SiPMs as detectors of Cherenkov photons

Peter Križan

University of Ljubljana and J. Stefan Institute

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Can G-APDs (SiPMs) do the job?

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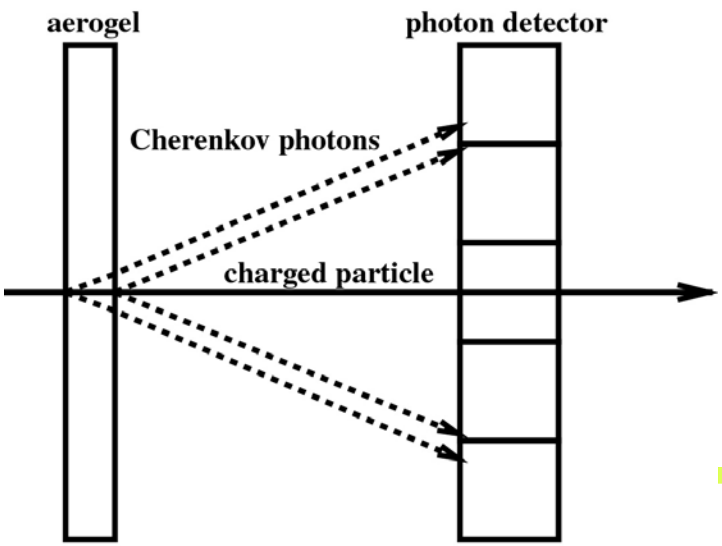
Summary

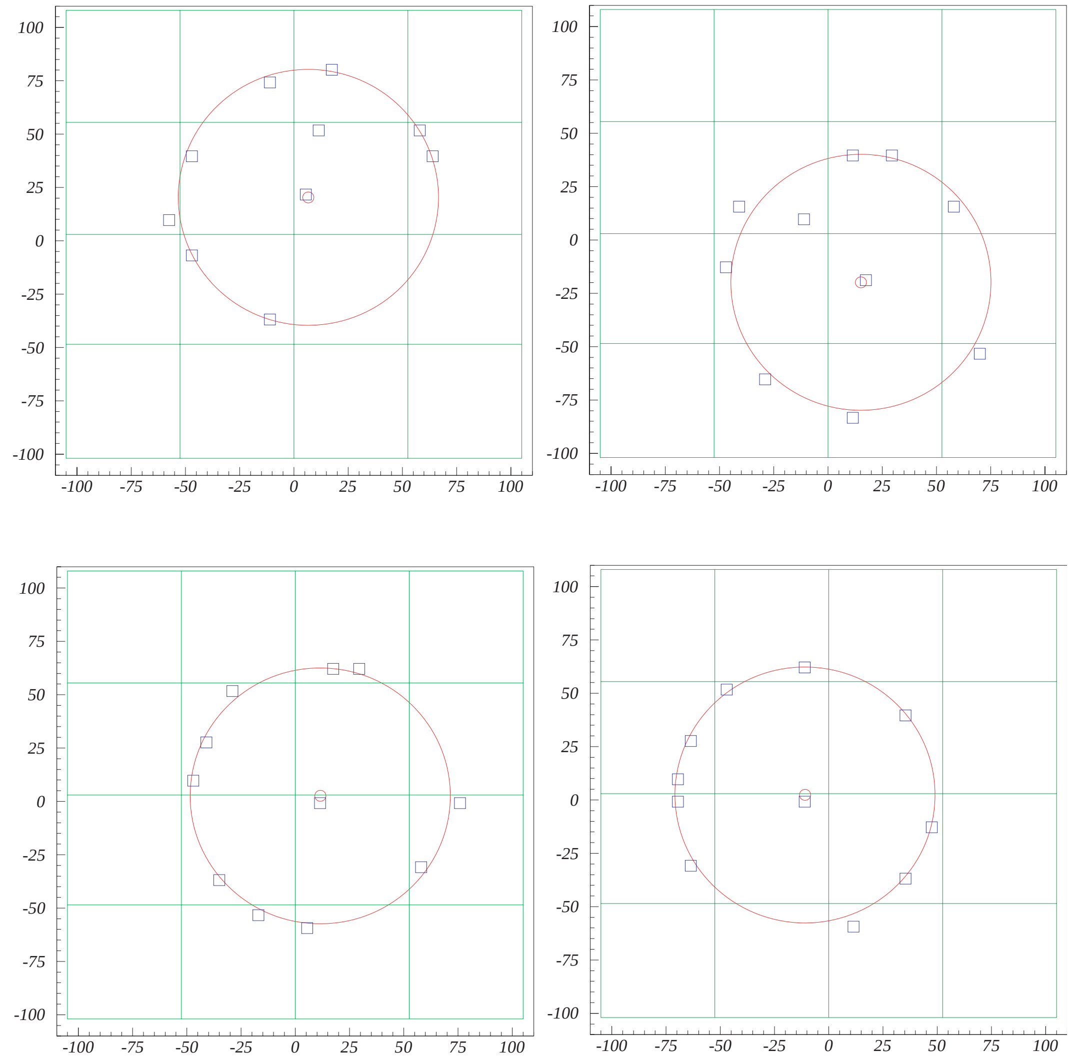
Measuring Čerenkov angle

From hits of individual photons → measure the angle.

Few photons detected

→Important to have a low noise detector



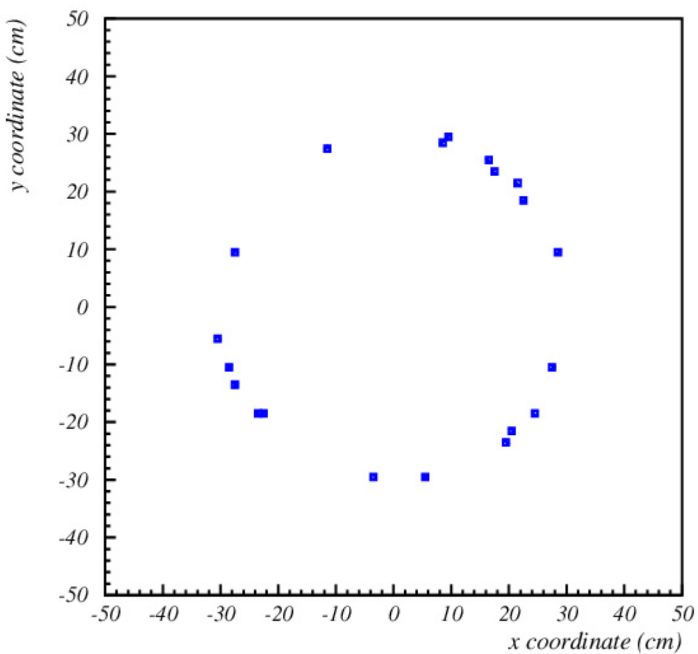


Photon detection in RICH counters

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)

Hot topics in photon detection for RICHes

For: super B factories

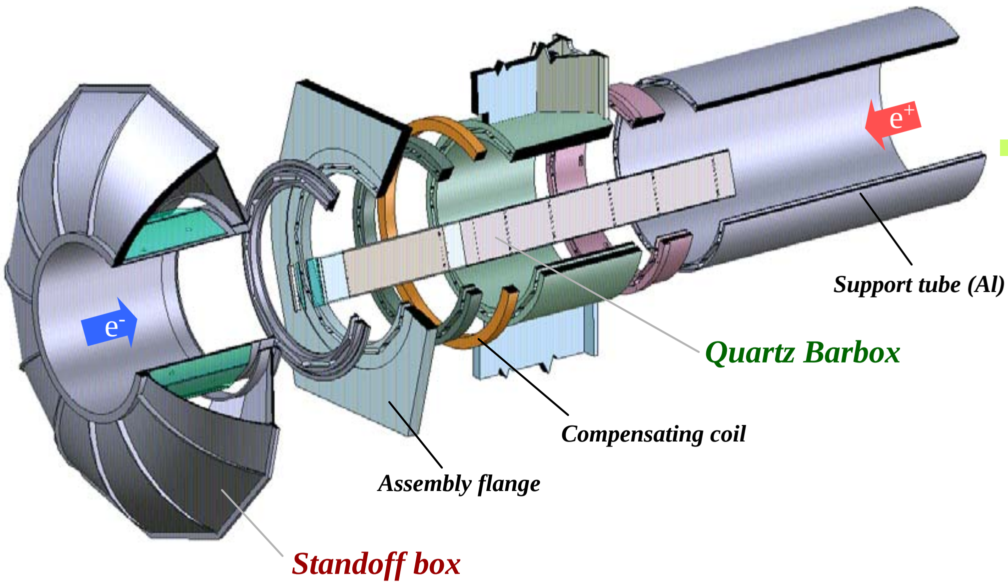
- Belle PID upgrade
- DIRC (BaBar) upgrade

Single photon detection with:

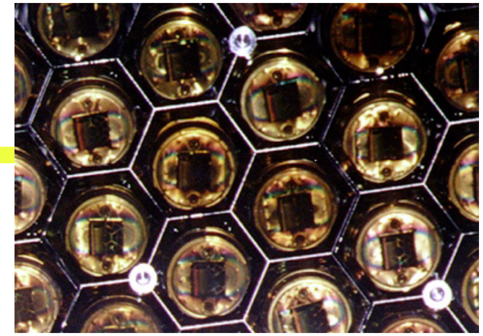
<u>Operation in high magnetic field (1.5T)</u>

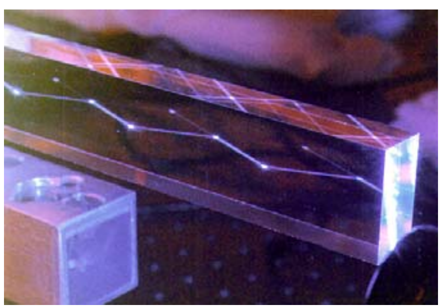
<u>Excellent timing (time-of-arrival information)</u>

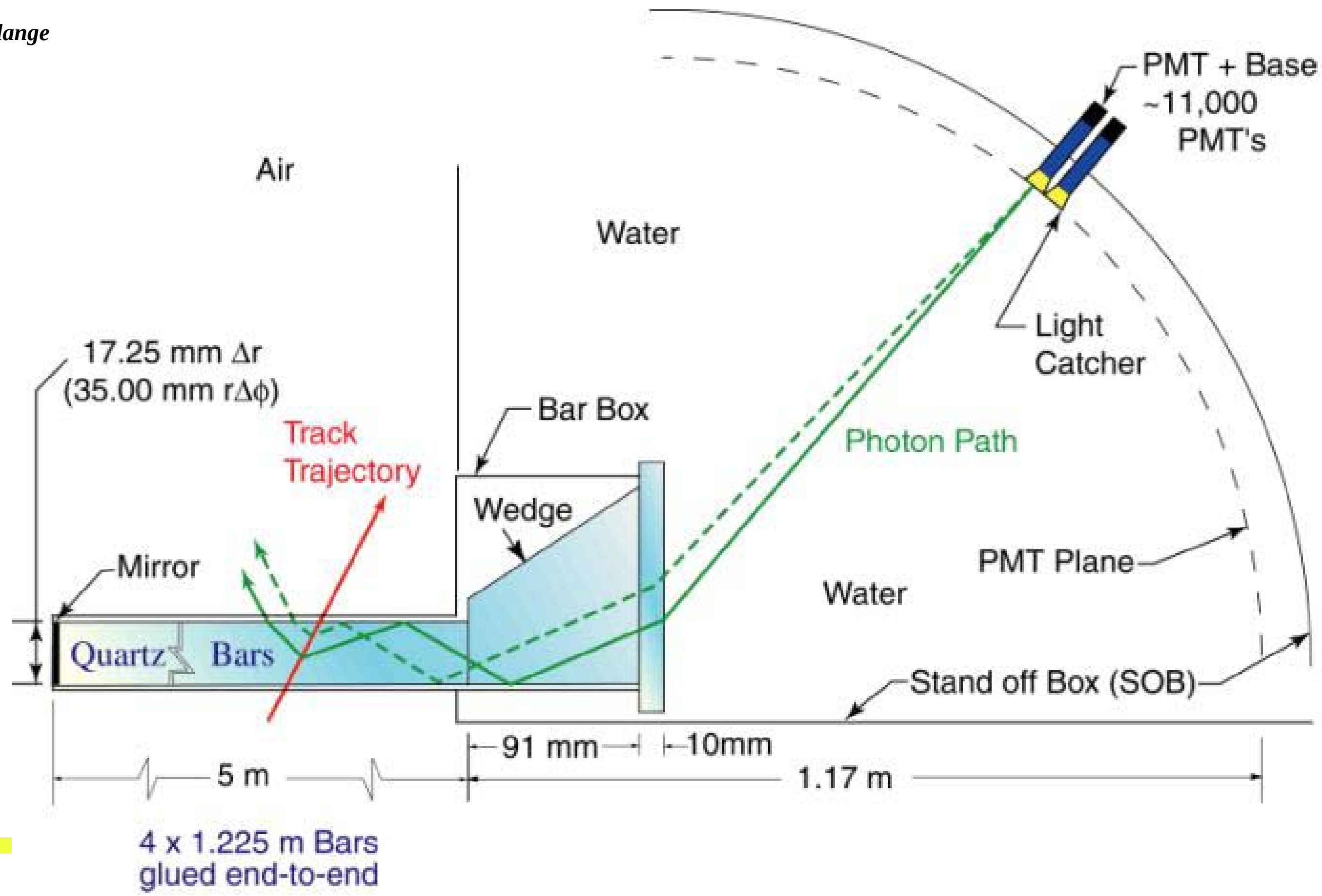
DIRC



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





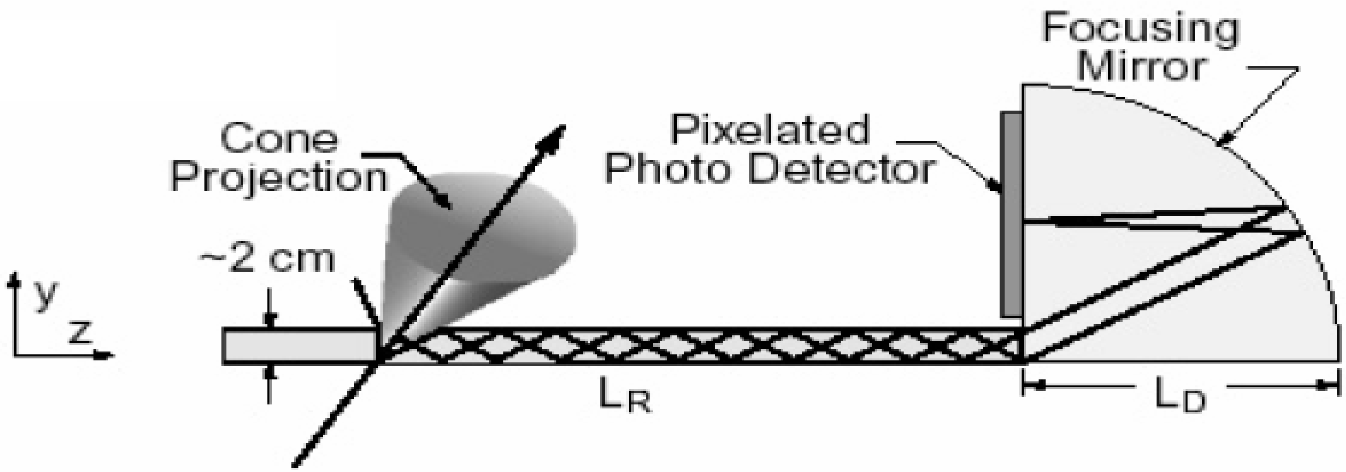


PMT + Base
~11,000
PMT's
Air
Water
Light
Catcher
17.25 mm Δr
(35.00 mm rΔϕ)
Bar Box
Track
Trajectory
Photon Path
Wedge
Mirror
PMT Plane
Water
Quartz
Bars
Stand off Box (SOB)
91 mm
10mm
5 m
1.17 m
4 x 1.225 m Bars
glued end-to-end

Focusing DIRC

Upgrade: remove the stand-off box → focusing DIRC

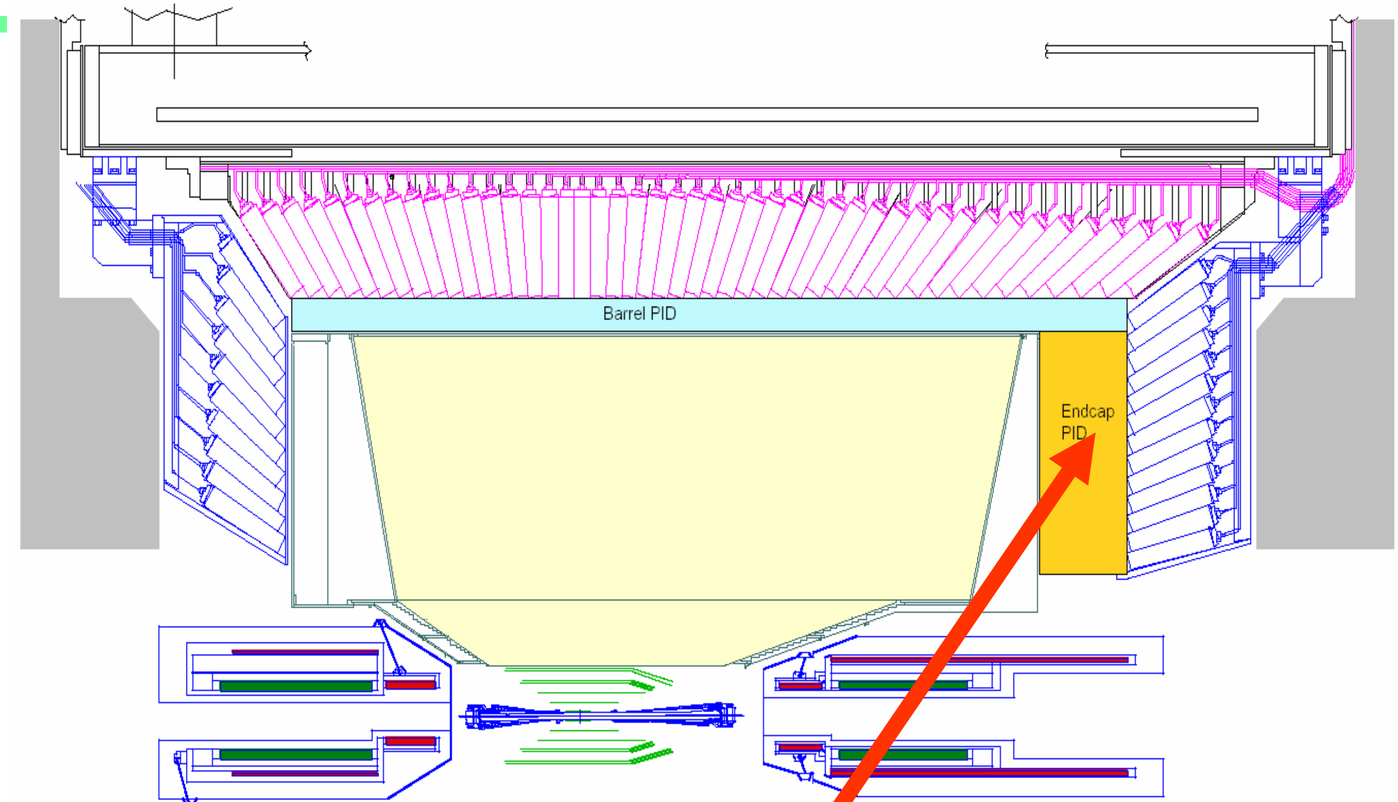
Use time of arrival to (partly) correct for the cromatic dispersion



Need:

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

Belle upgrade – side view

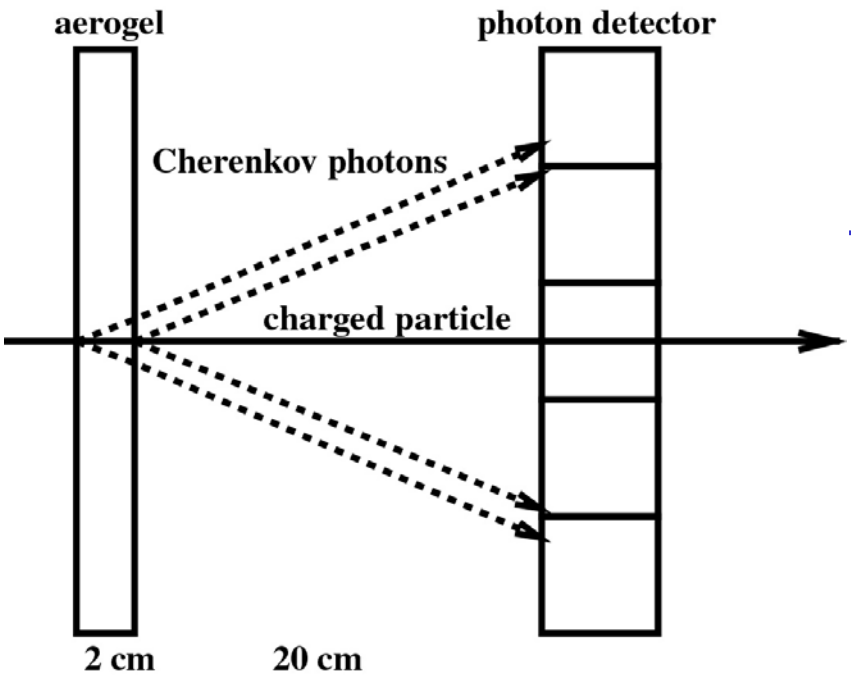


Two new particle ID devices, both RICHes:

Barrel: TOP or focusing DIRC

Endcap: proximity focusing RICH

Endcap: Proximity focusing RICH



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

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

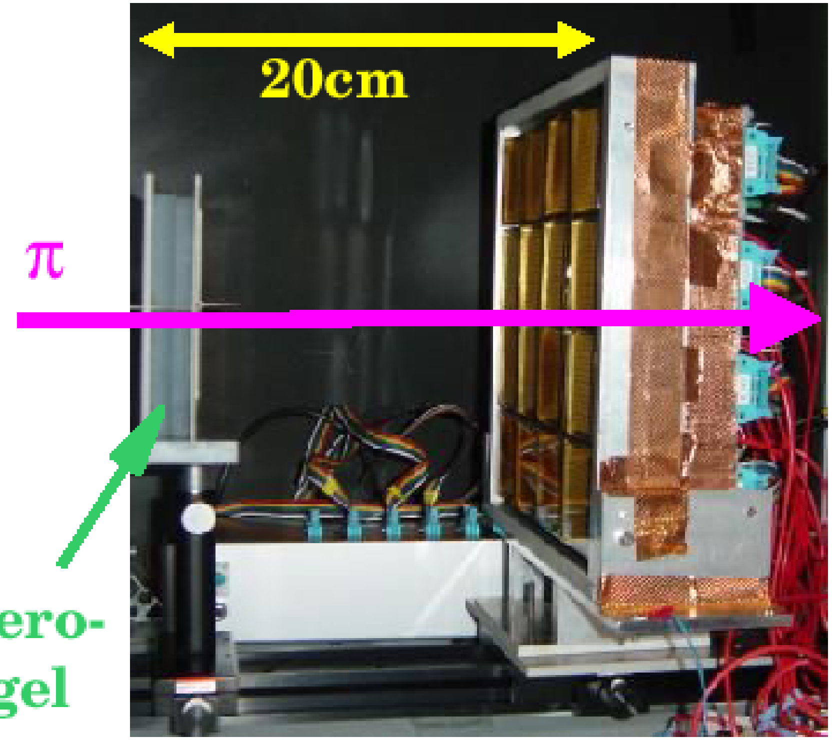
Per track: $$\sigma_{track} = \frac{\sigma_0}{\sqrt{N_{pe}}}$$

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

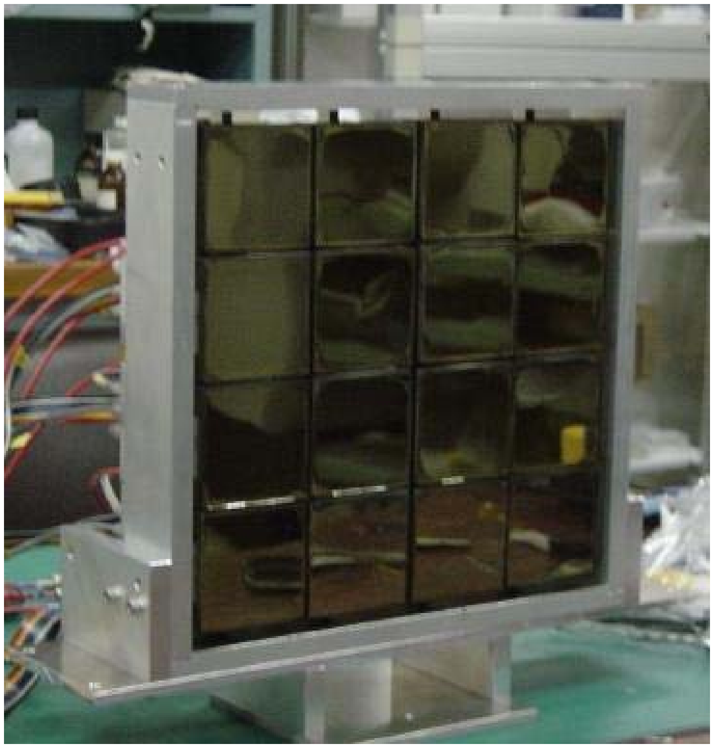
→ 5σ separation with N_{pe}~10

Beam tests

pion beam (π2) at KEK

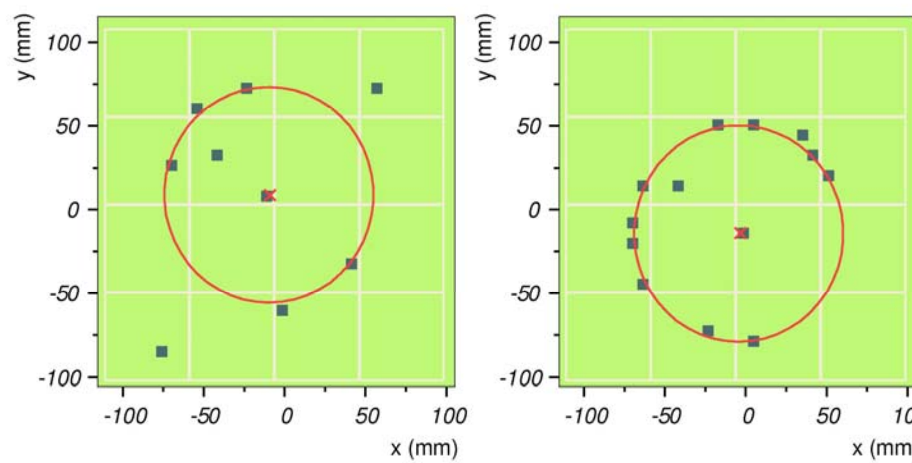


Aero-
gel



Photon detector: array of 16 H8500 (flat pannel) PMTs

Clear rings, little background

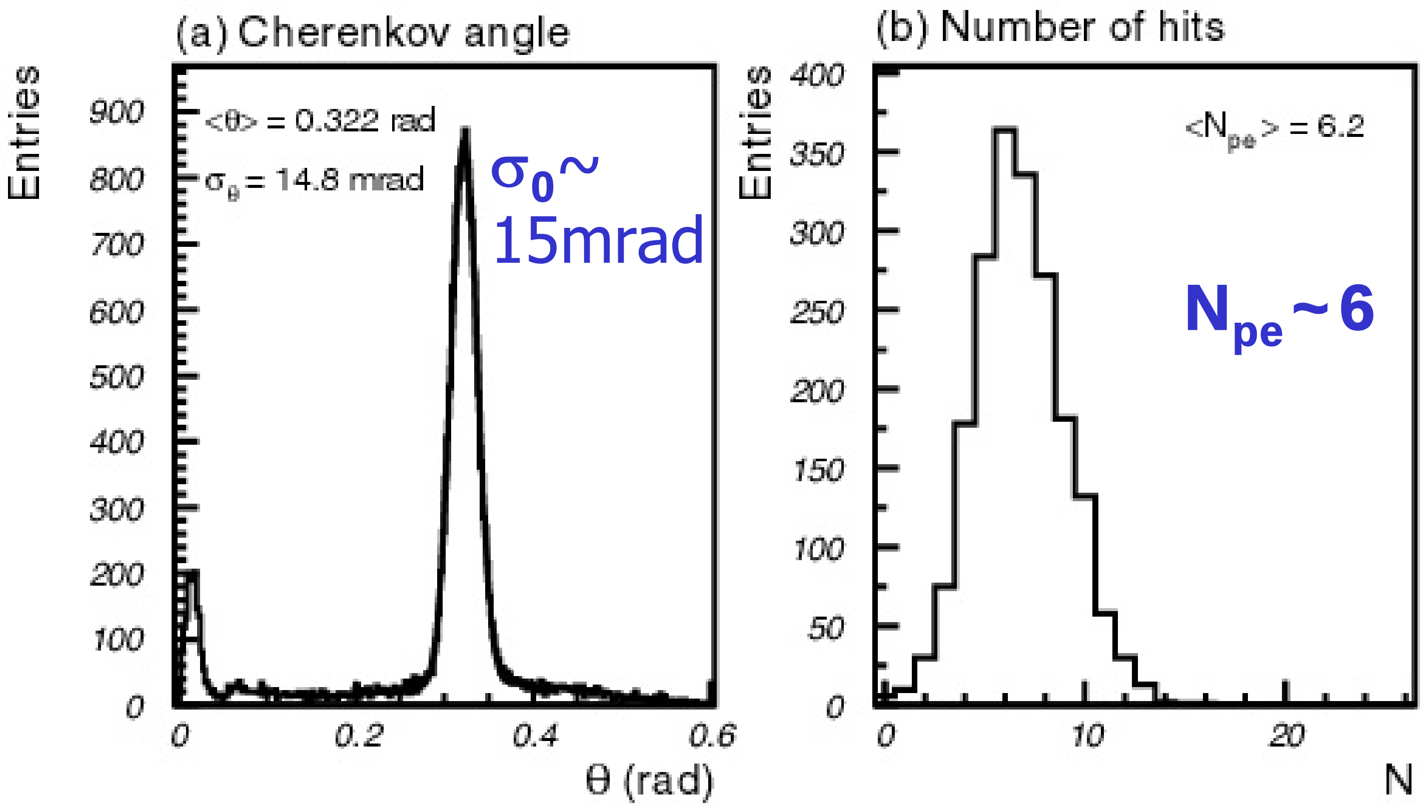


Beam test: Cherenkov angle resolution and number of photons

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

Beam test results with 2cm thick aerogel tiles:

>4σ K/π separation



→ This photon detector does not work in magnetic field

Photon detectors for the aerogel RICH

Photon detector candidates for 1.5T:

- BURLE 85011 microchannel plate (MPC) PMT → talk by Samo Korpar tomorrow
- Multichannel H(A)PD – R+D with Hamamatsu
- SiPM (G-APD)

SiPMs for the aerogel RICH – the group

R. Dolenec, S. Korpar, P. Križan, A. Petelin, R. Pestotnik

J. Stefan Institute, Ljubljana, Slovenia

University of Ljubljana, Slovenia

University of Maribor, Slovenia

K. Hara, T. Iijima, Y. Mazuka, M. Yamaoka

Nagoya University, Nagoya, Japan

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

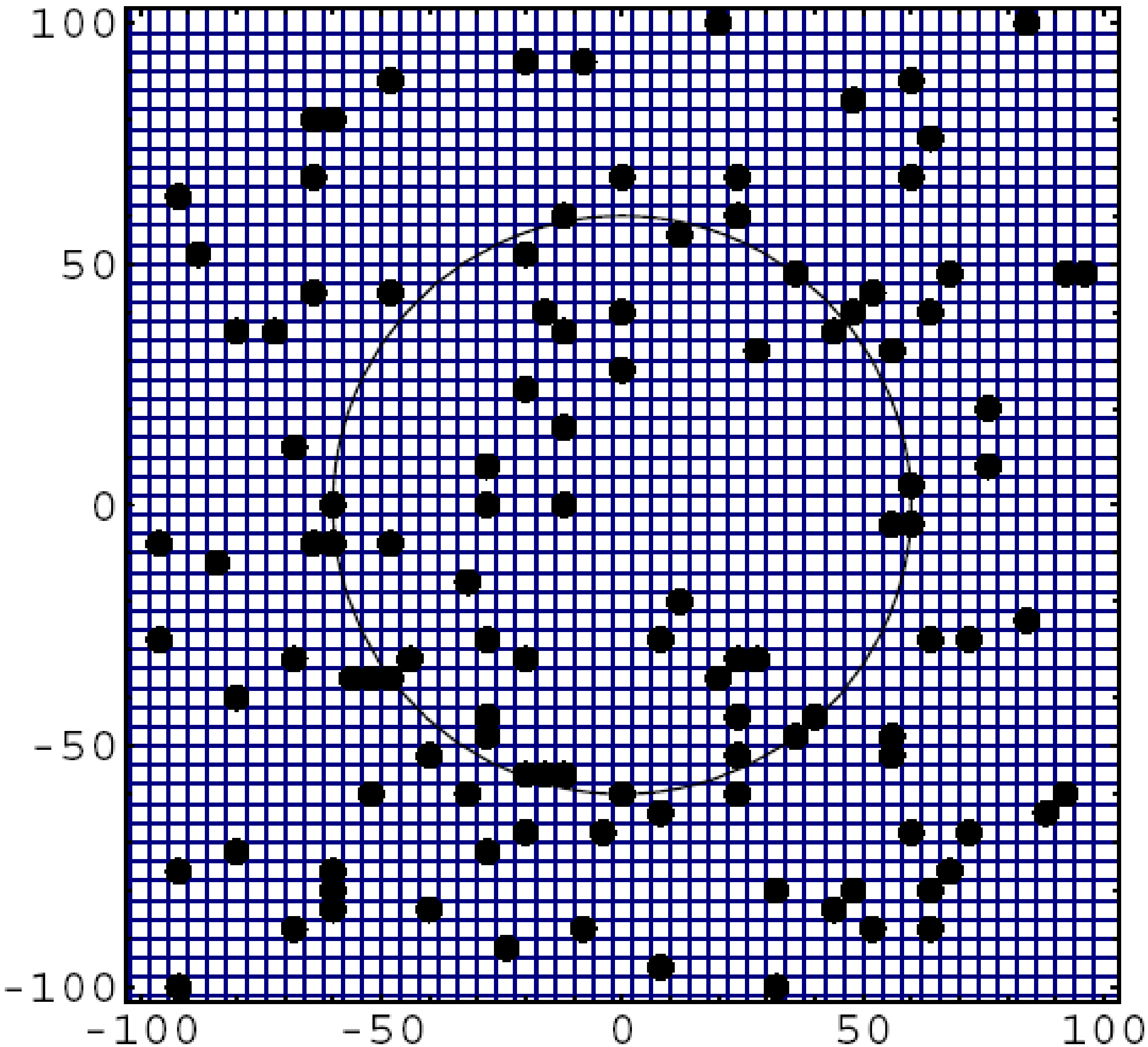
+easy to handle (thin, can be mounted on a PCB)

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

+no high voltage

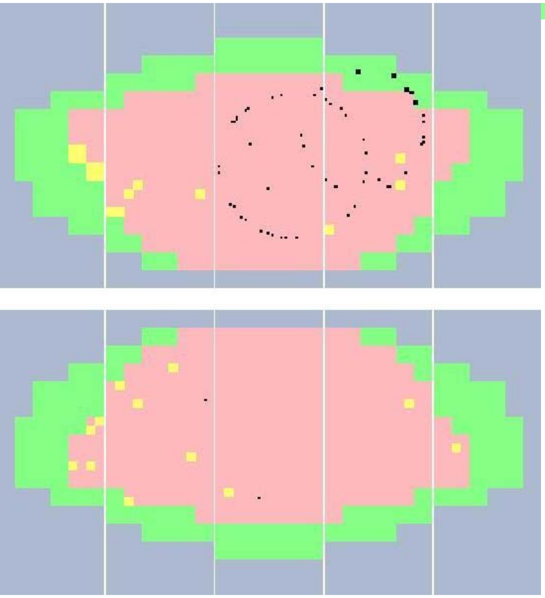
-very high dark count rate (100kHz – 1MHz) with <u>single photon pulse height</u>

Ring on a uniform background



Can such a detector work?

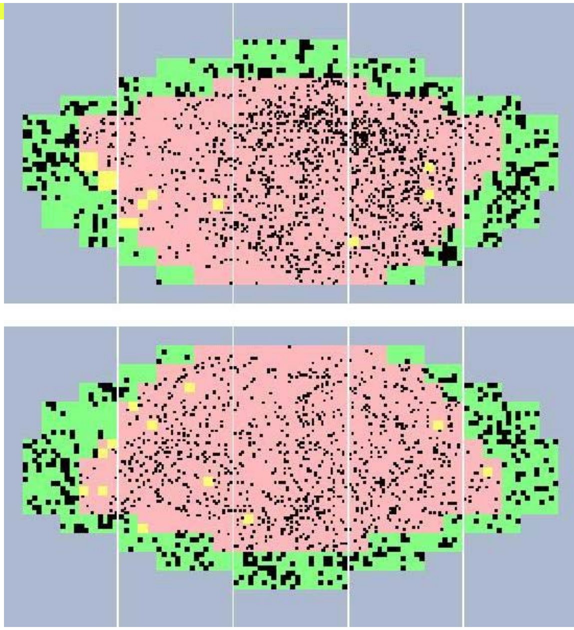
Can such a detector work?



HERA-B RICH experience:

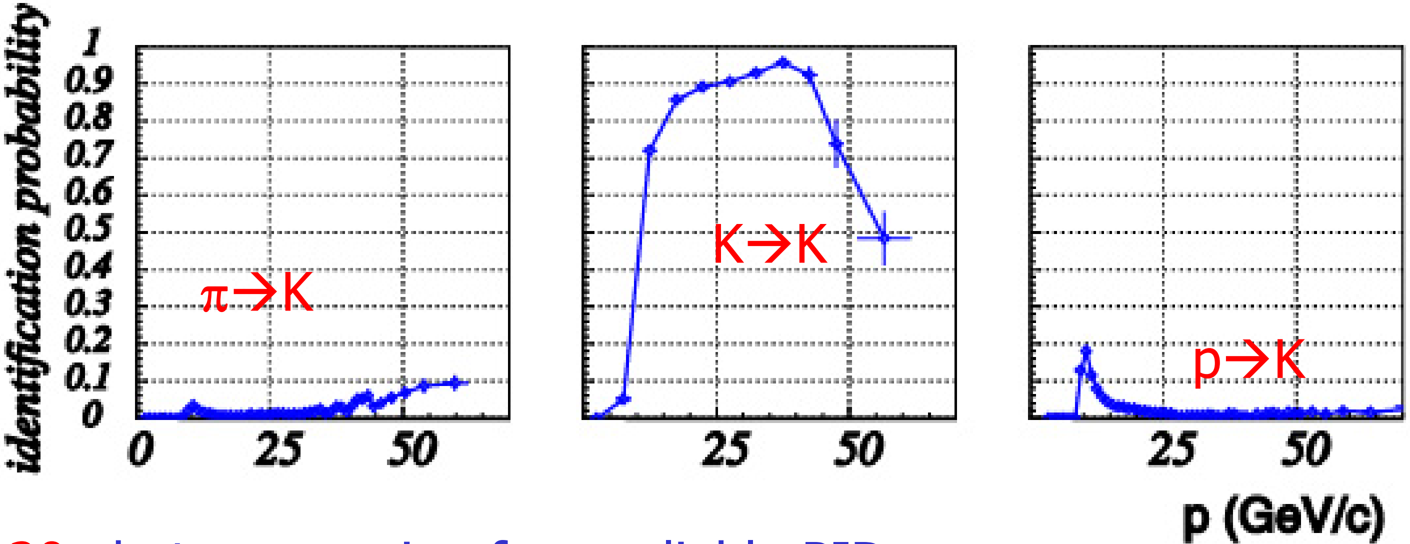
← Little noise, ~30 photons per ring

Typical event →



Worked very well!

Kaon efficiency and pion, proton fake probability



Need >20 photons per ring for a reliable PID.

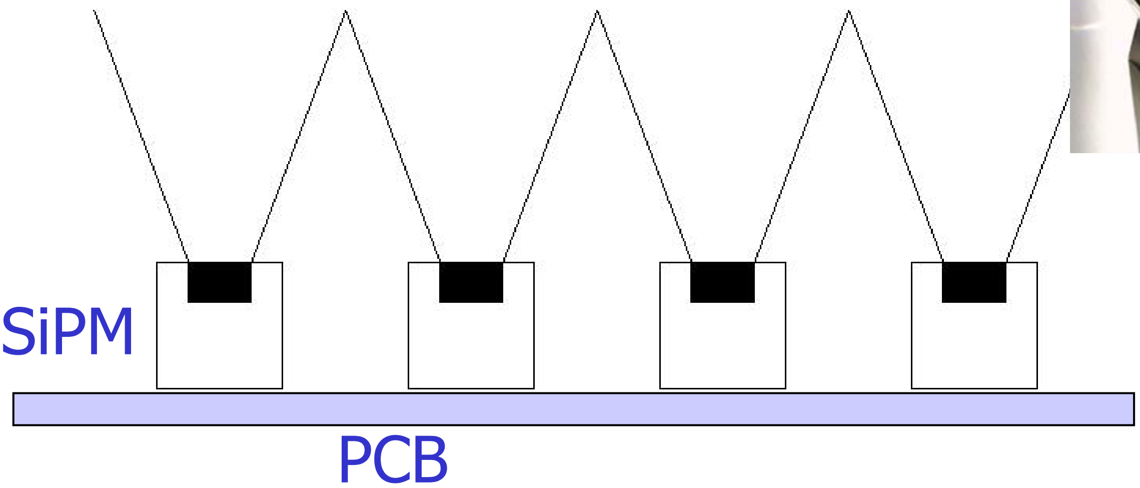
Can such a detector work?

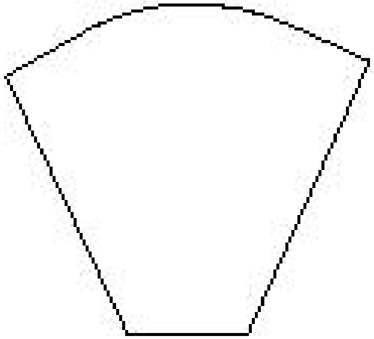
Improve the signal to noise ratio:

•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

Light collector with reflective walls



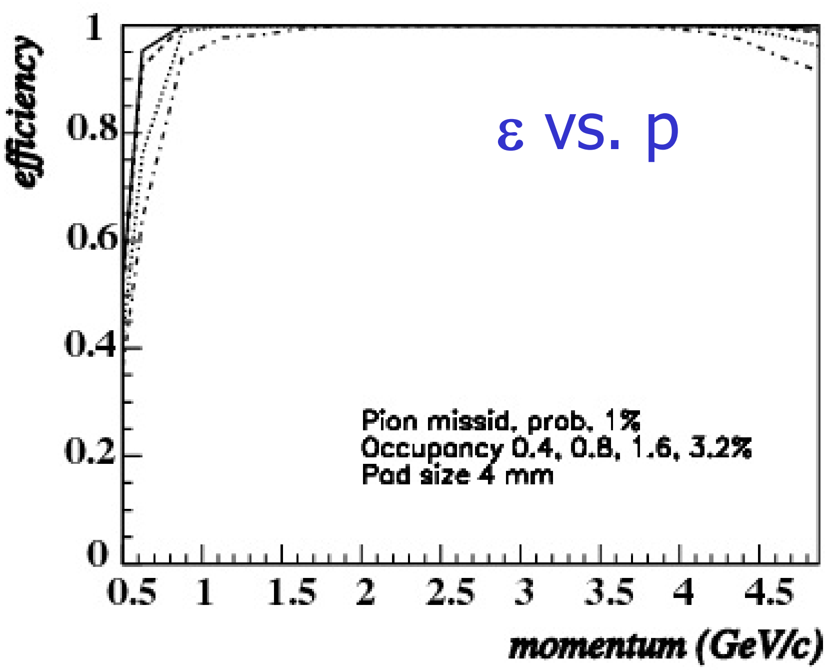


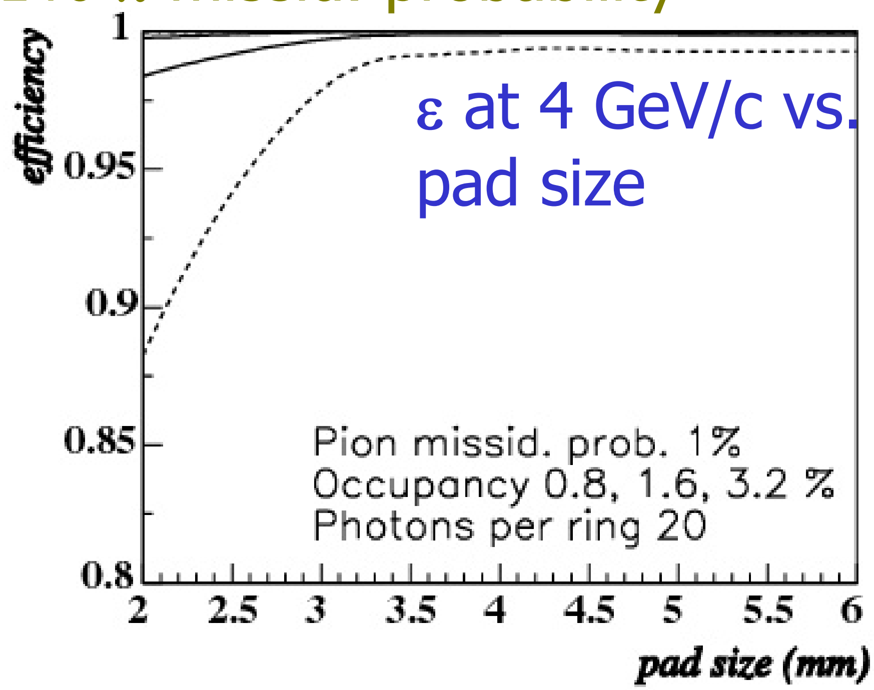
or combine a lens and mirror walls

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. Vary light collector demagnification (=pad size).

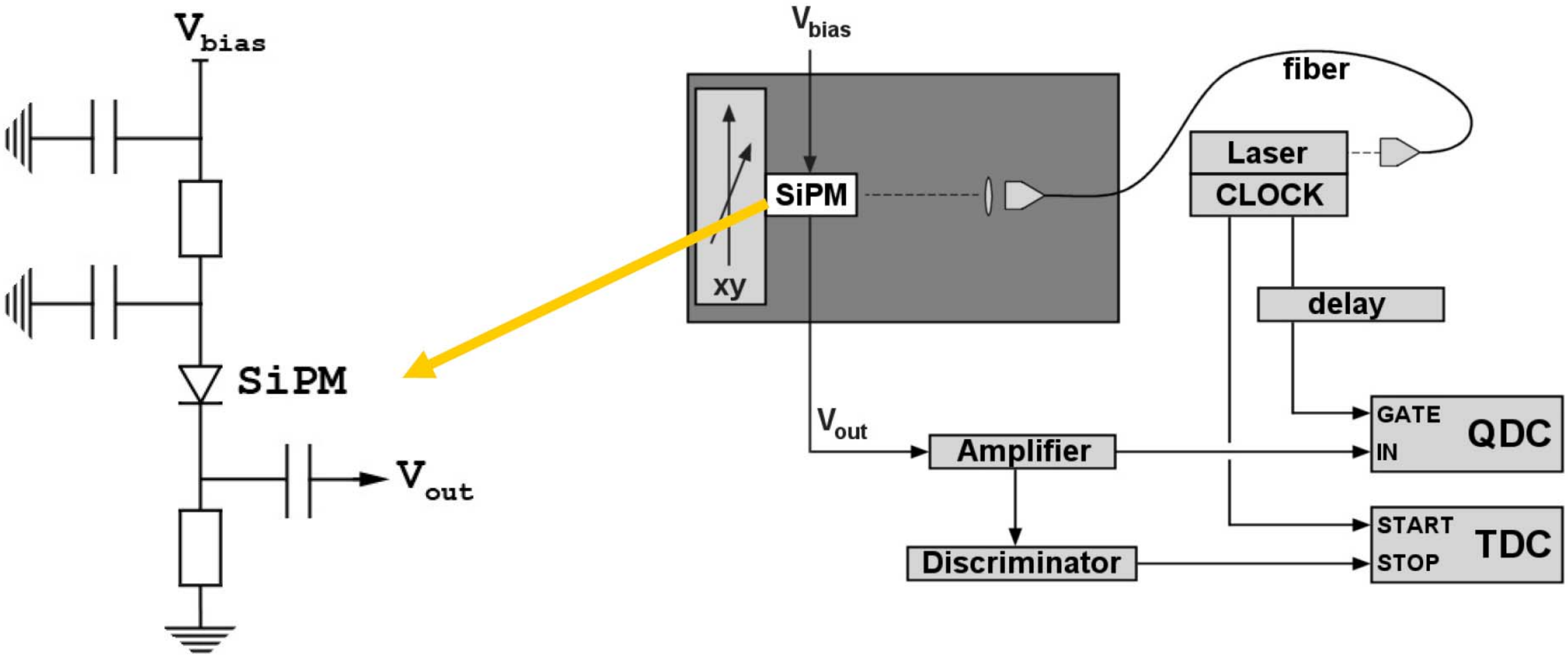
K identification efficiency at 1% π missid. probability





→ Looks OK!

Bench tests set up



- Light sources: pulsed pico-second lasers (404nm and 653nm) with $\sigma \approx 5\ \mu m$ spot size
- SiPMs mounted on a PC controled 2d stage, min. step 1 μm

Bench tests: sensors

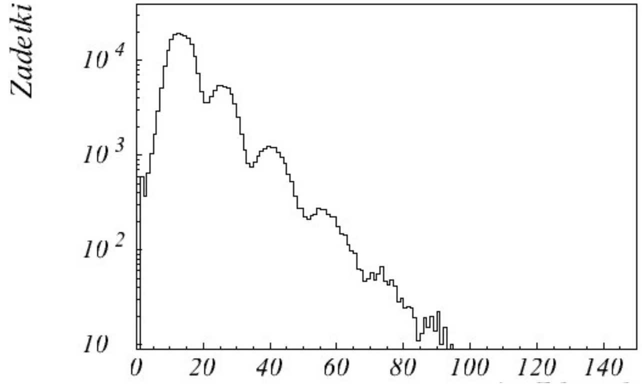
- Mephi: E407
- CPTA (Photonique): S137
- Hamamatsu MPPCs: H100C, H050C, H025C

producer data

sensor	size (mm^2)	pixels	pixel size (μm)	A_{pixel} / A_{total}	highest PDE	dark counts
E407	**1.2**	**1156**	**33**	-	-	-
S137	**1**	**556**	**43**	-	-	-
H100C		**100**	**100**	**78.5 %**	**65 %**	**372 kHz**
H050C	**1**	**400**	**50**	**61.5 %**	**50 %**	**232 kHz**
H025C		**1600**	**25**	**30.8 %**	**25 %**	**104 kHz**

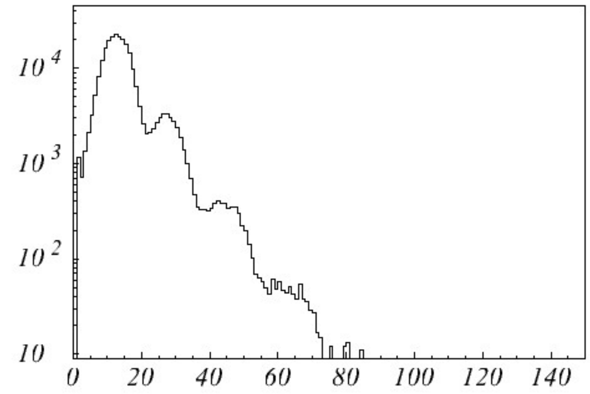
Pulse height spectra

E407



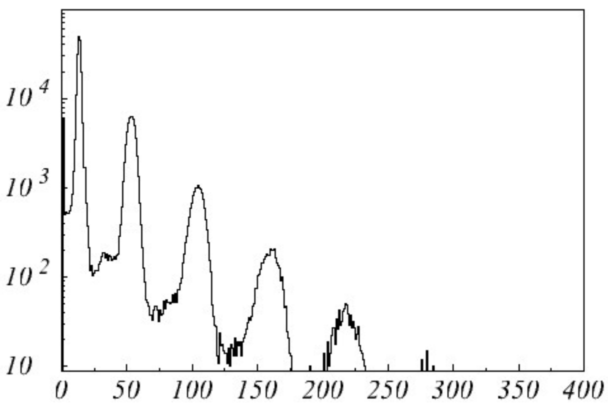
ADC channels

S137



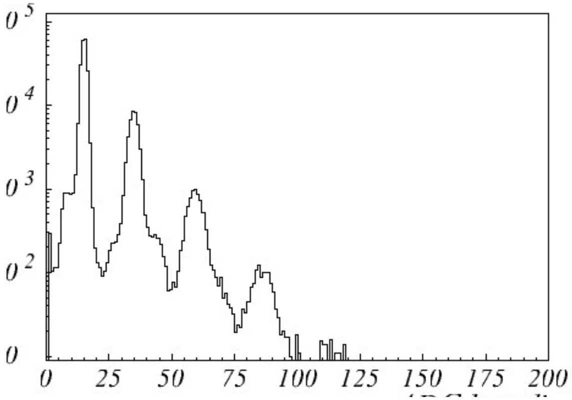
ADC channels

H100C



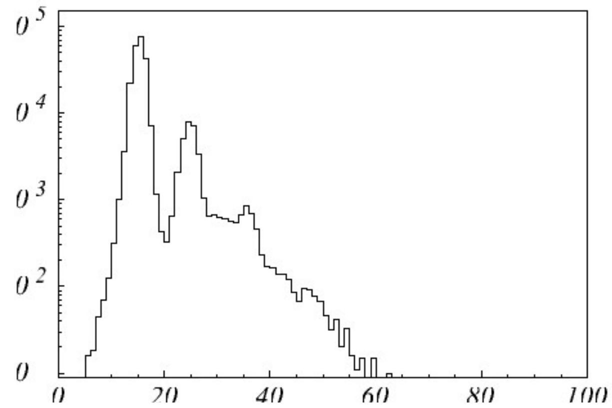
ADC channels

H050C



ADC channels

H025C



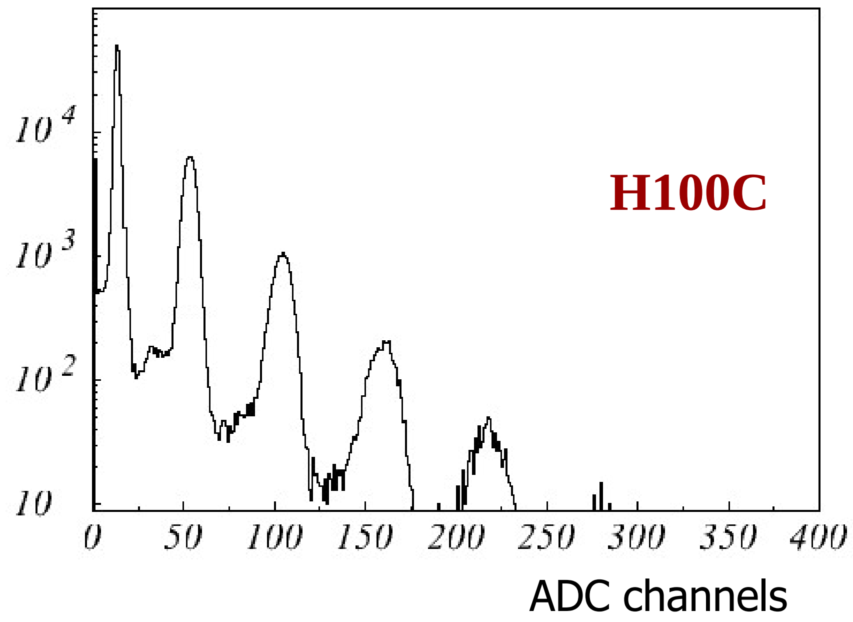
ADC channels

Can we distinguish single photon counts from multiple ones?

Given the narrow pulse-height distributions in the spectrum, how well can distinguish a single photon hit from a multi-photon hit?

Surprisingly enough, the answer is not as well as the spectrum form suggests.

Reason: photon feed-back.
'2 photon' peak is actually:
- 1 photon + feed-back and
- 2 photons + no feed-back

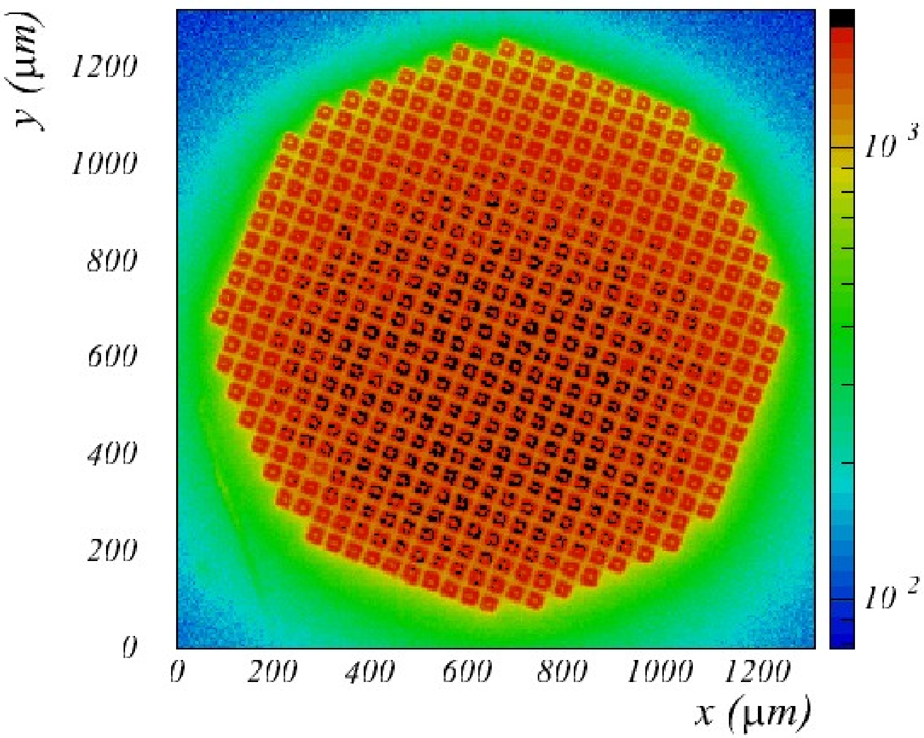


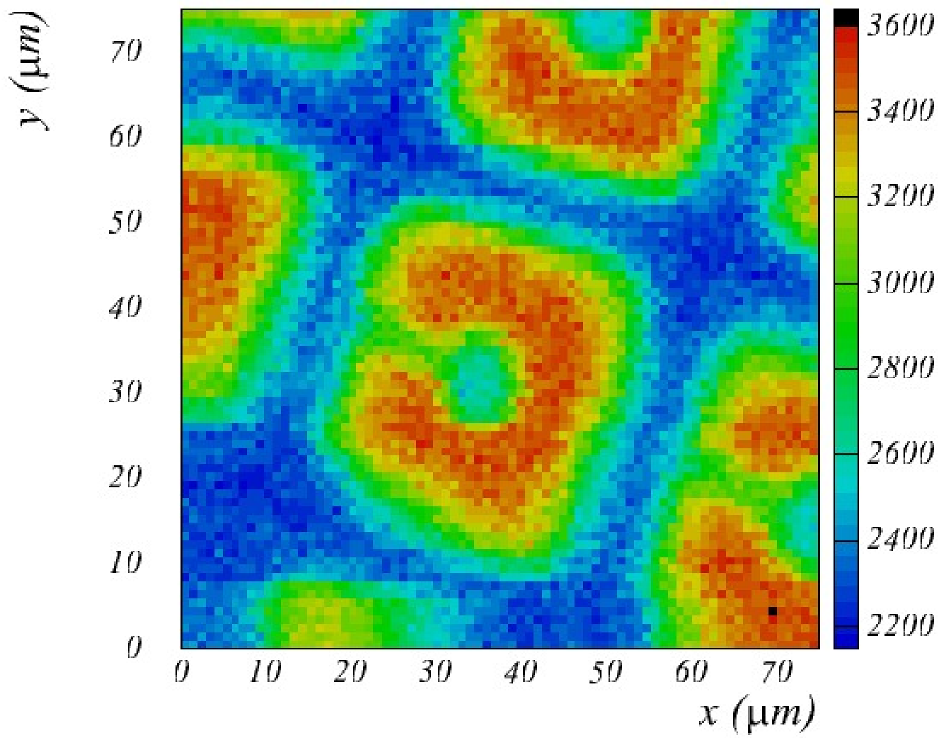
→Have to be carefull when advertizing the pulse height spectra

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

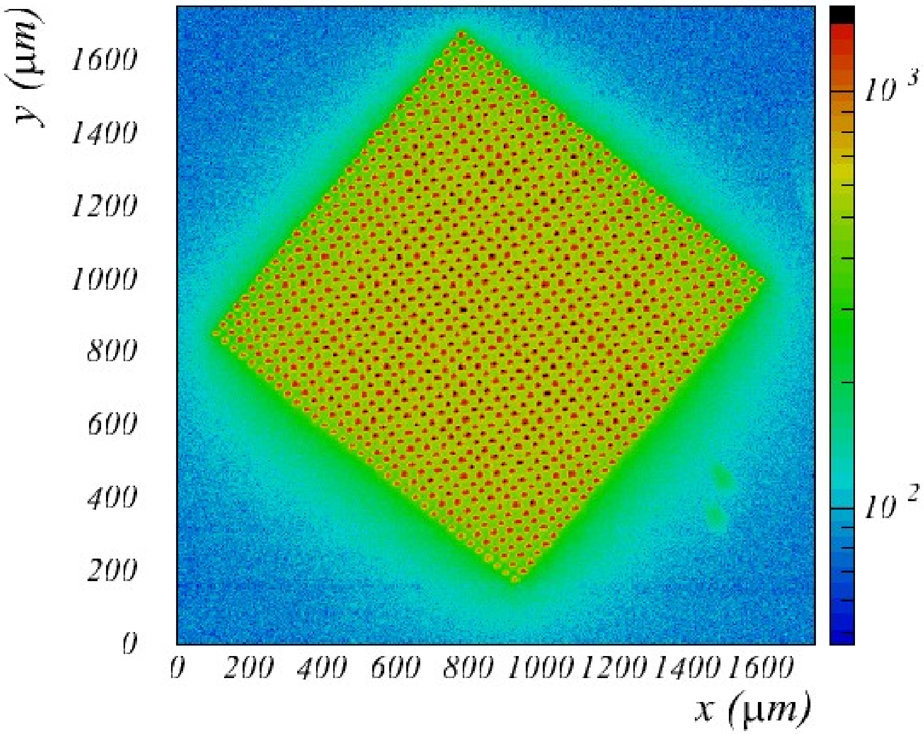
5 μm step size **S137** **Close up: 1 μm step size**

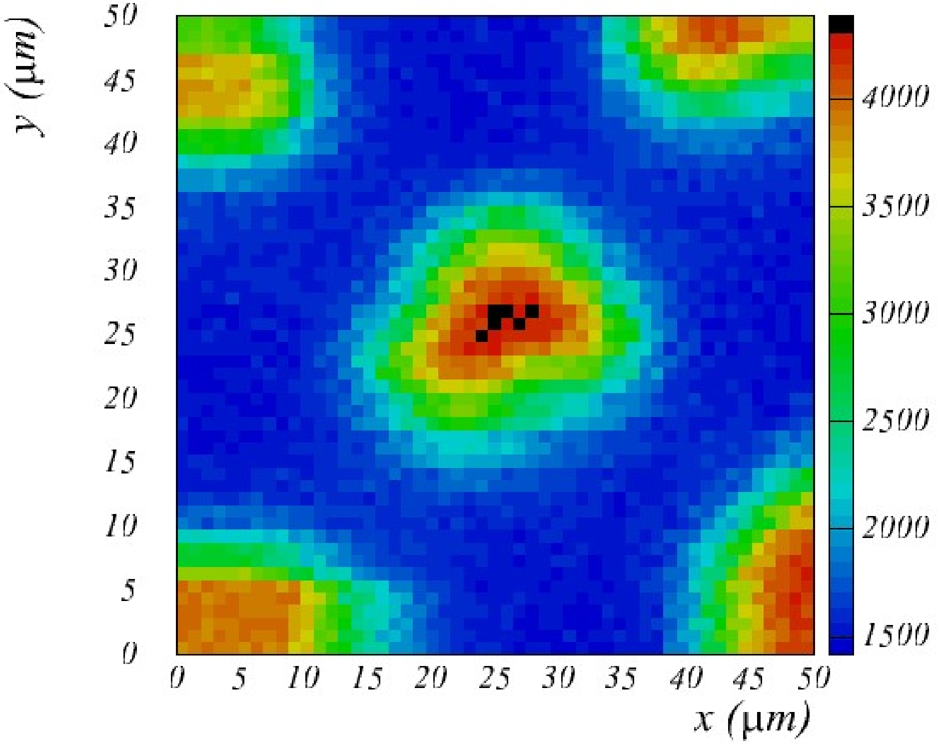




Surface sensitivity for single photons 2

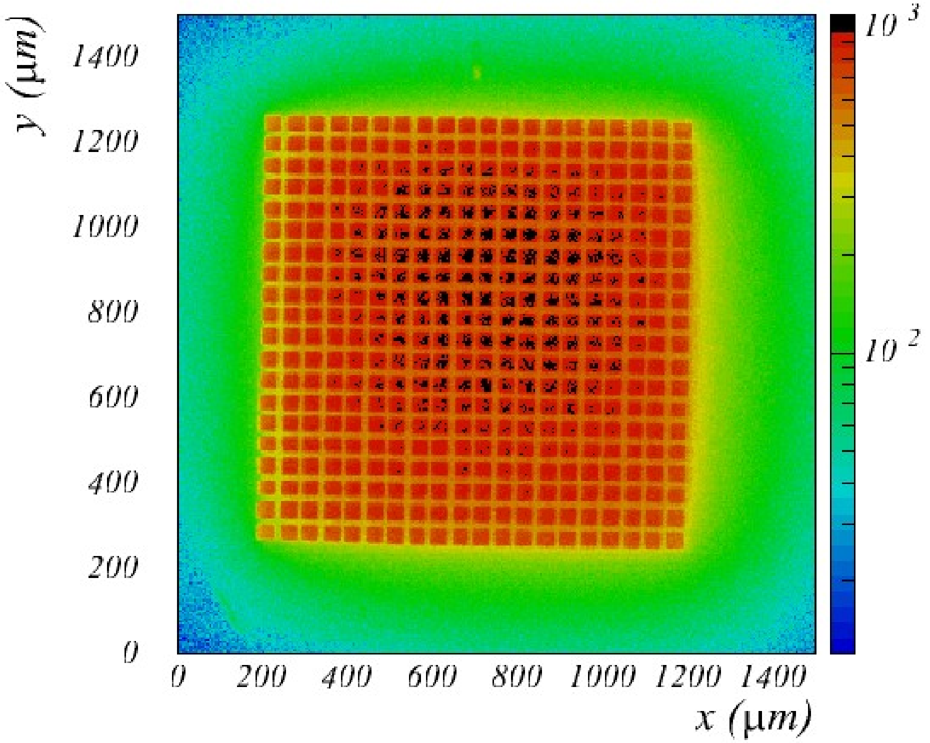
E407



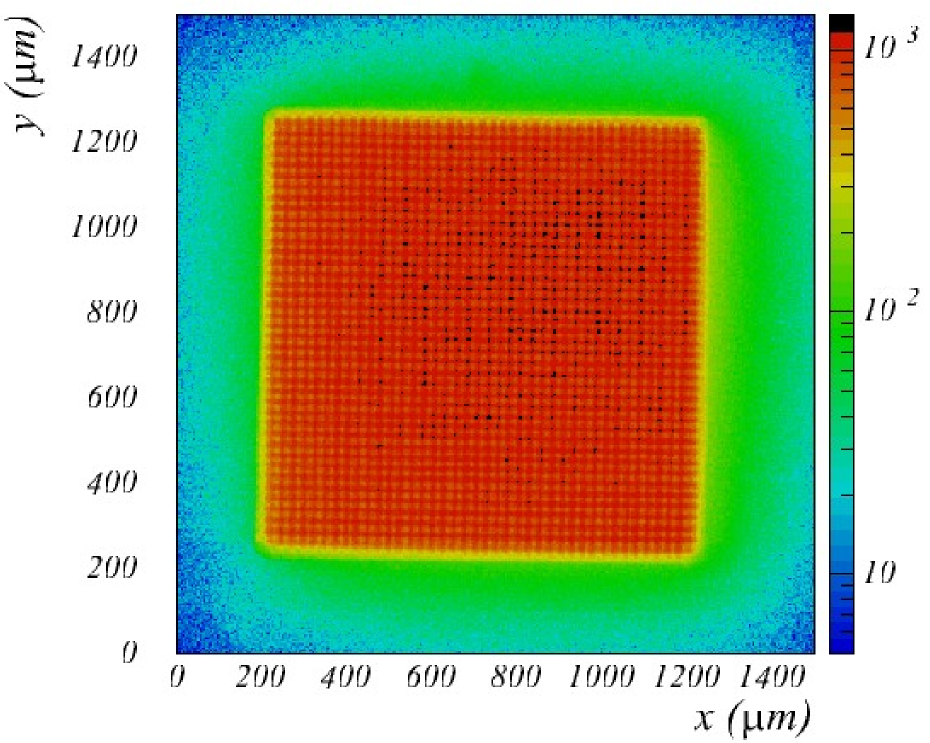


Surface sensitivity for single photons 3

H050C

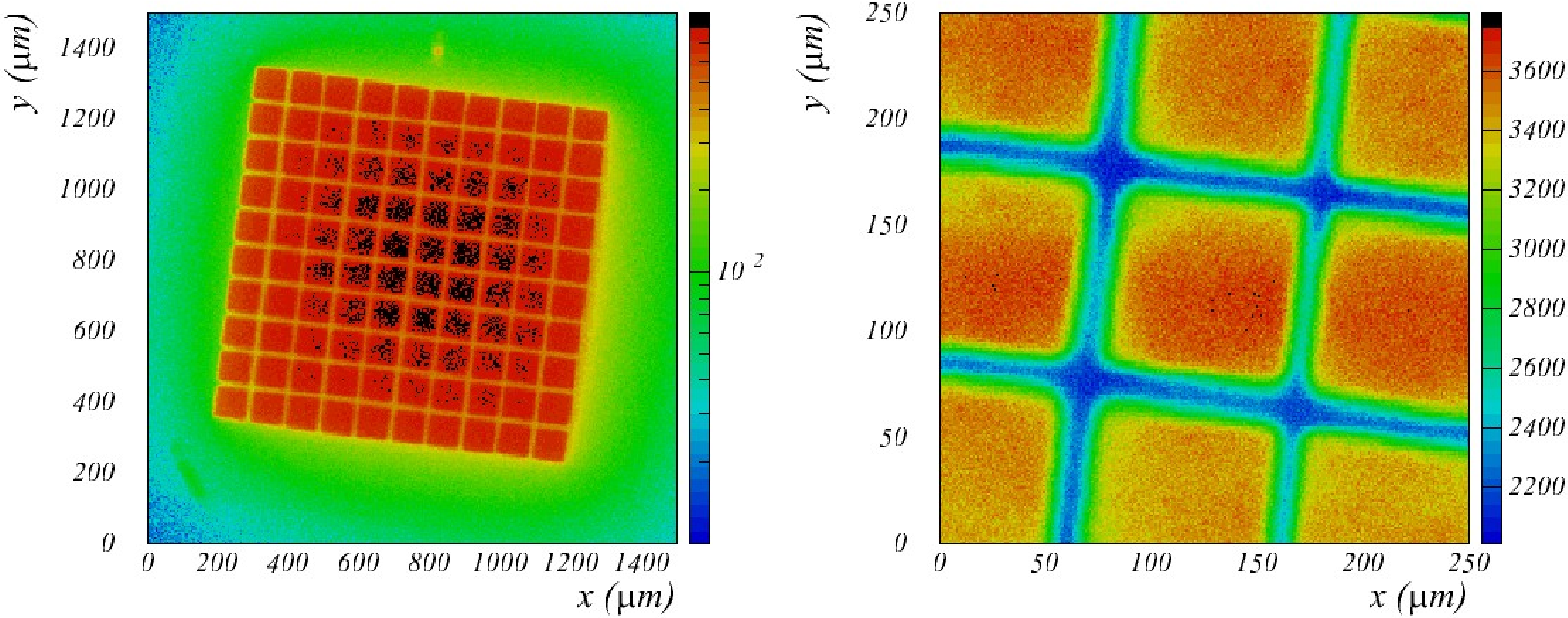


H025C



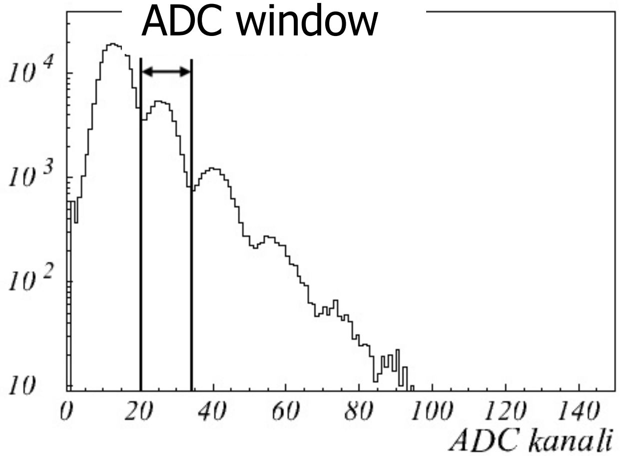
Surface sensitivity for single photons 4

H100C

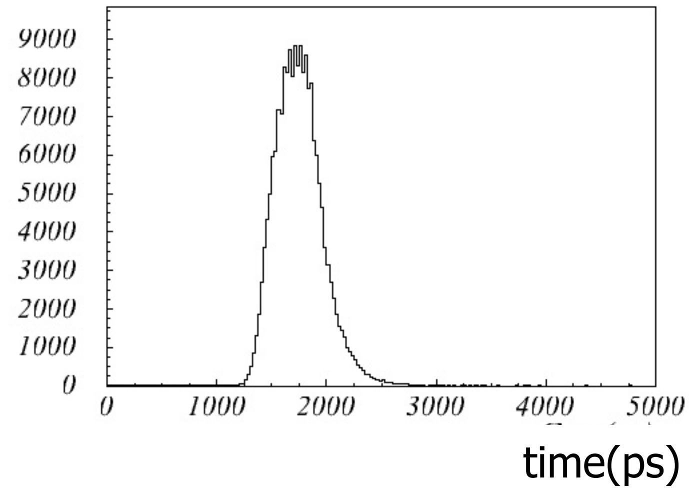


Time resolution: time walk correction

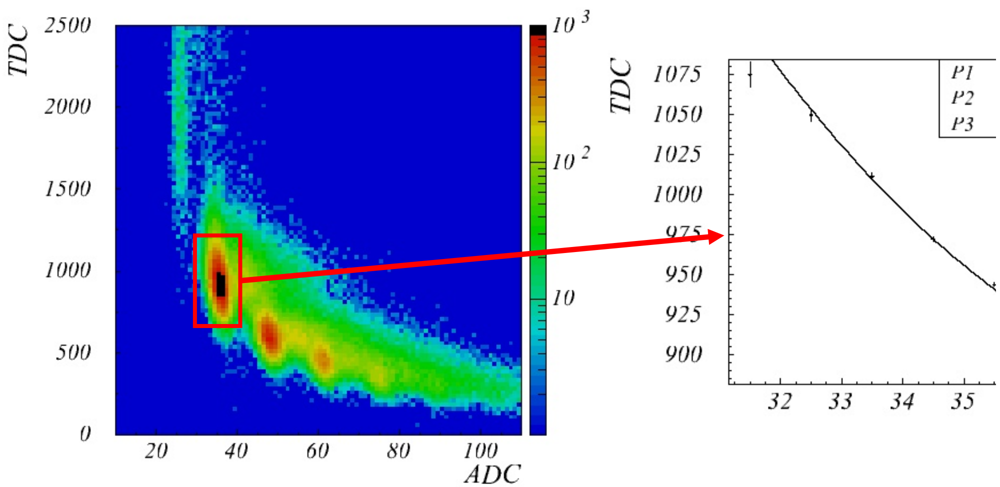
< < 1 photon

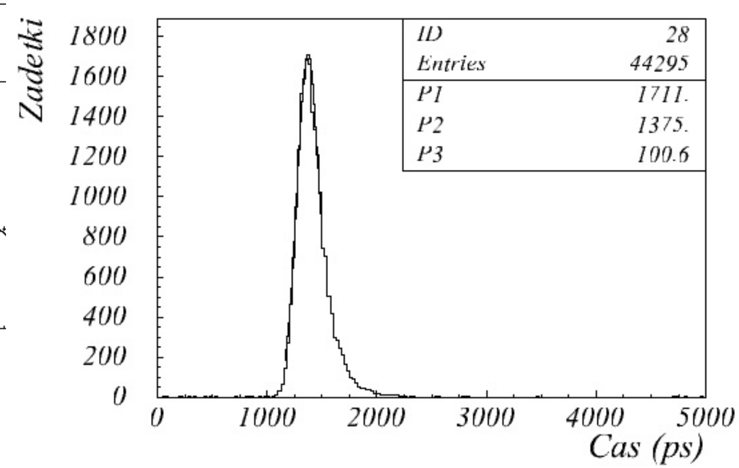


uncorrected TDC

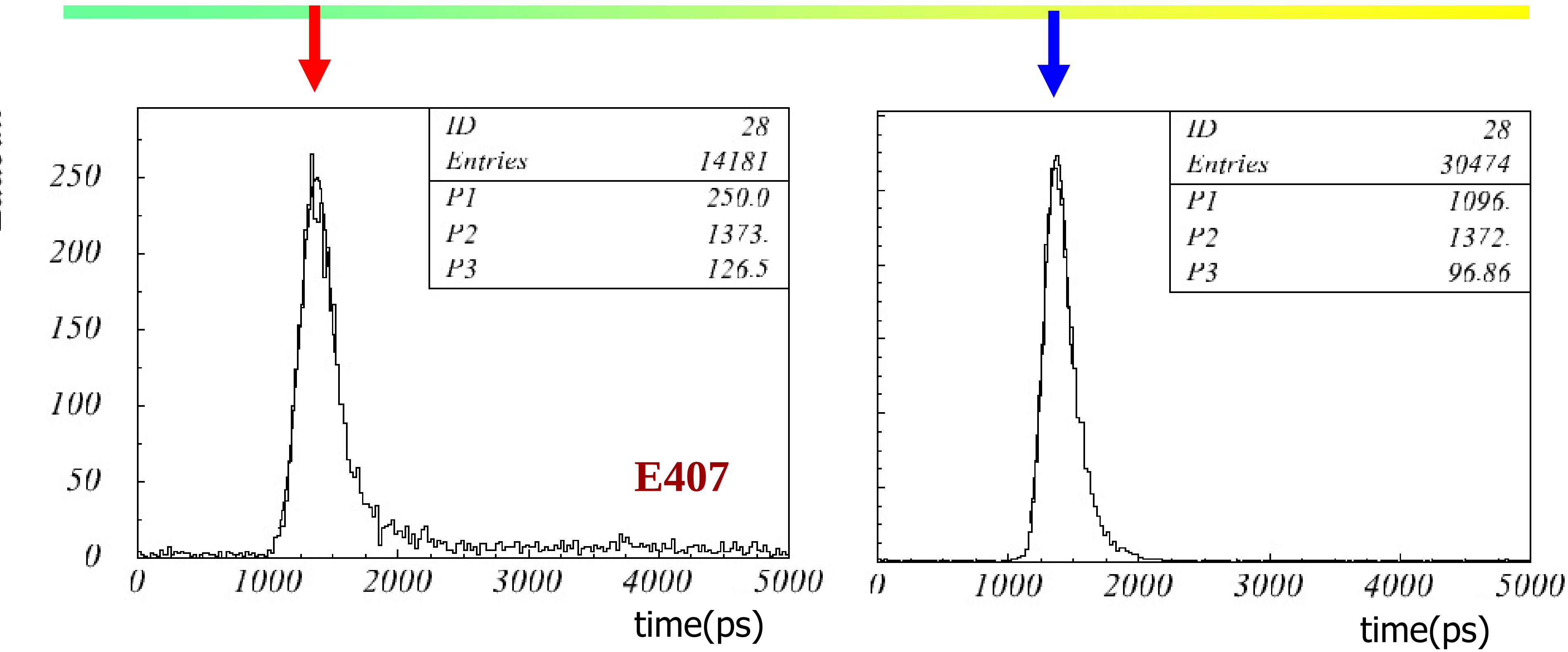


corrected TDC





Time resolution: blue vs red

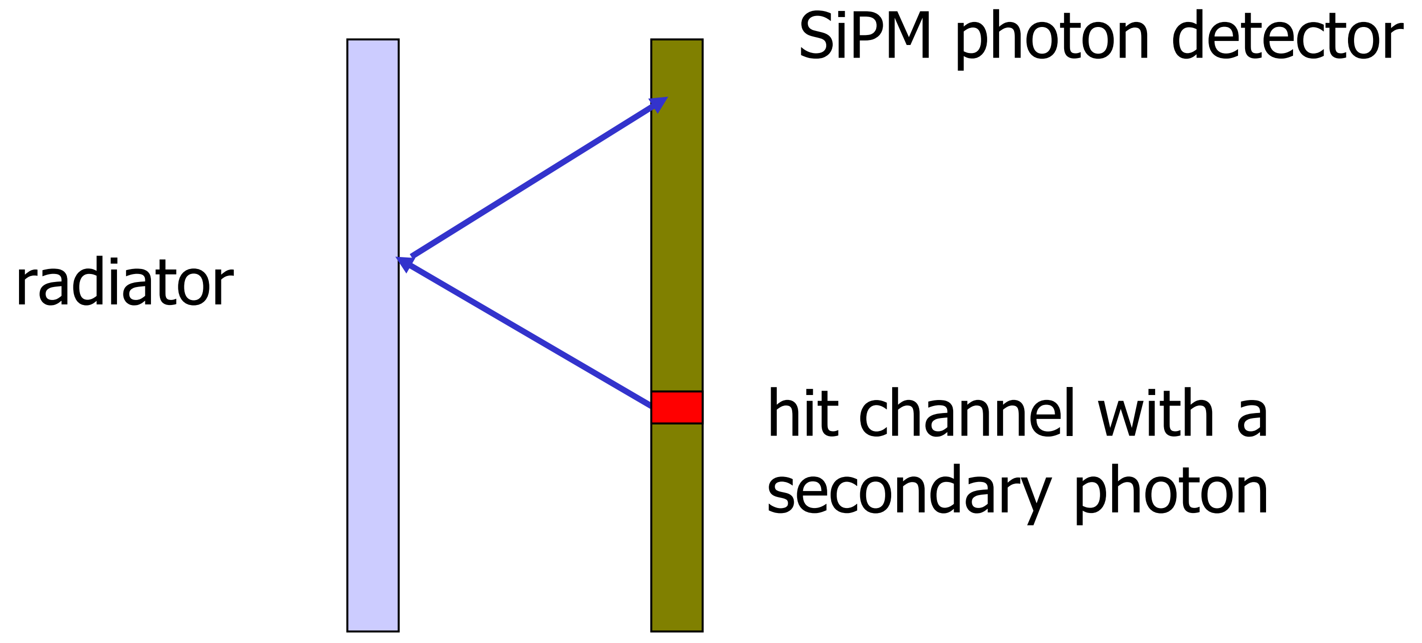


	E407	S137	H100C	H050C	H025C
σ_{red} (ps)	**127**	**182**	**145**	**212**	**154**
σ_{blue} (ps)	**97**	**151**	**136**	**358**	**135**

- $\sigma \approx 100$ ps
- $\sigma_{red} > \sigma_{blue}$

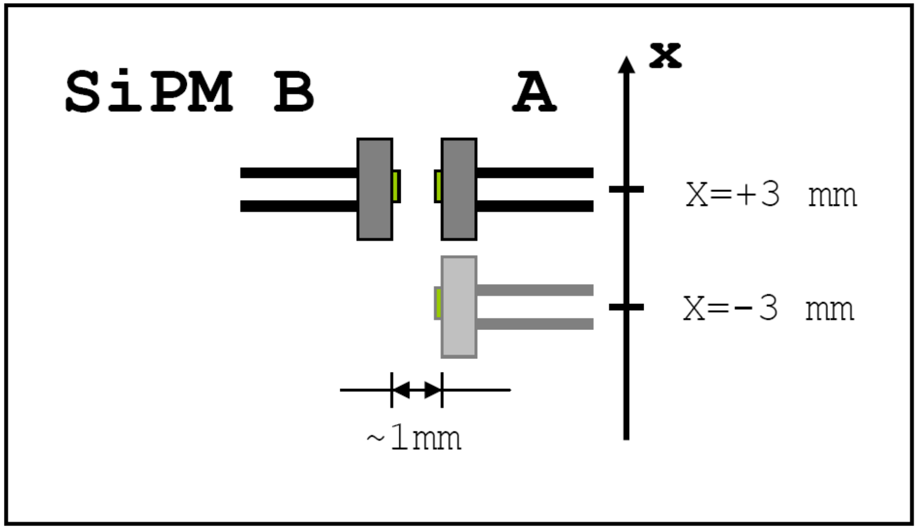
External secondary photon cross talk

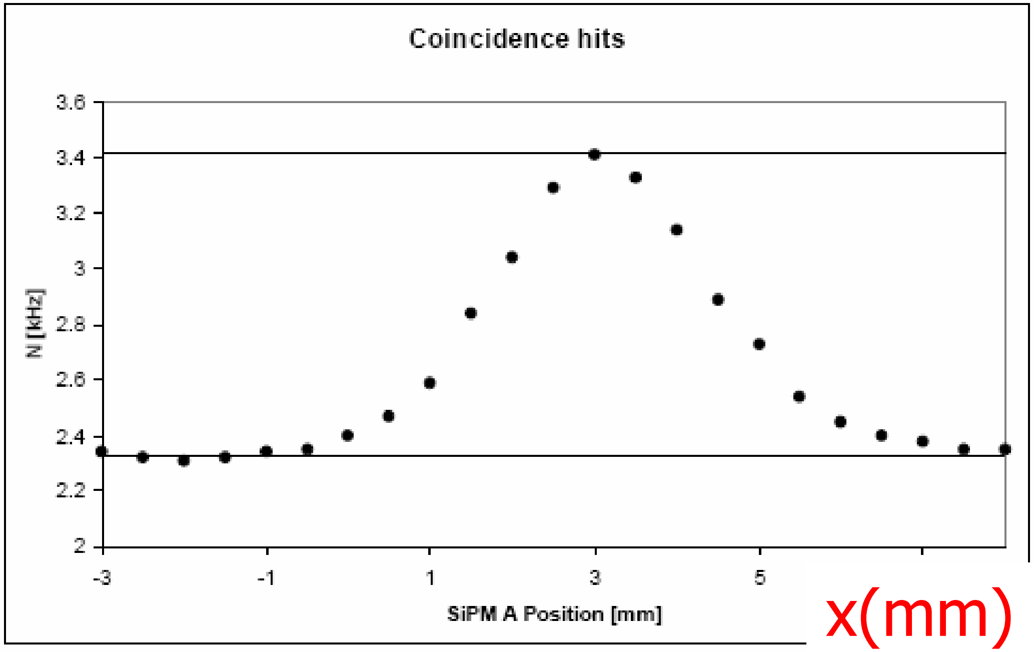
Worry: light emitted by SiPM can be reflected back to the photon detector surface



External secondary photon cross talk

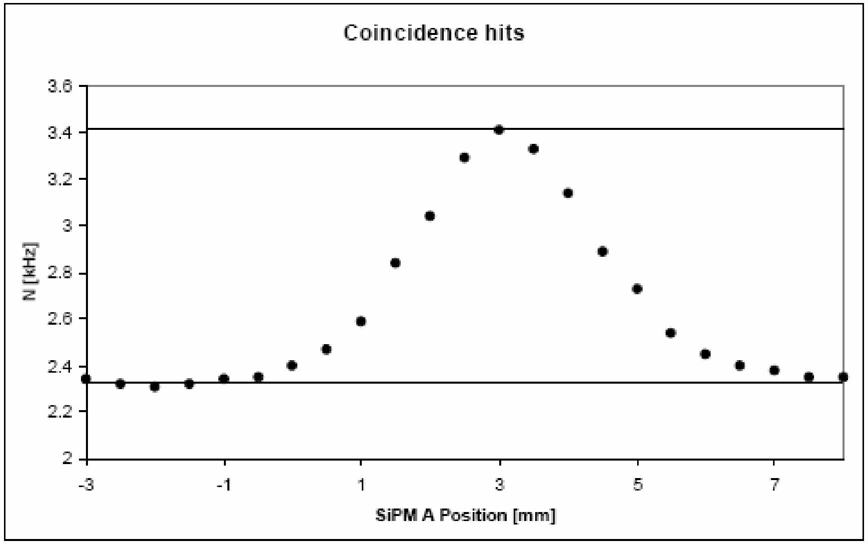
Scan a SiPM in front of a second one, observe coincidence rate





SiPM A and B: Hamamatsu MPPCs

External secondary photon cross talk



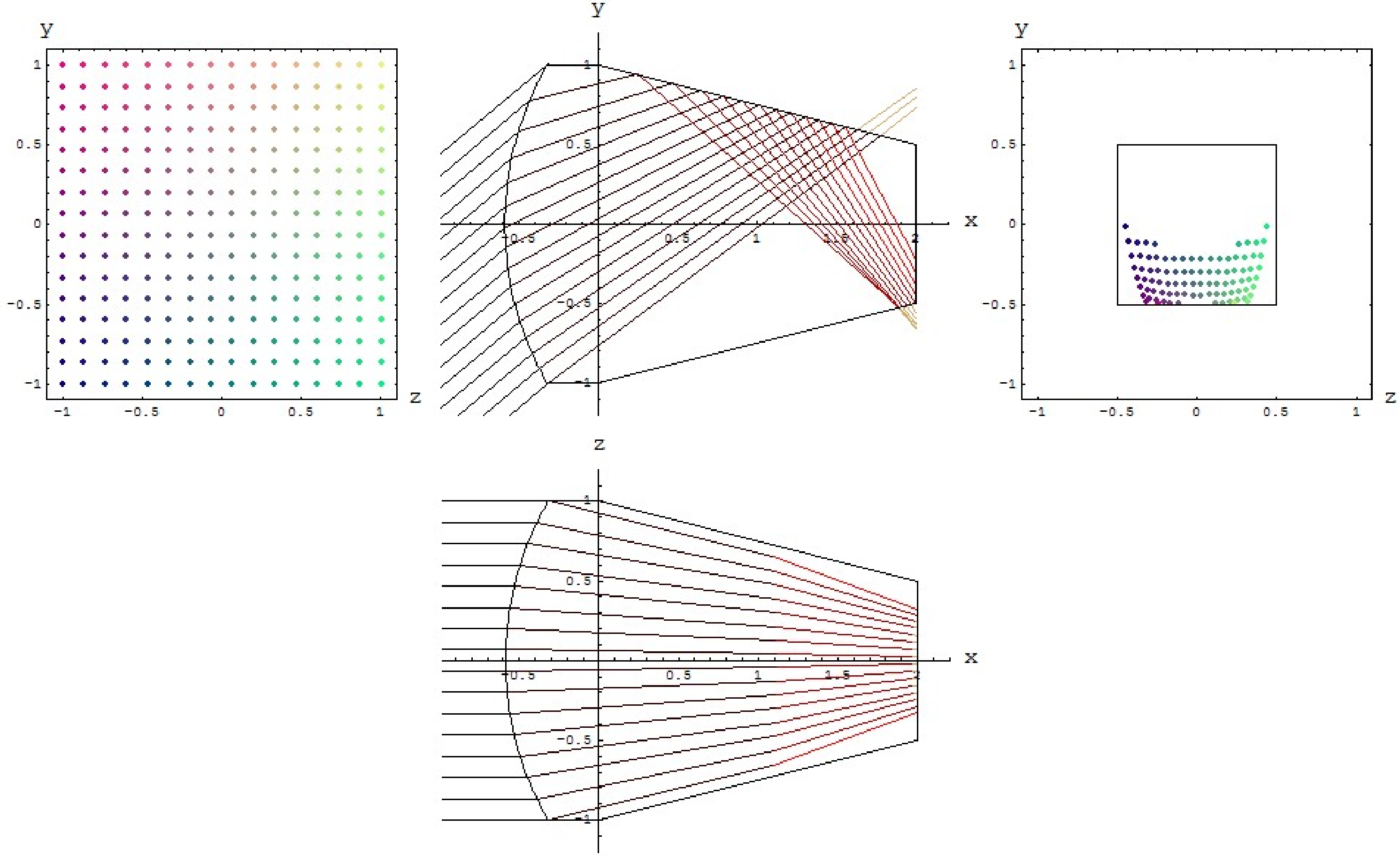
- single detector dark rate ~ 200 kHz
- coincidence background ~ 2.4 kHz
- when SiPMs overlap, coincidence rate increases by ~1 kHz
- 1mm active area 1mm away ~ 15% of 2π solid angle
- full (2π) solid angle: 1kHz/(2 x 200kHz) /15% **~ 2%**

→OK (even with an assumption of a 100% reflectivity of the radiator surface → gets reduced by two further orders of magnitude)

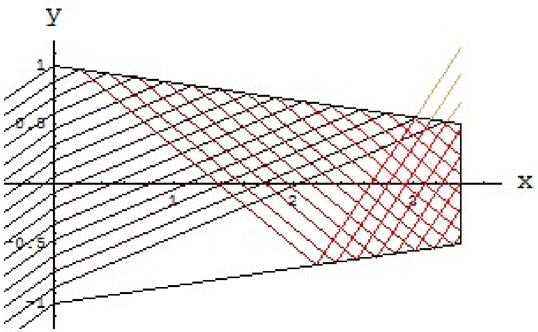
Light guides

– Effective increase of the active surface

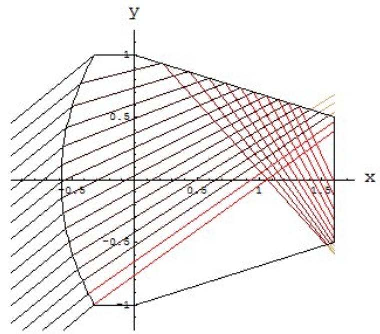
– Improvement of the signal/noise ratio (collecting more signal photons for fixed dark count rate)



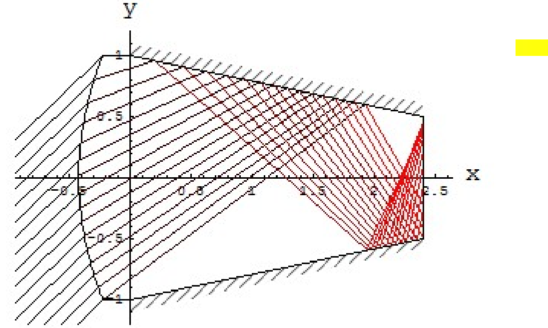
Planar entry window



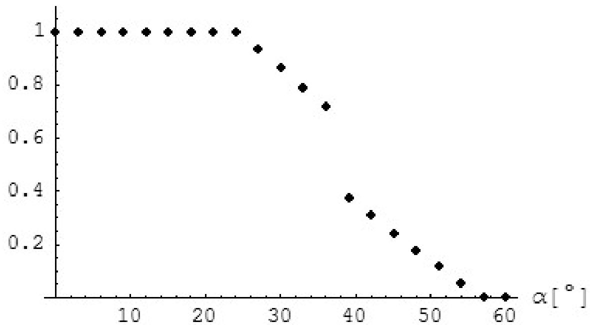
Spherical entry window

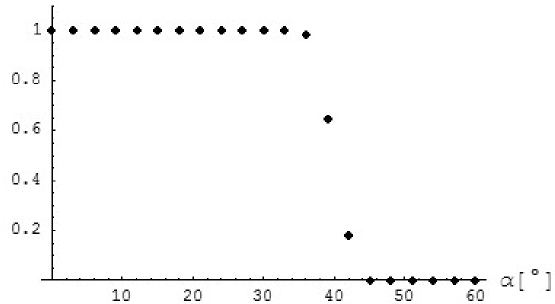


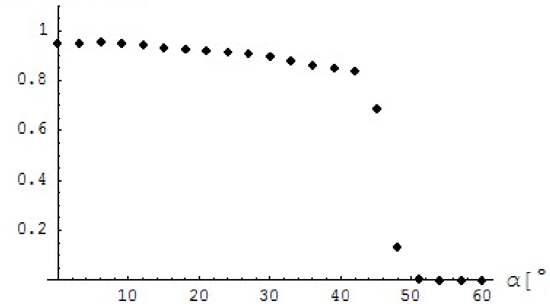
Spherical entry window, reflective sides



Efficieny vs. angle of incidence α



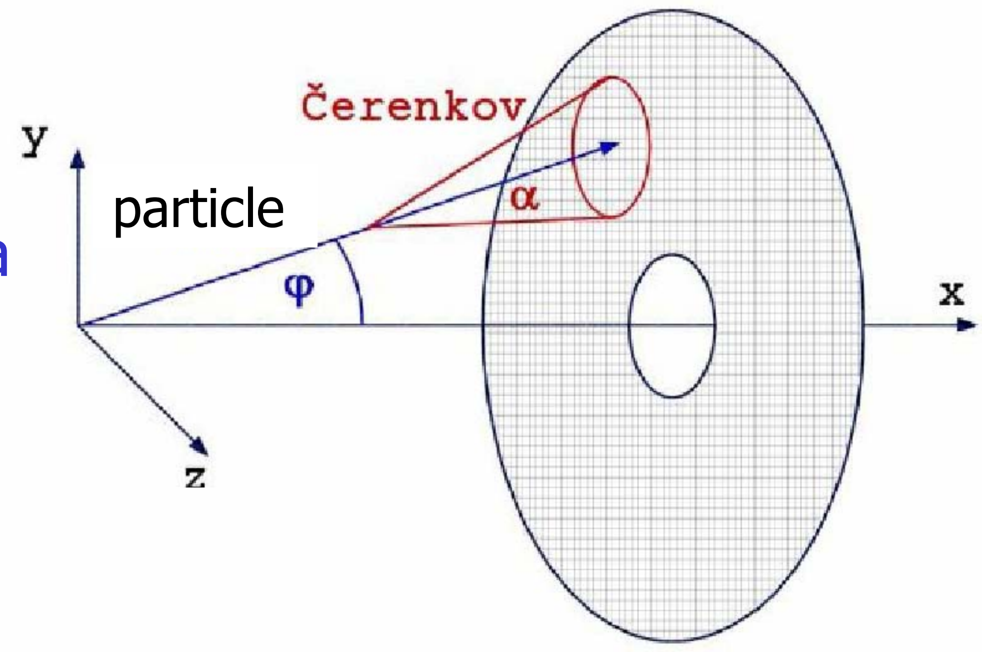


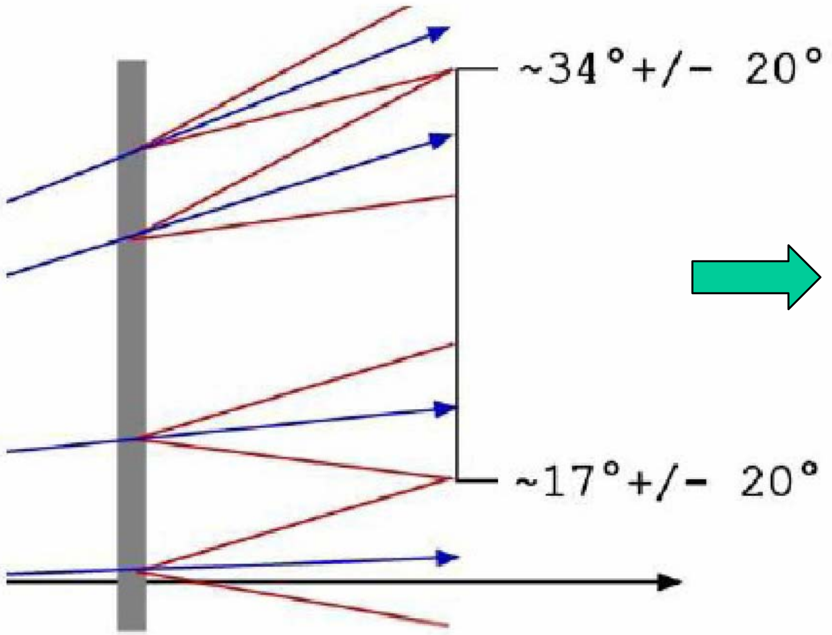


Light guide	d/a	R/a	α_{min}, α_{max}	I(-60°, 60°)
Planar entry	**3.4**	**-**	**-24°, 24°**	**64%**
Sph. entry	**1.6**	**2.0**	**-35°, 35°**	**66%**
Reflective sides	**2.4**	**2.6**	**-44°, 44°**	**69%**

Light collection: required angular range

For our application only a limited angular range of incident has to be covered at a given position on the detector



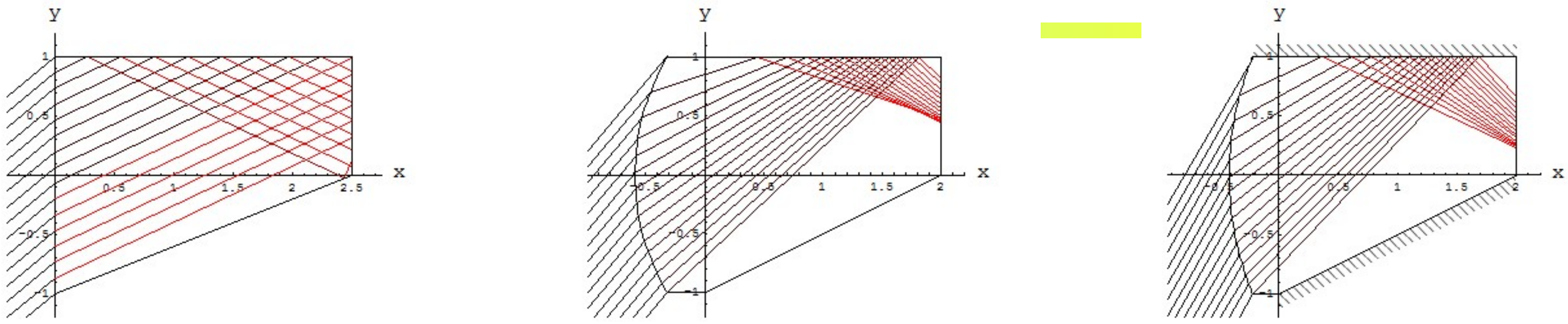


→ ~ −3°... 54°

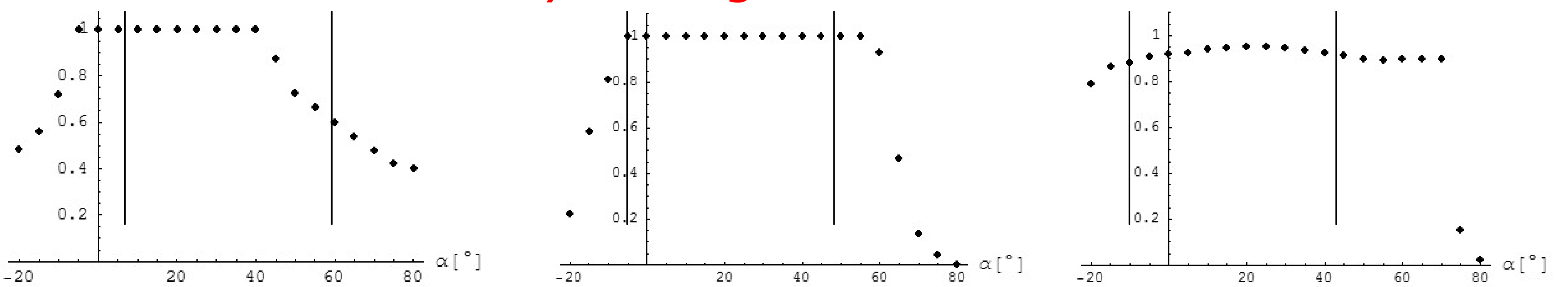
→ Take this asymmetry into account when designing the light collection system.

Peter Križan, Ljubljana

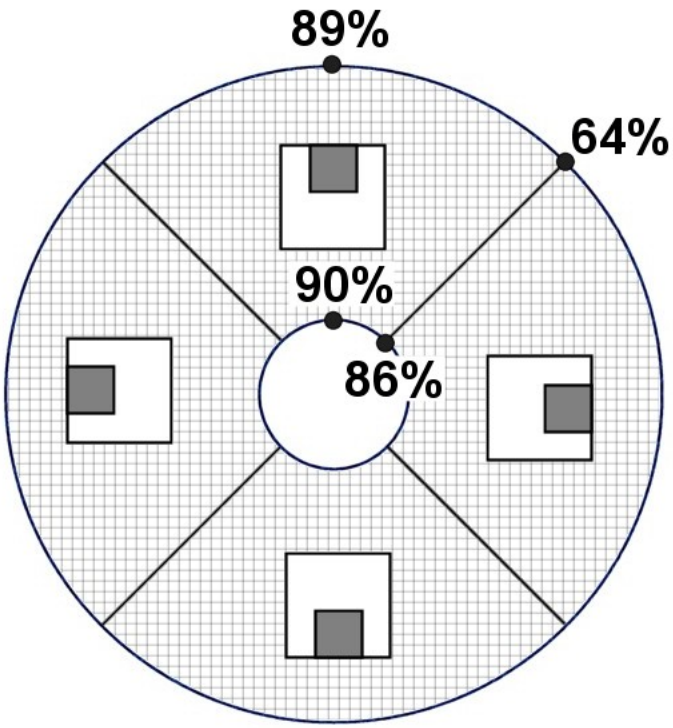
Planar entry window | **Spherical entry window** | **Spherical entry window, reflective sides**



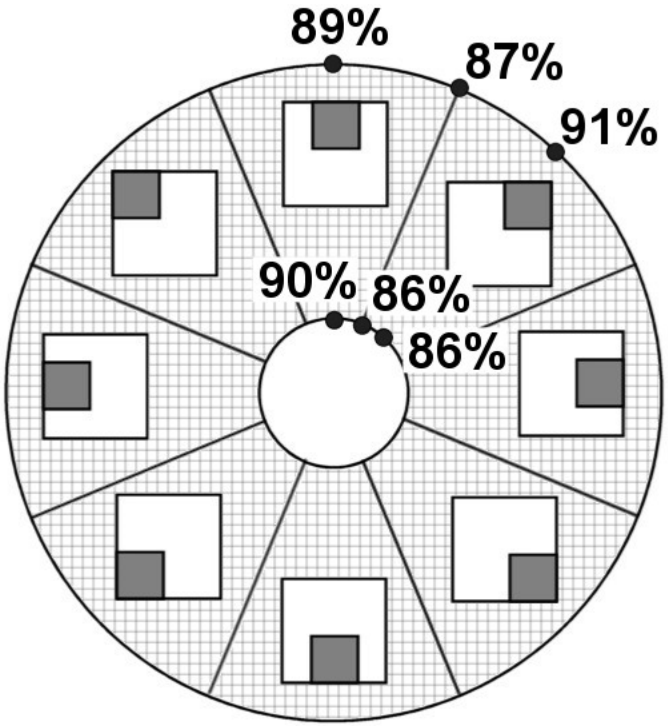
Efficieny vs. angle of incidence α



Light guide	D	R	α_{min}, α_{max}	I(-3°, 54°)
Planar entry	**3.4**	**-**	**-6°, 41°**	**95%**
Sph. entry	**1.6**	**2.0**	**-6°, 58°**	**100%**
Reflective sides	**2.4**	**2.6**	**-19°, 71°**	**93%**



Design with a single light guide type



Design with a two light guide types

Tests with cosmic rays

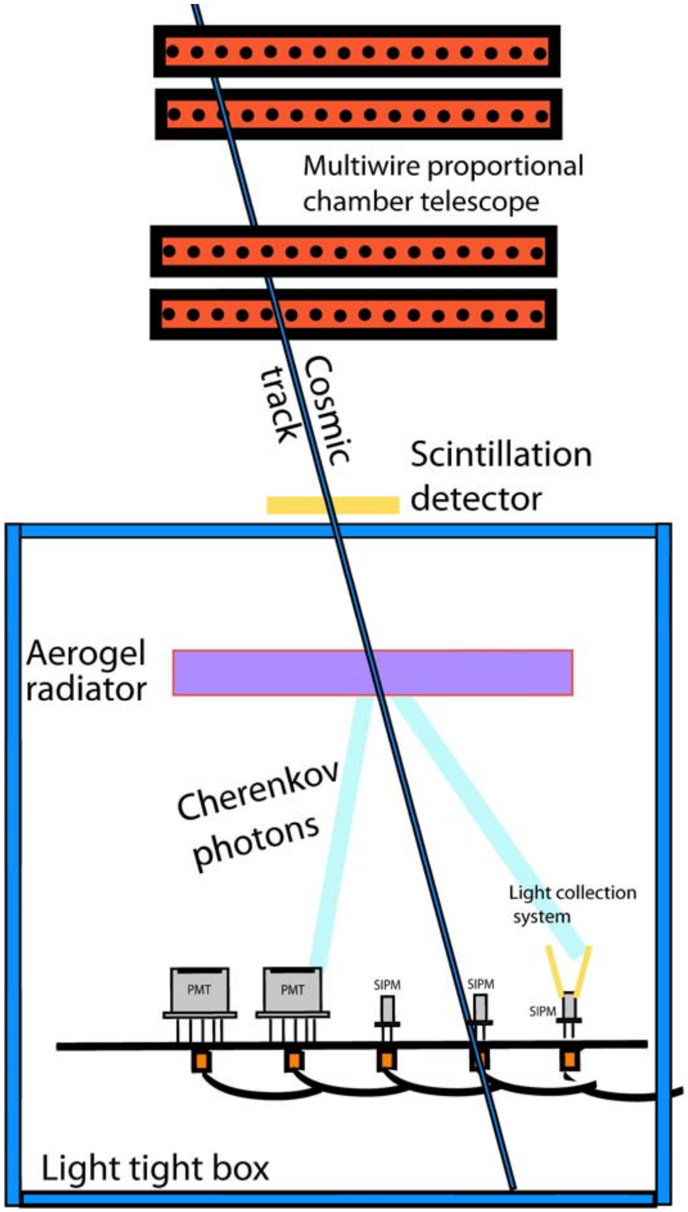
Photon detector:

•Array of 6 SiPMs

•Array of 12 R5900-M16 PMTs as reference

Set-up runs well, waiting for statistics to accumulate

→will have results ready for RICH07 and IEEE/NSS 2007



Summary

RICH counters of the next generation: new challenges, operation in high magnetic field with excellent timing

Several photon detectors are being studied

SiPMs (G-APDs) look like a viable candidate

Needed: light guides and operation with a well defined time window

Still some work to do...

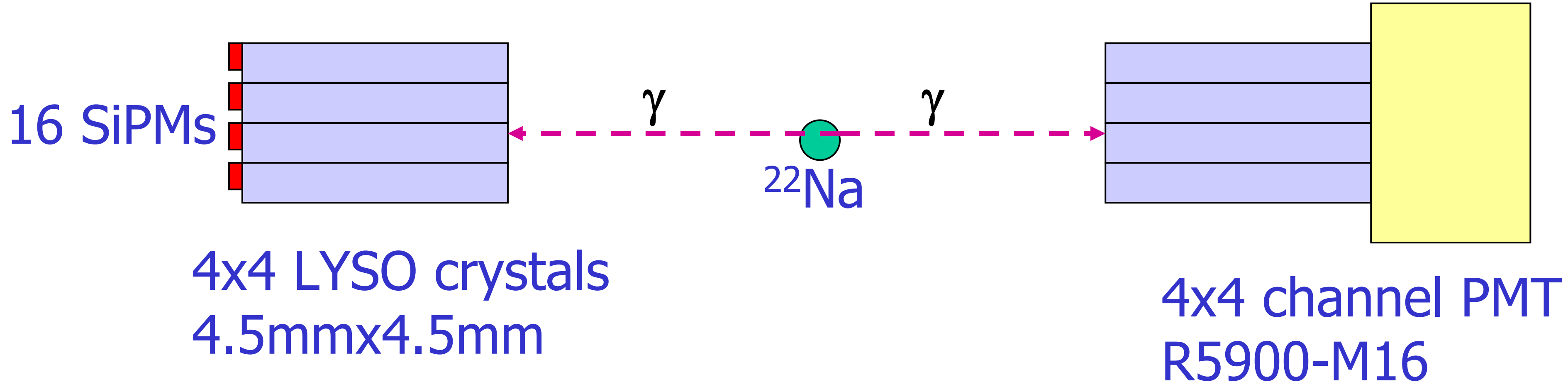
- Read-out electronics
- Light guide + sensor integration
- Radiation hardness studies

We also work on a PET module...

Test a PET module with:

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

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

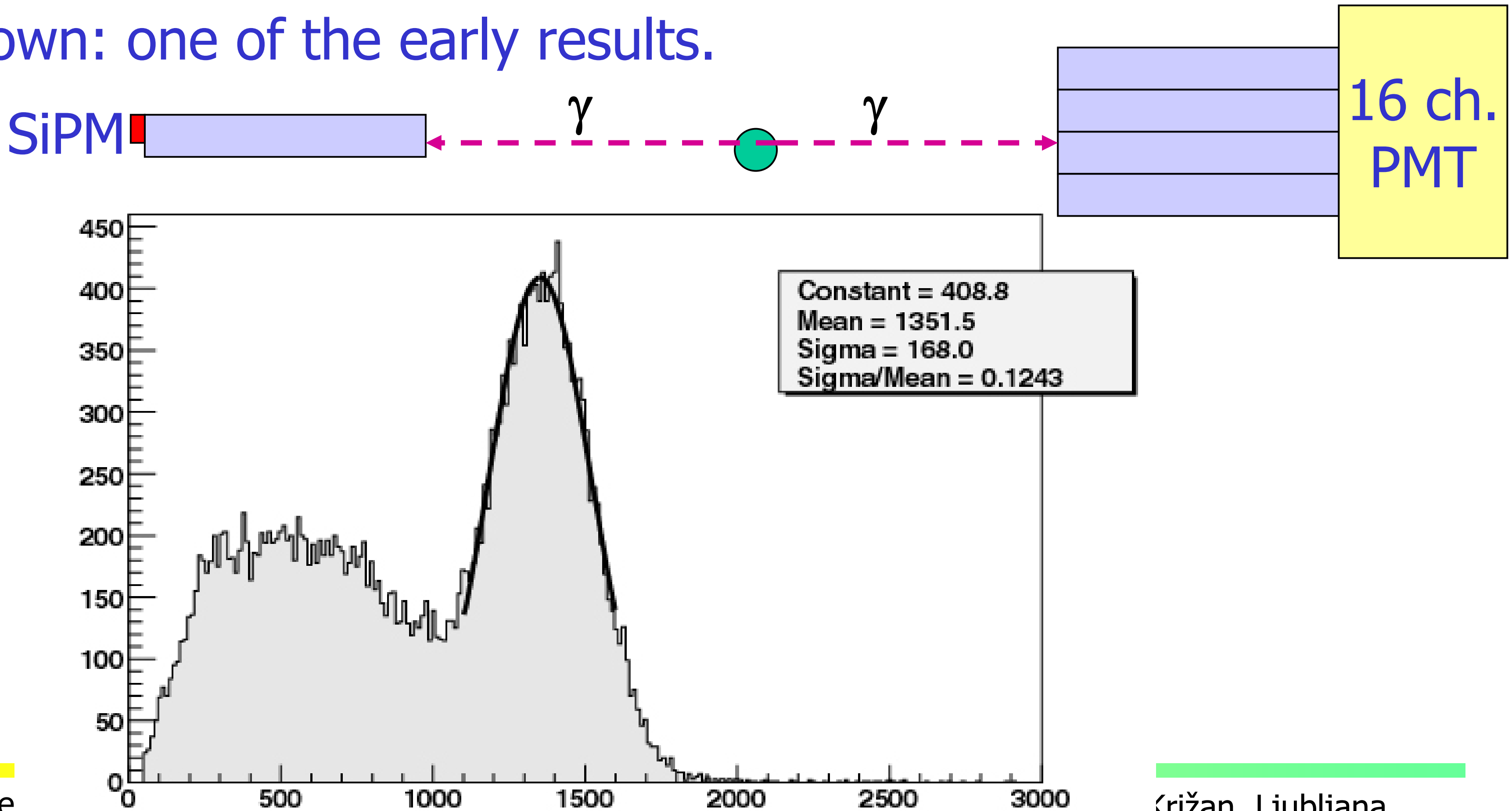


We also work on a PET module 2

Some tests with Na22 in coincidence with a 4x4 LYSO+MAPMT module

Best: ~9% (rms) energy resolution

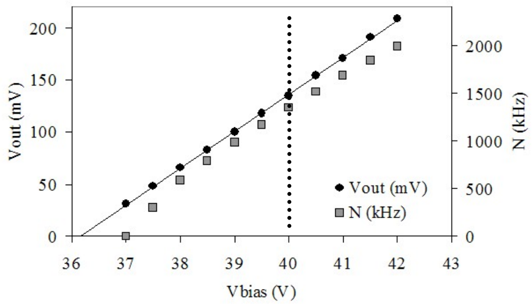
Shown: one of the early results.



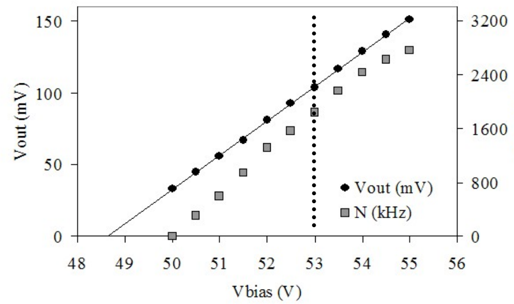
Back-up slides

Amplification and dark counts

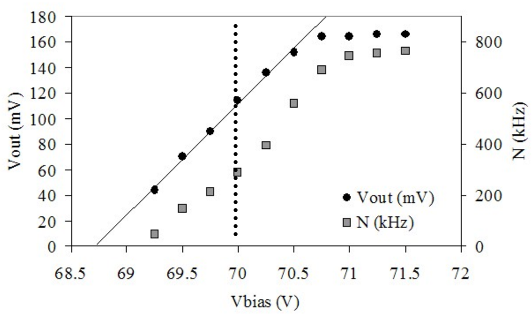
E407



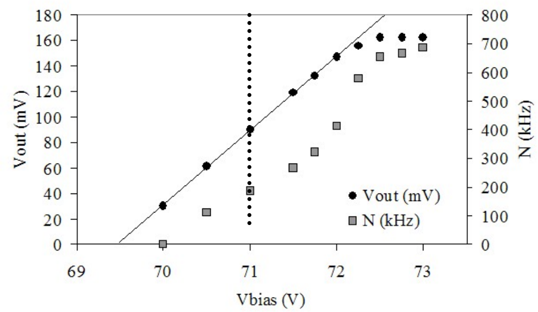
S137



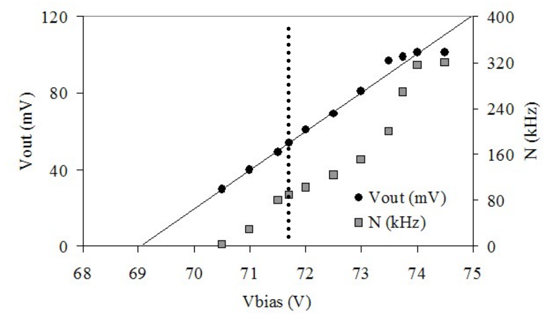
H100C



H050C



H025C

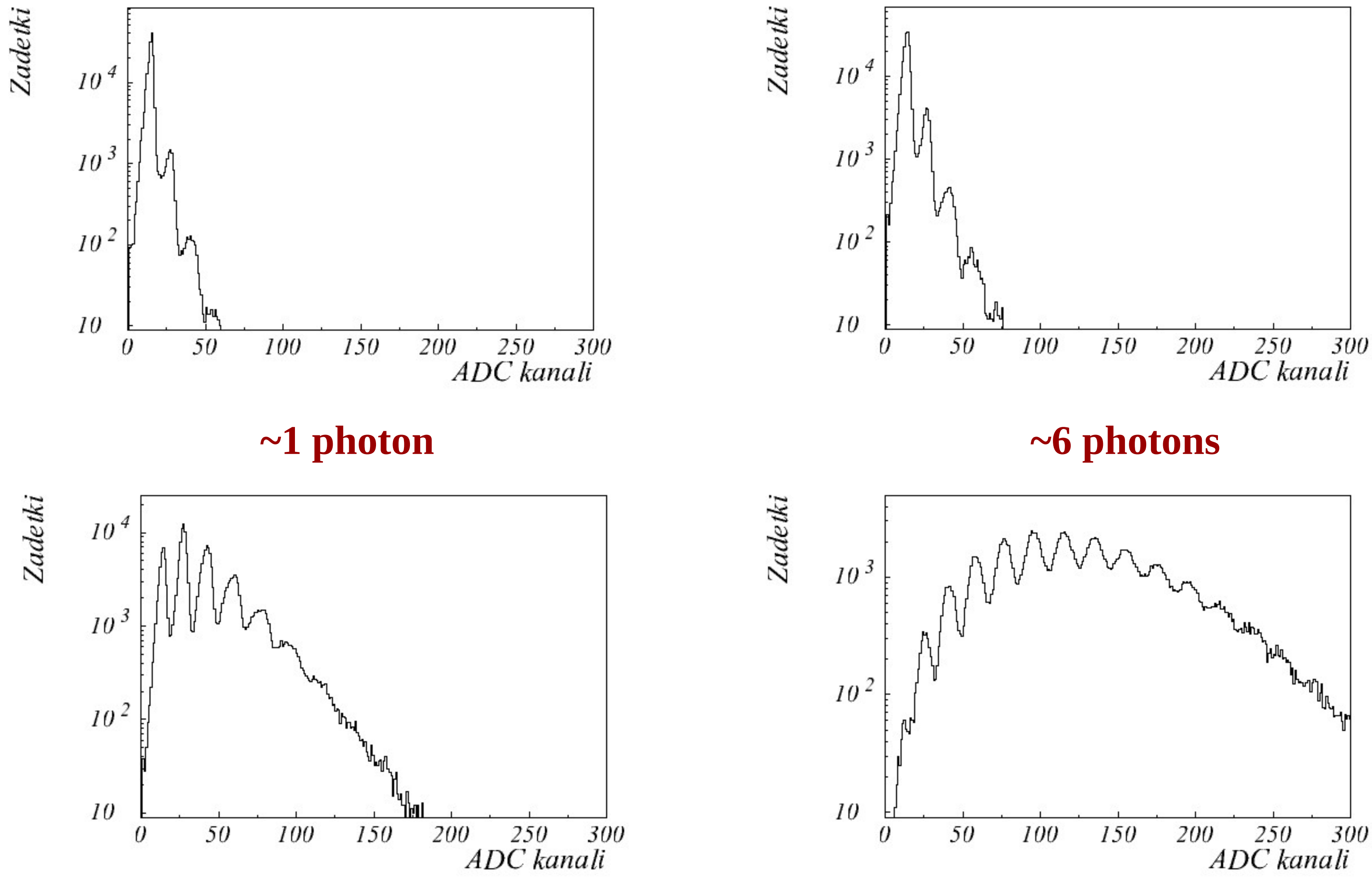


	E407	S137	H100C	H050C	H025C
V_{th} (V)	**36.9**	**49.2**	**69.0**	**69.9**	**69.4**
V_{bias} (V)	**40.0**	**53.0**	**70.0**	**71.0**	**71.7**
dark counts (producer data)	**-**	**-**	**372 kHz**	**232 kHz**	**104 kHz**
dark counts (measured)	**1.3 MHz**	**1.8 MHz**	**289 kHz**	**199 kHz**	**89 kHz**

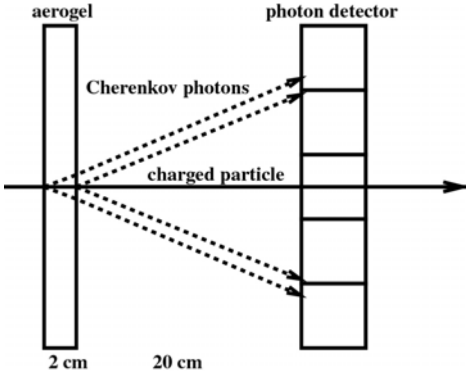
Detected charge

Dark counts **<< 1 photon**

~1 photon **~6 photons**

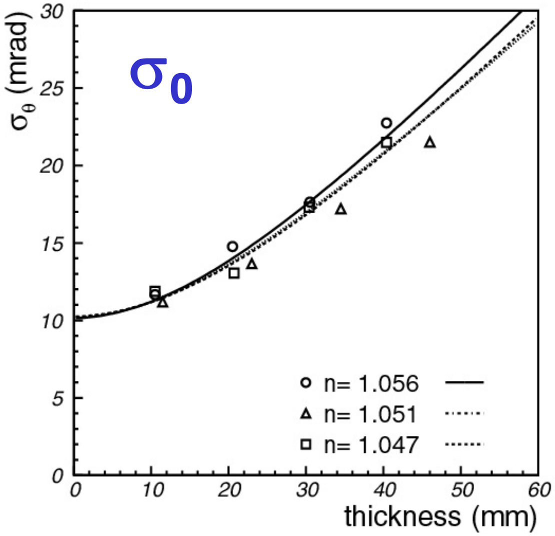


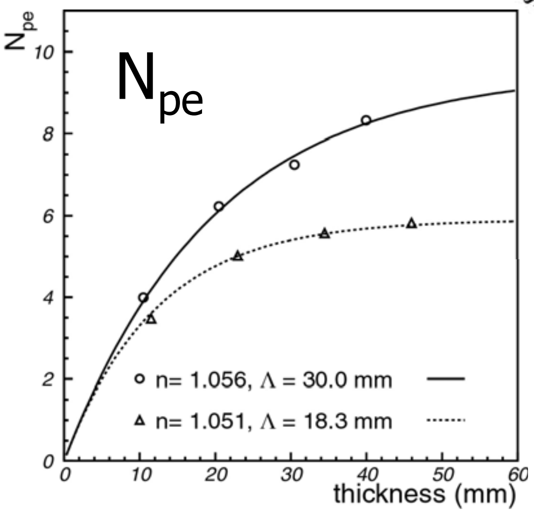
How to increase the number of photons?

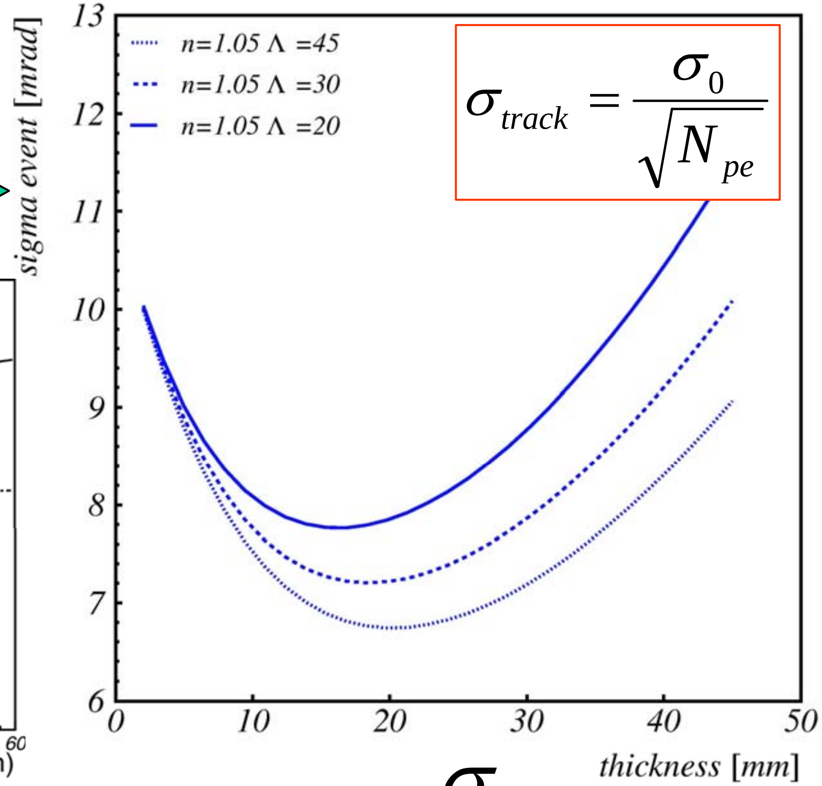


What is the optimal radiator thickness?

Use beam test data on σ_0 and N_{pe}







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

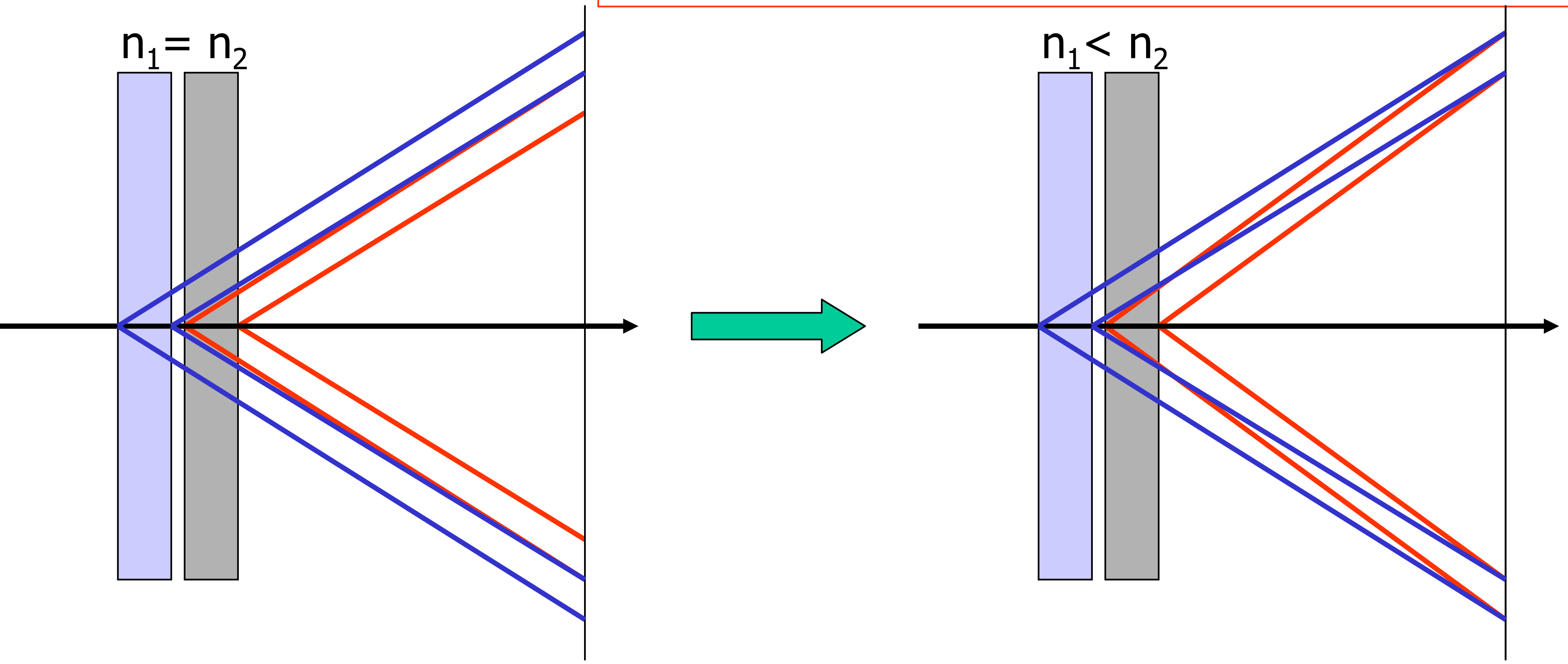
Optimum is close to 2 cm

Radiator with multiple refractive indices

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

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

normal

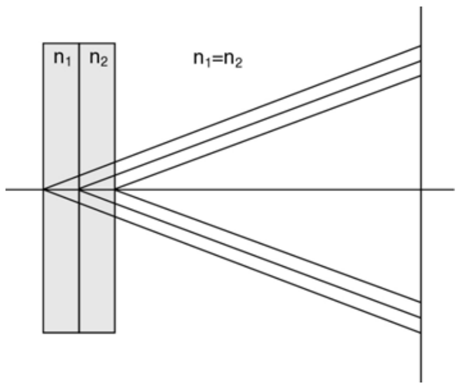


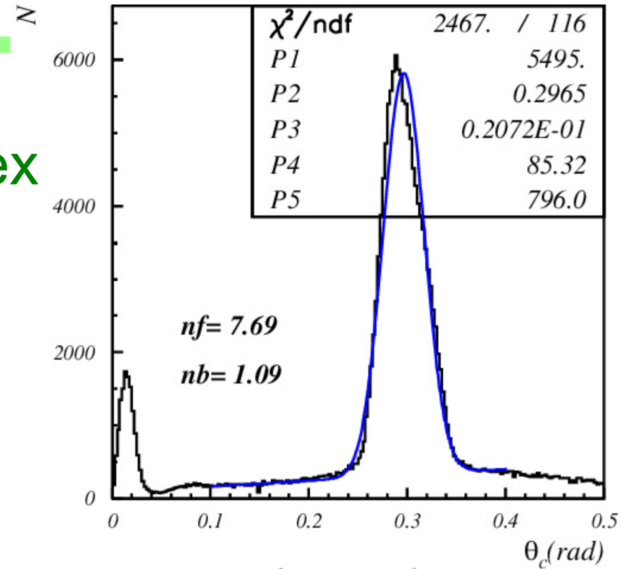
- NIM A548 (2005) 383

→ focusing radiator

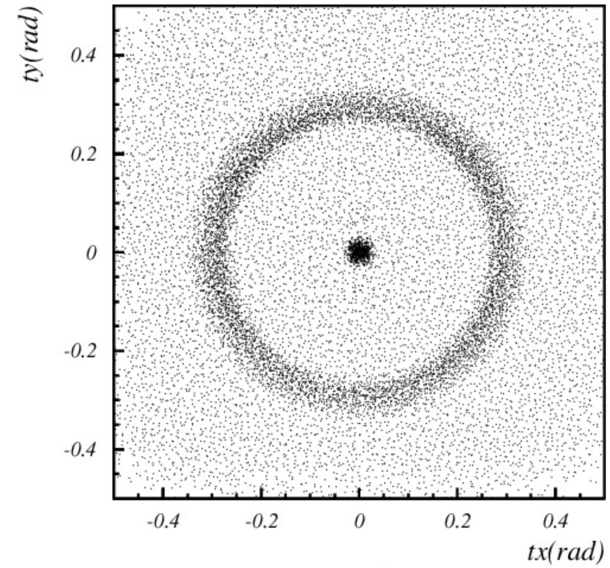
Focusing configuration – data

4cm aerogel single index



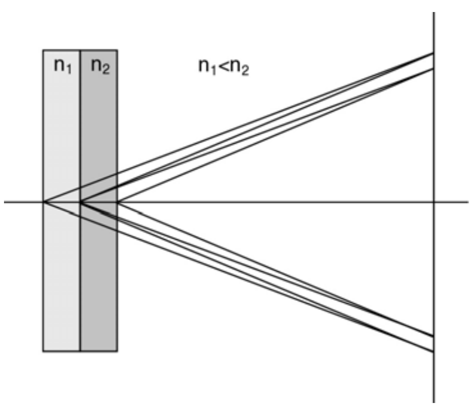


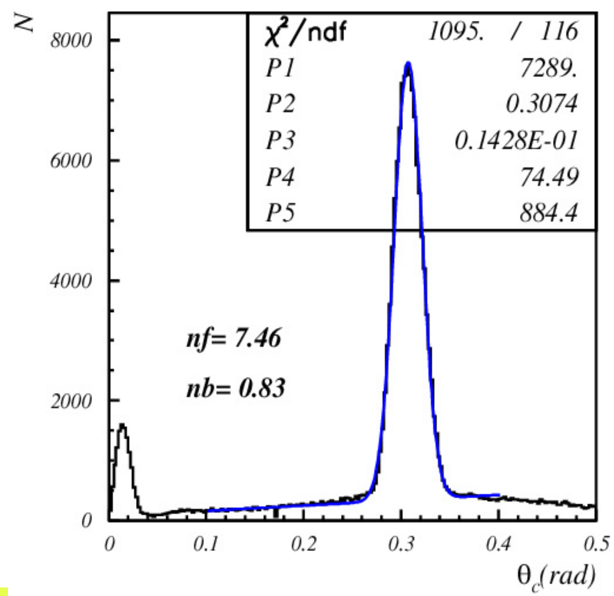
theta cerenkov

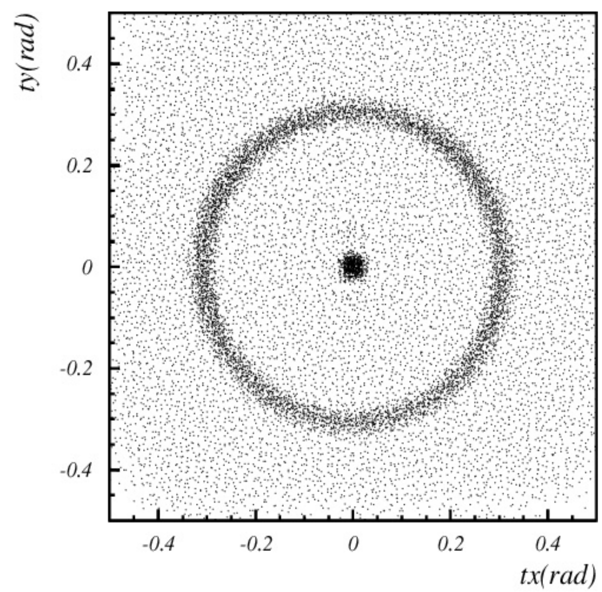


ring in cerenkov space

2+2cm aerogel



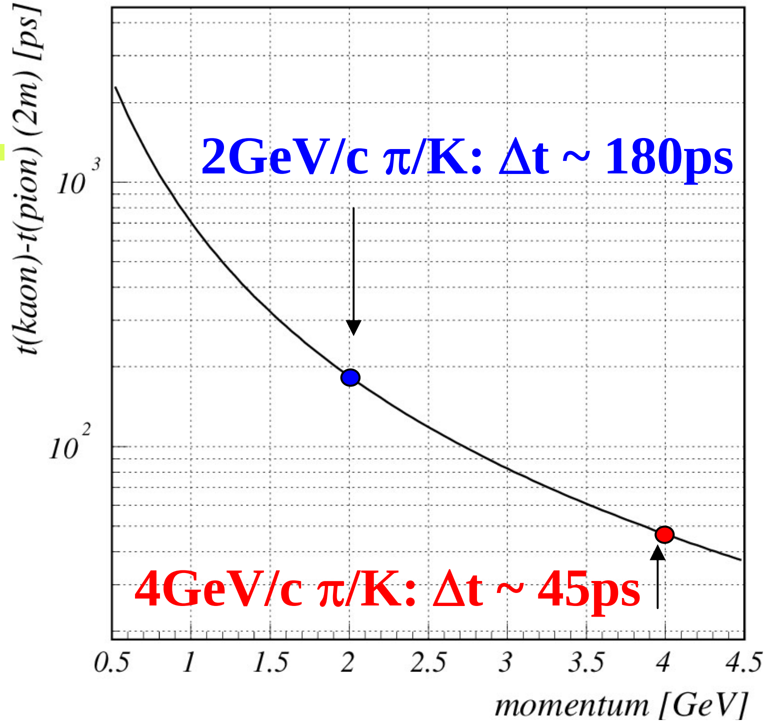


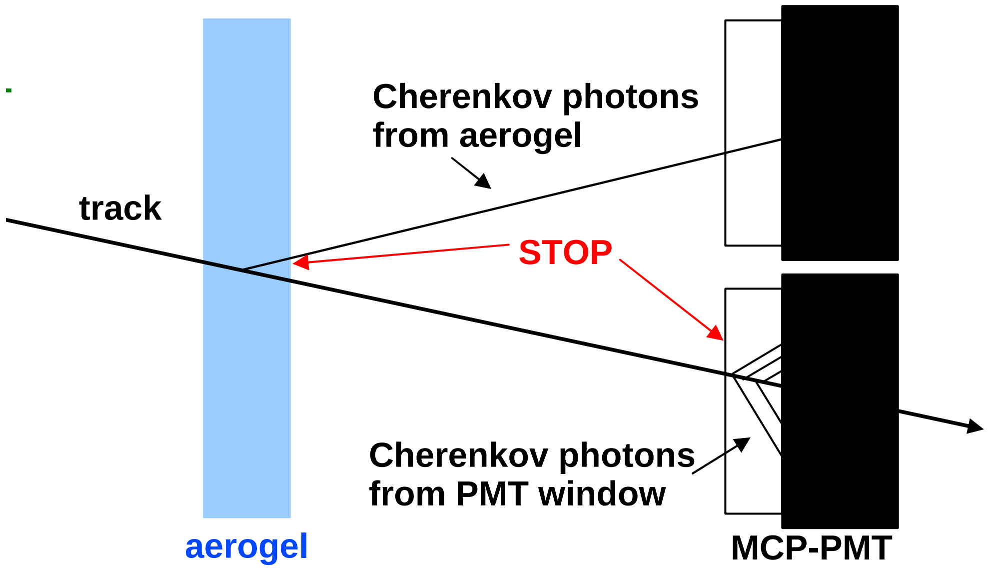


TOF capability

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 →





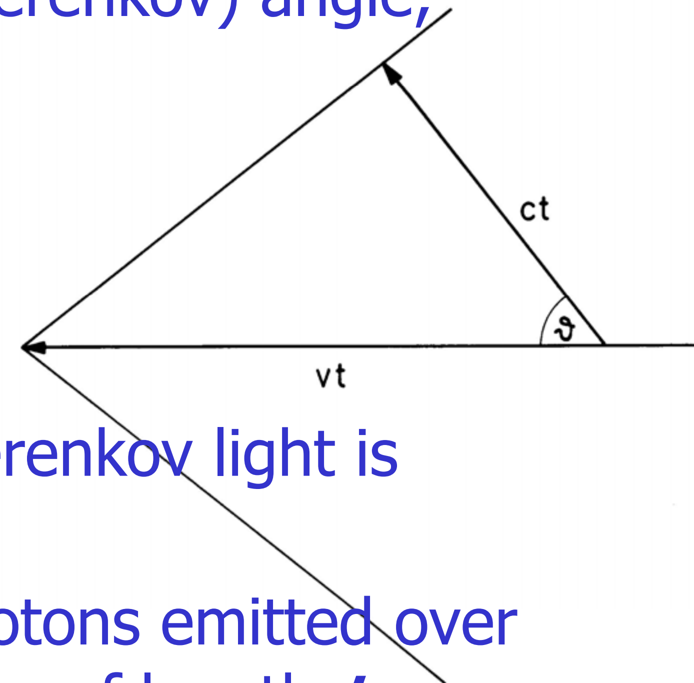
Cherenkov photons from two sources can be used:

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

Čerenkov radiation

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

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



Two cases:

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

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

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

Number of detected photons

Example: in 1m of air (n=1.00027) a track with $\beta=1$ emits N=41 photons in the spectral range of visible light ($\Delta E \sim 2$ eV).

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

In general: number of detected photons can be parametrized as

$N = N_0 \, L \sin^2\theta$

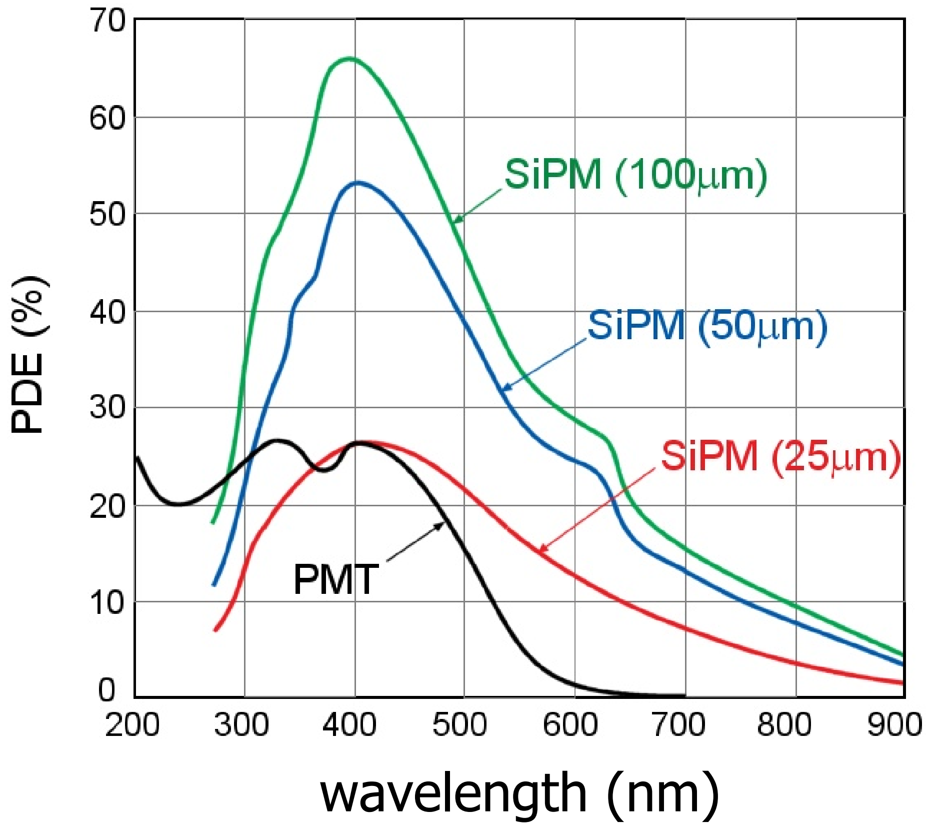
where N_0 is the figure of merit,

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

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

Typically: N_0 = 50 - 100 / cm

PDE for SiPMs

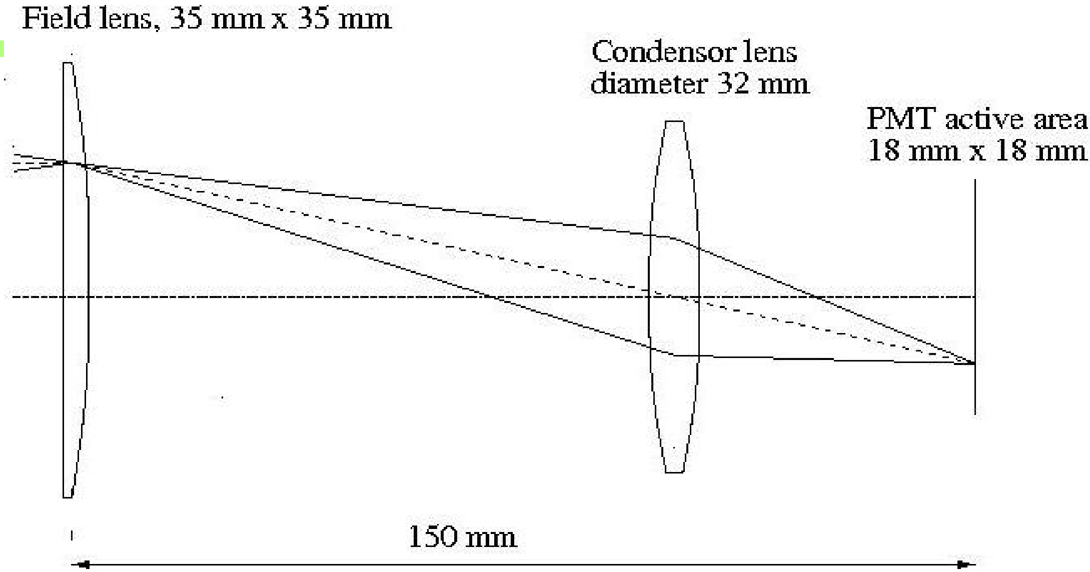


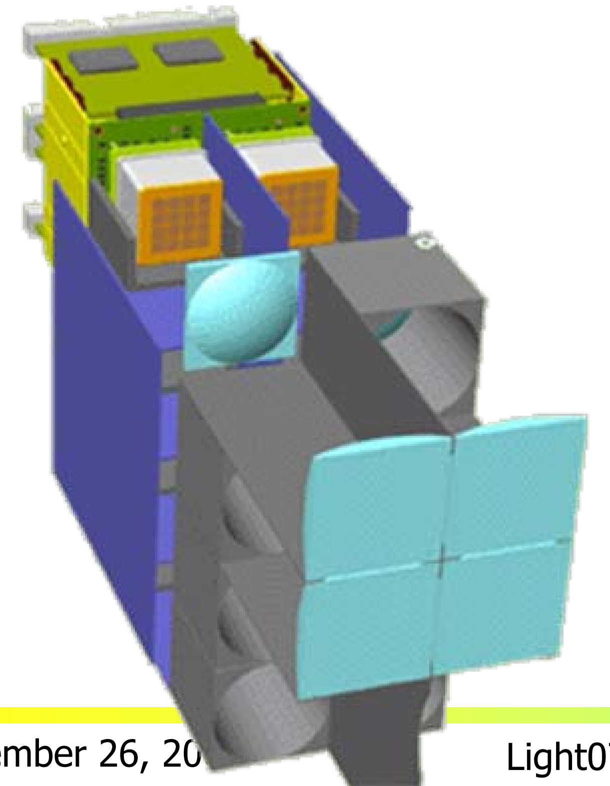
HERA-B RICH photon detector

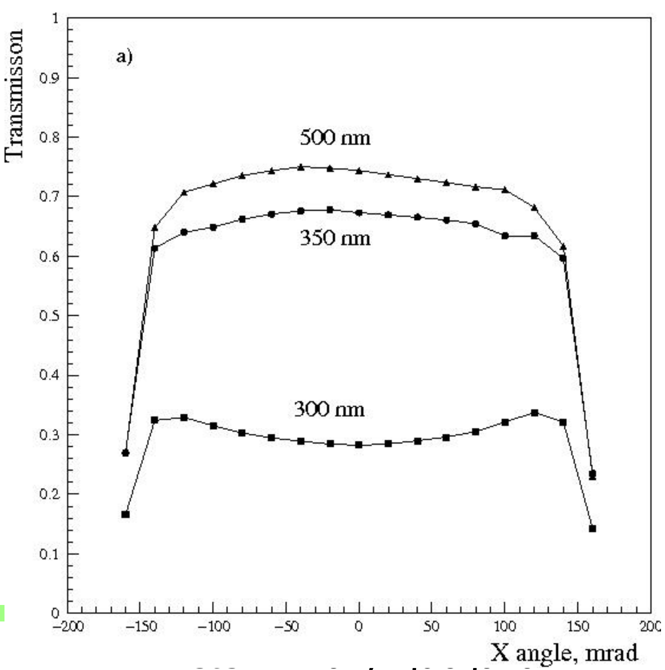
Light collection system (imaging!) to:

-Eliminate dead areas

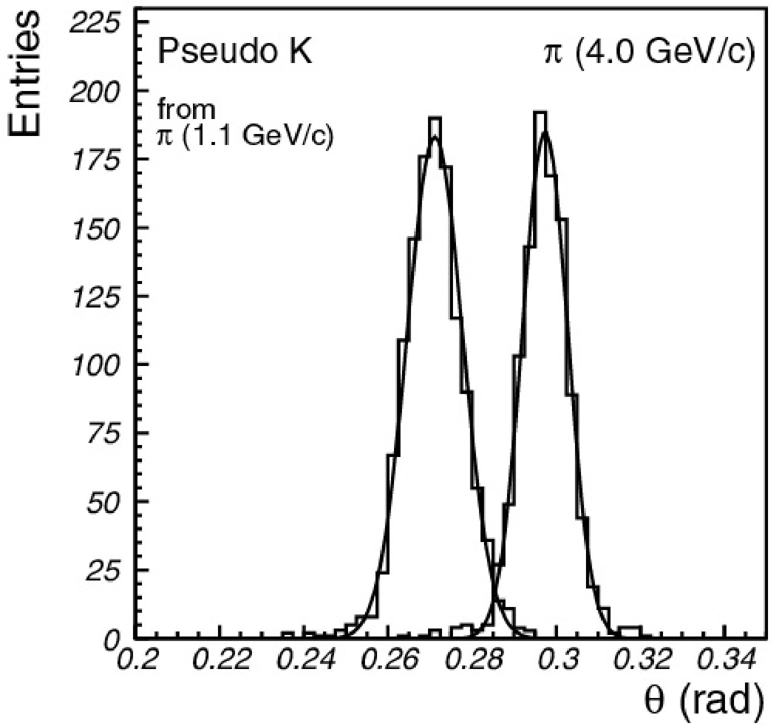
-Adapt the pad size







PID capability on test beam data



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

→ ~4σ π/K separation at 4GeV/c.

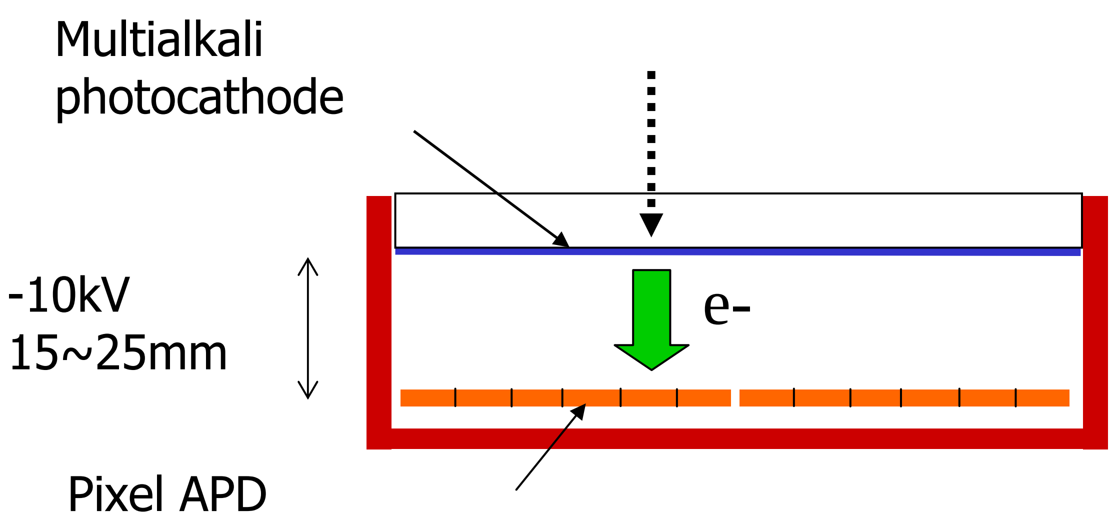
Illustration of PID performance: Cherenkov angle distribution for pions at 4GeV/c and 'kaons' (pions at 1.1GeV/c with the same Cherenkov angle as kaons at 4GeV/c).

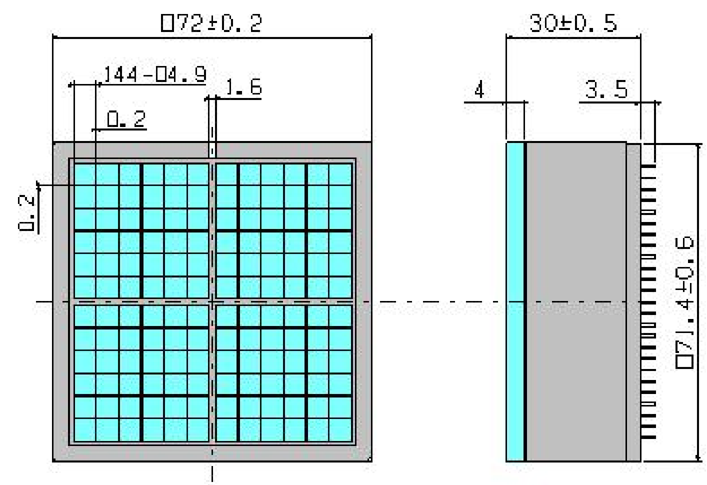
Photon detectors for the aerogel RICH requirements and candidates

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

Candidates:

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





HAPD R&D project in collaboration with HPK.

Long development time, now working test samples.

Belle Upgrade for Super-B