RICH with G-APDs

Samo Korpar

University of Maribor and Jožef Stefan Institute

G-APD Workshop

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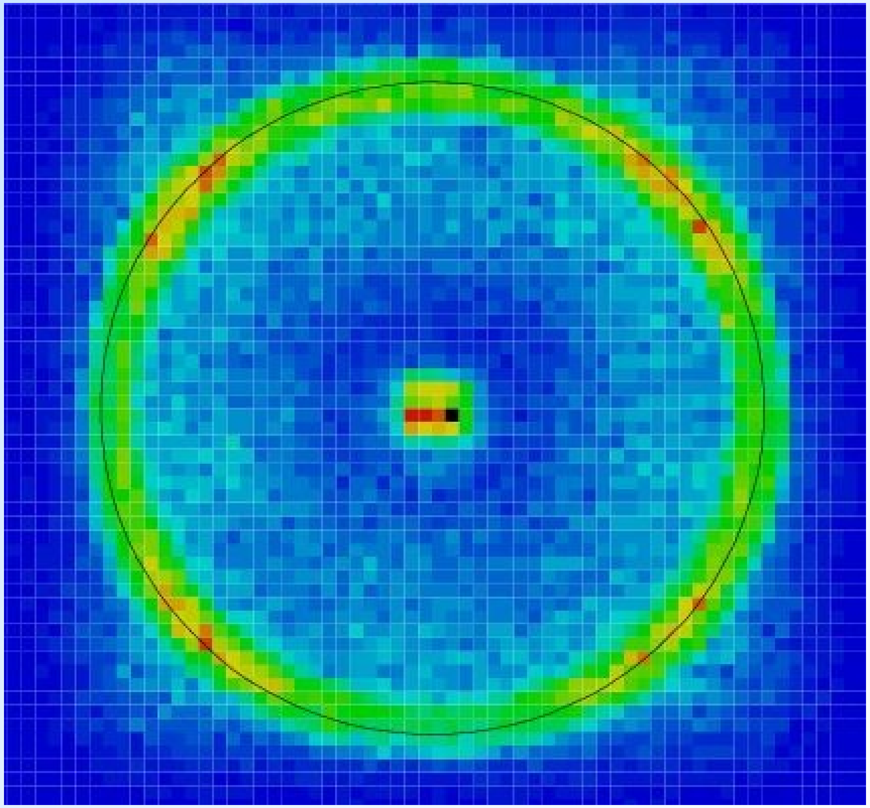
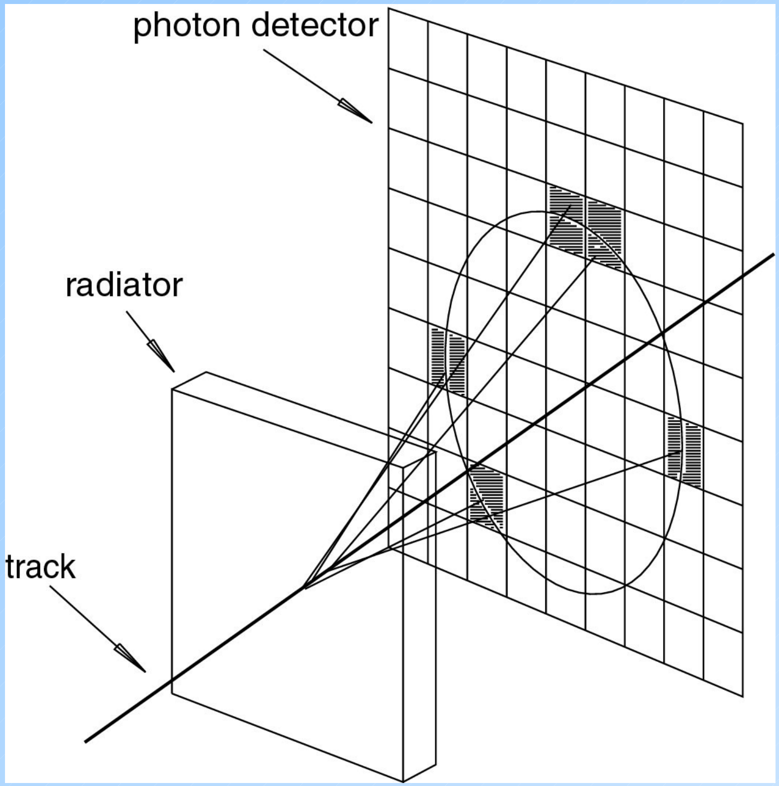
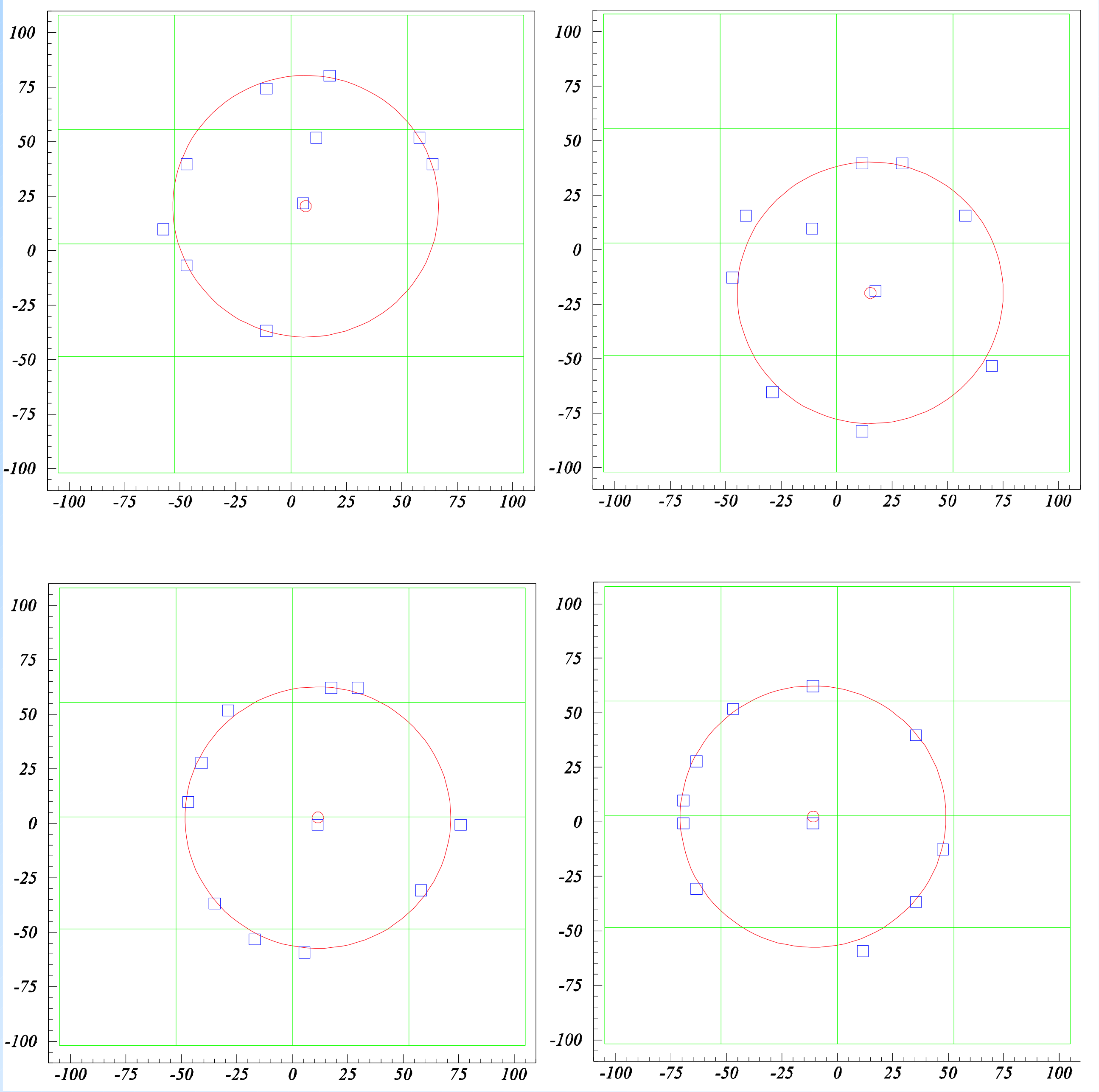
Outline:

- Aerogel RICH for Super Belle
- RICH with G-APDs (SiPMs, MPPCs ...)
- Beam test set-up and results
- Summary



Measuring Cherenkov angle

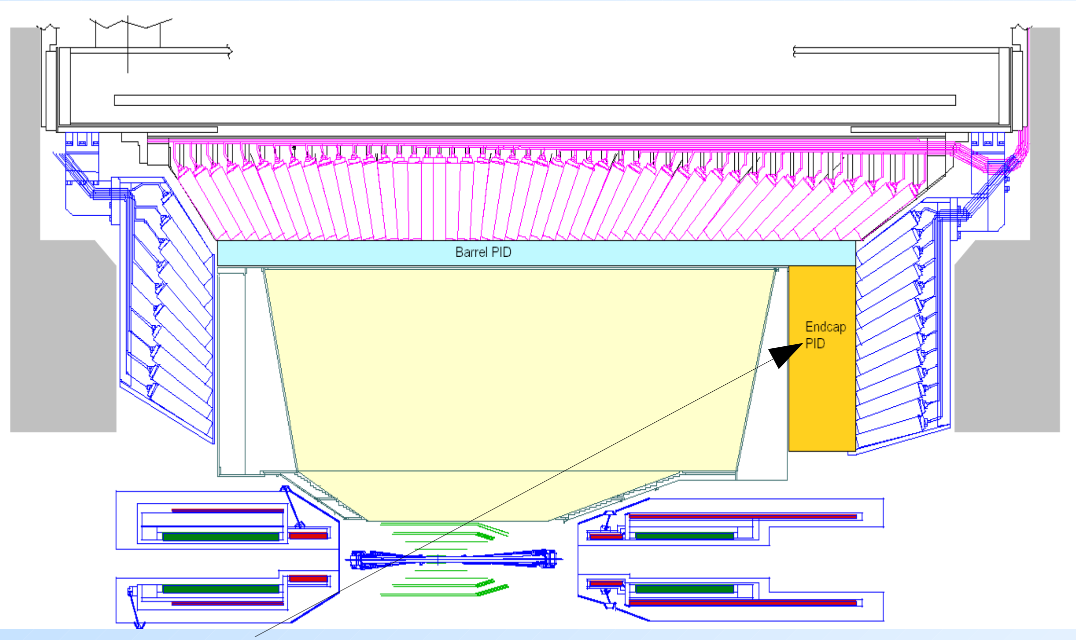




From hits of individual photons → measure the angle

Few photons detected → Important to have a low noise detector

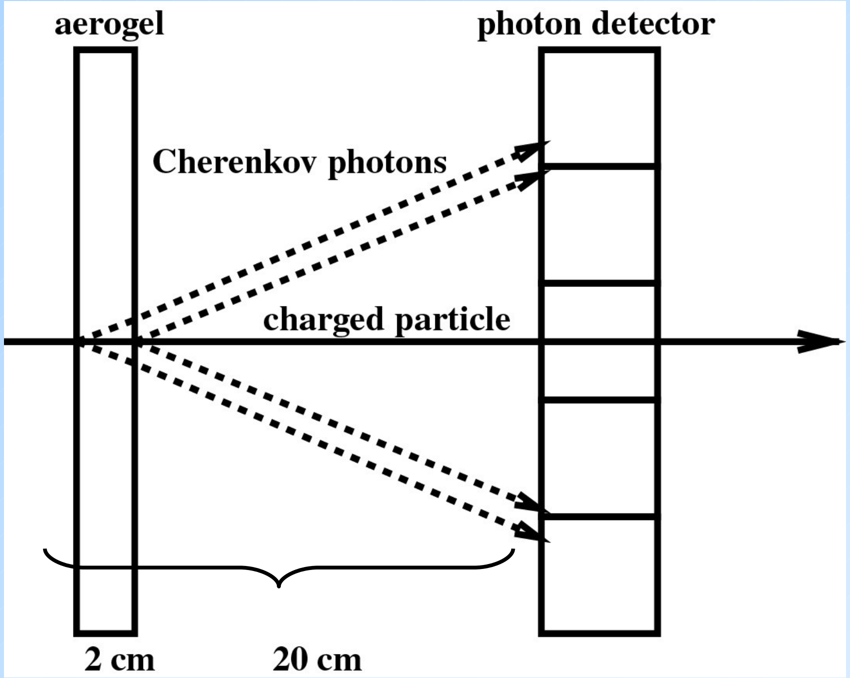
Forward PID for Super Belle



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**

Selected 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
- pion threshold 0.44 GeV/c, kaon threshold 1.54 GeV/c
- time-of-flight difference (2m from IP): $t(\pi) - t(K)$ = 180(45) ps @ 2(4) GeV/c

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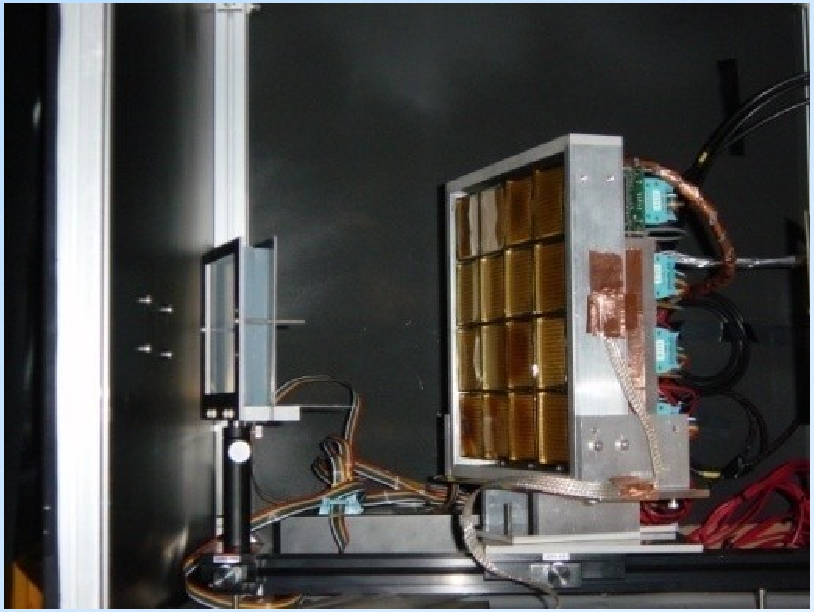
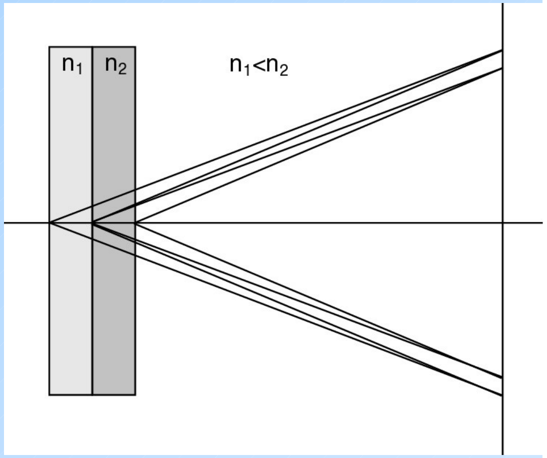
Beam test with flat-panel PMT array

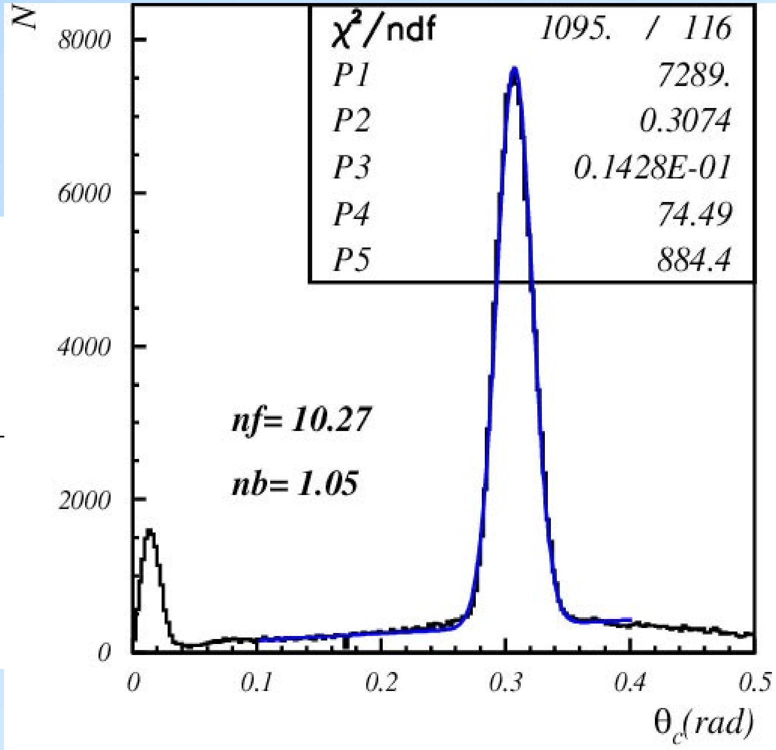


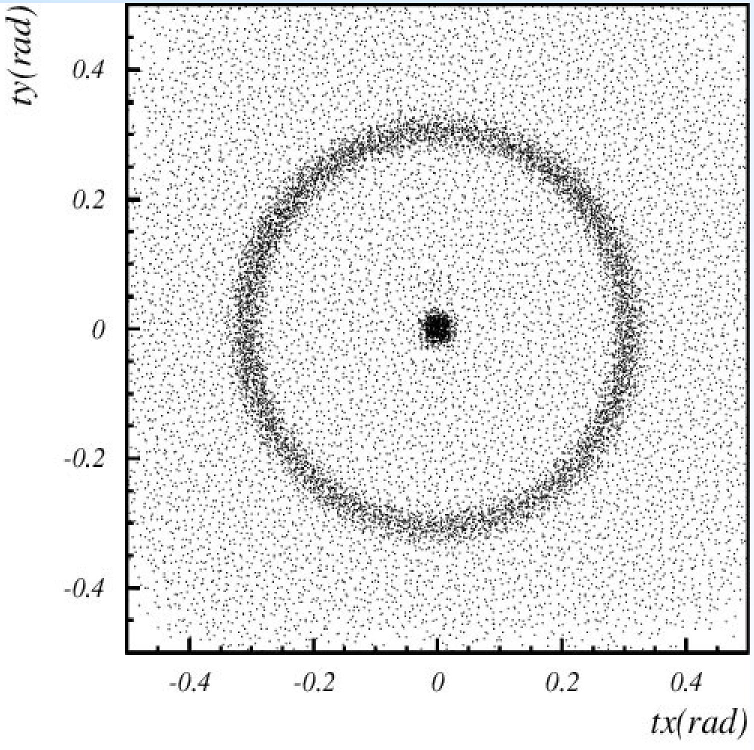
Study of aerogel radiator with flap-panel PMT array - standard configuration: 2cm(1.045)+2cm(1.055) focusing aerogel:

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

5σ at 4GeV/c

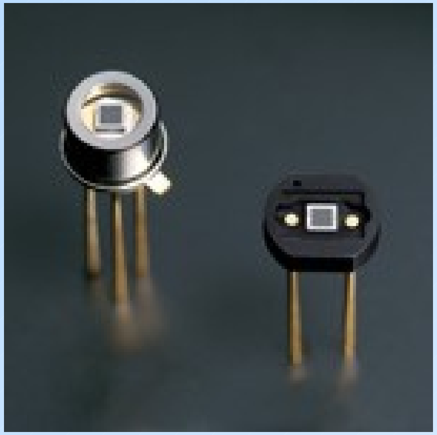


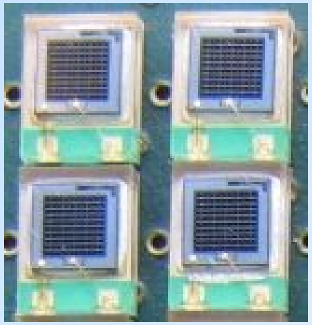




SiPM characteristics

- **works in magnetic field**
- low operation voltage ~ (10-100)V
- peak PDE (= QE x ε_{geiger} x ε_{geo}) up to 65% (@400nm - Hamamatsu data sheet)
- gain ~ 10^6
- time resolution ~ 100-200 ps
- dark counts ~ few 100kHz/mm^2
- radiation damage (p,n)

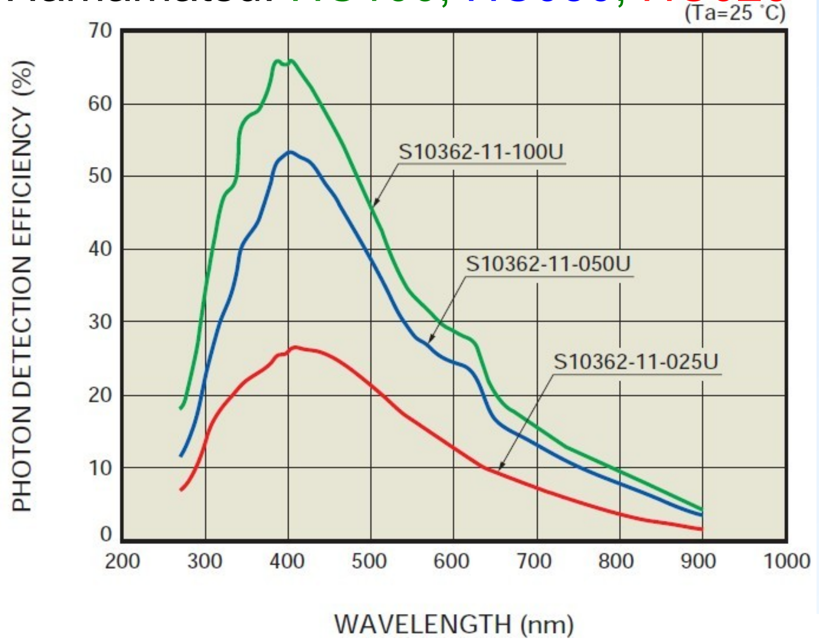


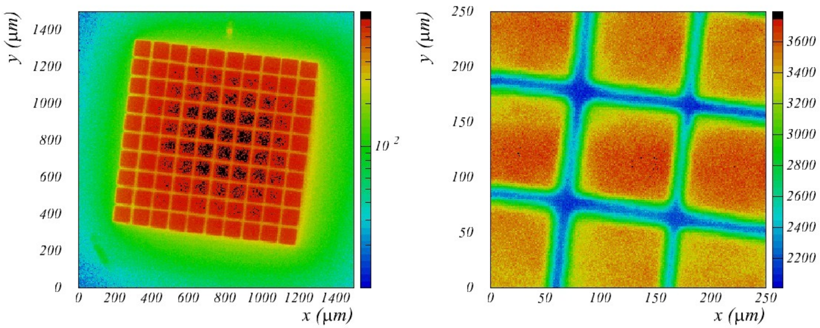


Can such a device be used in a RICH?

- detection of single photons
- linearity is not needed
- HC100 is preferred due to higher efficiency

Hamamatsu: HC100, HC050, HC025





First successful tests with cosmic rays NIM A594 (2008) 13

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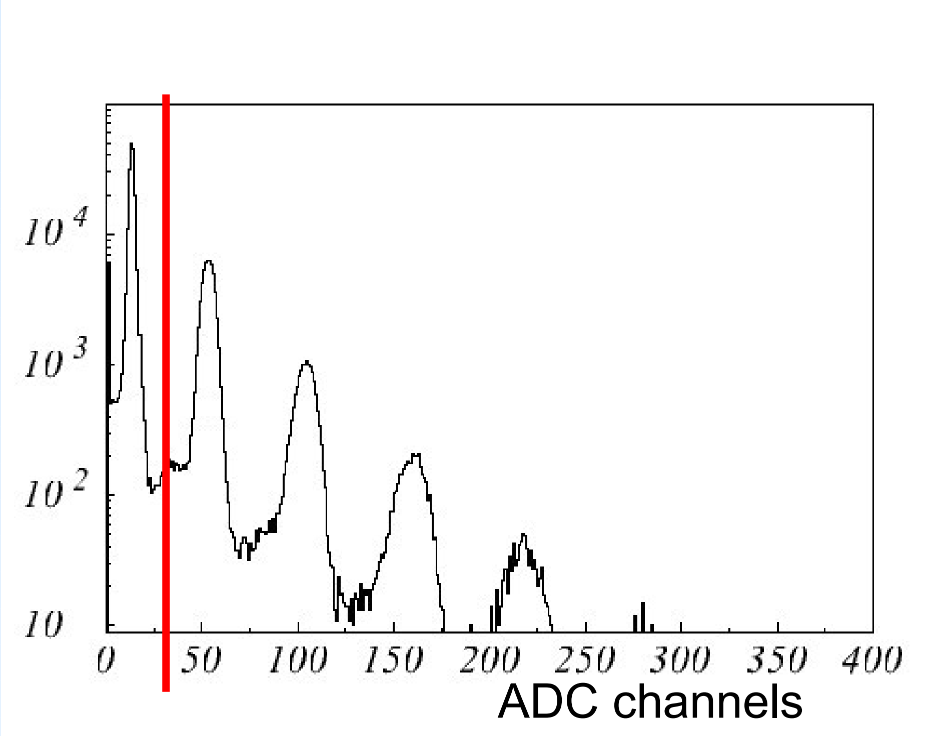
SiPM characteristics 2

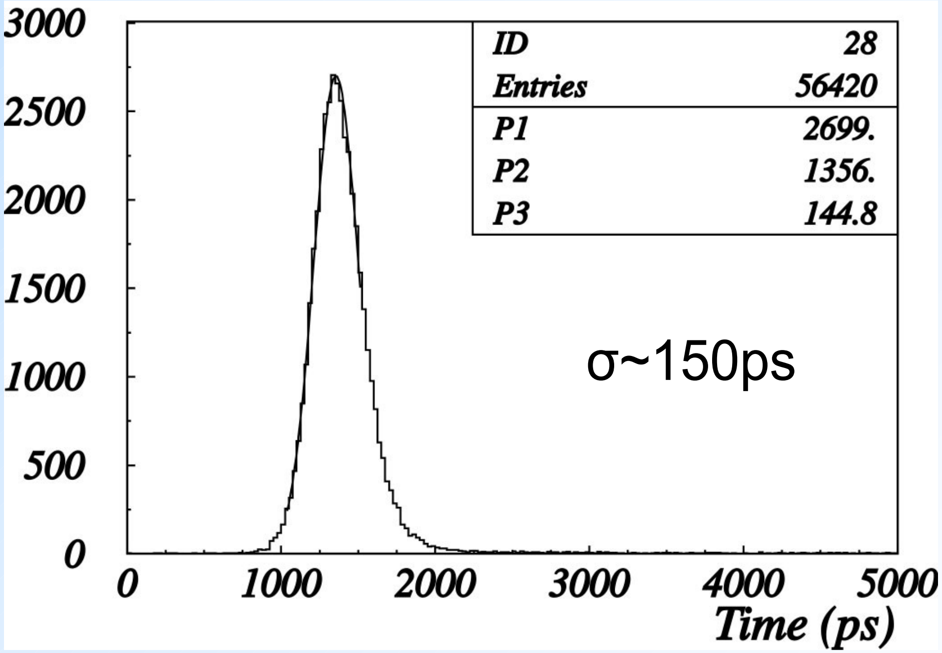
Typical pulse height distribution:

- signal is well separated from pedestal level
- single photon pulses are the same as dark current pulses



Typical timing distribution:

- narrow time window can be used to separate Cherenkov photons from dark current pulses

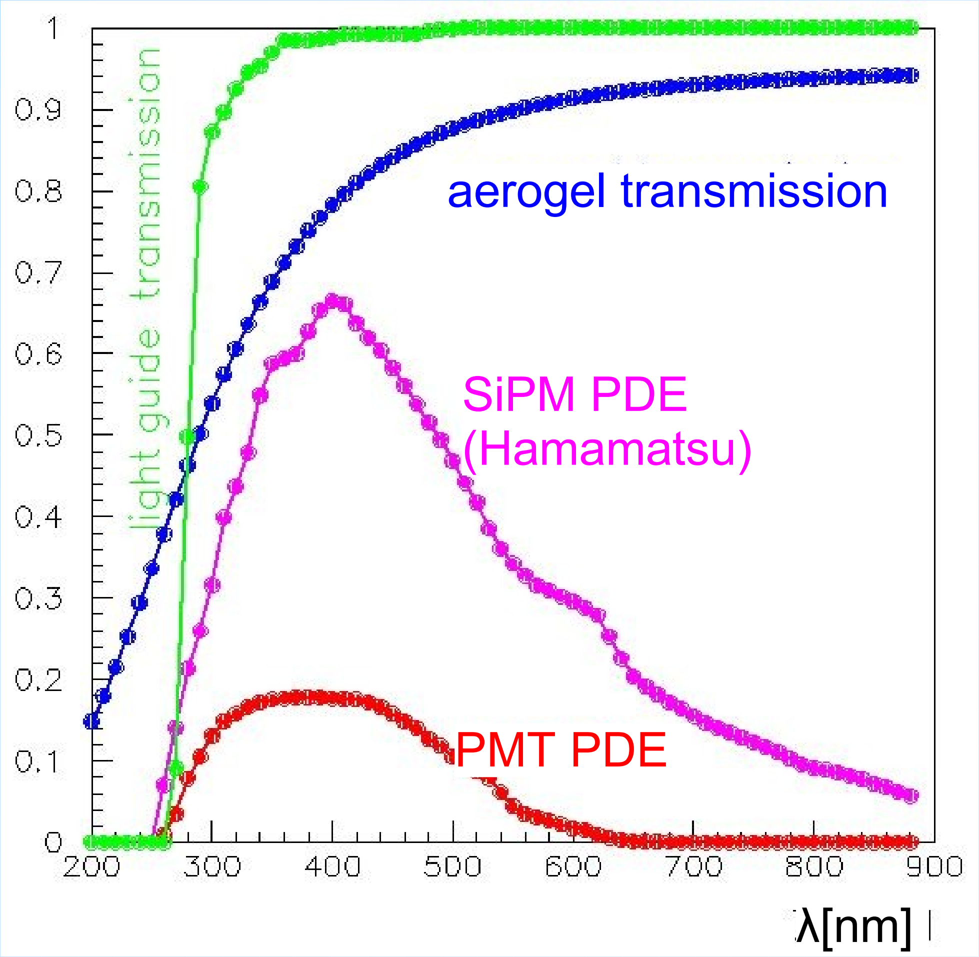


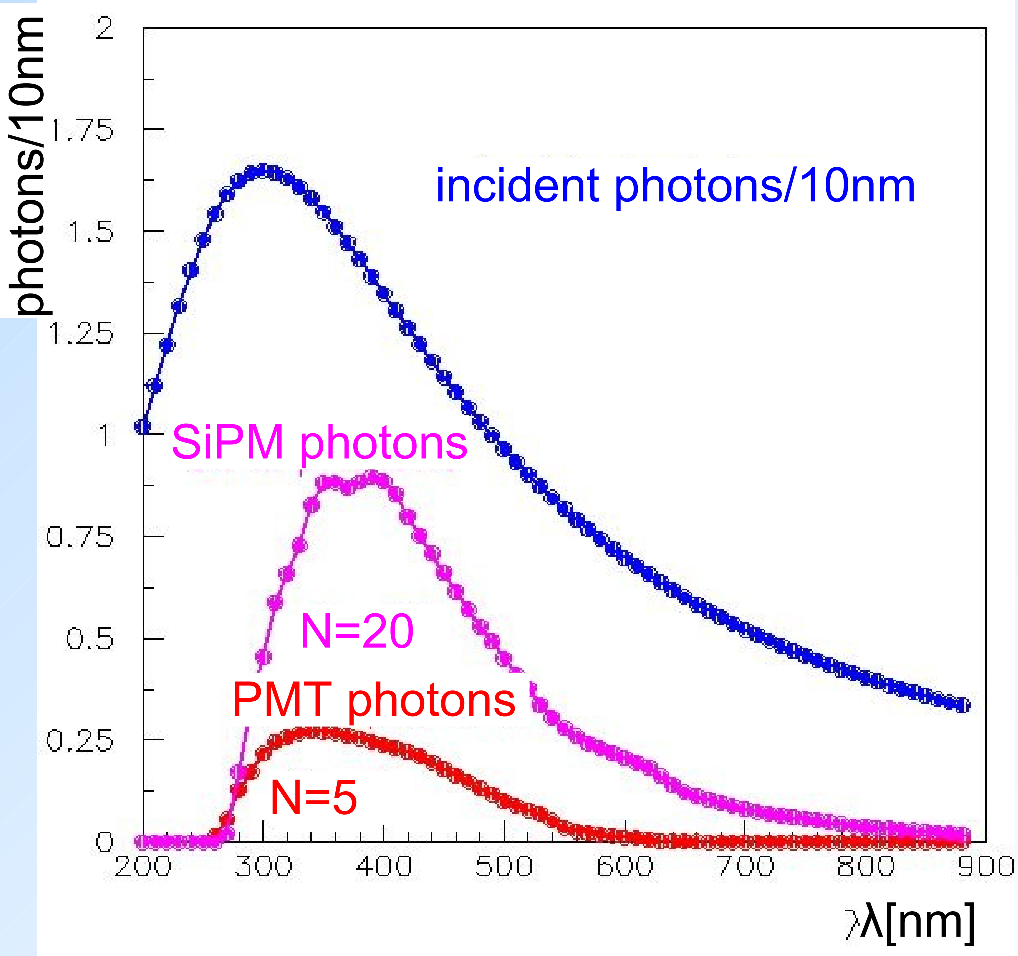
Expected number of photons

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

- multianode PMTs (peak QE ~ 25%, collection eff. ~ 70%) or MPPCs (HC100)
- aerogel radiator: thickness 1 cm, n = 1.03 and transmission length 2.5 cm (@400nm)

$N_{SiPM}/N_{PMT} \sim 4$

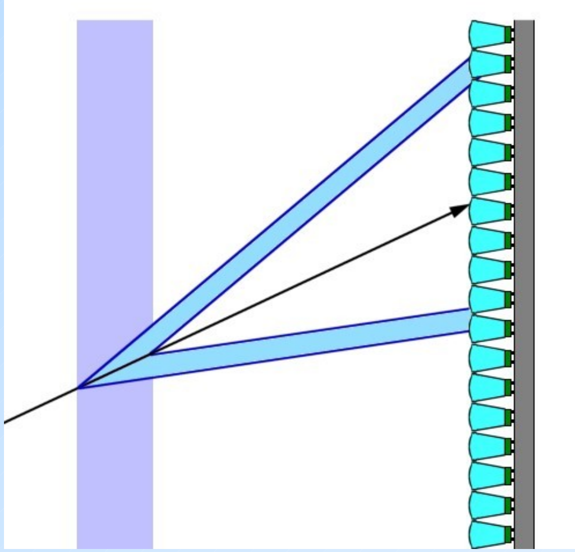




Signal to noise

Expected number of background hits depends on:

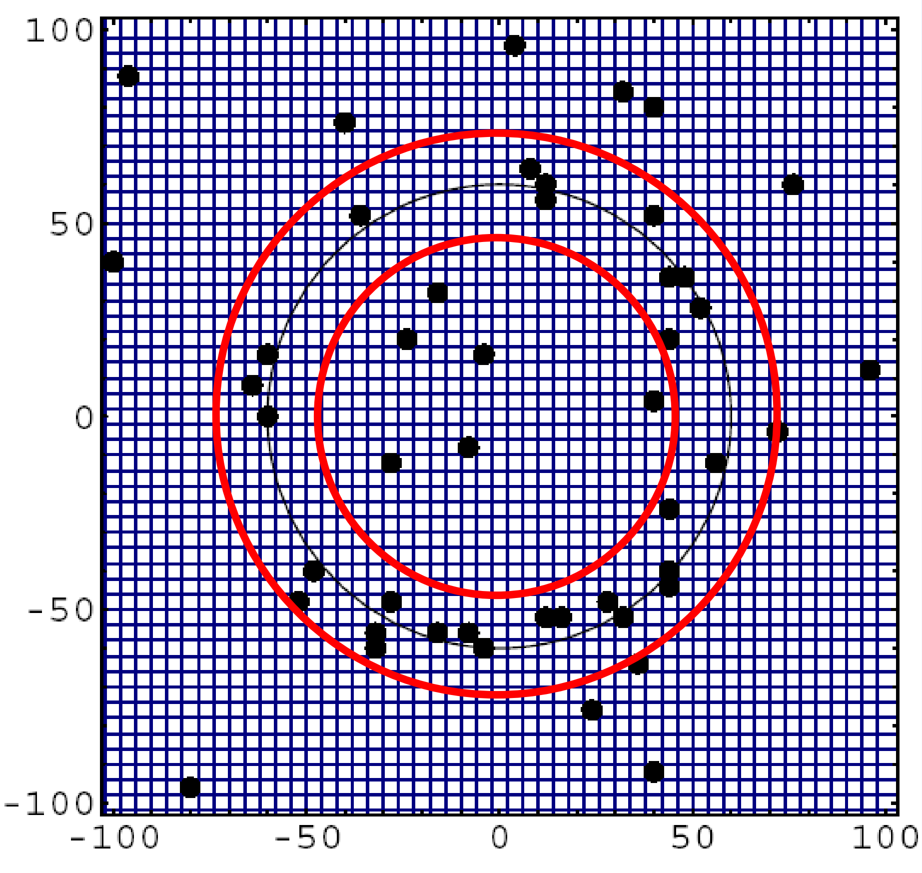
- ring area ~ 2000 mm^2
- dark count rate ~ 600kHz/mm^2
- coincidence window ~ 5ns



N_{dark} ~ 6 → N_{ph}/N_{dark} ~ 3.3

Ratio can be increased by:

- **smaller ring image area**
- **narrower time window**
- **use of light collection system (light guides) to increase effective area of the sensor**



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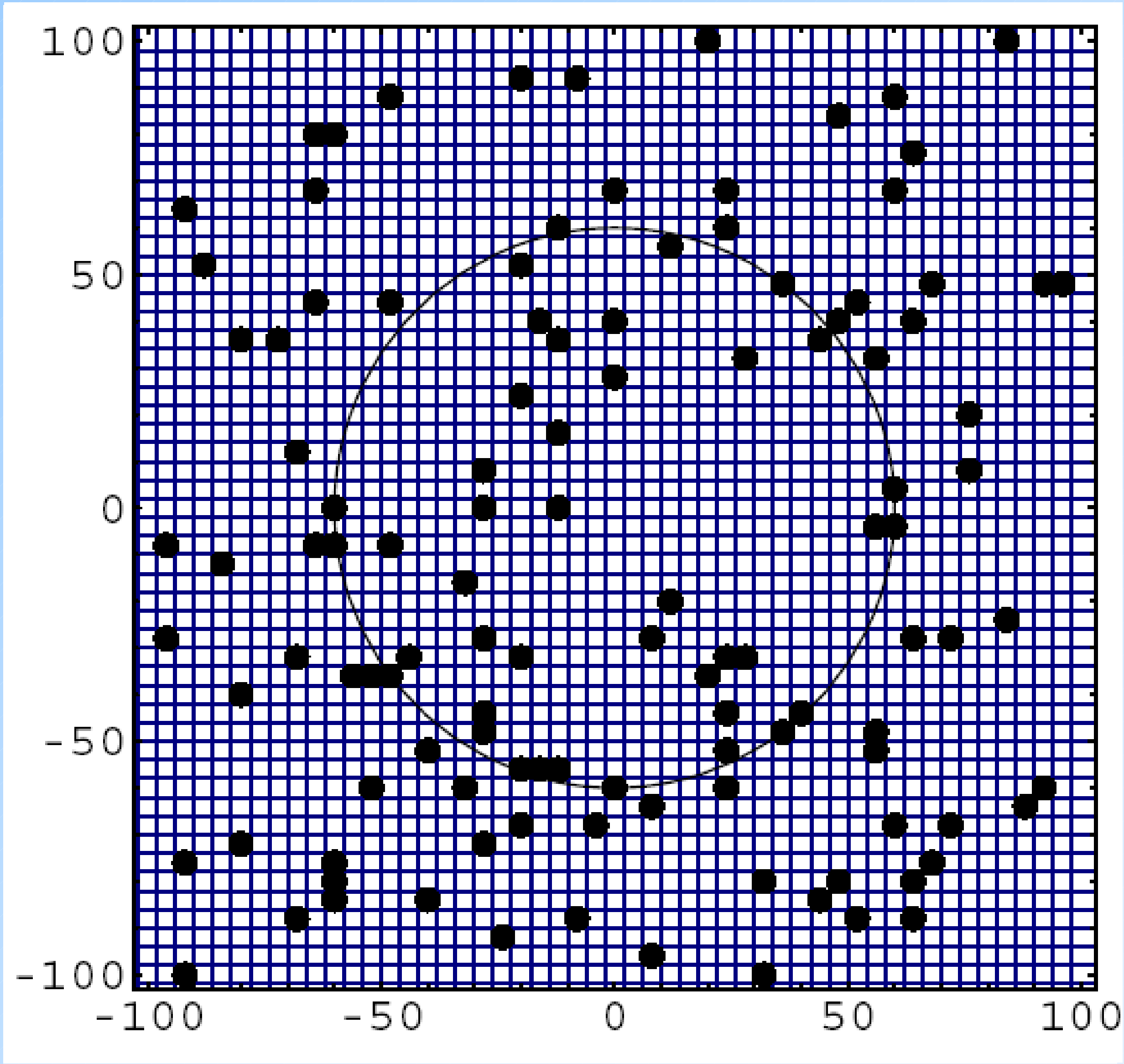
RICH with SiPM - expected hit distribution

- Ring on a uniform background



Can such a detector work?

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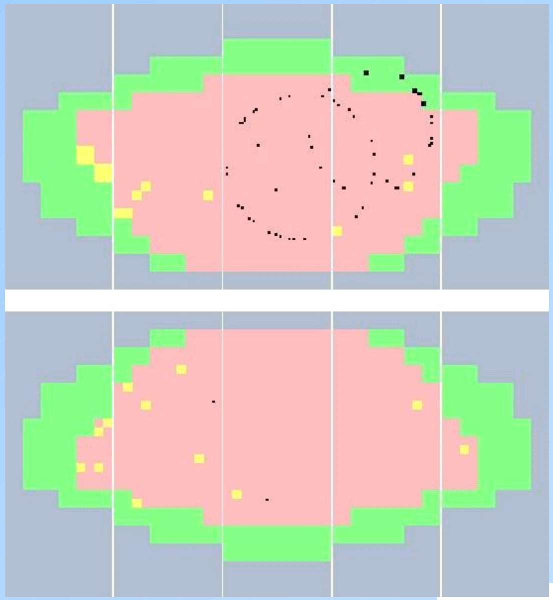
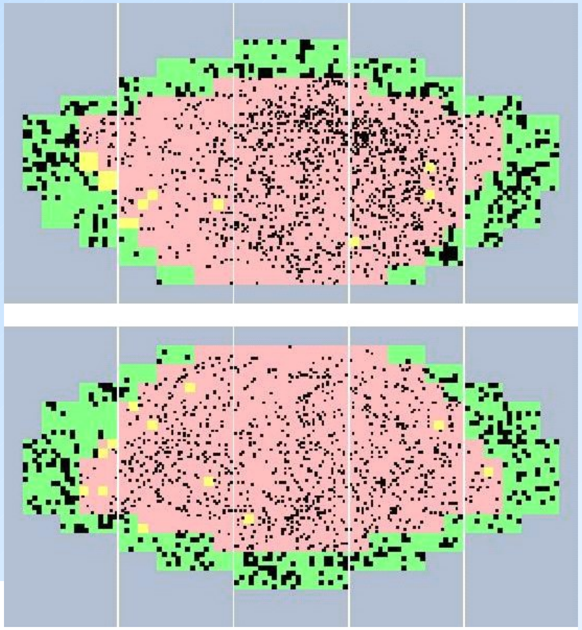


HERA-B RICH experience:

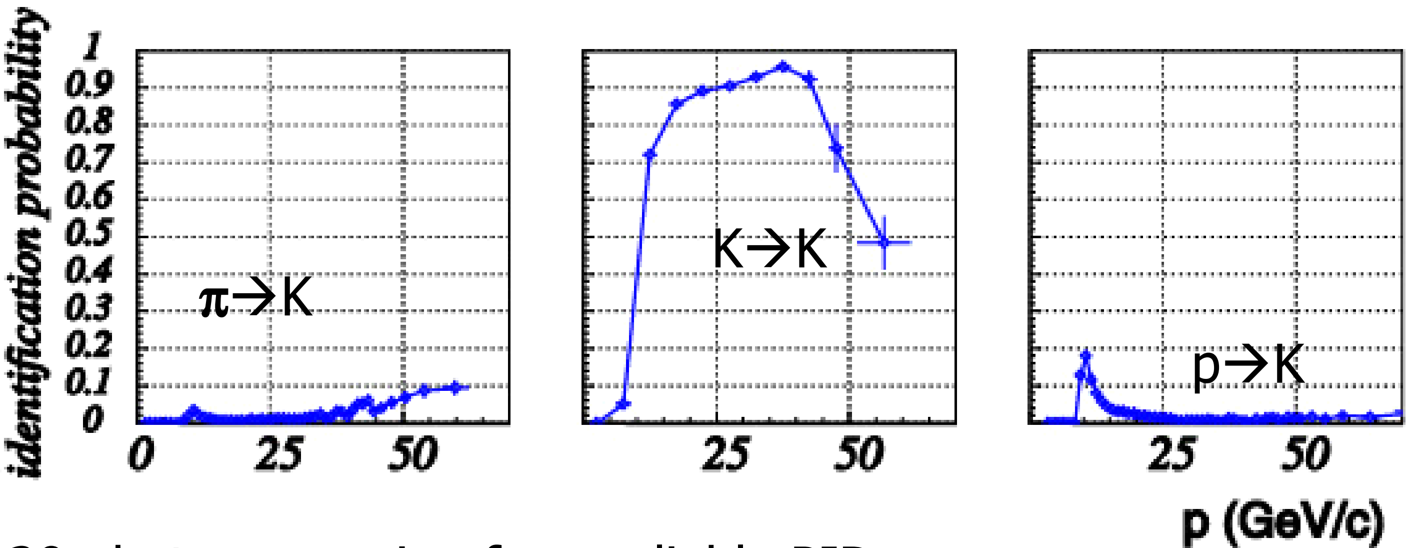
← Little noise, ~30 photons per ring

Typical event →



Worked very well!

Kaon efficiency and pion, proton fake probability

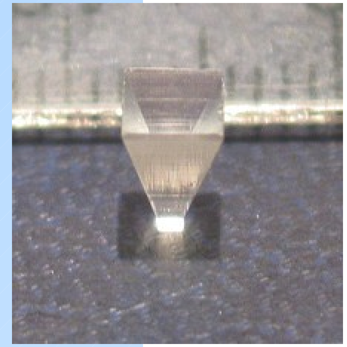


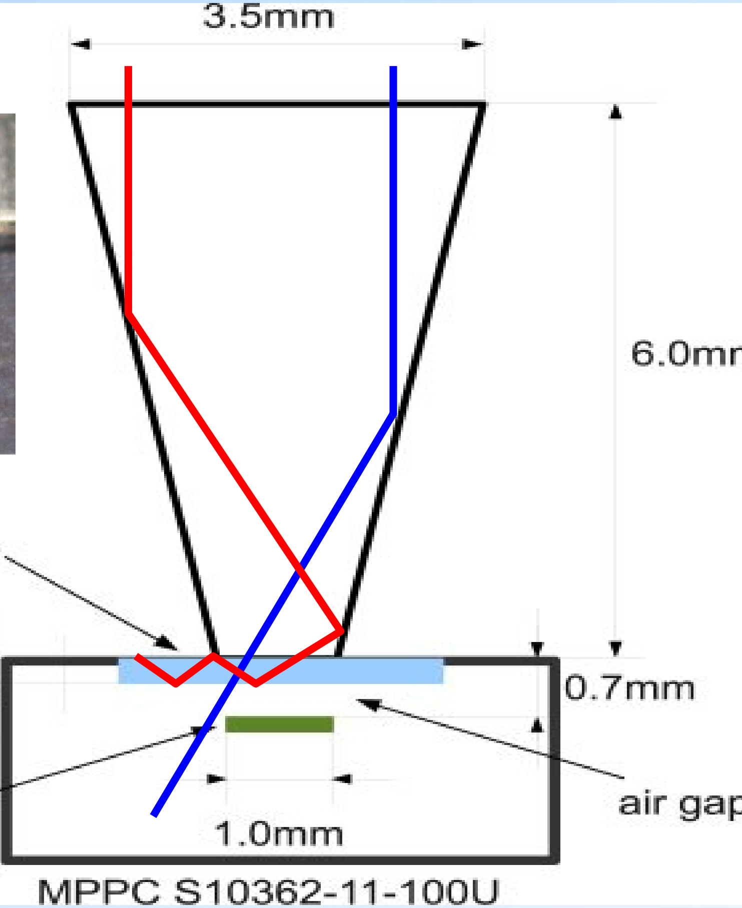
Need >20 photons per ring for a reliable PID.

Light guide 3.5x3.5mm² to 1x1mm²

First attempt to attach light guides to SiPMs.

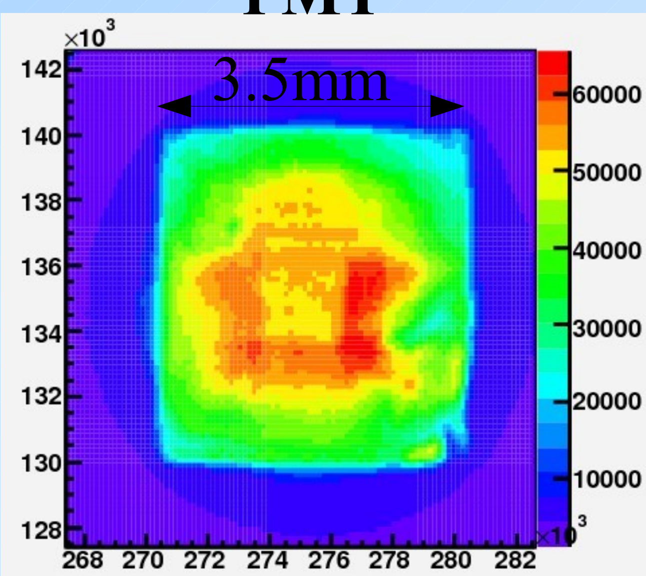
- area ratio ~ 12
- average efficiency ~ 0.5 (entrance to exit surface)



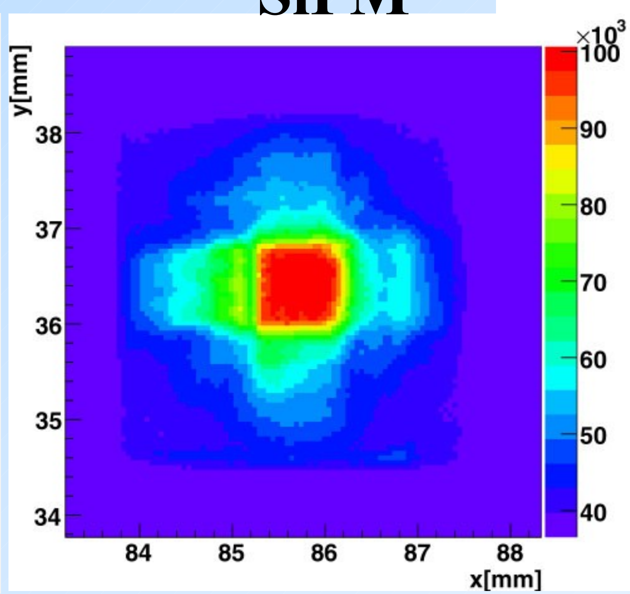


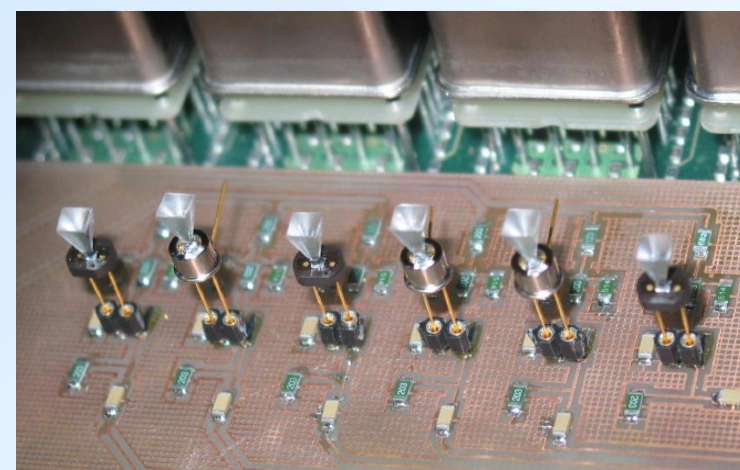
- light guide test with pencil beam (400nm, 90⁰)

PMT



SiPM

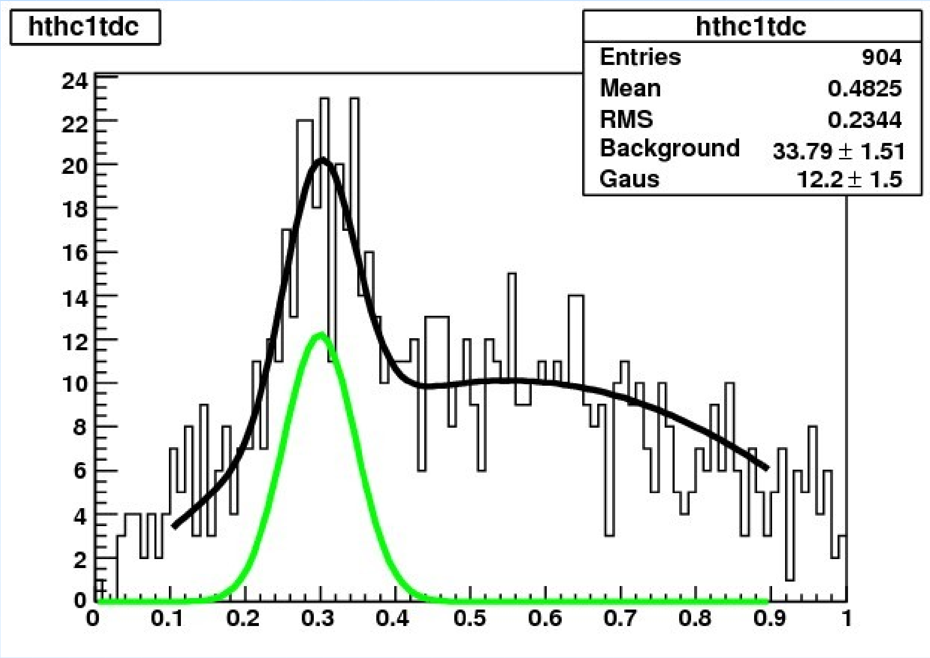




Cherenkov ph. with light guides

No light guides:

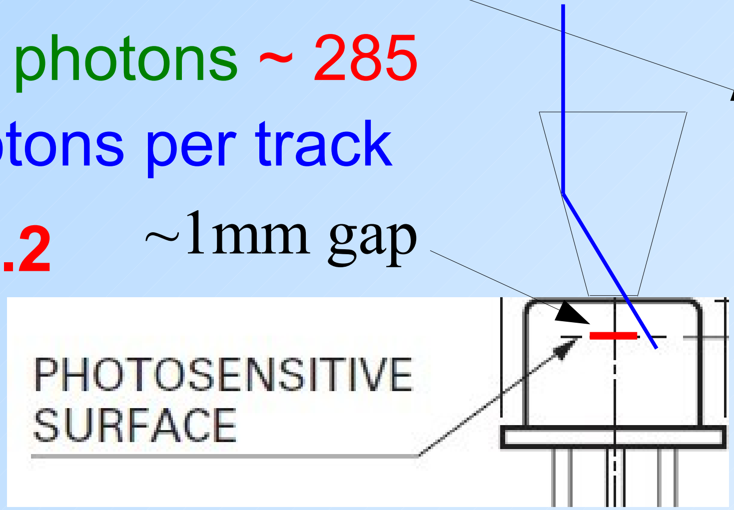
- 43600 tracks
- Cherenkov photons ~ 146
- 0.0033 photons per track

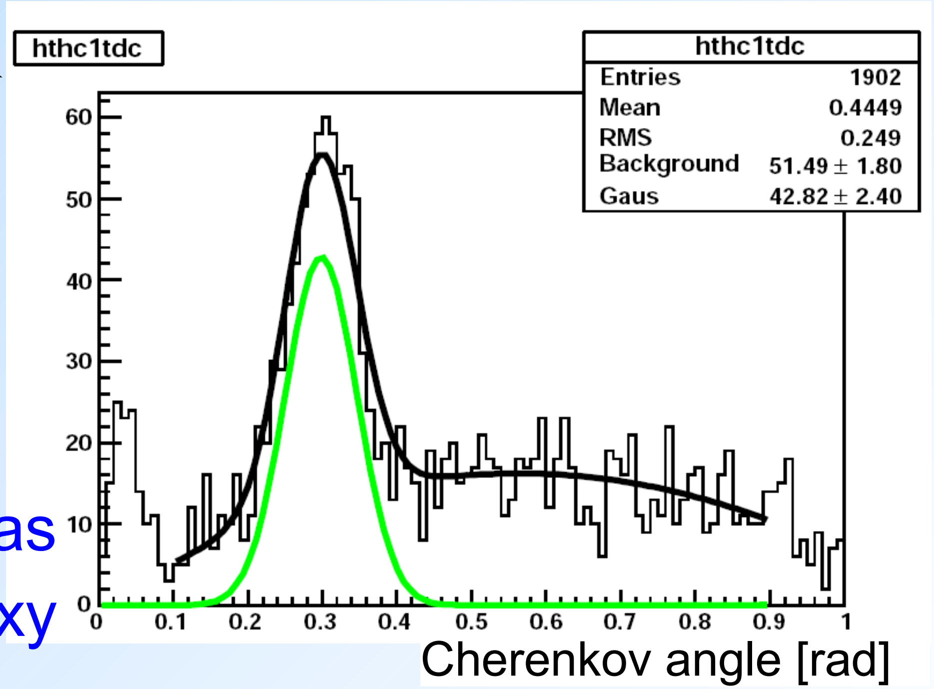


With light guides:

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

$N_{w/} / N_{w/o} \sim 2.2$



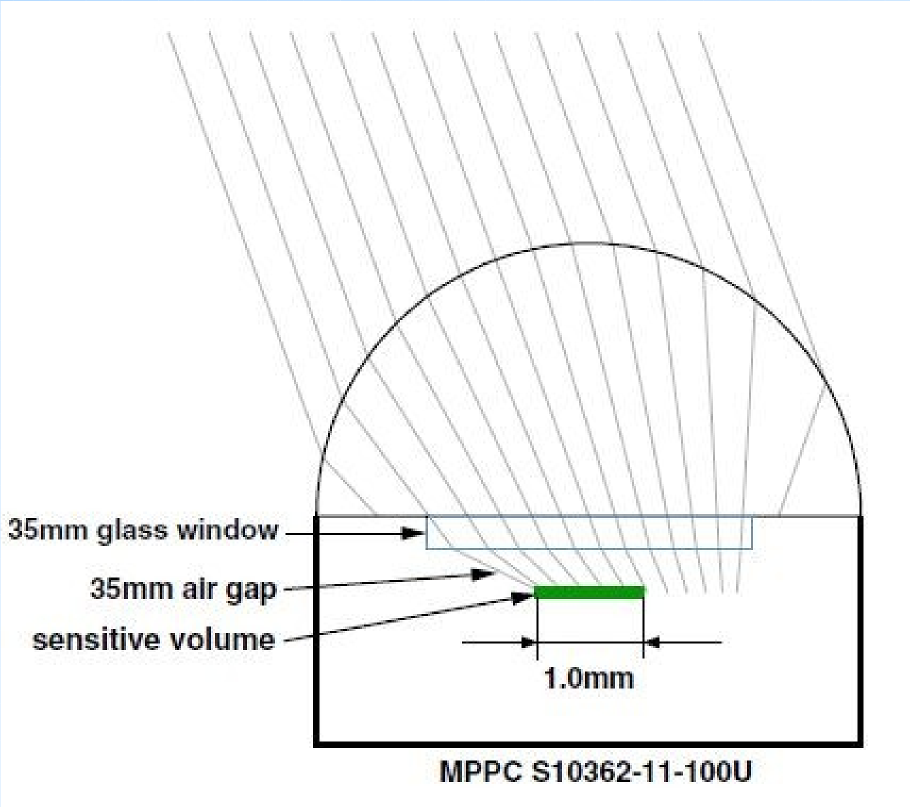


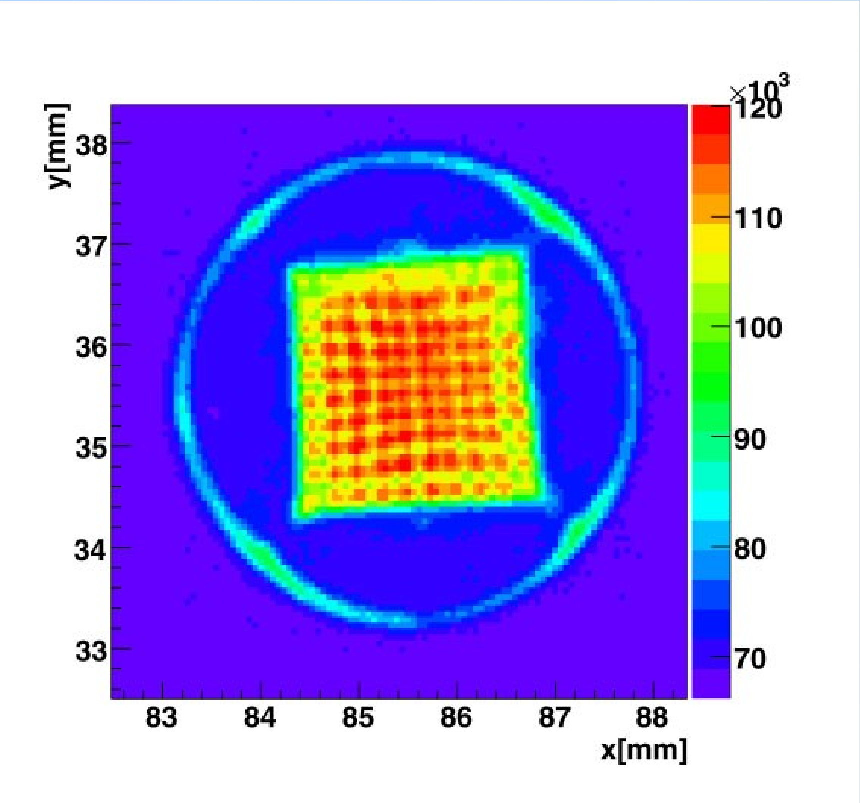
Light guide should be as close as possible to the SiPM surface (now: epoxy layer)

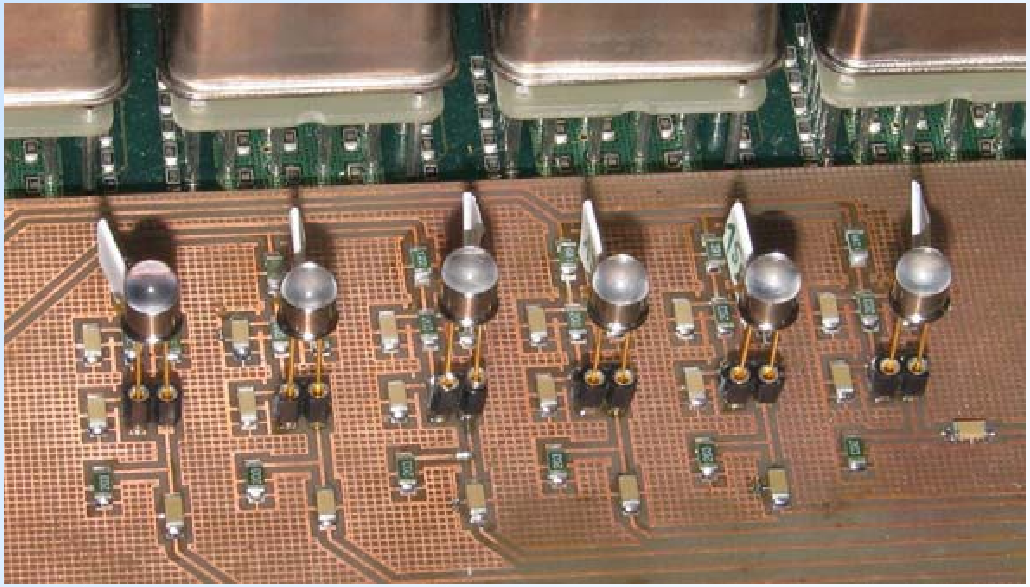
Cherenkov ph. with light guides

- Spherical light guides give better results with metal package:

$N_{w/} / N_{w/o} \sim 3.6$

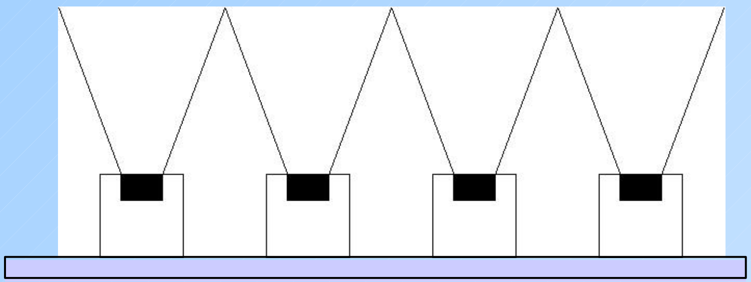


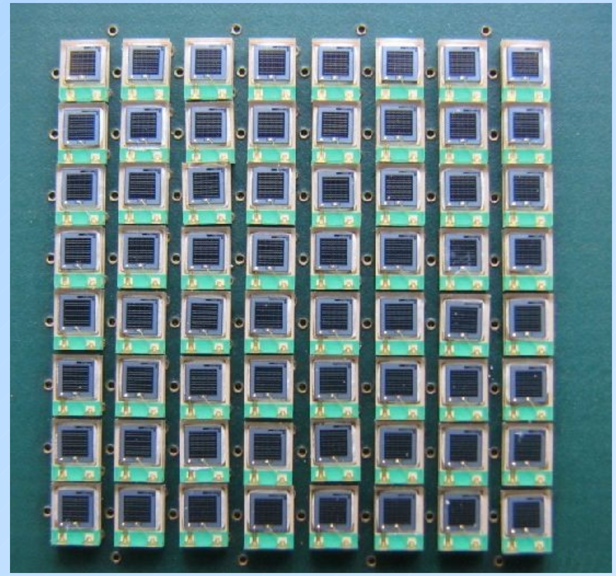


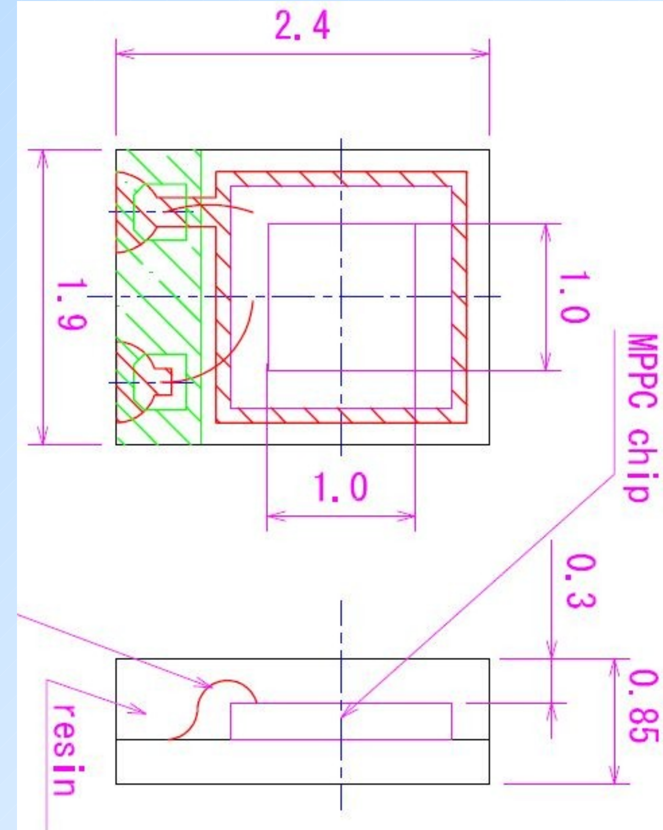


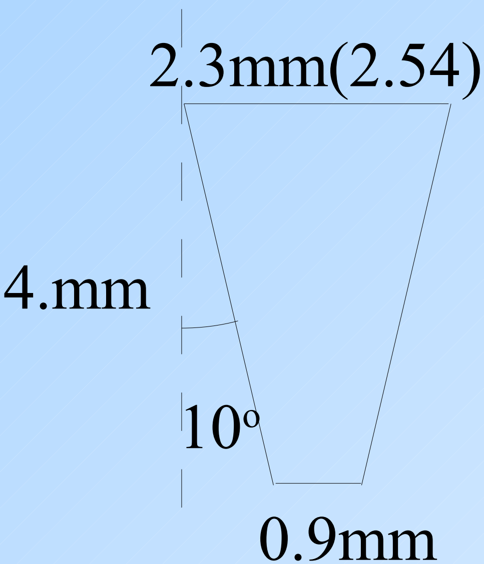
8x8 array of SMD-MPPCs

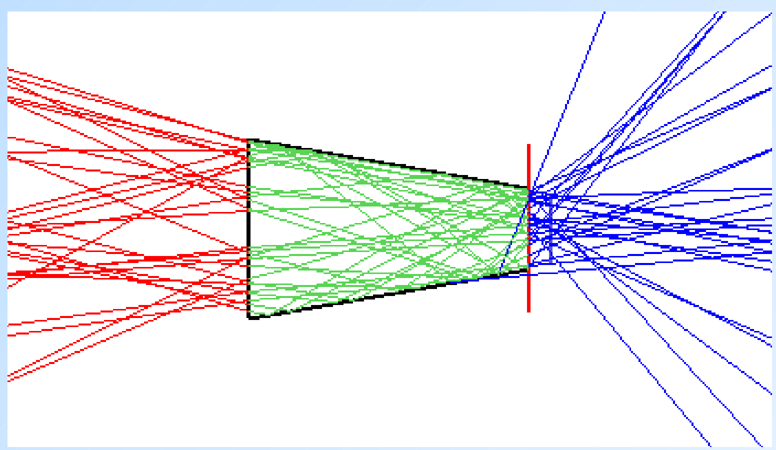
- Detector module with 8x8 array of SMD MPPCs at 2.54 mm pitch

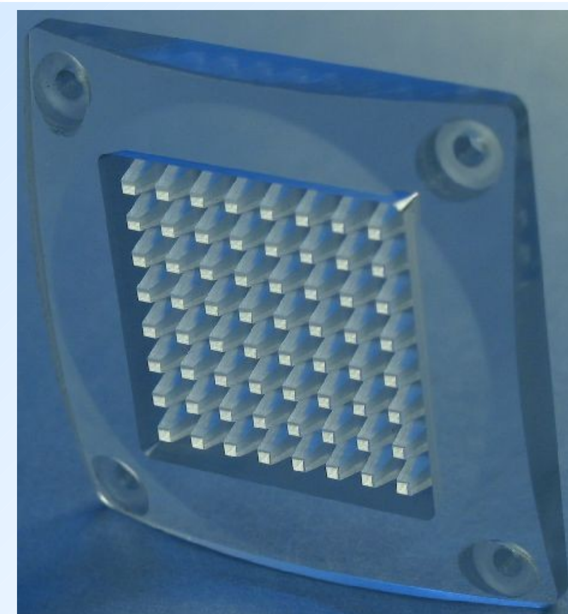








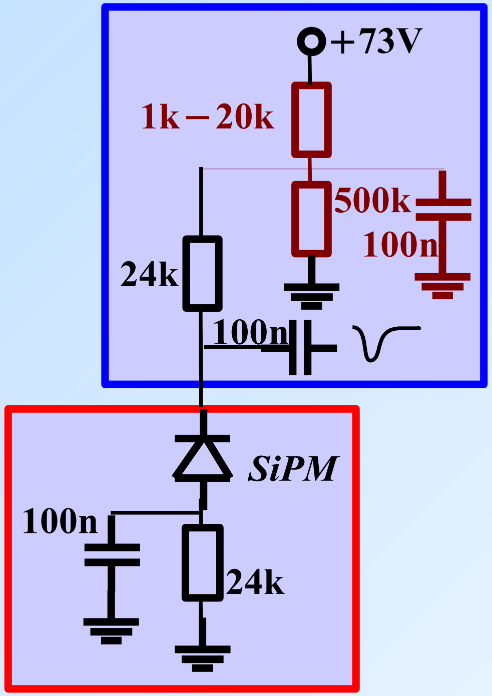


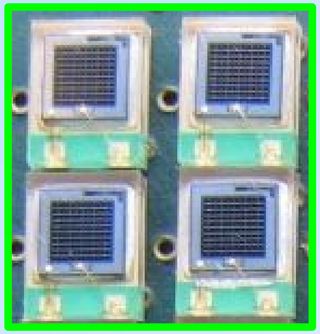


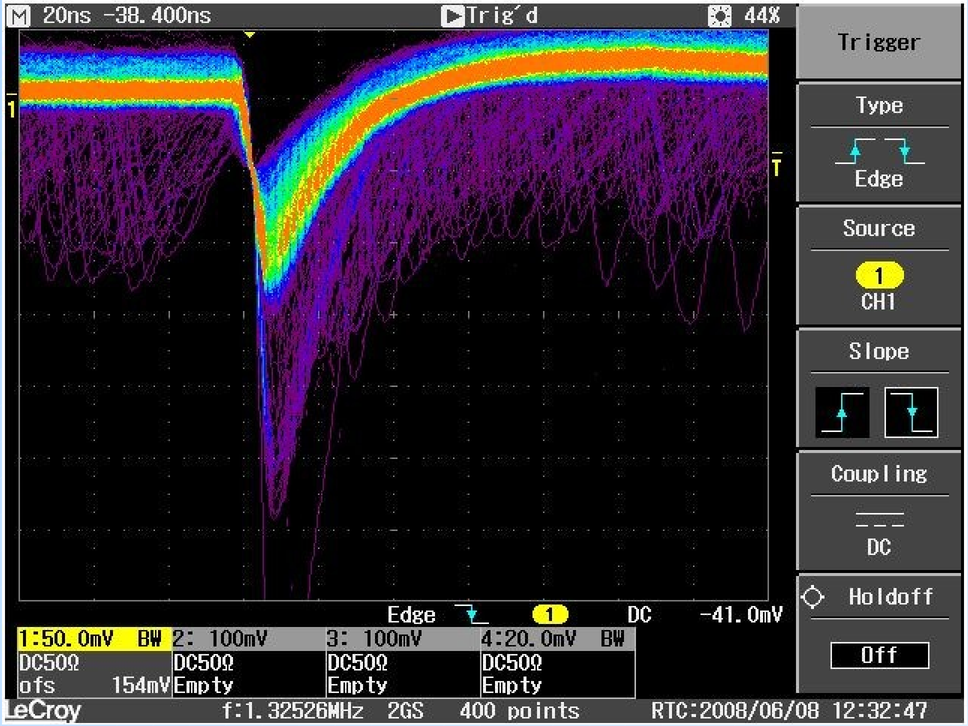
Light guides were machined from plastic (HERA-B lens material).

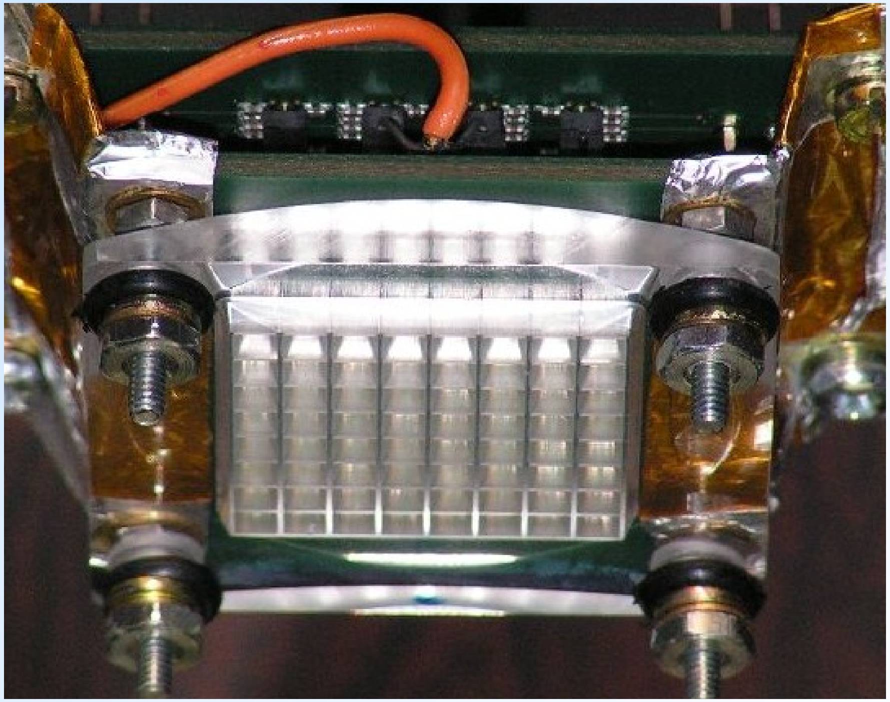
MPPC module

- 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









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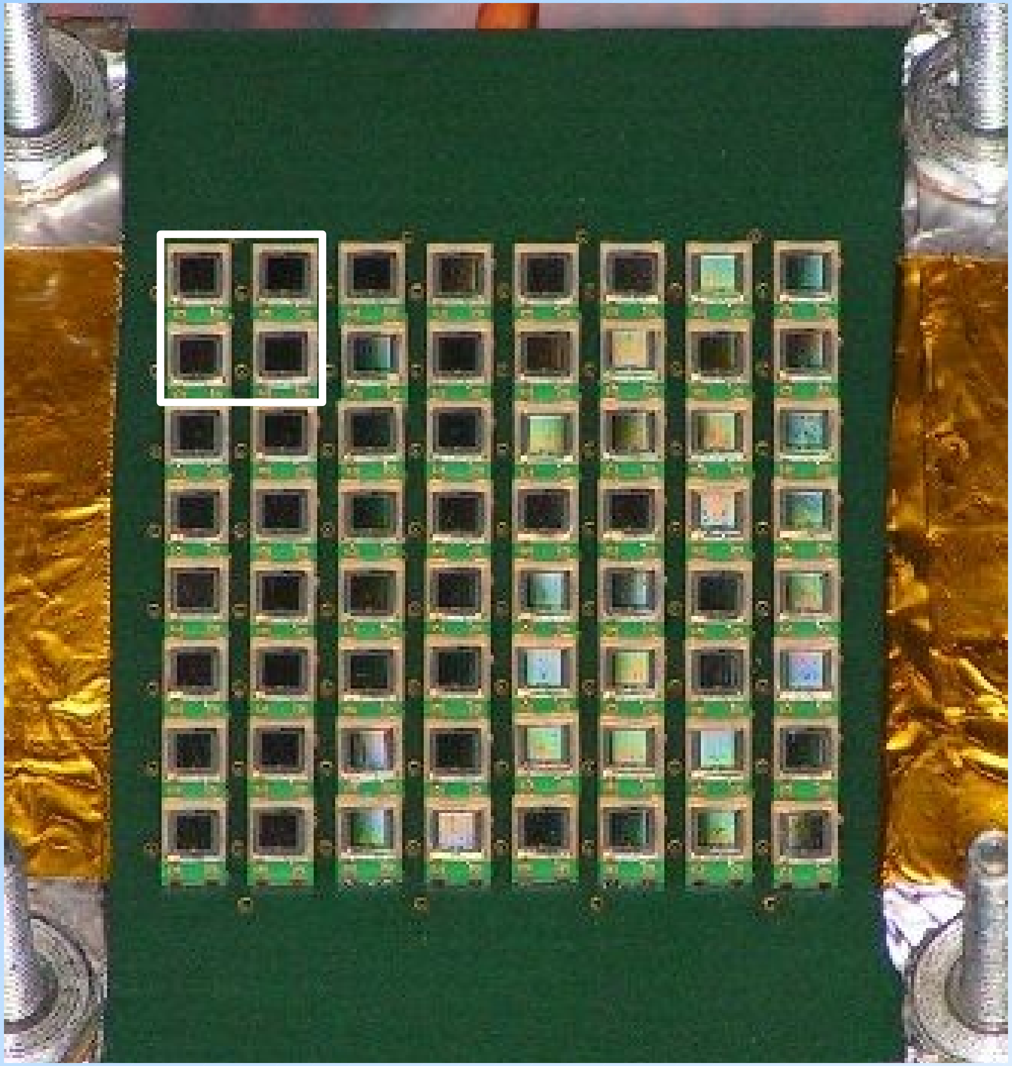
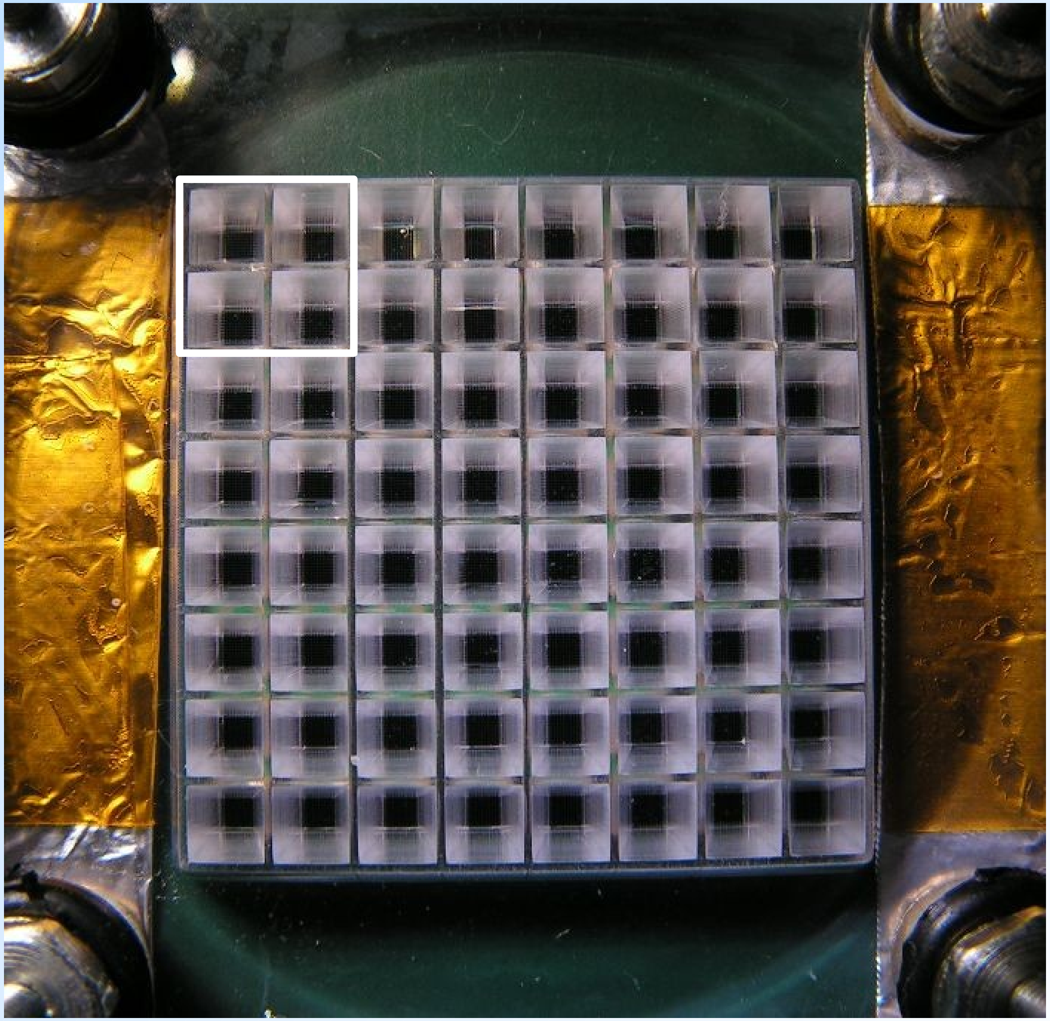
MPPC module 2

- pad size 5.08 mm, 4 mm2 active (15.5% w/o LG)





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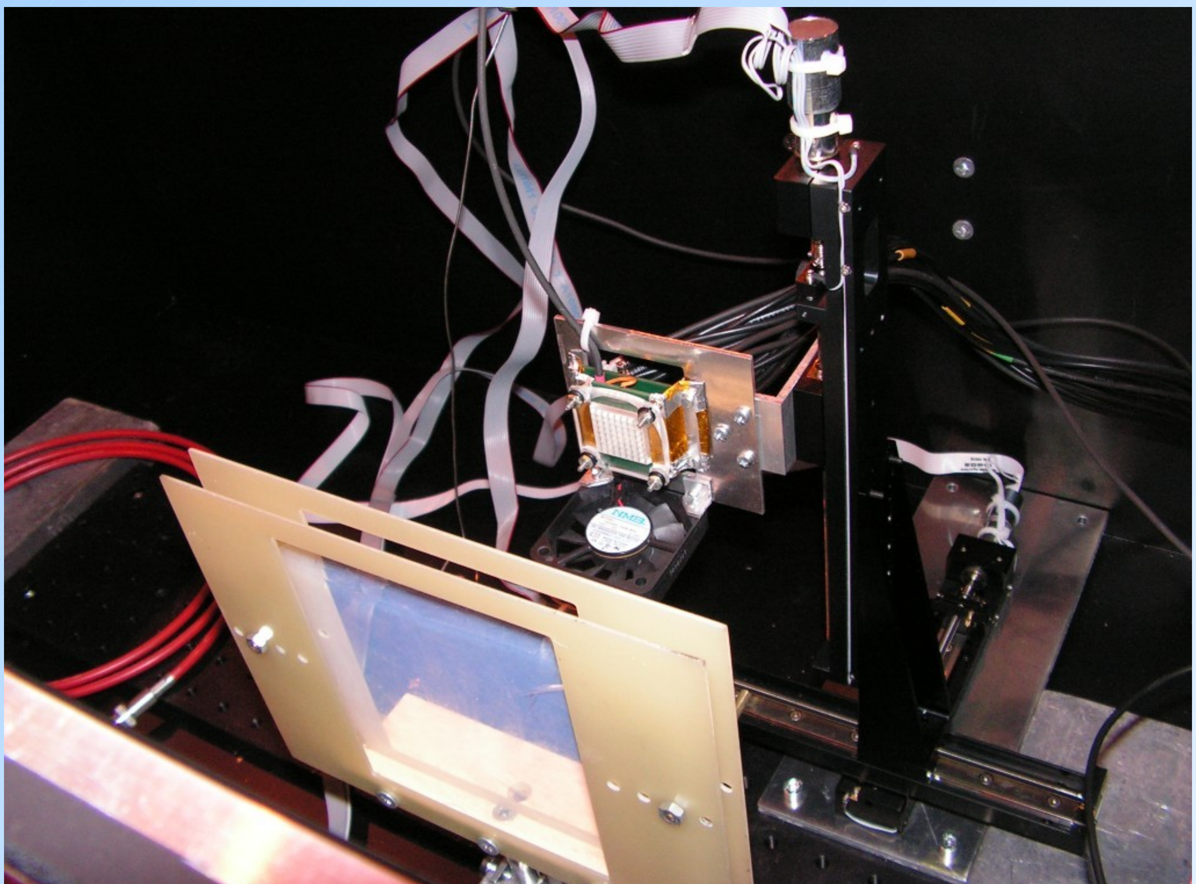
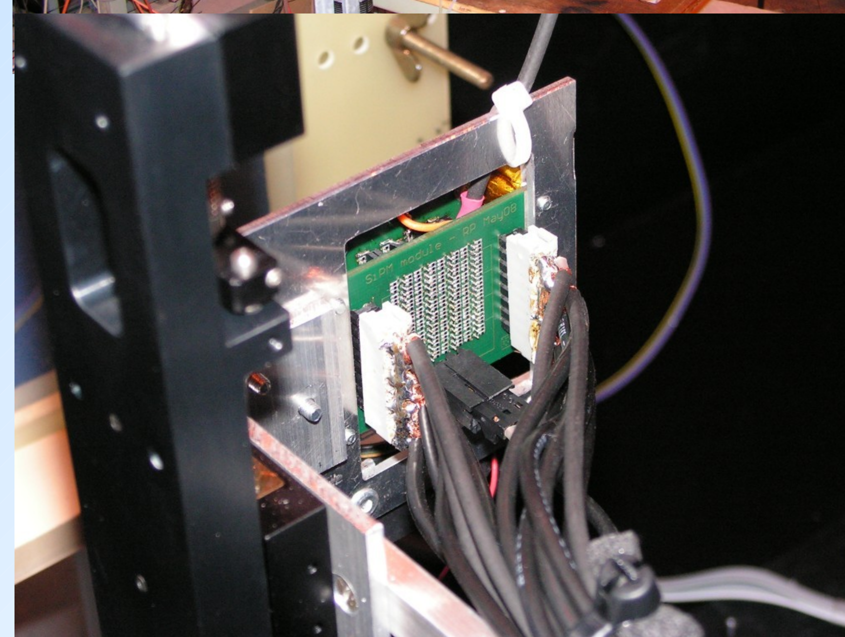
Beam test setup

- 2 MWPCs for tracking and scintillator for timing
- MPPC array w/o or w/ light guide mounted on 3D stage
- aerogel n=1.03, d=10mm (distance 130mm)
- hits detected by multi-hit TDC
- +120 GeV/c pions, beam size ~1cm^2

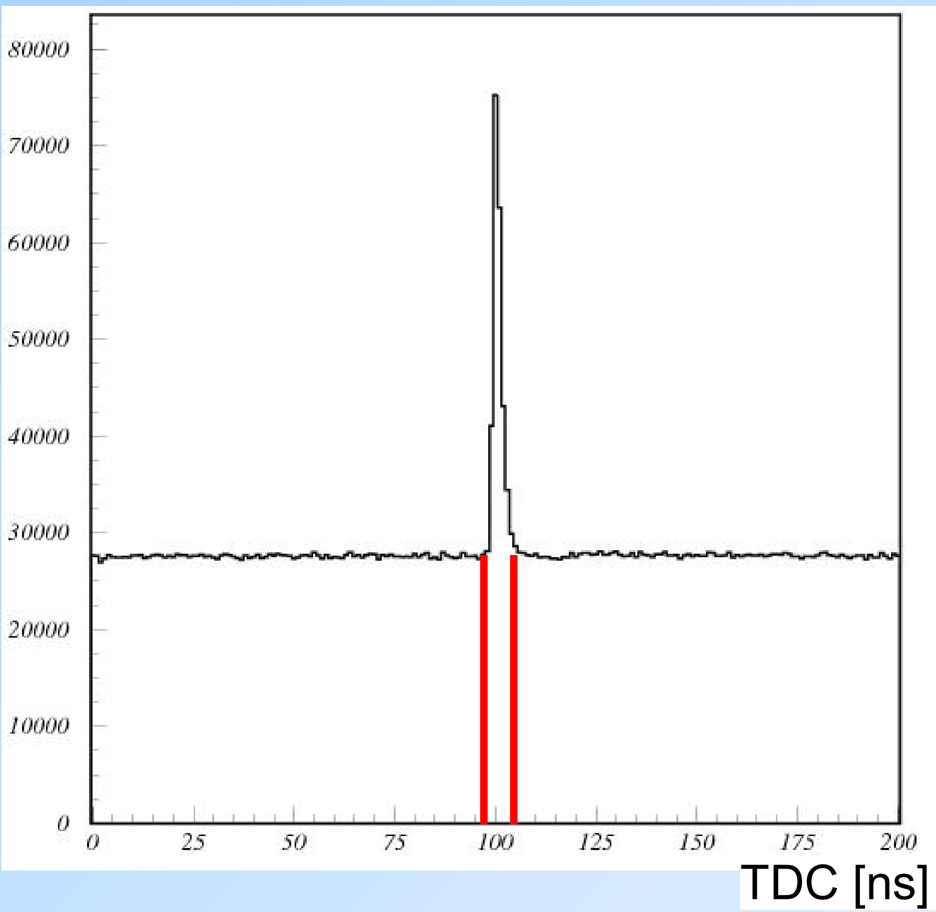




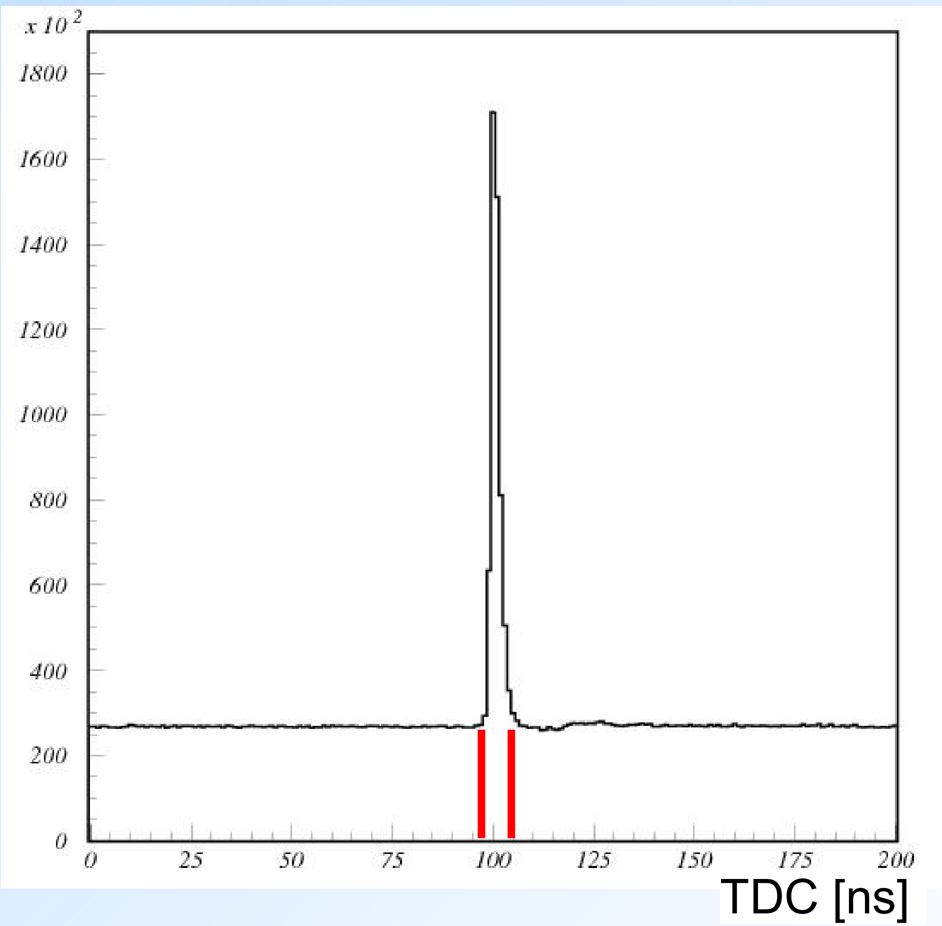
TDC distributions of MPPC hits for all events

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

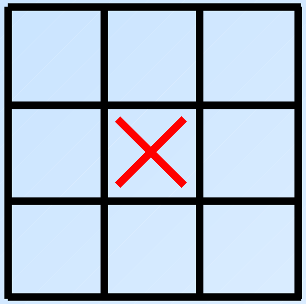
w/o light guides



w/ light guides

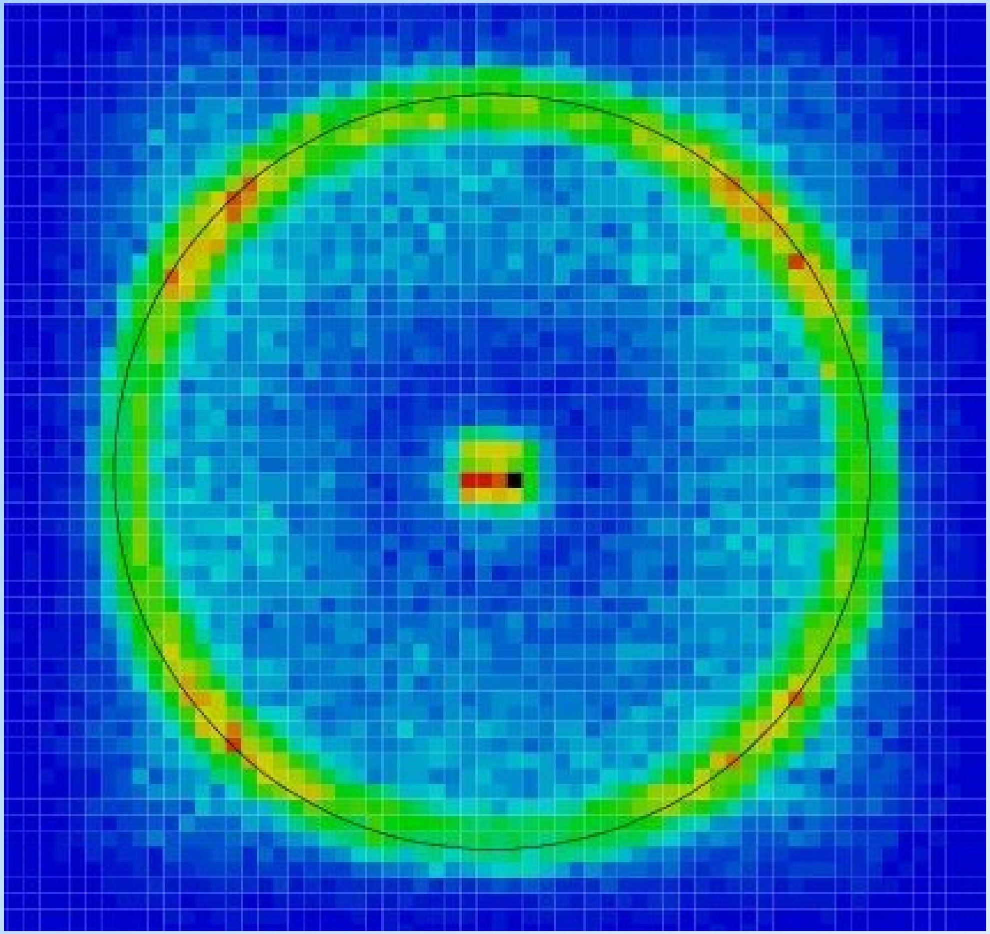


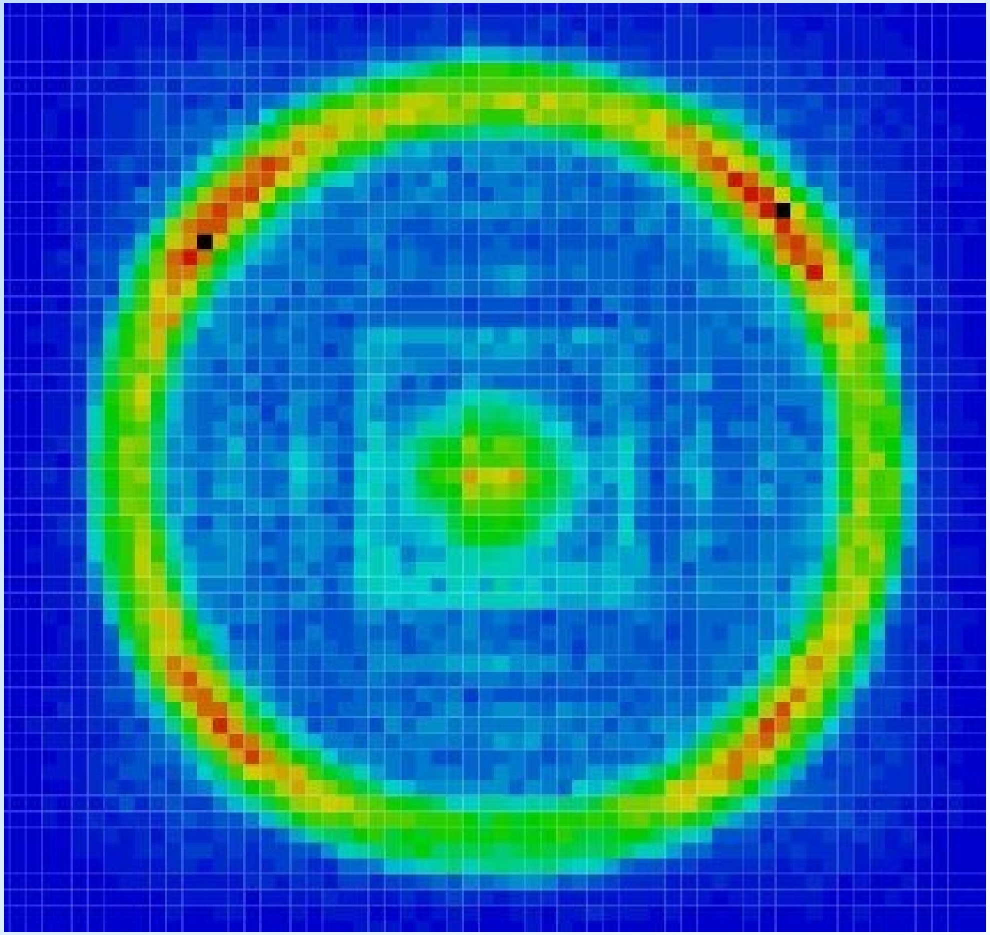
Ring images



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

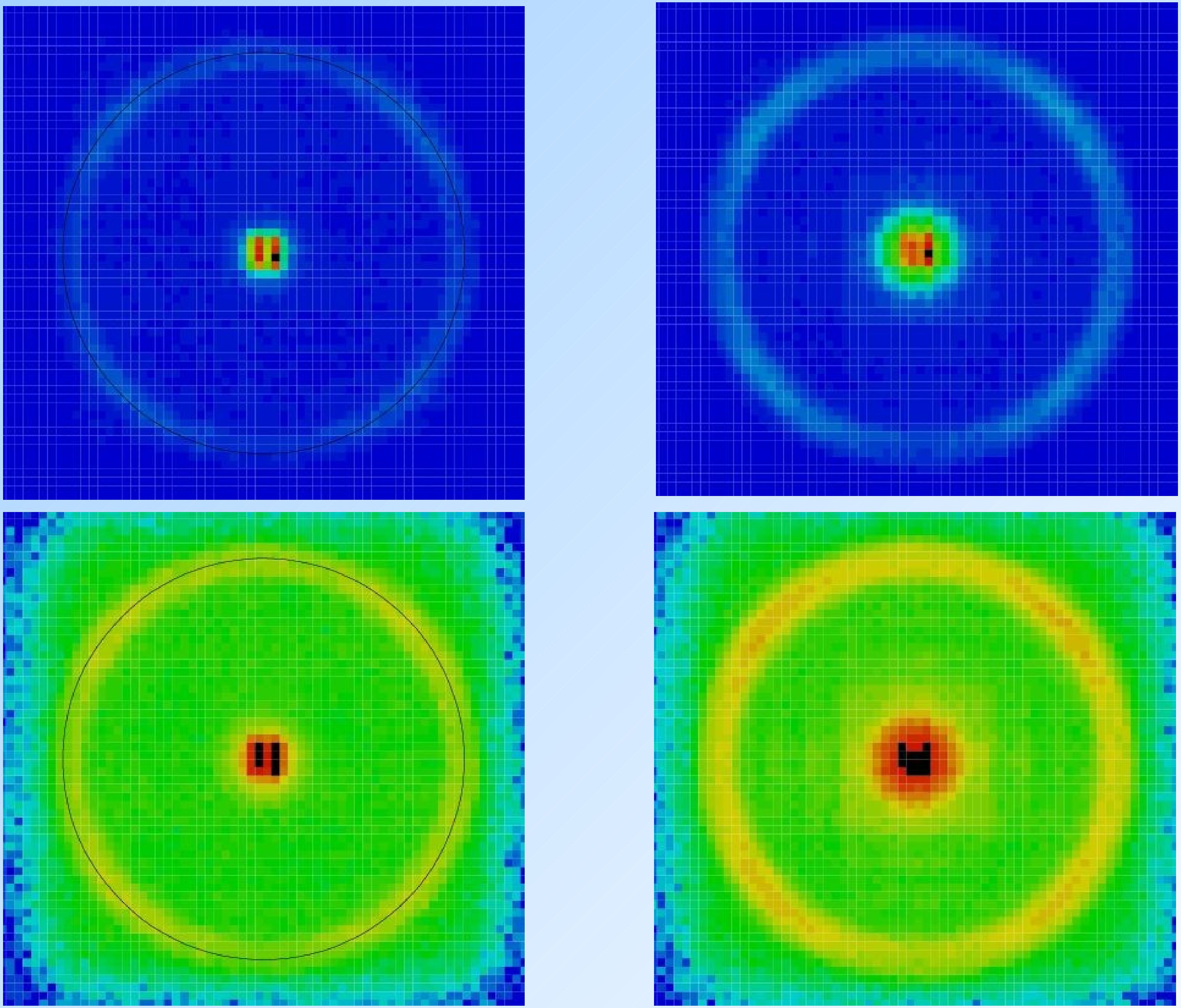
w/o light guides | **w/ light guides**





Ring images

w/o light guides | **w/ light guides**



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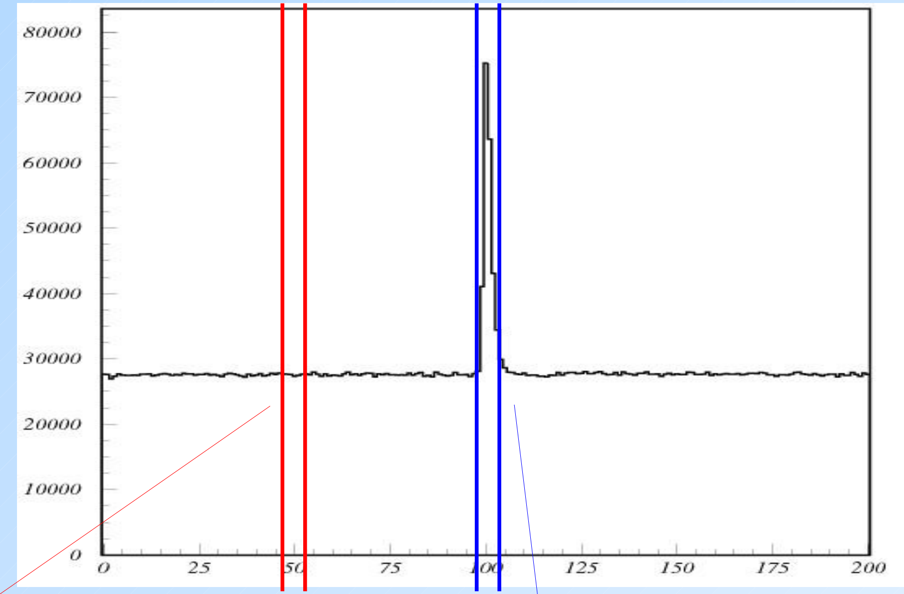
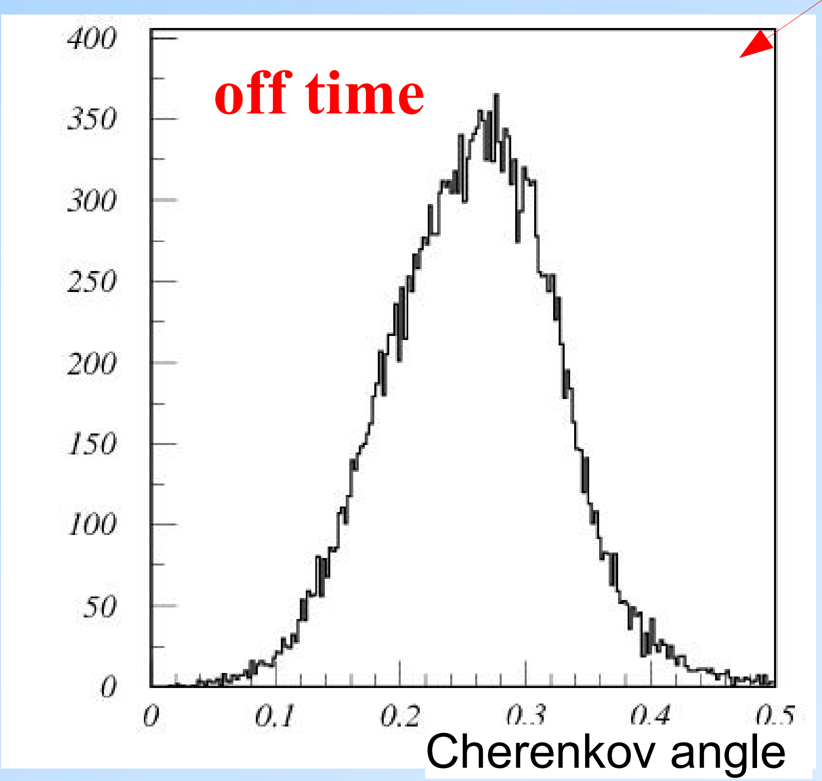
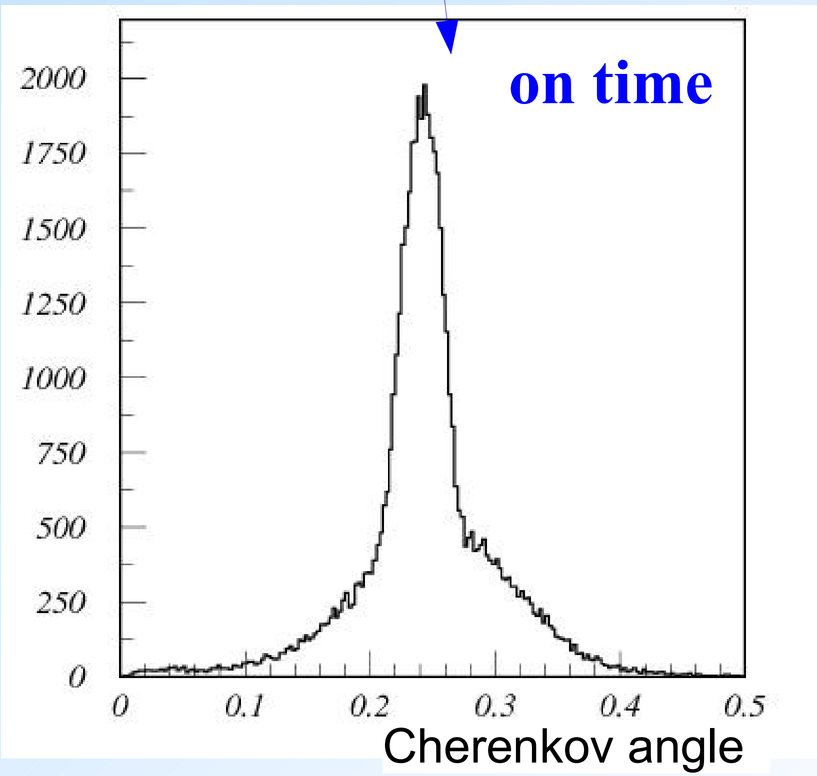
Cherenkov angle distributions

- background from SiPM noise hits is obtained from sideband in TDC distribution



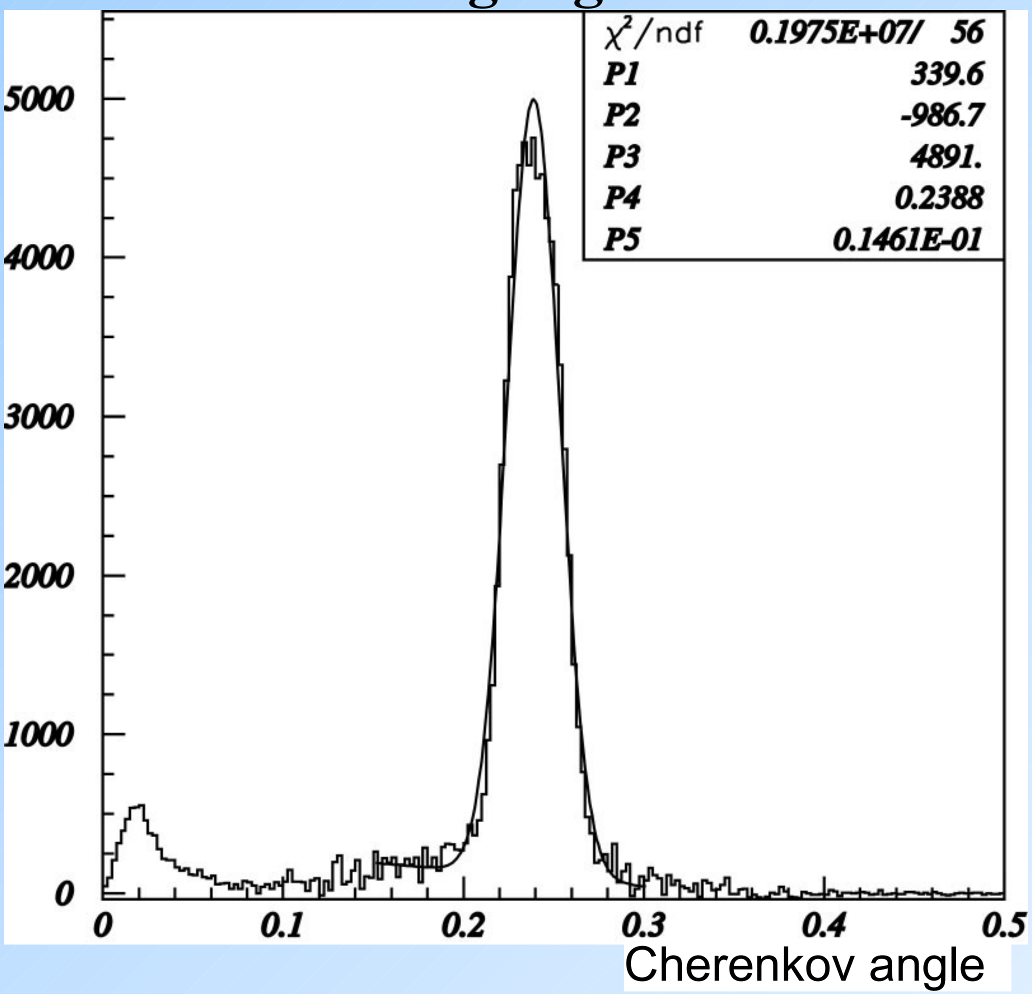




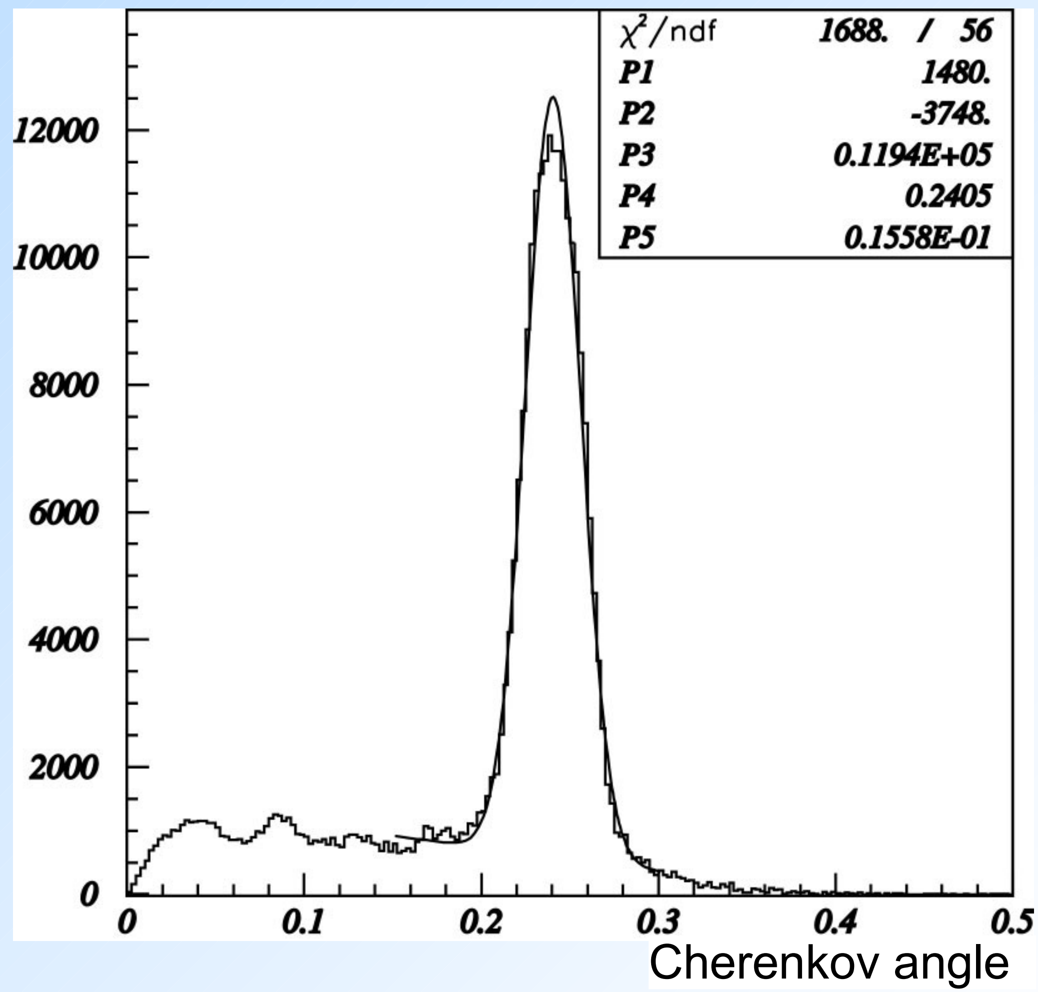
Cherenkov angle distributions

- 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



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

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**

Summary

• A photon detector module was constructed using 8x8 array of MPPCs (SMD package) and a light guide array

• A proximity focusing RICH with 1cm aerogel radiator (n=1.03) and the detector module was successfully tested in a test beam at CERN

• The number of detected photons per ring is about half of the expected number obtained using manufacturers PDE

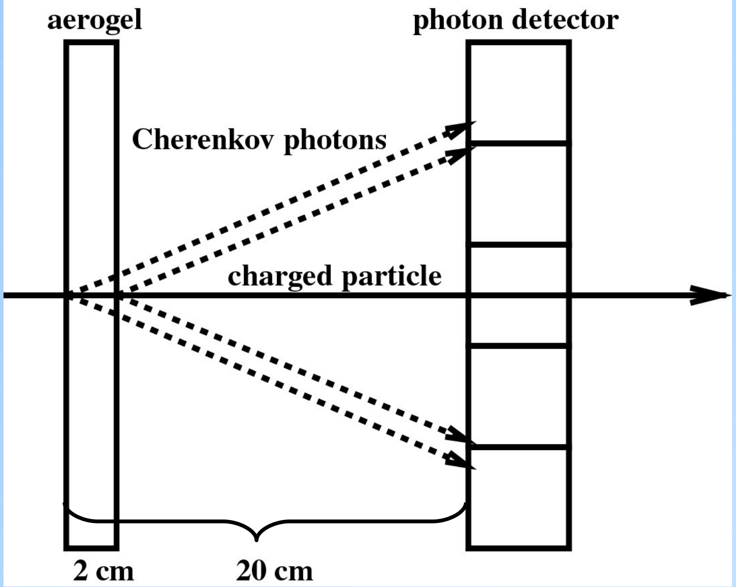
• Efficiency increase with light guides ~ 2.3 (area ratio ~5.5)

• **Silicon photomultiplier can be used as a detector of single photons in RICH counters.**

BACKUP SLIDES

RICH for Super Belle forward PID

Selected type: proximity focusing aerogel RICH

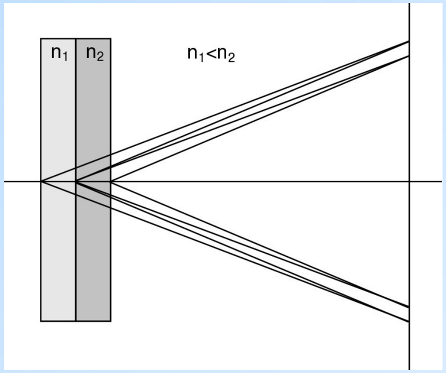


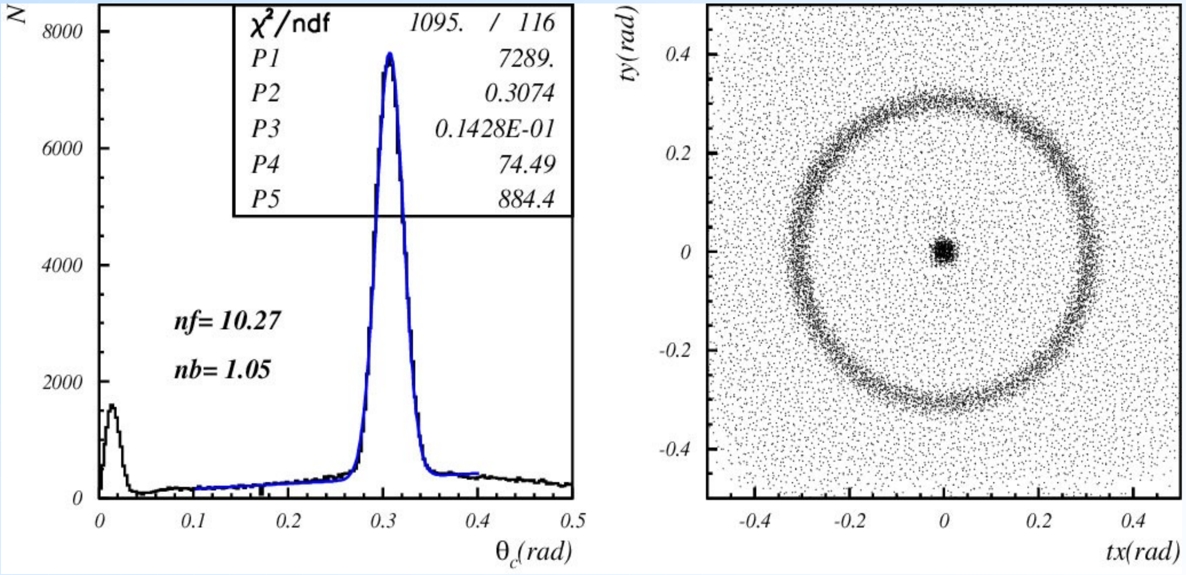
- n ~ 1.05 ($\vartheta_c(\pi)$ = 308 mrad and $\Delta\vartheta_c(\pi,K)$ = 23 mrad @ 4 GeV/c)
- limited space - distance from aerogel entrance window to photon detector ~ 200 mm
- operation in magnetic field 1.5 T
- photon detector candidates: HAPD, MCP-PMT, **SiPM**

Tests with 4x4 array of flat panel PMTs and 2cm+2cm focusing aerogel radiator:

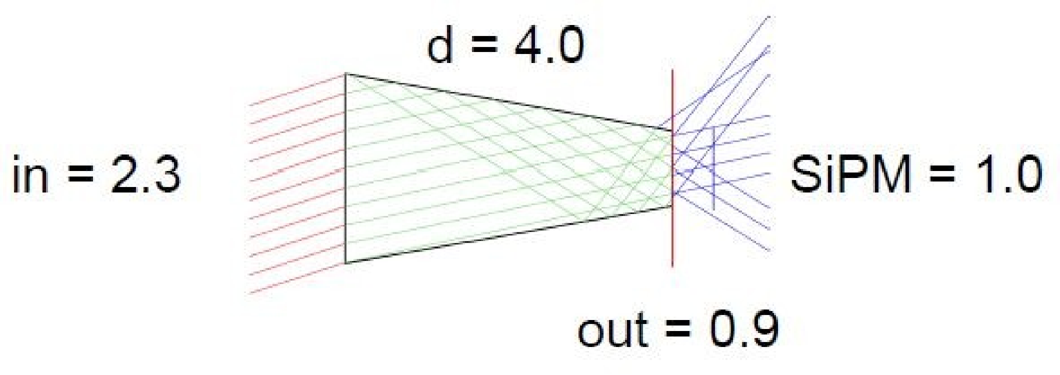
- $N_{ph.}$ ~ 10
- σ_{single}= 14 mrad
- σ_{track}= 4.6 mrad

5σ at 4GeV/c





Light guide simulation

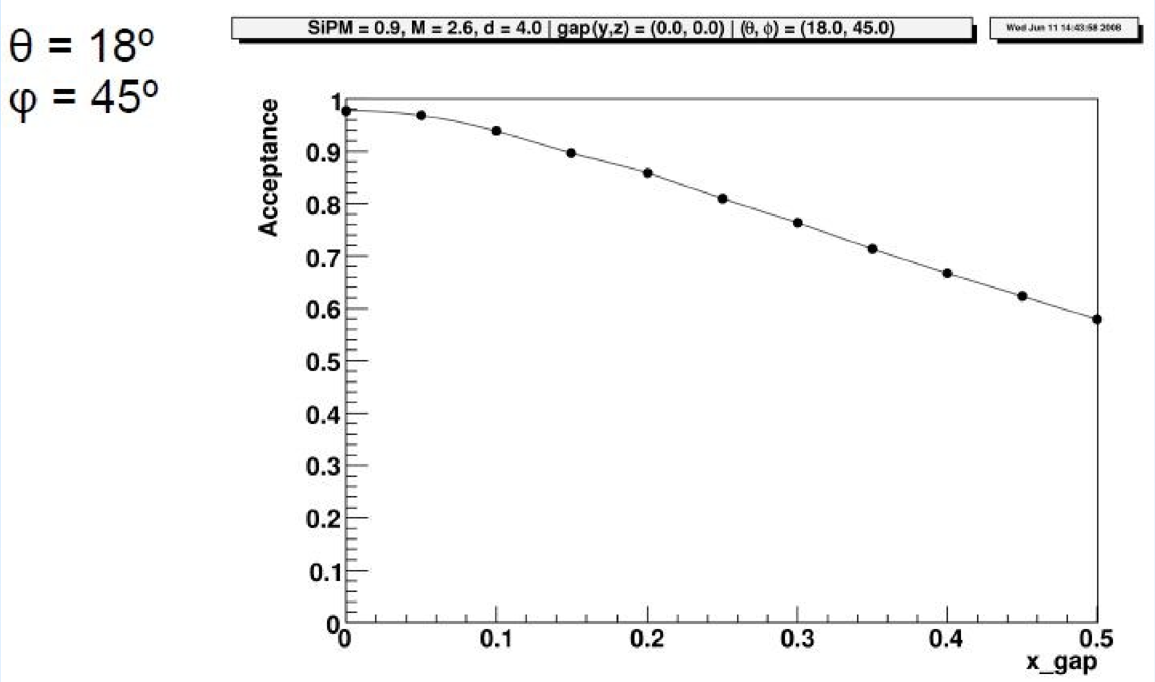


Simulation includes:

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

Not included:

- absorption
- imperfect surface



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

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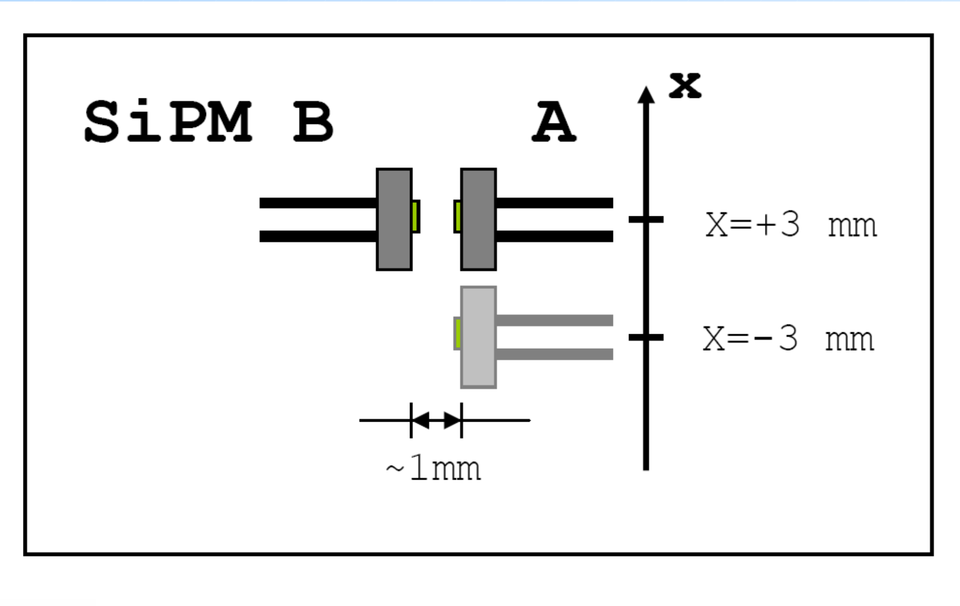
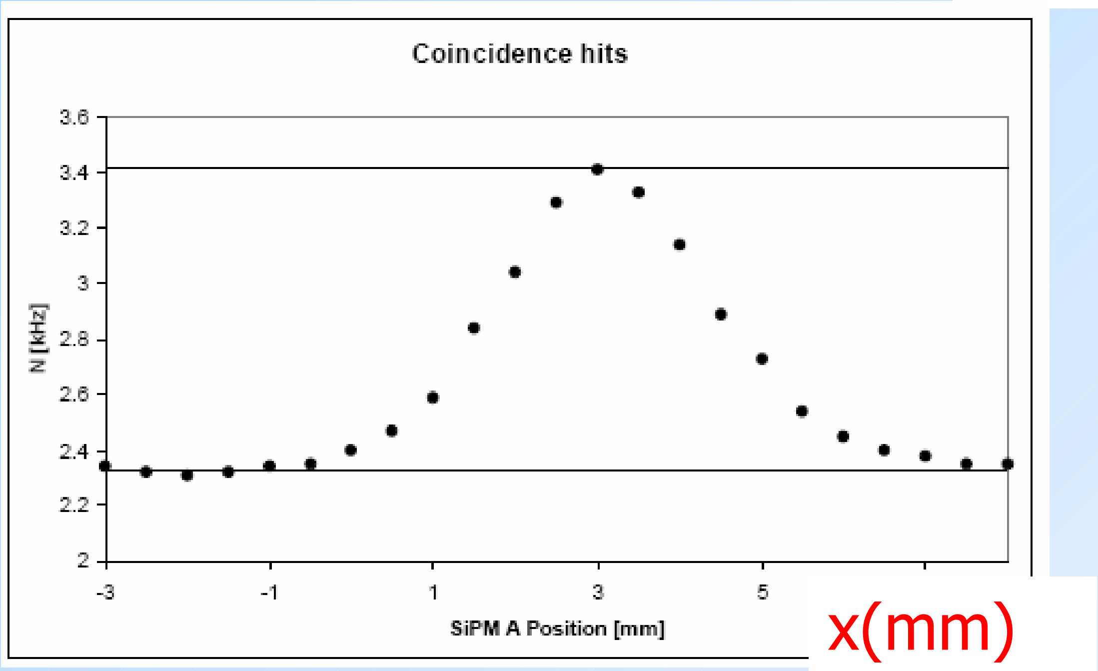
External secondary photon cross talk

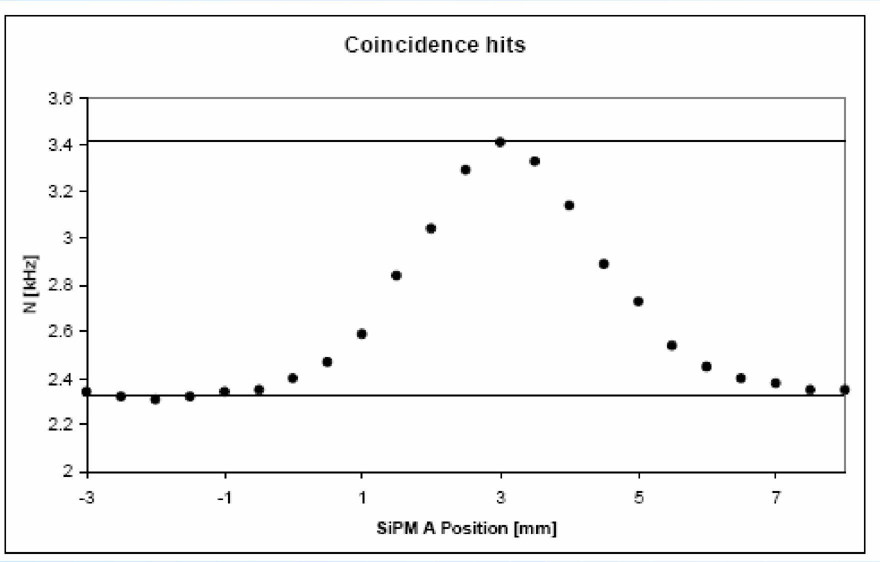
Scan a SiPM in front of a second one, observe coincidence rate





SiPM A and B: Hamamatsu MPPCs

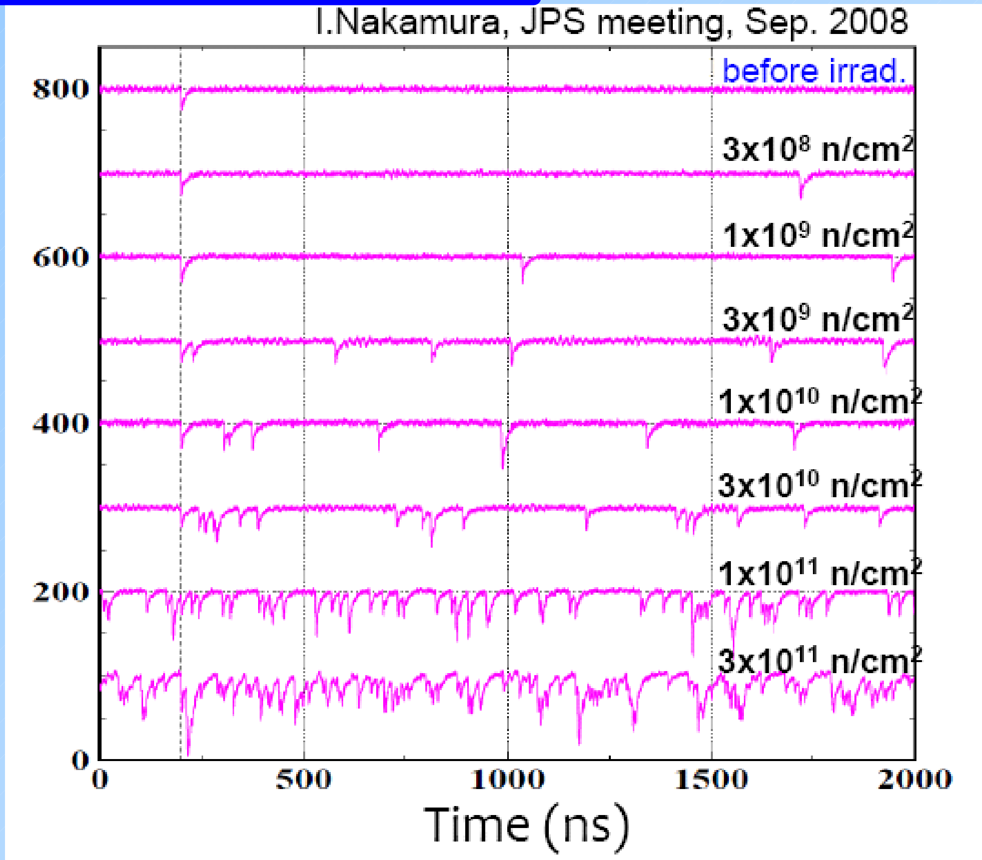
External secondary photon cross talk



- 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 2 π 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)

Neutron damage



Measured fluence:

90/fb → 1-10 10^9 n cm^{-2}

Expected fluence at 50/ab

→ if bckg x20: 2-20 10^{11} n cm^{-2}

→ Worst than the lowest line

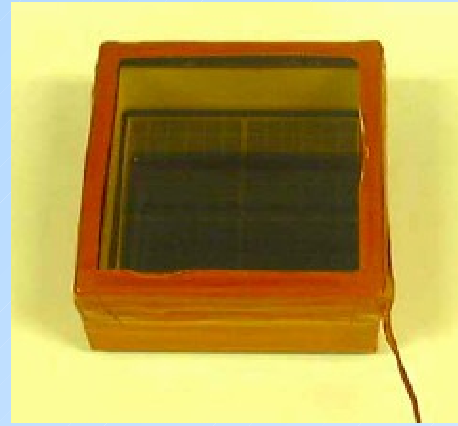
The monitoring diodes were not at the right place (mounted behind ECL instead of in front of it). However, n flux is probably quite similar – check with new data.

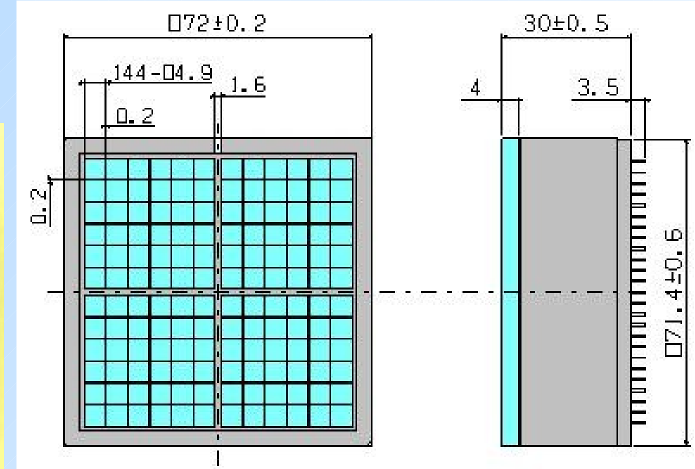
→Very hard to use present SiPMs as single photon detectors in Belle because of radiation damage by neutrons

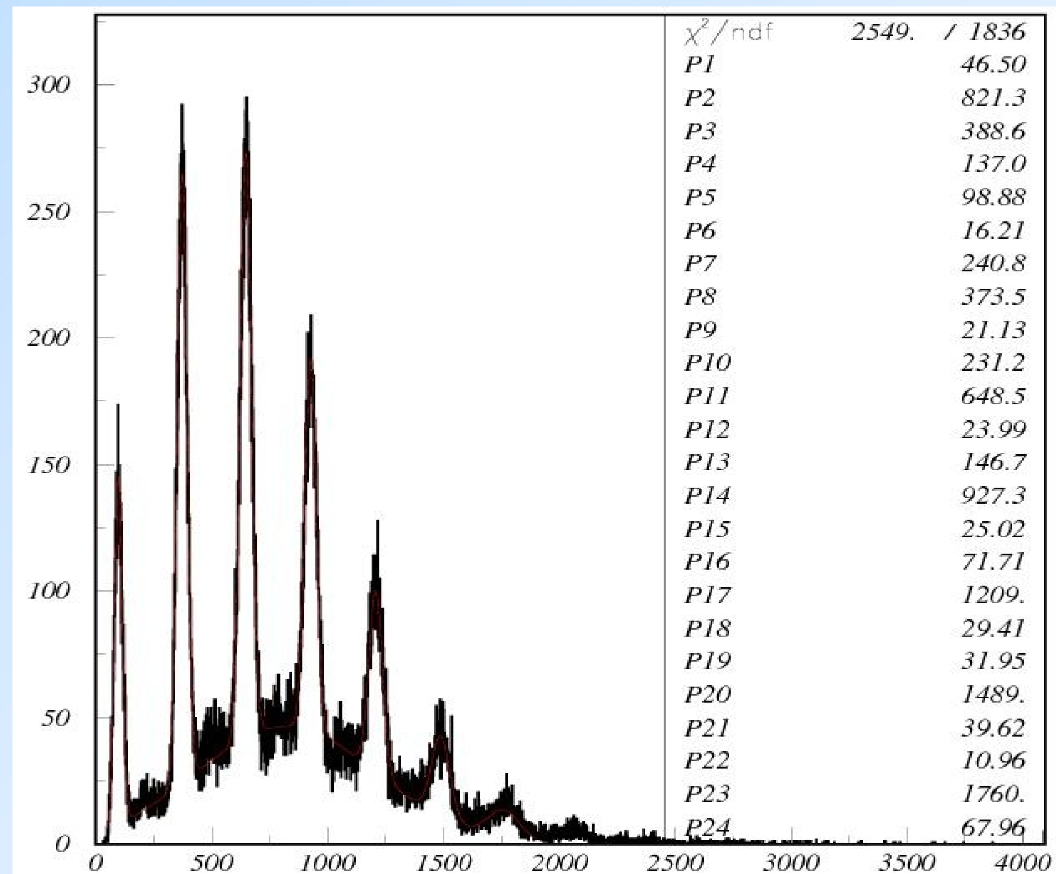
Photon detector candidate: HAPD

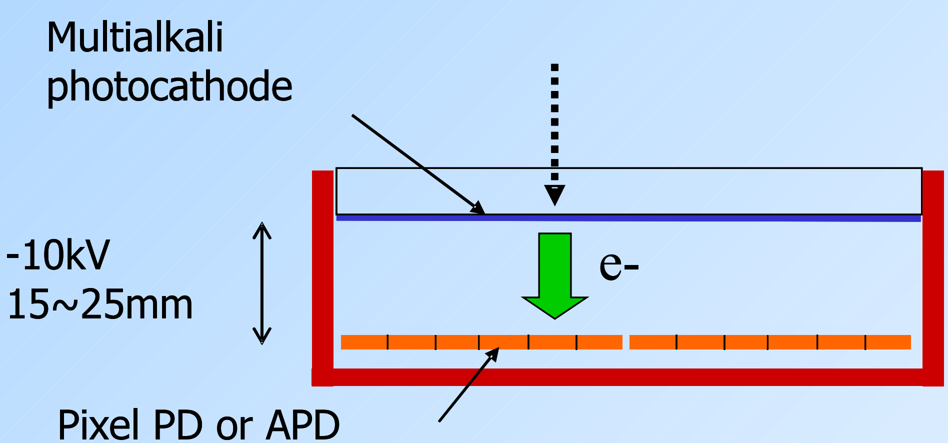
Hybrid avalanche photo diode - proximity focusing configuration:

- 12x12 channels (~5x5 mm^2)
- size ~ 74mm x 74mm
- ~ 65% effective area
- total gain ~ 10^4 - 10^5
- detector capacity ~ 80pF
- peak QE ~ 25%
- works in mag. field perpendicular to the entrance window





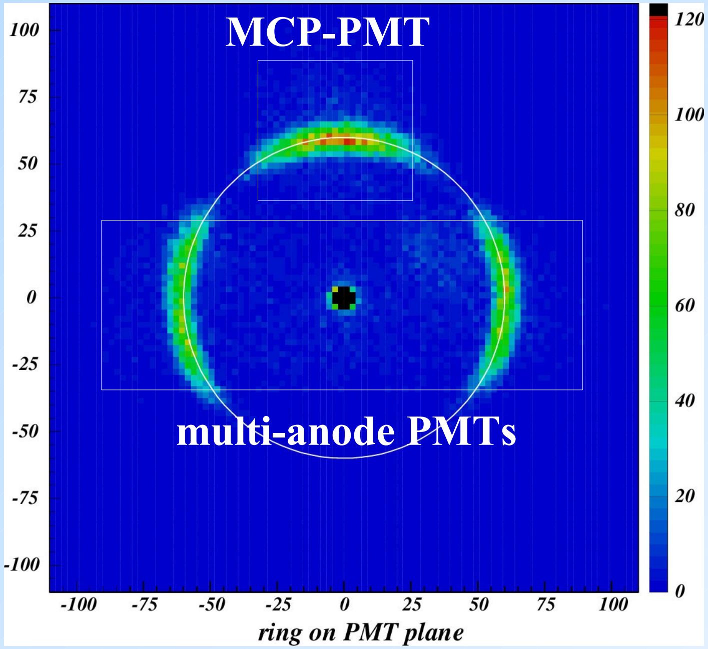


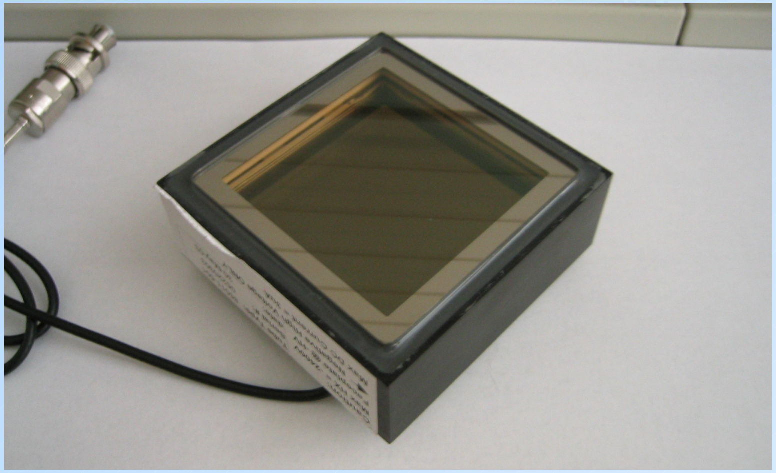


Photon detector candidate: MCP-PMT

BURLE 85011-501 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
- effective area ~ 52%
- excellent timing - ~50ps for single ph.





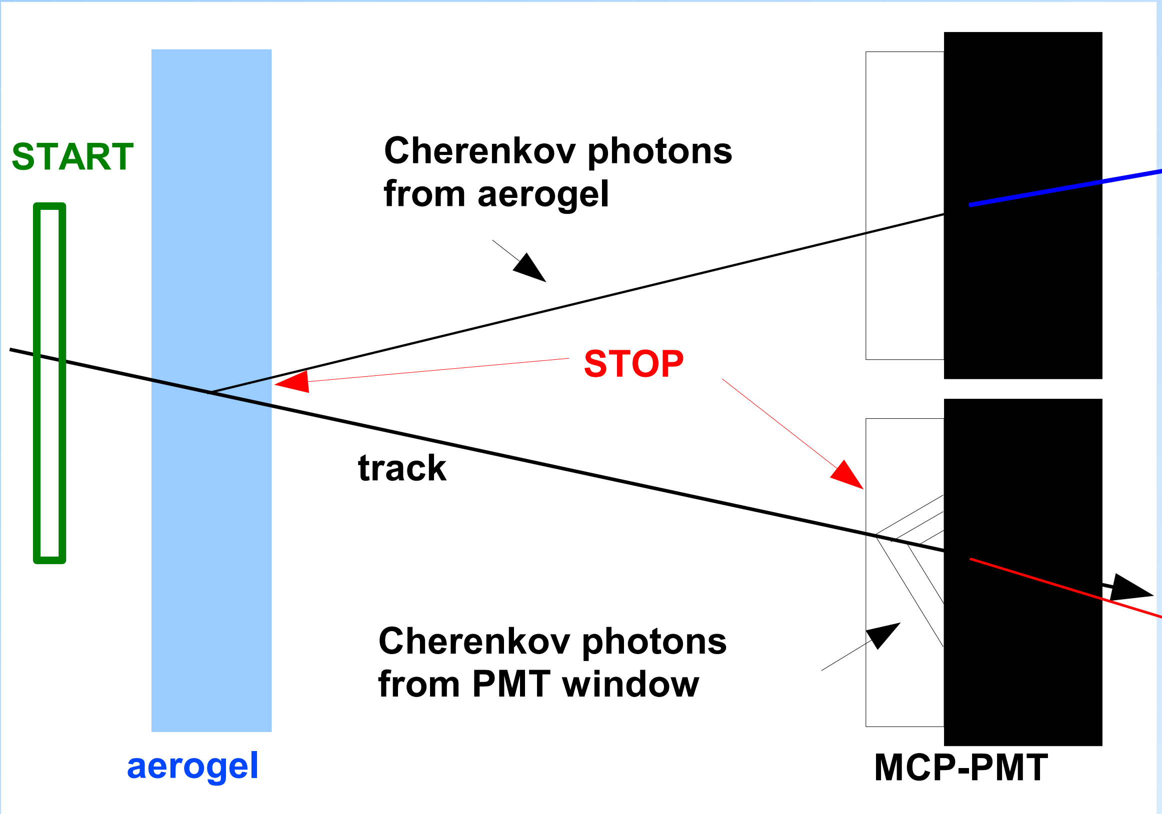
- Tested in combination with multi-anode PMTs

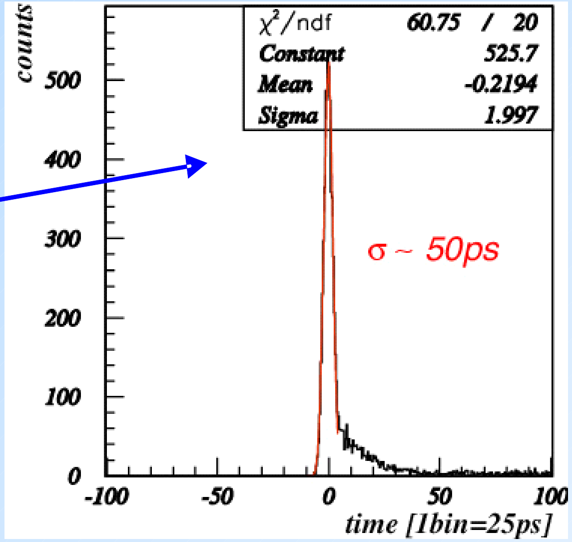
- σ_ϑ ~13 mrad (single cluster)
- number of clusters per track N ~ 4.5
- σ_ϑ ~ 6 mrad (per track)
- → ~ **4 σ π/K separation at 4 GeV/c**

- 10 μm pores required for 1.5T
- use new package with improved effective area
- aging study should be done

Additional feature: RICH+TOF

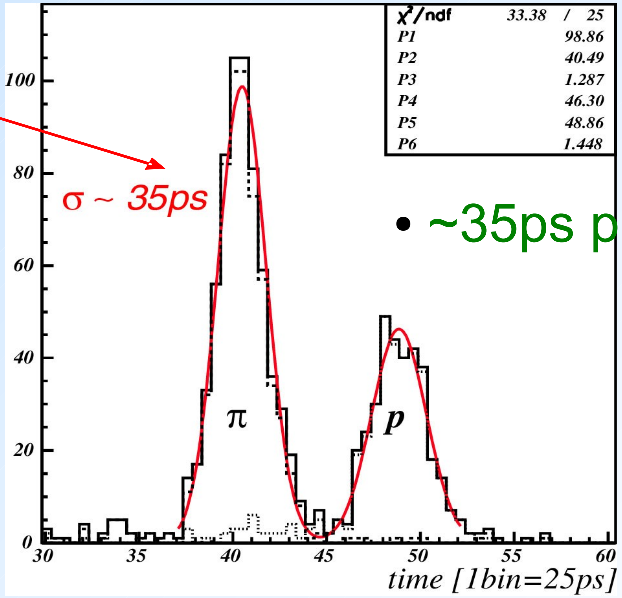
Make use of fast photon detectors: measure time-of-flight with Cherenkov photons from PMT window and aerogel





Beam test:

- 50ps per single photon (~20ps per track)

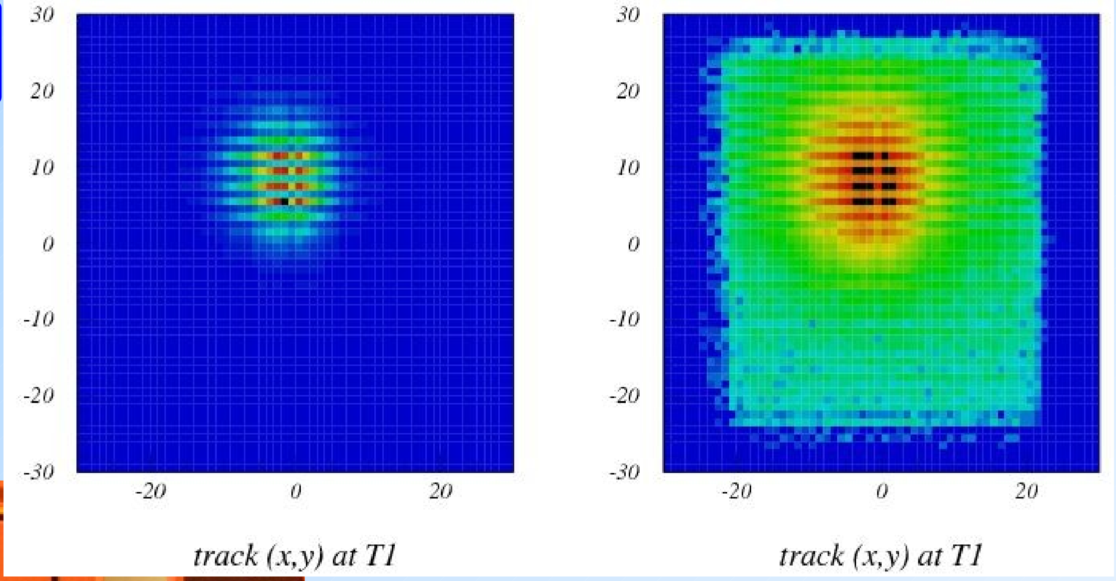


- ~35ps per track

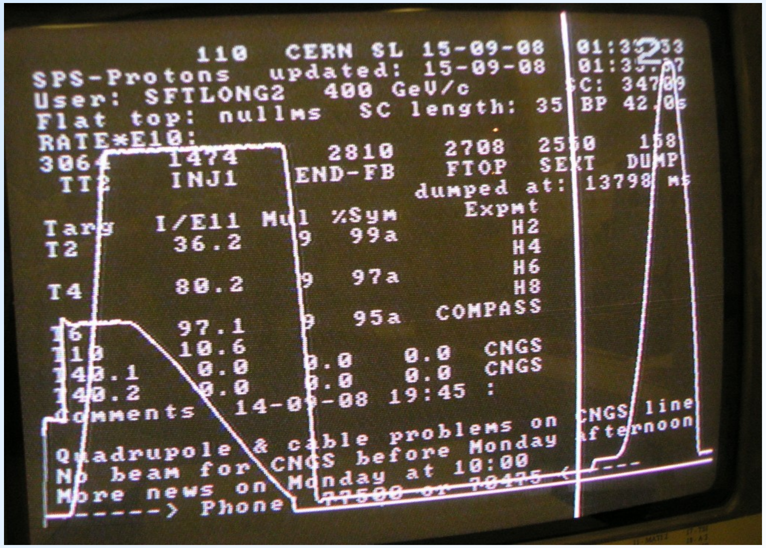
- Cherenkov photons from the window can be used to positively identifiy particles below the threshold in aerogel

Beam area T4-H6-B @ CERN

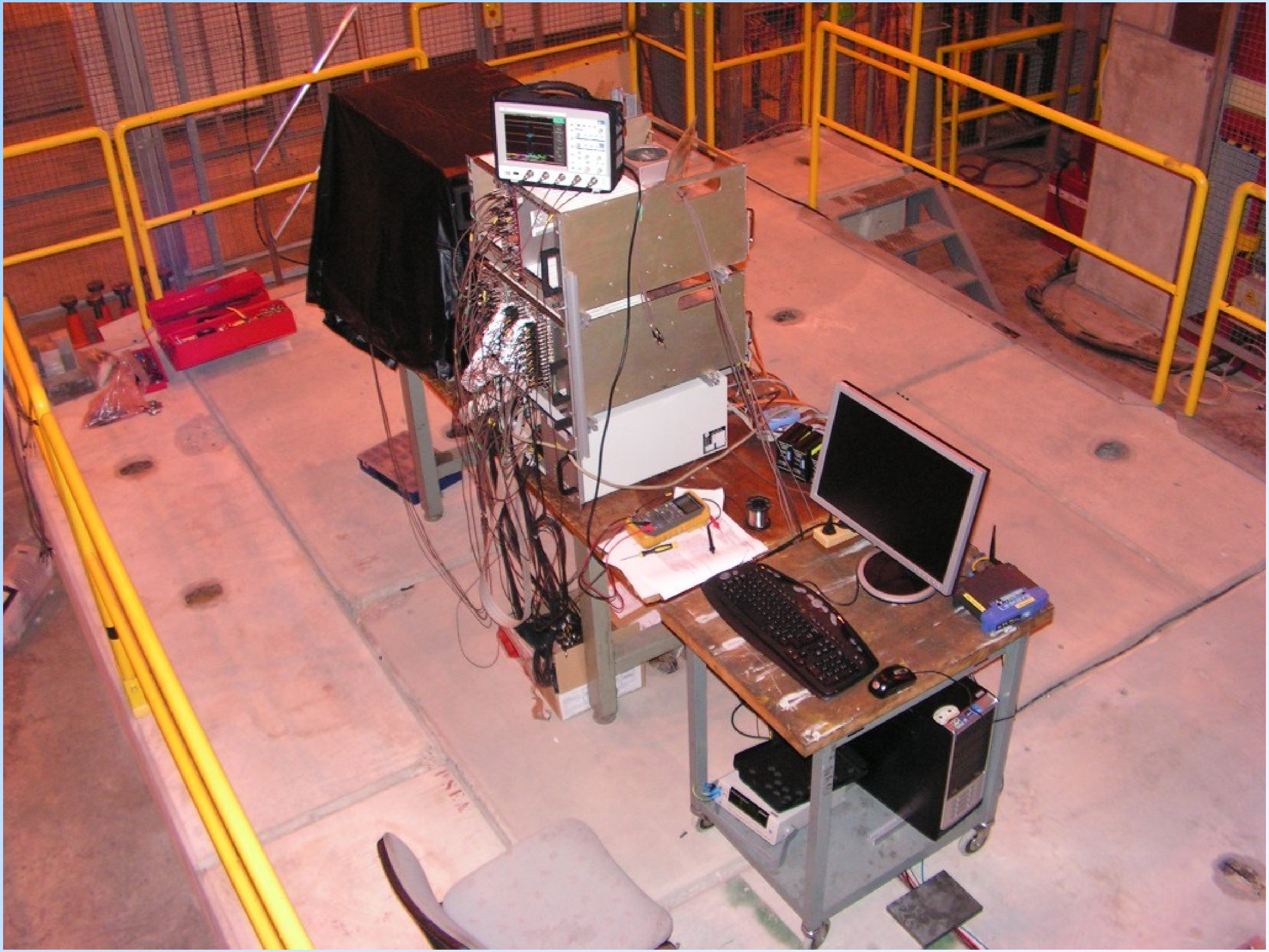
- +120 GeV/c pions
- spills every 42s for ~5s
- beam size ~1cm^2



- beam profile (scale in mm)

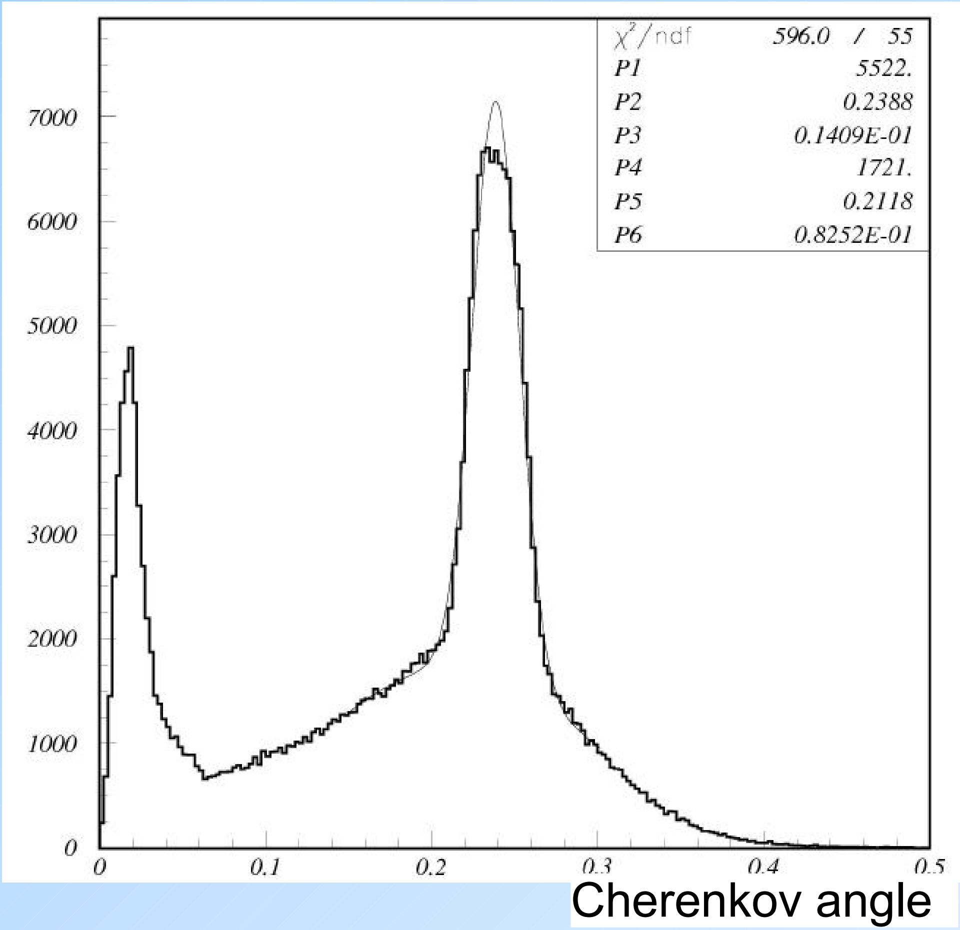


Beam area T4-H6-B

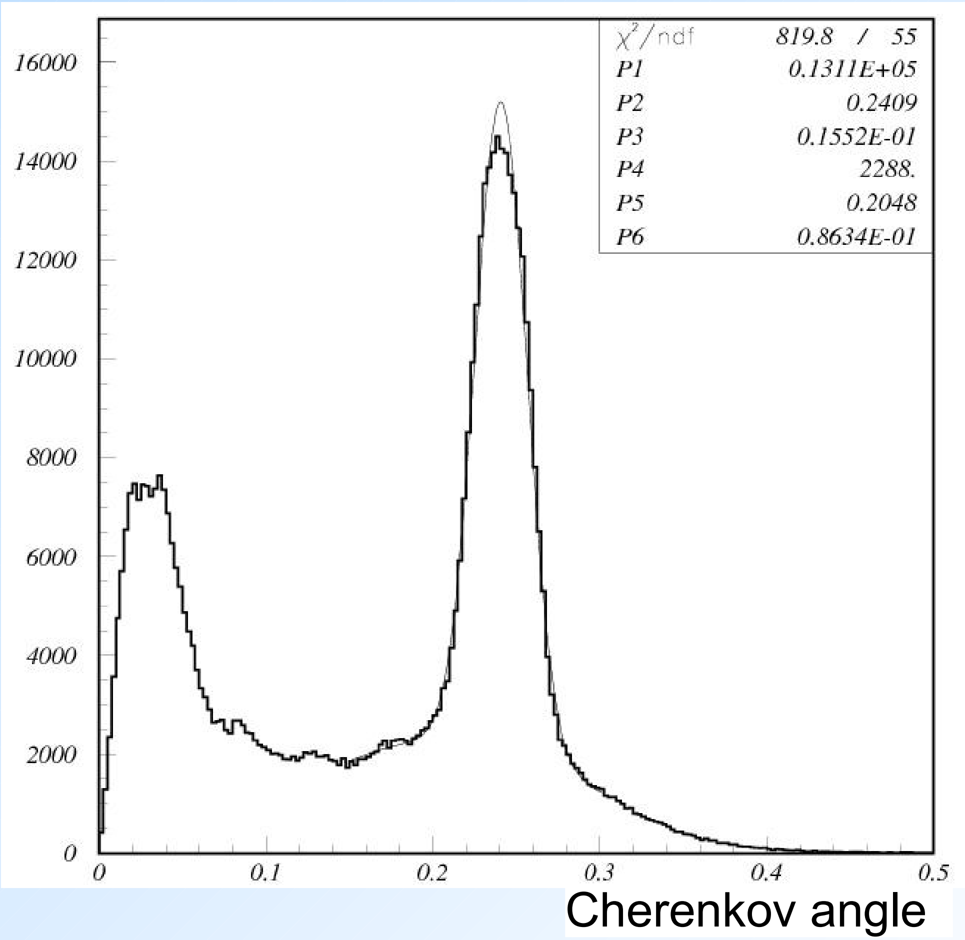


Cherenkov angle distributions

w/o light guides



w/ light guides

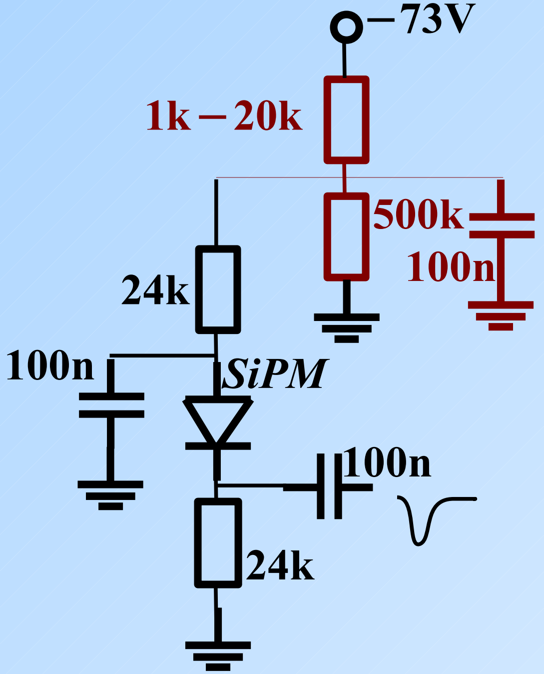


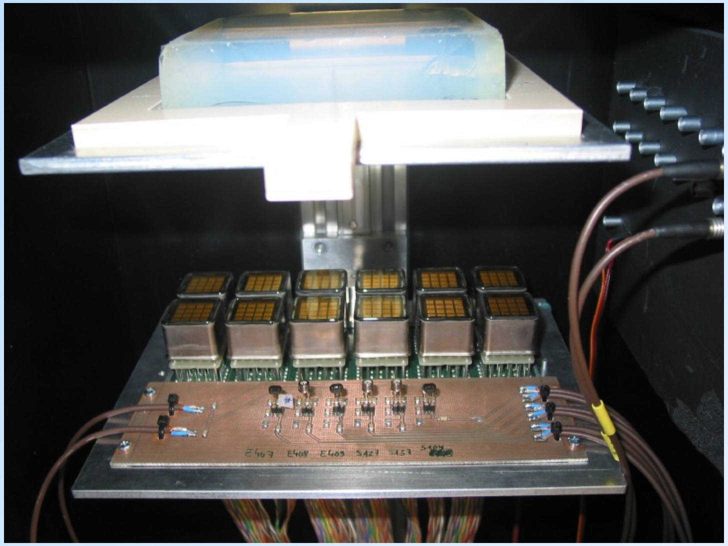
Cosmic test setup

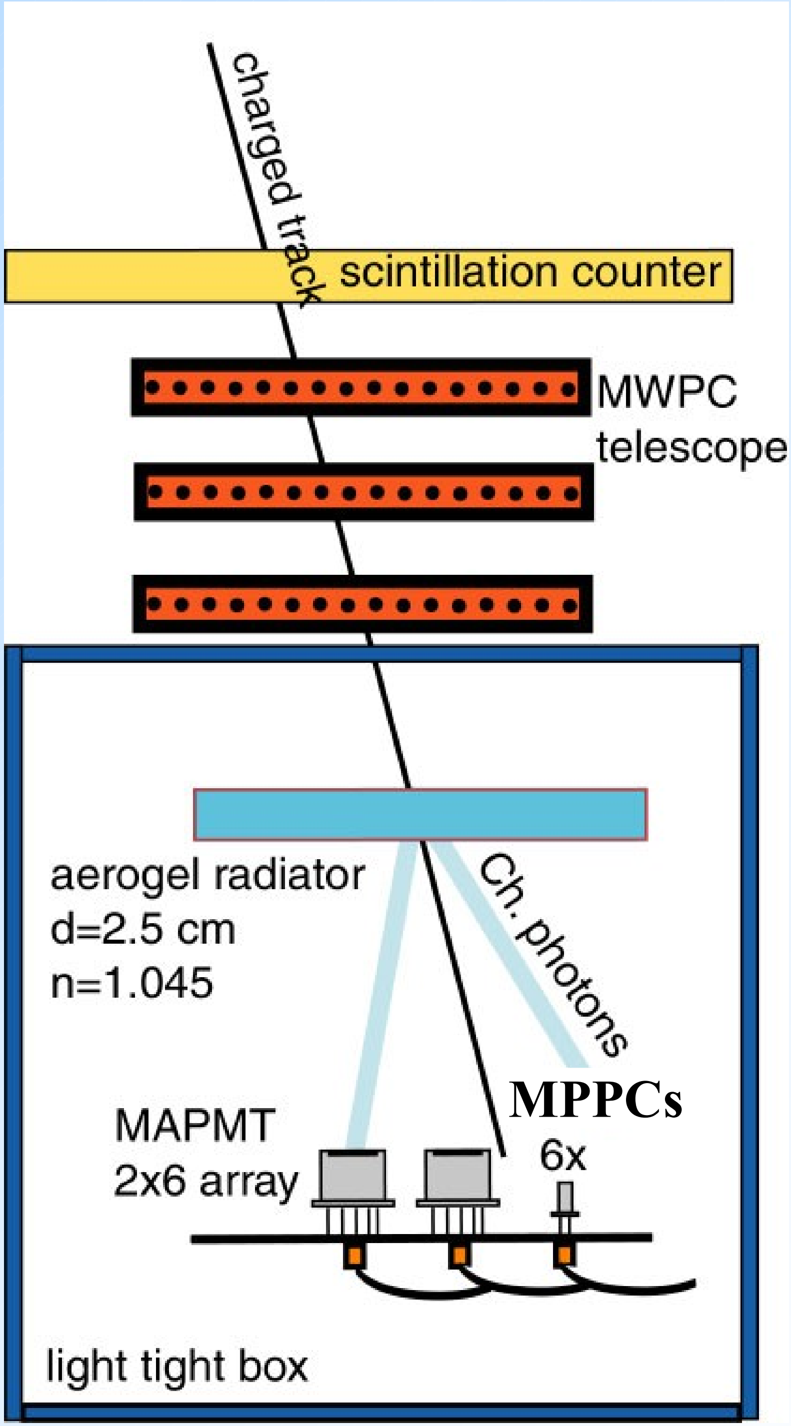
Two configurations of 6 Hamamatsu MPPCs were used:

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

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







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University of Maribor and Jožef Stefan Institute

SiPM: number of photons

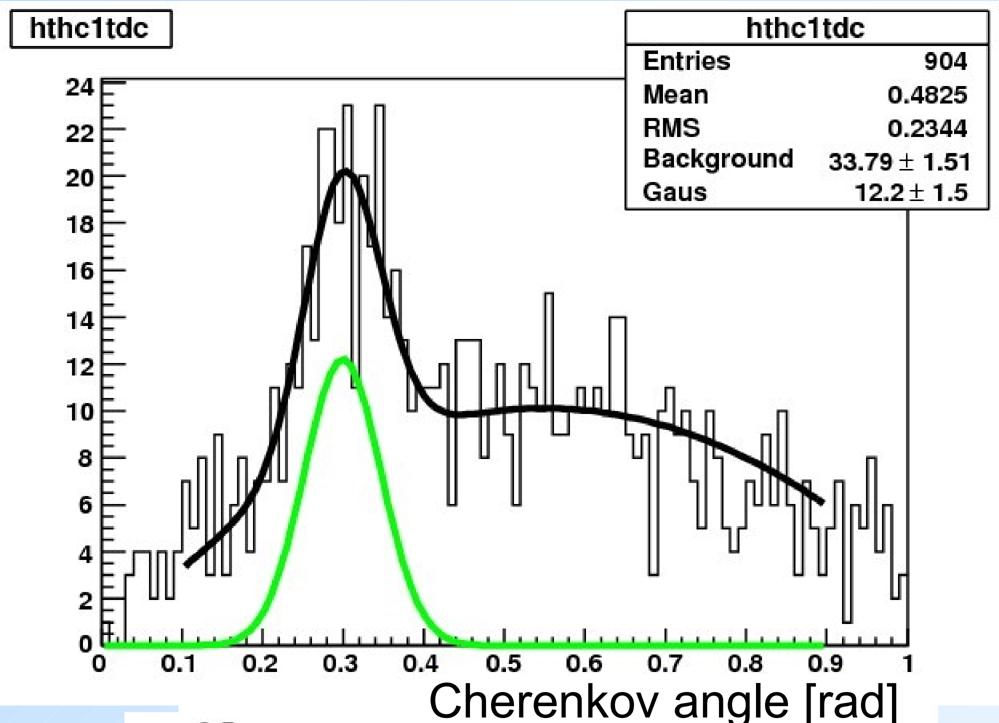
- 43600 tracks
- Cherenkov photons ~ 146
- ~ 0.0033 photons per track
- area ~ 6 mm^2

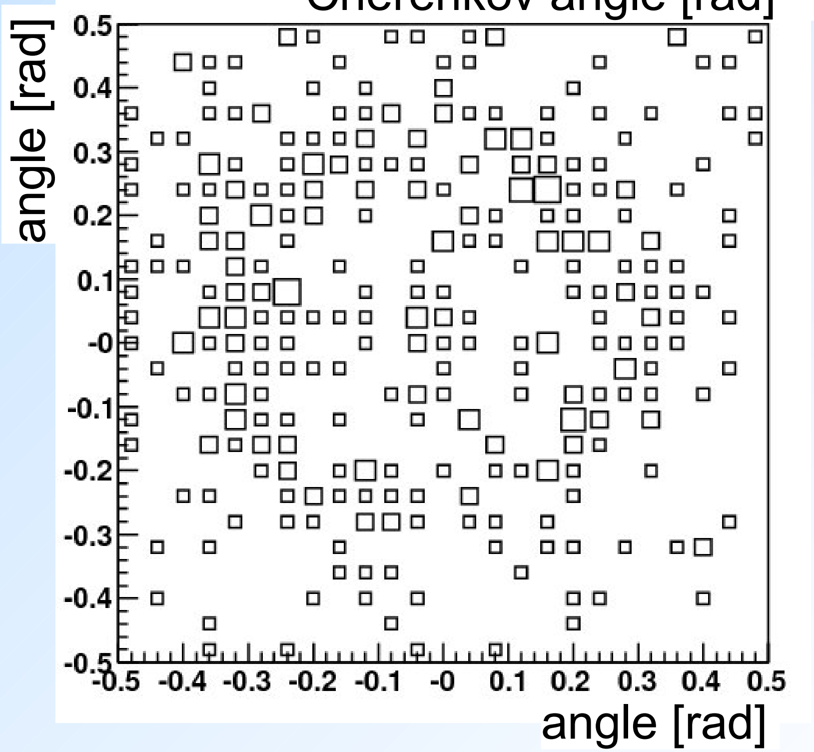
Compare with PMTs:

- Cherenkov photons ~ 22000
- active area ~ 3900 mm^2

N_{SiPM}/N_{PMT} x S_{PMT}/S_{SiPM} ~ 4.2

→ Per photon detector area SiPMs give 4 x more photons.





Cherenkov ph. with light guides

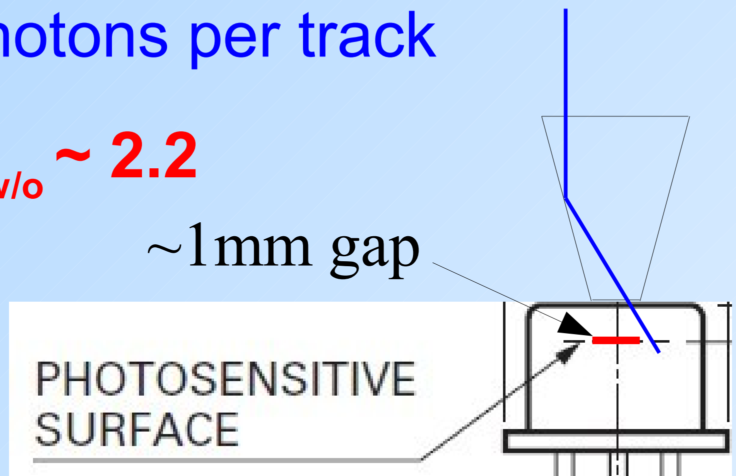
With light guides:

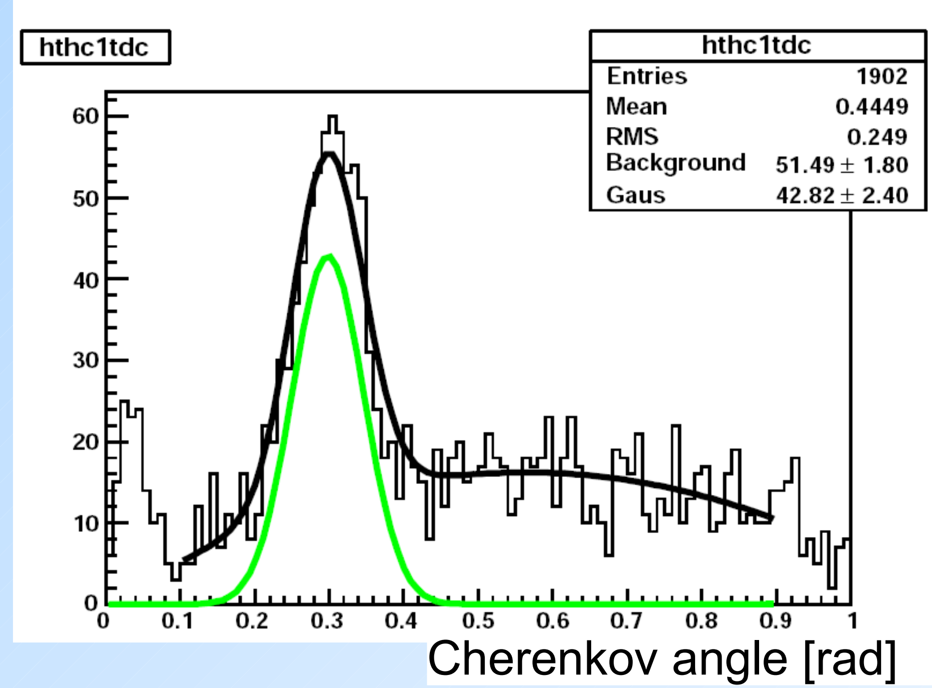
- 38100 tracks
- Cherenkov photons ~ 285
- 0.0072 photons per track

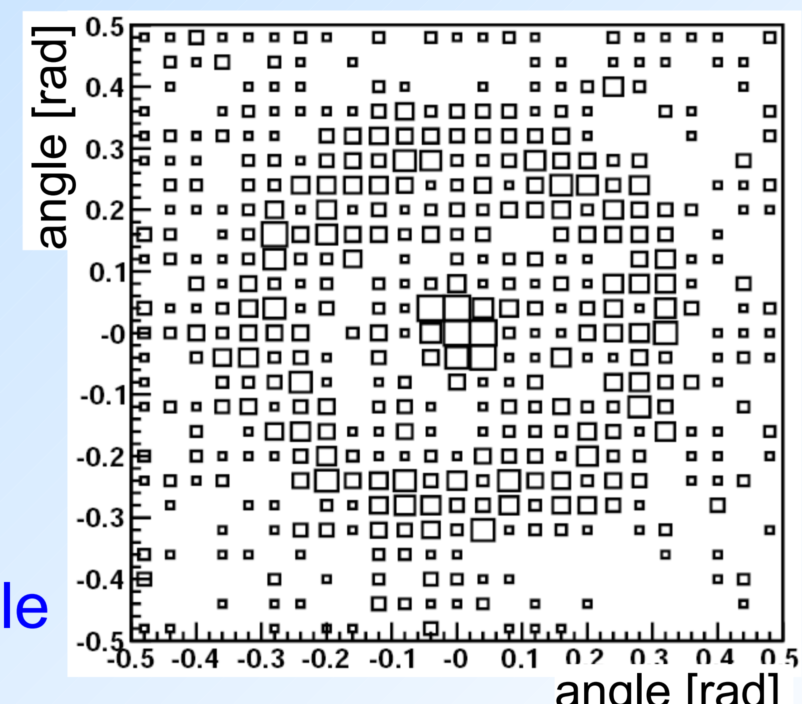
No light guides:

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

$N_{w/} / N_{w/o} \sim 2.2$

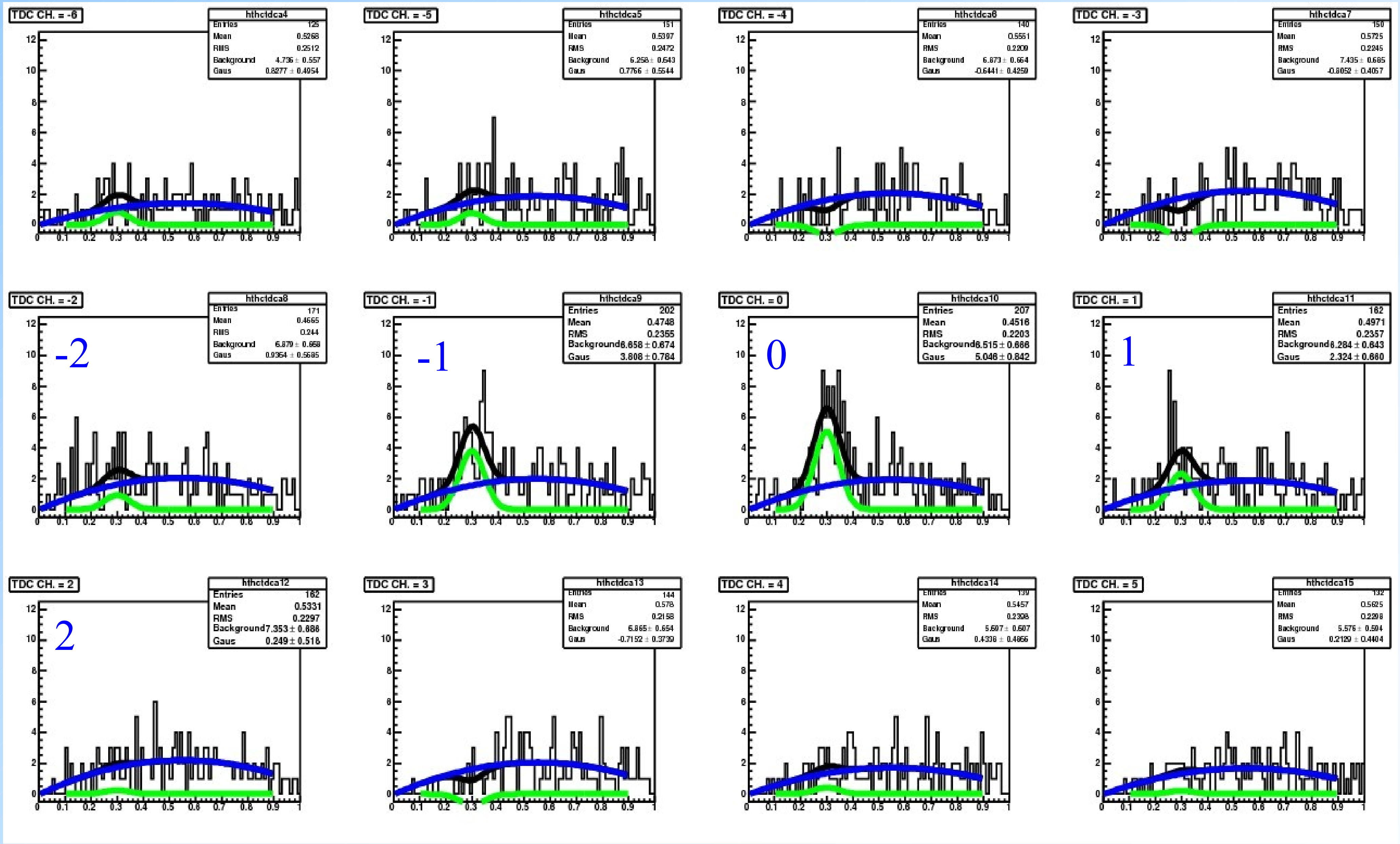






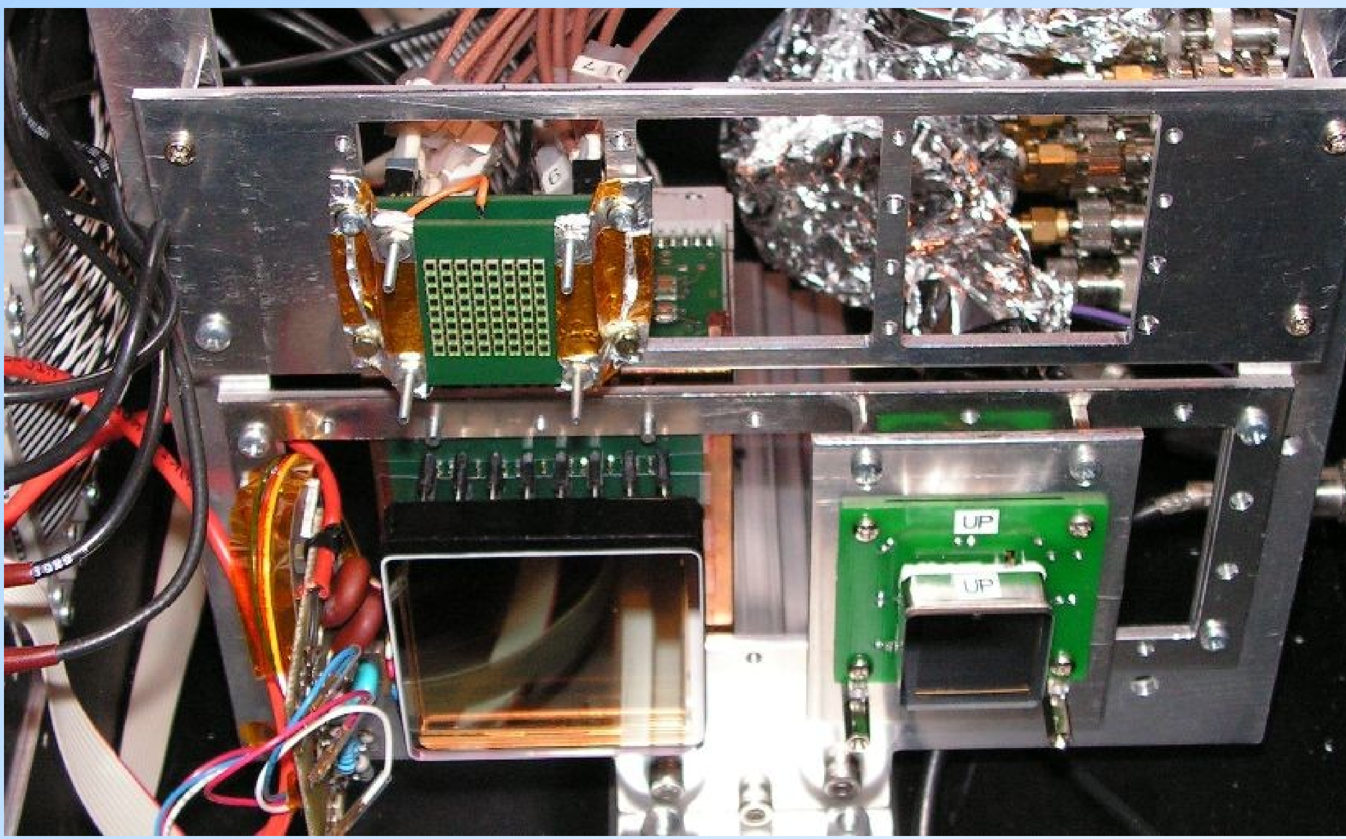
Light guide should be as close as possible to the SiPM surface (now: epoxy layer)

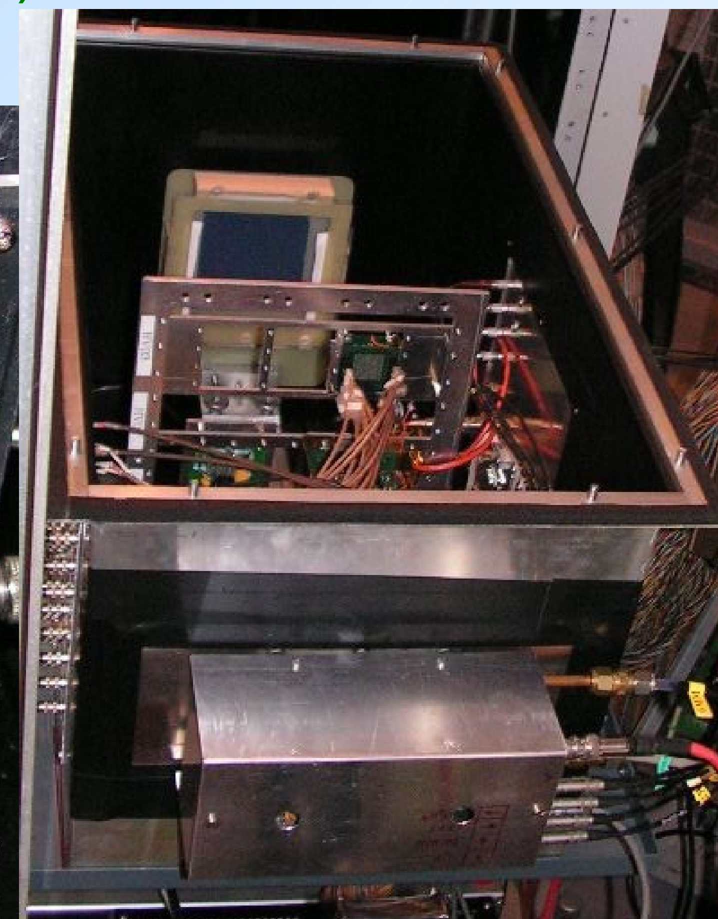
Cherenkov angle distributions for 1ns time windows



Beam test setup

- 2 MWPCs for tracking and scintillators for timing
- MPPC array w/o or w/ light guide (pad size ~5.1mm)
- Hamamatsu MCP-PMT (16 channel variant of TOP MCP-PMT, pad size ~ 5.5mm))
- aerogel n=1.045, d=20mm (distance 200mm)
- (Burle 64 channel MCP-PMT - not used)





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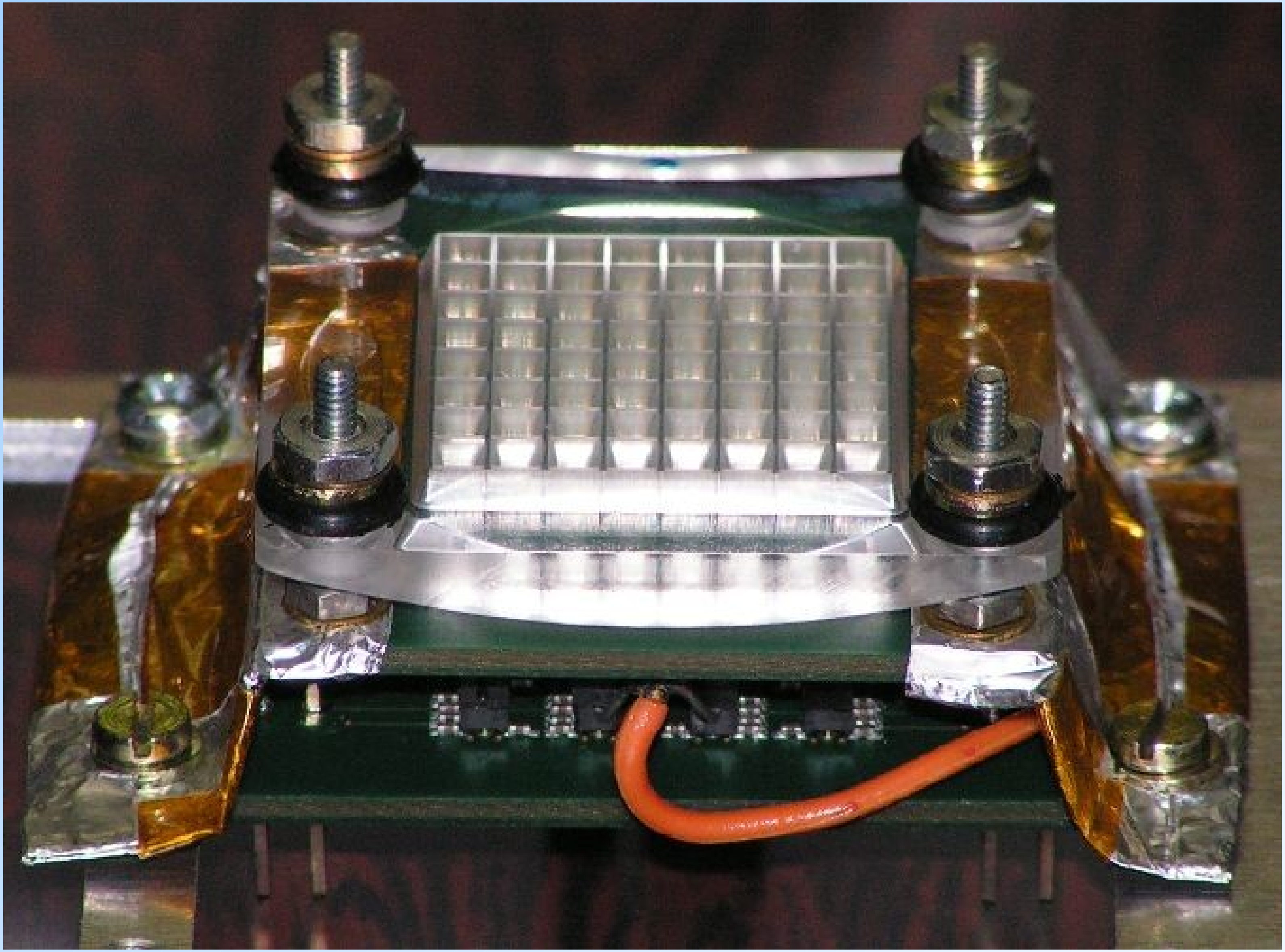
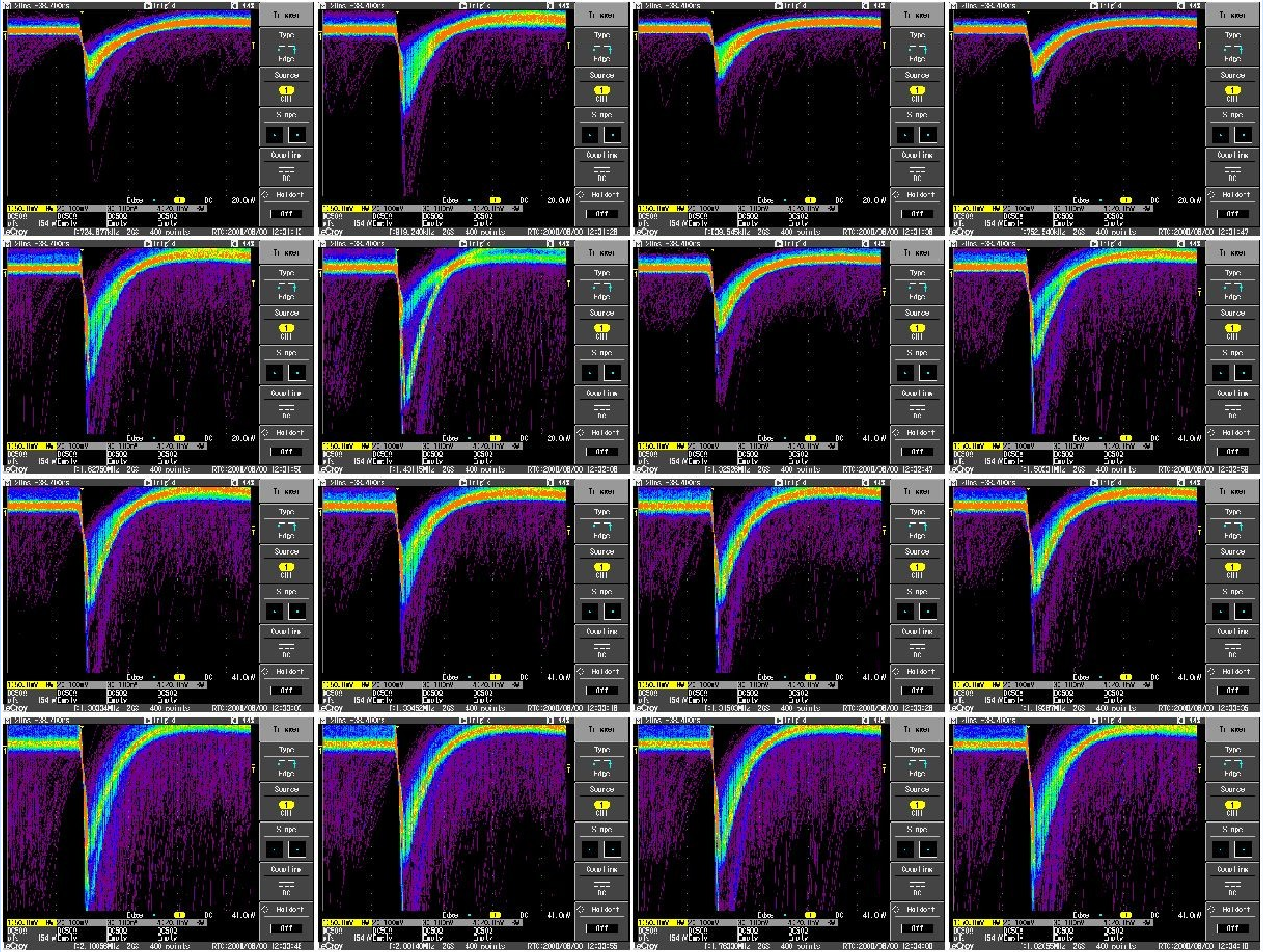
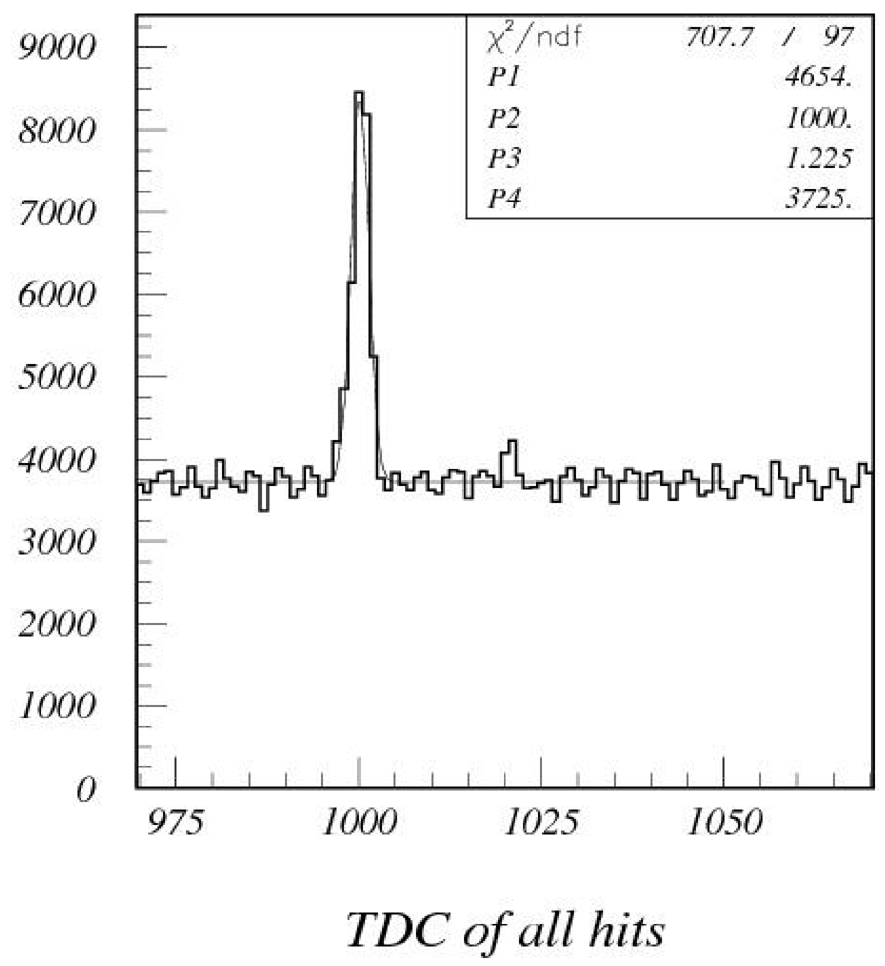




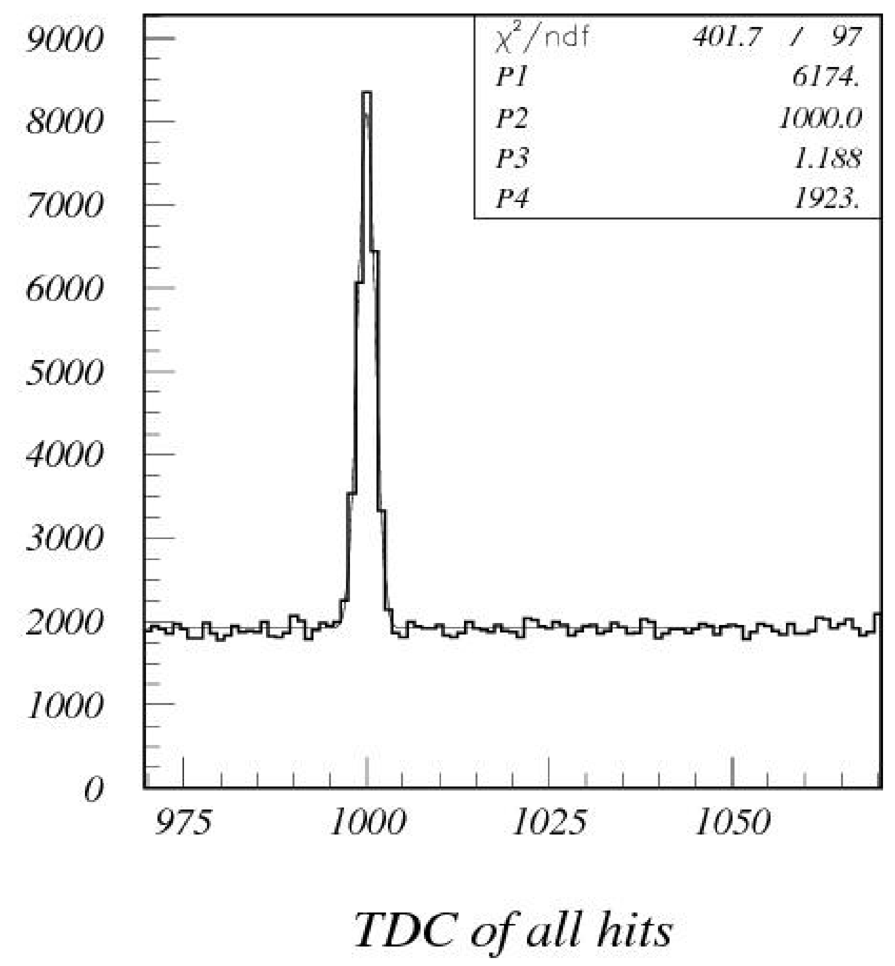
TDC distributions of MPPC hits for all events

- total noise rate ~ 27MHz (~400kHz/MPPC)
- signal to noise improves by factor ~2.6 with light guides

w/o light guides (~140k events)

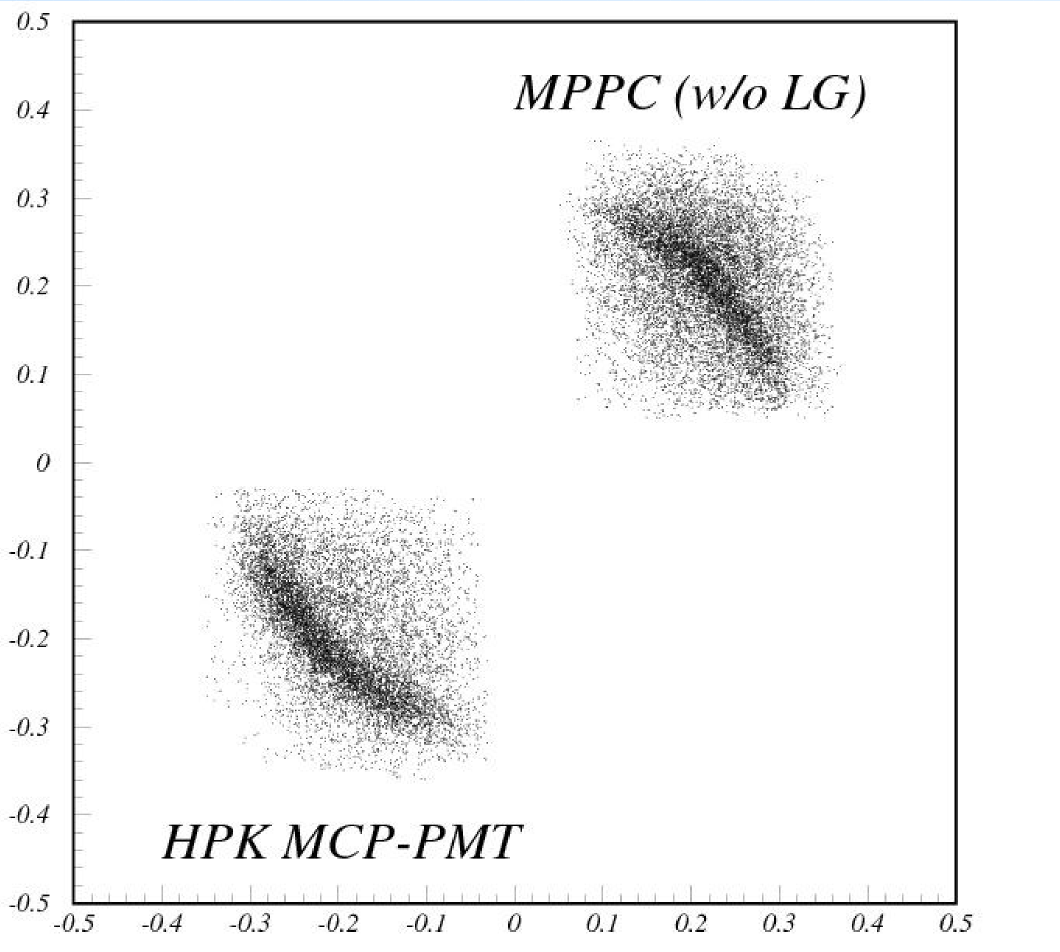


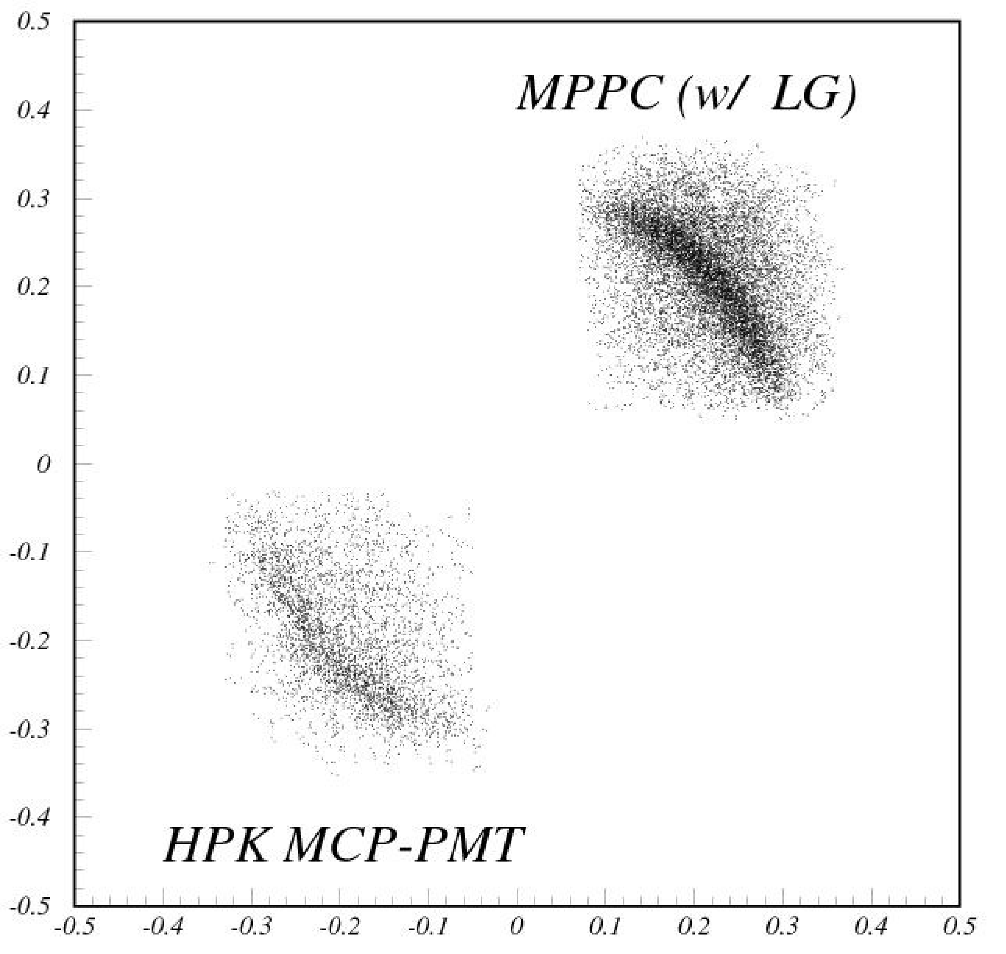
w/ light guides (~70k events)



Ring images

w/o light guides (~70k events) **w/ light guides (~35k events)**

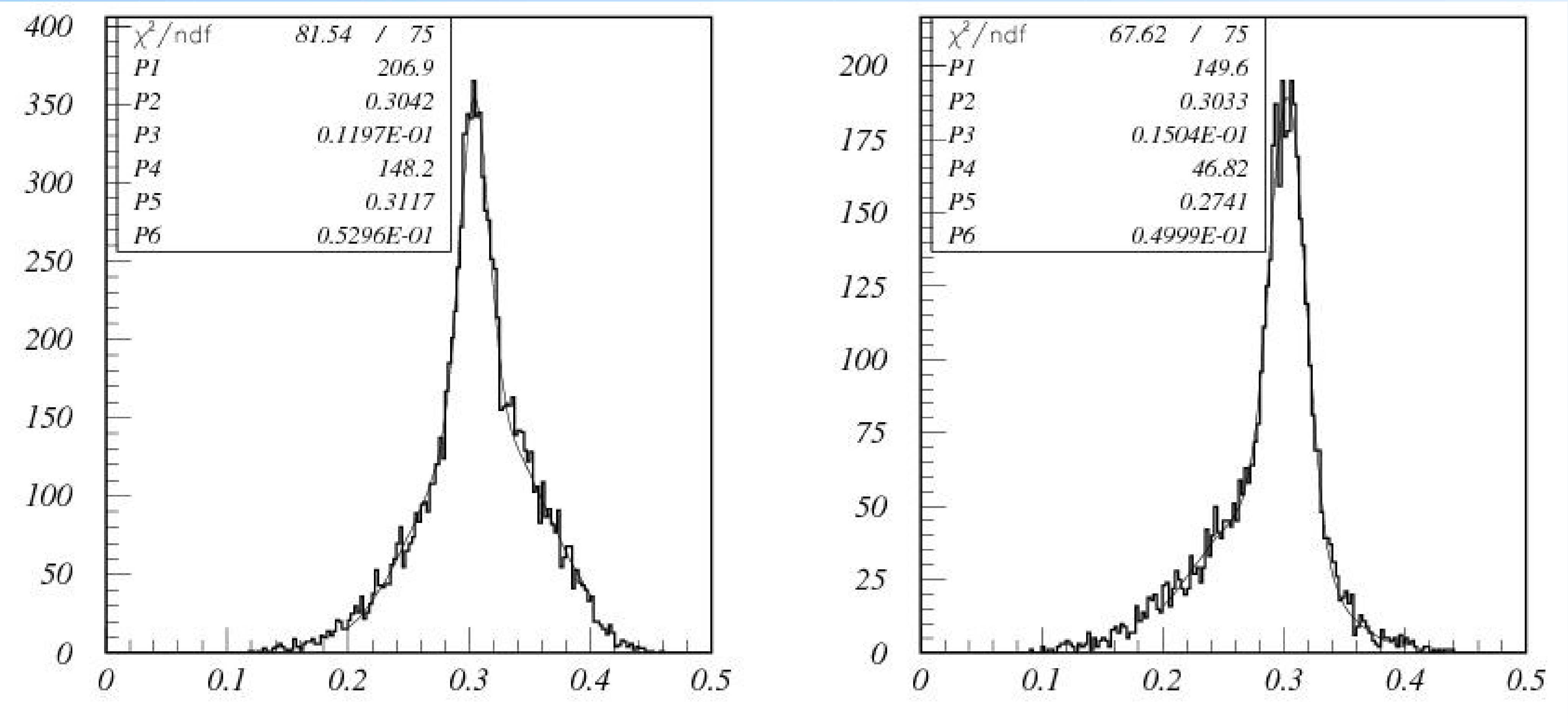




Cherenkov angle distributions - MPPCs w/o LG

- ratio of detected photons: ~ 1.1

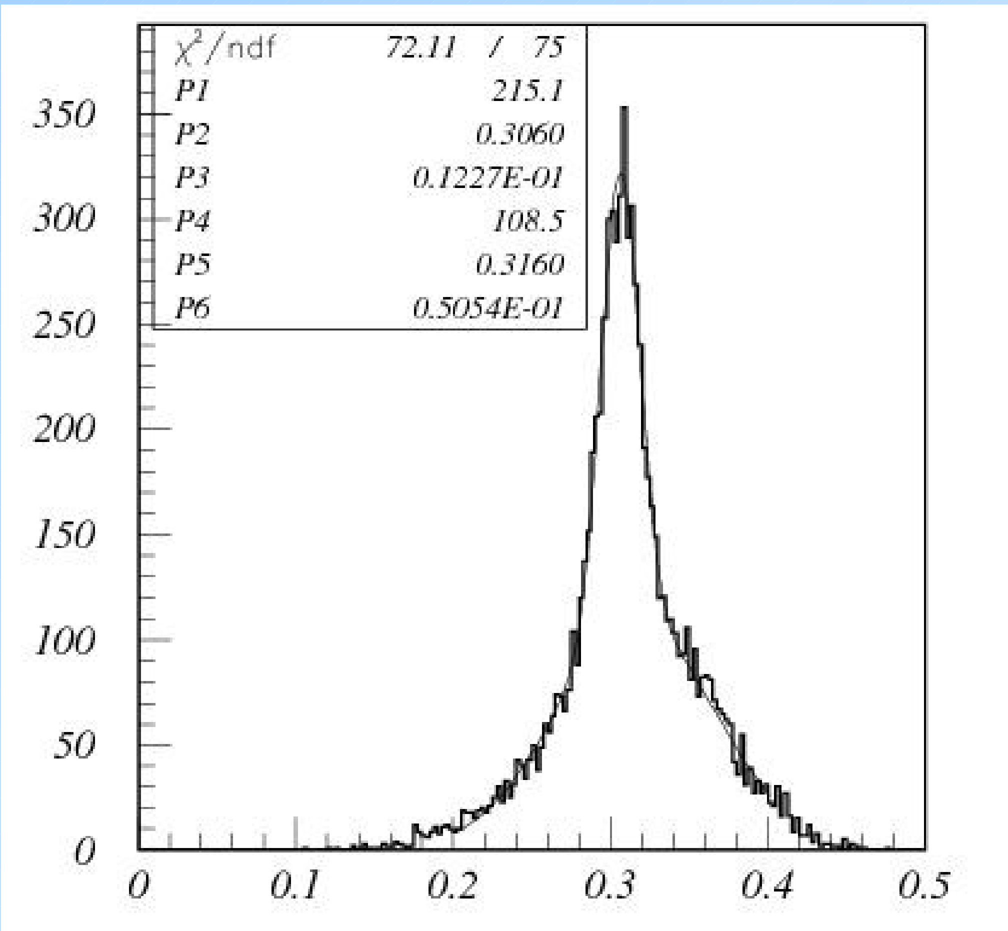
MPPCs w/o LG **MCP-PMT**



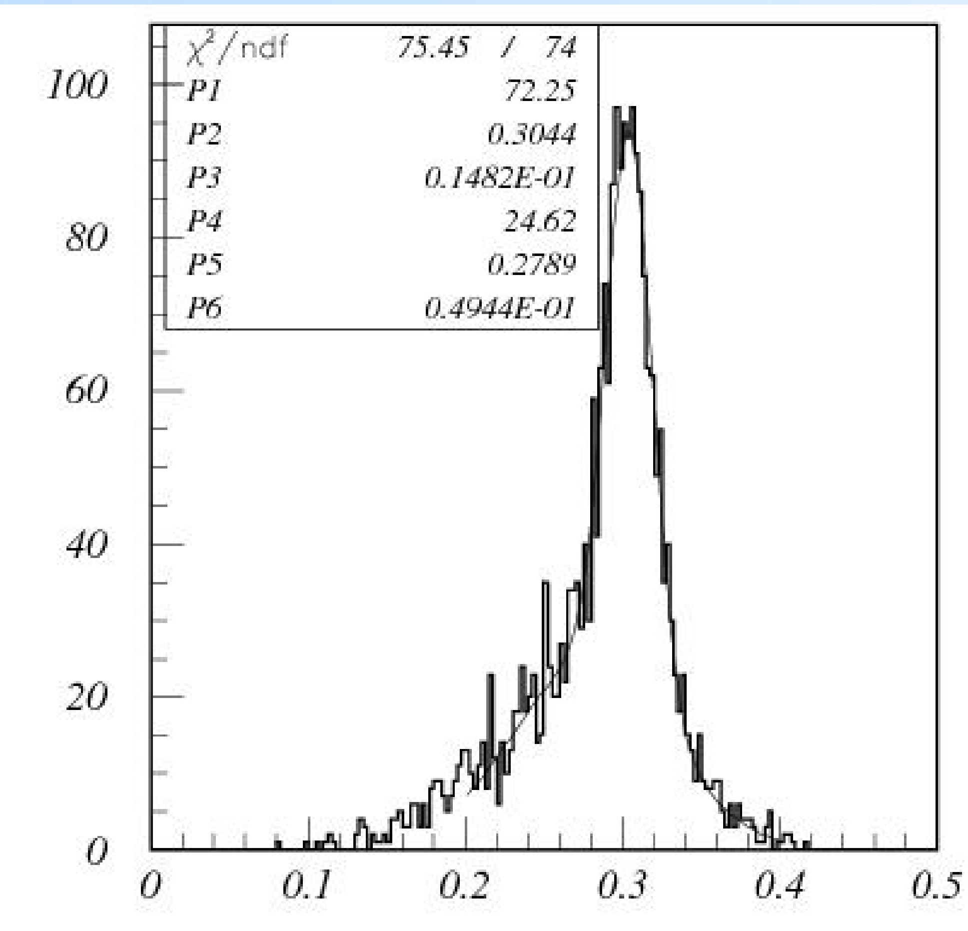
Cherenkov angle distributions - MPPCs w/ LG

- ratio of detected photons: ~ 2.5

MPPCs w/ LG

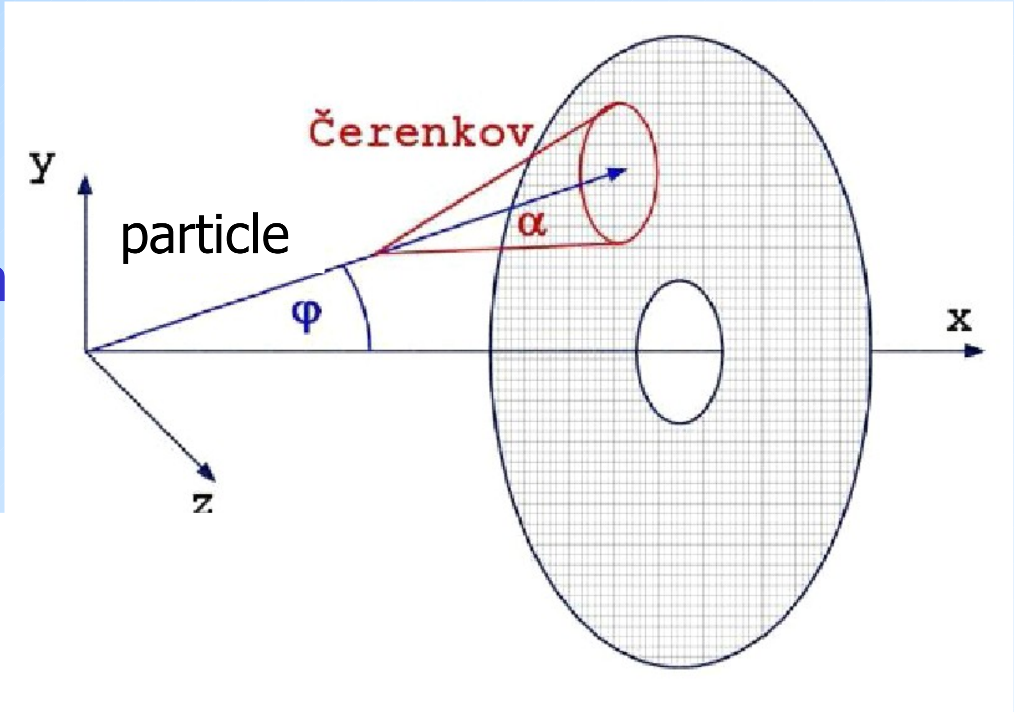


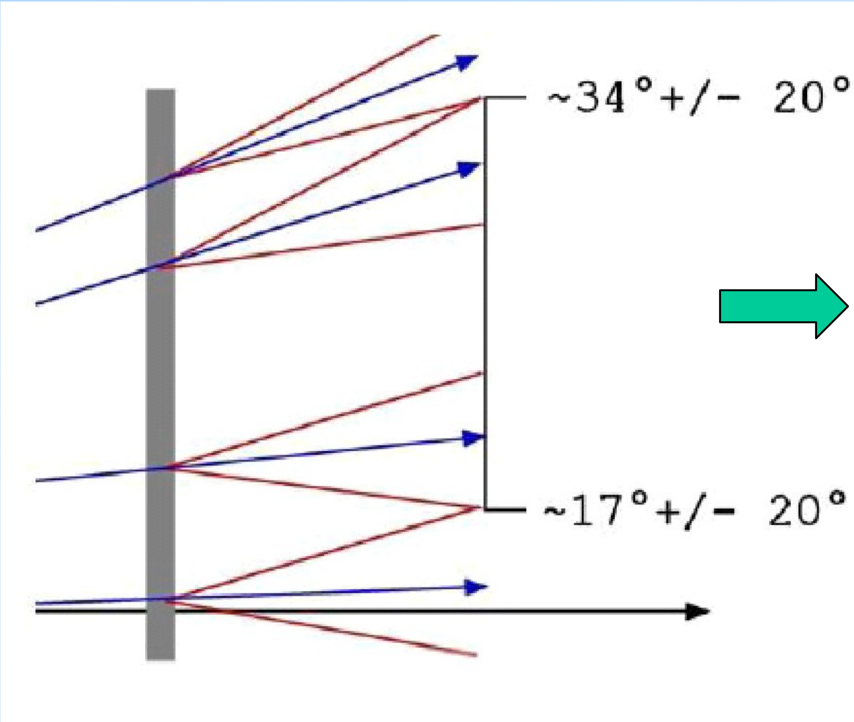
MCP-PMT



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



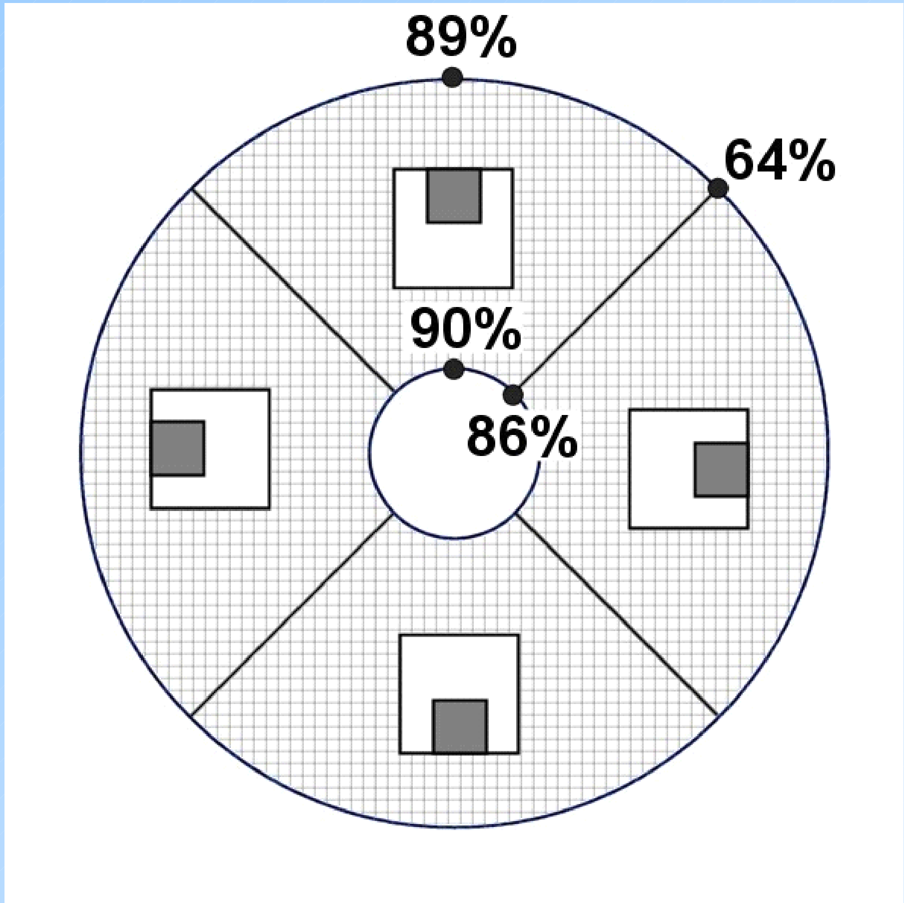


~ -3°... 54°

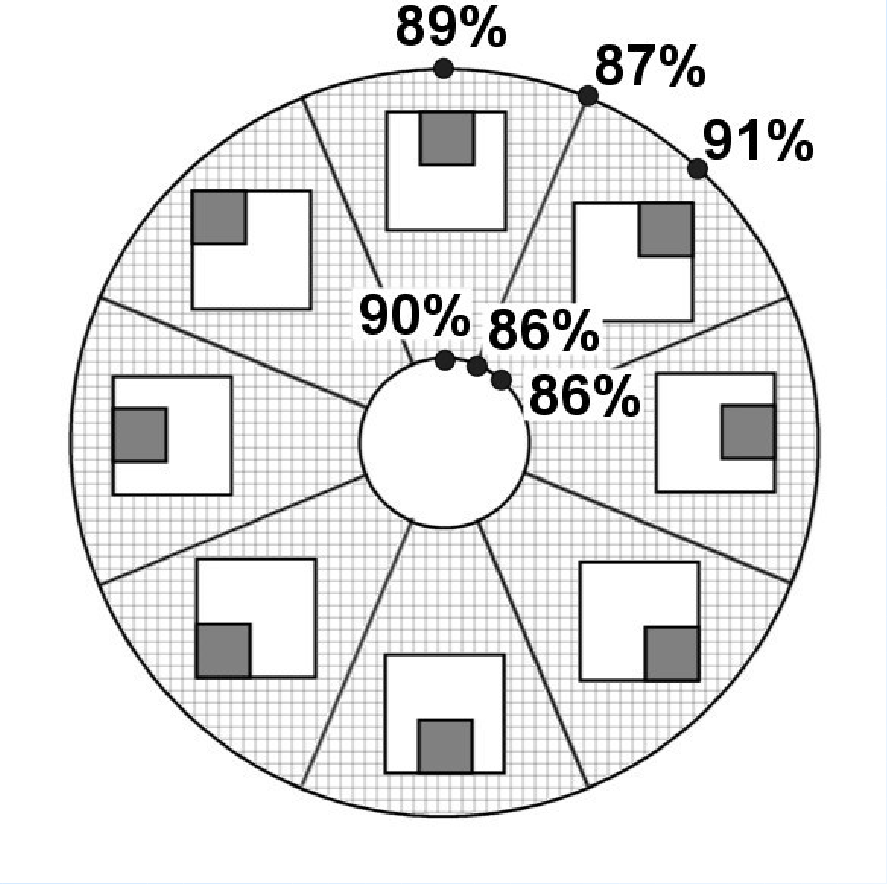
→ Take this asymmetry into account when designing the light collection system.

Samo Korpar
University of Maribor and Jožef Stefan Institute

Light collection: efficiency



Design with a single light guide type



Design with a two light guide types

Summary and plan

- Module was constructed using 8x8 array of MPPCs (SMD package) and light guide array
- Proximity focusing RICH with 1cm aerogel radiator (n=1.03) and module was successfully tested in the pion test beam at CERN
- The number of detected photons per ring is about half of the expected number obtained using manufacturers PDE
- Efficiency increase with light guides ~ 2.3 (area ratio ~5.5)

Plan:

- Use waveform sampling electronics
- Improve LG production
- Tests in 1.5T magnetic fielg
- Check the radiation damage

Samo Korpar
University of Maribor and Jožef Stefan Institute