Module of Silicon Photomultipliers as a single photon detector of Cherenkov photons

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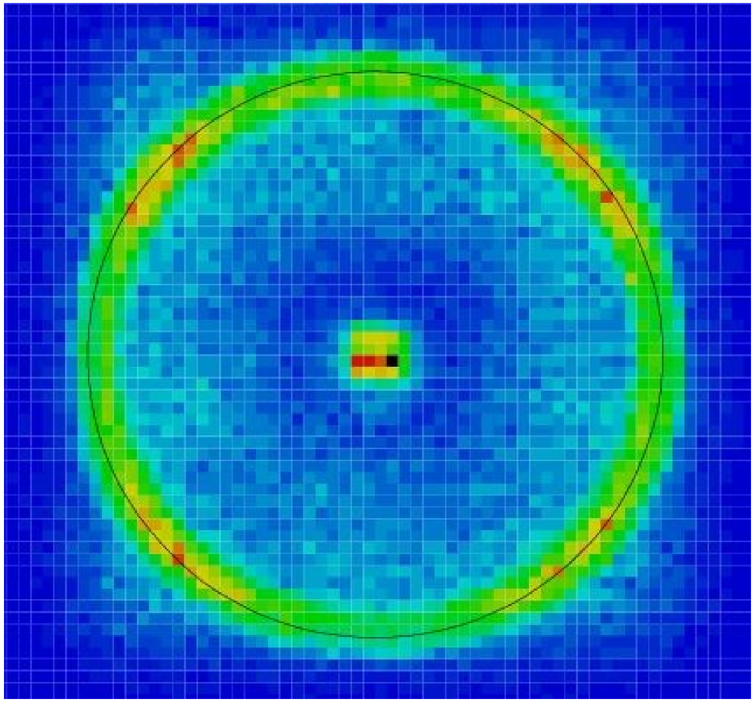
Outline:

- Motivation: Aerogel RICH for Belle II
- RICH with SiPMs
- Beam test set-up and results
- Summary

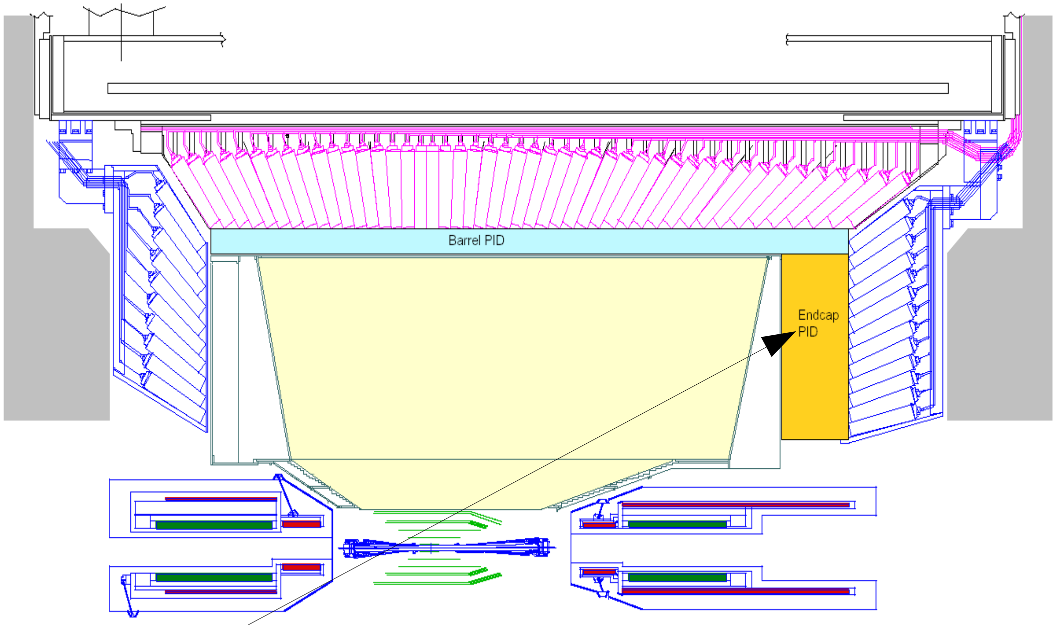


NIM A613 (2010) 195.

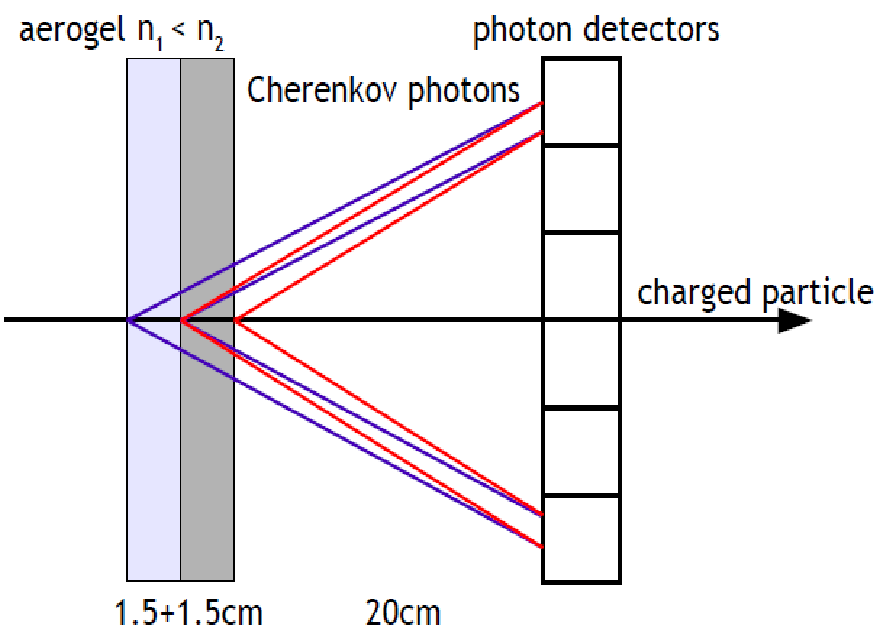
Forward PID for Belle II

Requirements and constraints:

- ~ 5 σ K/π separation @ 1-4 GeV/c
- limited available space ~ 250 mm
- operation in magnetic field 1.5T
- photon detector candidates: HAPD, MCP-PMT, **SiPM**



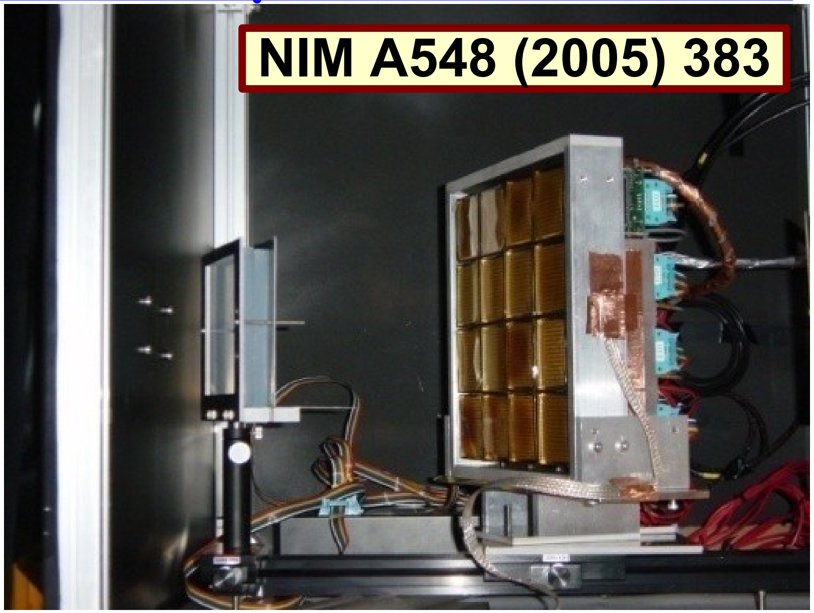
Chosen type: proximity focusing aerogel RICH



- <n> ~ 1.05 (focusing configuration)
- $\vartheta_c(\pi)$ = 308 mrad @ 4 GeV/c
- $\vartheta_c(\pi) - \vartheta_c(K)$ = 23 mrad @ 4 GeV/c
- π threshold 0.44 GeV/c,
  K threshold 1.54 GeV/c
- time-of-flight difference (2m from IP):
  $t(\pi) - t(K)$ = 180(45) ps @ 2(4) GeV/c

Rok Pestotnik
Jožef Stefan Institute

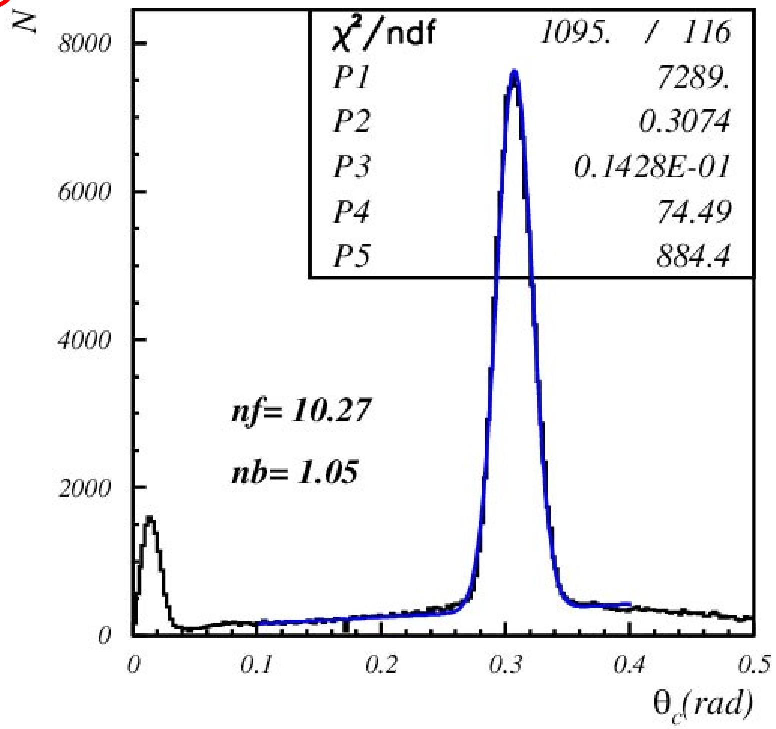
Beam test with flat-panel PMT array

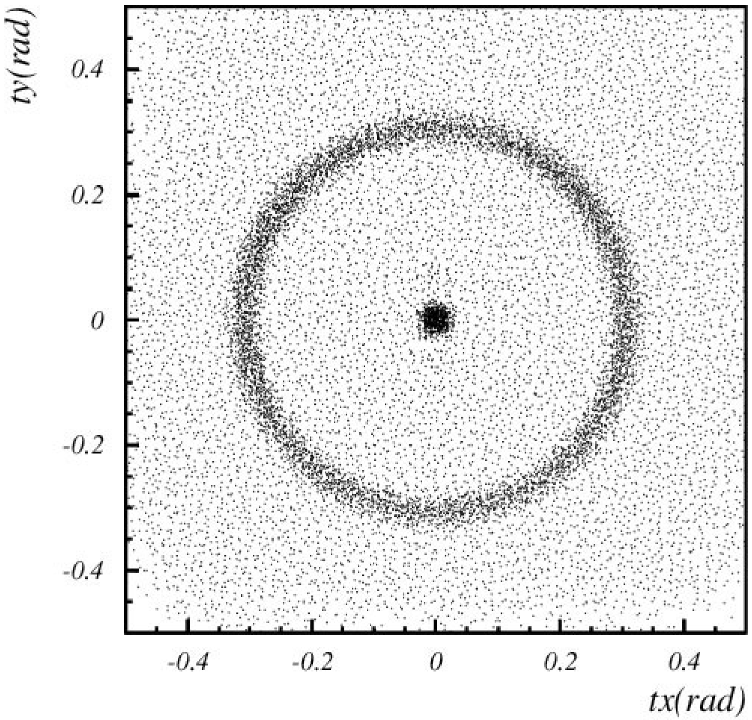


Study of aerogel radiator with flat-panel PMT array - standard configuration: 2cm(1.045)+2cm(1.055) focusing aerogel:

- N_{ph} ~ 10
- σ_{single} = 14 mrad
- σ_{track} = 4.6 mrad

5σ @ 4GeV/c



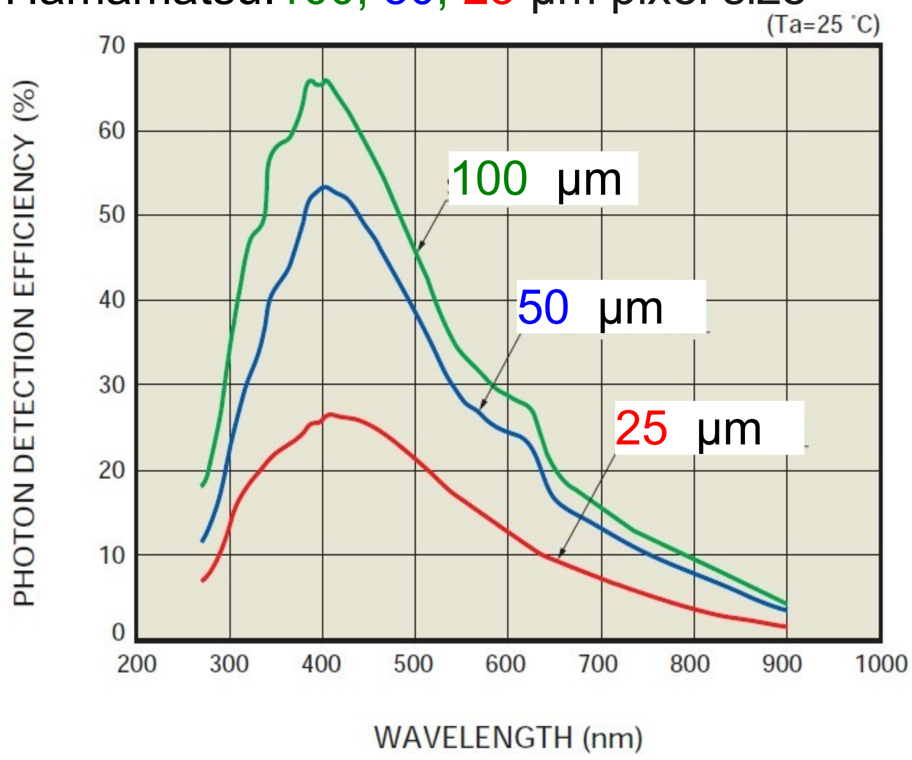


Why SiPM ?

Characteristics

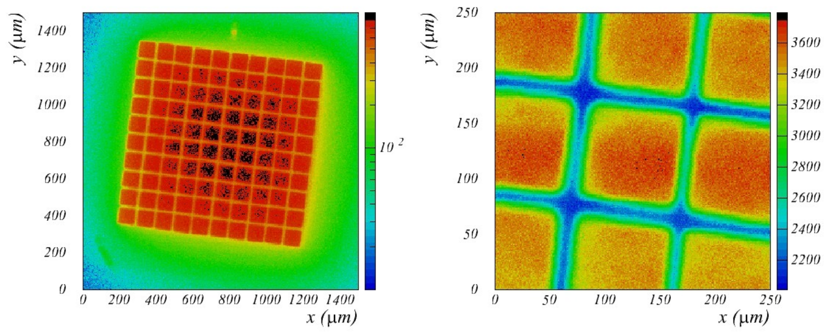
- **works perfectly in high magnetic field**
- low operation voltage ~ 10V-100V
- peak PDE up to 65% @400nm including ε_{geo}
- gain ~ 10^6
- time resolution ~ 100 ps
- dark counts ~ few 100kHz/mm^2
- radiation damage (p,n)

Hamamatsu:100, 50, 25 μm pixel size



Can such a device be used for detection of single photons in a RICH counter?

- linearity is not needed → larger pixel size preferred due to higher efficiency

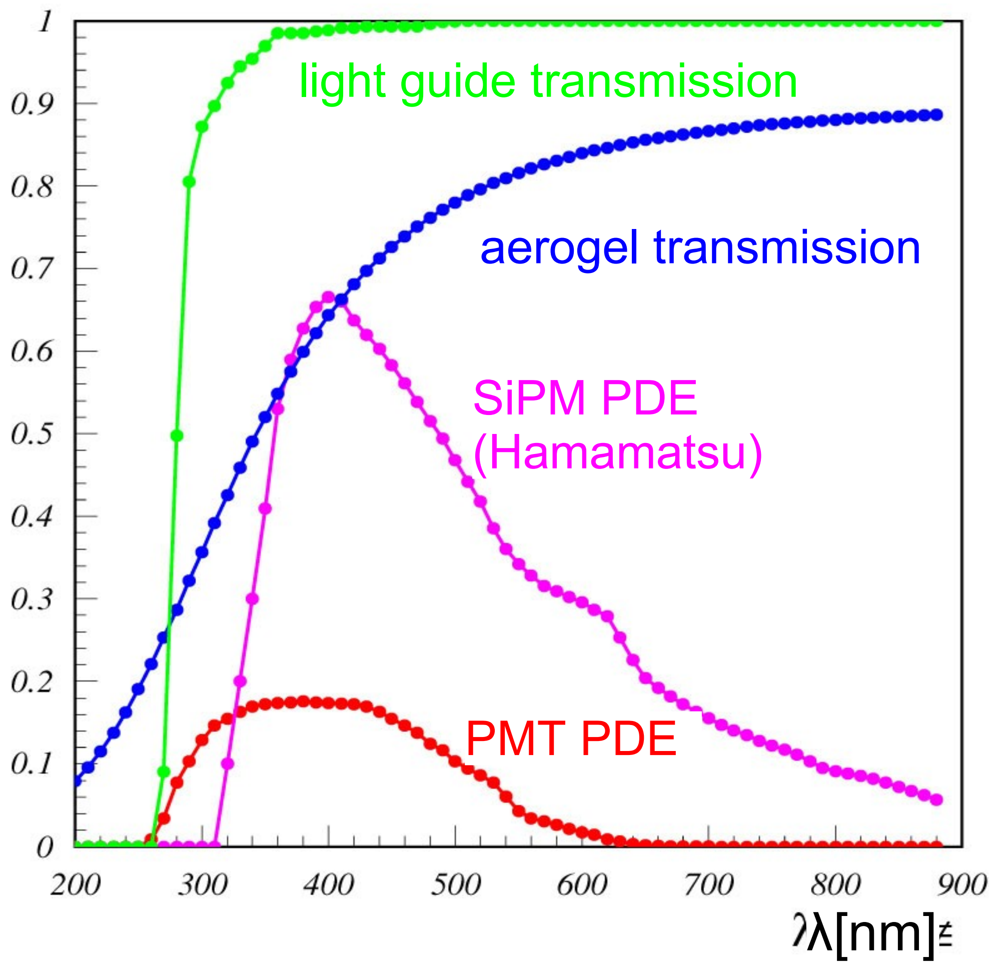


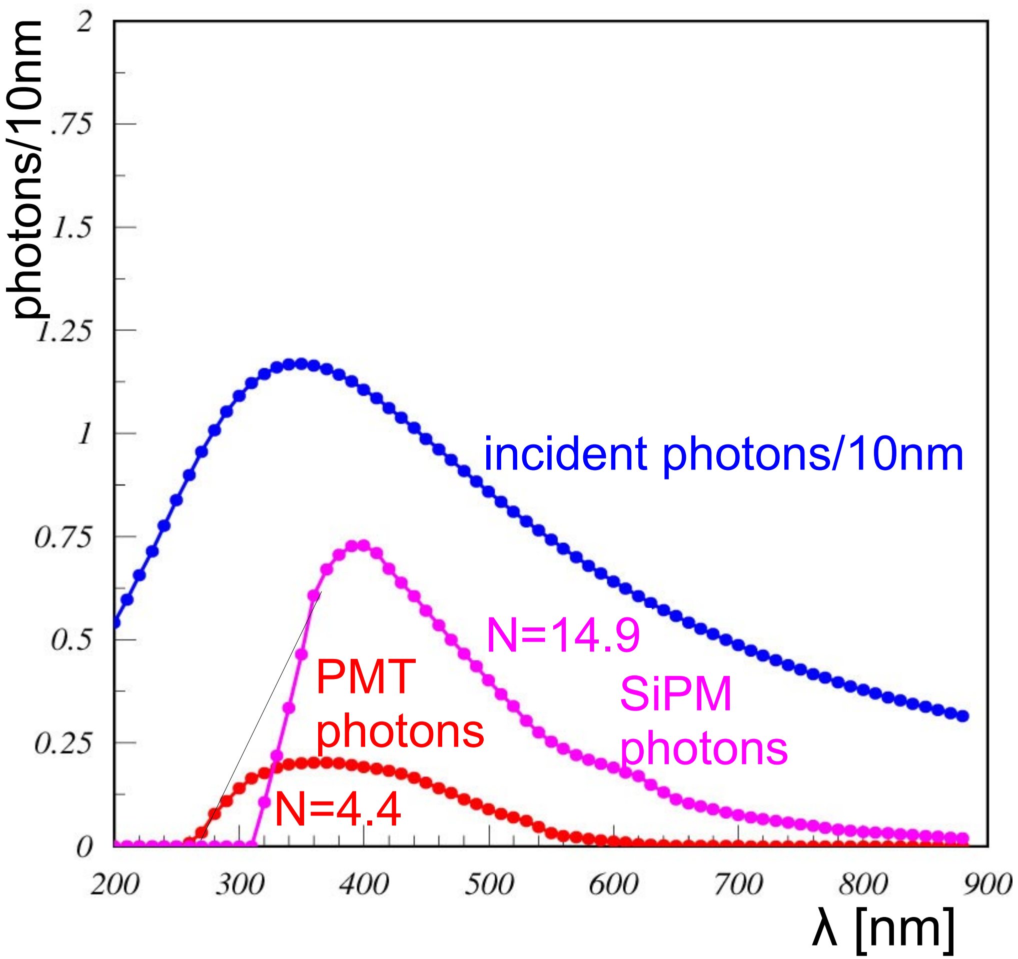
Expected number of photons

Expected number of photons for aerogel RICH (beam test prototype):

- MA-PMTs (peak QE ~ 25%, collection eff. ~ 70%) or MPPCs (100 µm)
- aerogel radiator: thickness 1 cm, n = 1.03 and transmission length 1.4 cm @400nm

$N_{SiPM} / N_{PMT} \sim 3.6$





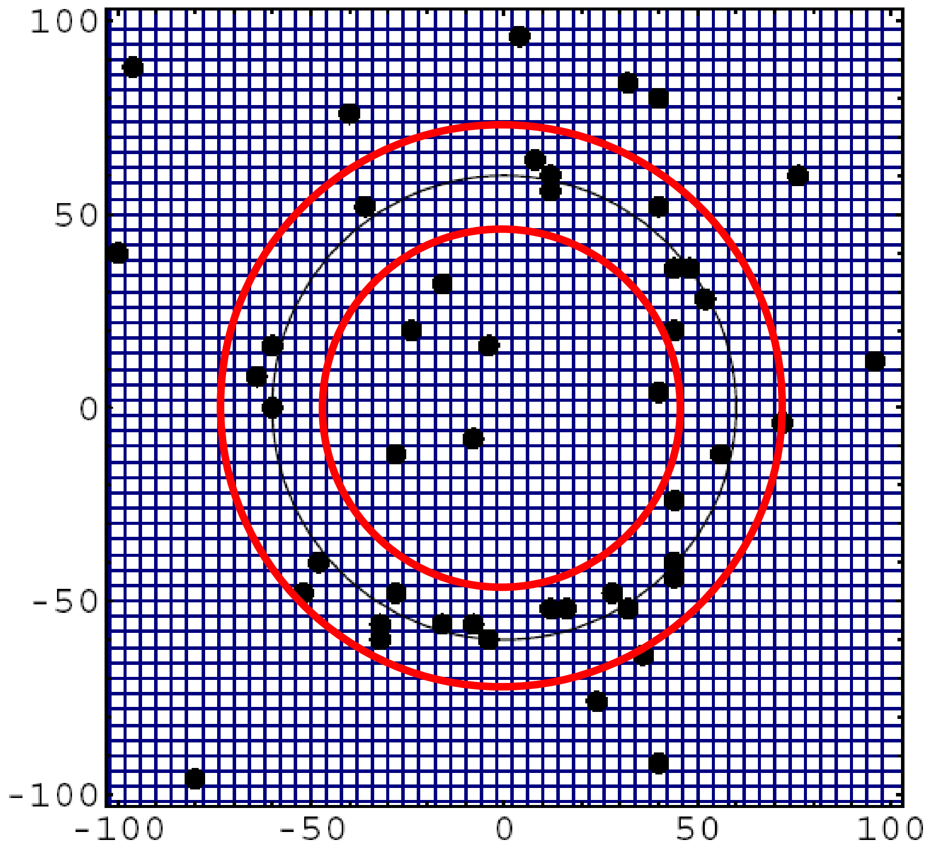
Signal to noise ratio

Dark noise signals have same height as single photon signals

Expected number of background hits depends on:

- ring area ~ 2000 mm^2 (±3σ)
- dark count rate ~ 600kHz/mm^2
- coincidence window ~ 5ns

N_{dark} ~ 6 → N_{ph}/N_{dark} ~ 3



Ratio can be increased by:

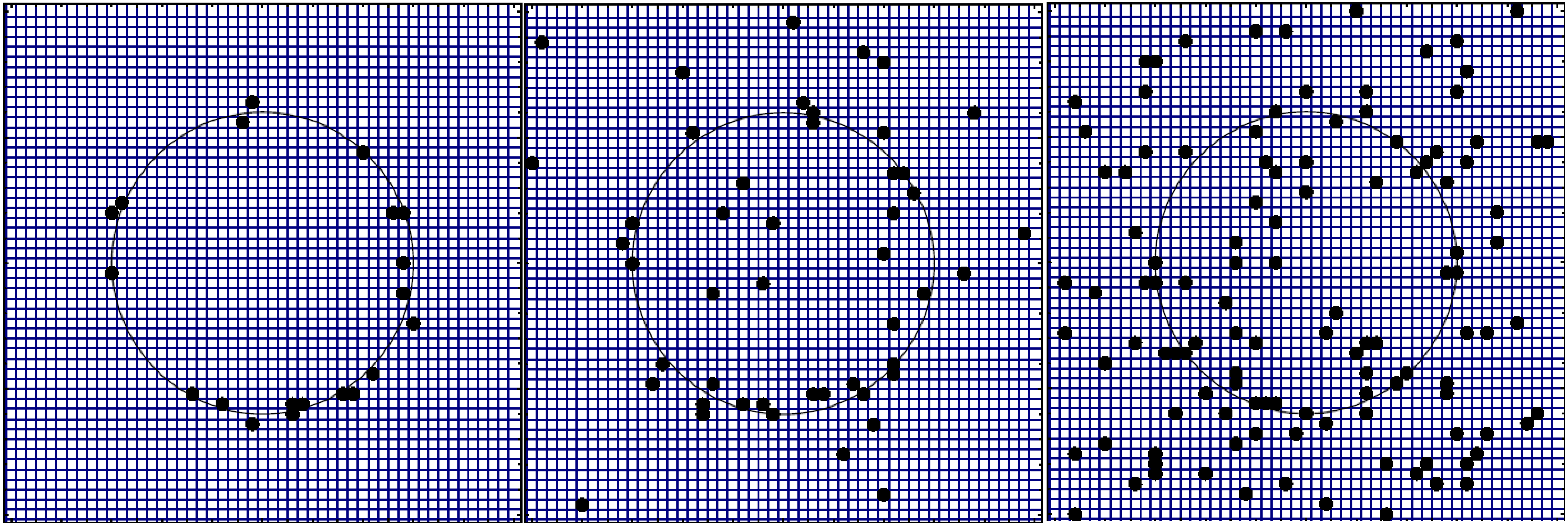
- **smaller ring image area → high Cherenkov photon density**
- **select only signals inside small time window**
- **use of light collection system → increase effective area of the sensor**

Example - expected hit distributions

Ring on a uniform background:

- 20 ph./ring, ring radius 60mm, pad size 4mm
- dark count occupancy:

0% 1% 4%

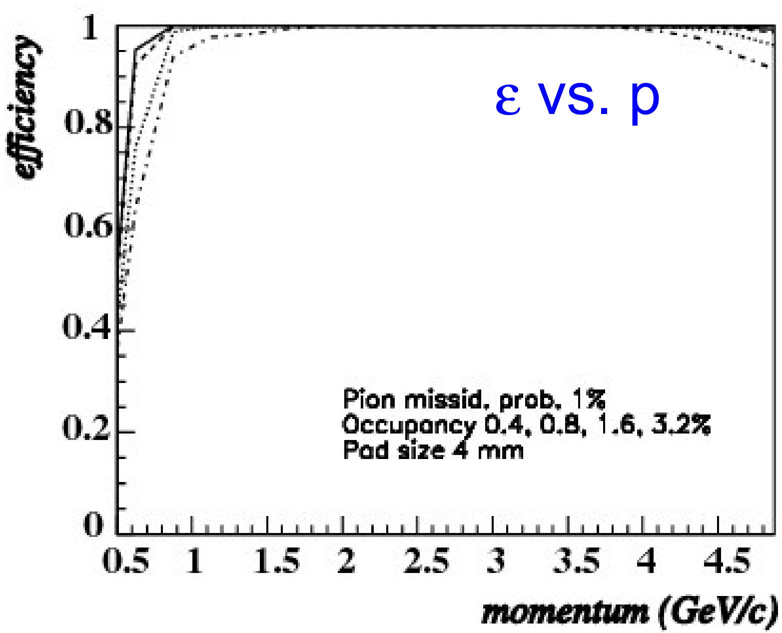


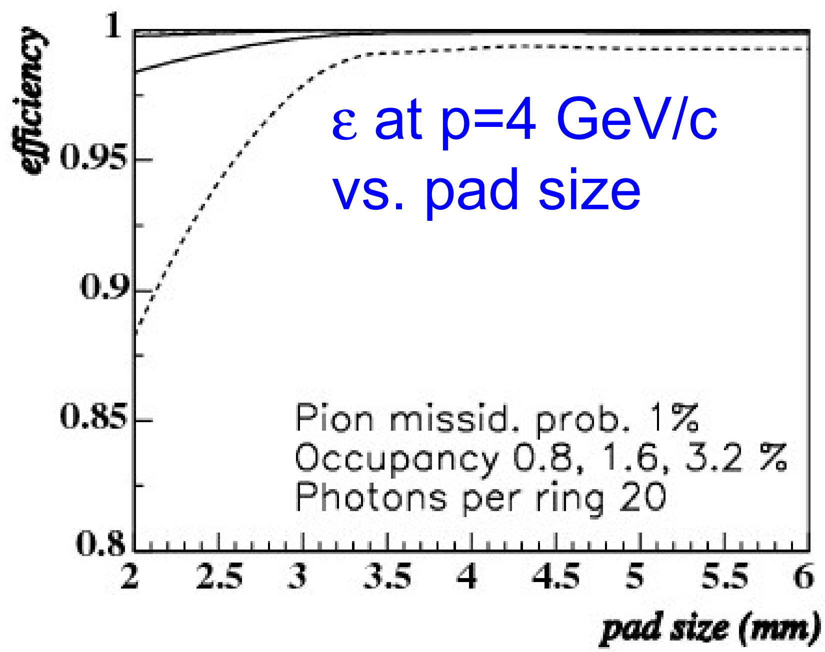
K identification efficiency for different dark count rates

MonteCarlo simulation of the detector response

- active area $1mm^2$
- dark count rate 0.8 / 1.6 / 3.2 MHz
- time window 5 ns
- Vary light collector demagnification (= pad size).

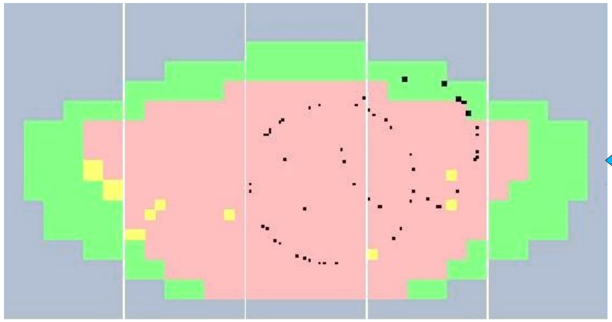
K identification efficiency at 1% π missid. probability



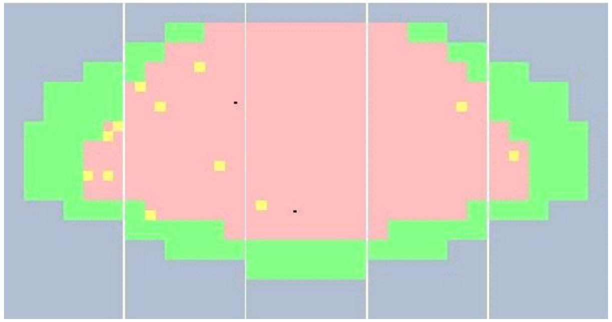


→ Looks OK!

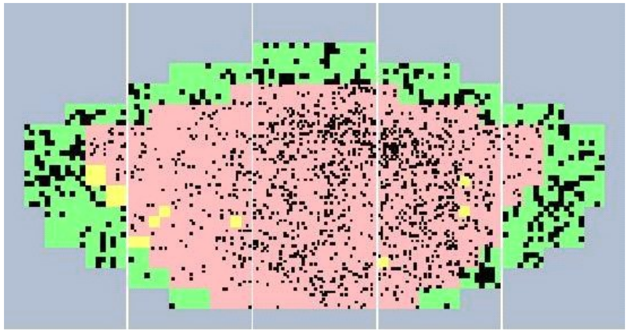
HERA-B RICH experience with high occupancy noise

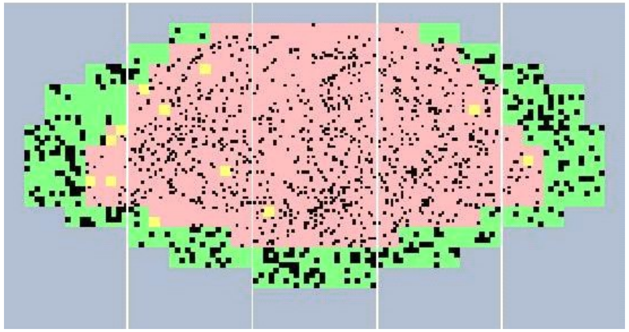


Little noise,
~30 photons per ring



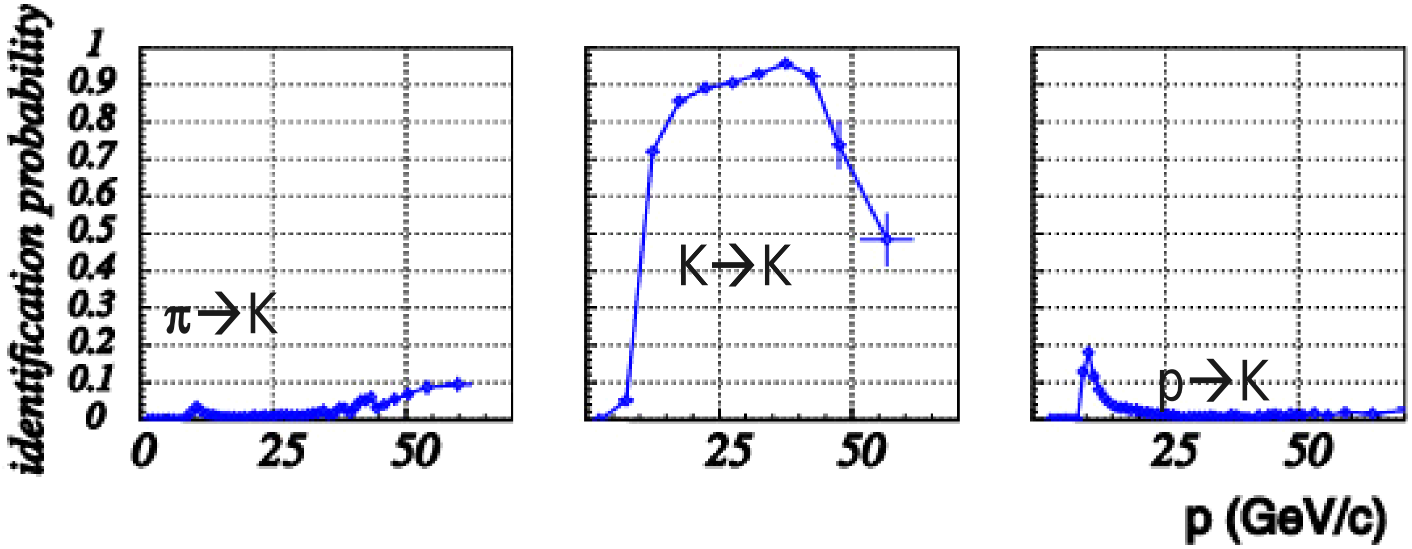
Typical event





The RICH worked very well!

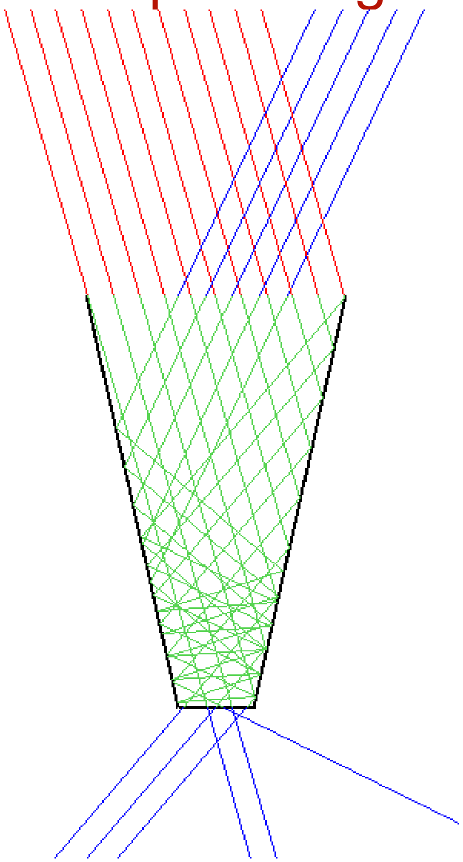
Kaon efficiency and pion, proton fake probability



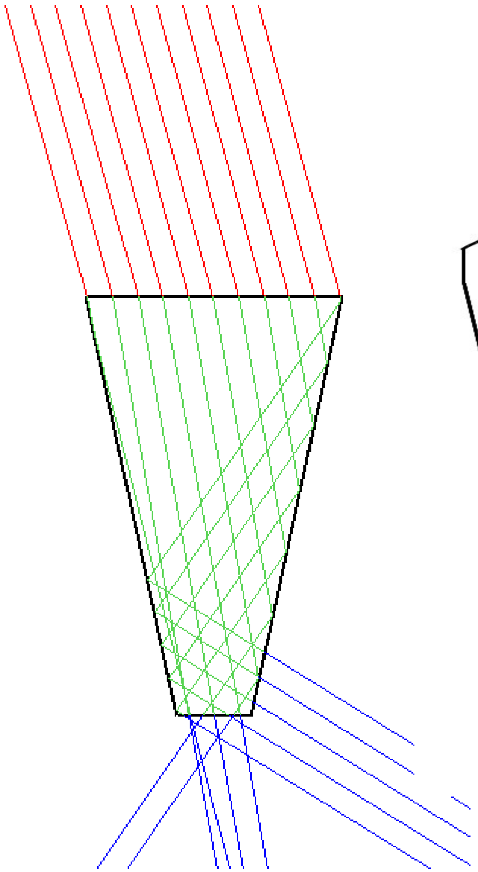
Light guides

concentrate light from larger surface
- increase number of detected photons per single sensor
- dark count remains the same

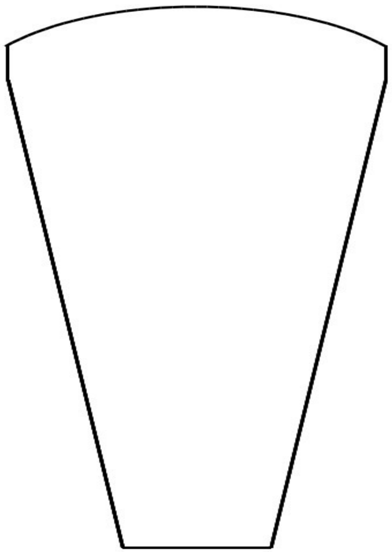
→ improve signal to noise ratio



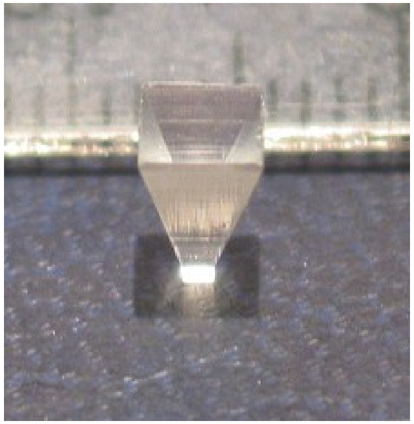
mirror walls



plastic truncated pyramid



lens + truncated pyramid



Light guide 3.5x3.5mm^2 to 1x1mm^2

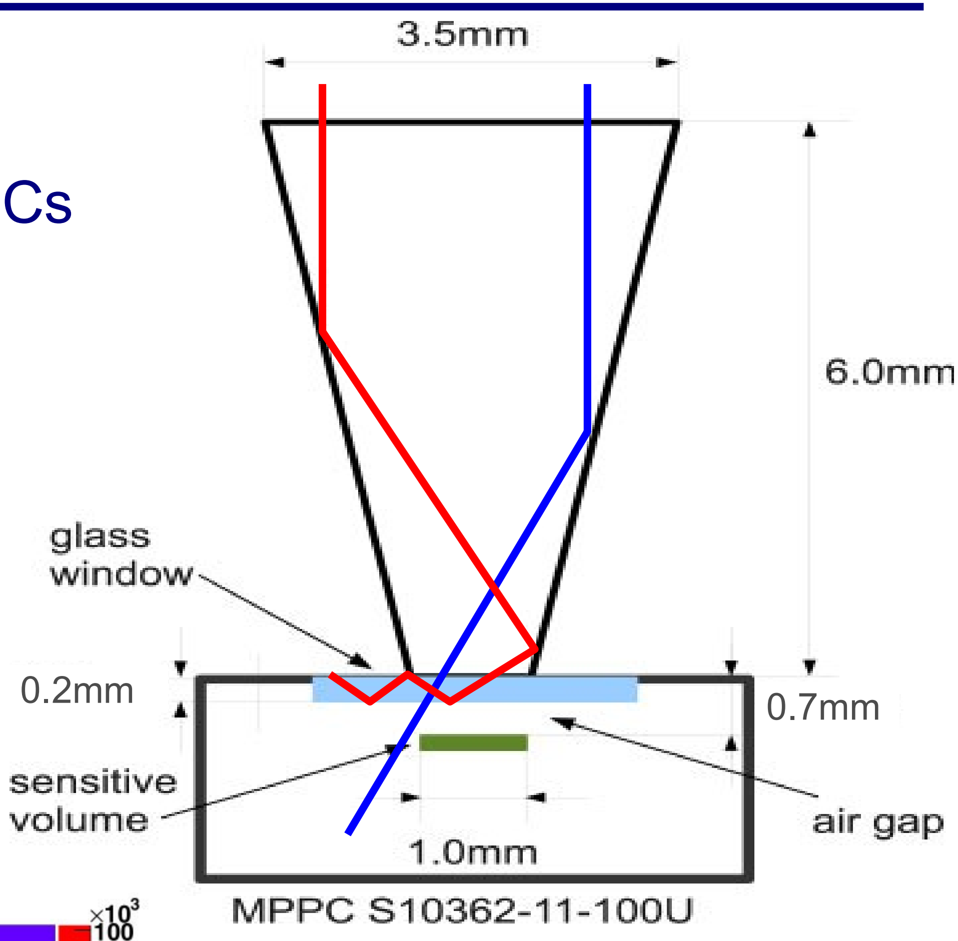
First attempt to attach light guides to MPPCs

- area ratio ~ 12
- average efficiency ~ 0.5

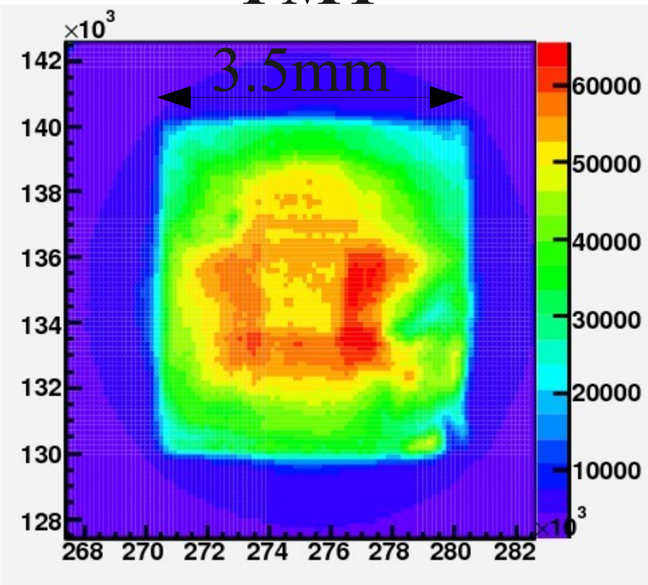
  gap between LG exit and SiPM surface:

  light exiting light guide under large angles misses SiPM active surface

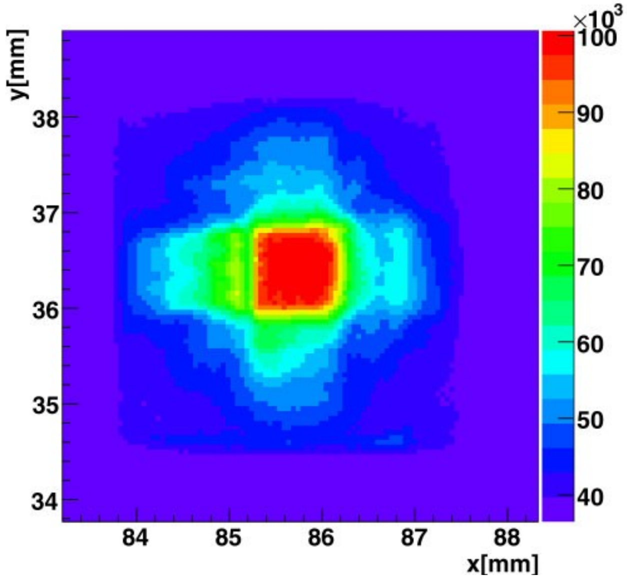
- light guide test with pencil beam (400nm, 90^0)

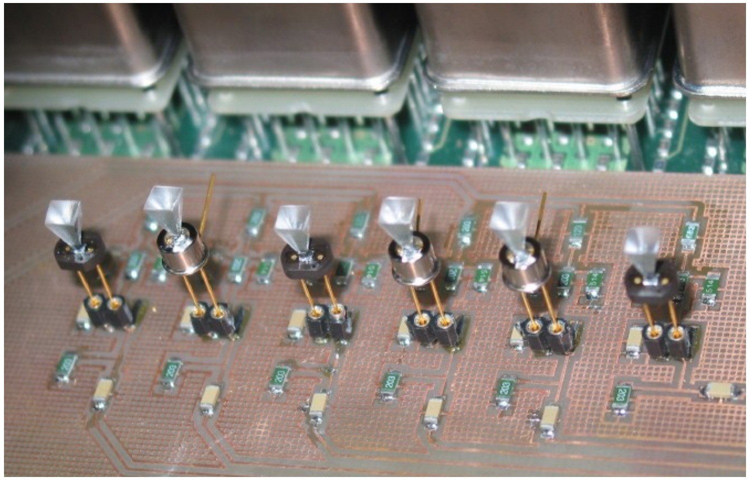


PMT



MPPC





Test with cosmic rays

First successful tests with cosmic rays:

Without light guides:

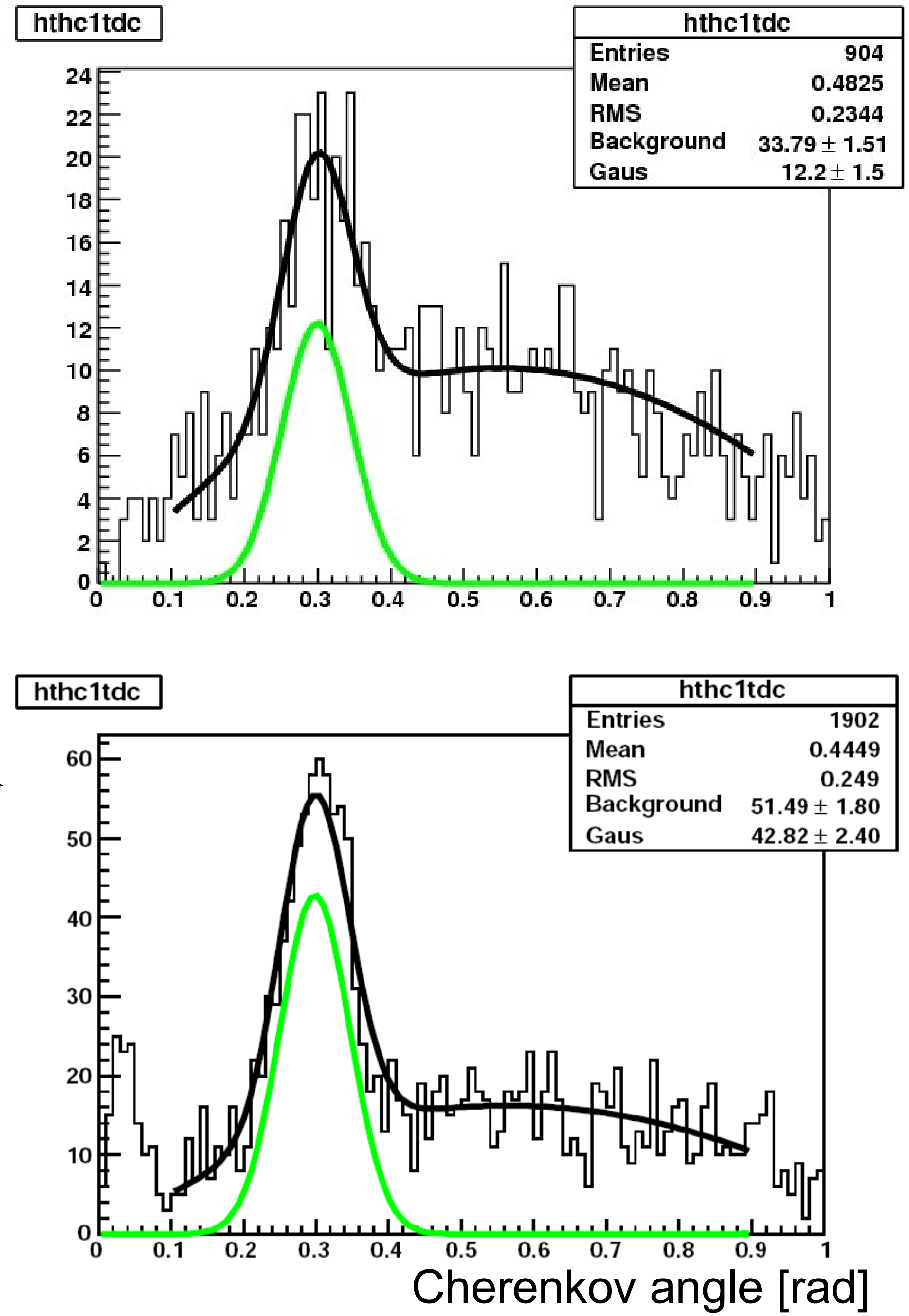
- 43600 tracks
- Cherenkov photons ~ 146
- 0.0033 photons per track

With light guides:

- 38100 tracks
- Cherenkov photons ~ 285
- 0.0072 photons per track

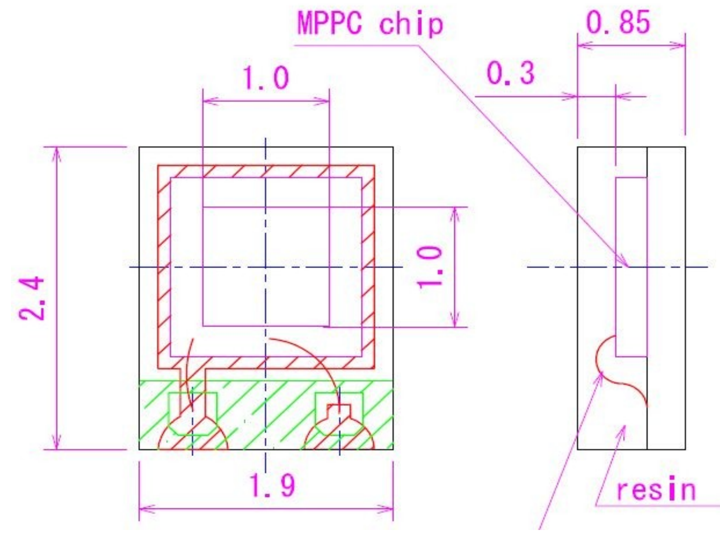
N_{w} / N_{wo} ~ 2.2

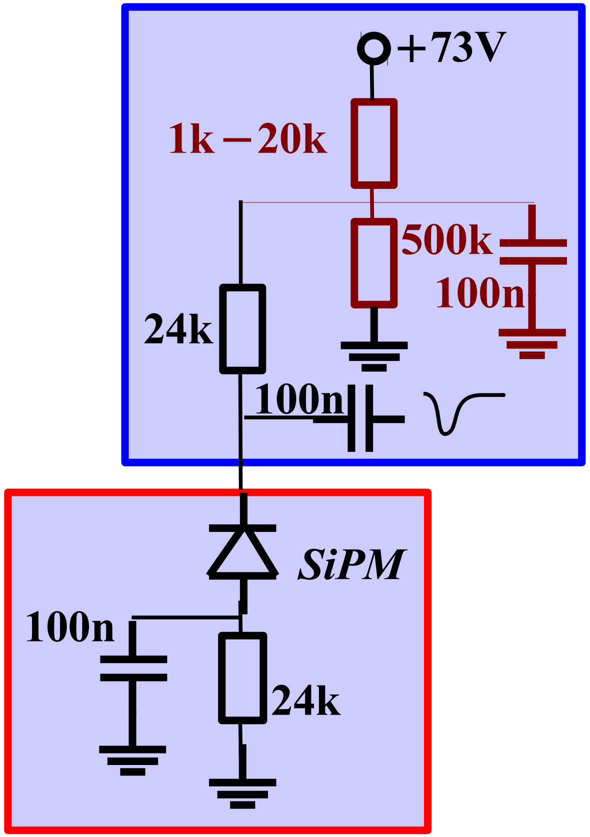
Light guide should be as close as possible to the MPPC surface.



MPPC module

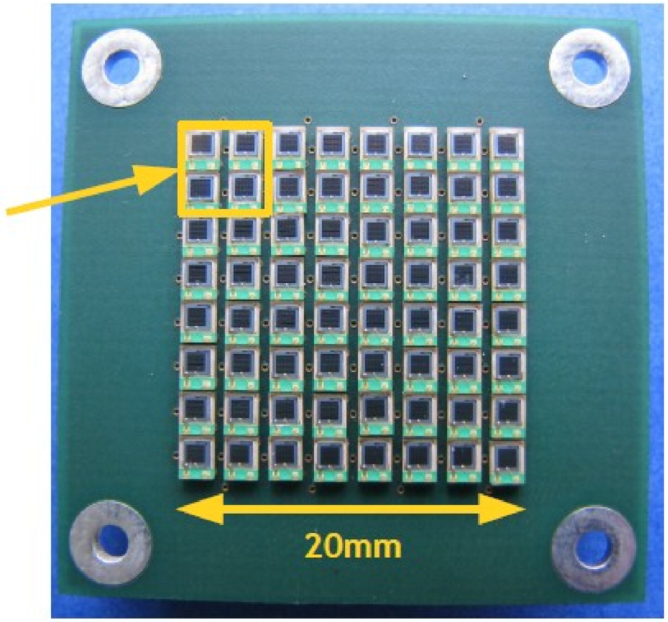
- main board with dividers, bias and signal connectors
- piggy back board with MPPCs
- light guides





64 Hamamatsu S10362-11-100P SMD MPPCs

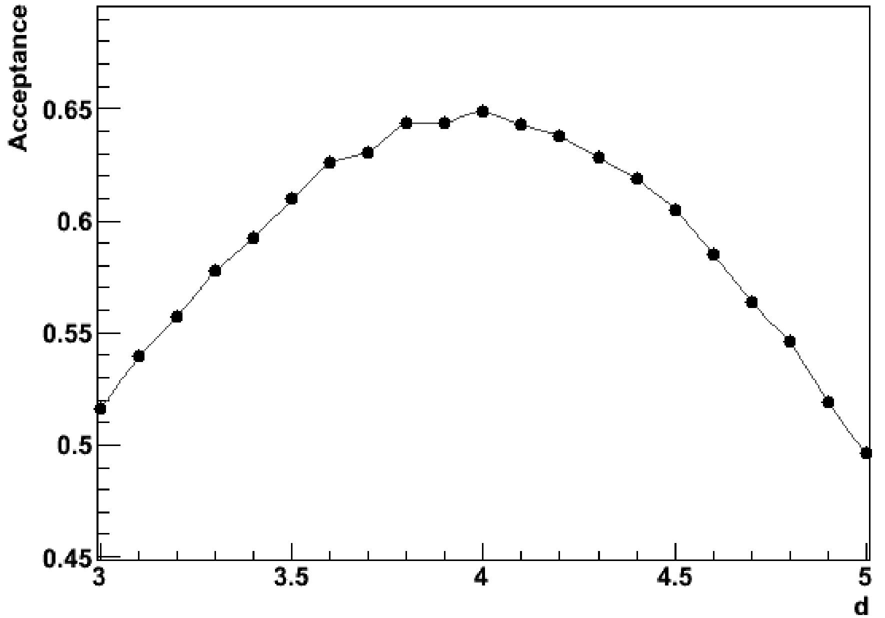
- 100μm cell size
- $1\times1\text{mm}^2$ active surface
- 0.3mm epoxy layer above active area
- dark noise ~ 600kHz/SiPM
- blocks of 2×2 MPPCs added into single channel
  - → 16 readout channels

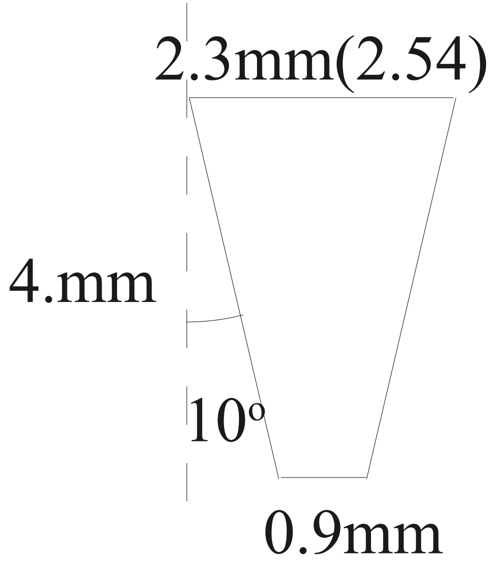


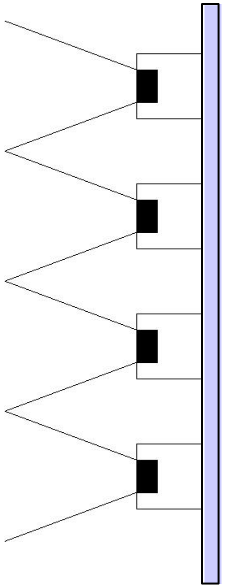
Light guide array

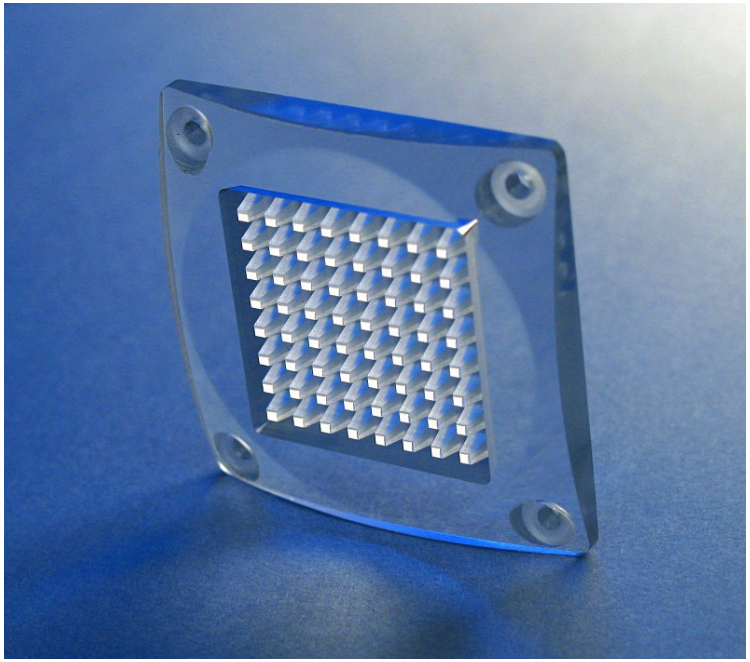
Design optimization of light guide length d:
- geometry constraints
  - fixed entrance ($2.54 \times 2.54 mm^2$)
  - fixed side angle (10° drill)
  - gap fixed at 0.3mm

d=4mm → acceptance=65%



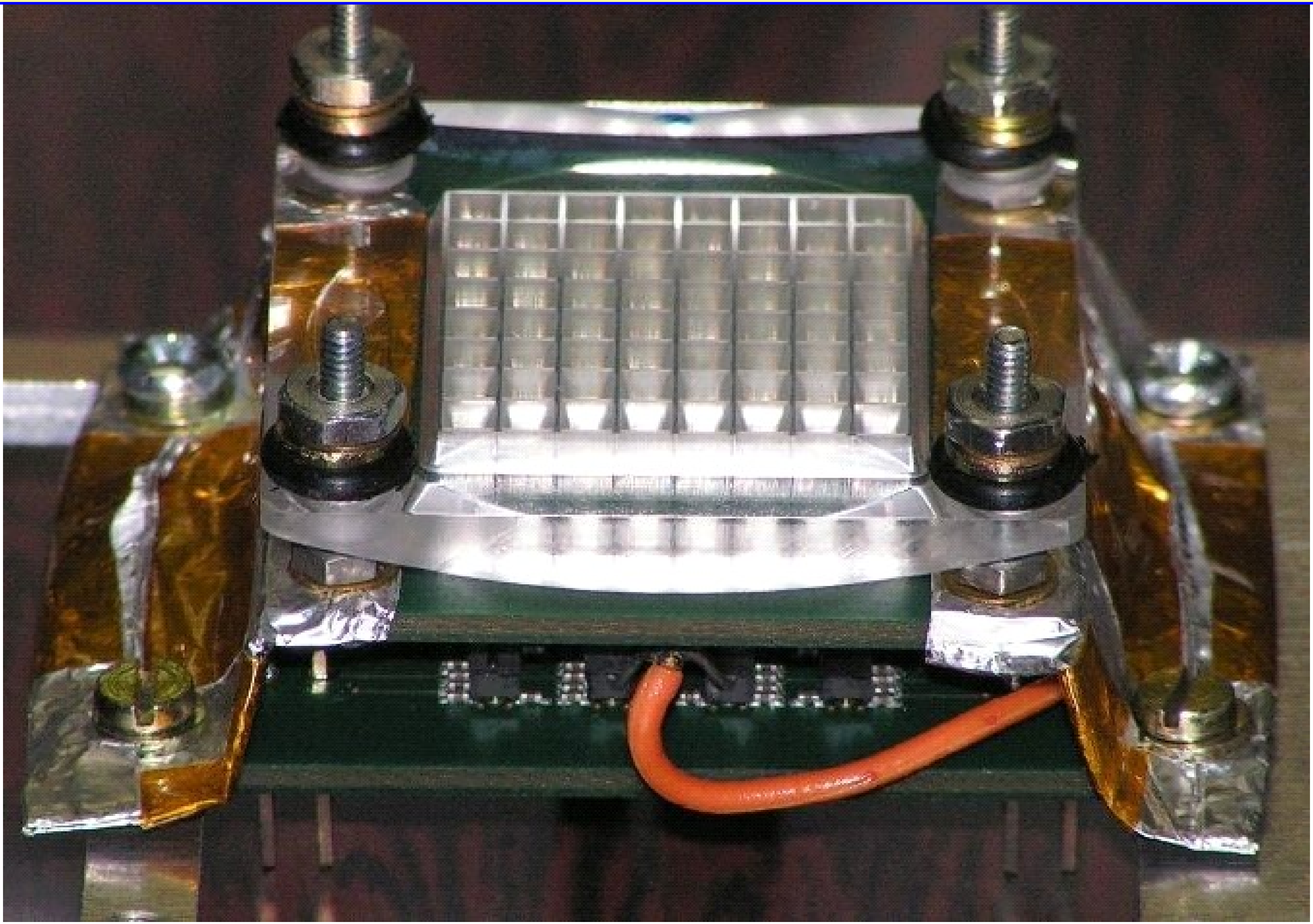






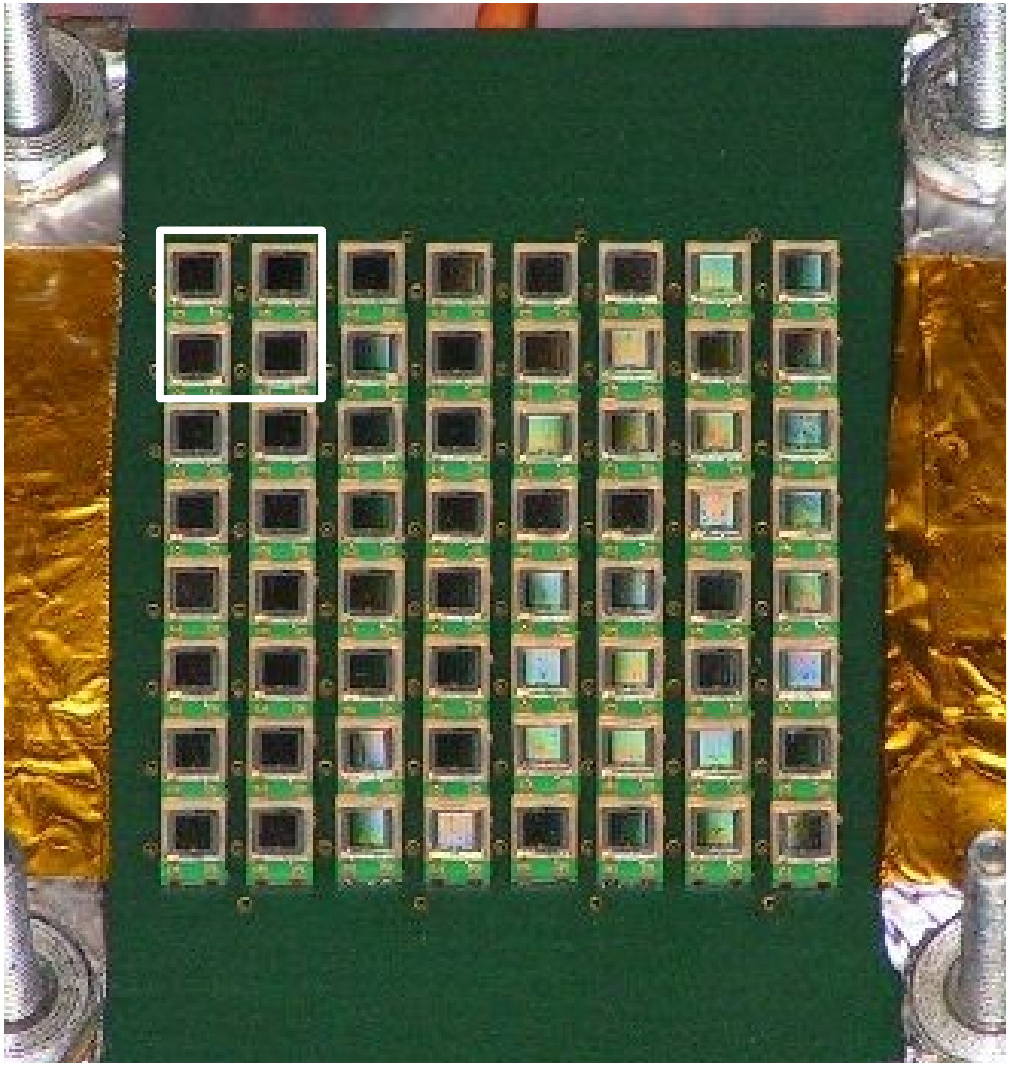
Light guides made of plastic used for HERA-B RICH lenses

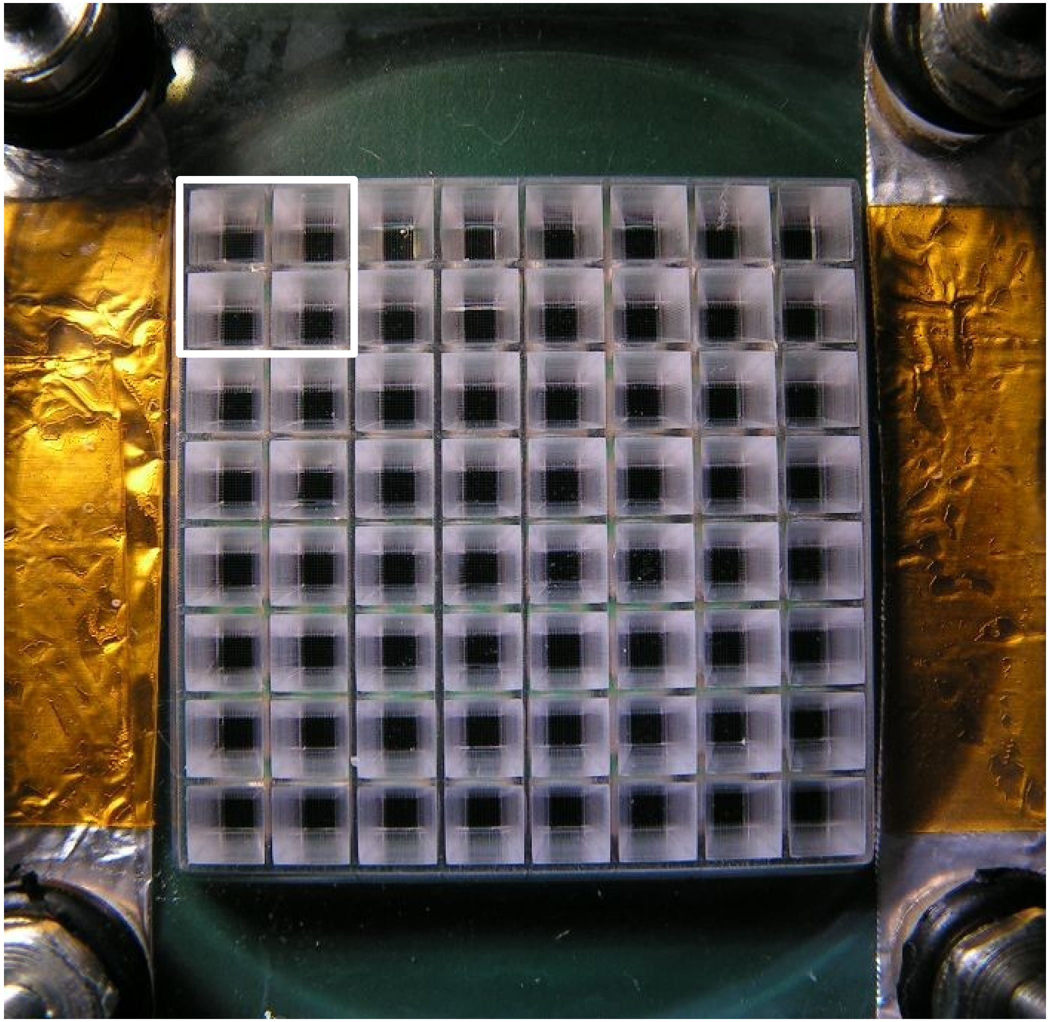
Final MPPC module



Final MPPC module - 2

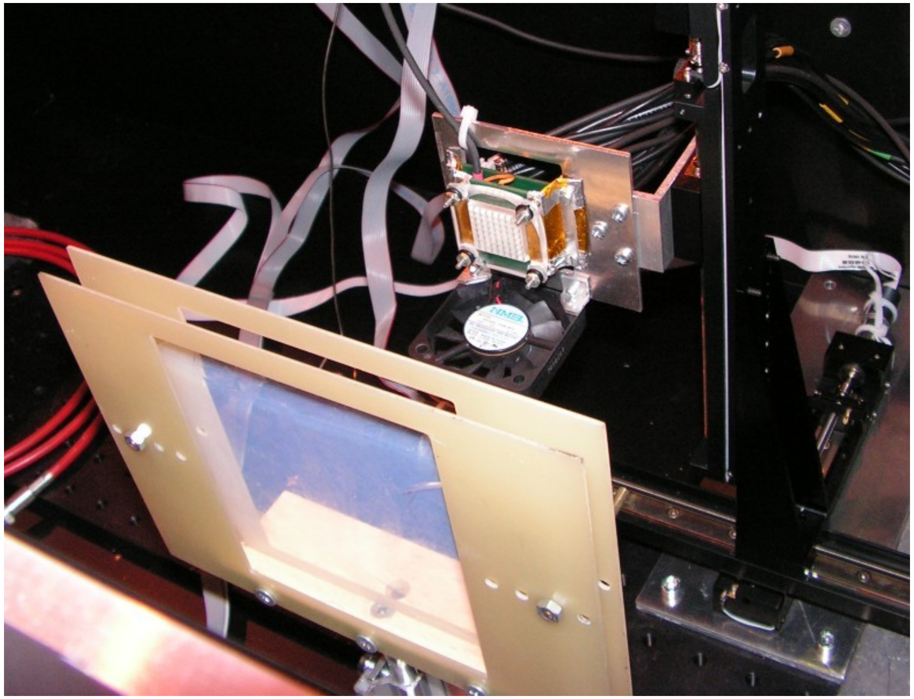
- pad size 5.08 mm, 4 mm^2 active (15.5% w/o LG)

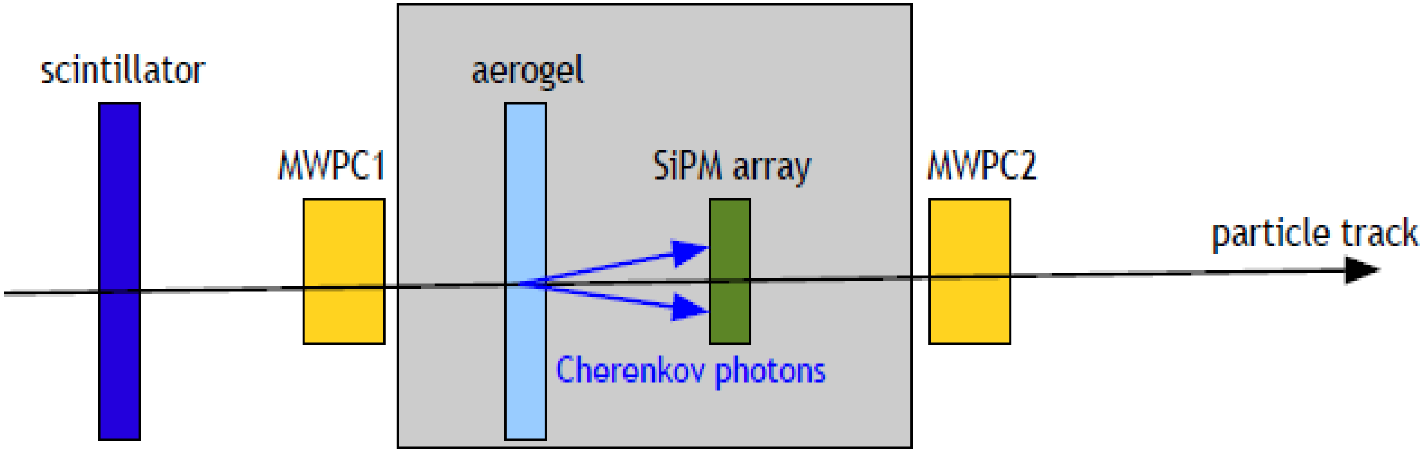


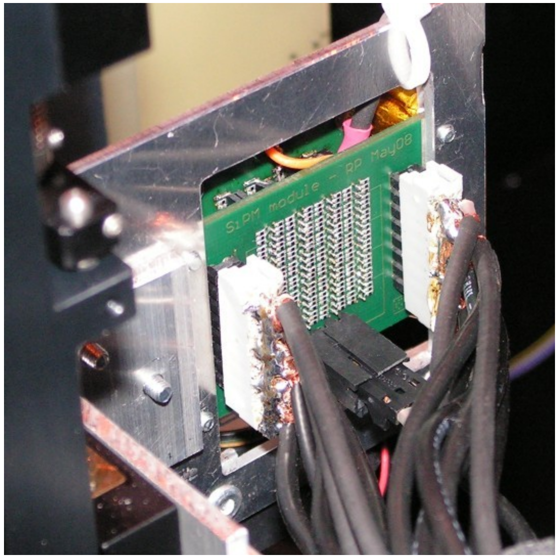


Beam test setup

- MPPC array w/o or w/ light guide mounted on a 3D stage
- Beam: +120GeV/c pions
- Timing: scintillator
- Tracking:
  - 2 MWPC with delay line readout
- Readout: multi hit TDC
- Radiator: aerogel
  - n=1.03, d=10mm,
  - attenuation length=14mm,
  - distance to photon detector 115mm



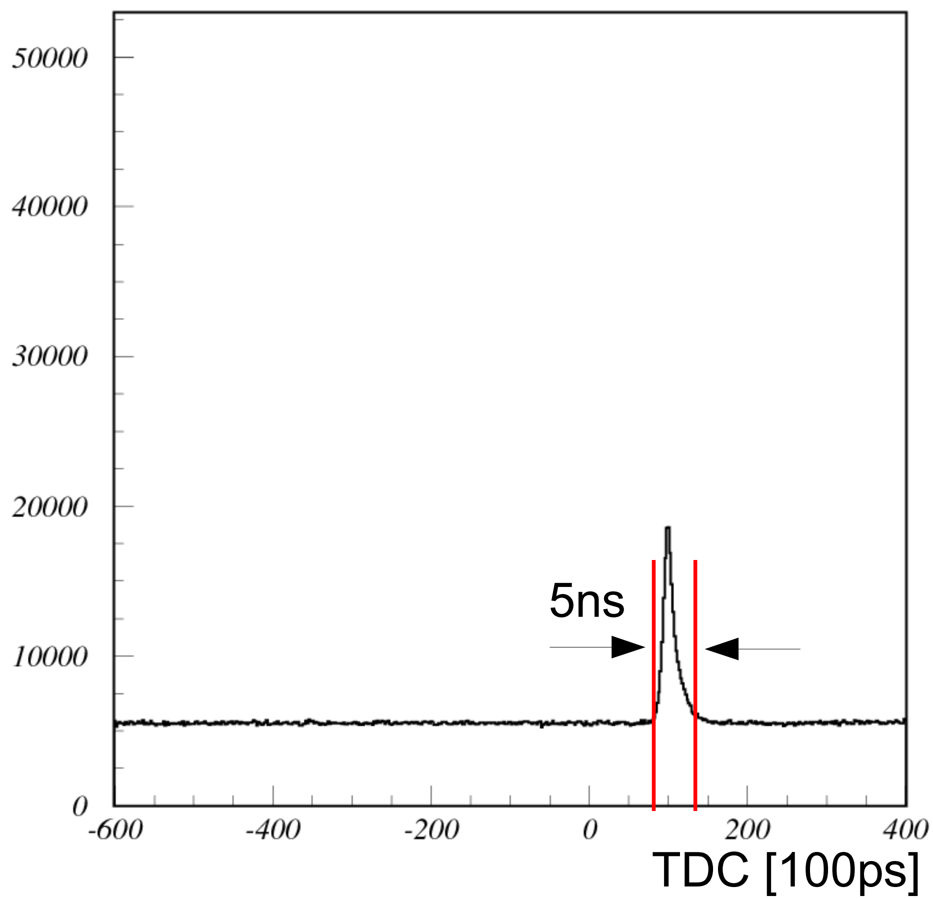




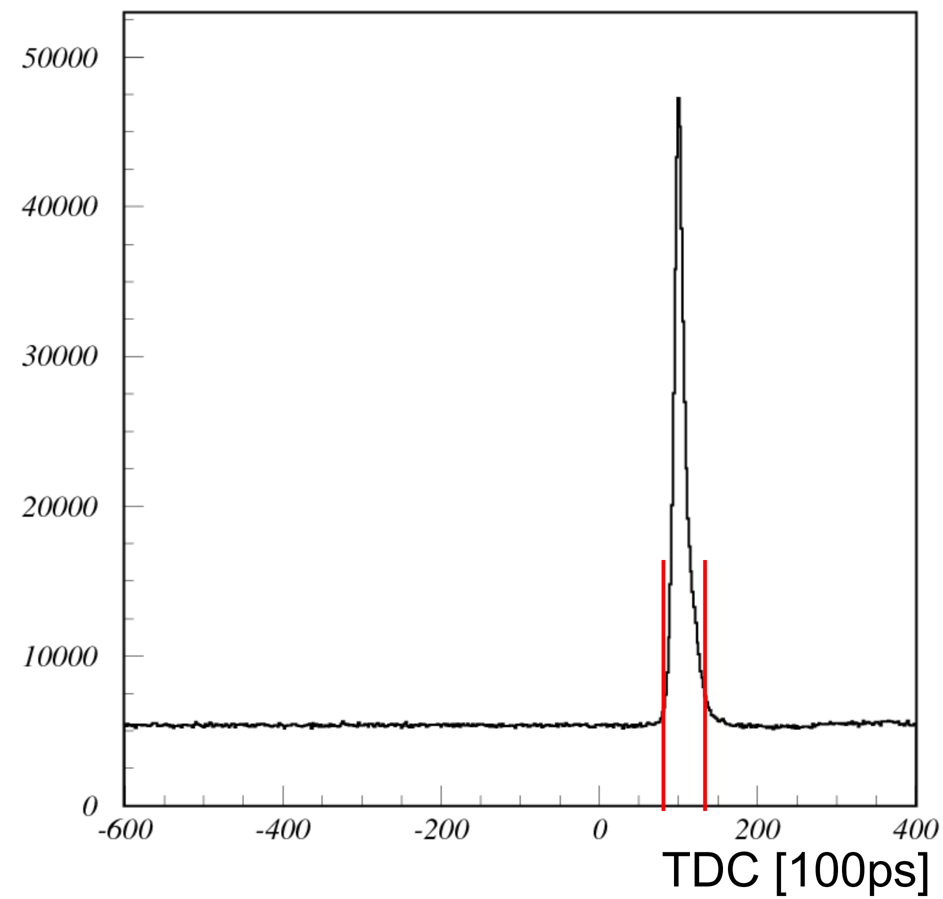
Results: TDC distributions of MPPC hits for all events

- total noise rate ~ 35MHz (~600kHz/MPPC, ~2.4MHz/ch.)
- hits in the time window of 5ns around the peak are selected for Cherenkov angle analysis

w/o light guides



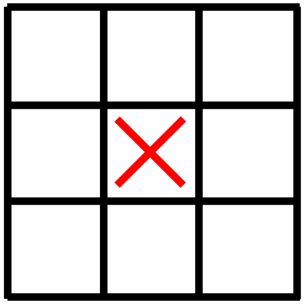
w/ light guides



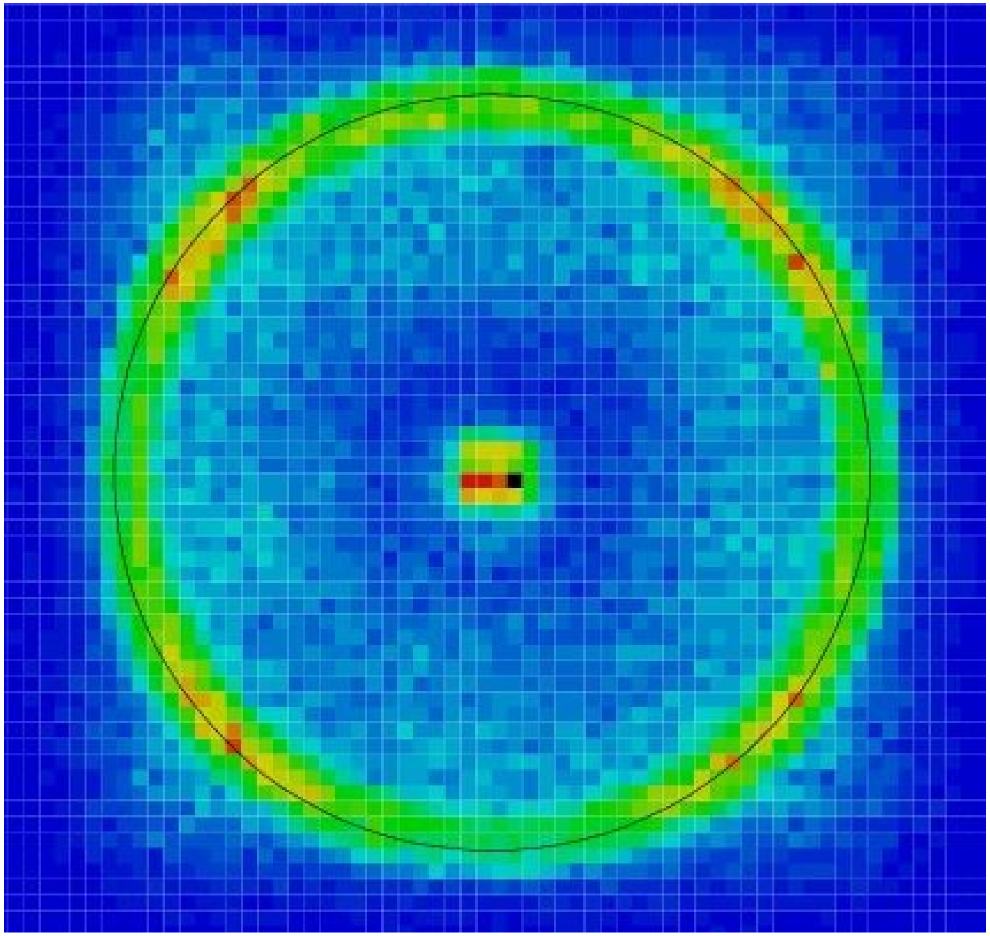
Results: Ring images

- module was moved to 9 positions to cover the ring area
- Shown on the plots:

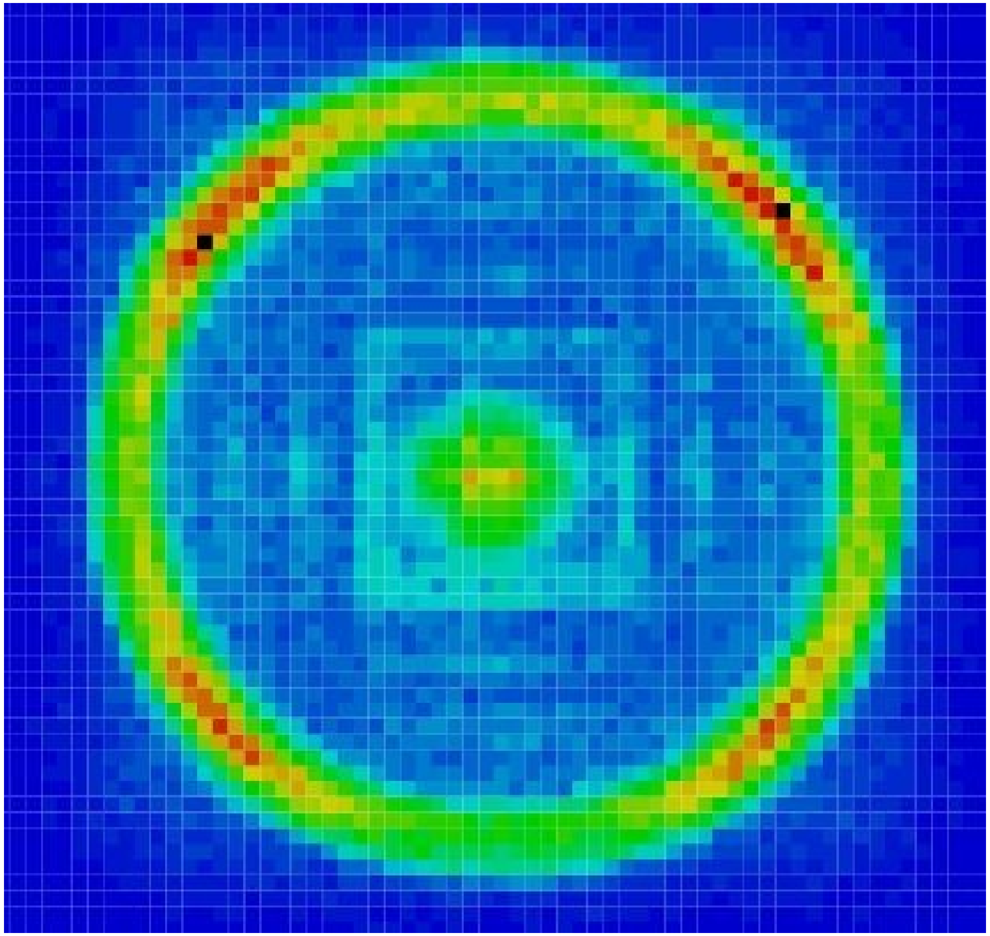
  superposition of 8 positions (center excluded)



w/o light guides

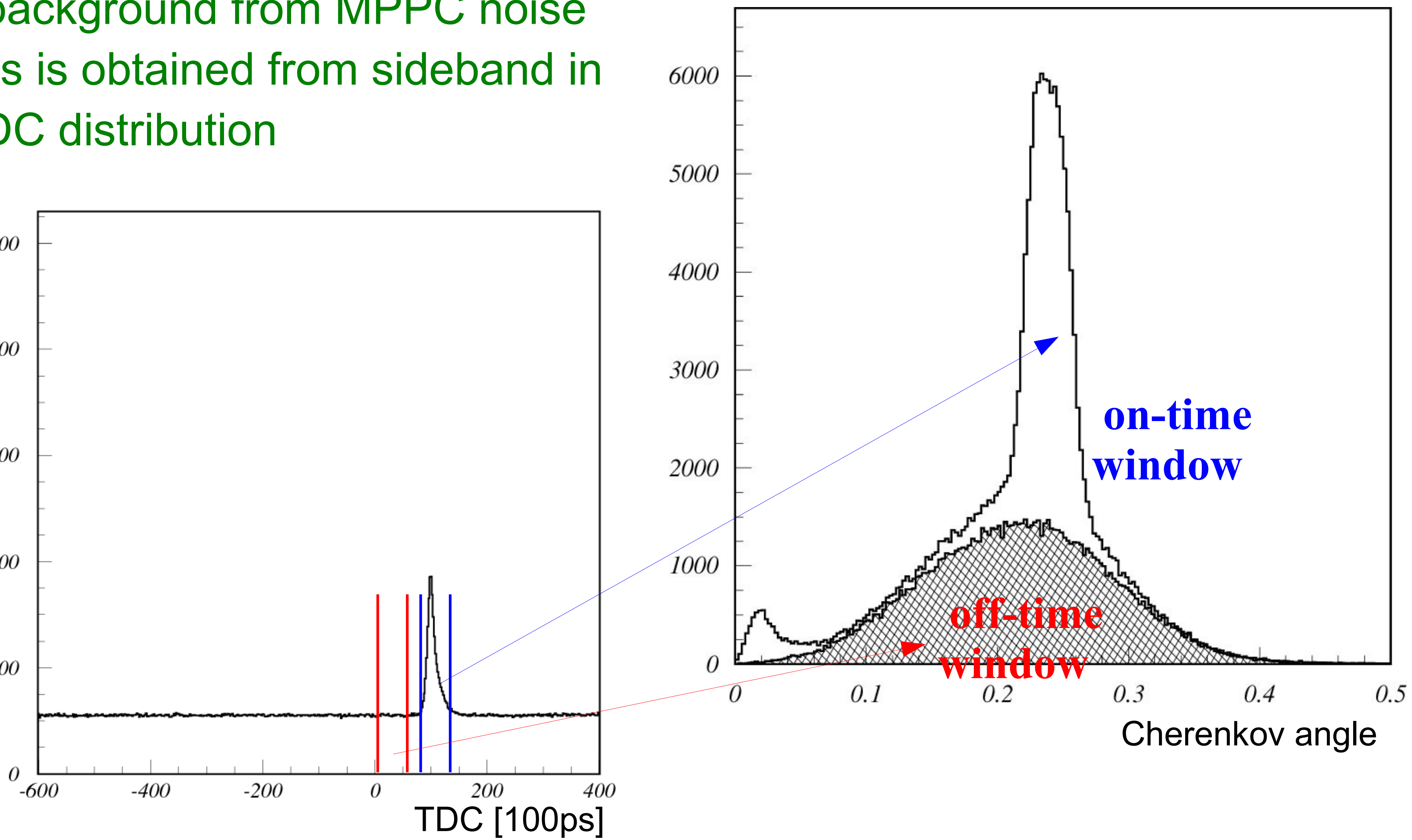


with light guides



Results: Cherenkov angle distributions

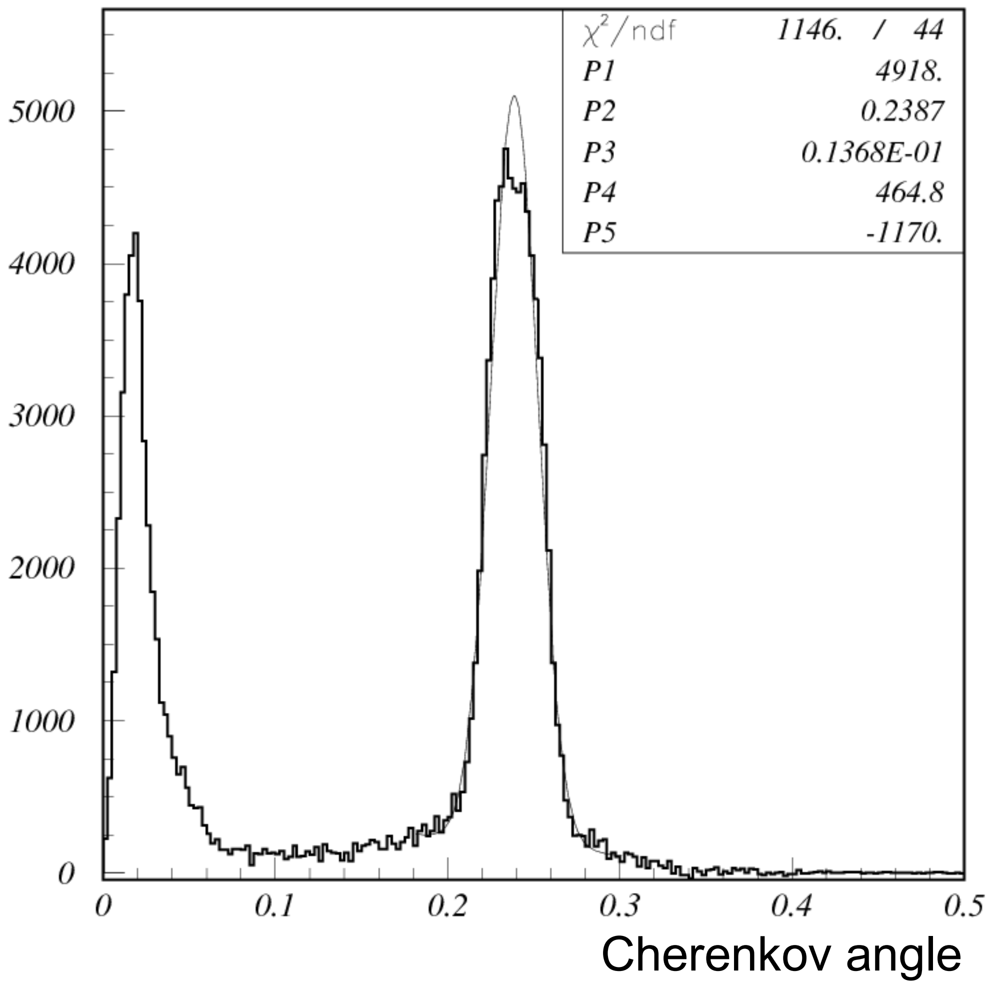
• background from MPPC noise hits is obtained from sideband in TDC distribution



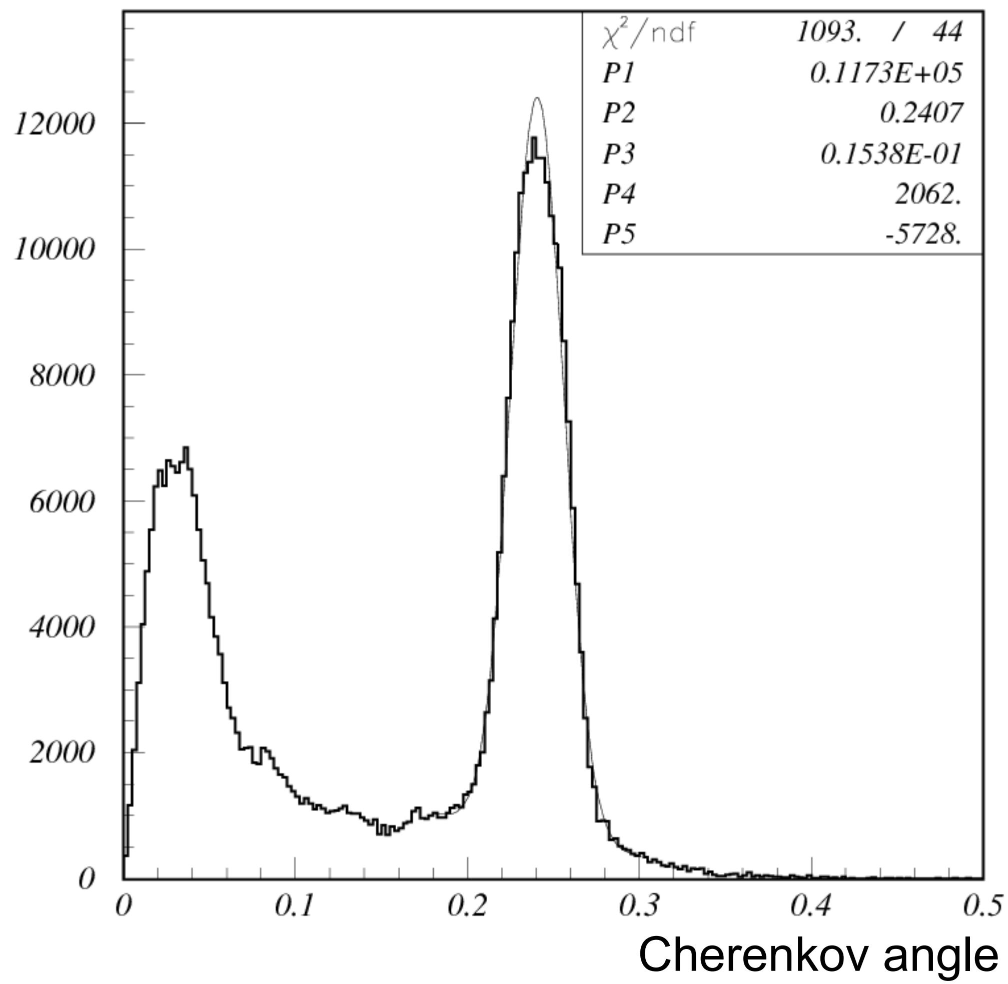
Cherenkov angle distributions – background subtracted

- background subtracted distributions
- ratio of detected photons w/ and w/o light guides: ~ 2.3
- resolution within expectations (~14mrad)

w/o light guides



w/ light guides



Results: Number of detected photons

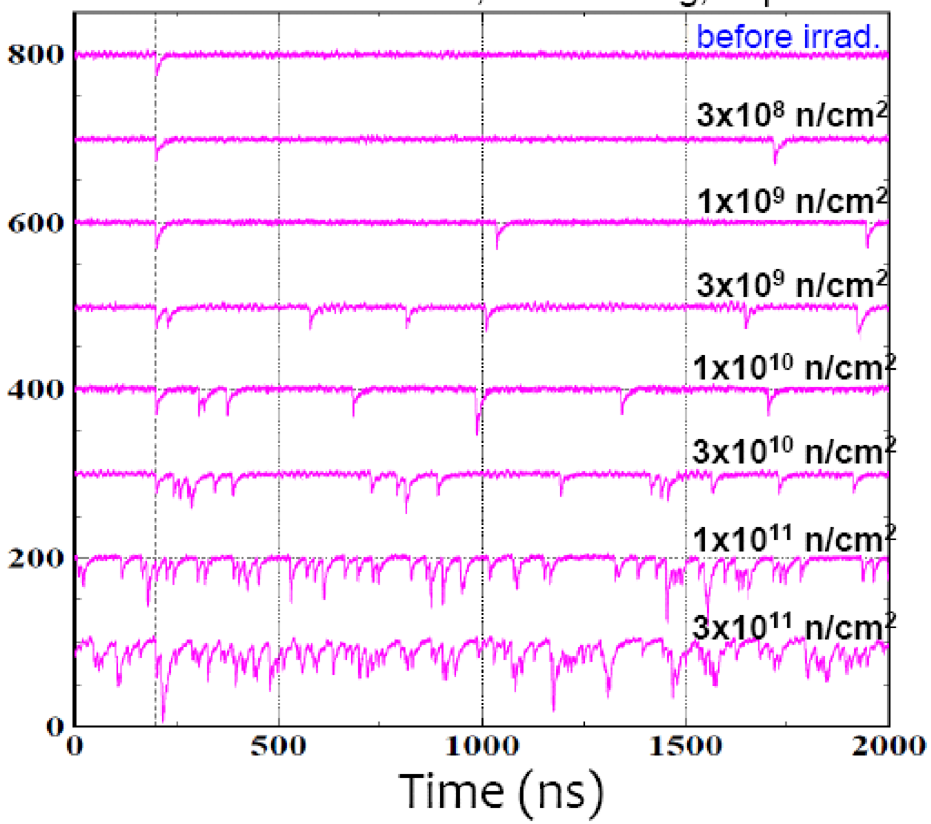
Expected number of photons is 2.2/full ring, this includes:
- Hamamatsu PDE
- aerogel: 1cm thickness, n=1.03, 14mm attenuation length
- dead time ~5%

Measured (extrapolated to full ring - acceptance corrected):
- w/o light guides ~ 1.6
- w/ light guides ~ 3.7

Estimated numbers for aerogel with n=1.05 and thickness of 4cm (~5x) and better quality of the surface of light guides (~2x) are
- w/o light guides ~ 8
- **w/ light guides ~ 37**

Expected neutron damage inside the BelleII spectrometer

I.Nakamura, JPS meeting, Sep. 2008



Measured fluence (Belle):
90/fb → 1-10 10^9 n/cm^2

Expected fluence at 50/ab
→ if backg. x20: 2-20 10^{11} n/cm^2
→ worst than the lowest line

The monitoring diodes were not at the right place (mounted behind ECL instead of in front of it). However, n flux is probably quite similar.

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

Summary

- a module of 64 SiPMs was tested in beam as a photon detector in RICH
  - dark noise suppressed by accepting only hits within 5ns window
  - detected 1.6 photons per ring

- light guides were used to improve signal to noise ratio
  - detected 3.7 photons per ring
  - improvement by 2.3× is less than expected 3.5× from simulations
    - light guide sides not polished
    - light guide exit surfaces not perfectly aligned with SiPM active surfaces

- this would be improved in the final detector:
  - use 30mm of aerogel with n=1.05 and better light attenuation length (5×)
  - improve light guide production and coupling to SiPMs (2×)

- expect ~ 30 photons per ring

SiPMs are excellent sensor for RICH counters

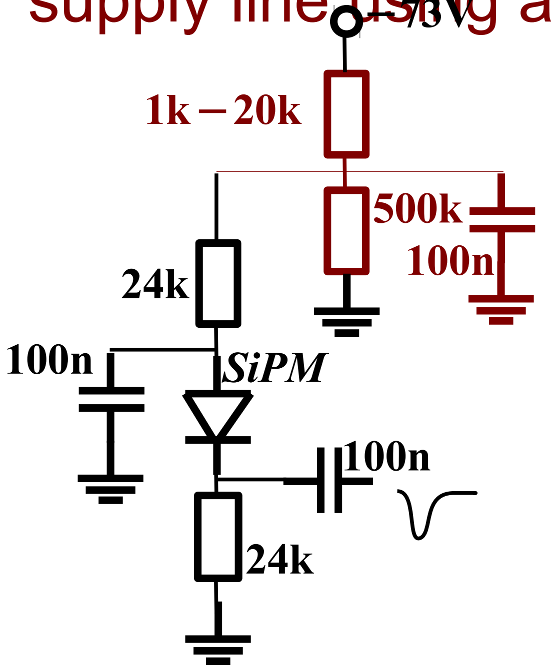
BACKUP SLIDES

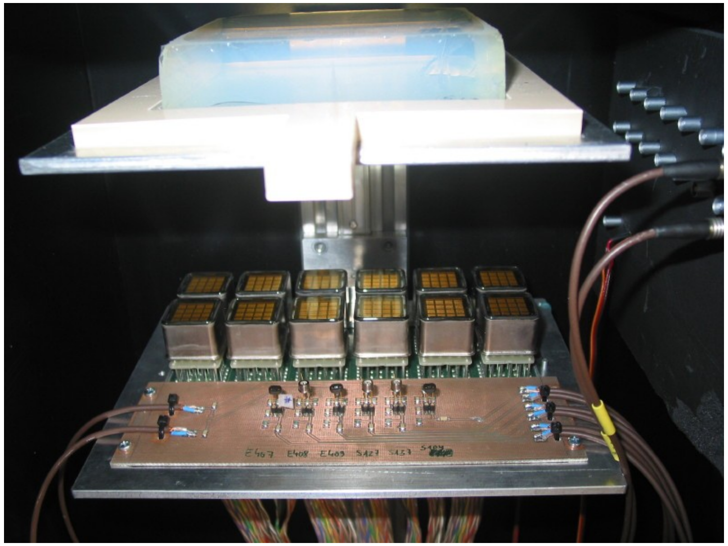
Cosmic test setup

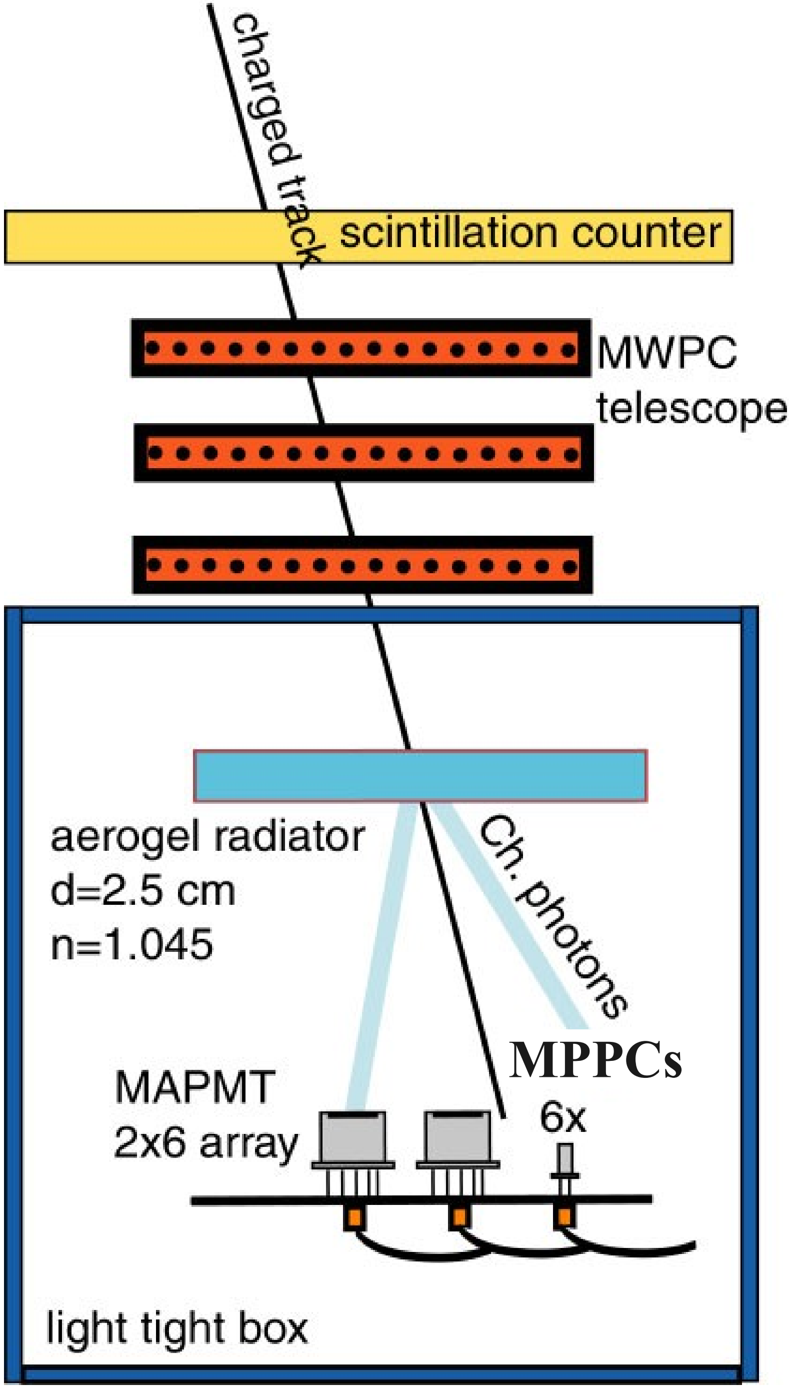
Two configurations of 6 Hamamatsu MPPCs were used:

- (HC100, HC050, HC025)x(metal, ceramic)
- 6 x HC100, metal

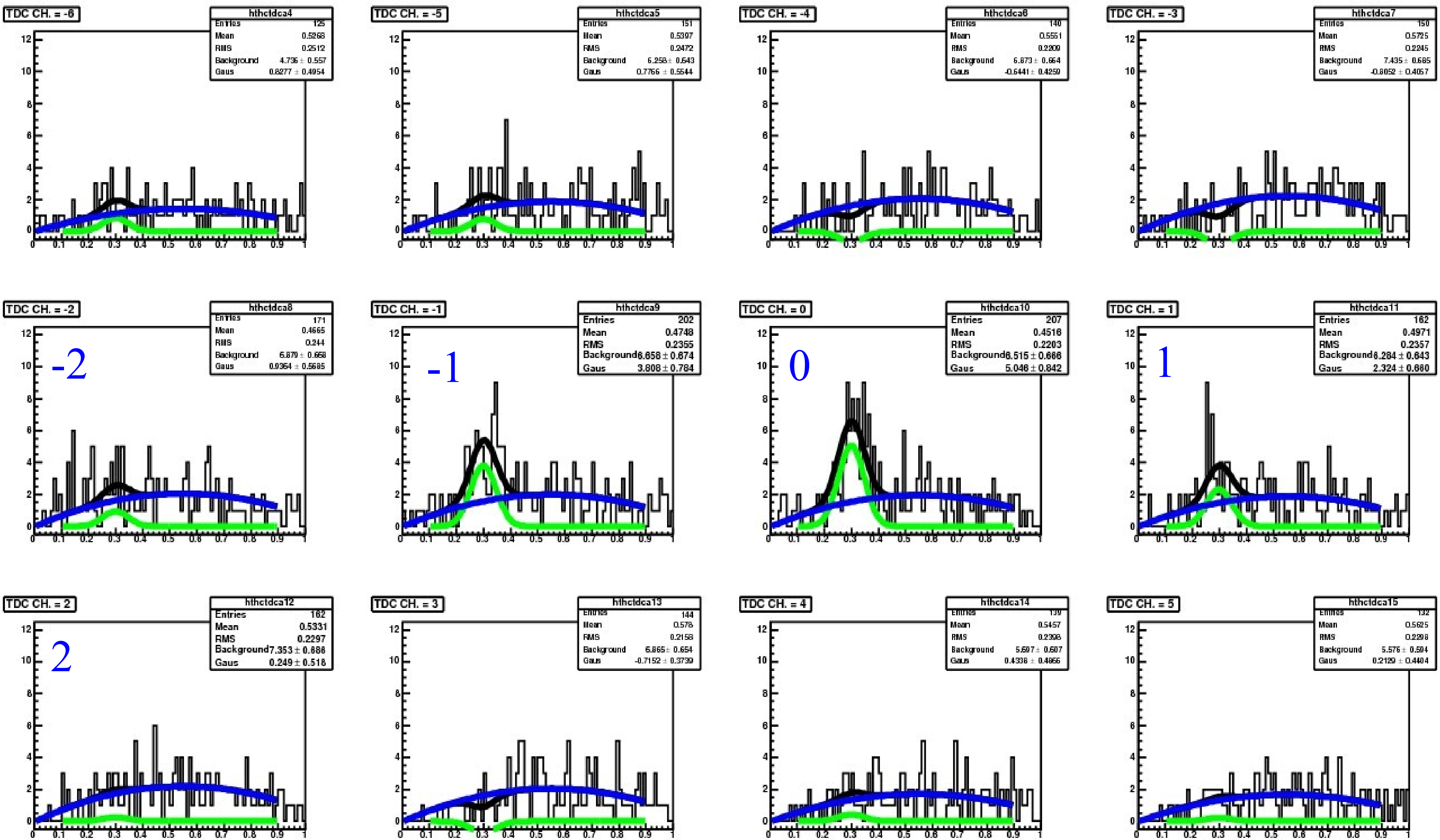
All six MPPCs were connected to same supply line using additional dividers:



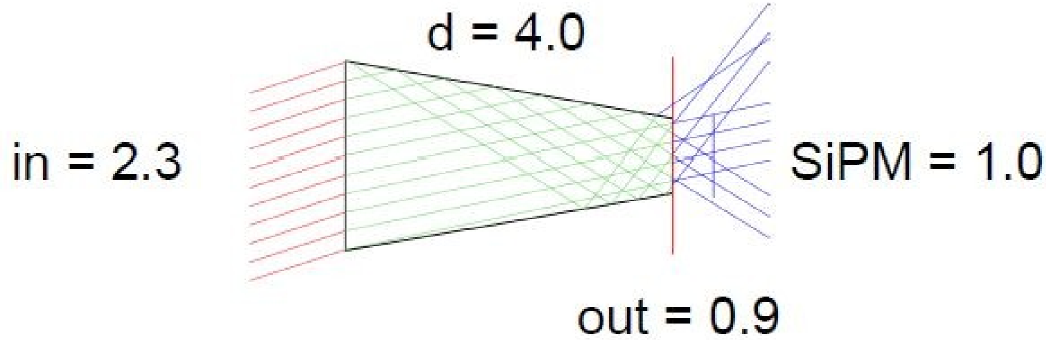




Cherenkov angle distributions for 1ns time windows



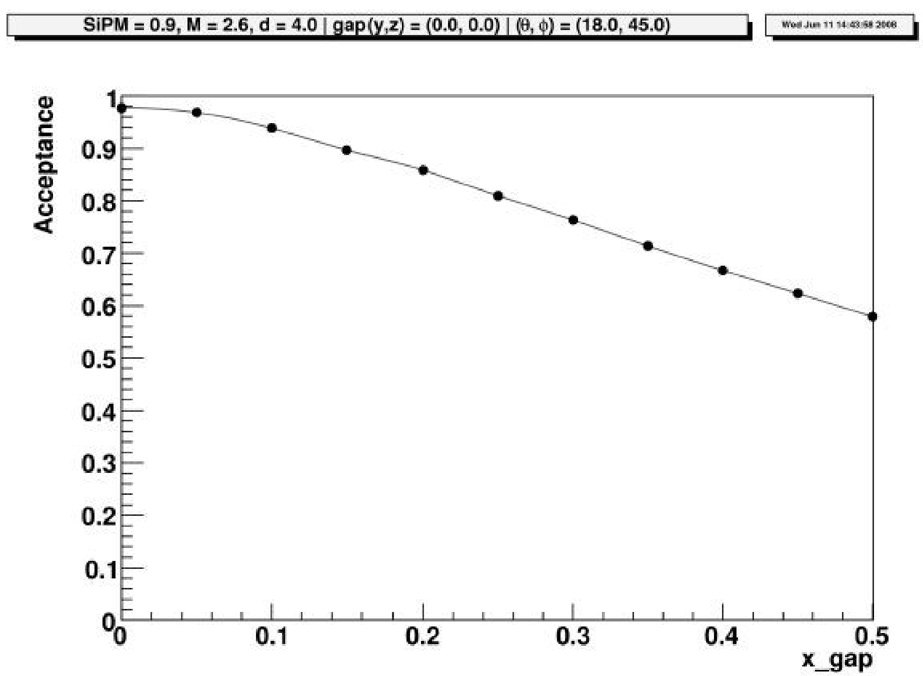
Light guide simulation



Simulation includes:
- refraction at LG entrance
- total reflection
- gap between LG exit and MPPC surface

Not included:
- absorption
- imperfect light guide surface

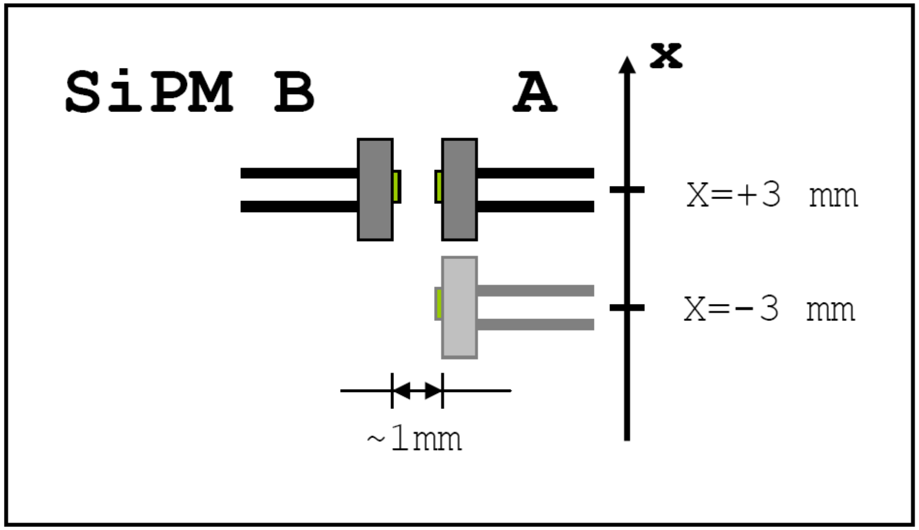
$\theta = 18^{o}$
$\varphi = 45^{o}$



t=18,p=45		
gap	w	w/o
	0.00	97.67
	0.05	96.62
	0.10	94.11
	0.15	89.68
	0.20	85.99
	0.25	81.06
	0.30	**76.12**
	0.35	71.49
	0.40	**66.85**
	0.45	62.44
	0.50	**58.39**

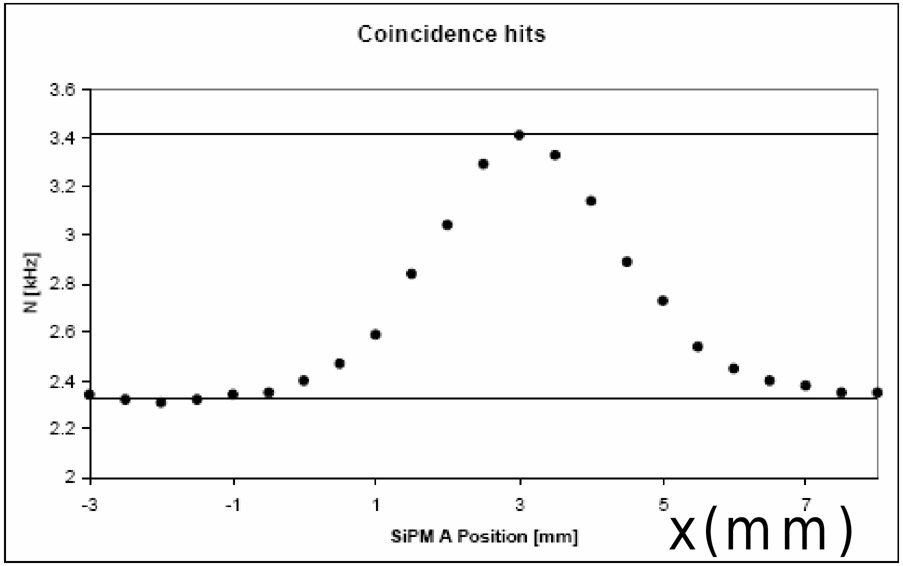
External secondary photon cross talk

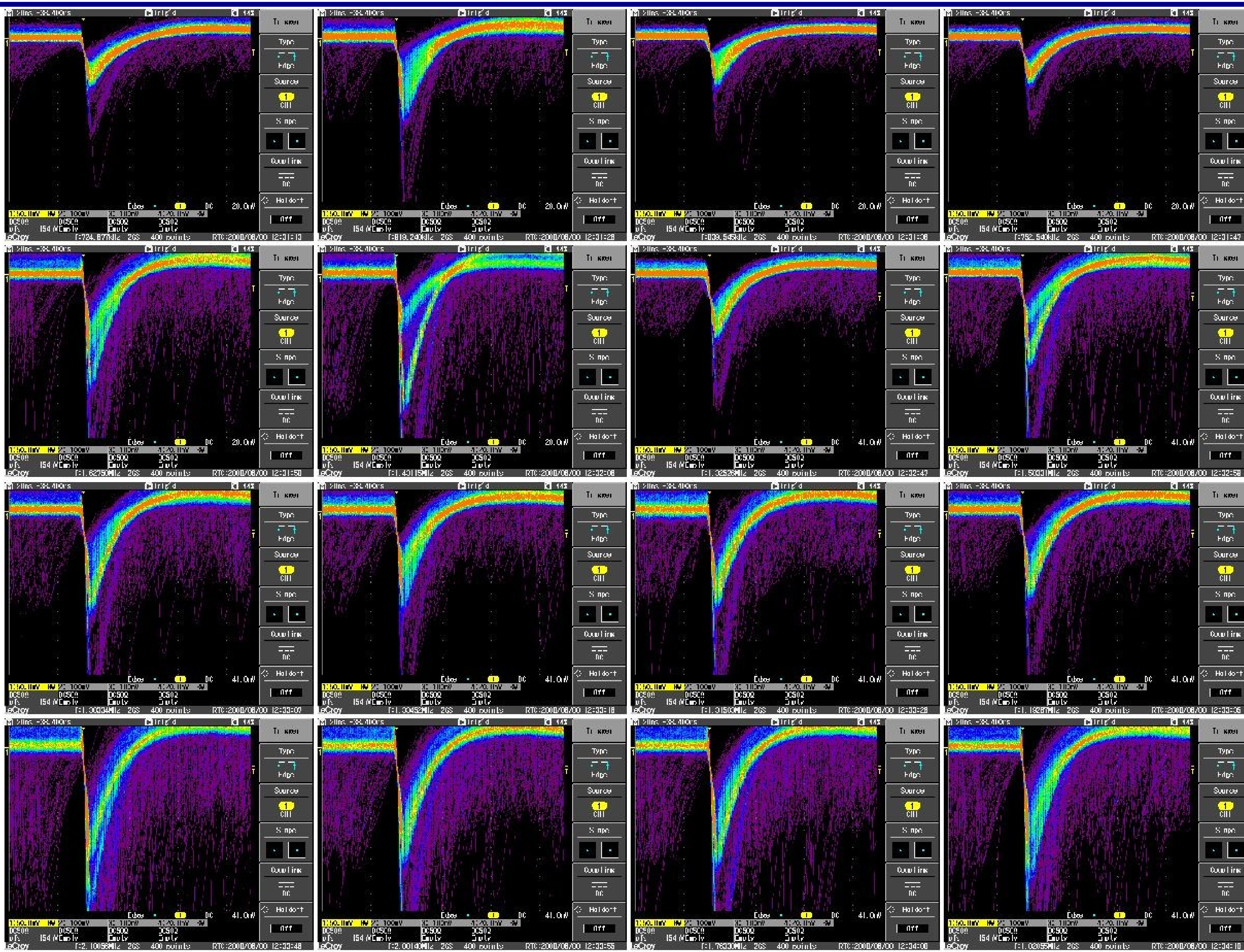
Will G-APDs “comunicate”?
Scan one G-APD in front of a second one and observe coincidence rate



- single sensor dark rate ~ 200 kHz
- coincidence background rate ~ 2.4 kHz
- coincidence rate increas when face to face ~ 1 kHz
- 1 mm active area 1 mm away
  → ~ 15% of 2π solid angle
- full (2π) solid angle:
  1kHz/(2x200kHz)/15% ~ 2%

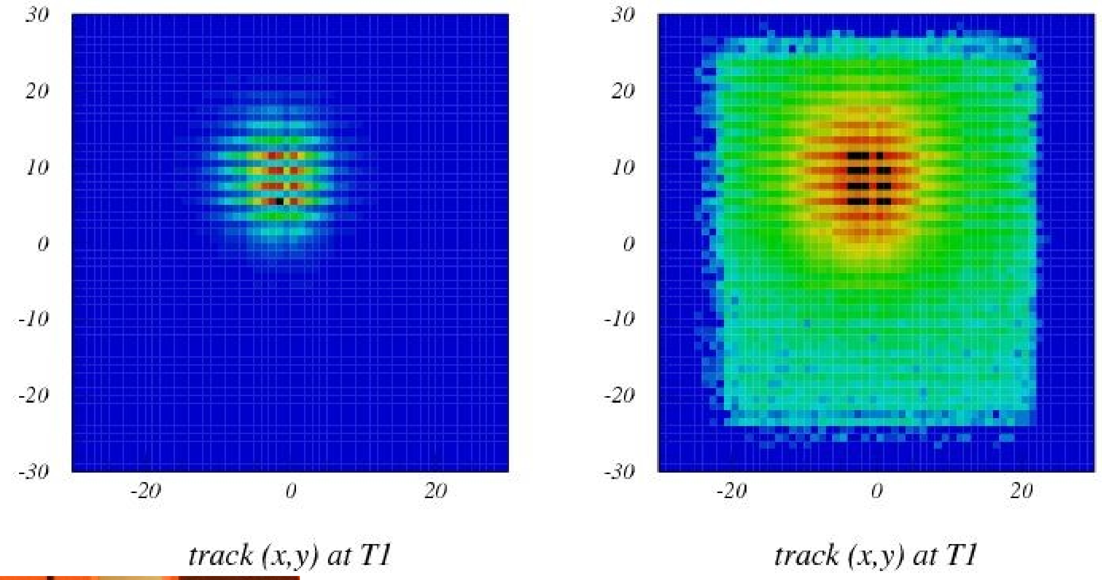
→ OK, increase of background at % level



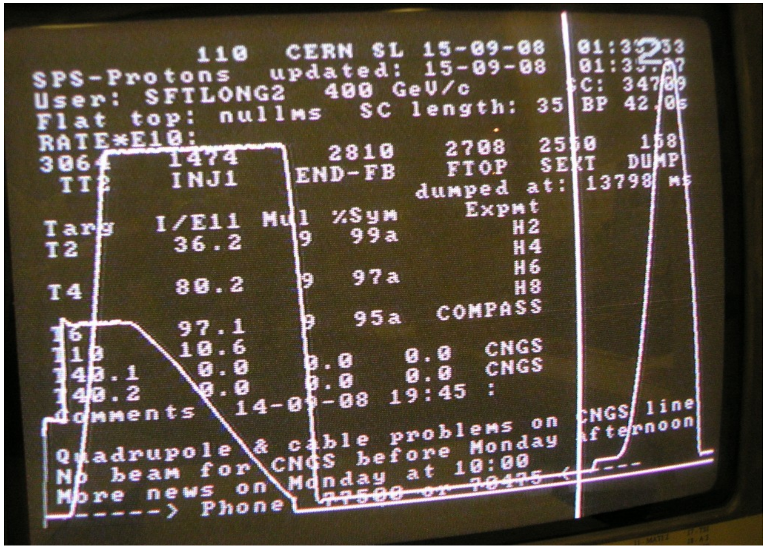


Beam area T4-H6-B @ CERN

- +120 GeV/c pions
- spills every 42s for ~5s
- beam size ~1cm^2



- beam profile (scale in mm)



Beam area T4-H6-B