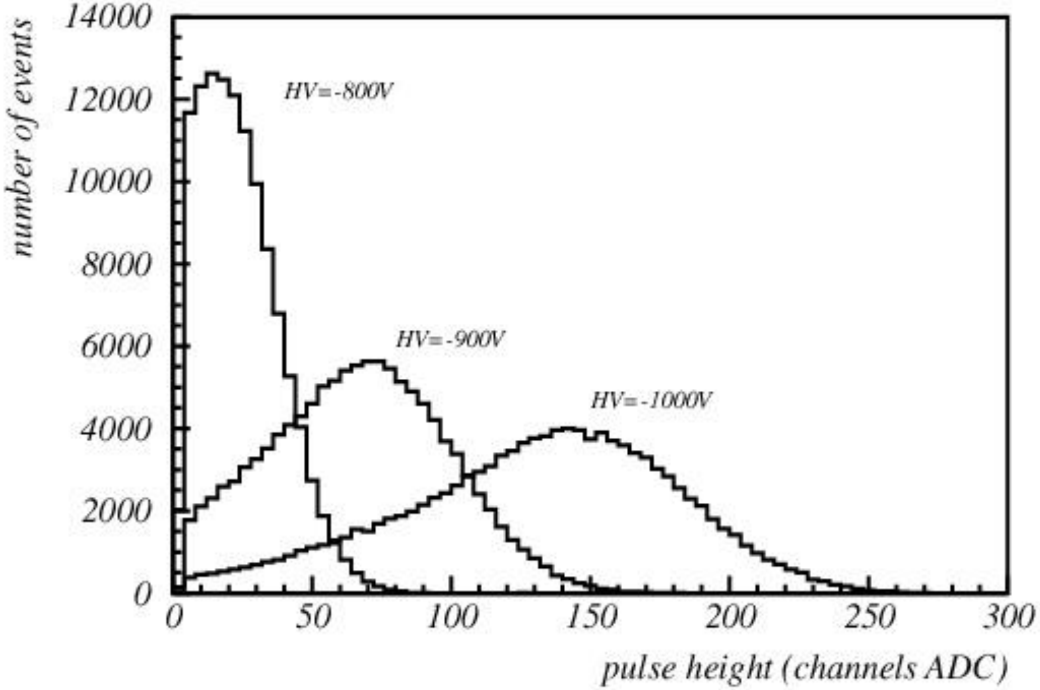
- High QE over ~3m^2
- Rates ~1MHz
- Long term stability

Multianode PMT Hamamatsu R5900-M16

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%)

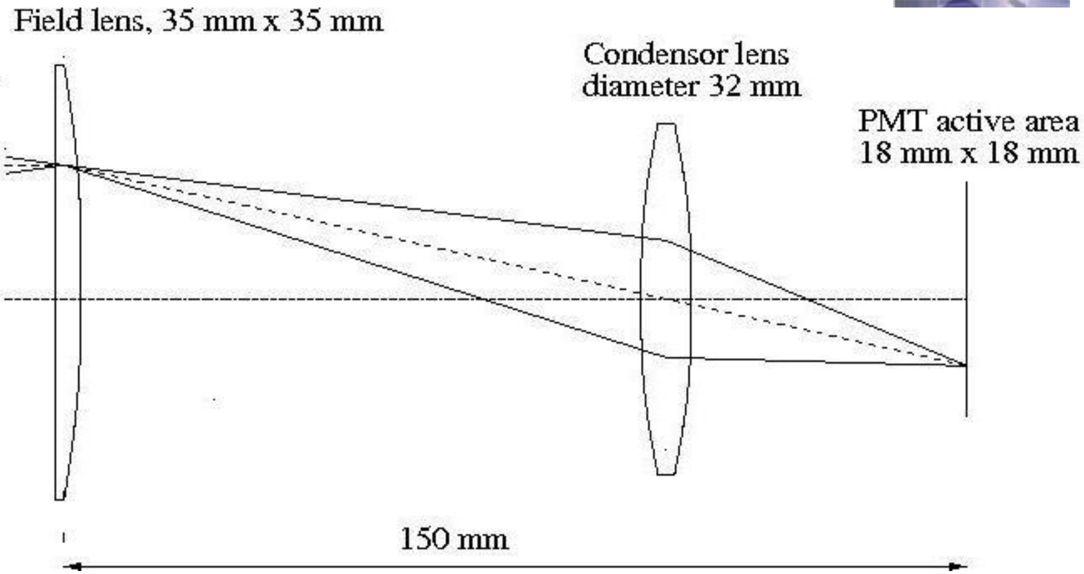
Giess → NIM A394 (1997) 27 na

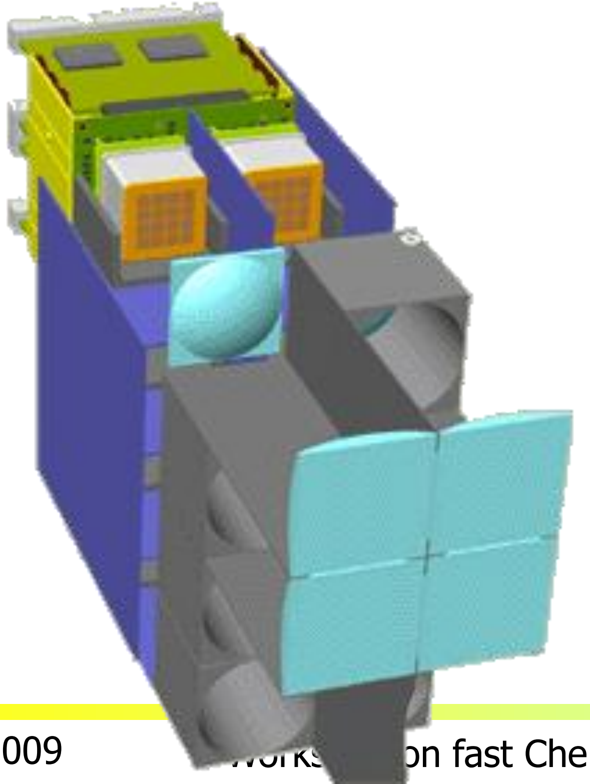
HERA-B RICH photon detector

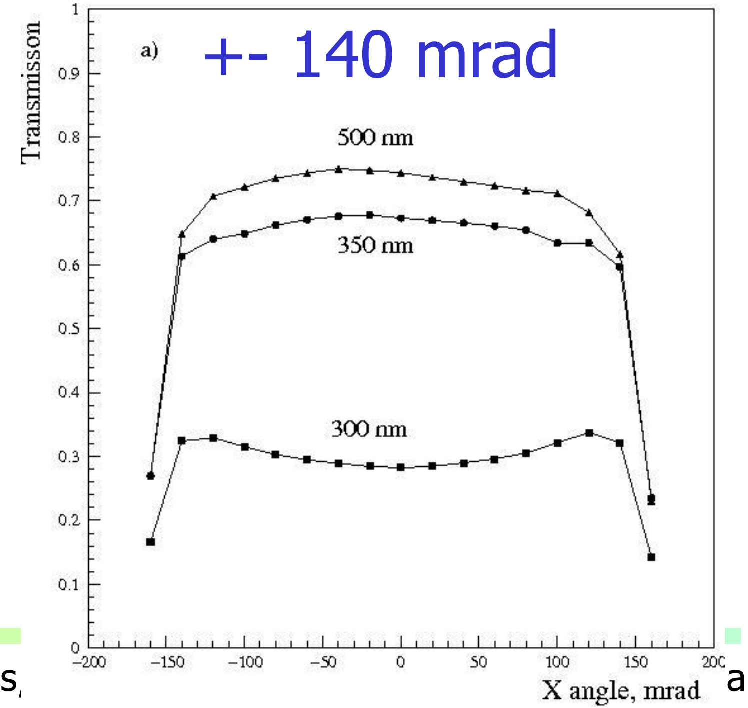
Light collection system (imaging!) to:

-Eliminate dead areas

-Adapt the pad size

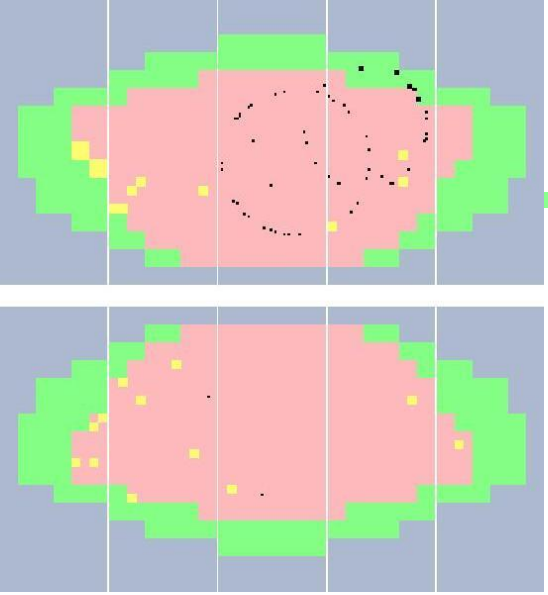






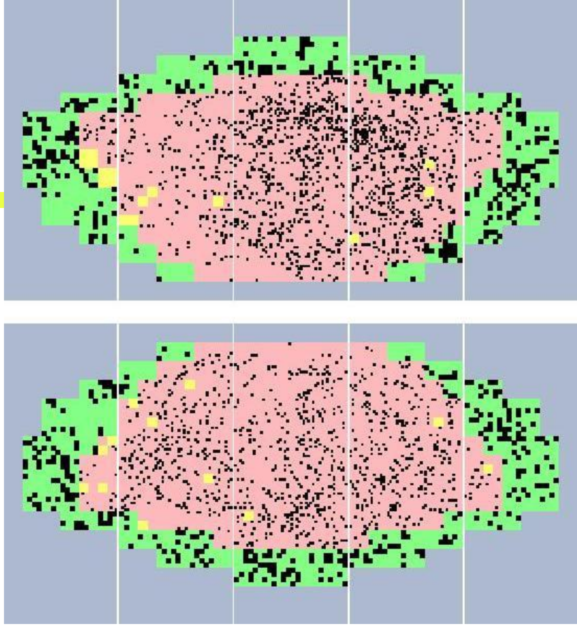
+- 140 mrad

HERA-B RICH

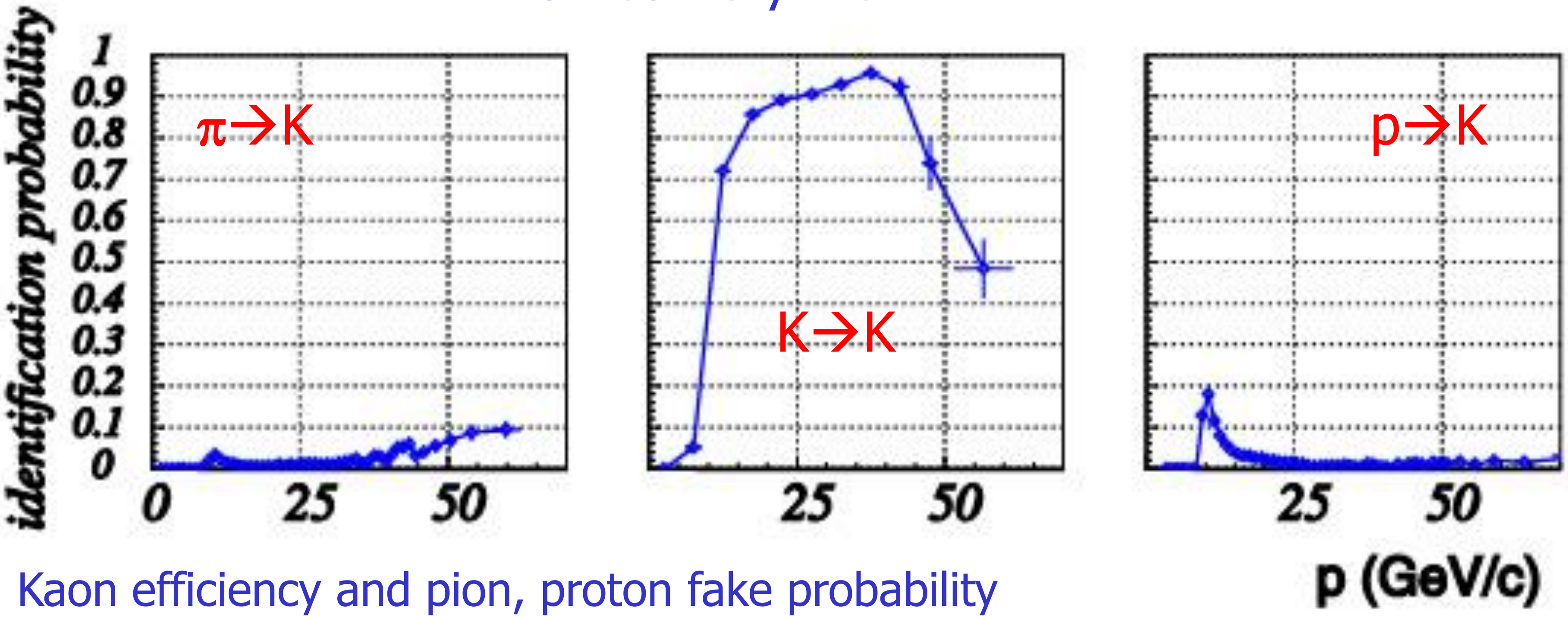


← Little noise, ~30 photons per ring

Typical event →



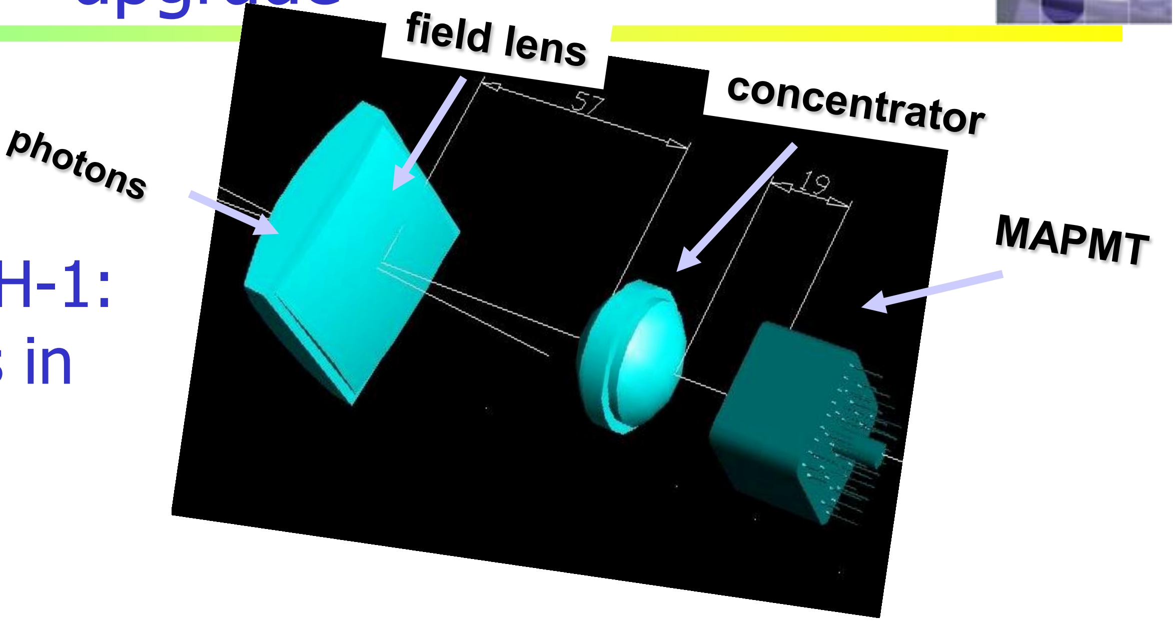
Worked very well!



Kaon efficiency and pion, proton fake probability

Photon detector for the COMPASS RICH-1 upgrade

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



New features:

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

COMPASS RICH-1 upgrade

Preliminary results:

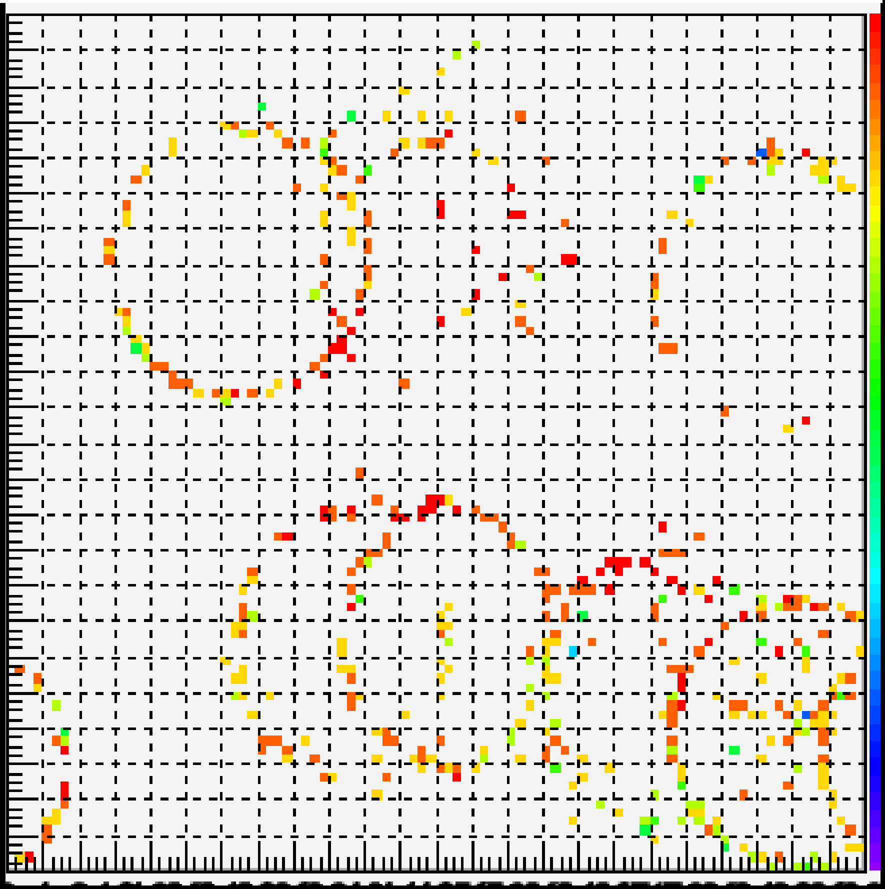
~ 60 detected photons per ring at saturation ($\beta = 1$) → N_0 ~66 cm^{-1}

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

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

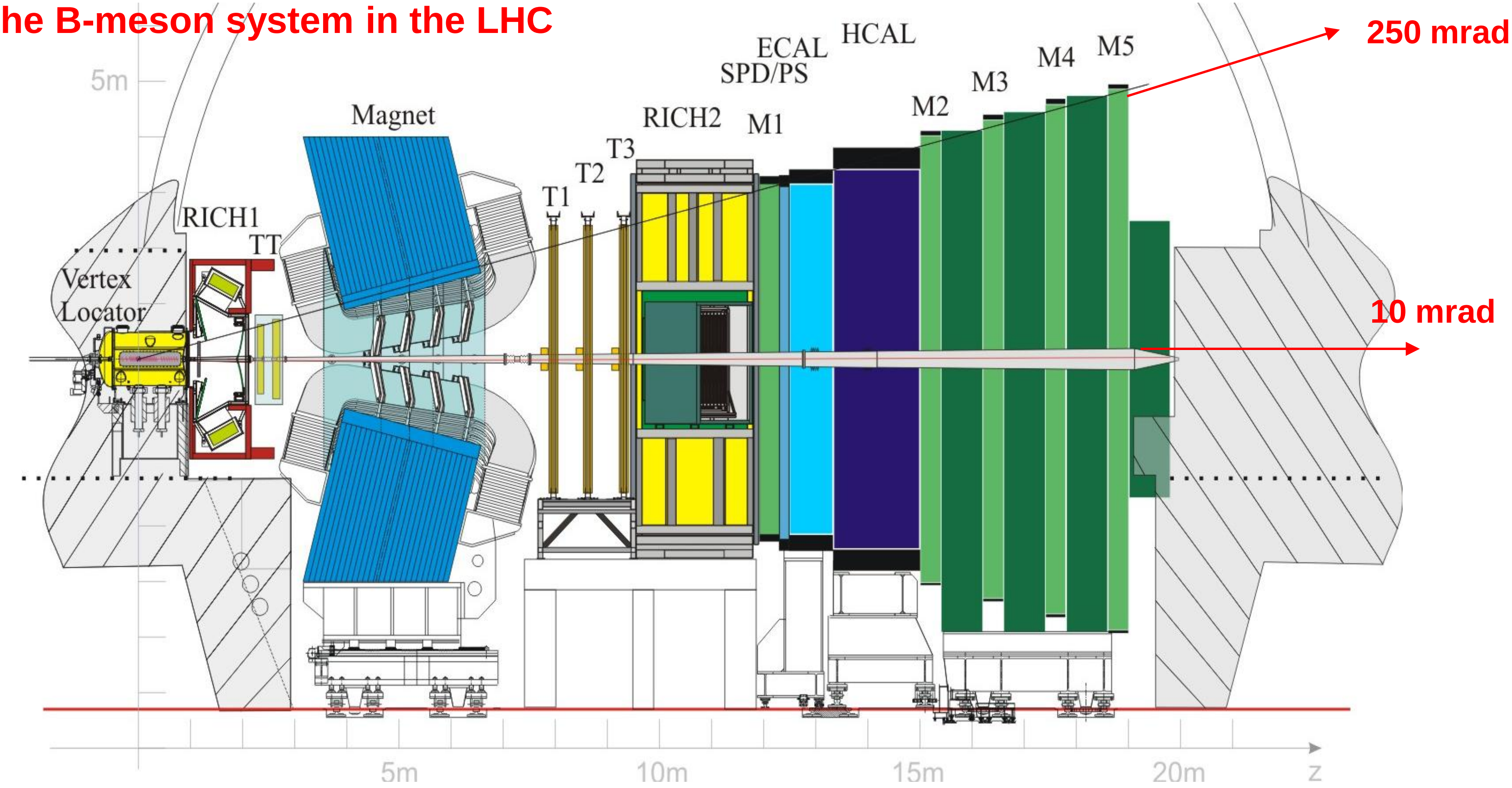
π → K misidentification ($\pi^\pm$ from K_s decay) ~ 1 %

IMAGE FROM THE ON-LINE EVENT DISPLAY



The LHCb RICH counters

Single arm spectrometer for precise CP Violation measurements and rare decays in the B-meson system in the LHC



Vertex reconstruction:
VELO

Trigger:
Muon Chambers
Calorimeters
Tracker

PID:
RICHes
Calorimeters
Muon Chambers

Kinematics:
Magnet
Tracker
Calorimeters

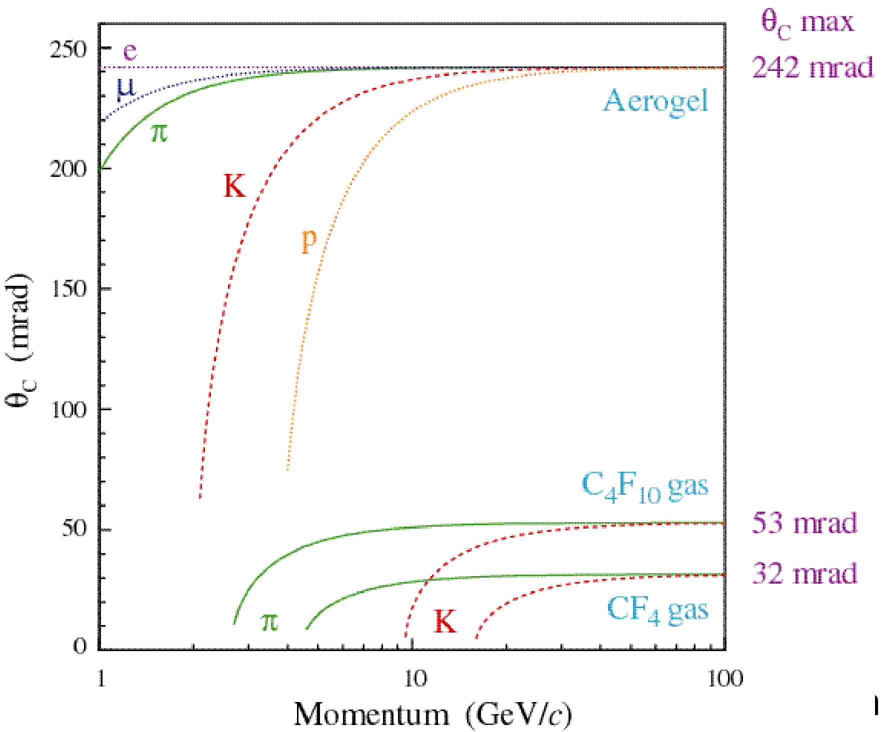
LHCb RICHes

Need:

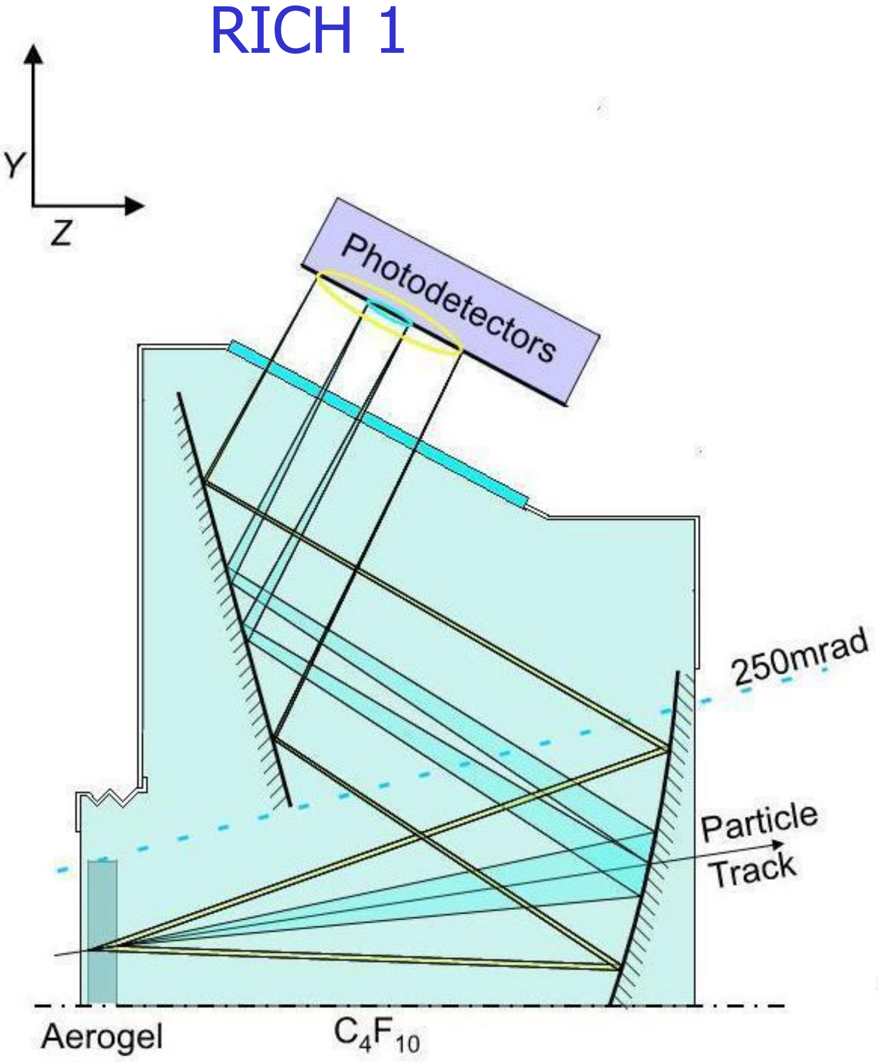
- Particle identification for momentum range ~2-100 GeV/c
- Granularity 2.5x2.5mm^2
- Large area (2.8m^2) with high active area fraction
- Fast compared to the 25ns bunch crossing time
- Have to operate in a small magnetic field

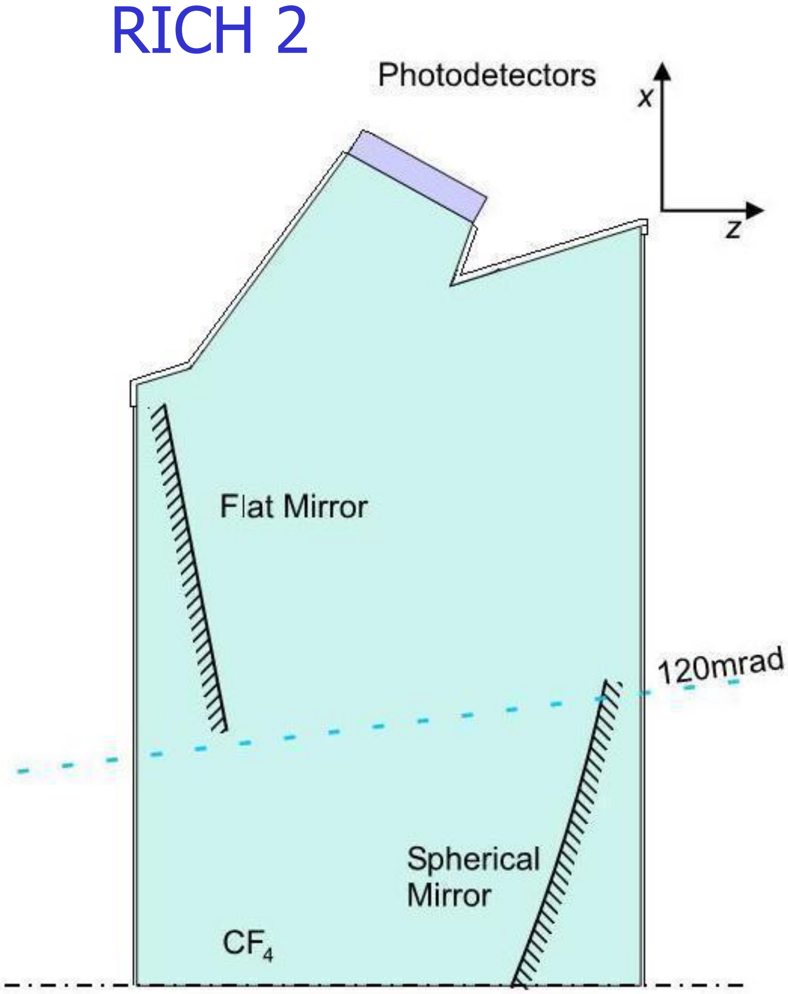
→3 radiators

(aerogel, CF_4, C_4F_{10})

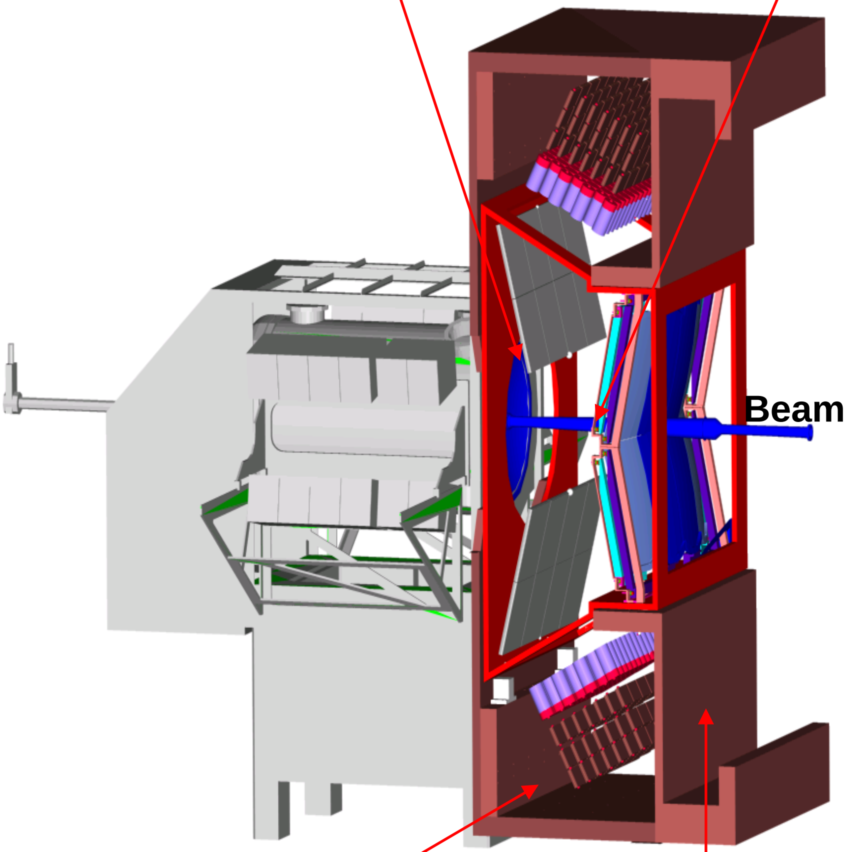


LHCb RICHes


RICH 1
Y
Z
Photodetectors
250mrad
Particle Track
Aerogel
C_4F_{10}


RICH 2
Photodetectors
x
z
Flat Mirror
120mrad
Spherical Mirror
CF_4

LHCb RICHes



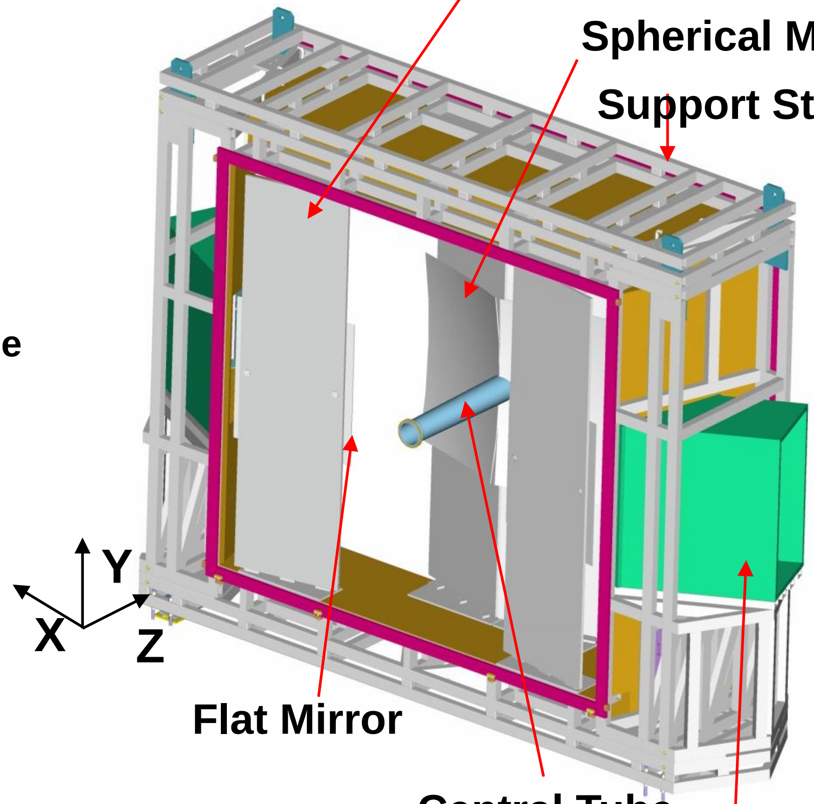
Flat mirrors

Spherical mirrors

Beam pipe

Photon detectors

Magnetic shielding
(16 tonnes of iron)



Mirror Support Panel

Spherical Mirror

Support Structure

Flat Mirror

Central Tube

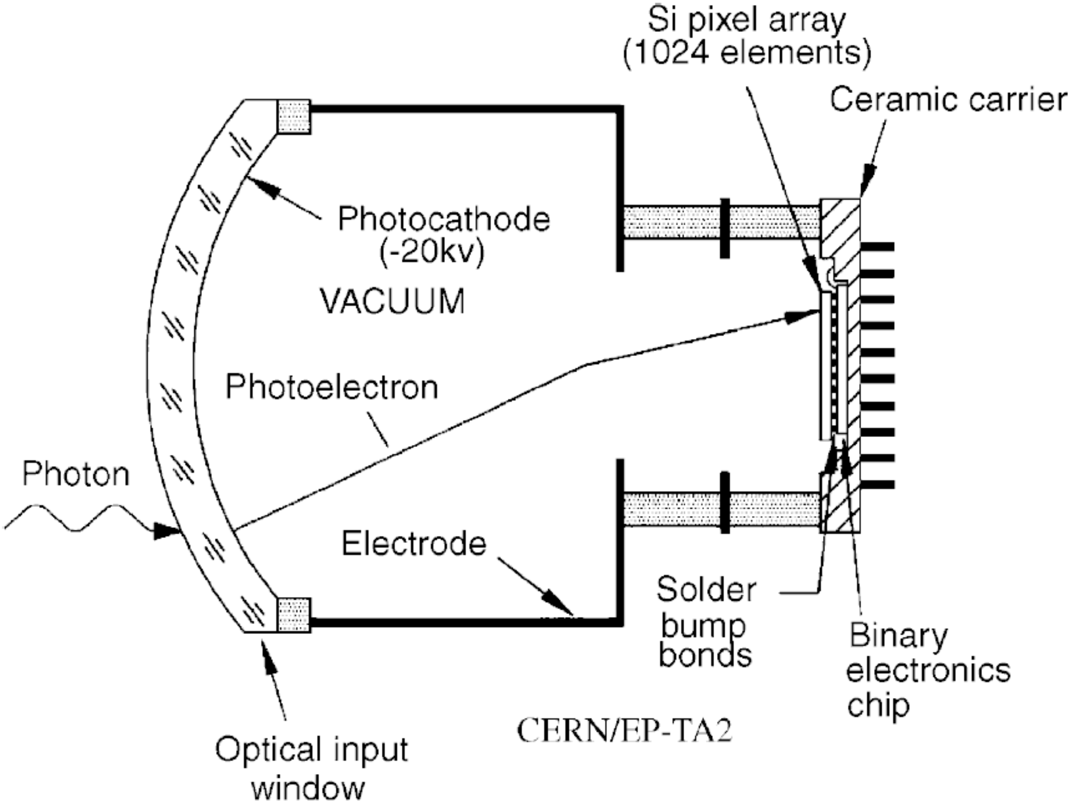
Photon funnel+Shielding

LHCb RICHes

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

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

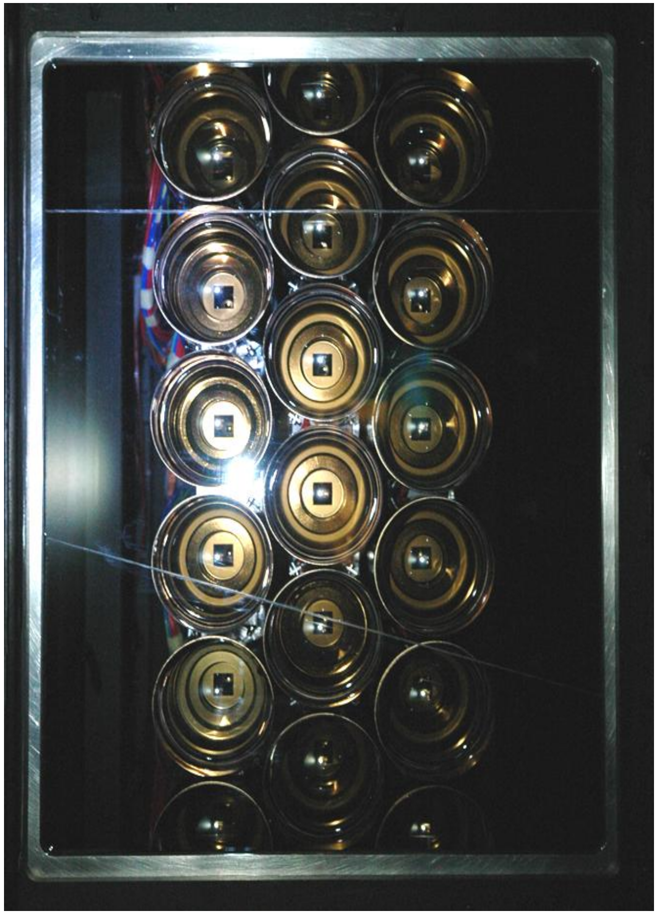
Hybrid PMT: accelerate photoelectrons in electric field (~10kV), detect it in a pixelated silicon detector.

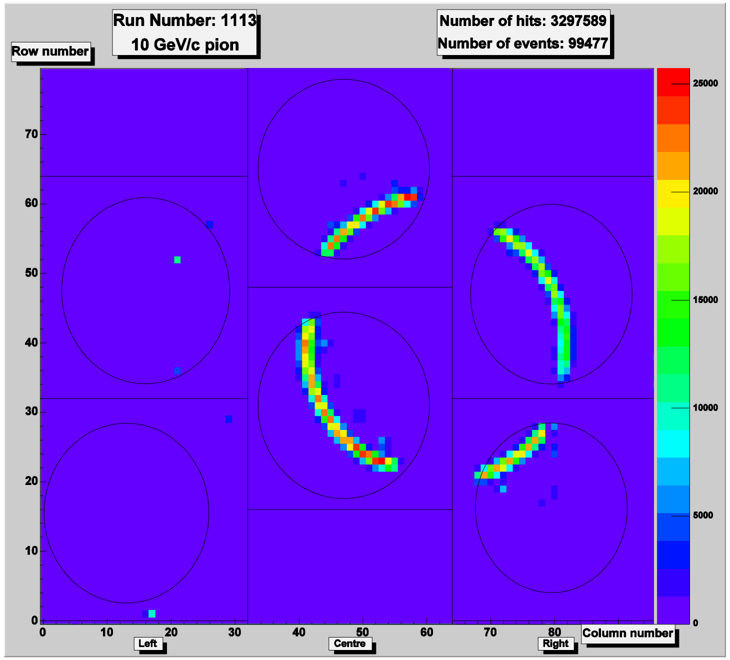


CERN/EP-TA2

NIM A553 (2005) 333

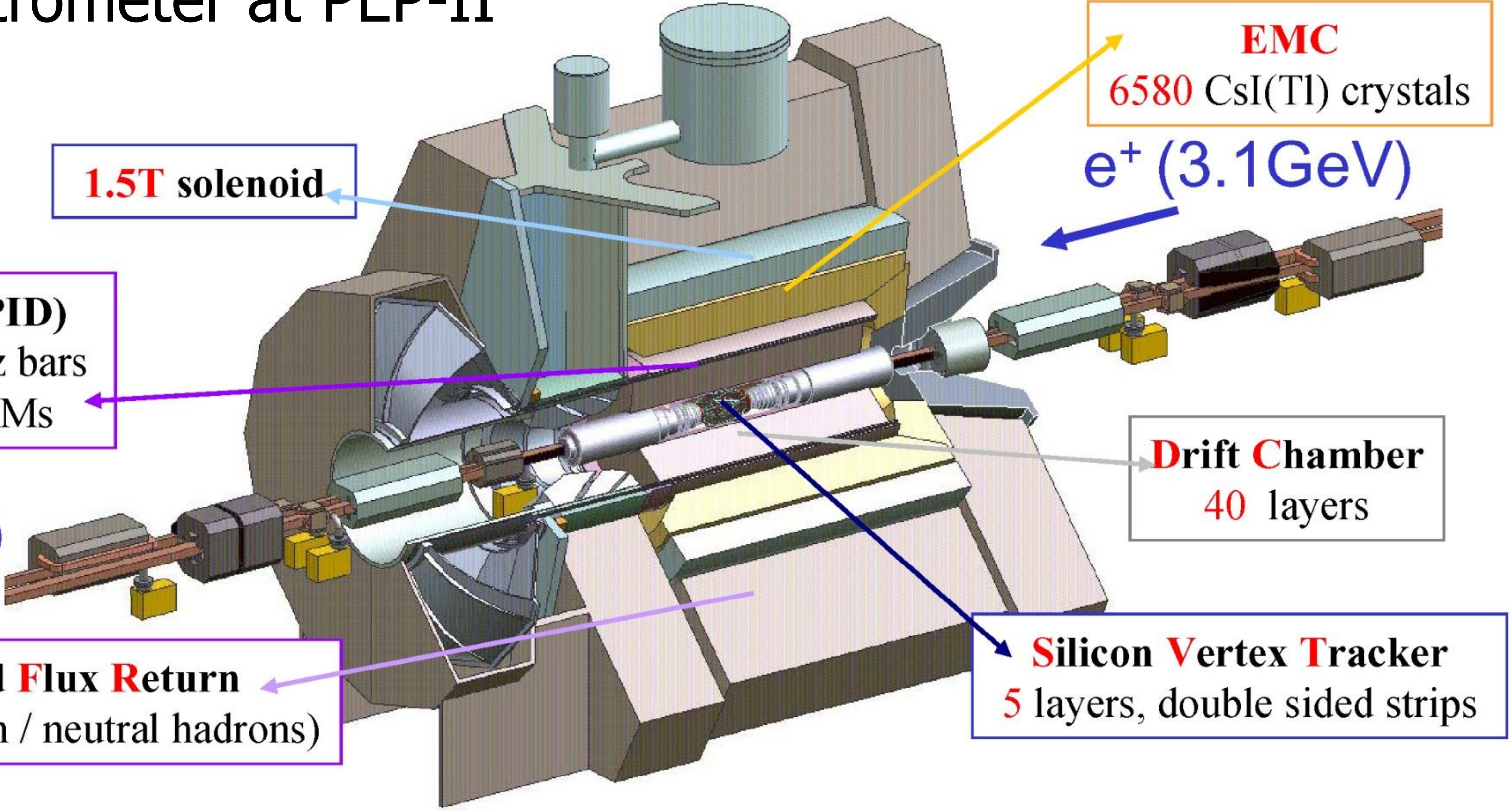
LHCb RICH System test





DIRC - detector of internally reflected Cherenkov light

BaBar spectrometer at PEP-II



EMC
6580 CsI(Tl) crystals

1.5T solenoid

DIRC (PID)
144 quartz bars
11000 PMs

e^+ (3.1GeV)

e^- (9GeV)

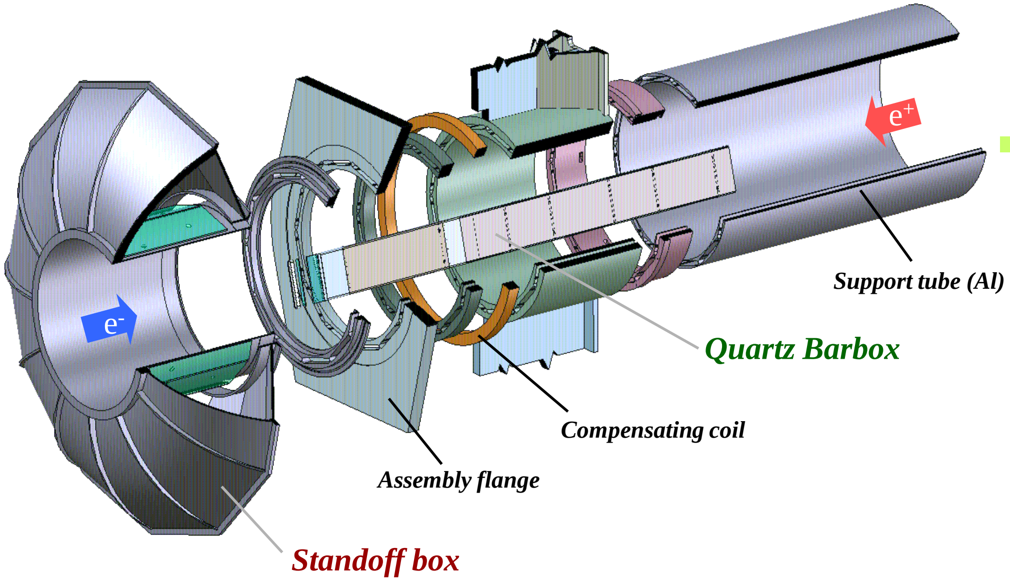
Drift Chamber
40 layers

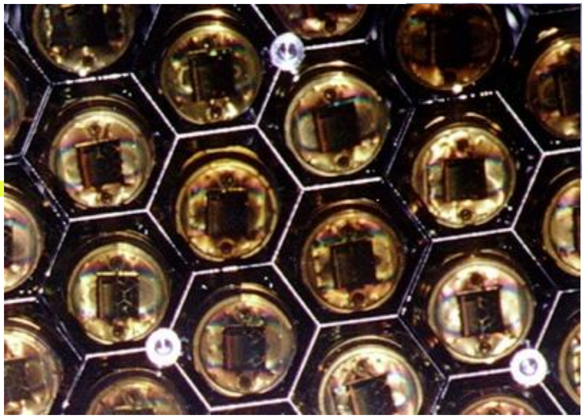
Instrumented Flux Return
iron / RPCs (muon / neutral hadrons)

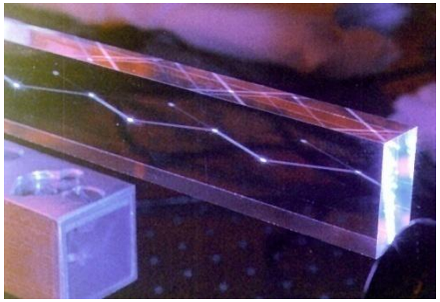
Silicon Vertex Tracker
5 layers, double sided strips

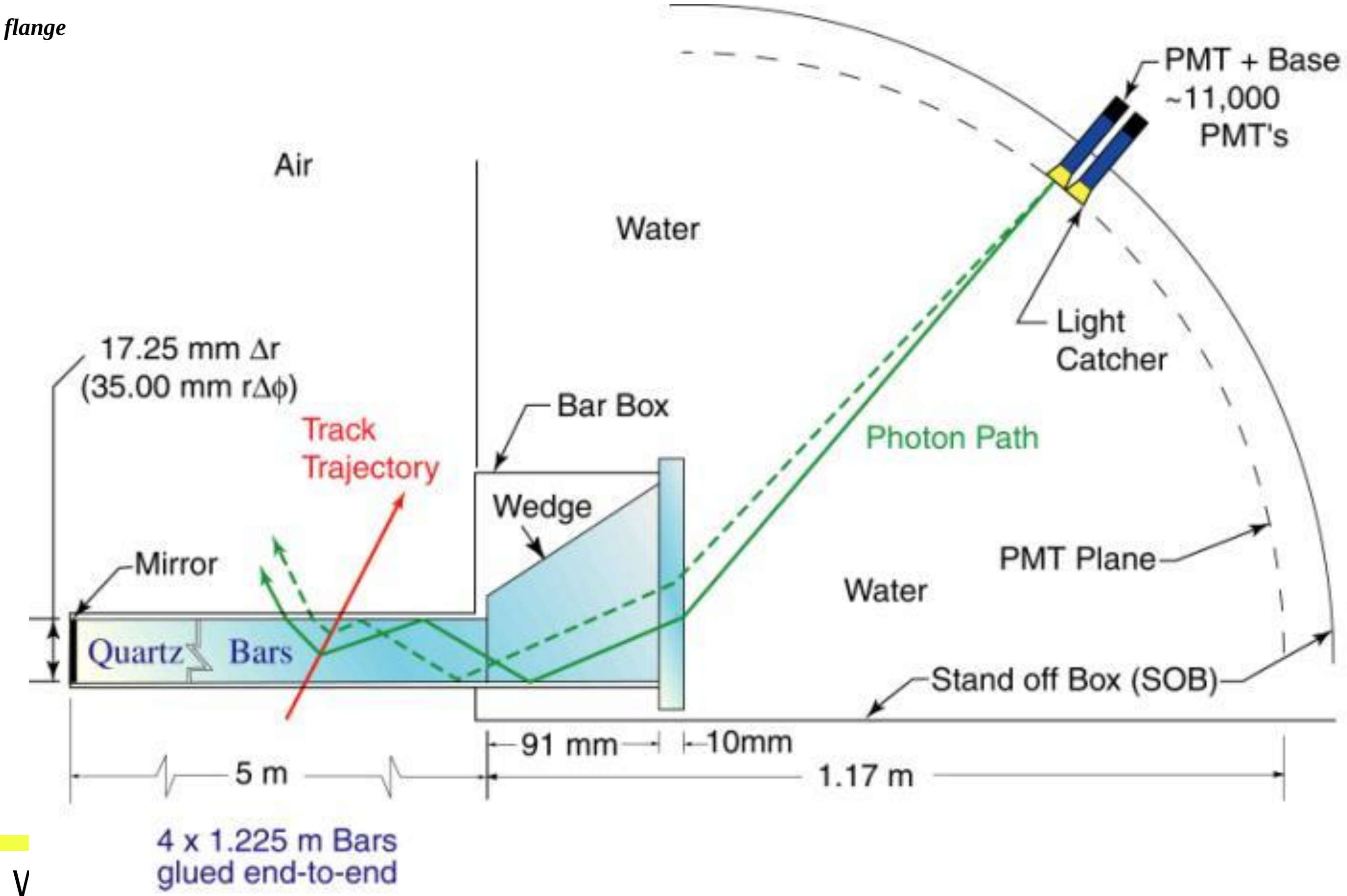
→ Talk by J. Schwiening

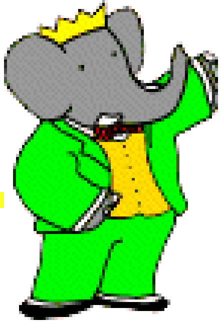
DIRC


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

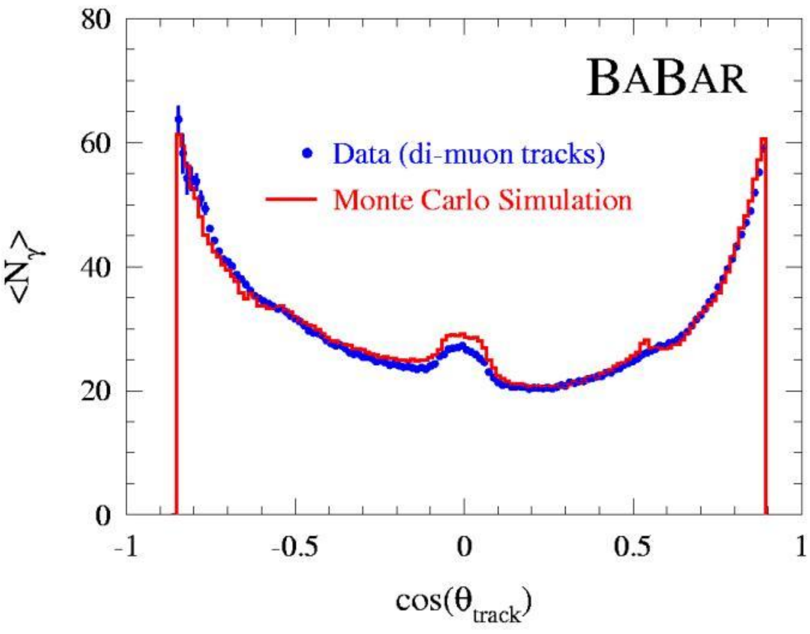





PMT + Base
~11,000
PMT's
Air
Water
Light
Catcher
17.25 mm Δr
(35.00 mm rΔϕ)
Bar Box
Track
Trajectory
Photon Path
Wedge
Mirror
PMT Plane
Water
Quartz
Bars
Stand off Box (SOB)
91 mm
10mm
5 m
1.17 m
4 x 1.225 m Bars
glued end-to-end

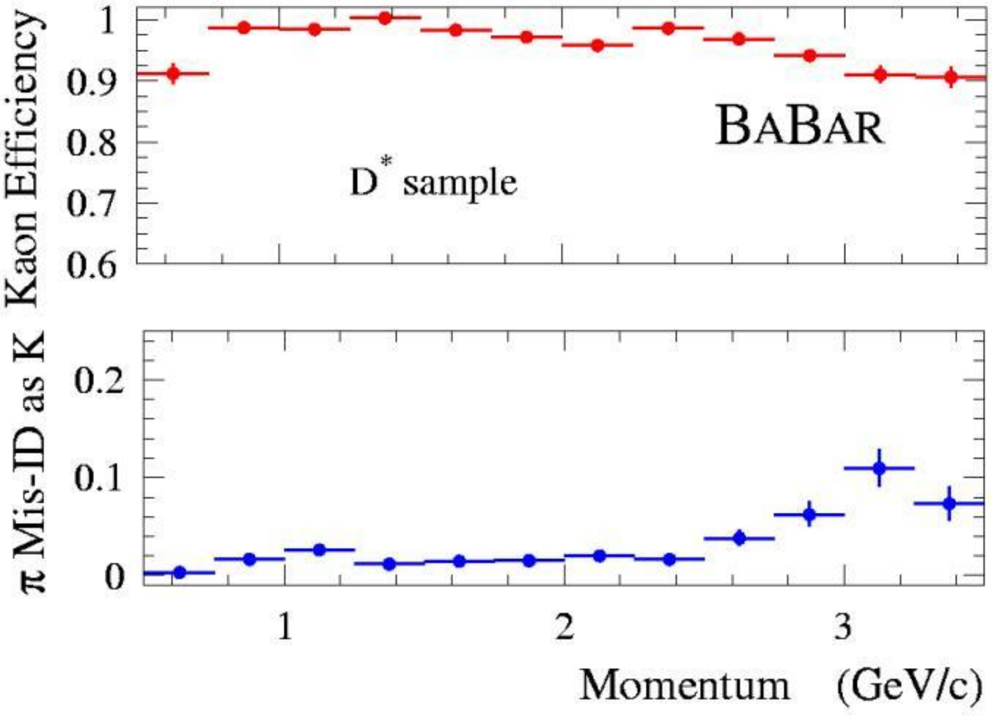


DIRC performance



← Lots of photons!

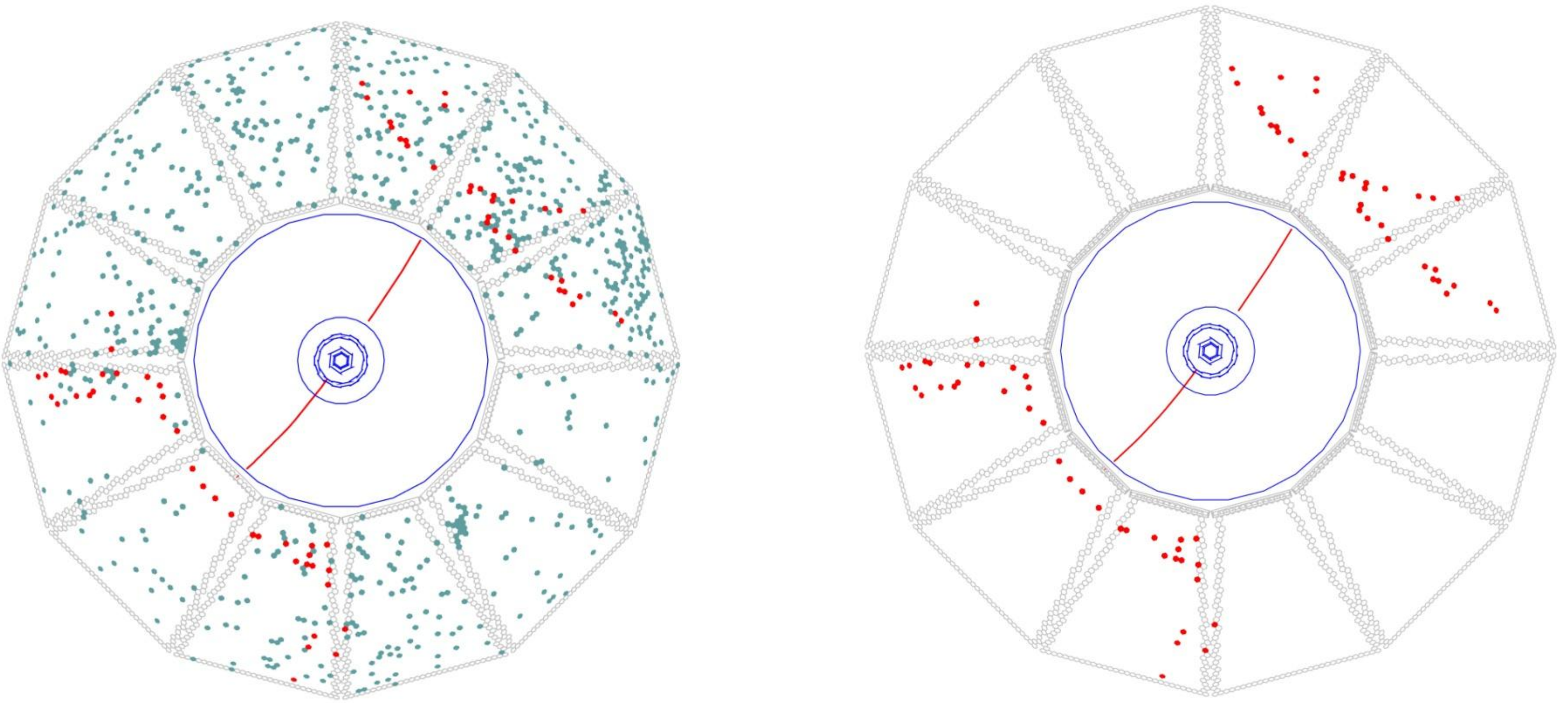
Excellent π/K separation



NIM A553 (2005) 317

DIRC

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



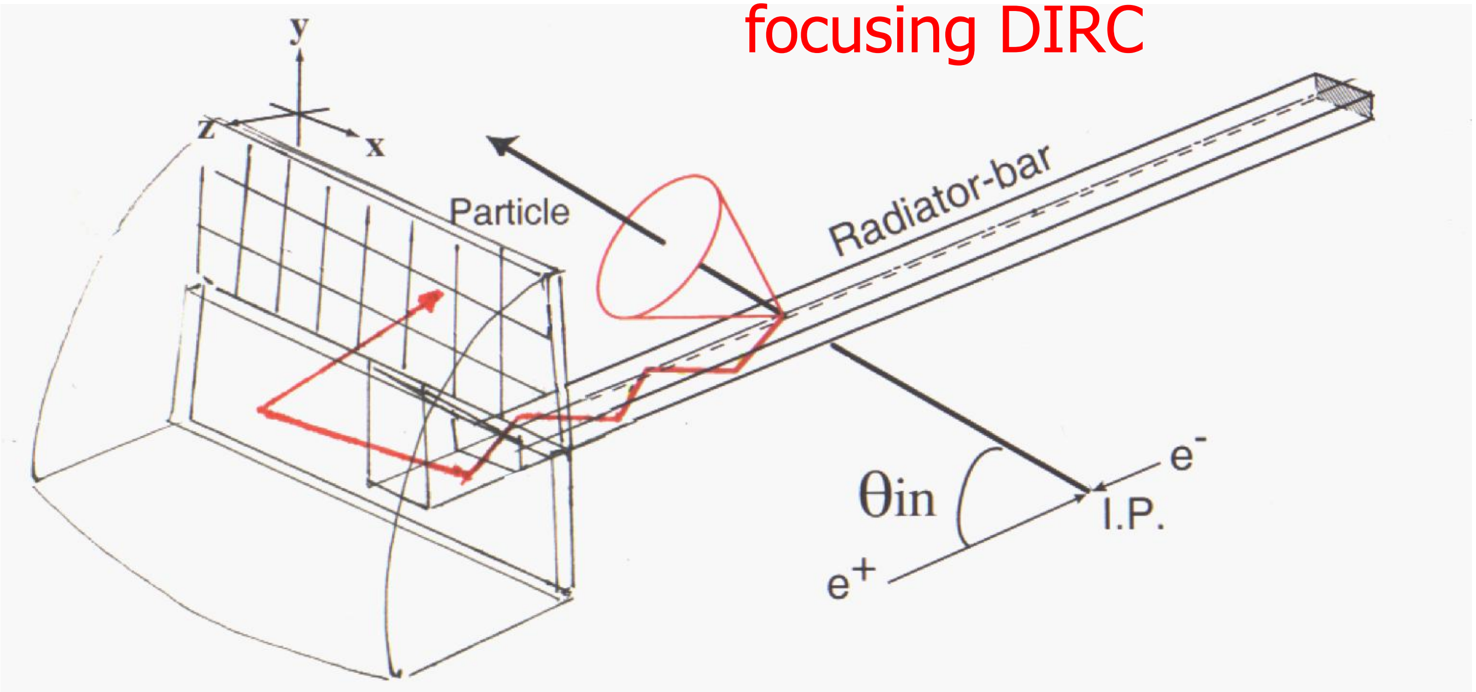
No time cut on the hits

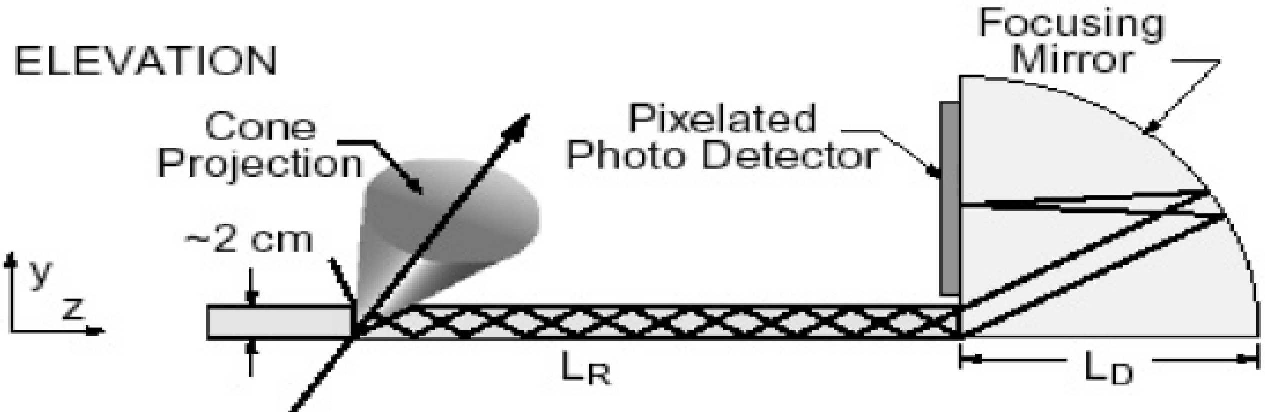
With a +-4ns time cut

Timing information is essential for background reduction

Focusing DIRC

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





Focusing DIRC

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) → $\sigma \leq$150-200ps (~10x better) allows a measurement of the photon group velocity $c_g(\lambda)$ to correct the chromatic error of θ_c.

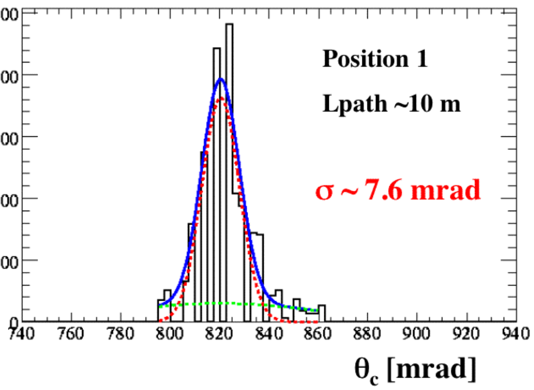
Photon detector requirements:

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

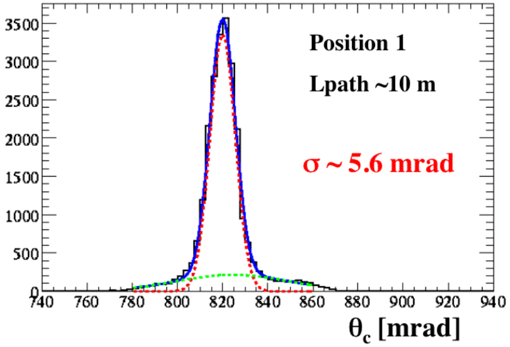
Focusing DIRC- the chromatic correction

Beam test results with BURLE/Photonis MCP PMT

Correction off:

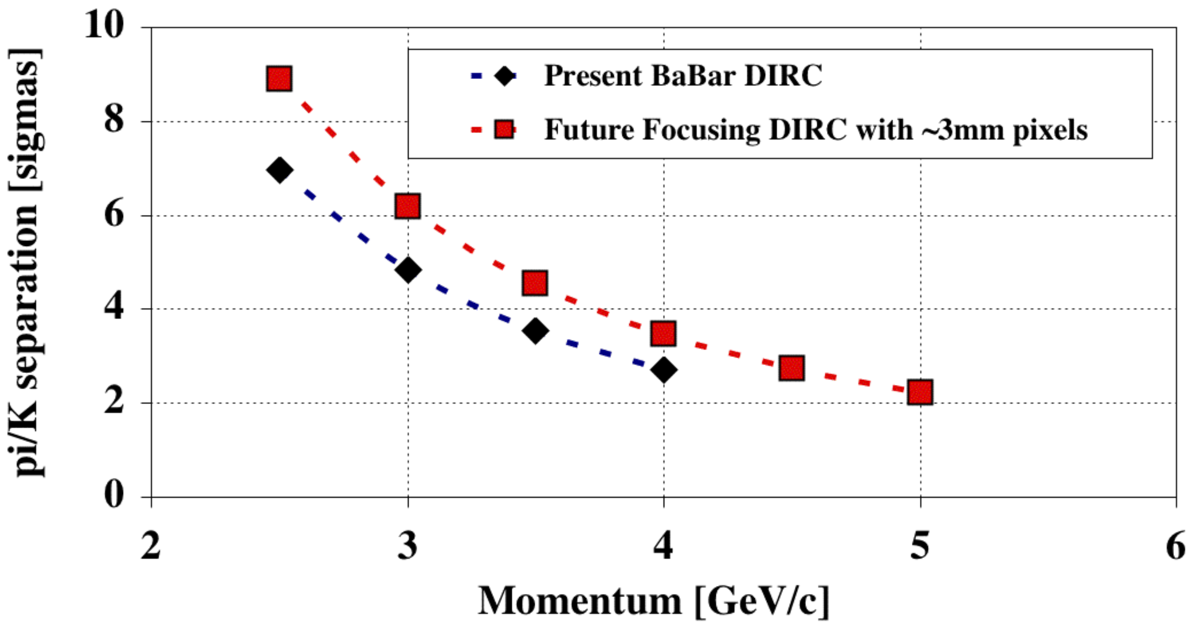


Correction on:



θ_C resolution and chromatic correction for 3mm pixels:

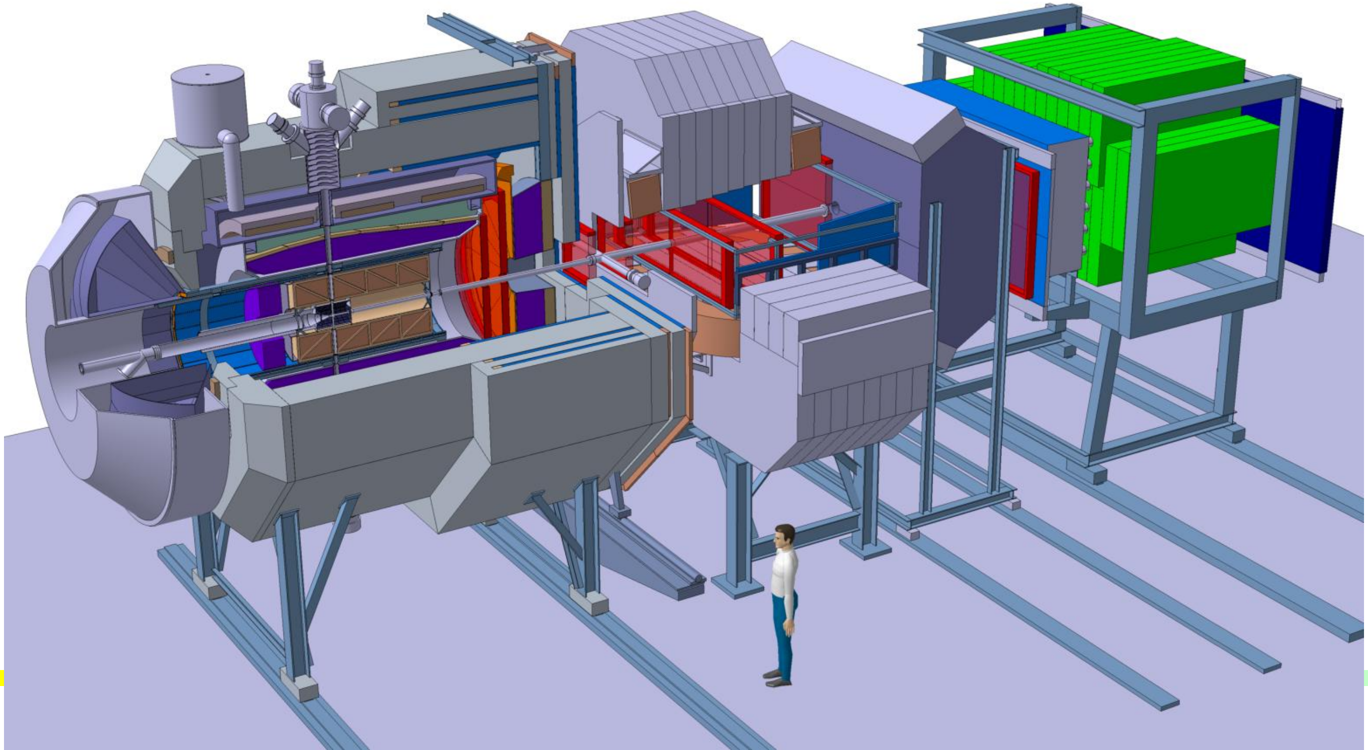
Expected PID performance:



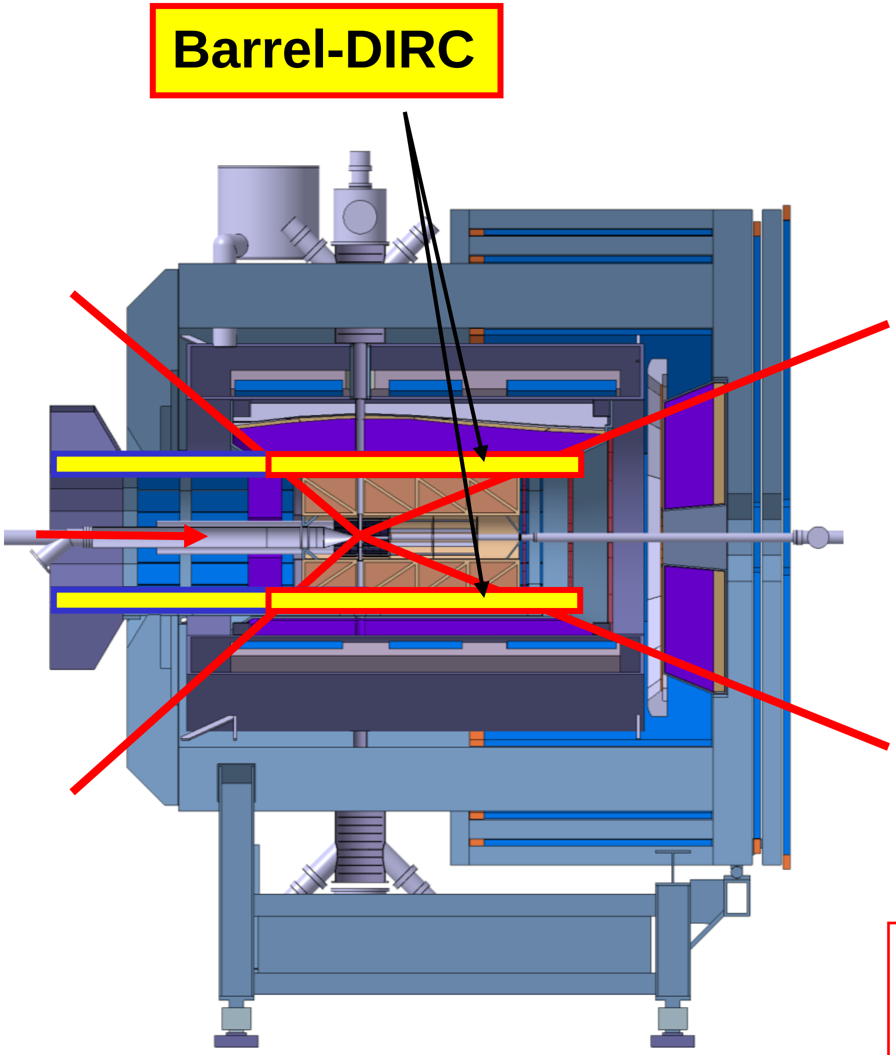
DIRC counters for PANDA (FAIR, GSI)

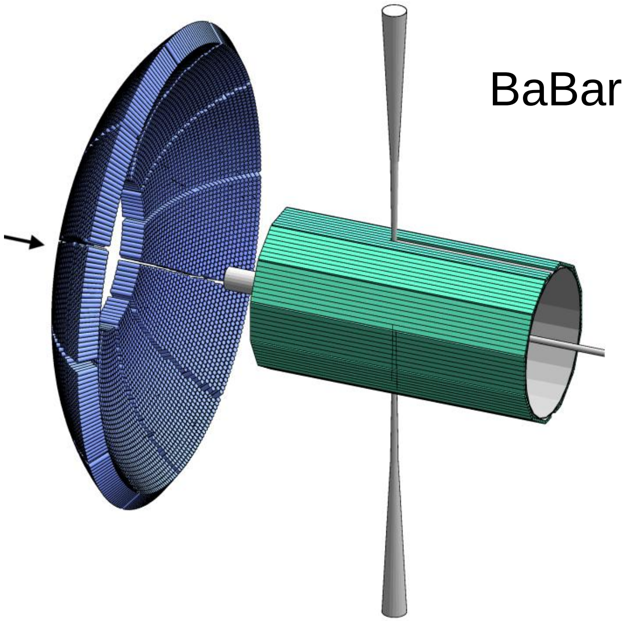
Two DIRC like counters are considered for the PANDA experiment:

- one very similar to the current DIRC in BaBar,
- the other of focusing type



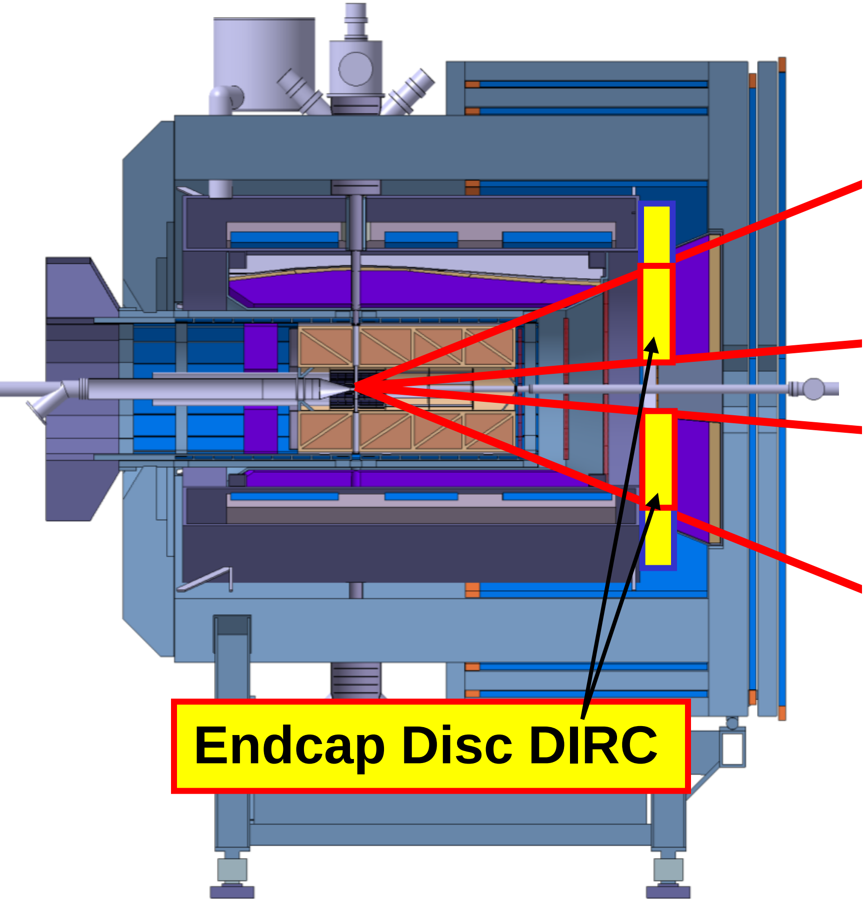
PANDA barrel DIRC




BaBar-like

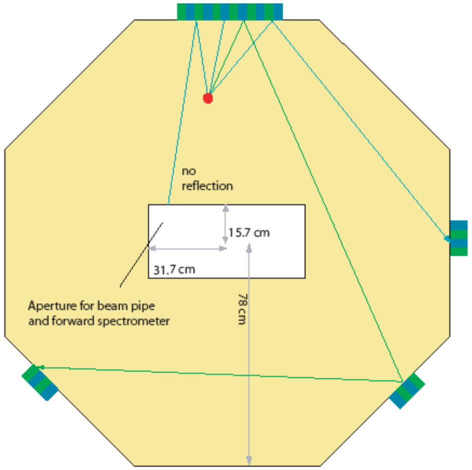
My slides on PANDA: probably hopelessly outdated – more during this workshop!

PANDA endcap DIRC



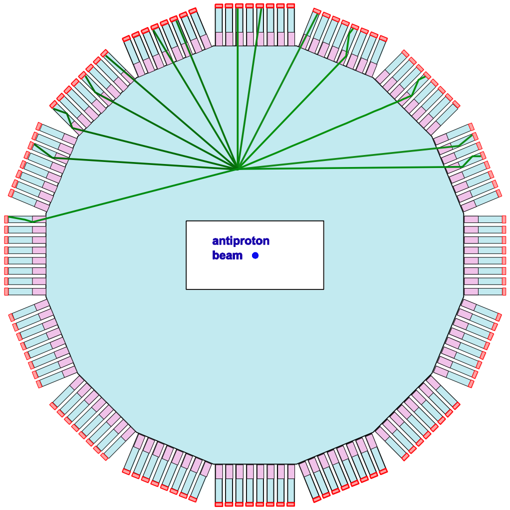
Two different readout designs:

Time-of-Propagation



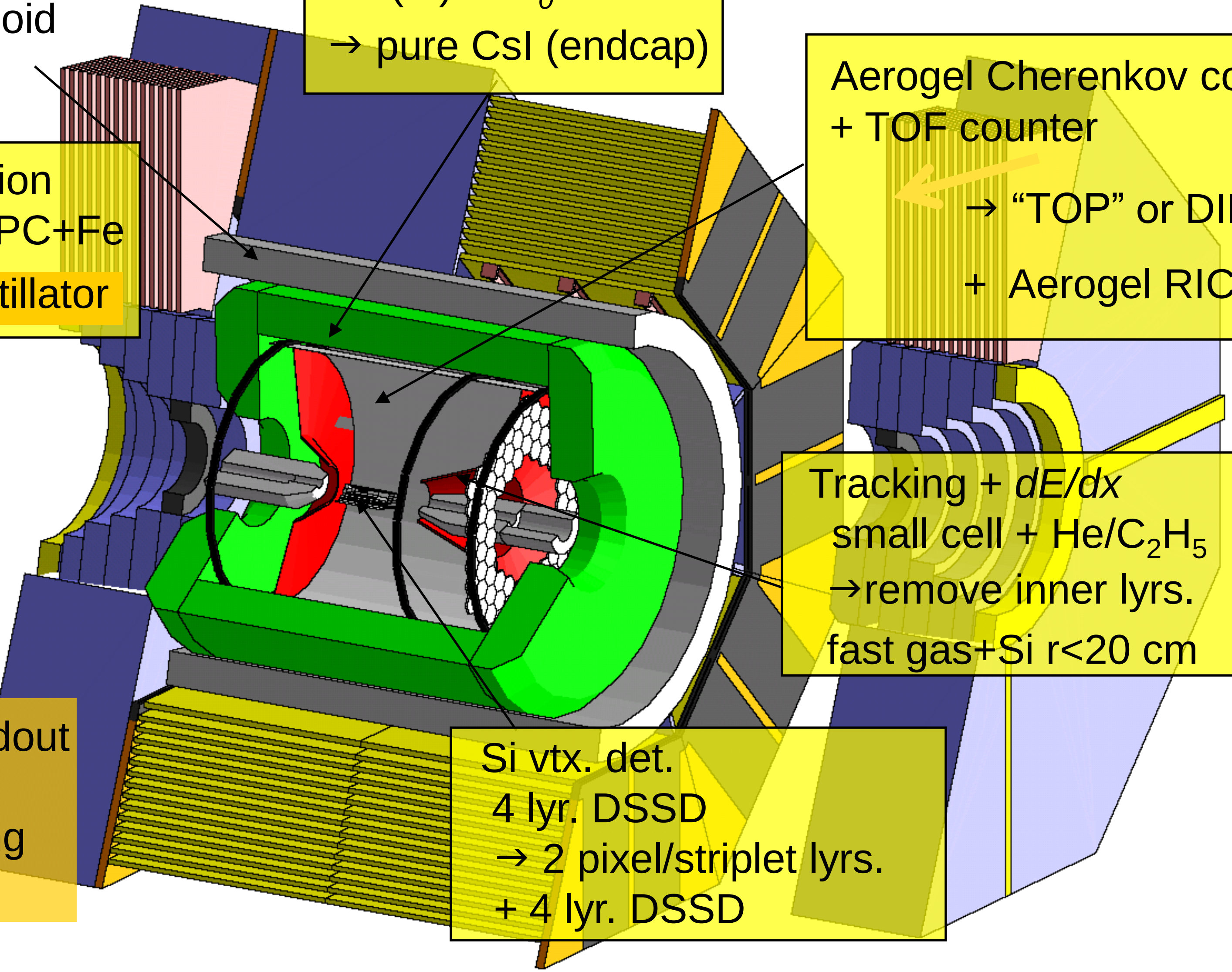
(1+1)D design

Focussing light guide



2D + t design

Belle upgrade → Belle-II



SC solenoid
1.5T

CsI(Tl) $16X_0$
→ pure CsI (endcap)

Aerogel Cherenkov counter
+ TOF counter
→ “TOP” or DIRC
+ Aerogel RICH

μ / K_L detection
14/15 lyr. RPC+Fe
→ tile scintillator

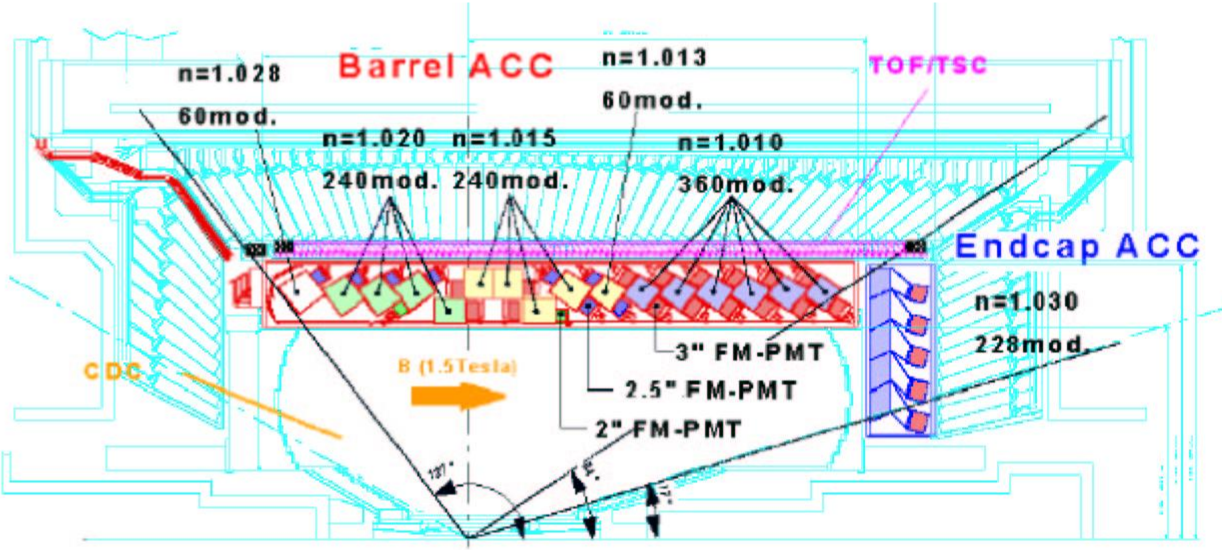
Tracking + *dE/dx*
small cell + He/C_2H_5
→remove inner lyrs.
fast gas+Si r<20 cm

New readout
and
computing
systems

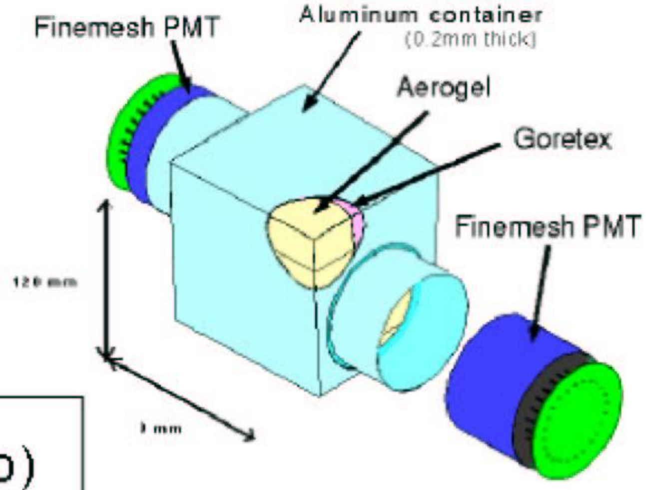
Si vtx. det.
4 lyr. DSSD
→ 2 pixel/striplet lyrs.
+ 4 lyr. DSSD

Present 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

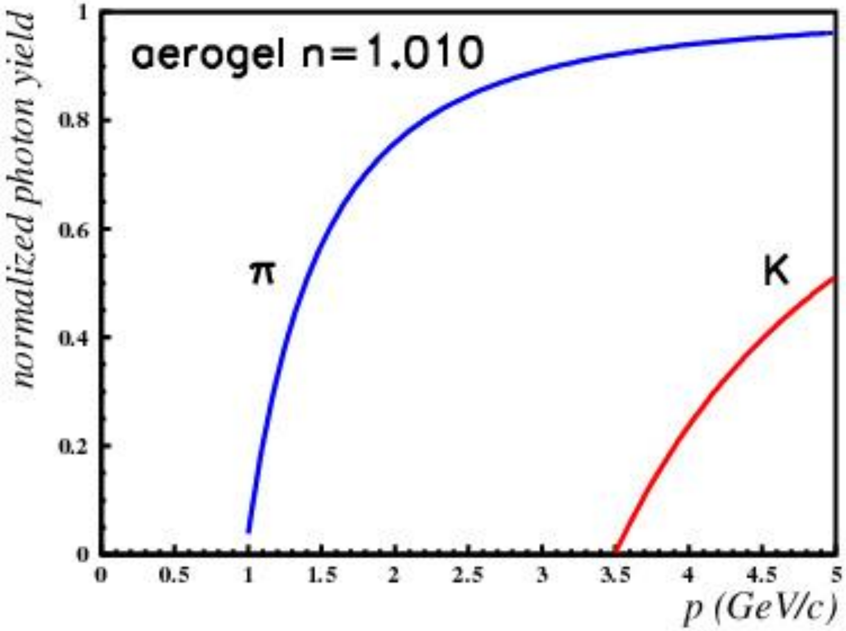


Fine-mesh PMT: works in high B fields

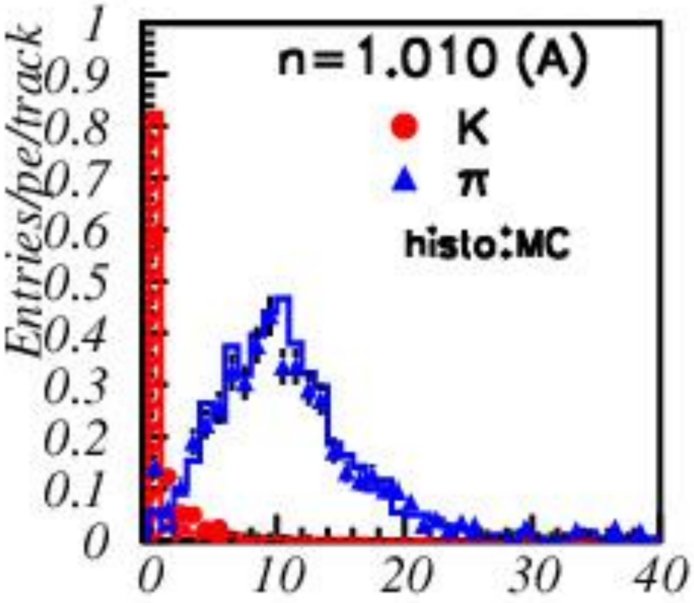
Belle ACC : threshold Cherenkov counter

expected yield vs p

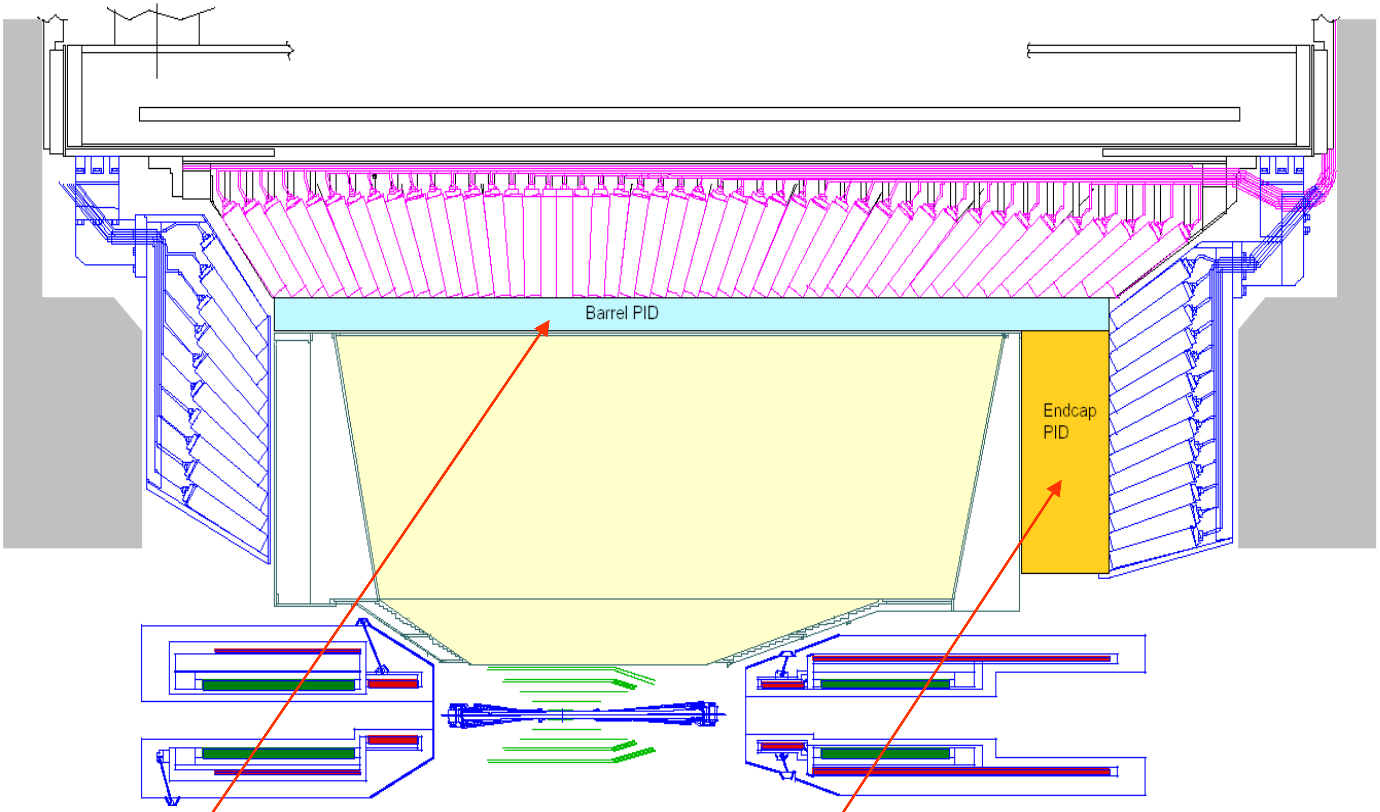
NIM A453 (2000) 321



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



Belle upgrade – side view

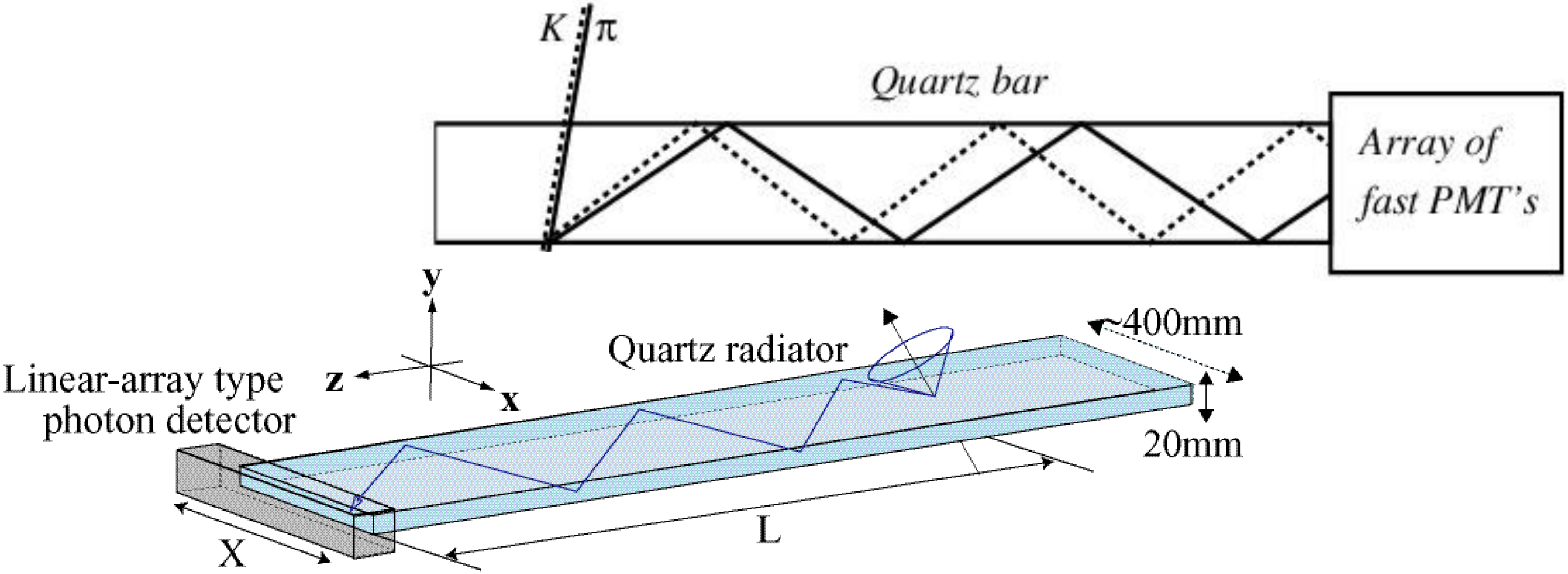


Two new particle ID devices, both RICHes:

Barrel: time-of-propagation (TOP) counter or focusing DIRC

Endcap: proximity focusing RICH

Time-Of-Propagation (TOP) counter



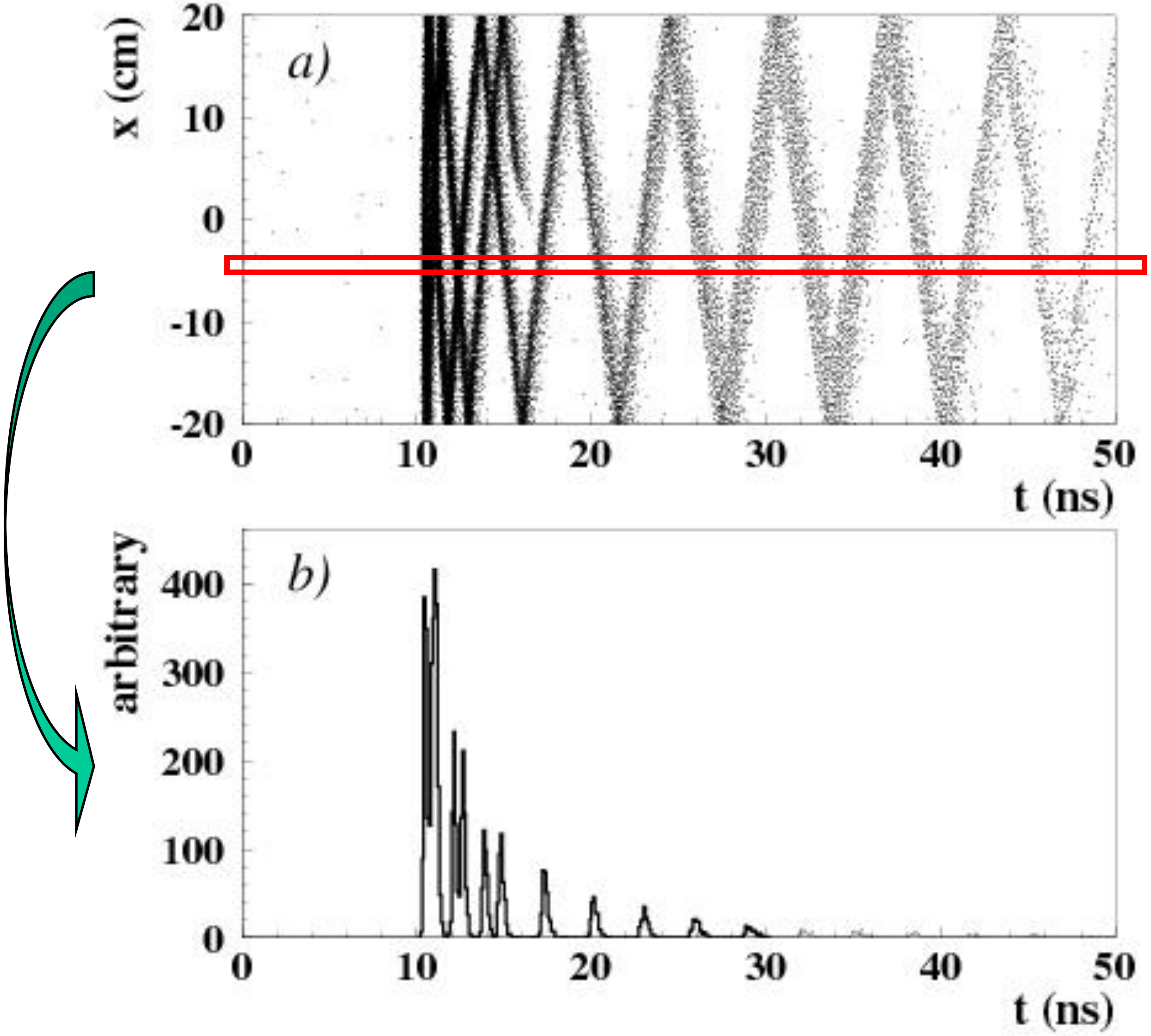
Similar to DIRC, but instead of two coordinates measure:

- – 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

→Talk by K. Inami

TOP image

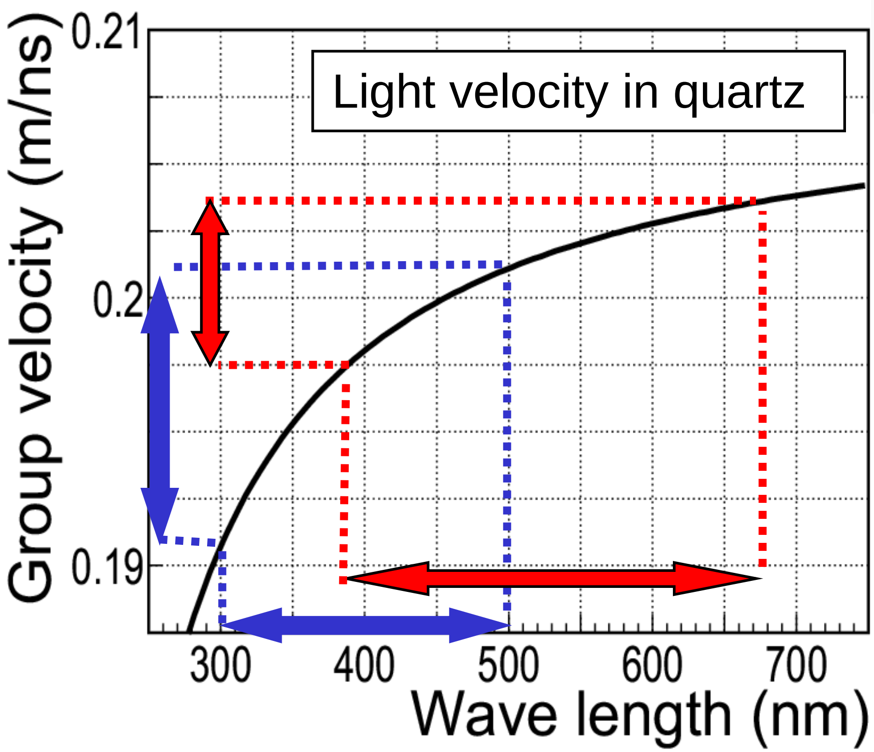


Pattern in the coordinate-time space (‘ring’) of a pion hitting a quartz bar with ~80 MAPMT channels

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

TOP counter MC

Time of arrival of photons depends on the group velocity: it turns out to be advantageous to use a photon detector which is sensitive at higher wavelengths → reduces the chromatic error



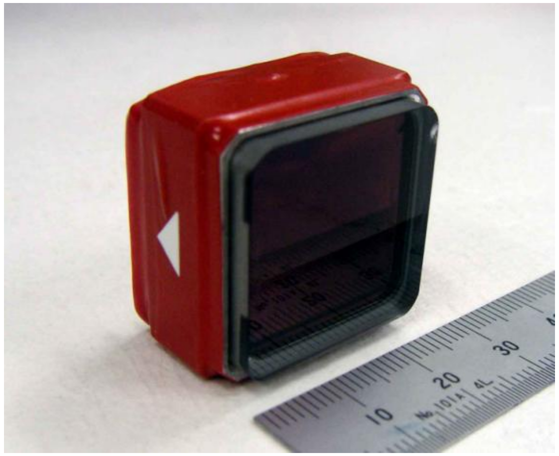
Blue: bialkali photocathode

Red: GaAsP photocathode

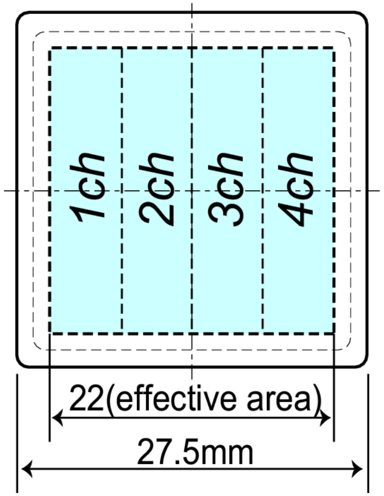
GaAsP MCP-PMT with pads

Nagoya University R+D with Hamamatsu

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

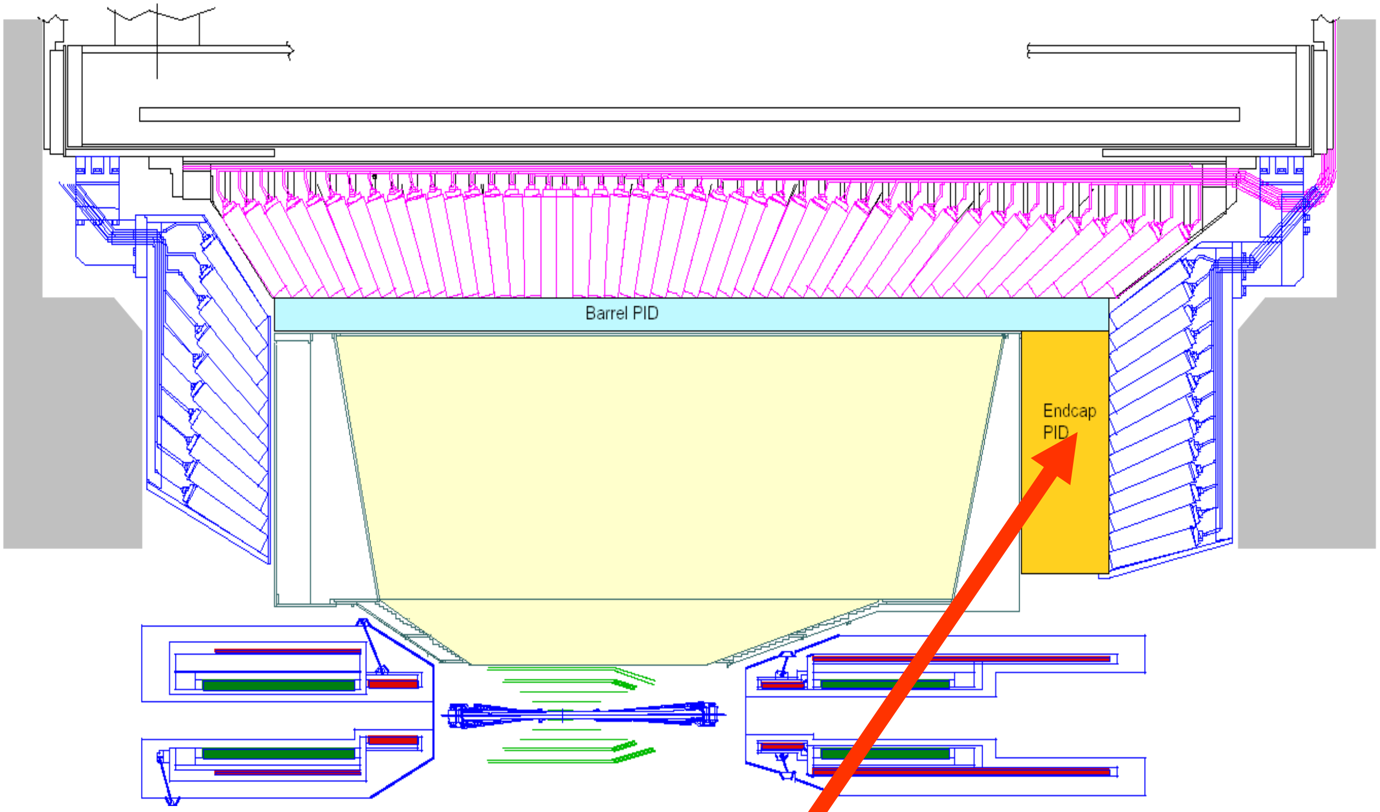


Target structure



- Enough gain to detect single photo-electron
- Good time resolution (TTS=42ps) for single p.e.
- Good uniformity
- Next: increase active area frac., study ageing

Belle upgrade – side view



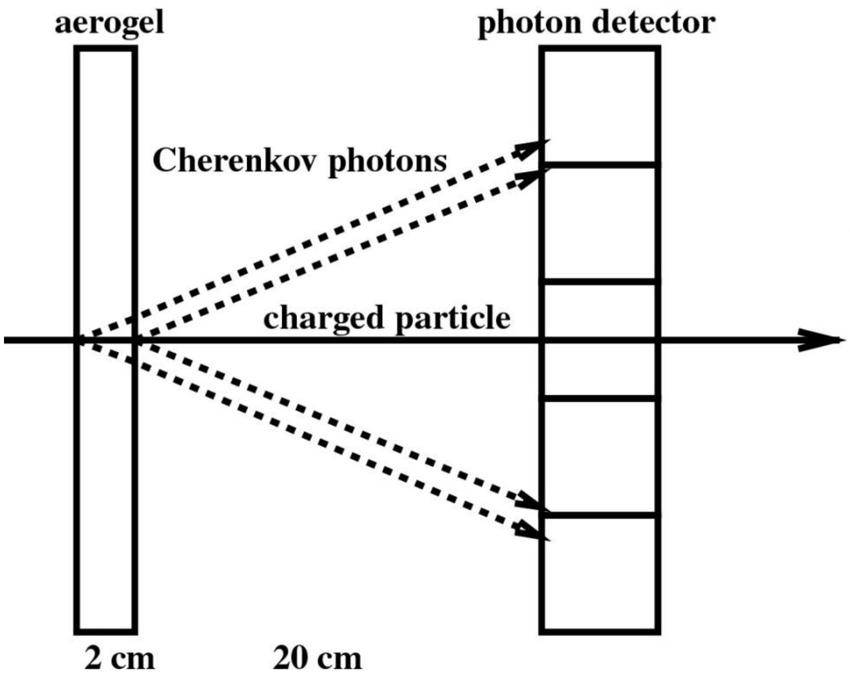
Two new particle ID devices, both RICHes:

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

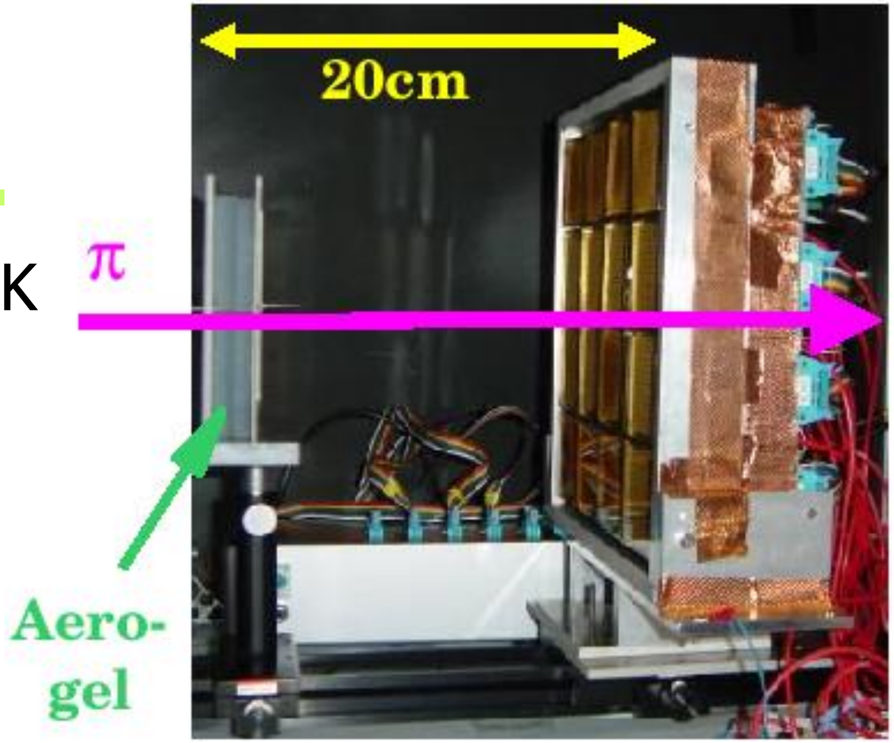
Per track: $$\sigma_{track} = \frac{\sigma_0}{\sqrt{N_{pe}}}$$

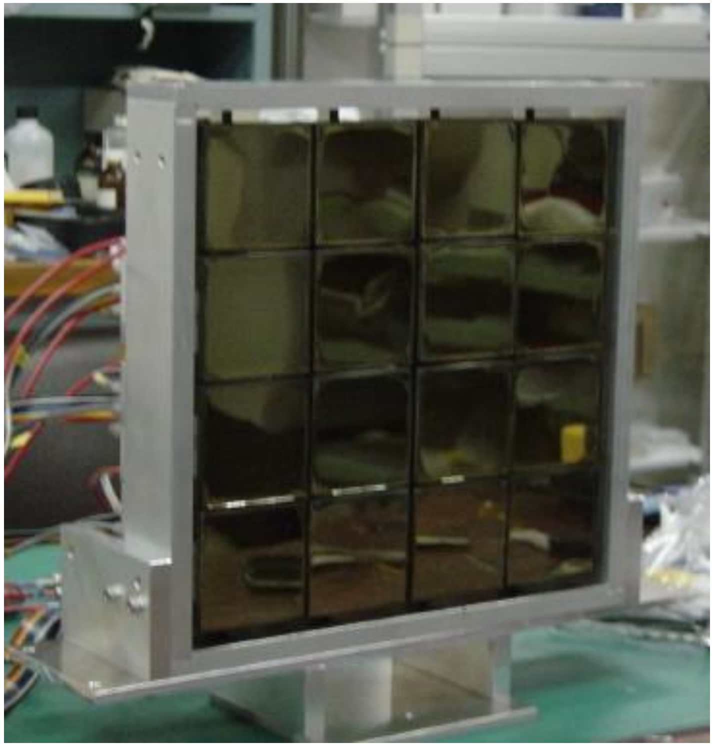
Separation: $[\theta_c(\pi) - \theta_c(K)]/\sigma_{track}$

→ 5σ separation with $N_{pe} \sim 10$

Beam tests

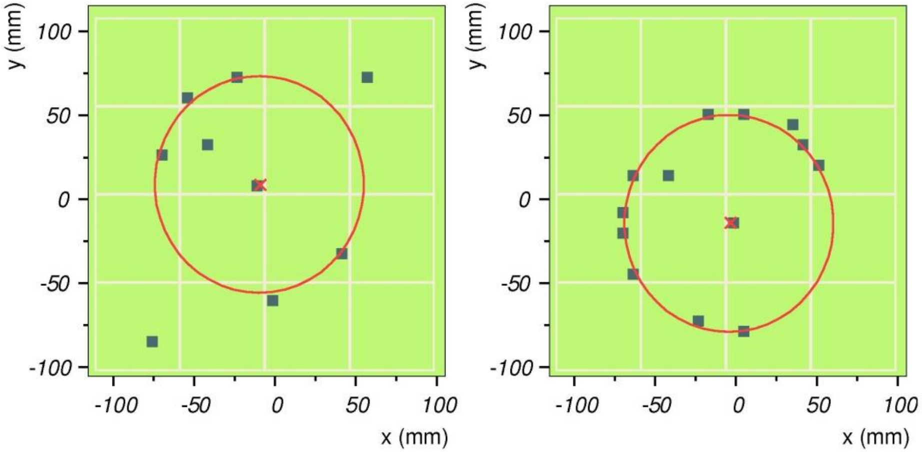
pion beam (π2) at KEK





Photon detector: array of 16 H8500 PMTs

Clear rings, little background

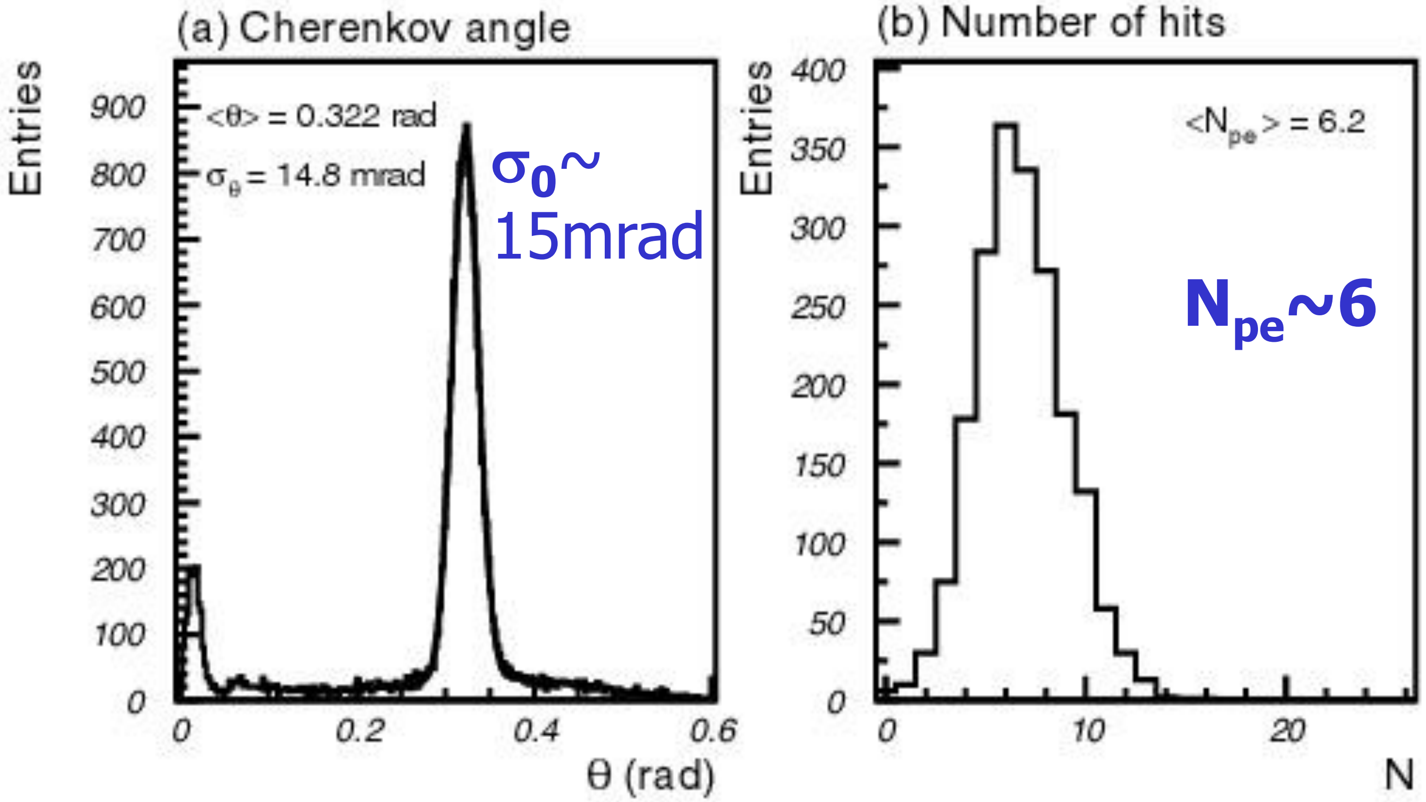


Beam test: Cherenkov angle resolution and number of photons

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

Beam test results with 2cm thick aerogel tiles:

>4σ K/π separation



σ_0~ 15mrad

N_{pe}~6

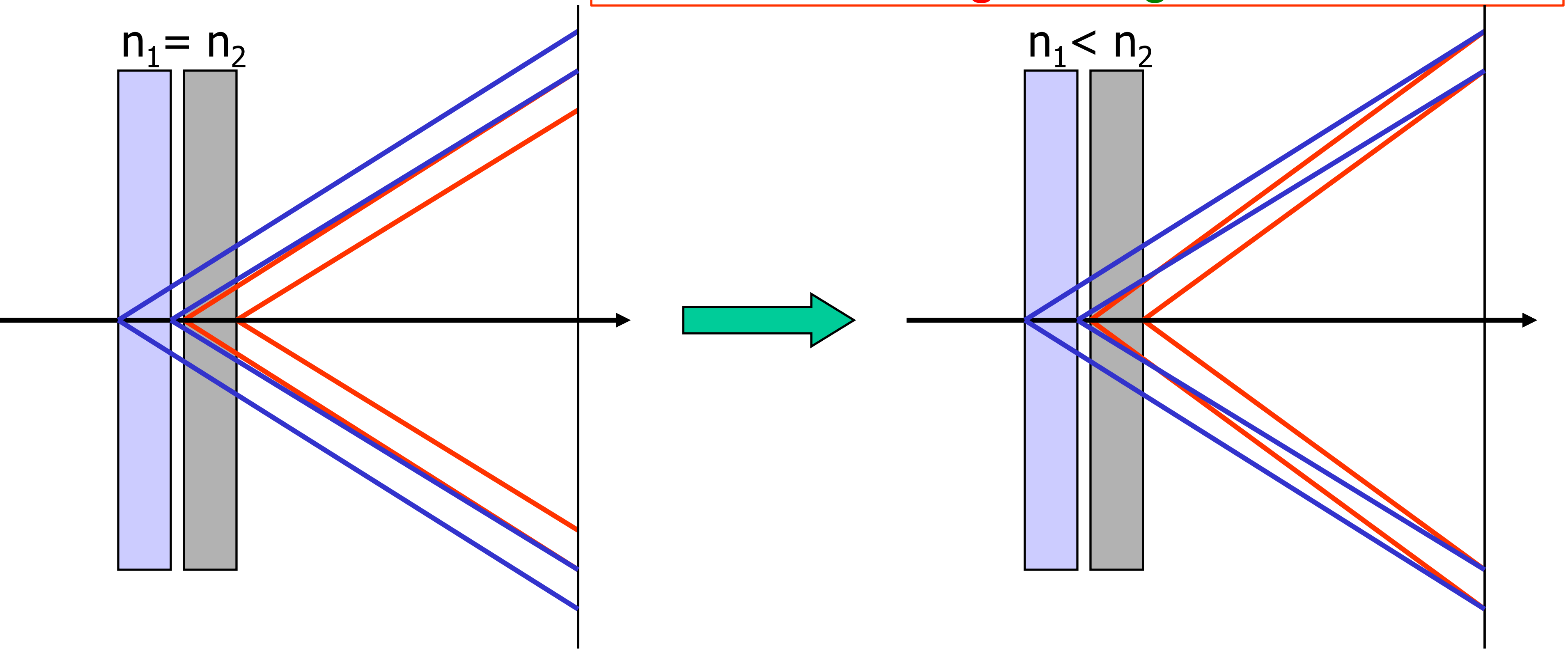
→ Number of photons has to be increased.

Radiator with multiple refractive indices

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

normal

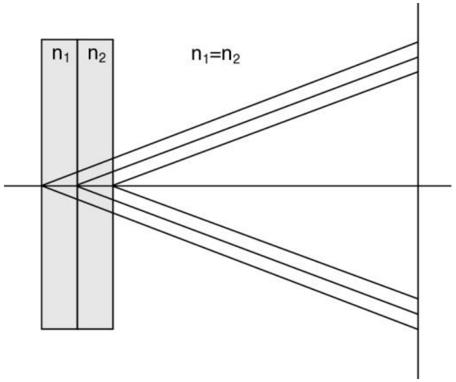
→ stack two tiles with different refractive indices: "focusing" configuration

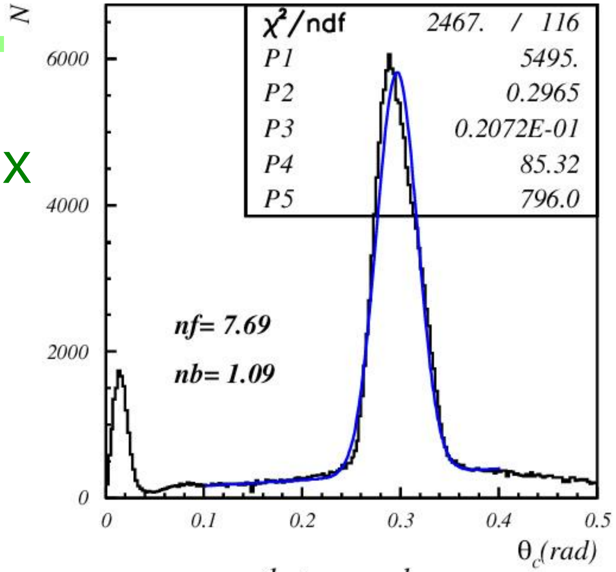


→ focusing radiator

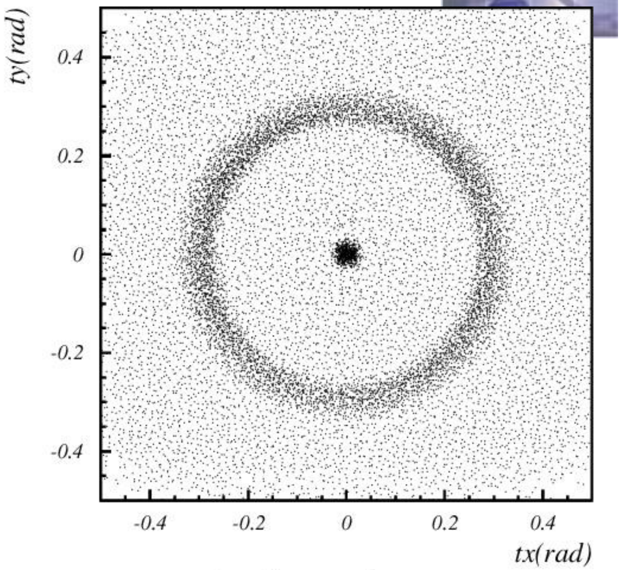
Focusing configuration – data

4cm aerogel single index



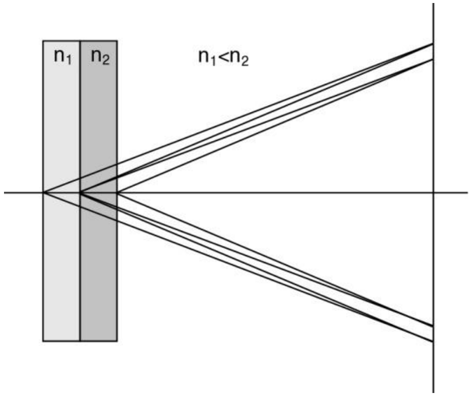


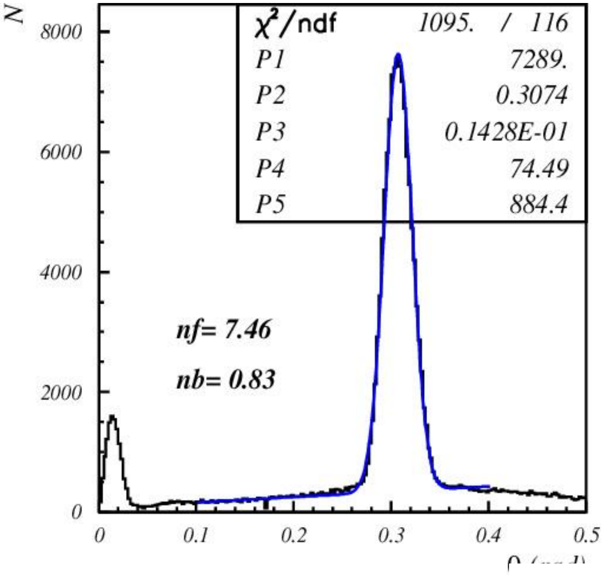
theta cerenkov

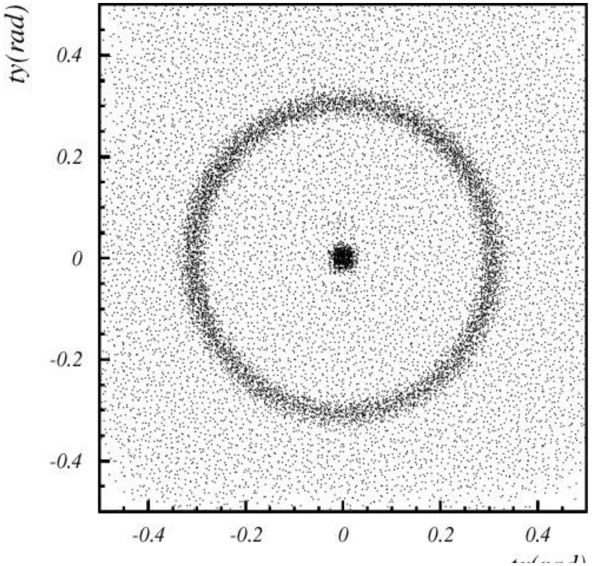


ring in cerenkov space

2+2cm aerogel

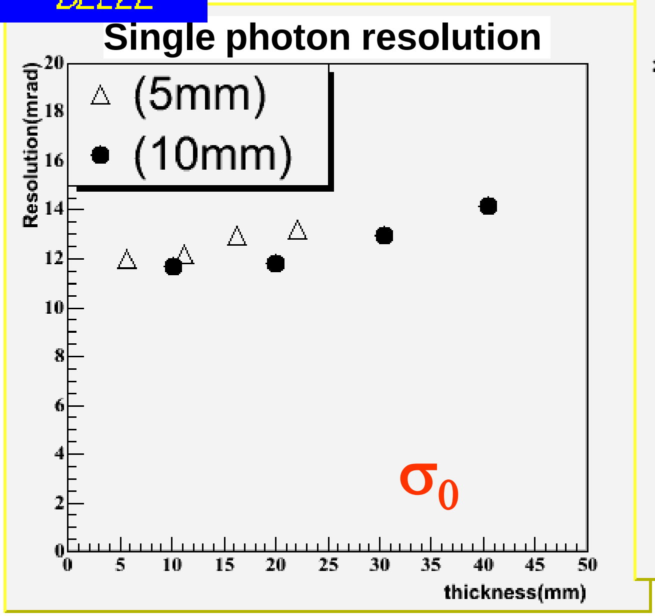


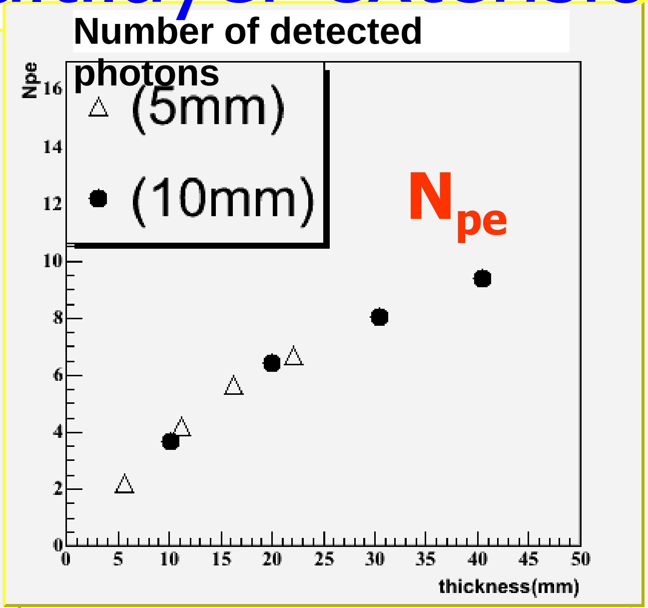


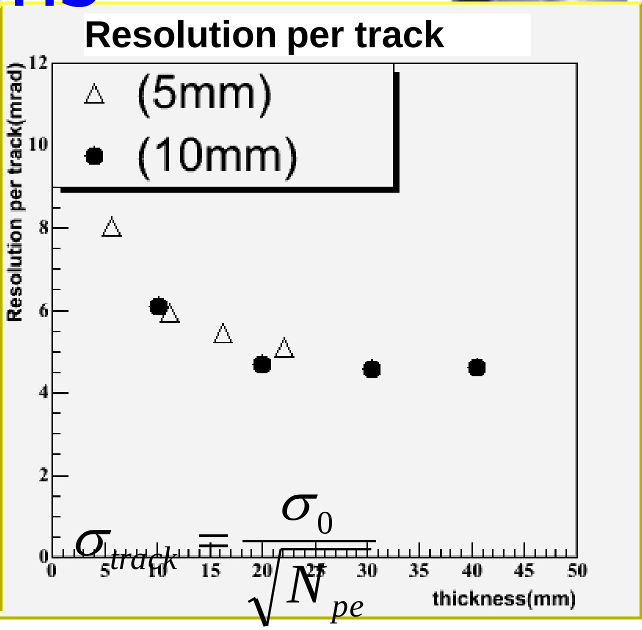


→NIM A548 (2005) 383

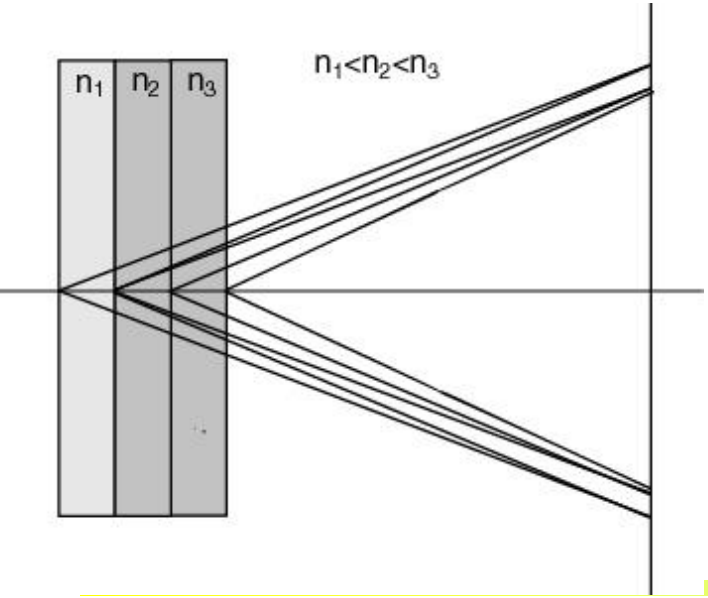
Multilayer extensions


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

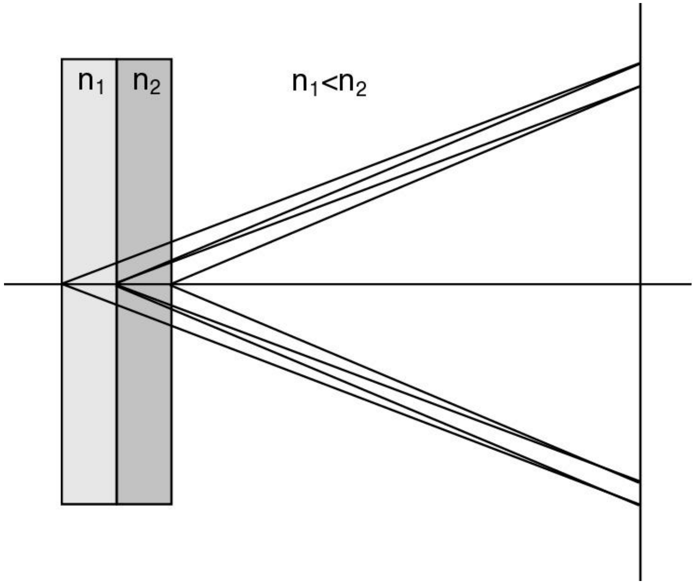
Several optimisation studies:

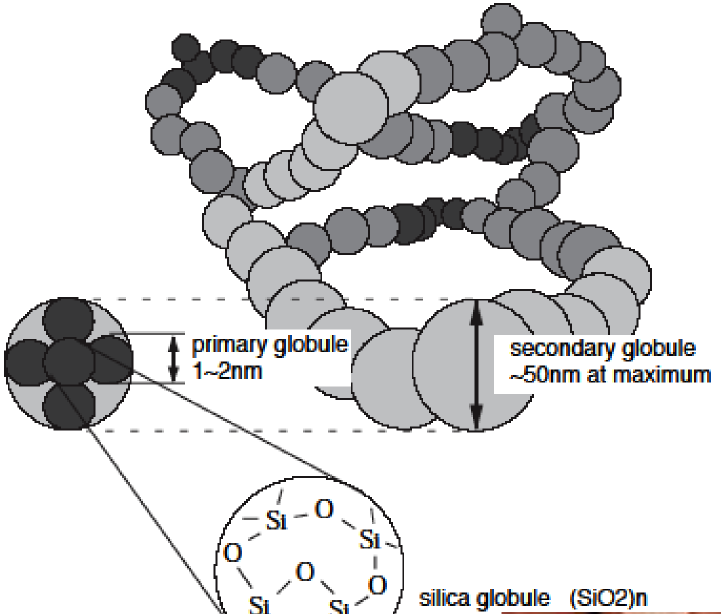
Križan et al NIMA 565 (2006) 457

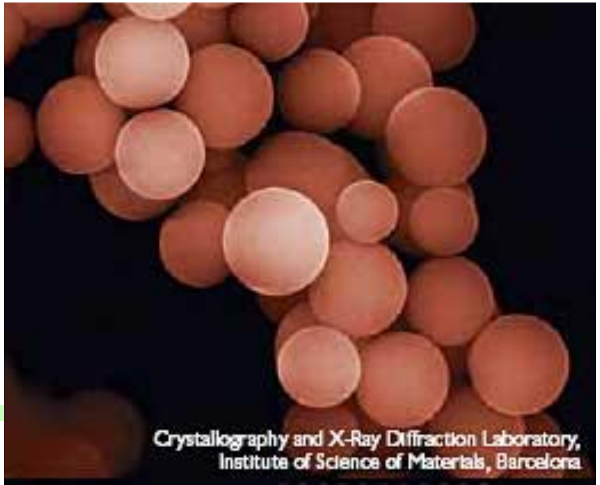
Barnyakov et al NIMA 553 (2005) 70

Radiator with multiple refractive indices

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.







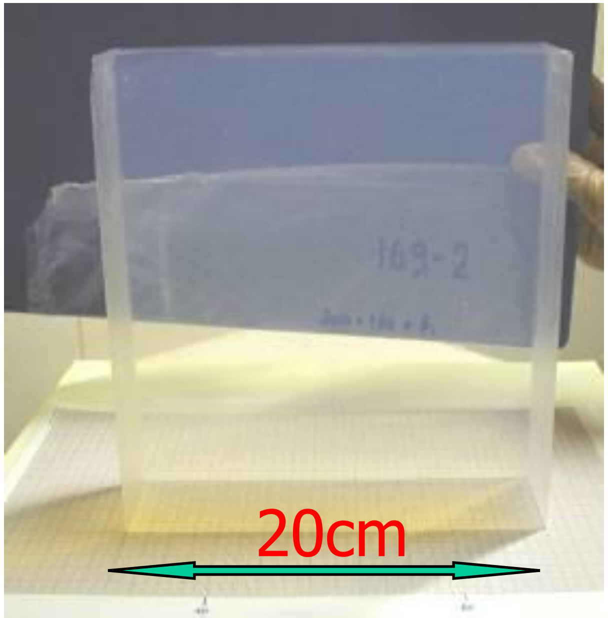
Crystallography and X-Ray Diffraction Laboratory, Institute of Science of Materials, Barcelona

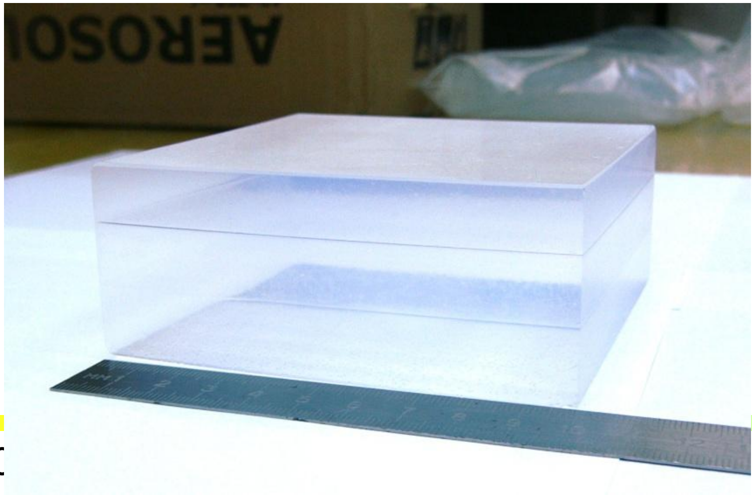
Aerogel production

Two production centers: Boreskov Institute of Catalysis, Novisibirsk, and KEK+Matsushita

Considerable improvement in aerogel production methods:

- Better transmission (>4cm for hydrophobic and ~8cm for hydrophylic)
- Larger tiles (LHCb: 20cmx20cmx5cm)
- Tiles with multiple refractive index





n1=1.046

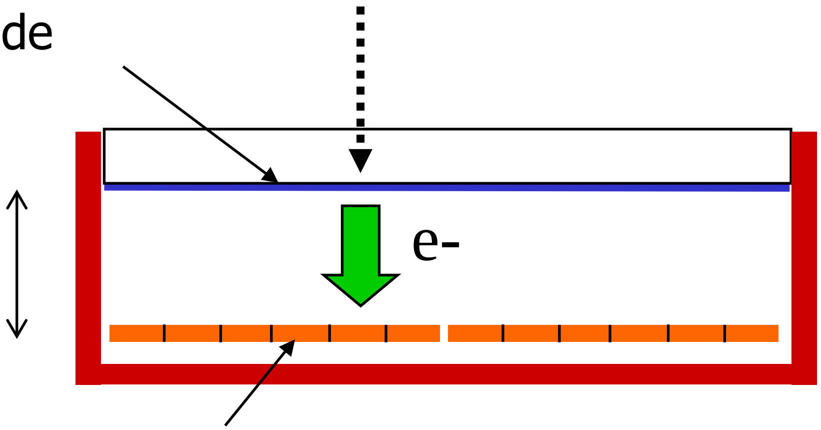
n2=1.041

n3=1.037

Photon detectors for the aerogel RICH requirements and candidates

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

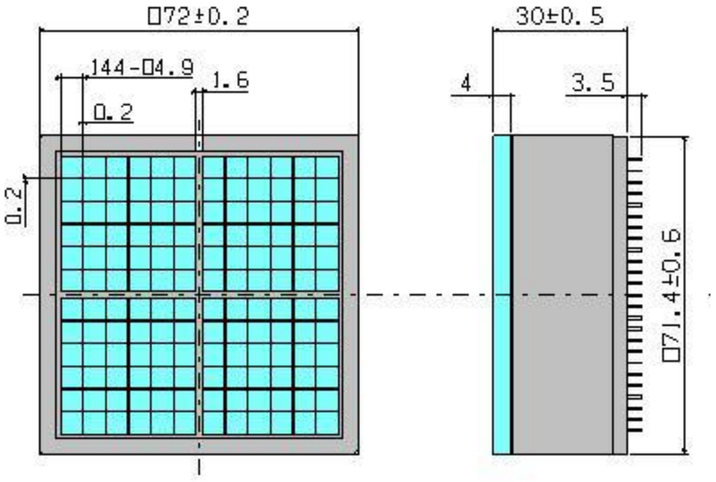
One of the candidates: large active area HAPD of the proximity focusing type



Multialkali photocathode

-10kV
15~25mm

Pixel APD



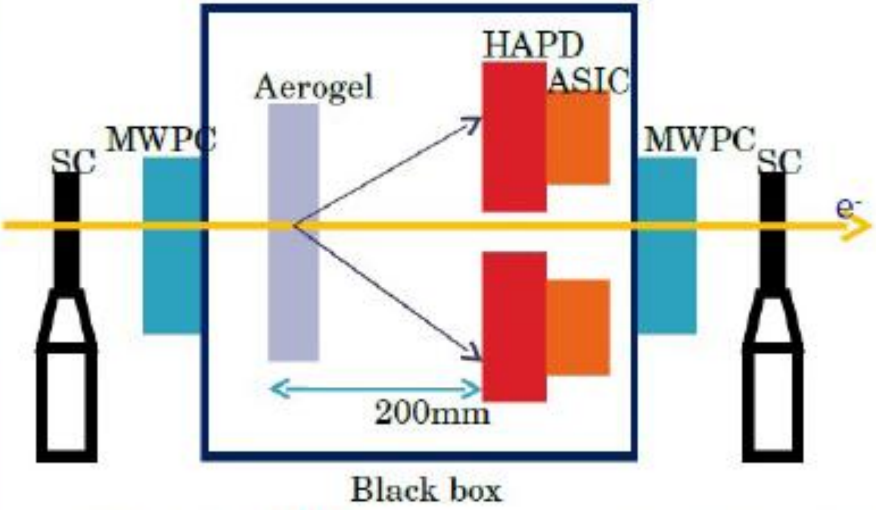
HAPD R&D project in collaboration with HPK.

Long development time

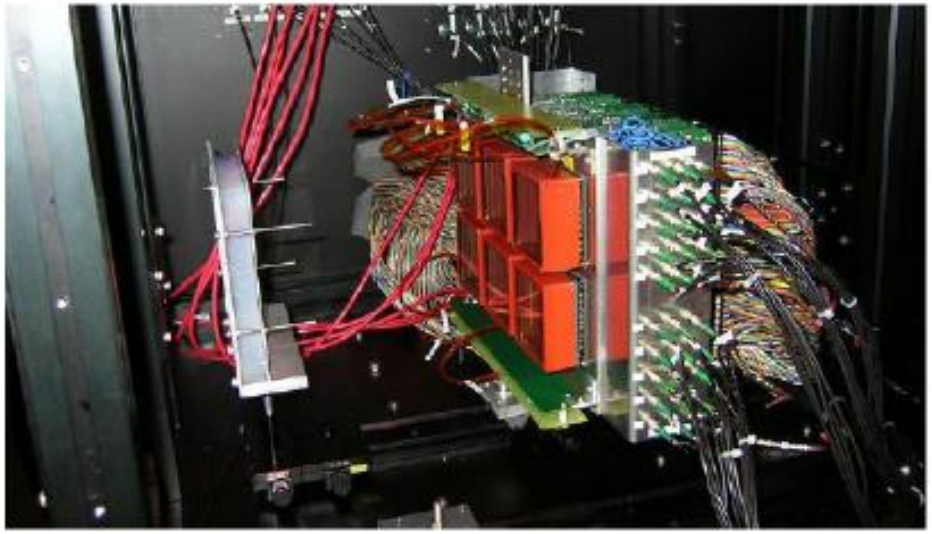
→ Finally enough working samples for a beam test at KEK last spring

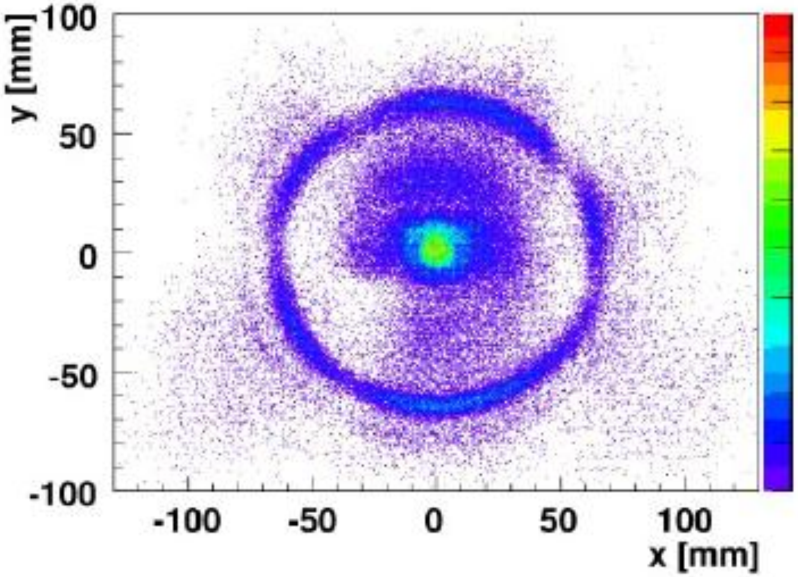
→ NIM A595 (2008) 180

Photon detector candidate: HAPD beam test



- Beam Test @ Fuji test beam line
- Prototype Aerogel RICH with 2 × 3 array of 144 ch HAPD
- Readout using 48 ASICs.
- Clear Cherenkov ring is observed.

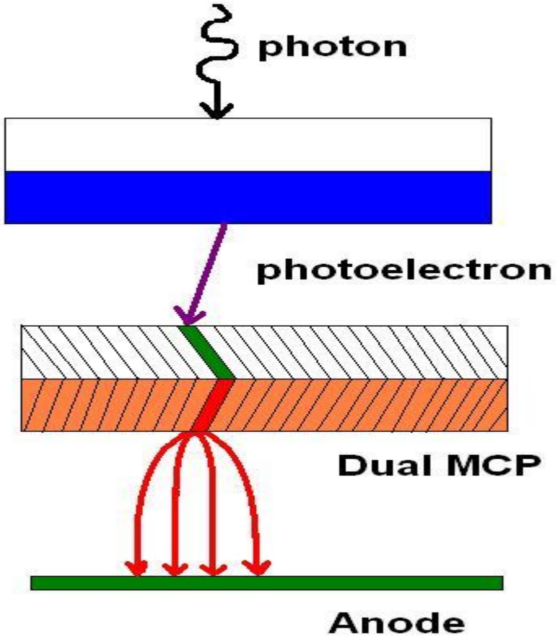


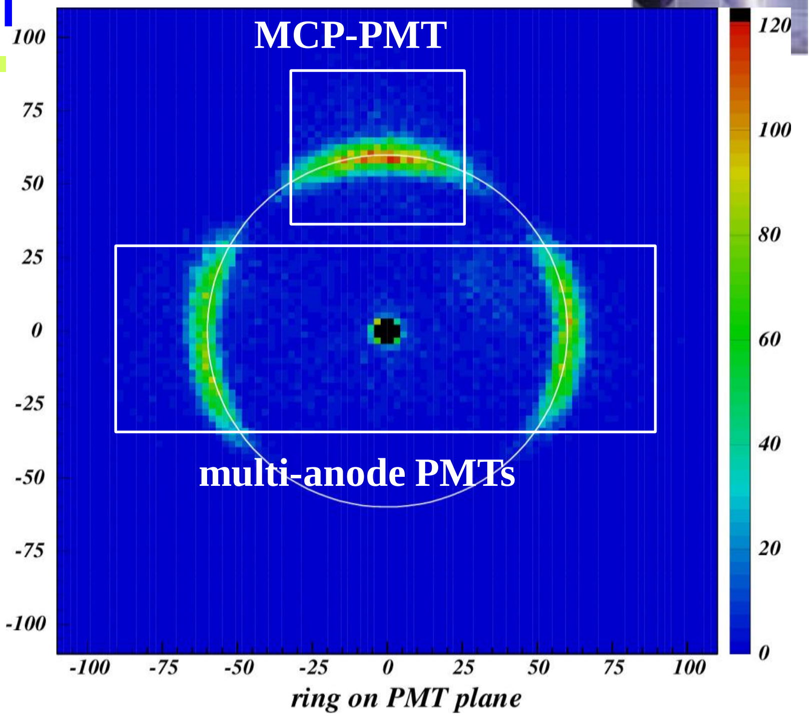


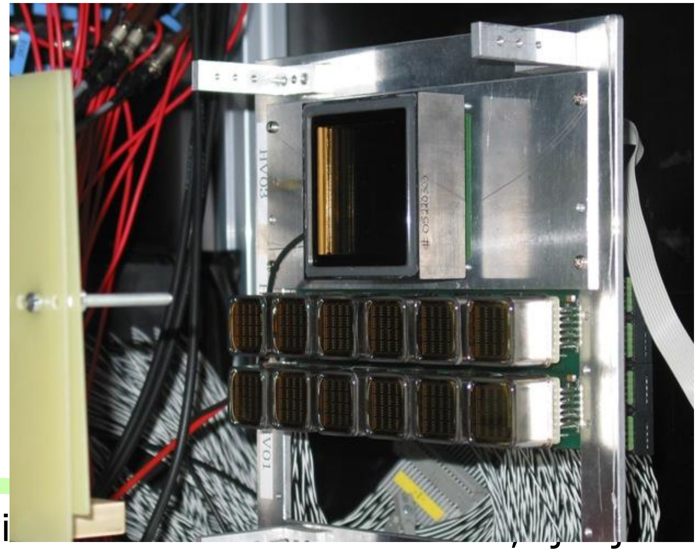
Open issues: long term stability and neutron irradiation damage – both under study

Photon detector candidate: BURLE/Photonis MCP-PMT

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







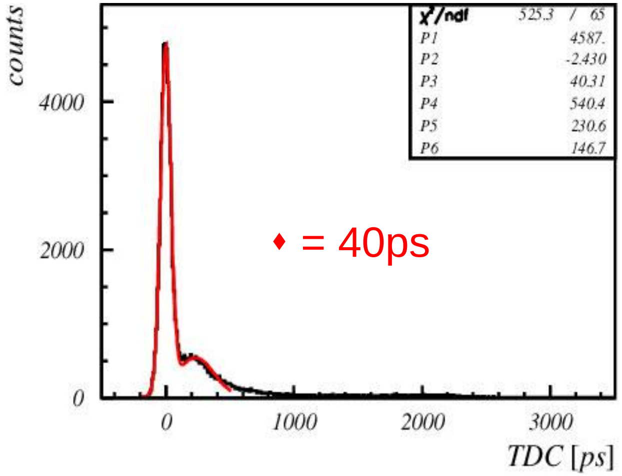
→good performance in beam and bench tests, NIMA567 (2006) 124

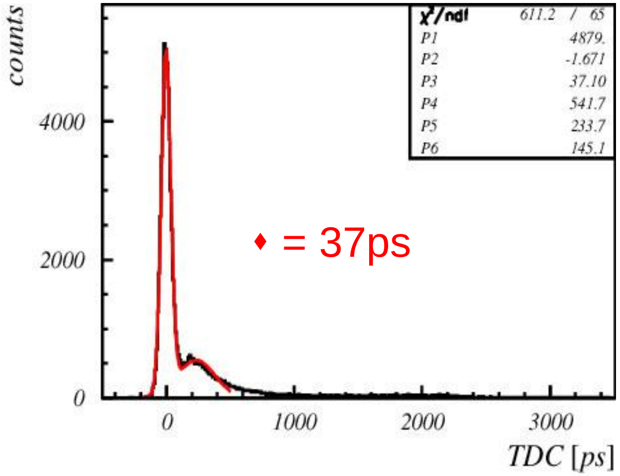
→ very fast

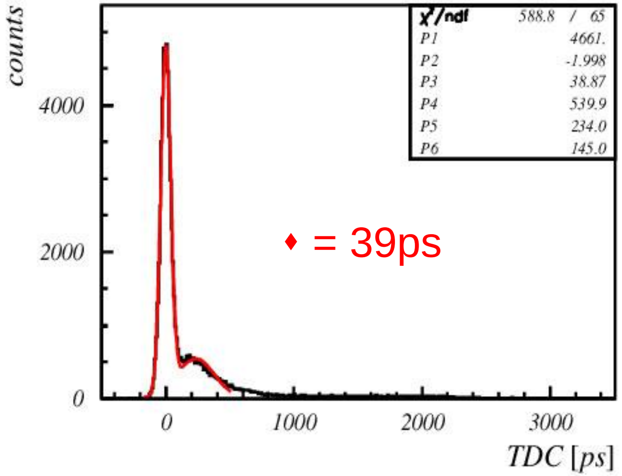
→ R+D: ageing

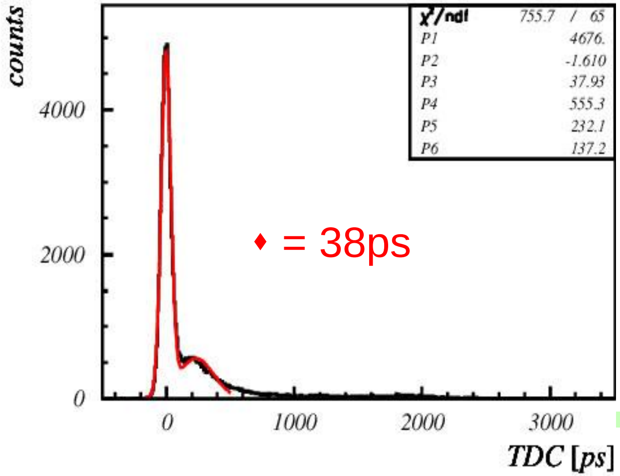
BURLE/Photonis MCP-PMT

BURLE 85011 microchannel plate (MCP) PMT: time resolution after time walk correction









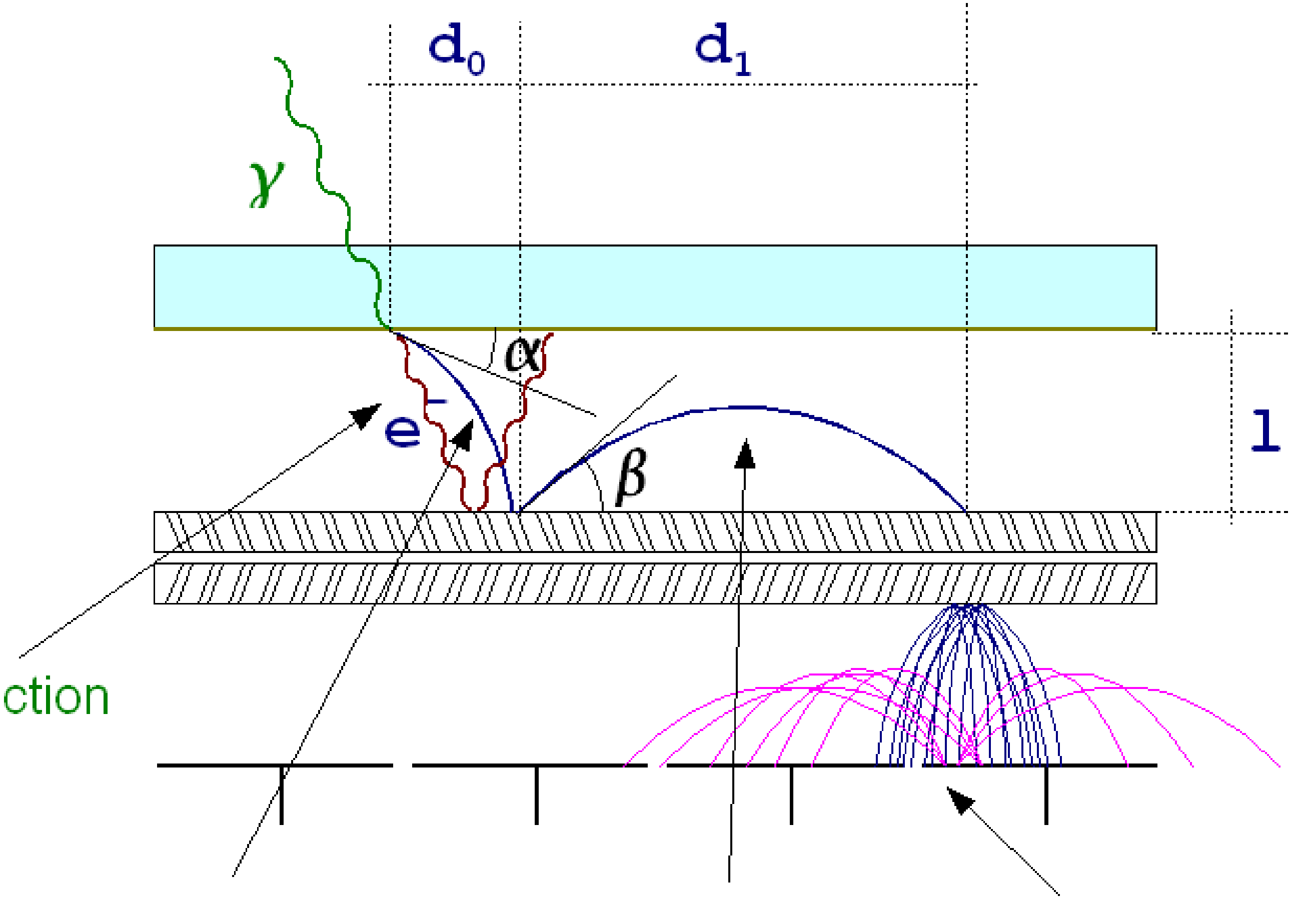
Tails can be significantly reduced by:

- decreased photocathode-MCP distance and
- increased voltage difference

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:

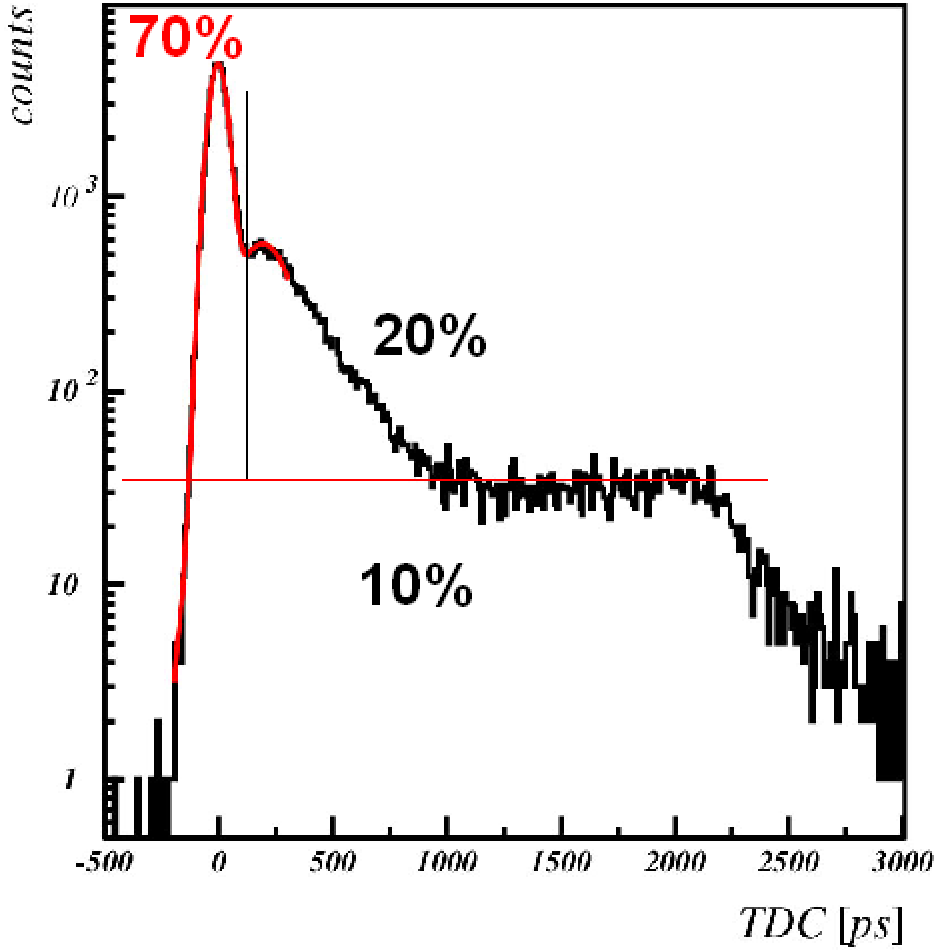
- $d_{0,max} \sim 0.8$ mm
- $t_0 \sim 1.4$ ns
- $\Delta t_0 \sim 100$ ps

Backscattering:

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

Charge sharing

MCP PMT timing



Tails can be significantly reduced by:

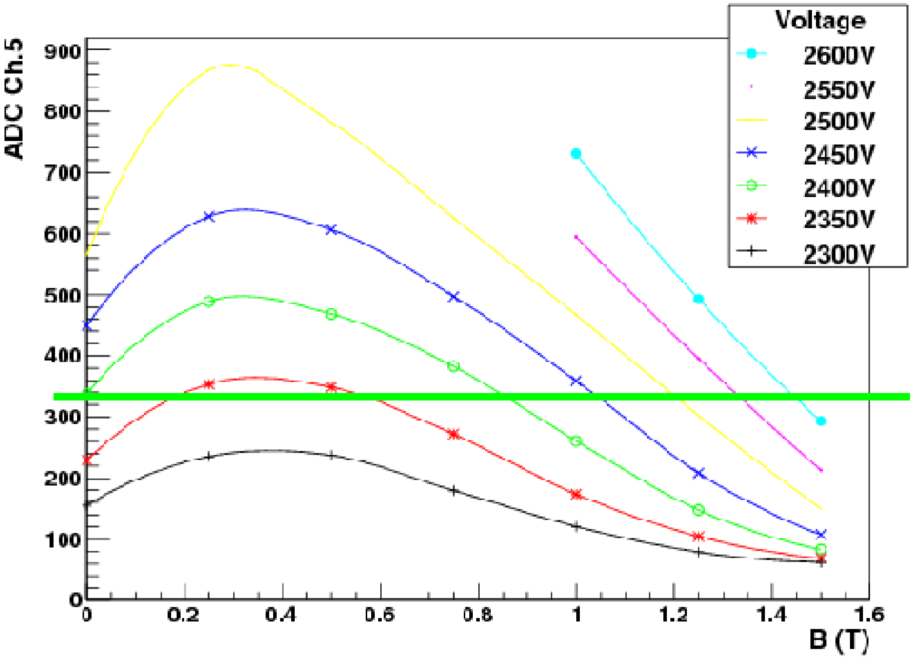
- decreased photocathode-MCP distance and
- increased voltage difference

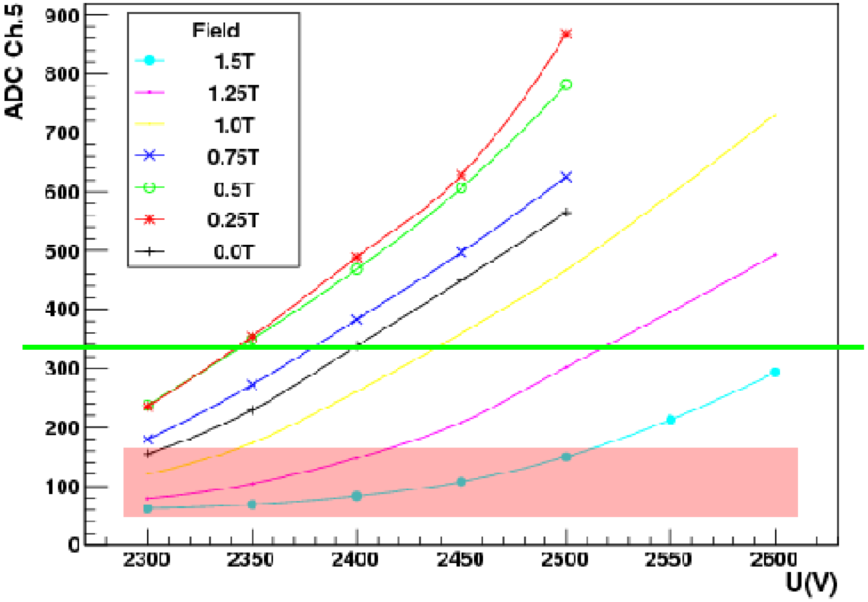
- prompt signal ~ 70%
- short delay ~ 20%
- ~ 10% uniform distribution

MCP PMT: Gain in magnetic field

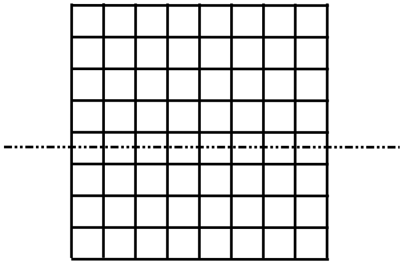
Gain as a function of magnetic field for different operation voltages and as a function of applied voltage for different magnetic fields.

.



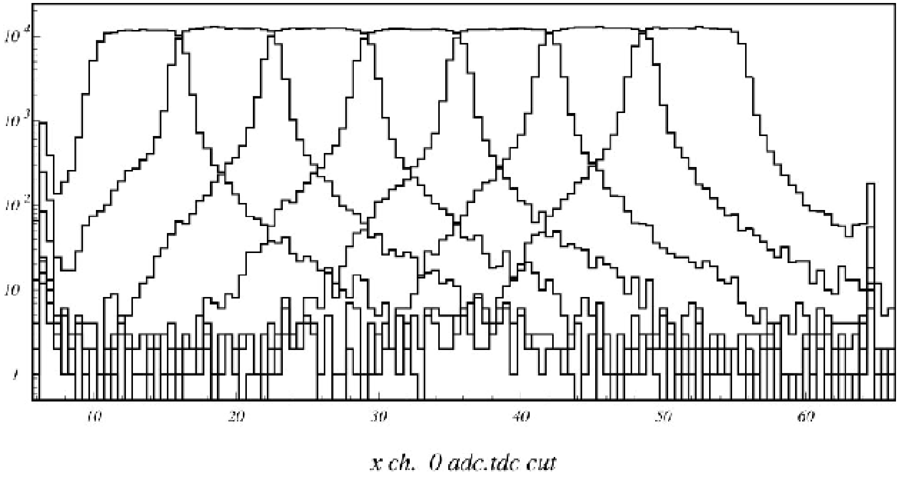


→ More talks on MCP PMTs during this workshop – W. Plass and A. Lehmann

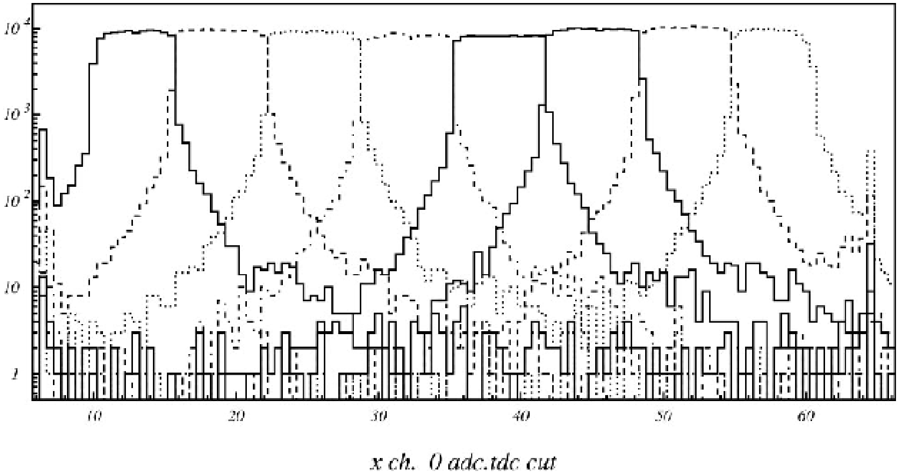


MCP PMT: sensitivity

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.

SiPM as photon detector?

Can we use SiPM (Geiger mode APD) as the photon detector in a RICH counter?

+immune to magnetic field

+high photon detection efficiency, single photon sensitivity

+easy to handle (thin, can be mounted on a PCB)

+potentially cheap (not yet...) silicon technology

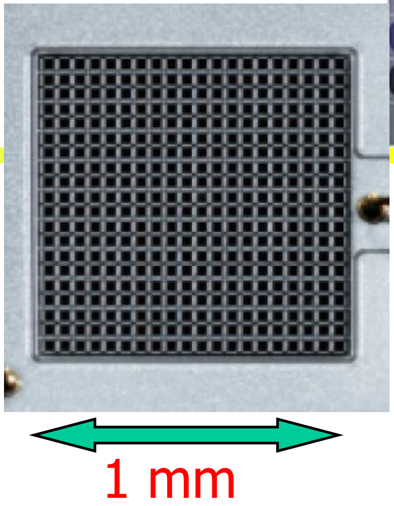
+no high voltage

-very high dark count rate (100kHz – 1MHz) with single photon pulse height

-radiation hardness

→Talk by D. Renker

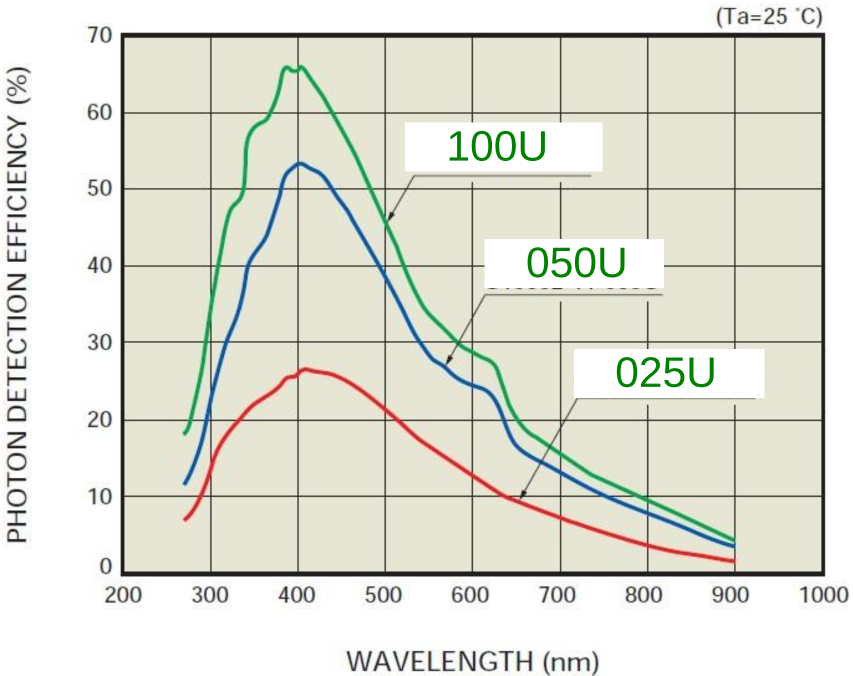
SiPMs as photon detectors?

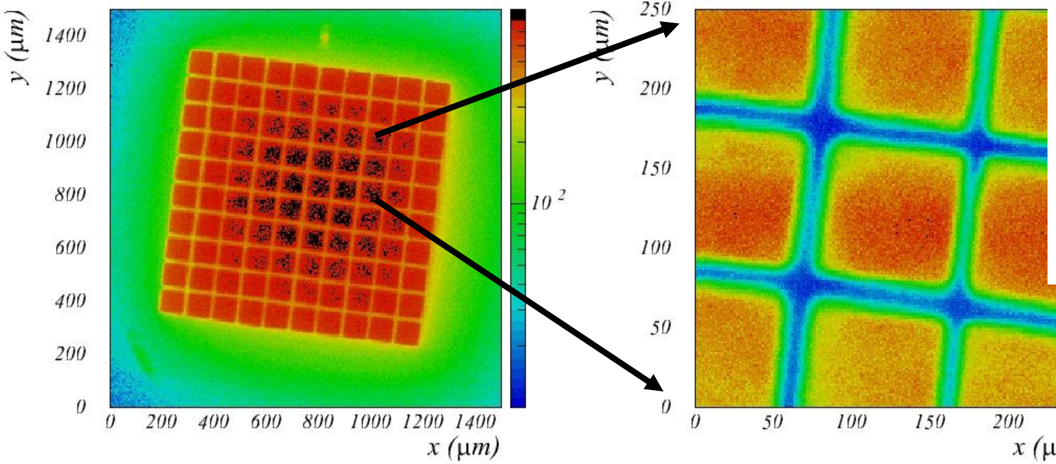


SiPM is an array of APDs operating in Geiger mode. Characteristics:

- low operation voltage ~ 10-100 V
- gain ~ 10^6
- peak PDE up to 65%(@400nm)

  PDE = QE x ε_{geiger} x ε_{geo}
- 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)





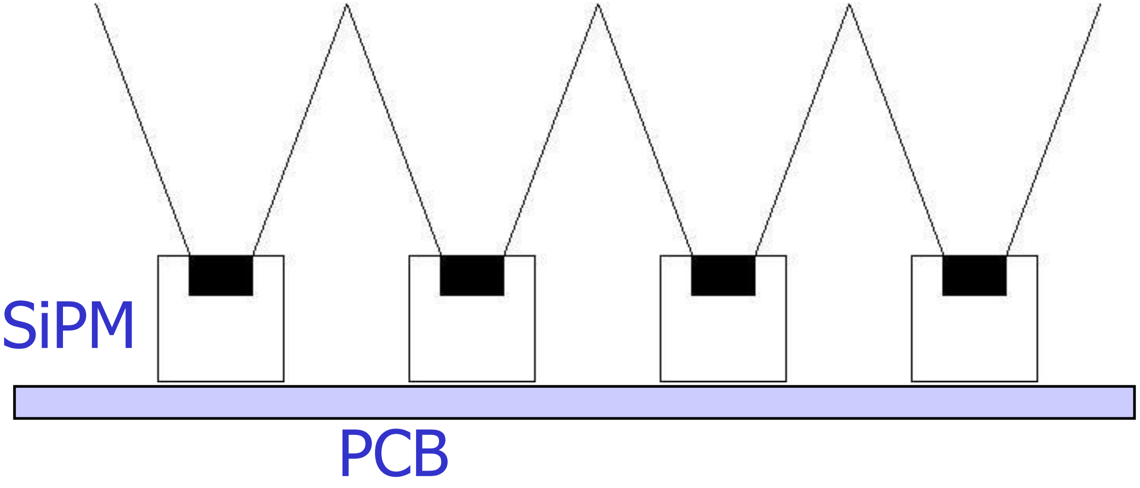
Hamamatsu MPPC: S10362-11

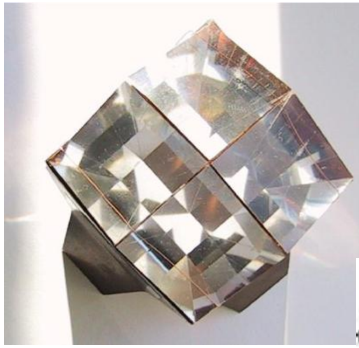
Can such a detector work?

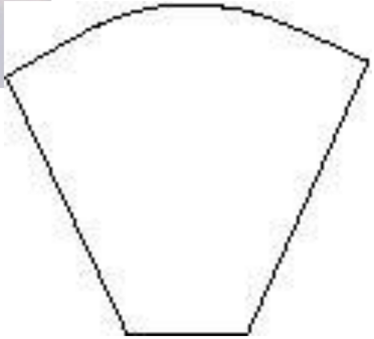
Improve the signal to noise ratio:

- 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







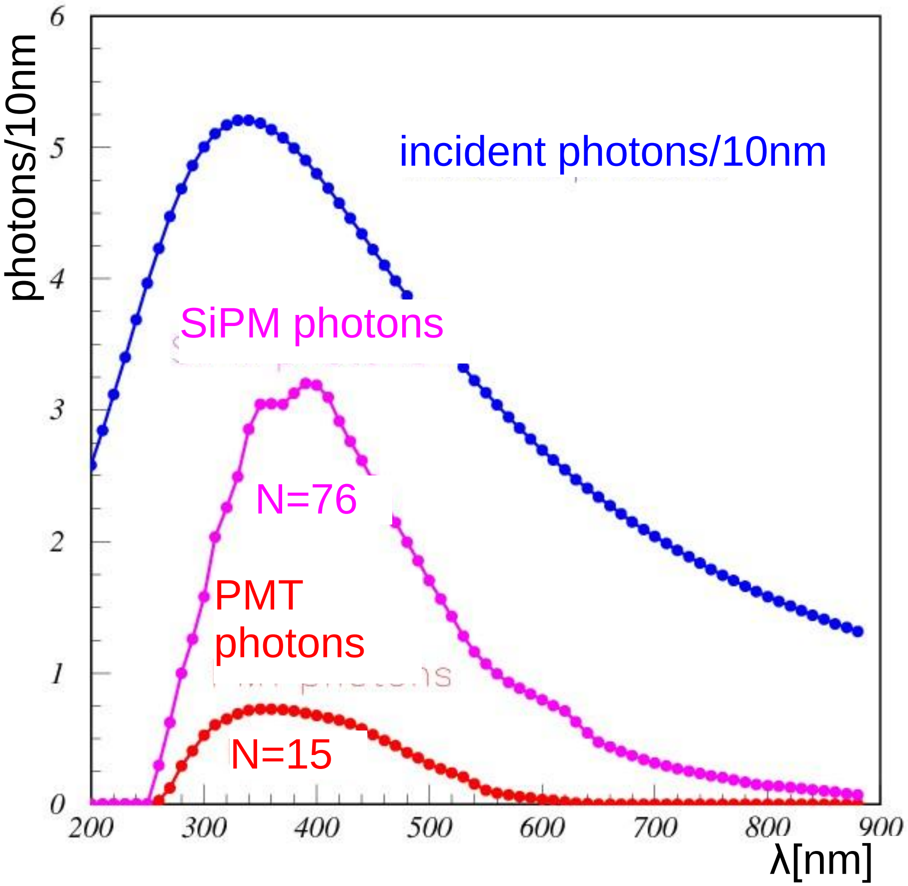
or combine a lens and mirror walls

Expected number of photons for aerogel RICH

with multianode PMTs or SiPMs(100U), and
aerogel radiator: thickness 2.5 cm, n = 1.045
and transmission length (@400nm) 4 cm.

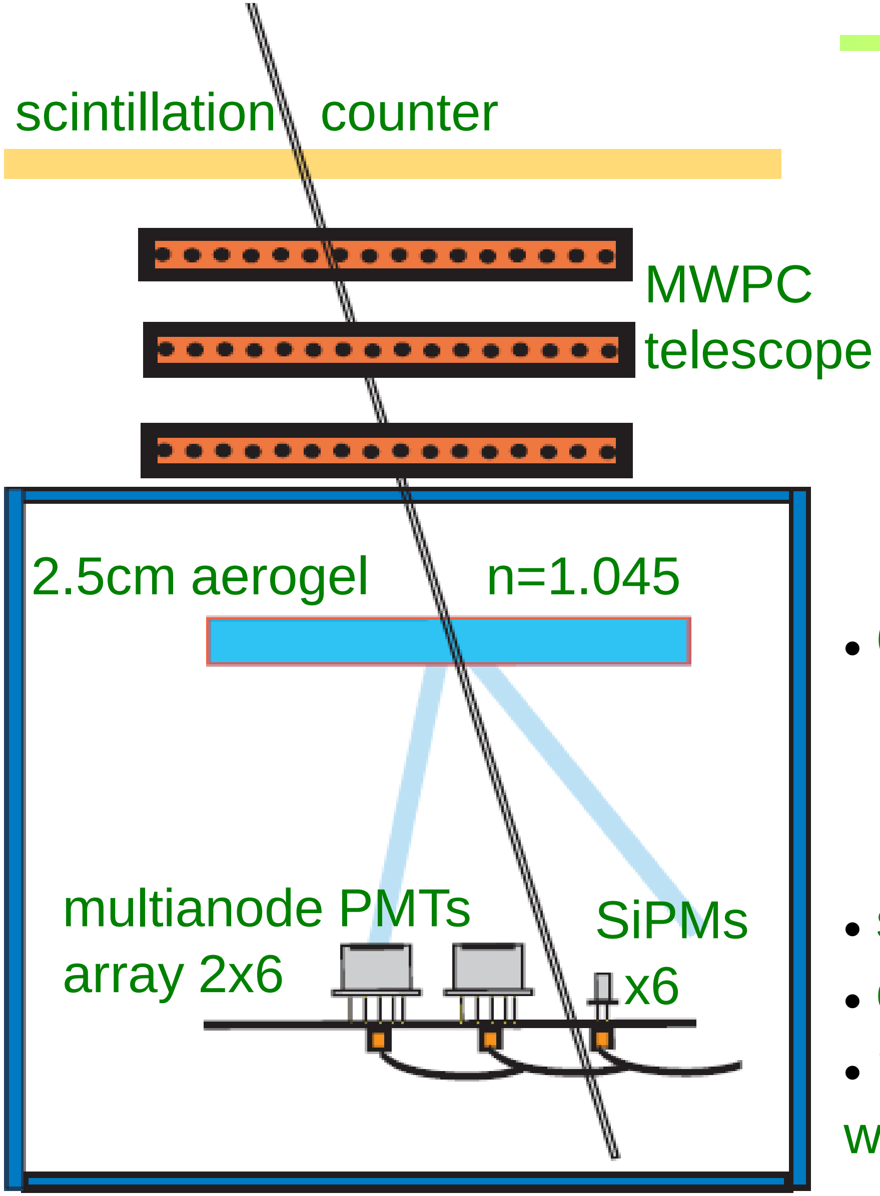
$N_{SiPM}/N_{PMT}\sim 5$

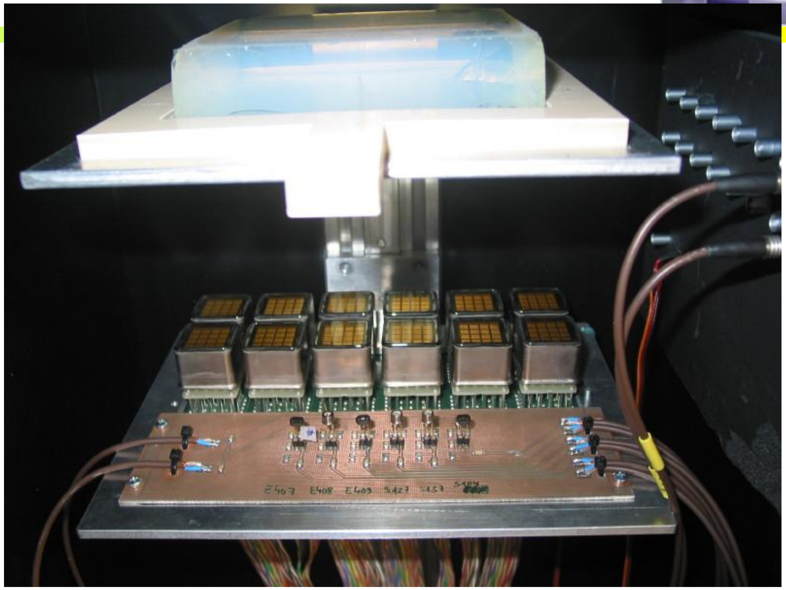
Assuming 100% detector active area



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)

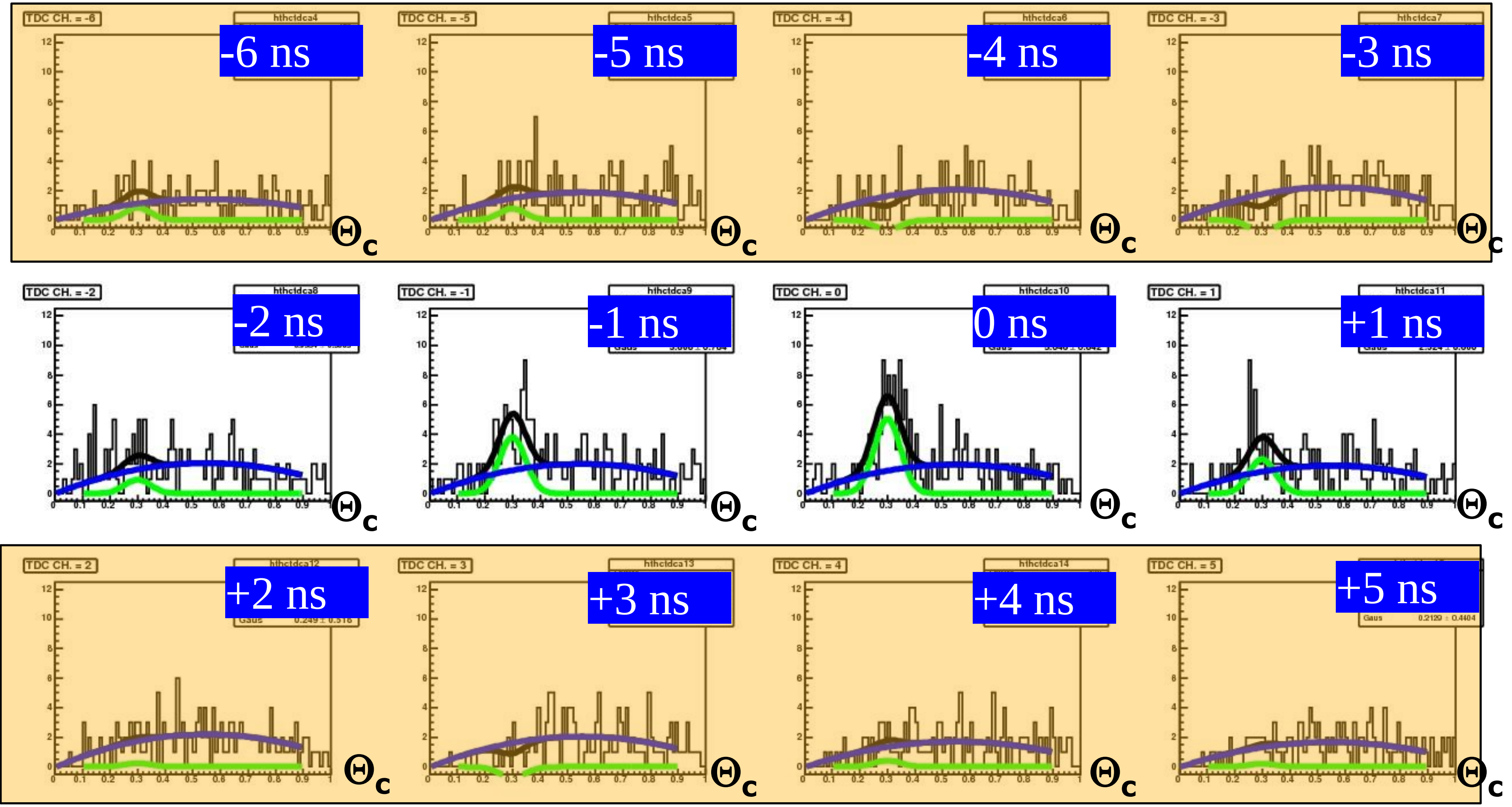
Cosmic test setup





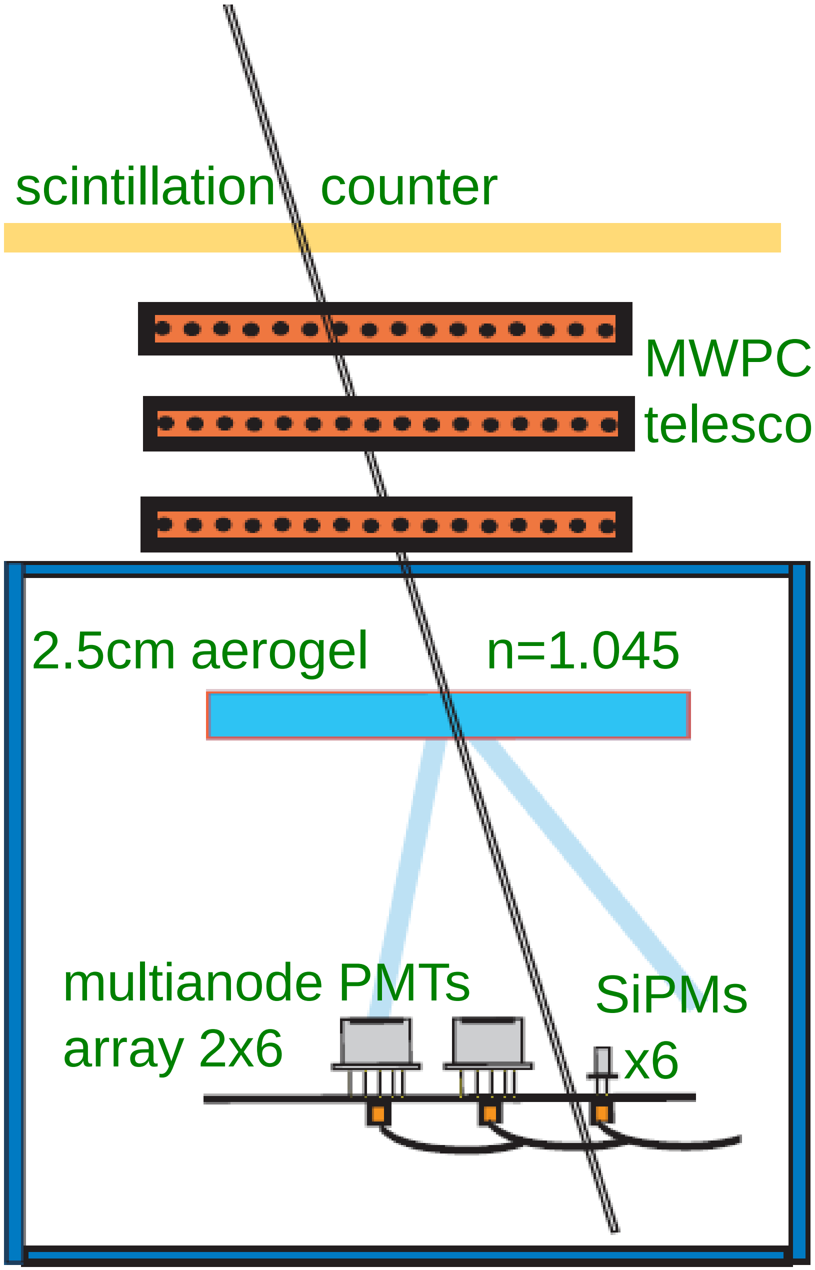
- 6 Hamamatsu SiPMs used:
  - 2x 100U; background ~400kHz
  - 2x 050U; background ~200kHz
  - 2x 025U; background ~100kHz
- signals amplified (ORTEC FTA820),
- discriminated (EG&G CF8000) and
- read by multihit TDC (CAEN V673A) with 1 ns / channel

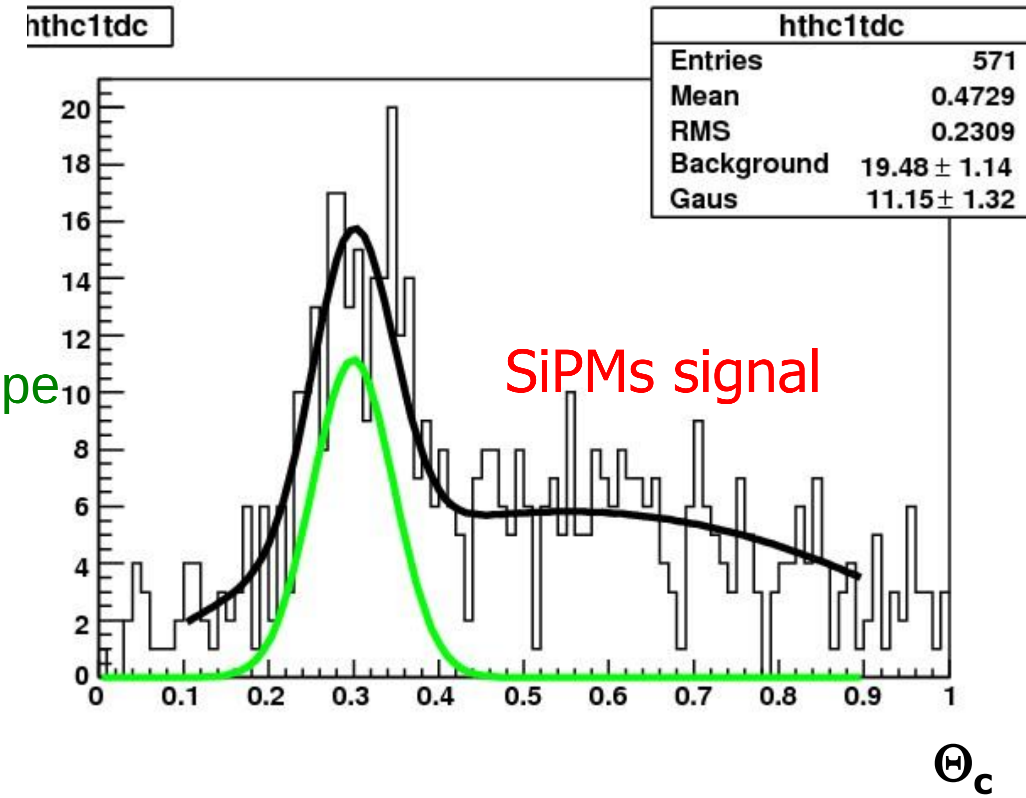
SiPM: Cherenkov angle distributions for 1ns time windows



Cherenkov photons appear in the expected time windows →
First Cherenkov photons observed with SiPMs!

SiPM Cherenkov angle distribution



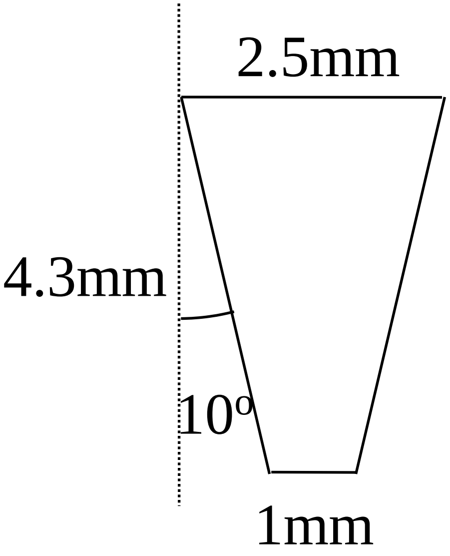


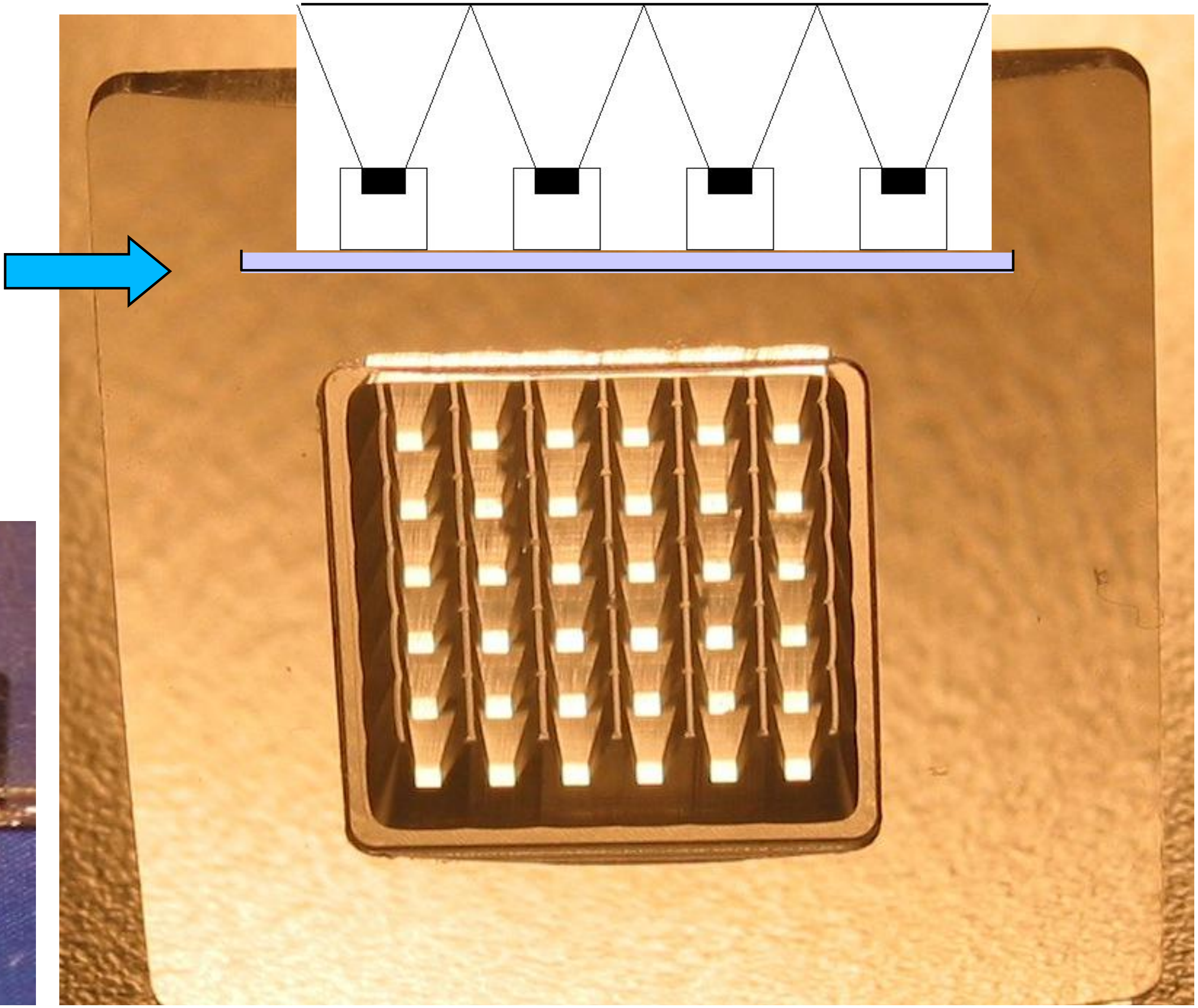
→ SiPMs give 4 x more photons than PMTs per photon detector area – in ~agreement with expectations

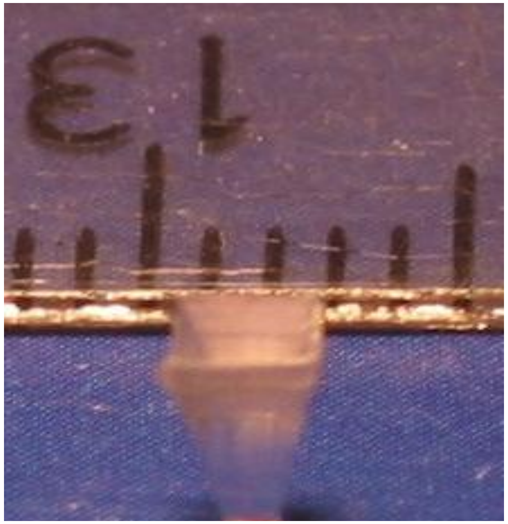
N.B. Signal/noise should improve by x3 with better tracking!

Detector module design

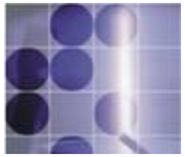
SiPM array with light guides







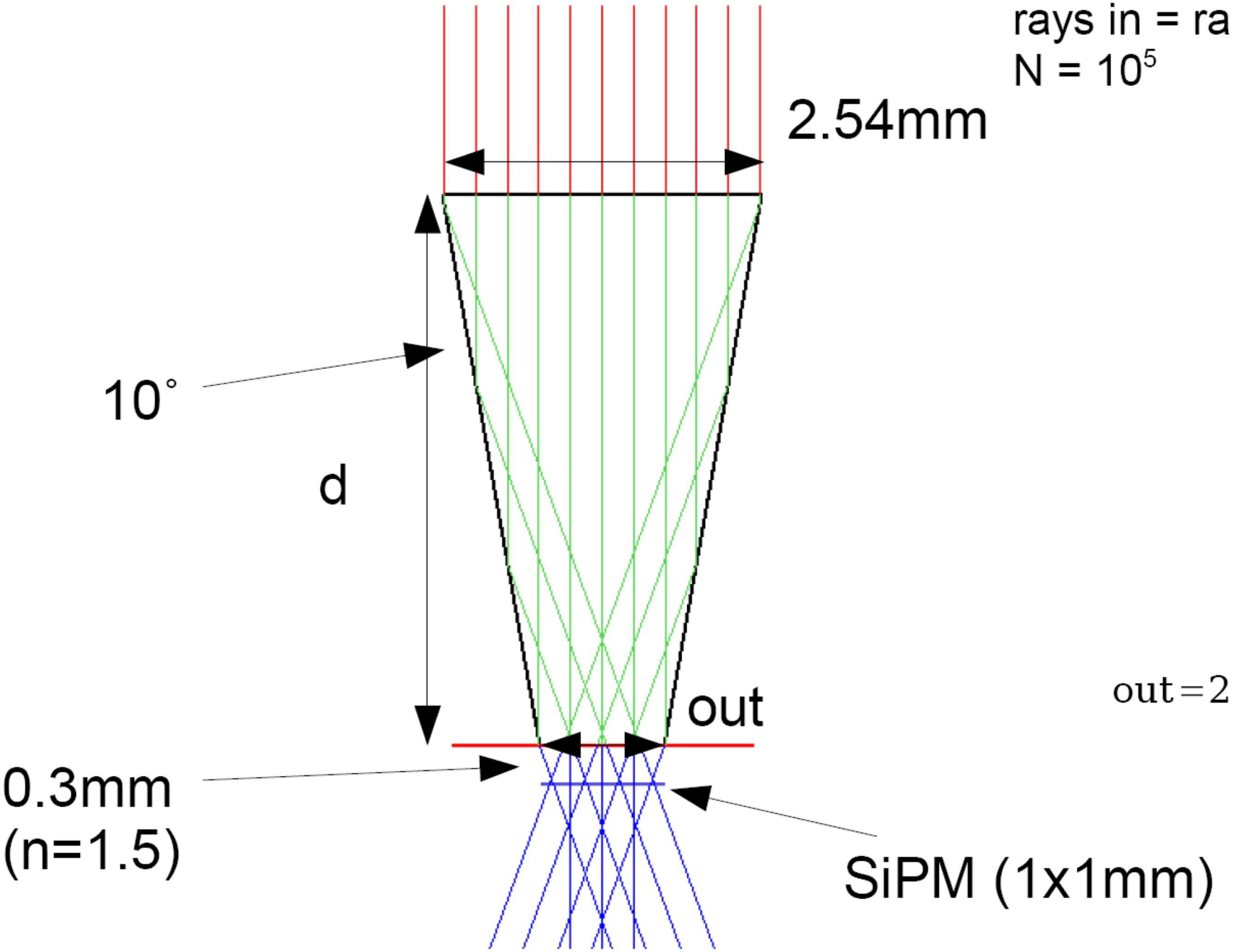
A multi-channel module prepared for a beam test at CERN



Light guide geometry optimisation

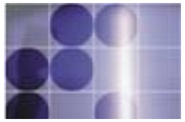
Light Guide Acceptance / (d and out)

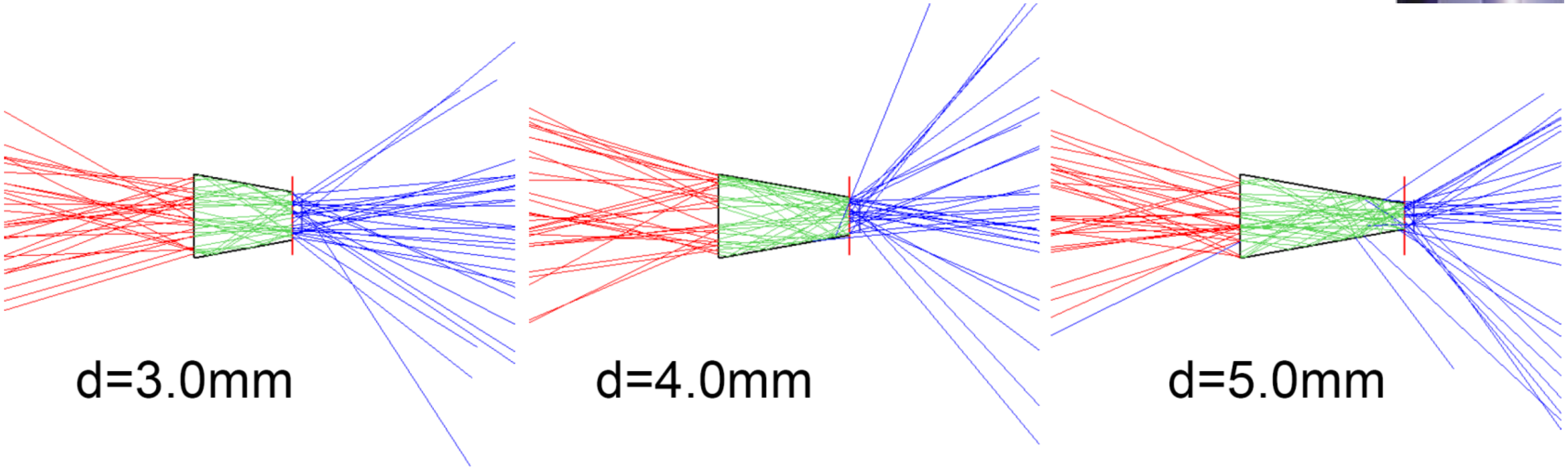
rays in = random isotropic 0-30°
$N = 10^5$



$$\text{out} = 2.54\text{mm} - 2 * d * \tan(10°)$$

Light guide geometry optimisation



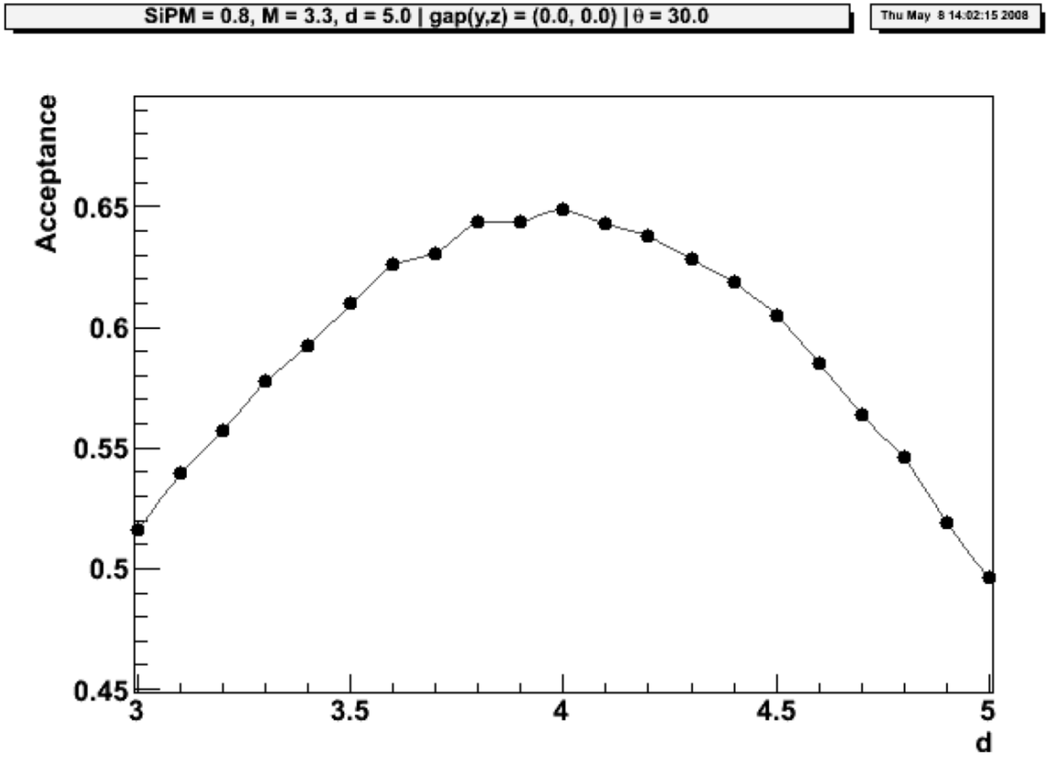


d=3.0mm

d=4.0mm

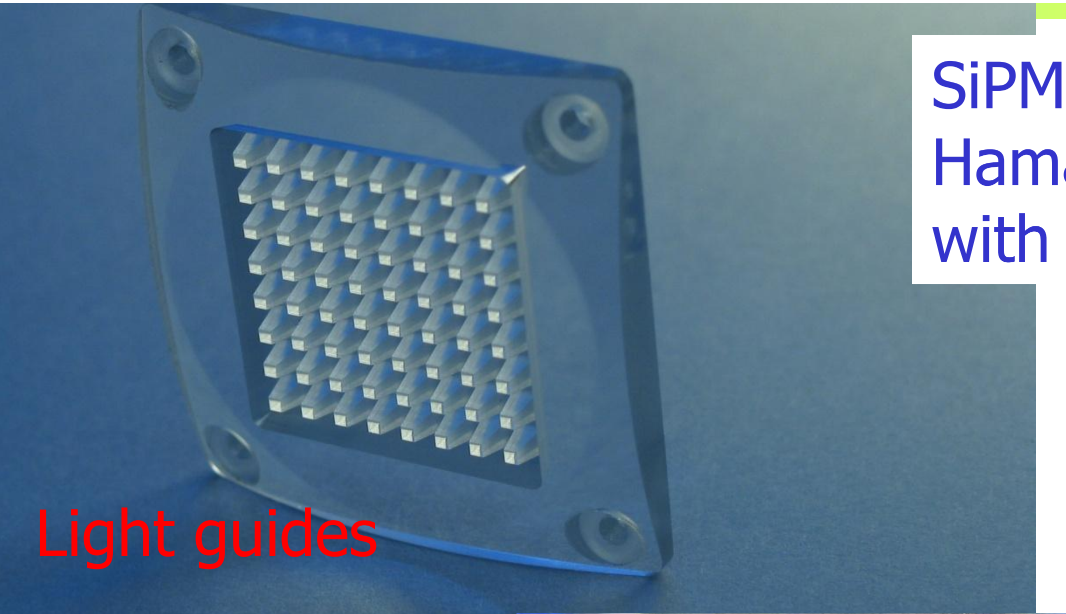
d=5.0mm

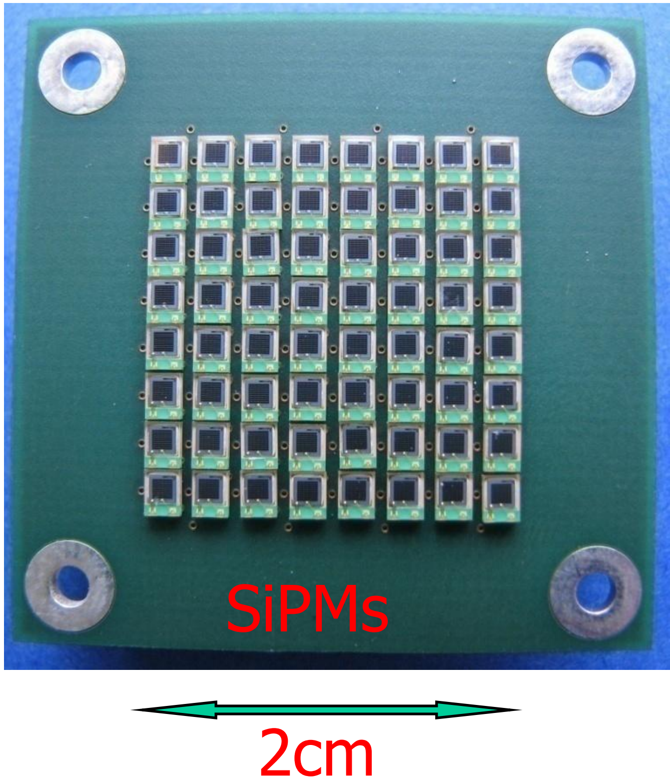
d (mm)	out (mm)	accept. (%)
3.0	1.48	51.6
3.1	1.45	54.0
3.2	1.41	55.7
3.3	1.38	57.8
3.4	1.34	59.2
3.5	1.31	61.0
3.6	1.27	62.6
3.7	1.24	63.1
3.8	1.20	64.4
3.9	1.16	64.4
4.0	**1.13**	**64.9**
4.1	1.09	64.3
4.2	1.06	63.8
4.3	1.02	62.8
4.4	0.99	61.8
4.5	0.95	60.5
4.6	0.92	58.5
4.7	0.88	56.4
4.8	0.85	54.6
4.9	0.81	51.9

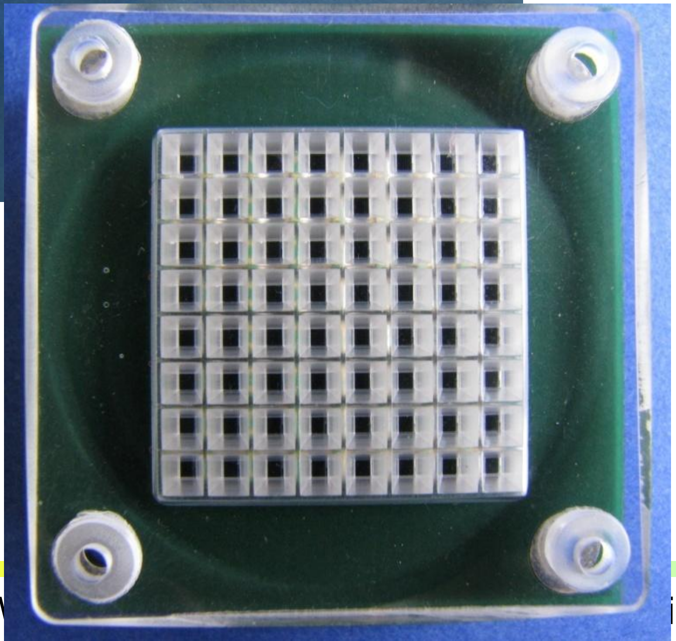


Detector module for beam tests at KEK

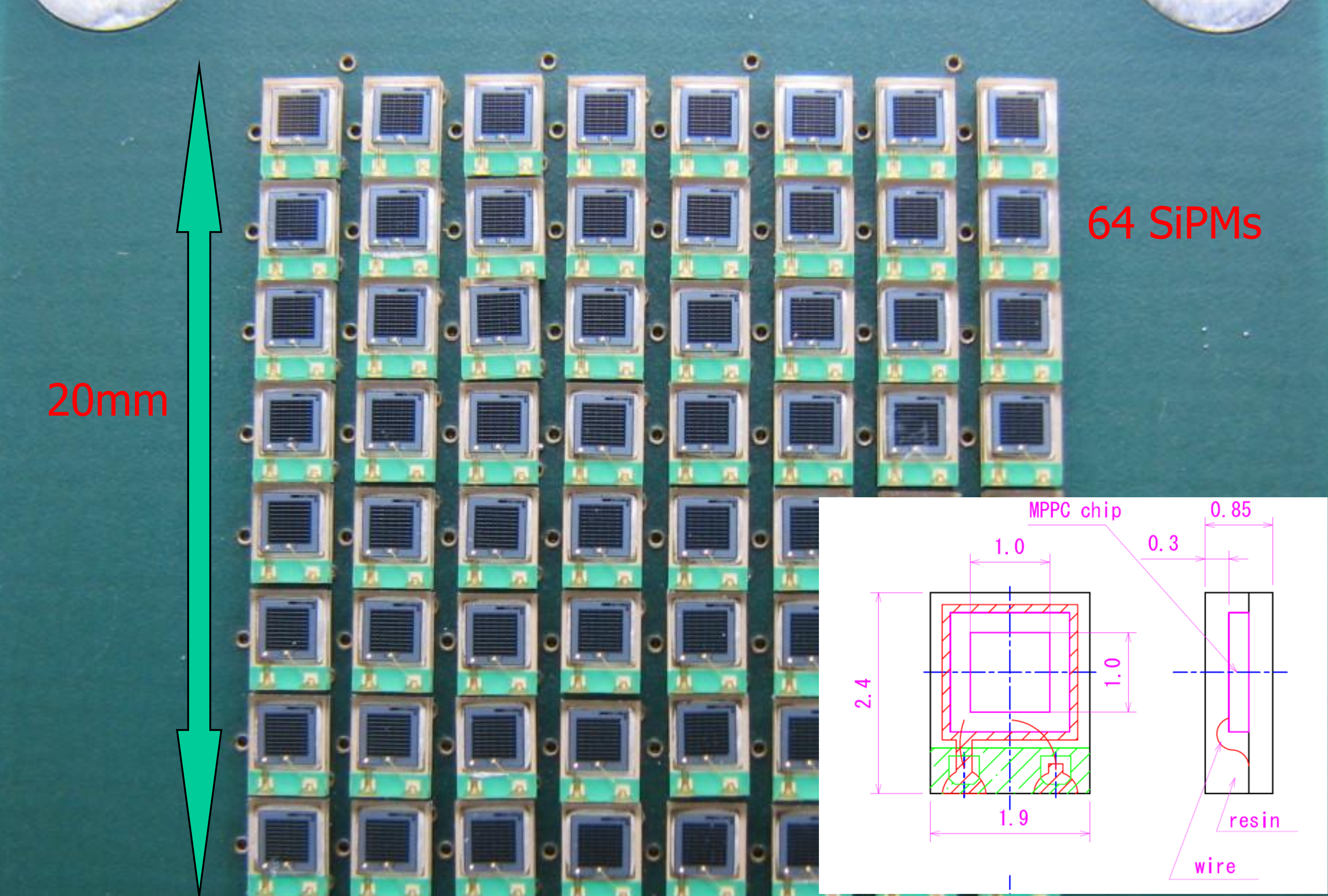
SiPMs: array of 8x8 SMD mount Hamamatsu S10362-11-100P with 0.3mm protective layer


Light guides


SiPMs


SiPMs + light guides

Photon detector for the beam test



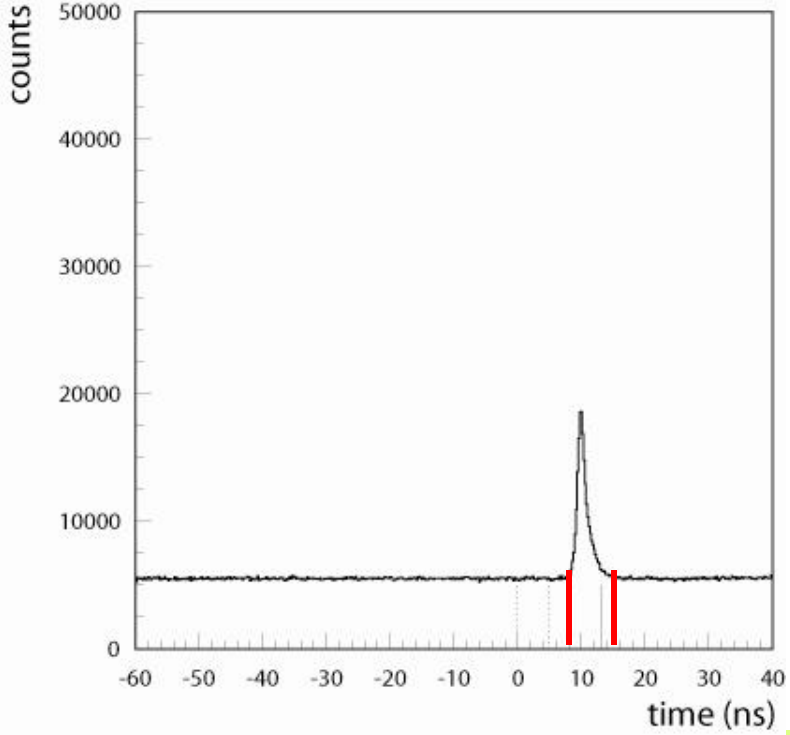
64 SiPMs

20mm

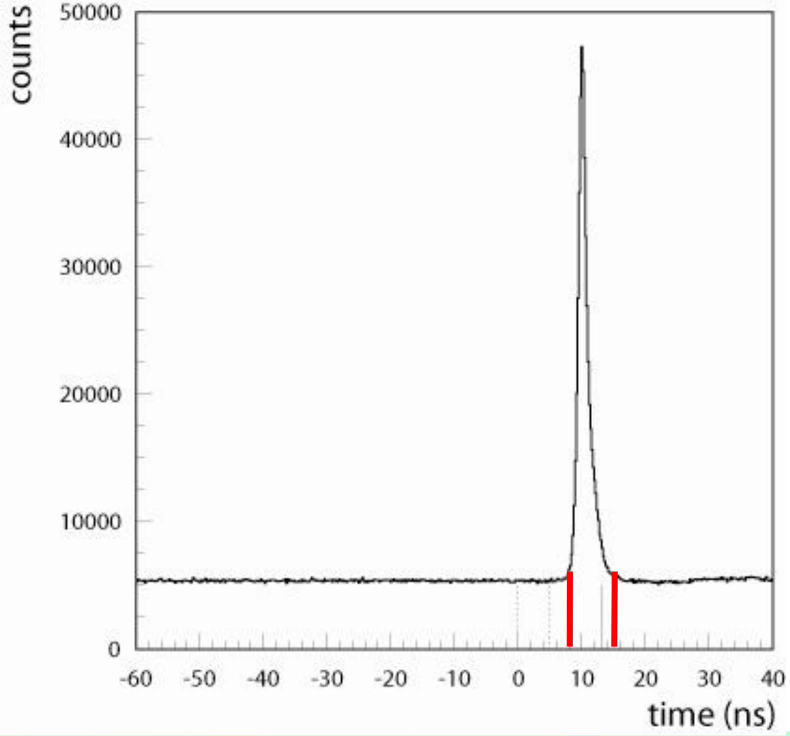
SiPM beam test: TDC distributions

- Total noise rate ~35 MHz (~600 kHz/MPPC)
- Hits in the time window of 5ns around the peak are selected for the Cherenkov angle analysis

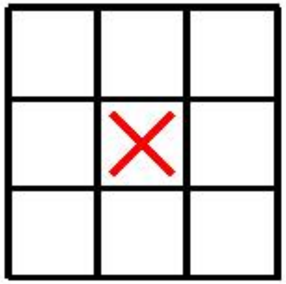
without light guides



with light guides

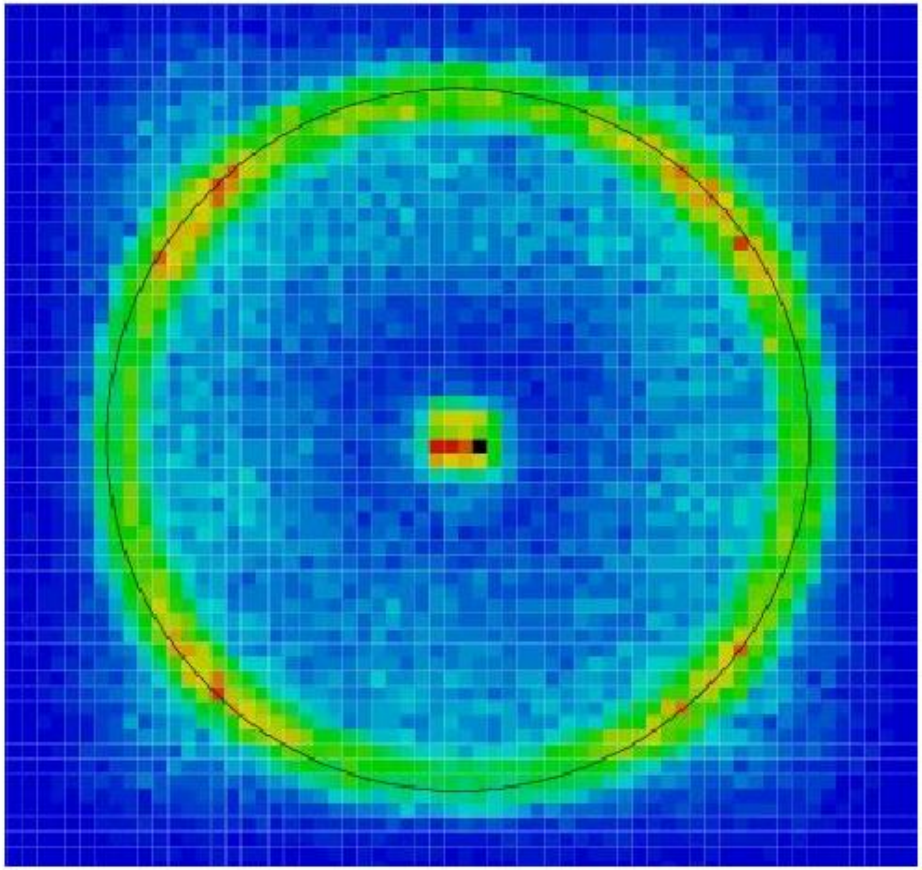


Ring images

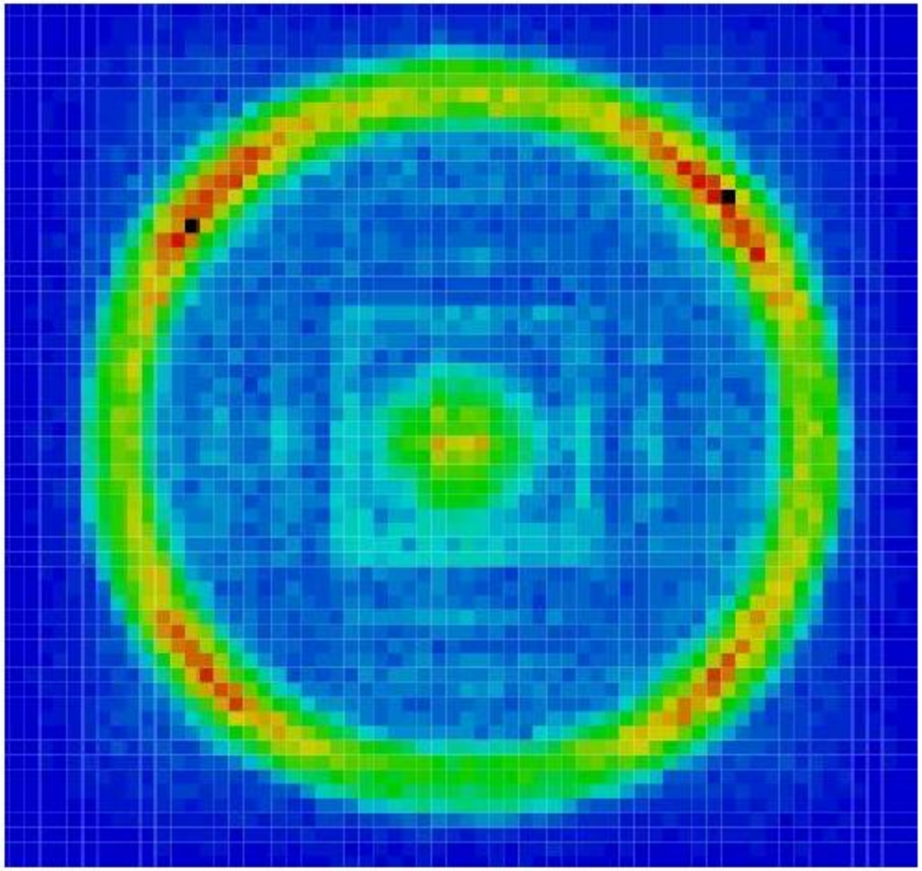


- module was moved to 9 positions to cover the ring area
- these plots show only superposition of 8 positions (central position is not included)

w/o light guides

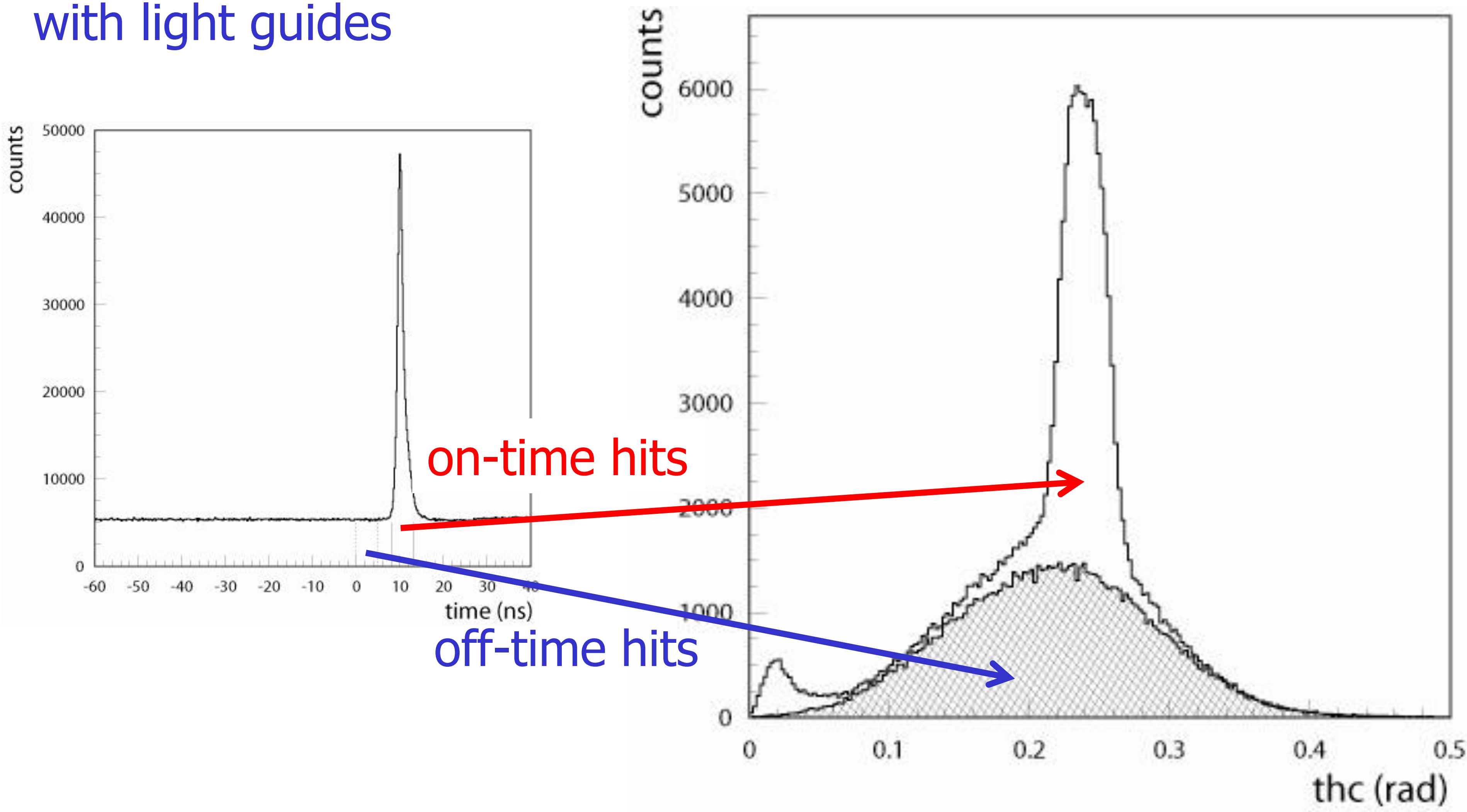


w/ light guides



SiPM beam test: Cherenkov angle distributions

with light guides



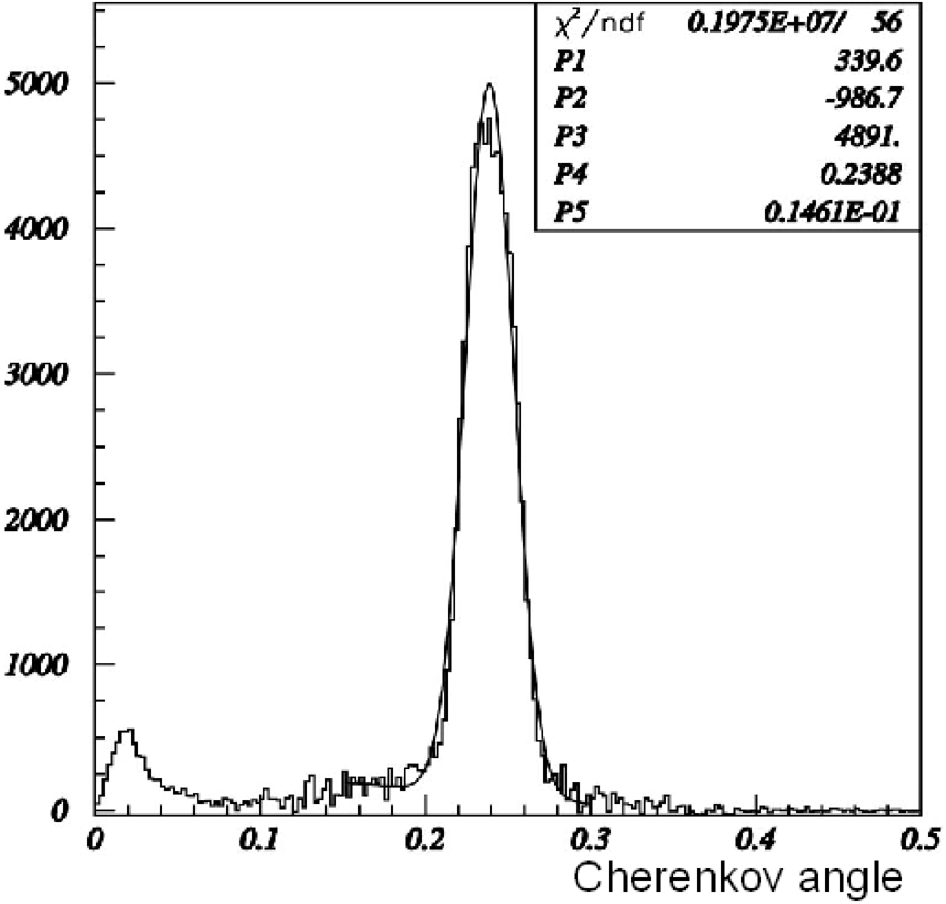
on-time hits

off-time hits

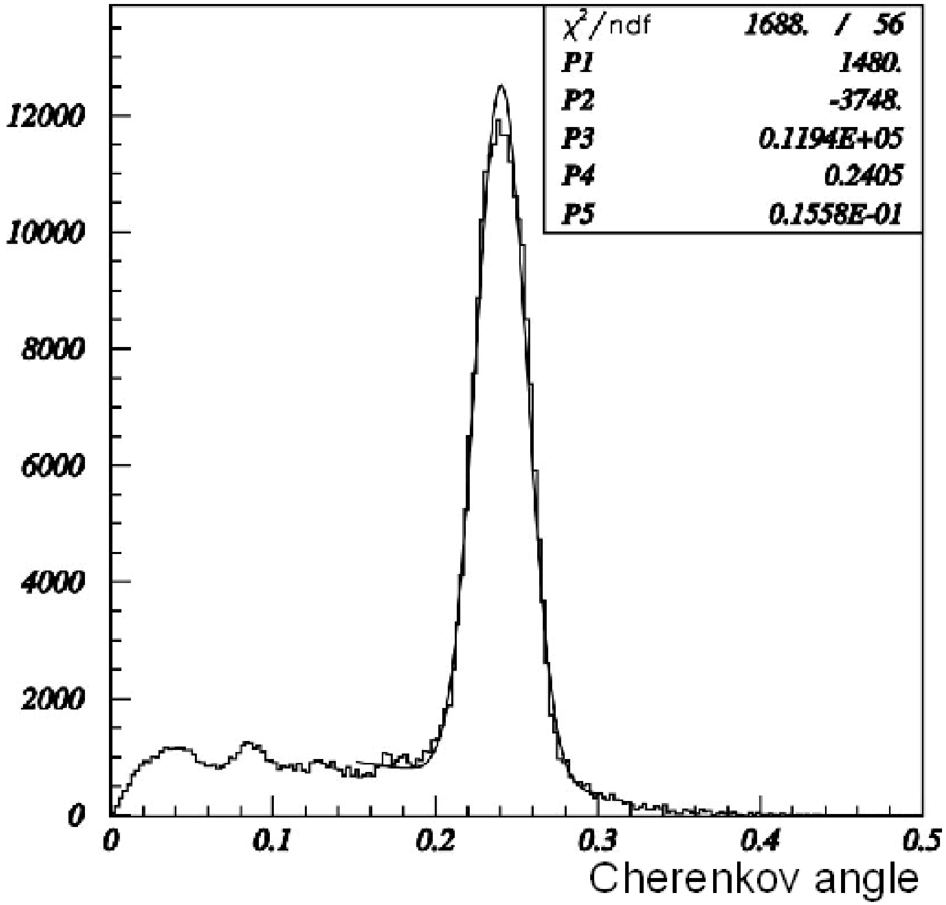
Cherenkov angle distributions

- background subtracted distributions
- ratio of detected photons w/ and w/o: ~ 2.3
- resolution within expectations (14.5mrad)

w/o light guides



w/ light guides



Background-subtracted distributions

Number of photons

Expected number of photons is ~3/full ring, this includes:

- Hamamatsu PDE
- aerogel: 1cm thickness, n=1.03, 25mm attenuation length
- dead time and double hit loss ~10%

Measured (extrapolated to full ring - acceptance corrected):

- w/o LG ~ 1.6
- w/ LG ~ 3.7

→discrepancy in QE values?
→ talks by D. Renker, Hamamatsu

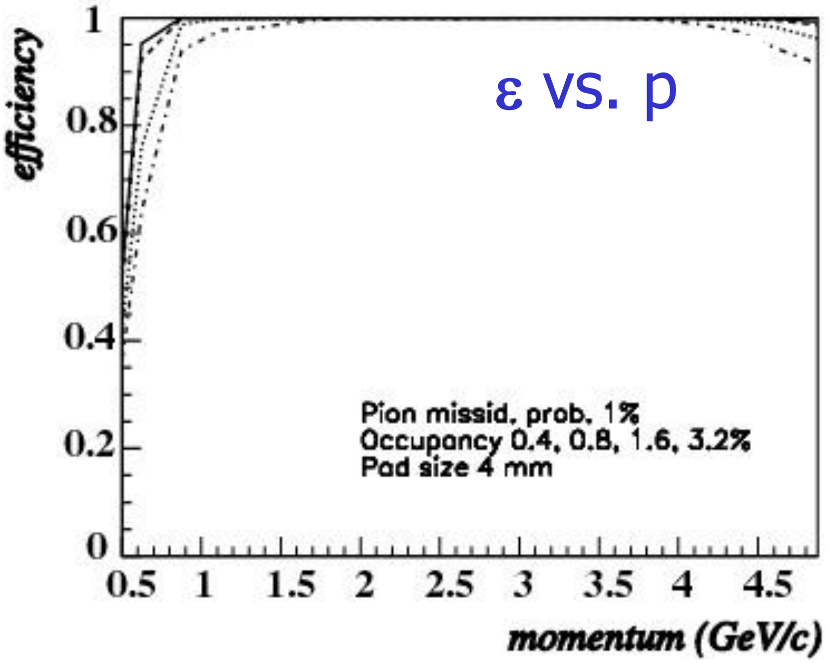
Estimated numbers for aerogel with n=1.05 and thickness of 4cm (~5x) and better quality of light guides (surface polishing: ~2x) are

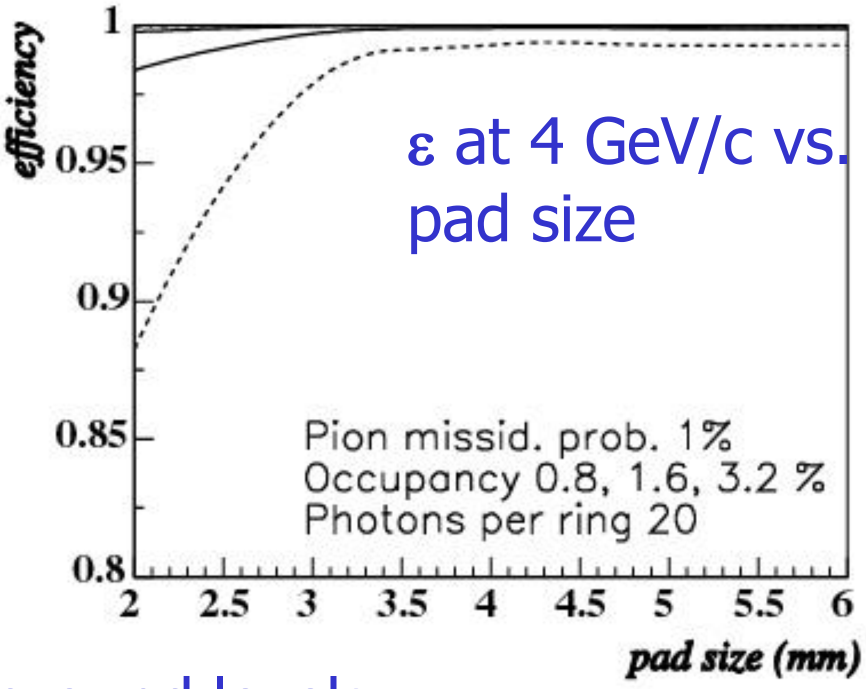
- w/o LG ~ 8
- **w/ LG ~ 37**

PID efficiency vs occupancy

MC simulation of the counter response: assume 1mm^2 active area SiPMs with 0.8 MHz (1.6 MHz, 3.2 MHz) dark count rate, 10ns time window

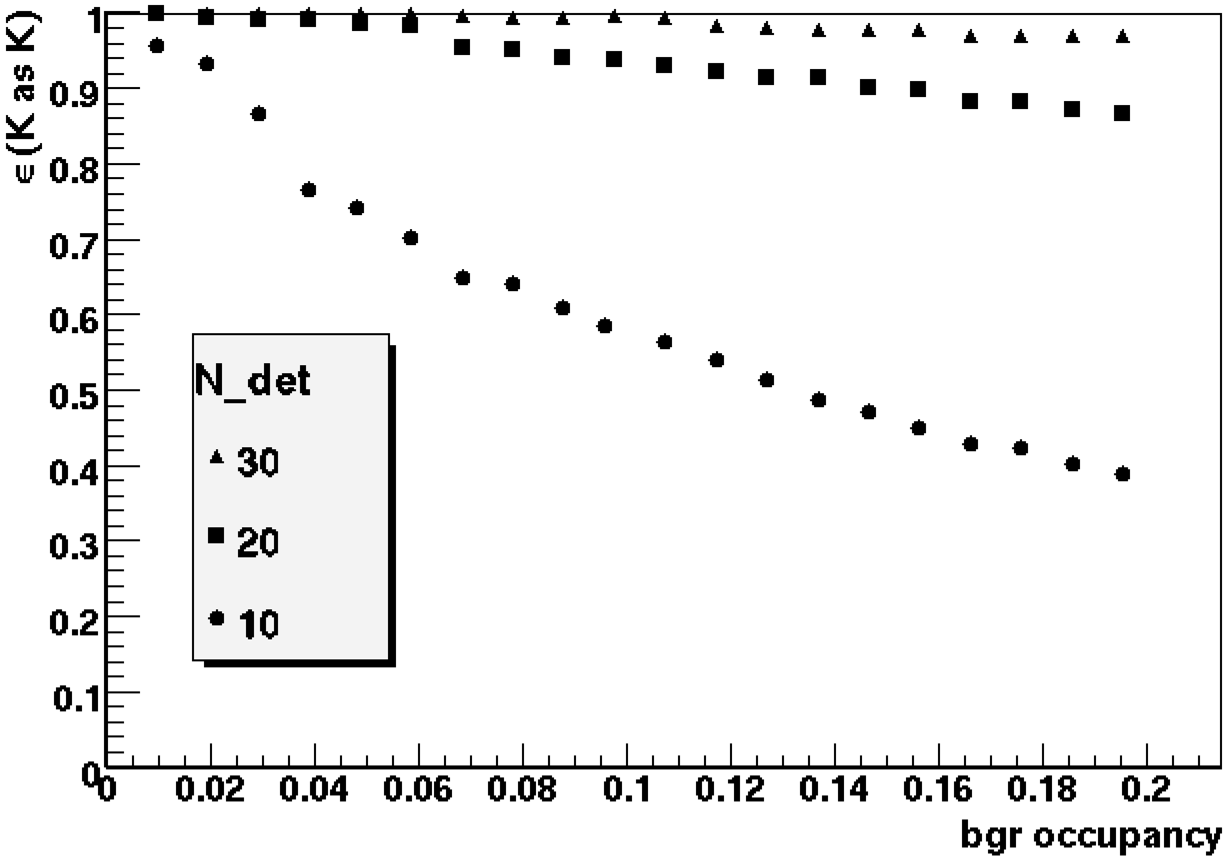
K identification efficiency at 1% π missid. probability


ε vs. p


ε at 4 GeV/c vs. pad size

For different background levels

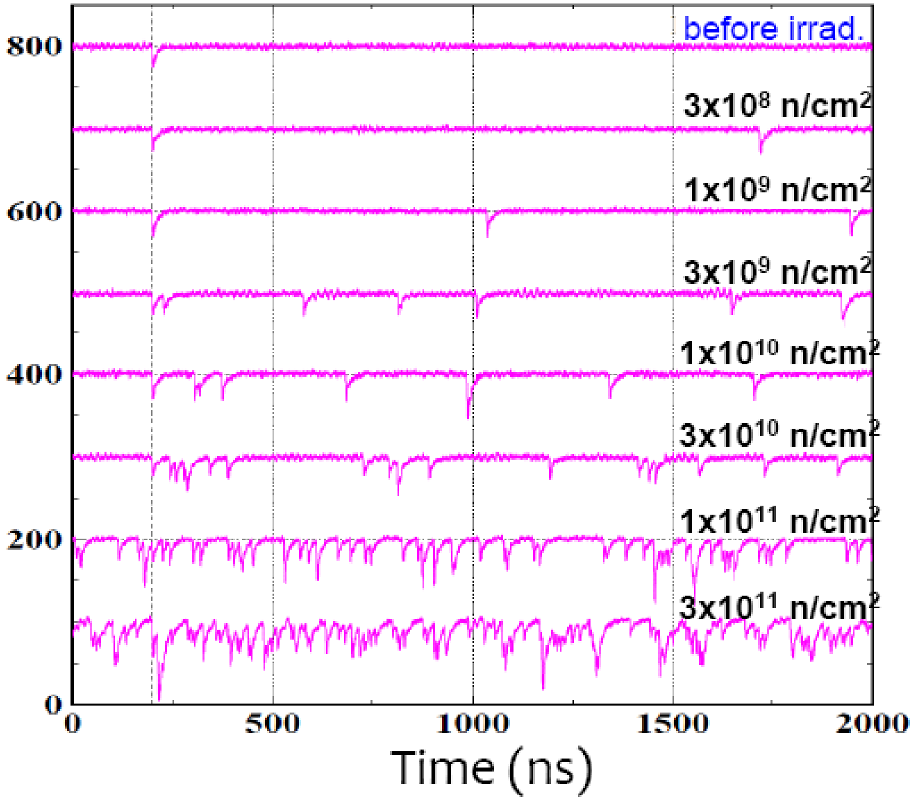
PID efficiency vs occupancy



~40MHz

For different number of photons per ring vs background level

Radiation damage


I.Nakamura, JPS meeting, Sep. 2008

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

→ Worst than the lowest line

→Very hard to use present SiPMs as single photon detectors in Belle because of radiation damage by neutrons

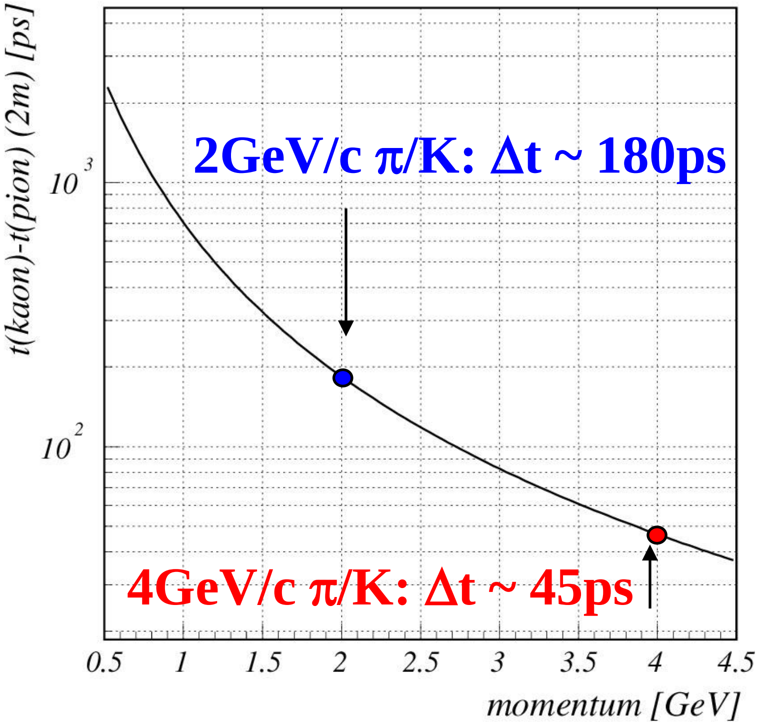
→Also: could only be used with a sofisticated electronics – wave-form sampling

→More talks on SiPMs later today S. Schmid, D. McNally, J. Howorth

TOF capability of a RICH

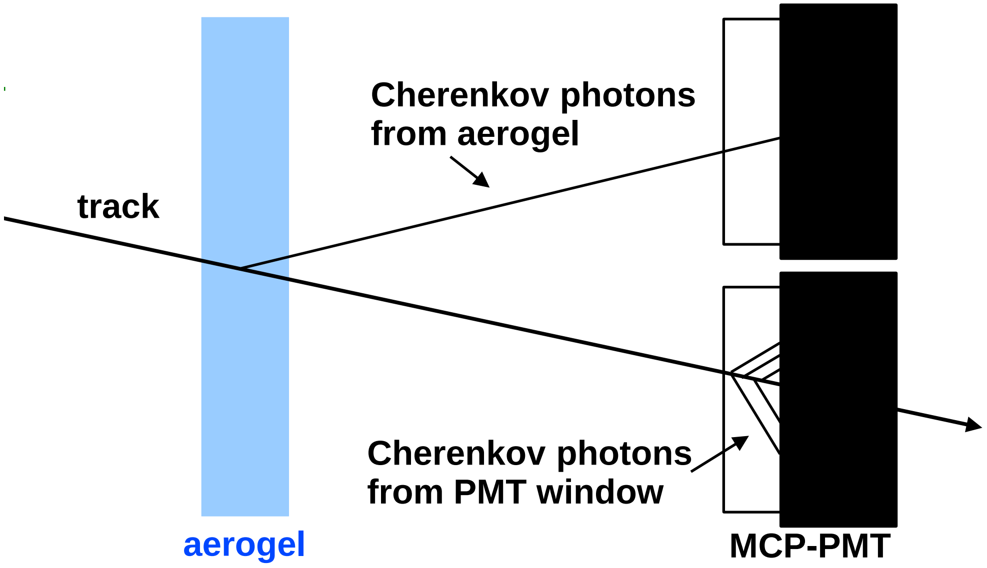
With a fast photon detector (MCP PMT), a proximity focusing RICH counter can be used also as a time-of-flight counter.

Time difference between π and K →



2GeV/c π/K: Δt ~ 180ps

4GeV/c π/K: Δt ~ 45ps

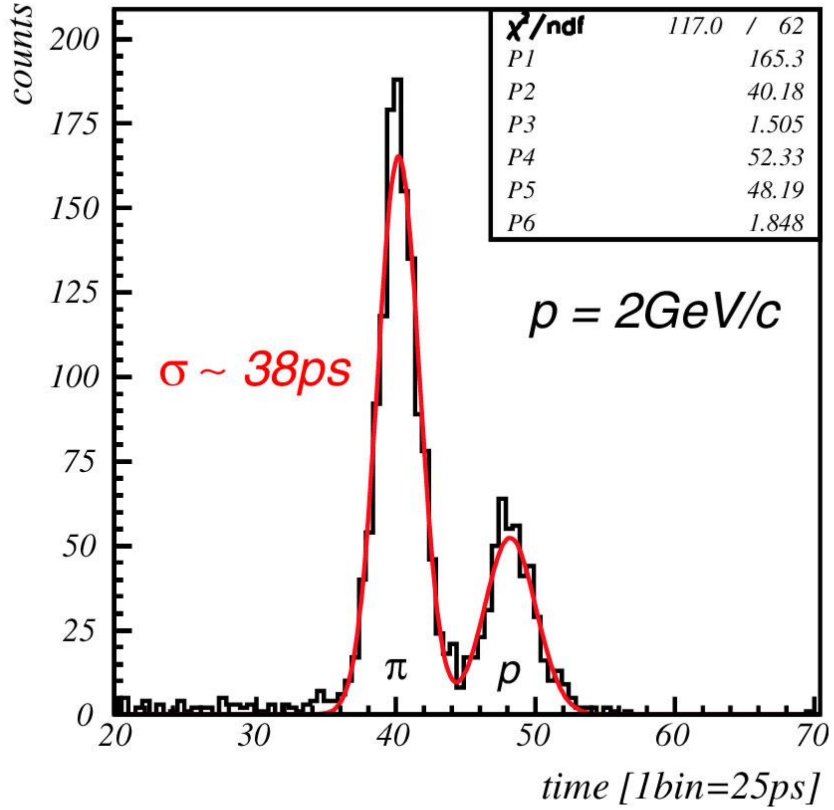


For time of flight: use Cherenkov photons emitted in the PMT window

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

→ In the real detector ~2m

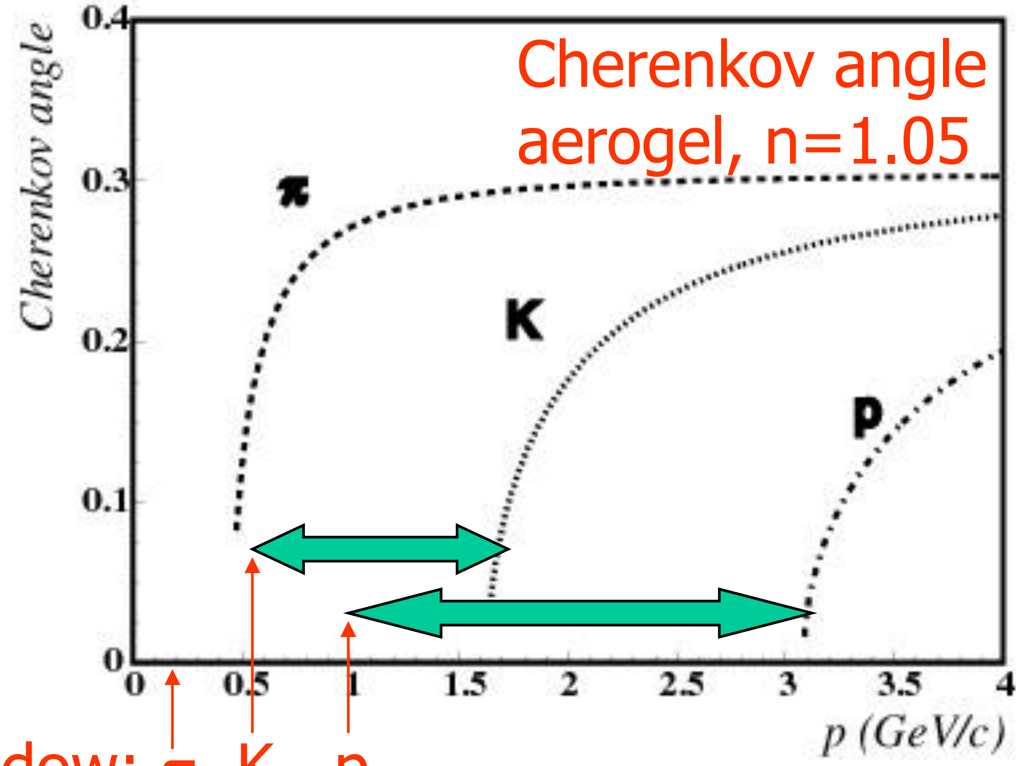
→ 3x better separation

NIM A572 (2007) 432

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.



Cherenkov angle aerogel, n=1.05

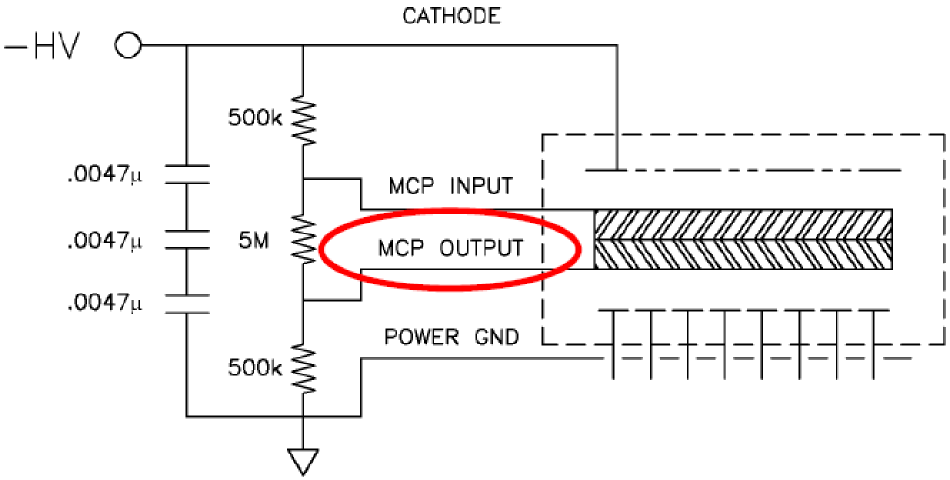
Threshold in the window: π K p

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

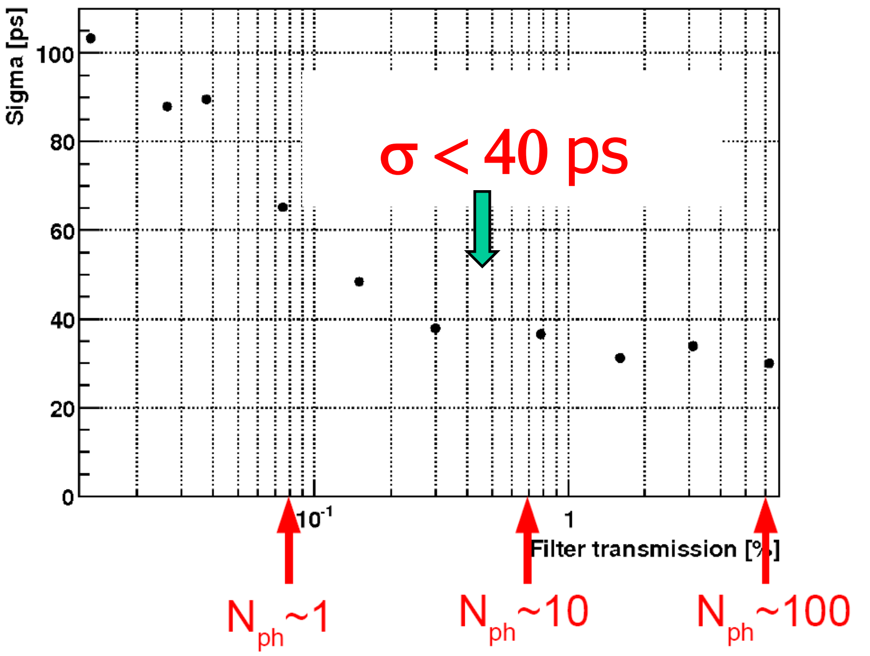
Timing with a signal from the second MCP stage

If a charged particle passes the PMT window, ~10 Cherenkov photons are detected in the MCP PMT; they are distributed over several anode channels.

Idea: read timing for the whole device from a single channel (second MCP stage), while 64 anode channels are used for position measurement



MCP second stage output



$\sigma < 40$ ps

N_{ph}~1

N_{ph}~10

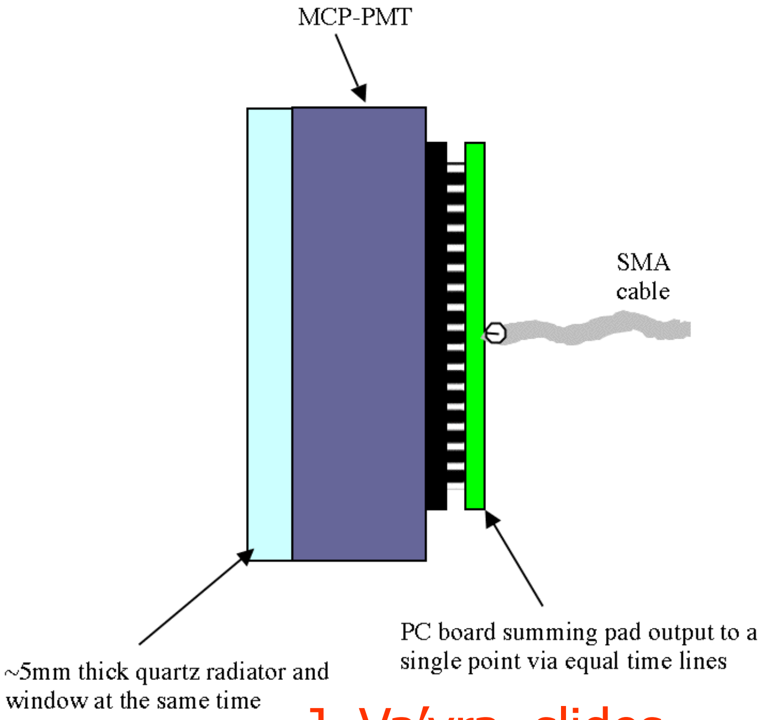
N_{ph}~100

Timing resolution as a function of light intensity

Time-of-flight: stand-alone, revisited

New ingredients:

- Faster photon detectors
- Use of Cherenkov light instead of scintillation photons
- Faster electronics



J. Va'vra, slides shown at RICH07

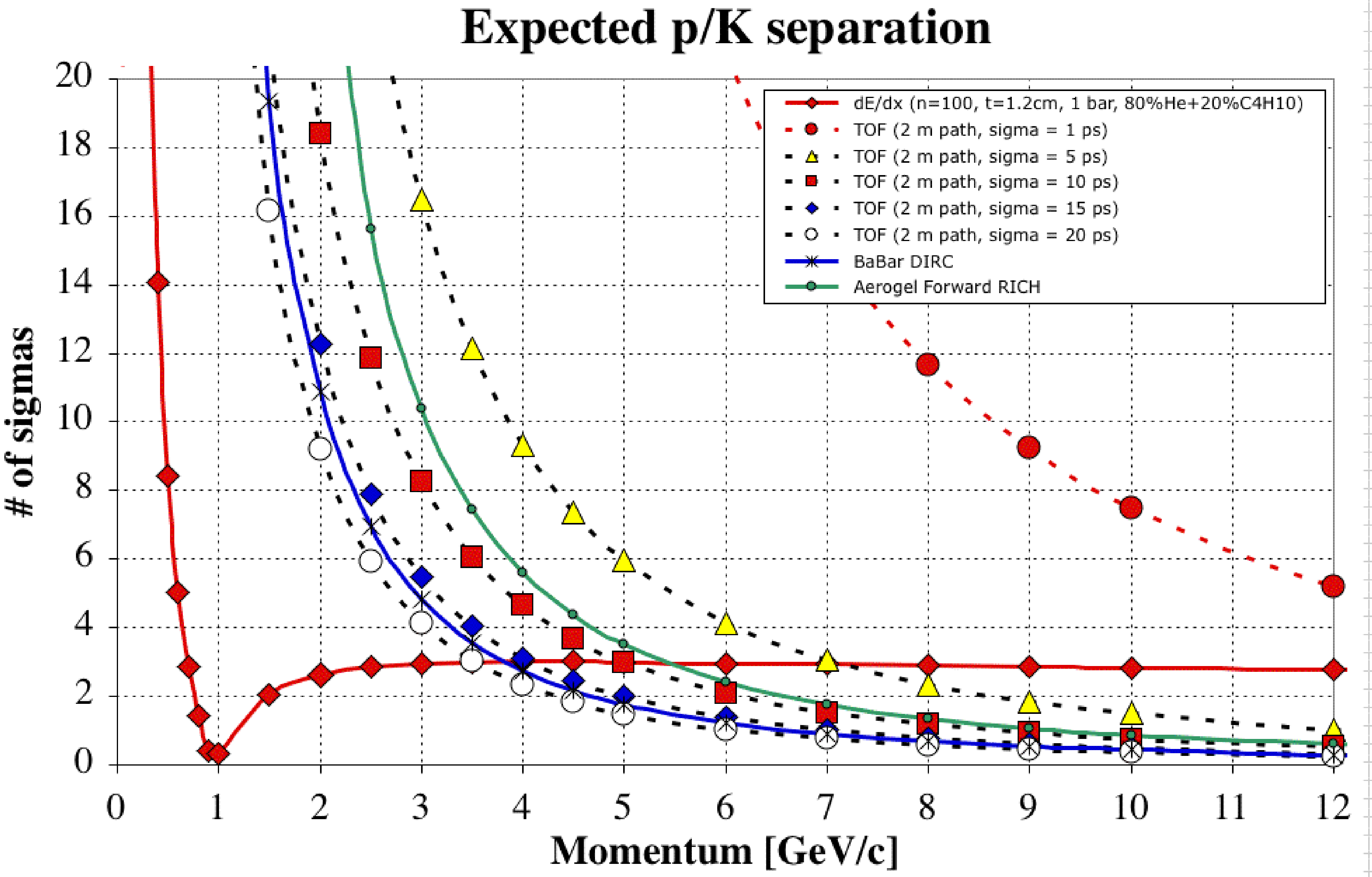
Recent results:

→resolution ~5ps measured

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

Open issues: read-out, start time

Time-of-flight: stand-alone, revisited

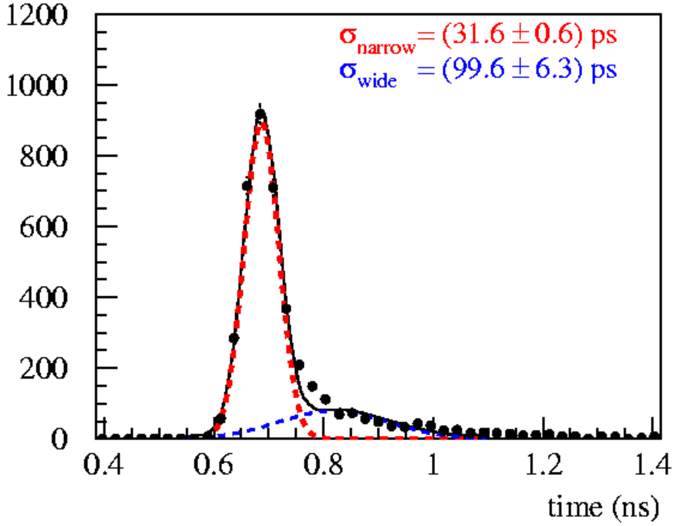


J. Va'vra, slides shown at RICH07

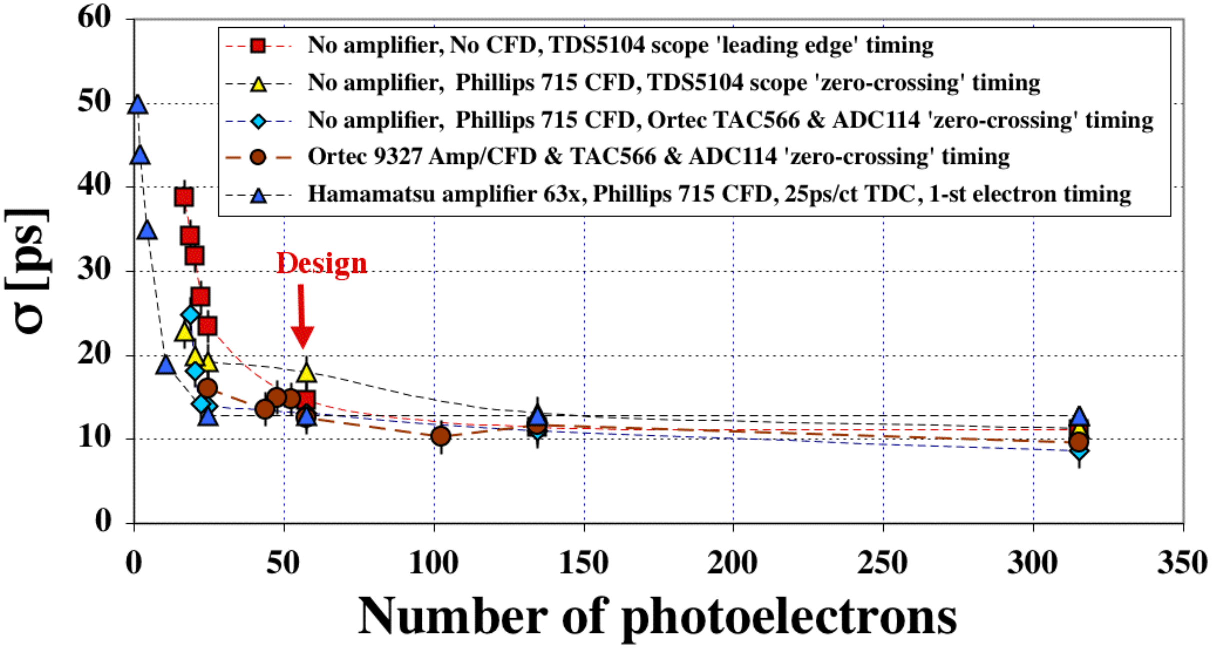
TOF counter with Burle/Photonis MCP-PMT

J. Va'vra, VCI2007

σ_{TTS} - single photo-electrons:

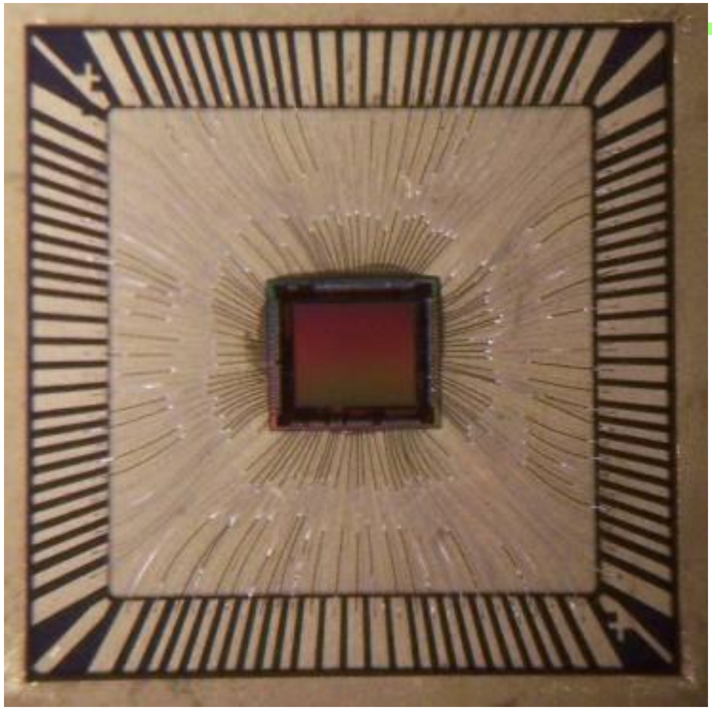


Timing resolution $\sigma = f(Npe)$:



- **TOF counter: Burle/Photonis MCP-PMT with a 1cm thick quartz radiator**
- **Present best results with the laser diode:**
    - **$\sigma \sim 12$ ps for Npe ~ 50-60**, which is expected from 1cm of the radiator.
    - **$\sigma_{TTS} \sim 32$ ps for Npe ~ 1**.
    - **Upper limit on the MCP-PMT contribution: $\sigma_{MCP\text{-}PMT} < 6.5$ ps**.
    - **TAC/ADC contribution to timing: $\sigma_{TAC\_ADC} < 3.2$ ps.**
    - **Total electronics contribution: $\sigma_{Total\_electronics} \sim 7.2$ ps**.

Read out: Buffered LABRADOR (BLAB1) ASIC



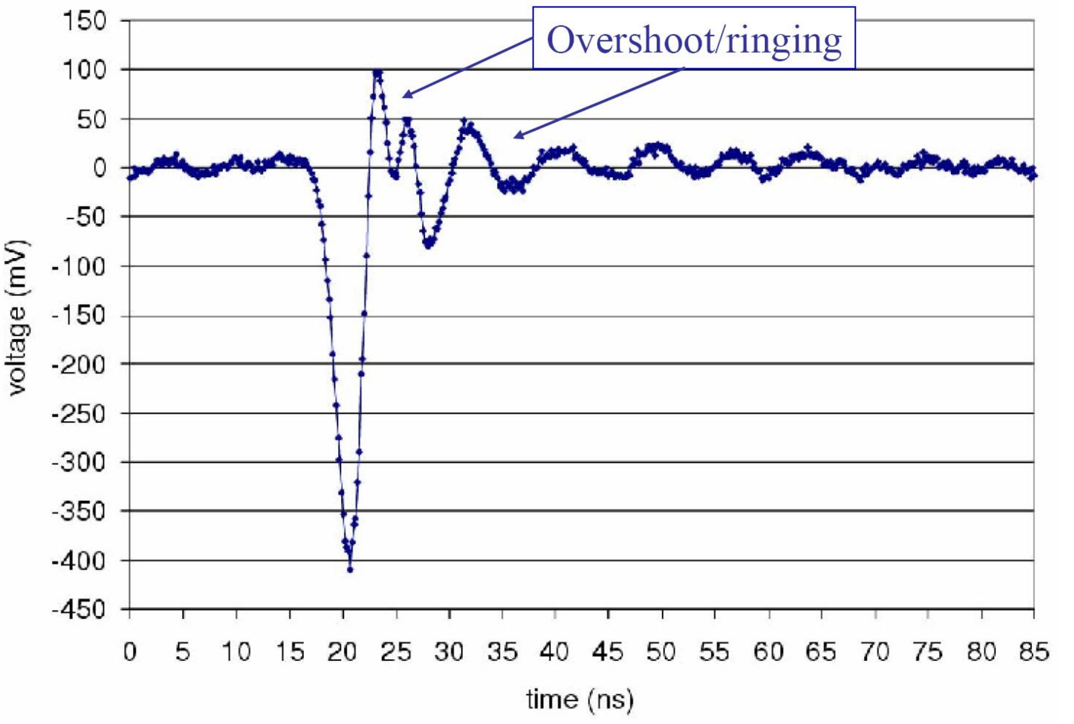
Gary Varner, Larry Ruckman (Hawaii)

Variant of the LABRADOR 3

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

3mm x 2.8mm, TSMC 0.25um

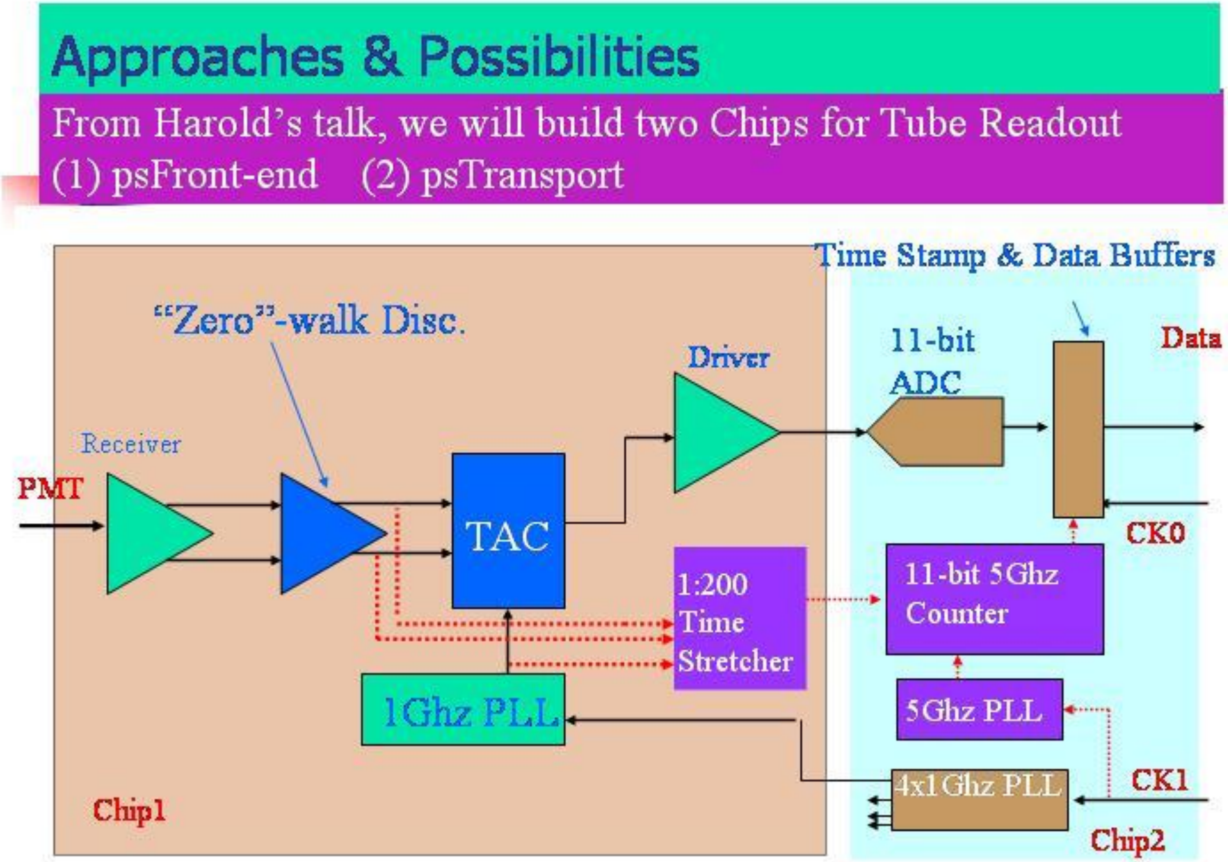
- 64k samples deep
- Multi-MSa/s to Multi-GSa/s



Typical single p.e. signal [Burle]

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

Summary

Particle identification is an essential part of several experiments, and has contributed substantially to our present understanding of elementary particles and their interactions.

Techniques based on Cherenkov radiation have become indispensable for PID

RICH counters have evolved into 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, SuperB factories, as well as at hadron structure experiments.

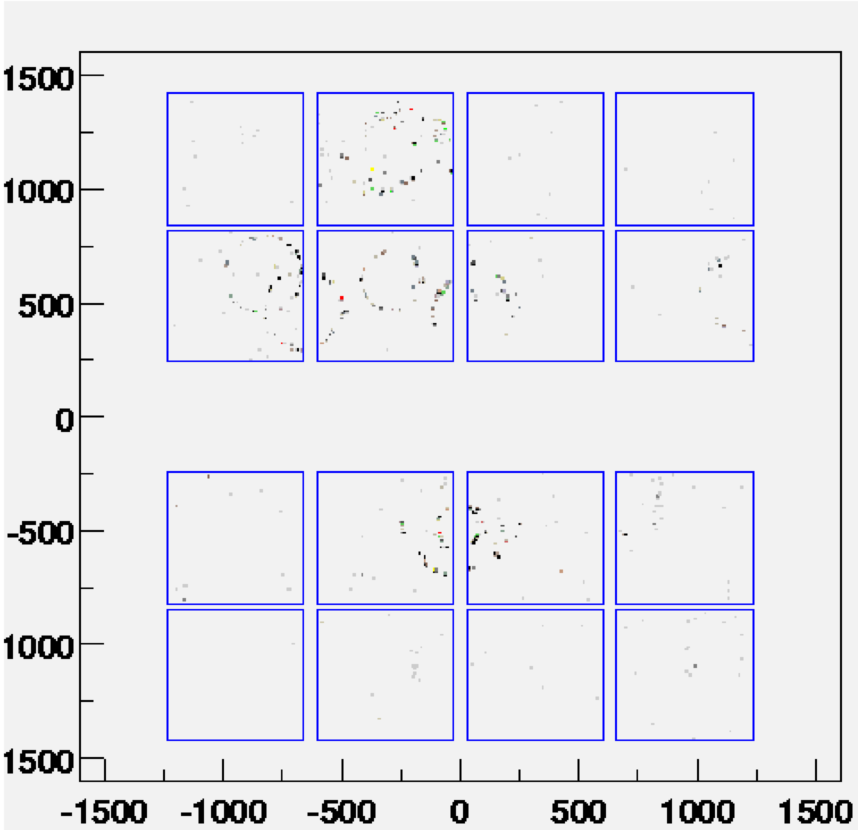
New concepts (focusing radiator, combination with time of flight) and new photon detectors are being developed.

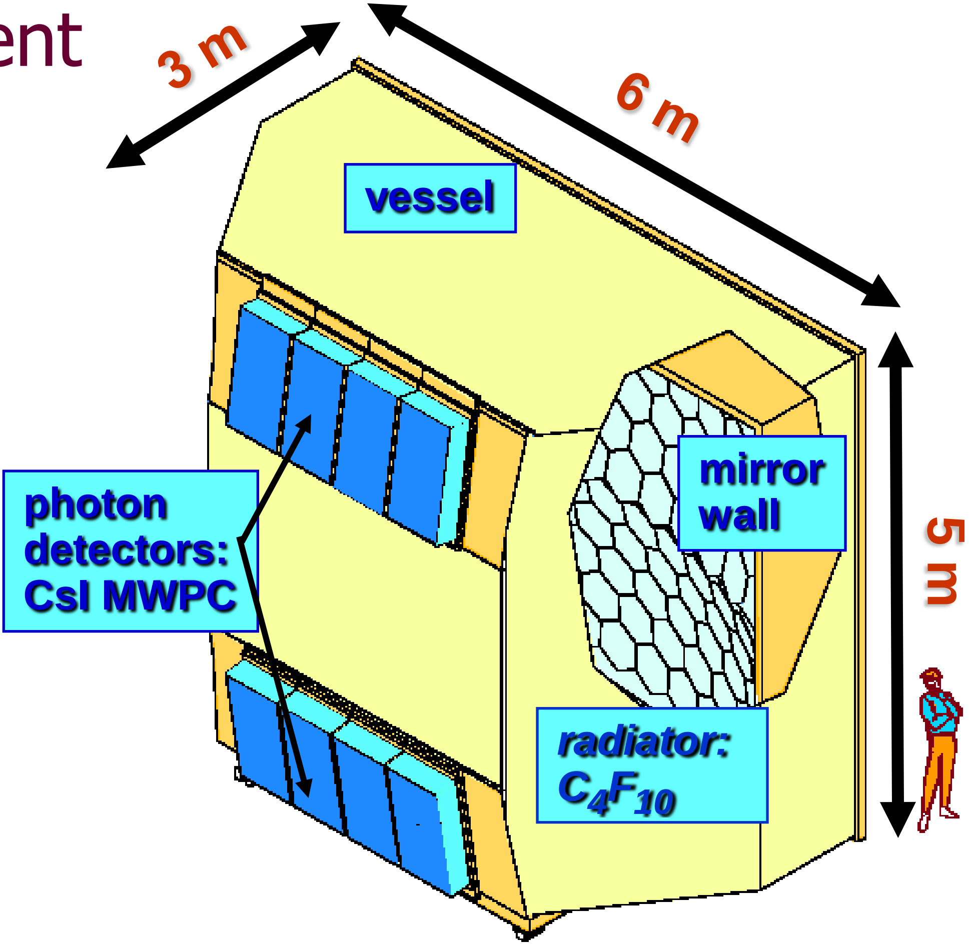
With new fast photon detectors there is a revived interest in the time-of-flight measurements, also in combination with a RICH counter.

Back-up slides

CsI based RICH counter: COMPASS

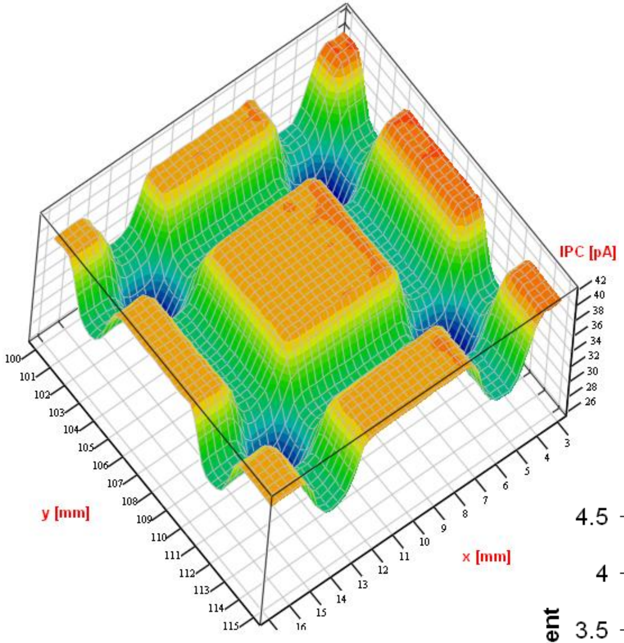
COMPASS: calibration event



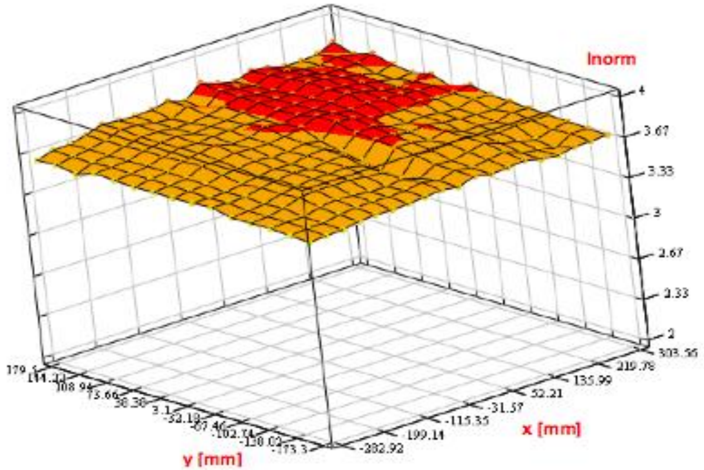


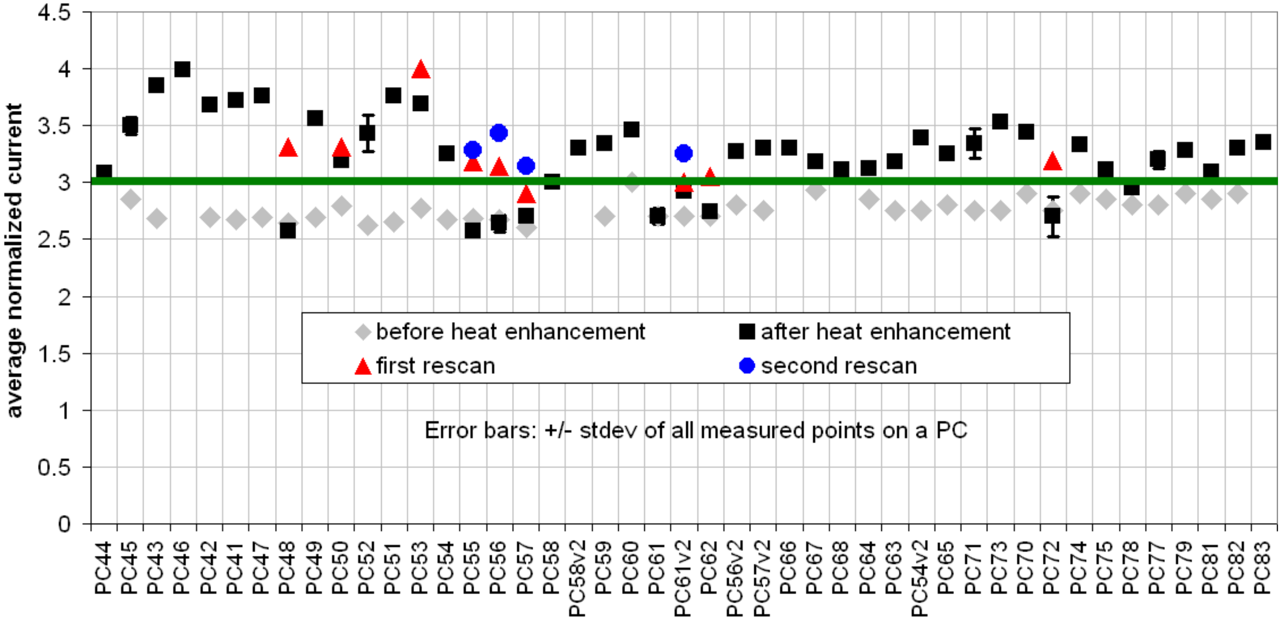
ALICE RICH: Surface sensitivity and production statistics

detailed scan across 2x2 pads□



full PC surface (80x48 pads)



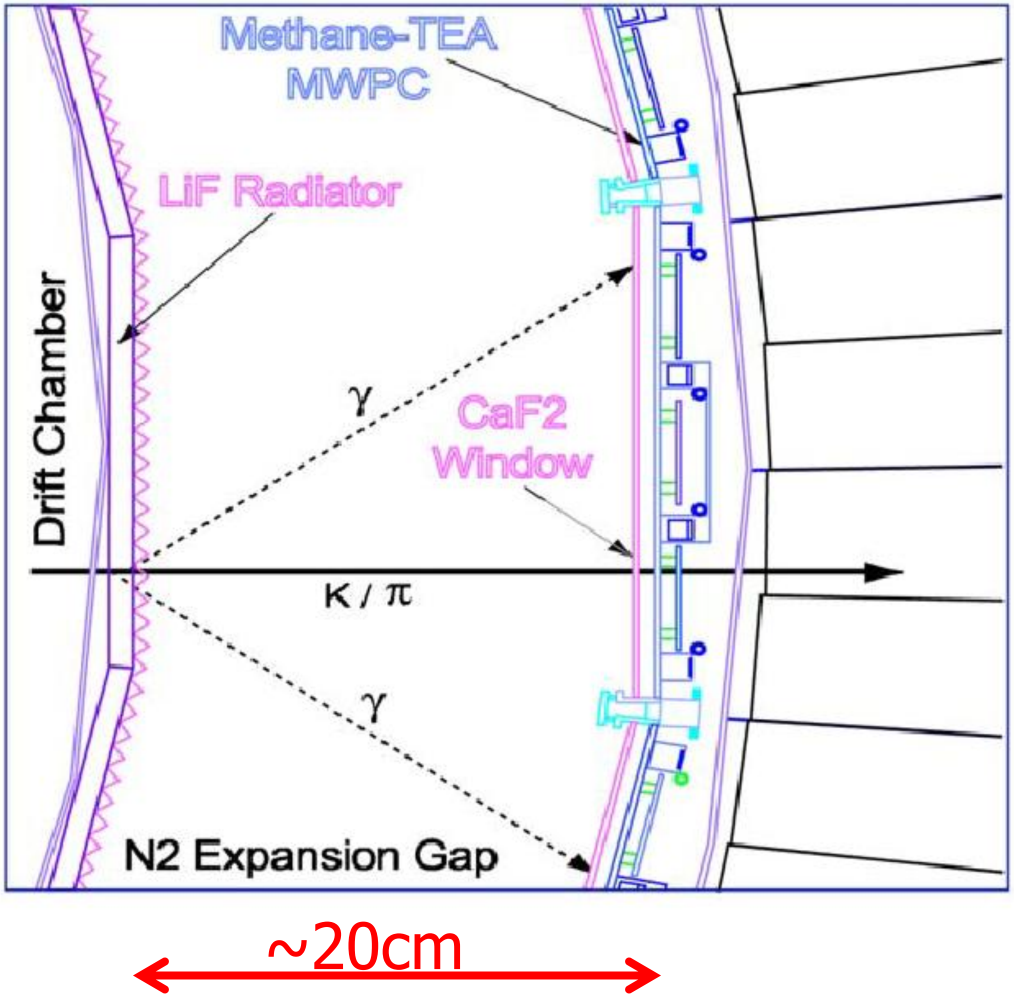


Error bars: +/- stdev of all measured points on a PC

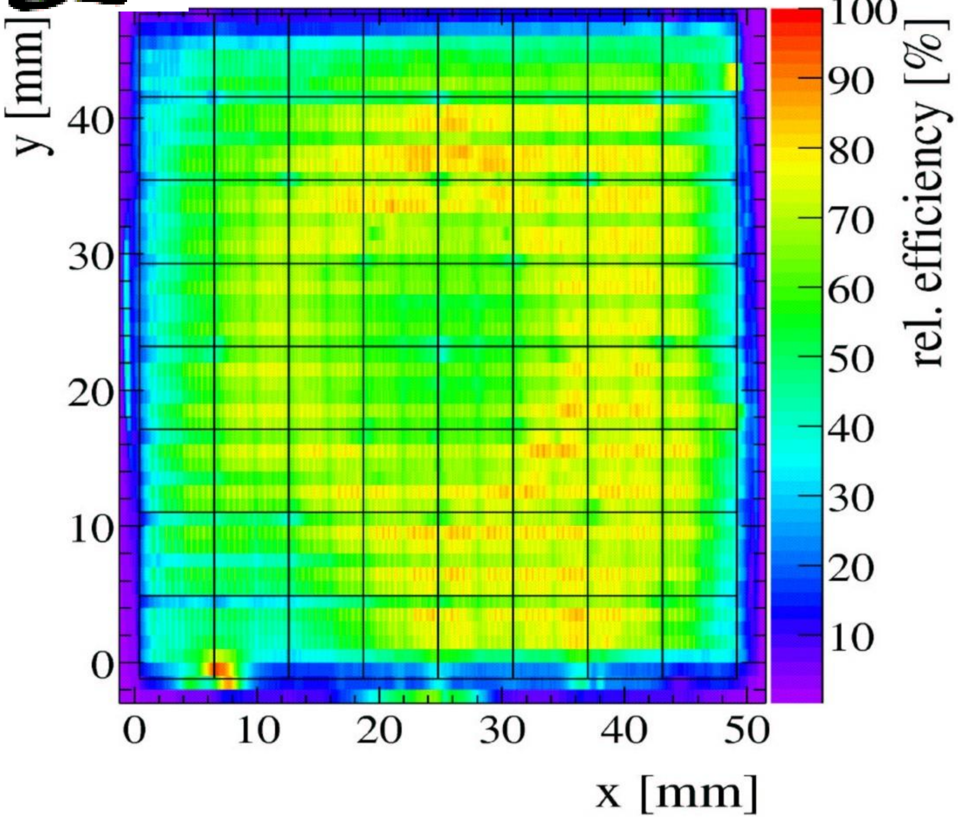
details: NIM A 566 (2006) 338

CLEOIII RICH

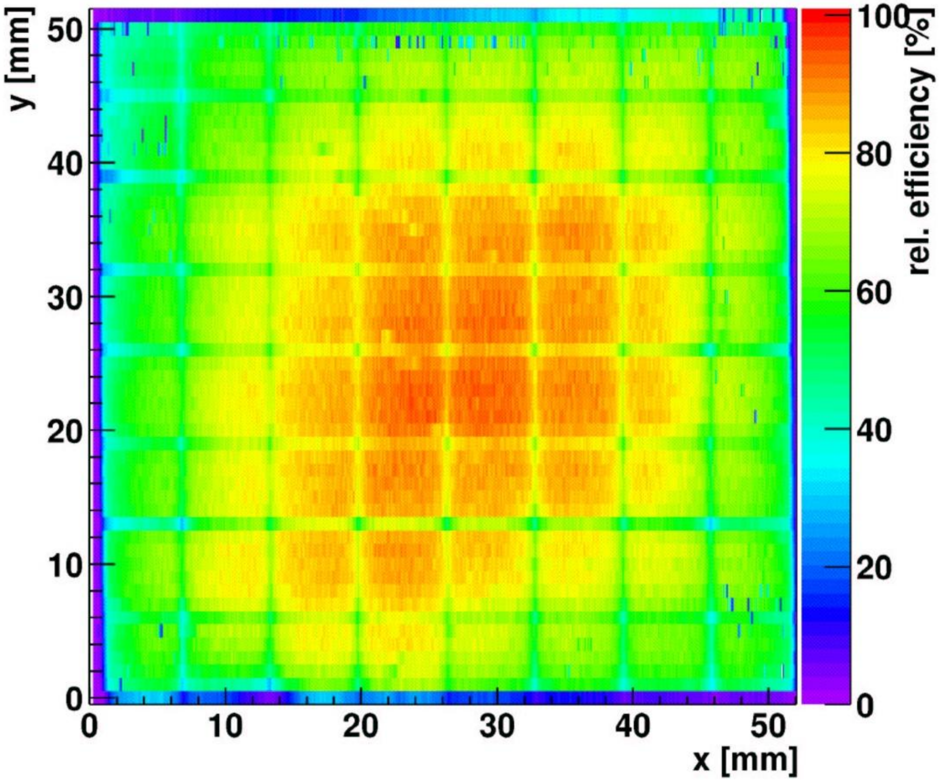
Photon detection in a wire chamber with a methane+TEA.



Focusing DIRC photon detectors: relative efficiency

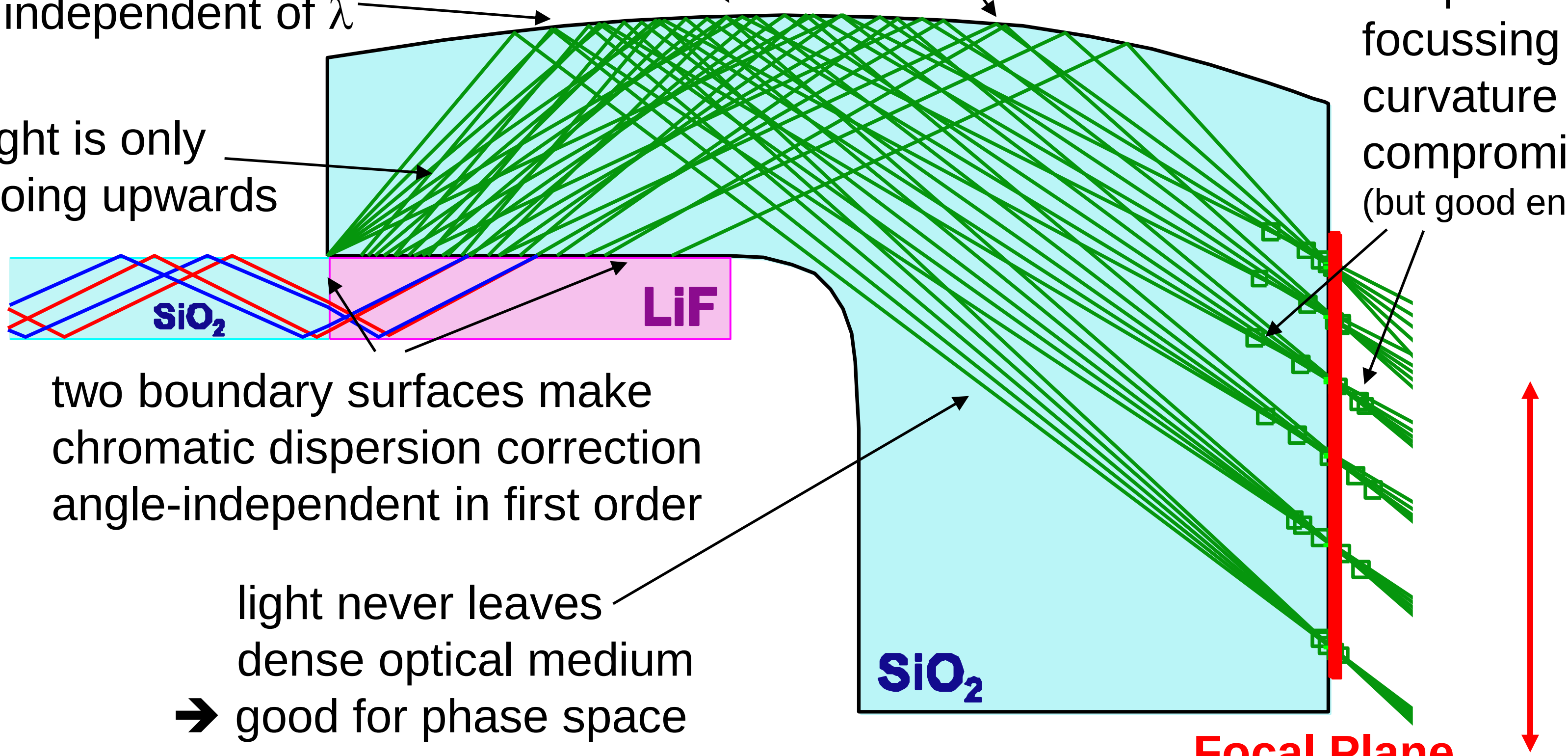


Hamamatsu H8500 (flat pannel)



Burle 85011 MCP-PMT

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

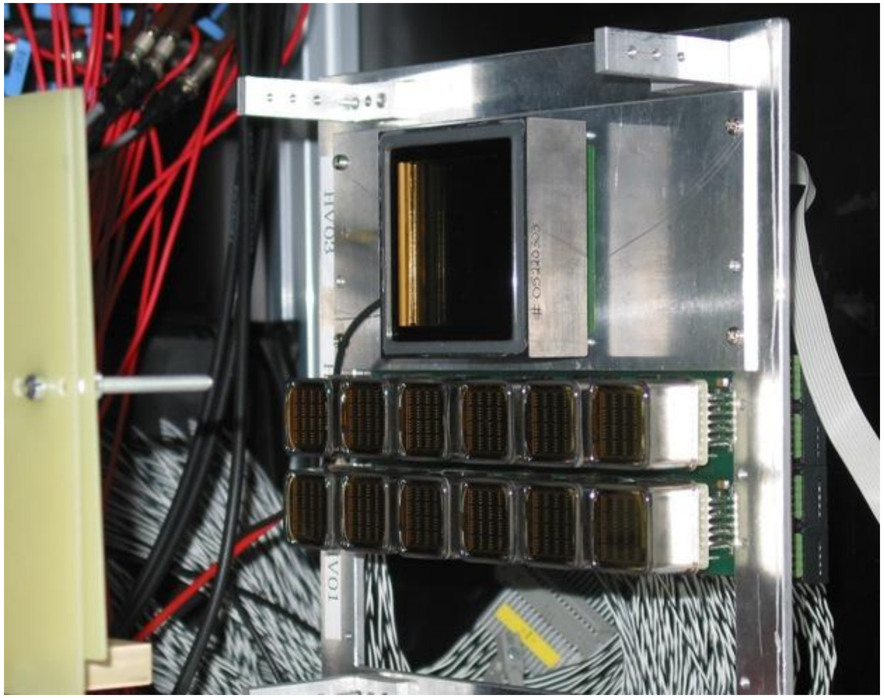
two boundary surfaces make chromatic dispersion correction angle-independent in first order

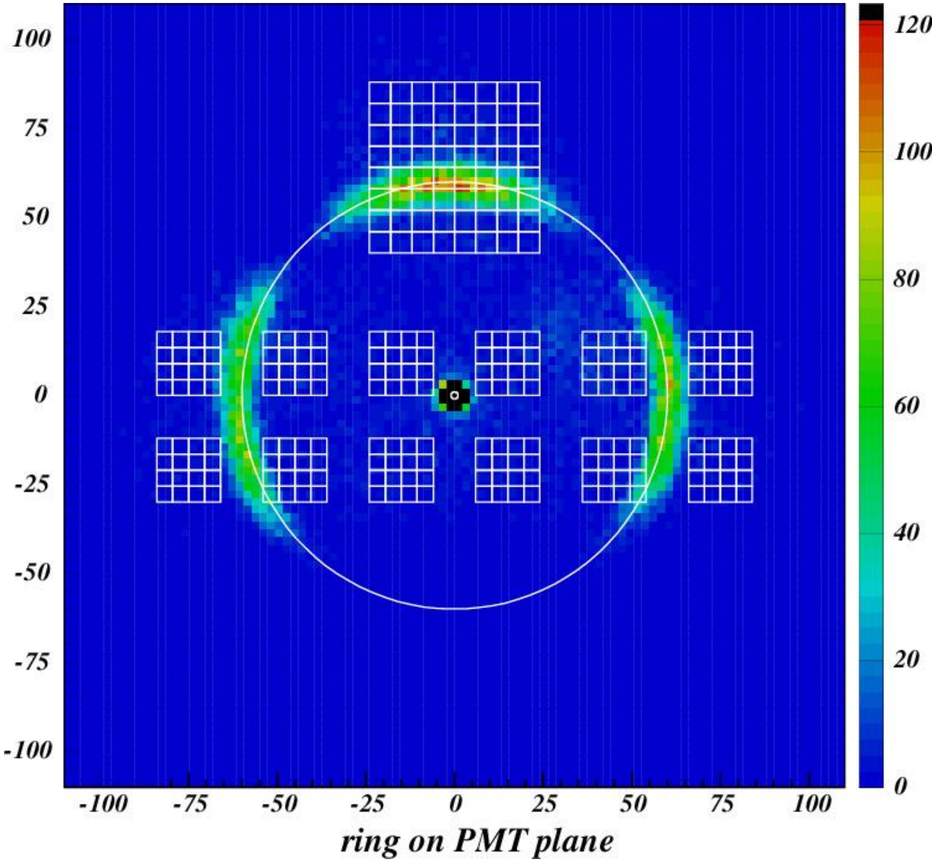
light never leaves dense optical medium
➔ good for phase space

Focal Plane
(dispersive direction)
1-dimensional readout

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)

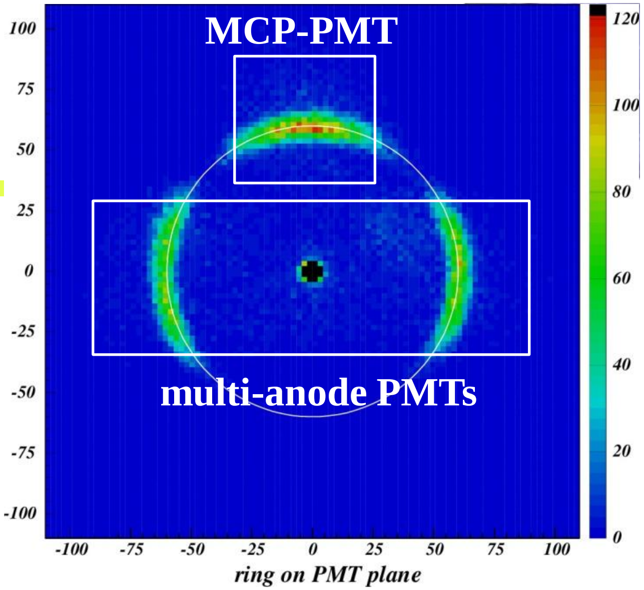




Photon detector candidate: MCP-PMT

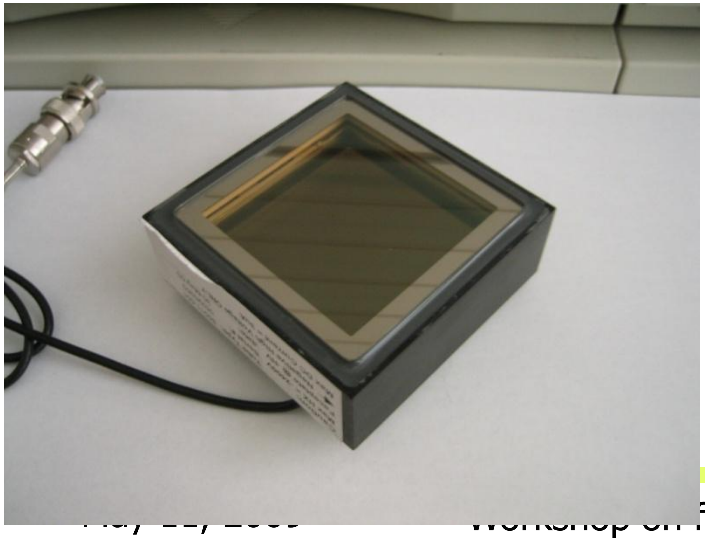
BURLE 85011 MCP-PMT:

- multi-anode PMT with two MCP steps
- 25 μm pores
- bialkali photocathode
- gain ~ 0.6 x 10^6
- collection efficiency ~ 60%
- box dimensions ~ 71mm square
- 64(8x8) anode pads
- pitch ~ 6.45mm, gap ~ 0.5mm
- active area fraction ~ 52%



- Tested in combination with multi-anode PMTs

- σ_ϑ~13 mrad (single cluster)
- number of clusters per track N ~ 4.5
- σ_ϑ~ 6 mrad (per track)
- **-> ~ 4 σ π/K separation at 4 GeV/c**

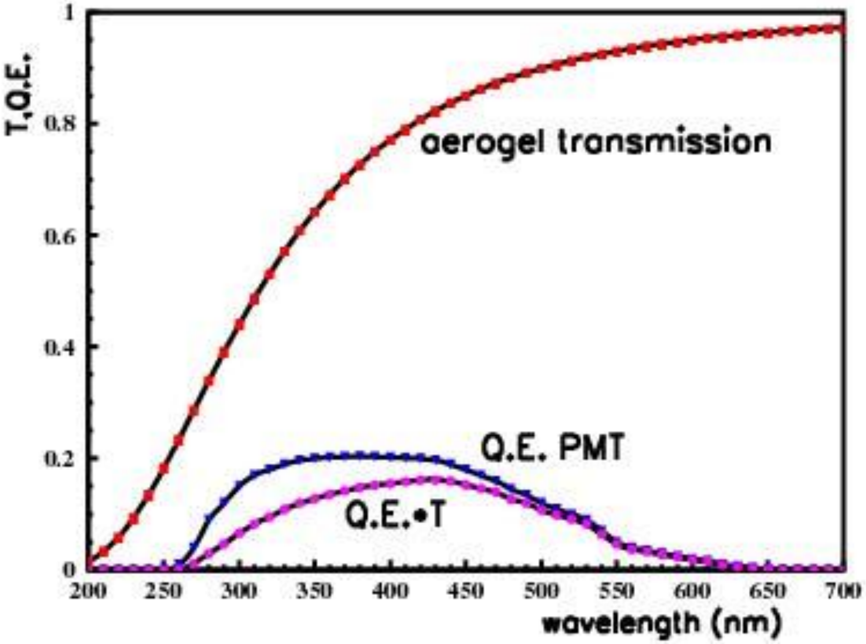


- 10 μm pores required for 1.5T
- collection eff. and active area fraction should be improved
- aging study should be carried out

Photon detectors for the aerogel RICH

Needs:

- Operation in high magnetic field (1.5T)
- High efficiency at λ>350nm
- Pad size ~5-6mm



Candidates:

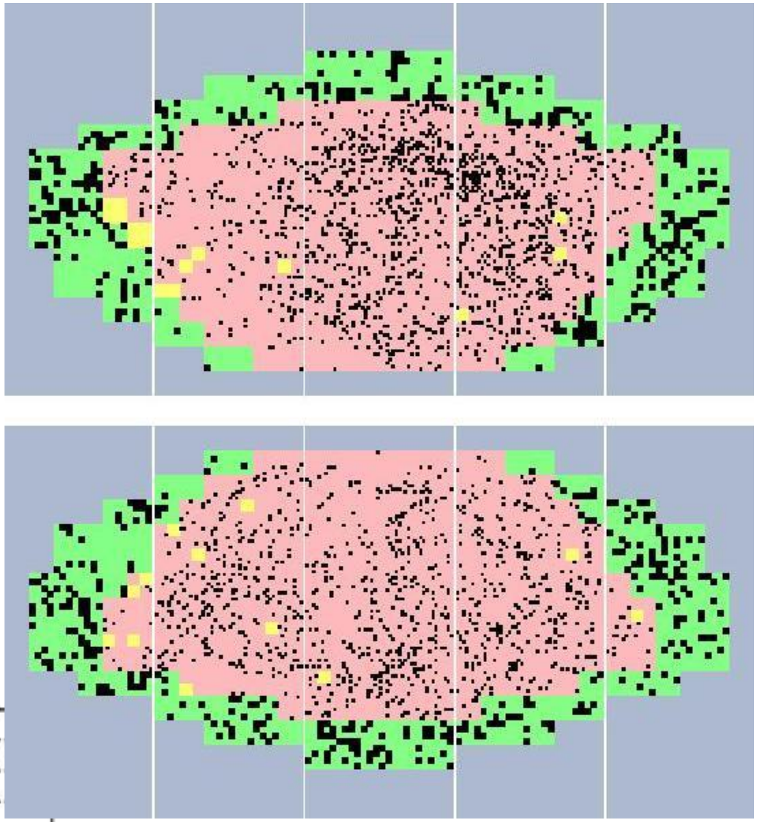
- large area HPD of the proximity focusing type
- MCP PMT (Burle 85011)

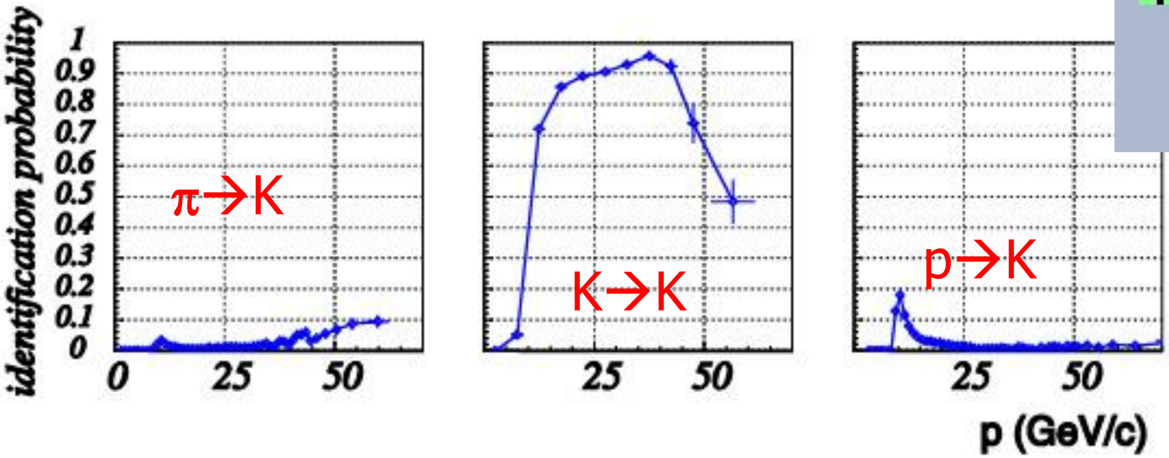
Can such a detector work?

Experience from HERA-B RICH: successfully operated in a high occupancy environment (up to 10%).

Need >20 photons per ring (had ~30) for a reliable PID.

HERA-B RICH event

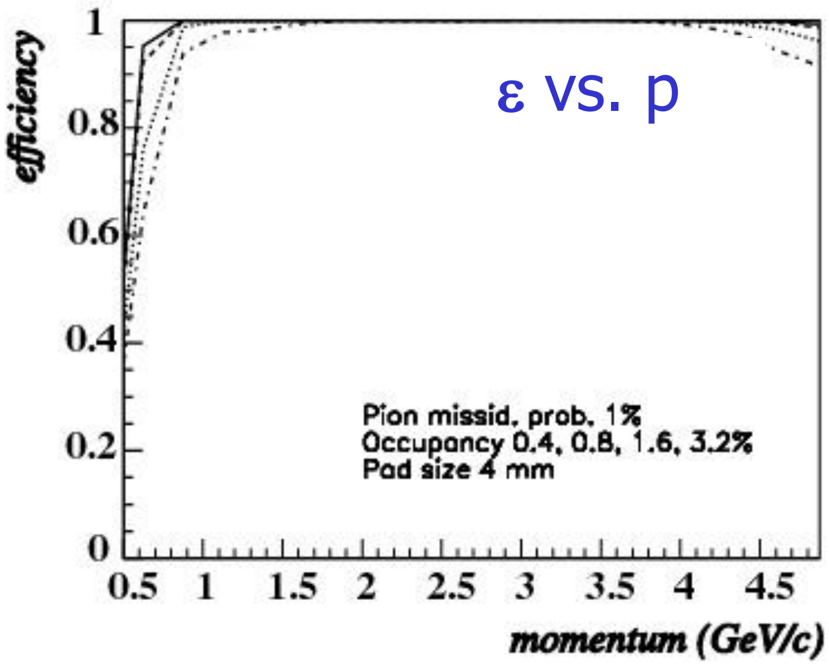


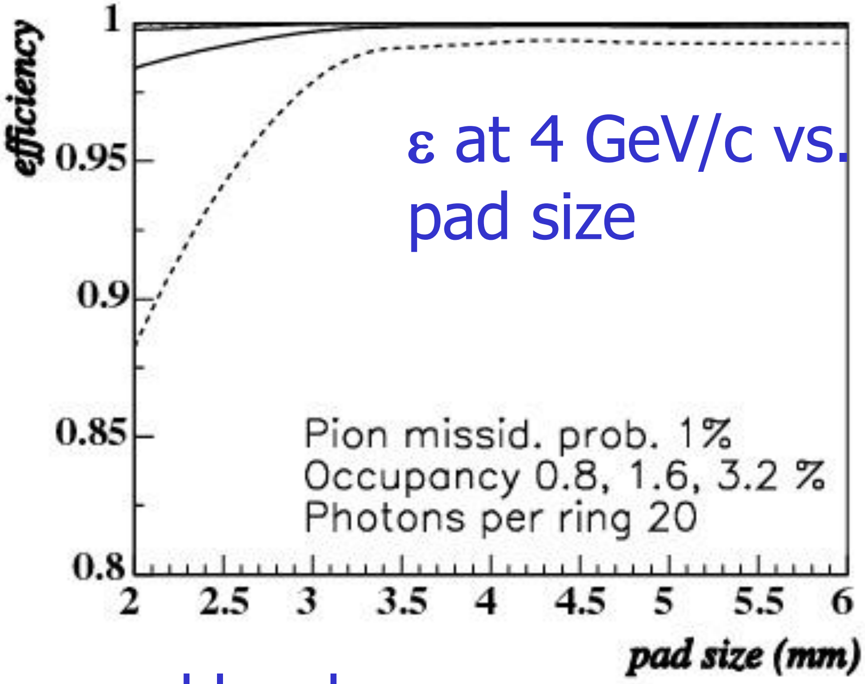


Can such a detector work?

MC simulation of the counter response: assume 1mm^2 active area SiPMs with 0.8 MHz (1.6 MHz, 3.2 MHz) dark count rate, 10ns time window

K identification efficiency at 1% π missid. probability



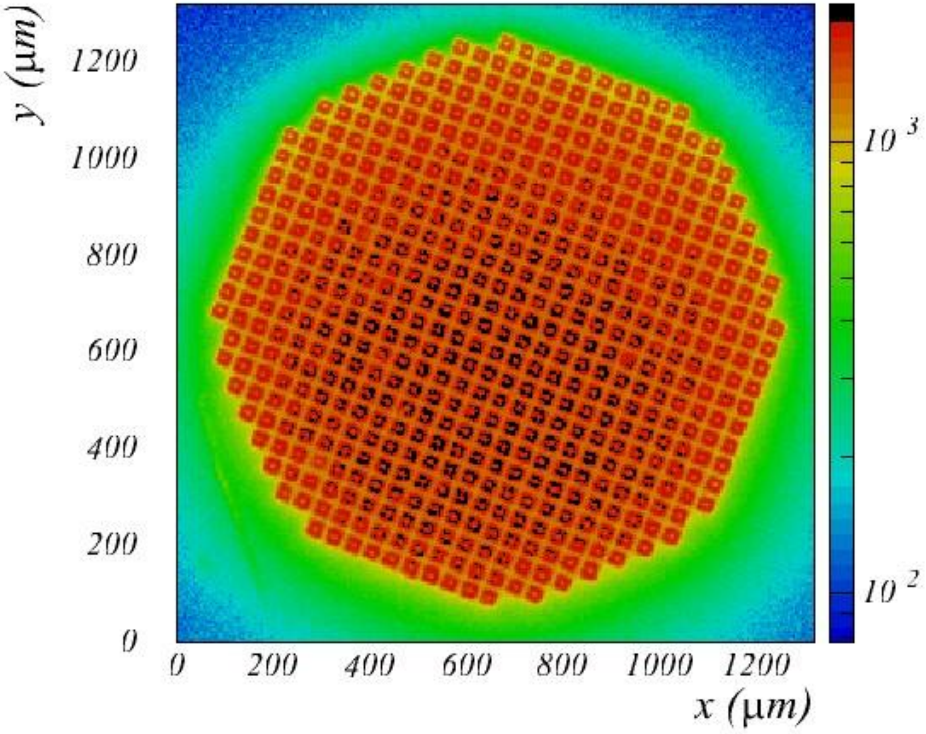


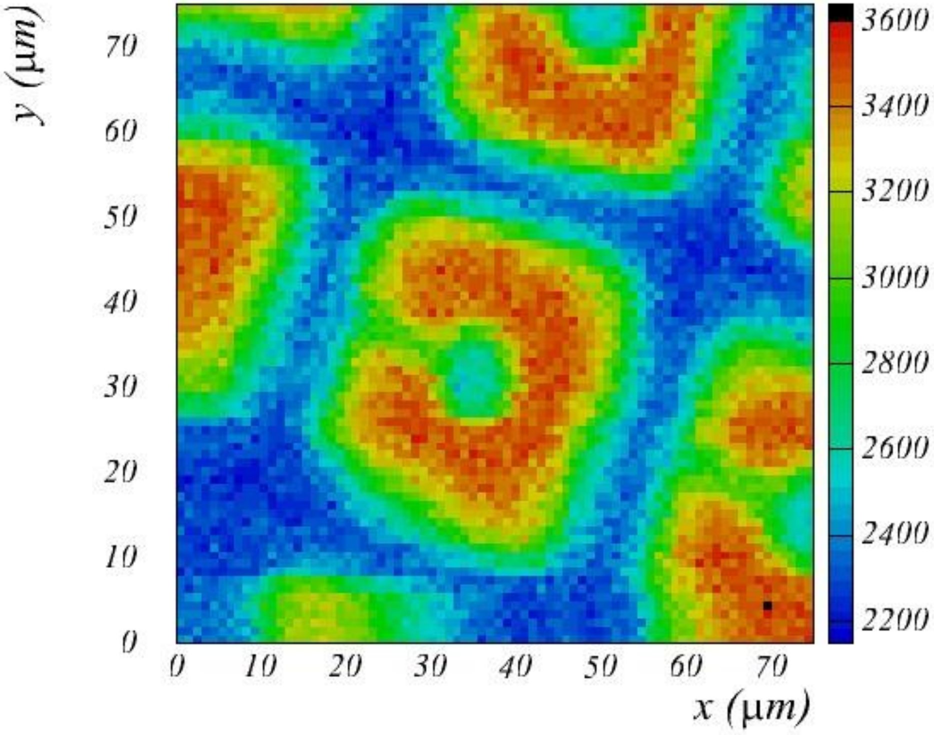
For different background levels

Surface sensitivity for single photons

- 2d scan in the focal plane of the laser beam ($\sigma \approx 5$ μm)
- intensity: on average << 1 photon
- Selection: single pixel pulse height, in TDC 10 ns window

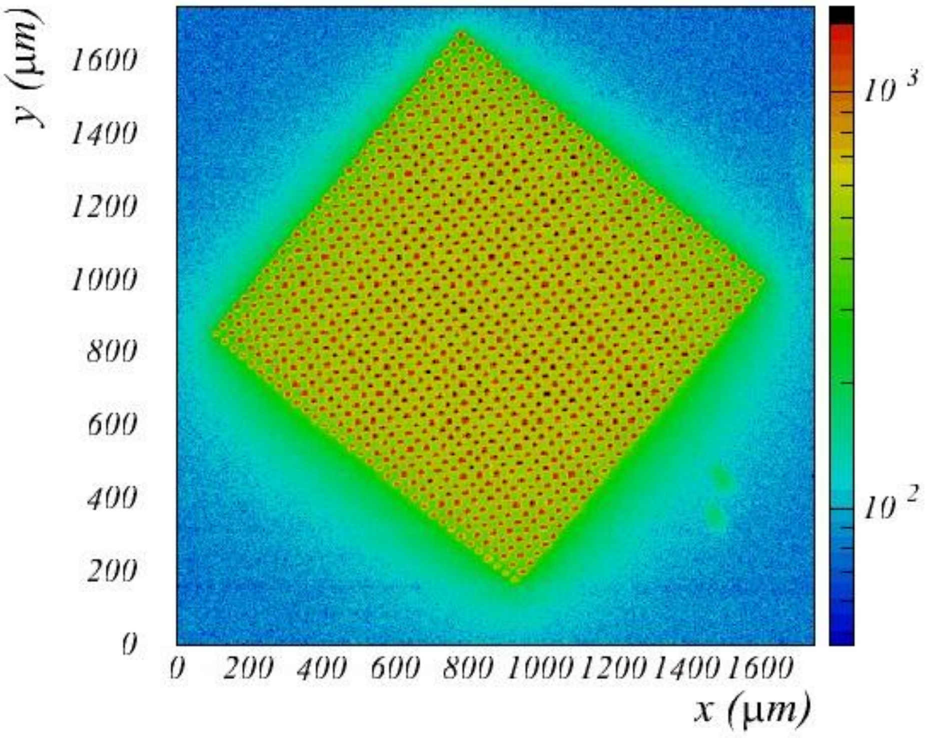
5 μm step size **S137** **Close up: 1 μm step size**

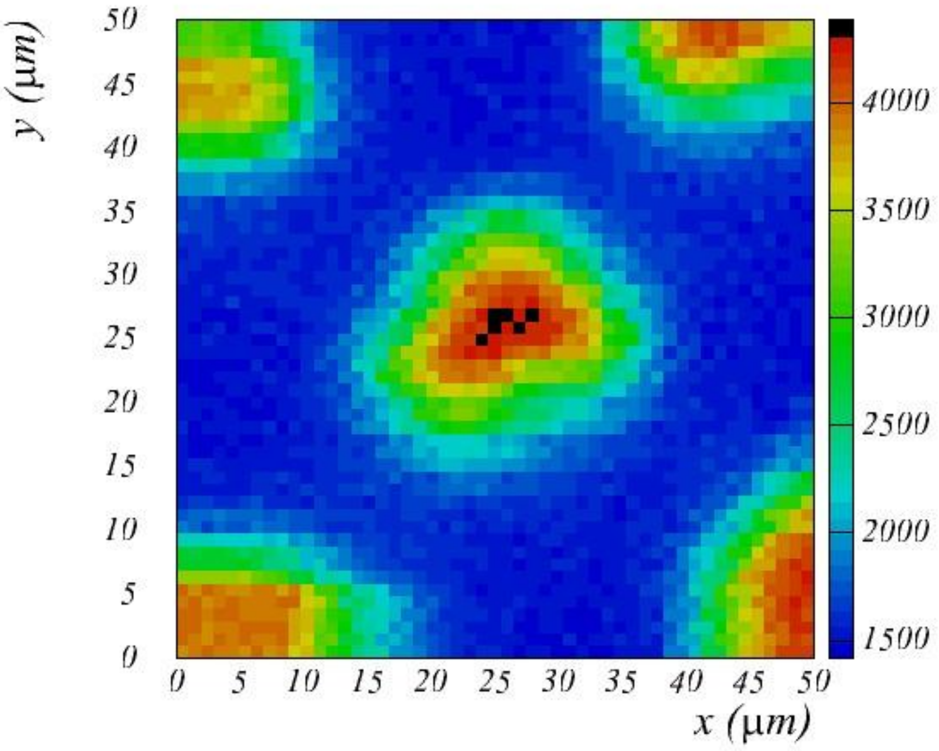




Surface sensitivity for single photons 2

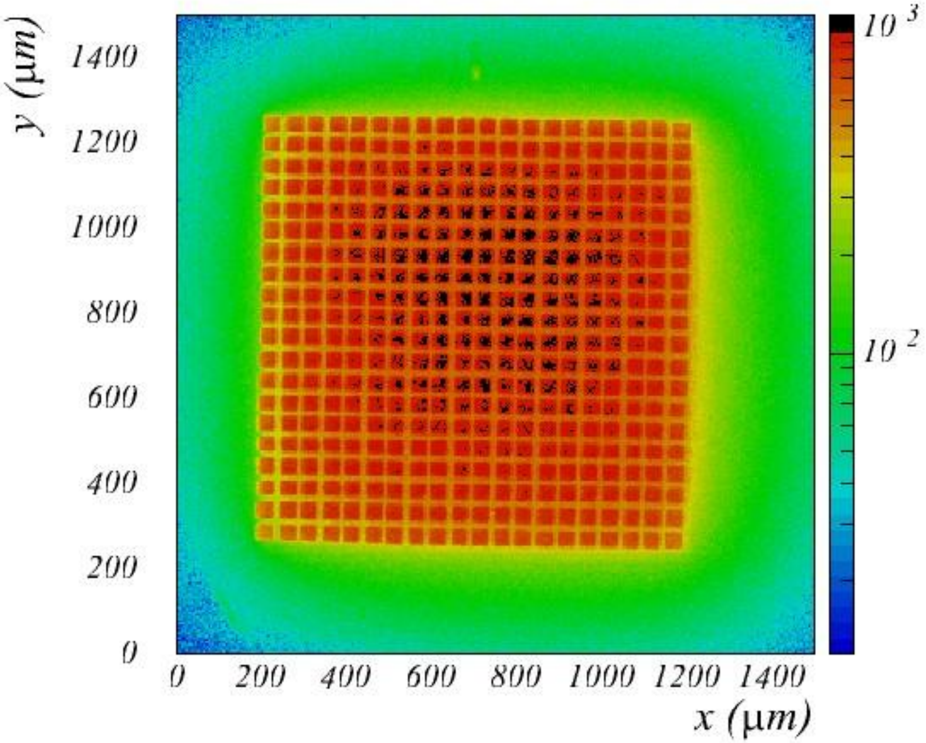
E407



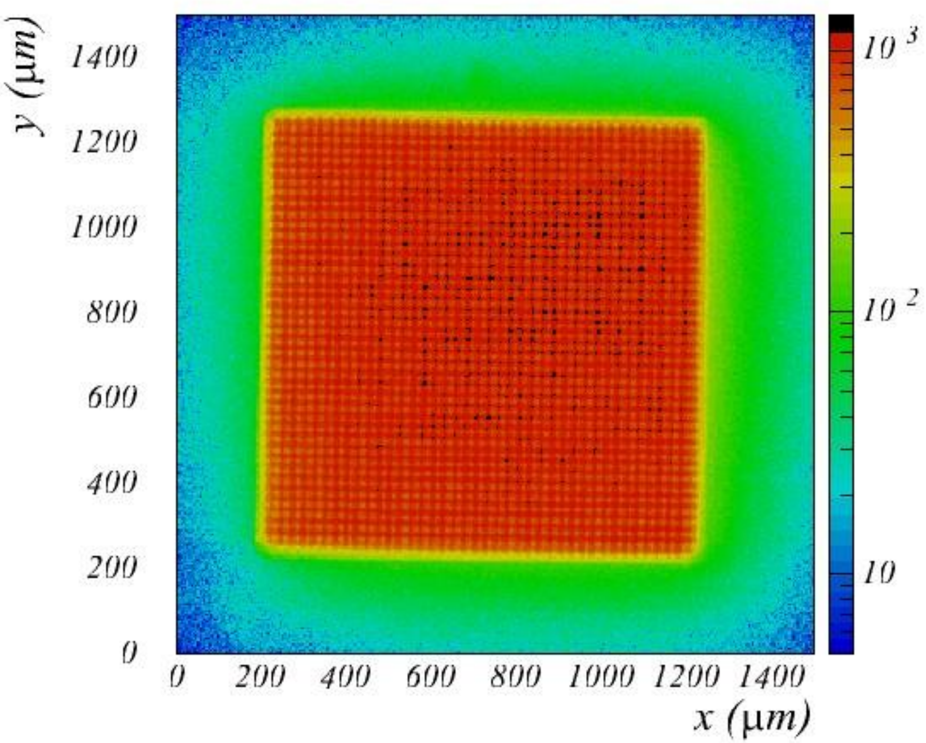


Surface sensitivity for single photons 3

H050C

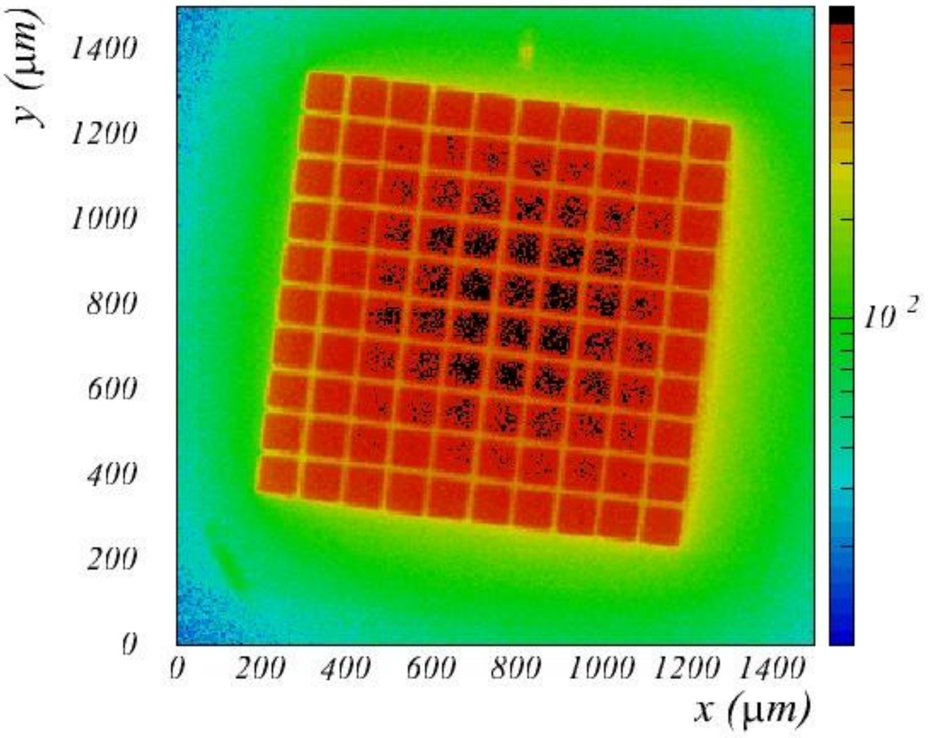


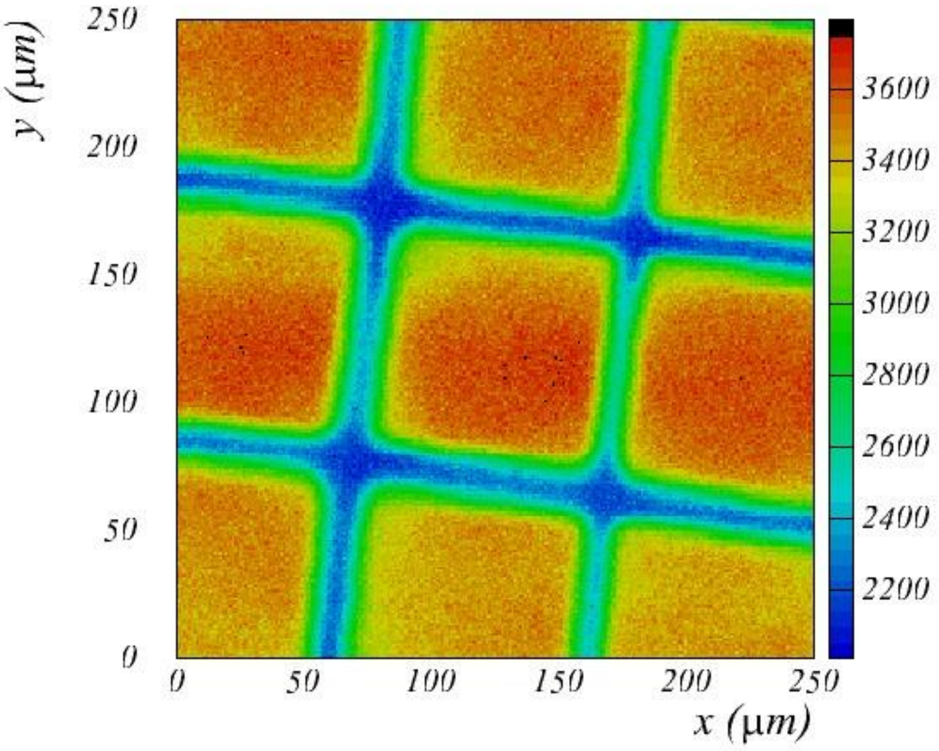
H025C



Surface sensitivity for single photons 4

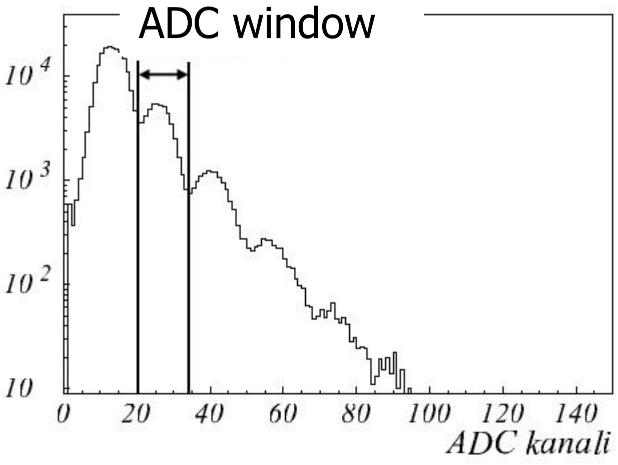
H100C



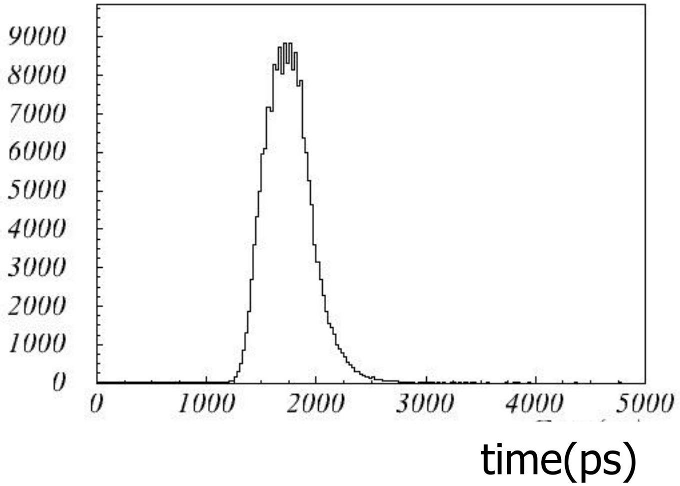


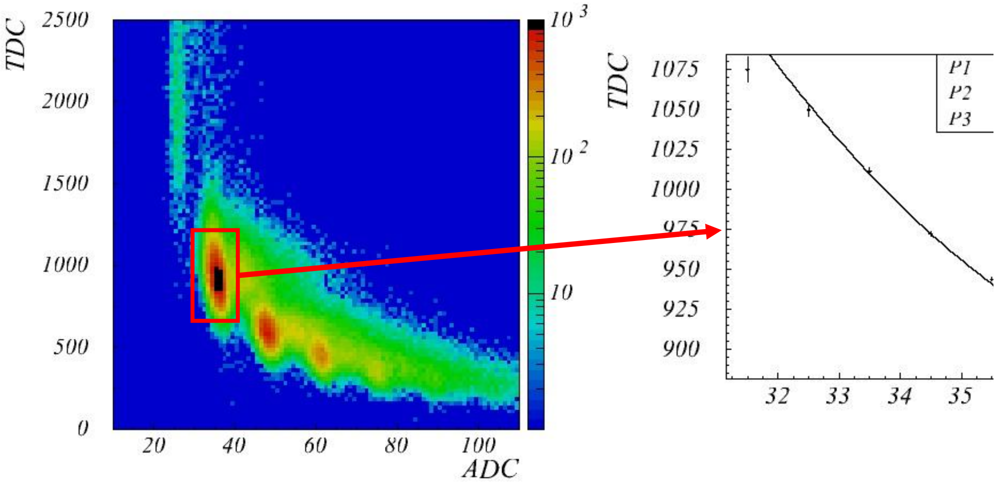
Time resolution: time walk correction

<< 1 photon

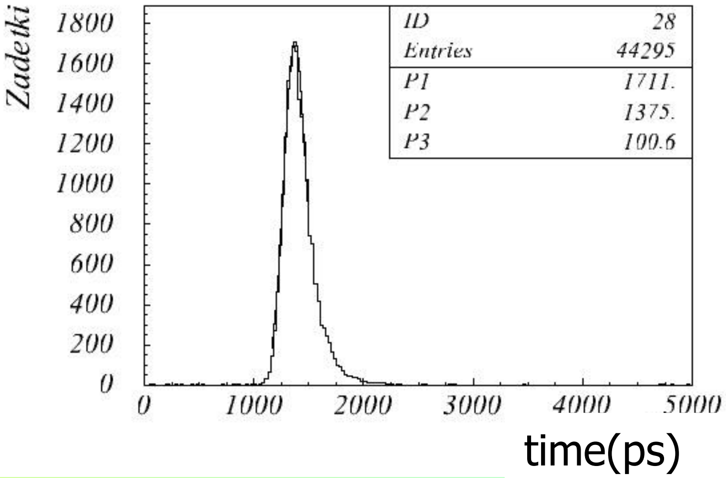


uncorrected TDC

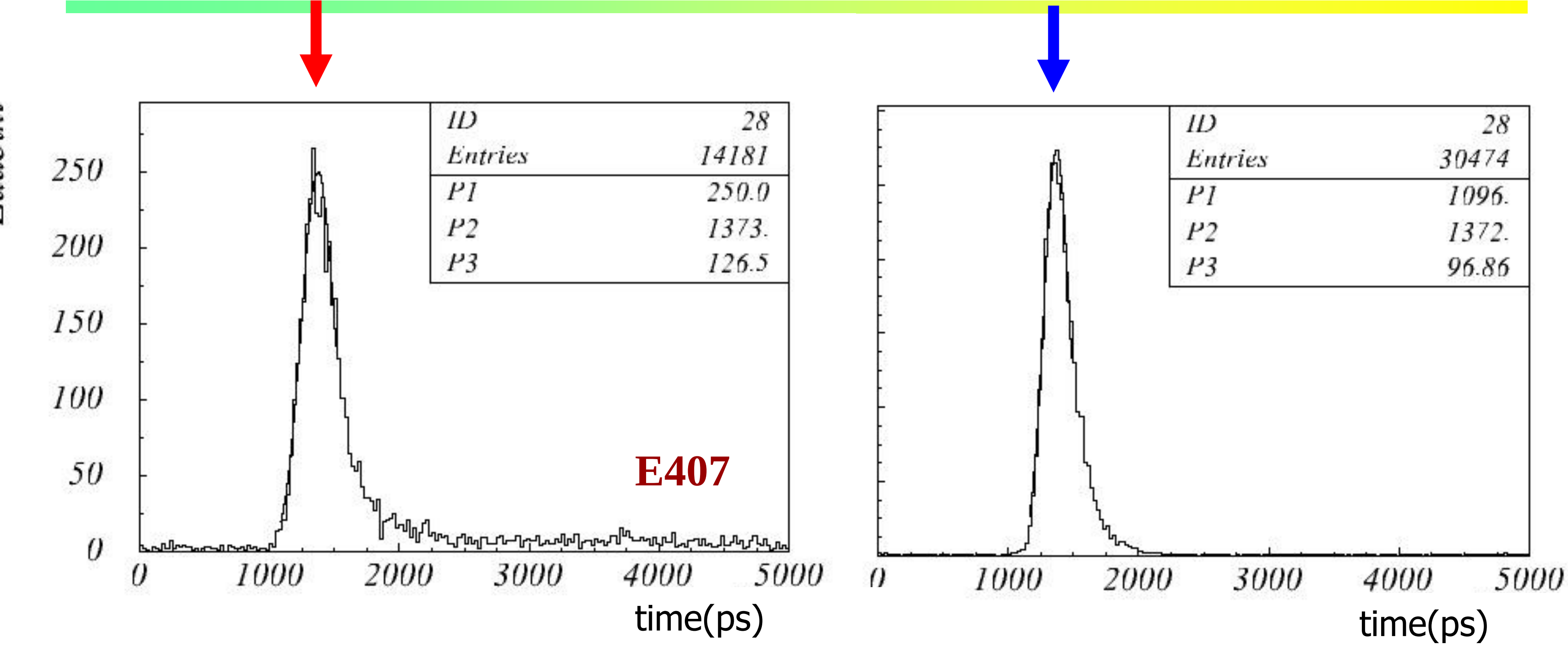




corrected TDC



Time resolution: blue vs red

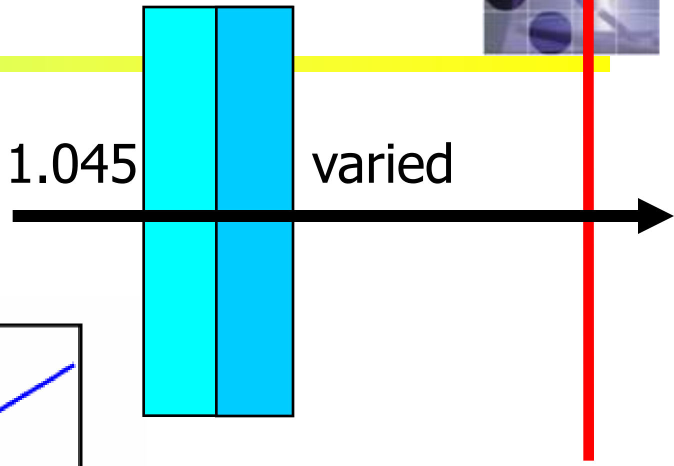


	E407	S137	H100C	H050C	H025C
σ_{red} (ps)	**127**	**182**	**145**	**212**	**154**
σ_{blue} (ps)	**97**	**151**	**136**	**358**	**135**

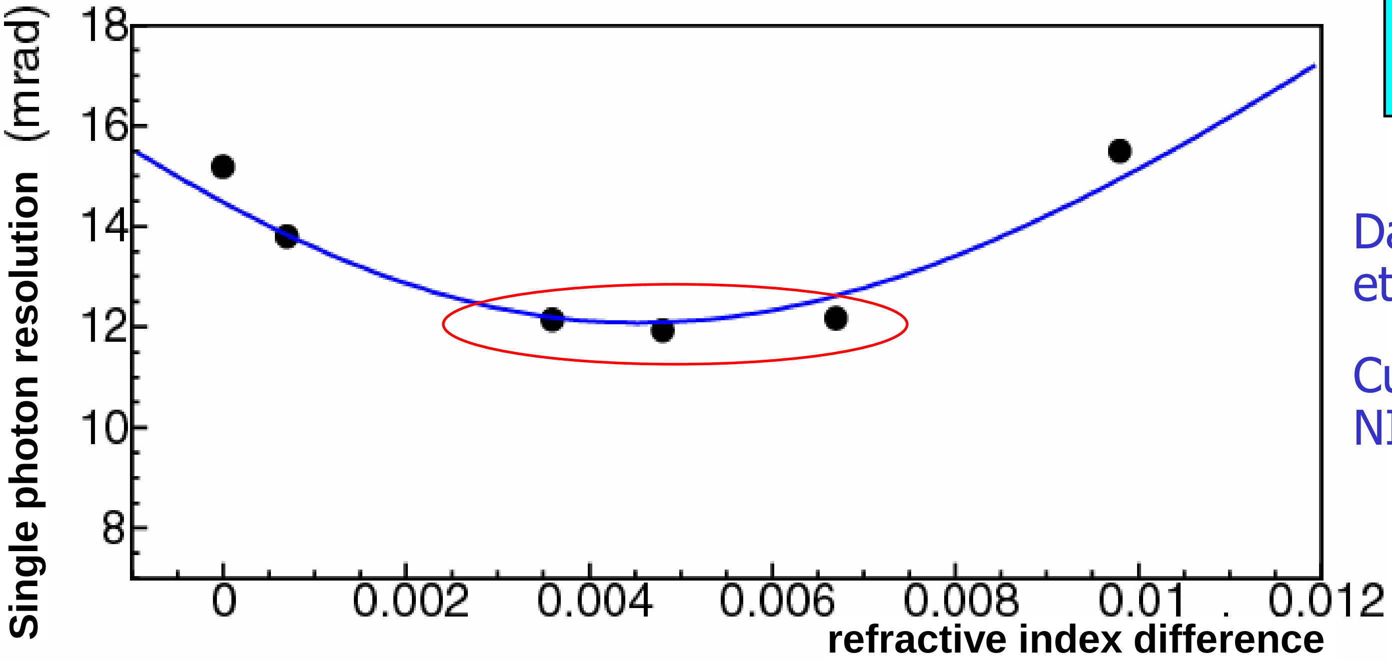
- $\sigma \approx 100$ ps

- $\sigma_{red} > \sigma_{blue}$

Focusing configuration – vary n_2-n_1



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



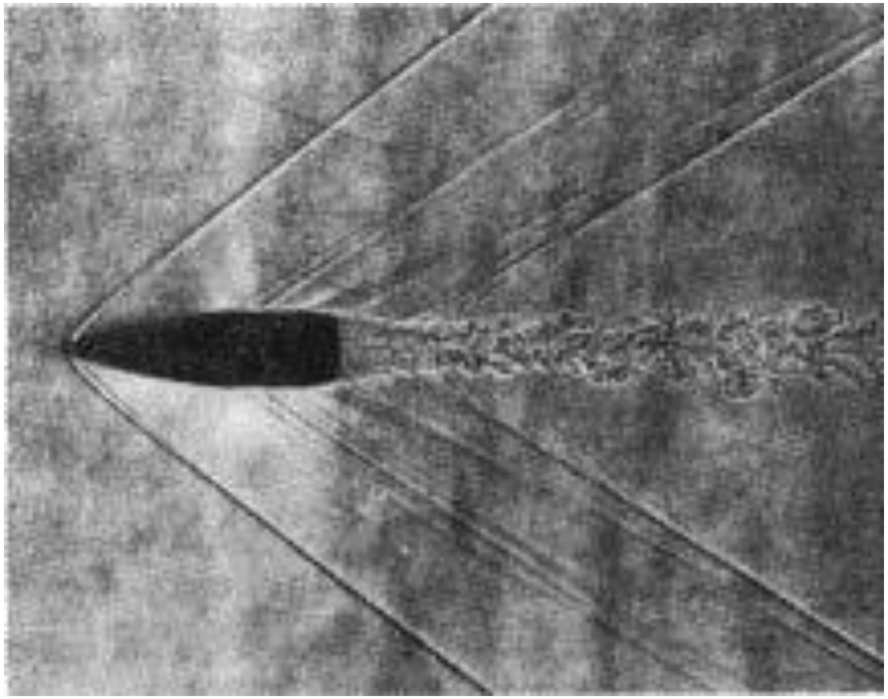
Data points: S. Korpar et al, Pisa meeting 2006.

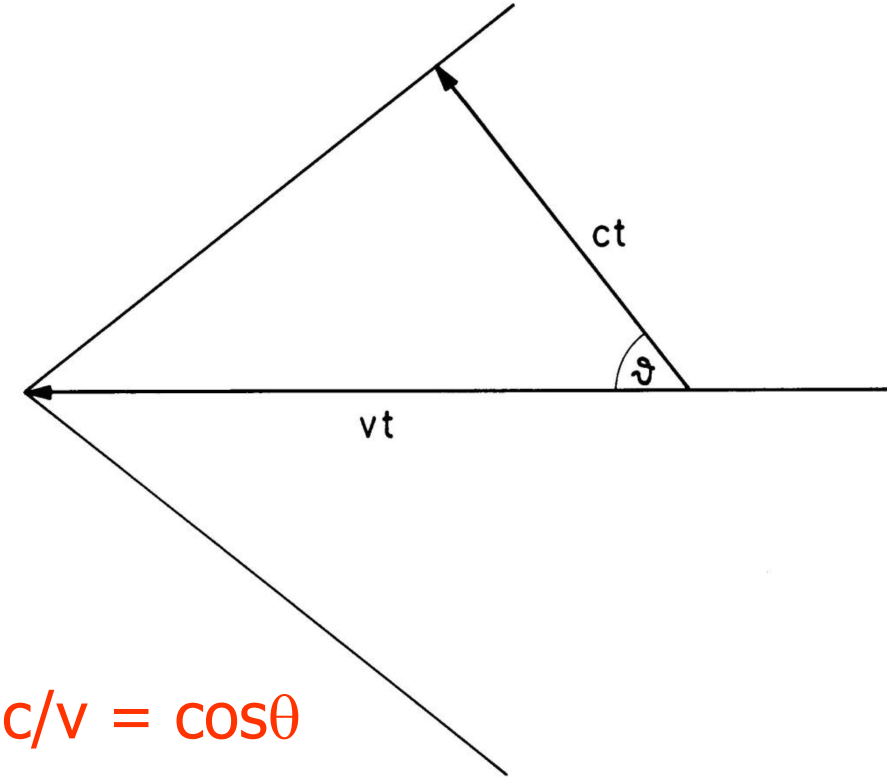
Curve: optimisation study NIM A565 (2006) 457

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

Velocity of a bullet

Determine the velocity of a bullet





$c/v = \cos\theta$

From the photograph:
angle 52°, $v = c/\cos\theta = 340\text{m/s} / \cos 52^{\circ} = 552\text{m/s}$

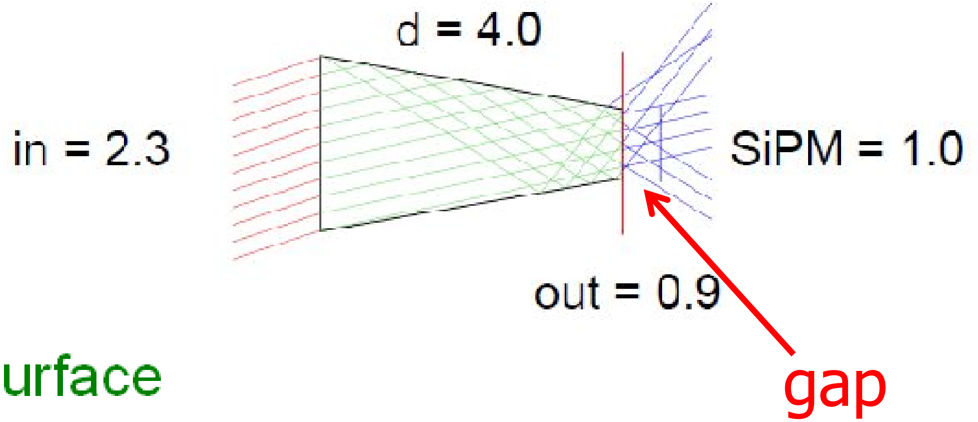
Light guide simulation

Simulation includes:

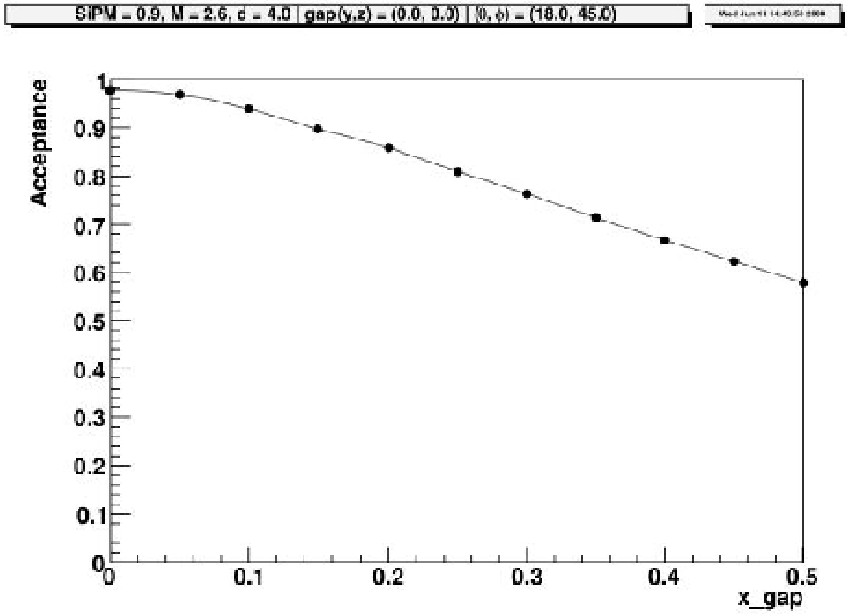
- refraction at LG entrance
- total reflection
- gap between LG exit and SiPM surface

Not included:

- absorption
- imperfect surface



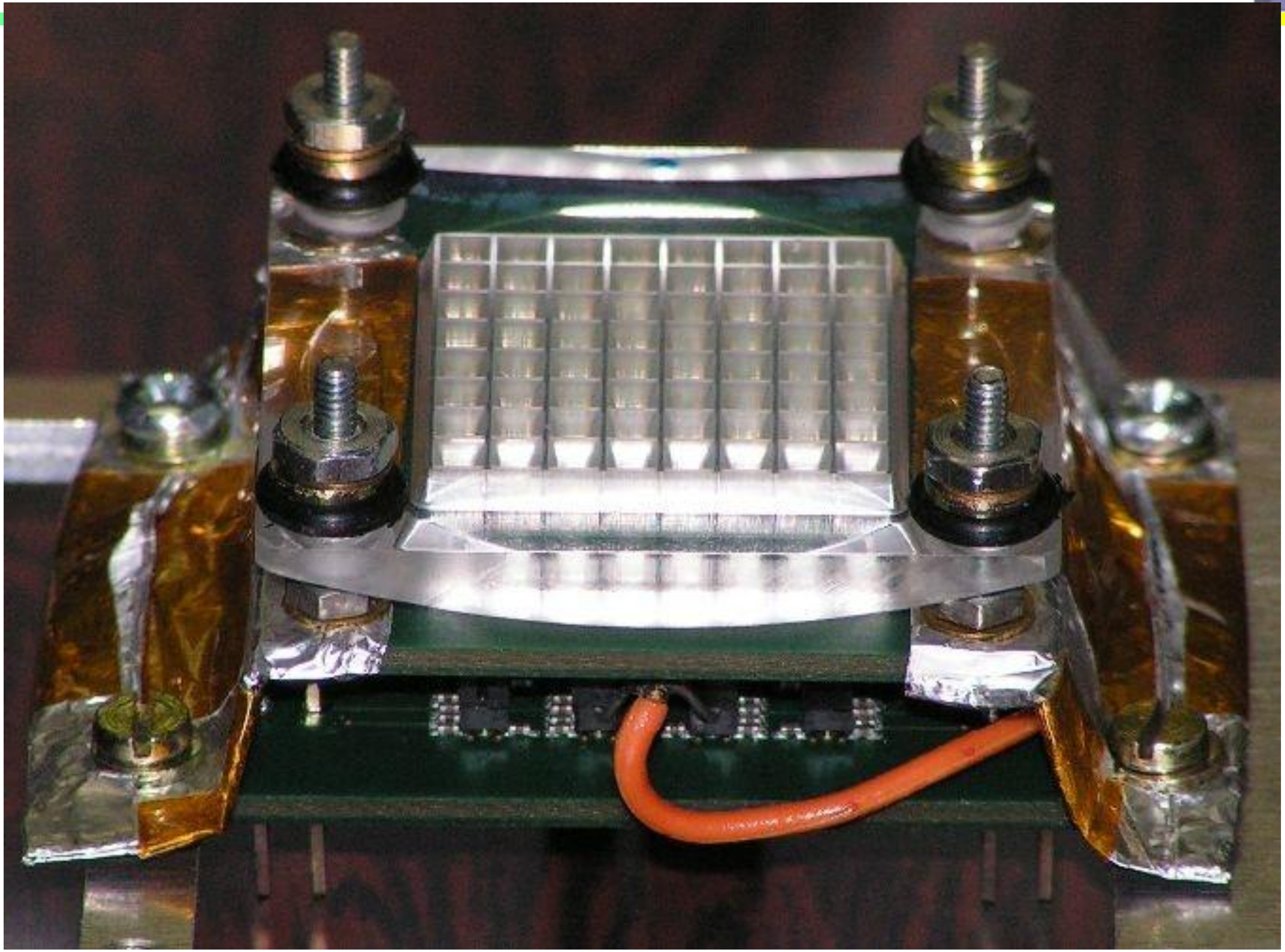
θ = 18°
φ = 45°



t=18,p=45			
gap	w	w/o	A
0.00	97.67	19.03	5.13
0.05	96.62	19.09	5.06
0.10	94.11	18.98	4.96
0.15	89.68	18.77	4.78
0.20	85.99	18.87	4.56
0.25	81.06	18.99	4.27
0.30	**76.12**	**19.1**	**3.99**
0.35	71.49	18.95	3.77
0.40	**66.85**	**19**	**3.52**
0.45	62.44	18.98	3.29
0.50	**58.39**	**19**	**3.07**

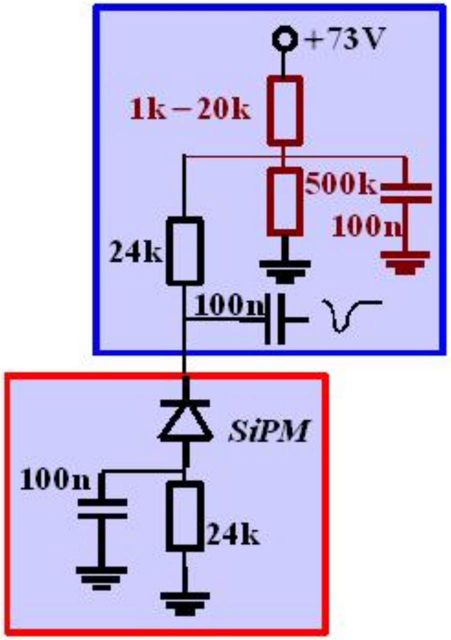
Acceptance vs gap size

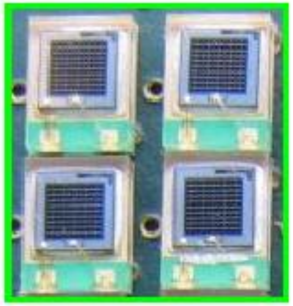
Fully assembled detector module

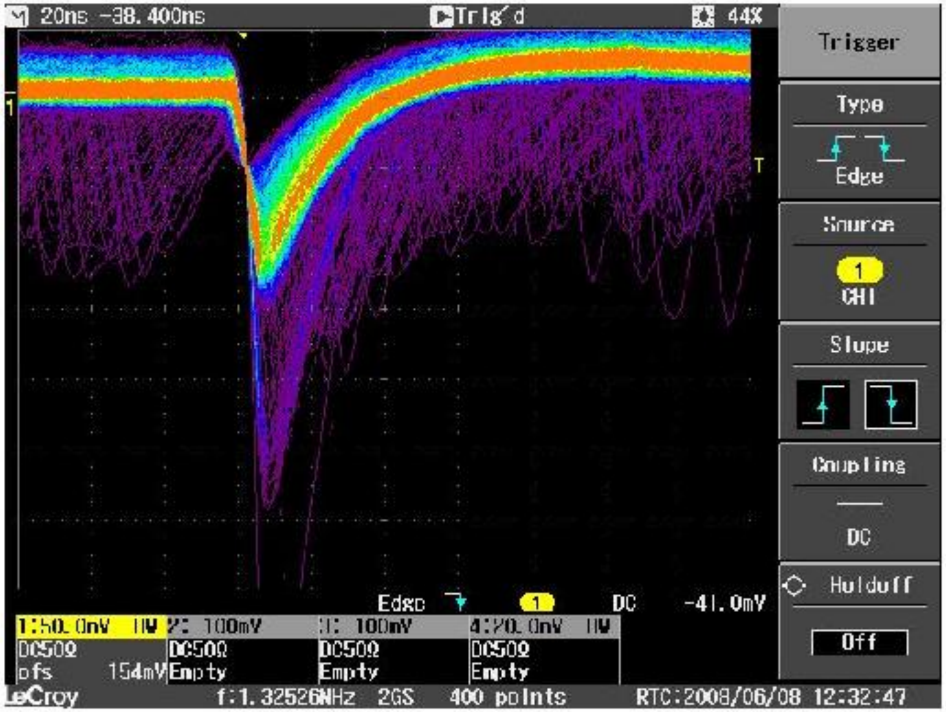


MPPC module

- main board with dividers, bias and signal connectors
- piggy back board with MPPCs (8x8 array of HC100 in SMD package; background ~ 400kHz/MPPC)
- light guides
- 16 electronics channels (4x4) - 4 MPPCs connected to single channel





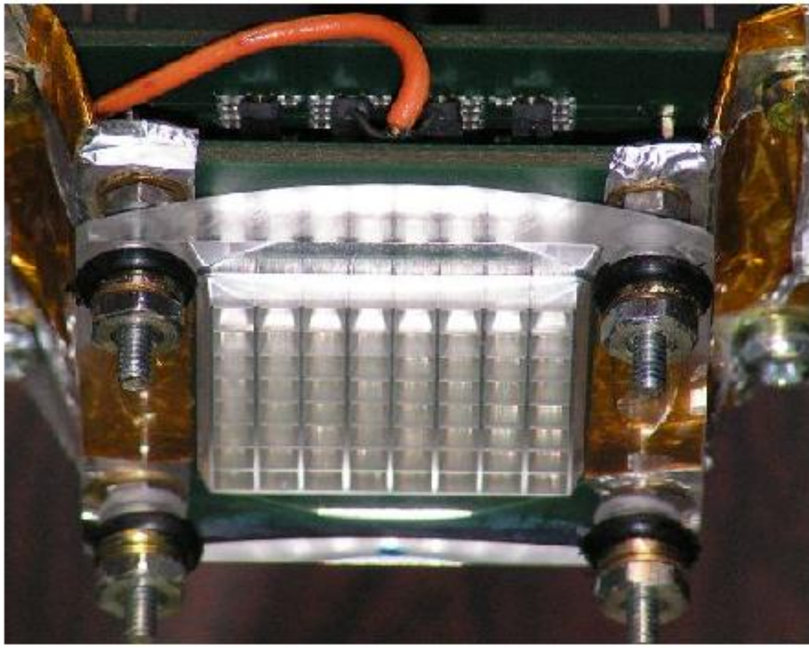


20ns -38.400ns Trig'd 44X

Edge 1 DC -41.0mV

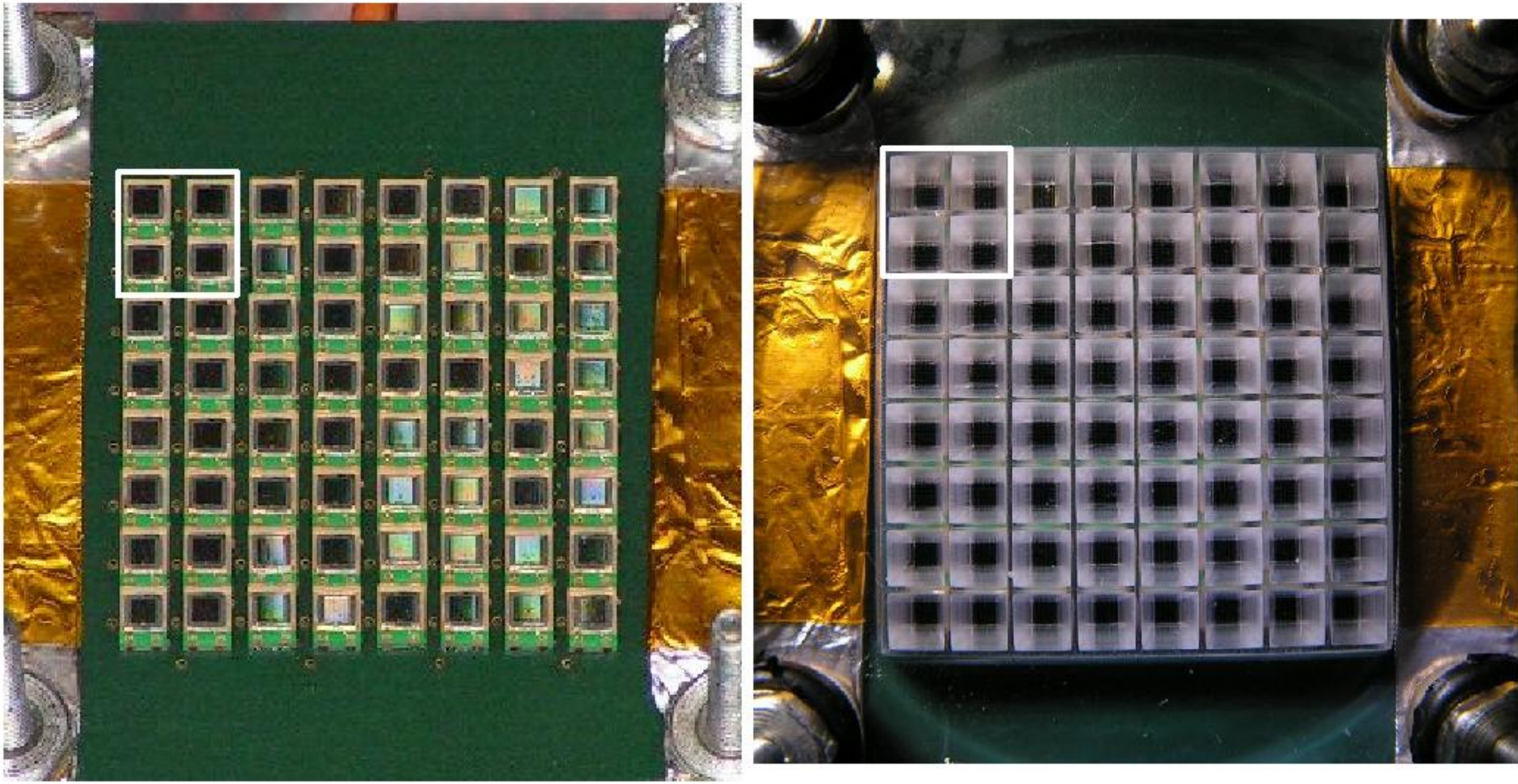
1: 50.0mV HW 2: 100mV 3: 100mV 4: 20.0mV HW
DC50Ω DC50Ω DC50Ω DC50Ω
pfs 154mV Empty Empty Empty

LeCroy f: 1.32526MHz 2GS 400 points RTC:2008/06/08 12:32:47



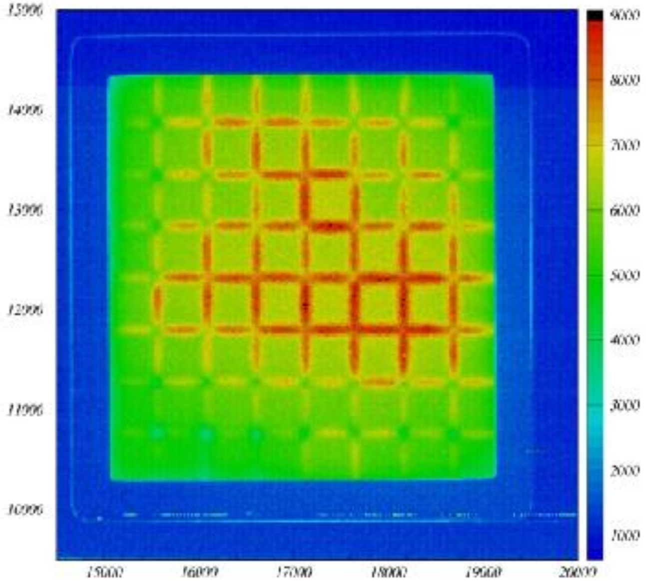
MPPC module 2

- pad size 5.08 mm, 4 mm2 active

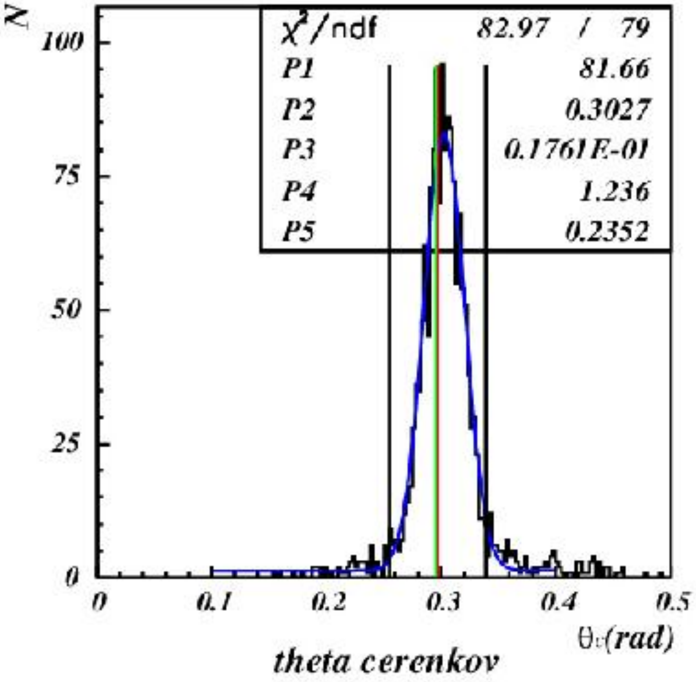


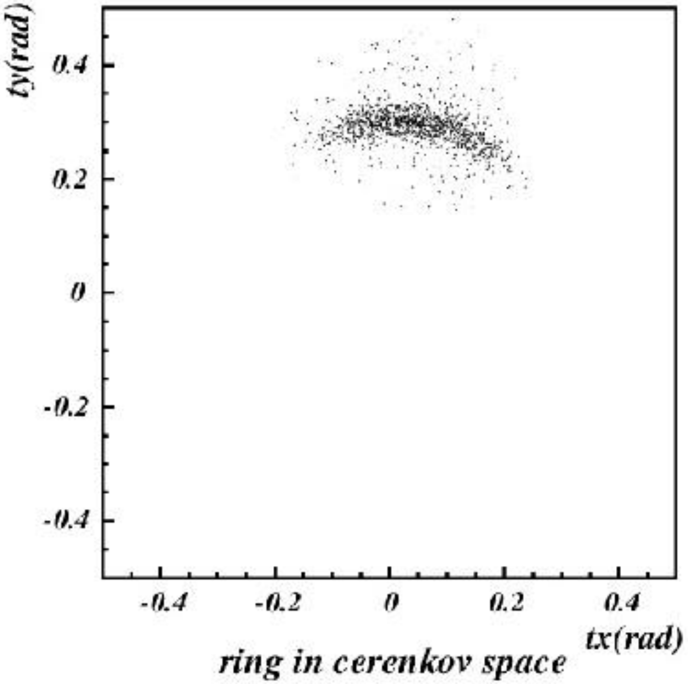
Cherenkov angle resolution

- charge sharing at the edges of the pads and backscattering affects the resolution
- in magnetic field this effects will be minimized and resolution will improve



σ_ϑ: 17.6 mrad → <15 mrad





Tests in magnetic field: charge sharing 2

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

- HV = 2400 V
- B = 0 T

- HV = 2500 V
- B = 1.5 T