Recent progres in PID detectors (coliding beams)

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Outline:

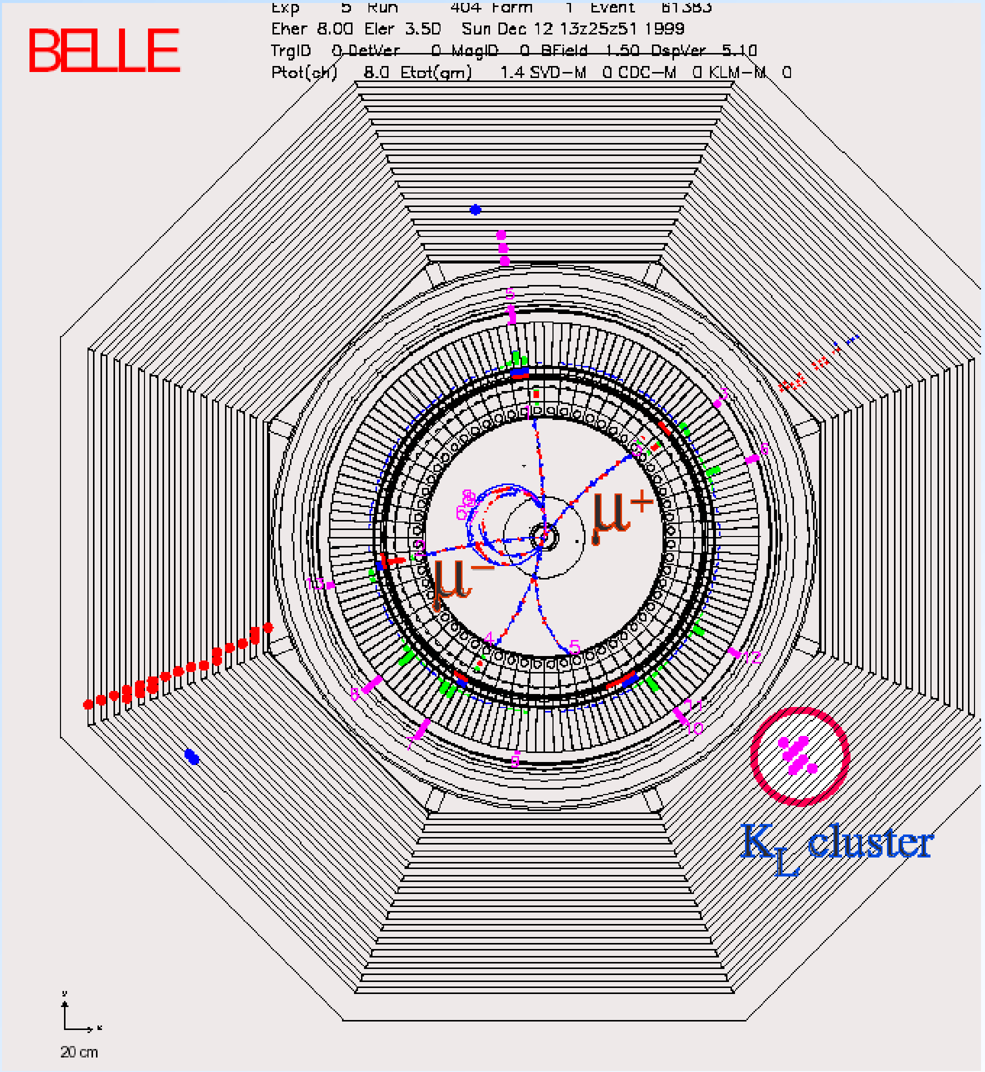
- Cherenkov based PID devices
  - Threshold
  - RICH (new concepts, photon sensors)
  - DIRC type PID devices
- Fast TOF detectors
- Tracking PID (TRD,dEdx)
- Summary

Particle IDentification - PID

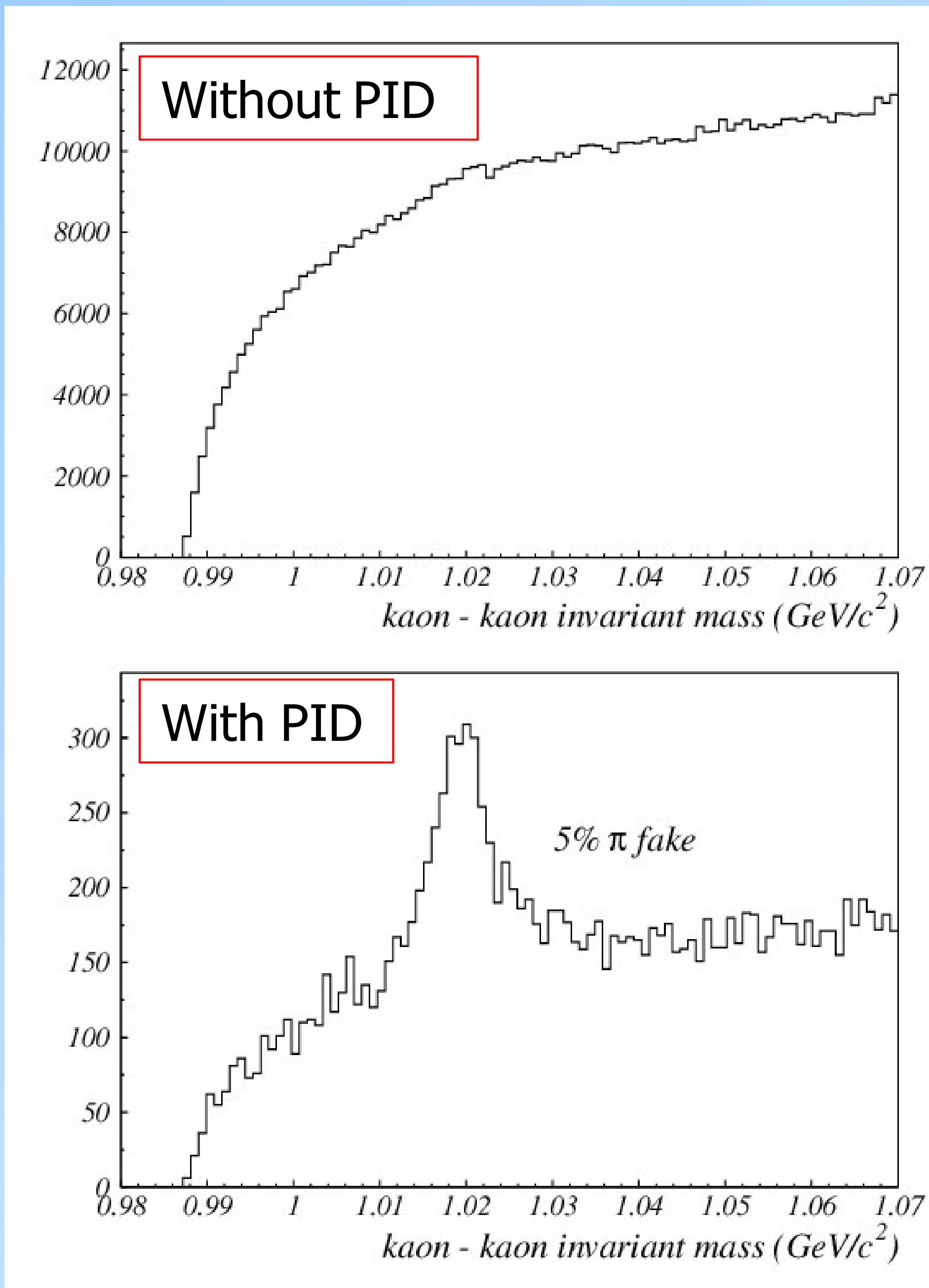
- particles are identified by their mass or interaction
- charged particle that live long enough to rich detectors:

$$e\,,\mu\,,\pi\,,K\,,p$$

- momentum is measured by track curvature in magnetic field
- in addition we can measure velocity:
  - Time Of Flight - TOF
  - energy loss - dE/dx
  - Cherenkov radiation (threshold, RICH,DIRC …)
  - transition radiation
- or identify by specific interaction:
  - electrons → Calorimeters
  - muons → Muon detectors



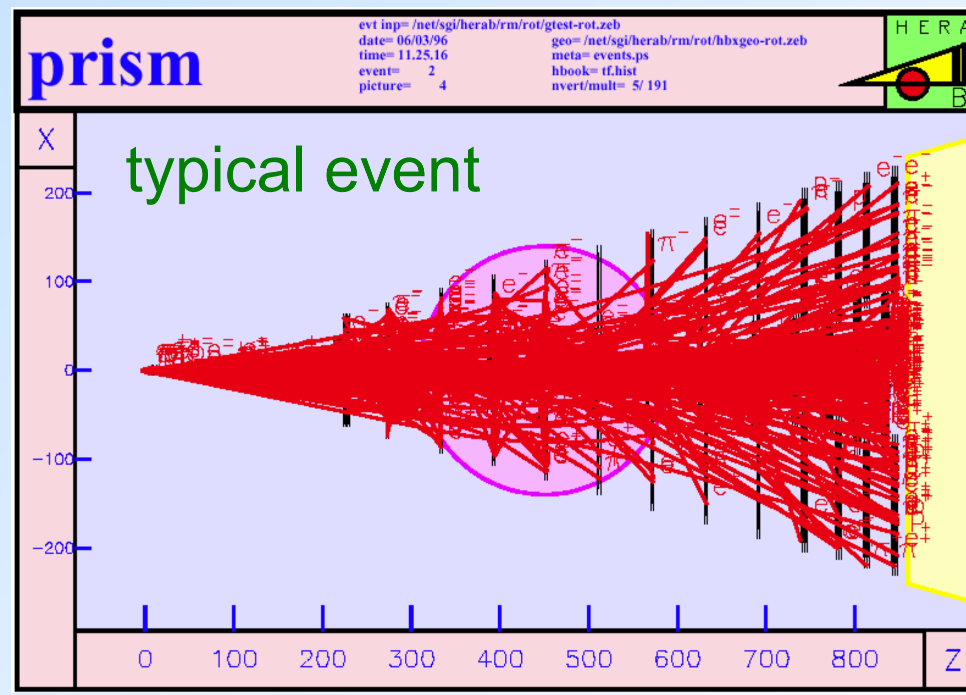
Why we need PID?



Example: HERA-B

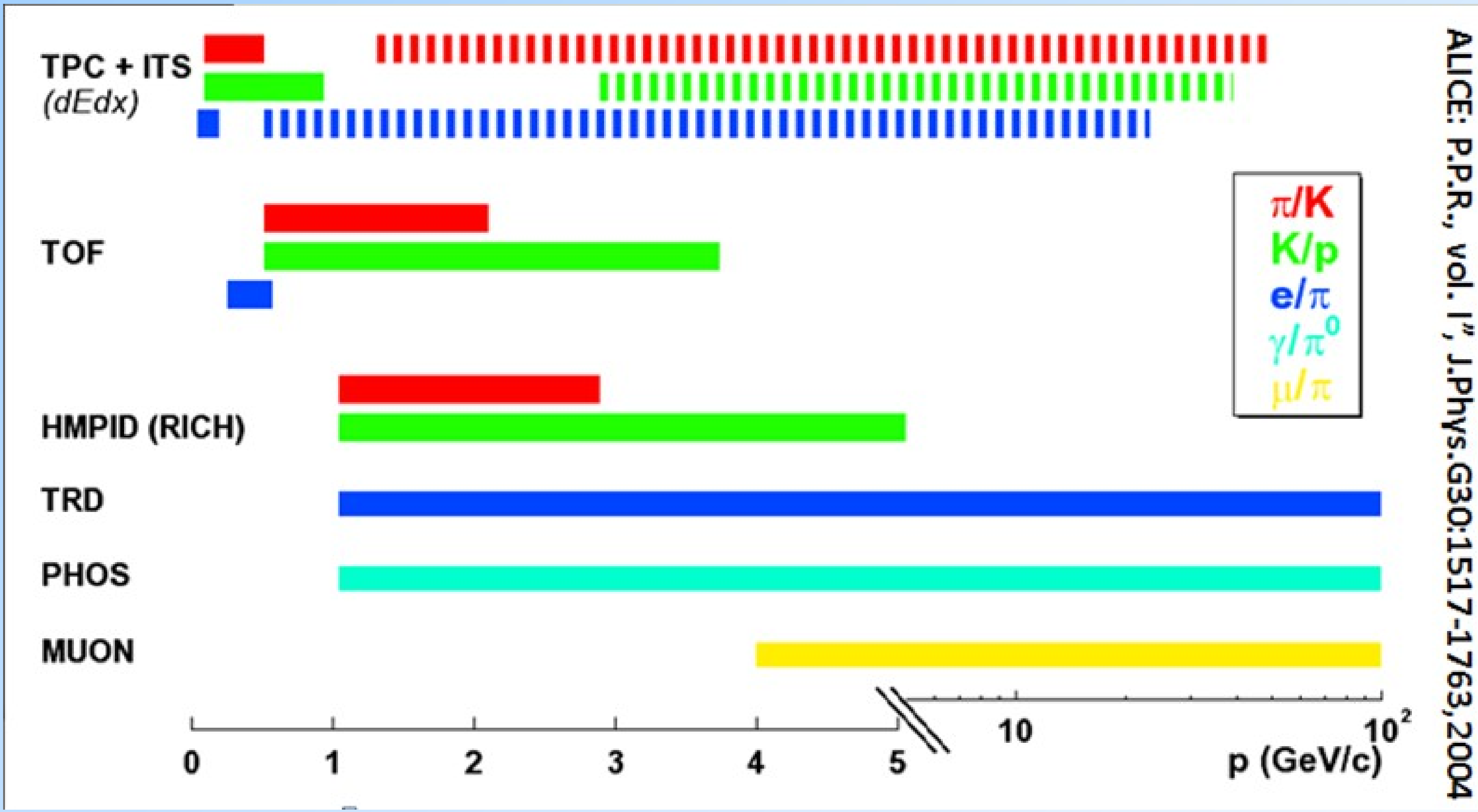
$K^+ K^-$ invariant mass.

The $\Phi \rightarrow K^+ K^-$ decay only becomes visible after the use of the particle identification



Momentum range for different PID methods

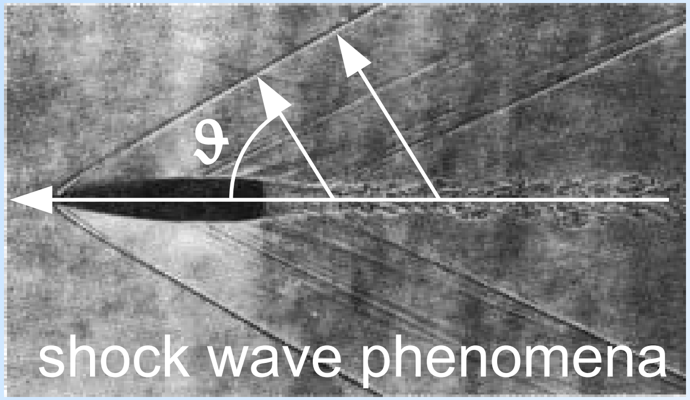
- example from ALICE experiment – they use all methods



Cherenkov radiation

• threshold - radiation is emitted when charged particle moves through the medium faster than the speed of light

$$\beta = \frac{v}{c} > \frac{1}{n}$$



• Cherenkov angle - angle between the particle and photon directions

$$\cos\vartheta_C = \frac{1}{\beta n}$$

• number of photons - depends on refractive index → Cherenkov angle

$$\frac{d^2N}{dE\,dl} \approx \frac{370}{eV\ cm}\sin^2\vartheta_C \qquad \left(\frac{dN}{d\lambda} = \frac{hc}{\lambda^2}\frac{dN}{dE}\right)$$

→ high sensitivity in blue to UV region

• prompt emission – no decay constant as with scintillators

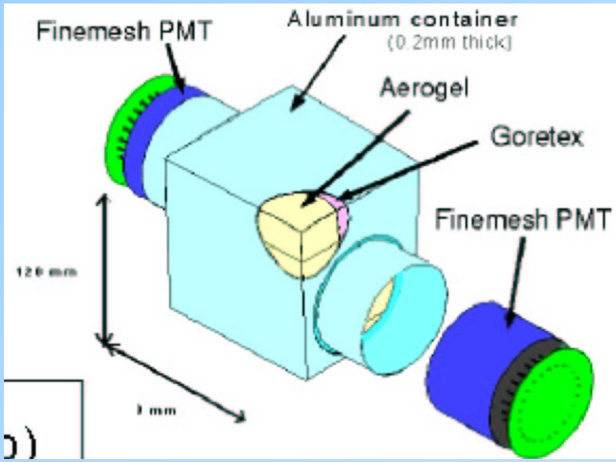
→ enables precise time measurements

• light is polarized – E lies in the plane defined by particle and photon momenta

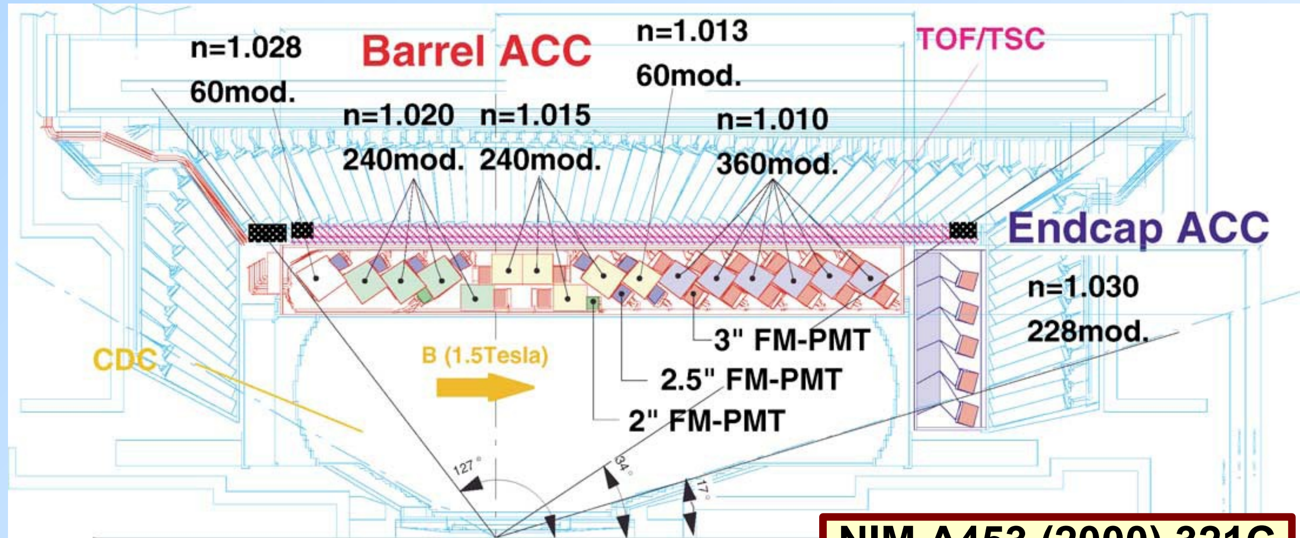
Threshold Cherenkov counters

$$p_{thr} = \frac{mc}{\sqrt{n^2-1}}$$

- ACC (Aerogel Cherenkov Counter) @ Belle (variable n=1.03,1.01,1.015, 1.02).



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



NIM A453 (2000) 321C

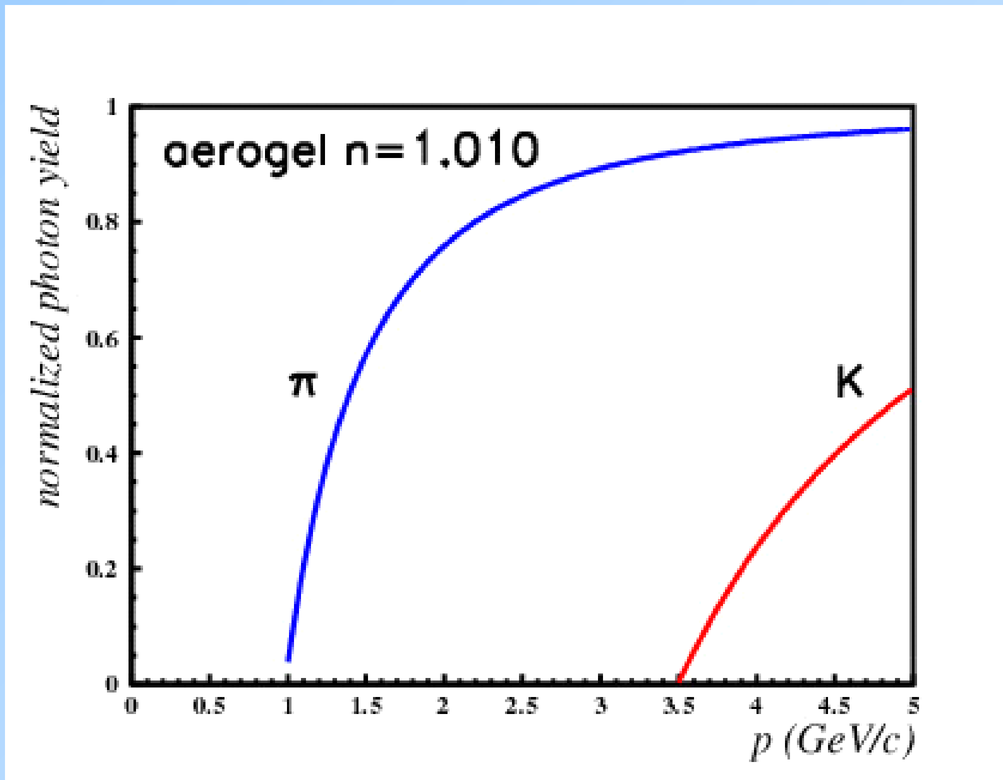
- ASHIPH (Aerogel SHIfter Photomultiplier) @ KEDR (n=1.05), SND(n=1.13): Cherenkov photon detection with WLS and MCP-PMT

- more by A. Barnyakov today @12:30 and posters

S.Kononov @AFAD2013

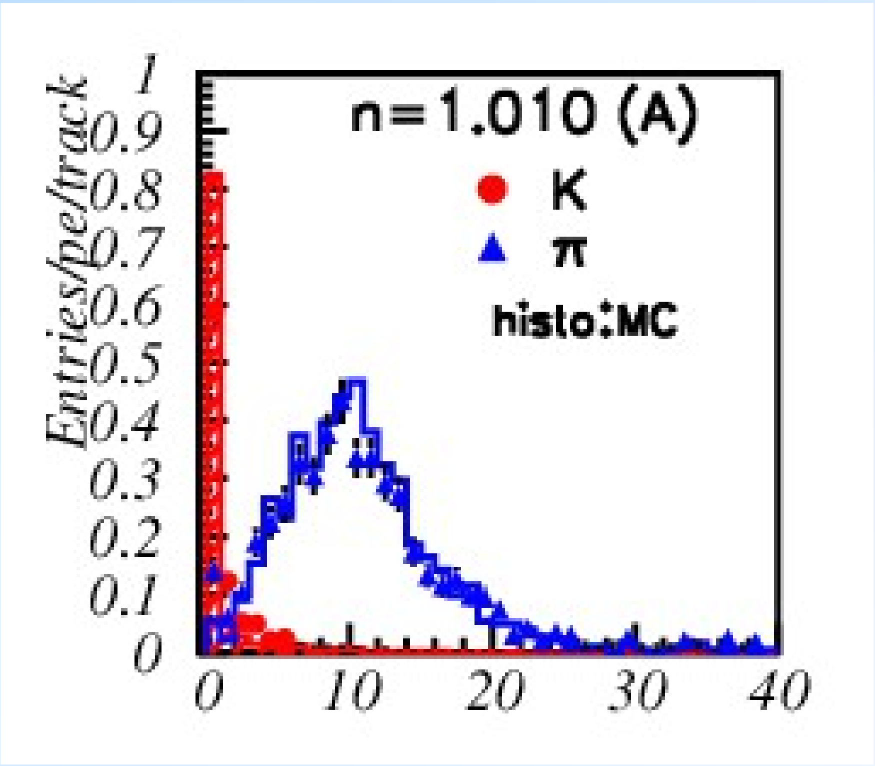
Belle ACC performance

NIM A453 (2000) 321

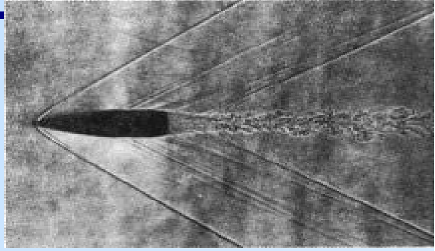


Normalized yield vs. momentum.

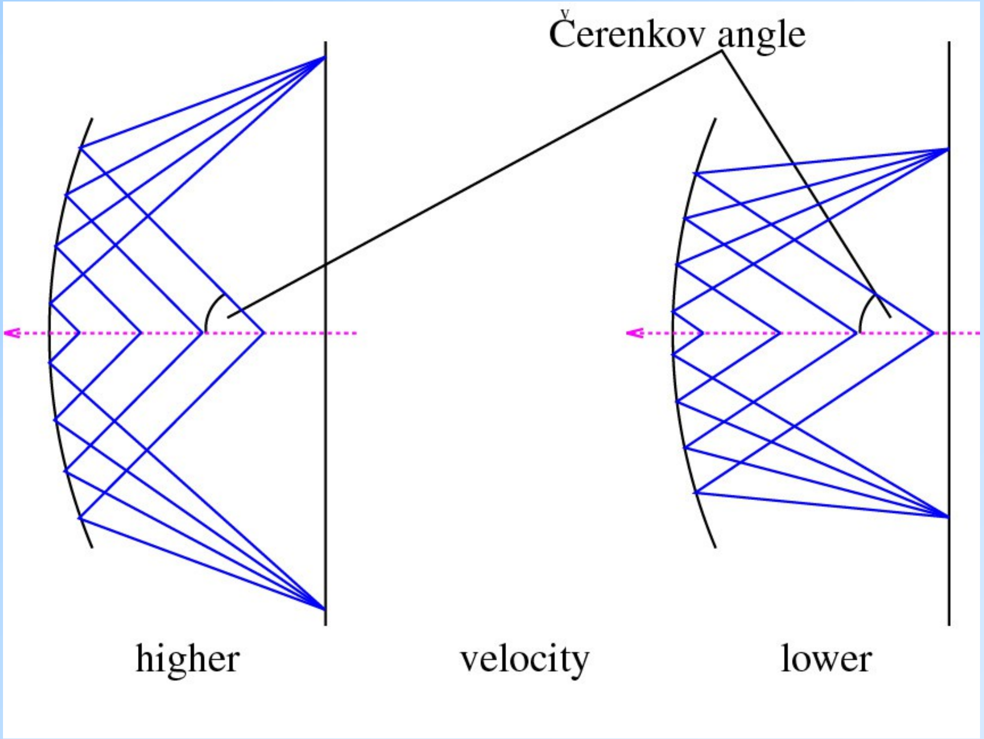
Yield for 2-3.5 GeV/c: expected and measured number of Ch. photons.



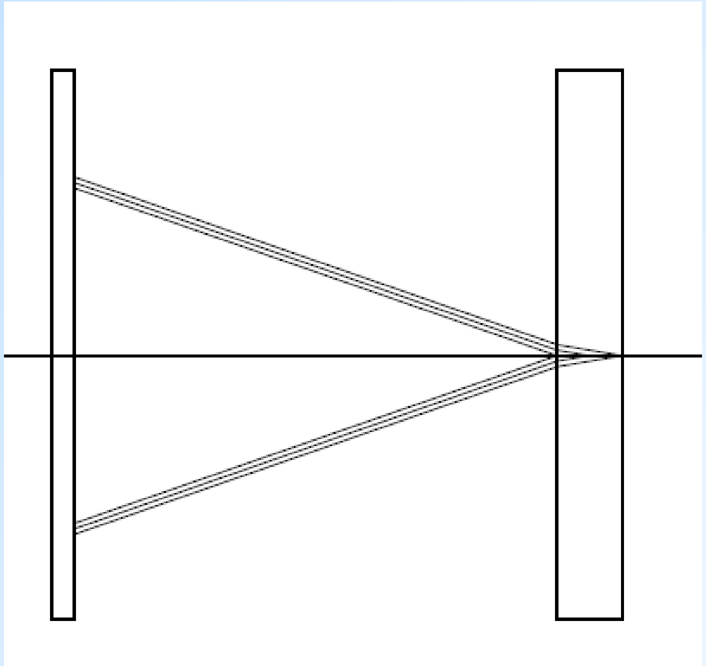
RICH detectors



Ring Imaging CHerenkov counter (RICH) → measurement of Cherenkov angle → particle velocity. Base designs:



detector with focusing mirror → gas radiator

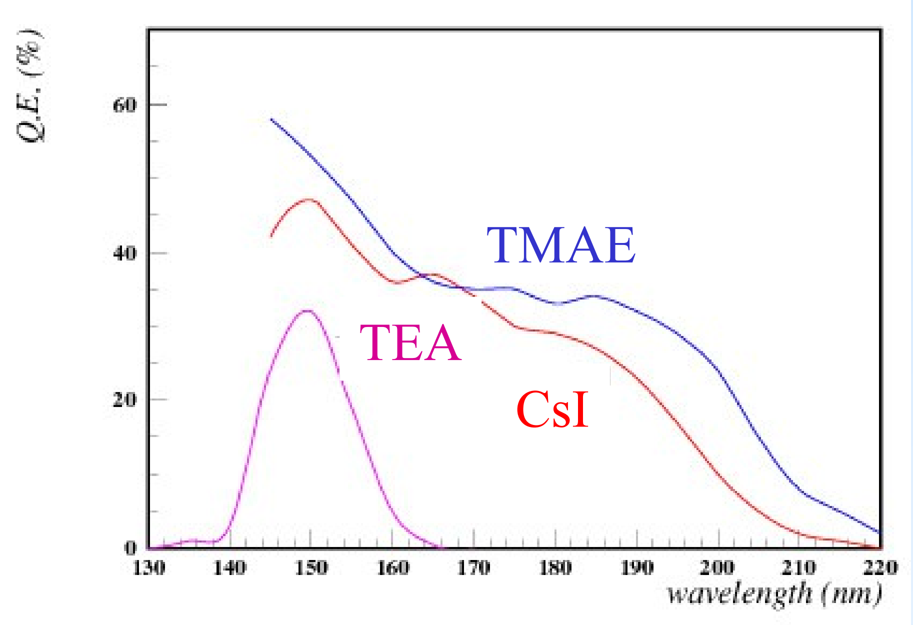


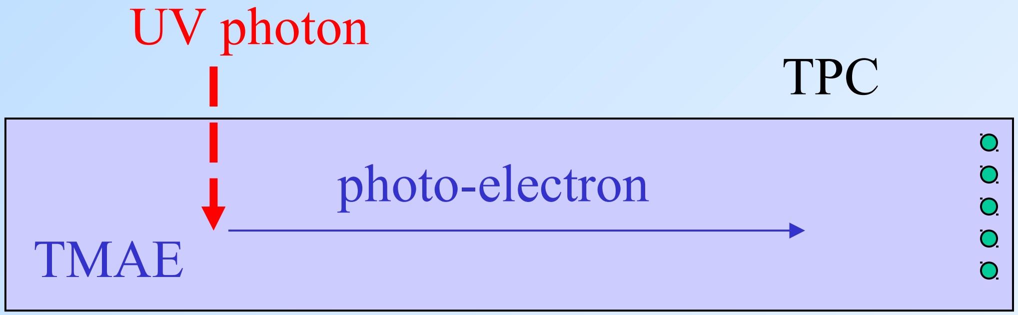
proximity focusing detector → solid or liquid radiator

Early RICH detectors

Detection of photons by gaseous detectors:

- photosensitive substance (TMAE, TEA) added to gas or deposited on one cathode (CsI)
- works in magnetic field
- low initial costs
- only UV transparent materials and high purity gas (not for aerogel)



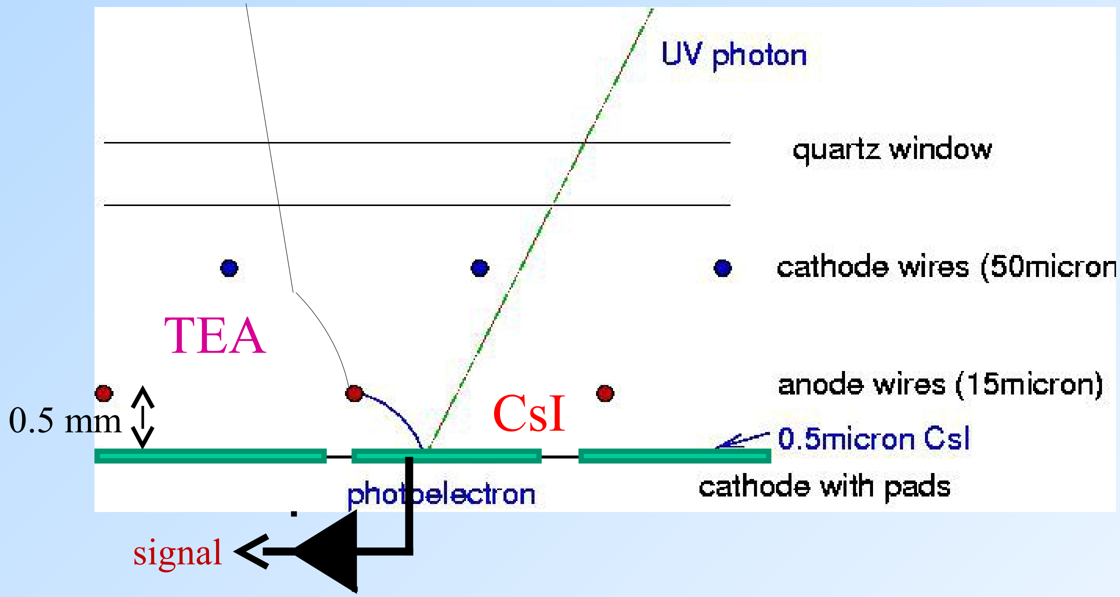


DELPHI, SLD, OMEGA RICH counters based on TMAE:

- long absorption length → thick wire chamber detector – TPC (UV photon → photo-electron → detection of a single electron in a TPC)
- slow – low rate
- aging

Faster wire ch. based RICH detectors

Thin multi-wire proportional chamber with cathode pad readout → short drift distance → fast detector

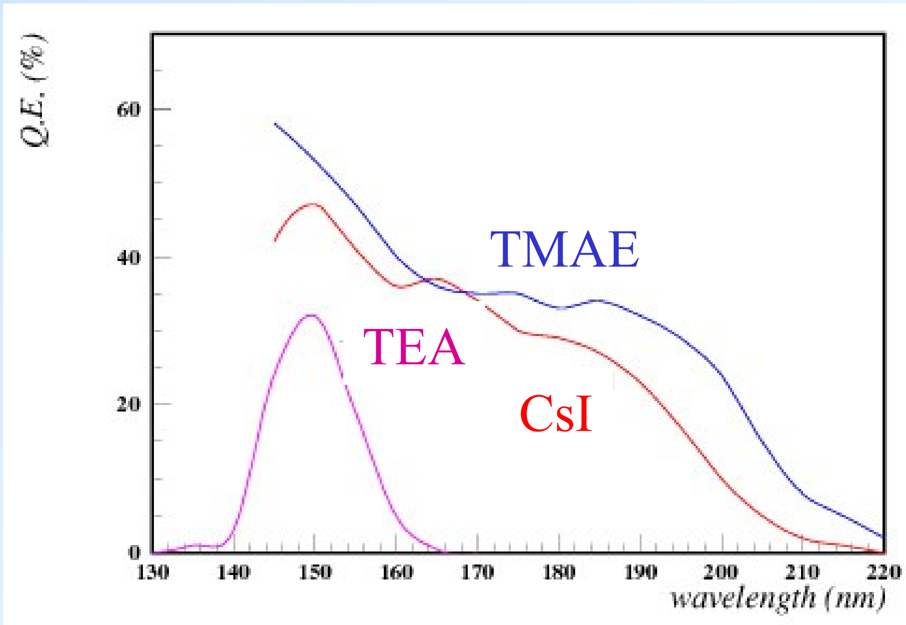


CLEO RICH:

- TEA → short absorption length
- sensitive only below 160 nm
- aging

HADES, COMPAS, ALICE RICH:

- thin CsI layer over photocathode pads
- high rate instabilities



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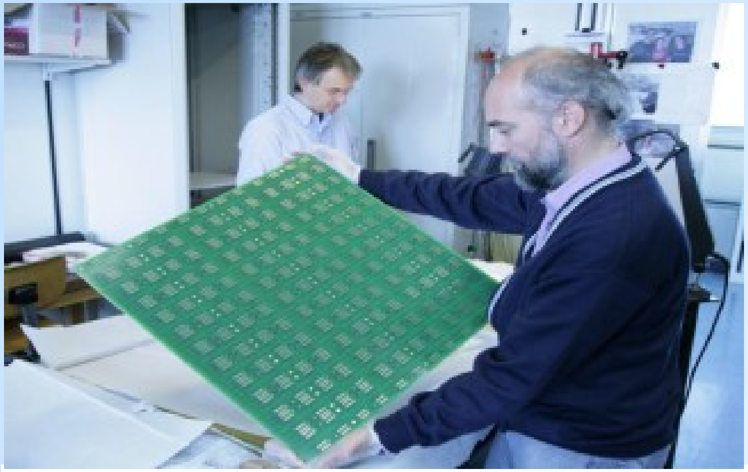
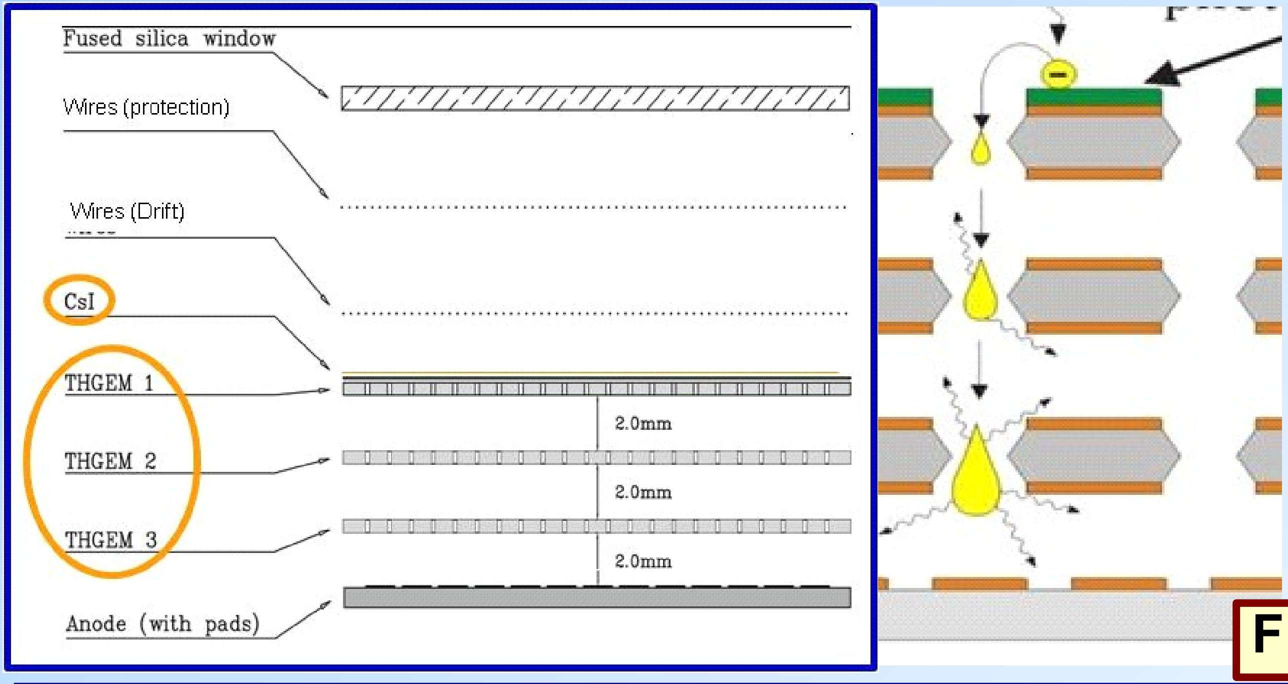
GEMs and THGEMs with CsI – gaseus detector comeback?

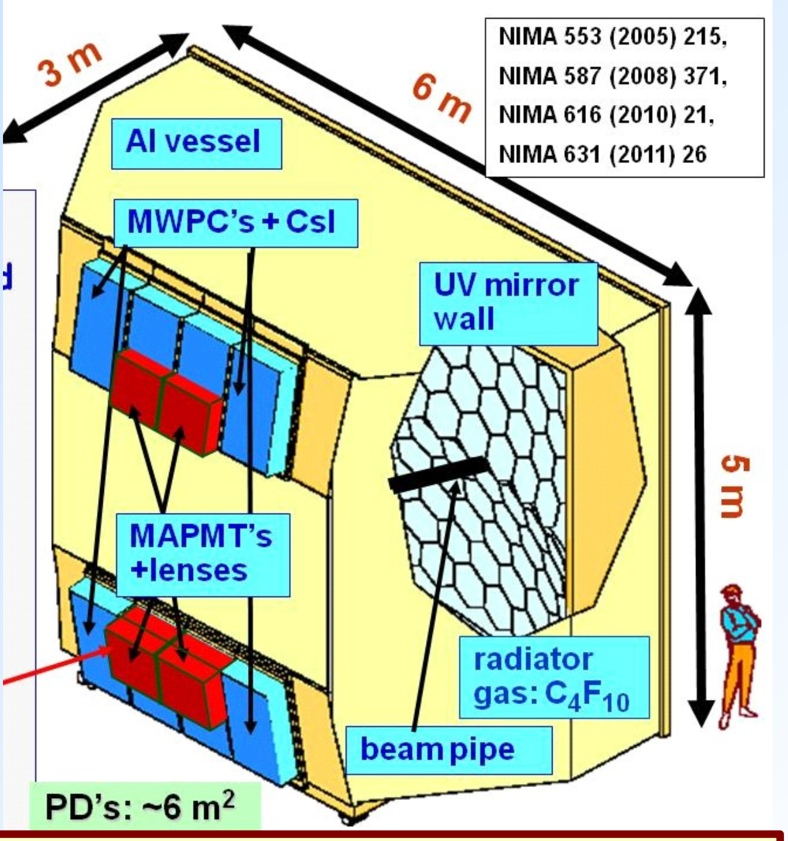
PHENIX HBD (Hadron Blind Detector)



COMPASS RICH-1 upgrade:

- THGEM + CsI – new development in gaseous photo detectors
- basic aspects have been validated and understood with small size prototypes

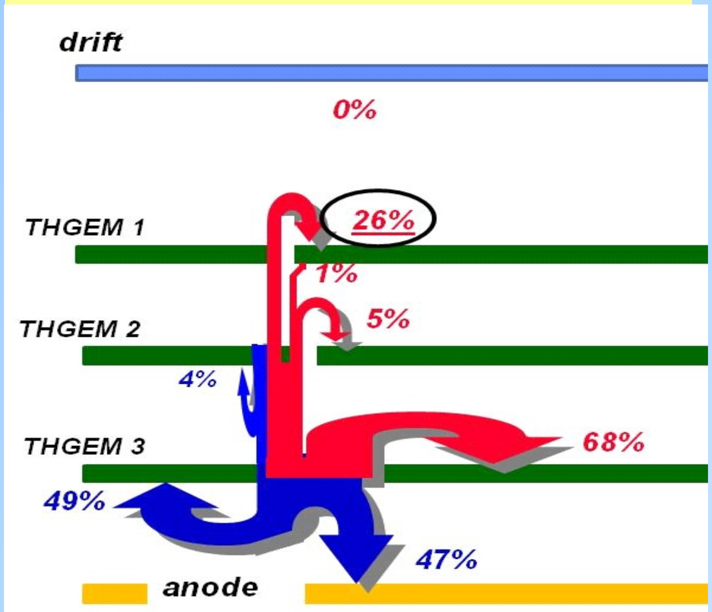




F. Tessarotto et al. @ PISA2012

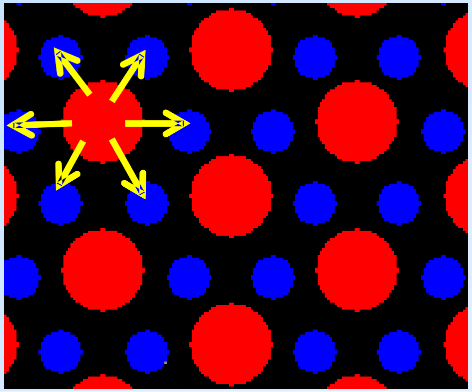
Ion back-flow reduction with "Flower THGEMs"

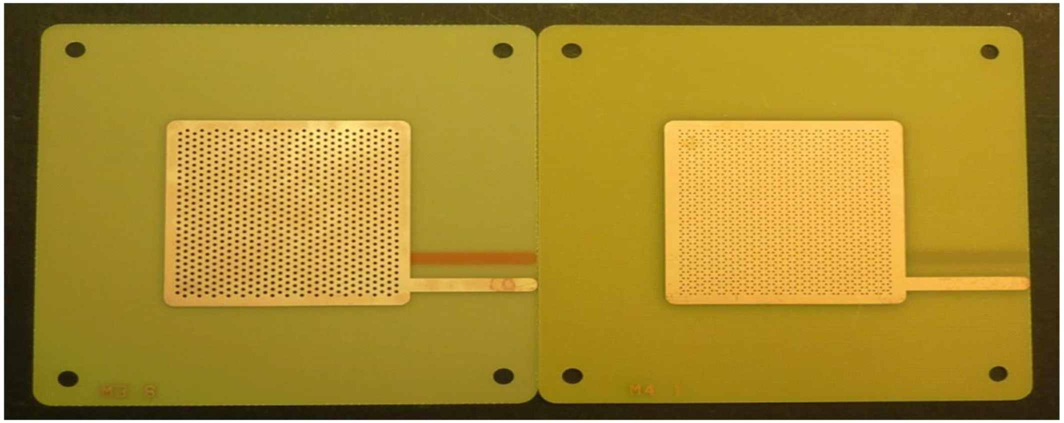
current flow for the standard triple THGEM configuration:



"Flower THGEM" configuration:
THGEM 1 has holes of 0.6 mm diameter, 1.2 mm pitch
THGEM 2 has holes of 0.3 mm diameter, 0.6 mm pitch, with 1/3 of the holes missing: the ones below the THGEM 1 holes

This configuration provides charge splitting and allows for ion backflow minimization

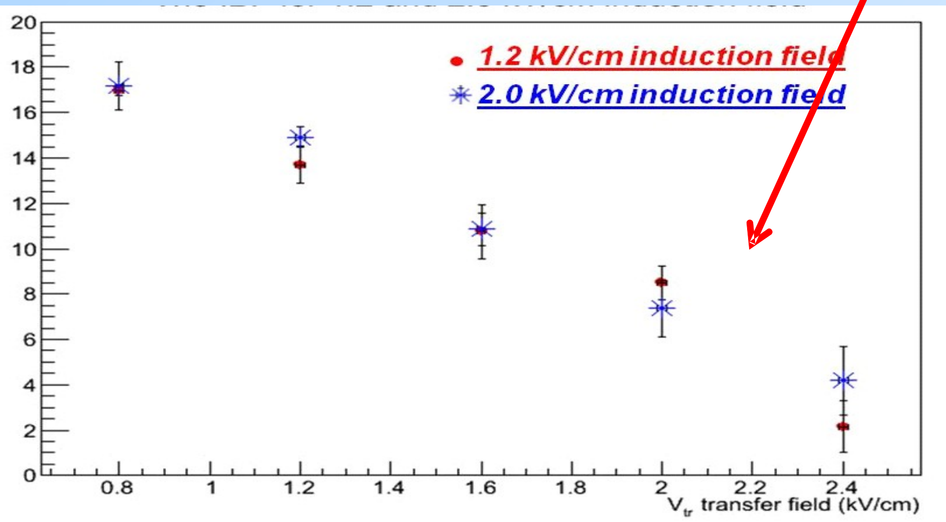




M3.9: T=0.4mm,R=0.6mm,P=1.2mm
M4.1: T=0.8mm,R=0.3mm,P=0.6mm

Drift dis. 10.6mm
Transfer dis. 2.5mm
Induction dis. 2.5mm

current on TOP of THGEM 1 in % for the "FLOWER" configuration:



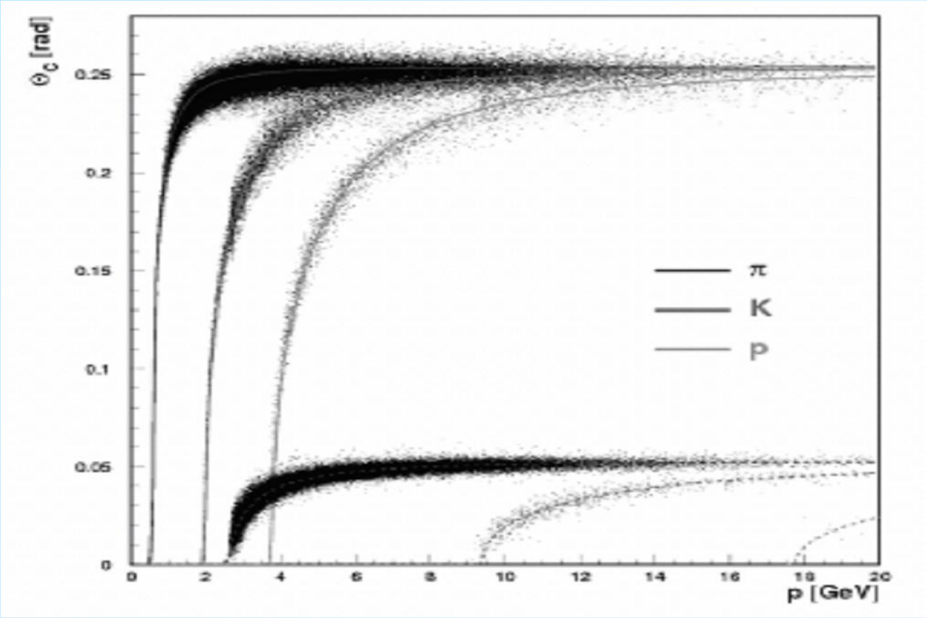
F. Tessarotto et al. @ PISA2012

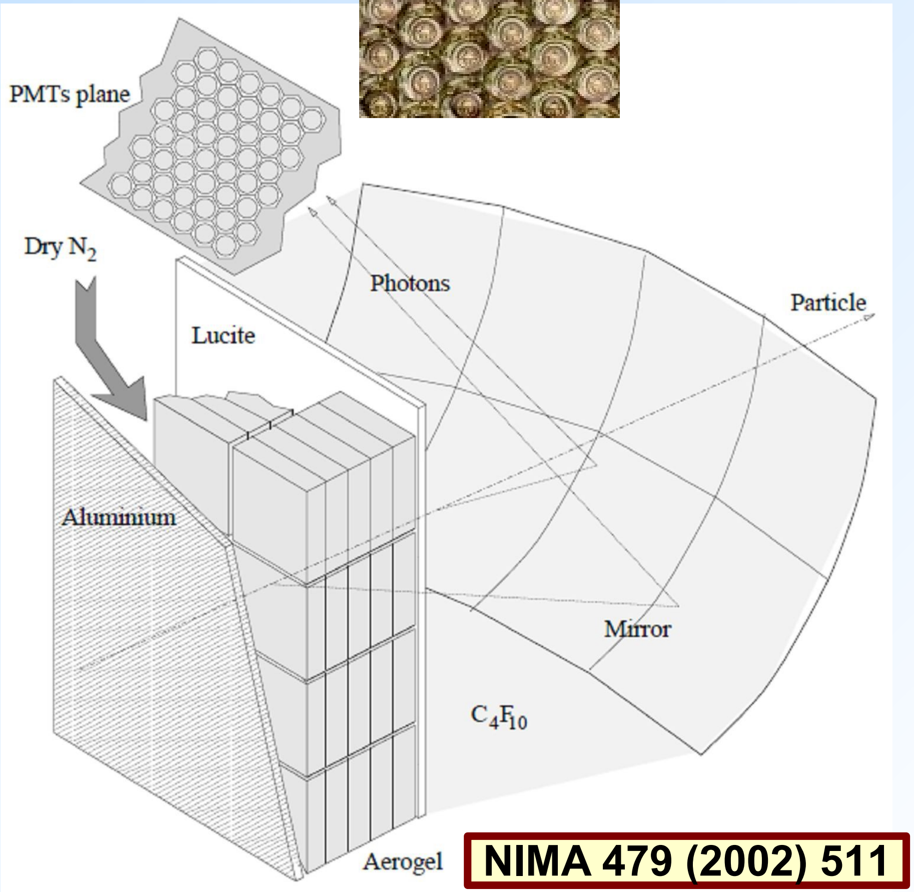
- more by S. Levorato on Friday @16:05

Move to vacuum based photon detectors - PMTs

- operation at high rates over longer periods
- sensitivity for visible light – compatible with aerogel radiator
- does not work in magnetic field

HERMES RICH (SELEX, PHENIX):
- dual radiator C_4F_{10} (n=1.00137 @ 633nm)+ aerogel (n=1.03 @ 633nm)
- single channel PMTs (¾ inch, Philips XP1911/UV)



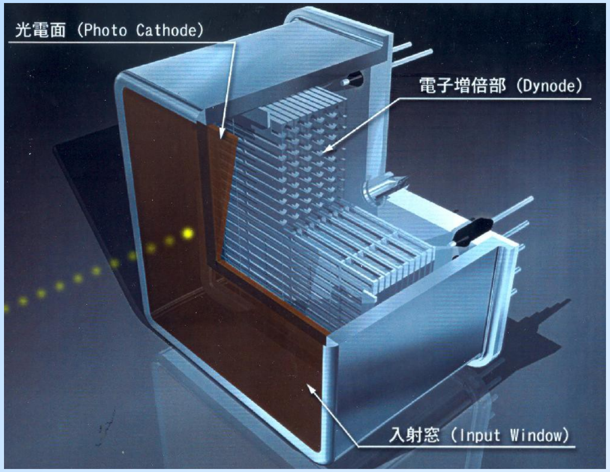


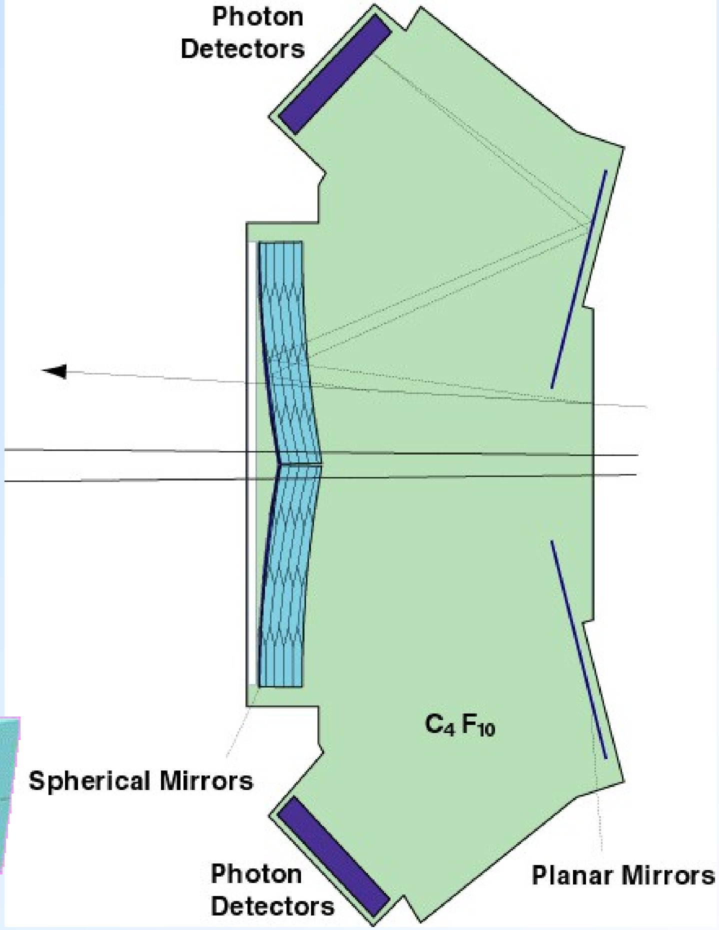
NIMA 479 (2002) 511

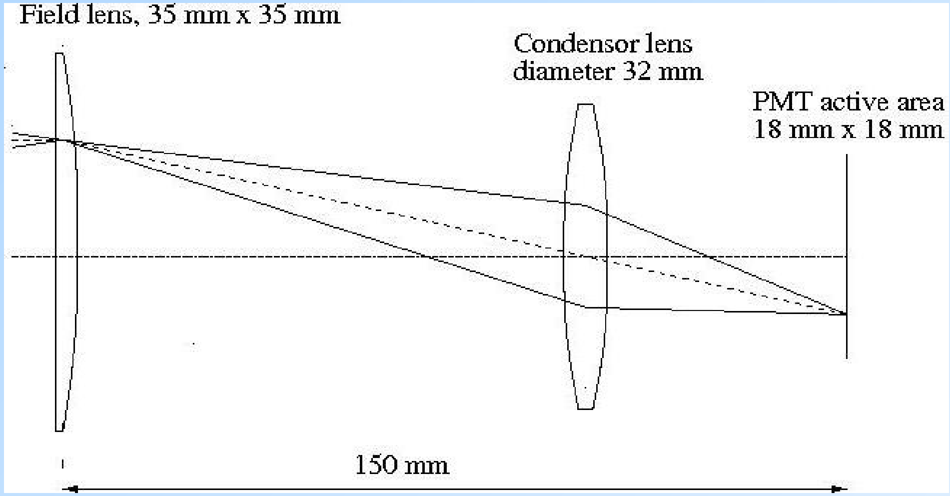
Multi-anode PMTs

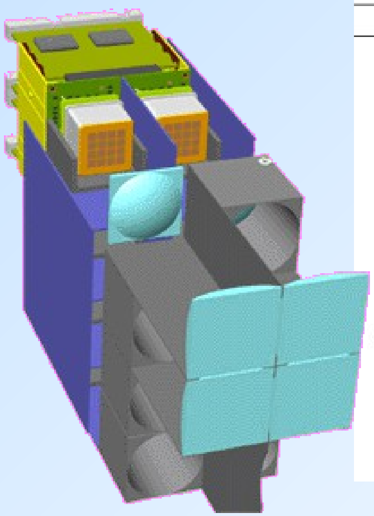
- smaller pad size → better resolution

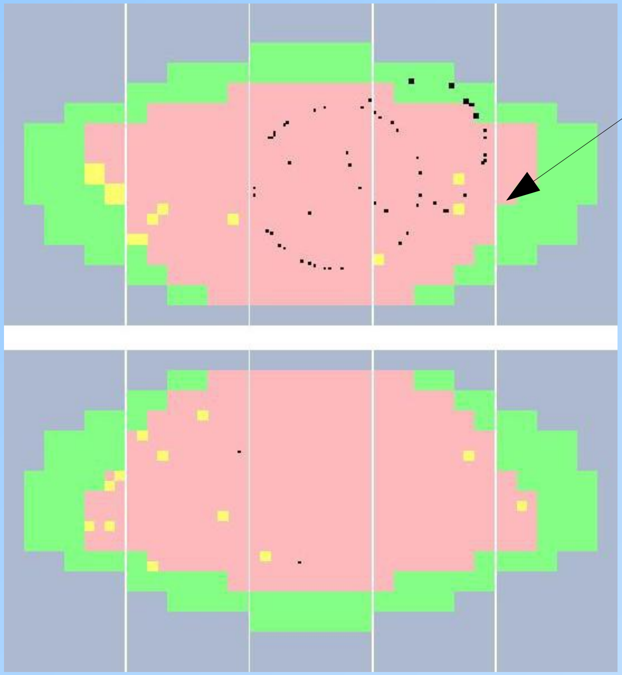
HERA-B RICH:
- high rate operation (>1MHz/cm^2) → wire chamber prototypes(CsI,TMAE) abandoned
- multi-anode PMTs (Hamamatsu) → first use on large scale
  - excellent single photoelectron detection
  - low noise (few dark counts/s/ch.)
  - low cross-talk (< 1%)
  - low active area ration (<50%) → imaging light concentrators (area ratio 4:1)



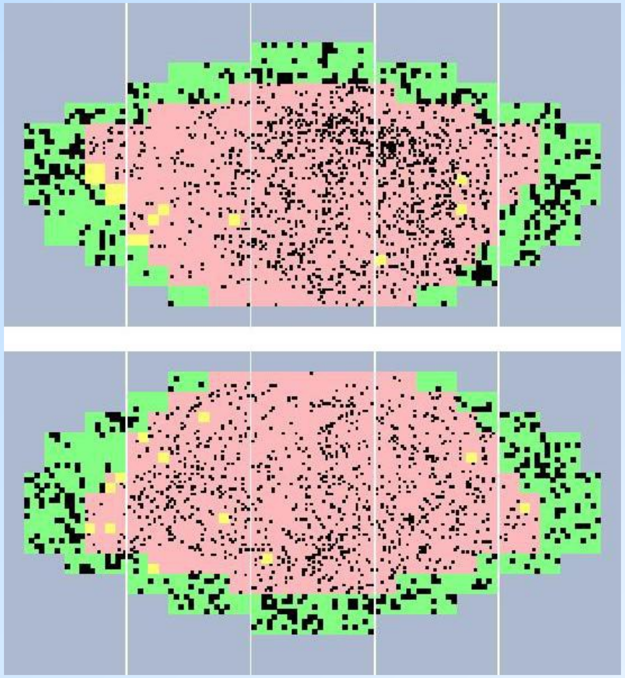


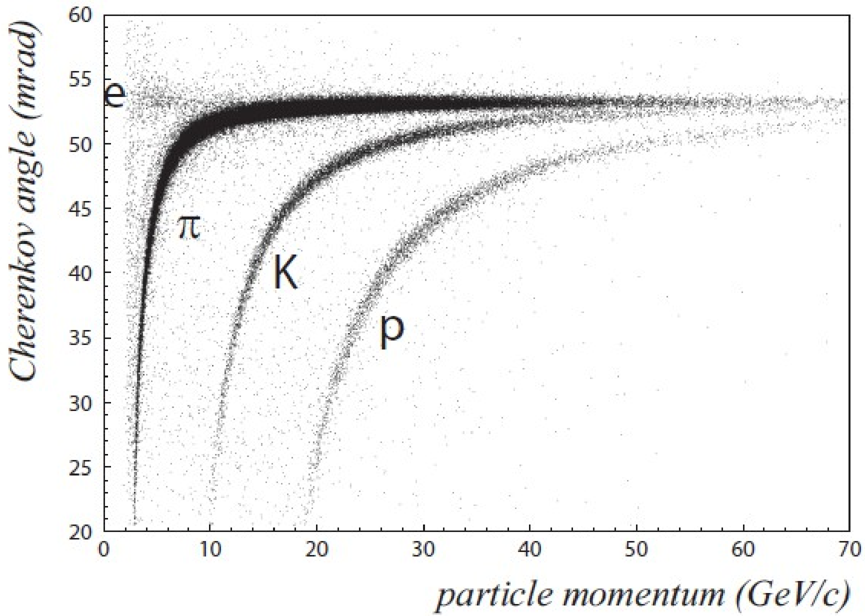


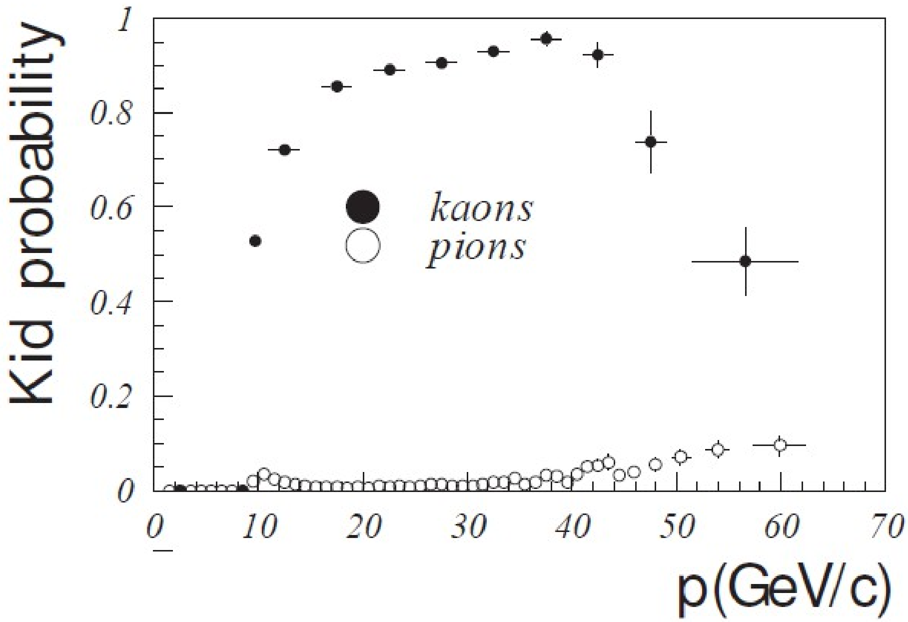




- low noise (few hits per event)
- 30 ph./ring(saturated)
- good performance even at high occupancy events (typical)

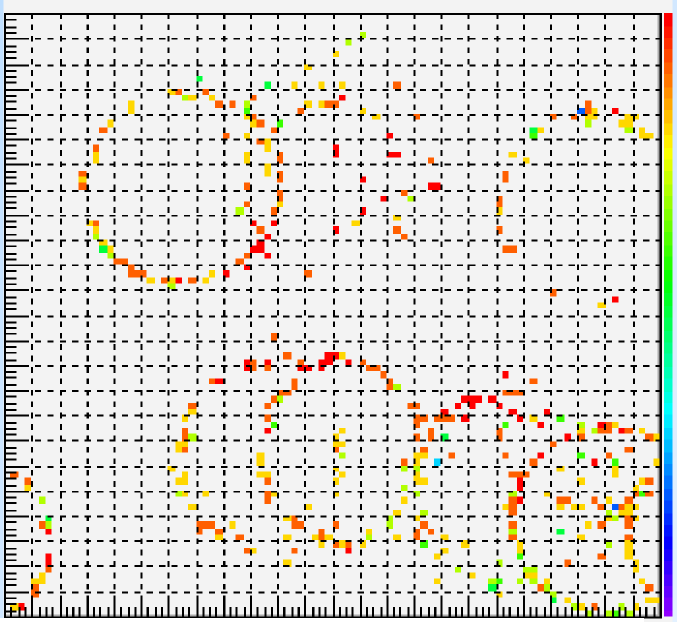


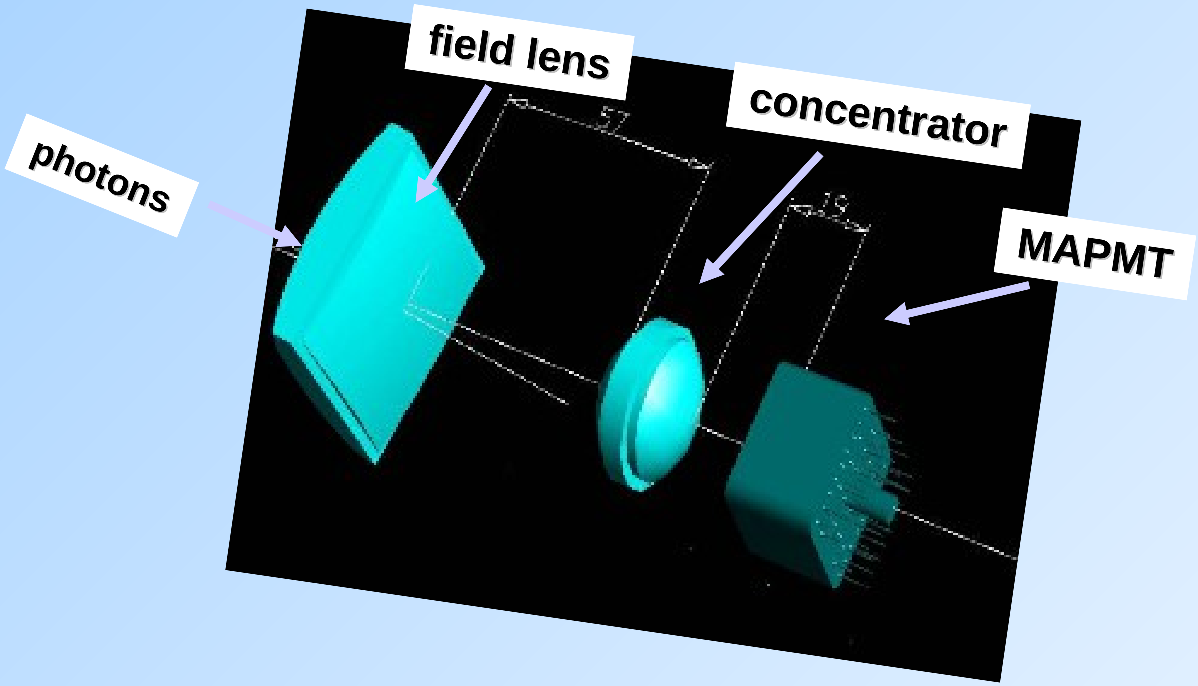


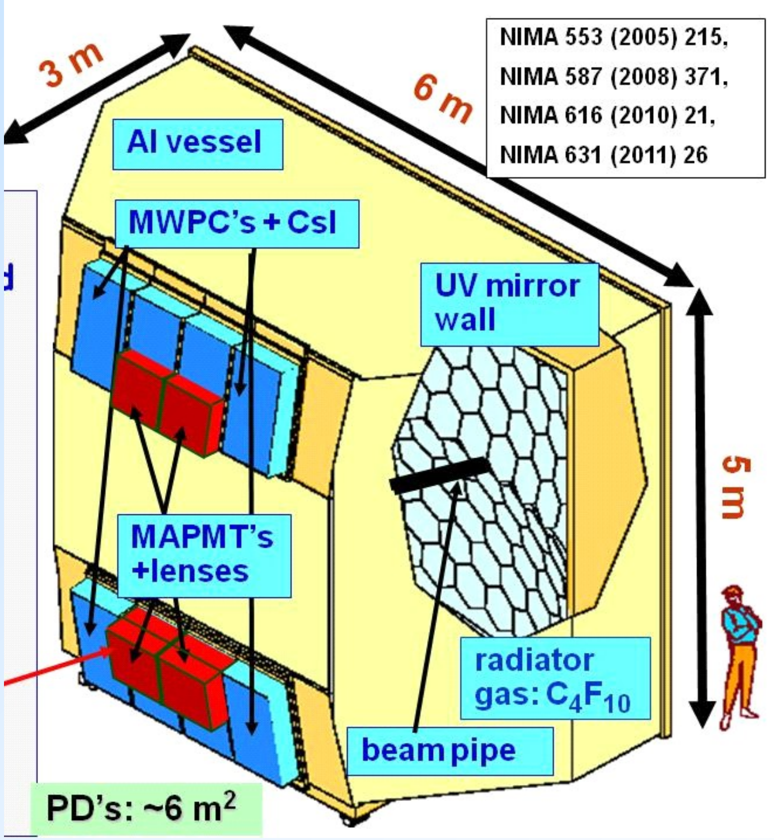


COMPAS RICH upgrade:

- CsI in central (high occupancy) part replaced with multi-anode PMTs
- similar imaging light concentrator system used
  - UV extended PMTs and optics (down to 200 nm)
  - area demagnification 7:1
  - 60 ph./ring, resolution 0.3 mrad ...



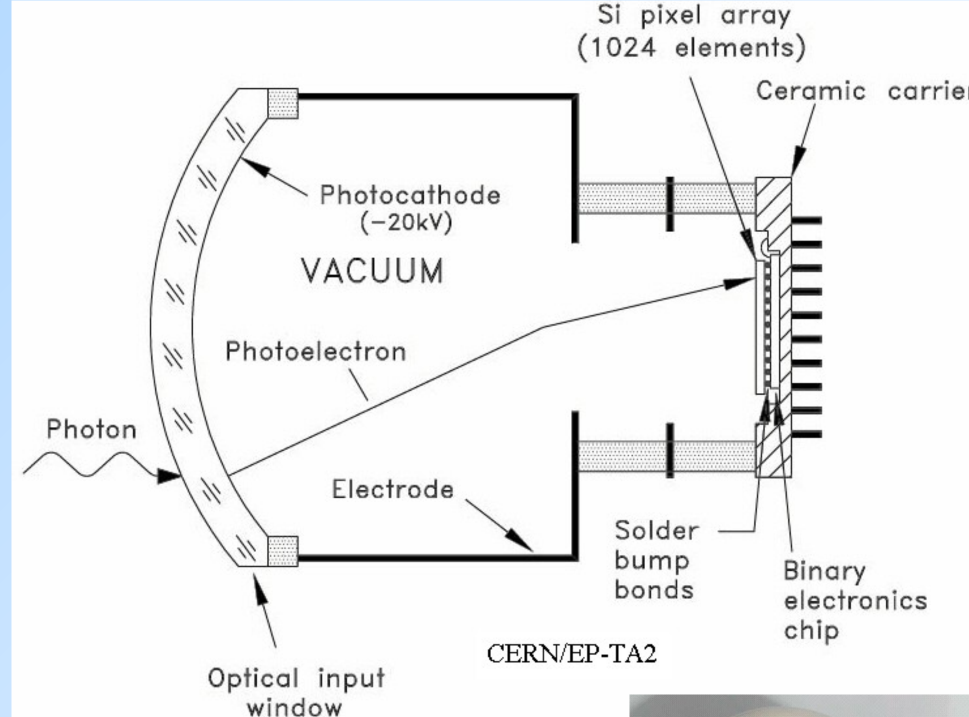


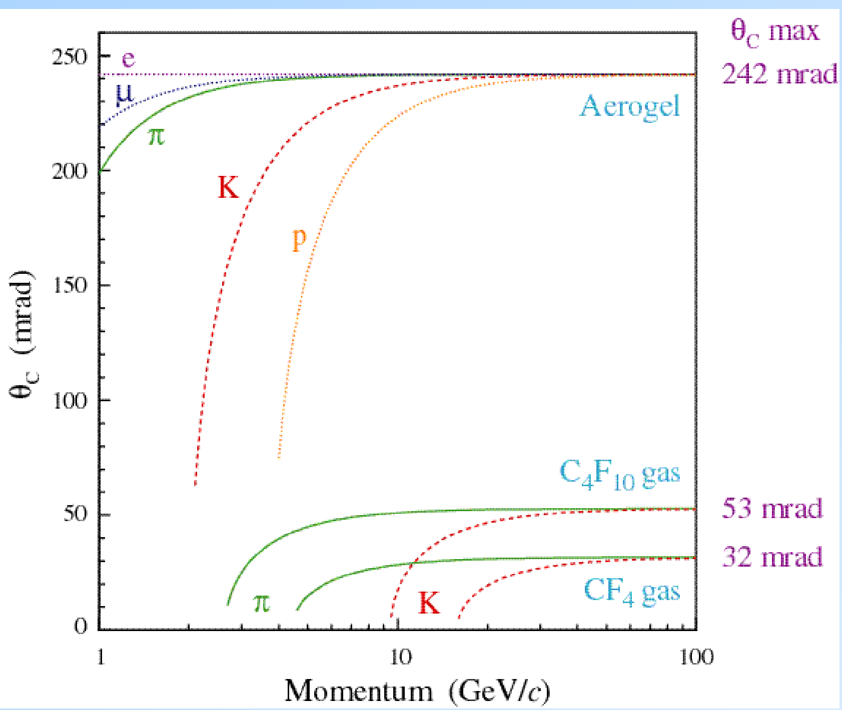


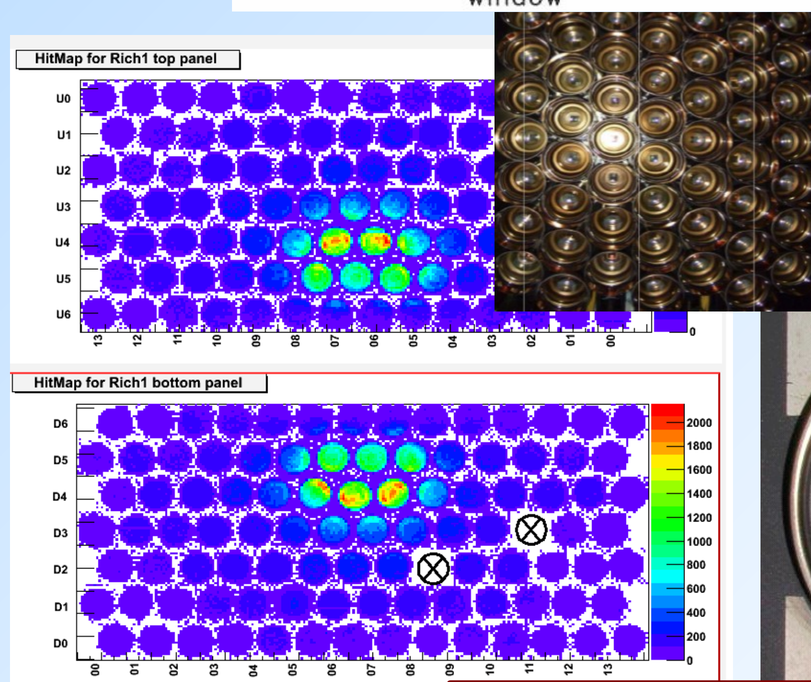
- more by F. Tessarotto today @12:05

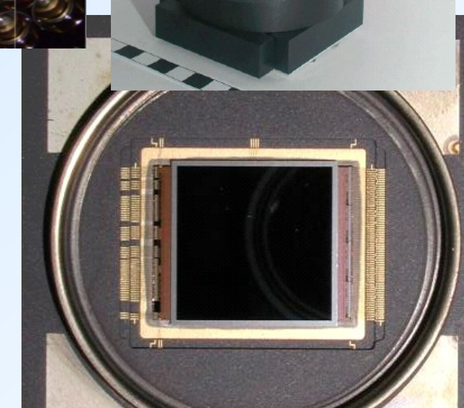
HPD - LHCb RICH

- 2 RICHs with 3 radiators (aerogel, C_4F_{10}; CF_4)
- Hybrid Photon Detector introduced
  - electron optics → 5x demagnification
  - sensitive to magnetic field
  - HV ~20kV, gain ~5k
  - CERN+DEP-Photonis









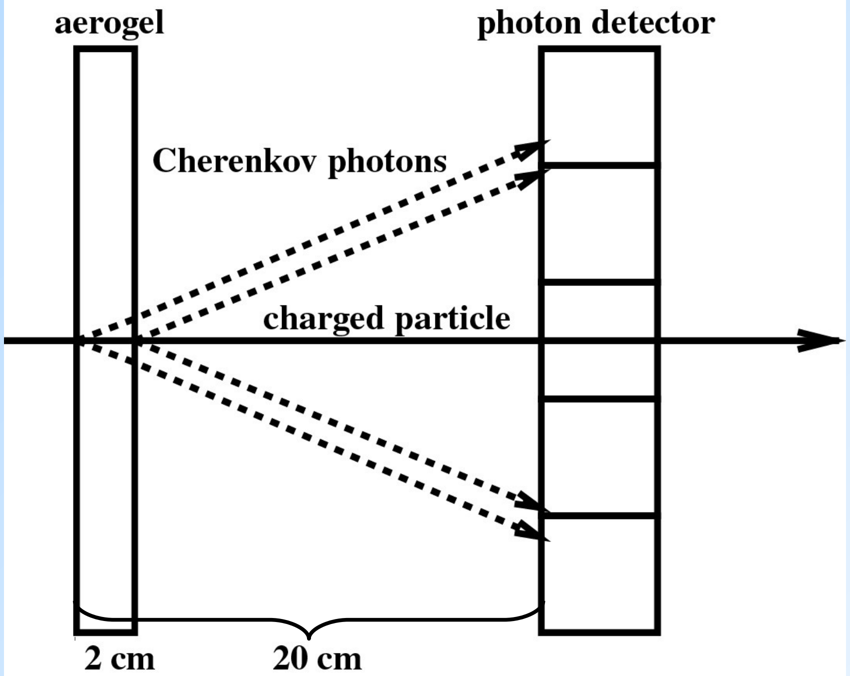
M Adinolfi et al., NIM A 603 (2009) 287

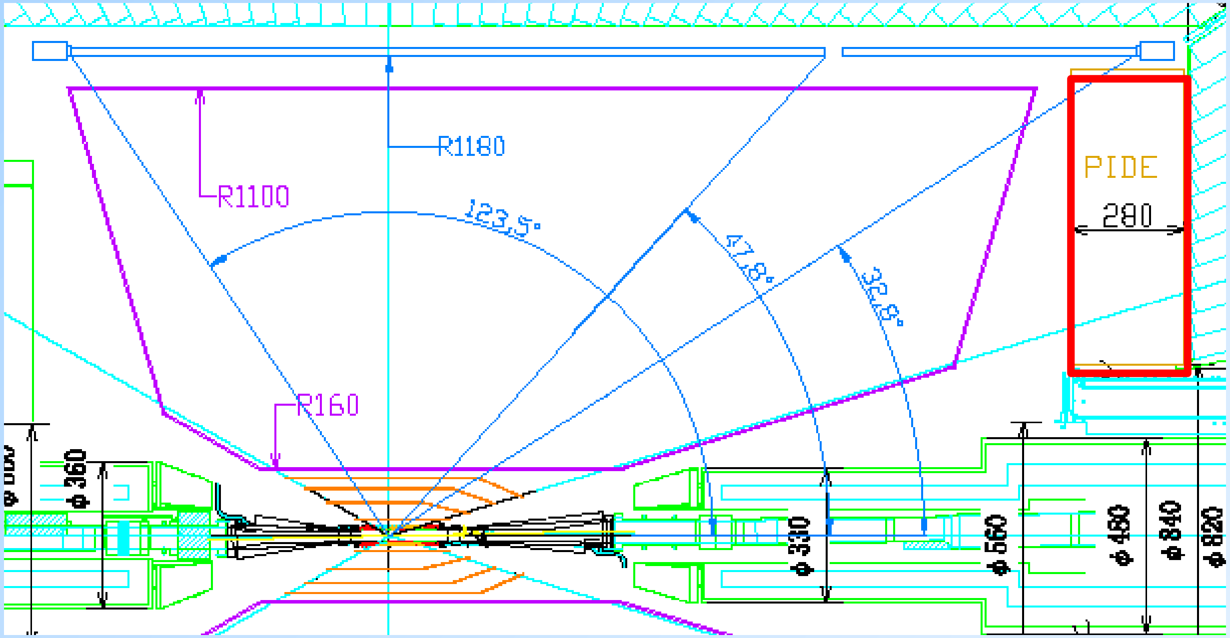
Belle II Aerogel RICH

Belle II forward PID - **ARICH**

Goals and constraints:

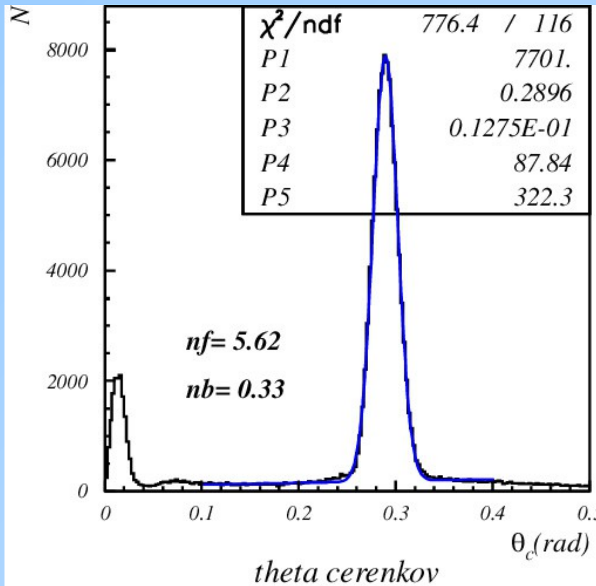
- > 4 σ K/π separation @ 1-3.5 GeV/c
- operation in magnetic field 1.5T
- limited available space ~250 mm

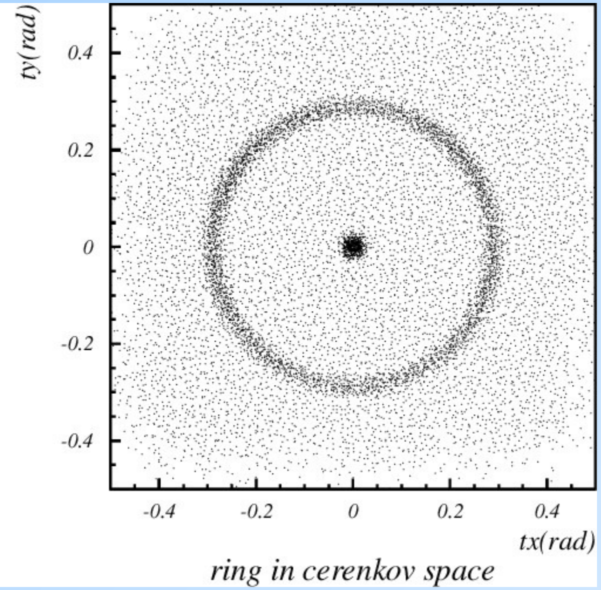




- n ~ 1.05
- $\vartheta_c(\pi) \approx$ 307 mrad @ 3.5 GeV/c
- $\vartheta_c(\pi) - \vartheta_c(K)$ = 30 mrad @ 3.5 GeV/c
- pion threshold 0.44 GeV/c, kaon threshold 1.54 GeV/c

Proximity focusing aerogel RICH

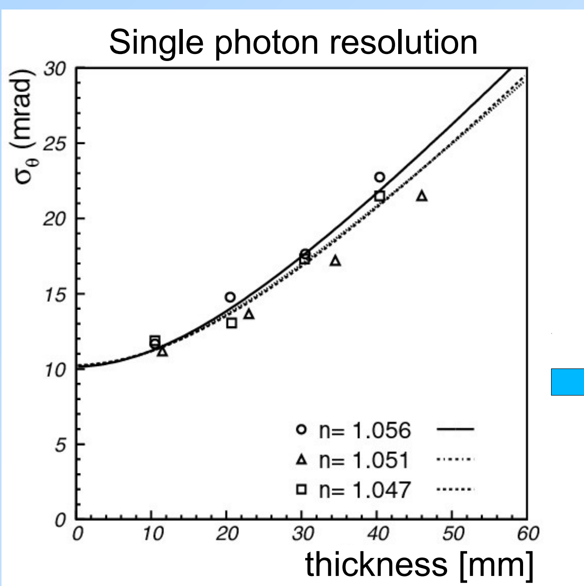


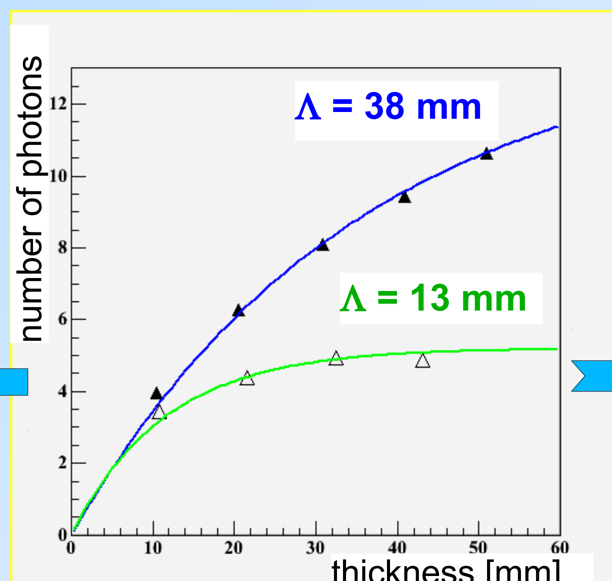


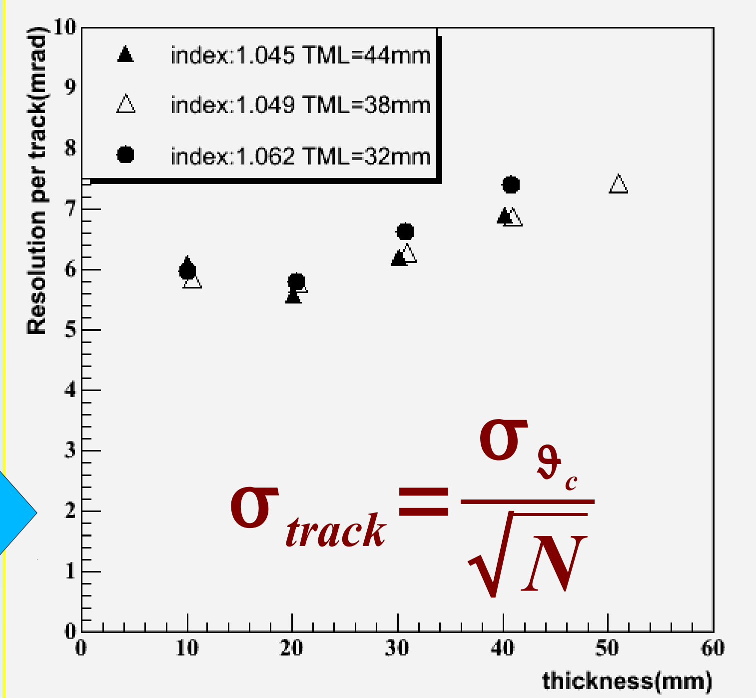
- Typical distributions for 2cm sample, obtained in the pion beam tests → N_{ph}, ϑ_C

Cherenkov angle resolution per track is optimal at ~ 2cm

- Radiators of different thicknesses and refractive indices were tested (2001,2003)





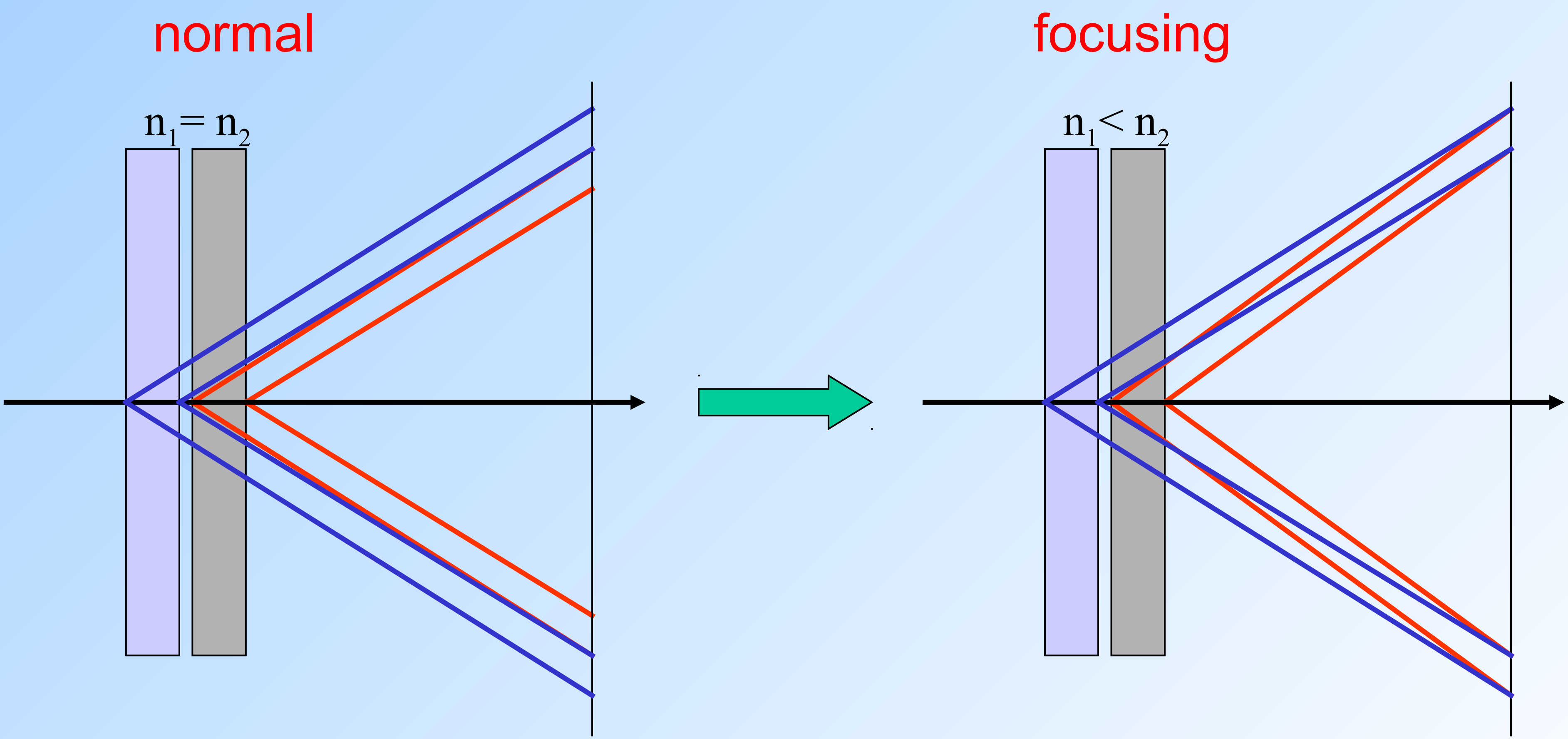


$$\sigma_{track} = \frac{\sigma_{\vartheta_c}}{\sqrt{N}}$$

Multilayer focusing configuration

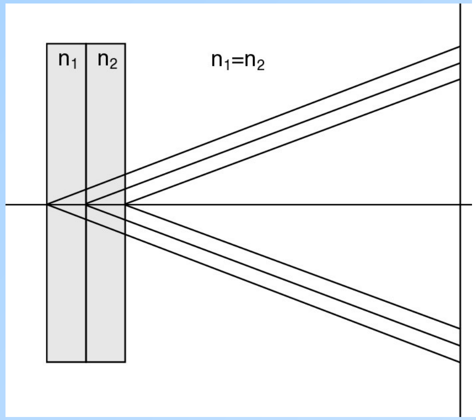
How to increase number of photons without degrading the resolution?

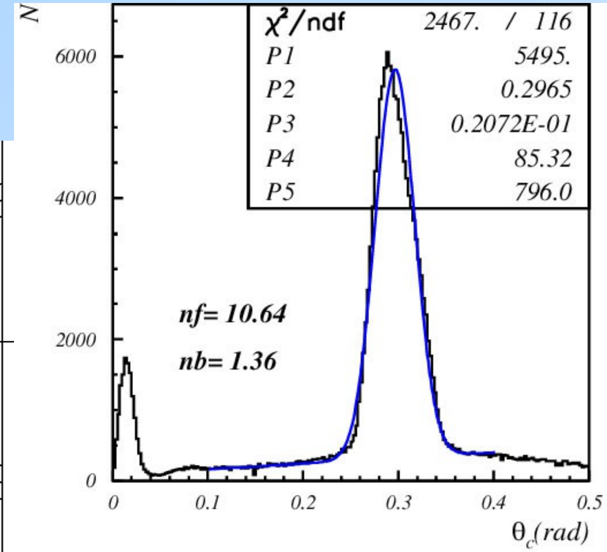
Use radiator with gradually increasing refractive index in downstream direction - “focusing radiator”

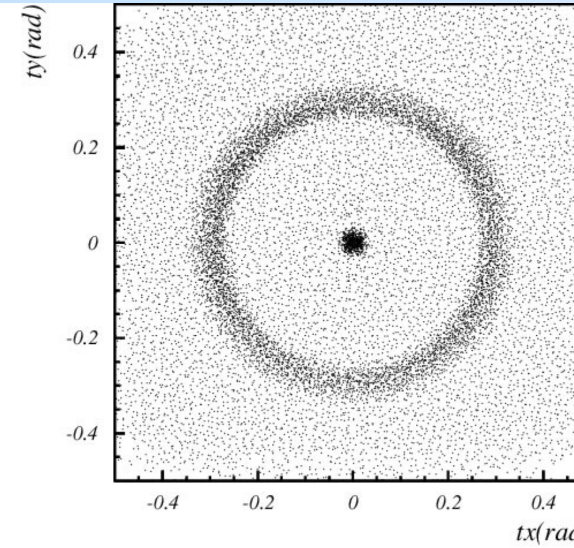


Focusing aerogel radiator

- 2cm+2cm single index aerogel

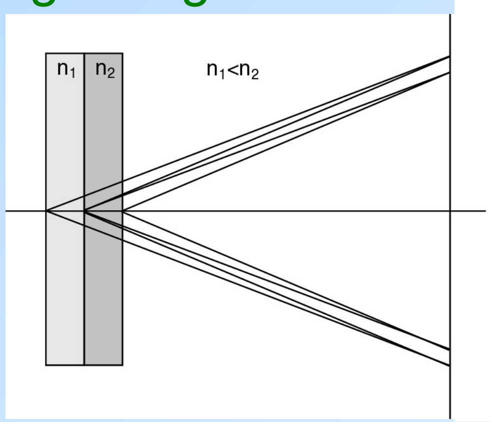


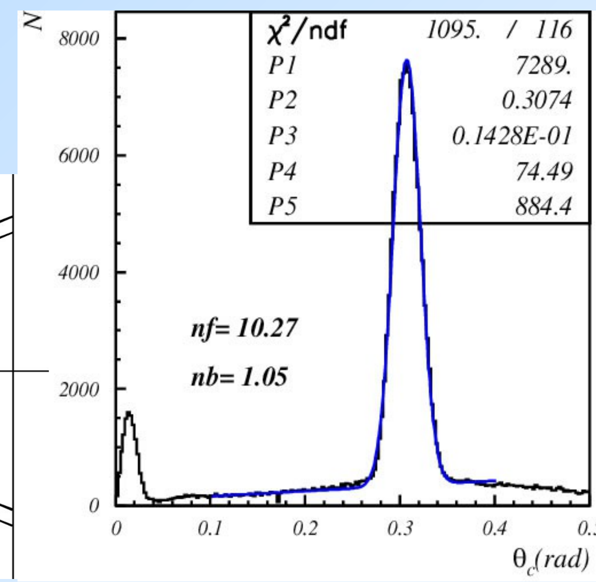


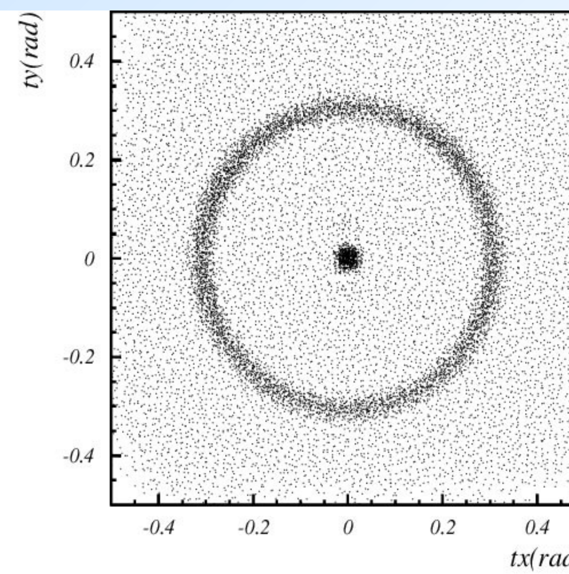


- σ_{single}= 21 mrad
- σ_{track}= 6.4 mrad

- 2cm+2cm focusing aerogel







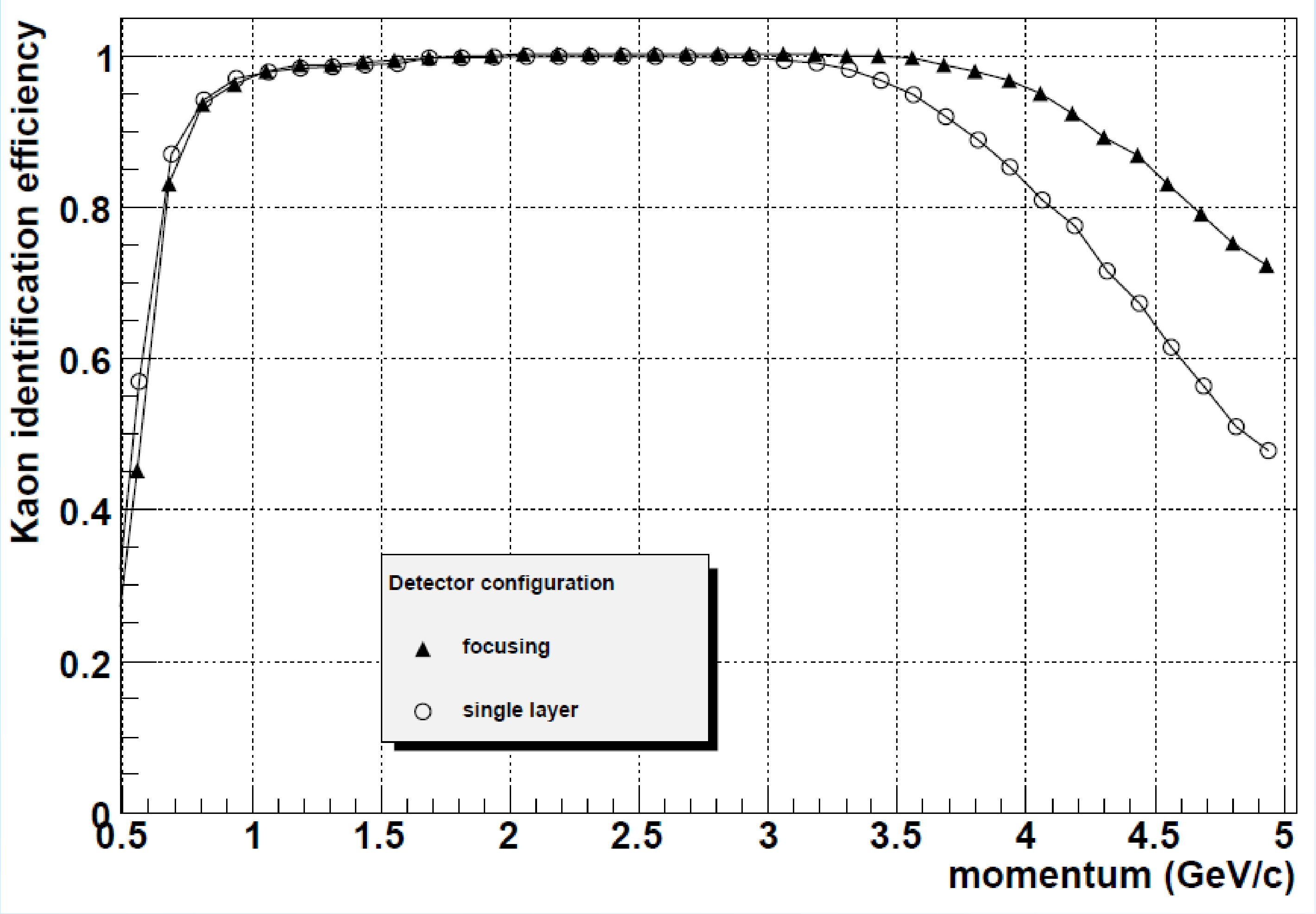
- σ_{single}= 14 mrad
- σ_{track}= 4.6 mrad

>6σ at 3.5GeV/c

NIM A548 (2005) 383, NIM A553 (2005) 64

PID capability - MC results, focusing configuration

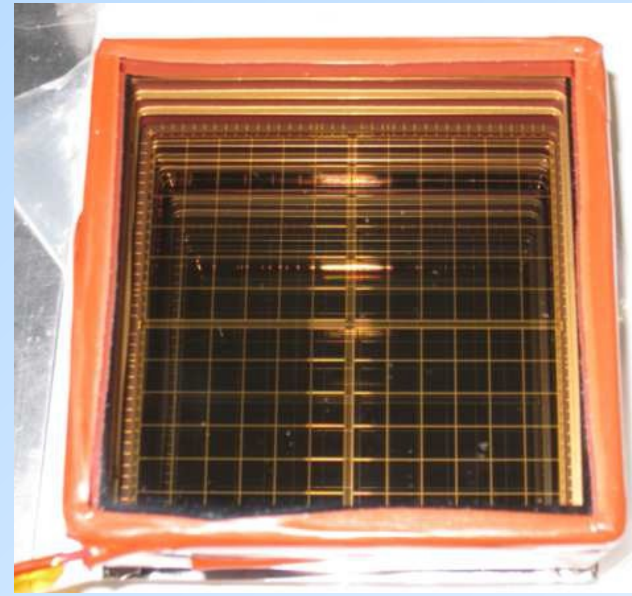
- 3cm single radiator (○) compared to 2x1.5cm focusing radiator (n~1.05)
- focusing radiator improves PID for momenta above ~3GeV

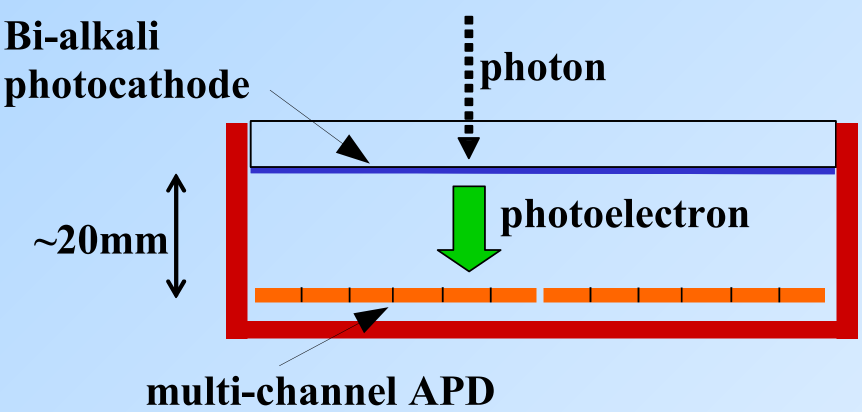


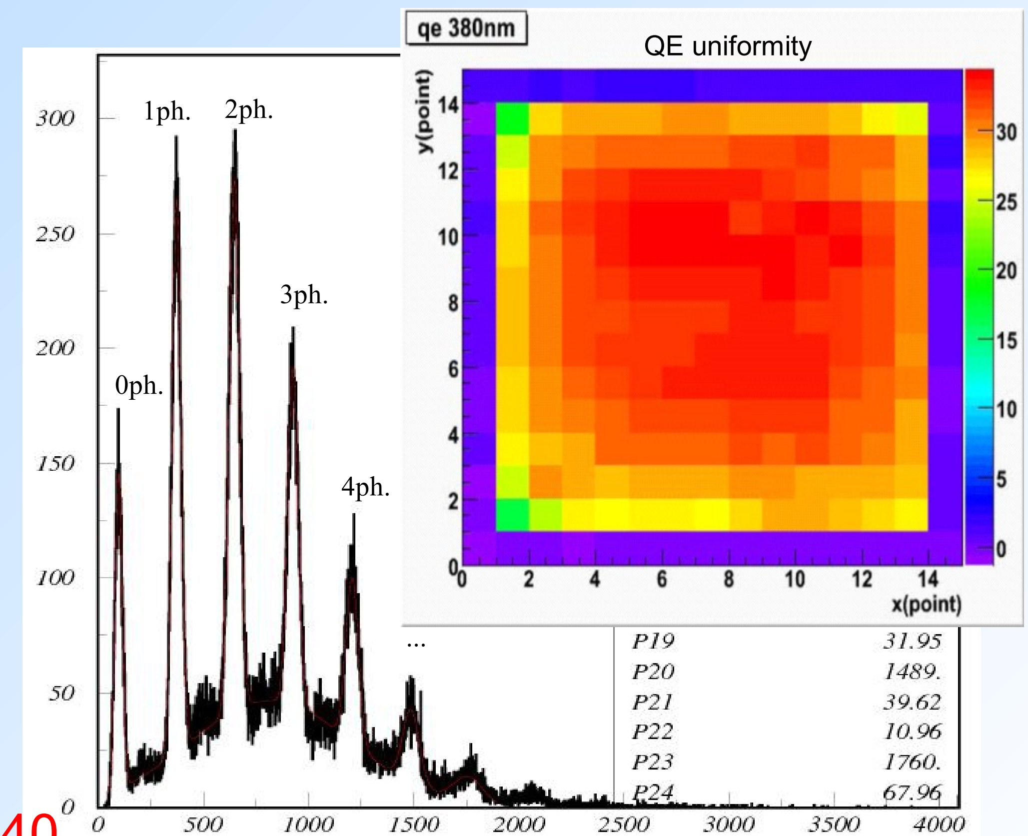
HAPD photon detector for ARICH

Hybrid avalanche photo-detector developed in cooperation with Hamamatsu (proximity focusing configuration):

- 144=12x12 channels (~5x5 mm^2)
- size ~ 73mm x 73mm (65% effective area)
- total gain ~ 4.5x10^4
(bombardment >1500, avalanche >40)
- typical peak QE ~ 28% (>24%)
- works in magnetic field
(~perpendicular to the entrance window)







Good photon counting

- more about ARICH by Y. Yusa today @14:40

Photon detector candidate: SiPM

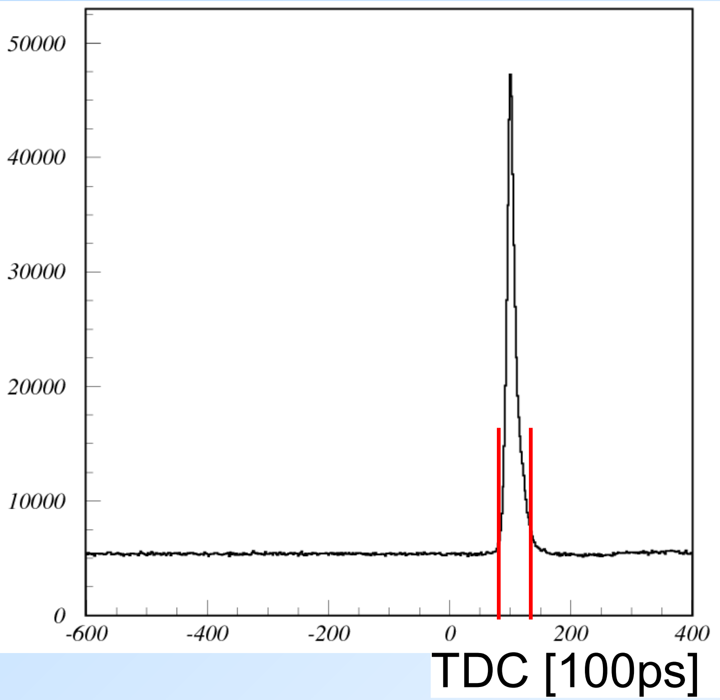
- immune to magnetic field
- high photon detection efficiency (PDE)
- good timing properties (< 300ps FWHM)
- no high voltage
- low material budget
- high noise rate ~ 0.1MHz/mm^2
- radiation damage - increase of dark noise

Possible candidate:

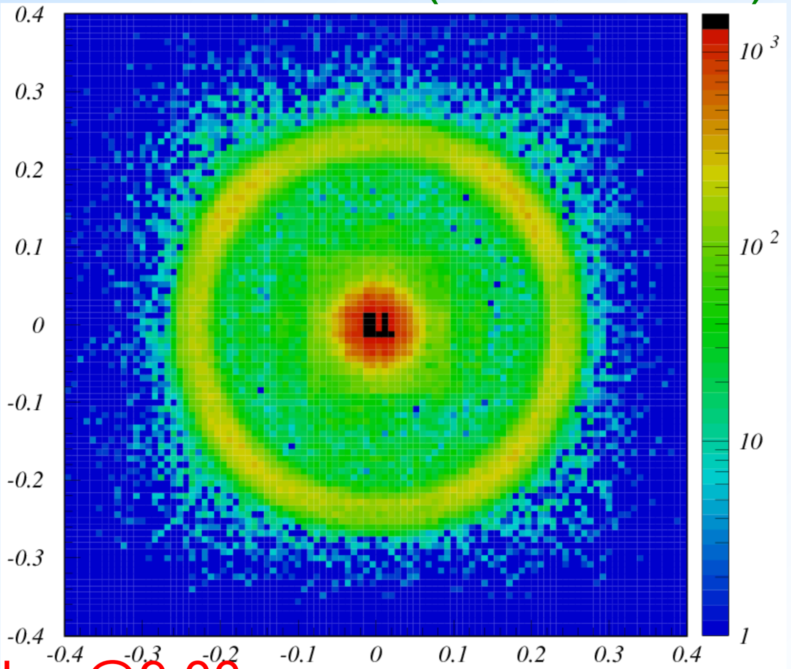
- array of Hamamatsu S10362-11-100P

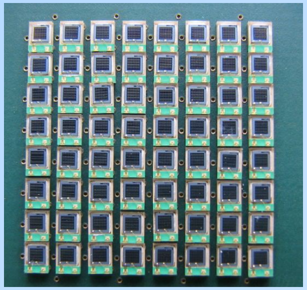
Improve signal to noise ratio by:

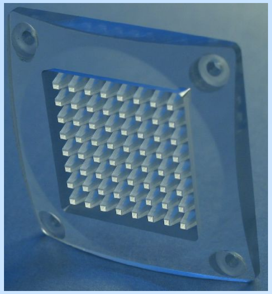
- narrow time window
- use of light concentrators

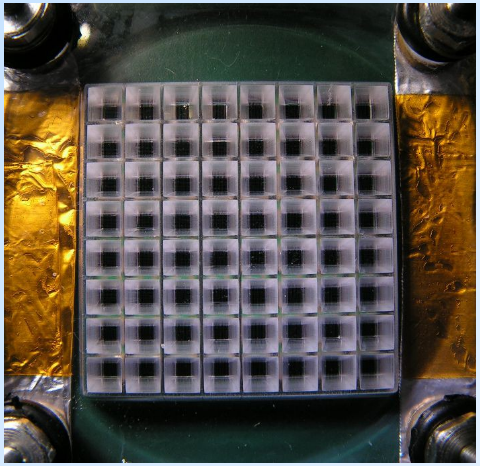


- beam test result (1cm,n=1.03)





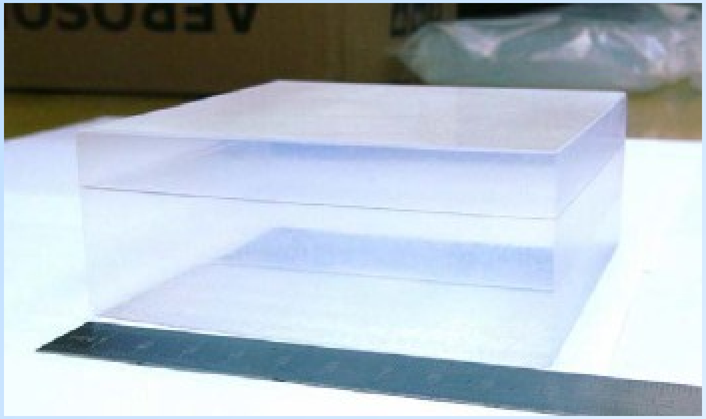


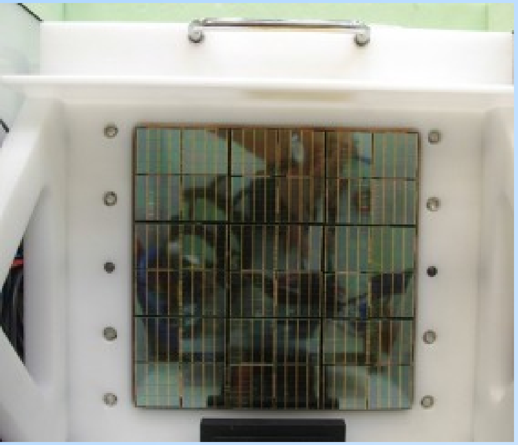


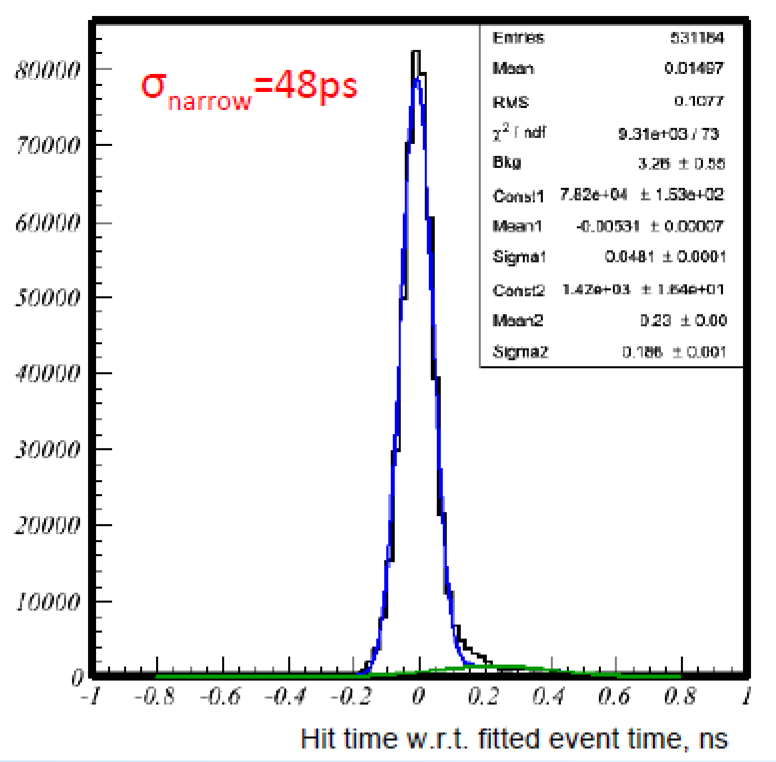
- more about solid state sensorsby Y. Musienko Thursday @9:00

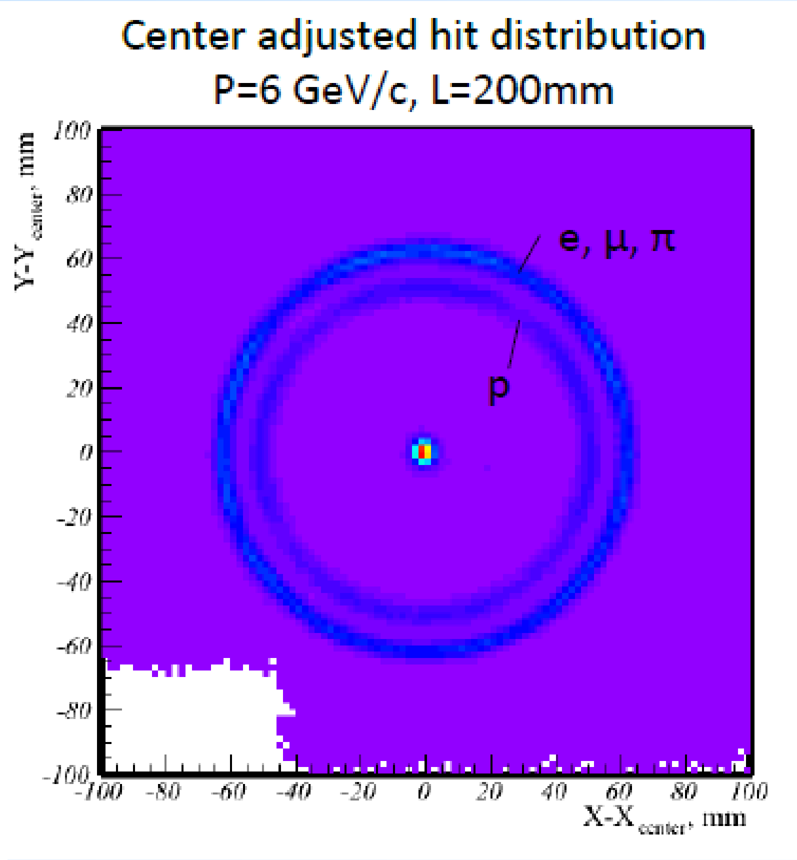
FARICH (Focusing Aerogel RICH) kandidate for ALICE, PANDA, Super c-τ, (SuperB):

- another focusing aerogel development
- SiPM photon detector
- first use of digital SiPMs from Philips
  - tested at CERN
  - excellent timing
  - still some open questions ...







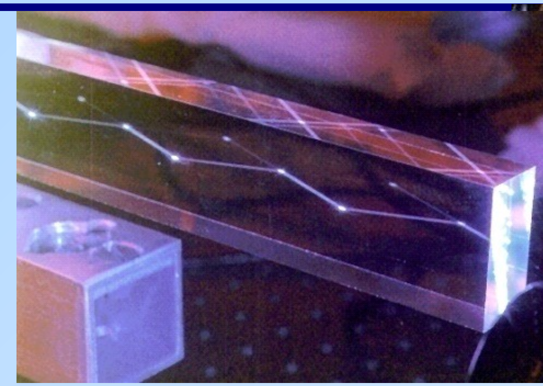


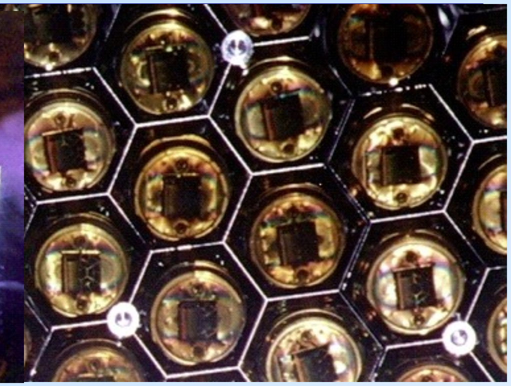
- more by S. Kononov Thursday @9:30

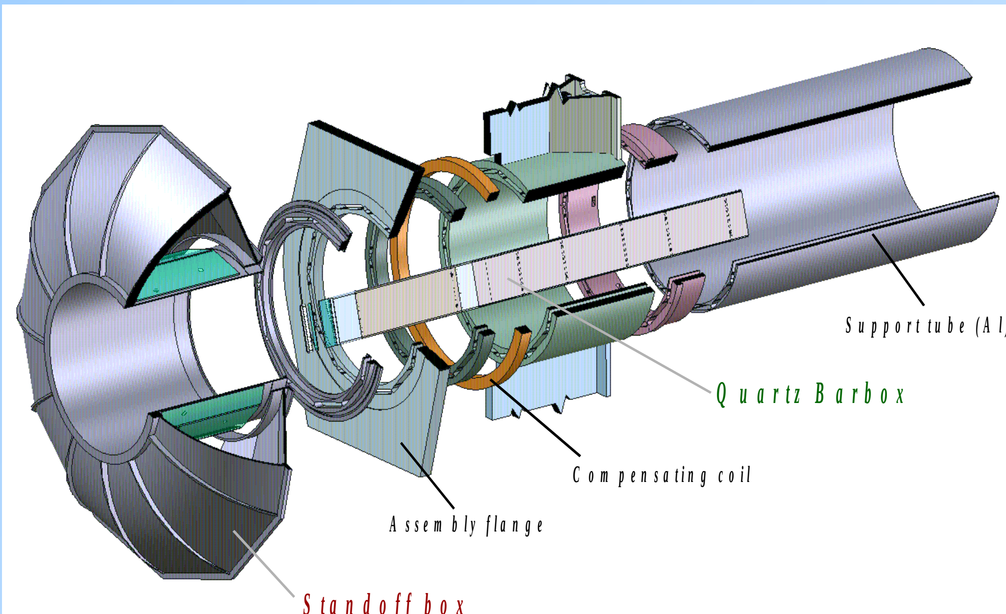
S.Kononov @AFAD2013

DIRC detector @ BaBar

- quartz bar as radiator and light guide
- water filled expansion volume with PMTs outside magnetic field

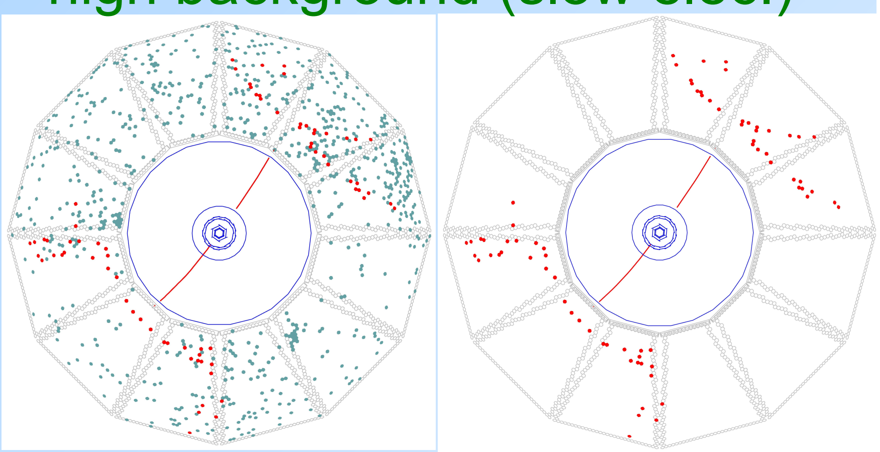


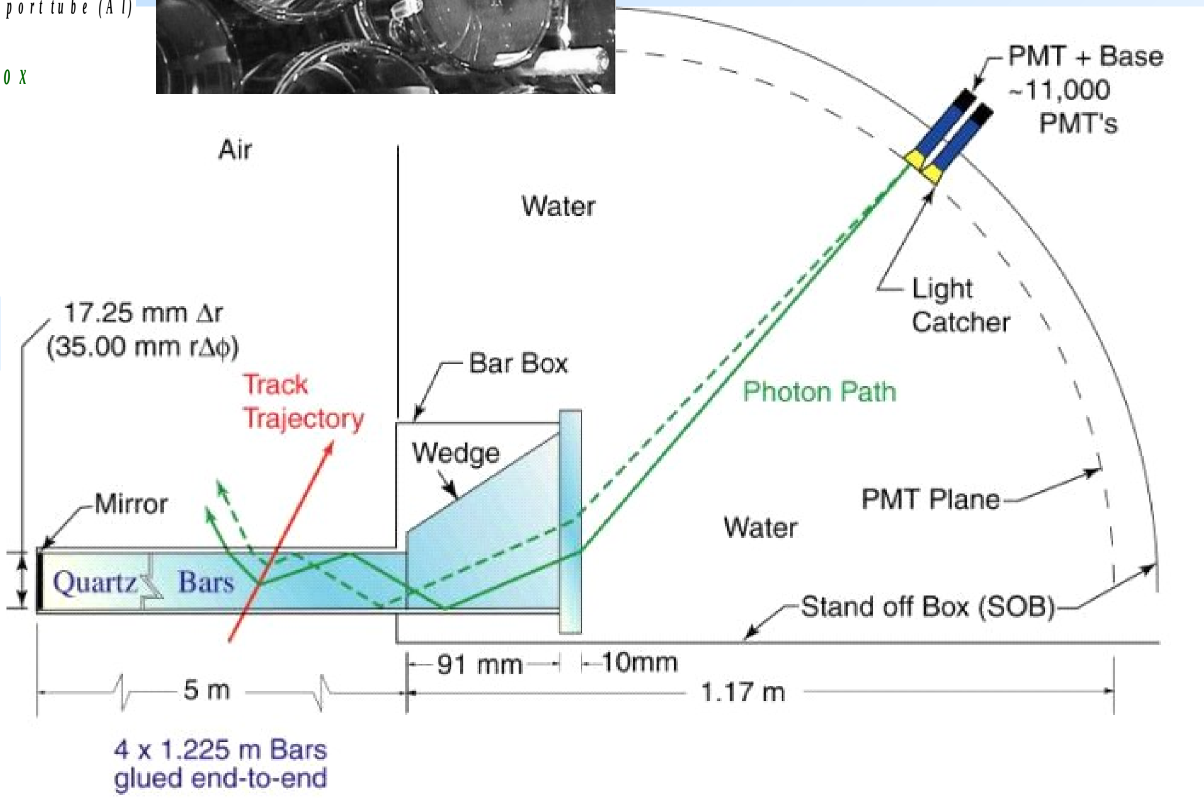




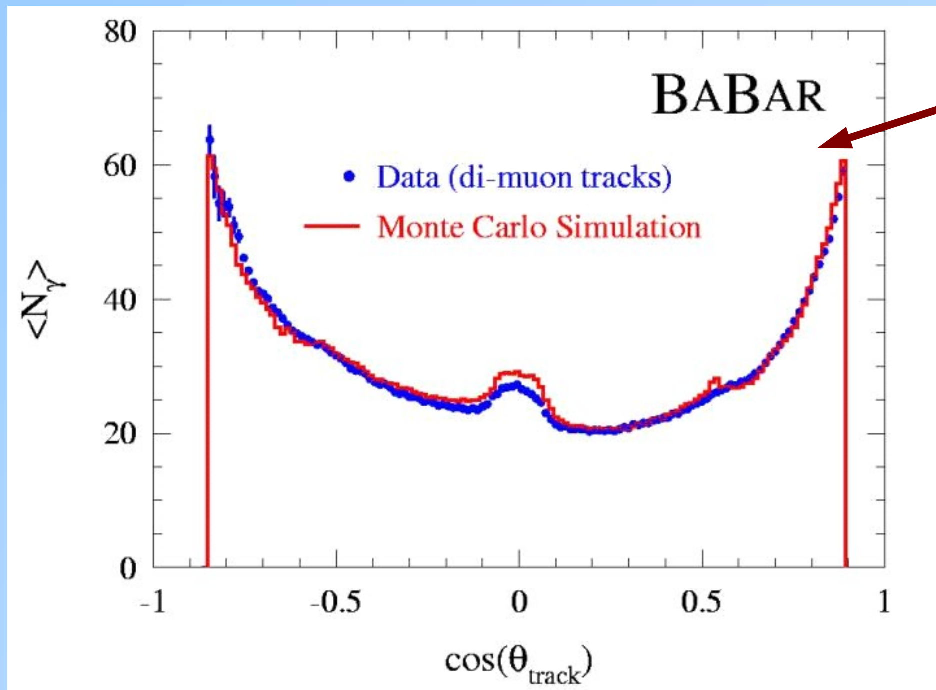
- some damaged PMTs

- high background (slow elec.)

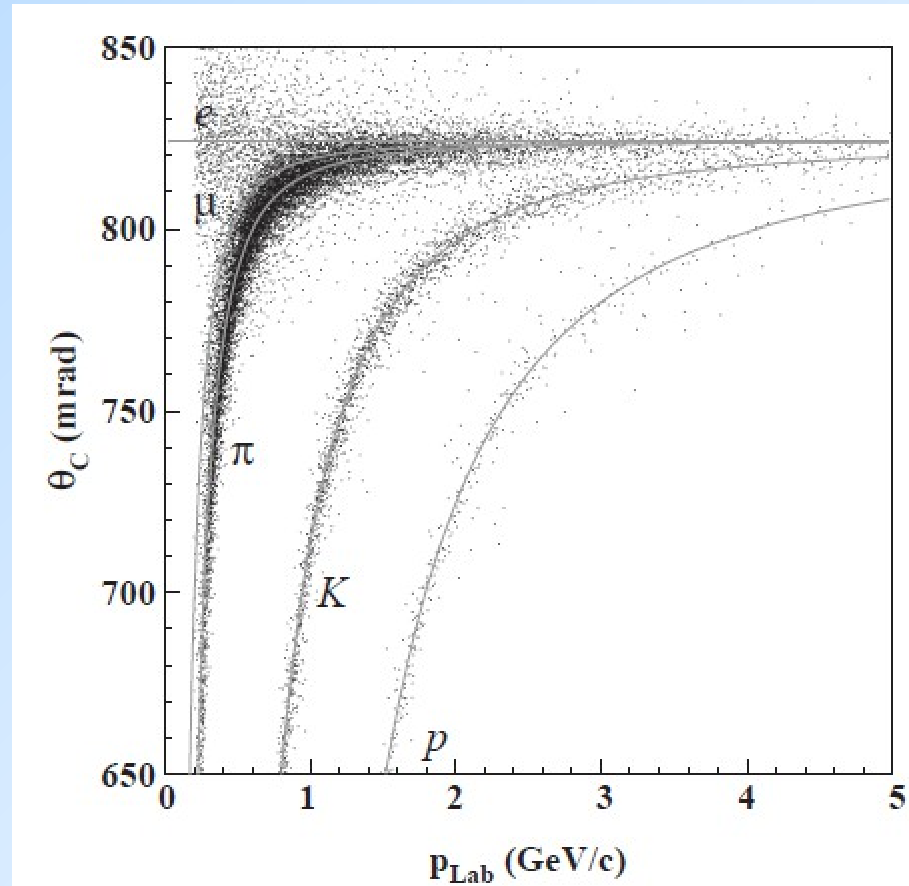


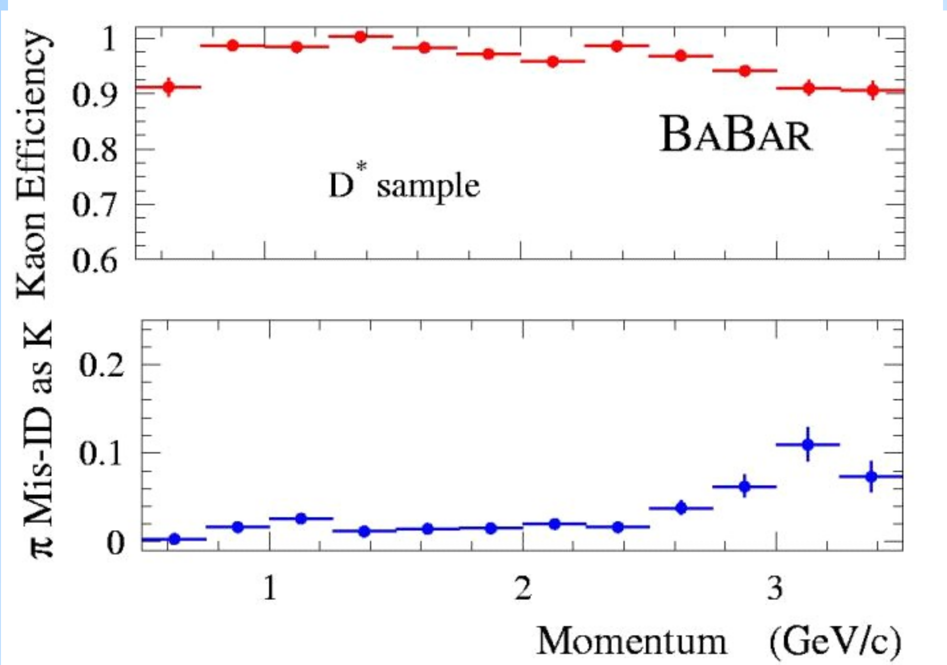


DIRC performance



Lots of photons





Excellent π/K separation

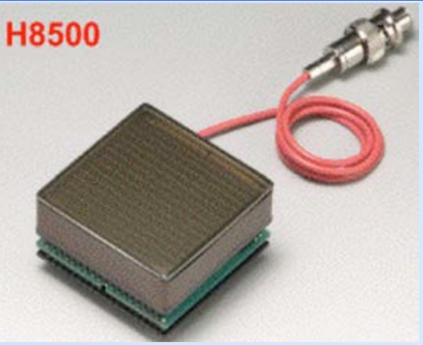
NIM A538 (2005) 281, NIM A553 (2005) 317

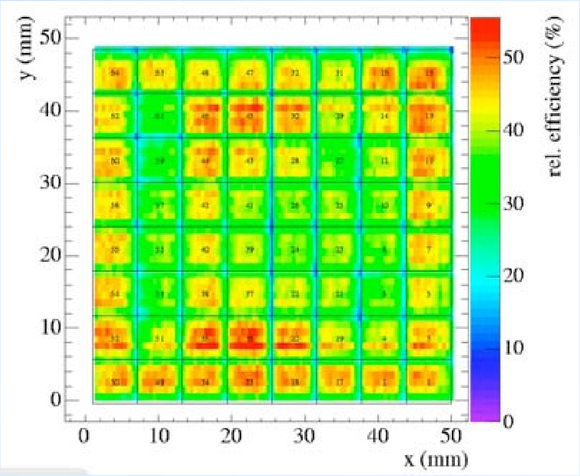
FDIRC design

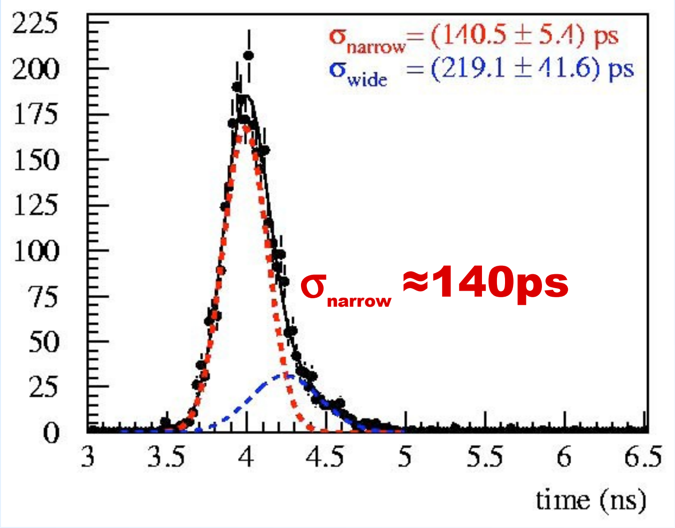
(SuperB), PANDA

- additional wedge and expansion volume with mirror made from quartz → smaller volume less sensitive to neutrons
- flat-panel PMT Hamamatsu H8500 for photon detection → better time resolution

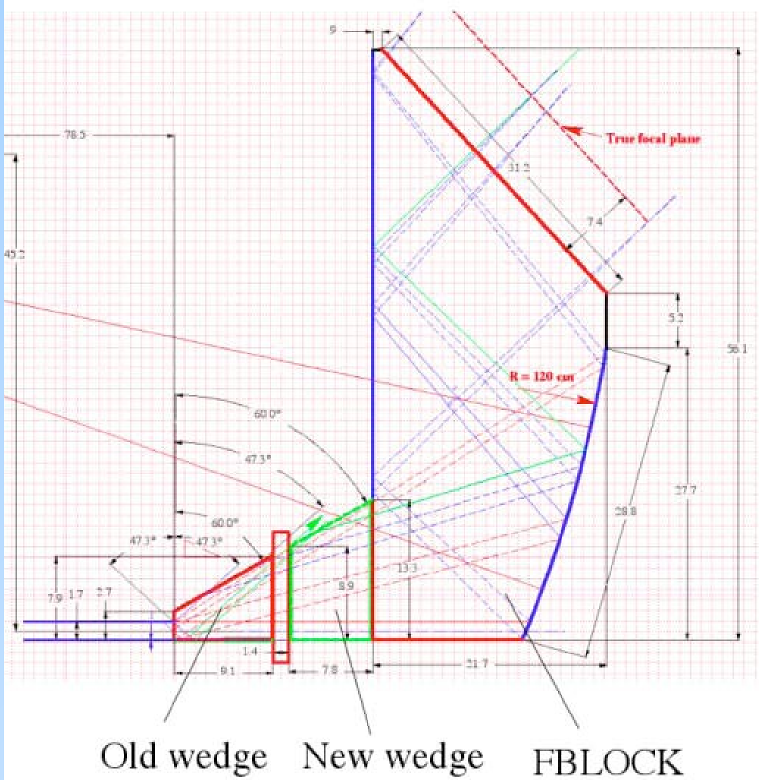
Background suppresion x25 (volume) x10 (timing).



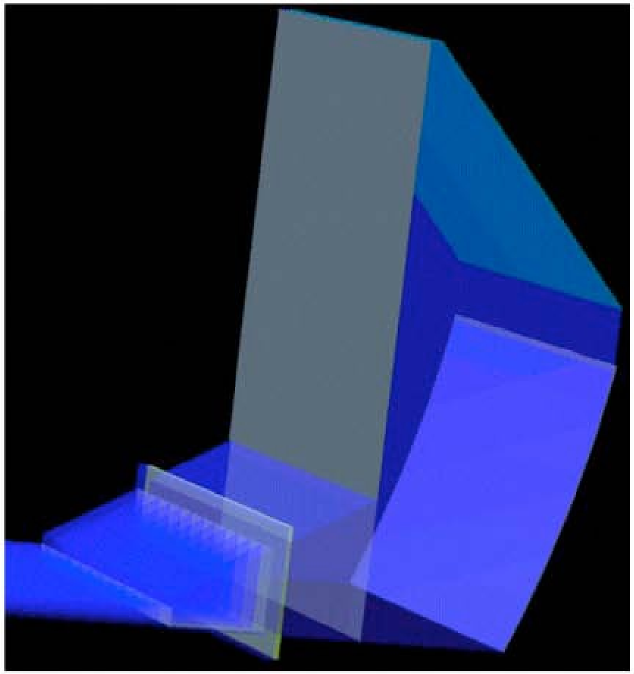




Ray tracing:



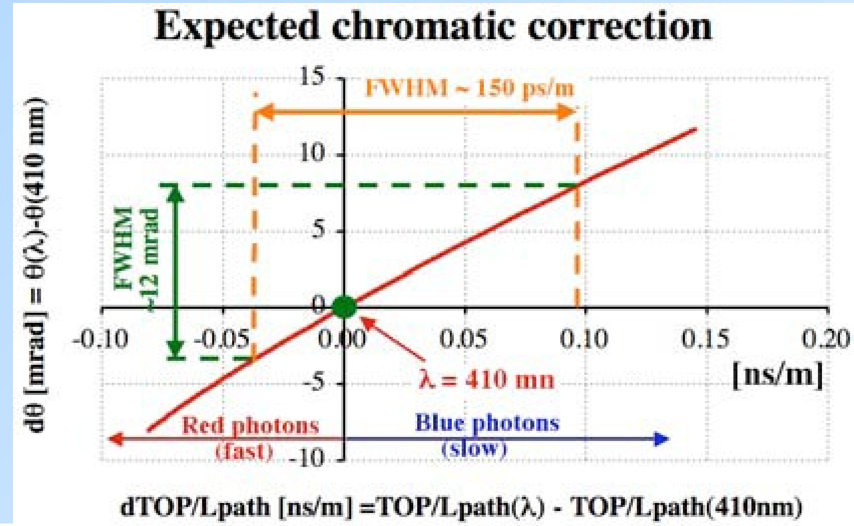
Geant 4 model:

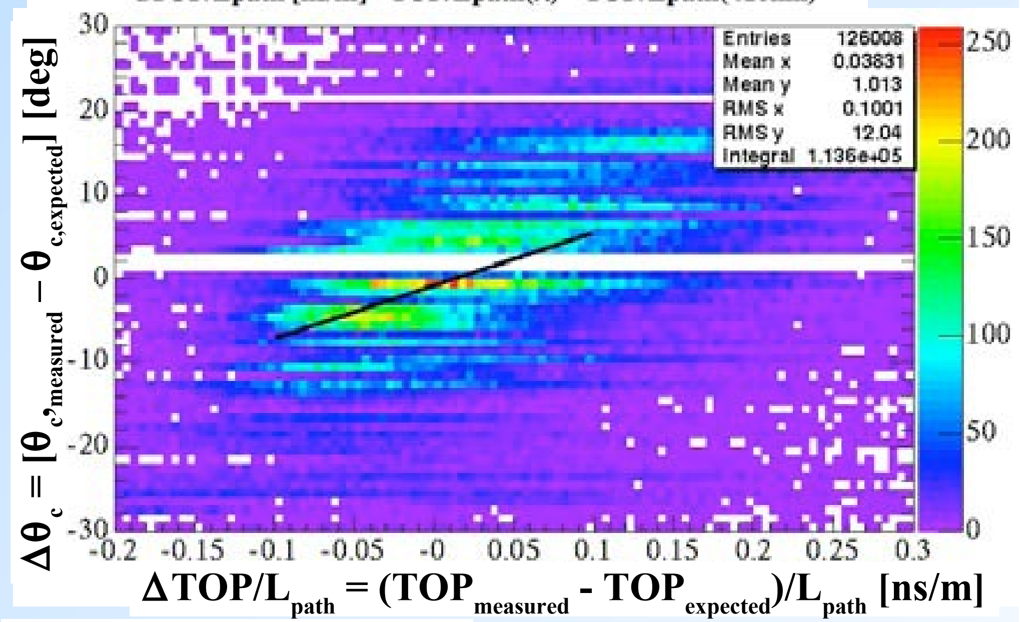


SLAC-PUB-13464, 2008

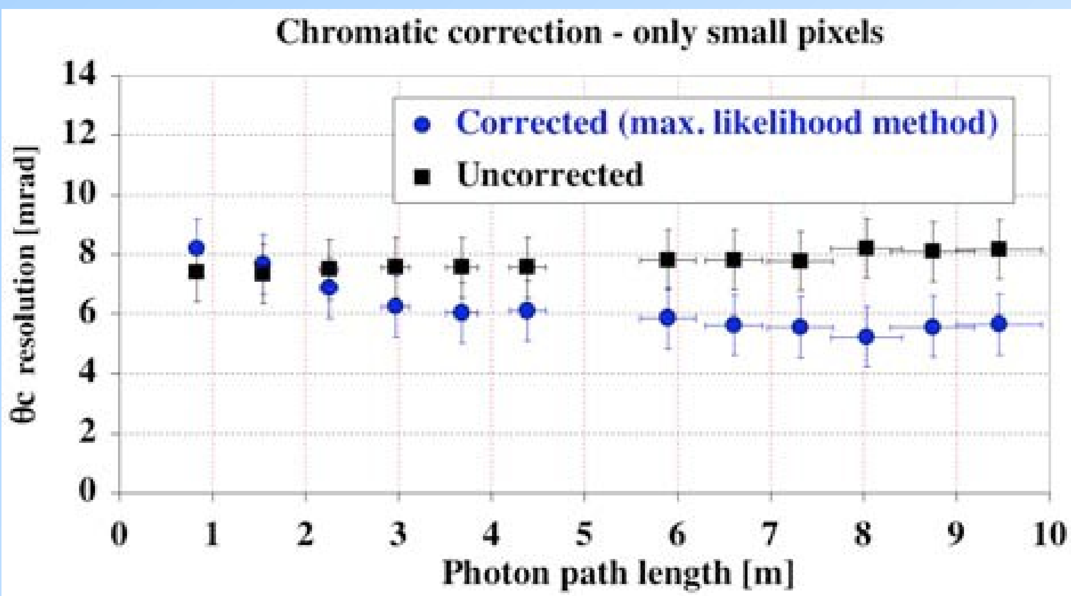
FDIRC chromatic error correction

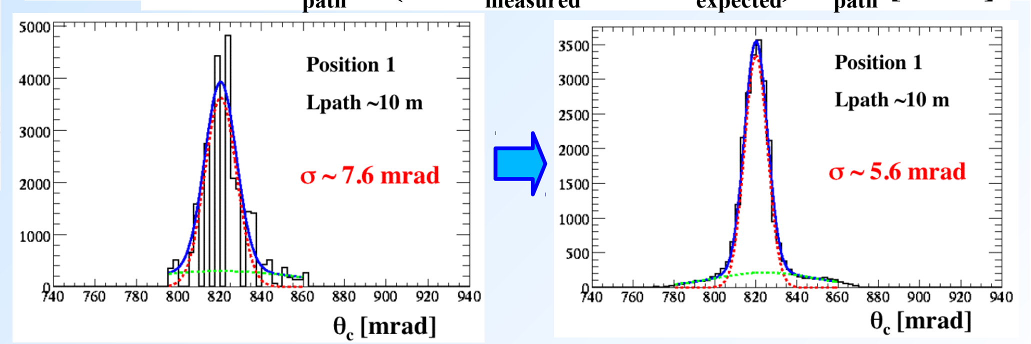
- correlation between the propagation time (L/c_g) and Cherenkov angle ($\cos\vartheta = c/vn$) is used to improve the angular resolution





Chromatic correction with 3mm pixel size





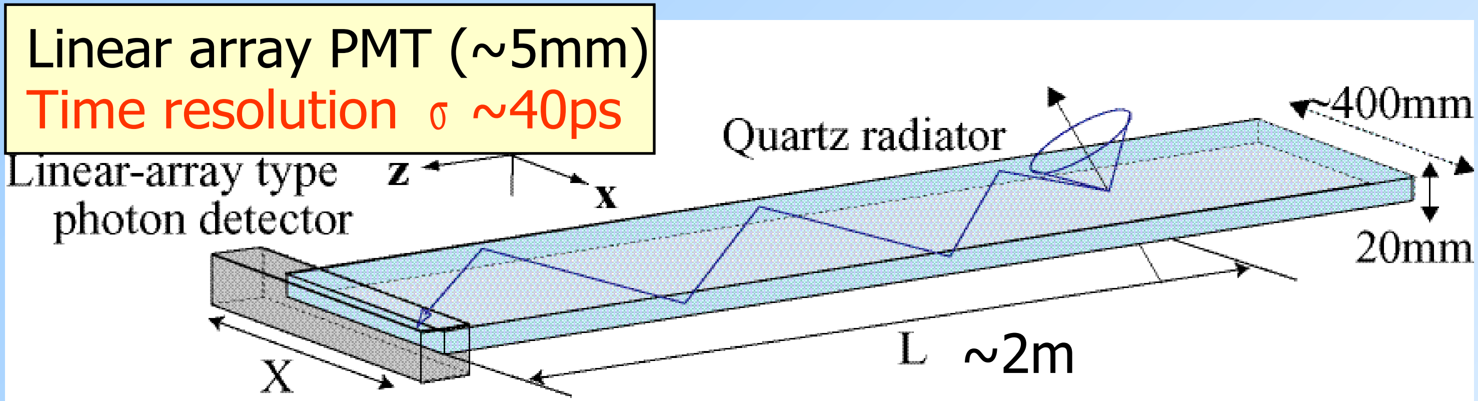
TOP principle - Belle II barrel PID

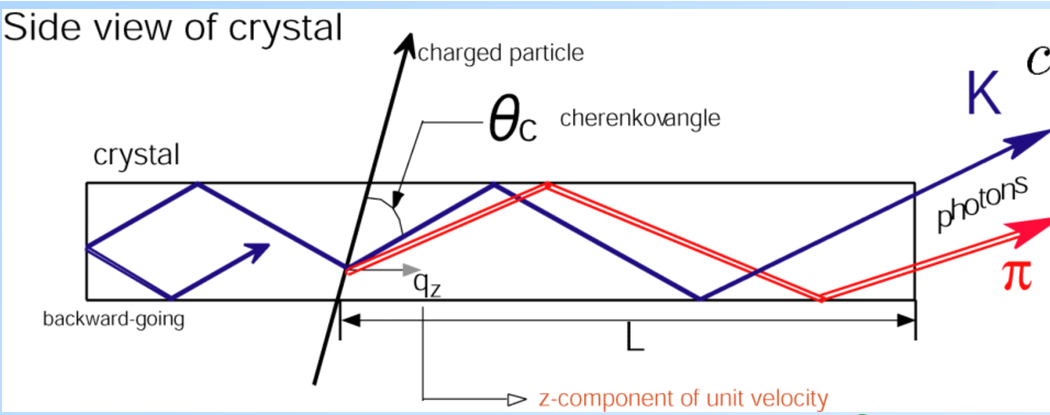
Based on a DIRC concept:

- instead of 2D imaging → 1D + Time Of Propagation (TOP, path length)

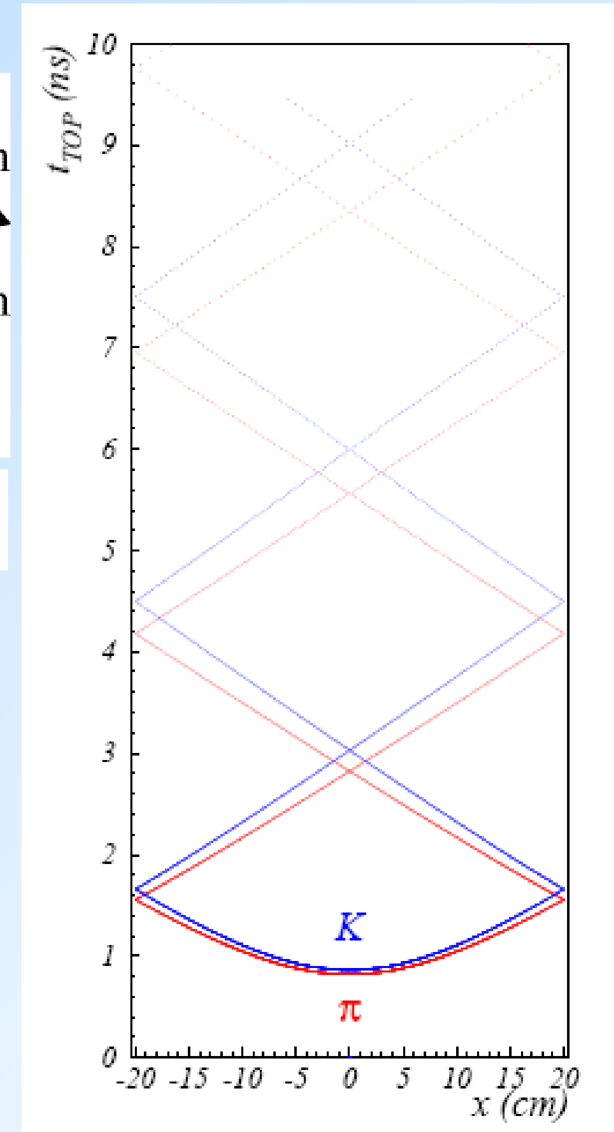
→ **compact detector**

Linear array PMT (~5mm)
Time resolution σ ~40ps





$$cos\theta_c = \frac{1}{n(\lambda)\beta}$$

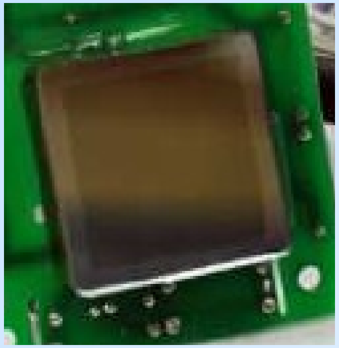


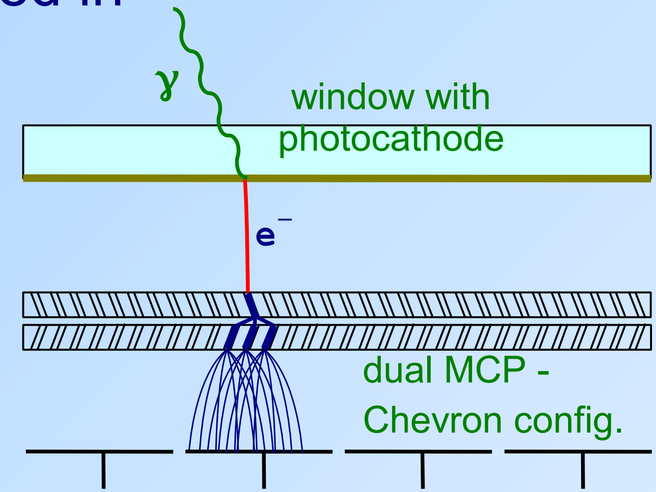
- measured time is a combination of photon propagation time and time of flight from the interaction point to the quartz bar

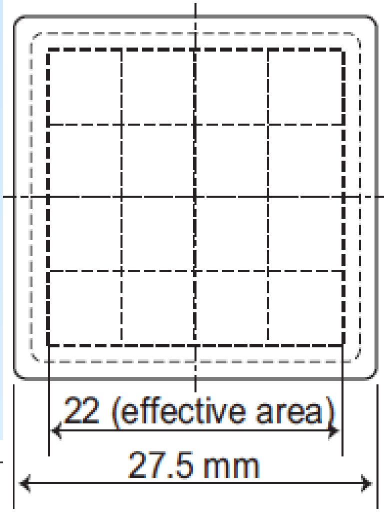
Fast photon detection: MCP-PMT (Hamamatsu SL10)

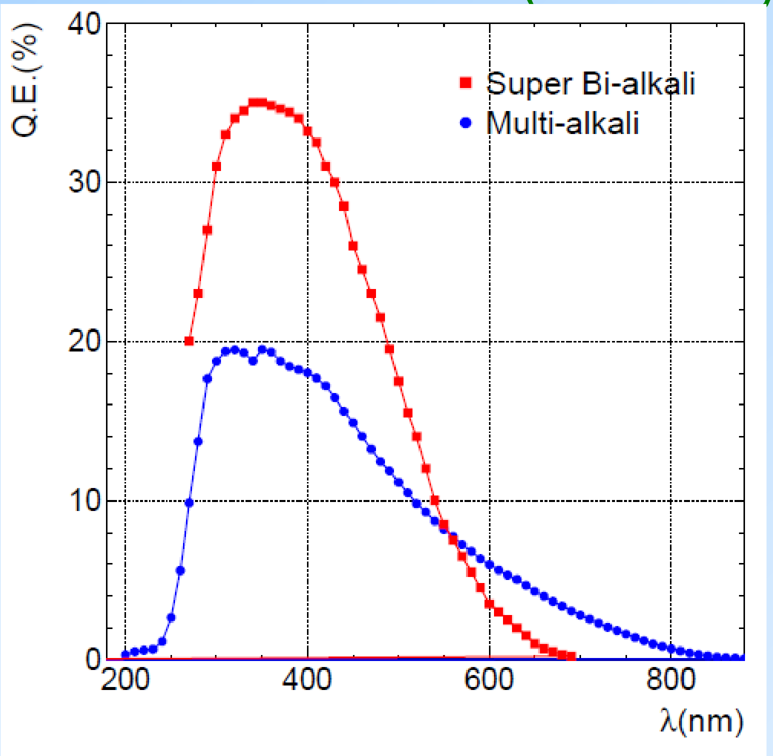
Multiandode MCP-PMT was developed in cooperation with Hamamatsu:

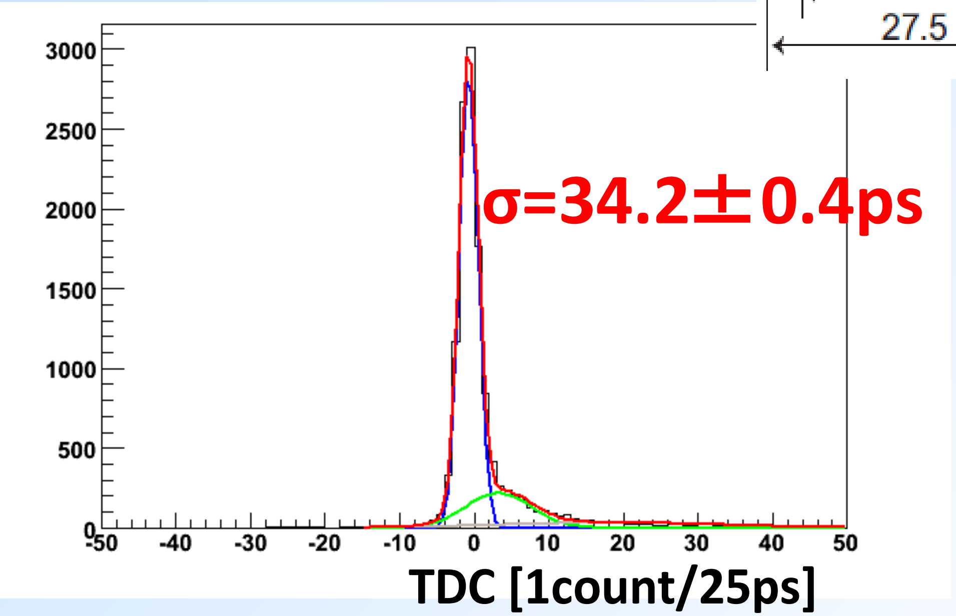
- bi-alkali photocathode
- gain ~1.5x10[6] @ 1.5 T
- single photon time resolution ~35ps @ 1.5T
- pad size ~5mm x 5mm (4x4 array)









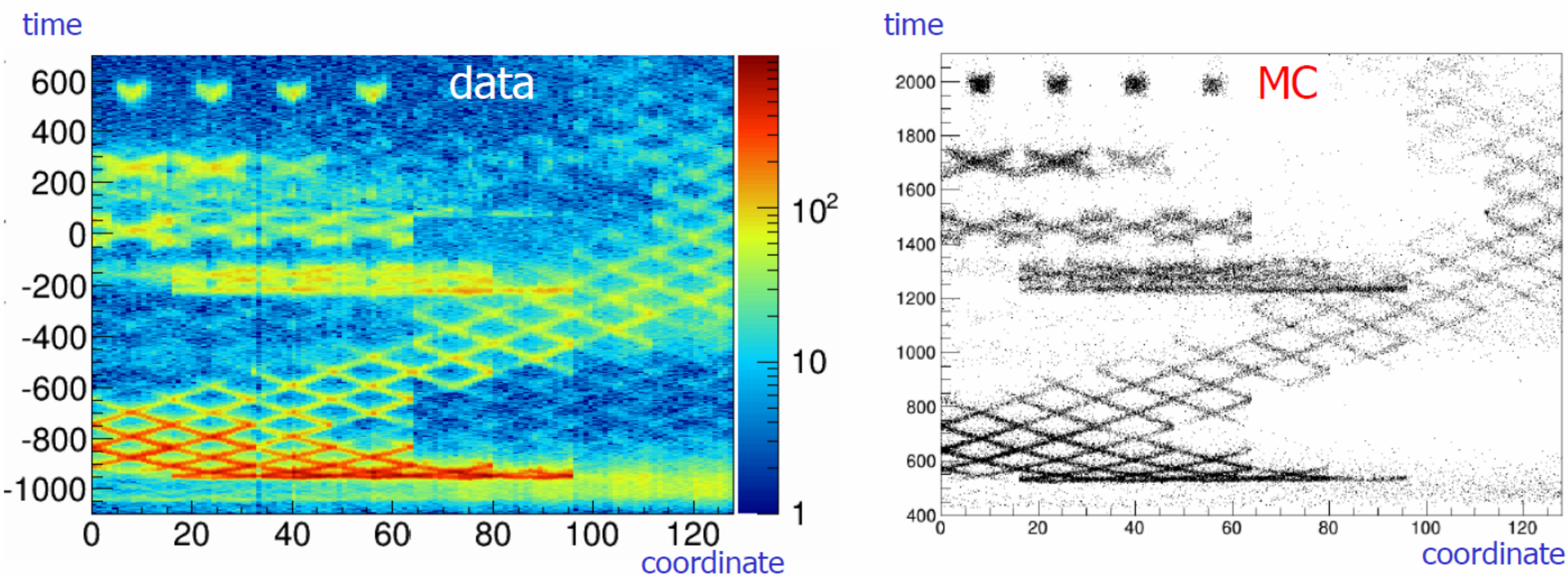


- more on different MCP-PMTs by M. Barnjakov today @15:30

TOP “ring” image

Pattern in the coordinate-time space (‘ring’) – different for kaons and pions.

Recorded by the CFD-based read-out.

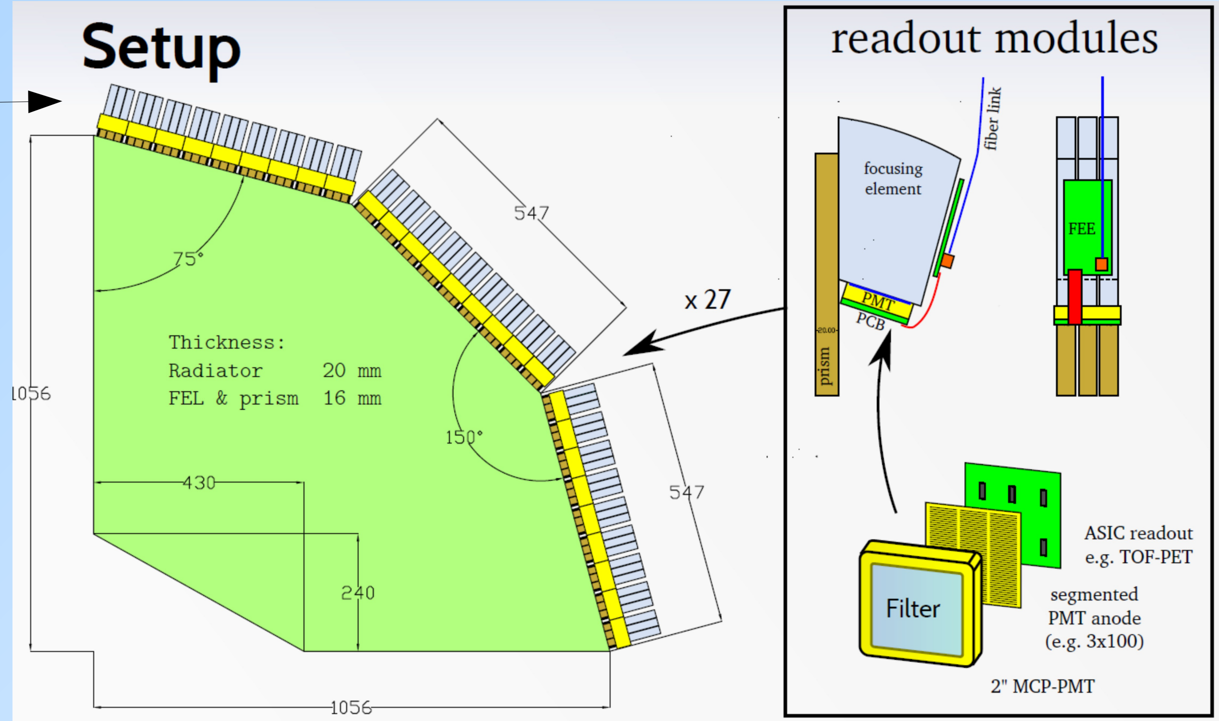


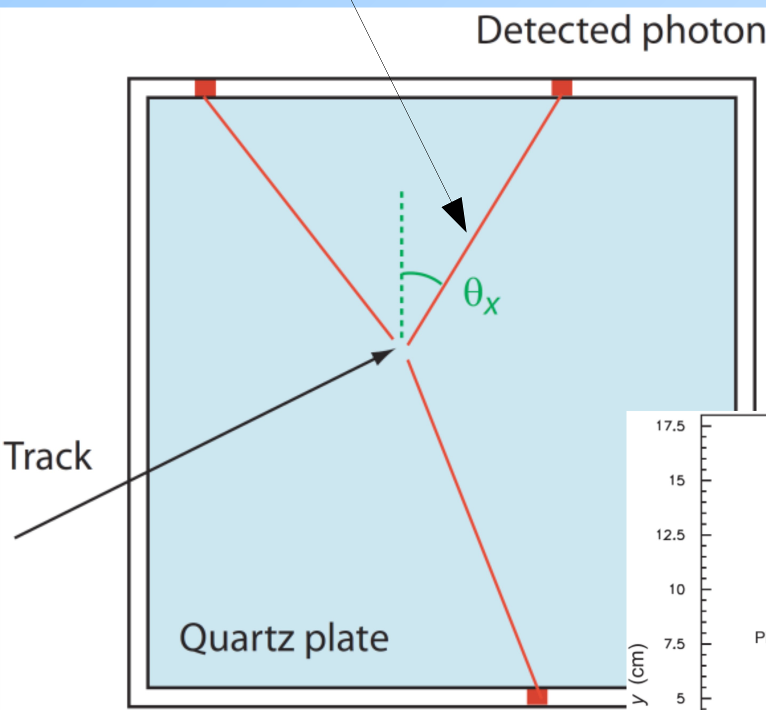
Excellent agreement between beam test data and MC simulated patterns.

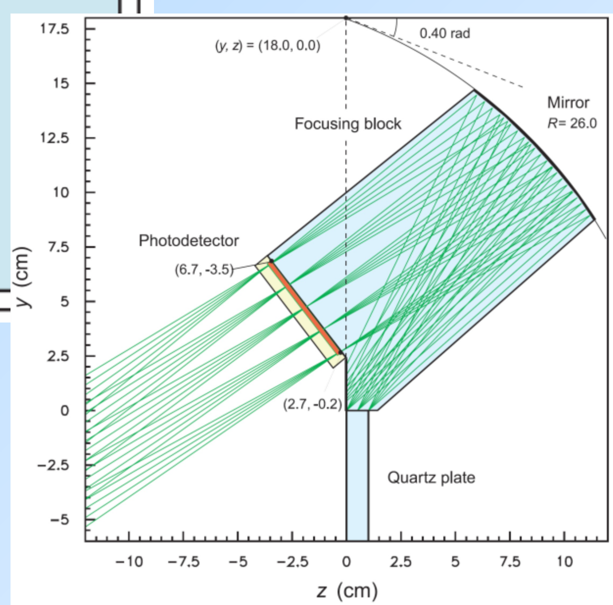
- more about TOP by K. Suzuki today @14:15

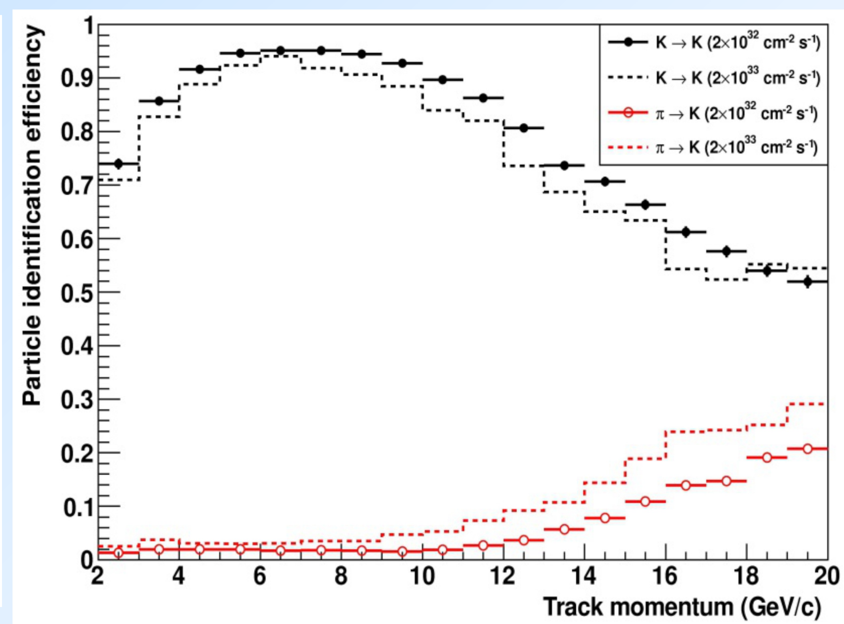
TOP like TOF disc detector developments

- **FTOF** (SuperB)
- **Disc DIRC** for PANDA
- **TORCH** for LHCb upgrade



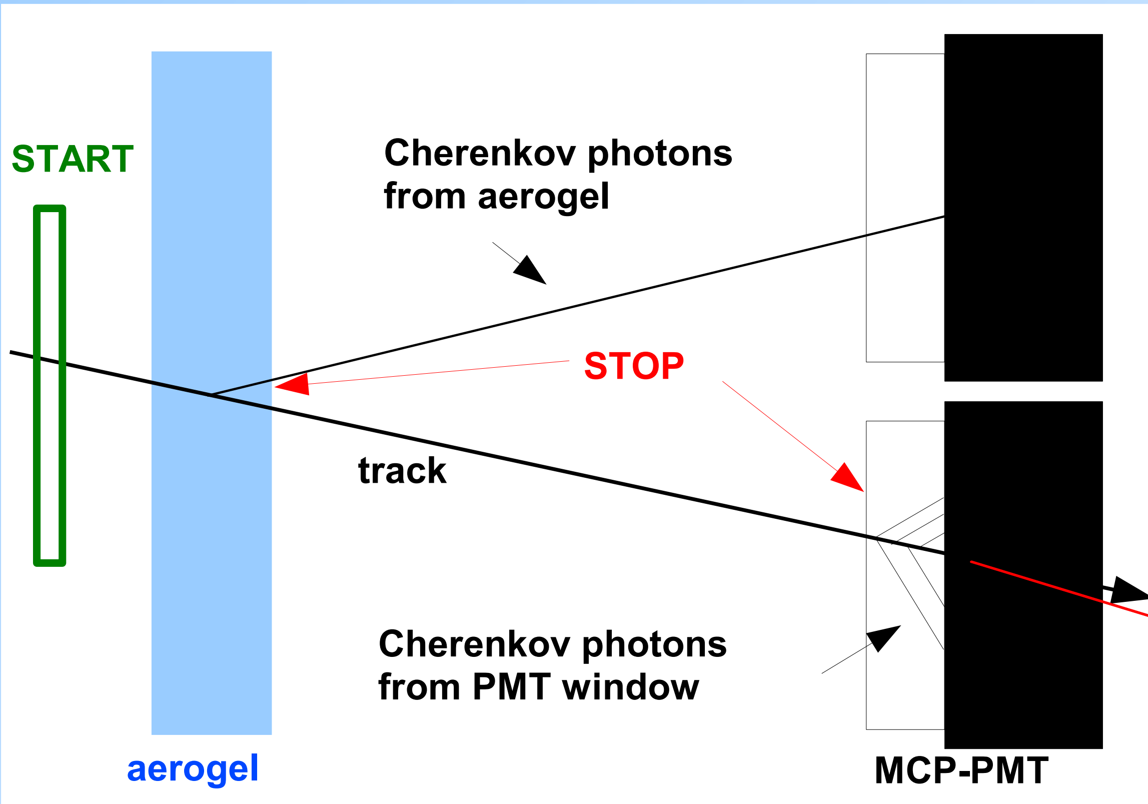


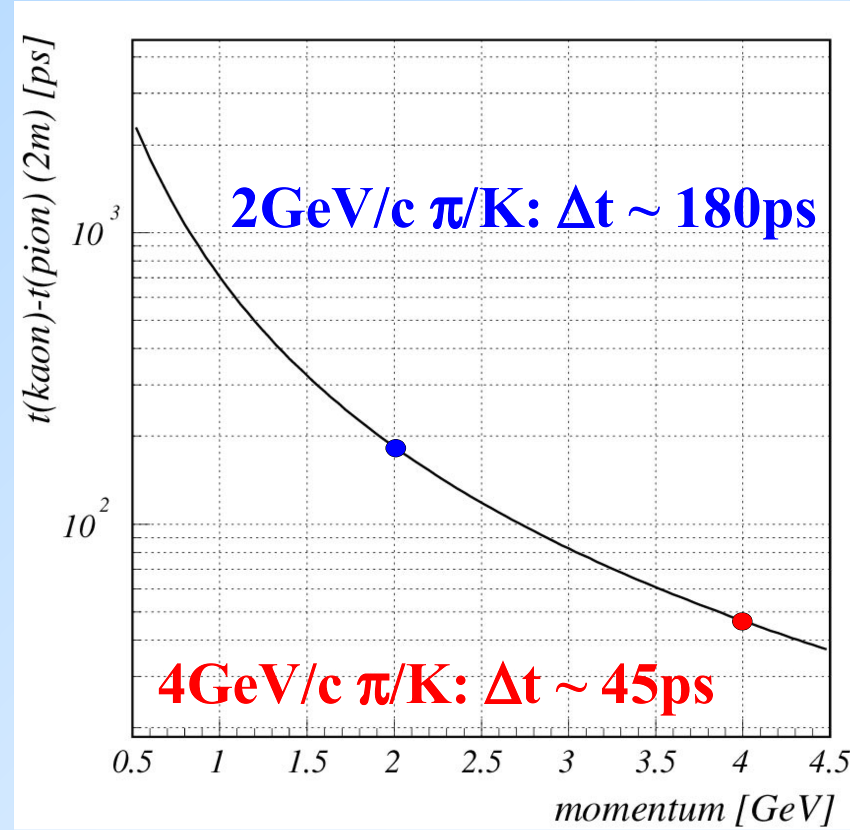


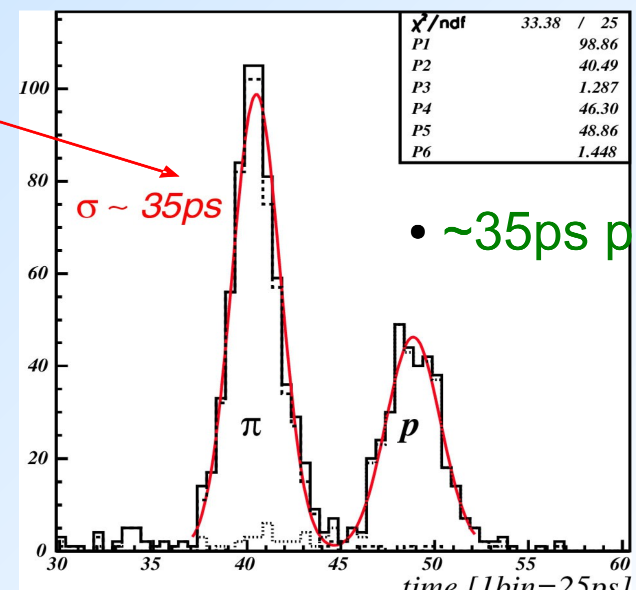


RICH+TOF combination

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







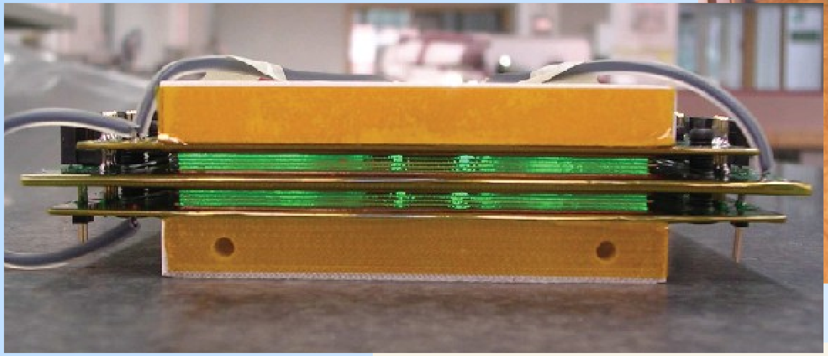
- ~35ps per track

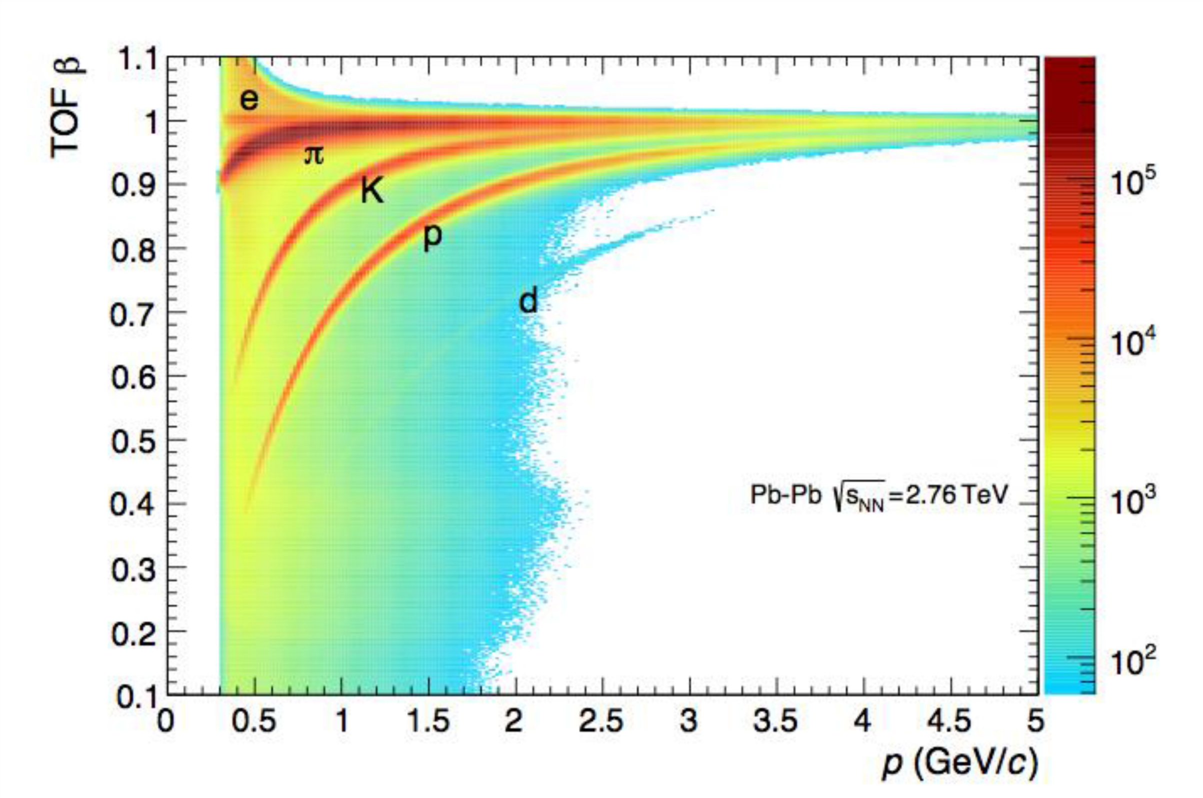
- Cherenkov photons from the window can be used to positively identifiy particles below the threshold in aerogel

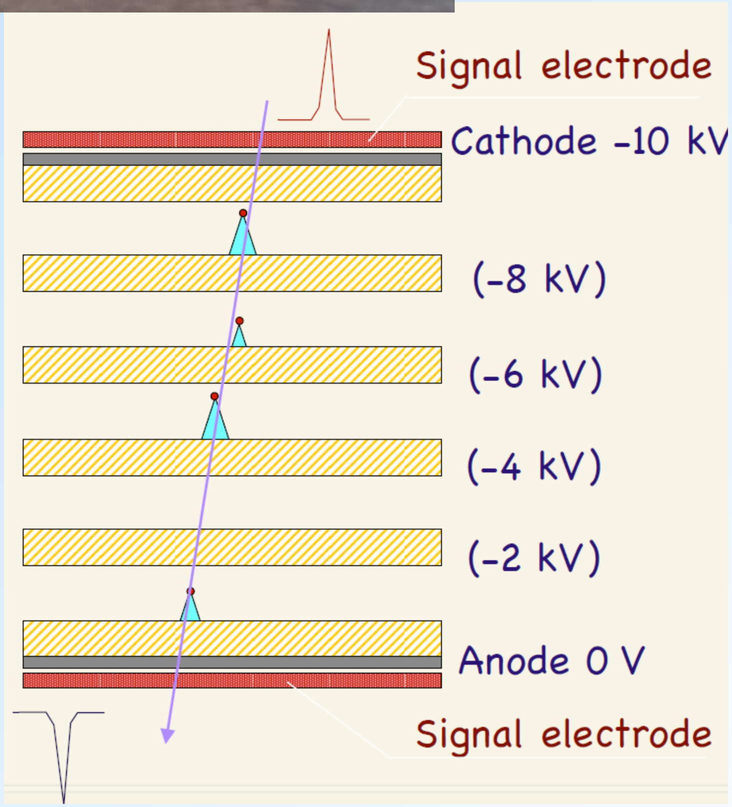
ALICE TOF with MRPCs

Multigap Resistive Plate Chambers:

- 2 x 5 multigaps – 250um
- 80 ps timig resolution
- K/π separation up to ~2.5 GeV
- requires many tracks for t_0



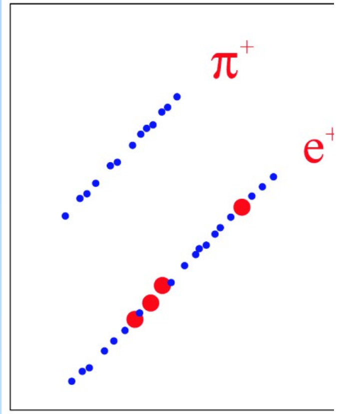


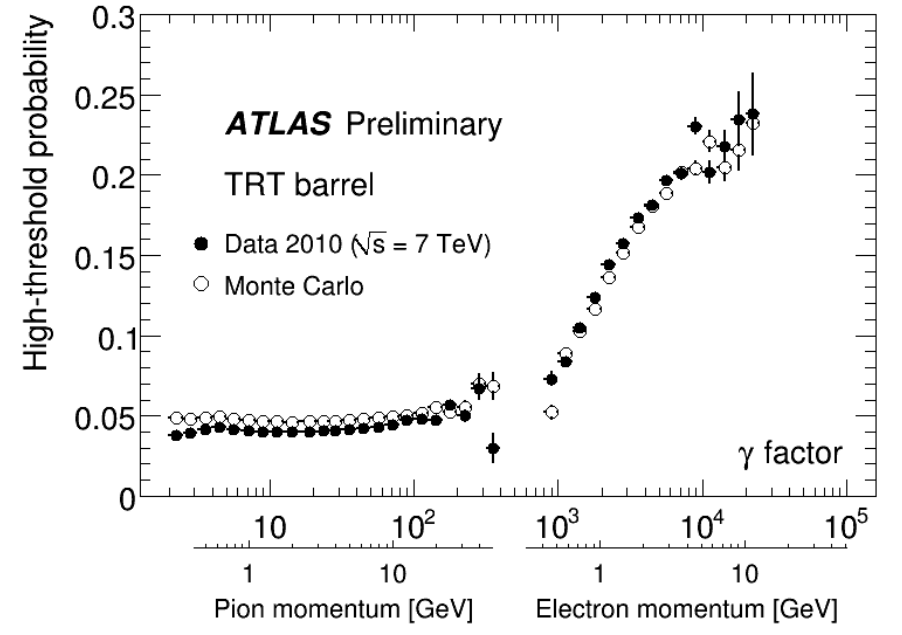


Eur.Phys.J.Plus 128(2013)44

ATLAS and ALICE TRD detectors

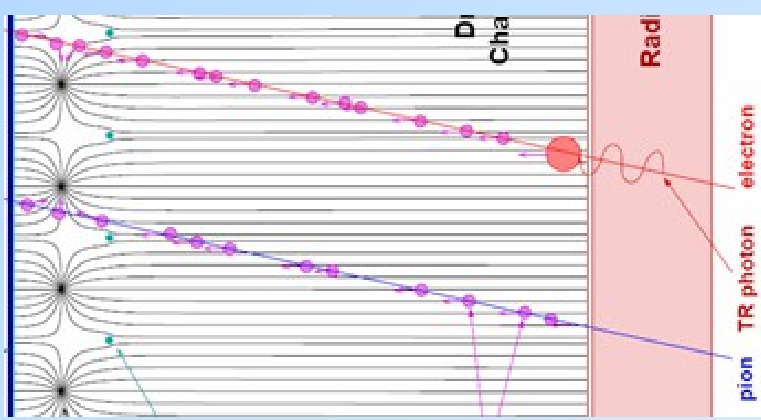
- **ATLAS TRT** in Inner Detector
- tracking + electron ID
- ~15 polypropylene foils - fibres (barrel) and foils (disk)
- 70% Xe + 27% CO_2 + 3% O_2
- straw tubes type - faster

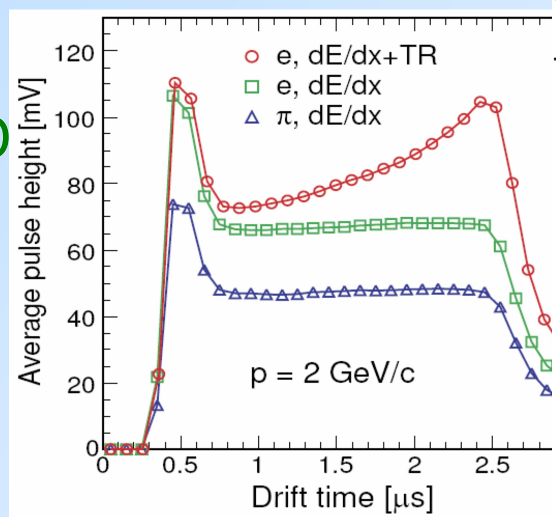




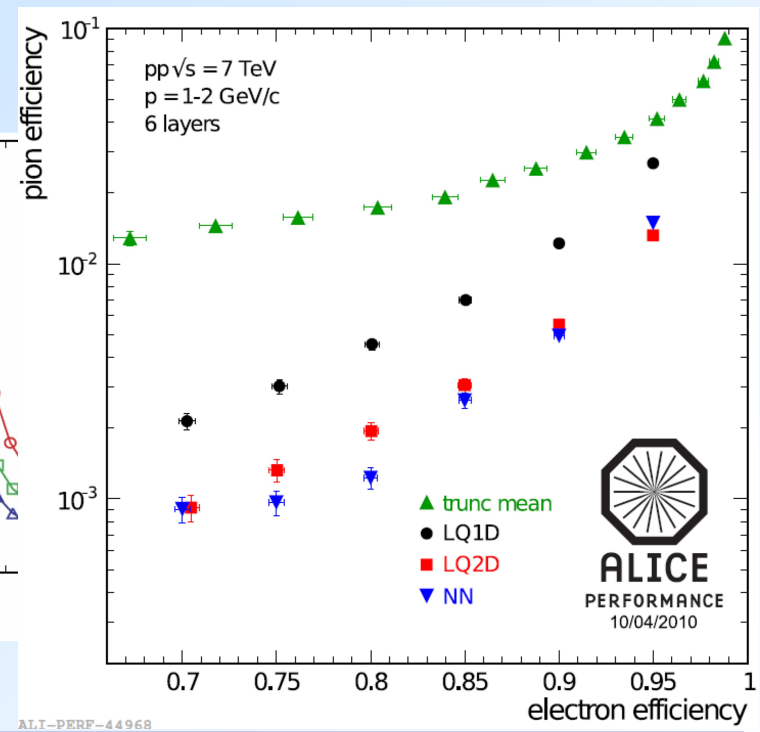
NIM A 540 (2005) 140

- **ALICE TRD**
- tracking + electron ID
- ~100 foils traversed
- 85% Xe + 15% CO_2
- drift chamber type – better ID



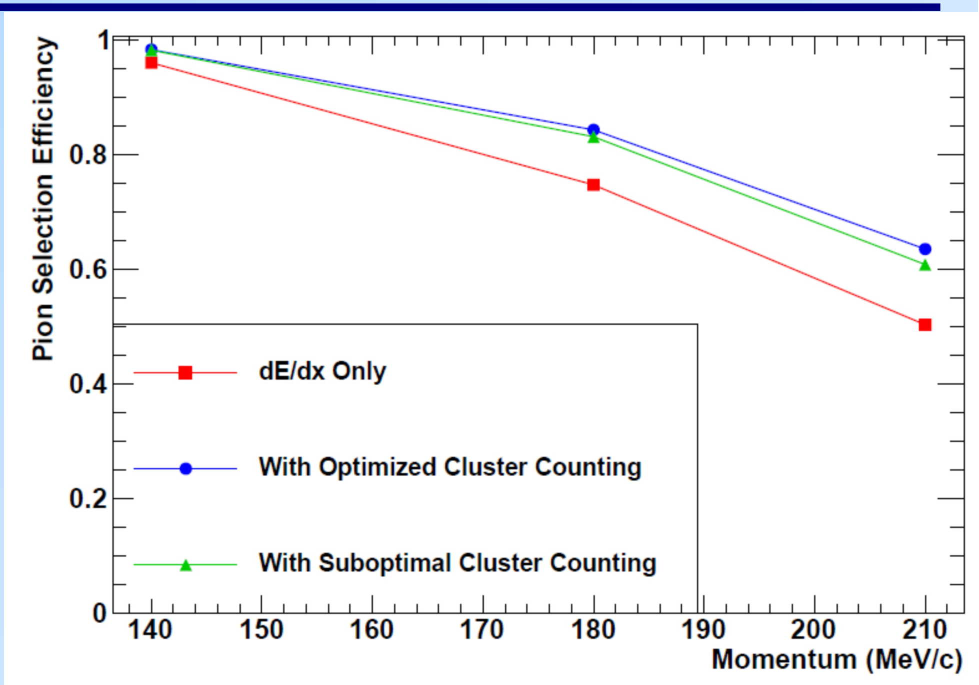


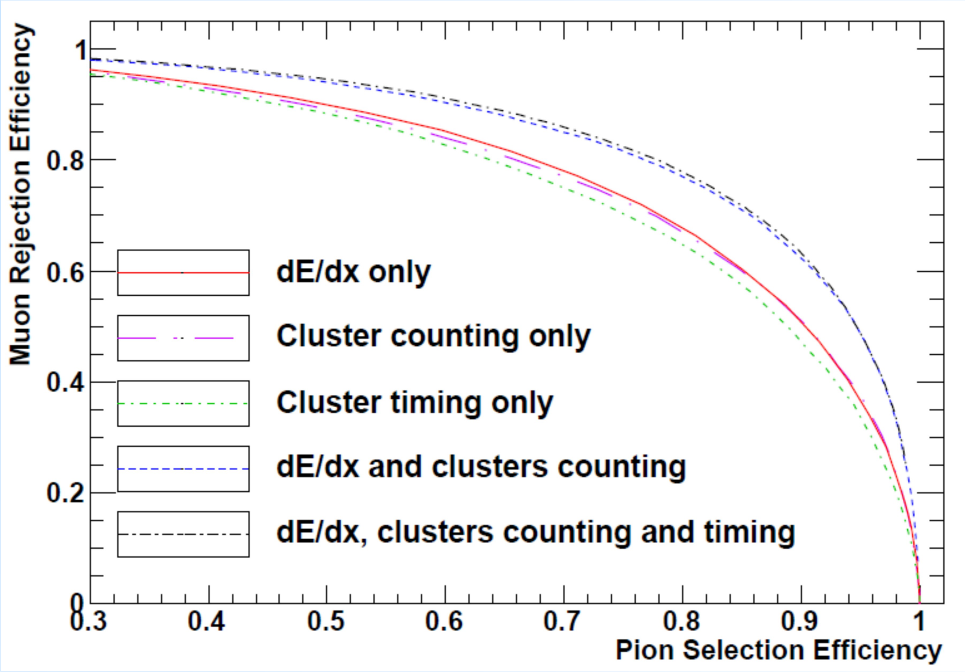
NIM A706(2013) 16

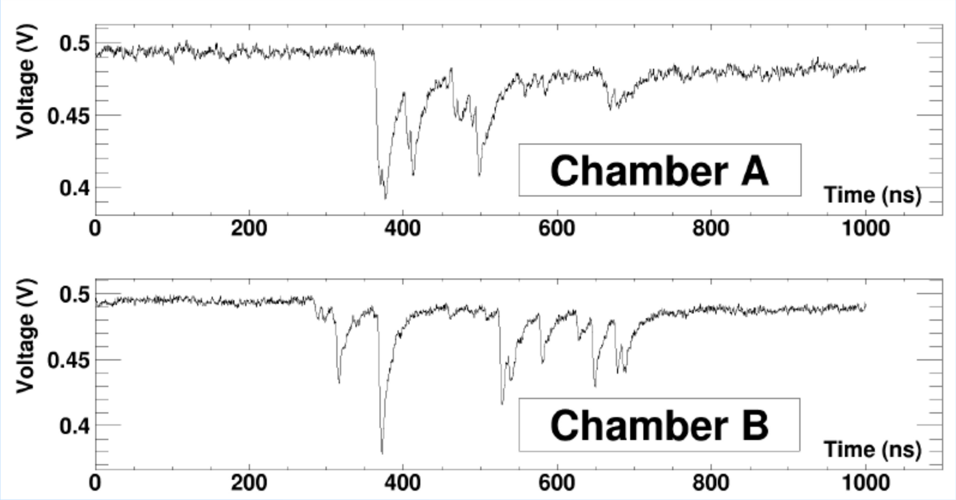


Cluster counting – dN/dx (SuperB)

- Number of clusters per track follows Poissonian statistics → better PID performance
- Timing of individual clusters in single cell → better tracking
- Single cell prototype with gas mixture 90%He+10%iC_4H_{10}
- Beam test with 210 MeV e,μ,π
- Combination of dN/dx and dE/dx → improved performance
- Waiting for large scale implementation







J.F.Caron et al. arXiv:1307.8101

Summary

Many new techniques and photon sensors were introduced/improved during the development of PID detectors in recent years:

- new photon sensors: HAPD, MCP-PMT, SiPM
- focusing aerogel radiator was introduced to proximity focusing RICH to allow thicker radiator without the resolution degradation (optional TOF capability with MCP PMTs)
- DIRC detector evolved in FDIRC, and for the first time the photon propagation time was used to reduce chromatic error
- TOP counter was developed, which is based on DIRC concept but uses Time-Of-Propagation of photons in combination with one coordinate for “ring imaging”
- many TOP type TOF detectors are in development based on Cherenkov light and fast photon detectors (MCP PMT or SiPM)
- waveform sampling based cluster counting methods are being developed to improve dEdx PID capability of central tracking devices
- new TRD devices at LHC perform as expected

BACKUP SLIDES

Multi-anode PMTs

- smaller pad size → better resolution

HERA-B RICH:

- multi-anode PMTs (Hamamatsu) → first use on large scale
  - excelent single photon detection
  - low noise (few dark counts/s/ch.)
  - low cross-talk (< 1%)
- high rate (>1MHz/cm^2)
-
-
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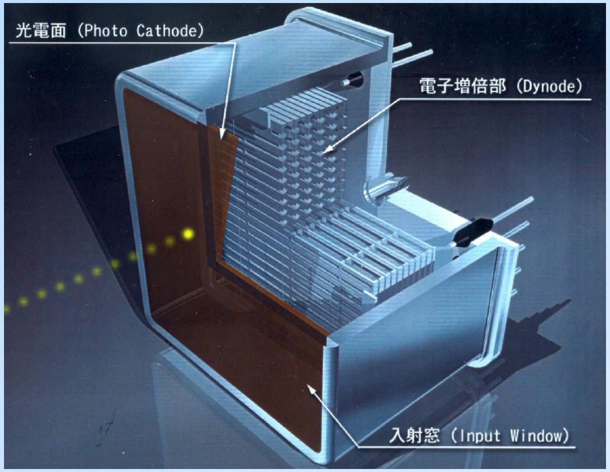
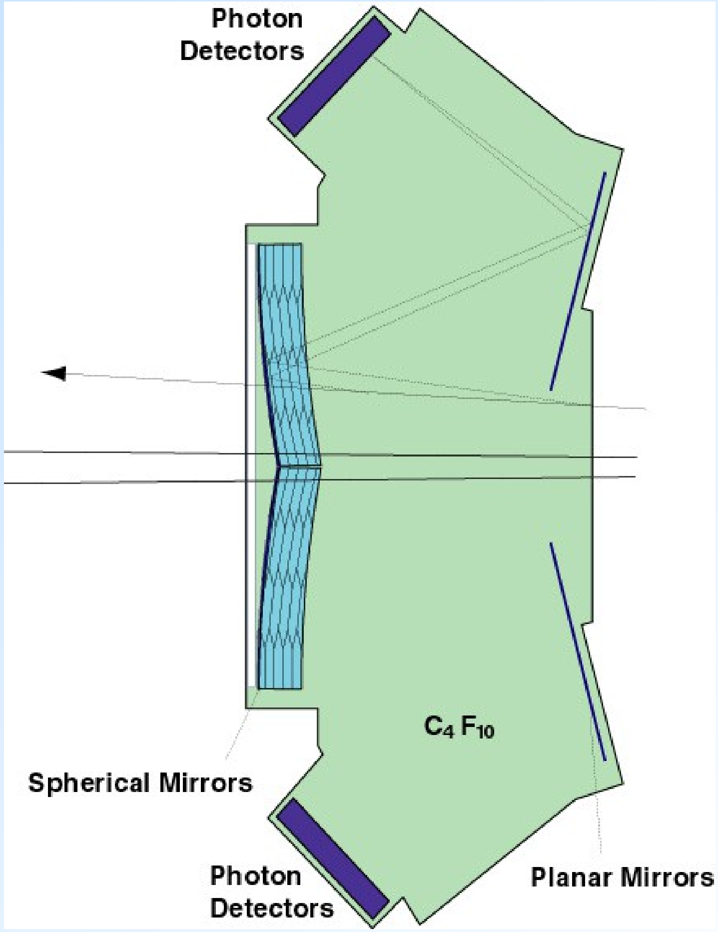
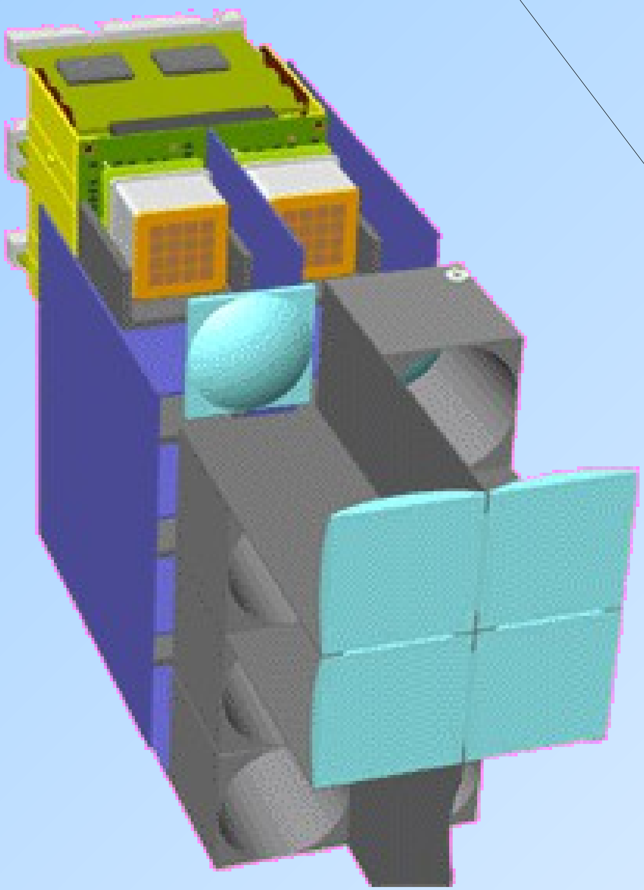
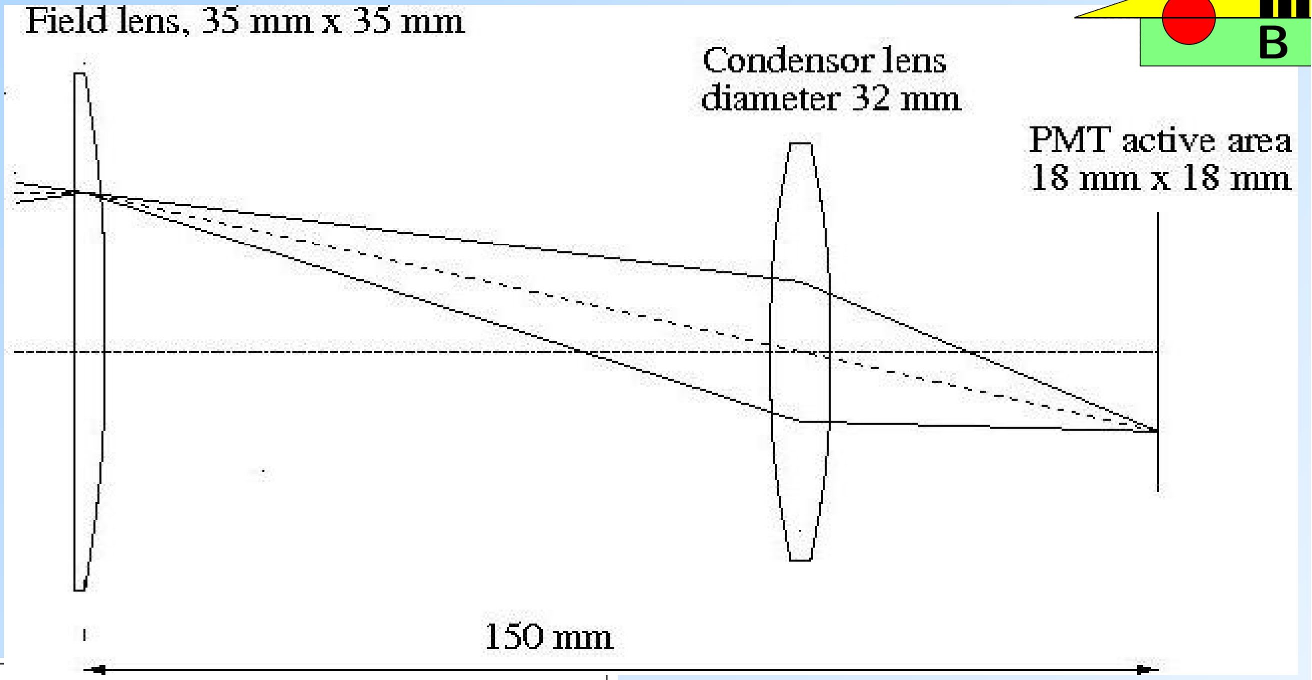


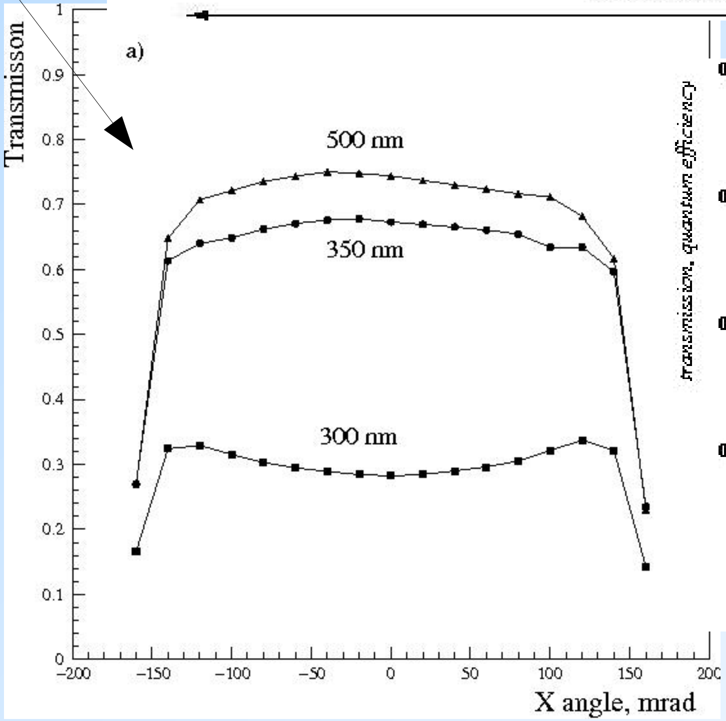


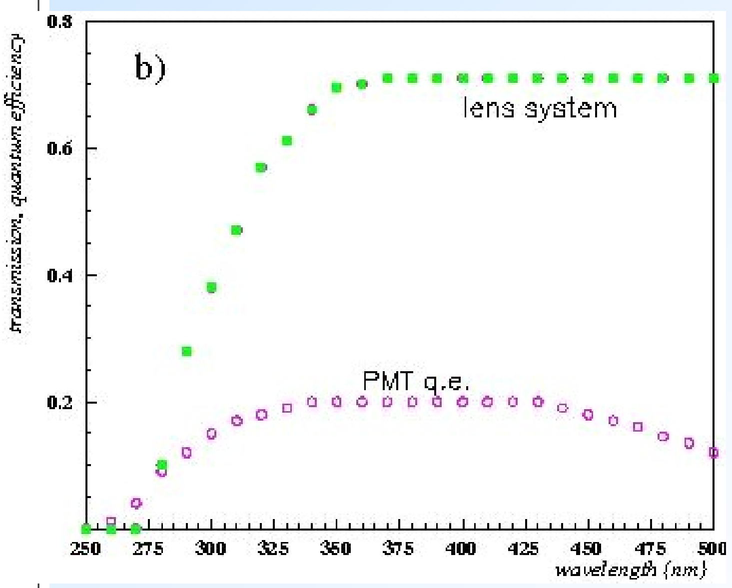
Light concentration system

Light concentration system:
- imaging type (~ 2x)
- adopt the pad size
- eliminate dead space
- limited angular acceptance



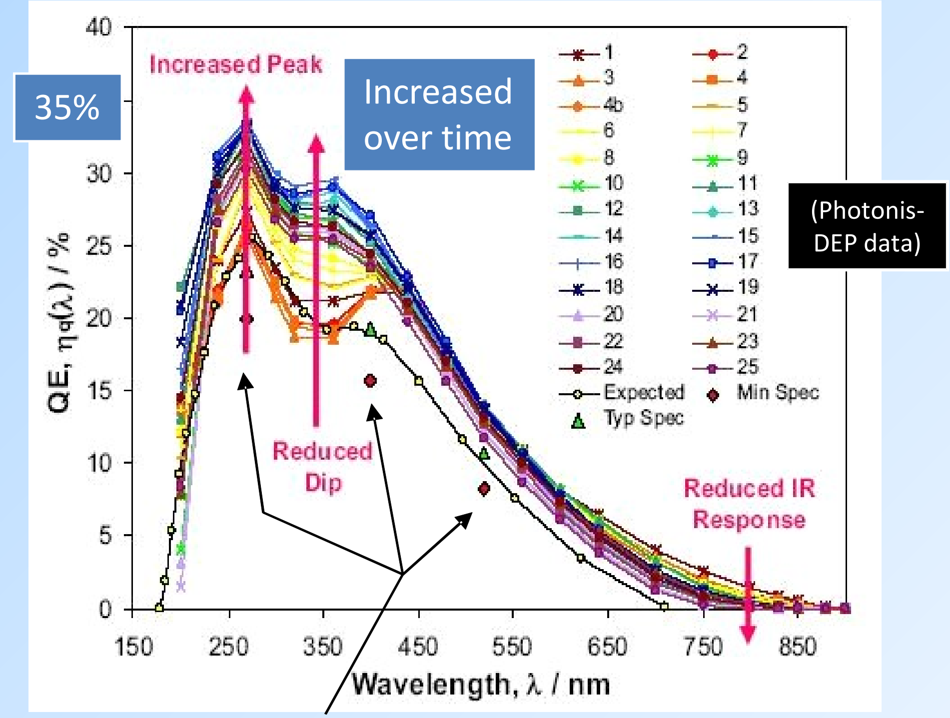




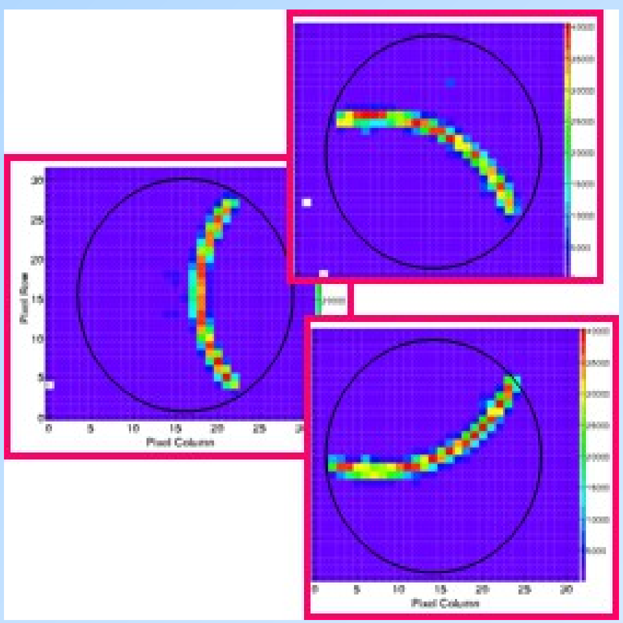


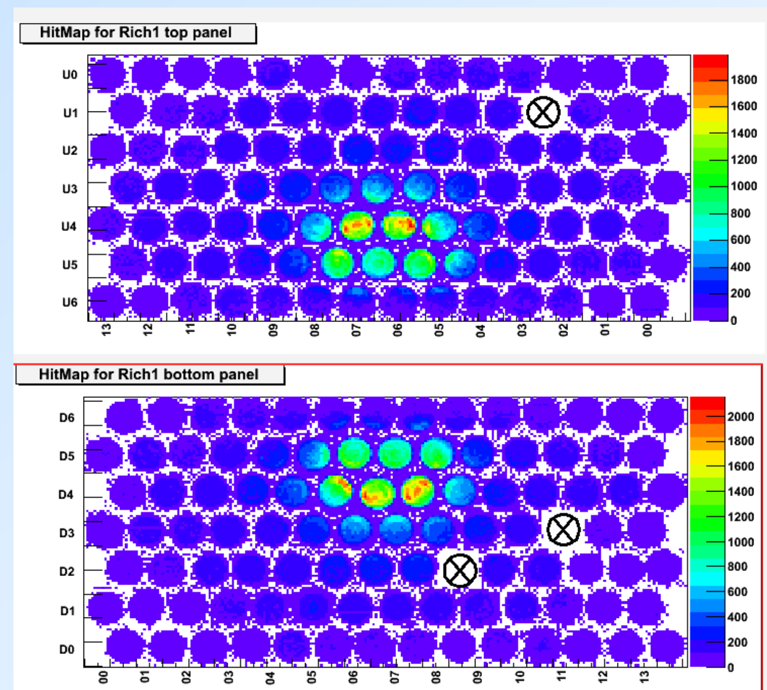
HPD: LHCb RICH

- Must cover 200-600nm wavelength range
- Multi-alkali S20 (KCsSbNa2)
- Improved over production
- Resulted in a $\int Q_E dE$ increased by 27% wrt the original specifications



Cherenkov rings from 80 GeV/c π - through C_4F_{10}

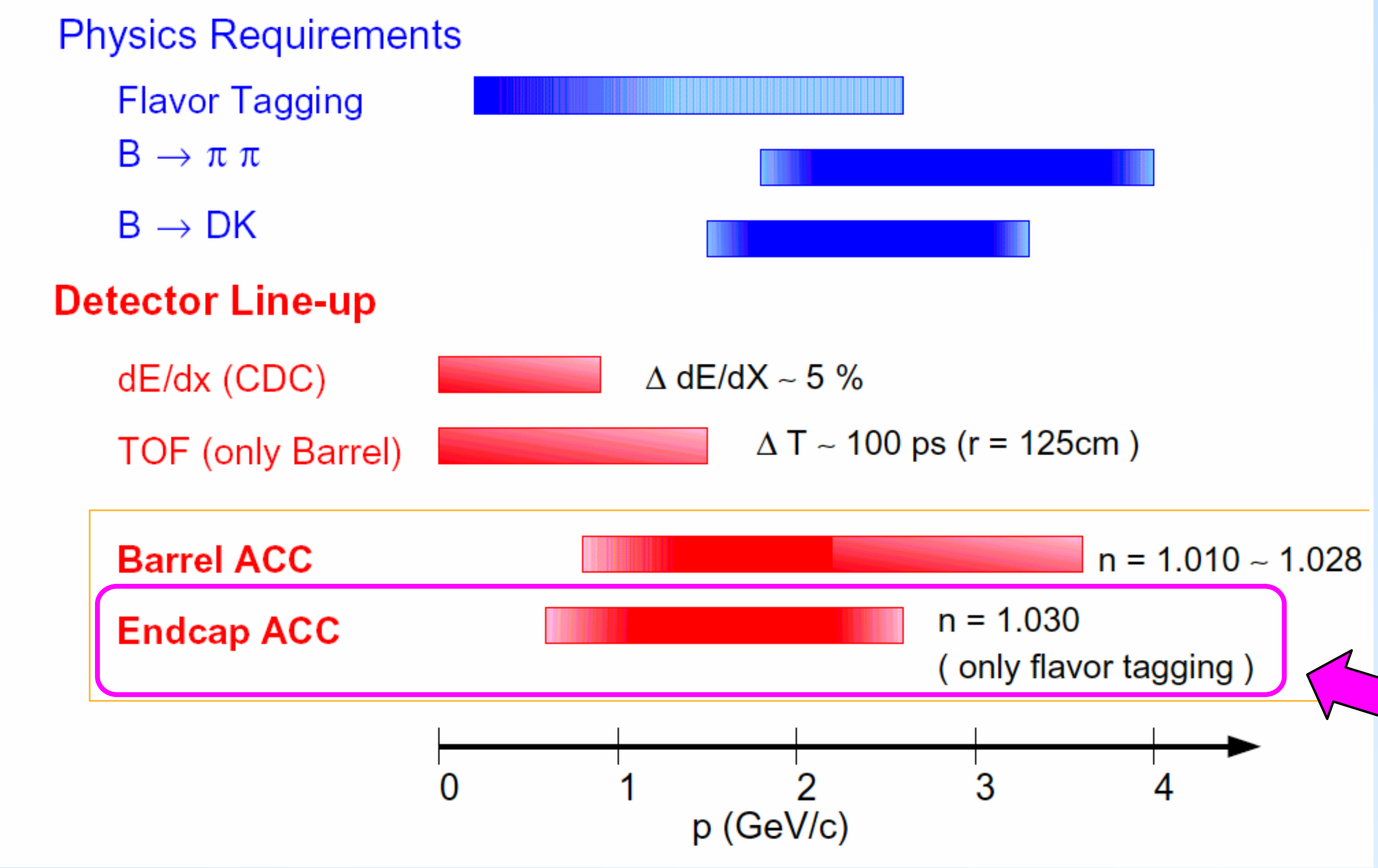




M Adinolfi et al., NIM A 603 (2009) 287

Particle ID performance

Present Belle PID performance

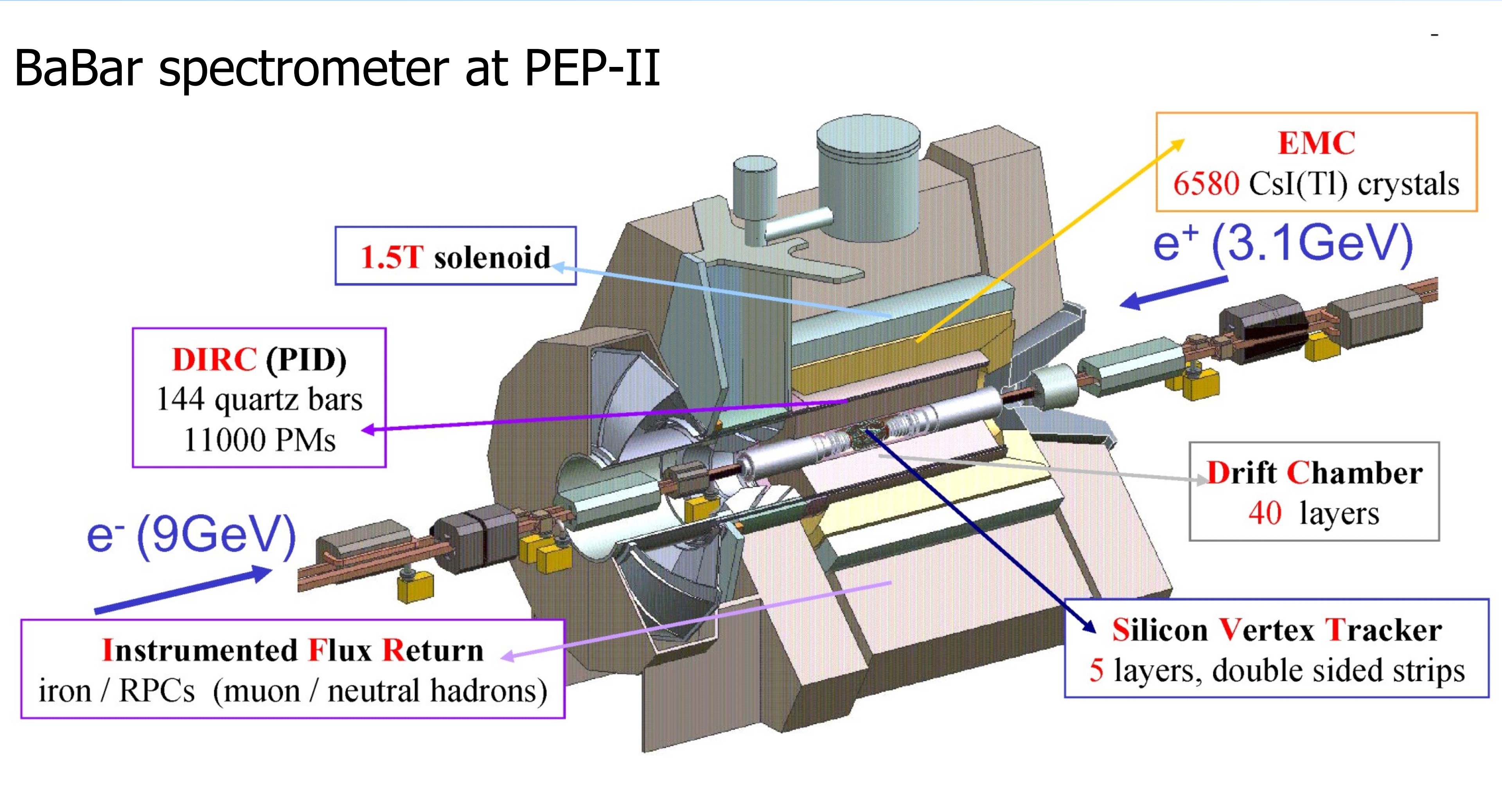


- Kaon identification: ~85% efficiency at <10% π fake probability.
- No PID for high momentum tracks in the forward end-cap (only flavor tagging)

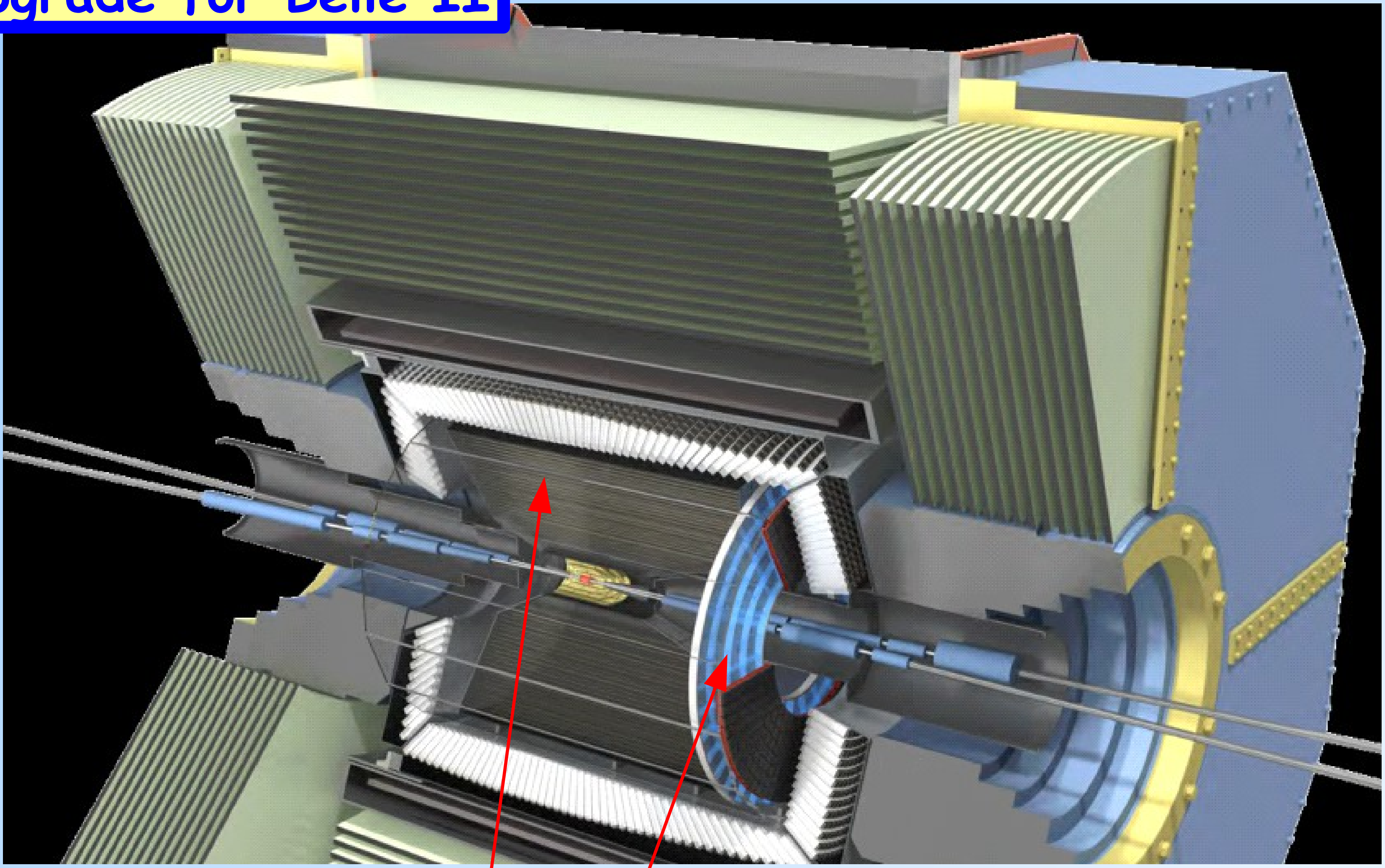
Belle PID detectors not suitable for higher luminosity/background at future super B factories.

BaBar PID

- Detector of Internaly Reflected Cherenkov light - DIRC
- DCH: dE/dx



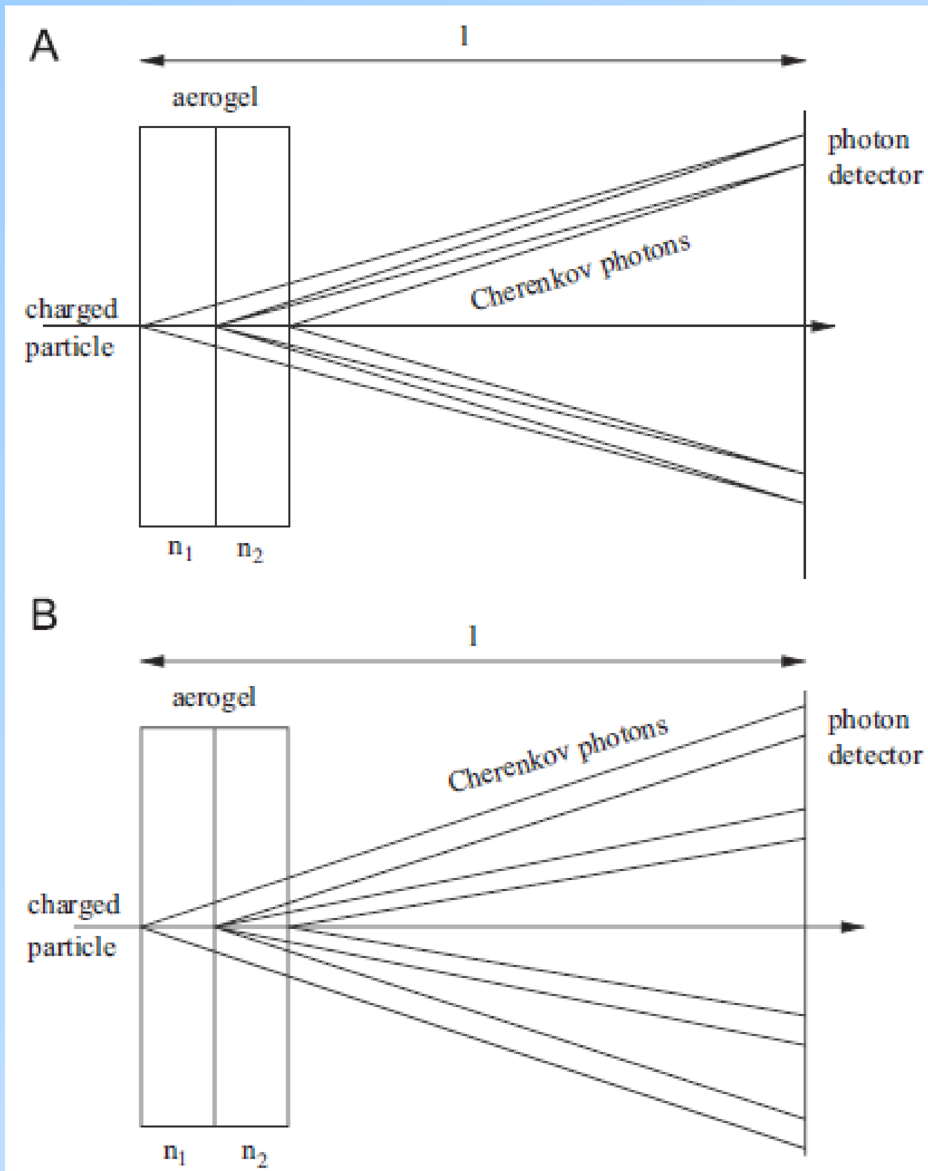
PID upgrade for Belle II

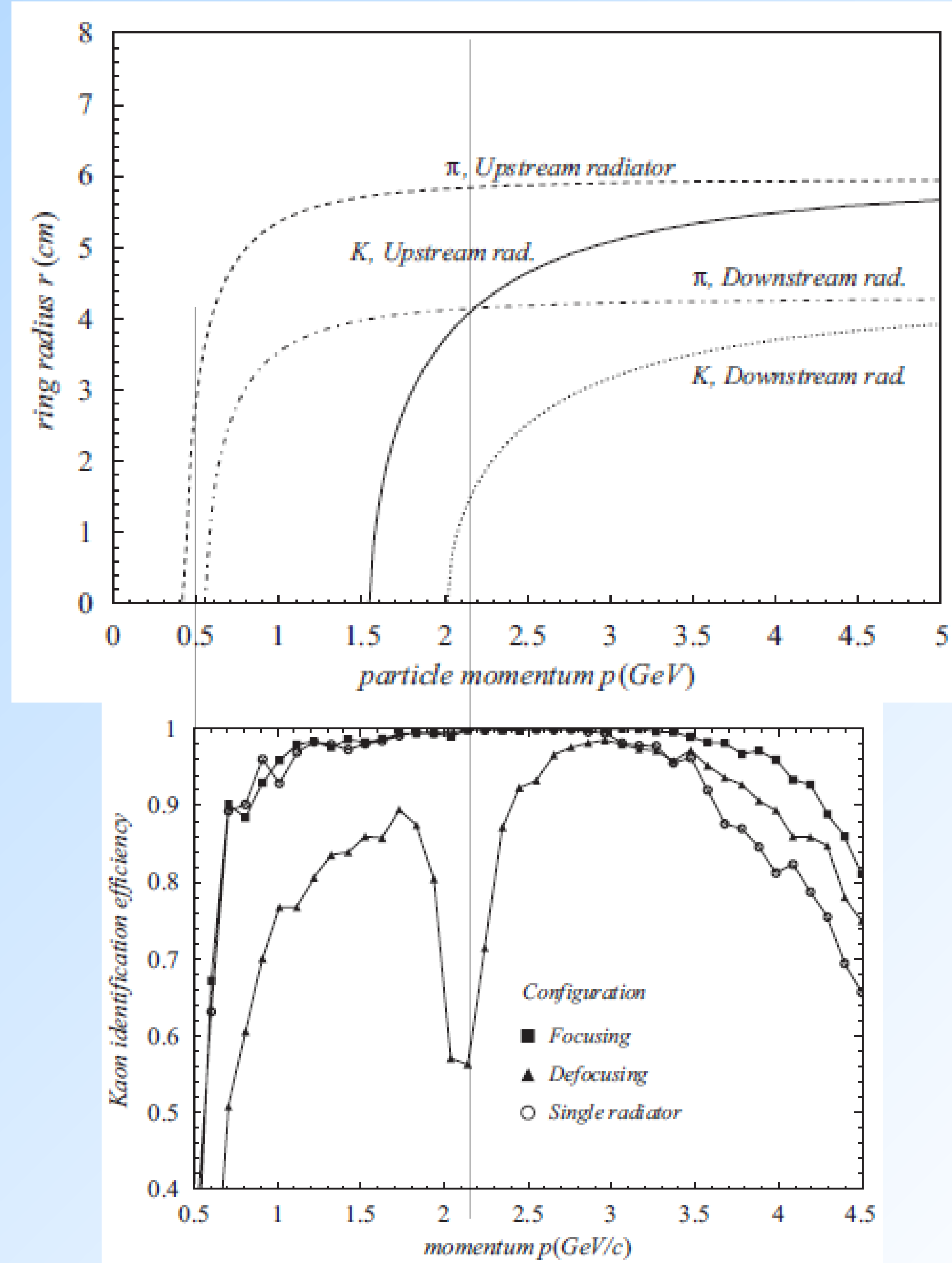


Two new particle ID devices - both RICHes - designed to fit into available space:

- Barrel: Time-Of-Propagation (TOP)
- End-cap: focusing aerogel RICH

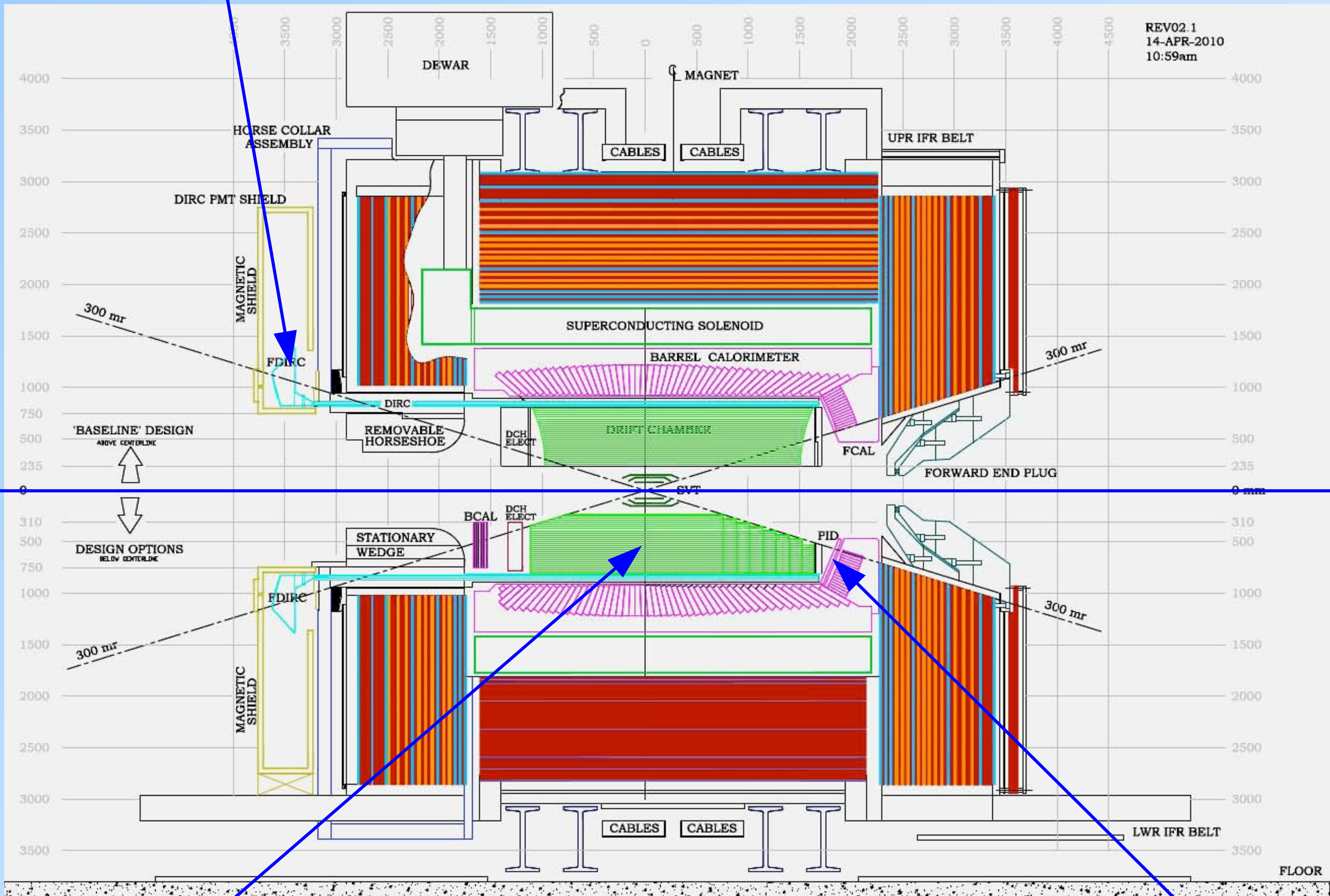
Focusing vs. defocusing aerogel combination





PID upgrade for SuperB

Focusing DIRC



Baseline design

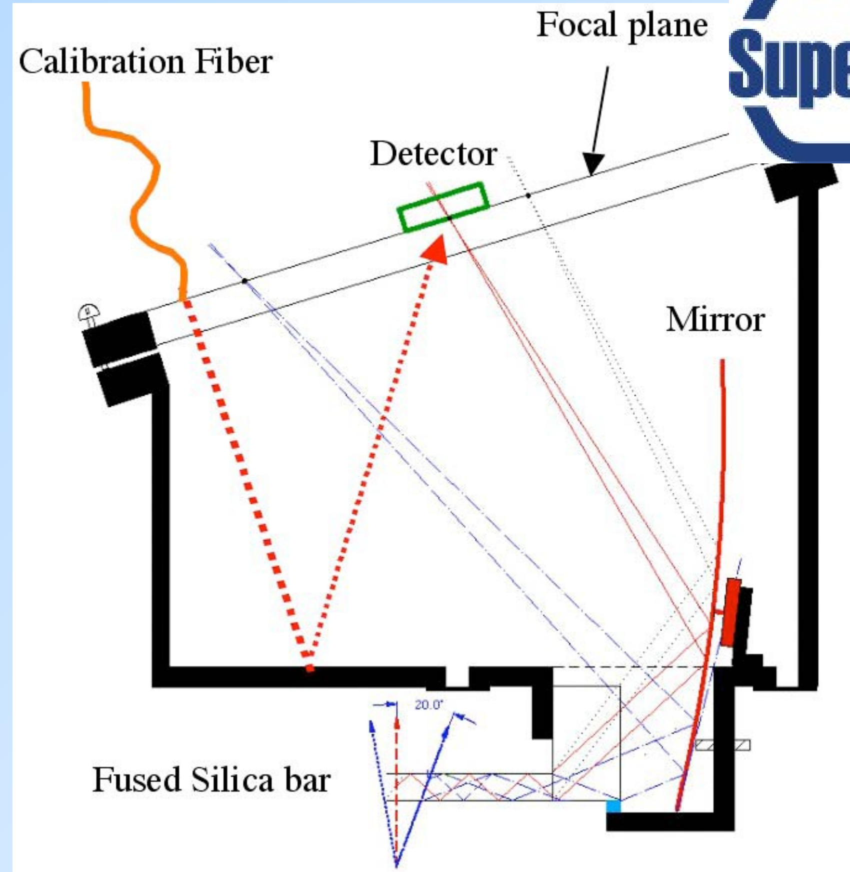
Design options

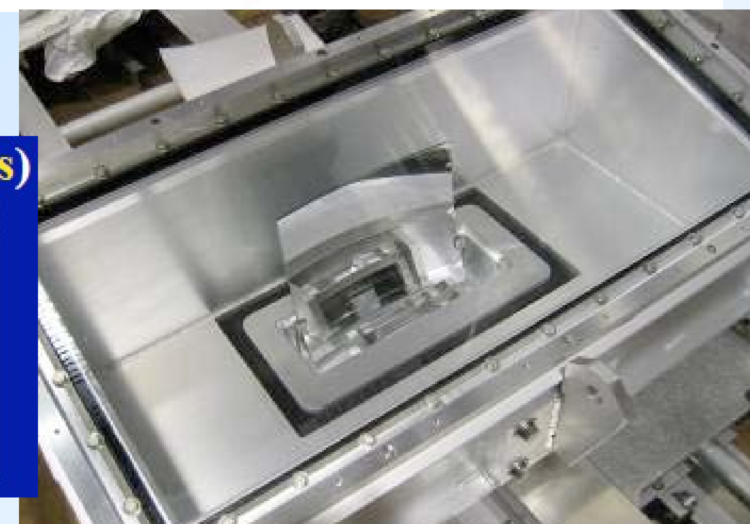
dN/dx (cluster counting) in DCH ??

Forward PID (FARICH or FTOF) ??

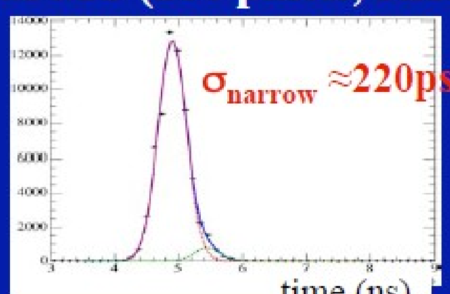
FDIRC prototype tests

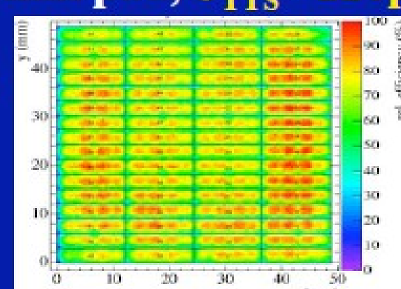
- standoff box with spherical mirror to focus the rings to the detector plane
- box filled with mineral oil for optical coupling
- two types of flat panel PMTs (Hamamatsu) and MCP PMT (Photonis) were used to prove the principle of focusing and chromatic error correction





H-9500 Flat Panel MaPMT (256 pixels, 3x12mm pad, σ_{TTS} ~220ps)

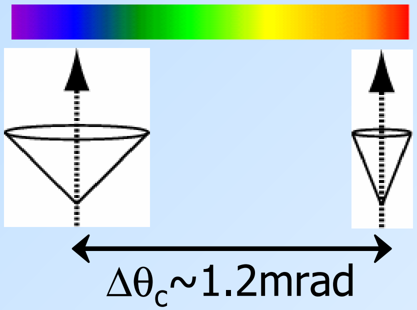


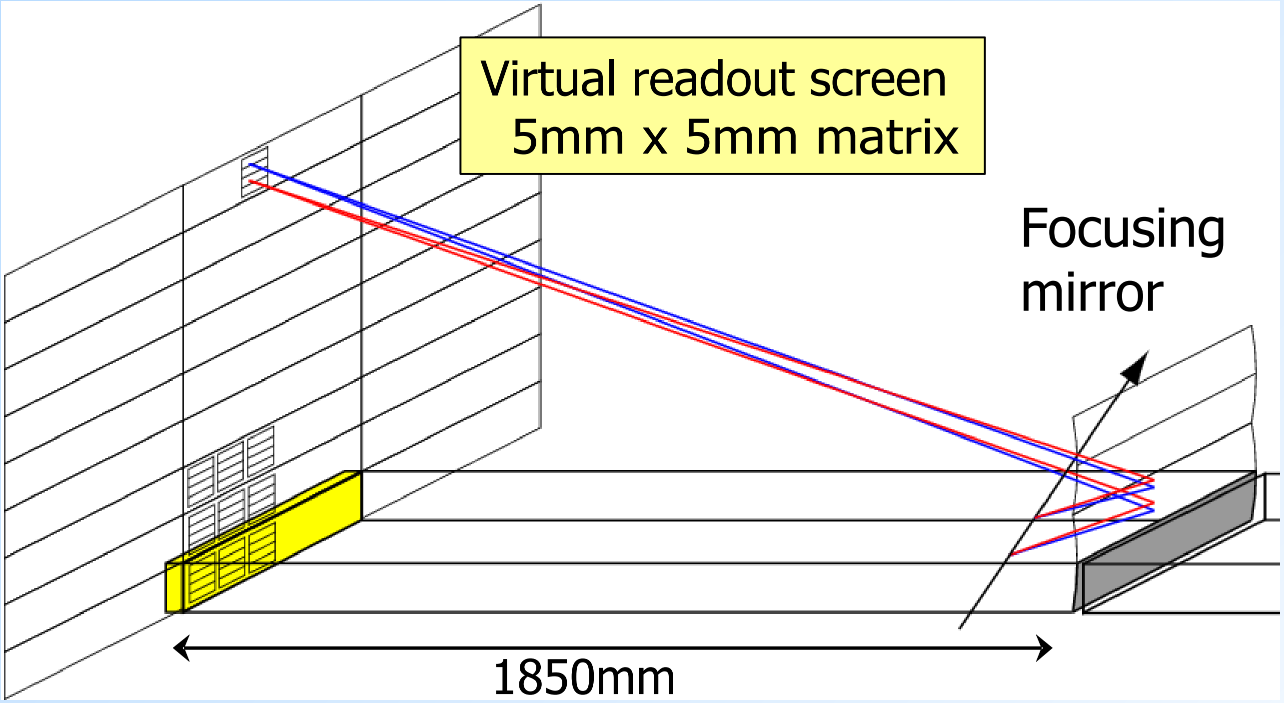


Focusing TOP

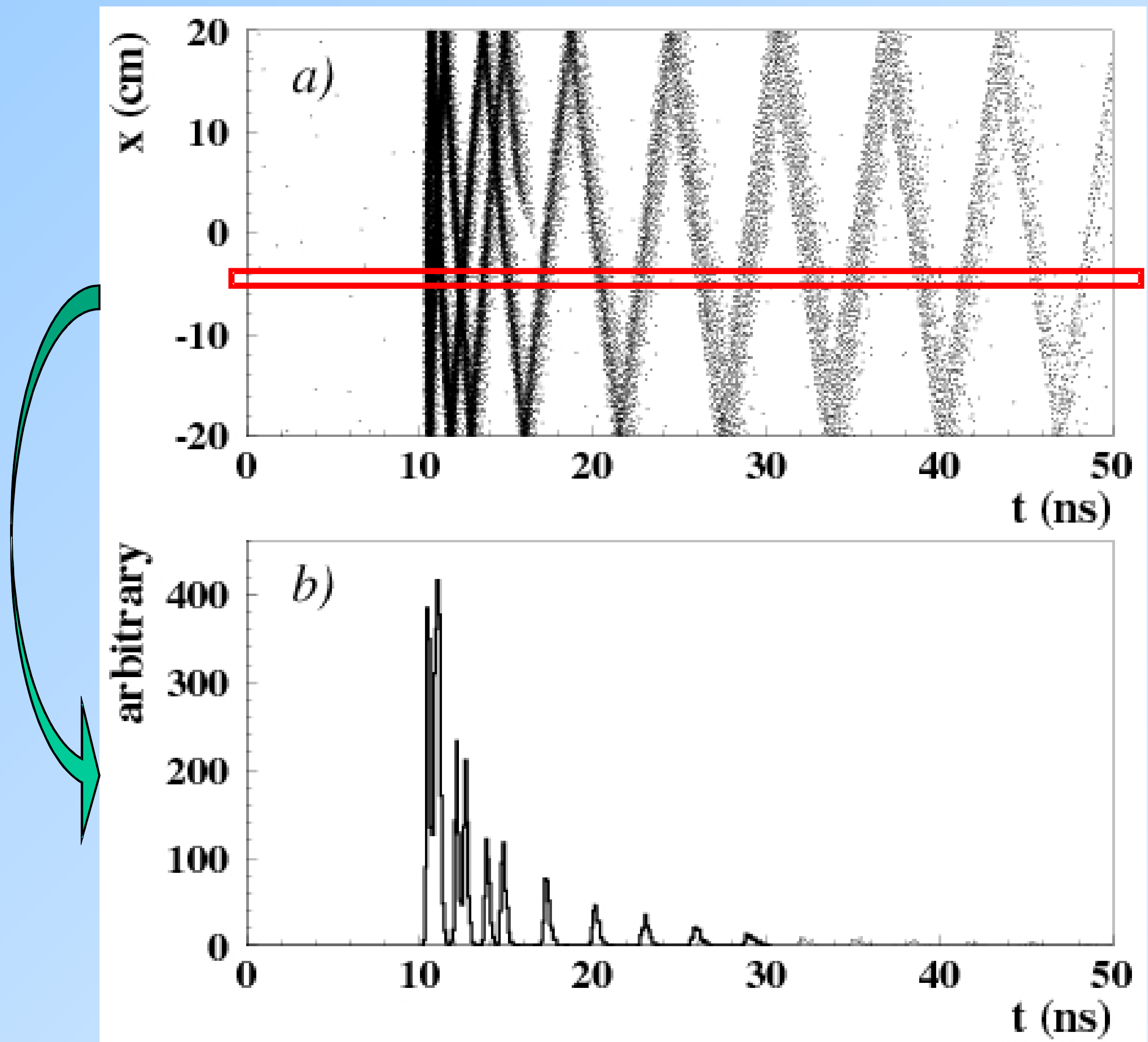
Using λ dependence of Cherenkov angle for chromatic error correction:

- Angle information → y position
- Use t, x and y for ring image reconstruction
- good color separation due to the long path





TOP image

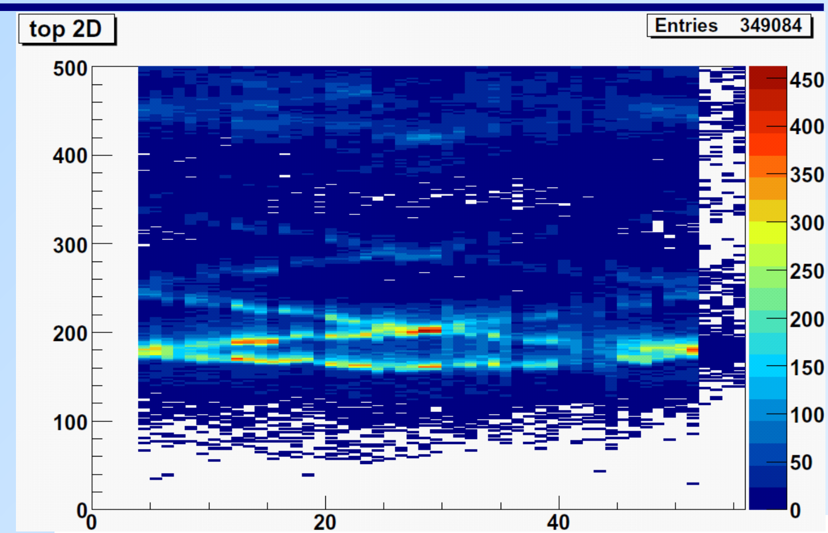


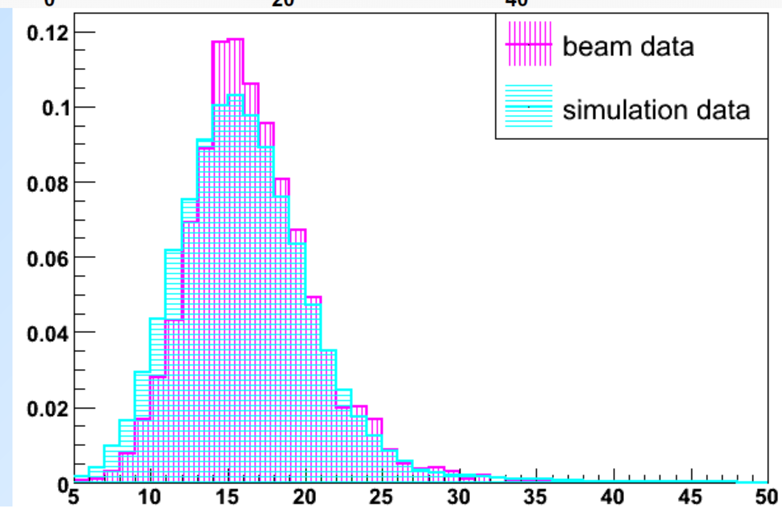
Pattern in the coordinate-time space ('ring') of a pion hitting a quartz bar with ≈80 PMT channels.

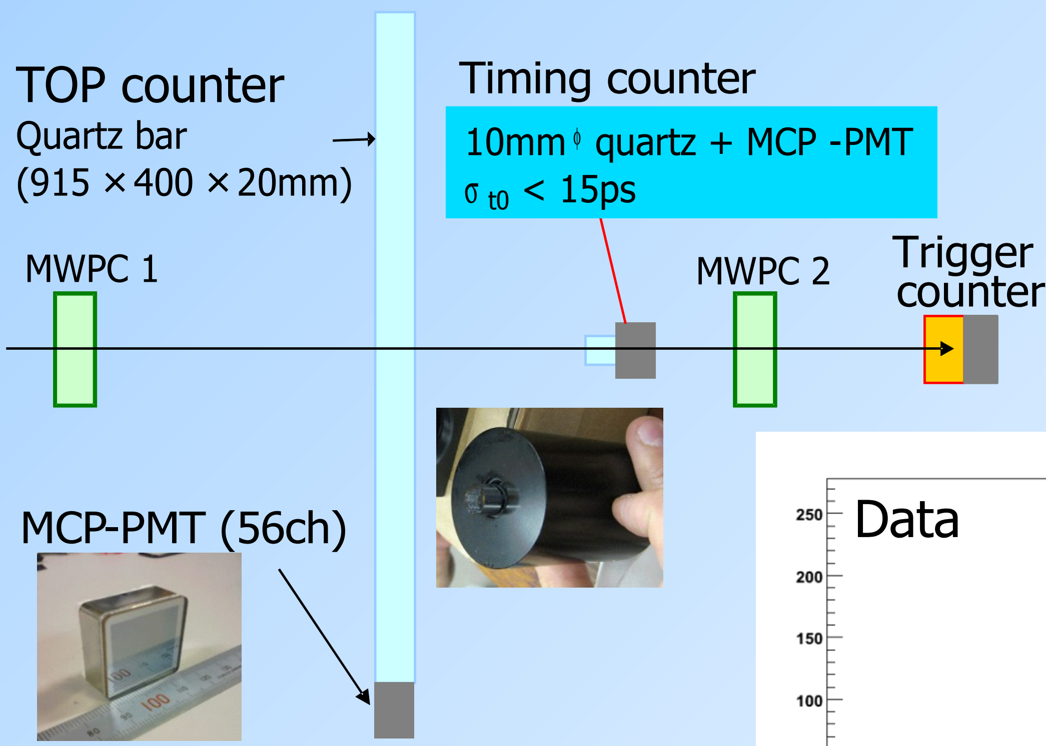
Time distribution of signals recorded by one of the PMT channels: different for π and K.

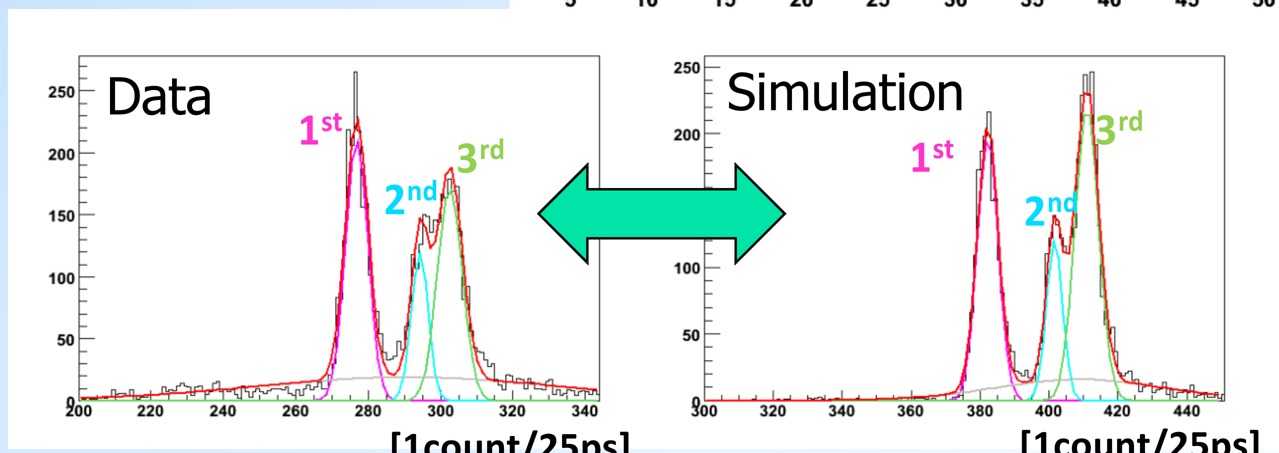
TOP prototype beamtest

- "ring image" similar to the simulated one
- average number of photons ~ 16 → in agreement with the simulation
- measured time distribution on individual channels also agrees with the simulation



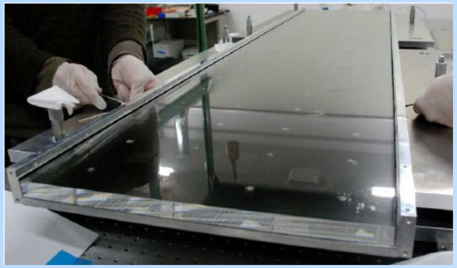


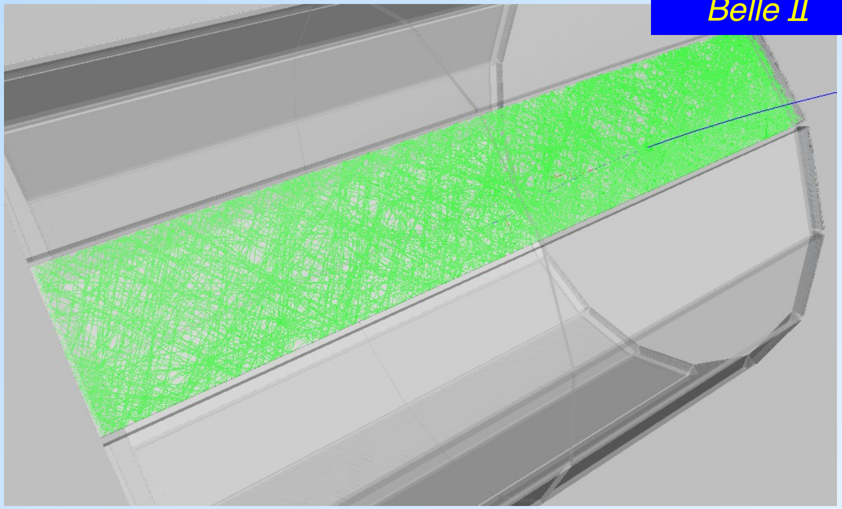


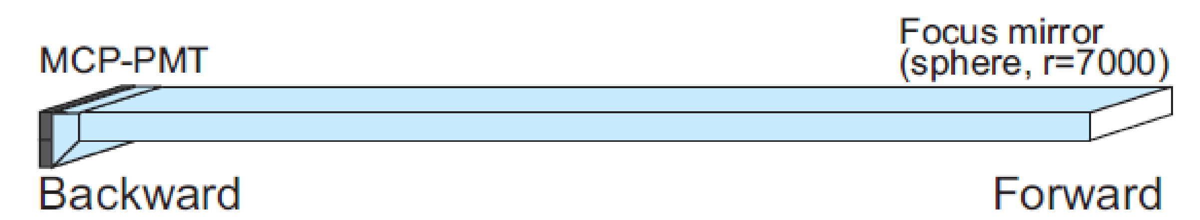


TOP design and performance

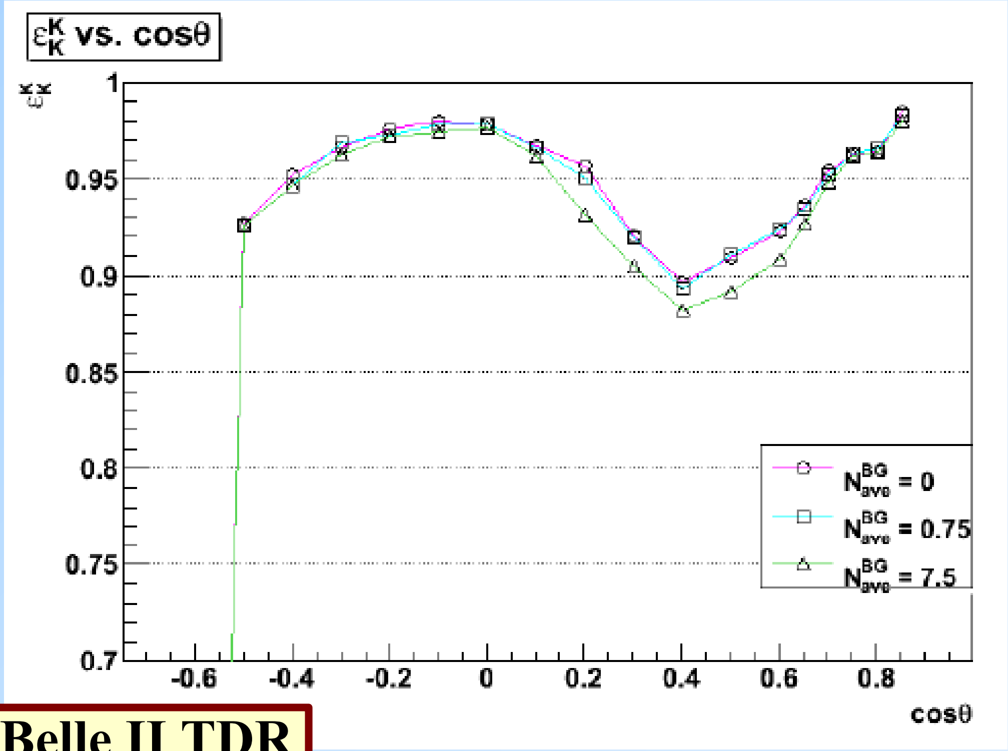
- Single bar focusing TOP with expansion volumen

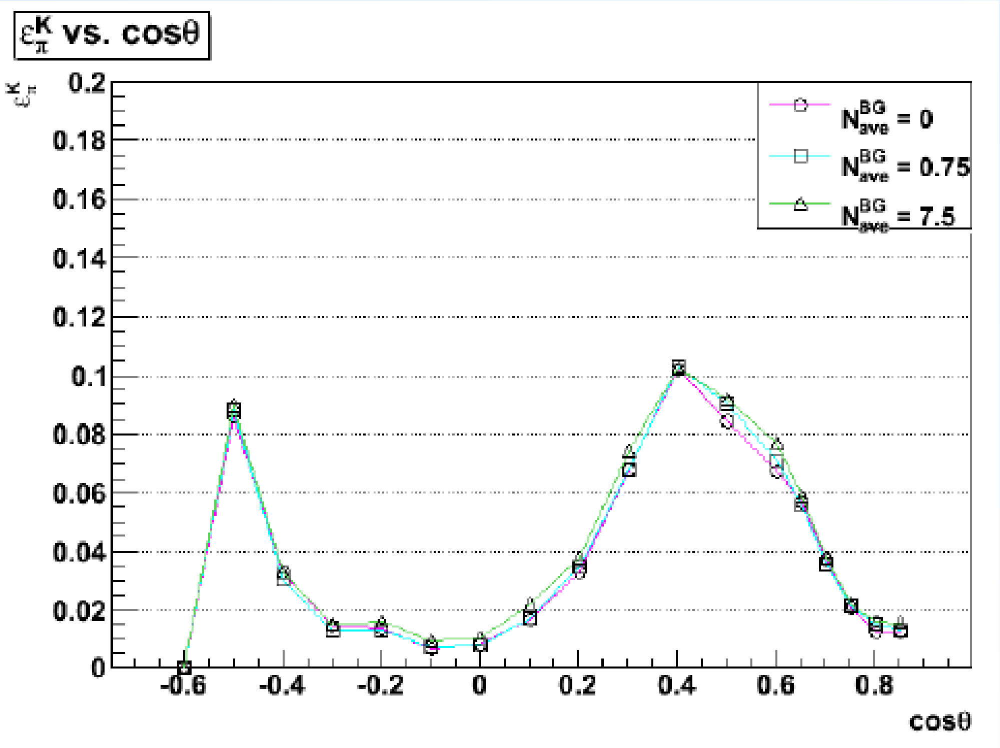






- efficiency and fake rate vs. cos(ϑ) @ 3GeV/c





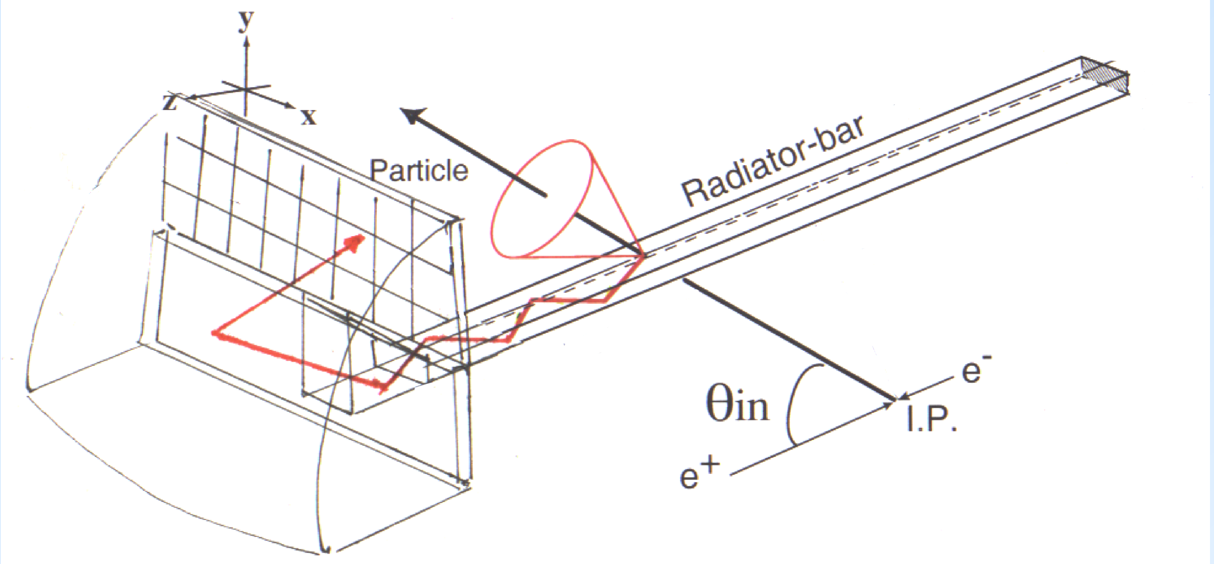
Belle II TDR

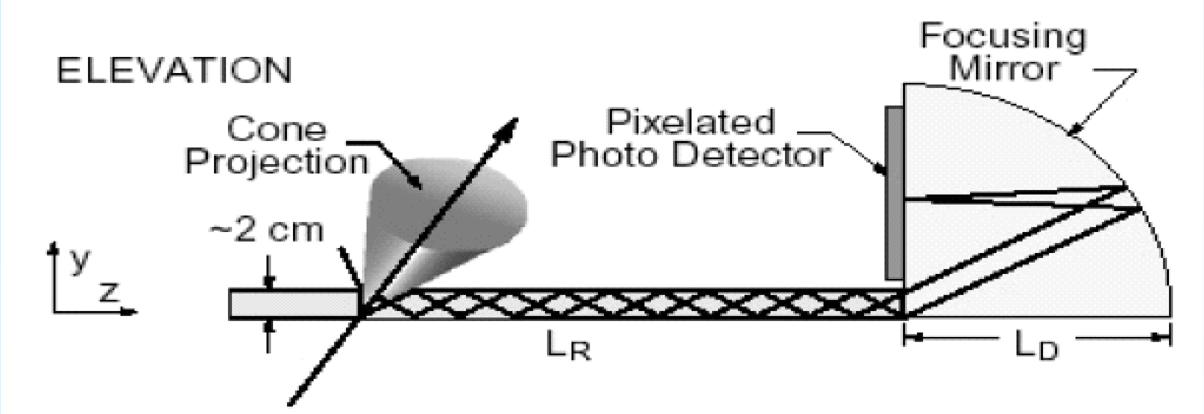
Focusing DIRC - FDIRC

(SuperB), PANDA

Strategy to cope with higher background at 100x luminosity:

- reduce the size of the standoff box → focusing and higher granularity of the photon detector
- reduce the time window → photon detector with faster response



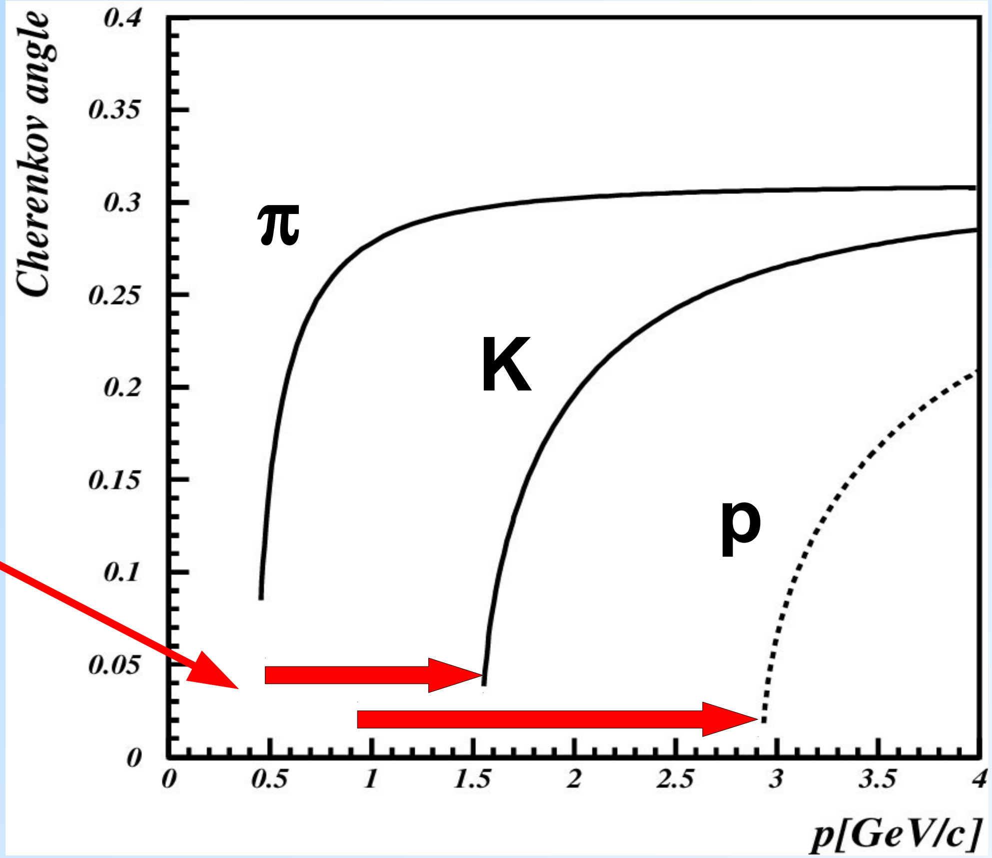


Faster detector can be used to measure the propagation time of the Cherenkov photons and use it to correct for chromatic error.

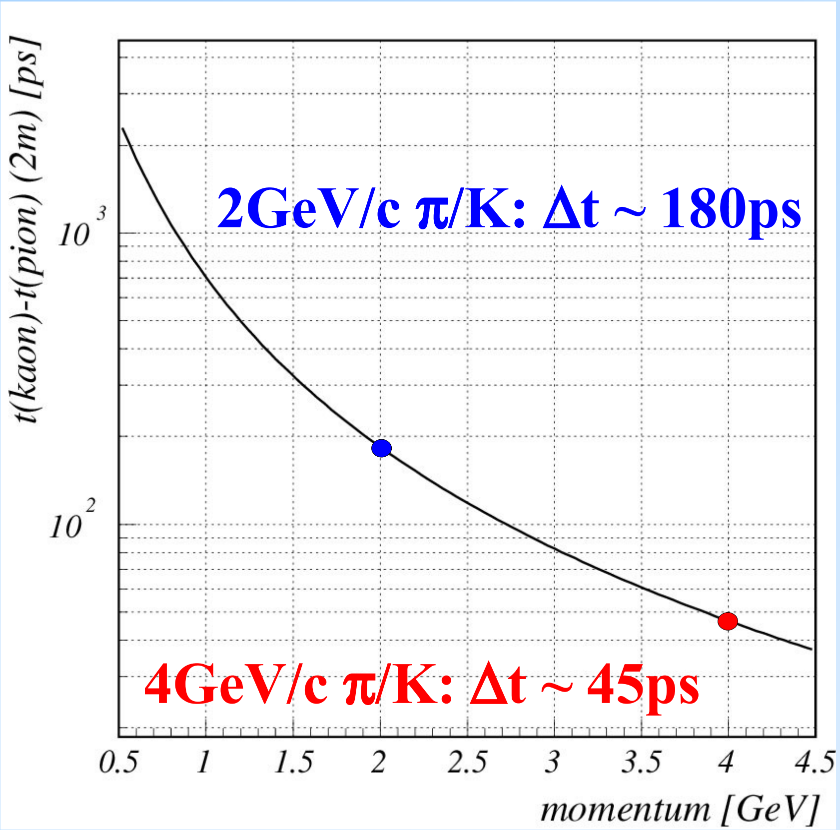
Photon detector is outside the magnetic field → flat panel PMT can be used.

TOF with Cherenkov light

Using Cherenkov photons emitted in the PMT window (n~1.46) PID can be extended into the lower momentum region:
Kaons and protons can be positively identified below the Cherenkov threshold in aerogel (n~1.05).



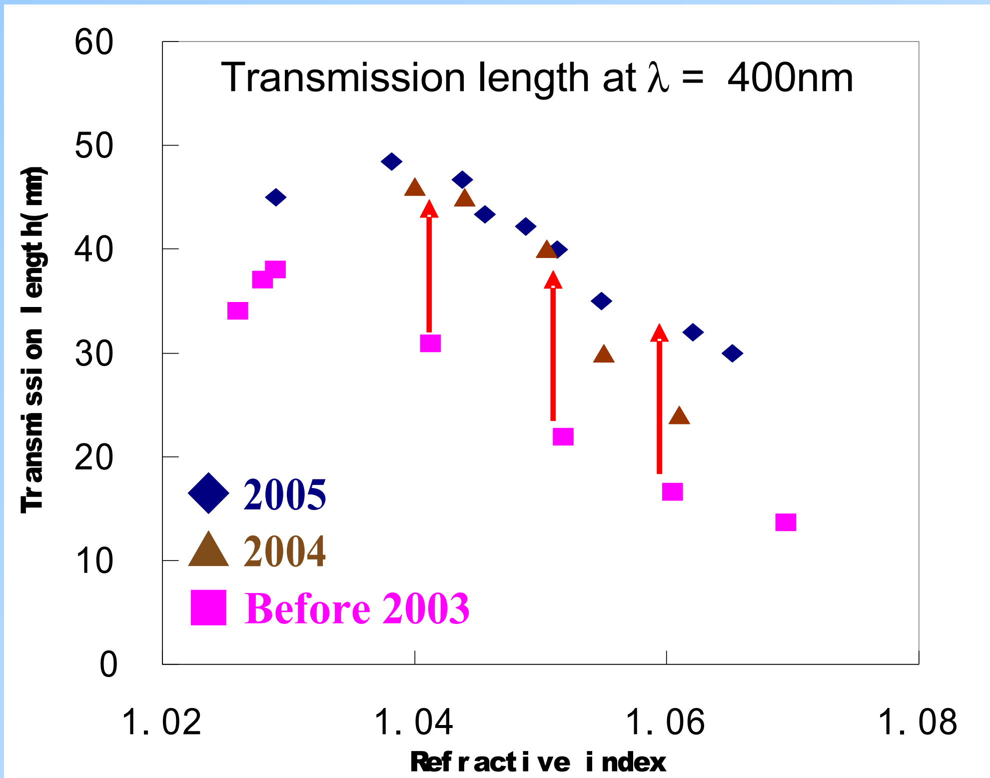
Cherenkov angle in aerogel (n=1.05) for pion, kaon and proton.

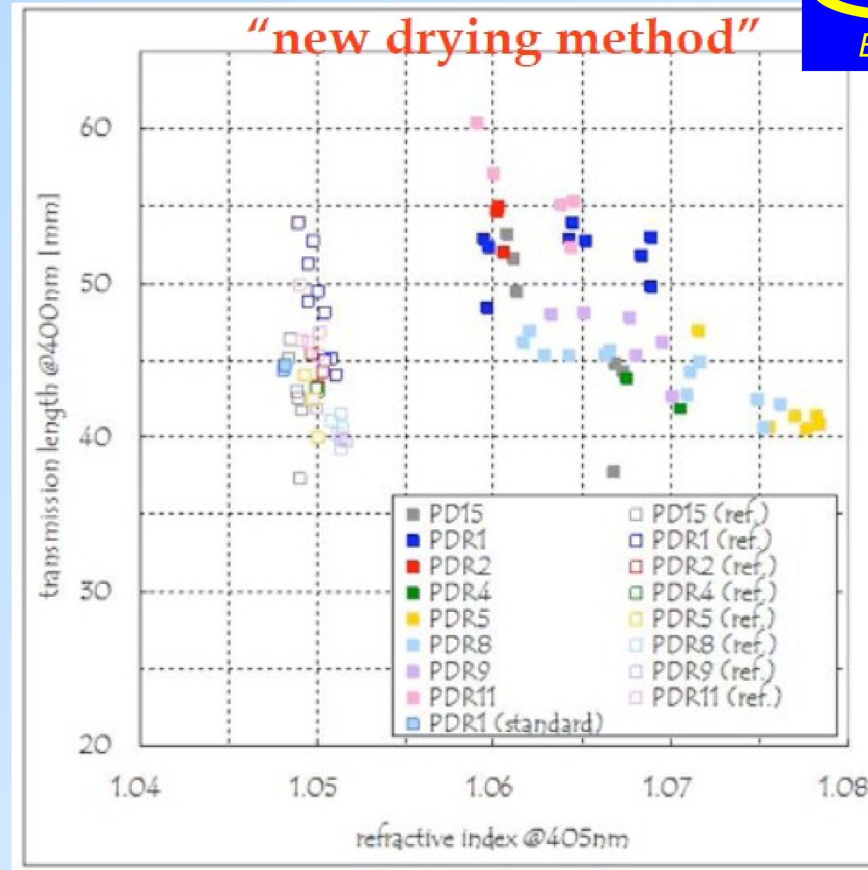


Time-of-flight difference for pions and kaons from IP to forward PID (2m).

Aerogel production

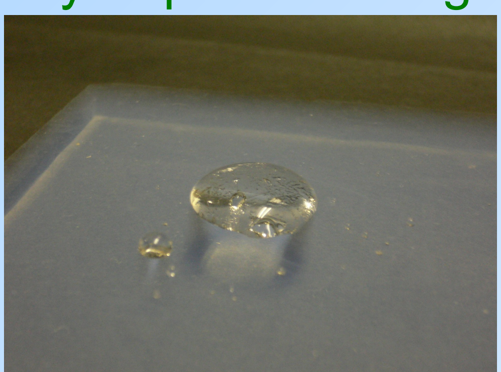
- transparency greatly improved

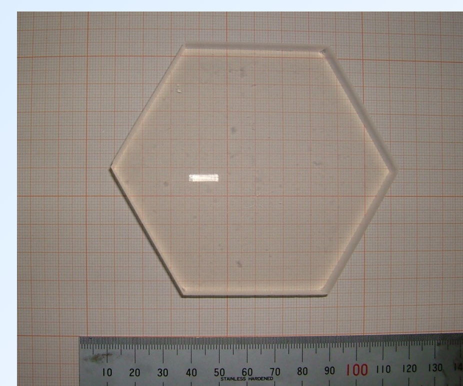




M. Tabata et. al. @ TIPP 2011

- Hydrophobic aerogel - alows water jet cuting

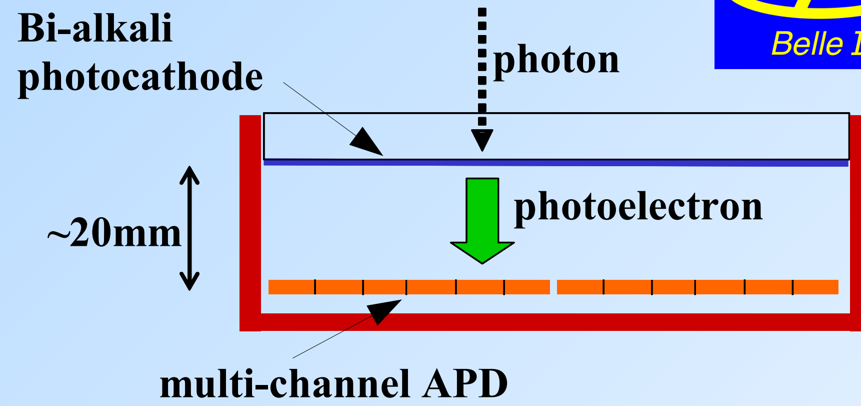


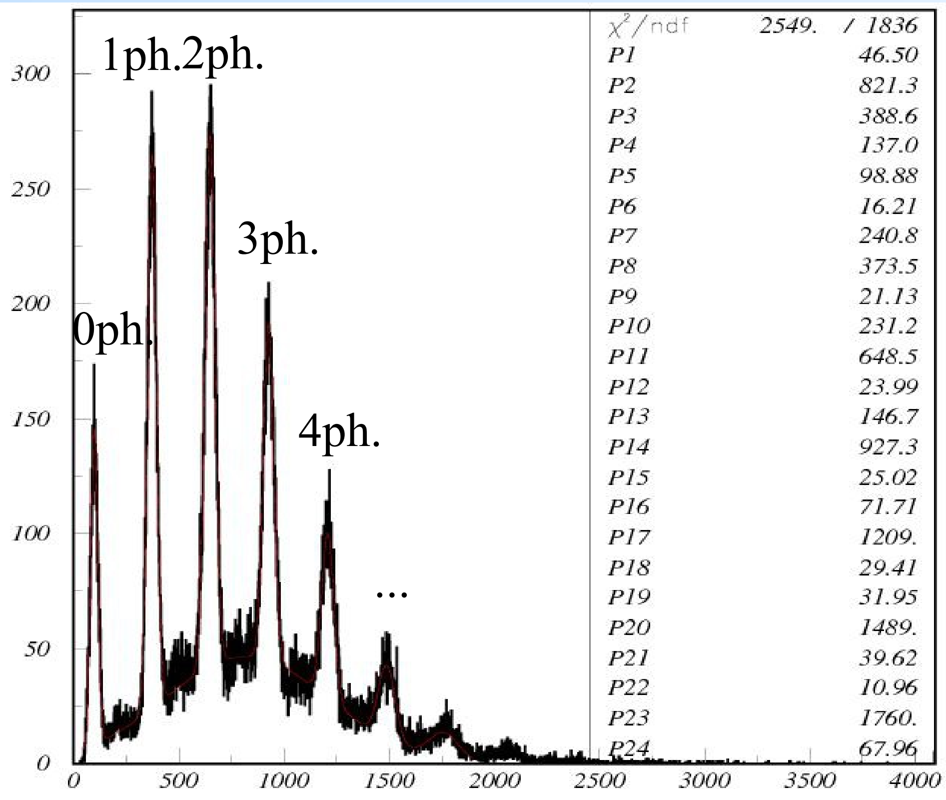


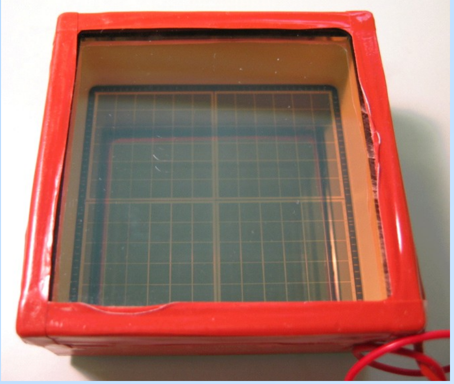
ARICH photon detector: HAPD

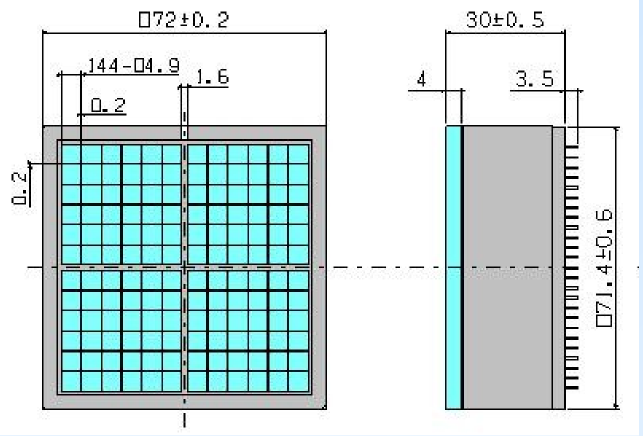
Hybrid avalanche photo-detector developed in cooperation with Hamamatsu (proximity focusing configuration):

- 12x12 channels (~5x5 mm^2)
- size ~ 72mm x 72mm
- ~ 65% effective area
- total gain ~ 10^4 – 10^5 (bombardment~1000, avalanche~40)
- detector capacitance ~ 80pF/ch.
- typical peak QE ~ 30%
- works in mag. field (~perpendicular to the entrance window)



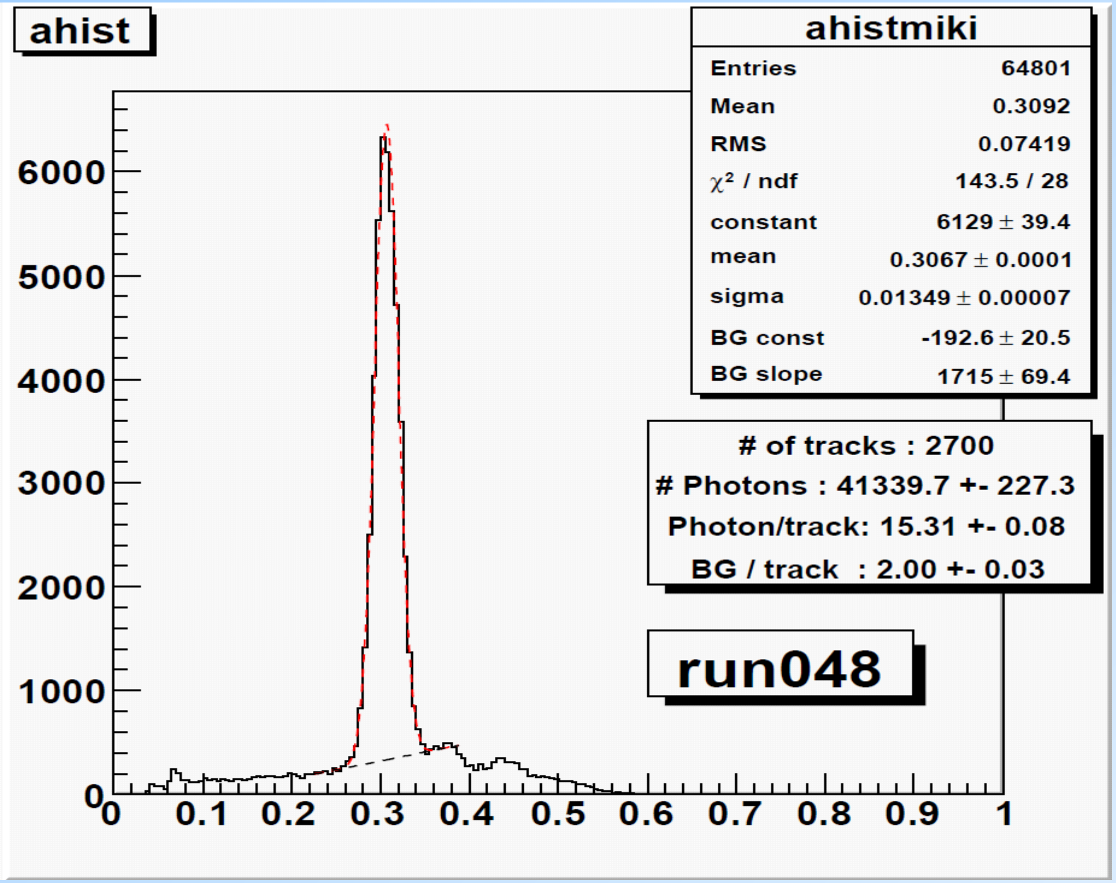


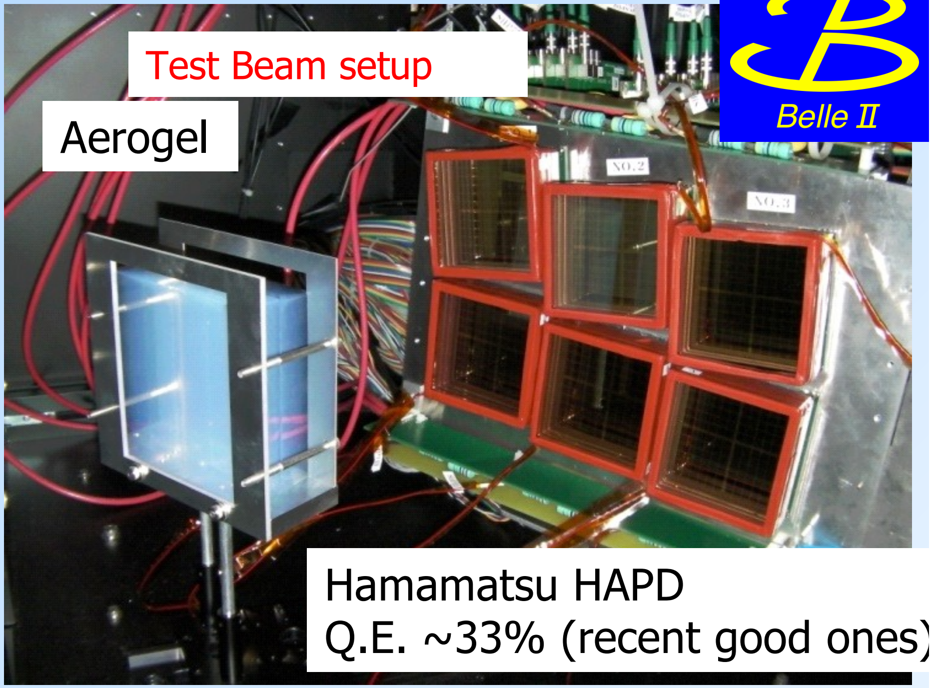


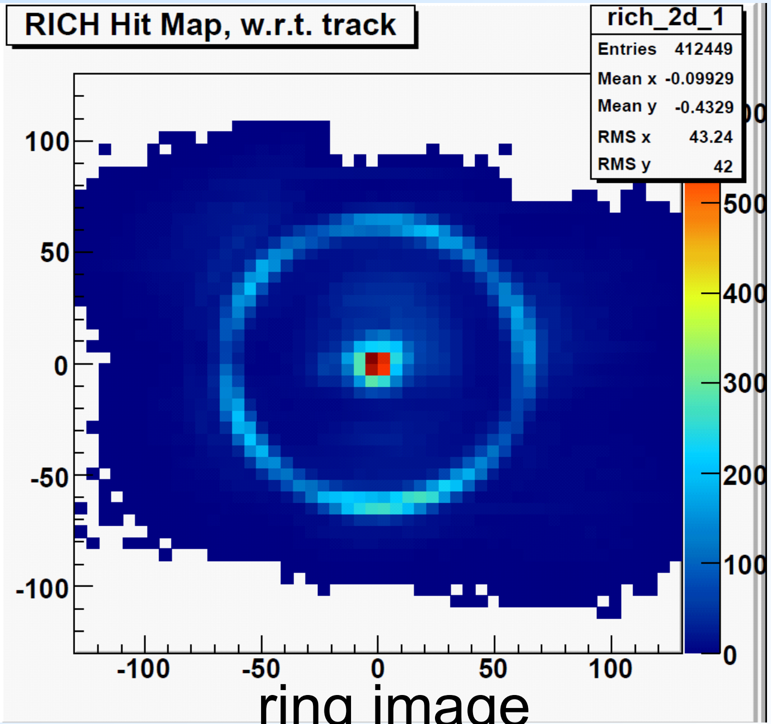


Beam test results

- test with 2 GeV/c electrons @ KEK
- detected number of photons: ~ 15
- Cherenkov angle resolution: ~ 13 mrad







ring image

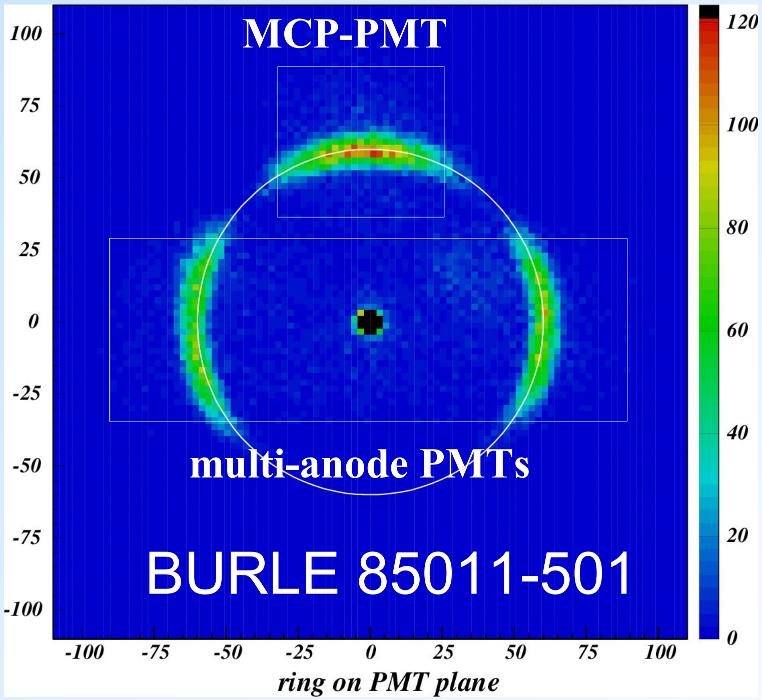
Better than 6 σ p/K separation @ 4 GeV/c

NIM A595 (2008) 180

Photon detector candidate: Photonis MCP-PMT

Model 85015/A1:

- two MCP steps - chevron configuration
- 8x8 anode pads @6.5 mm pitch, gap ~ 0.5mm
- bialkali photocathode
- gain ~ 0.6 x 10^6 (@2400V)
- 10μm pores → operates up to 1.5 T
- size ~ □59mm
- effective area fraction ~ 80%
- excellent timing < 40ps - single photon
- window thickness 1.5mm



Beam test result of 25μm sample:

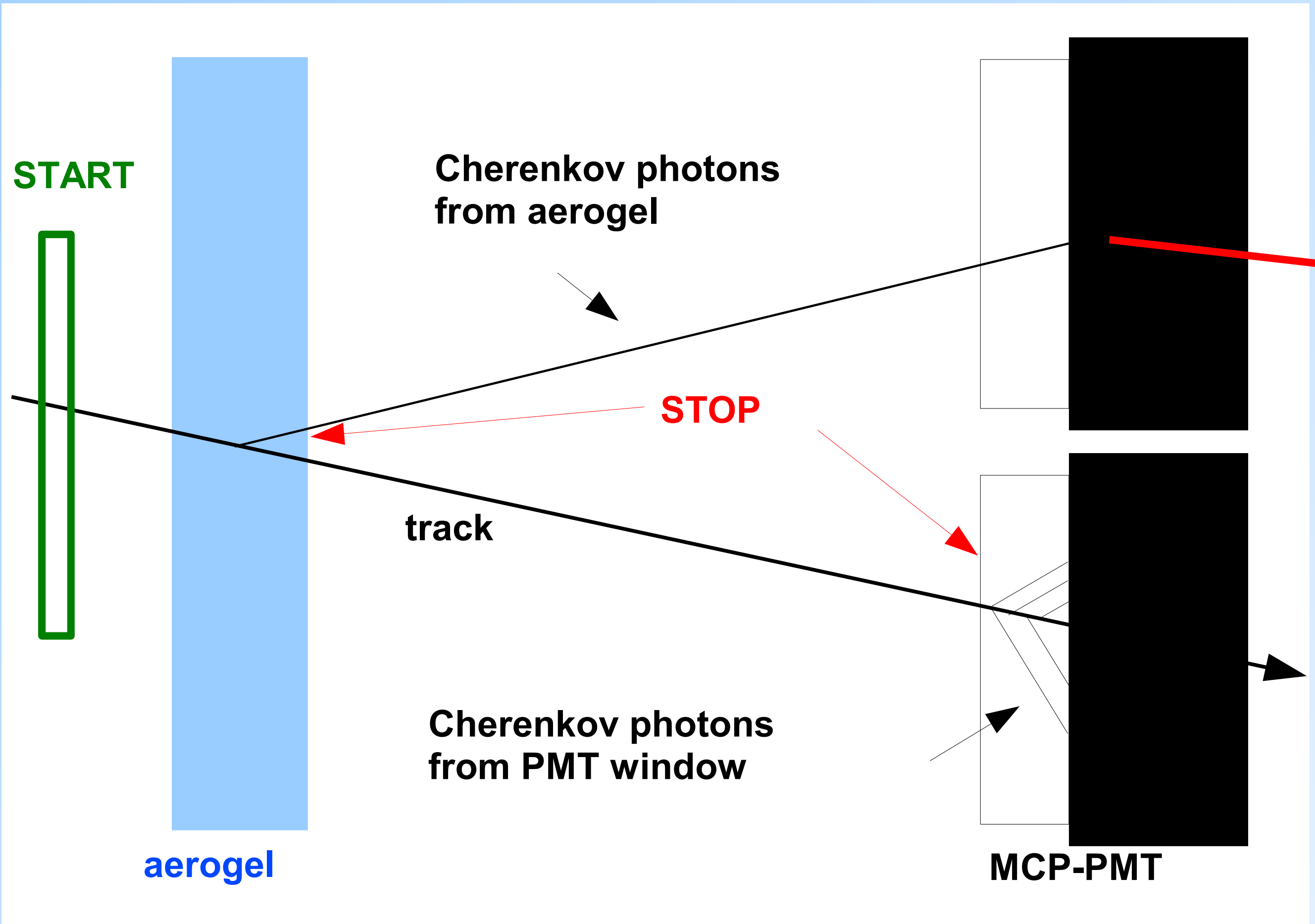
- σ_ϑ~13 mrad (single cluster)
- number of clusters per track N ~ 4.5
- σ_ϑ~ 6 mrad (per track)
- **→ ~ 4 σ π/K separation at 4 GeV/c**

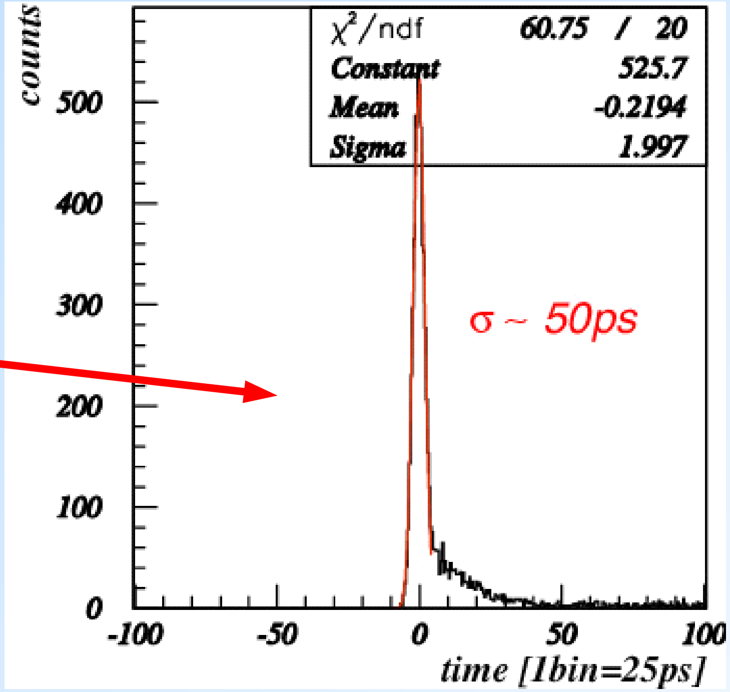
- Tested in combination with multi-anode PMTs

NIM A567 (2006) 124

Additional feature: ARICH+TOF

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





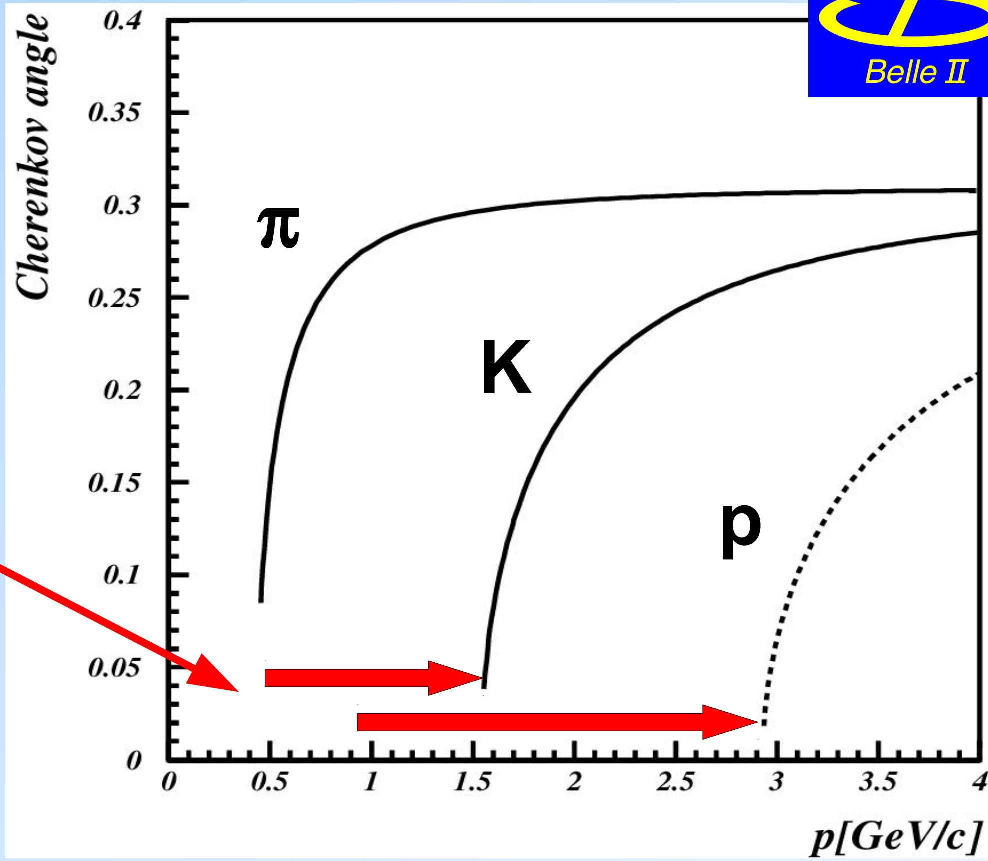
Beam test:

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

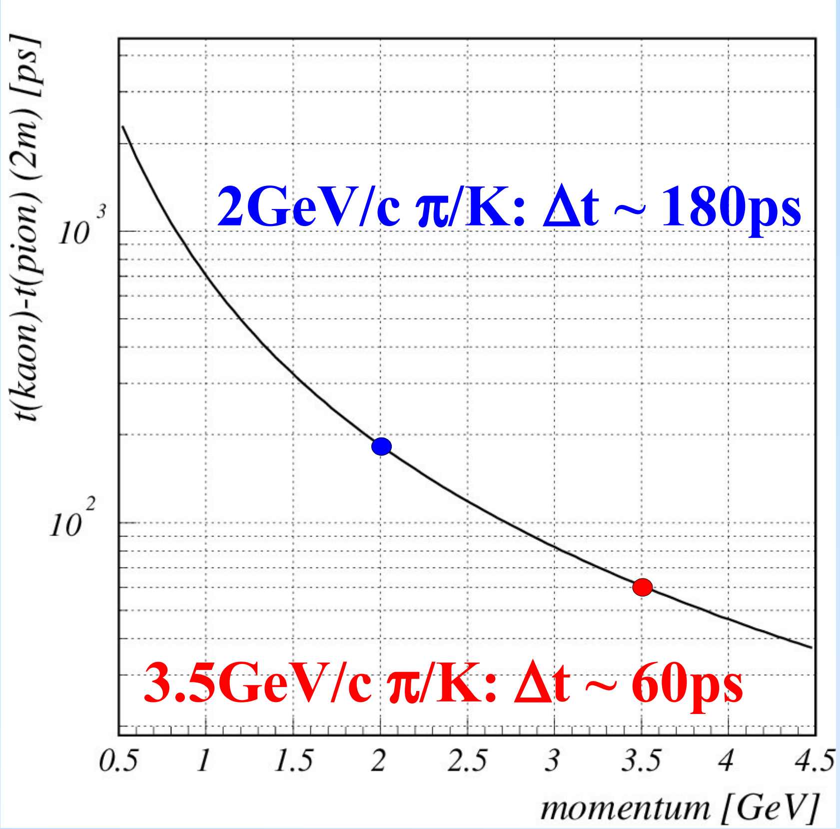
NIM A572 (2007) 432

ARICH TOF capability

Using Cherenkov photons emitted in the PMT window (n~1.46) PID can be extended into the lower momentum region:
Kaons and protons can be positively identified below the Cherenkov threshold in aerogel (n~1.05).



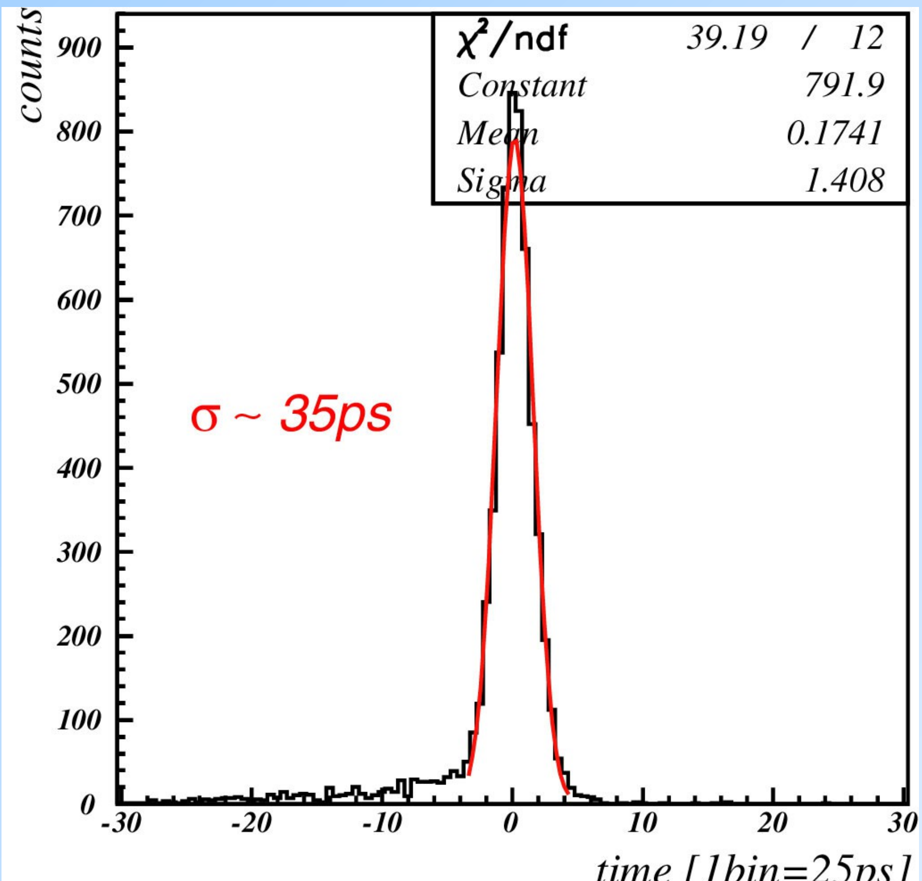
Cherenkov angle in aerogel (n=1.05) for pion, kaon and proton.

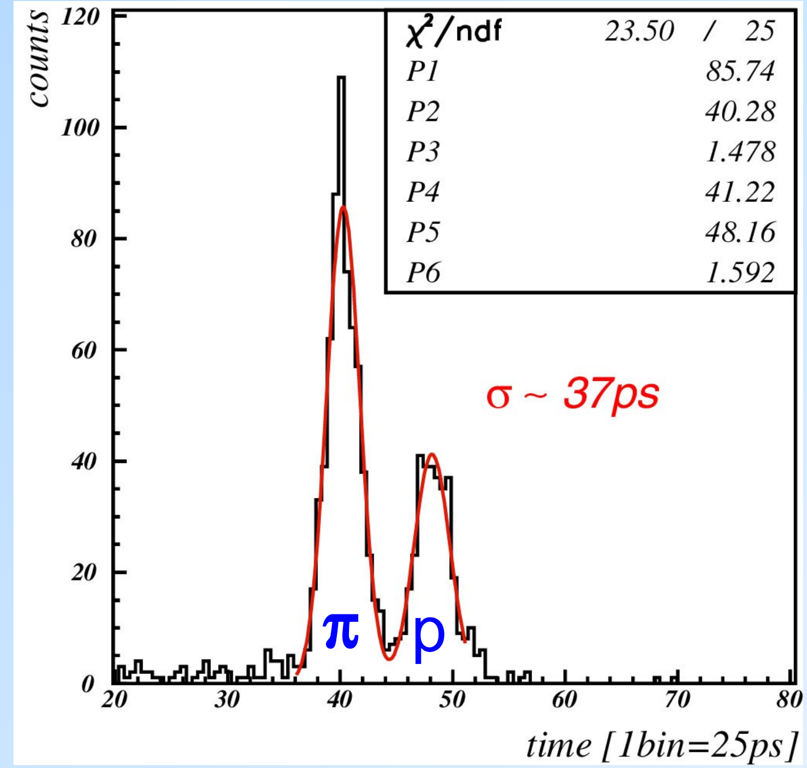


Time-of-flight difference for pions and kaons from IP to forward PID (2m).

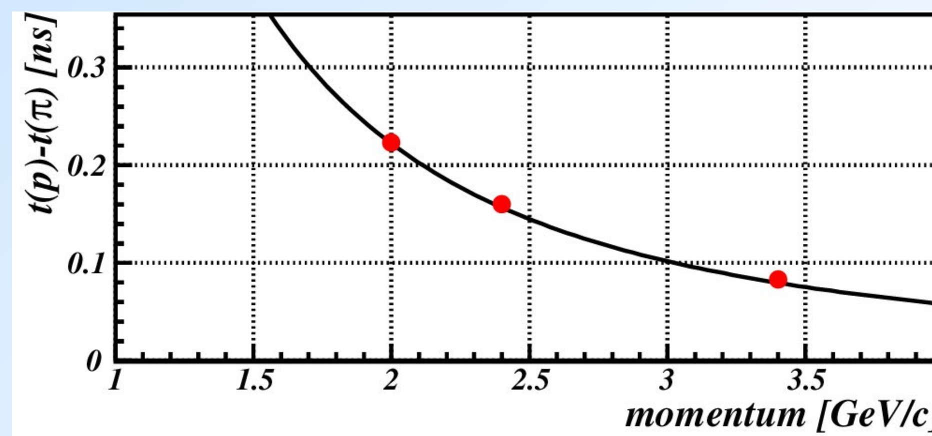
TOF with window photons

- expected number of detected Cherenkov photons emitted in the PMT window(2mm) is ~ 12 and expected resolution ~ 32 ps
- obtained resolution for window photons is ~ 35ps





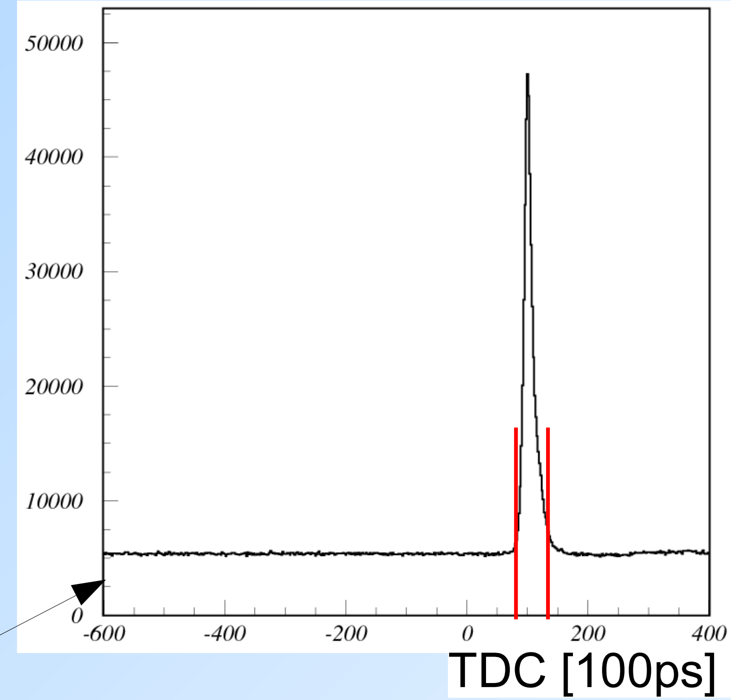
- TOF test with pions and protons at 2 GeV/c
- distance between start counter and MCP-PMT is 65cm



NIM A572 (2007) 432

Photon detector candidate: SiPM

- immune to magnetic field
- high photon detection efficiency (PDE)
- good timing properties (< 300ps FWHM)
- no high voltage
- low material budget
- high noise rate ~ 1MHz/mm^2
- radiation damage - increase of dark noise



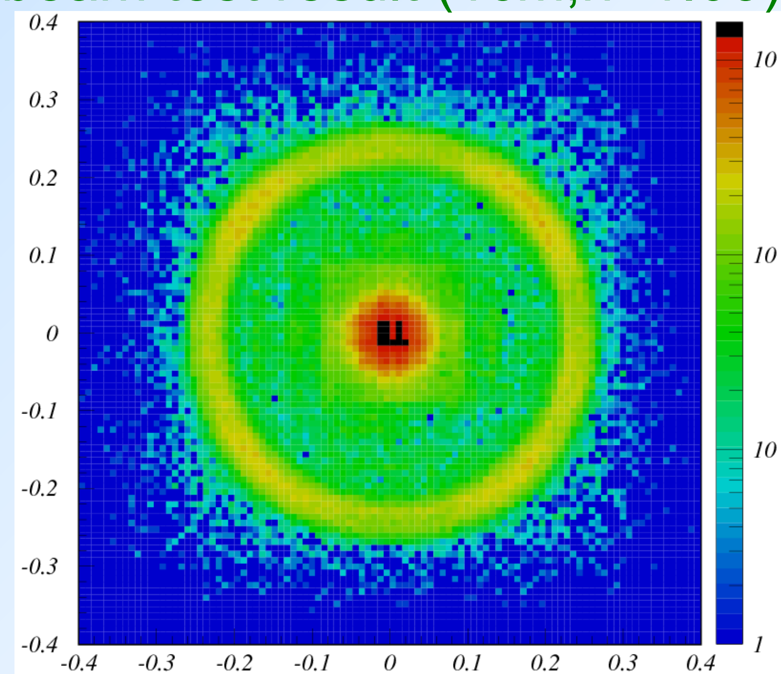
Possible candidate:

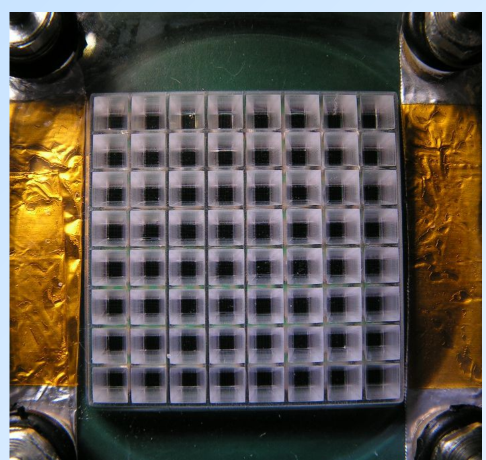
- array of Hamamatsu S10362-11-100P

Improve signal to noise ratio by:

- narrow time window
- use of light concentrators

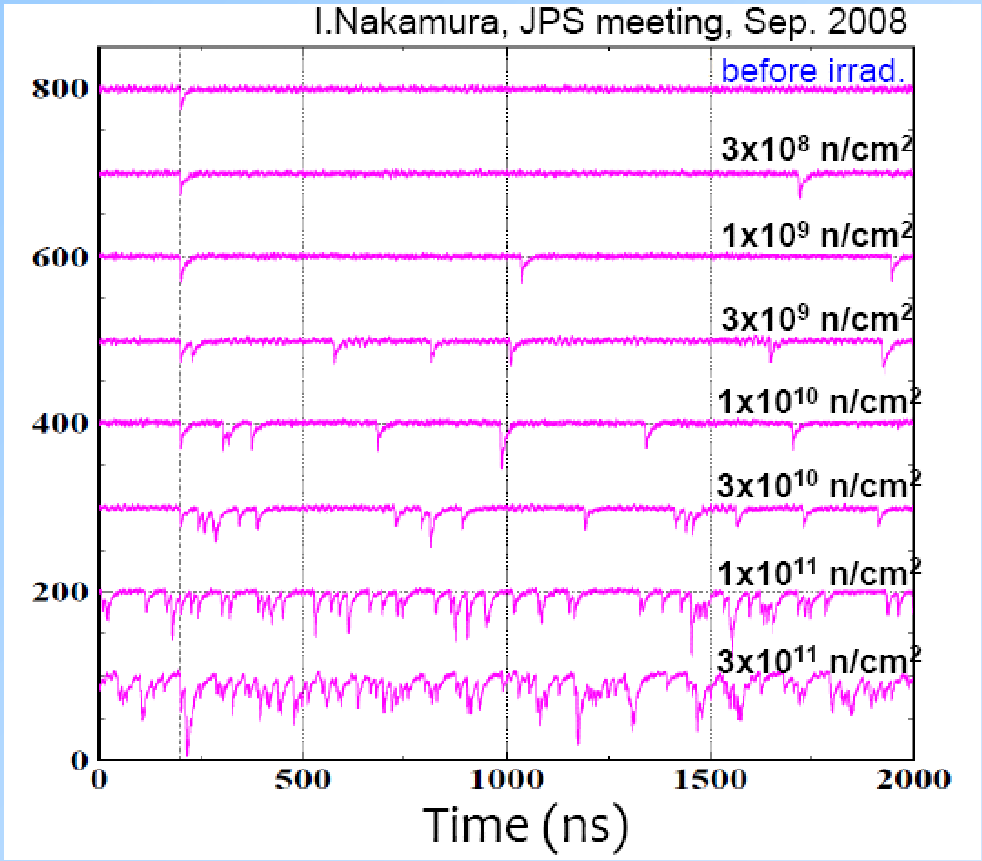
- beam test result (1cm,n=1.03)





NIM A613 (2010) 195

Neutron damage



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

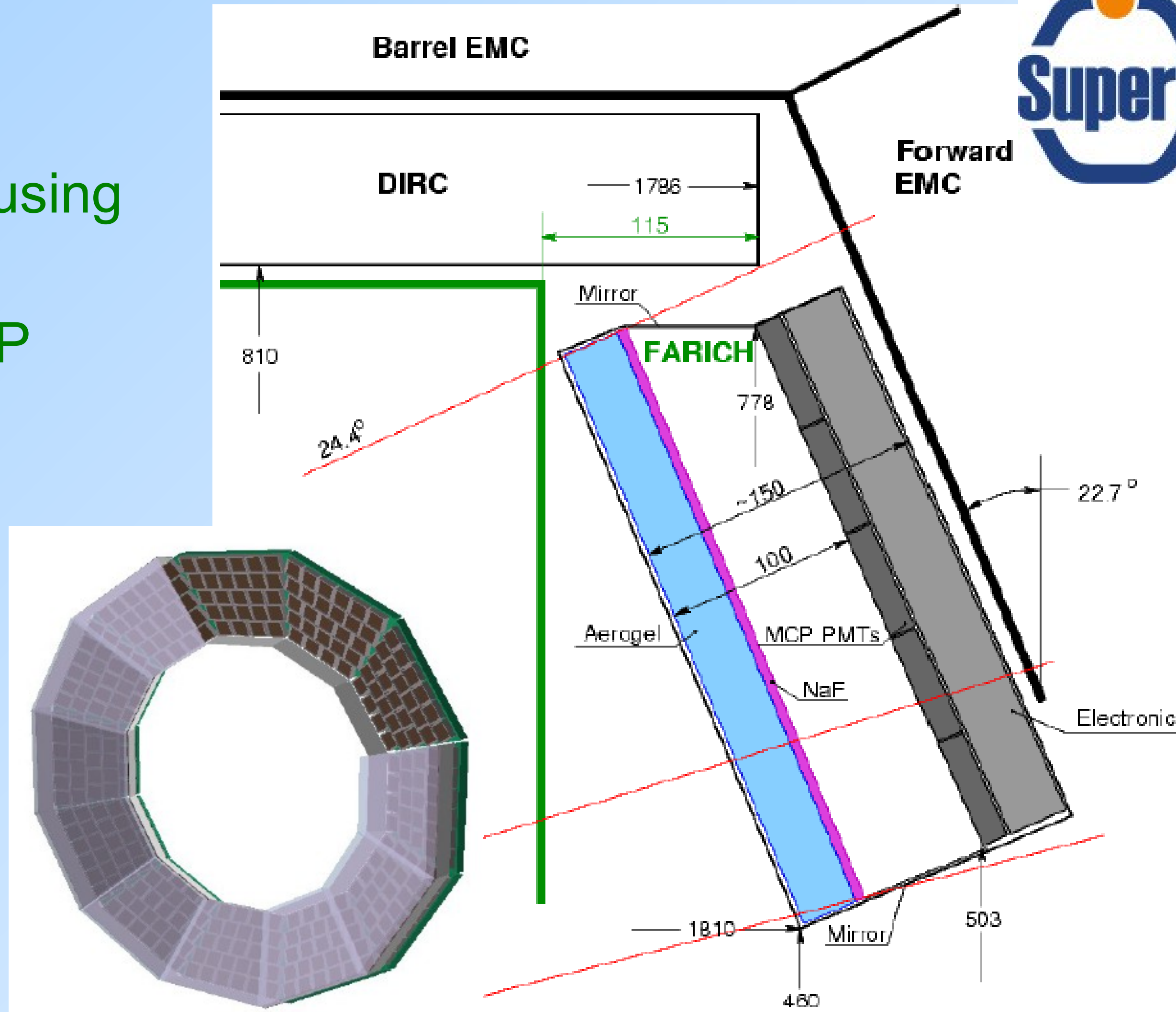
Expected fluence at 50/ab
→ if backg. x20: 2-20 10^{11} n/cm^2
→ worst than the lowest line

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.

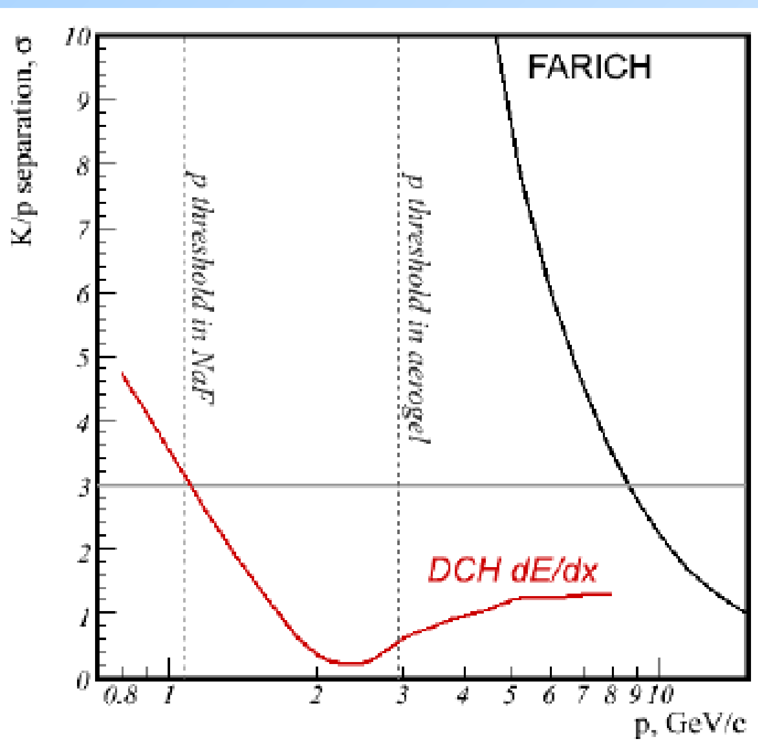
→ Very hard to use present G-APDs as single photon detectors in Belle II because of radiation damage by neutrons

SuperB FARICH

- Radiator: NaF + two layer focusing aerogel
- Photon detector Photonis MCP PMT XP85012 (or SiPM?)



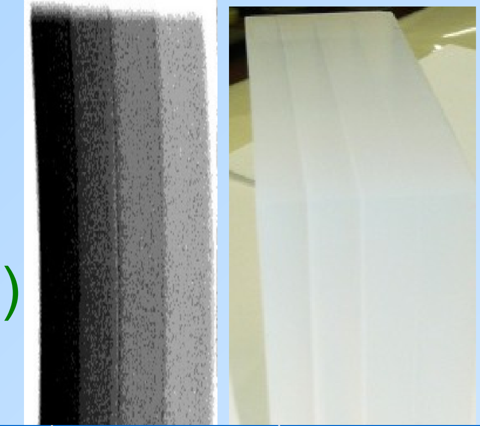
π/K separation power vs. p

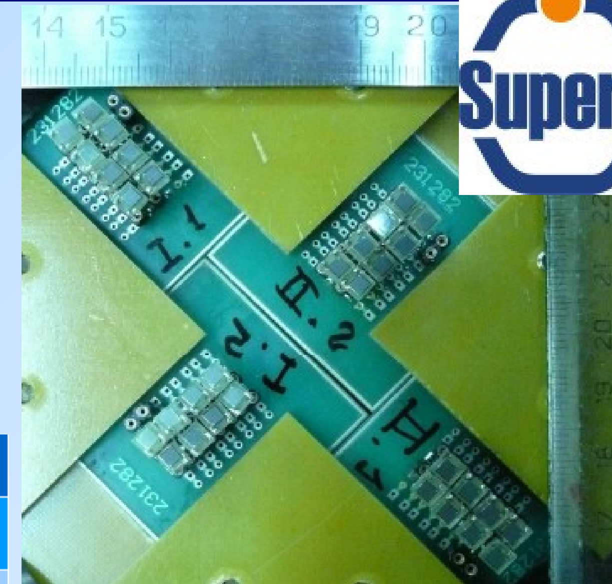


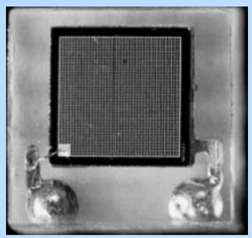
layer	marerial	n(400nm)	t, mm
1	aerogel	1.039	16.2
2	aerogel	1.050	13.8
3	NaF	1.332	5.0

SuperB FARICH beamtest

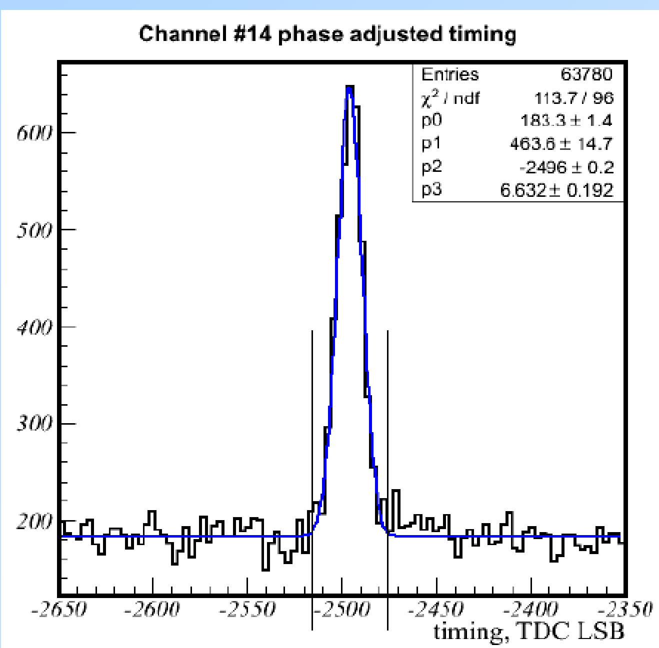
- 4 layer focusing aerogel radiator (43 mm attenuation length @400nm)
- CPTA MRS APD, 2.1x2.1 mm^2
- 5-10 MHz dark count rate
- 40% PDE @600nm
- Prove of principle

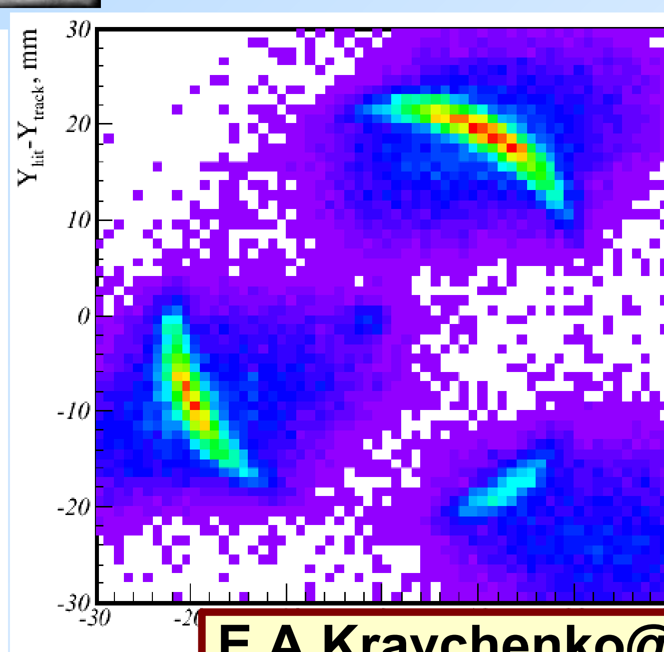


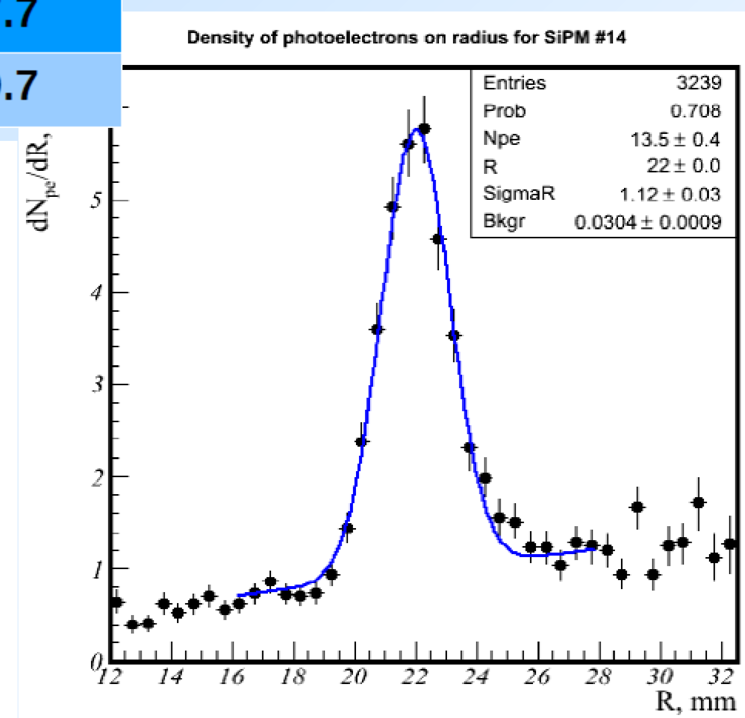




	n	h, mm
Layer 1	1.050	6.2
Layer 2	1.041	7.0
Layer 3	1.035	7.7
Layer 4	1.030	9.7



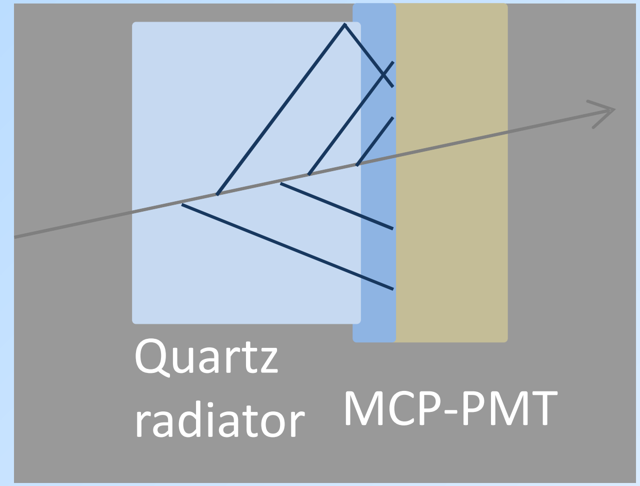


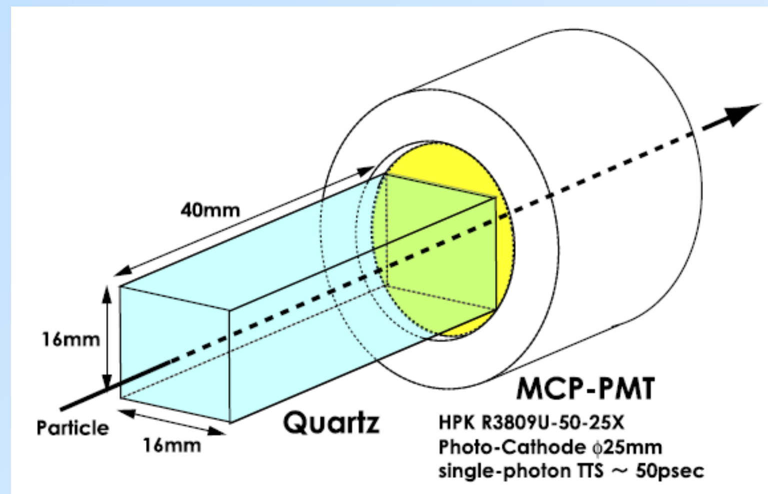


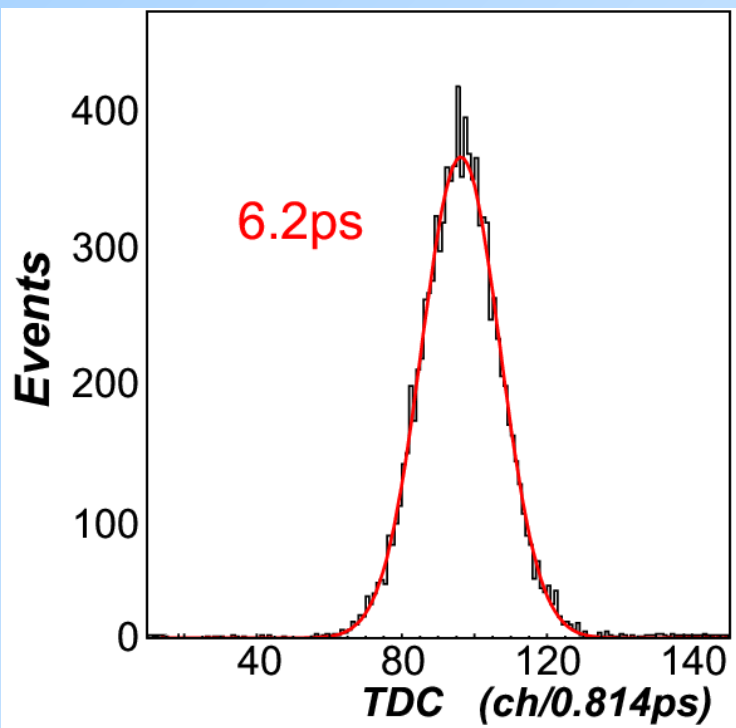
E.A.Kravchenko@17th SuperB Workshop (2011)

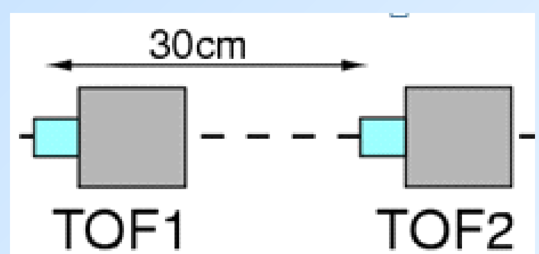
Belle II 10 ps TOF

- Excellent timing can be acheived by coupling Cherenkov radiator directly to the MCP-PMT
- Can be used as dedicated TOF

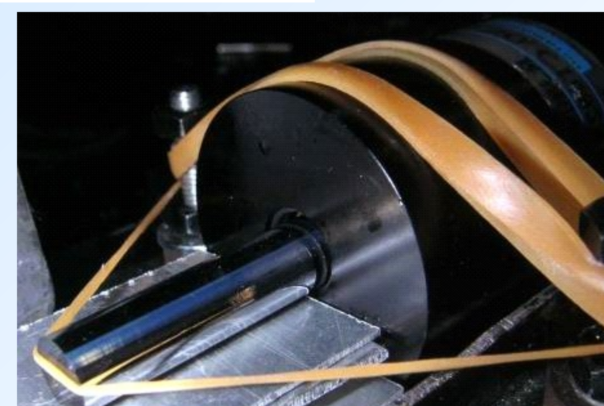








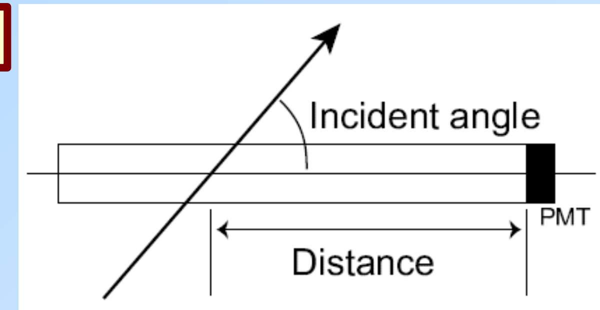
K. Inami @ PD07

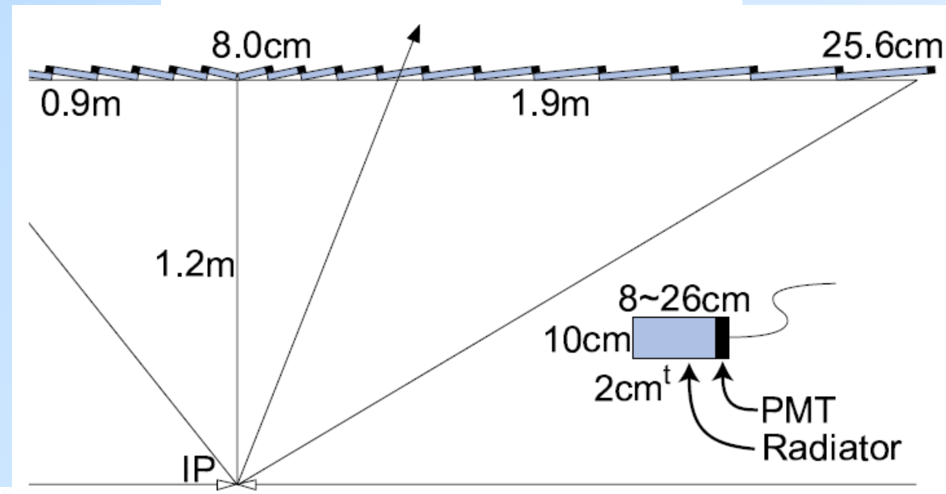


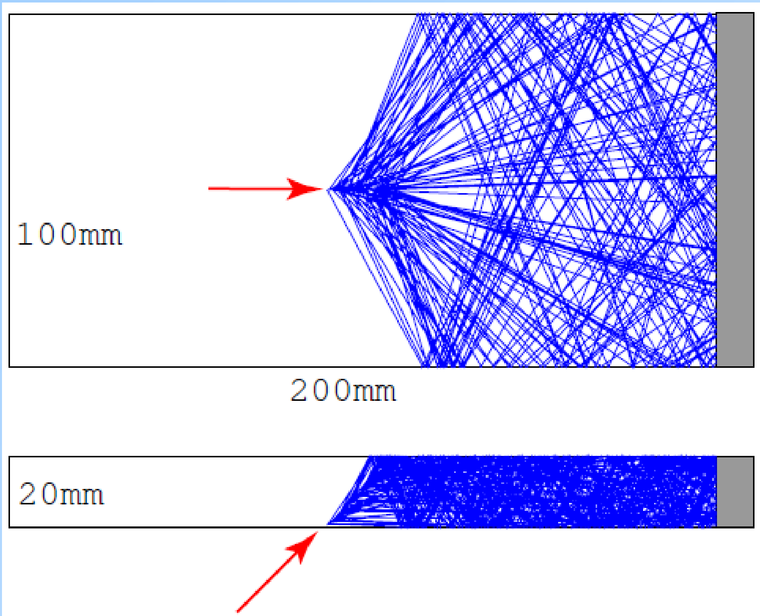
Belle II 10 ps TOF

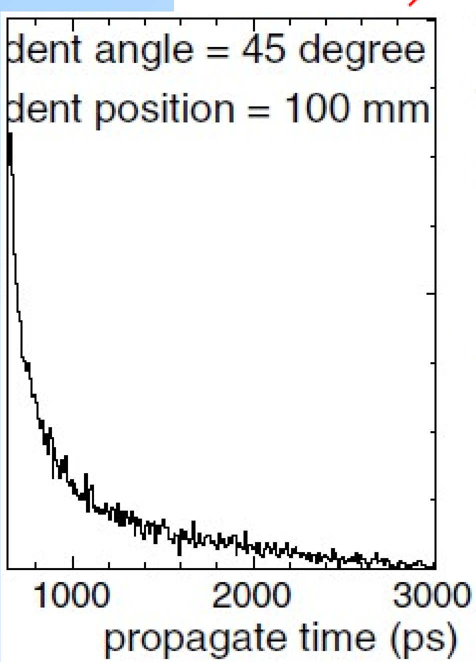
Belle II LoI

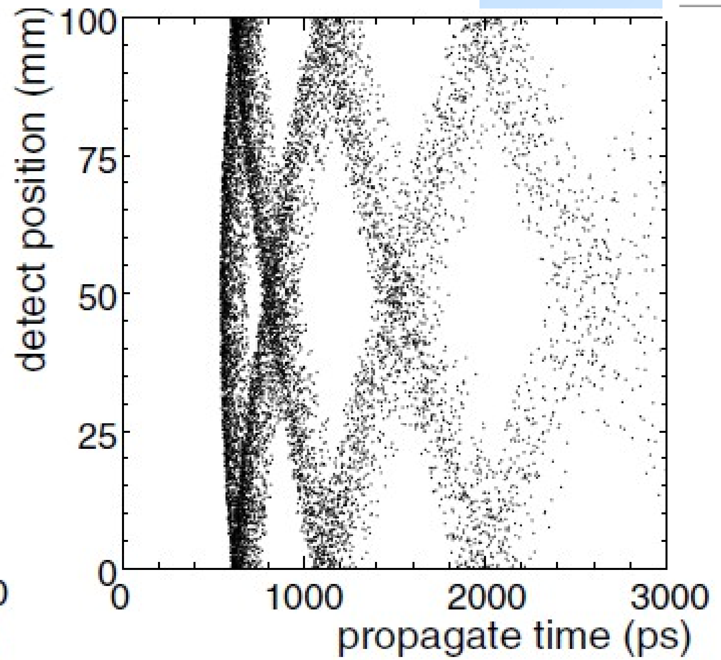
- t_0 - interaction time ??

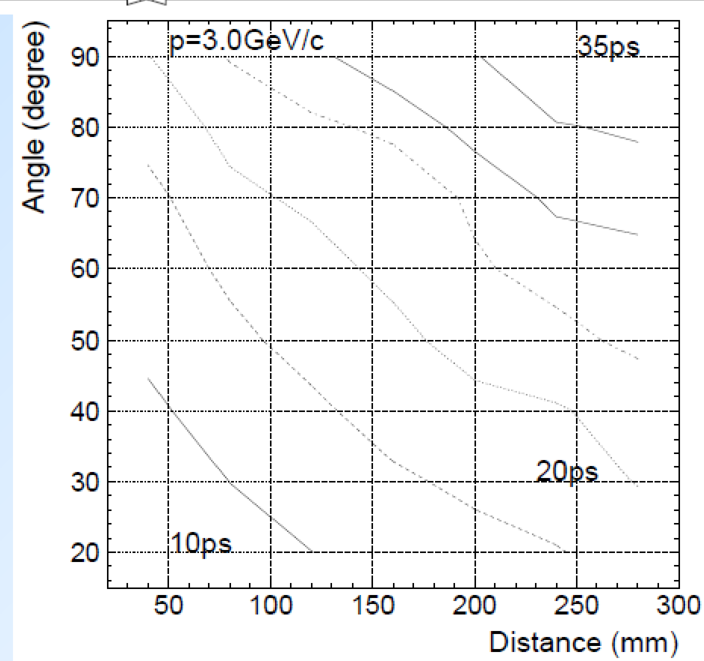






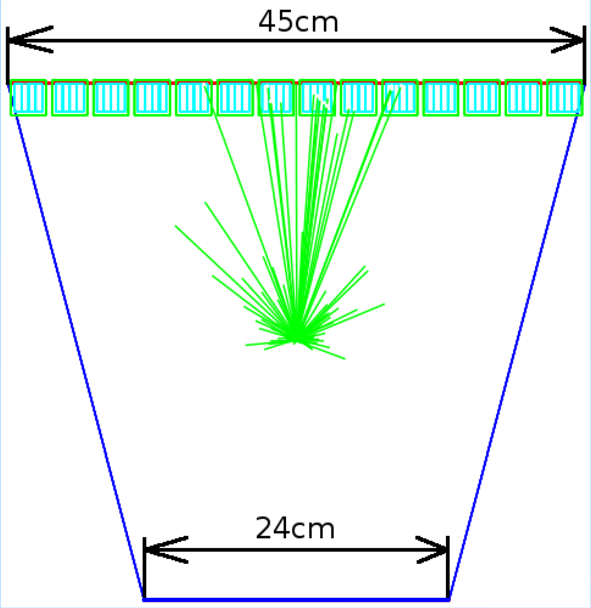


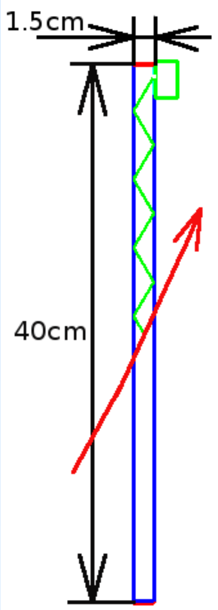


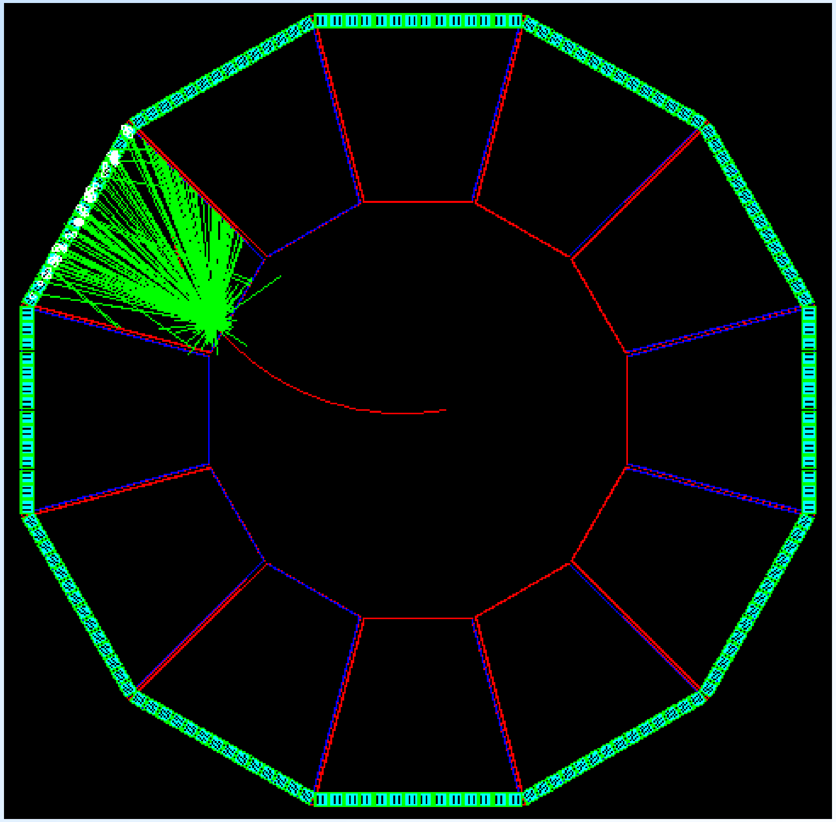


SuperB FTOF

- Detector made of 12 quartz sectors
- The quartz used as radiator of Cherenkov photons and as a light guide (DIRC technique)
- Each sector is readout by 14 MCP – PMT SL10 (TTS~40 ps).
- Thickness of the detector is 1.5 cm (12 % of X0)
- Located at ~2 m from interaction point (IP)
- R_{min} ~ 50 cm, R_{max} ~ 90 cm
- Very similar to the TOP counter in Belle II



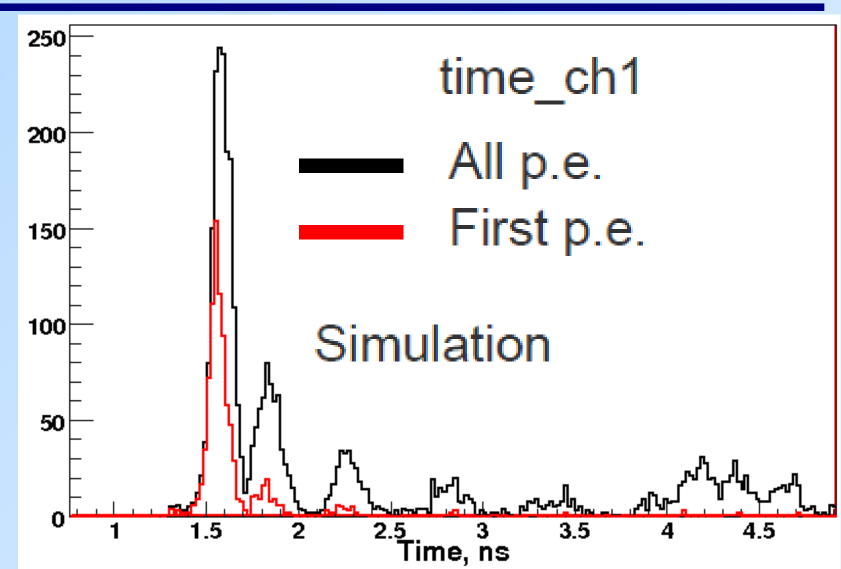




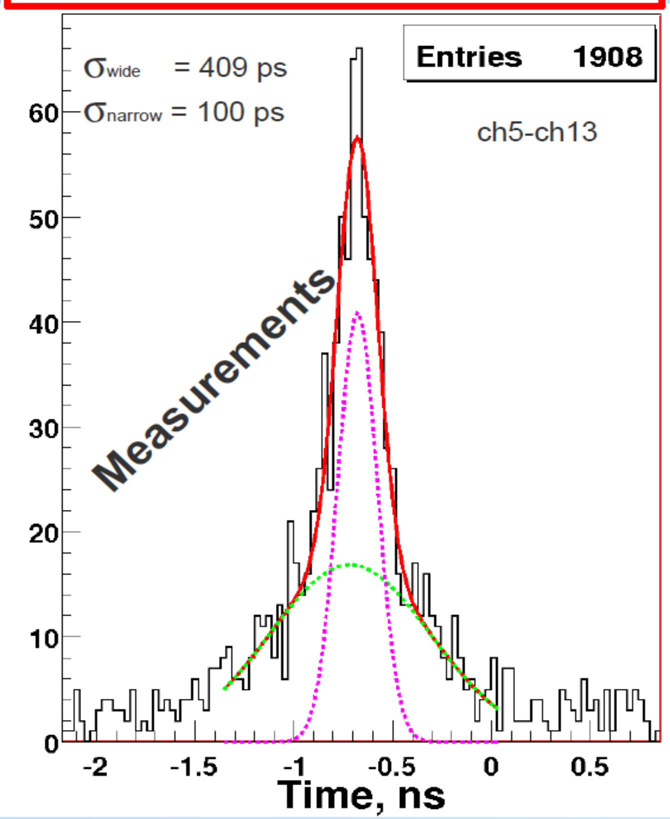
L. Burmistrov et. al. @ TIPP 2011

SuperB FTOF beamtest

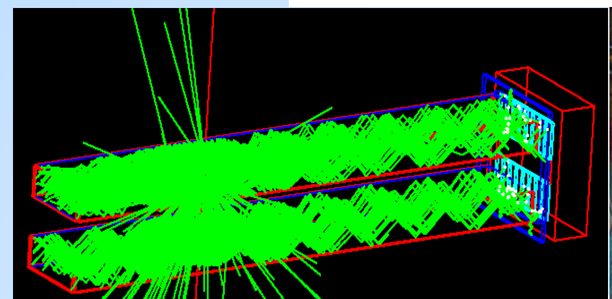
- Test with two quartz bars attachet to single MCP PMT
- Resolution of timing difference between two channels, one from each bar, is ~100 ps → single bar resolution ~70 ps

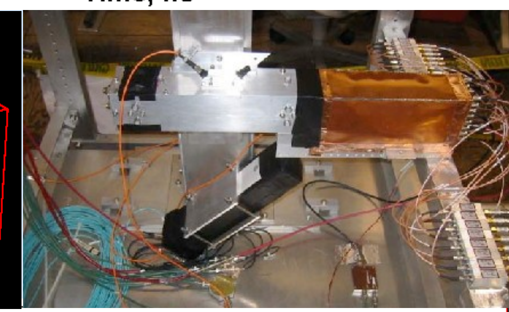


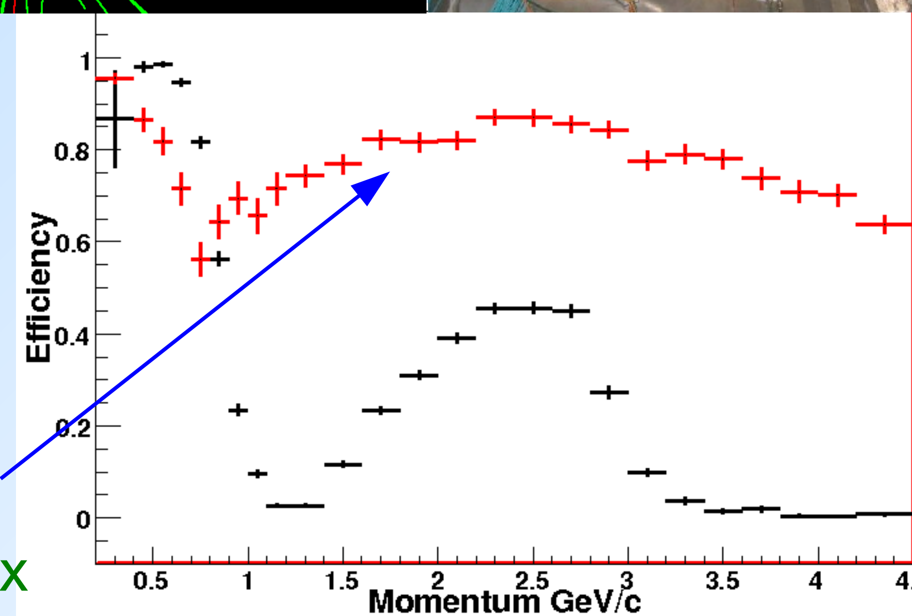
σ_{narrow}/sqrt(2) ~ 70 ps per p.e.



L. Burmistrov et. al. @ TIPP 2011



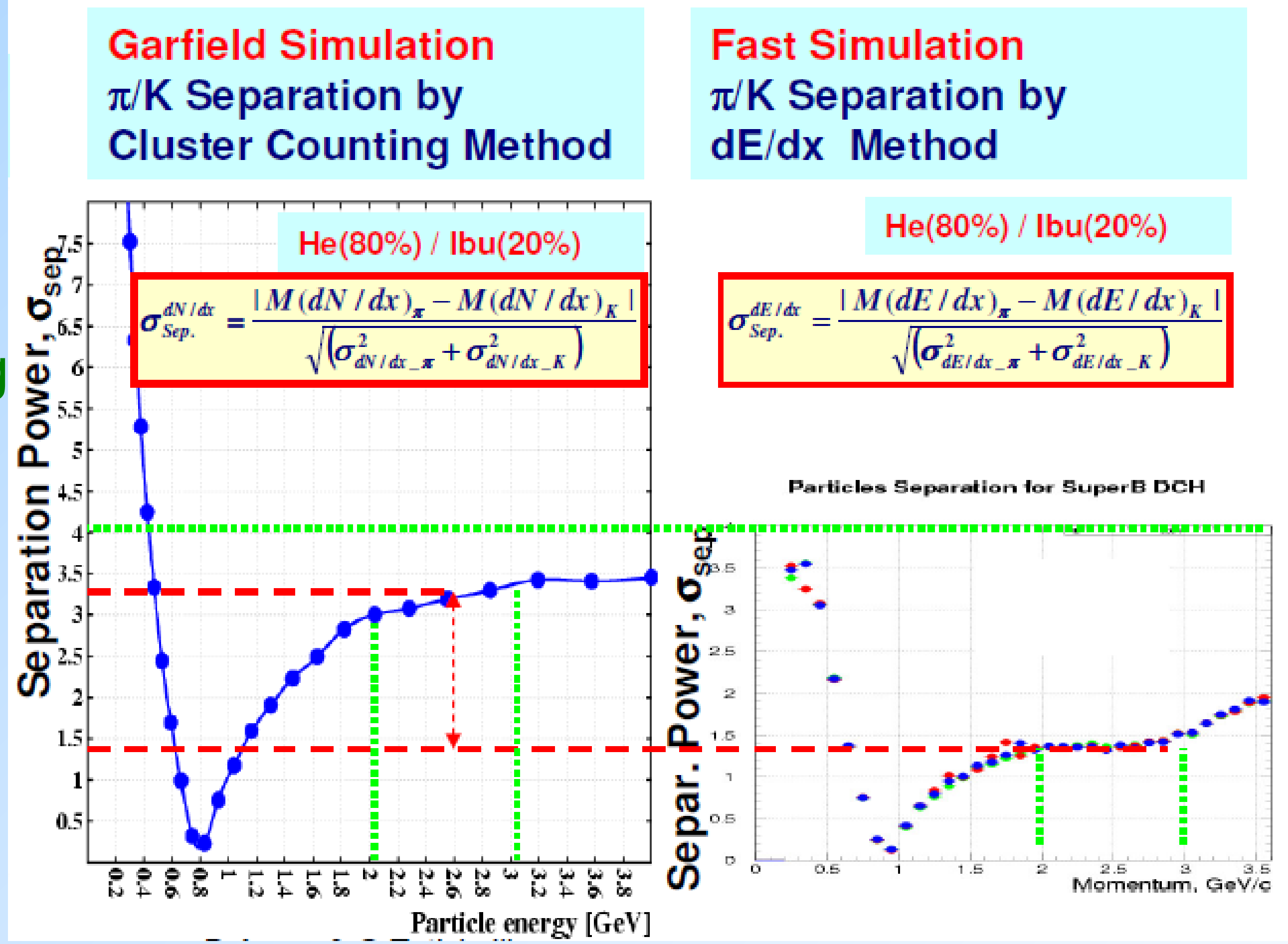




- improvement of K PID efficiency compared to dE/dx

SuperB dN/dx

- Number of clusters per track follows Poissonian statistics → better PID performance
- Timing of individual clusters in single cell → better tracking
- Simulation studies show improved performance in PID and tracking with gas mixture 20%He+80%iC_4H_{10}
- Waiting for experimental confirmation



D.Asner,G.Tatishvili @12th SuperB Workshop (2010)

More on clusters this afternoon → F. Grancagnolo (INFN Lecce): Historical Review and Perspectives of the Cluster Counting/Timing Technique

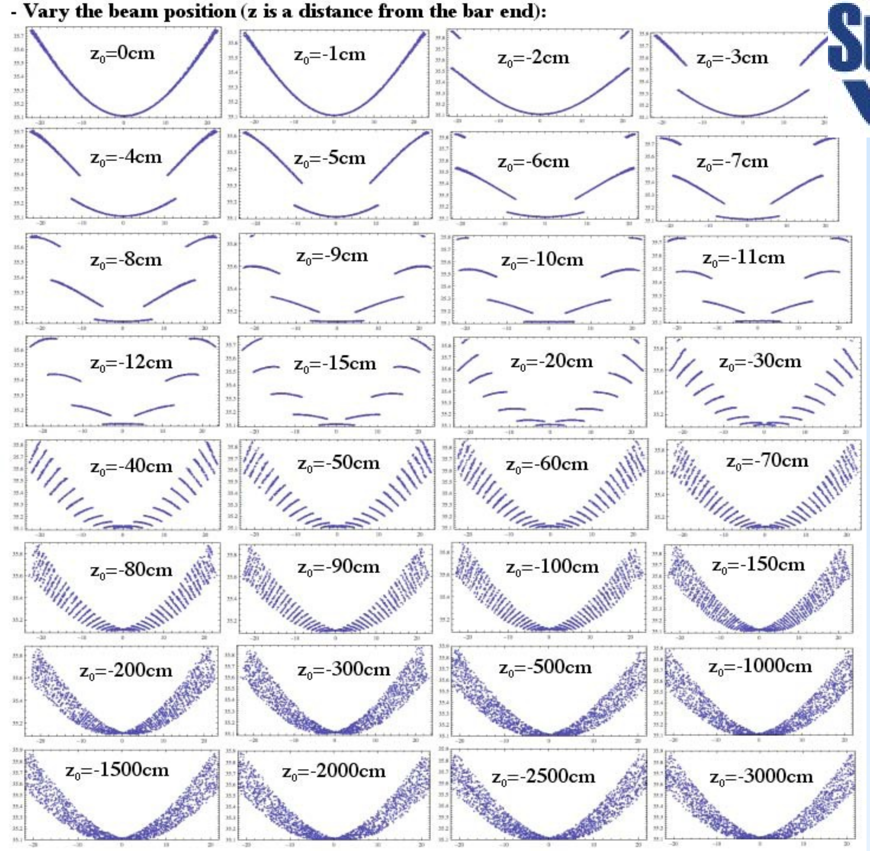
Summary

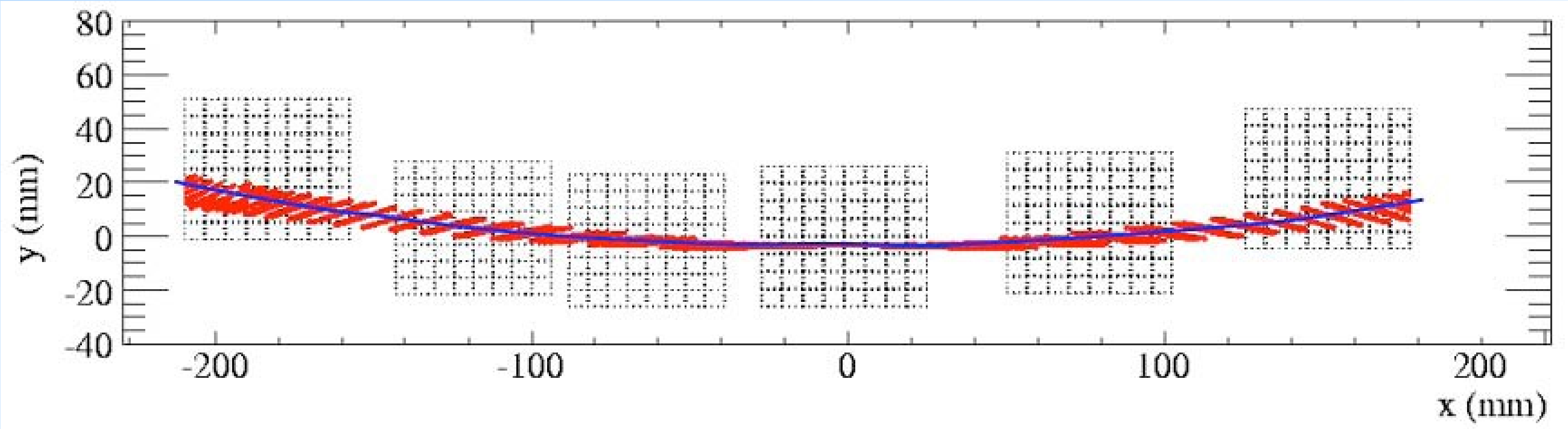
Many new techniques were introduced/upgraded during the development of PID detectors for super B factories:

- focusing was introduced to DIRC detector, and for the first time the photon propagation time was used to reduce chromatic error
- TOP counter was developed, which is based on DIRC concept but uses Time-Of-Propagation of photons in combination with one coordinate for "ring imaging"
- focusing aerogel radiator vas introduced to proximity focusing RICH to allow thicker radiator without the resolution degradation, it also has optional TOF capability with MCP PMTs
- prompt Cherenkov light in combination with fast MCP PMTs was explored in different types of very fast TOF detectors
- cluster counting is reexamined to improve PID capability of central tracking devices

FDIRC aberration error

- distortion of the ring due to the reflections in the quartz bar





SLAC-PUB-13464, 2008

PID upgrade motivation

- Improve π/K separation in the forward (high momentum) region for few-body decays of B's
- Good π/K separation for $b \to d\gamma$, $b \to s\gamma$
- improve purity in fully reconstructed B decays ('full reconstruction tag')
- Low momentum (<1GeV/c) $e/\mu/\pi$ separation ($B \to Kll$)
- Keep high the efficiency for tagging kaons
- High rate and background tolerant operation

Read-out electronics

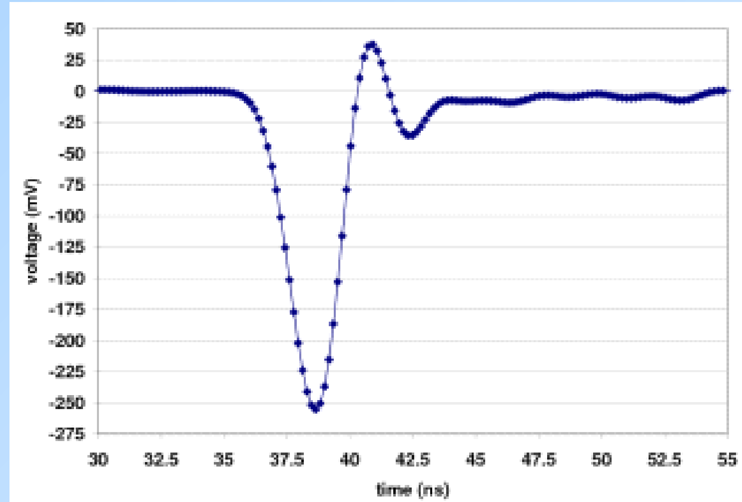
TOP counter:

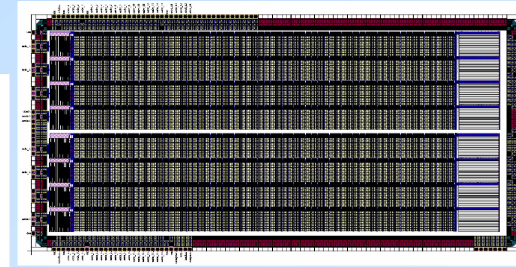
- fast amplifier
- waveform sampling chip BLAB3

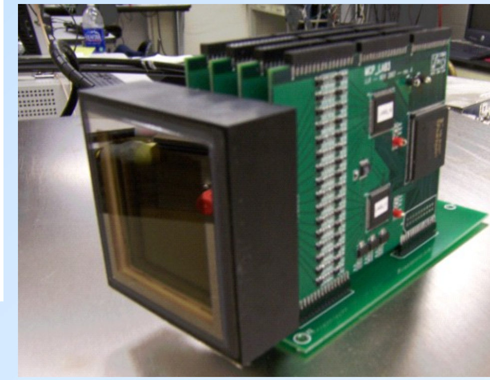
(8ch. with 32k samples, 4GSa/s)

- FPGA for digital data processing

(possibly also for RICH)

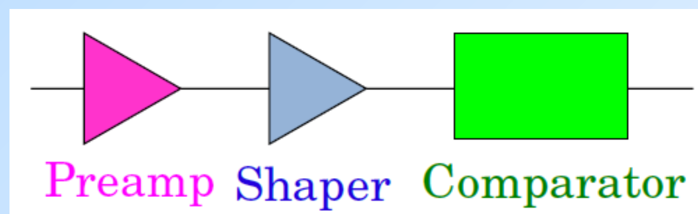


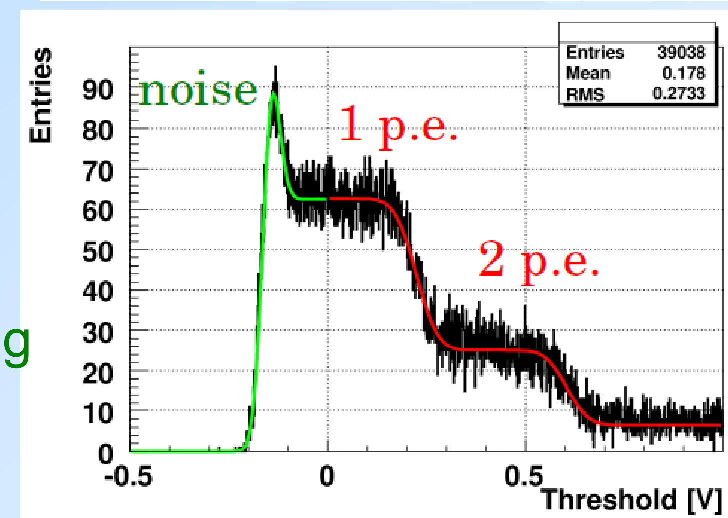


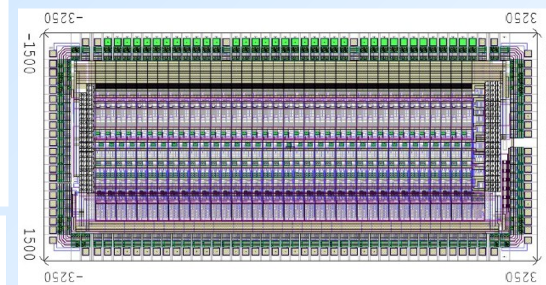


RICH counter:

- ASIC with preamplifier, shaper, comparator:
  - 36 channels/chip (one APD)
  - low noise ENC~1000e
- FPGA for digital data processing

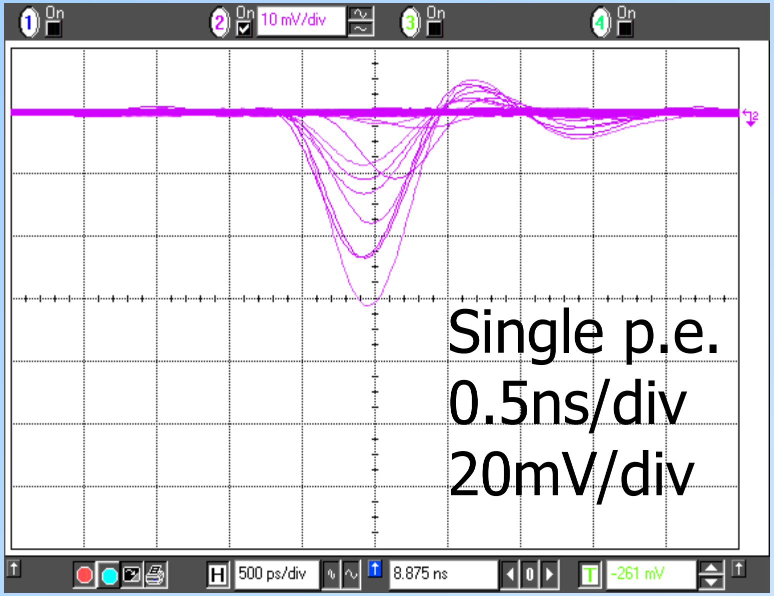


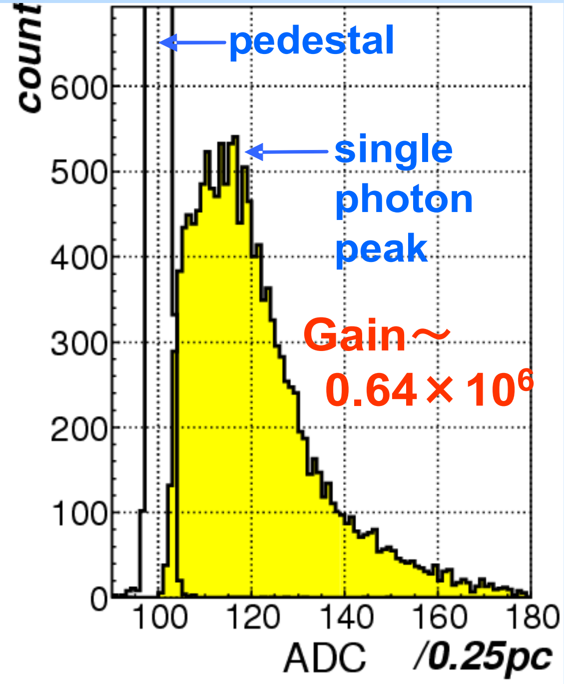


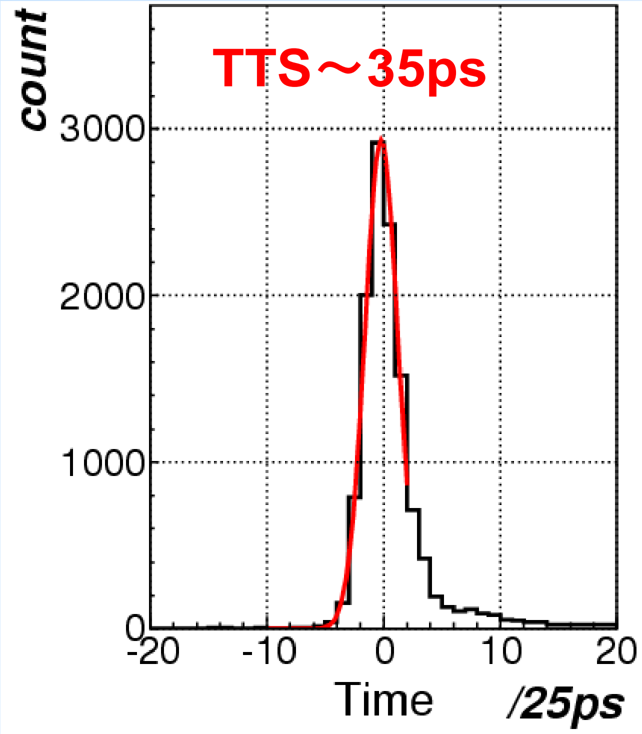


GaAsP MCP-PMT performance

Wave form, ADC and TDC distributions for single photons







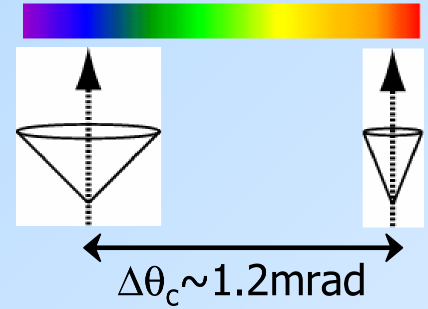
Similar performanc as bi-alkali MCP-PMT:

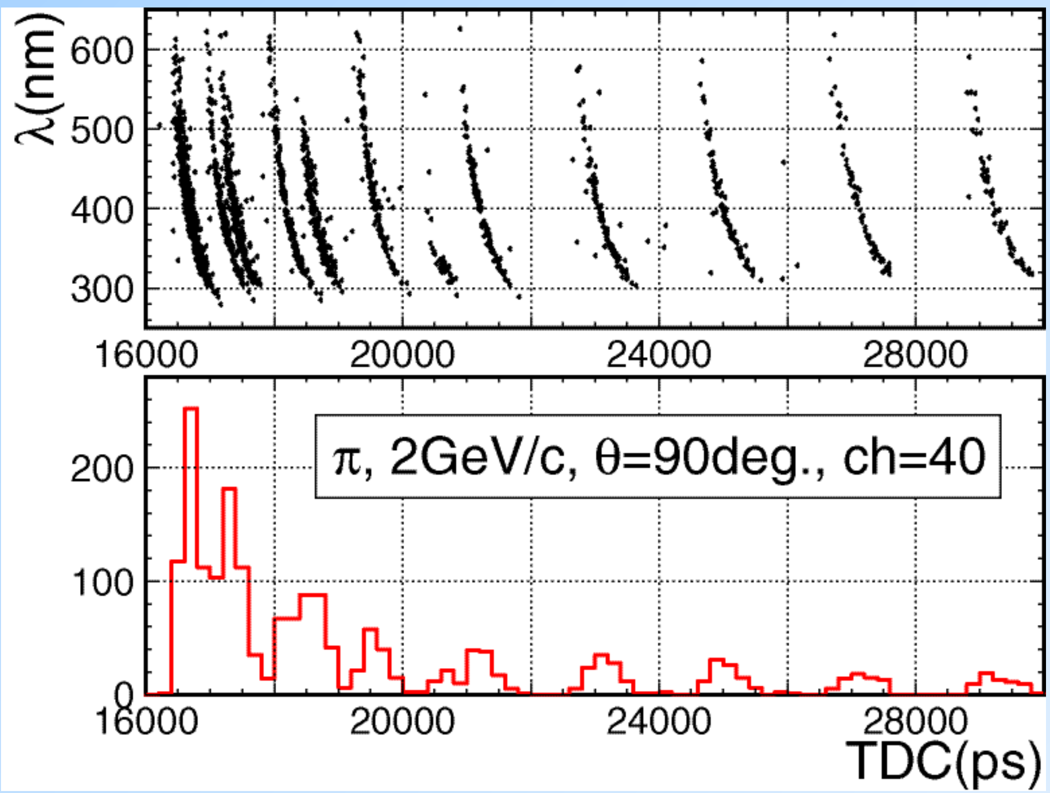
- Gain large enough to detect single photons
- Goot time resolutio for single photons ~ 35ps

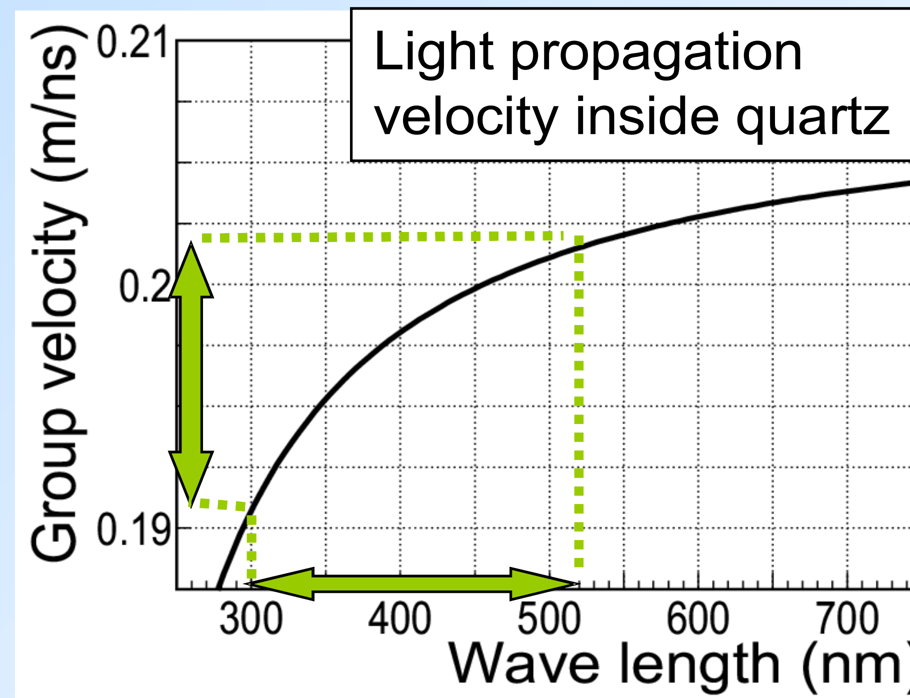
Chromatic dispersion

- photon propagation time depends on the wavelength due to chromatic dispersion
- peaks in the time distribution are broadened

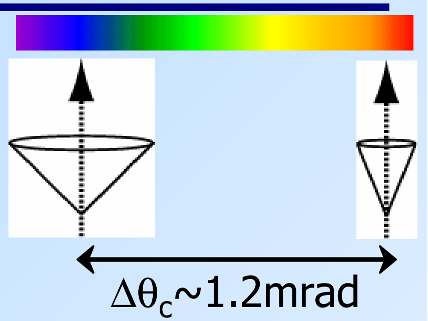
→ reduced separation power



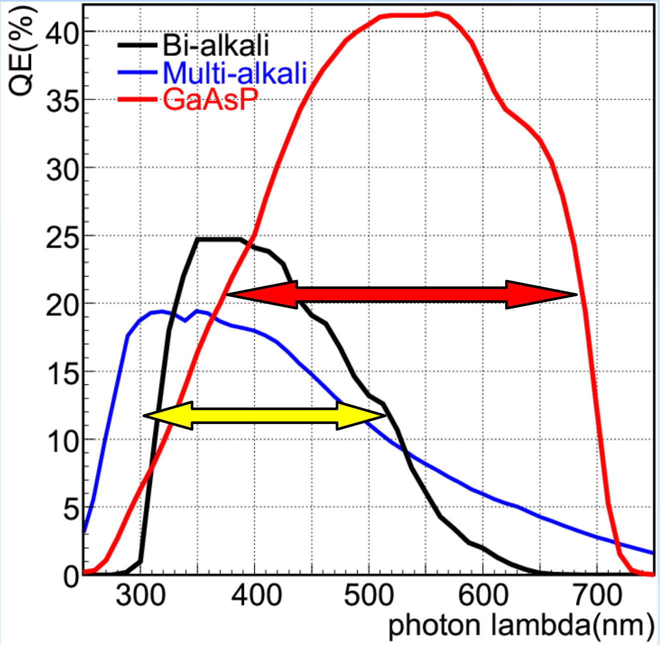


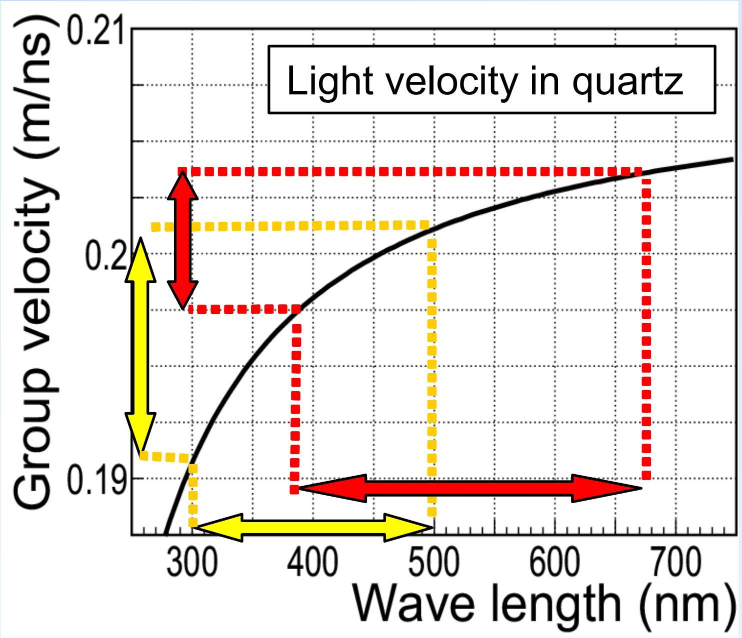


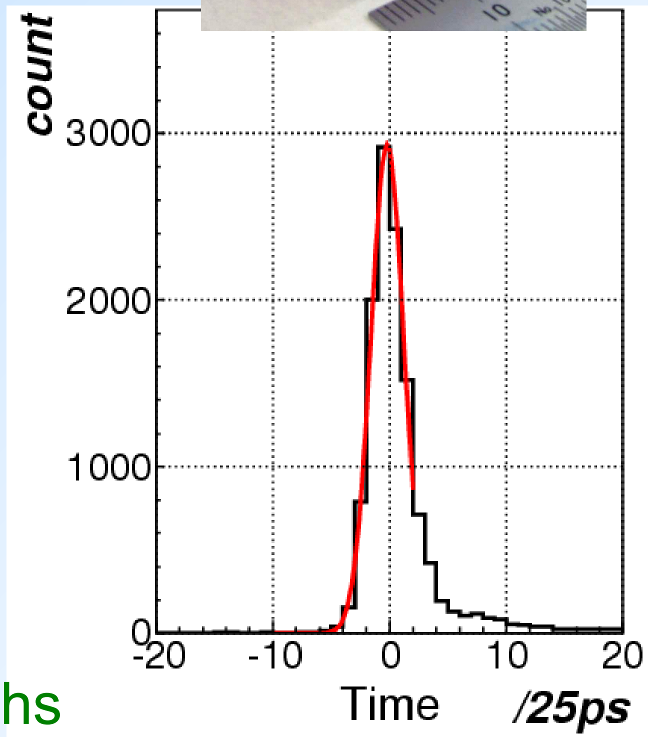
GaAsP photo-cathode



- possible solution is to use the sensor with GaAsP photocathode:
  - high quantum efficiency
  - sensitive at longer wavelengths → lower chromatic error
- first prototype produced and shows similar signal characteristics as multialkali type
- will probably not be ready for mass production in time



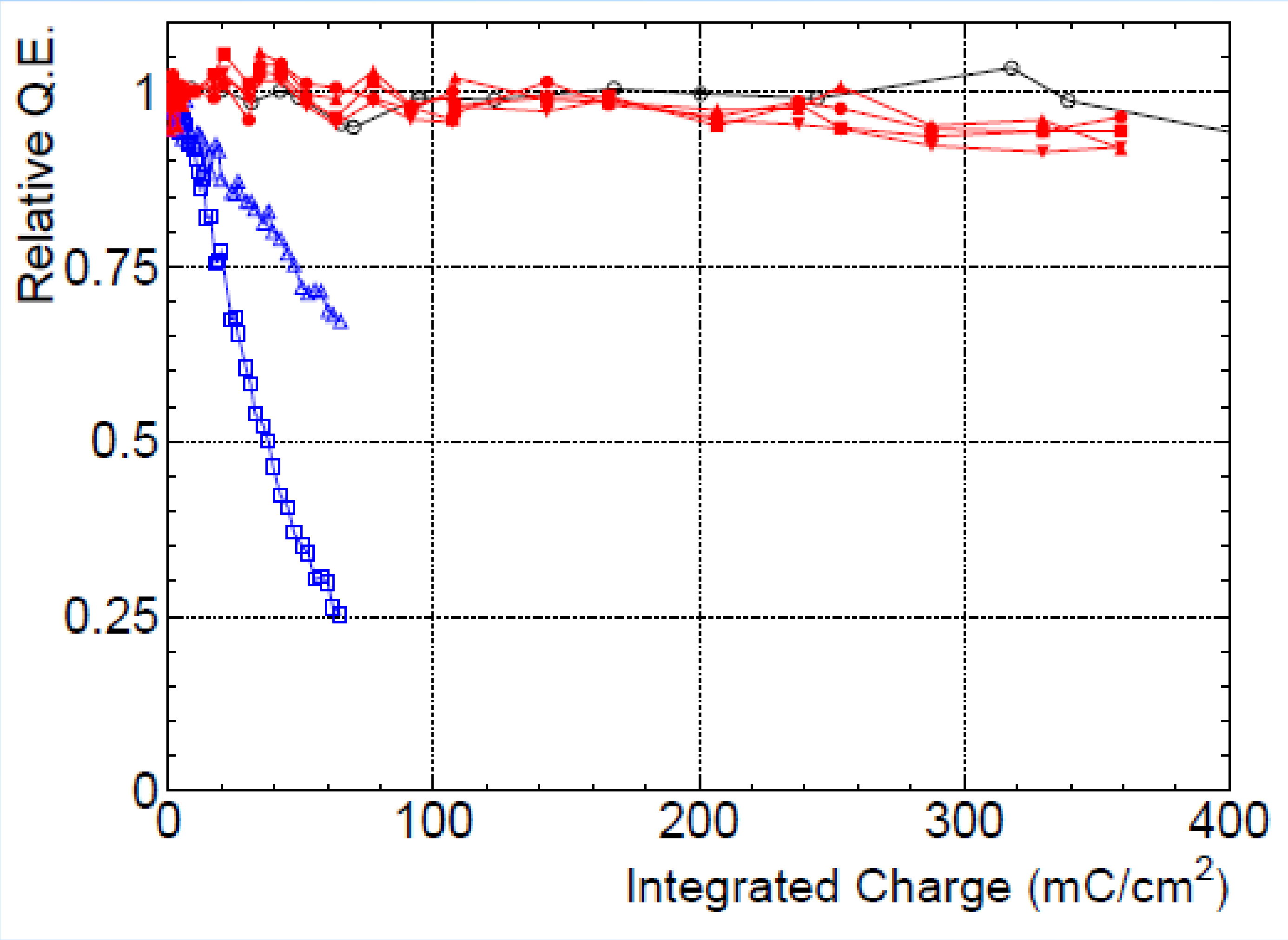




- filters can also be used to limit the region of wavelengths

MCP-PMT aging

Ageing tests of MCP-PMTs with multi-alkali photo chatode:



- MCP-PMT with Al protectiv layer would survive > 13 years of Belle II operation

Beam tests

At KEK-PS

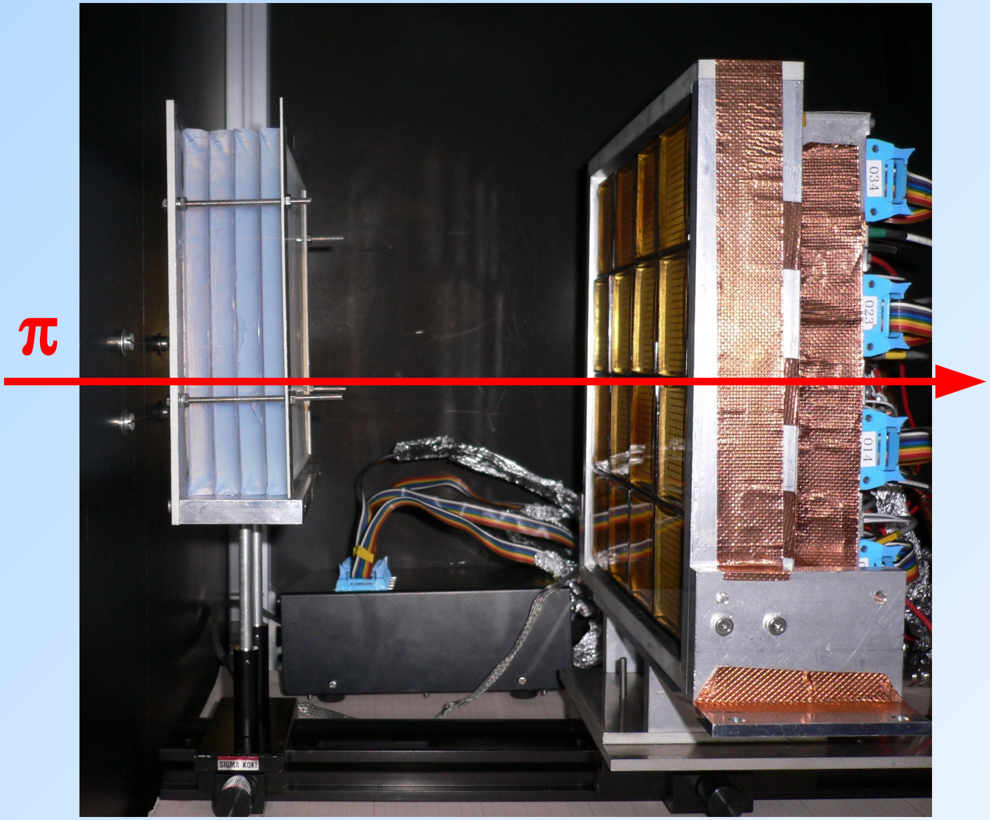
- march 2004 π2 (0.5-4 GeV/c)
- june 2004 T1 (0.5-2 GeV/c)
- december 2005 π2 (0.5-4 GeV/c)

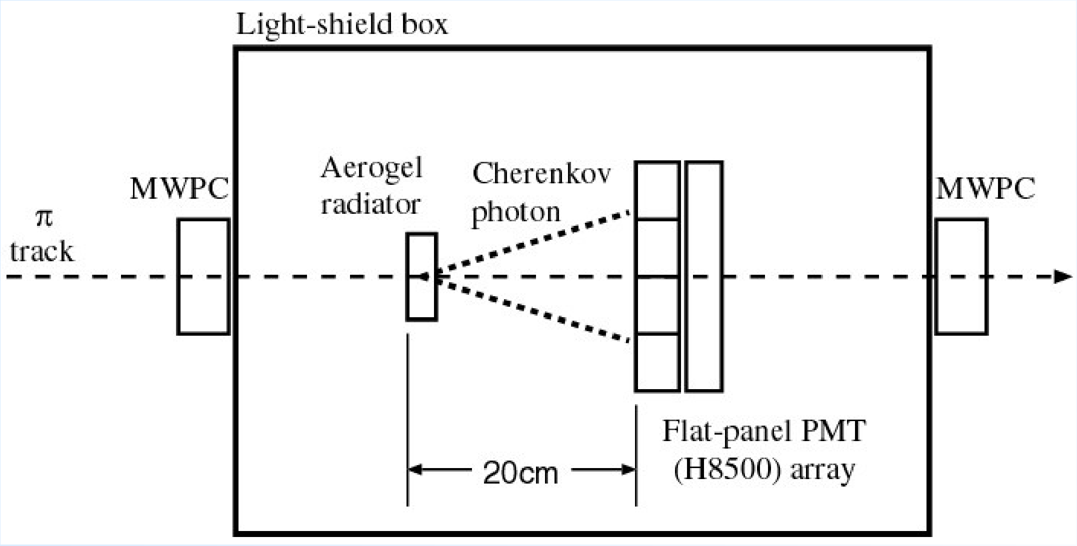
Photon detector

- 4x4 array Hamamatsu H8500
- 1024 channels
- 52.5 mm pitch (84% eff. area)

- two MWPCs for tracking

Radiator optimization: different aerogel configurations and photon detectors were tested

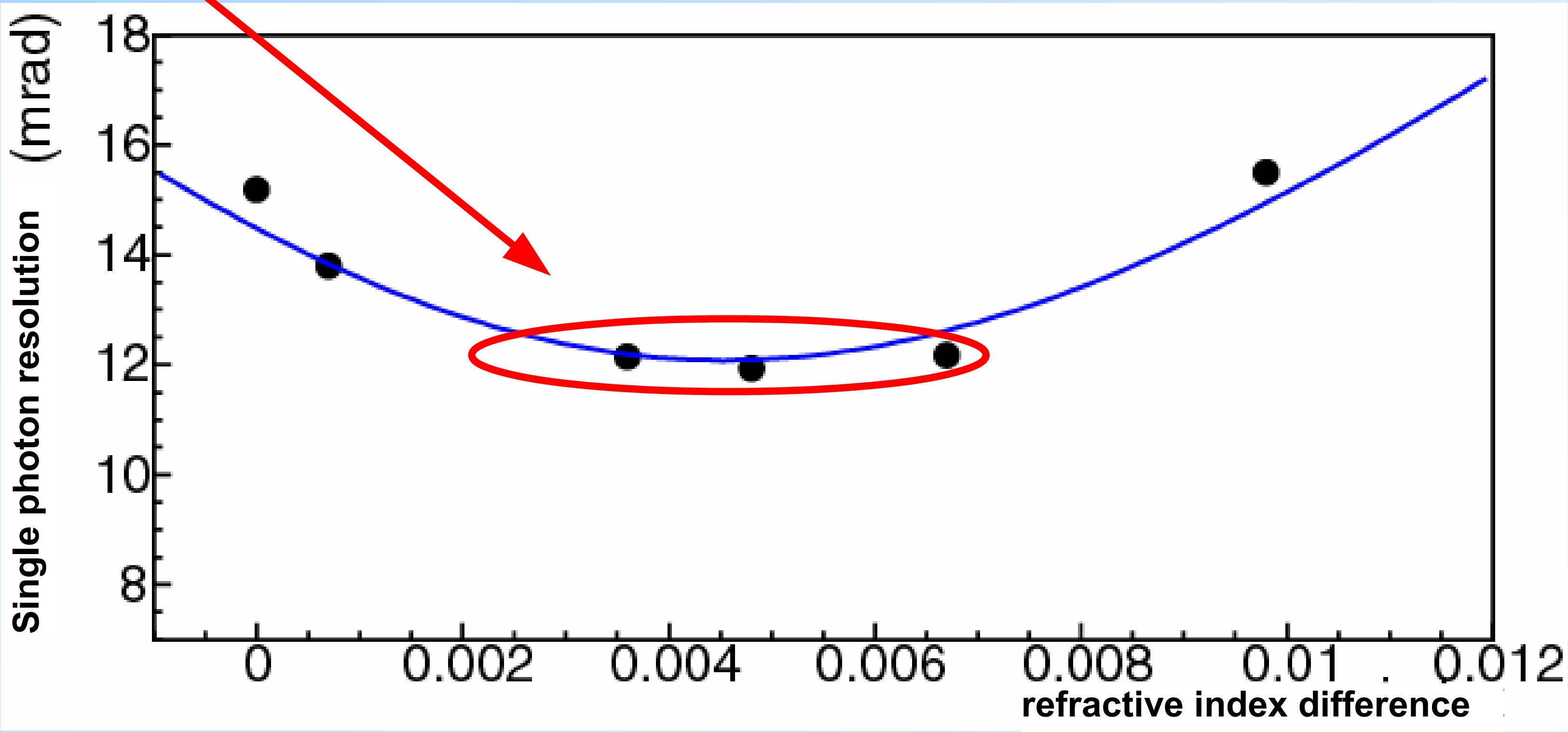




Optimization of radiator parameters

NIM A565 (2006) 457

- upstream aerogel: d=11mm, n=1.045
- different downstream aerogels
- measured resolution in good agreement with prediction
- wide minimum allows some tolerance in aerogel production

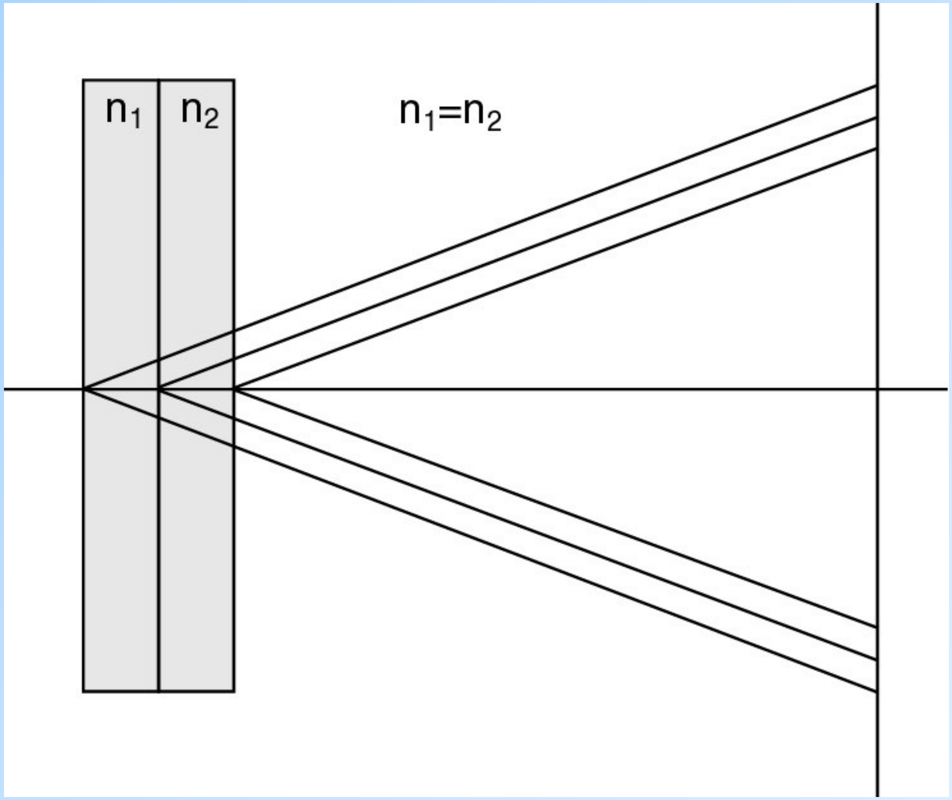


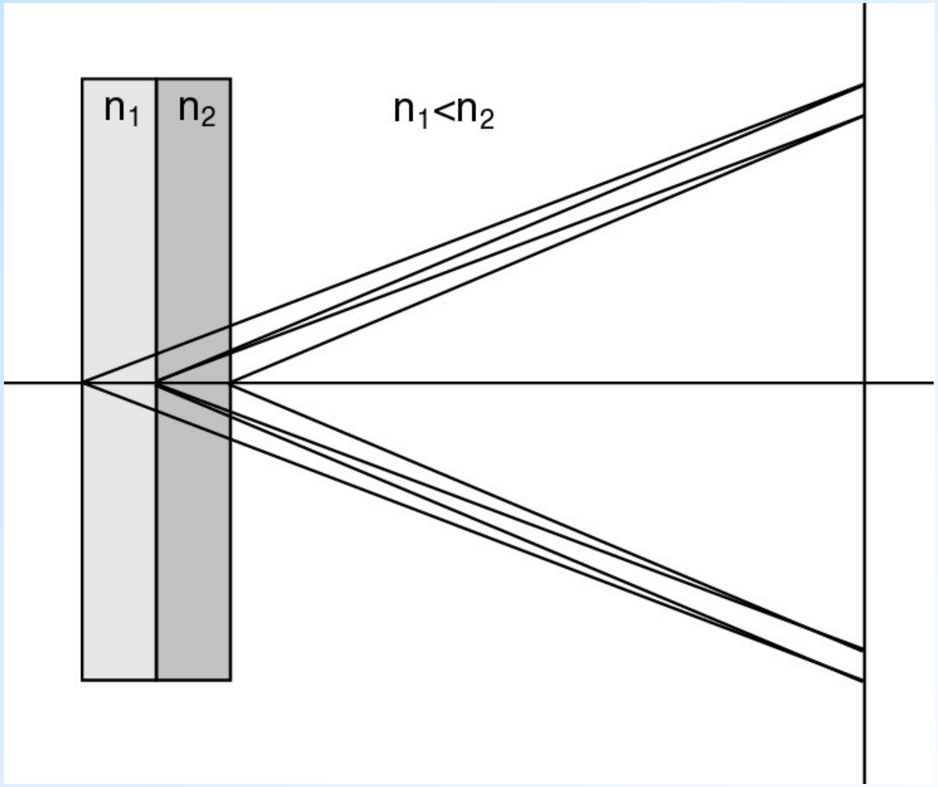
Dual refractive index configuration

How to increase number of photons without degrading the resolution?

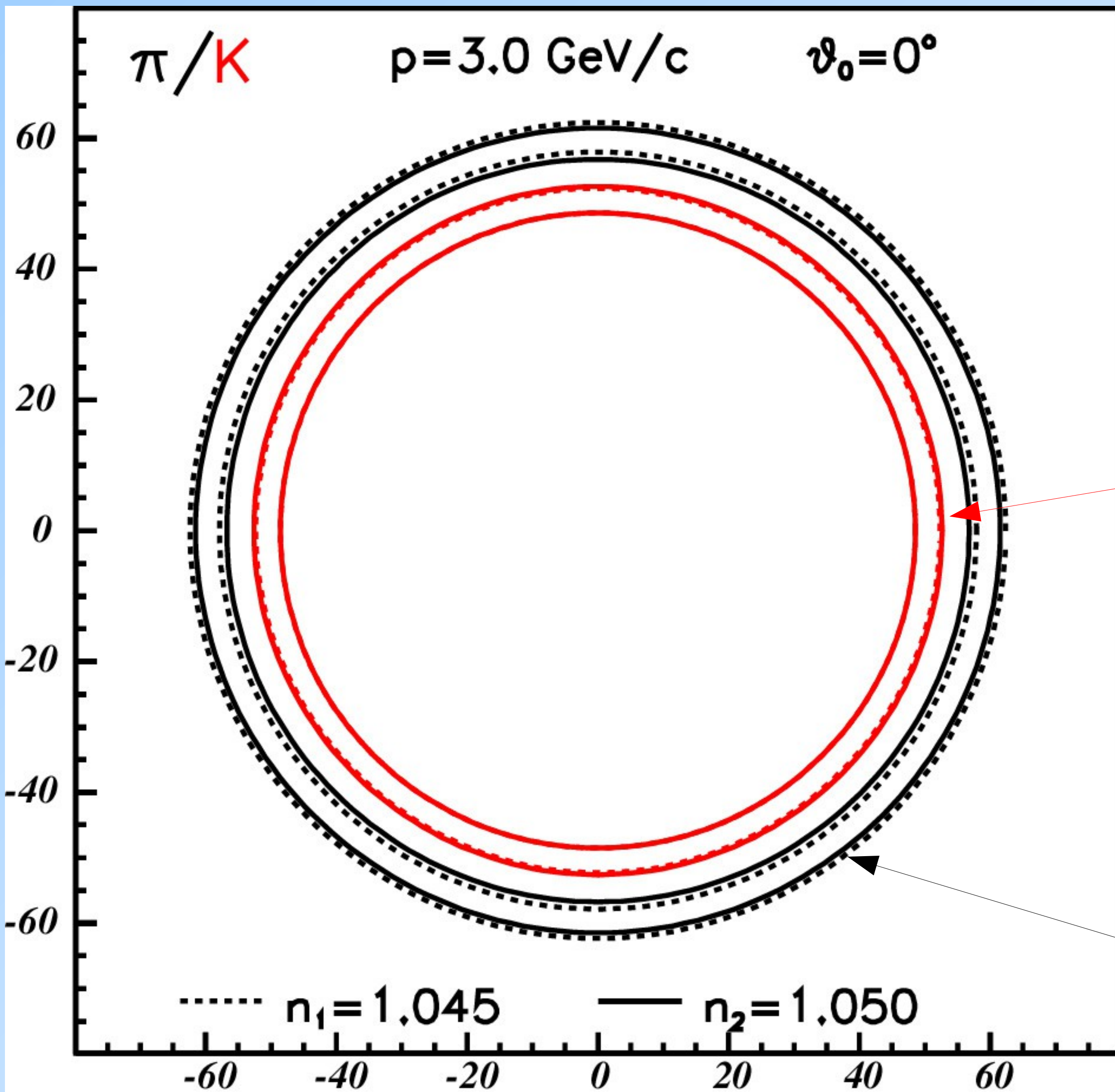
Use radiator with gradually increasing refractive index in downstream direction - "focusing radiator"

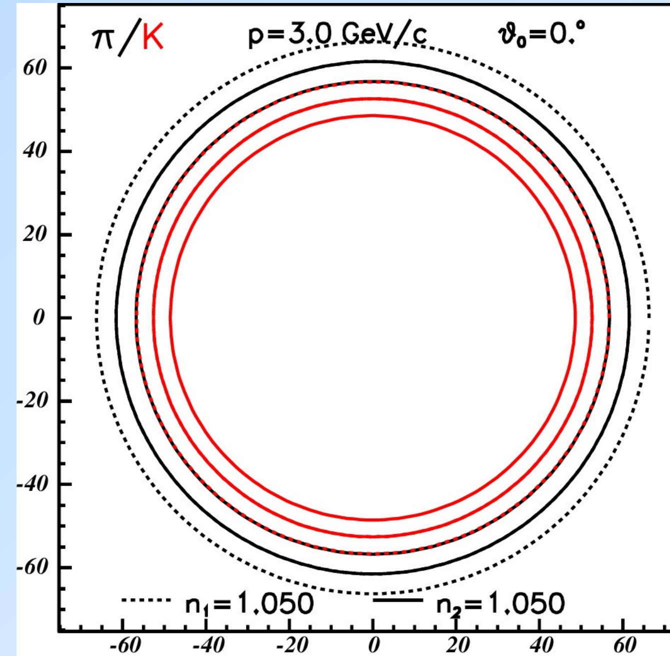
- all layers with the same refractive index - "normal" configuration
- measure overlapped rings - "focusing" configuration





Focusing configuration @ 3 GeV/c





normal

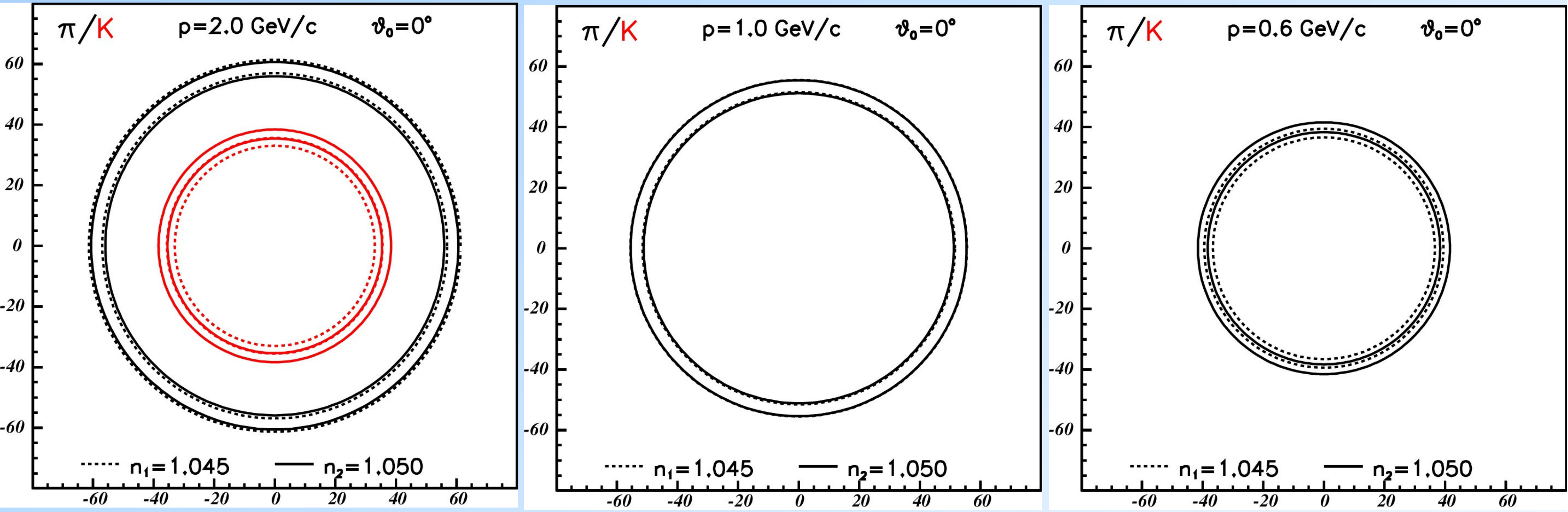
kaon

pion

- layer thickness 15mm
- $n_2 - n_1 = 0.005$

Focusing configuration - low momentum

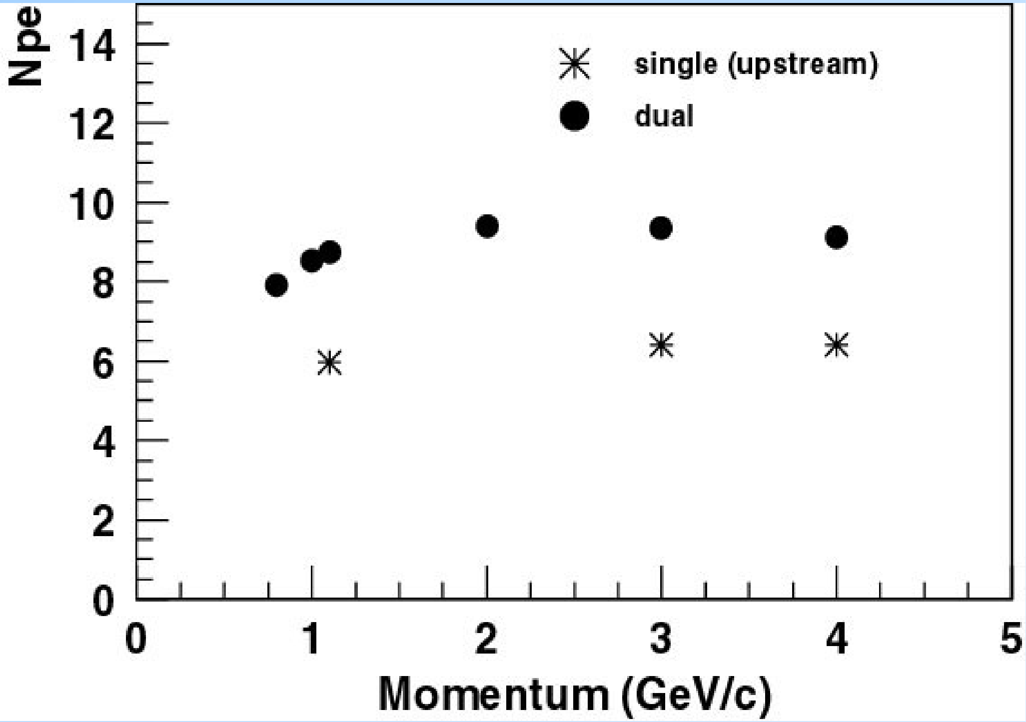
- overlapping of rings for low momentum tracks



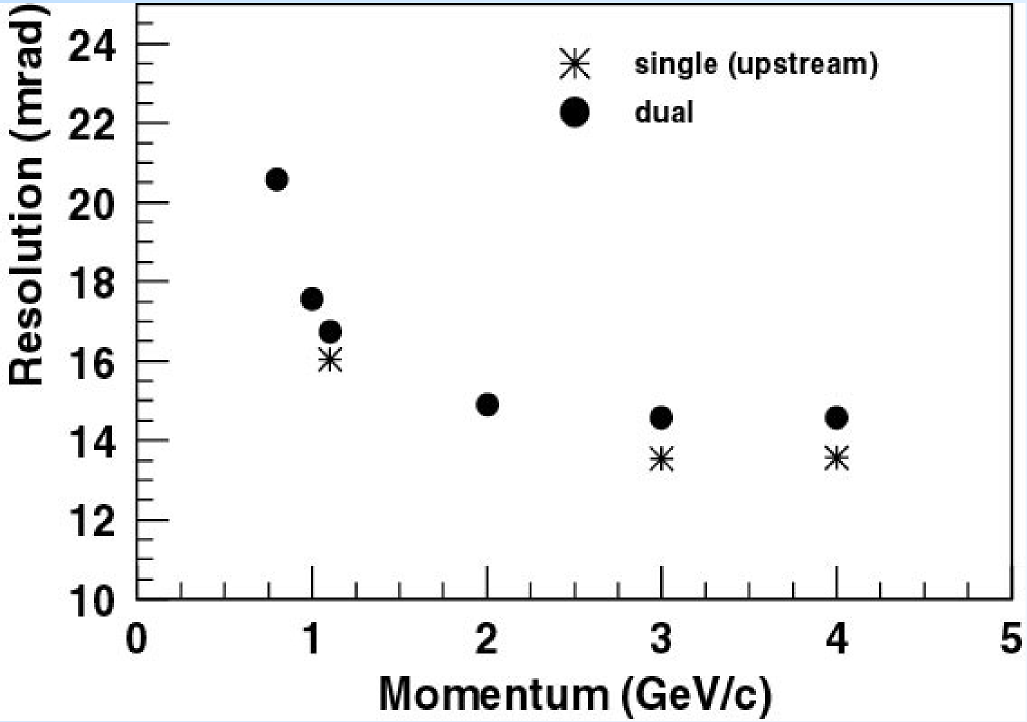
Good overlapping down to 0.6 GeV/c

Focusing configuration - momentum scan, data

• number of detected hits as function of momentum

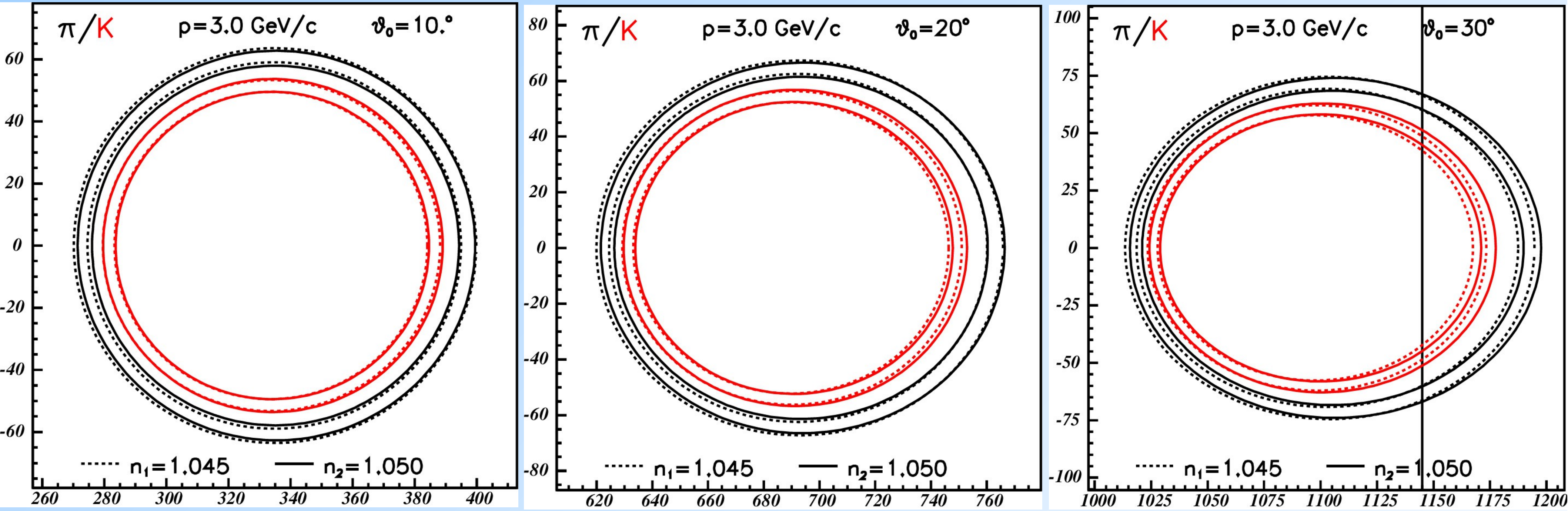


• single photon resolution as function of momentum



Focusing configuration - different incidence angles

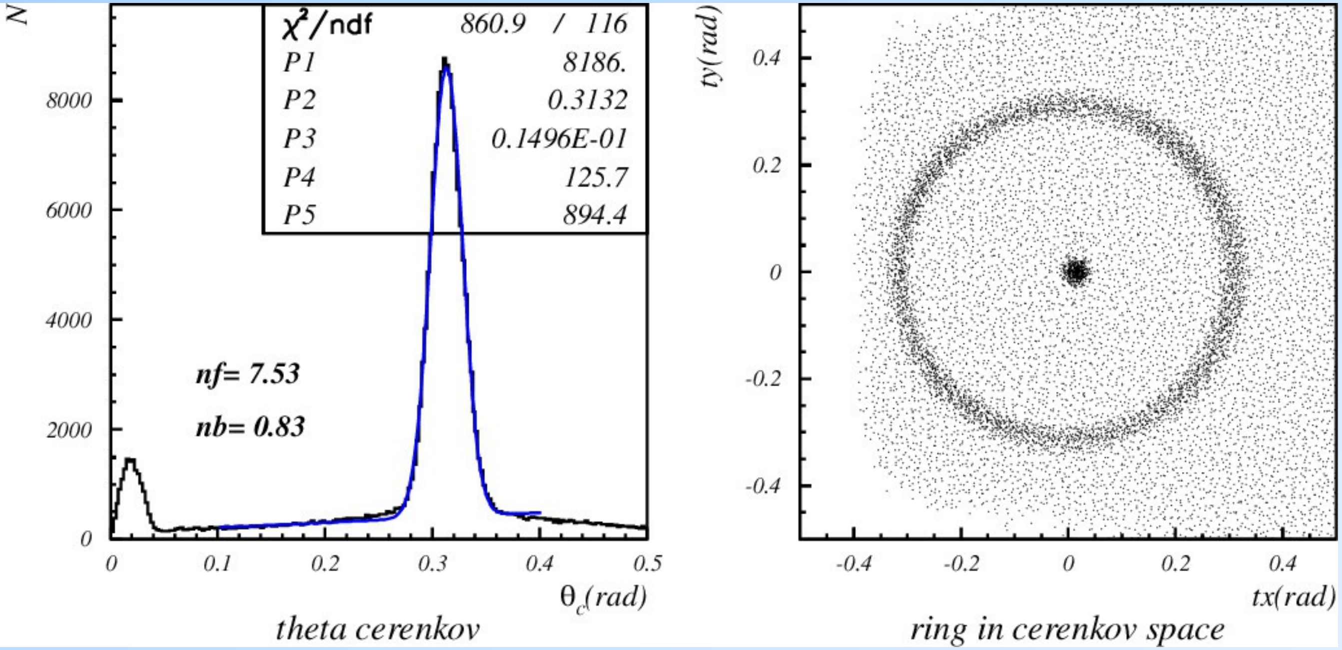
- overlapping of rings for inclined tracks
- expected range ~ 17^{o}-34^{o}



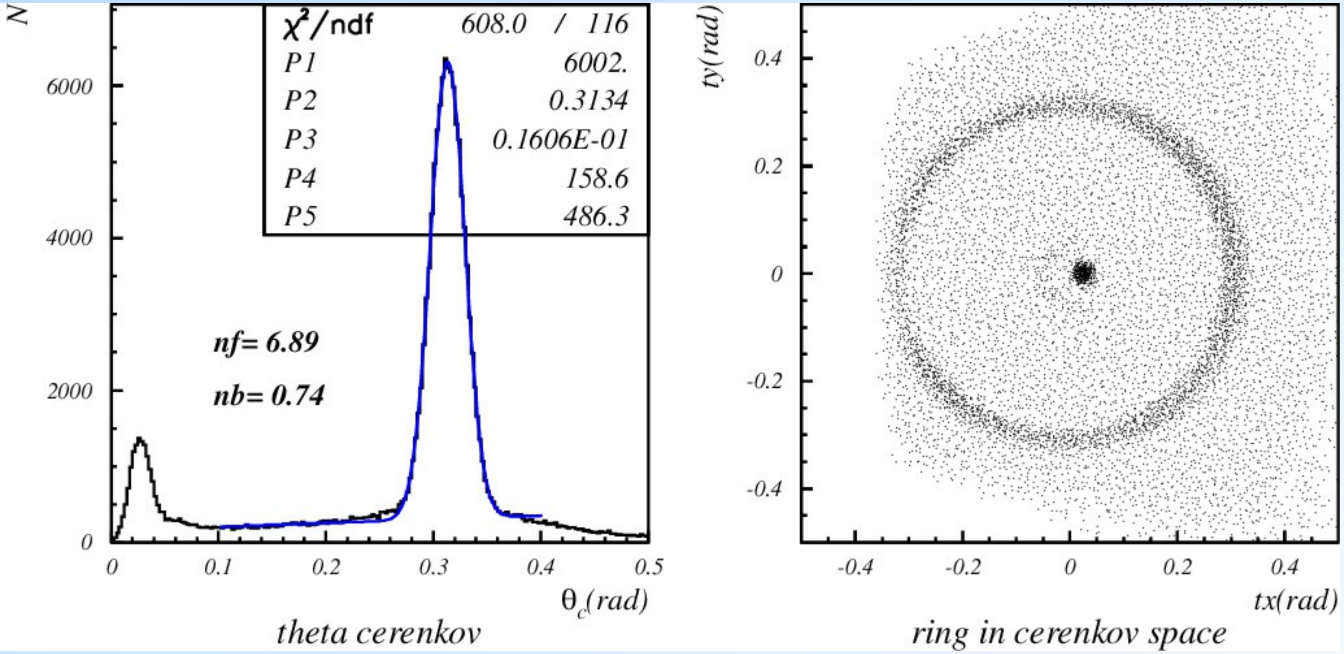
Good overlapping up to 30^{o}

Focusing configuration - inclined tracks, data

- angle 20°



- angle 30°



PID capability: likelihood calculation

- distribution of Cherenkov photons from both radiators can be approximated by

$$n_{cf}(\vartheta,\varphi,m) \approx \frac{1}{2\pi}\left(\frac{1}{\sqrt{2\pi}\sigma_1} e^{-\frac{(\vartheta-\vartheta_1(m))^2}{2\sigma_1^2}} + \frac{1}{\sqrt{2\pi}\sigma_2} e^{-\frac{(\vartheta-\vartheta_2(m))^2}{2\sigma_2^2}}\right)$$

- uniform background is assumed

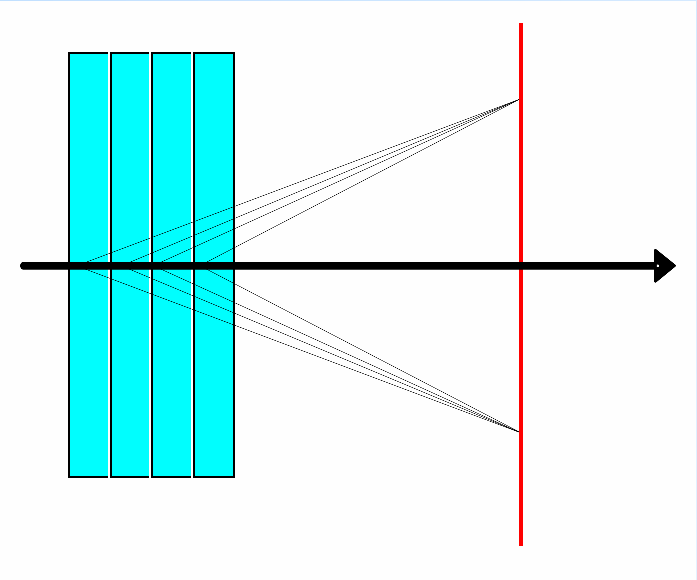
$$n_{bf}(\vartheta,\varphi,m) \propto \vartheta$$

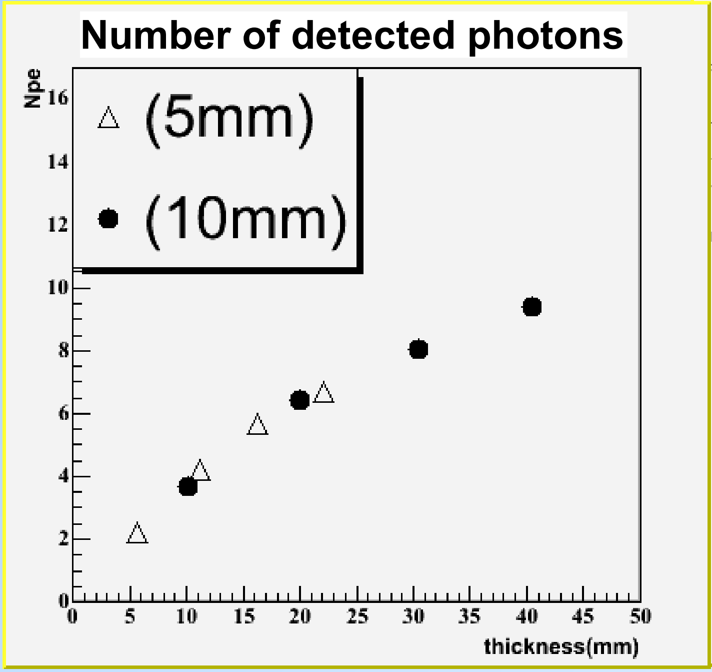
- likelihood function

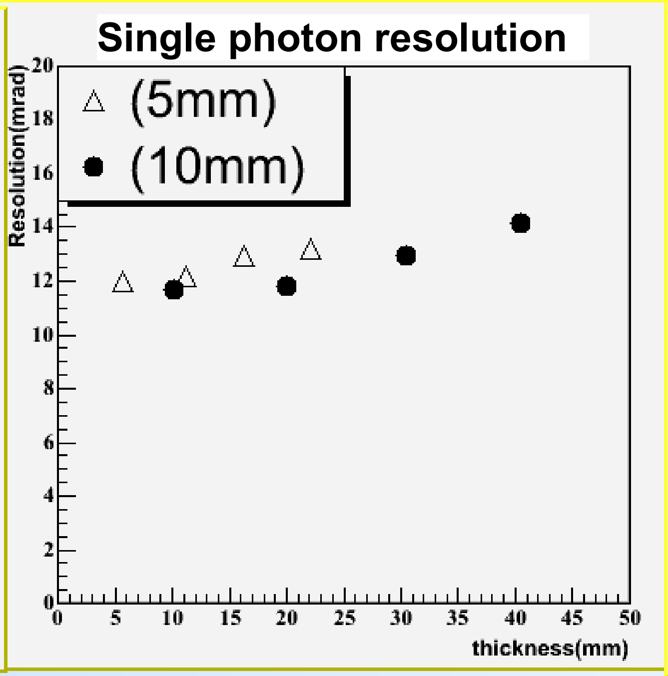
$$L(m) = \prod_{no\ hit\ i} e^{-\bar{n}_i(m)} \prod_{hit\ i} \left(1-e^{-\bar{n}_i(m)}\right)$$

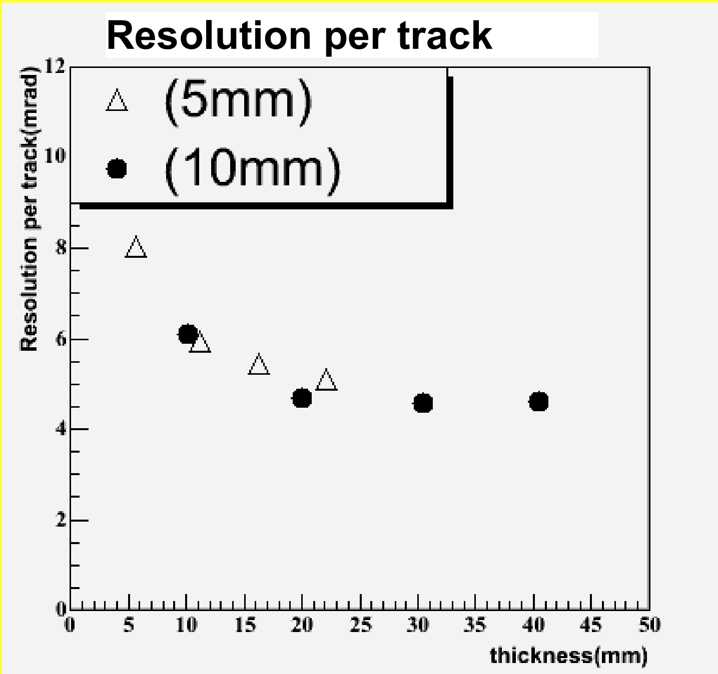
Multilayer focusing radiator

- natural extension of dual layer configuration
- radiators combined from 5mm and 10mm samples were tested
- obtained Cherenkov angle resolution per track is around 4.3 mrad
- → K/π separation better than 5σ

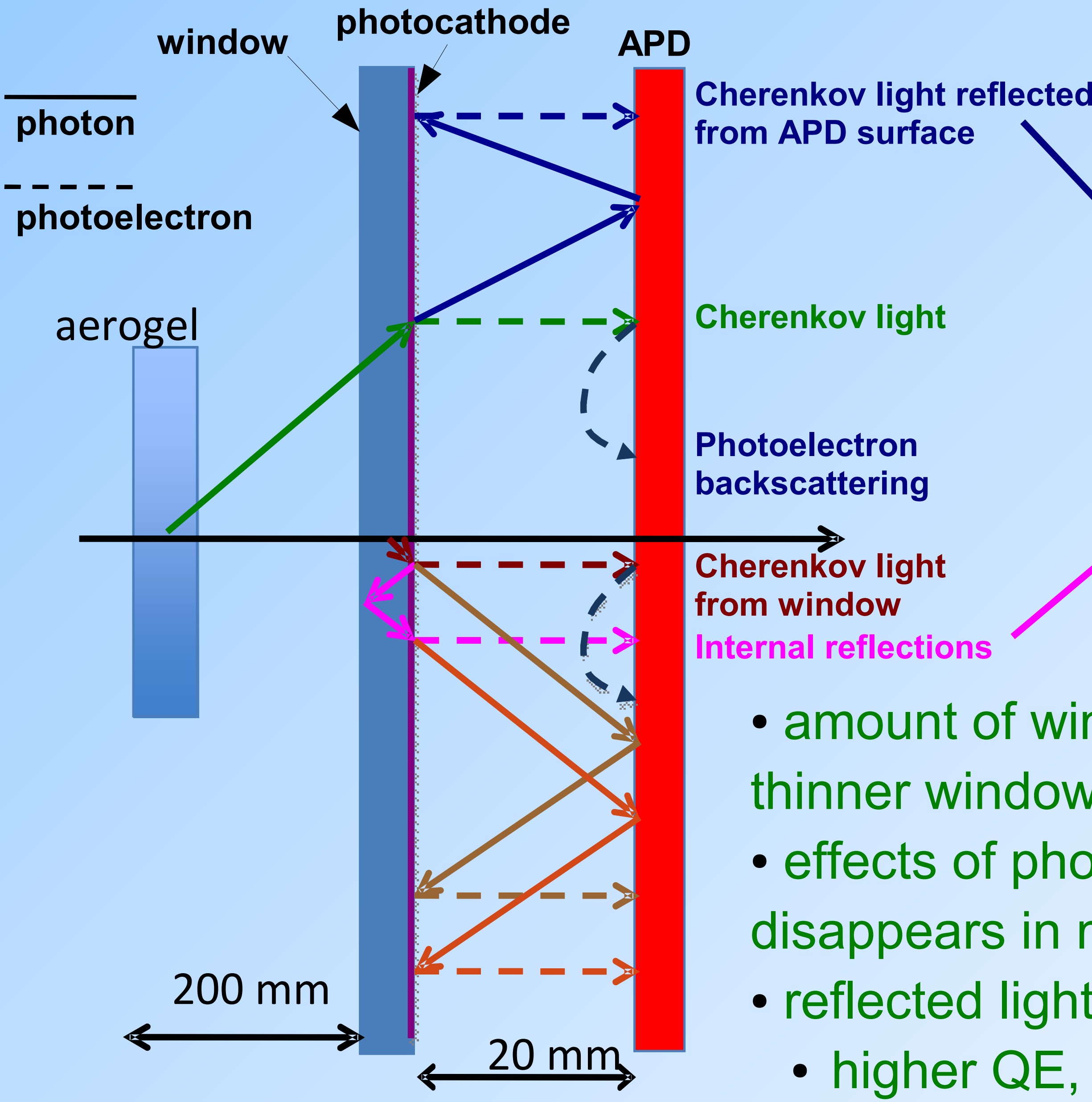


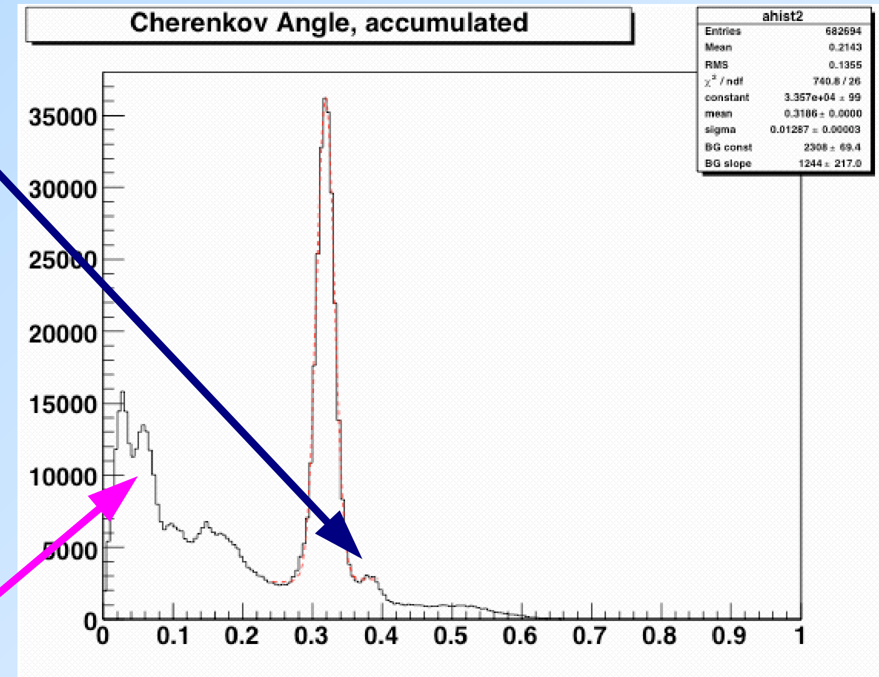






Background contributions

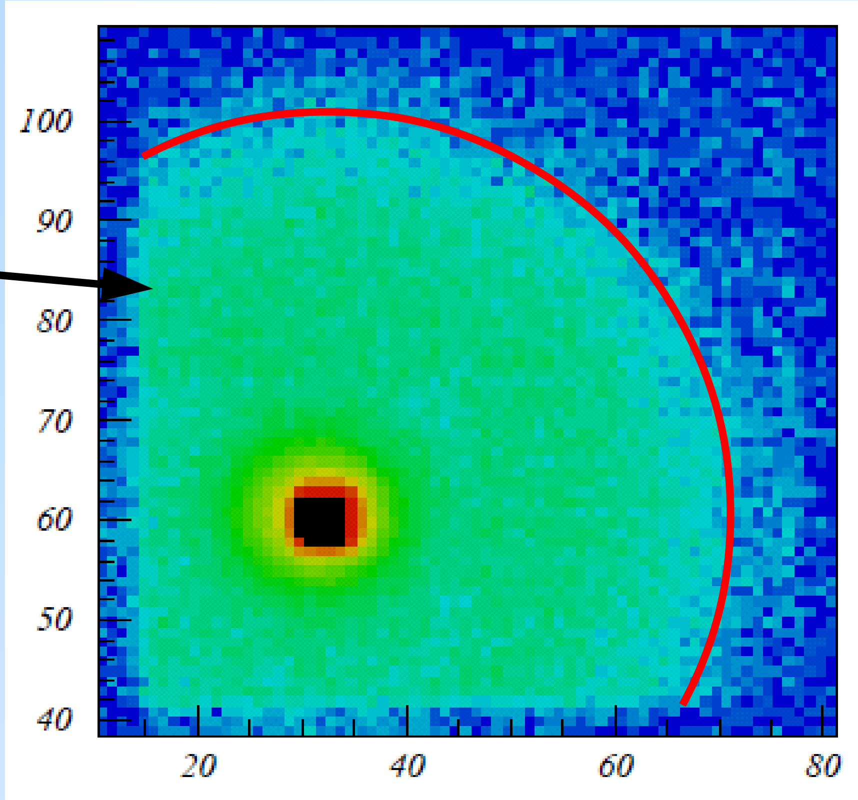


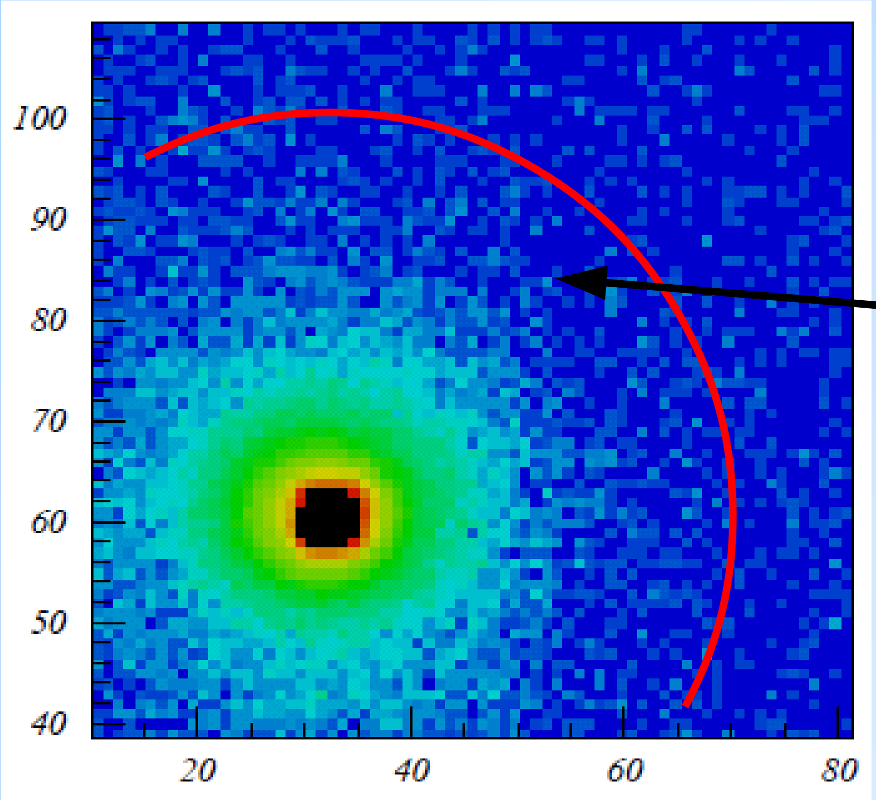


- amount of window light can be reduced by thinner window
- effects of photoelectron backscattering disappears in magnetic field
- reflected light:
  - higher QE, more absorption at first pass
  - anti-reflective coating?

Test in magnetic field 1.5 T

- around 20% of photoelectrons back-scatter and the maximum range is twice the distance from photocathode to APD ~40mm

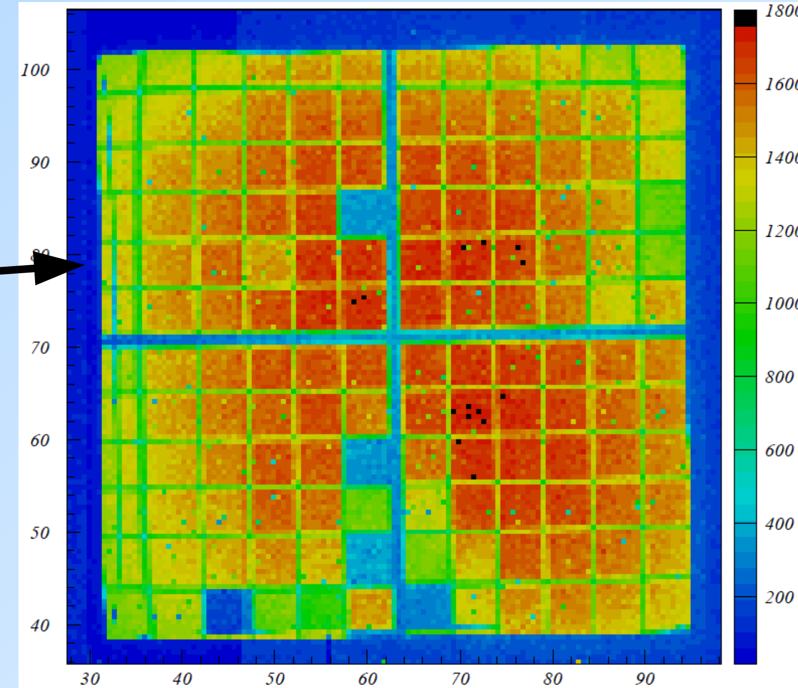




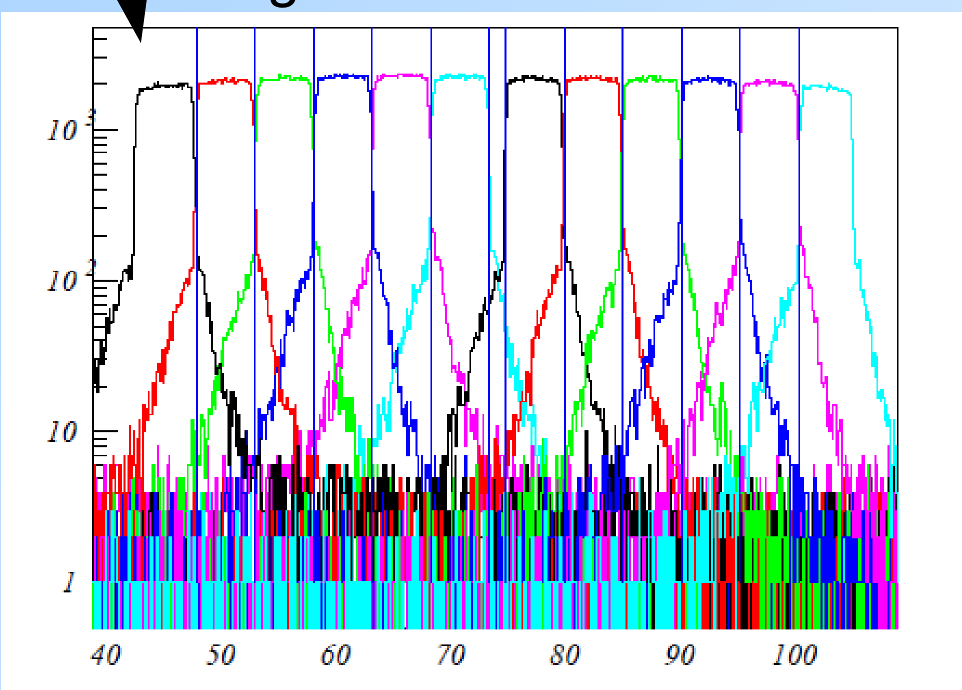
- again in magnetic field these photoelectrons follow magnetic field lines ad fall back on the same place

Test in magnetic field 1.5 T

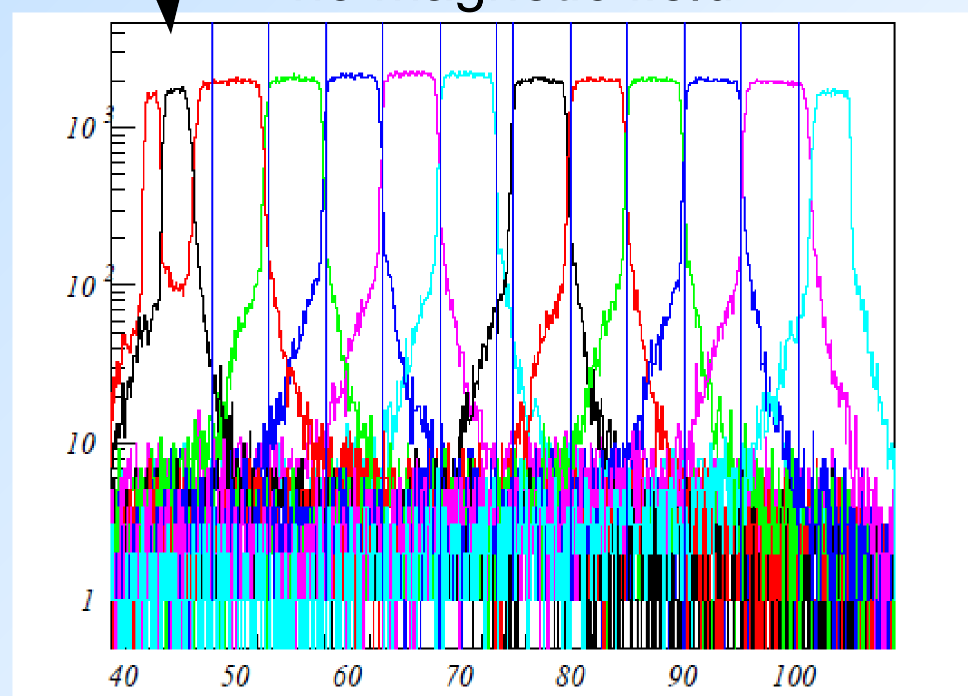
- distortion of electric field lines at HAPD edge produces irregular shapes of areas covered by each channel
- in magnetic field photoelectrons circulate along the magnetic field lines and distortion disappears



magnetic field 1.5 T



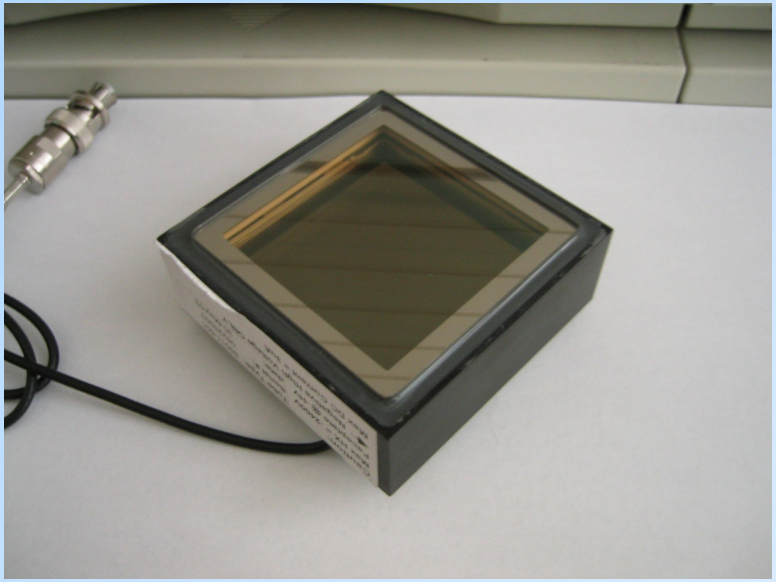
no magnetic field

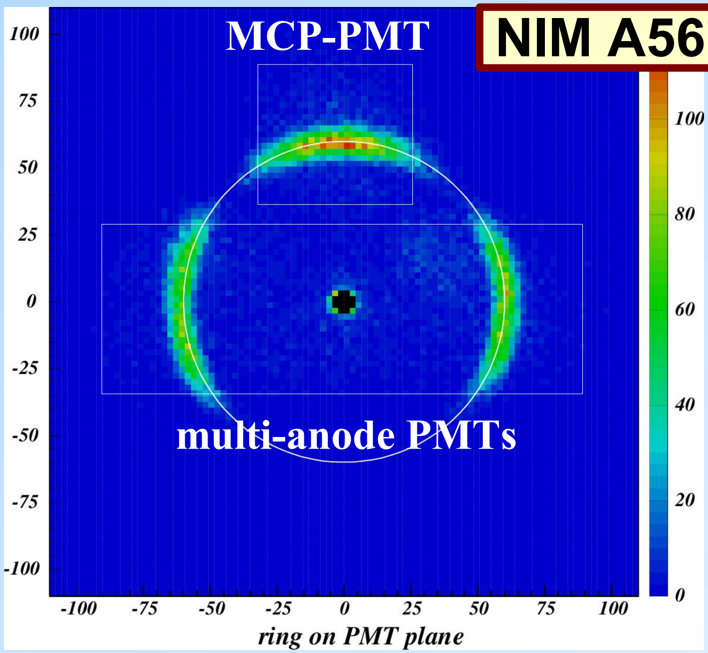


Photon detector: MCP-PMT

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
- active area fraction ~ 52%





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- Tested in combination with multi-anode PMTs

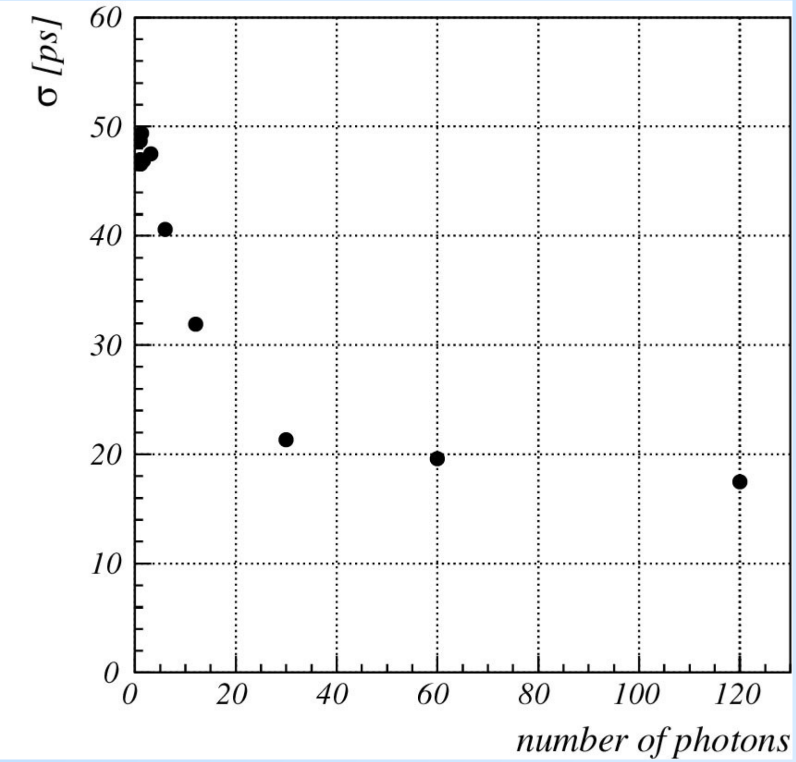
- σ_ϑ~13 mrad (single cluster)
- number of clusters per track N ~ 4.5
- σ_ϑ~ 6 mrad (per track)
- → ~ **4 σ π/K separation at 4 GeV/c**

- 10 μm pores required for 1.5T
- collection efficiency and active area fraction should be improved
- aging study should be done

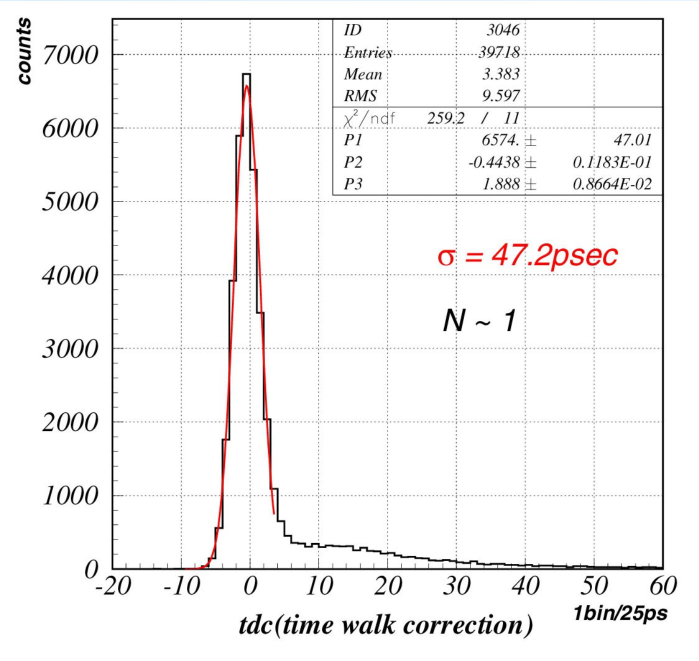
BURLE MCP-PMT timing properties

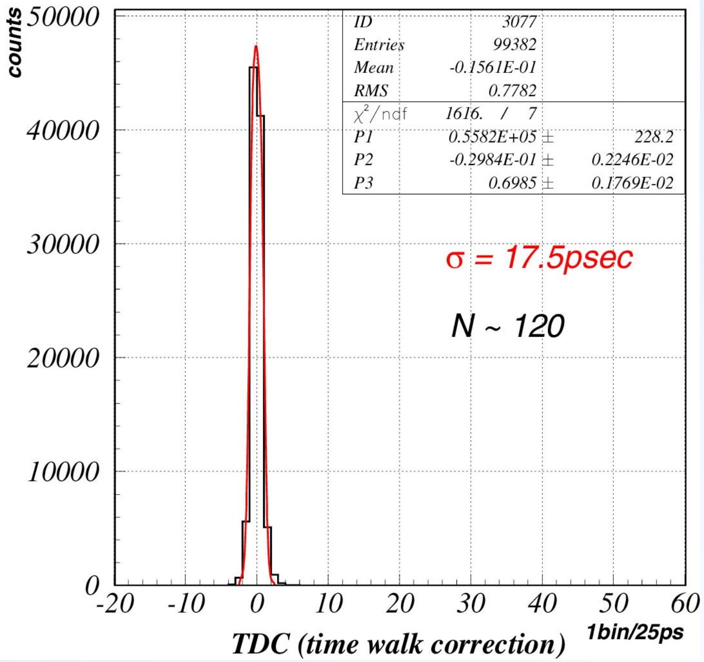
Bench tests with pico-second laser:

- amplifier ORTEC FTA820A
- discriminator PHILIPS 308
- CAMAC TDC Kaizu works KC3781A, 25ps LSB
- CAMAC charge sensitive ADC



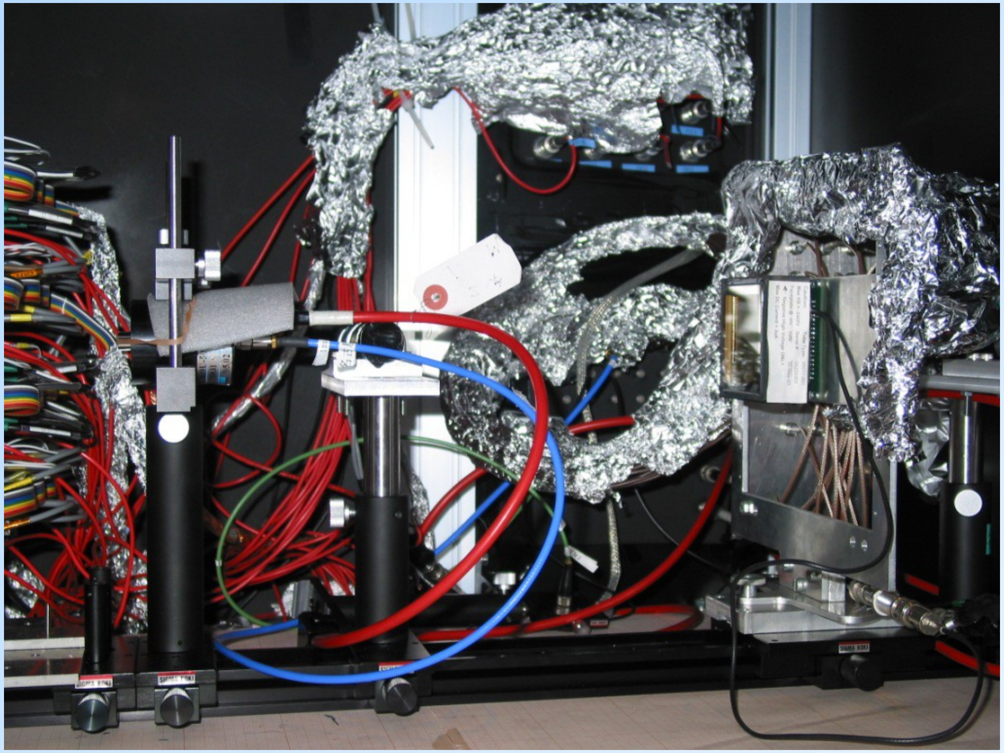
Time resolution as a function of the number of detected photons.

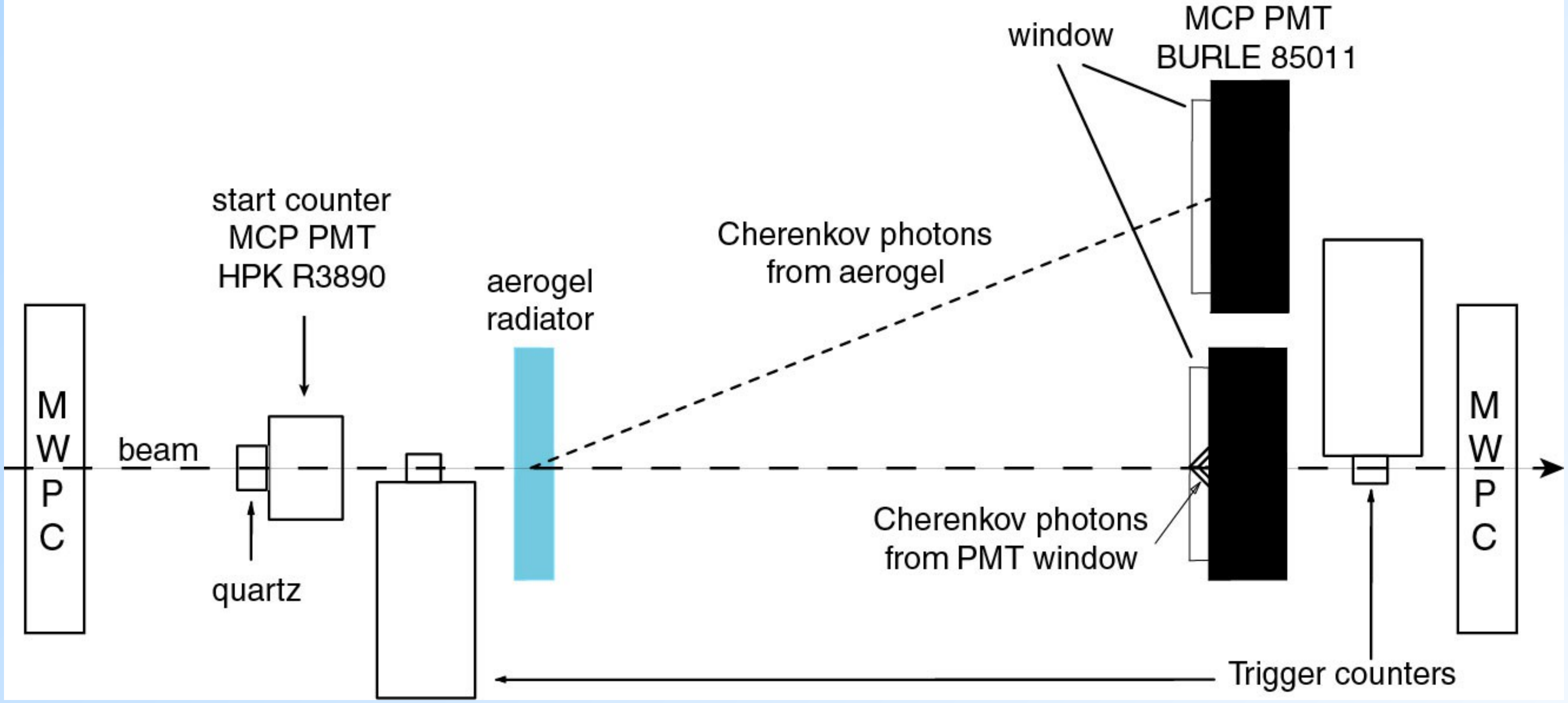




TOF: Beamtest setup

- MWPC tracking
- trigger counters
- aerogel for ring photons tests
- start counter: Hamamatsu MCP-PMT R3890 with 1cm quartz (σ~10ps)
- BURLE MCP-PMT at beam or ring position
- same electronics as for the bench tests (13 channels instrumented)

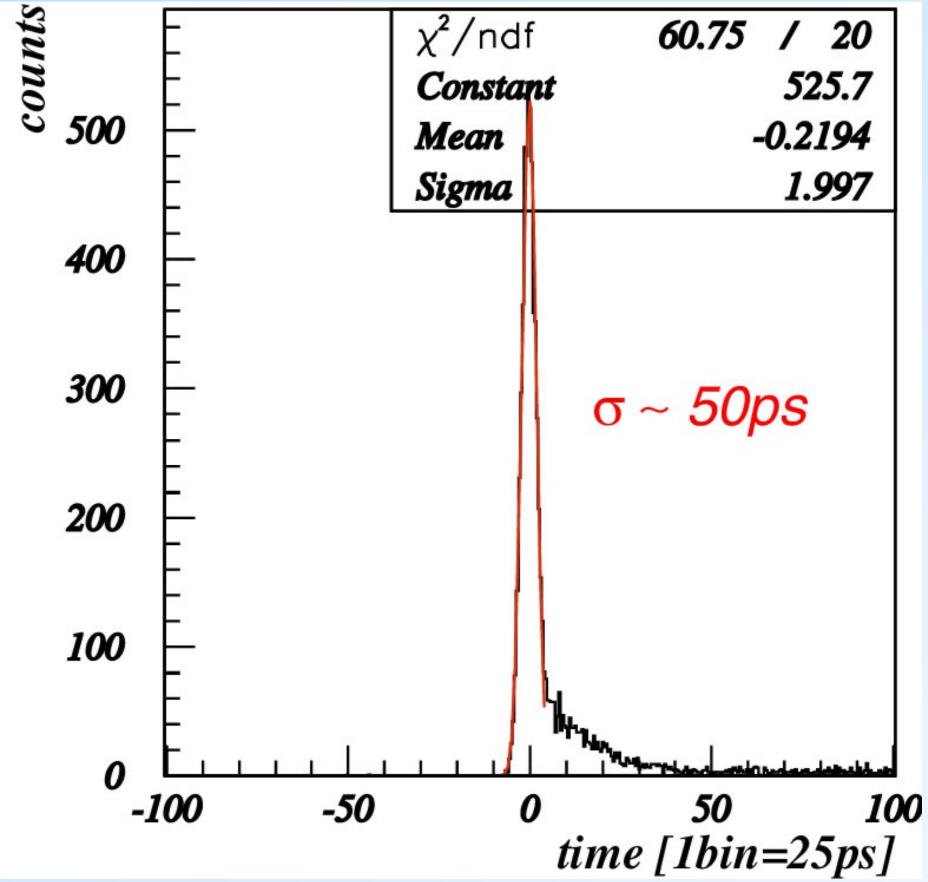


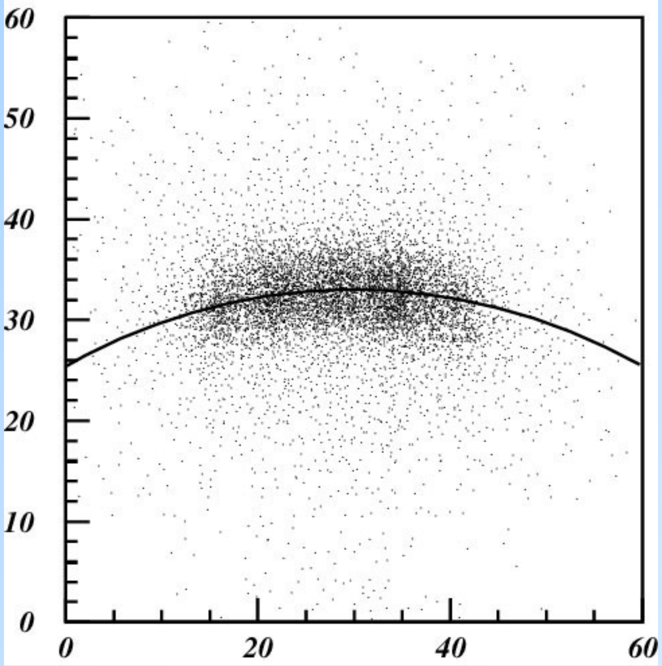


TOF: Ring photons

- obtained time resolution for Cherenkov photons from the aerogel radiator is 50ps, and agrees well with the value from the bench tests

- resolution for full ring (10 photons) would be around 20 ps

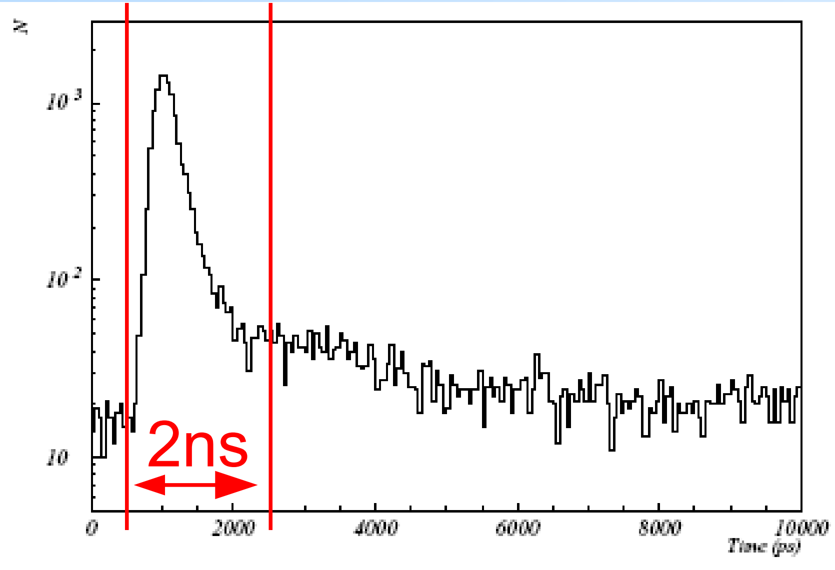




- part of the ring, measured by MCP-PMT (13 channels were instrumented)

Photon detector: SiPM

- immune to magnetic field
- high photon detection efficiency (PDE)
- good timing properties (< 300ps FWHM)
- no high voltage
- low material budget
- high noise rate ~ 1MHz/mm^2
- radiation damage - increase of dark noise

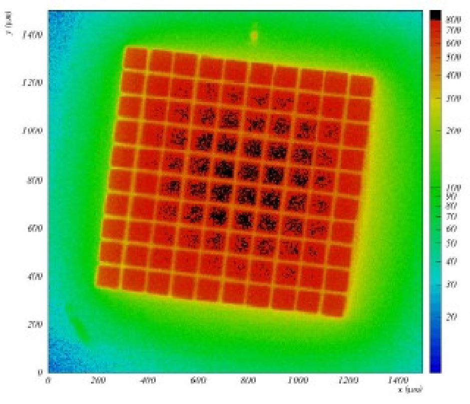


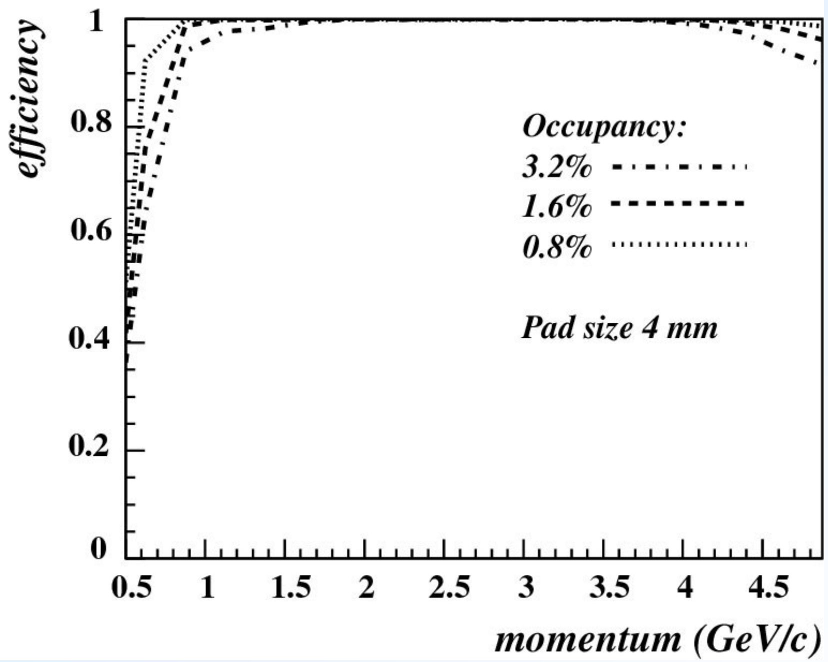
Increase signal to noise ratio by using narrow time (<10ns) window and light guides.

Possible candidate:

Hamamatsu S10362-11-100X

- 1mm x 1mm (10 x 10 pix.)
- PDE ~ 65%
- noise rate ~ 400 kHz

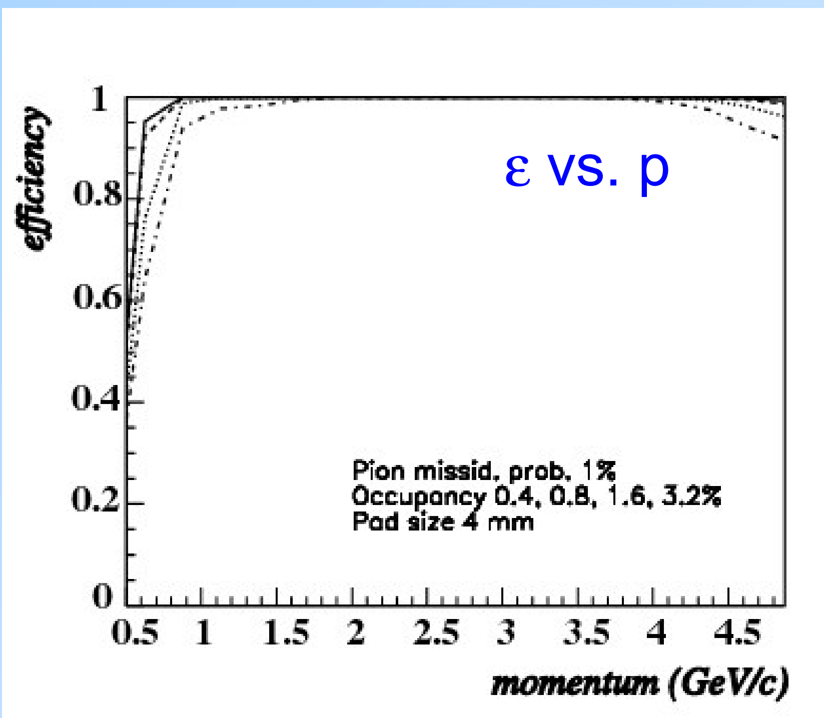


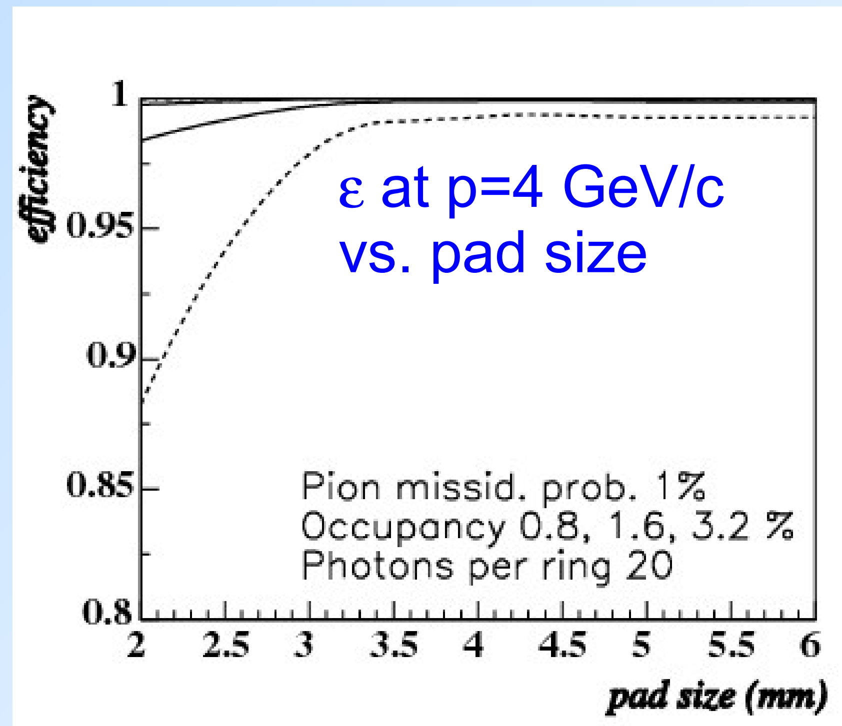


Can such a detector work?

MC simulation of the counter response: assume $1 mm^2$ – active area G-APDs with 0.8 MHz (1.6 MHz, 3.2 MHz, 6.4 MHz) dark count rate, 5 ns time window. Vary light collector demagnification (= pad size).

Kidentification efficiency at 1% π missid. probability

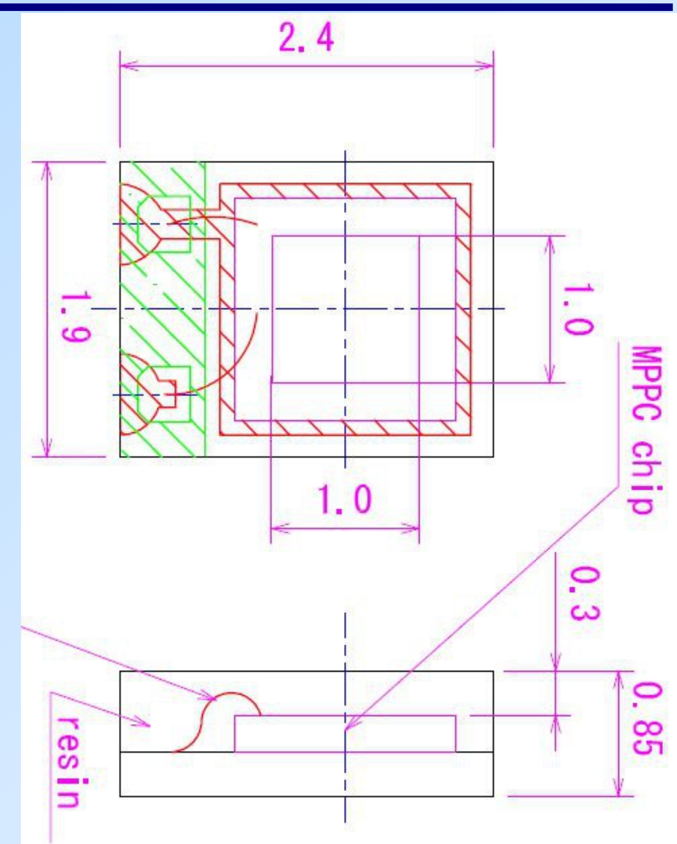


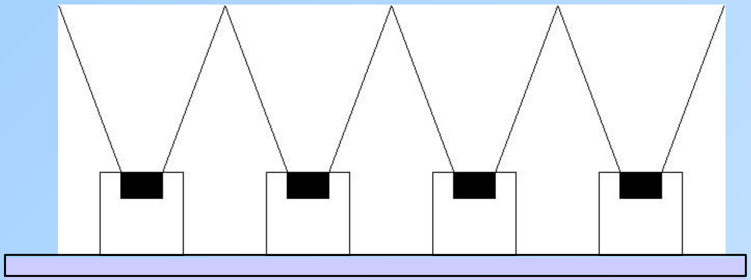


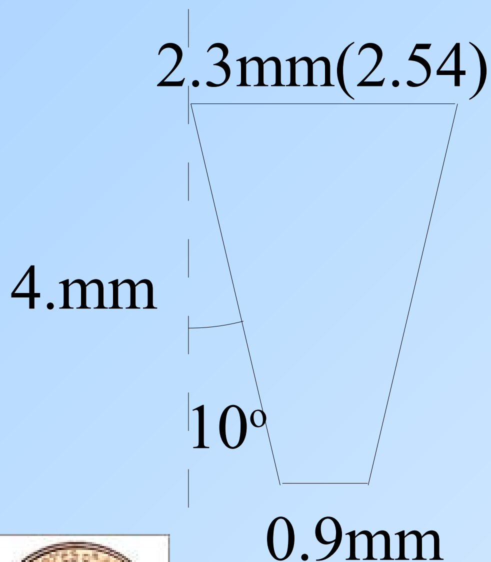
→ Looks OK!

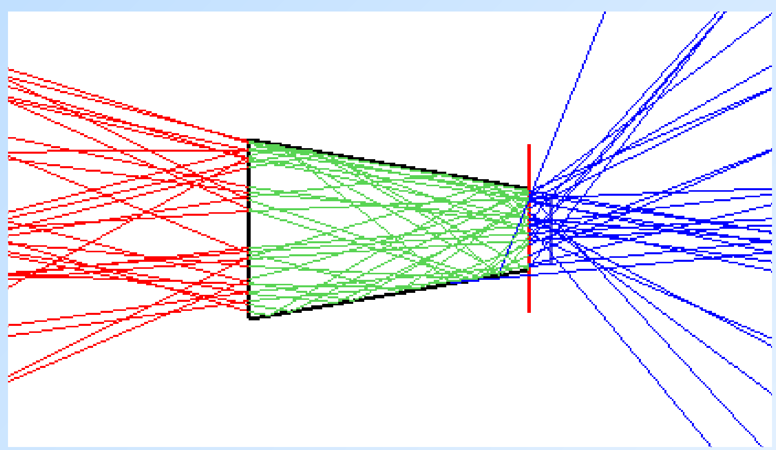
8x8 array of SMD-MPPCs

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





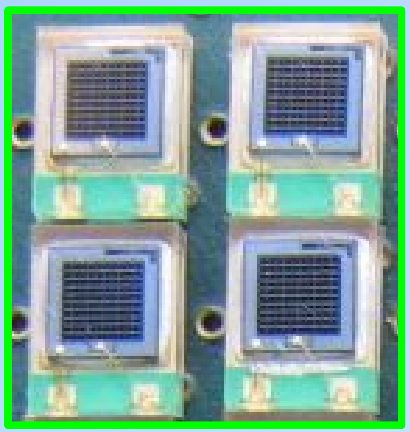


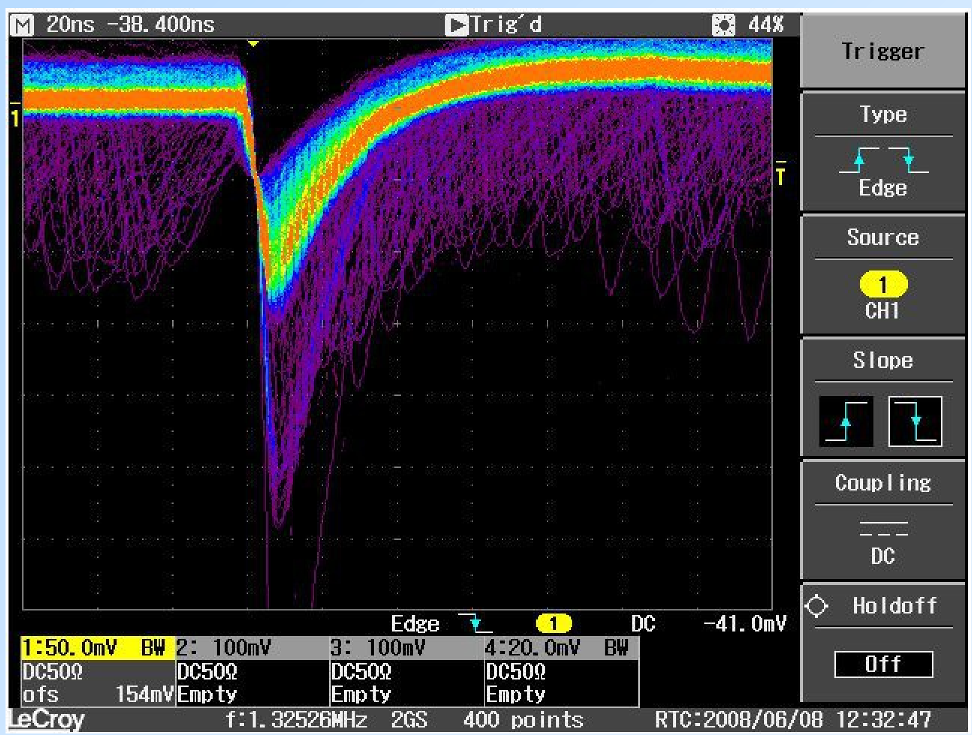


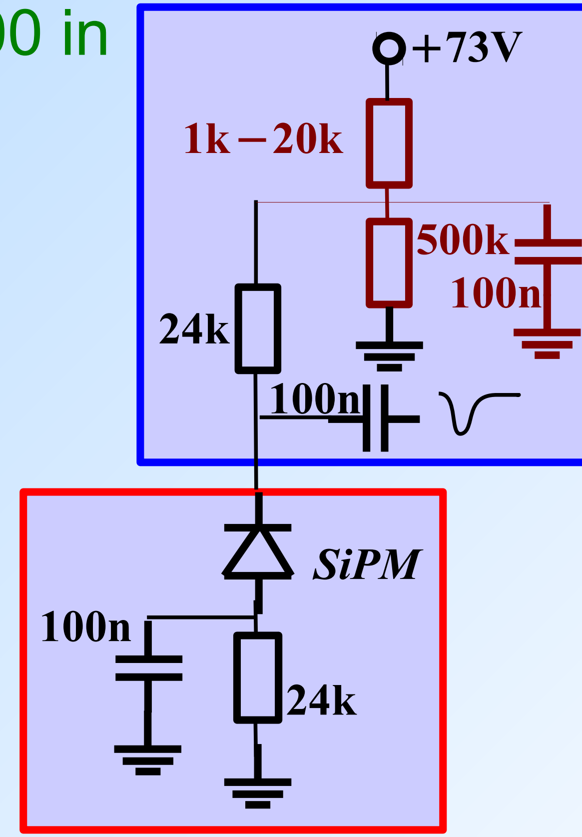
Light guides were machined from plastic (HERA-B lens material).

MPPC module

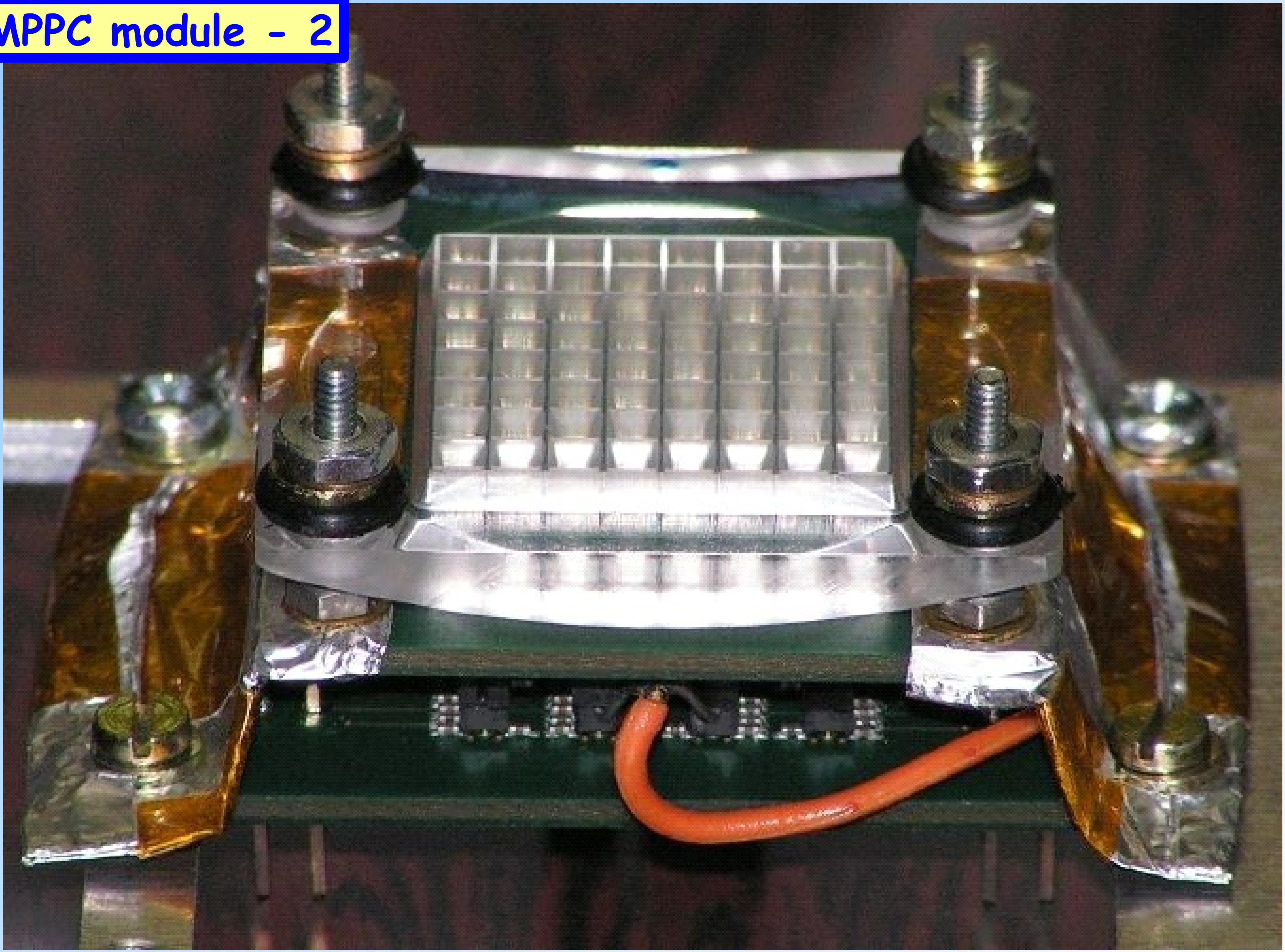
- main board with dividers, bias and signal connectors
- piggy back board with MPPCs (8x8 array of HC100 in SMD package; background ~ 600kHz/MPPC)
- light guides
- 16 electronics channels (4x4) - 4 MPPCs connected to single channel





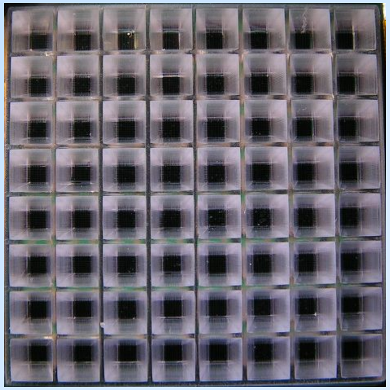


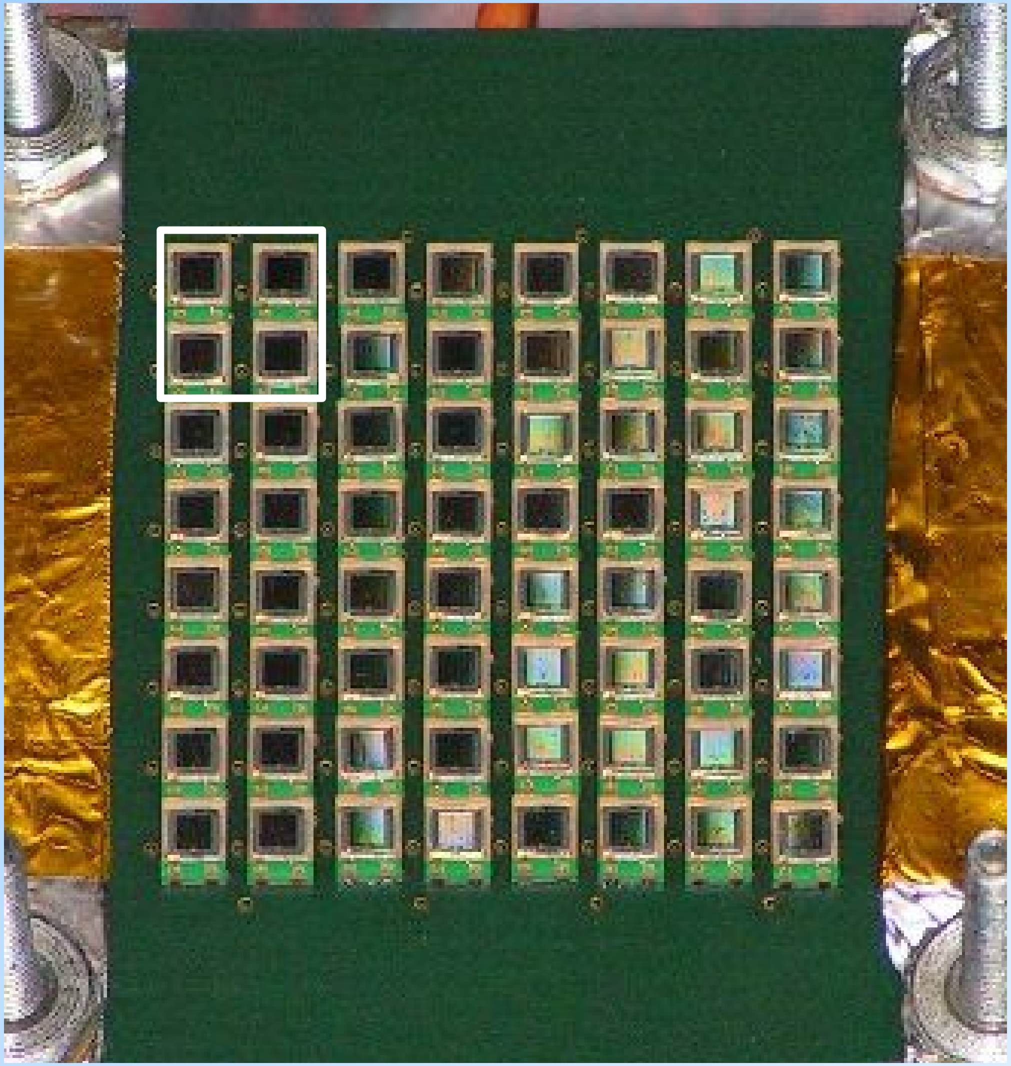
MPPC module - 2

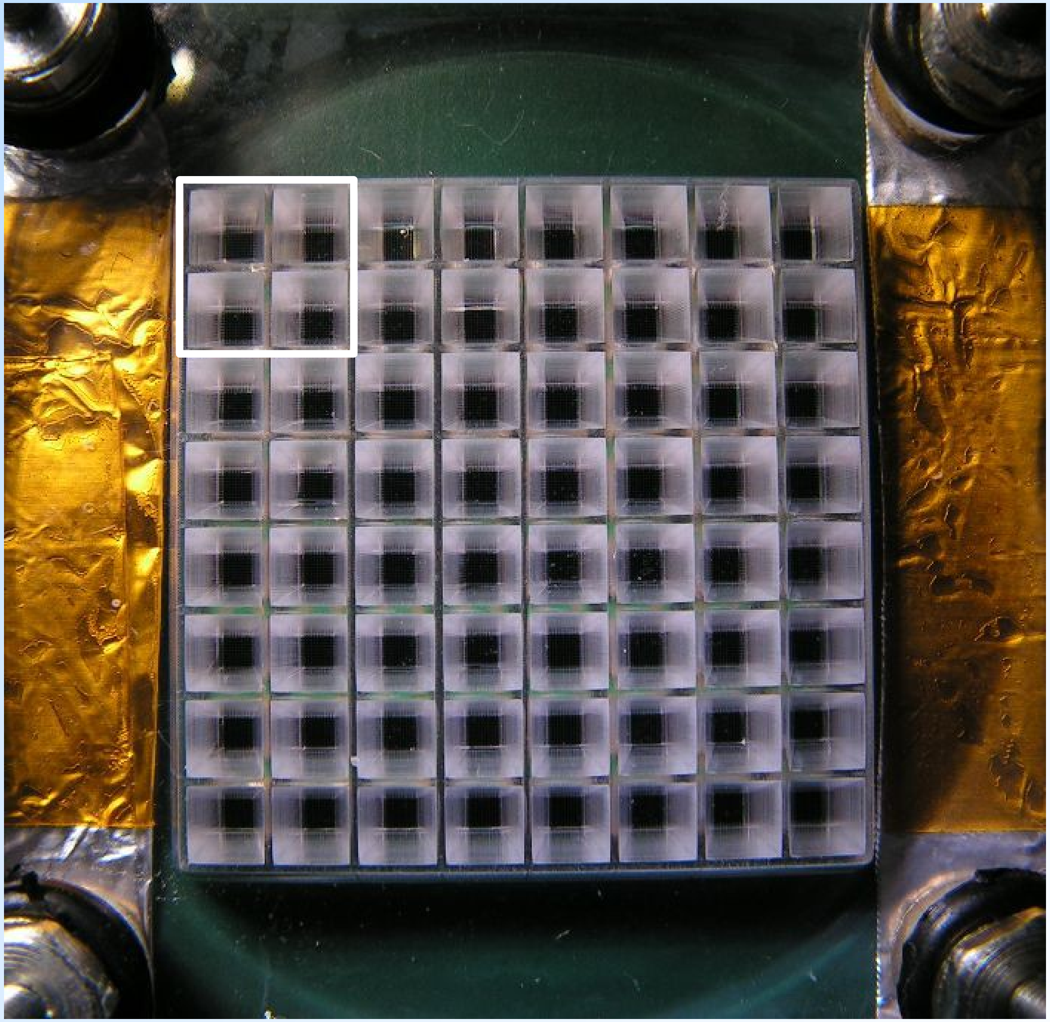


MPPC module - 3

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







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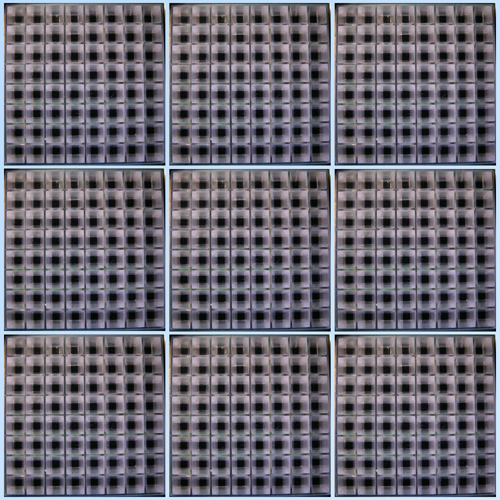
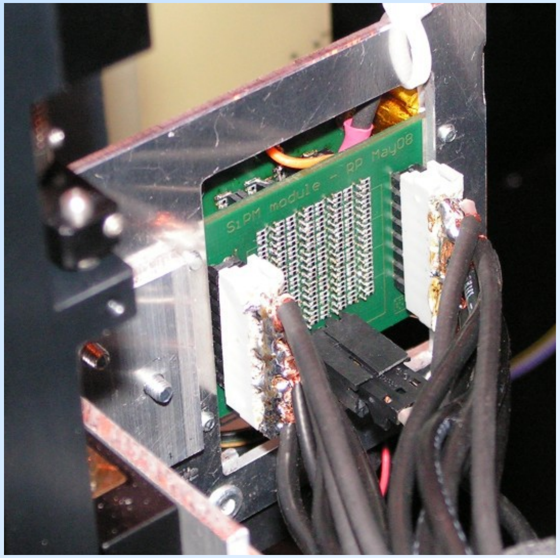
Beam test setup

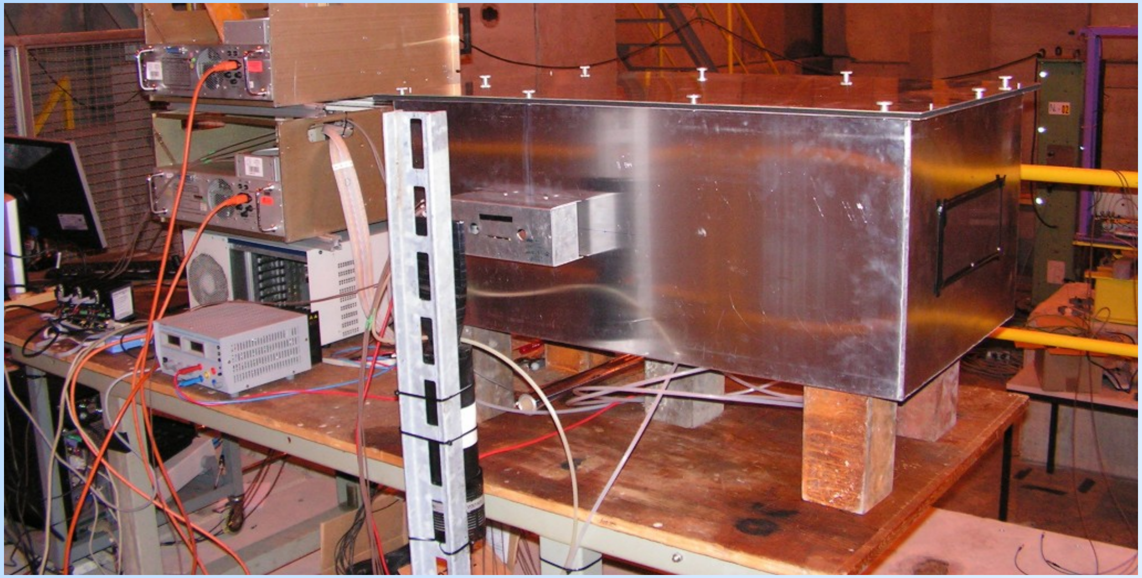
- MPPC array w/o or w/ light guide mounted on 3D stage

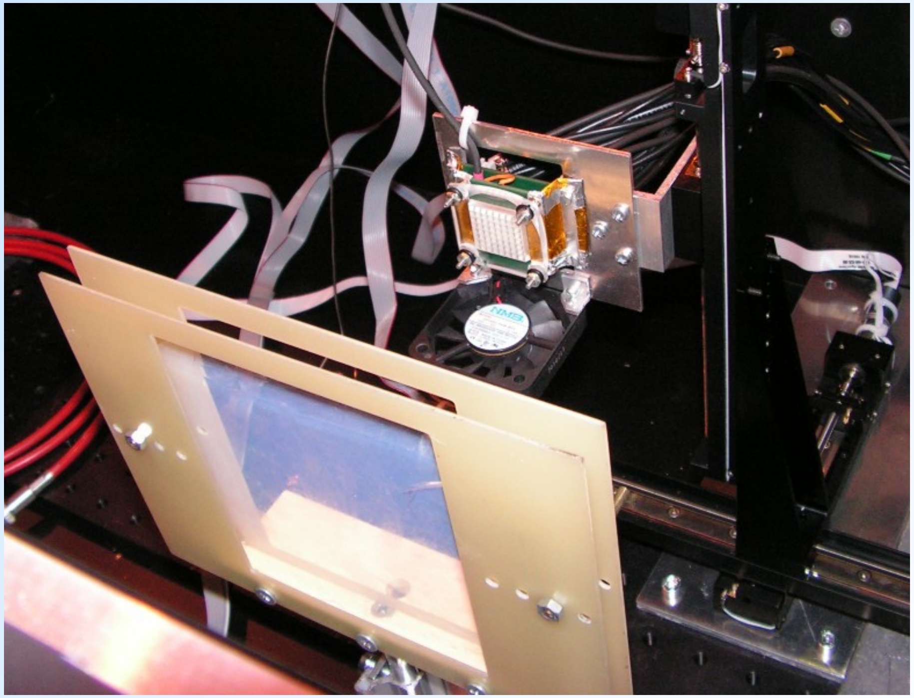
→ effective detector size 3x3

- aerogel n=1.03, d=10mm (distance 130mm)
- hits detected by multi-hit TDC
- +120 GeV/c pions, beam size ~1cm^2
- 2 MWPCs for tracking
- plastic scintillator for timing





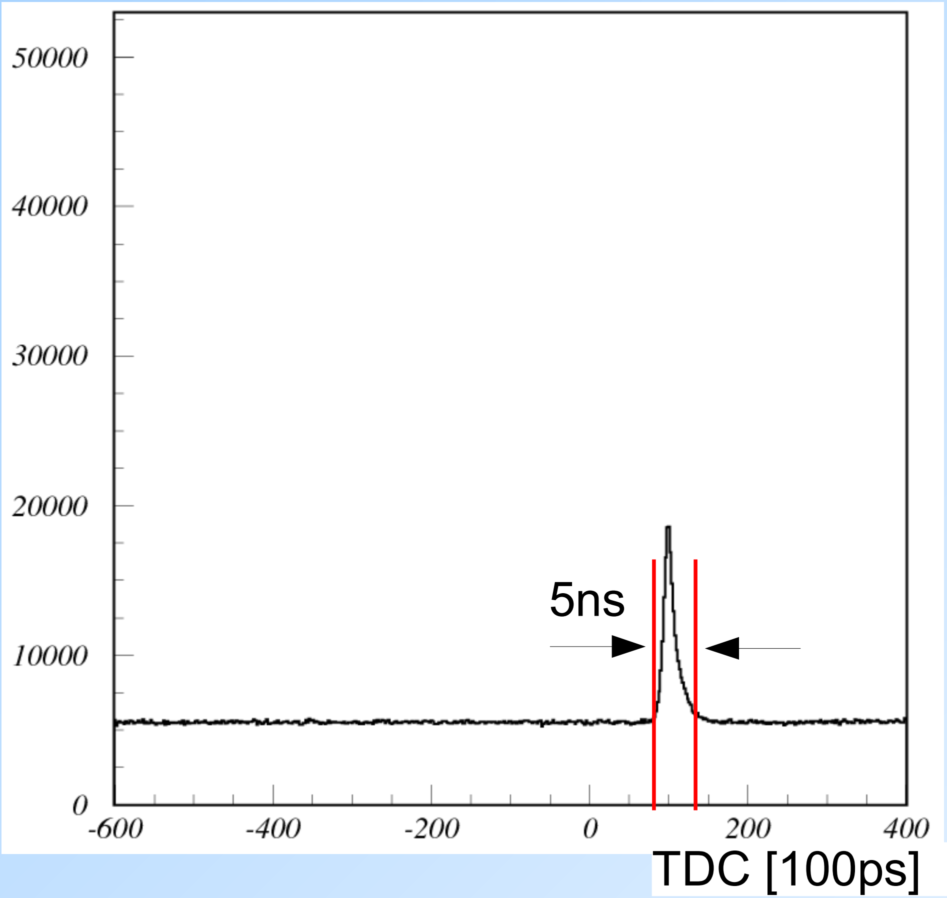




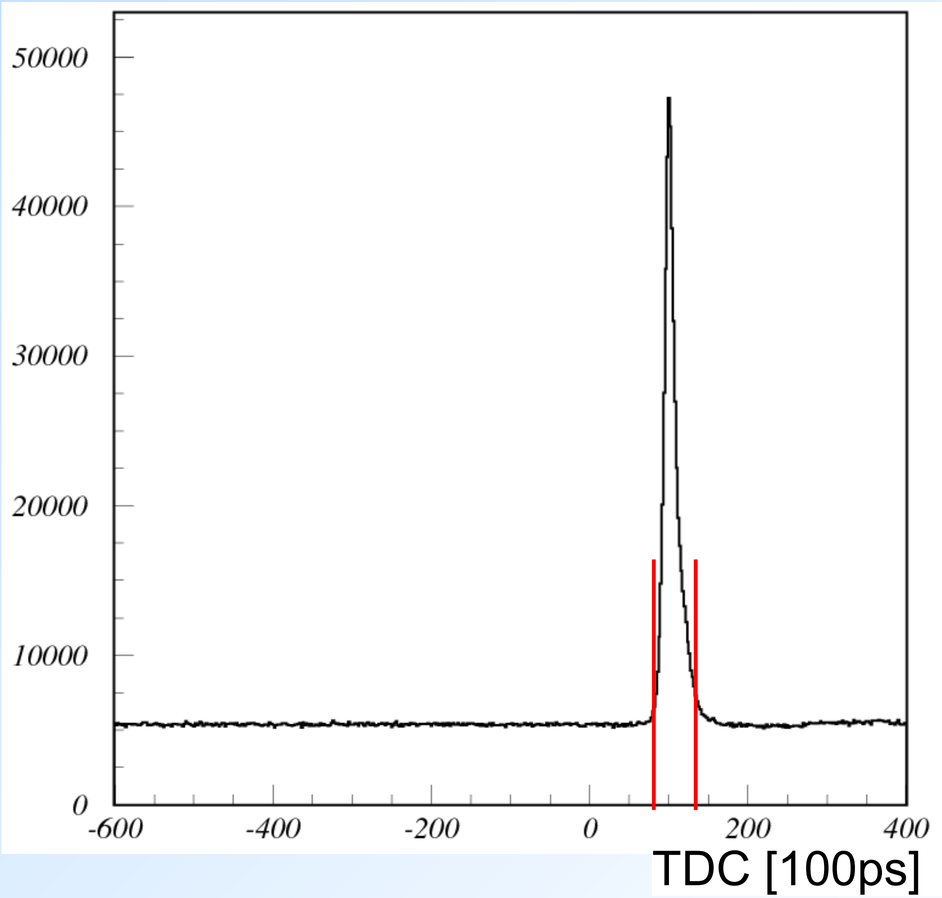
TDC distributions of MPPC hits for all events

- 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

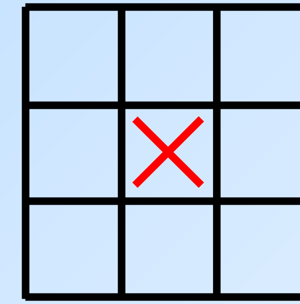
w/o light guides



w/ light guides

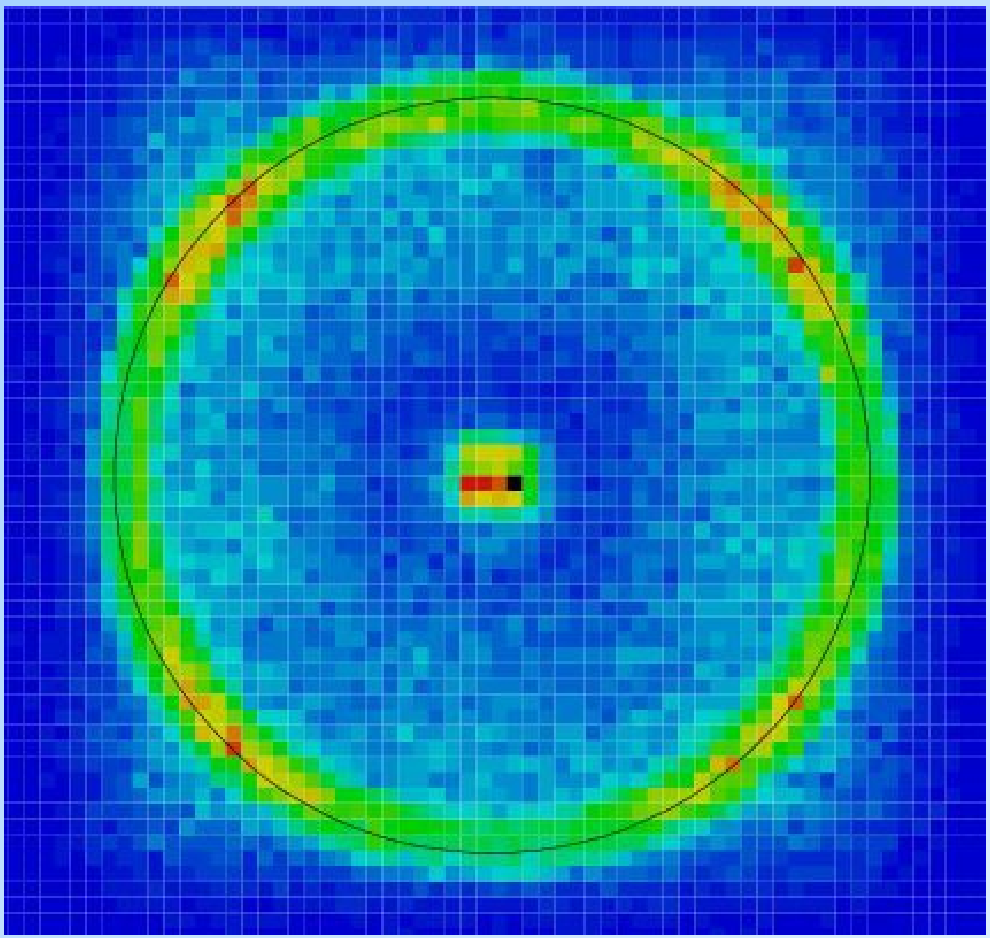


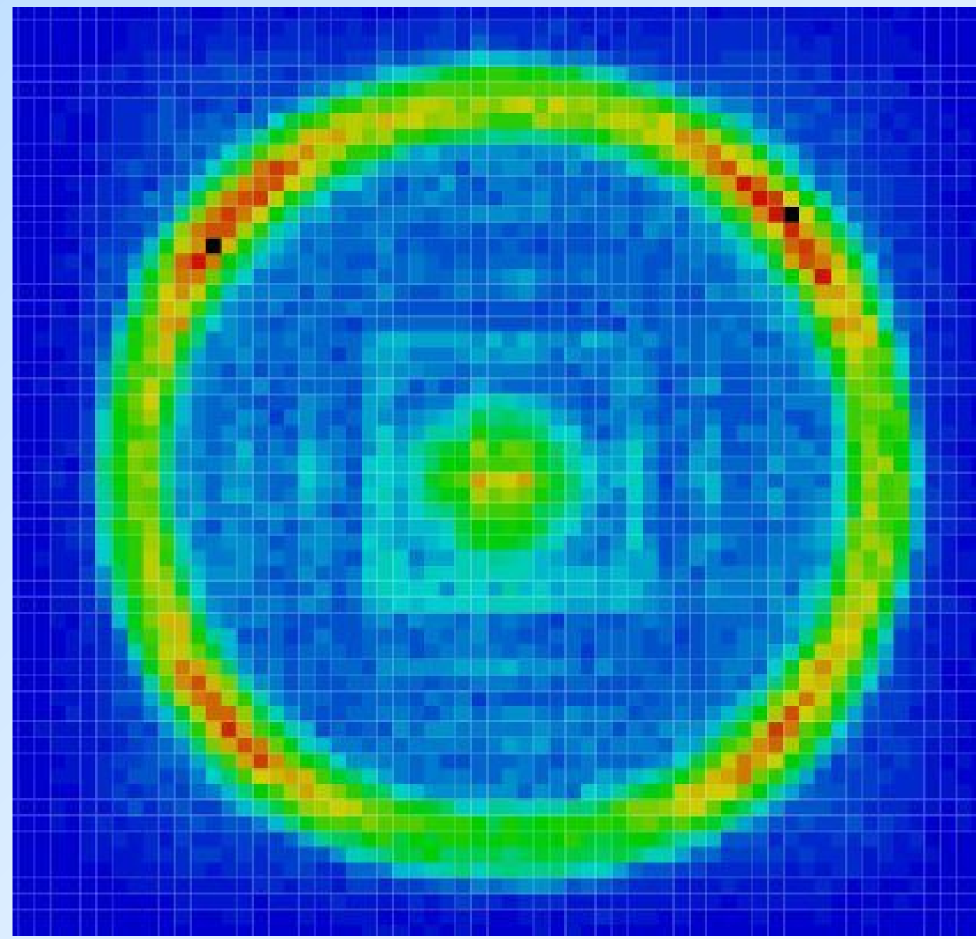
Ring images



- 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**





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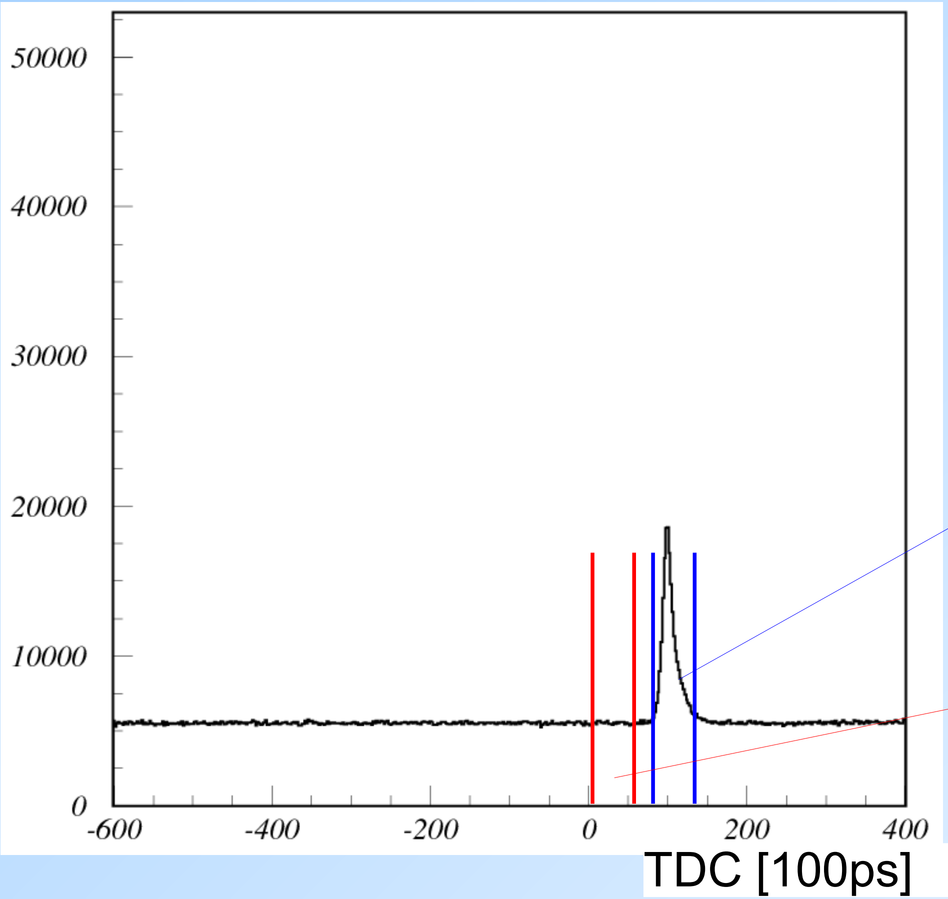
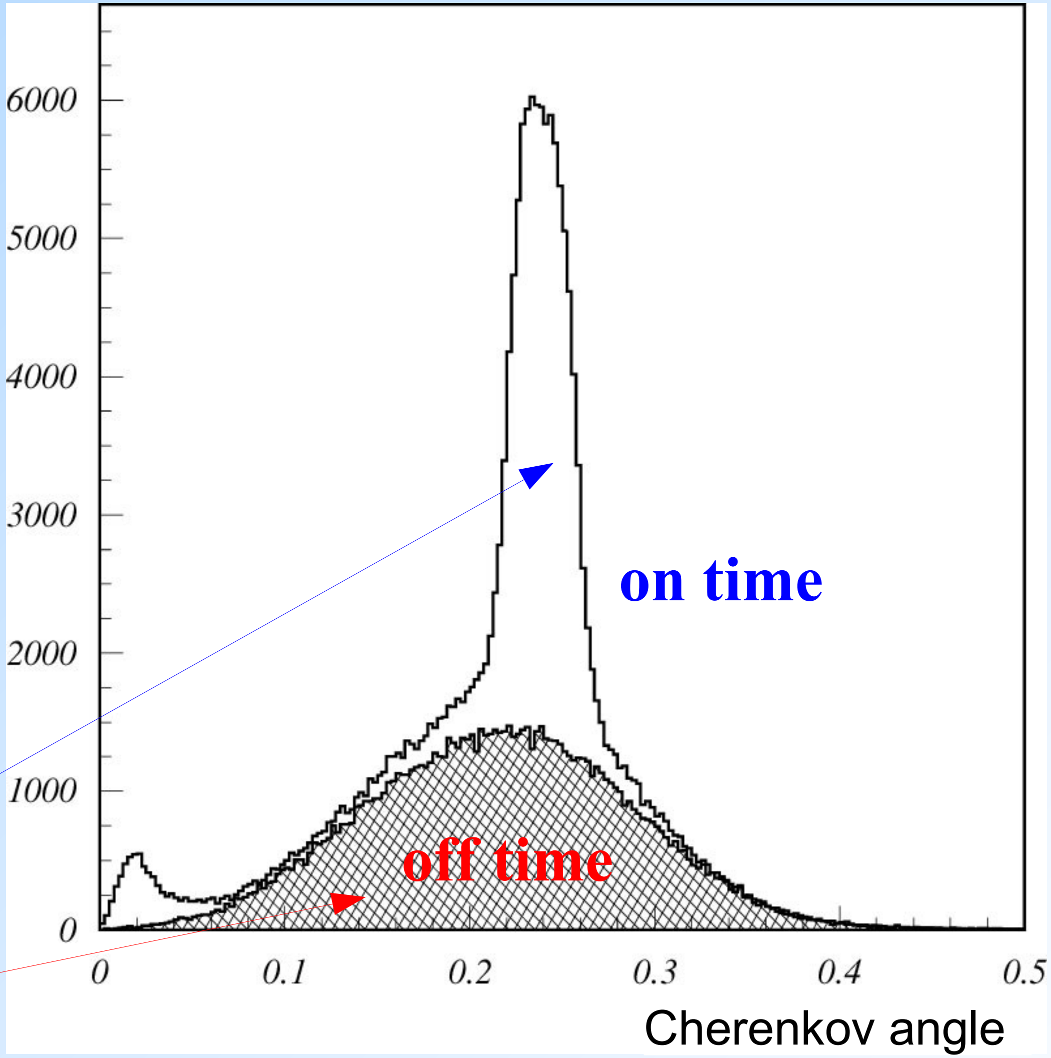
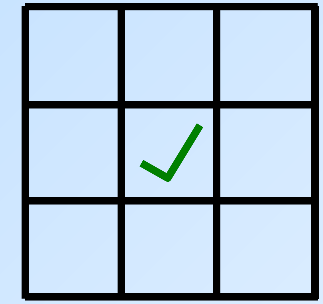
Cherenkov angle distributions

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

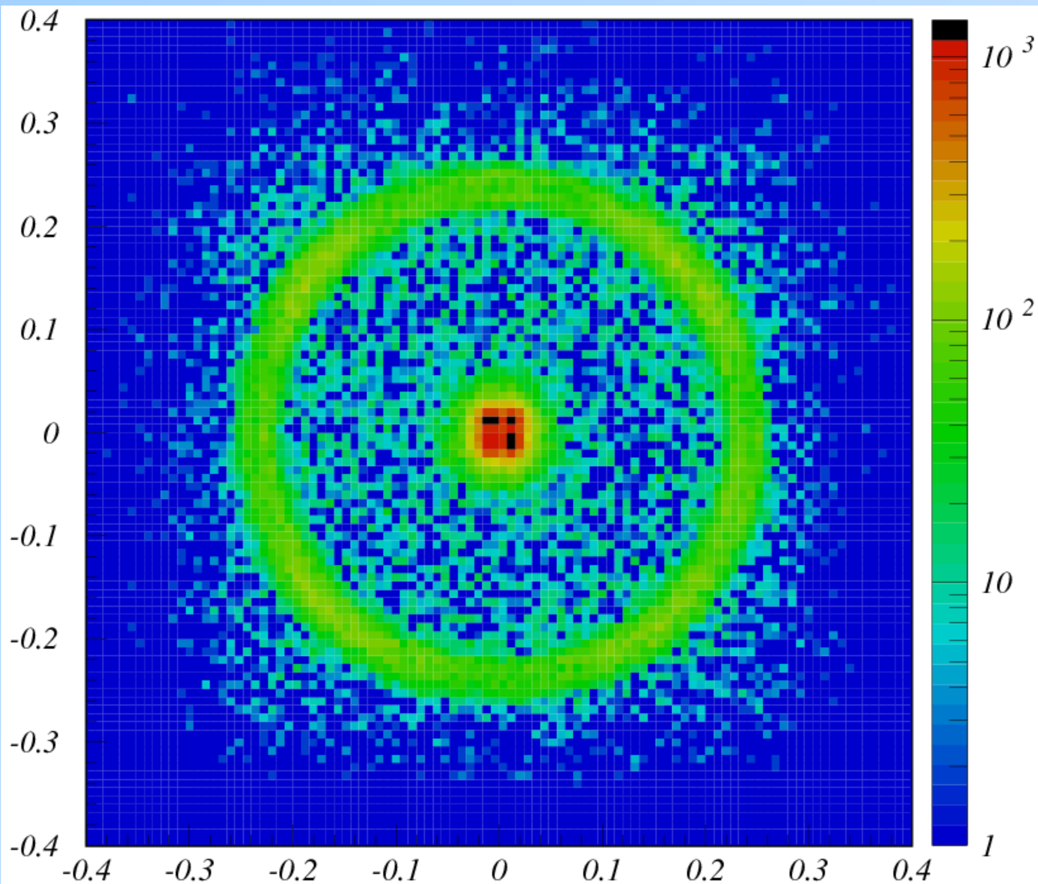




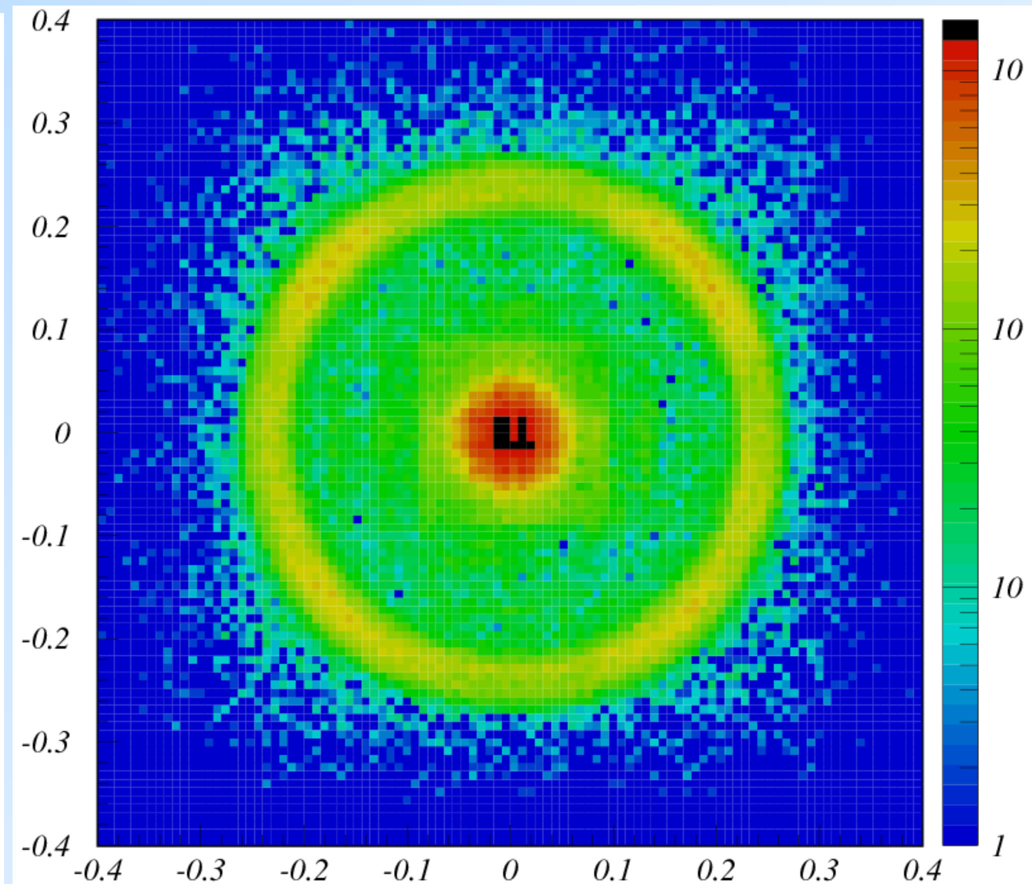
Ring images – background subtracted



w/o light guides



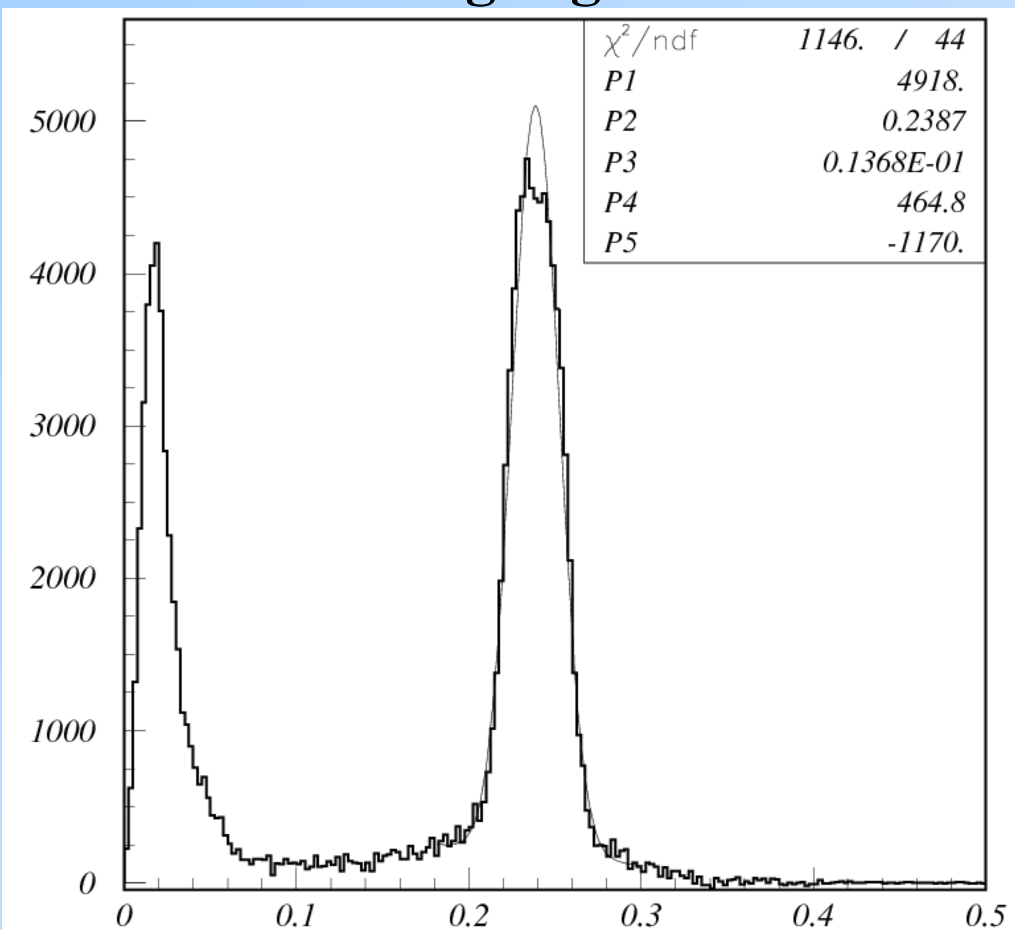
w/ light guides



Cherenkov angle distributions

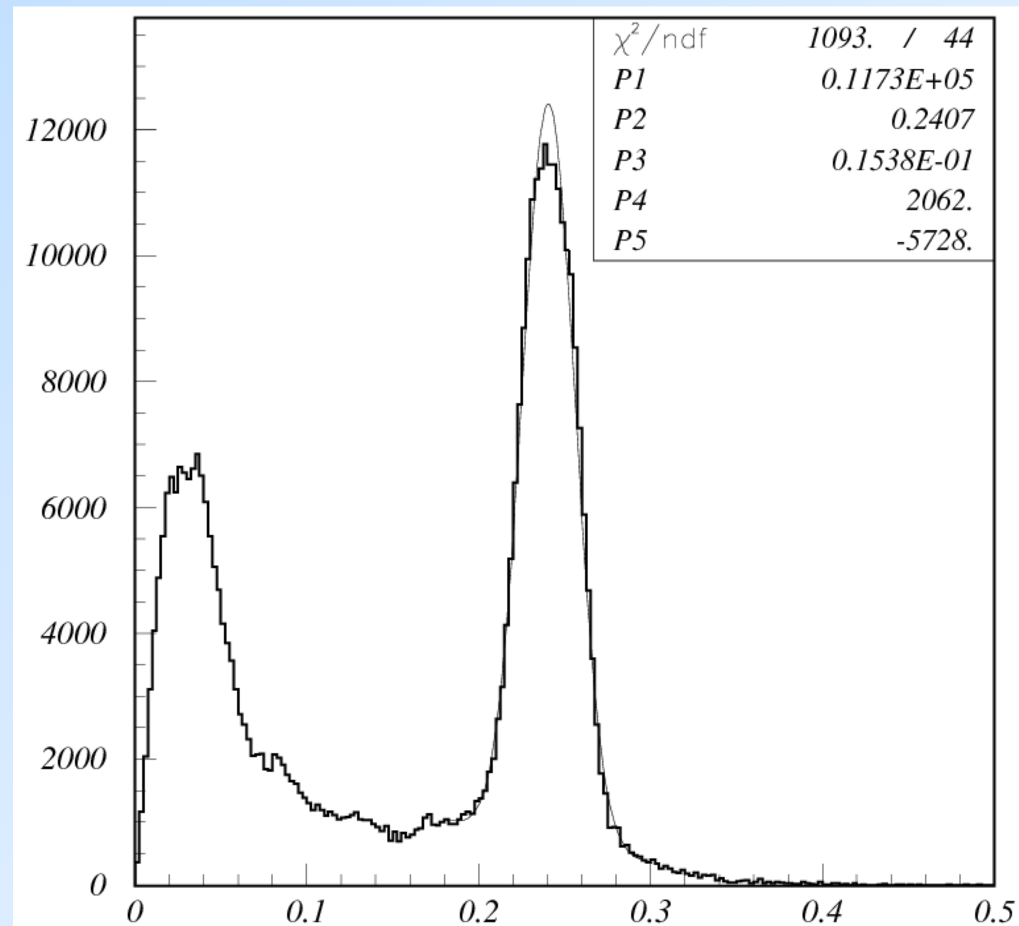
- background subtracted distributions
- ratio of detected photons w/ and w/o light guides: ~ 2.3
- resolution within expectations (~14mrad)

w/o light guides



Cherenkov angle

w/ light guides



Cherenkov angle

Number of 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 LG ~ 1.6
- w/ LG ~ 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 LG ~ 8
- **w/ LG ~ 37**