Novel sensors for Cherenkov counters

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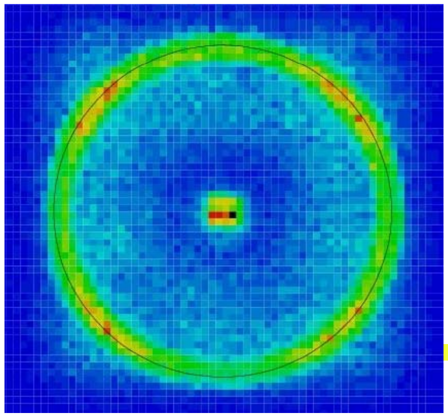


Advanced Instrumentation Seminar,
SLAC, June 10, 2009

Contents

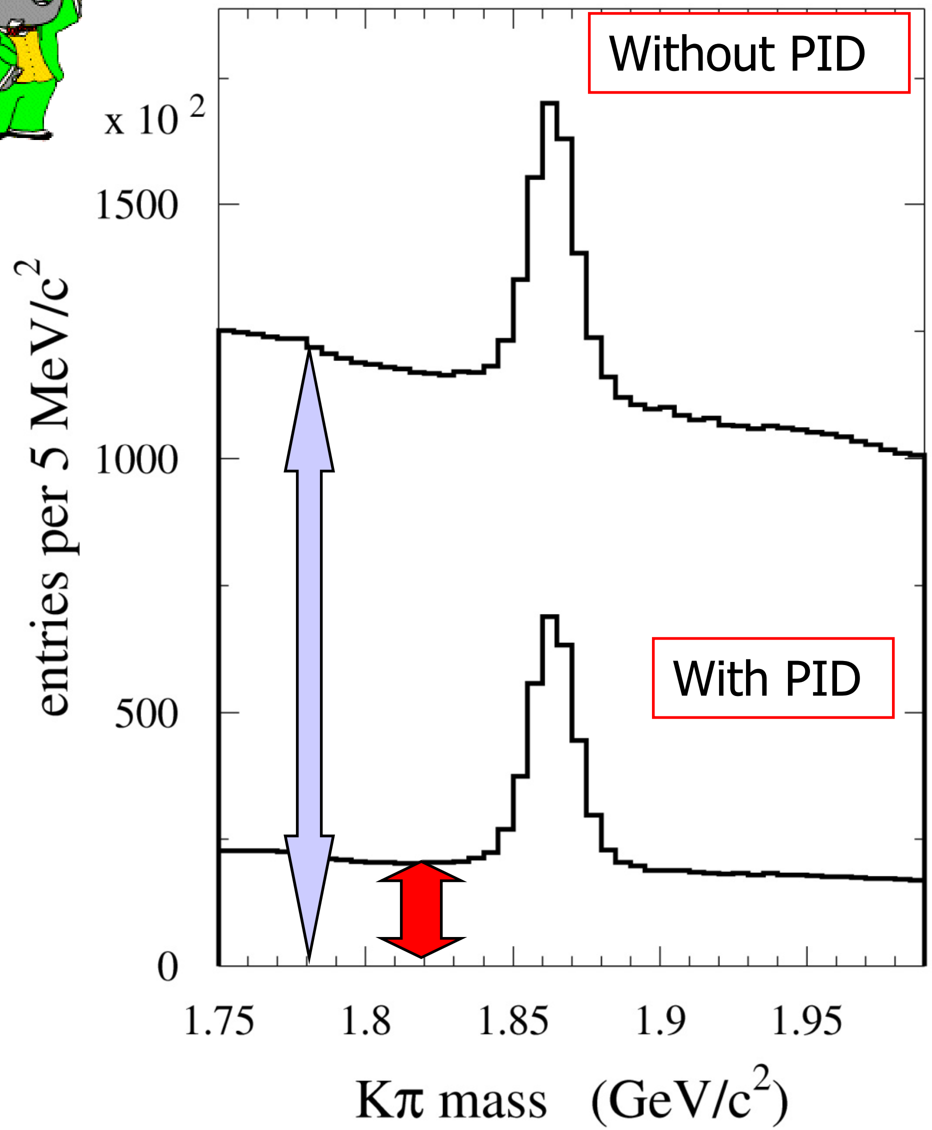
Why particle identification?

Ring Imaging CHerenkov counters

Novel photon sensors: HAPD, MCP PMT, G-APD

Summary and outlook

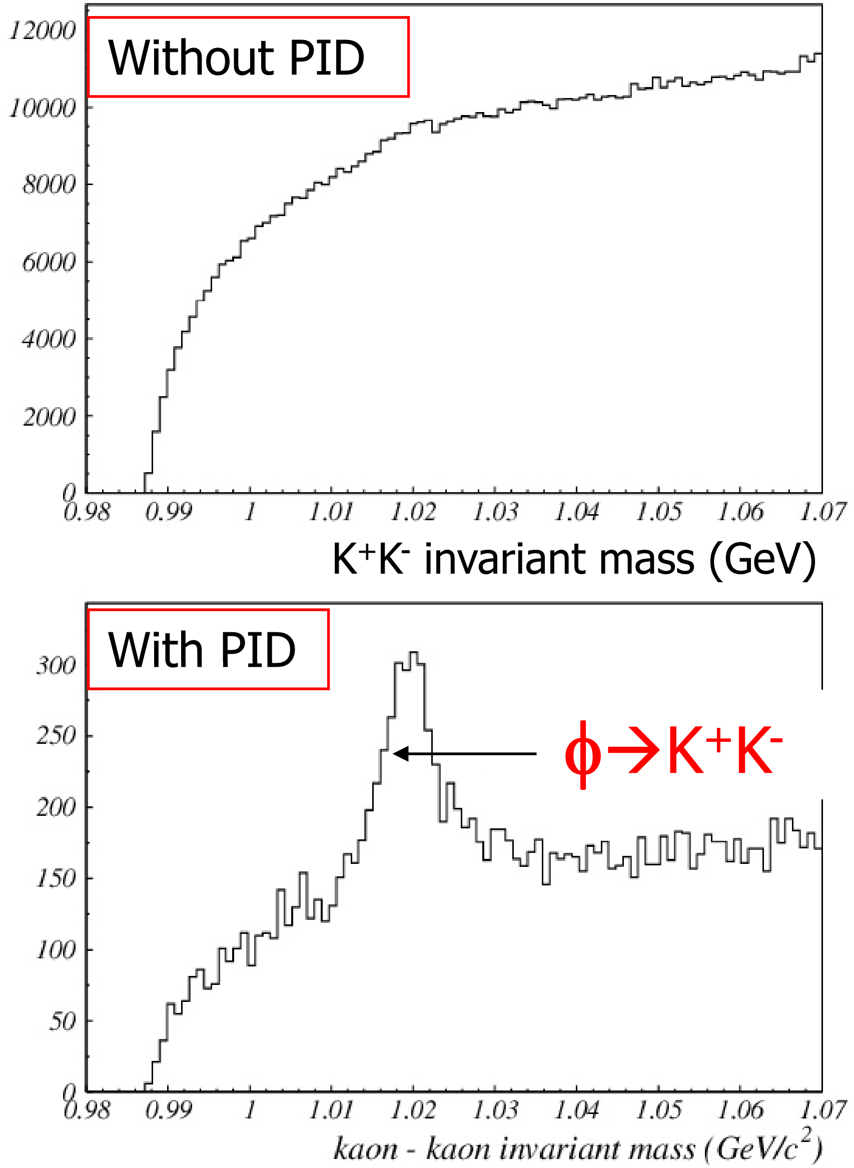
Why particle ID?



Example 1: B factory

Particle identification reduces the fraction of wrong $K\pi$ combinations (combinatorial background) by ~6x

Why particle ID?

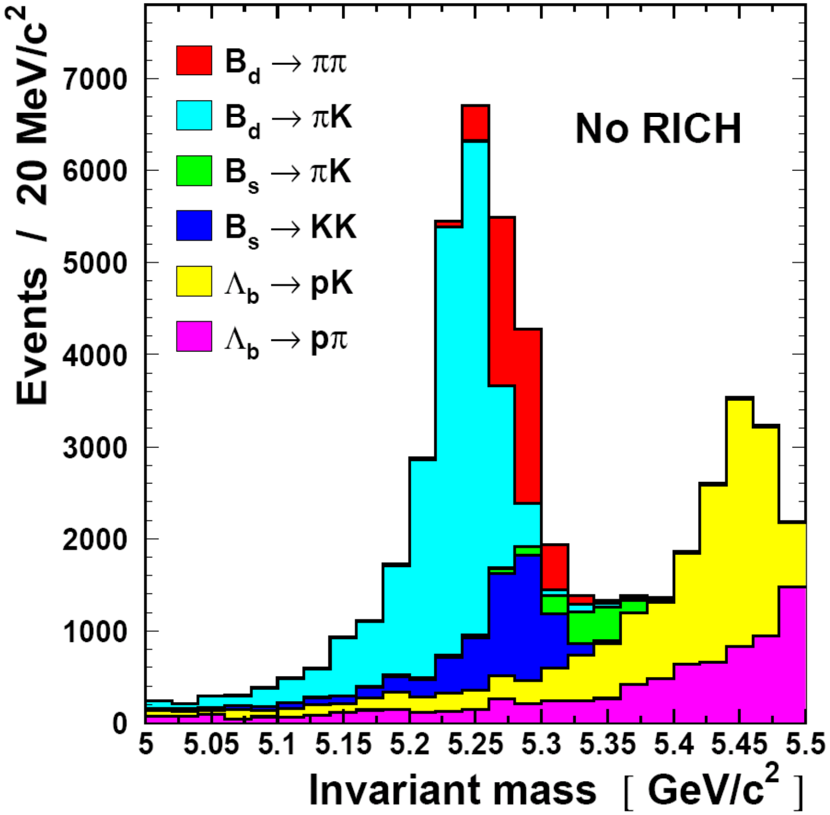


Example 2: HERA-B

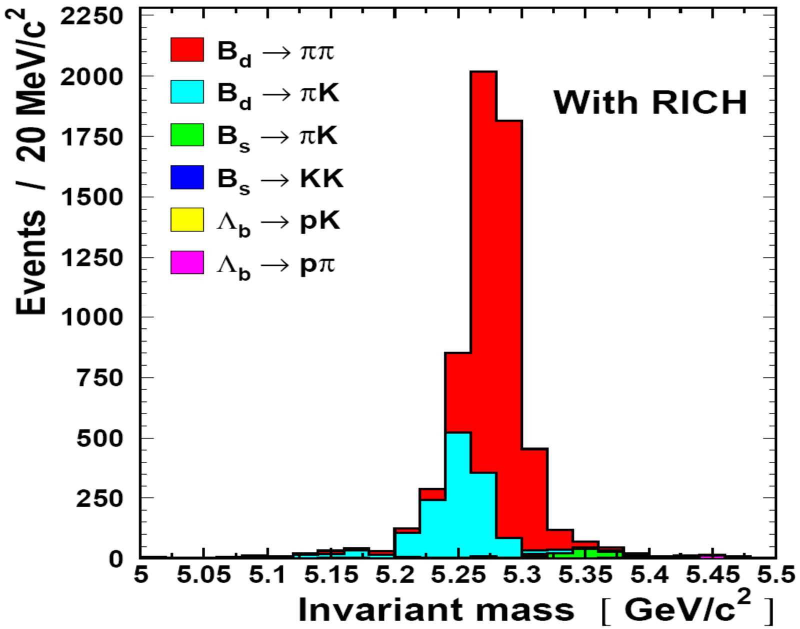
K^+K^- invariant mass.

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

Why particle ID?



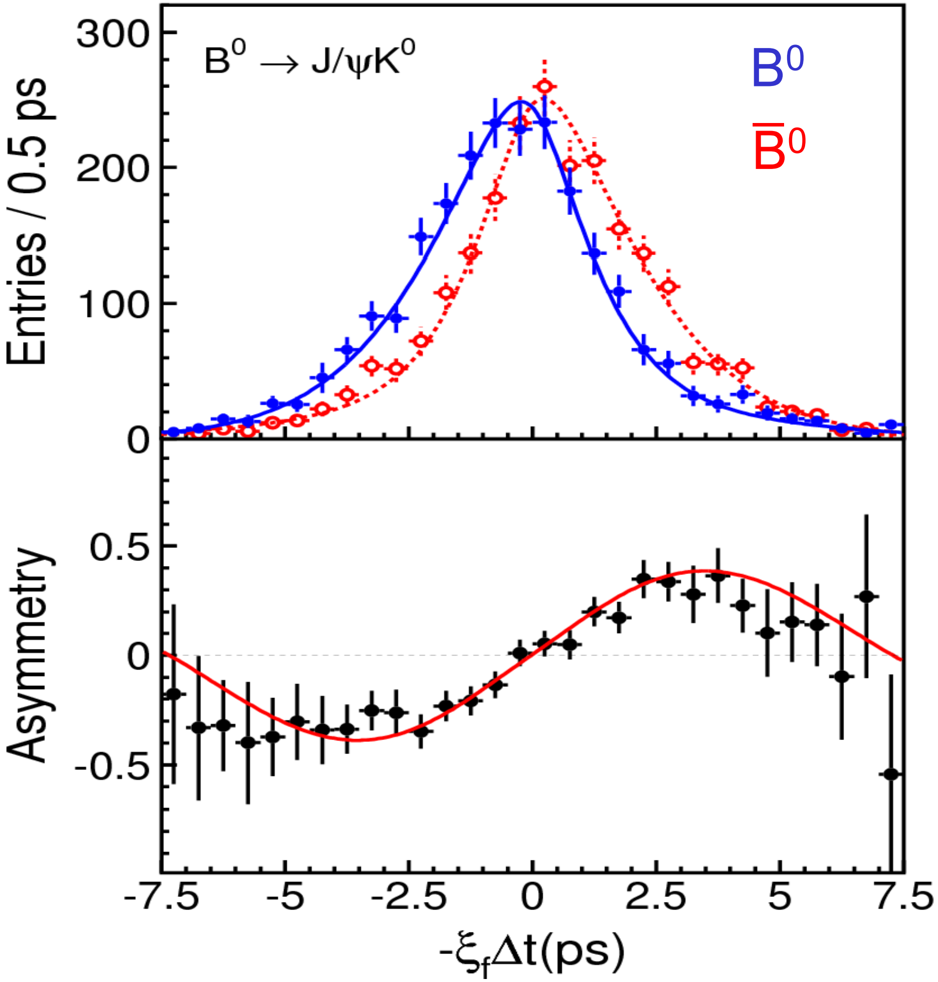
Example 3: LHCb
(MC prediction)



Need to distinguish $B_d \to \pi\pi$ from other similar topology 2-body decays

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

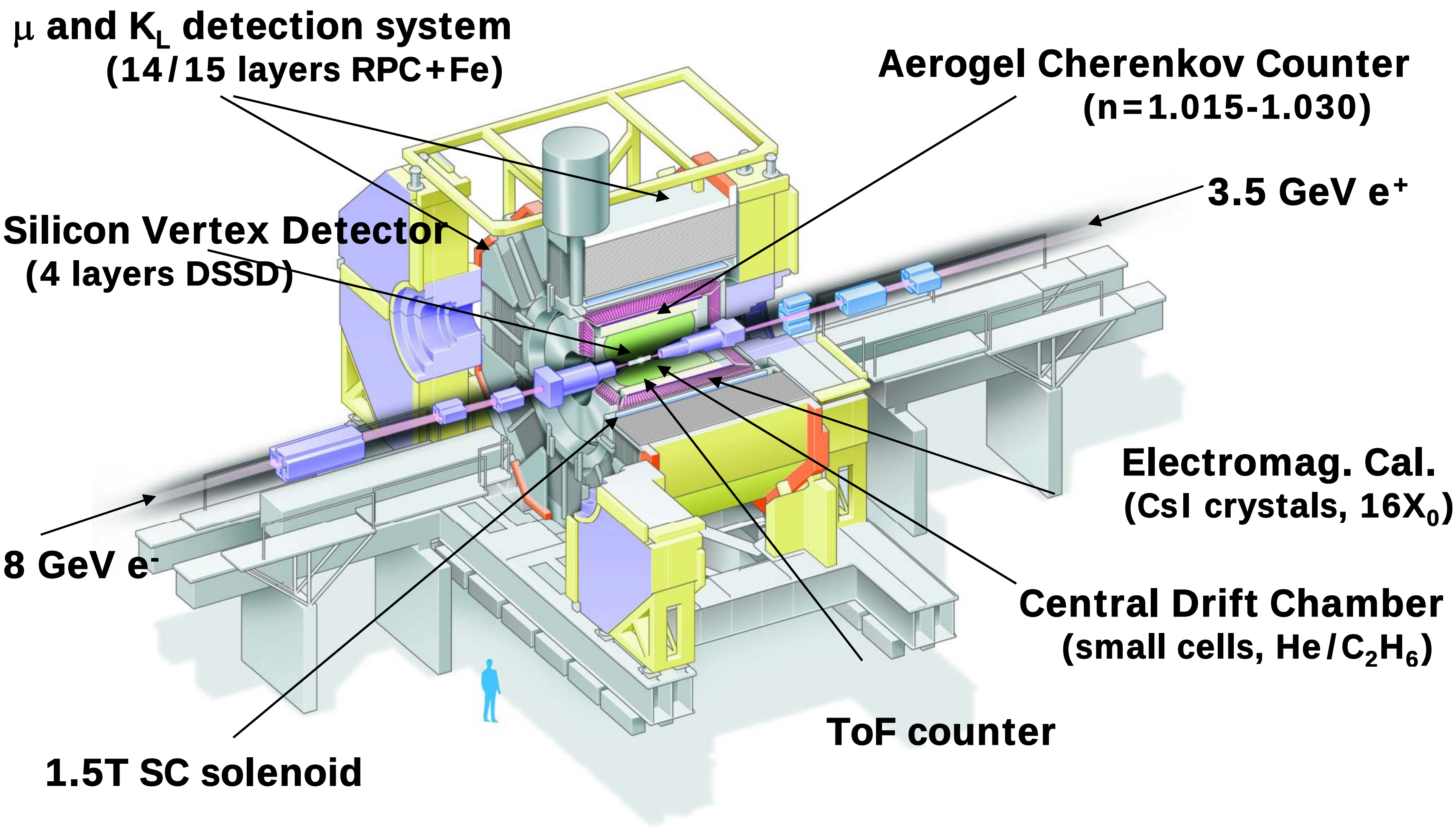
→particle ID is compulsory

Why particle ID?

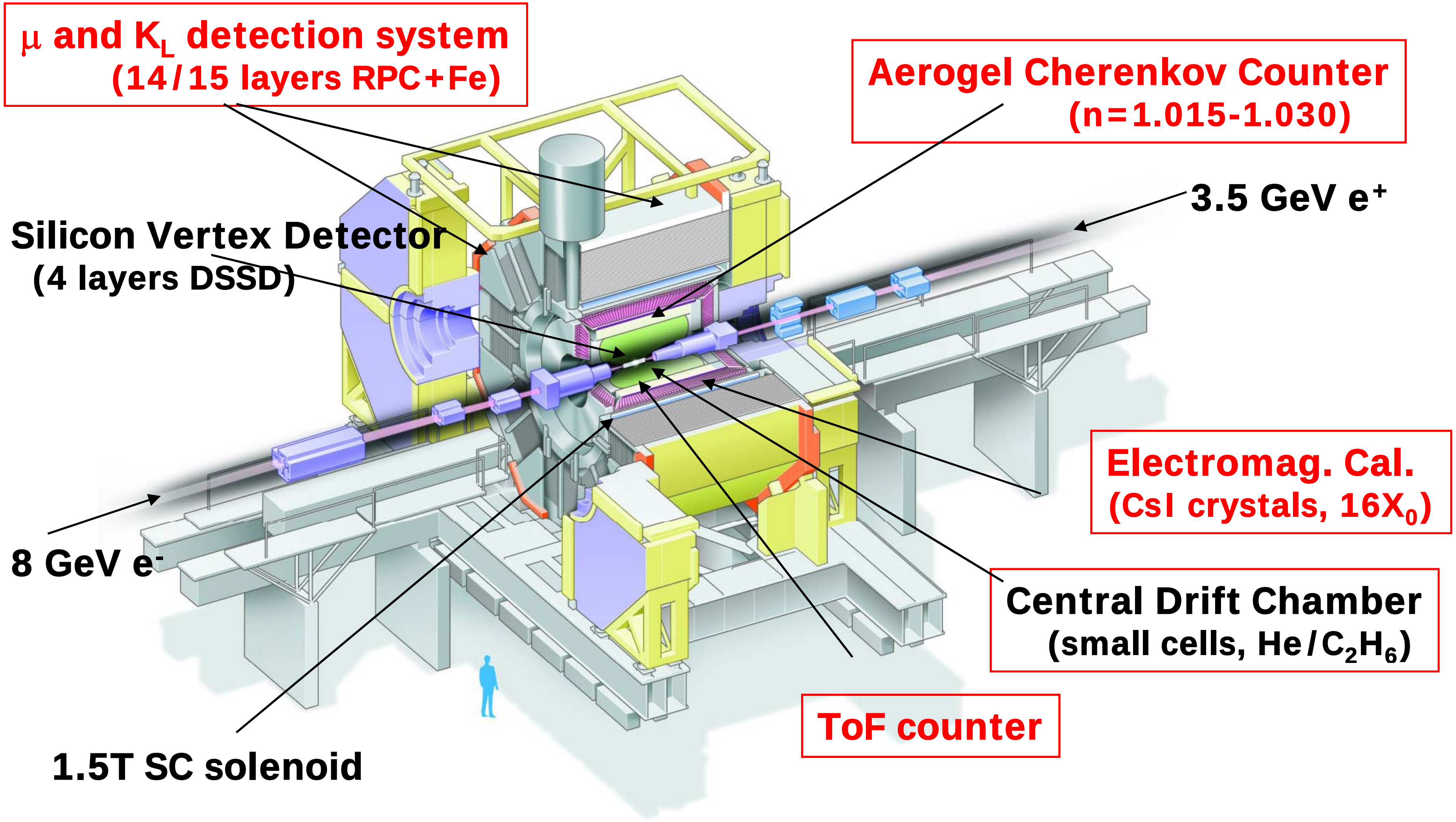
PID is also needed in:

- 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)

Example: Belle



Particle identification systems in Belle



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

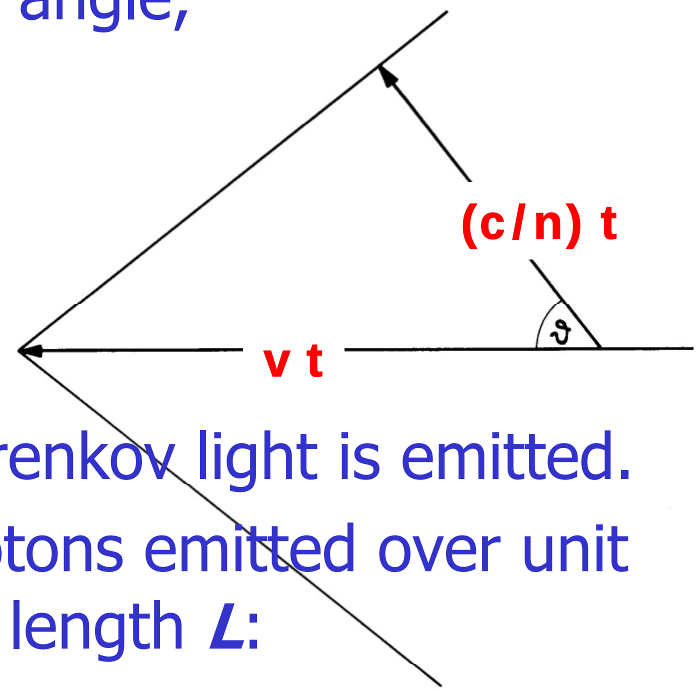
Mainly used for the identification of hadrons.

Identification through interaction: electrons and muons

Cherenkov radiation

A charged track with velocity $v=\beta c$ 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:

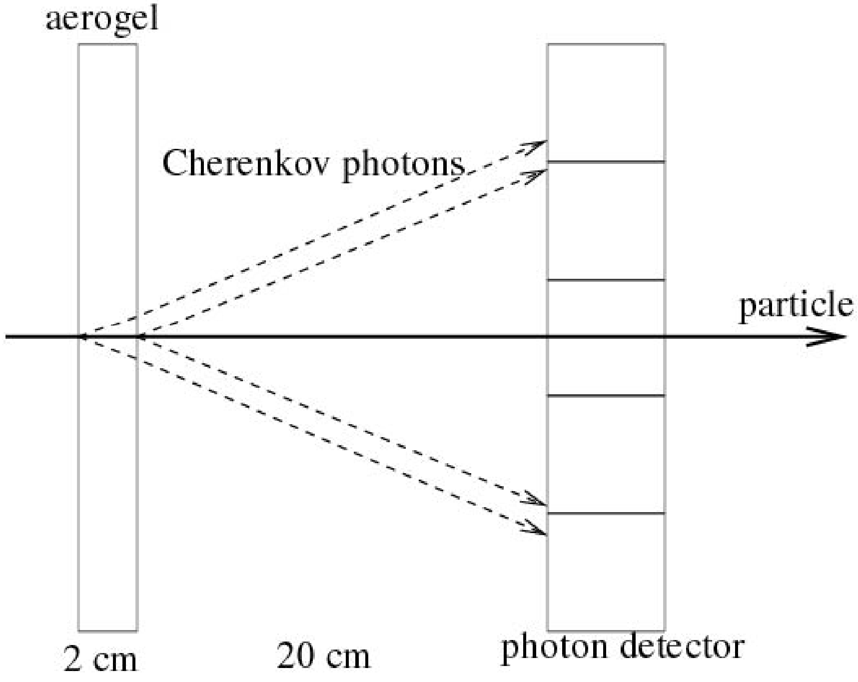
→ $\beta < \beta_t = 1/n$: below threshold no Cherenkov light is emitted.

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

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

→Few detected photons

Measuring Cherenkov angle

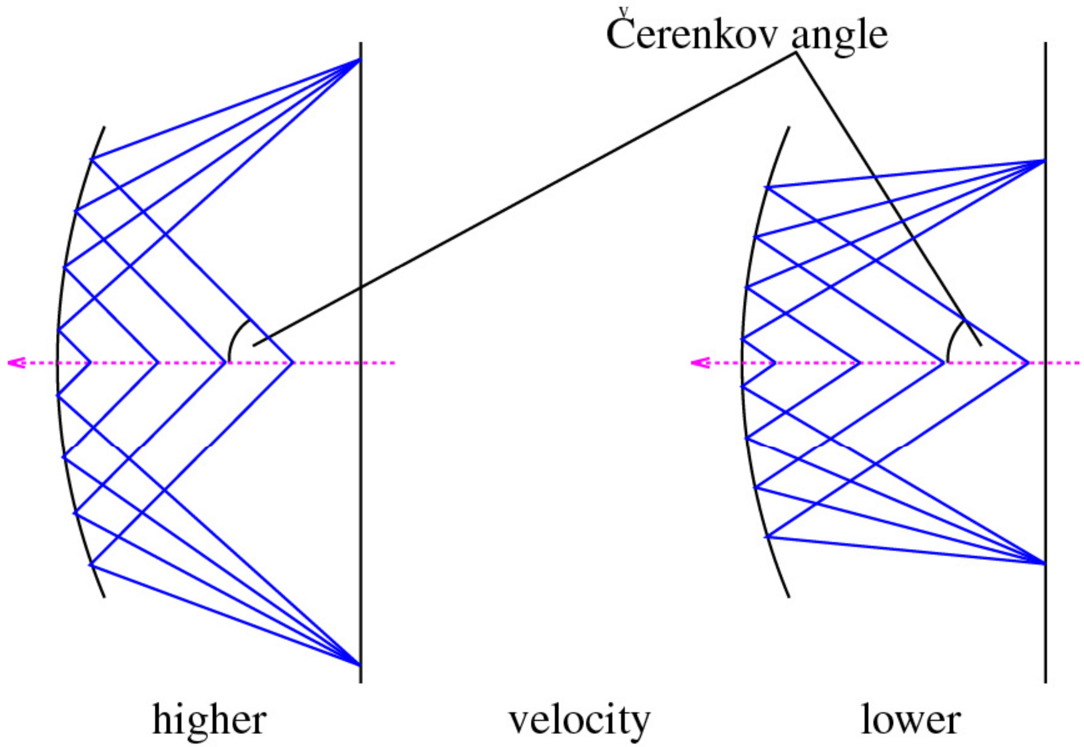


Idea: transform the direction into a coordinate →

ring on the detection plane

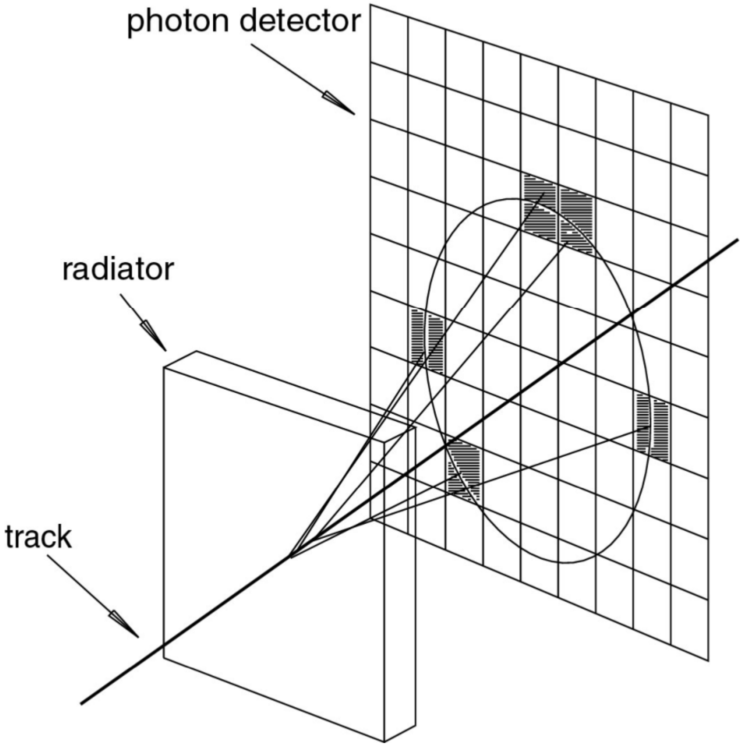
→ Ring Imaging CHerenkov

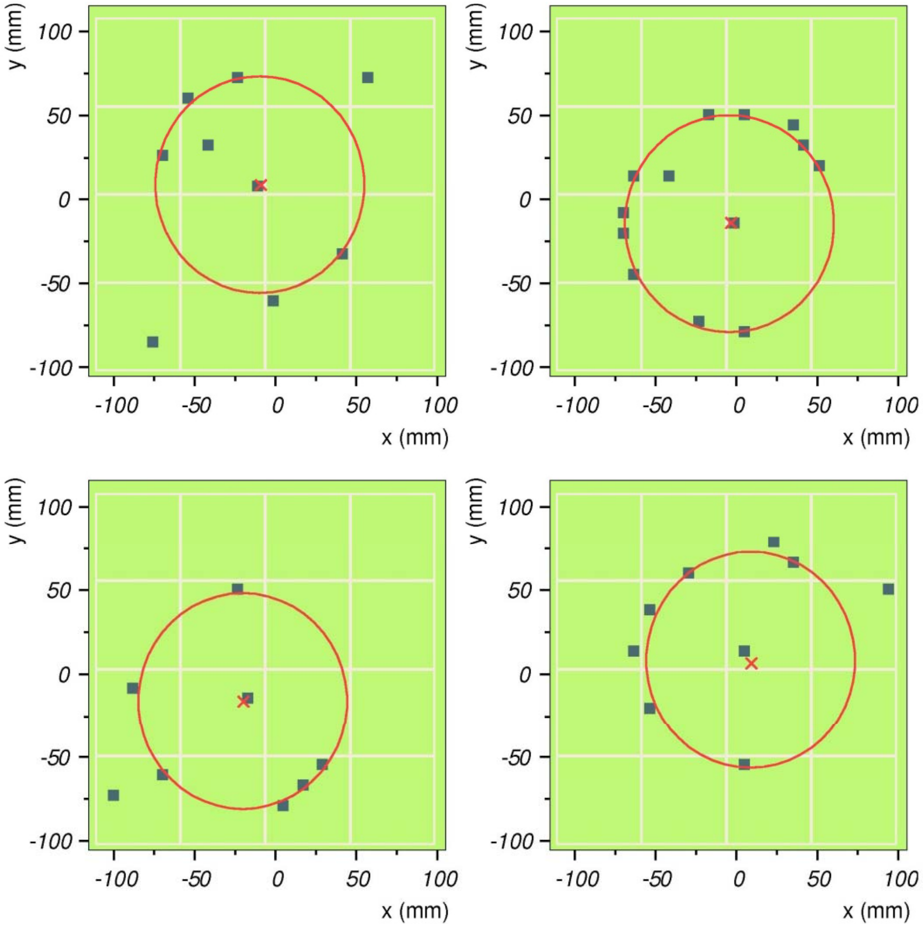
Proximity focusing RICH



RICH with a focusing mirror

Measuring Cherenkov angle





ring radius on the detection plane

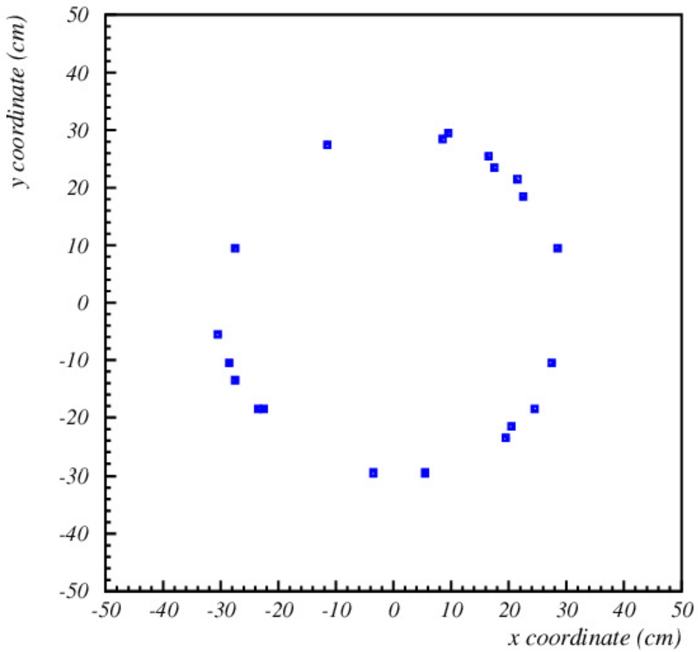
→ Cherenkov angle

Photon detection in RICH counters

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

→ detection of single photons with

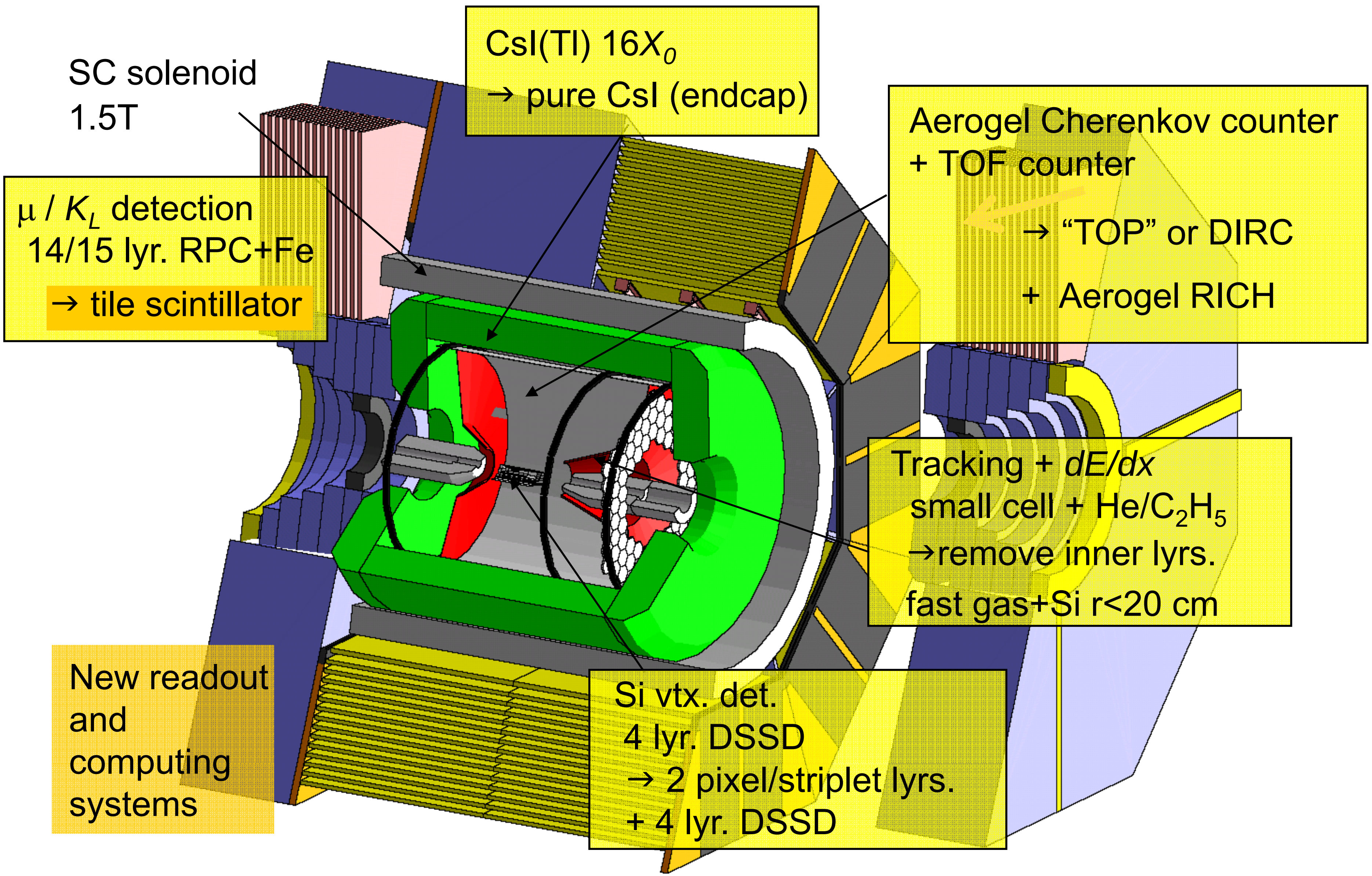
- sufficient spatial resolution
- high efficiency and good signal-to-noise ratio
- over a large area (square meters)



Special requirements:

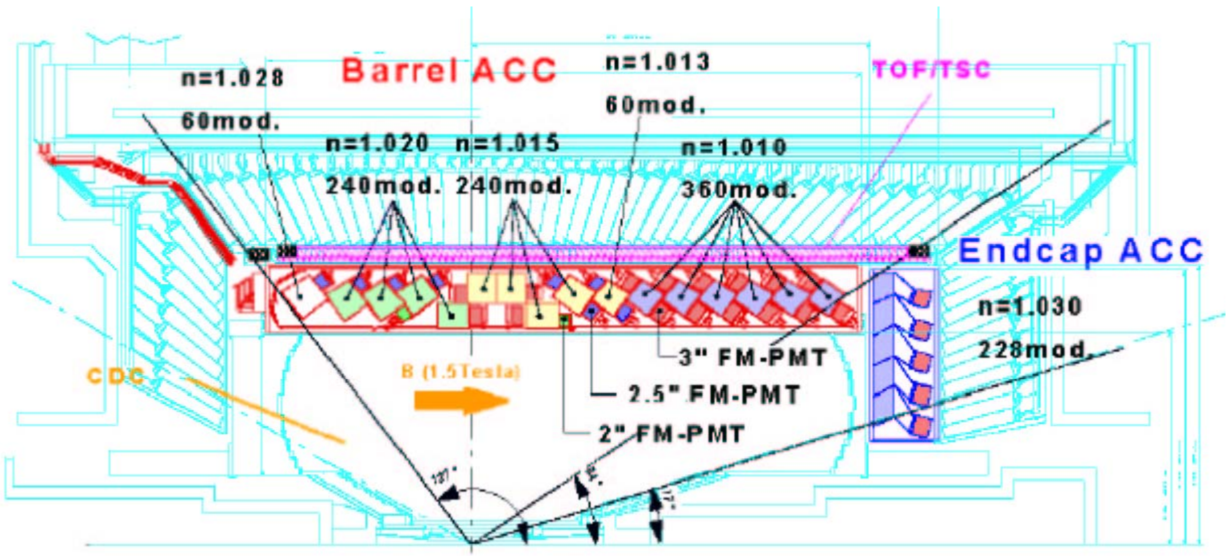
- Operation in magnetic field
- High rate capability
- Excellent timing (time-of-arrival information)

Belle upgrade → Belle-II

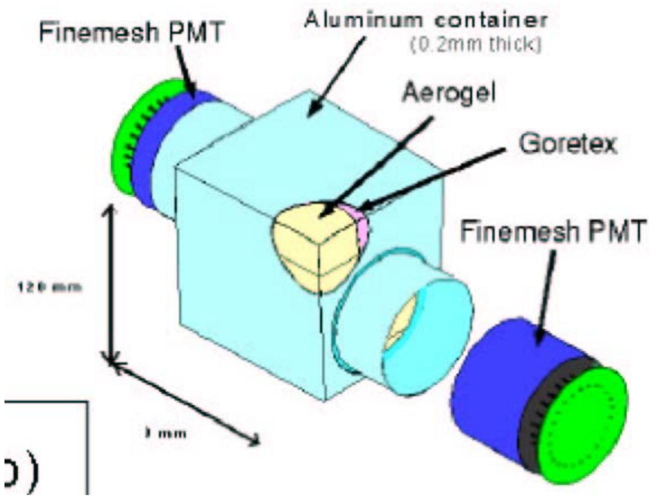


Present Belle: threshold Cherenkov counter ACC (aerogel Cherenkov counter)

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



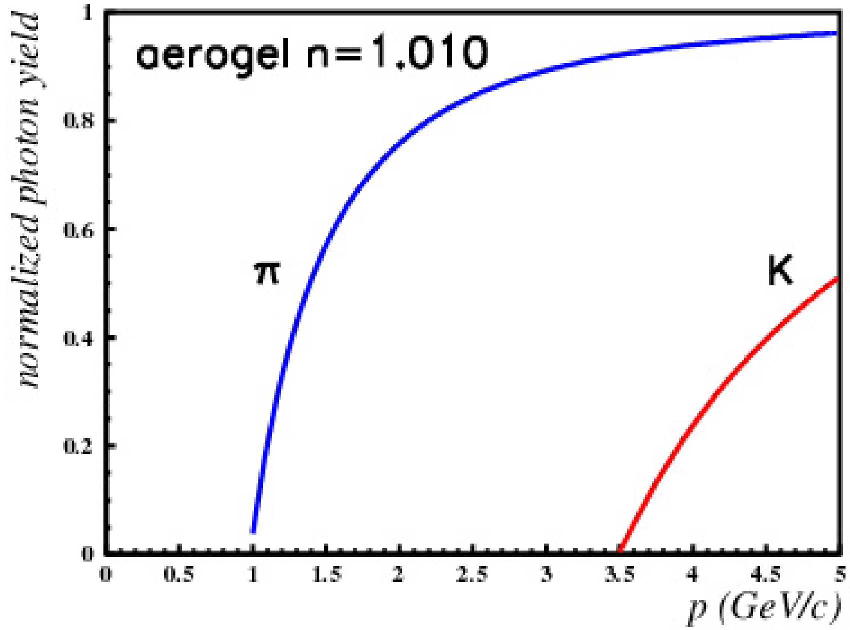
Detector unit: a block of aerogel and two fine-mesh PMTs



Fine-mesh PMT: works in high B fields

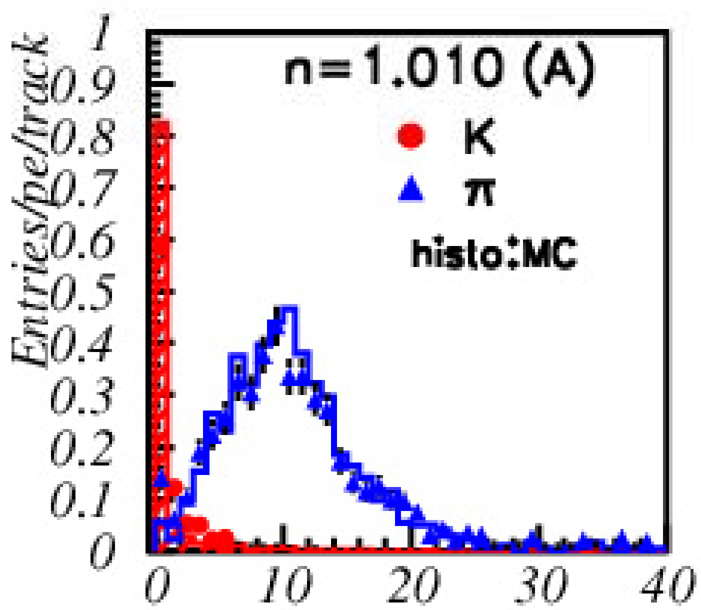
Belle ACC : threshold Cherenkov counter

expected yield vs p

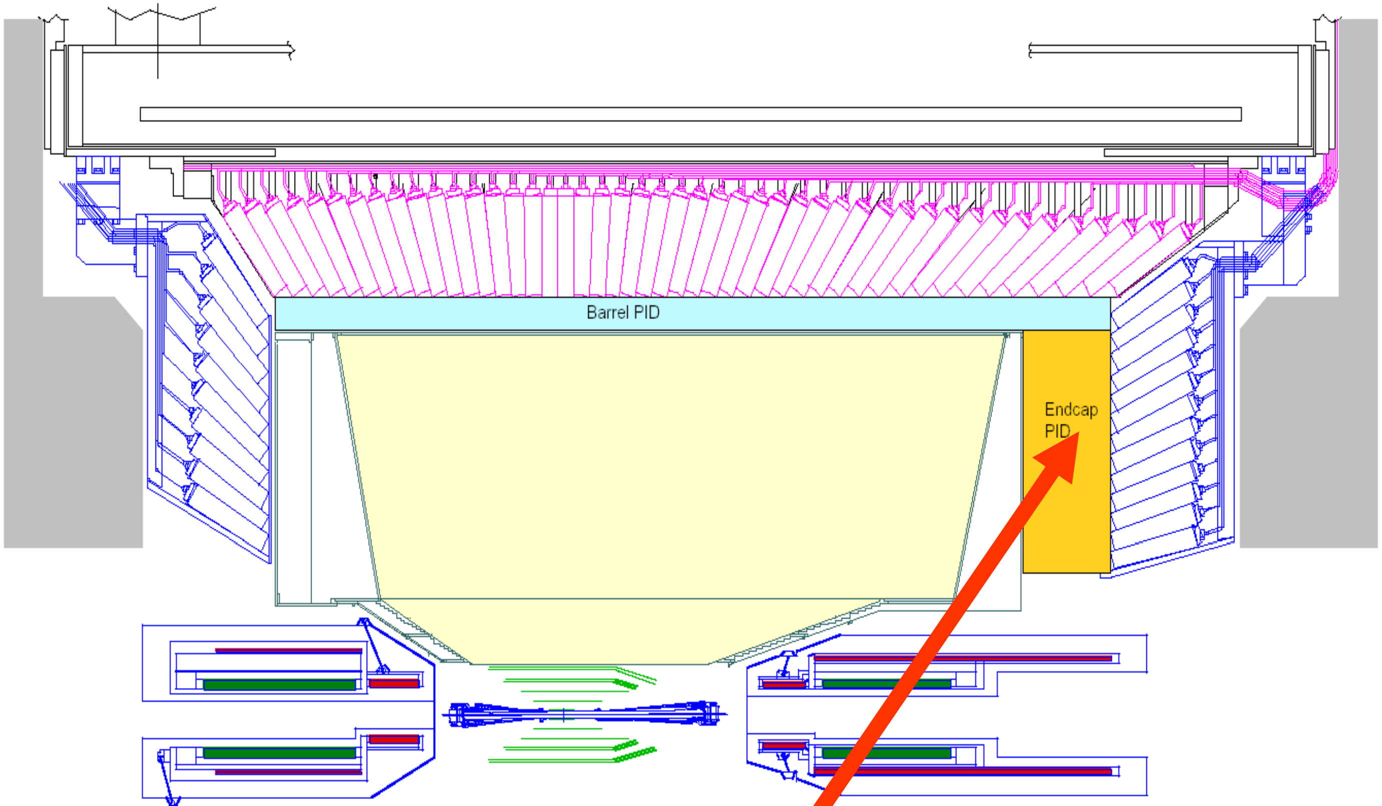


NIM A453 (2000) 321

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



Belle upgrade – side view

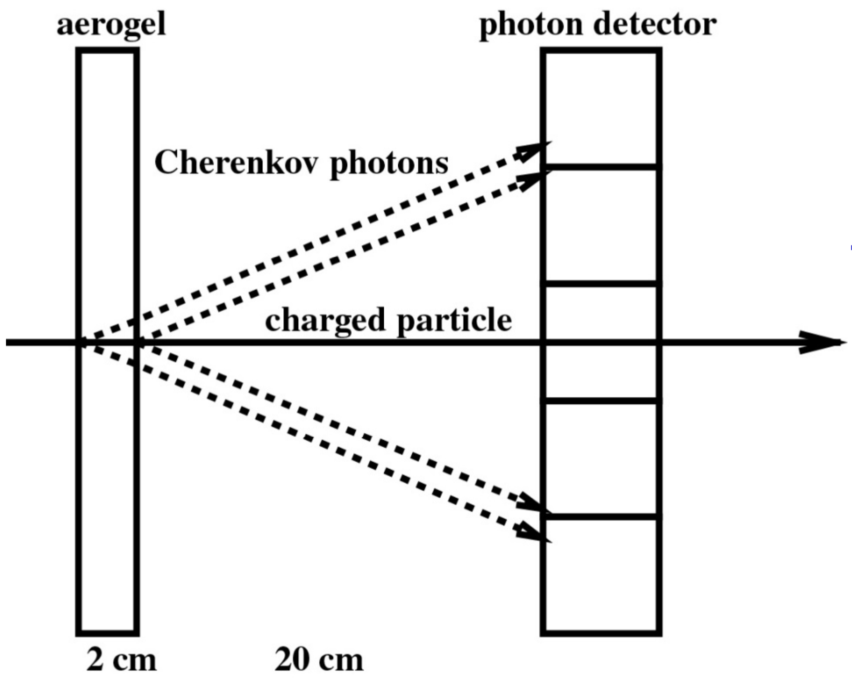


Two new particle ID devices, both RICHes:

Barrel: TOP or focusing DIRC

Endcap: proximity focusing RICH

Endcap: Proximity focusing RICH



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

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

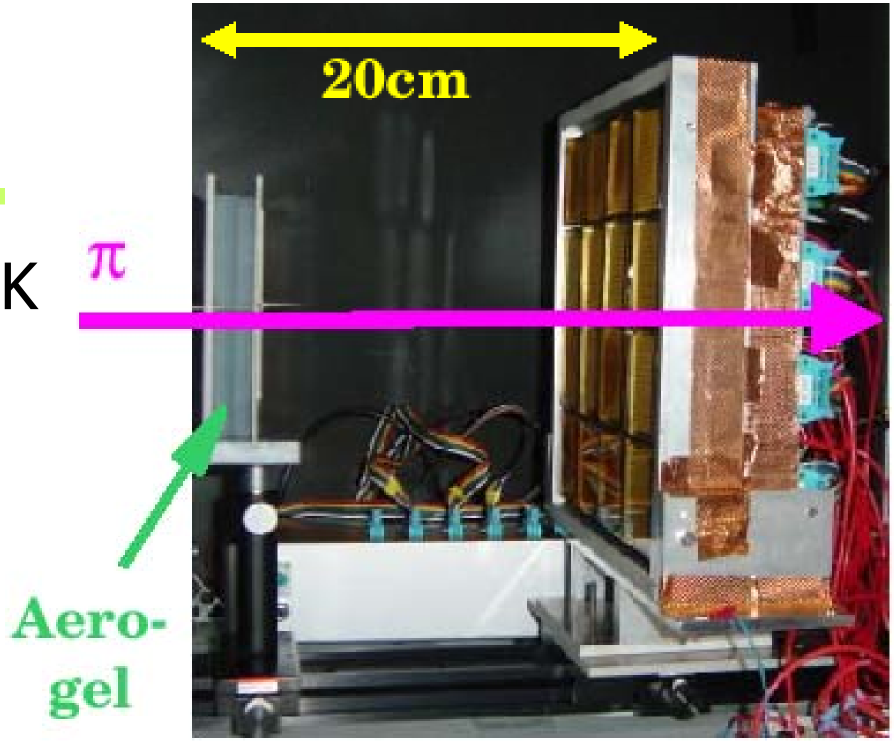
Per track: $$\sigma_{track} = \frac{\sigma_0}{\sqrt{N_{pe}}}$$

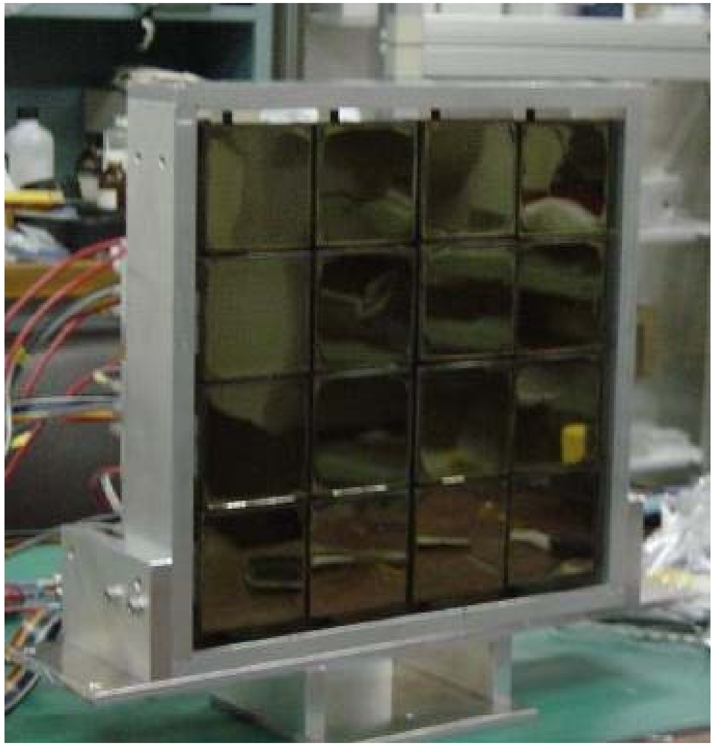
Separation: $[\theta_c(\pi) - \theta_c(K)]/\sigma_{track}$

→ 5σ separation with $N_{pe} \sim 10$

Beam tests

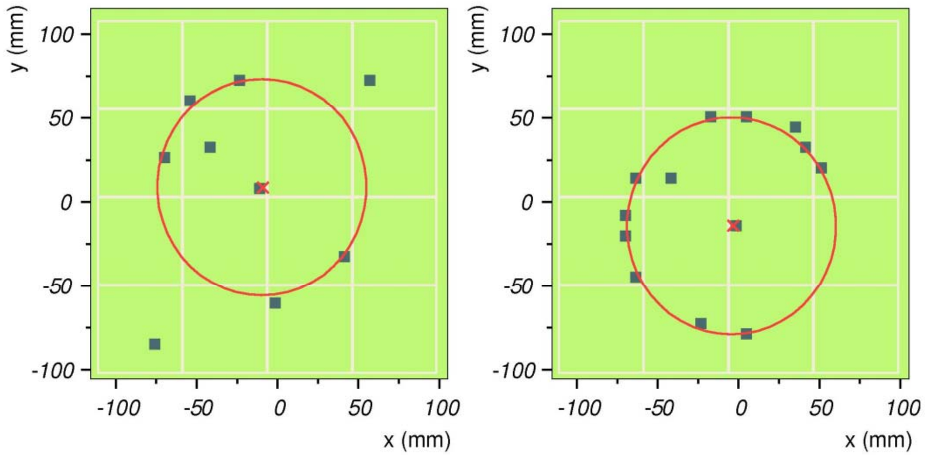
pion beam (π2) at KEK





Photon detector: array of 16 H8500 PMTs

Clear rings, little background

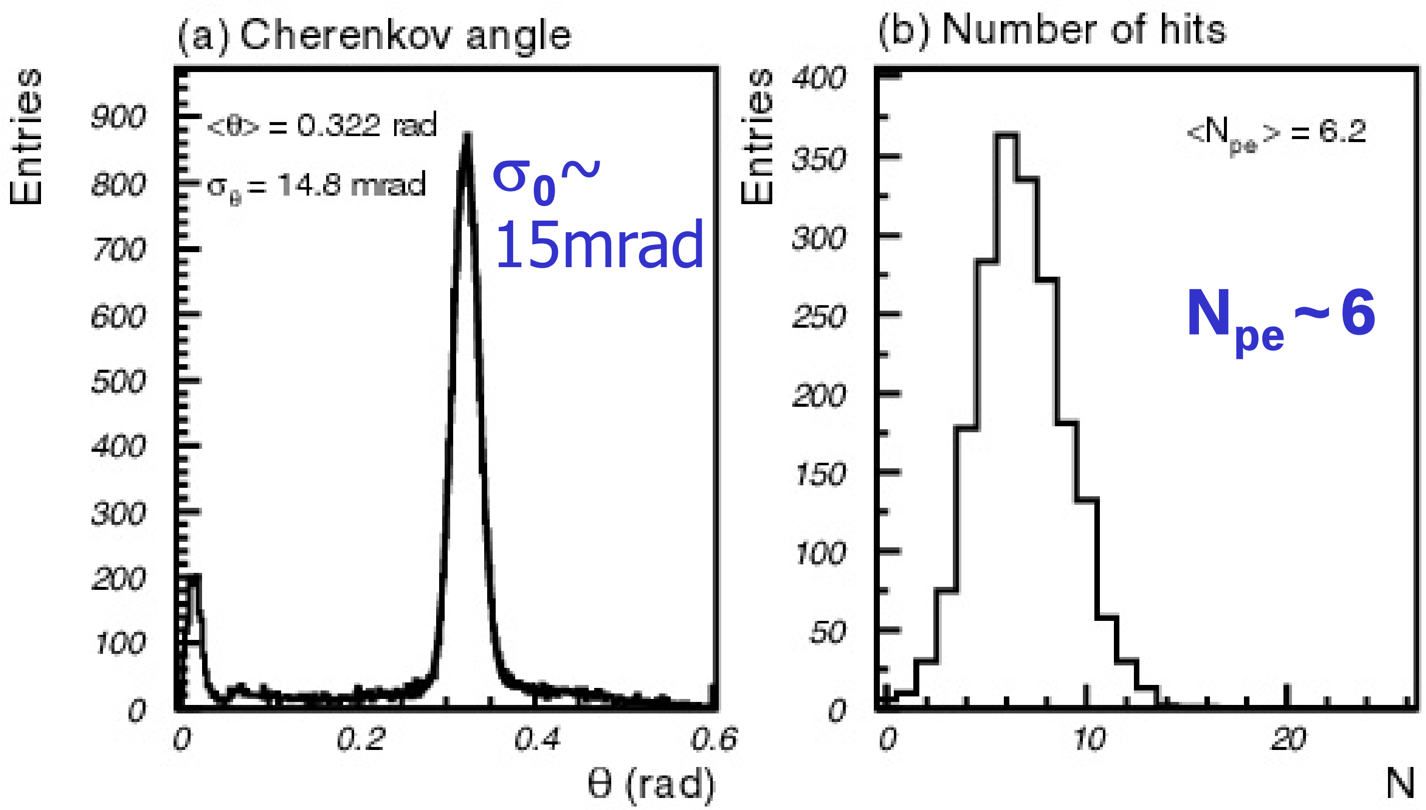


Beam test: Cherenkov angle resolution and number of photons

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

Beam test results with 2cm thick aerogel tiles:

>4σ K/π separation



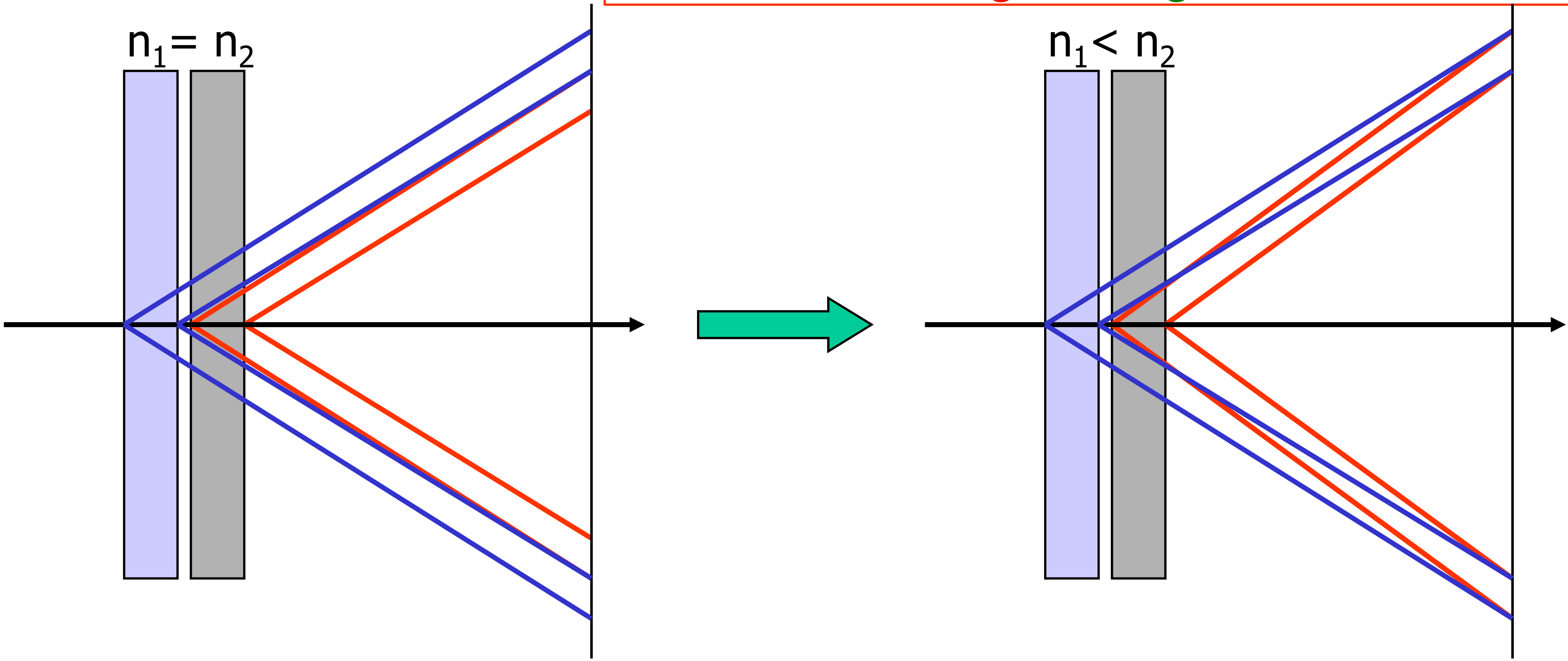
→ Number of photons has to be increased.

Radiator with multiple refractive indices

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

normal

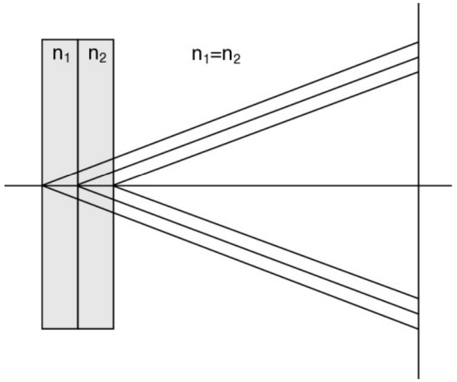
→ stack two tiles with different refractive indices: "focusing" configuration

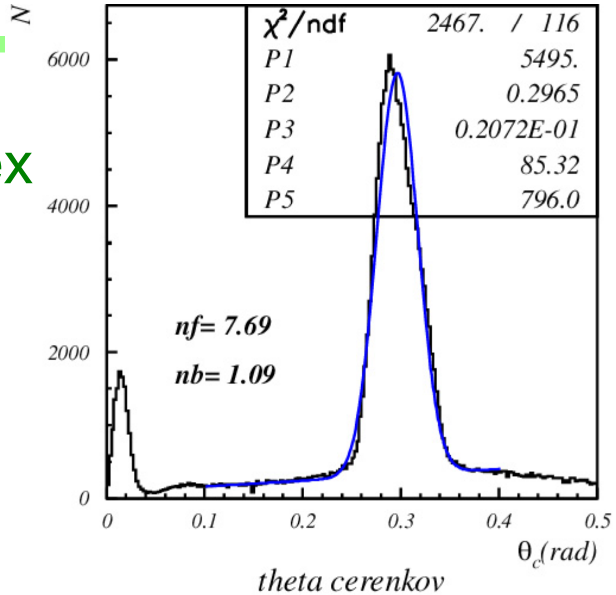


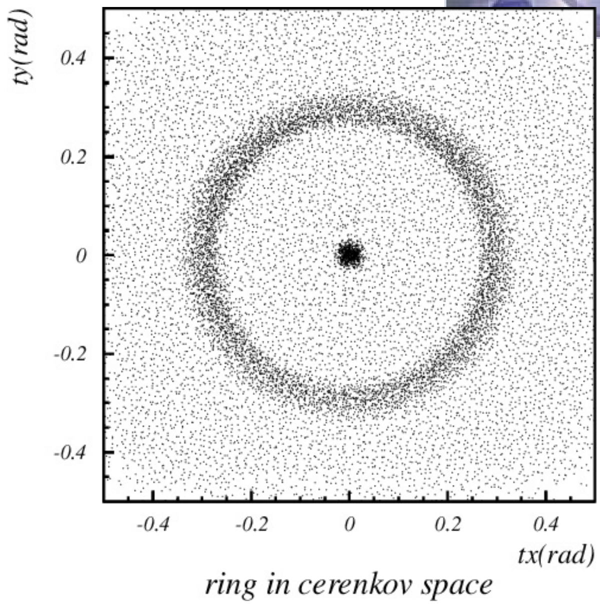
→ focusing radiator

Focusing configuration – data

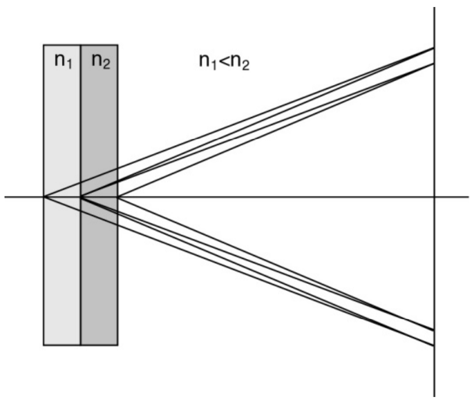
4cm aerogel single index

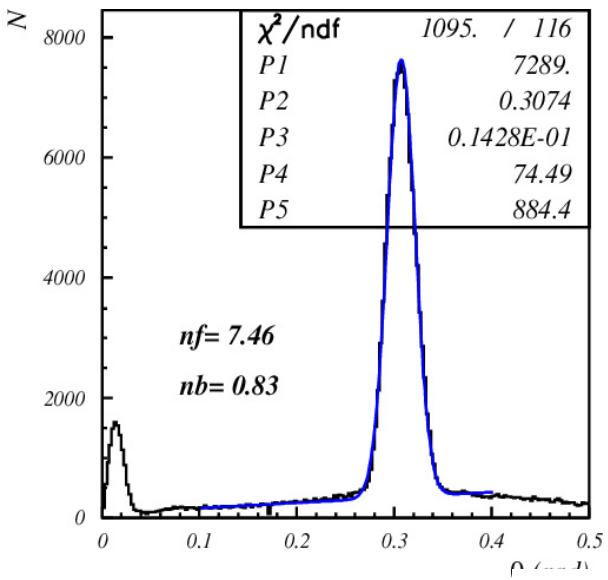


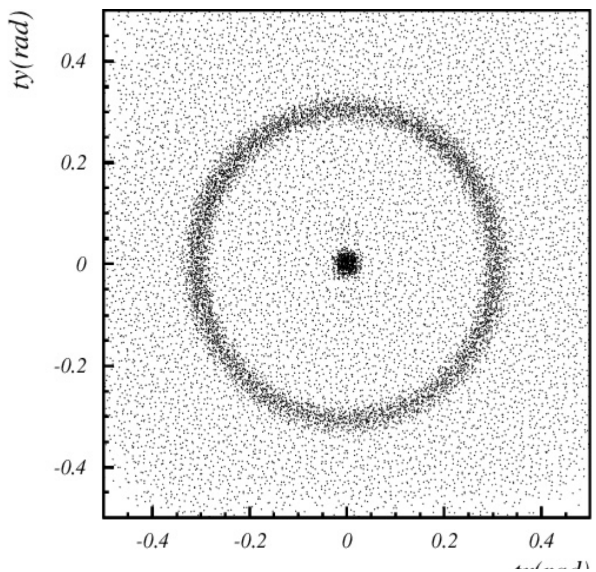




2+2cm aerogel



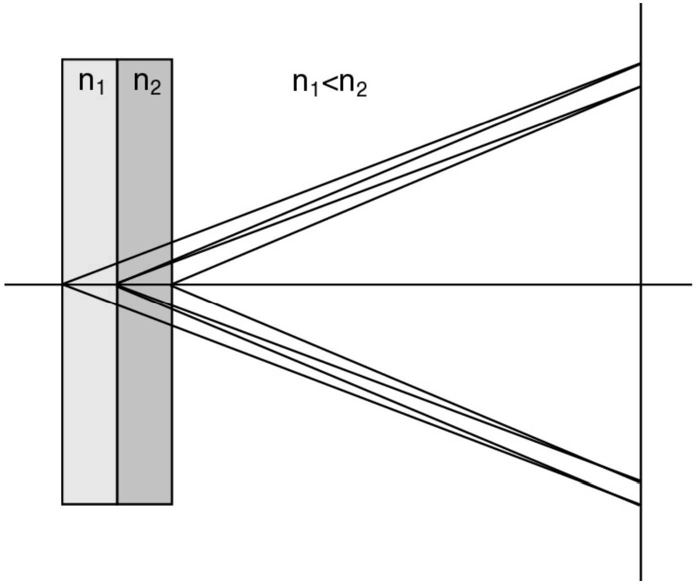


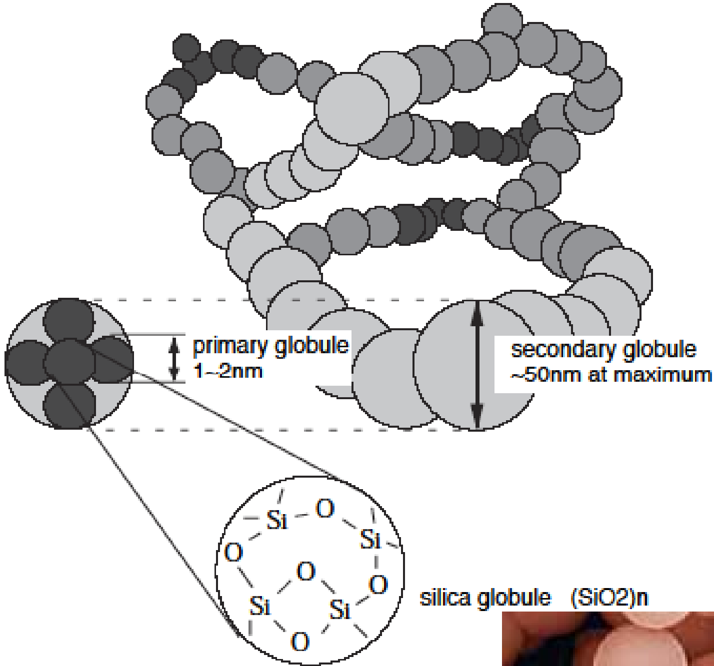


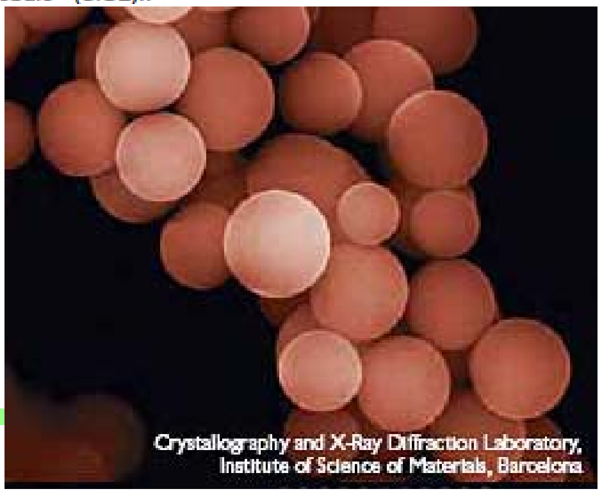
→NIM A548 (2005) 383

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.



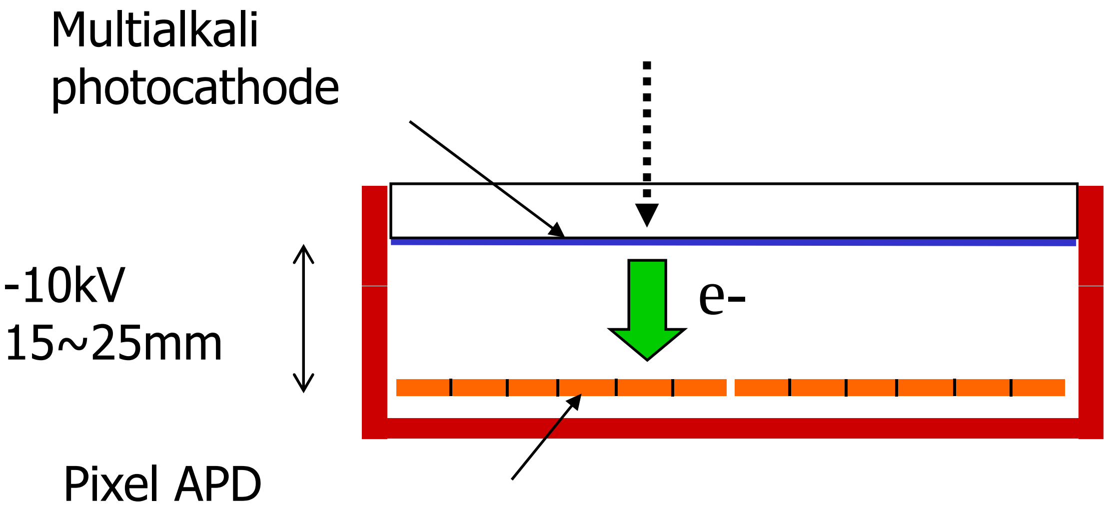


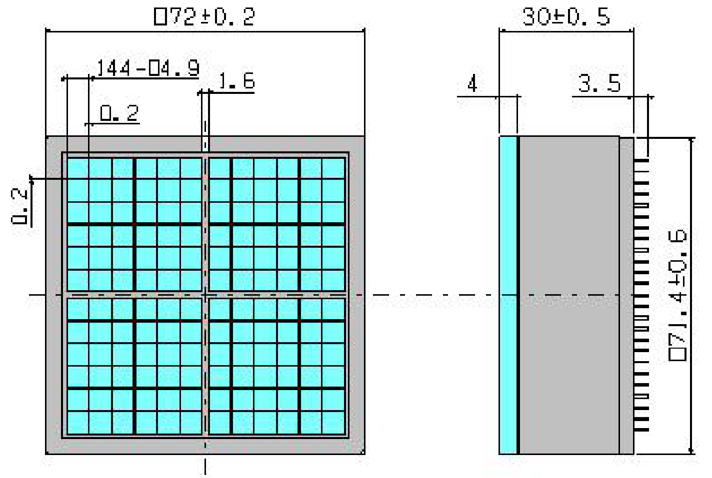


Photon detectors for the aerogel RICH requirements and candidates

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





HAPD R&D project in collaboration with HPK.

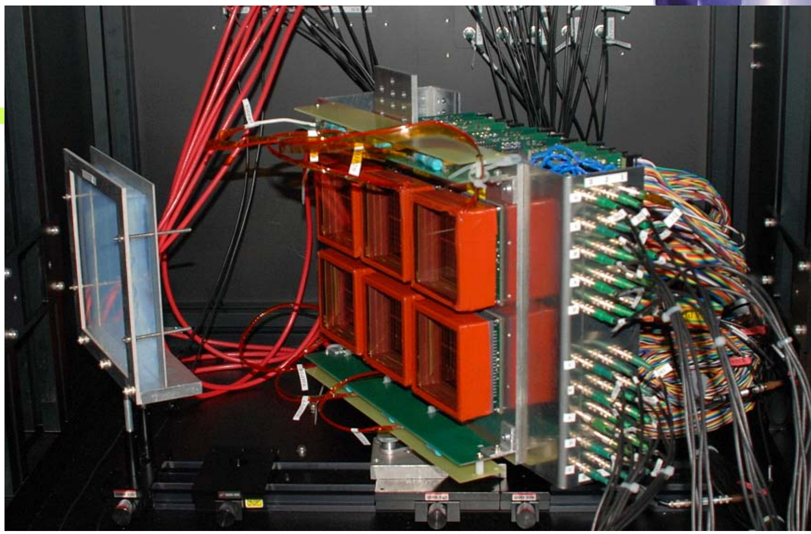
Long development time

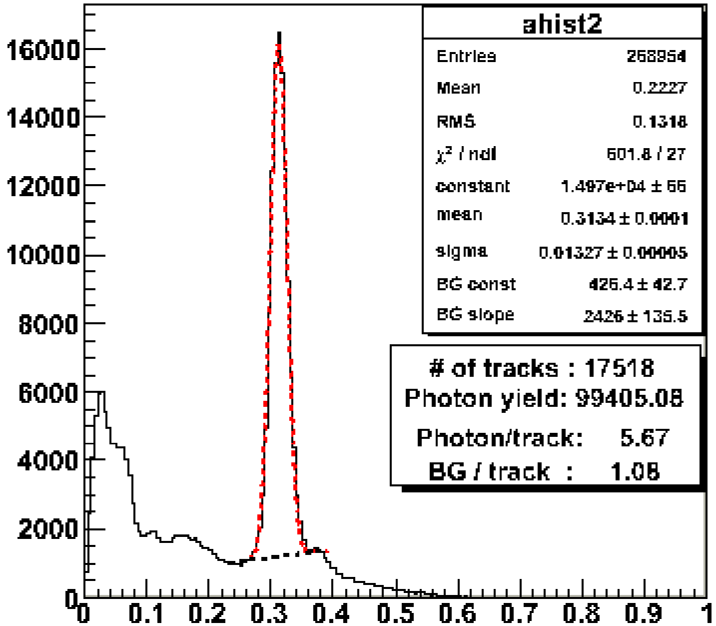
→ Finally enough working samples for a beam test at KEK last spring

→ NIM A595 (2008) 180

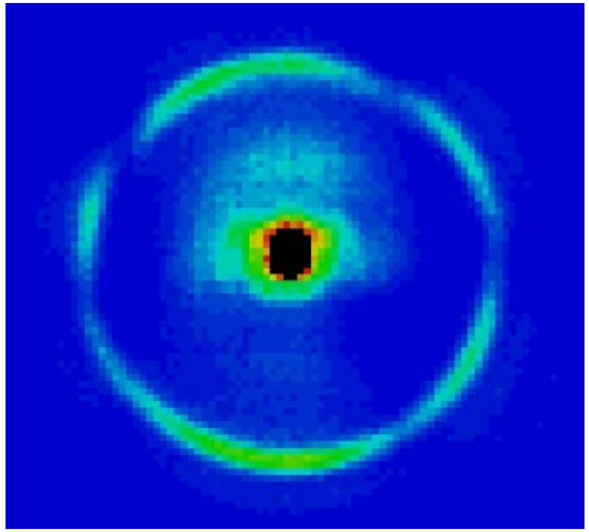
Photon detector candidate: HAPD beam test

• test with 2 GeV/c electrons @ KEK
• detected number of photons: ~ 6
• Cherenkov angle resolution: ~ 13mrad
• large background due to the Cherenkov photons produced in the HAPD window
• second ring due to reflection on APD





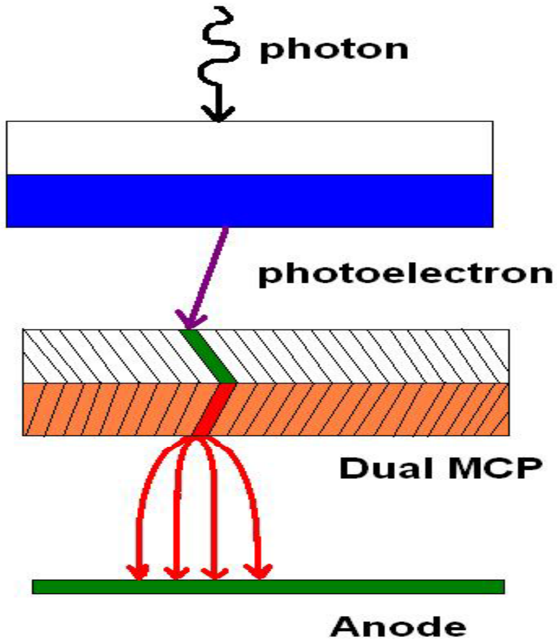
Better than 4σ π/K separation @ 4GeV/c



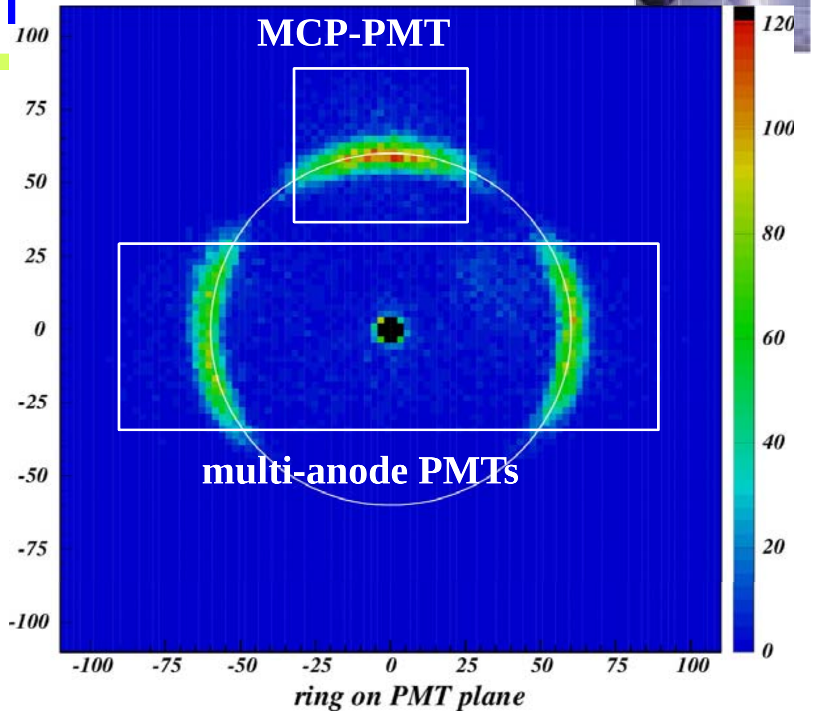
Open issues: long term stability and neutron irradiation damage – both under study

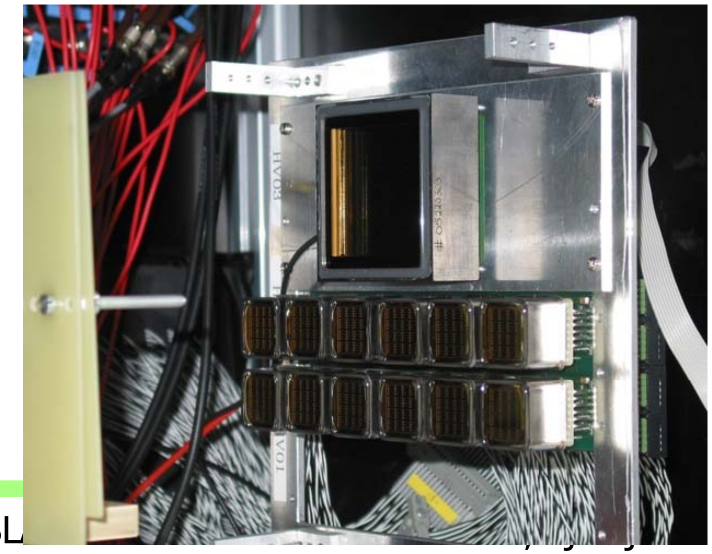
Photon detector candidate: BURLE/Photonis MCP-PMT

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



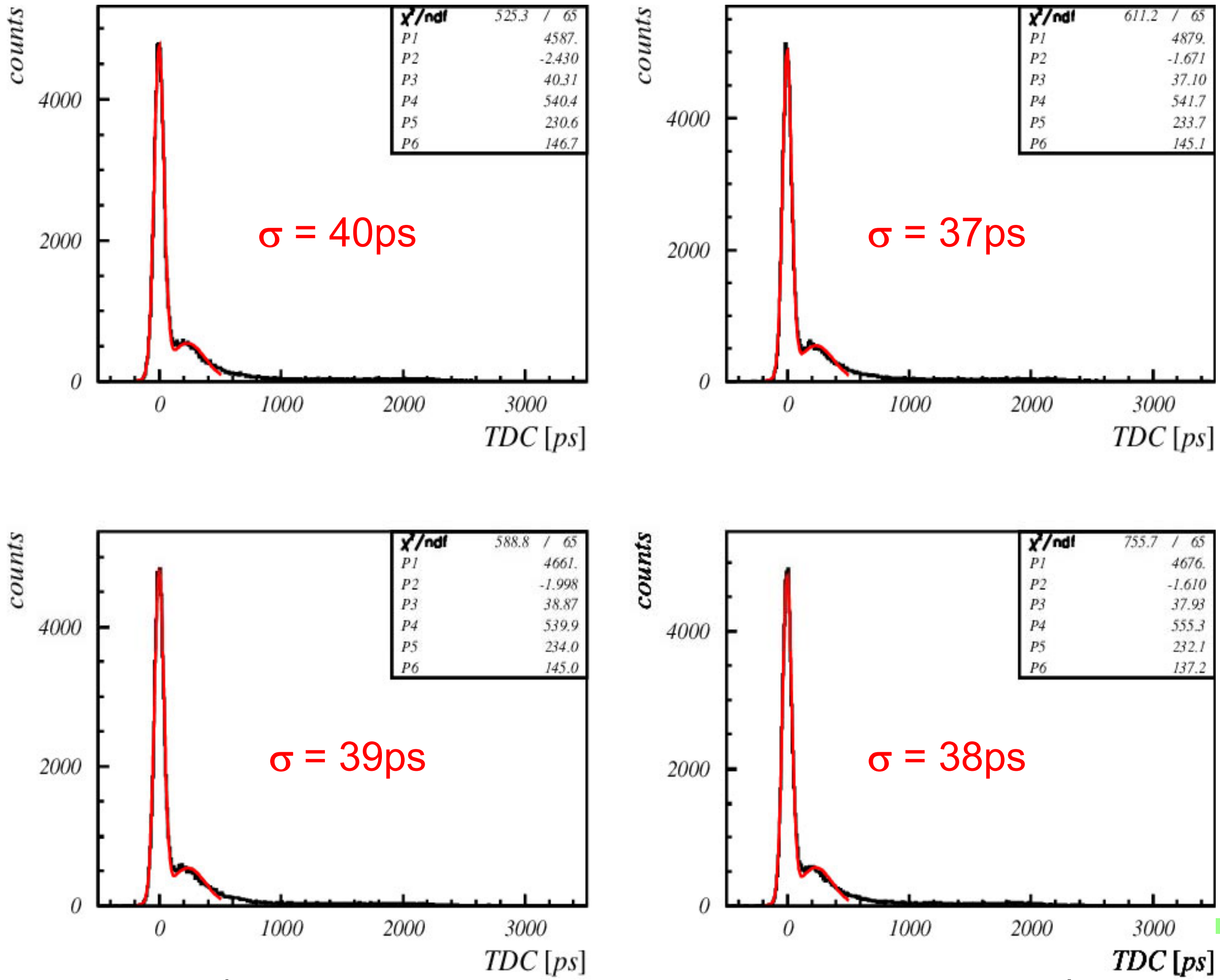
→good performance in beam and bench tests, NIMA567 (2006) 124
→ very fast
→ open issue: ageing





BURLE/Photonis MCP-PMT

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



Tails can be significantly reduced by:

- increased cathode-MCP voltage difference
- decreased photocathode-MCP distance

Geiger-APDs as photon detector?

Can we use SiPMs (Geiger mode APDs) 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

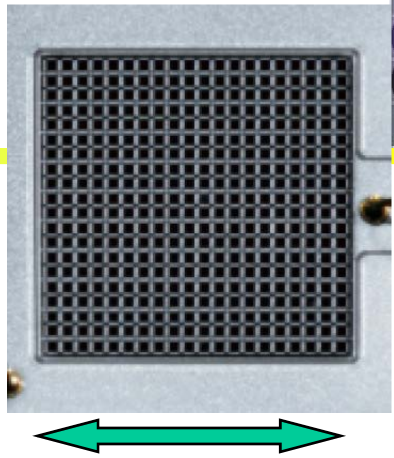
-radiation hardness

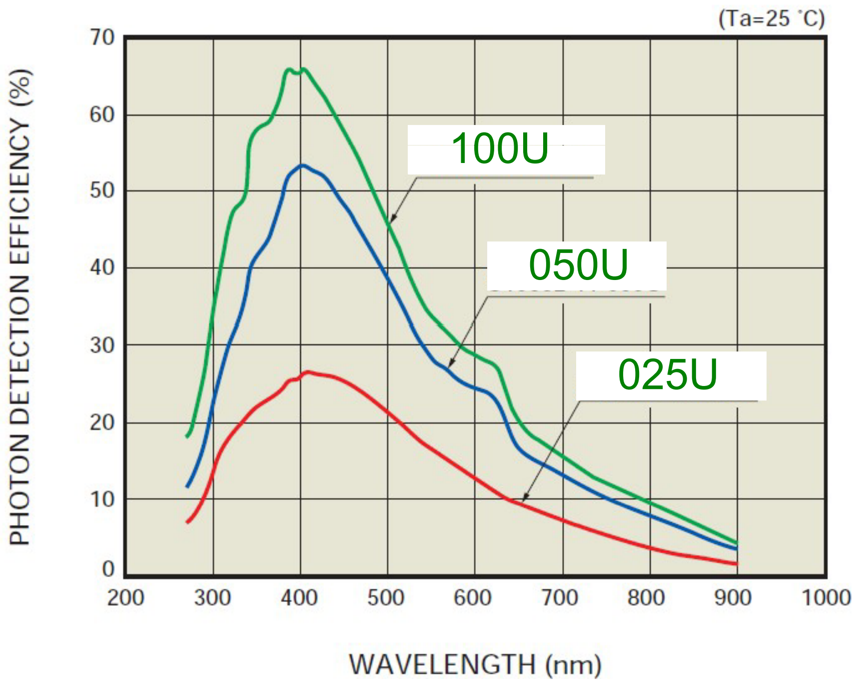
SiPMs as photon detectors?

SiPM is an array of individual APDs operating in Geiger mode; a resistor is used to quench the pulse. Characteristics:

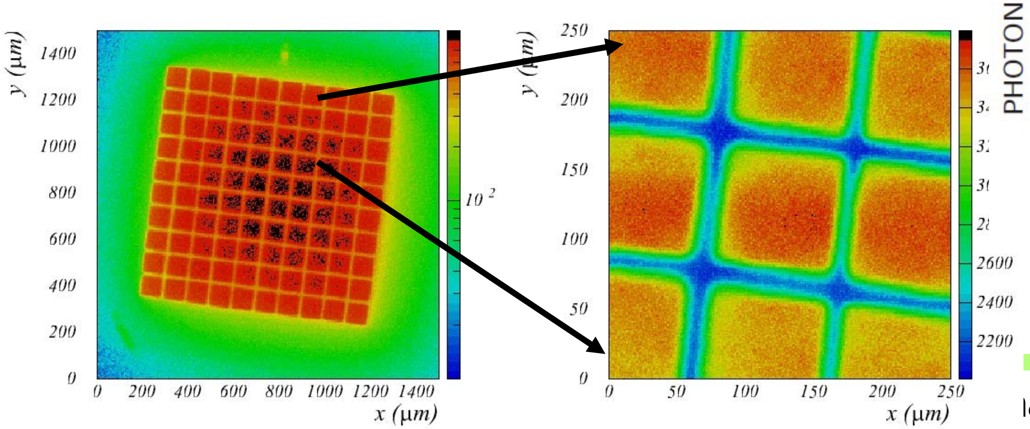
- low operation voltage ~ 10-100 V
- gain ~ 10^6
- peak PDE up to 65%(@400nm)

  $PDE = QE \times \varepsilon_{geiger} \times \varepsilon_{geo}$
- ε_{geo} – dead space between the cells
- time resolution ~ 100 ps
- work in high magnetic field
- dark counts ~ few 100 kHz/mm^2
- radiation damage (p,n)



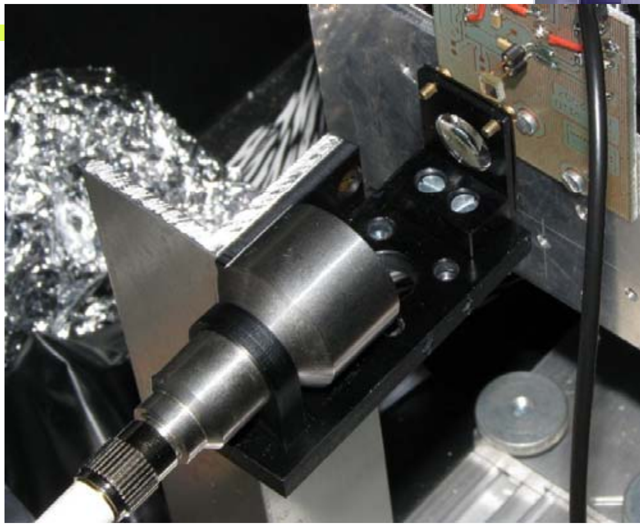


Hamamatsu MPPC: S10362-11

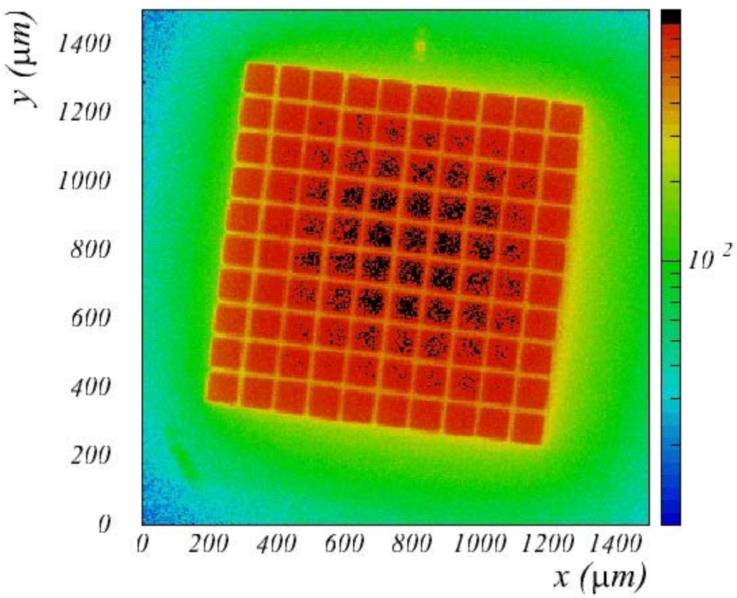


Surface sensitivity for single photons

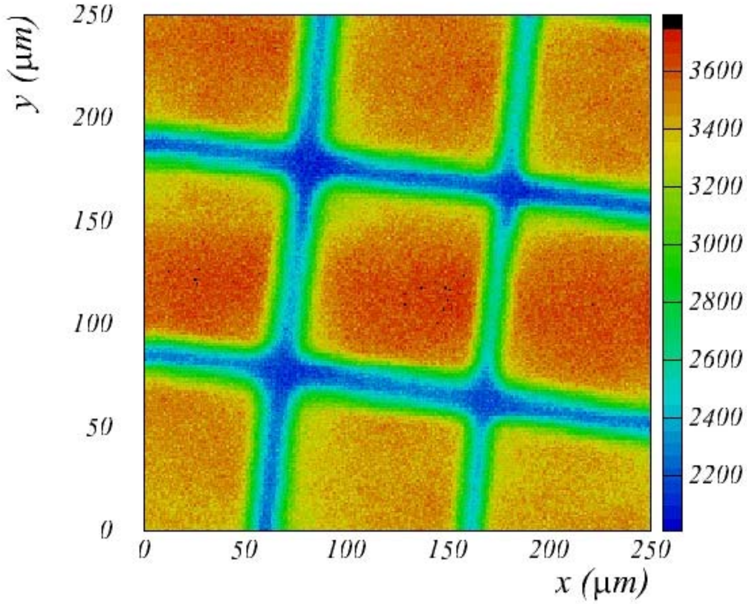
- 2d scan in the focal plane of the laser beam ($\sigma \approx 5\ \mu m$)
- intensity: on average << 1 photon
- Selection: single pixel pulse height, in a 10 ns window



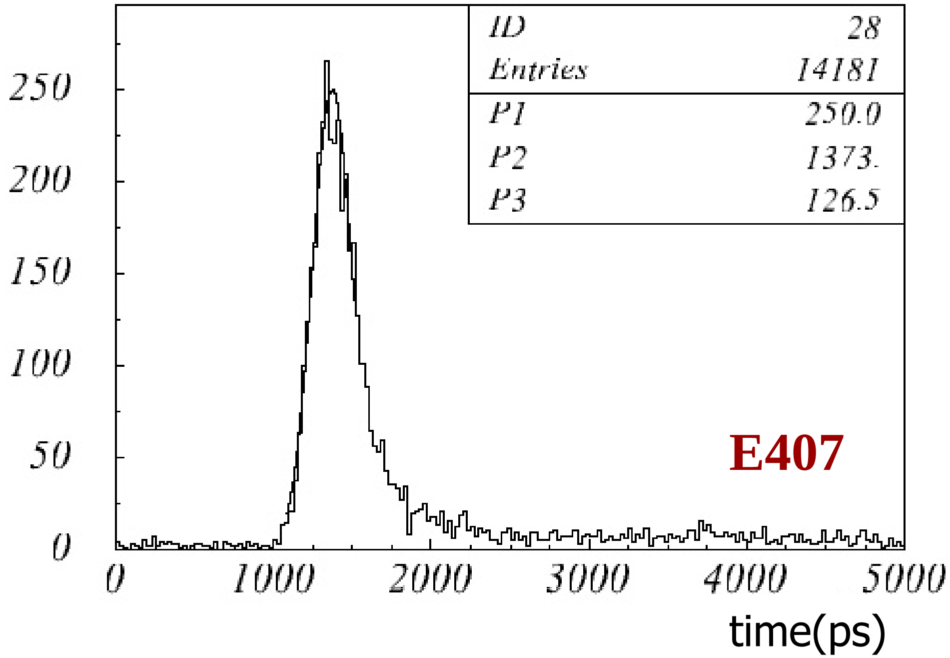
5 μm step size

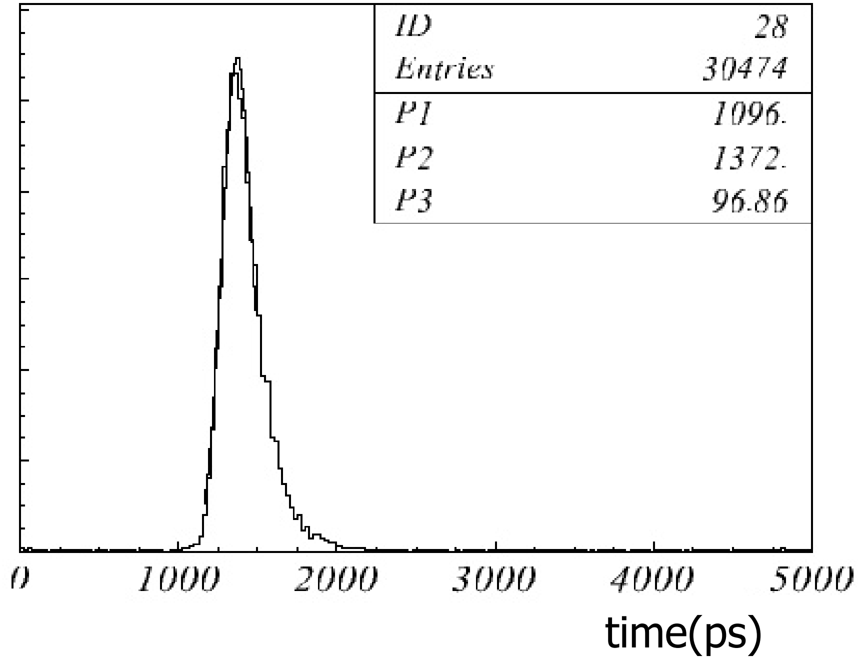


Close-up: 1 μm step size



Time resolution after time walk correction





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

- $\sigma \approx$ 100-200 ps

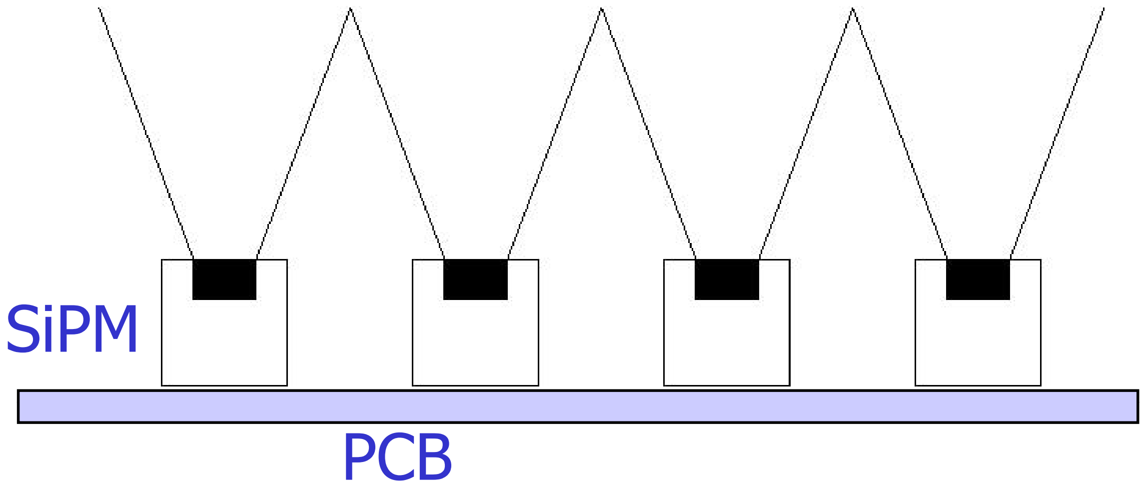
- $\sigma_{red} > \sigma_{blue}$

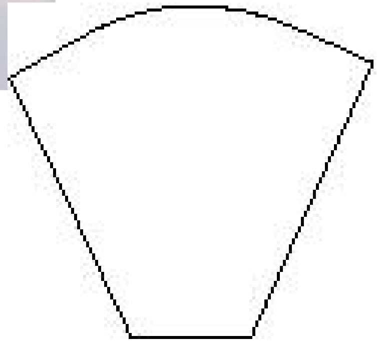
Can such a detector work?

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





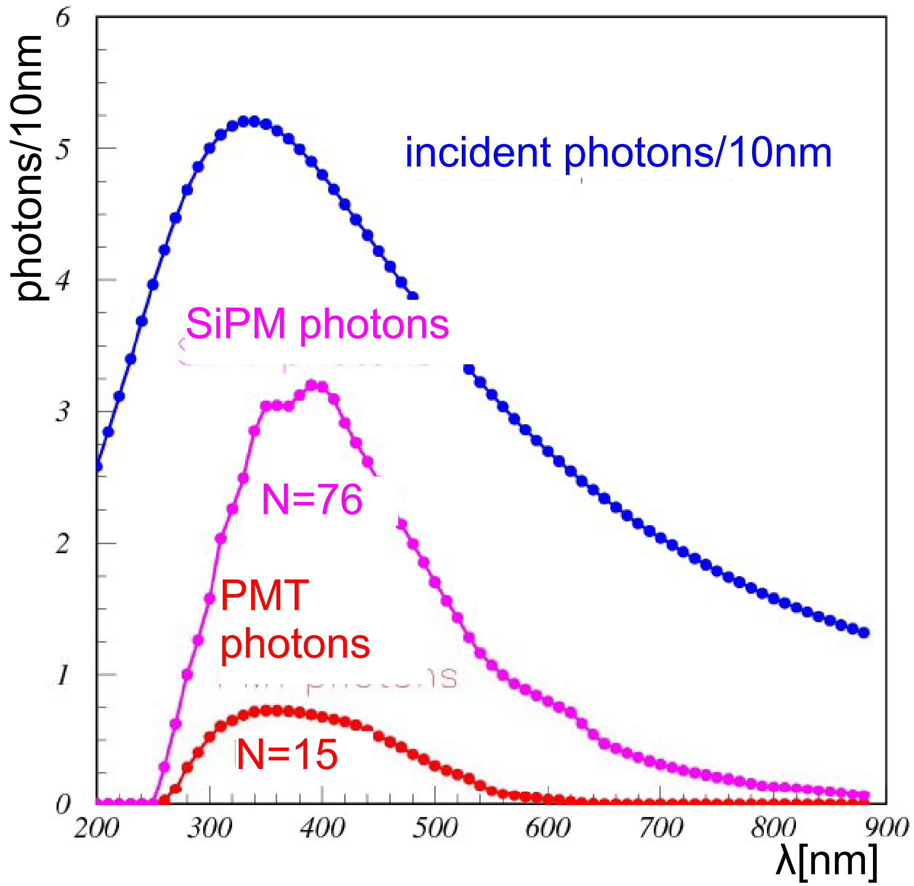
or combine a lens and mirror walls

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.

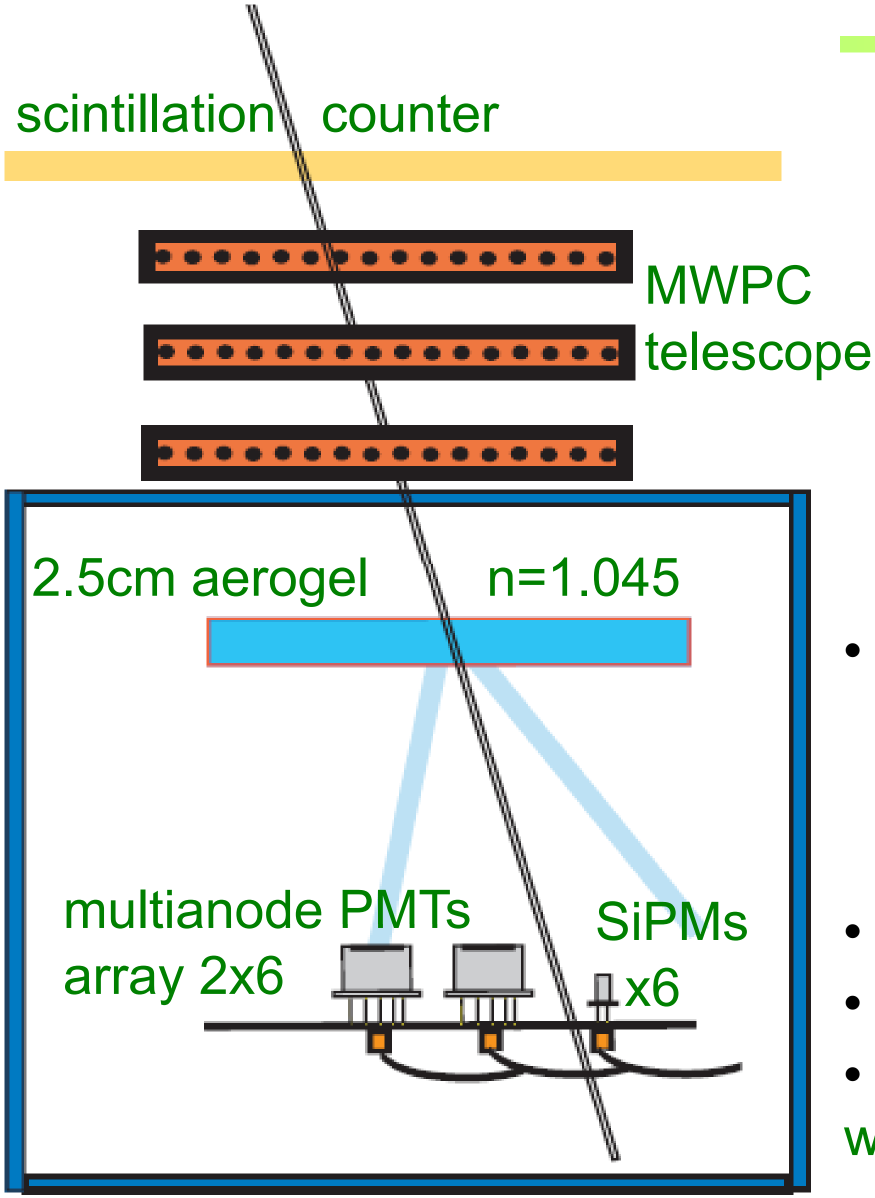
N_{SiPM}/N_{PMT}~5

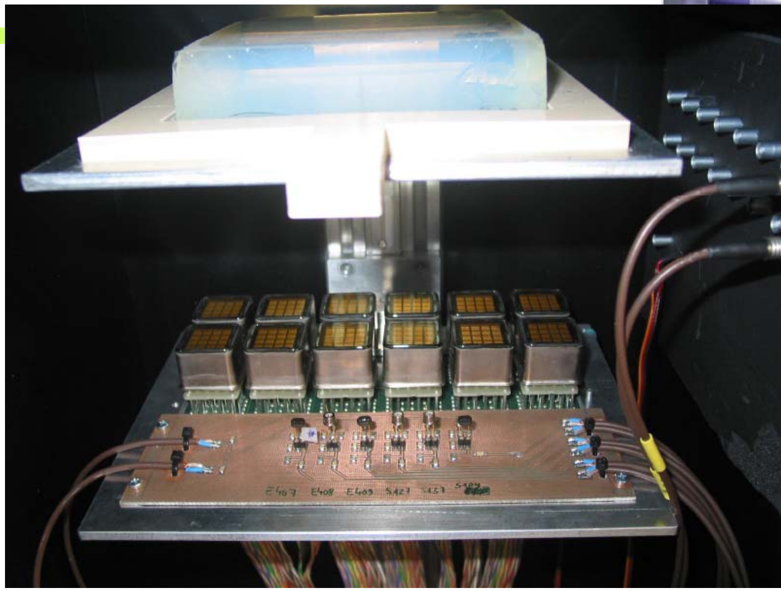
Assuming 100% detector active area



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)

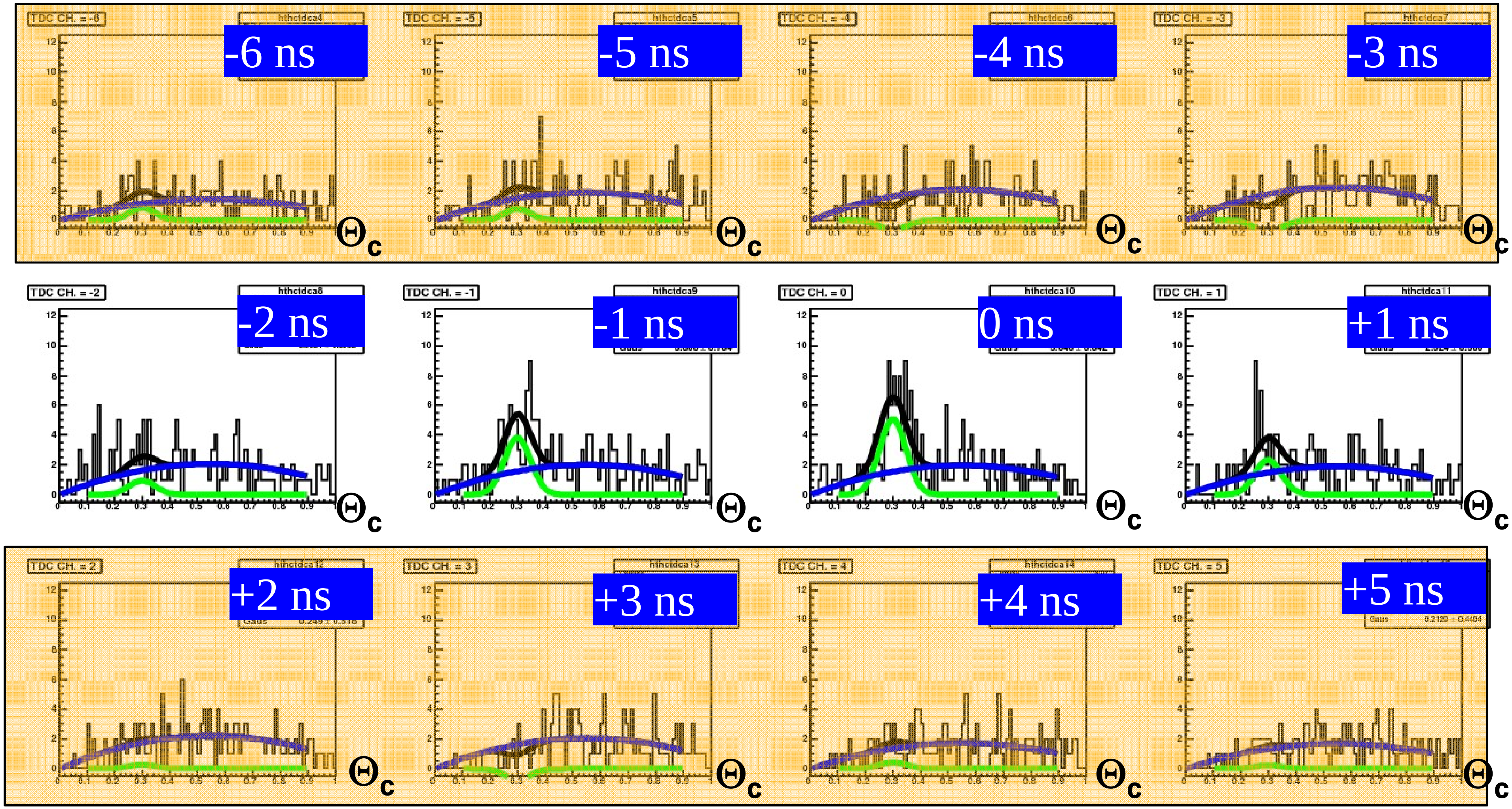
Cosmic test setup





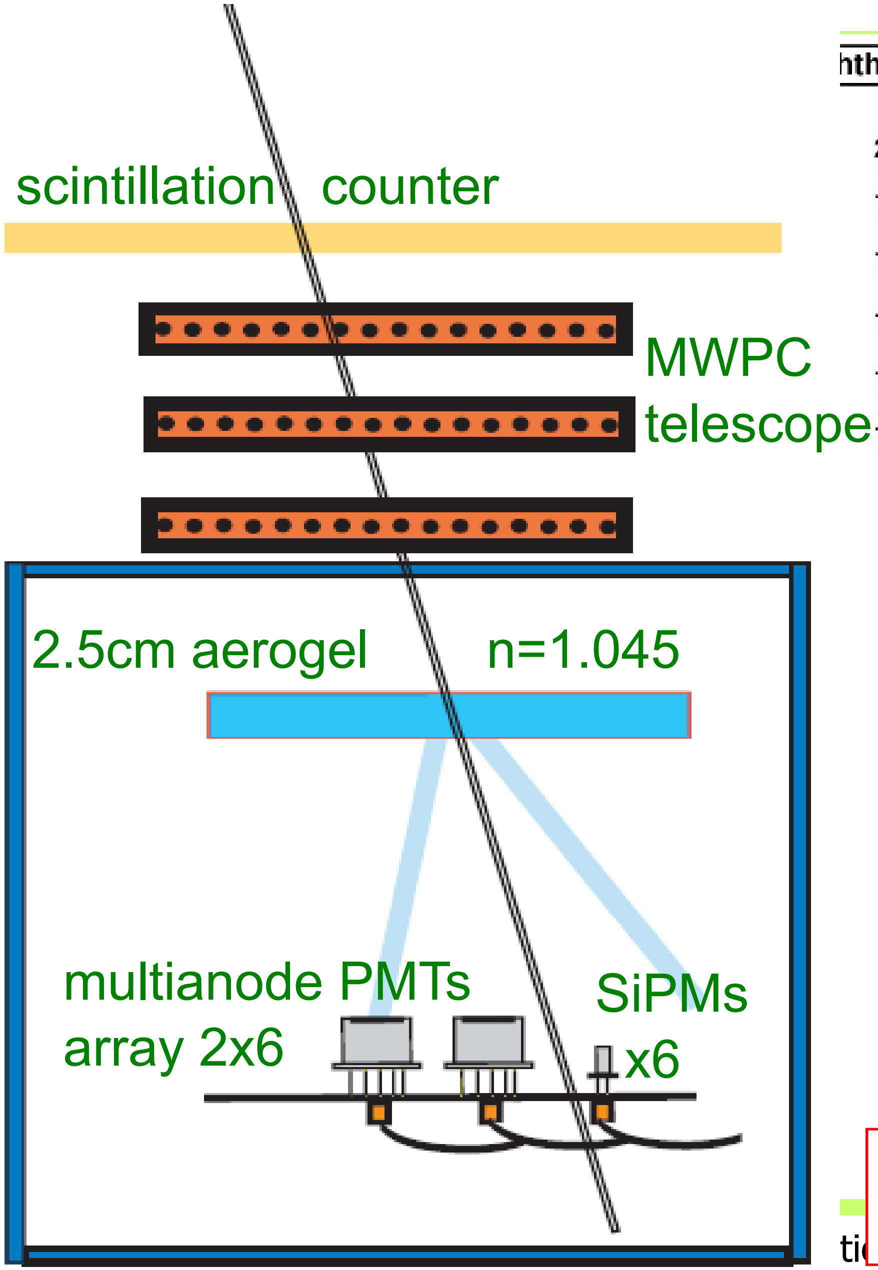
- 6 Hamamatsu SiPMs used:
  - 2x 100U; background ~400kHz
  - 2x 050U; background ~200kHz
  - 2x 025U; background ~100kHz
- signals amplified (ORTEC FTA820),
- discriminated (EG&G CF8000) and
- read by multihit TDC (CAEN V673A) with 1 ns / channel

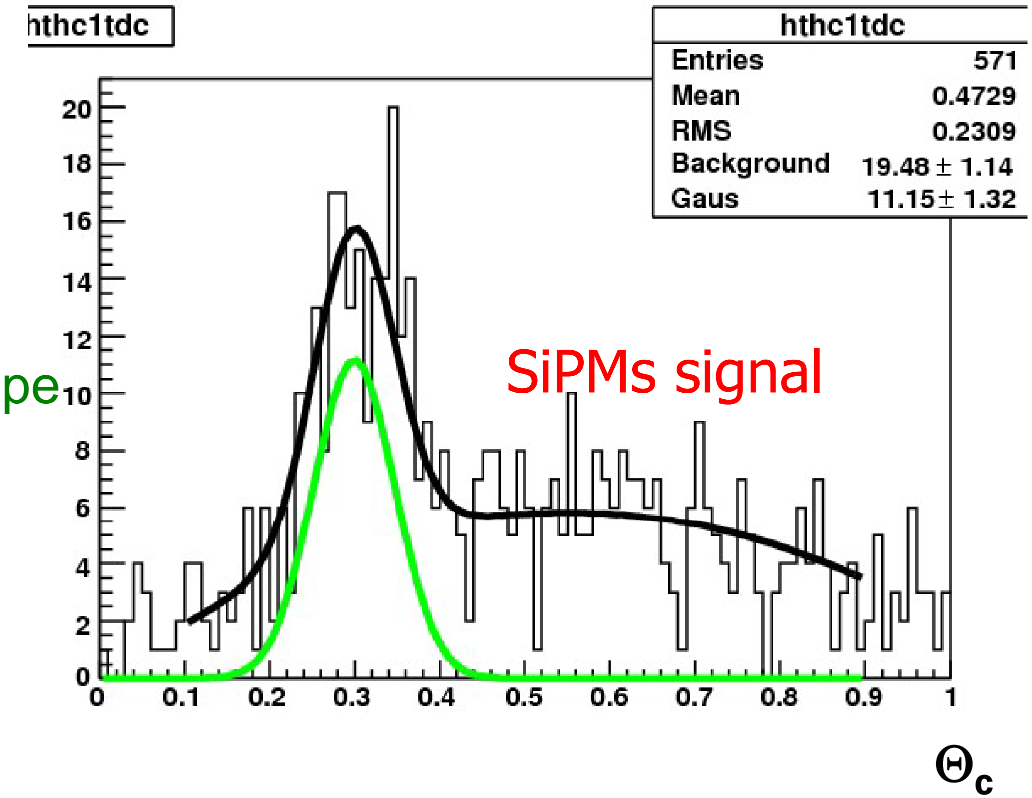
SiPM: Cherenkov angle distributions for 1ns time windows



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

SiPM Cherenkov angle distribution



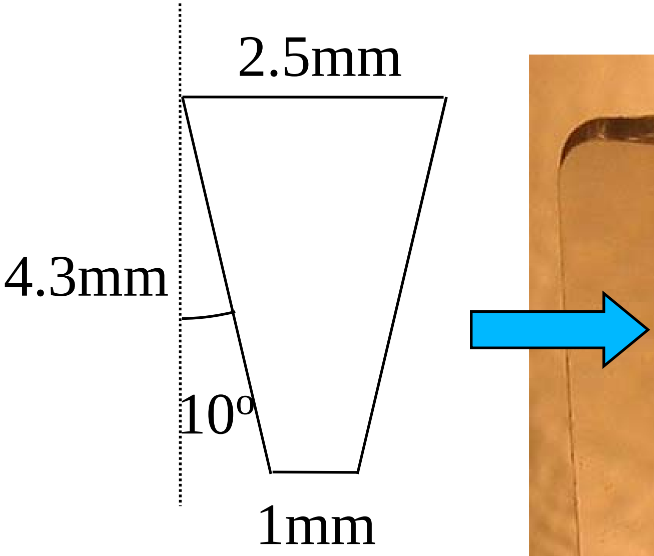


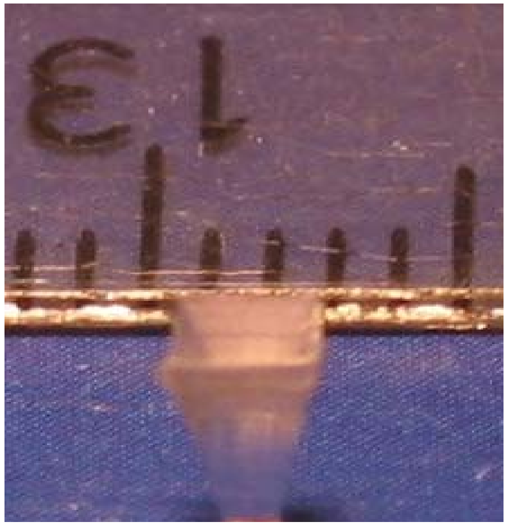
→ SiPMs give 4 x more photons than PMTs per photon detector area – in ~ agreement with expectations

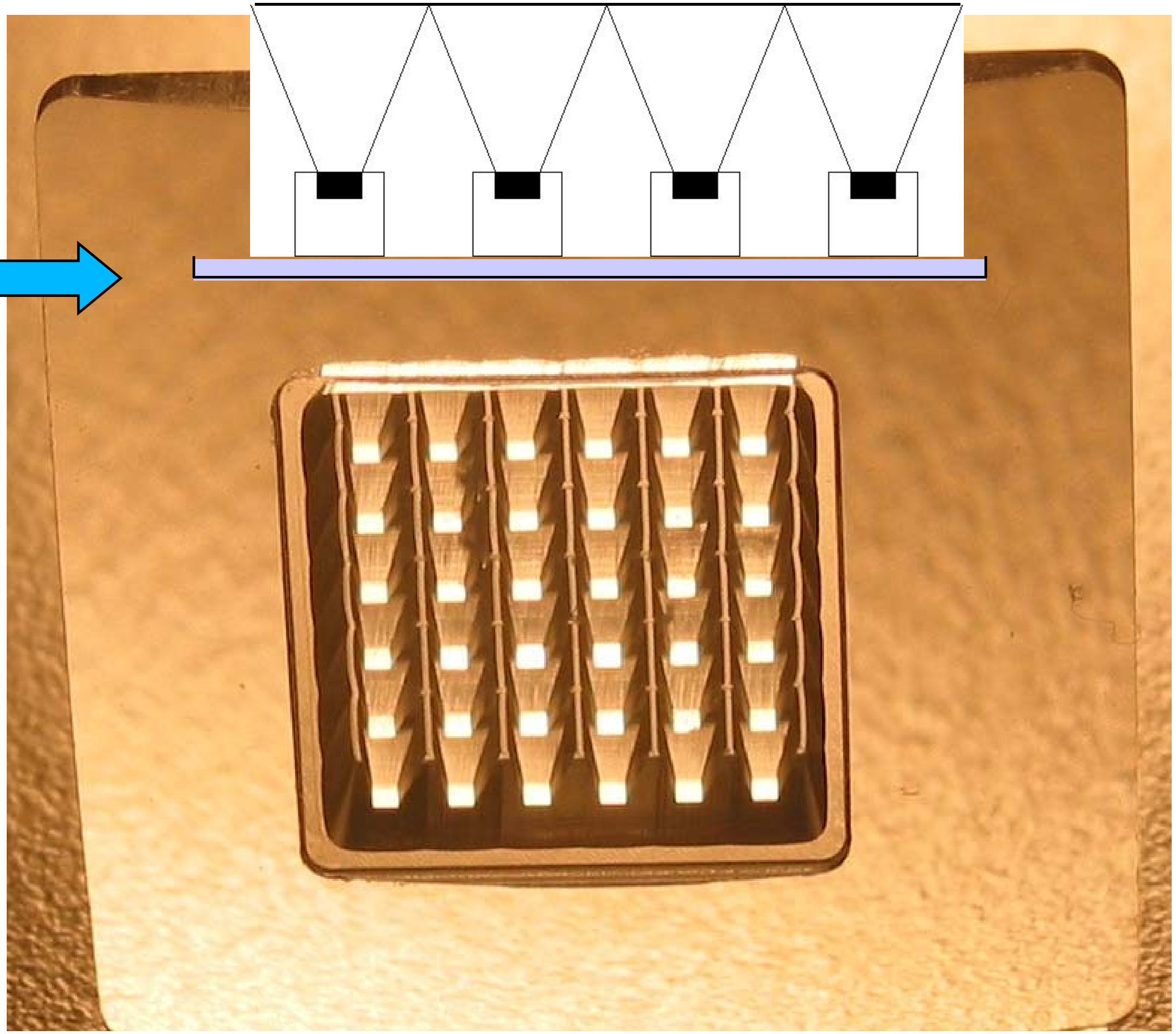
N.B. Signal/noise should improve by x3 with better tracking!

Detector module design

SiPM array with light guides



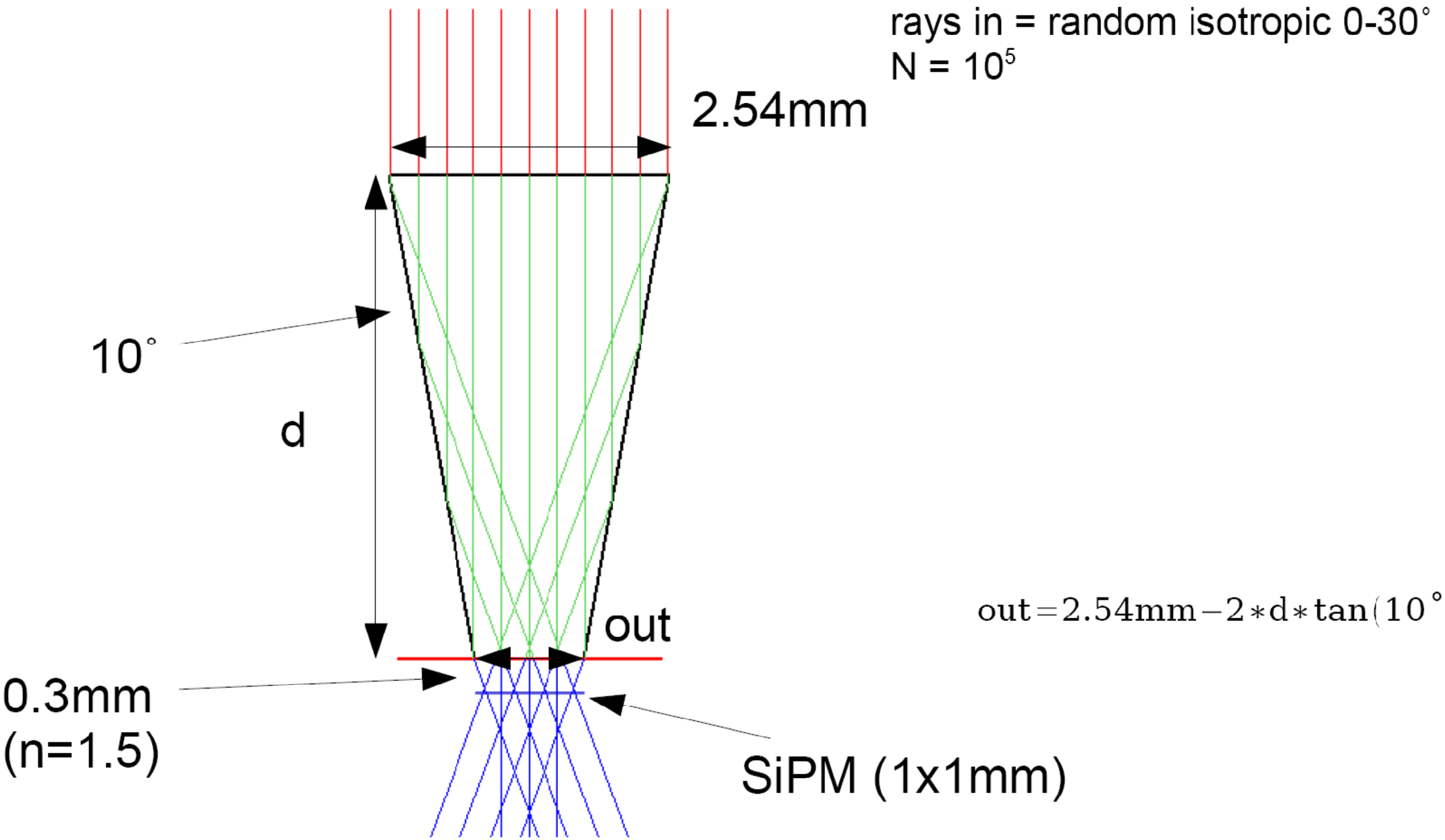




A multi-channel module prepared for a beam test at CERN

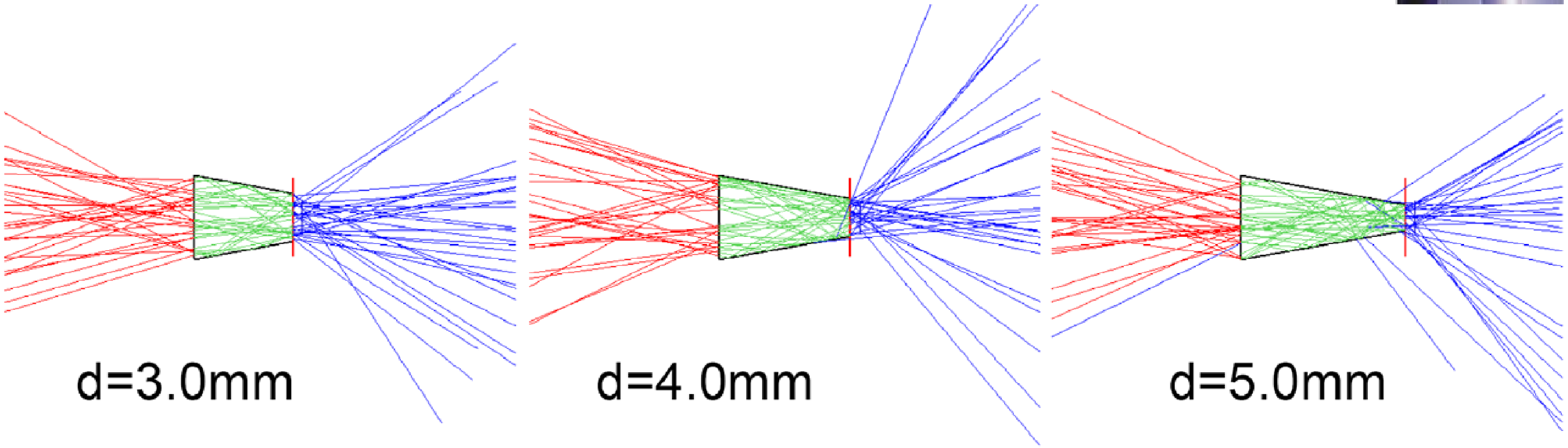
Light guide geometry optimisation

Light Guide Acceptance / (d and out)



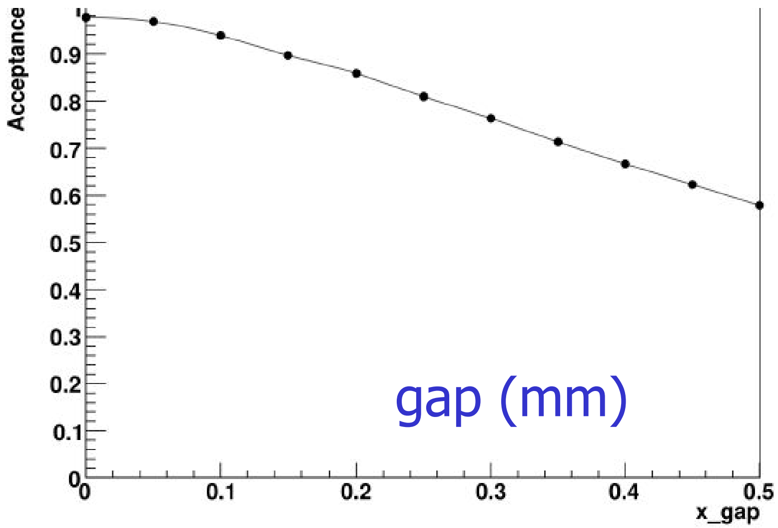
$$out = 2.54mm - 2*d*\tan(10^\circ)$$

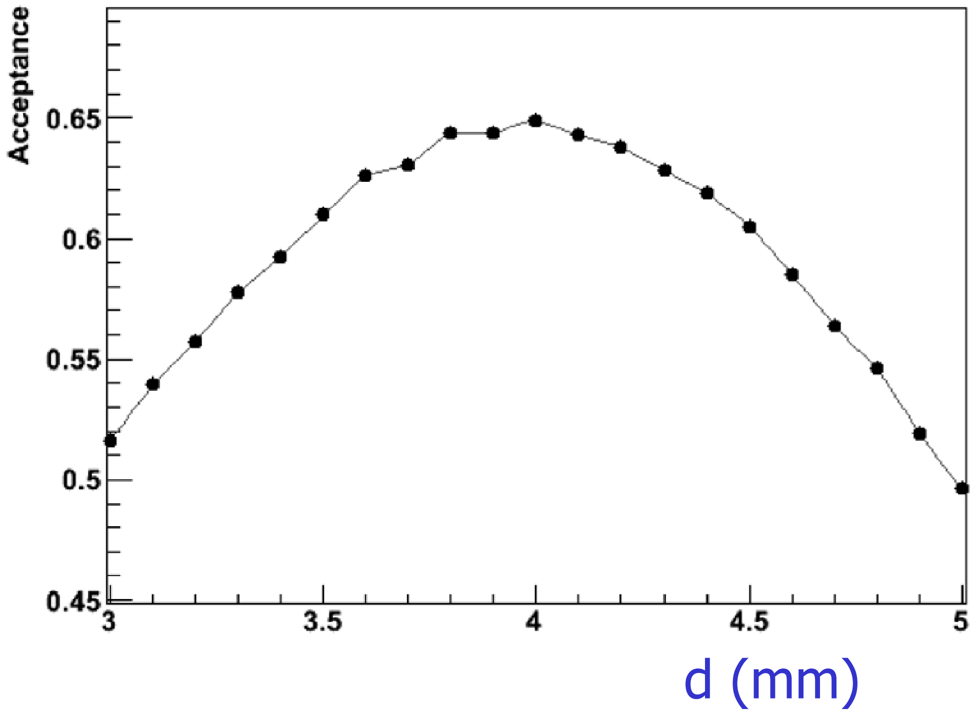
Light guide geometry optimisation



Light guide length optimisation

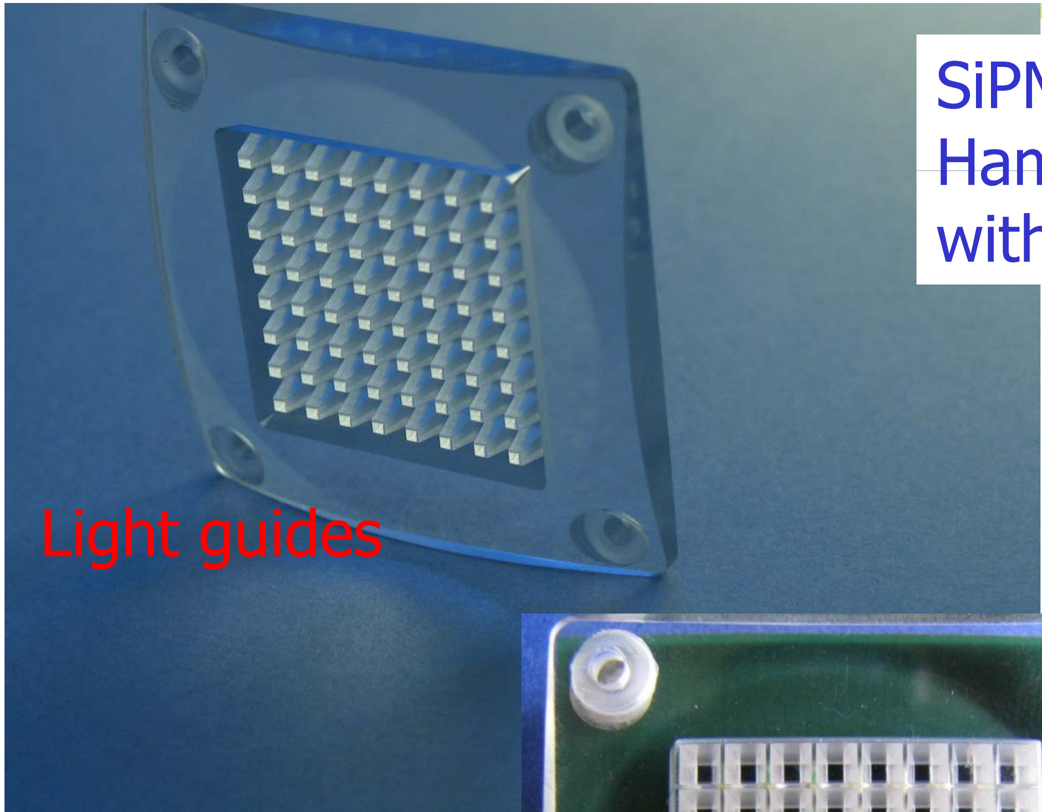
Light guide – SiPM gap

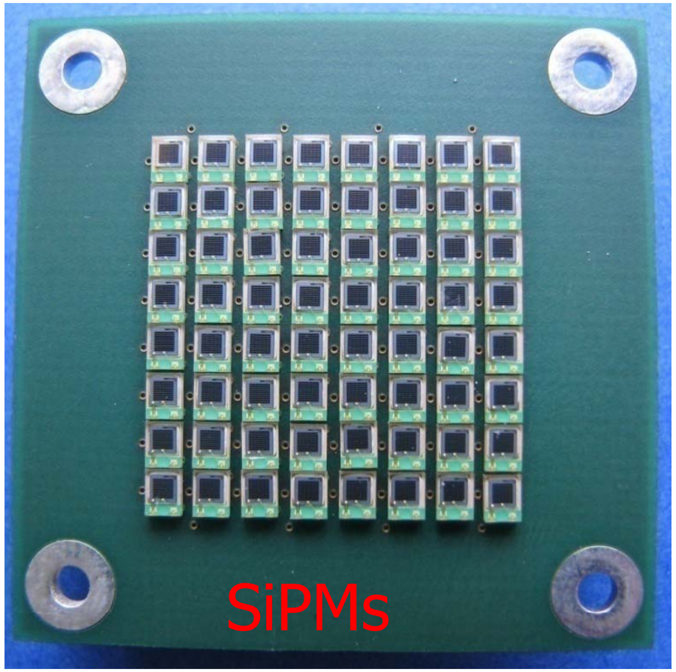




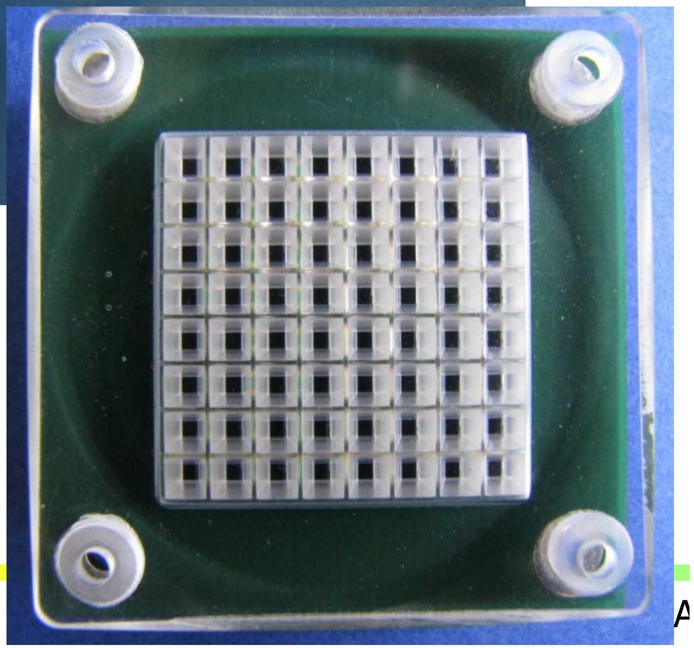
Detector module for beam tests at KEK

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



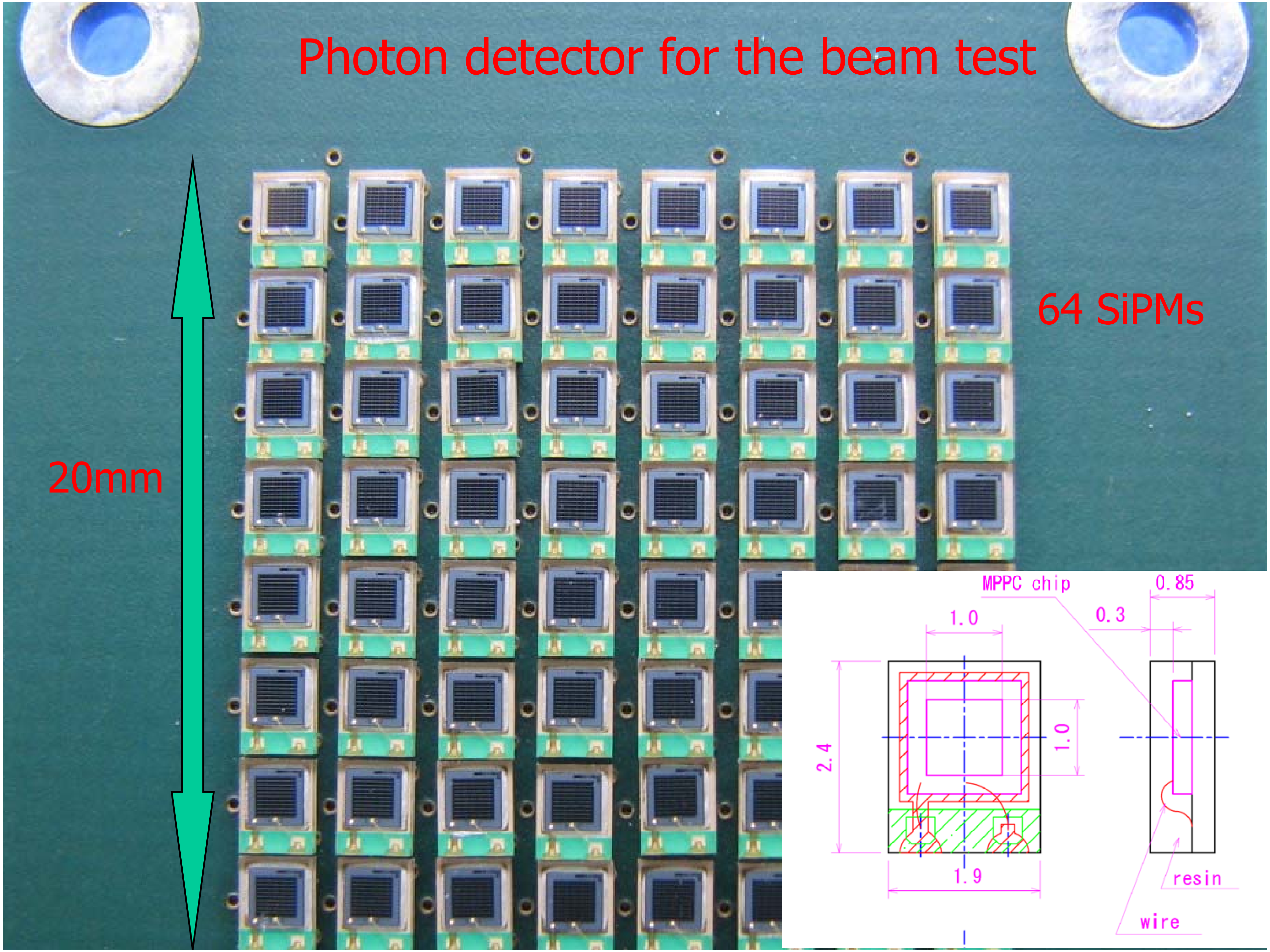


2cm

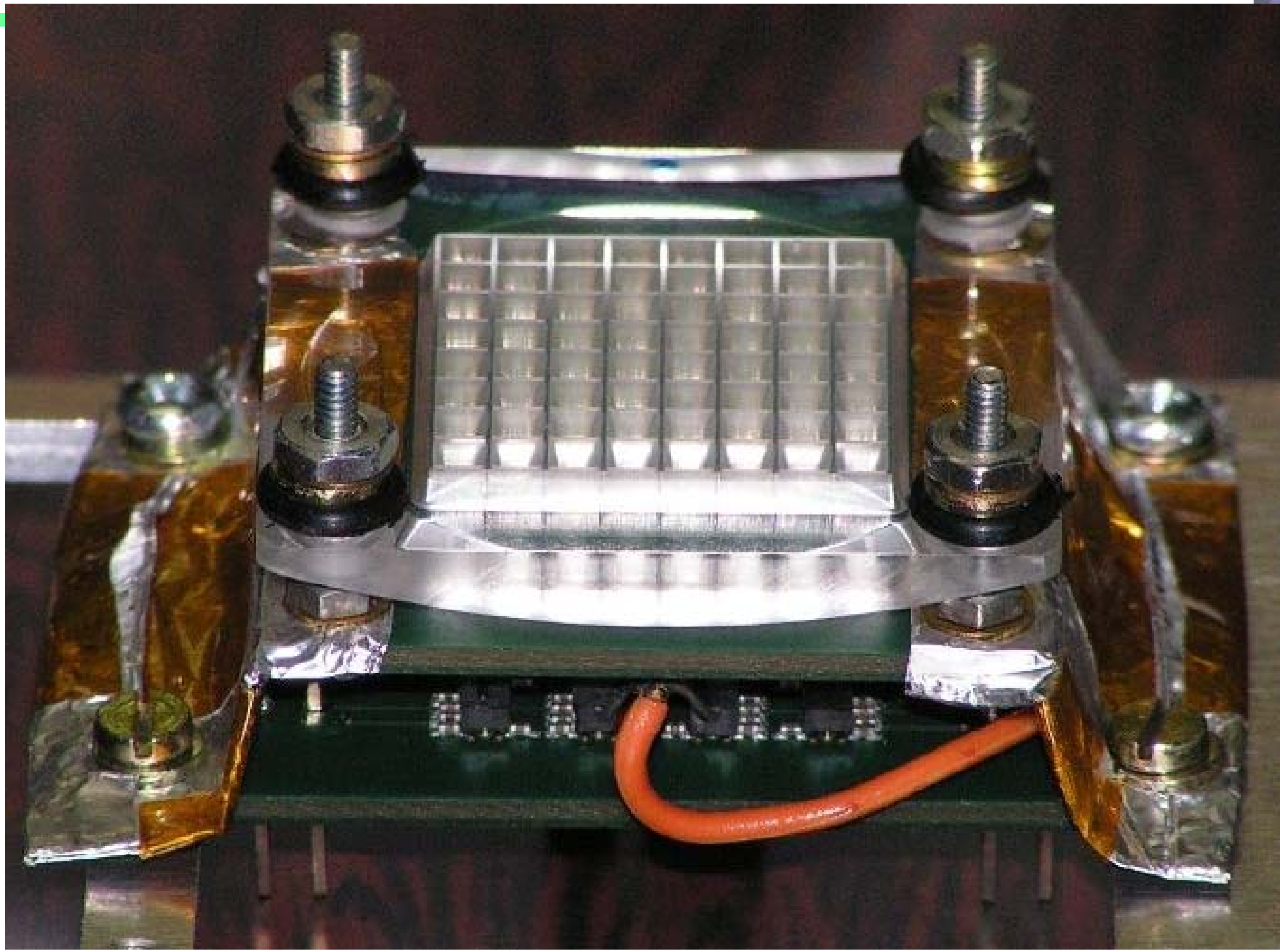


SiPMs + light guides

Photon detector for the beam test

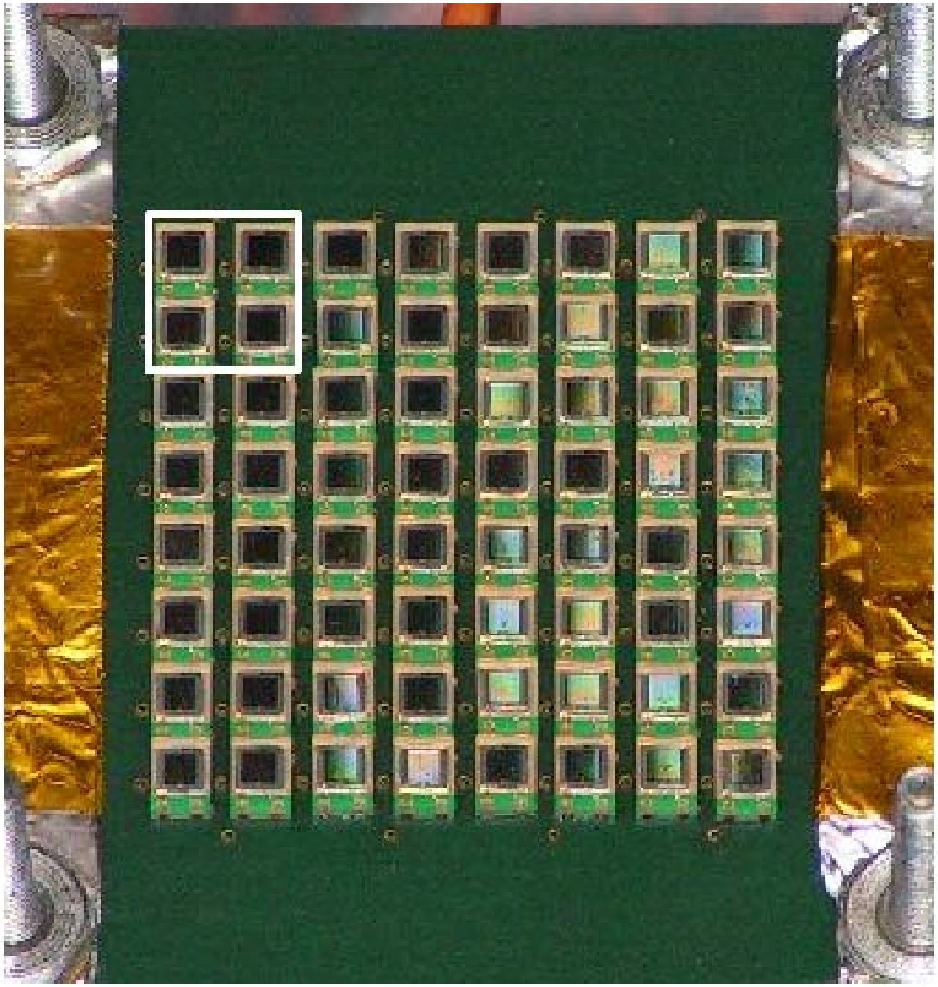
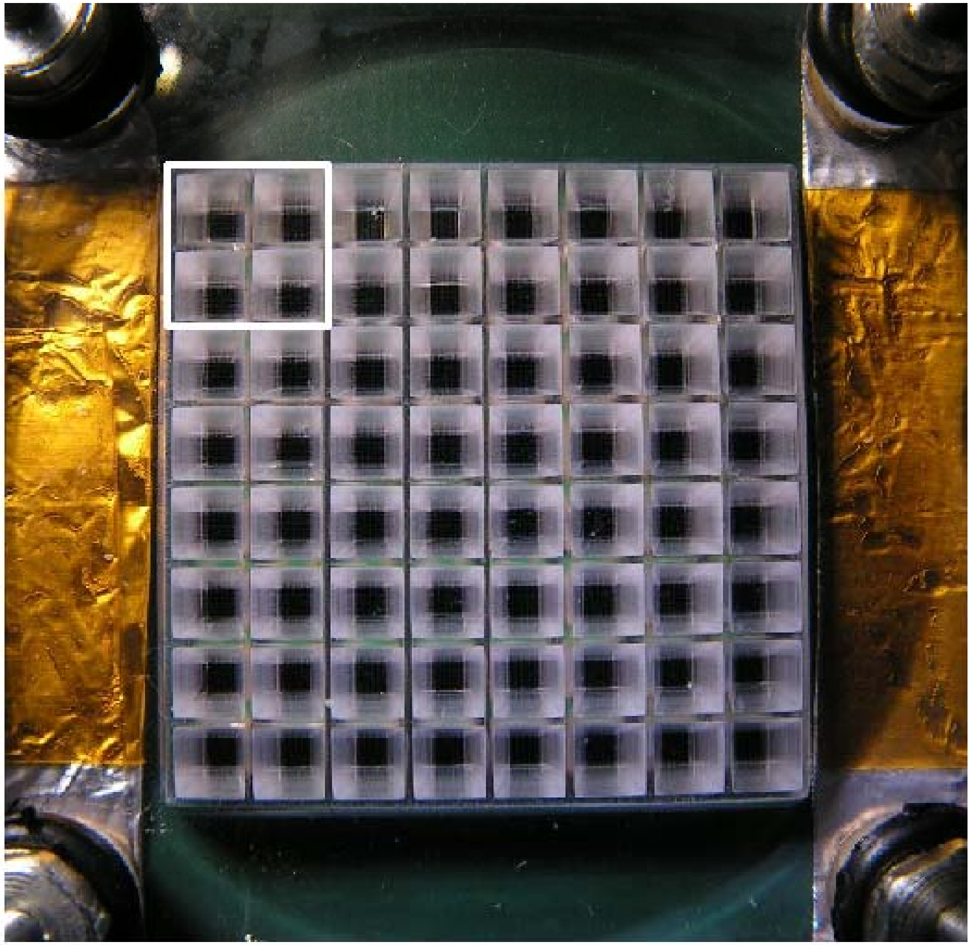


Fully assembled detector module



MPPC module 2

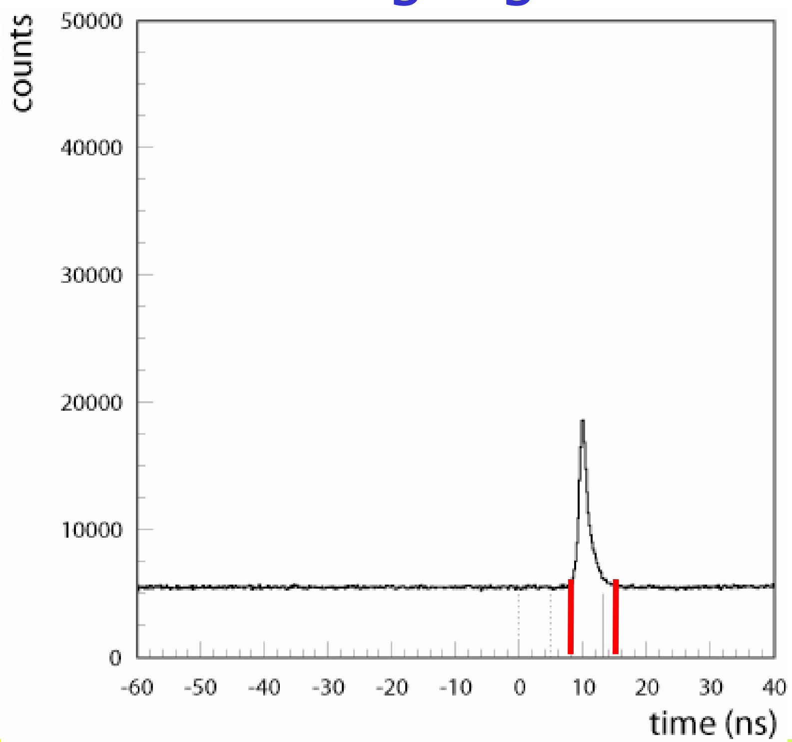
- pad size 5.08 mm, 4 mm2 active

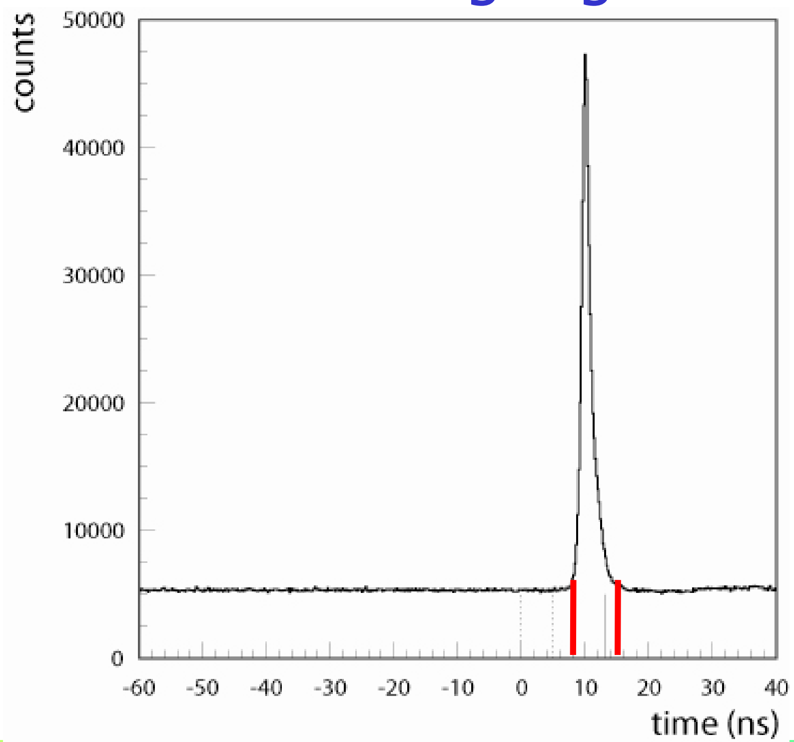
SiPM beam test: TDC distributions

- 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

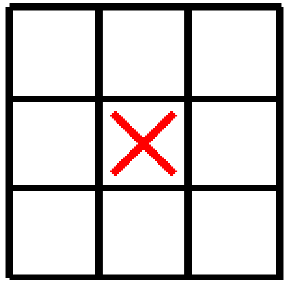
without light guides



with light guides

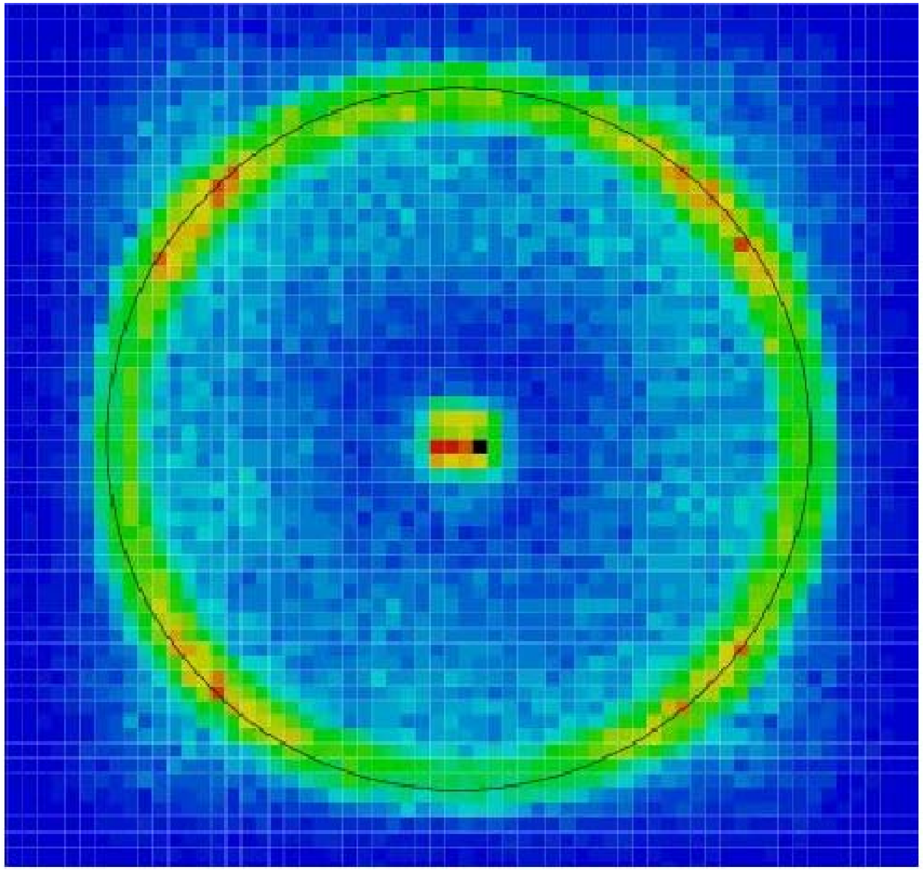


Ring images

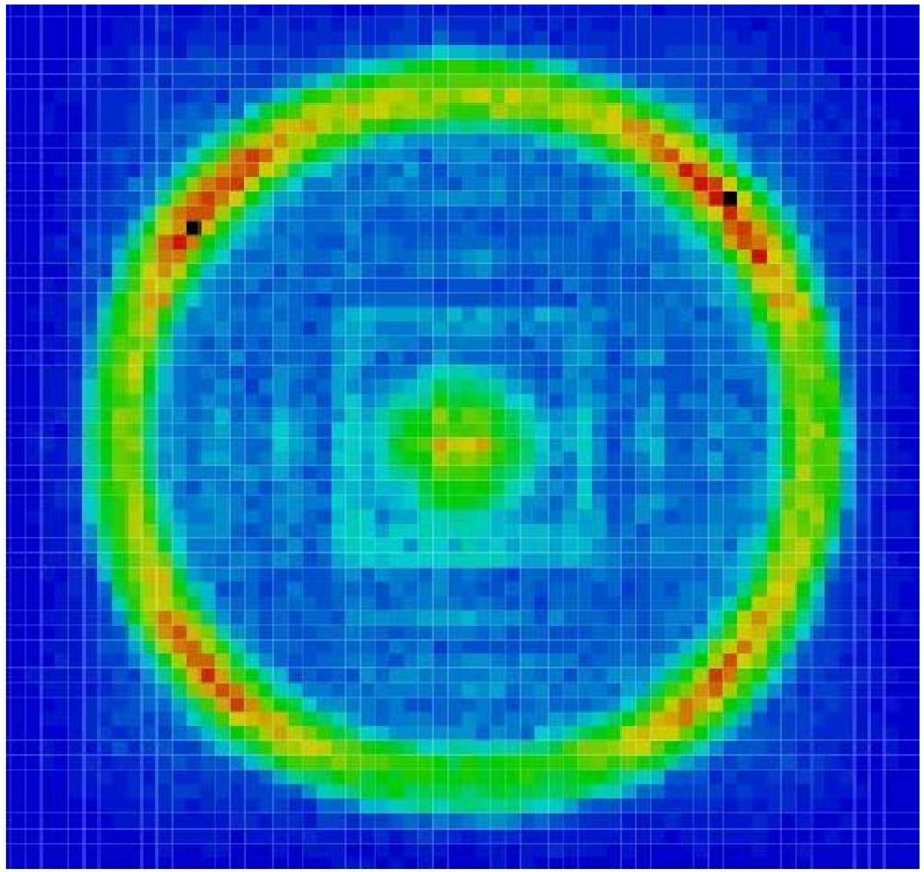


- module was moved to 9 positions to cover the ring area
- these plots show only superposition of 8 positions (central position is not included)

w/o light guides

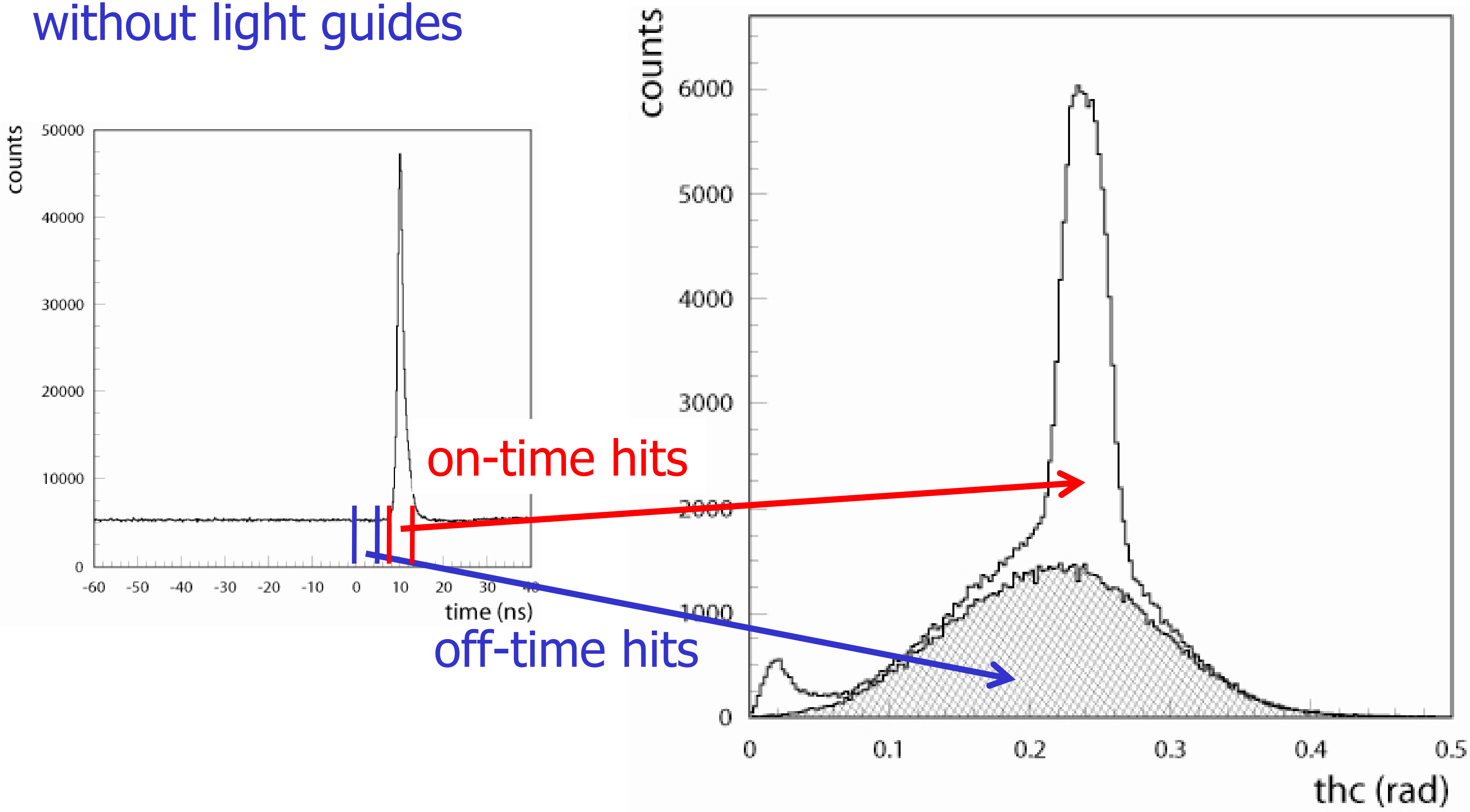


w/ light guides



SiPM beam test: Cherenkov angle distributions

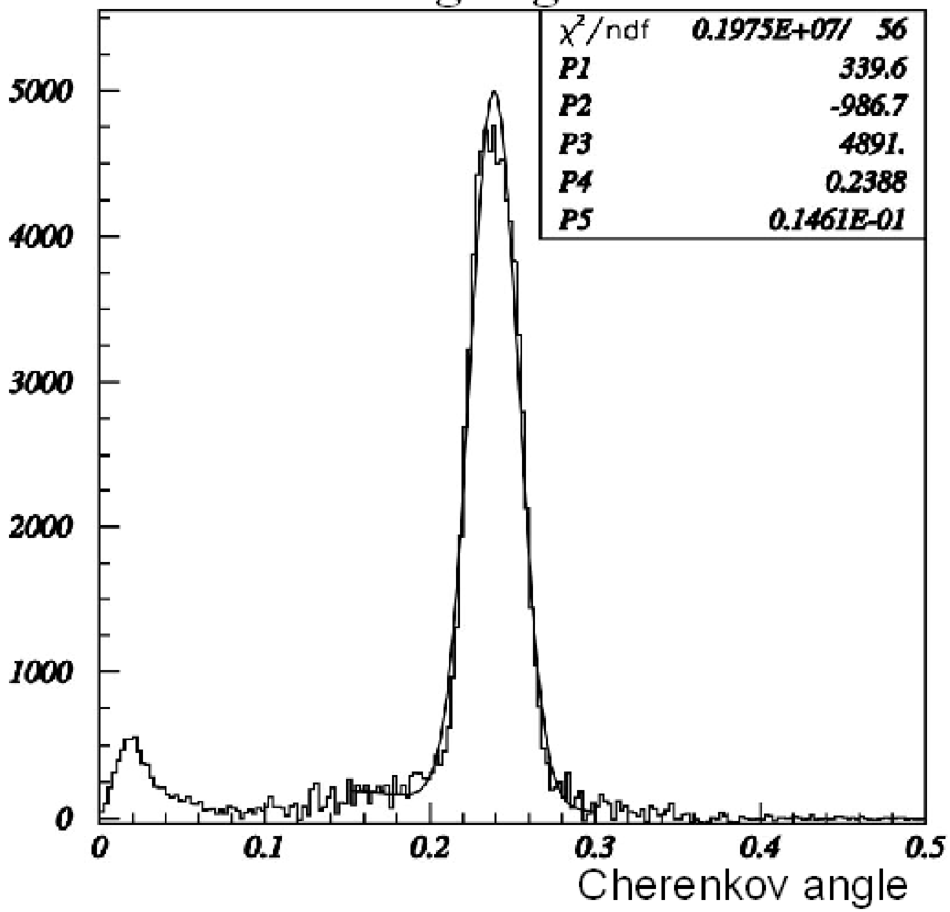
without light guides



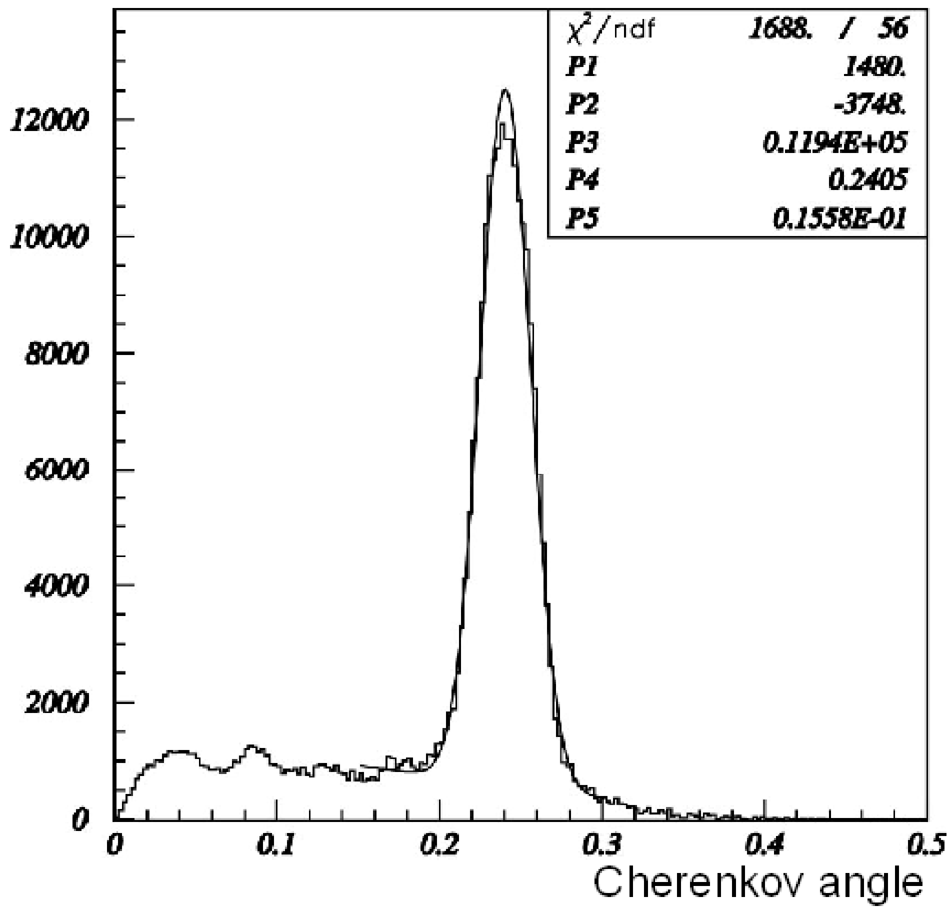
Cherenkov angle distributions

- 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 with PDE values as given by the producer, observed also by other groups

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**

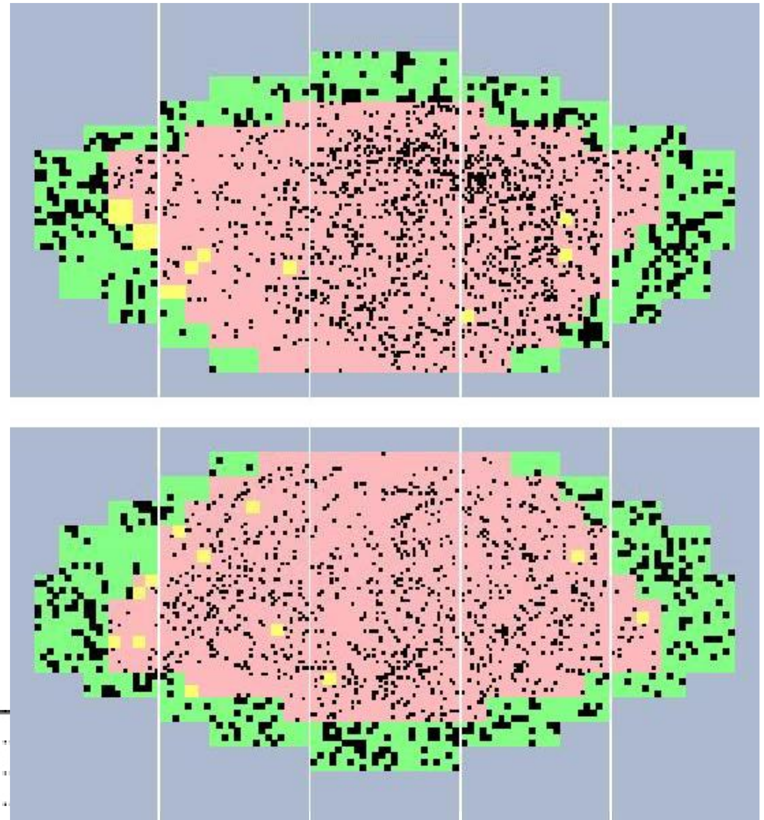
Can such a detector work?

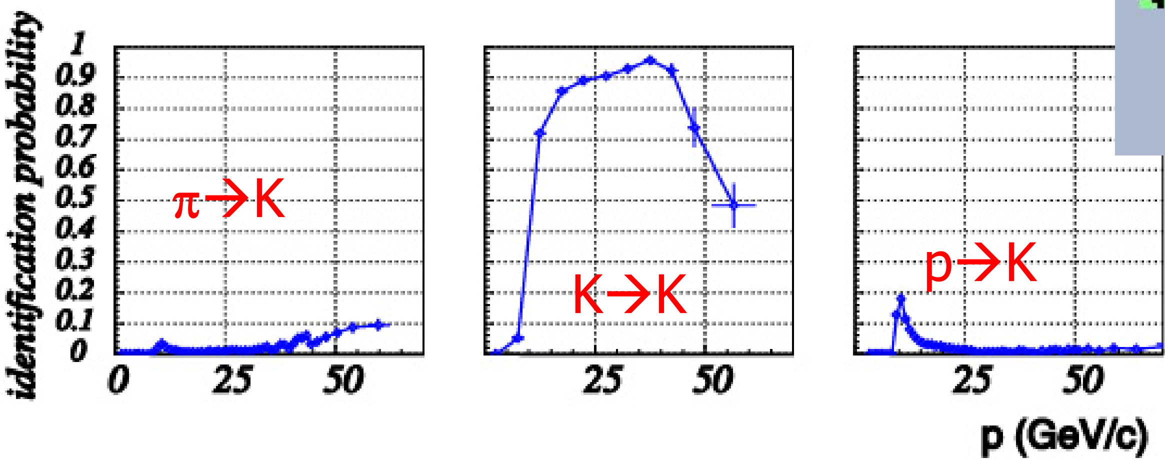
Using all the tricks, the background occupancy will still be high.

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.

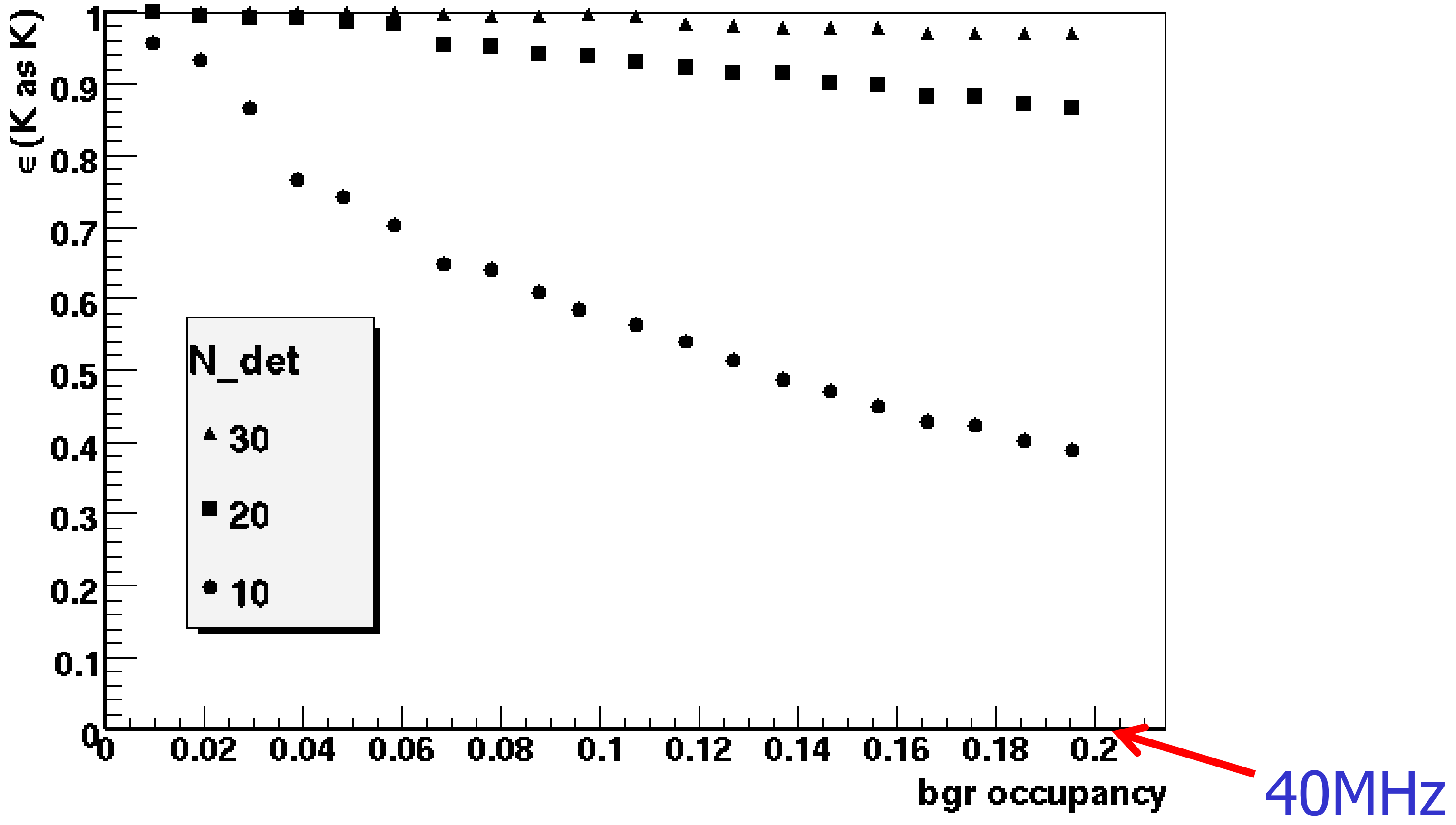
HERA-B RICH event





PID efficiency vs occupancy

K identification efficiency at 1% π missid. probability for different number of photons per ring vs background level



→ Again OK if the number of photons >20

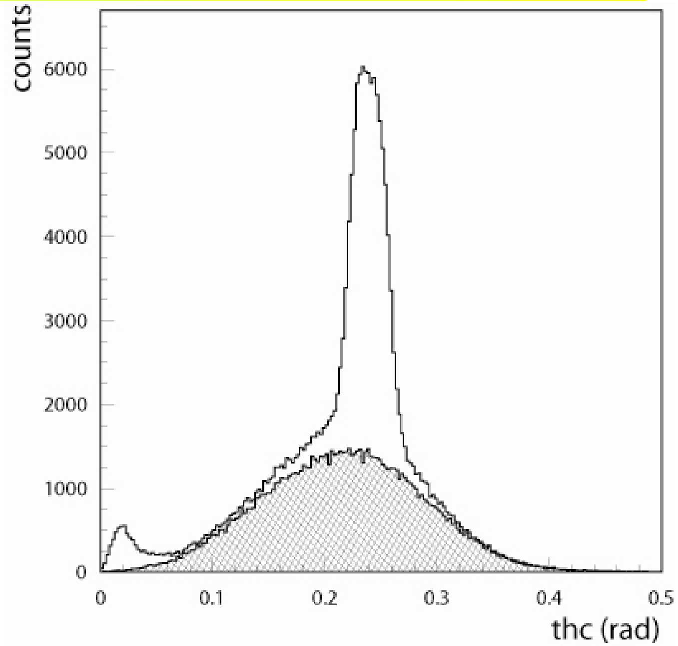
Summary of tests

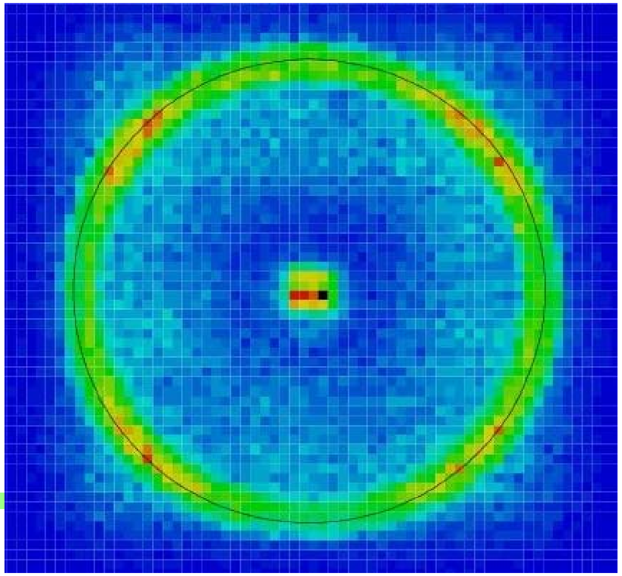
We have proven that SiPMs can be used as single photon sensors in Ring Imaging Cherenkov (RICH) counters.

Light guides improved signal/noise.

The sensor is easy to operate, robust.

The number of photons is high enough to allow for sufficient kaon/pion separation even at high dark count rates.



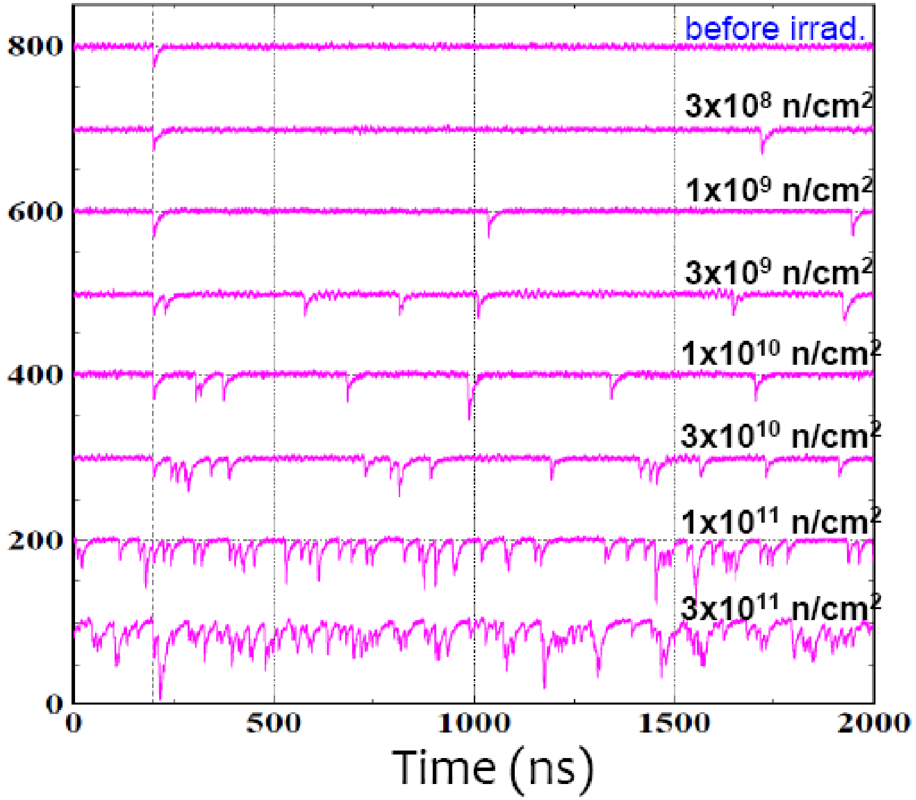


Can we use it in Belle-II?

- Cost
- Radiation damage

Radiation damage

I.Nakamura, JPS meeting, Sep. 2008



Becomes very hard to operate above the neutron fluence of 10^{11} n cm^{-2}

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

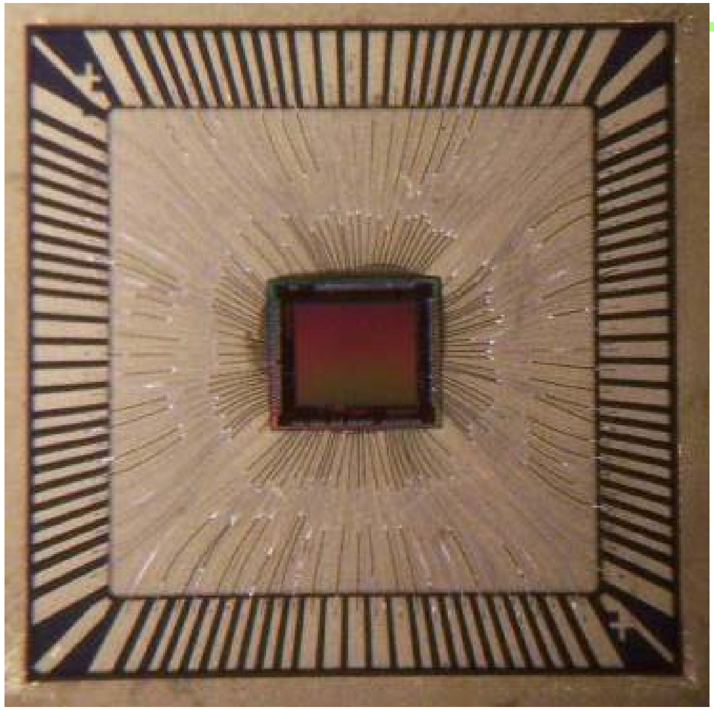
→ Worst than the lowest line

→Very hard to use the presently available SiPMs as single photon detectors for the whole lifetime of a Super B factories because of radiation damage by neutrons

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

Read out: Buffered LABRADOR (BLAB1) ASIC

Gary Varner, Larry Ruckman (Hawaii)

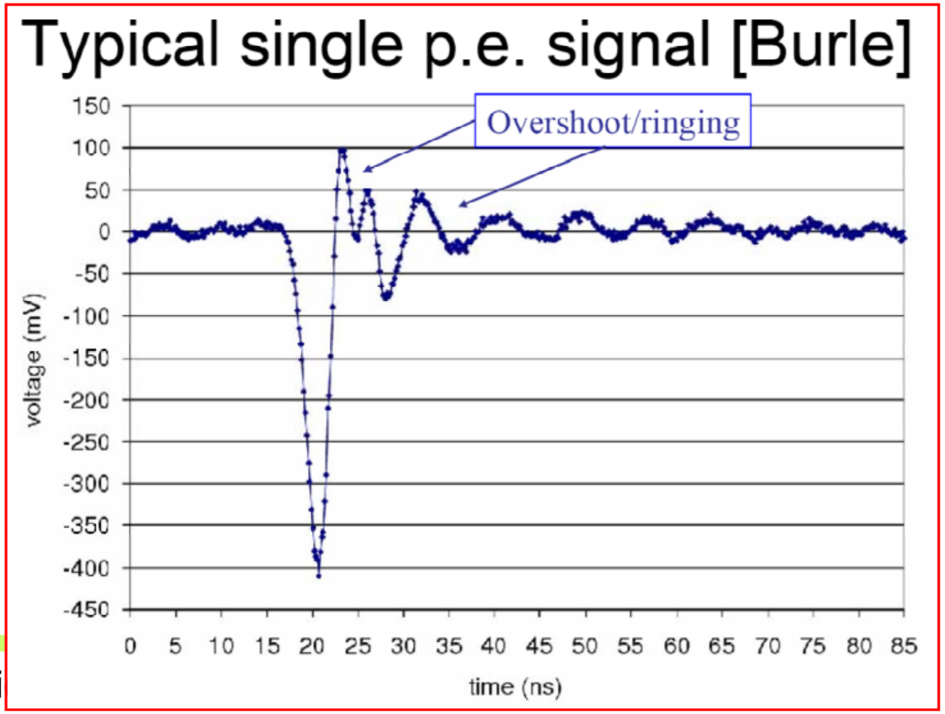


3mm x 2.8mm, TSMC 0.25um

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

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

Being used in the focusing DIRC tests at SLAC



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.

Novel photo-detectors are being developed for operation in high magnetic fields. They will play an essential role in the next generation of B physics experiments at Super B factories, as well as at hadron structure experiments.

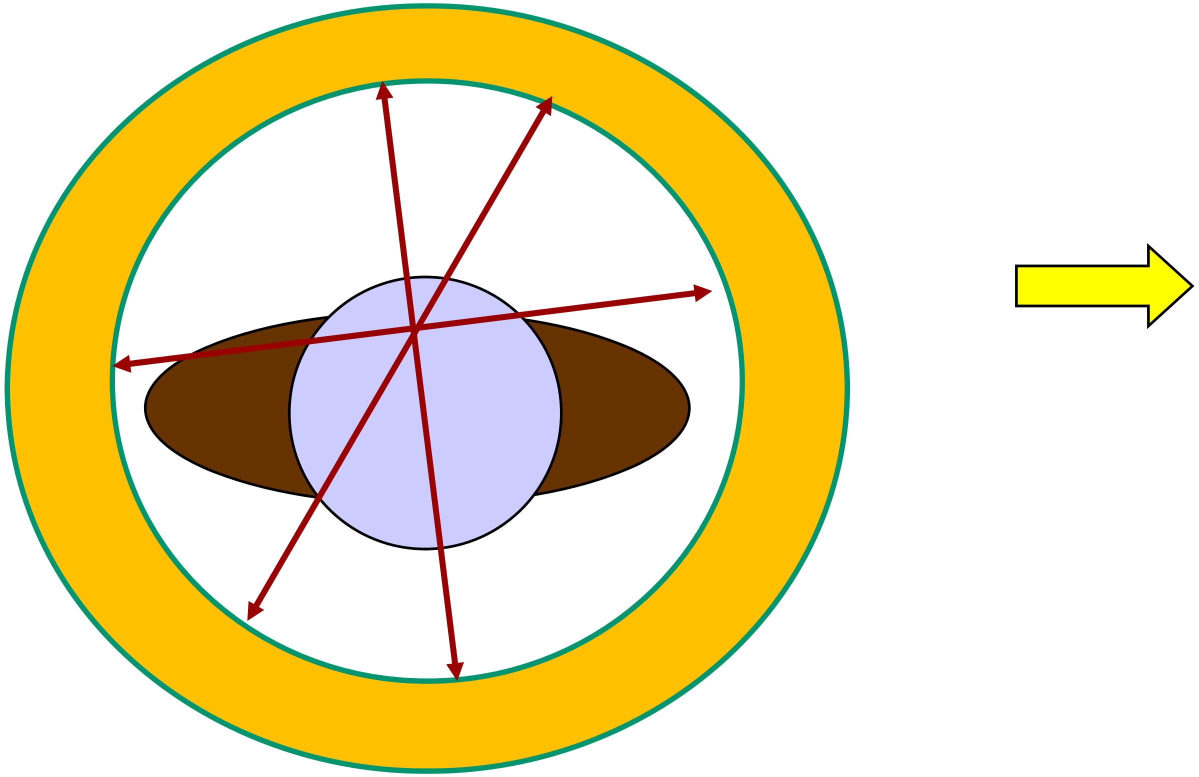
Geiger mode APDs (SiPMs) have been demonstrated to work well as single photon detectors in spite of the high dark count rates.

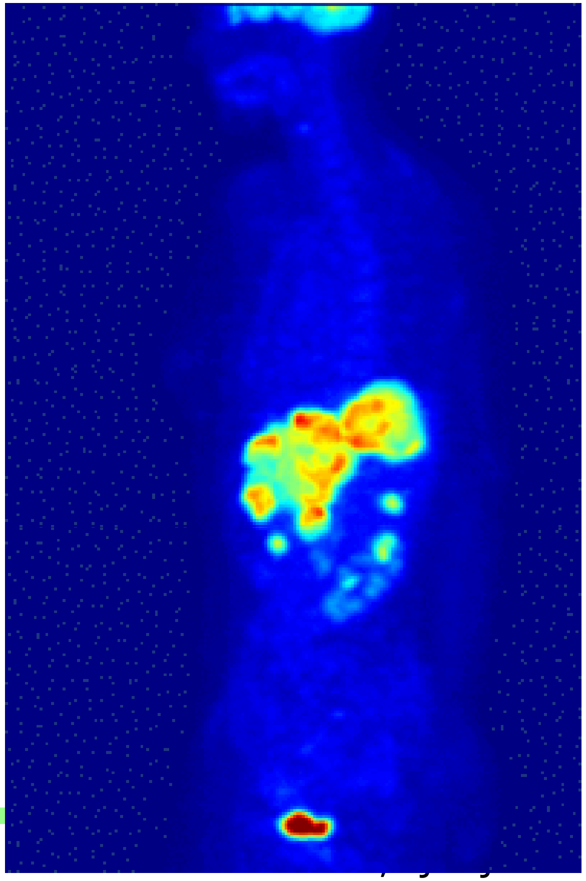
Radiation damage of the available devices is at present limiting their use in Super B factories.

A very interesting application of SiPMs as scintillation light sensors for PET imaging is opening a new field of research.

PET: positron emission tomography

Beta+ emitters (e.g. radioactive fluor) produce two collinear gamma rays. These gamma rays are detected by a combination of a scintillation crystal and a photo-sensor. From the lines given by the hit pairs, the source distribution is reconstructed.

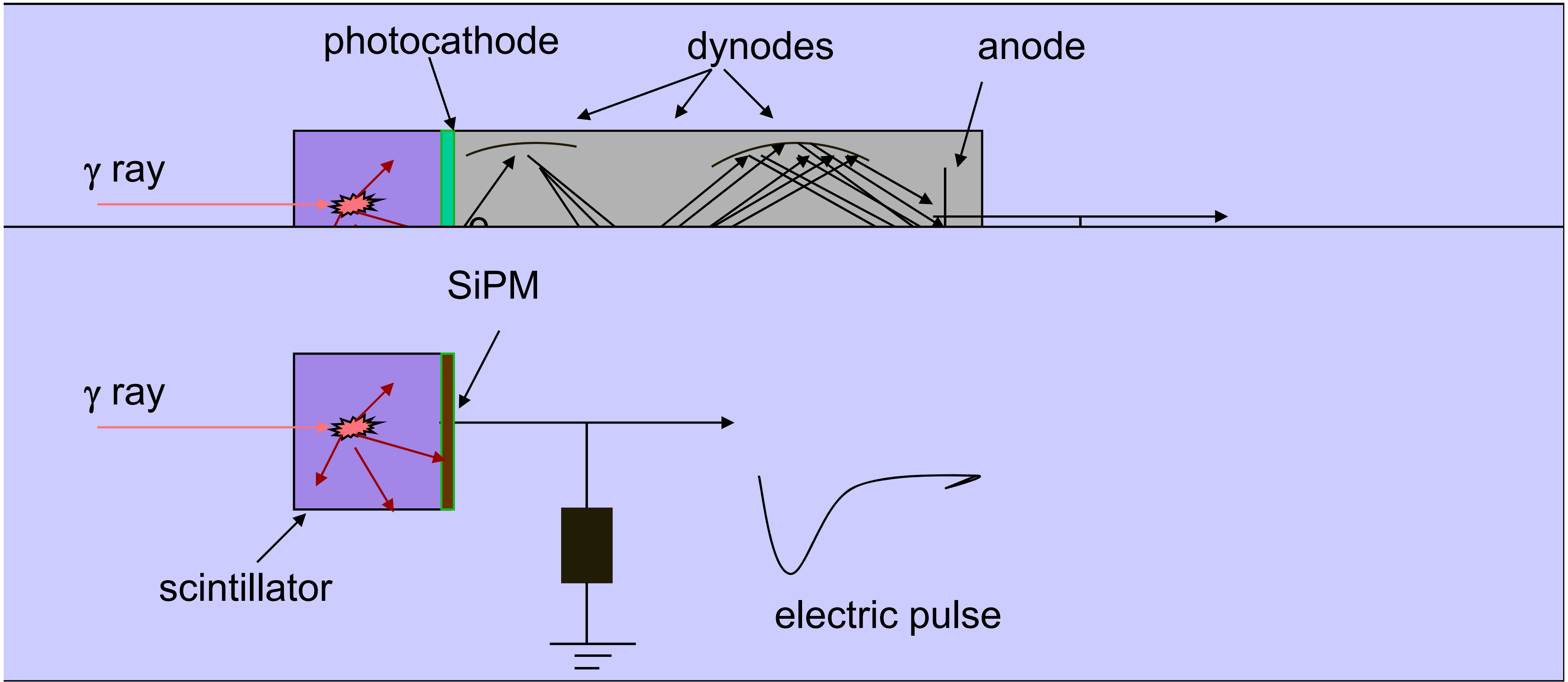




PET with SiPMs

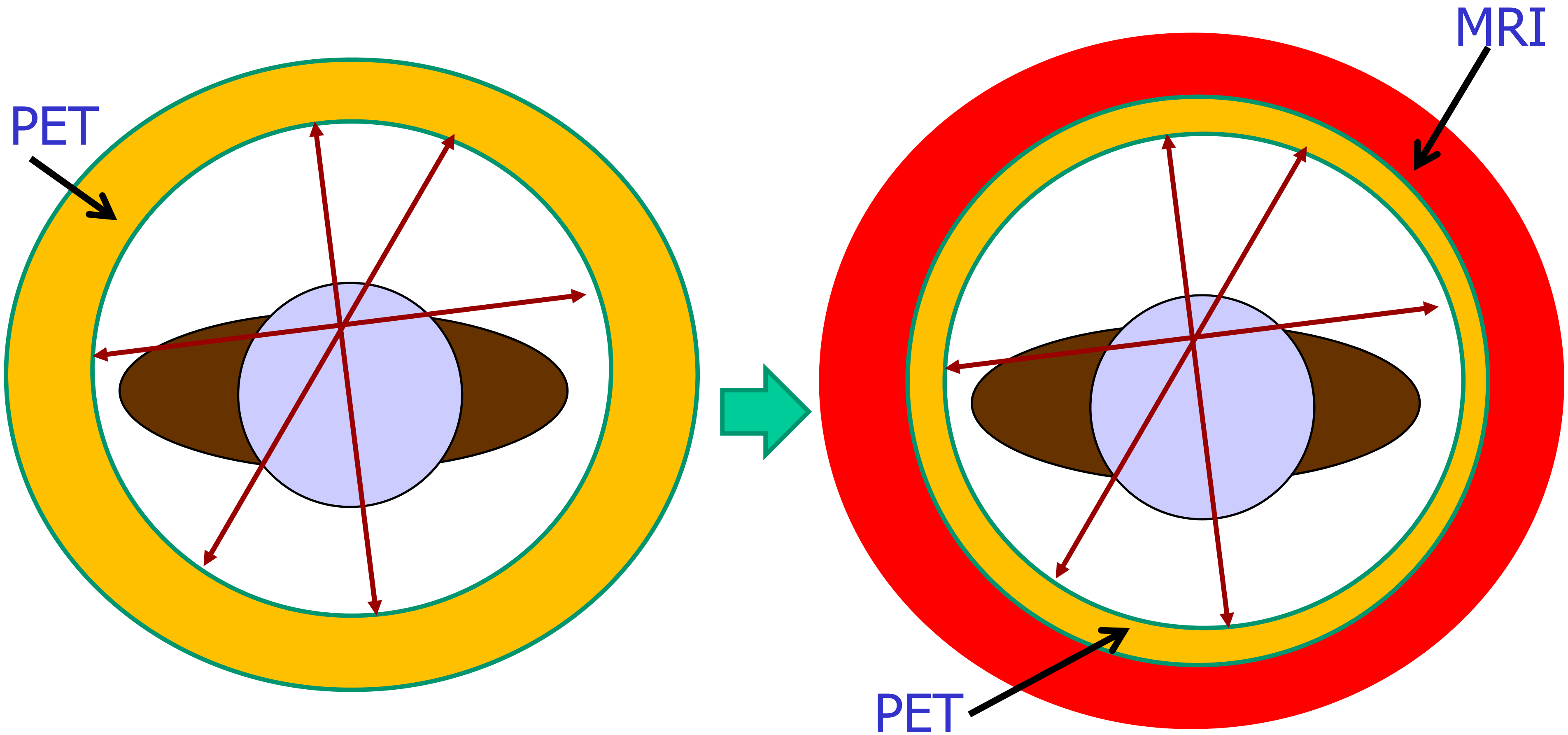
Traditionally, PMTs are used as light sensors for PET scanners.

SiPMs: much smaller, no high voltage needed, works in high magnetic fields (several T).

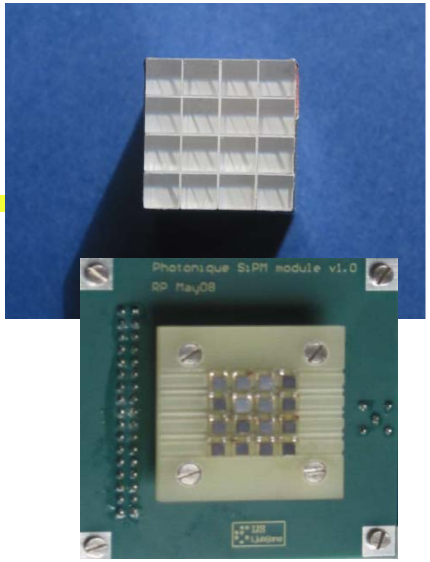


PET with SiPMs

The use SiPMs could allow for a dual modality imaging – at the same time perform magnetic resonance (MRI) **and** PET imaging – an important improvement for a faster and better diagnostics!



PET with SiPMs: tests

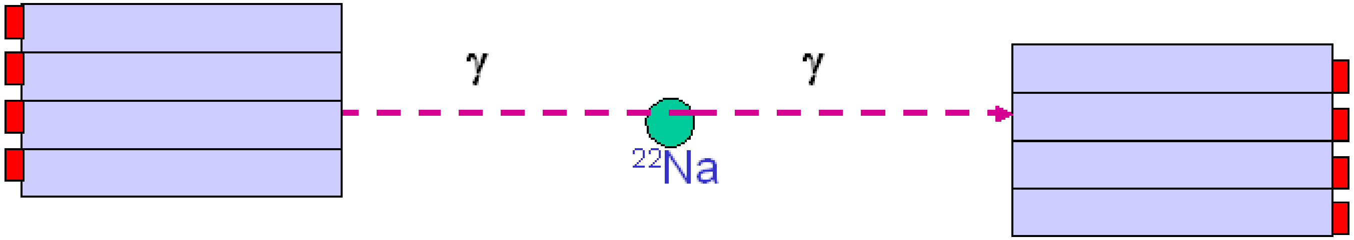


Test PET modules with:

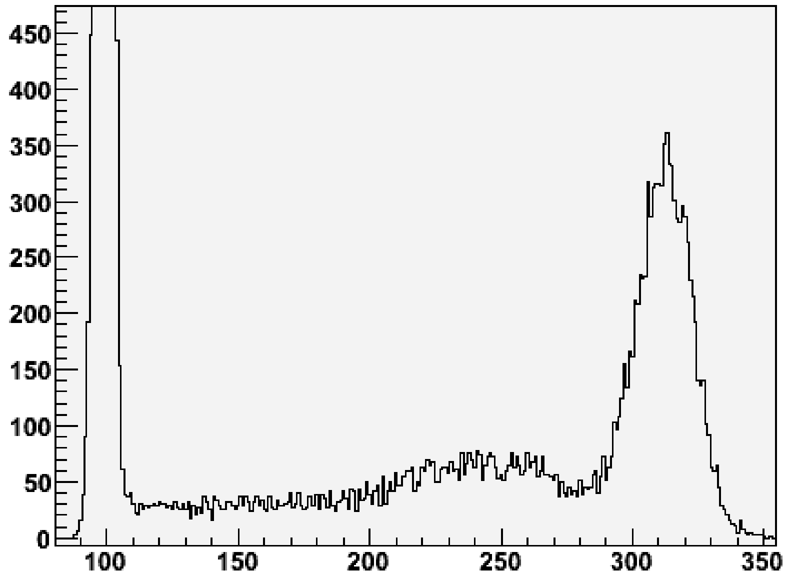
4x4 arrays of LYSO crystals (4.5 x 4.5 x 20(30) mm^3)

16 SiPMs (Photonique 2.1x2.1 mm^2)

16 SiPMs (Hamamatsu 3x3 mm^2)



One channel used as a trigger



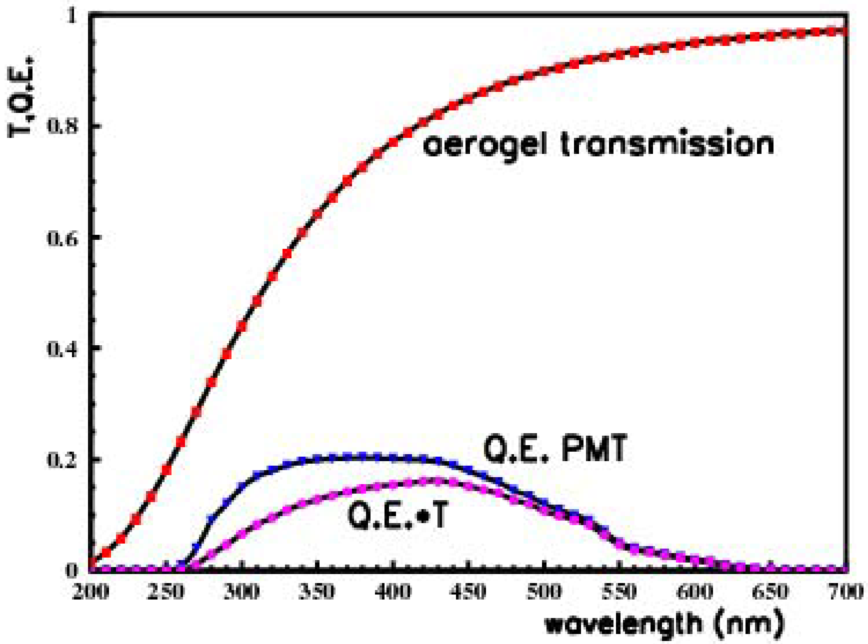
Also interesting: SiPMs have a fast response (~100ps rms)
→ important for TOF-PET

Back-up slides

Photon detectors for the aerogel RICH

Needs:

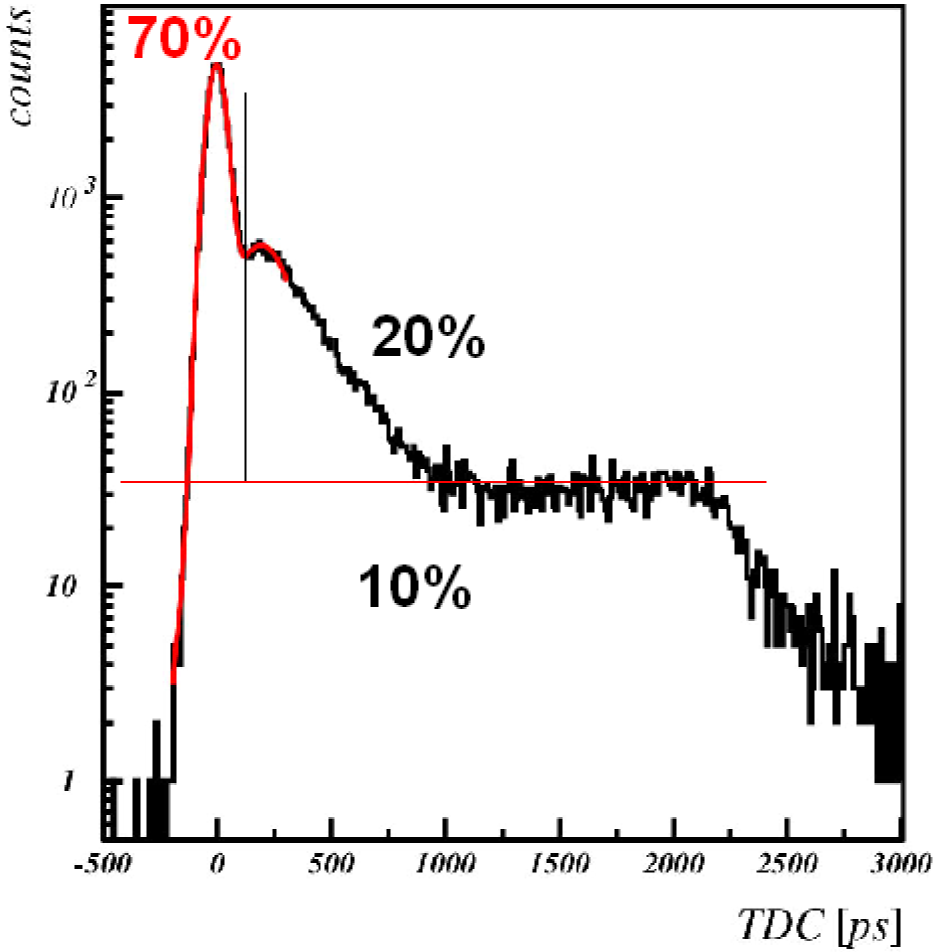
- Operation in high magnetic field (1.5T)
- High efficiency at λ>350nm
- Pad size ~5-6mm



Candidates:

- large area H(A)PD of the proximity focusing type
- MCP PMT (Burle 85011)
- SiPMs

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.

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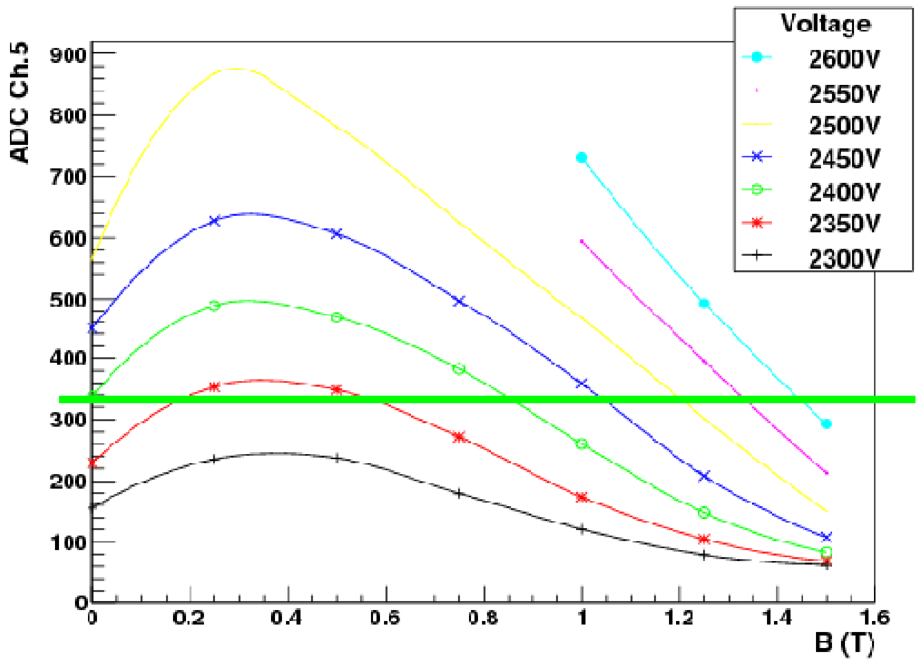
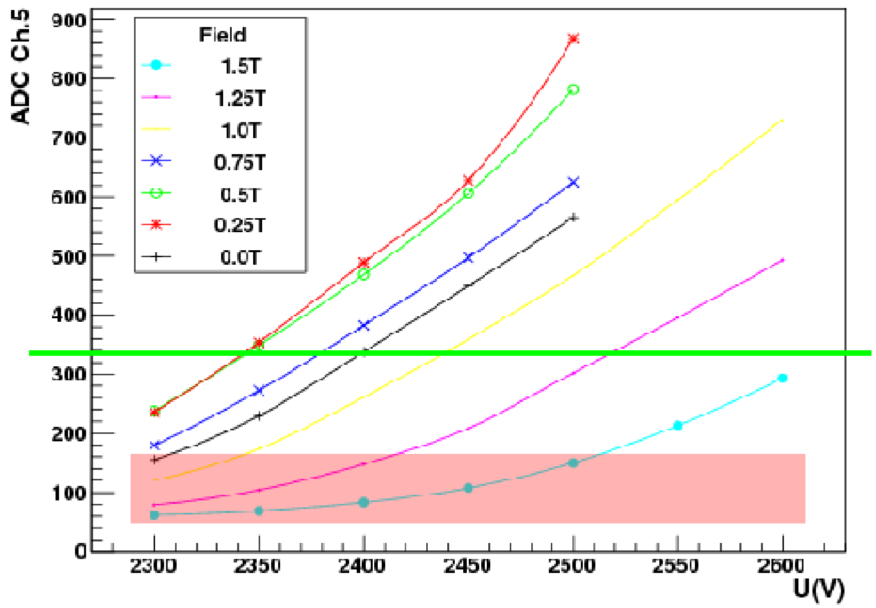
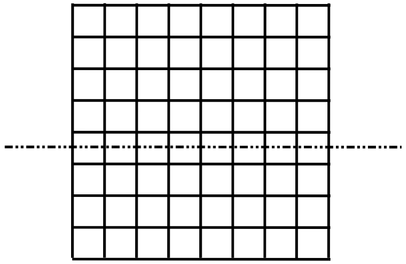
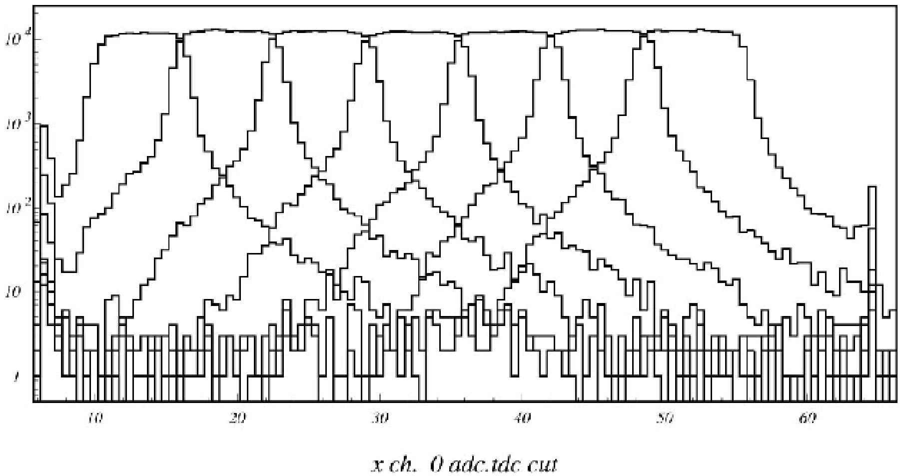




→ More talks on MCP PMTs during this workshop – W. Plass and A. Lehmann

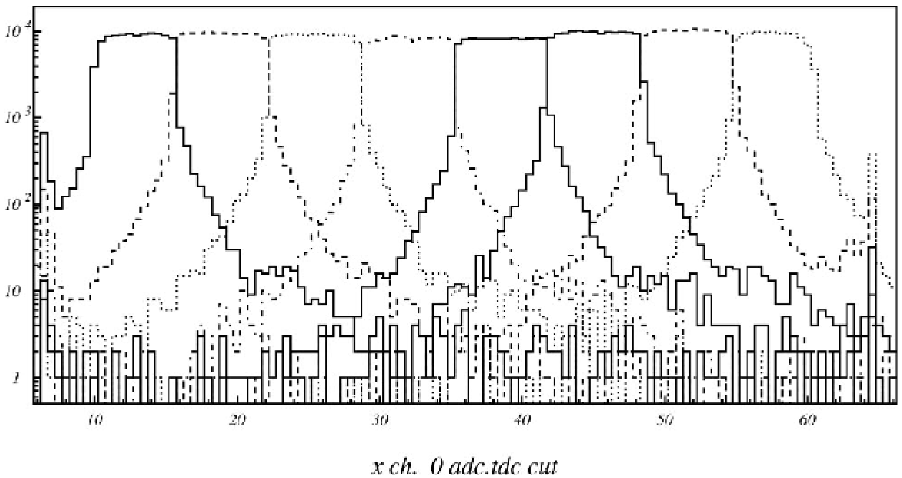
MCP PMT: sensitivity





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

B = 0 T,
HV = 2400 V

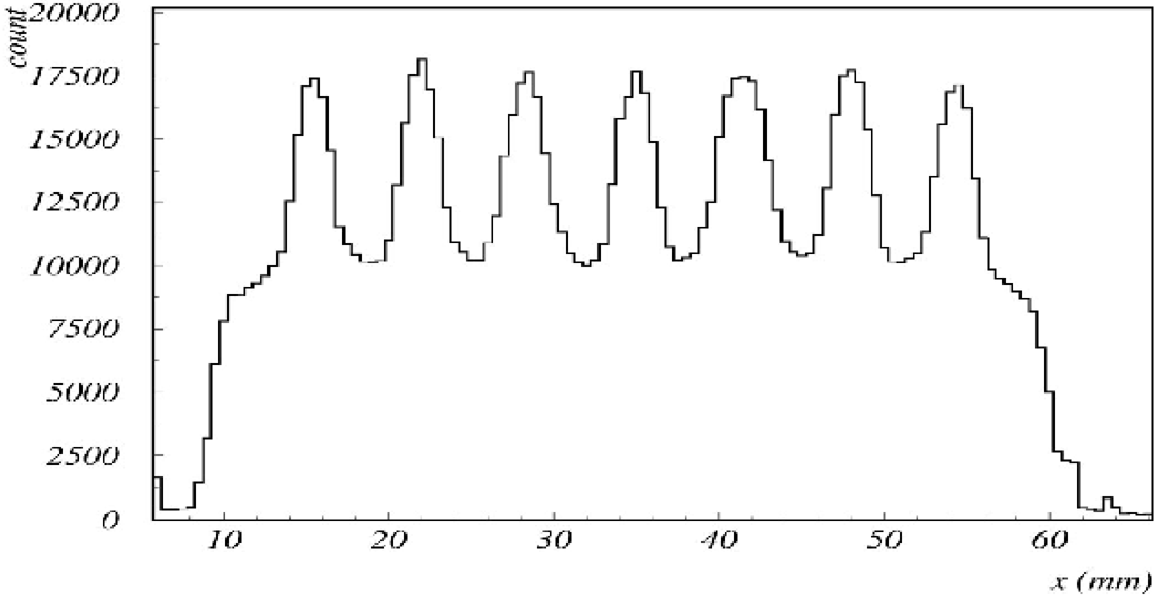


B = 1.5 T,
HV = 2500 V

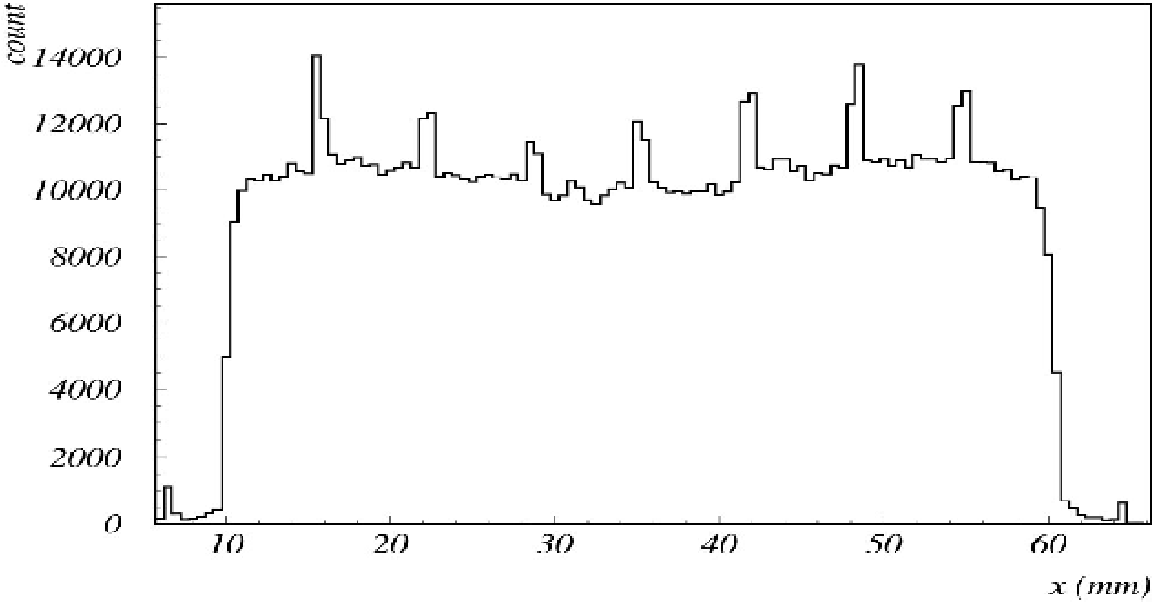
In the presence of magnetic field, charge sharing and cross talk due to long range photoelectron back-scattering are considerably reduced.

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

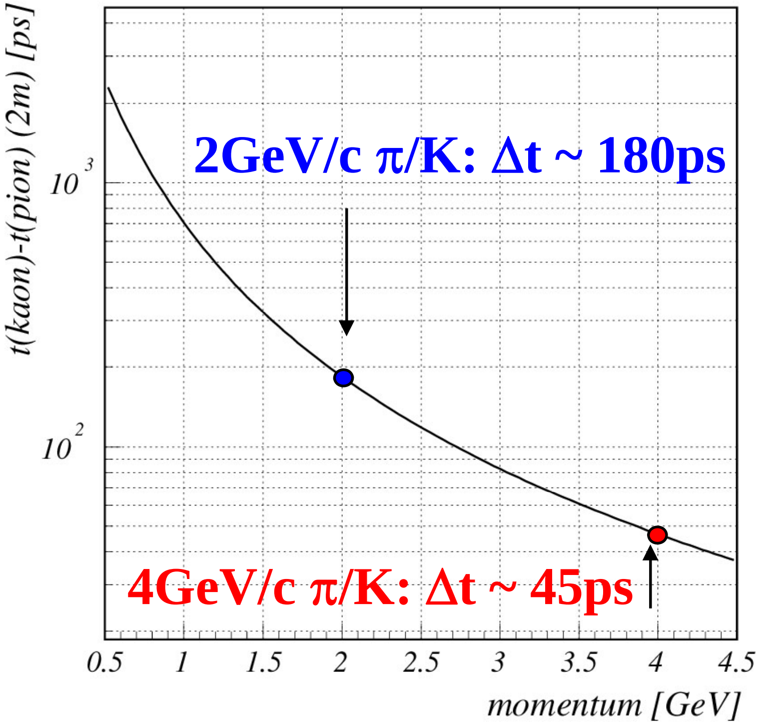


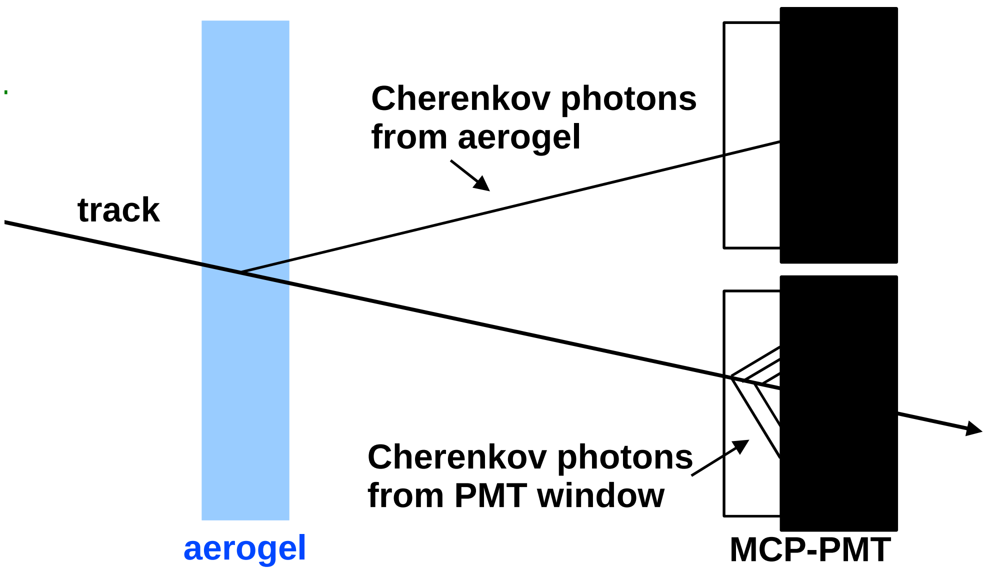
- HV = 2500 V
- B = 1.5 T

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 →



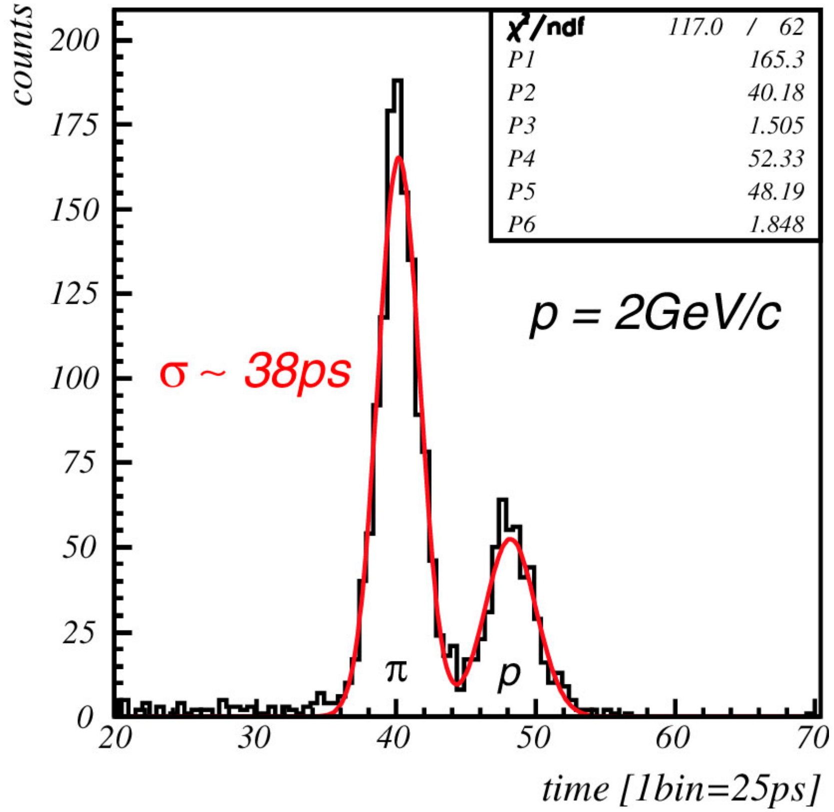


For time of flight: use Cherenkov photons emitted in the PMT window

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

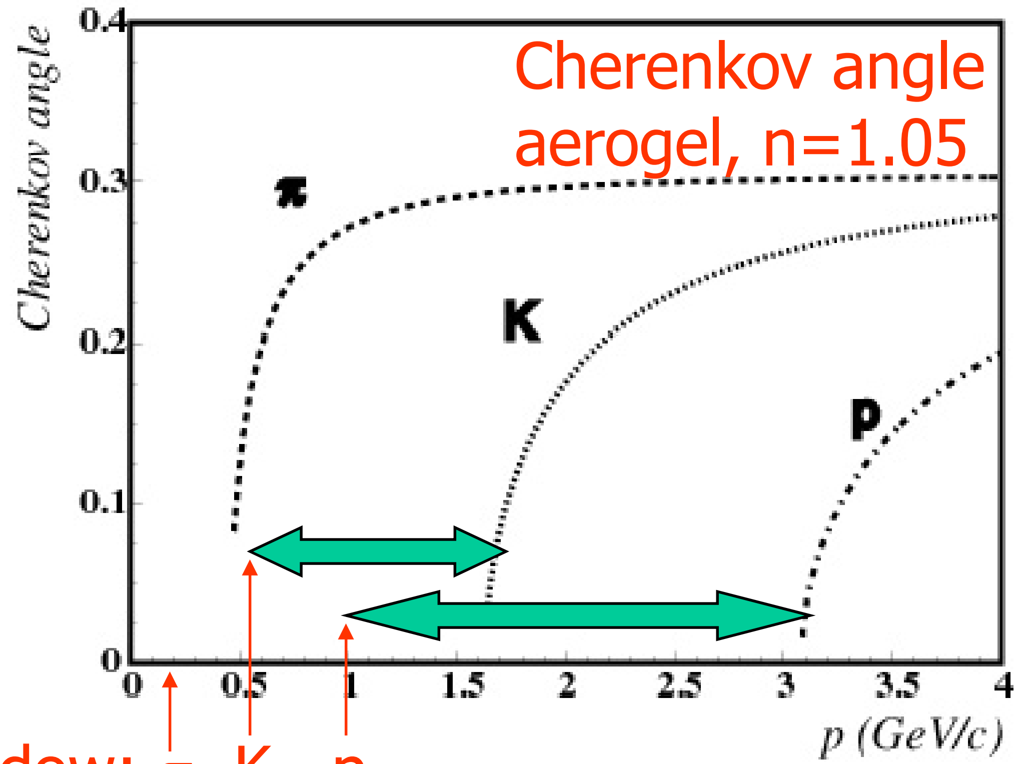
→ 3x better separation

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.



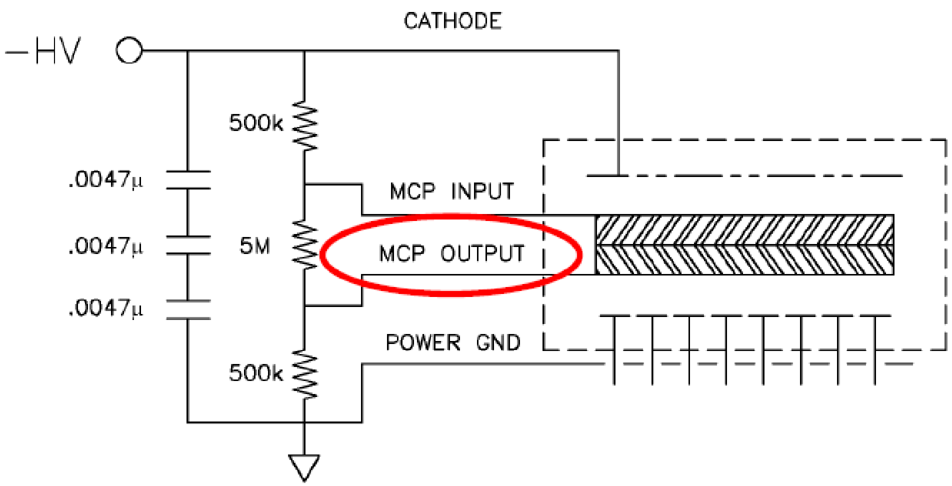
Threshold in the window: π K p

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

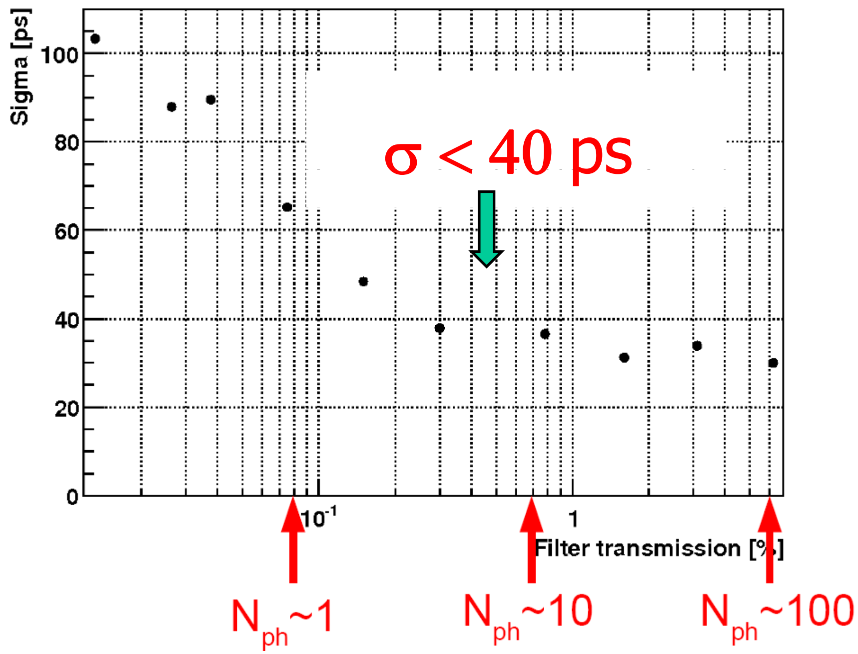
Timing with a signal from the second MCP stage

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



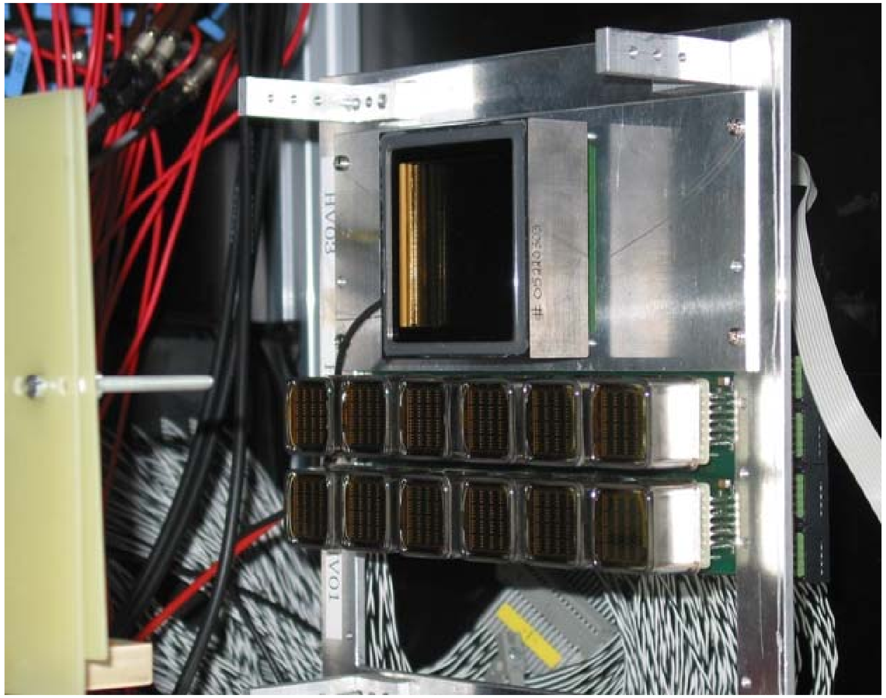
MCP second stage output

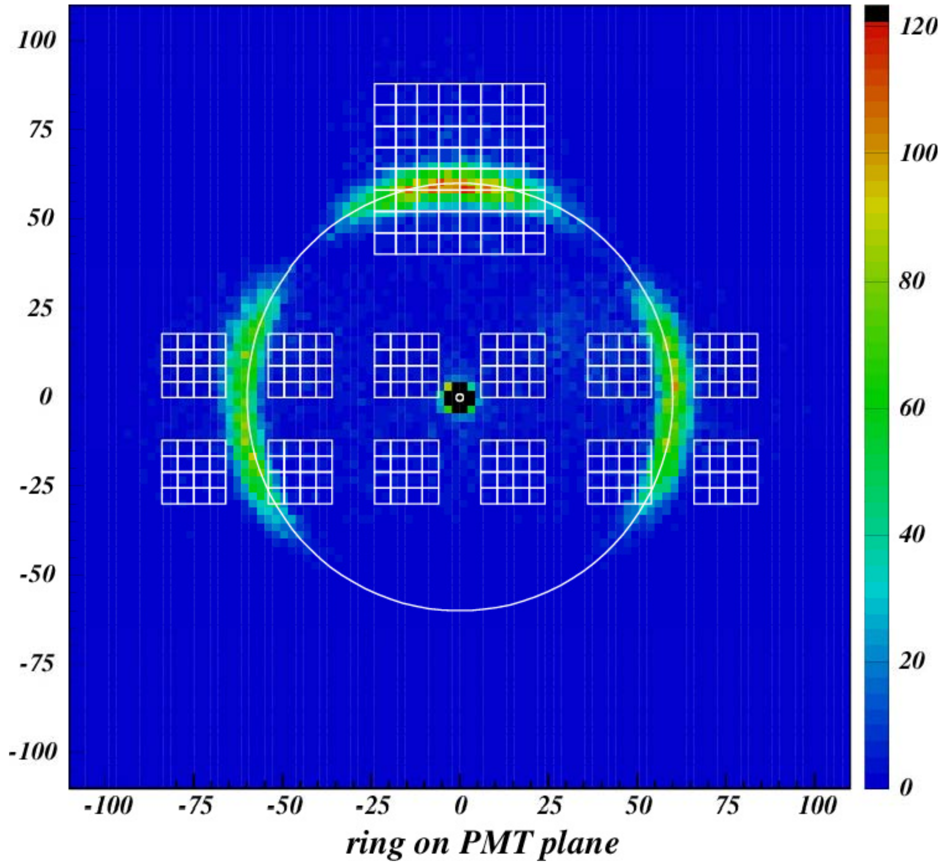


Timing resolution as a function of light intensity

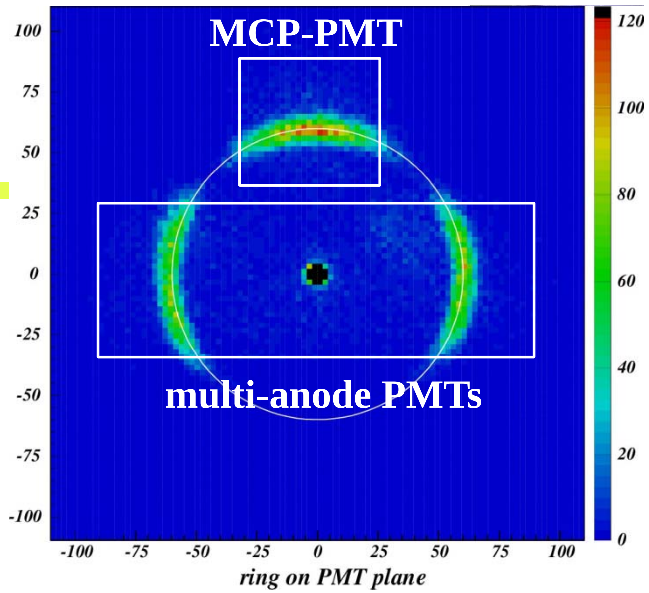
Burle MCP PMT beam test

- **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

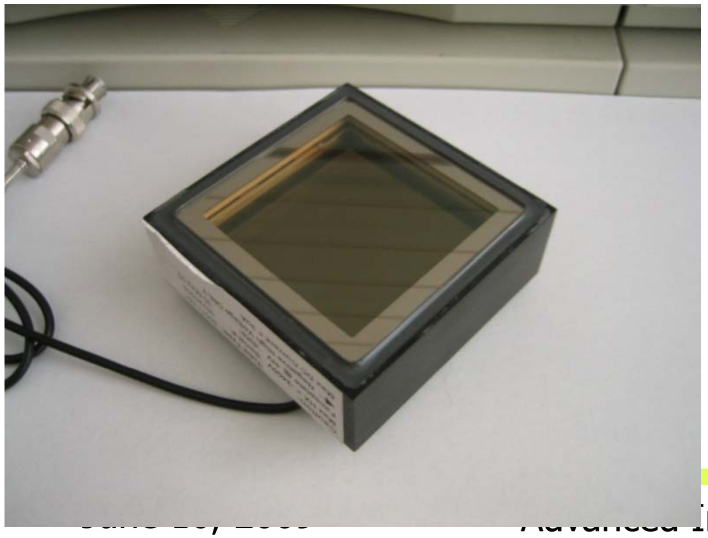


BURLE 85011 MCP-PMT:

- 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

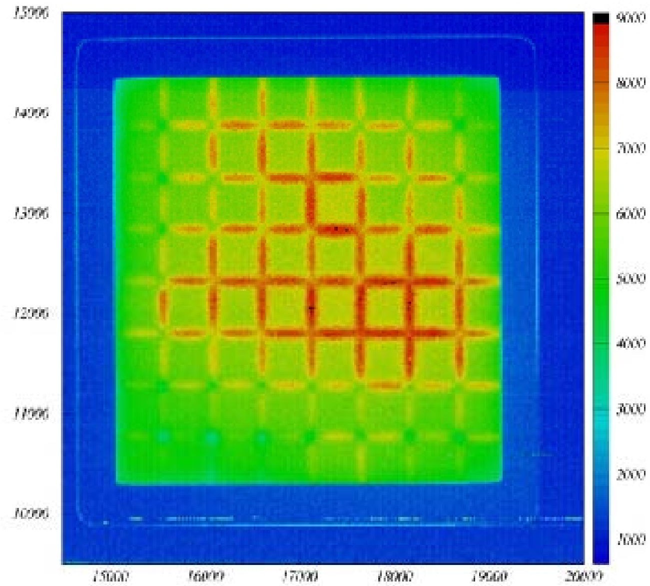
- σ_ϑ~13 mrad (single cluster)
- number of clusters per track N ~ 4.5
- σ_ϑ~ 6 mrad (per track)
- **-> ~ 4 σ π/K separation at 4 GeV/c**



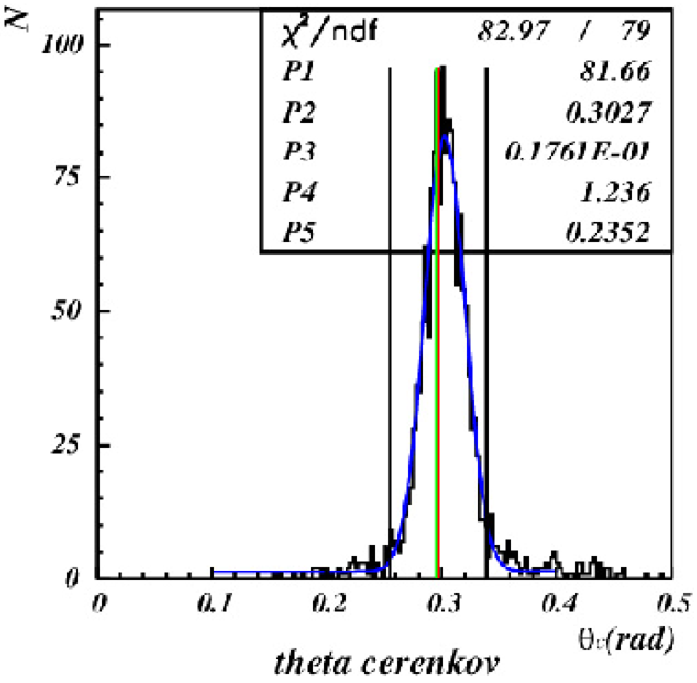
- 10 μm pores required for 1.5T
- collection eff. and active area fraction should be improved
- aging study should be carried out

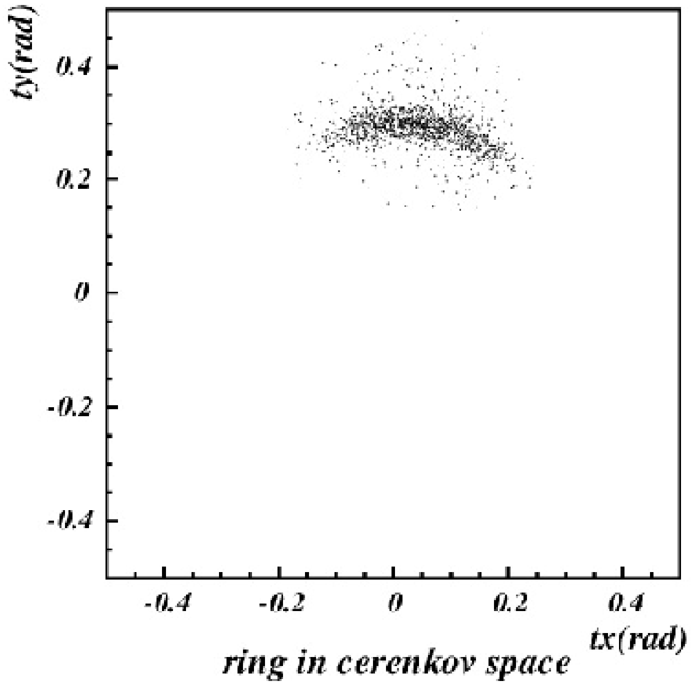
Cherenkov angle resolution

- 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

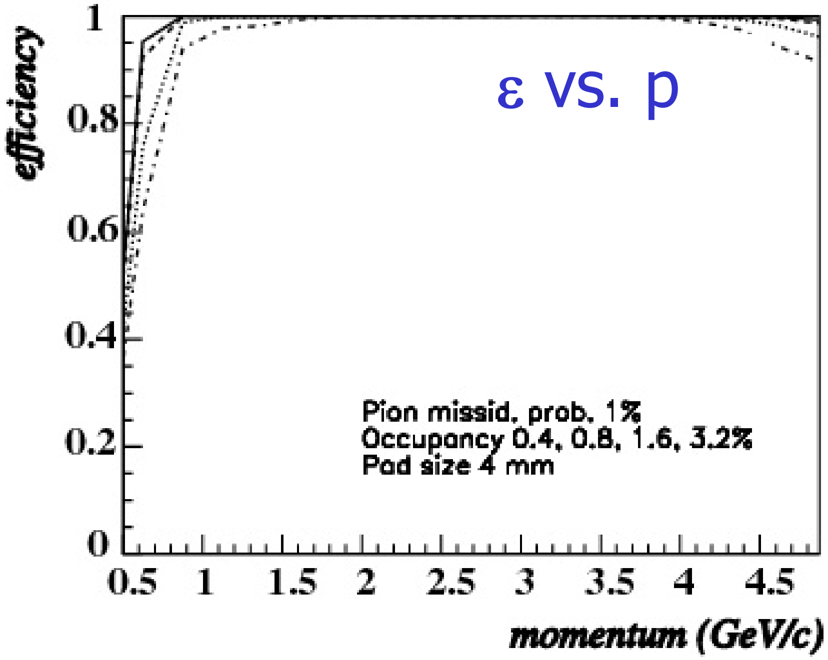


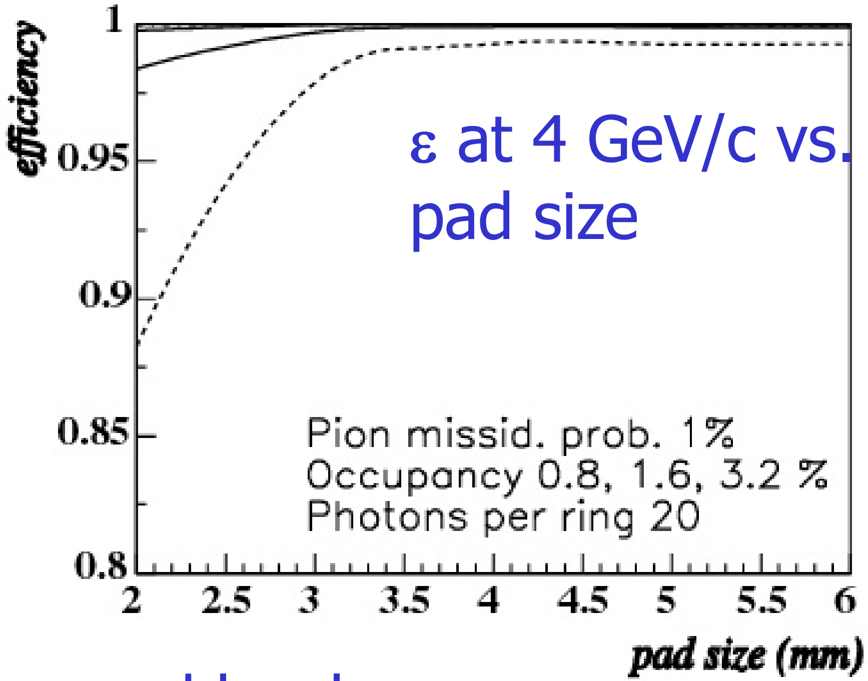


Can such a detector work?

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





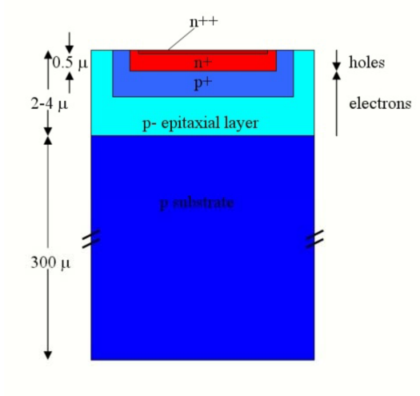
For different background levels

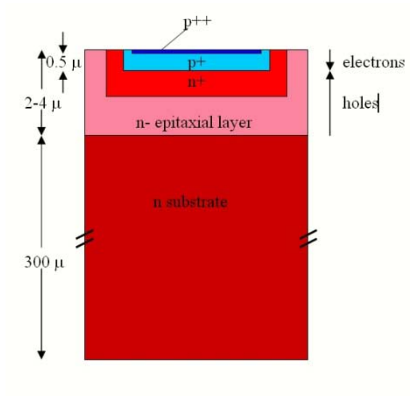
SiPM Photon Detection Efficiency (PDE)

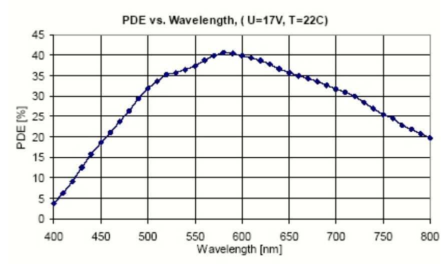
Photons with short wavelengths will be absorbed in the very first layer of Si and create there an electron-hole pair.

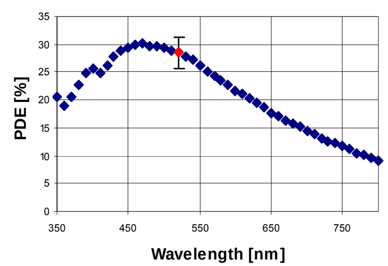
In a structure with a n-type substrate (right) the electrons drift towards the high field of the p-n junction and trigger with high probability a breakdown. A G-APD made on a n-type substrate will be preferential sensitive for blue light.

A G-APD made on a p-type substrate (left) needs long wavelengths for the creation of electrons in the p-layer behind the junction and will have the peak sensitivity in the green/red.









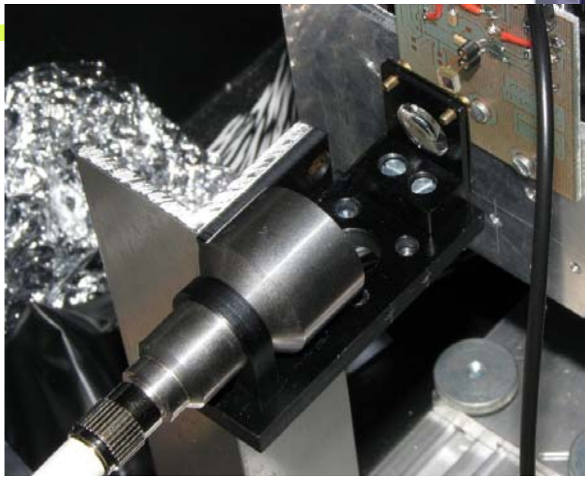
Photonique/CPTA
(SSPM_0710G9MM)

Hamamatsu
(PSI-33-050C)

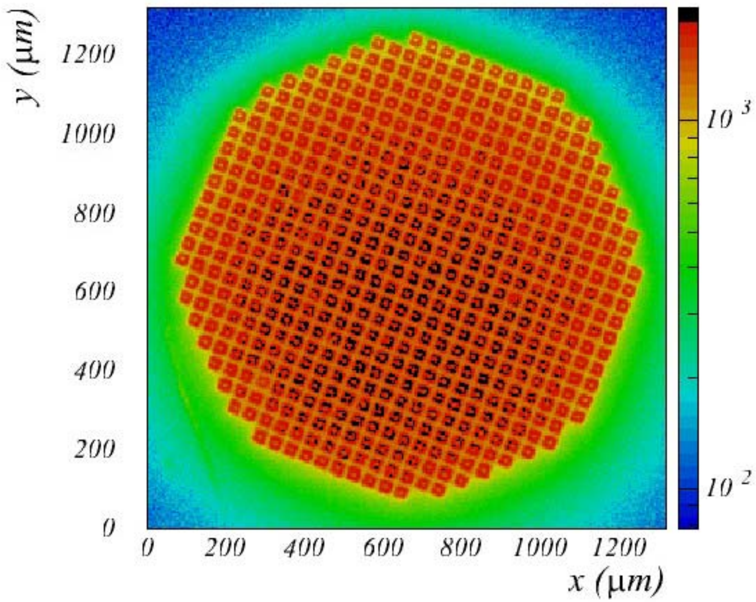
D. Renker, RICH Workshop, Giessen, May 2009

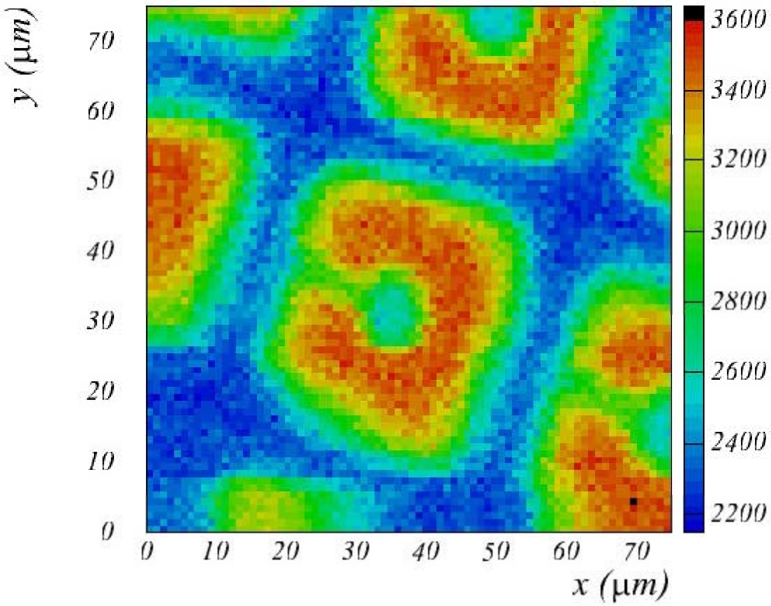
Surface sensitivity for single photons

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



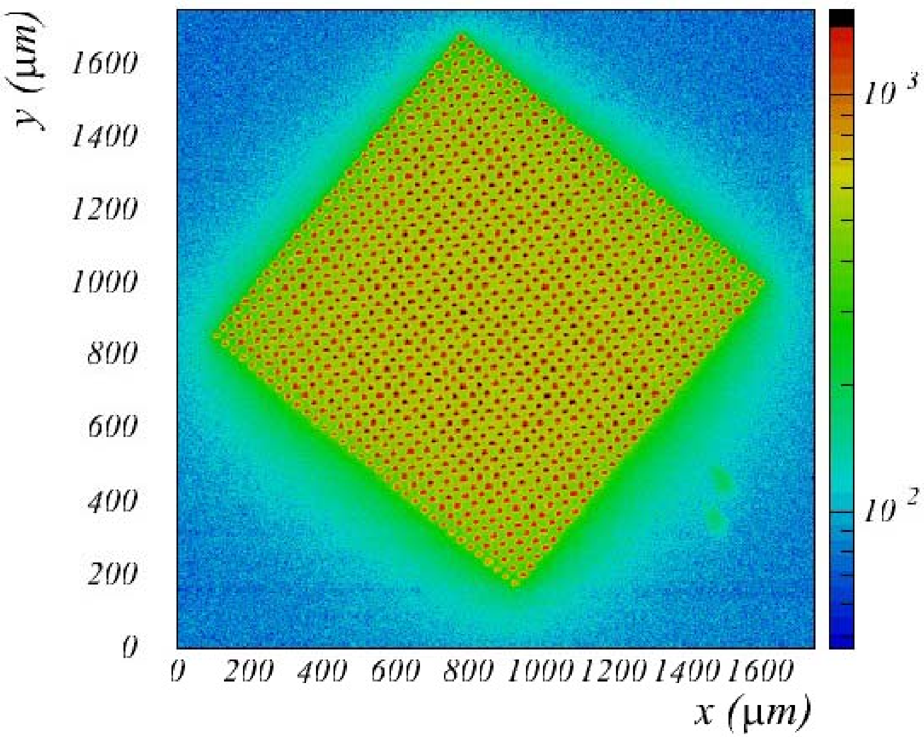
5 μm step size **S137** **Close up: 1 μm step size**

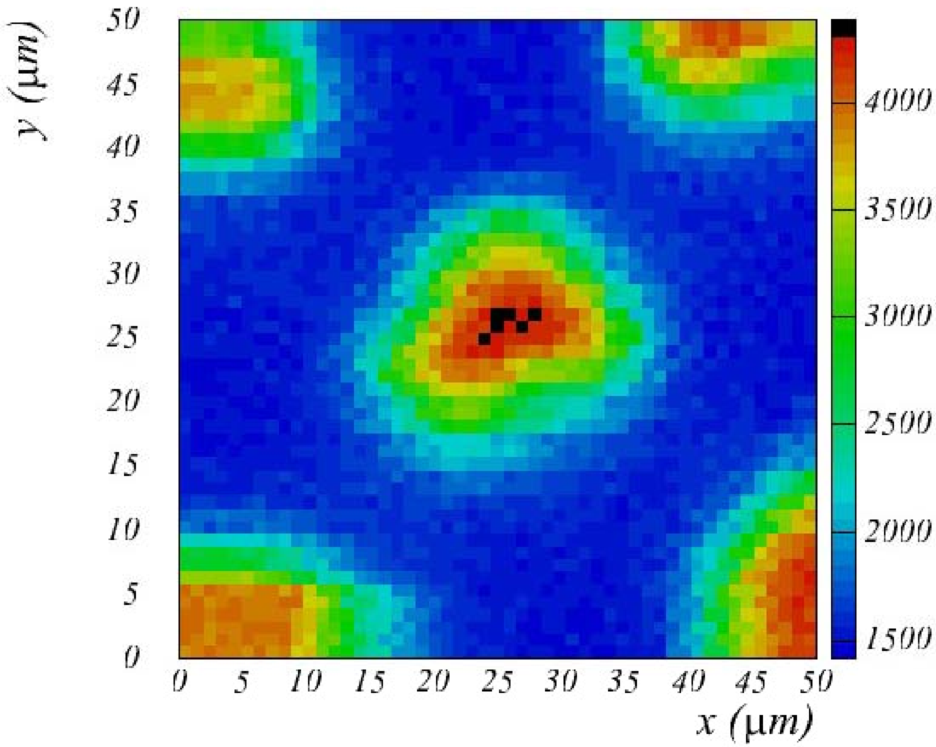




Surface sensitivity for single photons 2

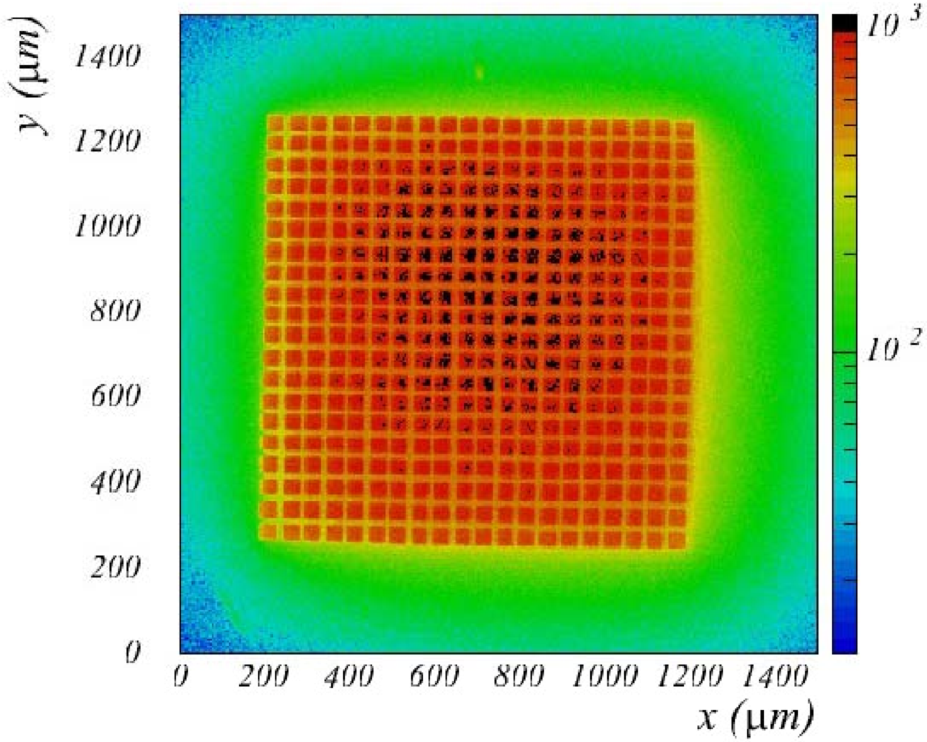
E407



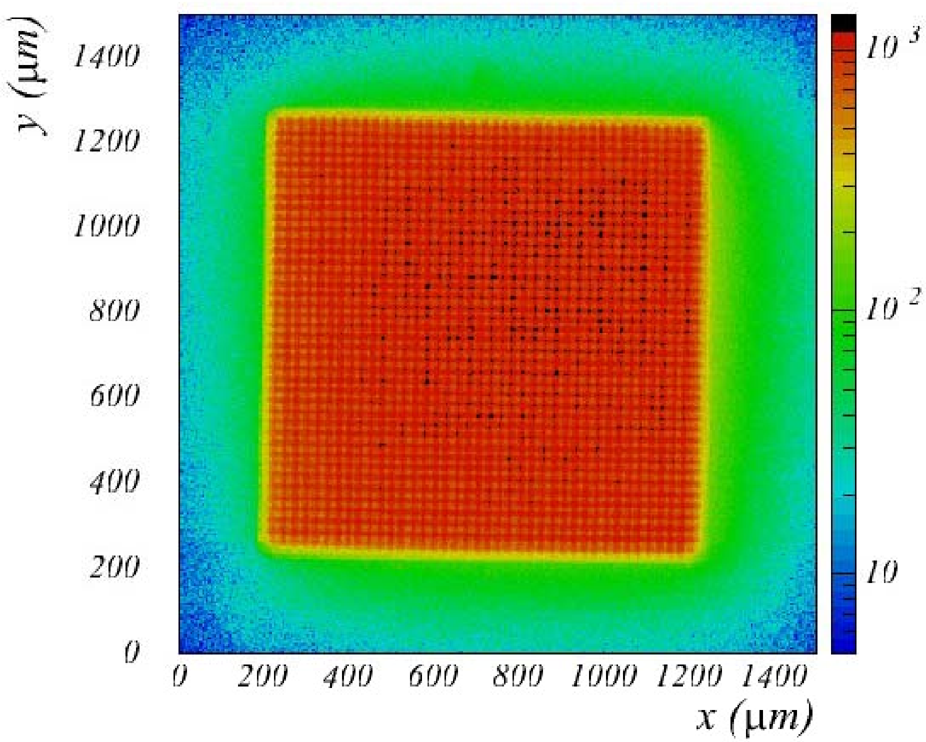


Surface sensitivity for single photons 3

H050C

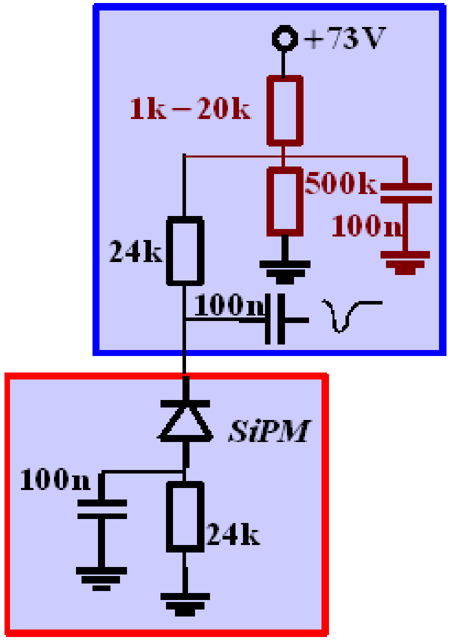


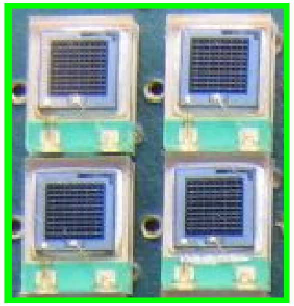
H025C

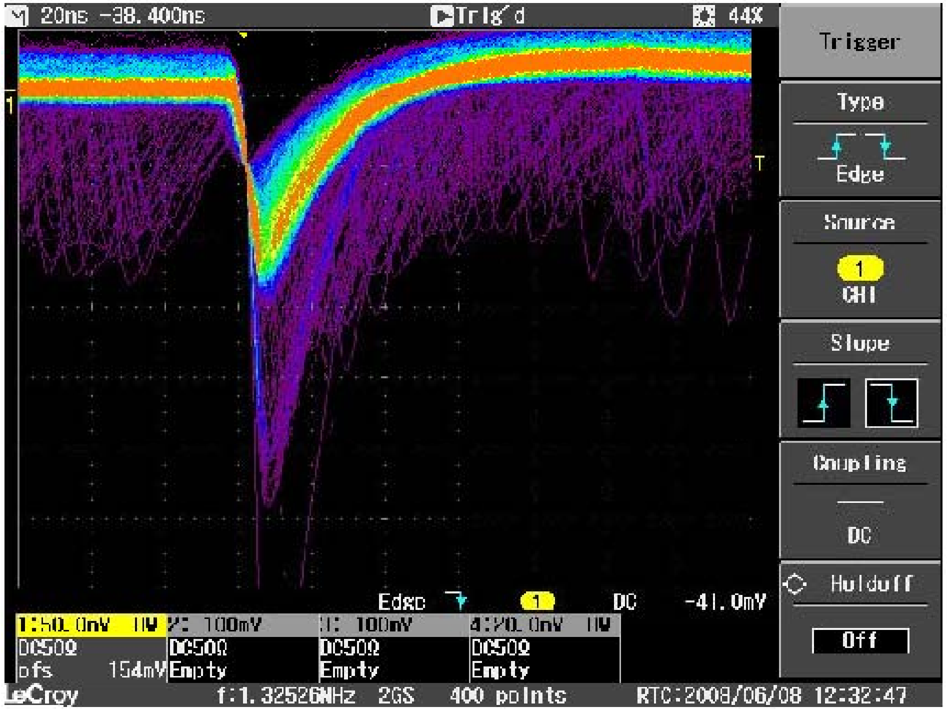


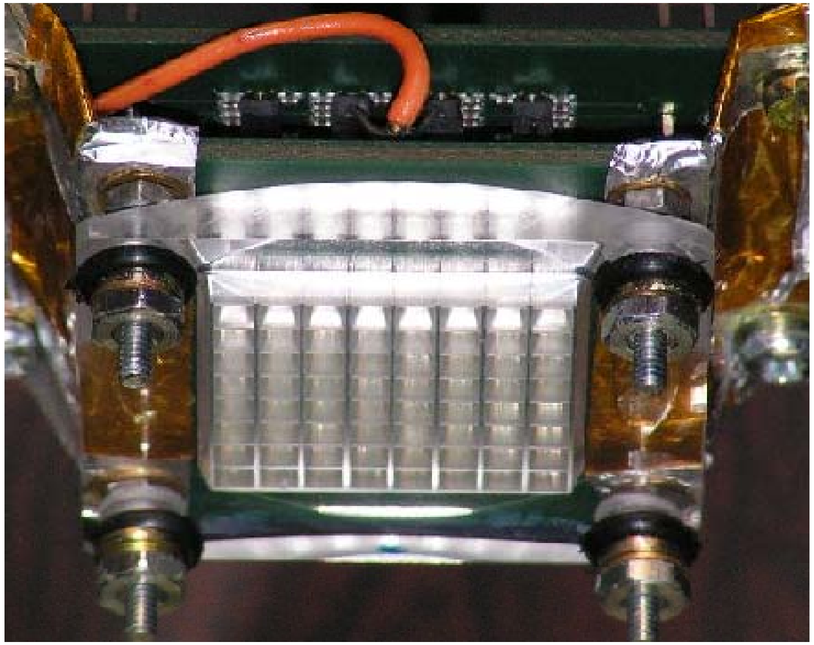
MPPC module

- 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

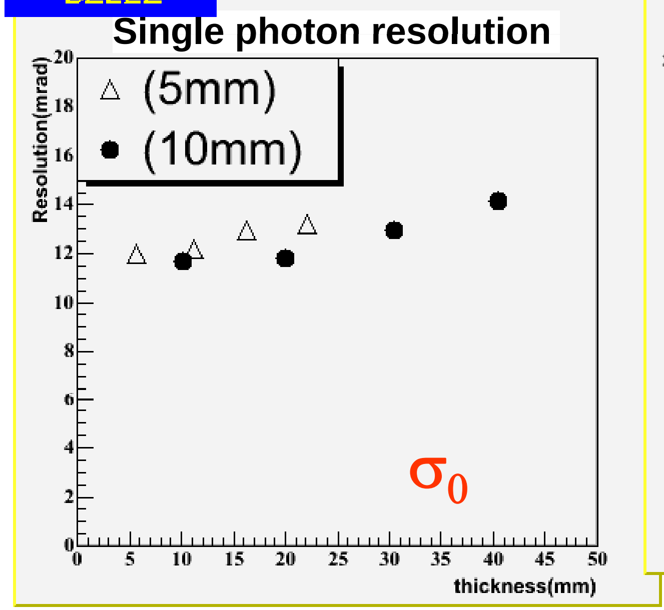


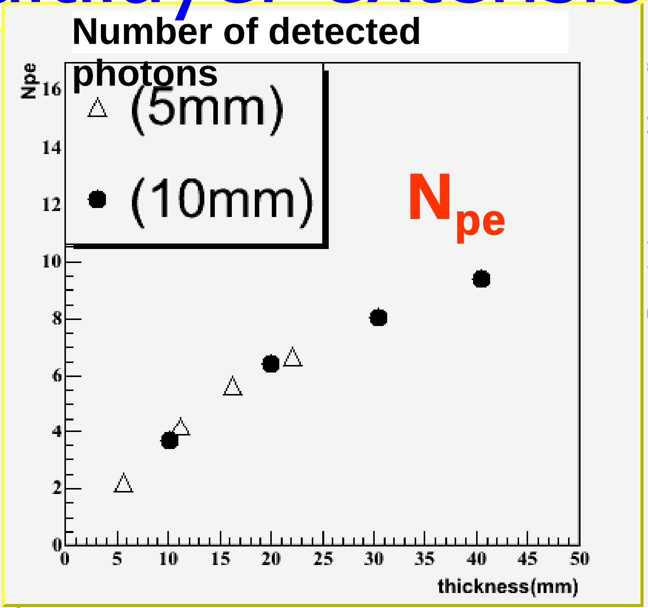


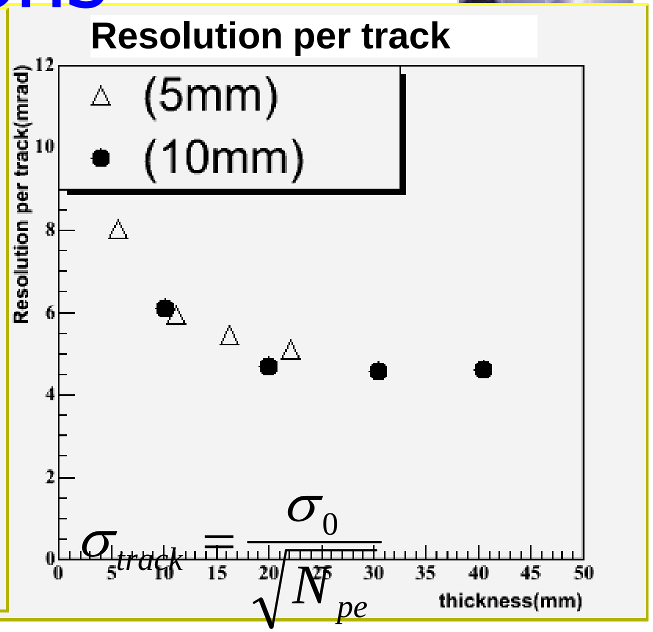




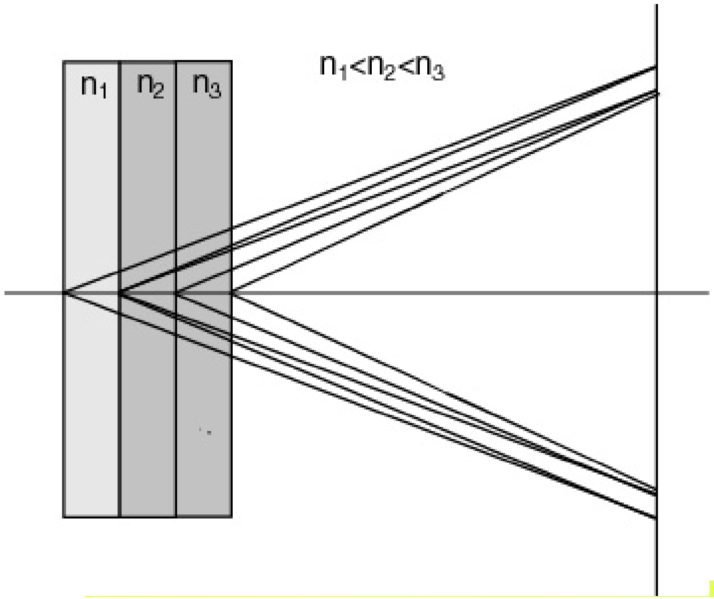
Multilayer extensions







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



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

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