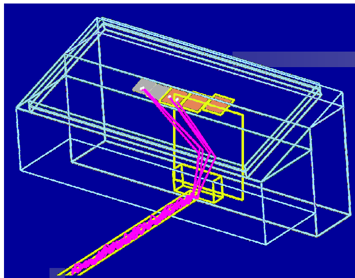
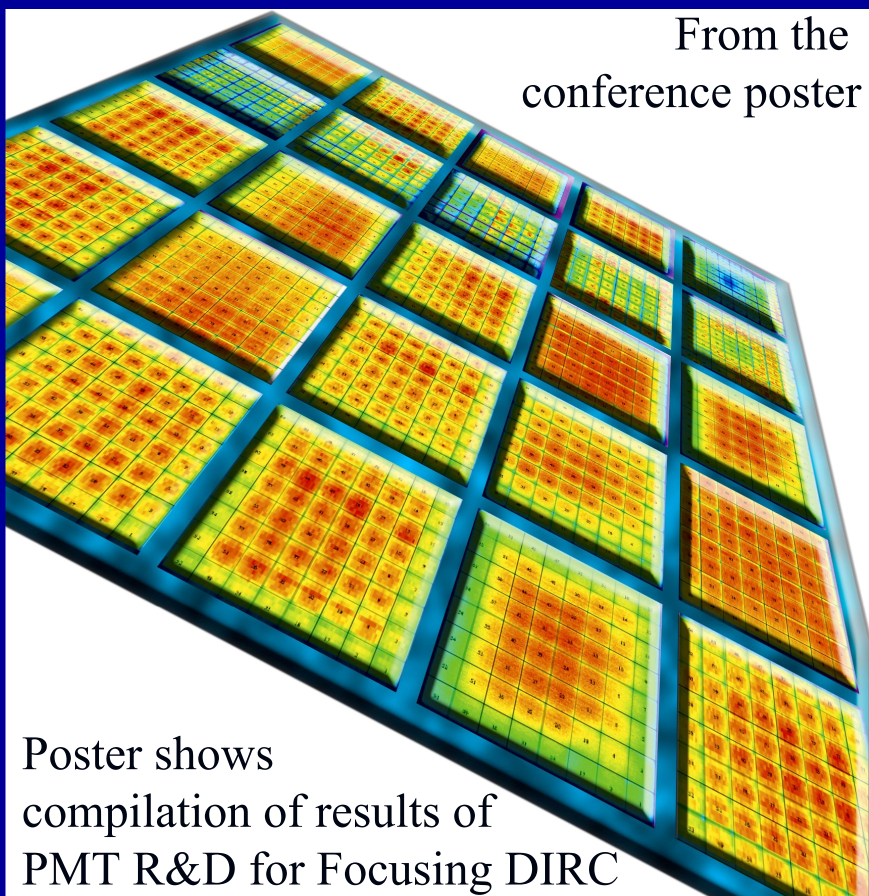


New Results on Focusing DIRC

Outline:

- DIRC Concept
- BABAR-DIRC Performance
- R&D for Focusing DIRC
  - Prototype Design
  - Photodetector Selection
  - Performance in Beam Test



From the conference poster

Poster shows compilation of results of PMT R&D for Focusing DIRC

Jochen Schwiening

for the Focusing DIRC group at SLAC

Detection of Internally Reflected Cherenkov Light

Novel Ring Imaging CHerenkov detector §
based on total internal reflection of Cherenkov light
used for the first time in BABAR for hadronic particle identification

Recent improvements in photon detectors have motivated R&D efforts to improve the successful BABAR-DIRC and make DIRCs interesting for future experiments (Super B-Factory, Panda, GlueX, ILC)

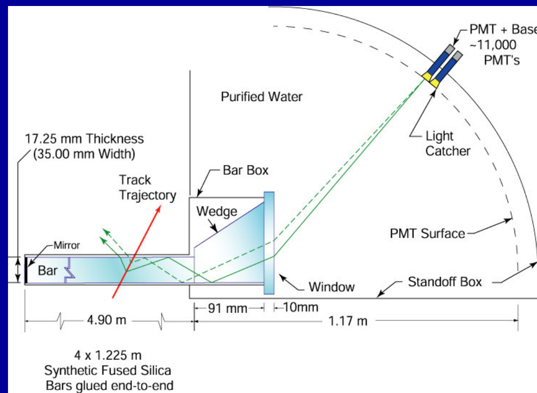
Focusing DIRC R&D group at SLAC:

- Ivan Bědajánek
- Jonathon Coleman
- Gholam Mazaheri
- Jochen Schwiening
- Jaroslav Va'vra
- Jose Benitez
- David W.G.S. Leith
- Blair N. Ratcliff
- Josef Uher

Acknowledgements:
- M. McCulloch and B. Reif (prototype construction)
- M. Barnyakov, M. Ji, S. Kononov, and K. Suzuki (beam test)

§ *B.N. Ratcliff, SLAC-PUB-6047 (Jan. 1993)*

DIRC Designs



<u>BABAR-DIRC</u> *operating since 1999*

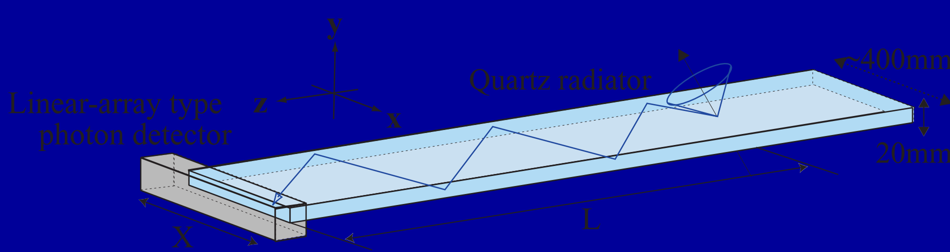
3D imaging

a) x-coordinate

b) y-coordinate

c) time ($\sigma \approx 1.7$ns)

PID primarily from x&y coordinates



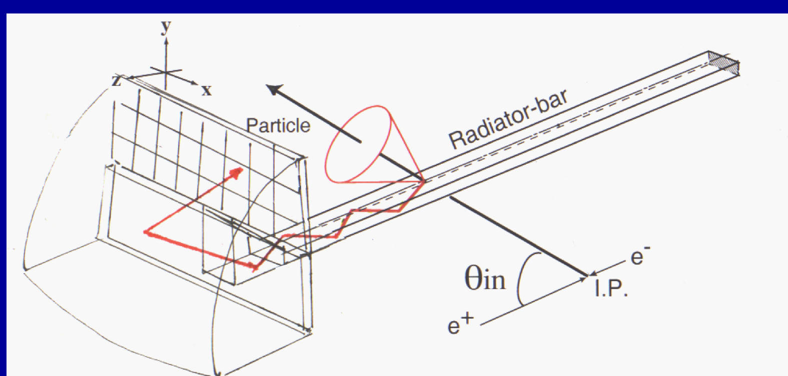
<u>TOP counter (Nagoya)</u> *proposed for BELLE*

2D imaging

a) x-coordinate

b) time ($\sigma < 100$ps)

PID from x&time coordinates



<u>Focusing DIRC prototype (SLAC):</u>

3D imaging

a) x-coordinate

b) y-coordinate

c) time ($\sigma < 130$ps)

PID from all three coordinates

Focusing DIRC R&D Roadmap

Work with manufacturers to develop and characterize one or more fast, pixelated photon detectors including;

- basic issues such as cross talk, tube lifetime, and absolute efficiency
- operation in 15 kG field

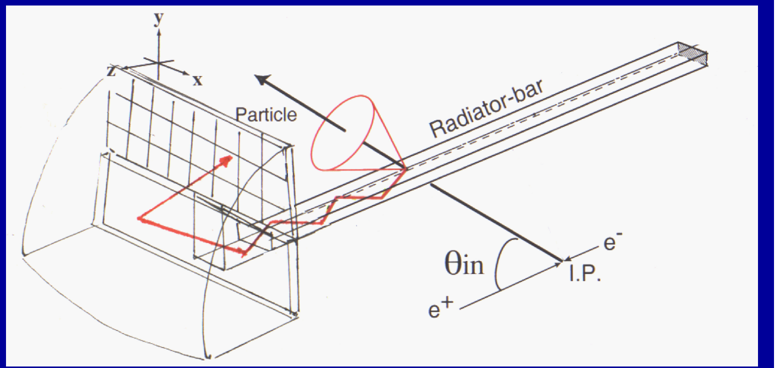
Measure timing resolution, uniformity, and cross talk in lab using f… …tem

Measure single photon Cherenkov angular resolution in a t…

- use a prototype with a small expansion region and mirr… …strumented with a number of candidate pixelated photon detectors … ps) timing electronics.
- use 3D imaging (x&y coordinate and time) over-constraint very useful to deal with backgrounds and to develop corrections
- demonstrate performance parameters
- demonstrate correction of chromatic production term via precise timing
- measure N_0 and timing performance of candidate detectors.

ALL FOCUSING DIRC RESULTS SHOWN TODAY ARE PRELIMINARY.

See also poster #222
"Progress on the Focusing DIRC R&D"
J. Benitez et al.



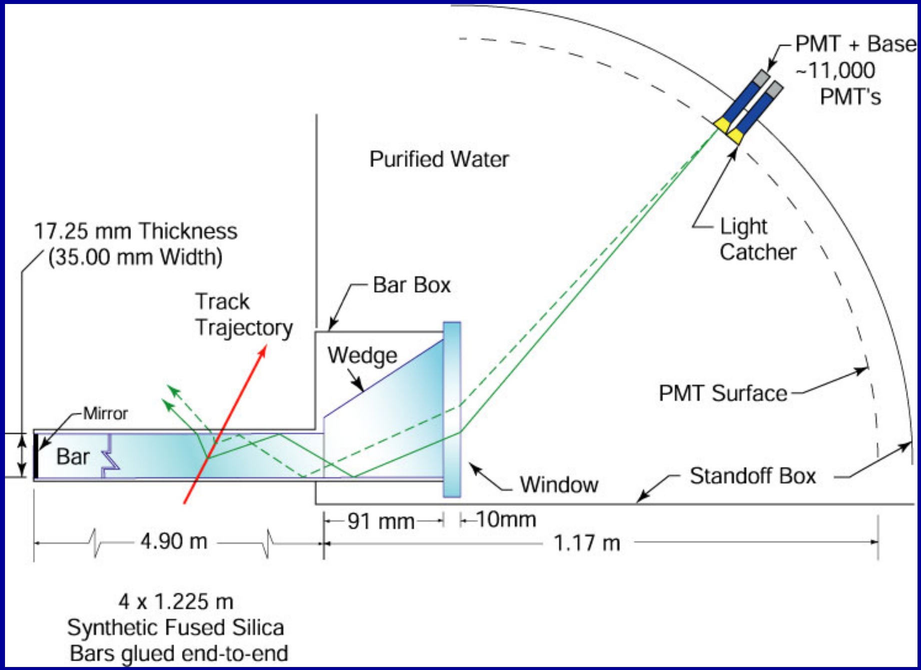
BABAR-DIRC Principle

- Charged particle traversing a radiator with refractive index n with $\beta = v/c > 1/n$ emits Cherenkov photons on cone with half opening angle $\cos\theta_c = 1/\beta n(\lambda)$.

- If $n>\sqrt{2}$ some photons are always totally internally reflected for $\beta\approx 1$ tracks.

- Radiator and light guide: Long, rectangular Synthetic Fused Silica ("Quartz") bars

  (*Spectrosil:* average $<n(\lambda)> \approx 1.473$, radiation hard, homogenous, low chromatic dispersion)



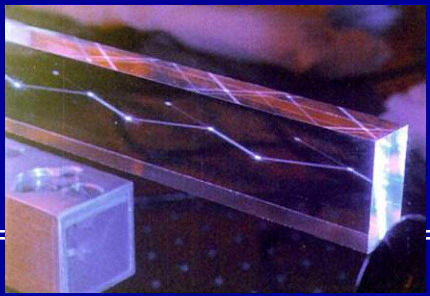
- Photons exit via wedge into expansion region (filled with $6m^3$ pure, de-ionized water).

- Pinhole imaging on PMT array (bar dimension small compared to standoff distance).

  (10,752 traditional PMTs ETL 9125, immersed in water, surrounded by hexagonal "light-catcher", transit time spread ~1.5nsec, ~30mm diameter)

- BABAR-DIRC is a 3-D device, measuring: x, y and time of Cherenkov photons, defining θ_c, ϕ_c, $t_{propagation}$ of photon.

  (time measurement used primarily for rejecting accelerator background and resolving ambiguities)



Over six years of experience in PEP-II/BABAR B-factory mode [§]:

DIRC is reliable, robust, easy to operate

- DIRC reached performance close to design within first year of running.
- DIRC plays significant role in almost all BABAR physics analyses.
- Calibration constants stable to typically *rms* < 0.1ns per year.
- 98% of channels fully functional after 7+ years immersed in ultra-pure water.
- No problems with water or gas systems.

Most significant operational issue: sensitivity to accelerator induced background interacting in the water of the Standoff Box (primarily a DAQ issue)

→ Added additional shielding; upgraded TDCs in 2002.

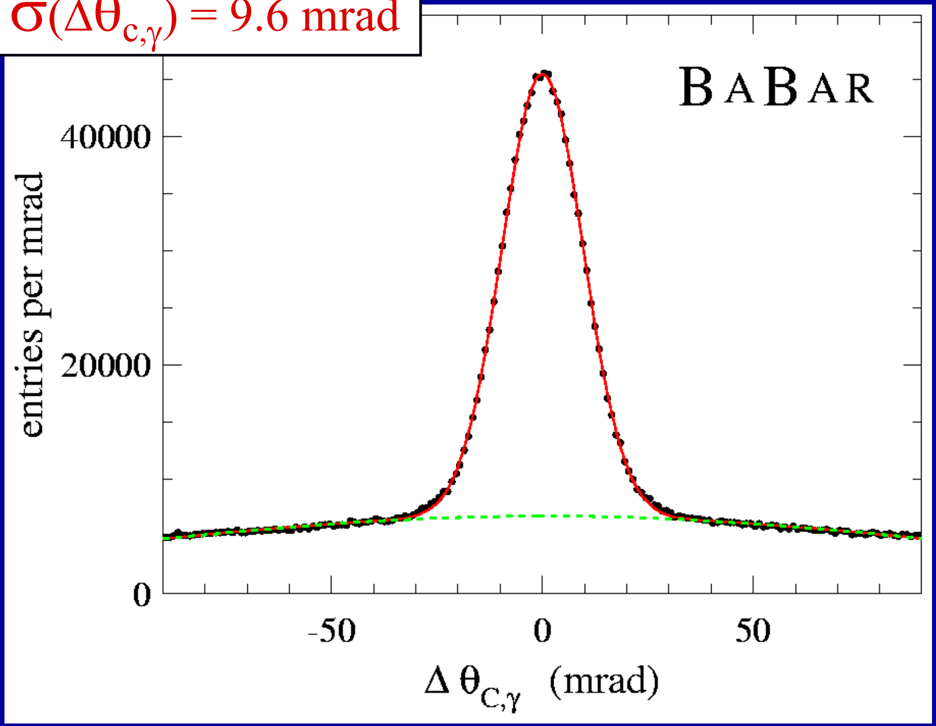
→ Time measurement essential in dealing with backgrounds.

[§]*Nucl. Instrum. Meth. A502 (2003) 67*

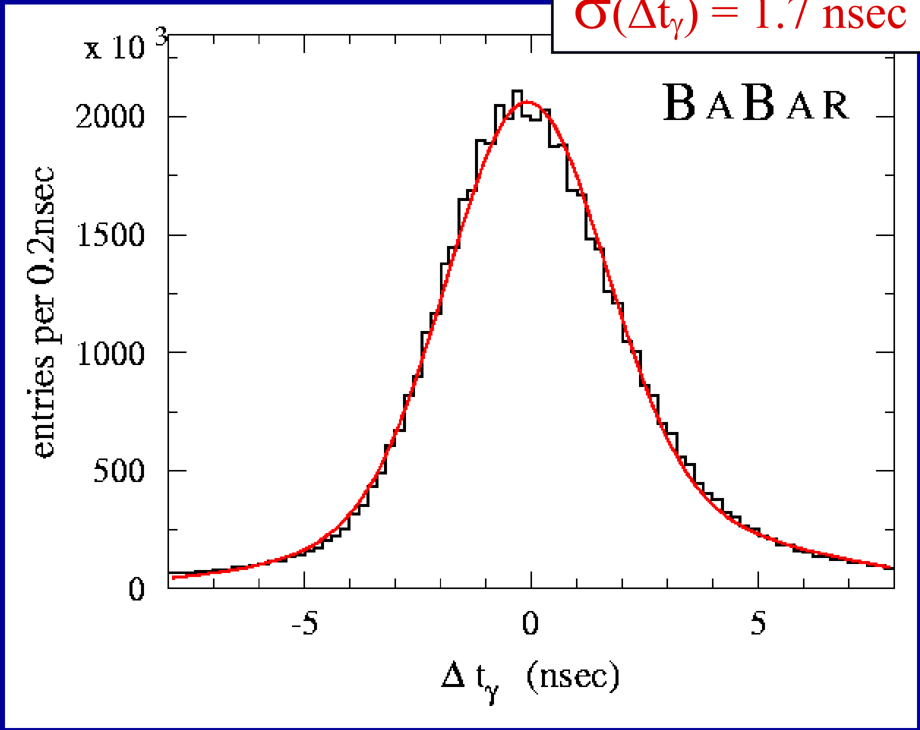
BABAR-DIRC Resolution

Single Photon resolution

$\sigma(\Delta\theta_{c,\gamma}) = 9.6$ mrad



$\sigma(\Delta t_\gamma) = 1.7$ nsec



$\Delta\theta_{c,\gamma}$: difference measured $\theta_{c,\gamma}$ per photon and expected track θ_c (di-muons)

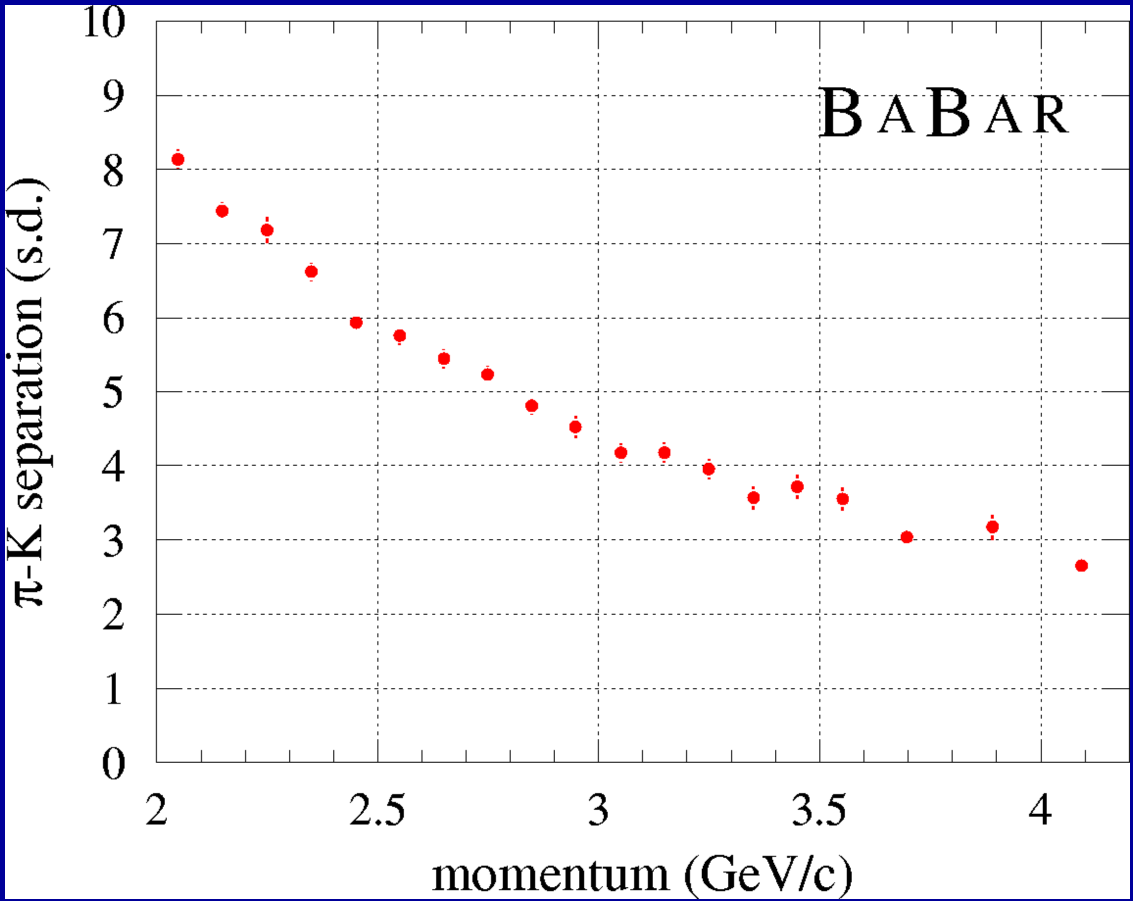
Δt_γ: difference between measured and expected photon arrival time

Nucl. Instrum. Meth. A502 (2003) 67

π/K separation power:

Measure Cherenkov angle resolution as function of track momentum for pions and kaons, kinematically identified in D* decays ($D^{*-} \to D^0 \pi^-$, $D^0 \to K^- \pi^+$).

→ about 4.3σ separation at 3GeV/c, close to 3σ separation at 4GeV/c



Nucl. Instrum. Meth. A502 (2003) 67

BABAR-DIRC Performance

Typical PMT hit rates: 200kHz/PMT *(few-MeV photons from accelerator interacting in water)*

Timing resolution: 1.7ns per photon *(dominated by transit time spread of ETL 9125 PMT)*

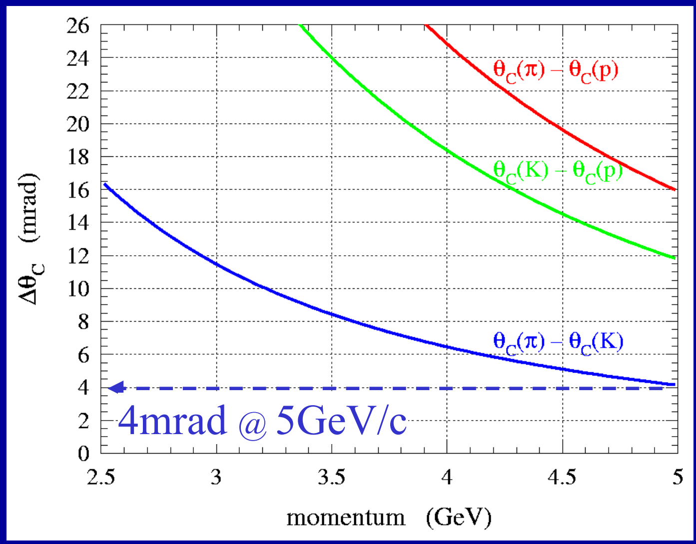
Photon yield: 18-60 photoelectrons per track *(depending on track polar angle)*

Cherenkov angle resolution: 9.6mrad per photon → 2.4mrad per track

Limited by	*BABAR-DIRC*	*Improvement strategy*
Size of bar image	~ 4.1mrad	Focusing optics
Size of PMT pixel	~ 5.5mrad	Smaller pixel size
Chromaticity (n=n(λ))	~ 5.4mrad	Better timing resolution

Focusing DIRC

→ Improve single photon timing and angular resolution, decrease size of Cherenkov ring expansion region

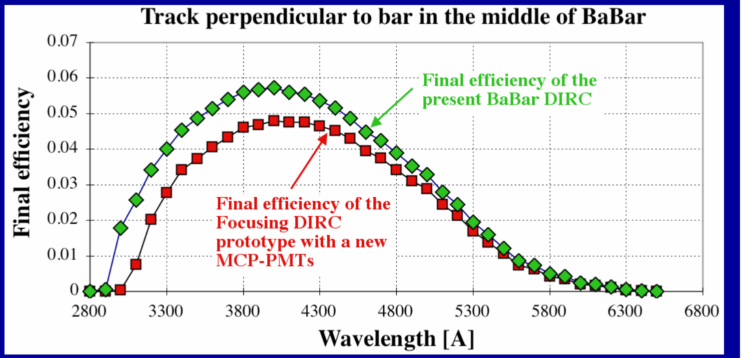


DIRC detector bandwidth

Defined by choice of photodetector, glue, medium in expansion region, and loss during photon propagation.

Optimization: smaller bandwidth →
fewer signal photons, smaller chromatic error

Typical DIRC bandwidth: λ=300…650nm, <λ>=410nm



Chromatic effect at Cherenkov photon production

Cherenkov photons produced according to $\cos\theta_c(\lambda) = 1/\beta n(\lambda)$

$n(\lambda)$: refractive (phase) index $n(\lambda)$=1.49…1.46

$\theta_c(\lambda)$: opening angle of Cherenkov cone $\theta_c(\lambda,\beta=1)$=835…815mrad

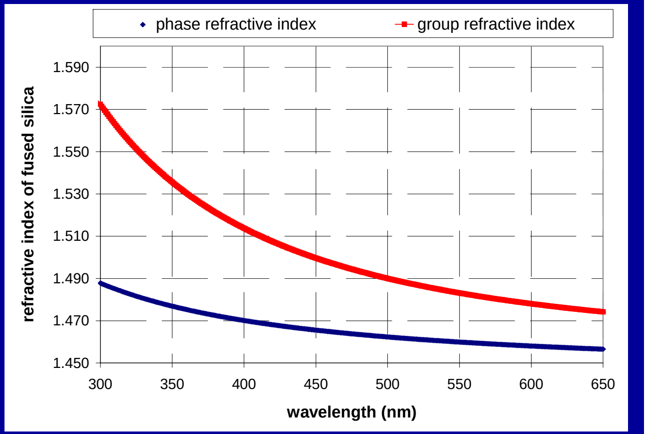
Chromatic time dispersion during photon propagation

Photons propagate in dispersive medium with group index $n_g(\lambda)$

time-of-propagation = path-in-bar $\cdot\, n_g(\lambda)/c_0$

$n_g(\lambda)$: group index $n_g(\lambda)$=1.57…1.47

Red photons propagate faster than blue photons



Photodetector Selection

Main criteria for selection

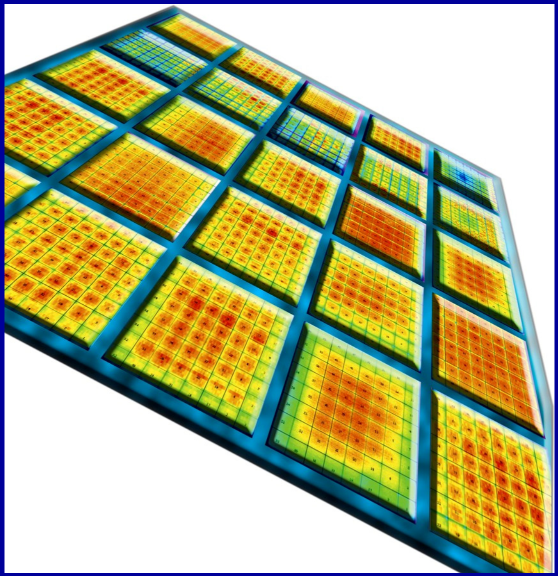
- Timing resolution
  timing resolution σ_t < 200ps required for chromatic correction
- Pixel size
  small pixels allow reduction of size of expansion region without compromising angular resolution
- Single photon efficiency
  need quantum efficiency ~20-30% and >70% packing efficiency to match BABAR-DIRC photon yield

Main candidates

- Burle 85011-501 MCP-PMT
- Burle 85011-430 MCP-PMT
- Burle 85021-600 MCP-PMT
- Hamamatsu H-8500 Multianode PMT
- Hamamatsu H-9500 Multianode PMT

Measure timing resolution, uniformity, and cross talk

- PiLas laser diodes (35ps FWHM, λ = 407 / 635 nm)
- Scan PiLas across PMT face using motion-controlled x&y stage (typical step size 200-500µm)



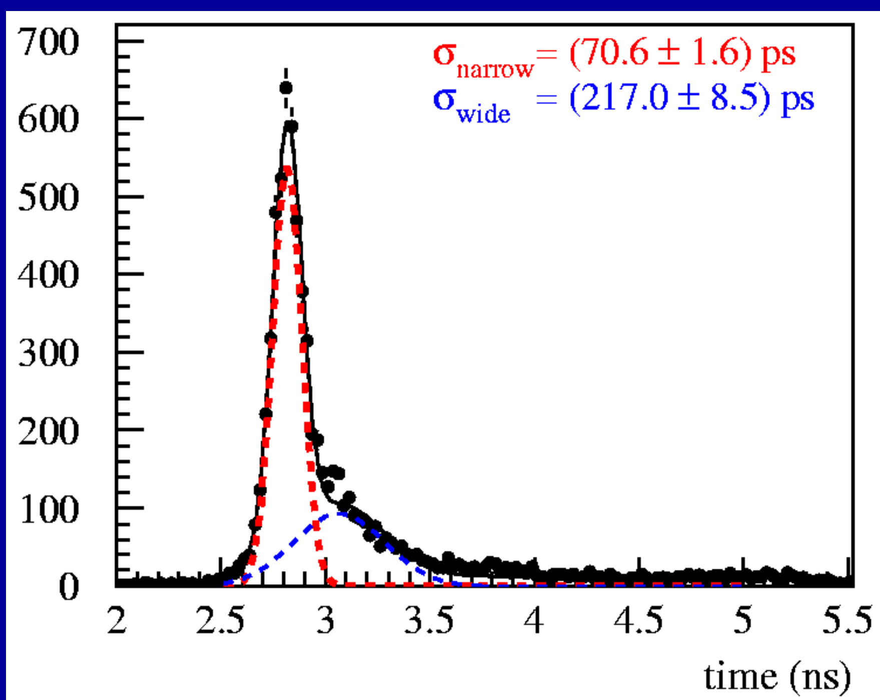
Compilation of 25 scans
different PMTs and wavelengths

Burle 85011-501

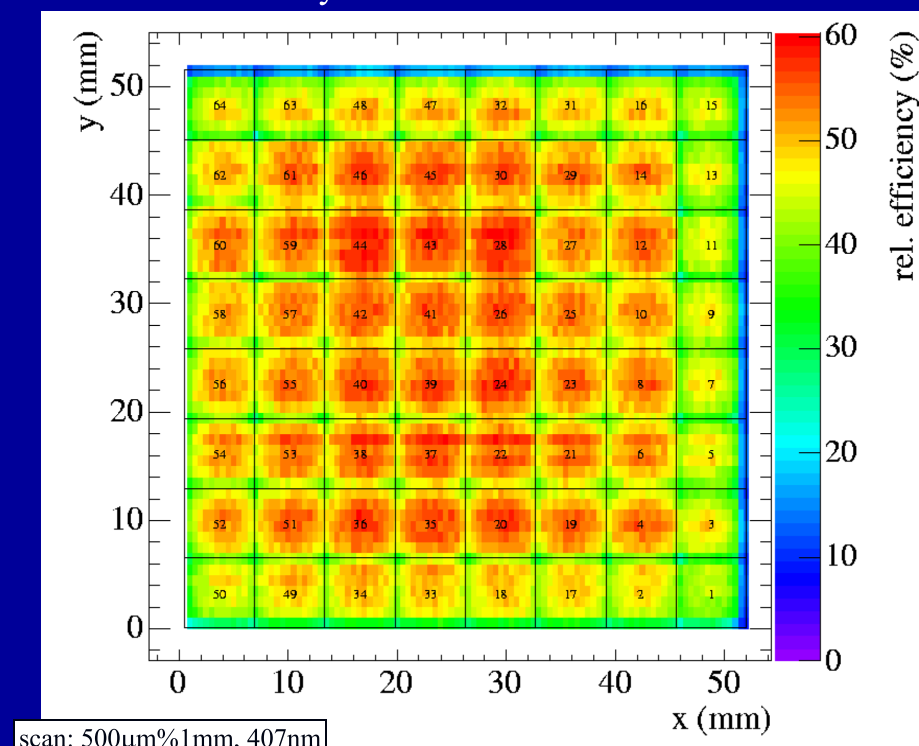
Burle 85011-501 MCP-PMT

- 64 pixels (8×8), 6.5mm pitch
- bialkali photocathode
- 25µm pore MCP, 6mm MCP-cathode distance
- gain ~5×10^5
- timing resolution ~70ps, distribution has tail
- good uniformity

→ IEEE NSS 2003



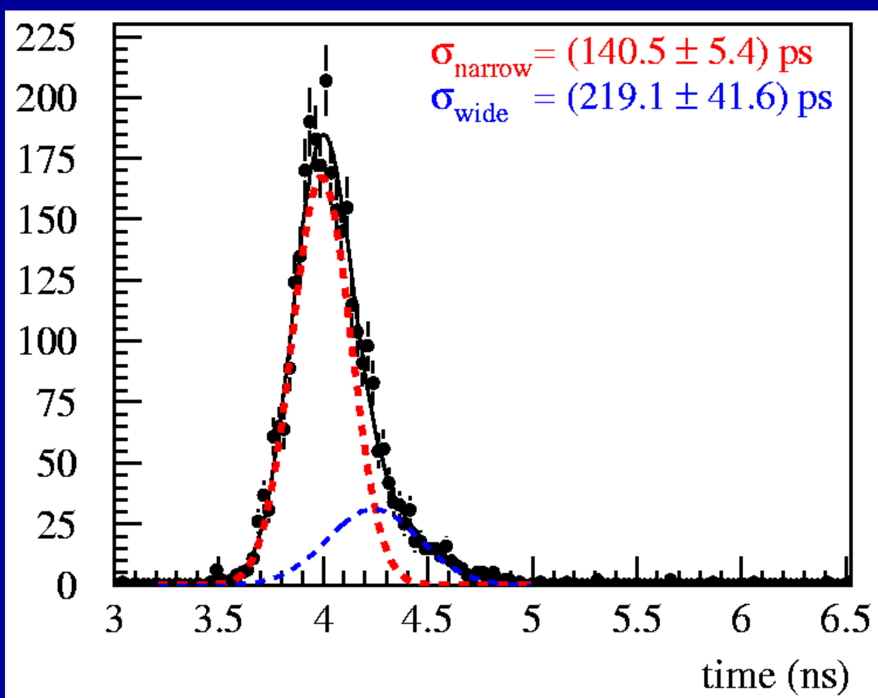
Efficiency relative to Photonis PMT



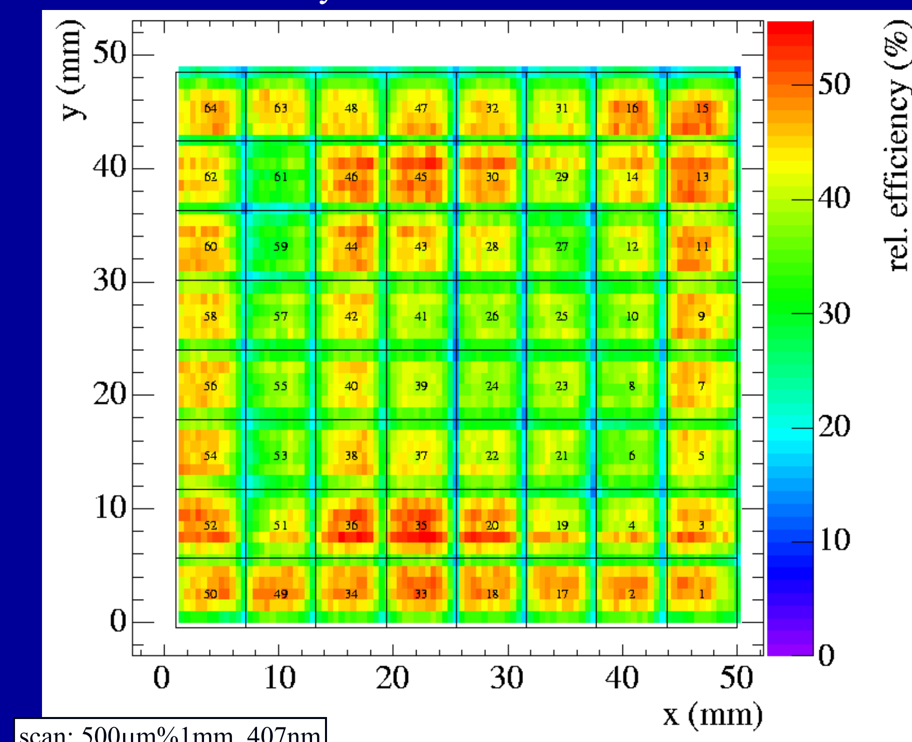
Hamamatsu H-8500 Flat Panel Multianode PMT

- 64 pixels (8×8), 6.1mm pitch
- bialkali photocathode
- 12 stage metal channel dynode
- gain ~10^6
- timing resolution ~140ps

→ IEEE NSS 2003



Efficiency relative to Photonis PMT



Detector Optics

Radiator

- use 3.7m-long bar made from three spare high-quality BABAR-DIRC bars
- use same glue as BABAR-DIRC (Epotek 301-2), wavelength cut-off at 300nm

Expansion region

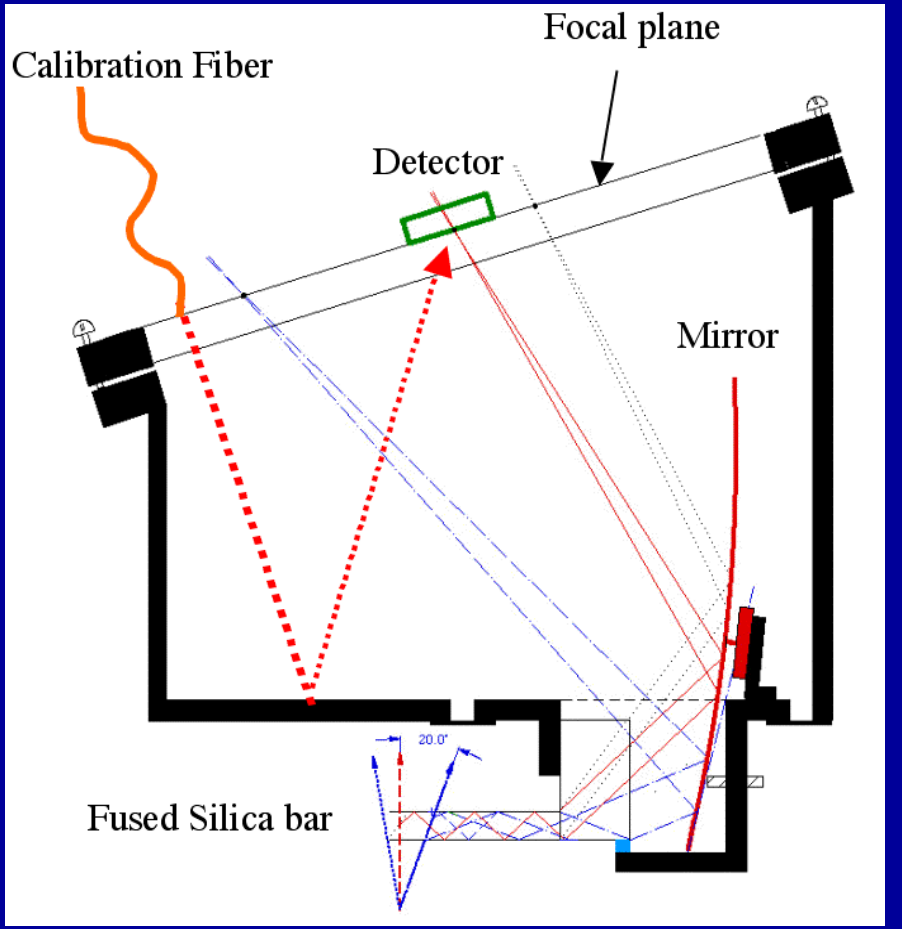
- use smaller stand-off distance (25% of BABAR-DIRC)
- coupled to radiator bar with small fused silica block (RTV SES-403)
- filled with mineral oil (KamLand experiment) to match fused silica refractive index
- include optical fiber for electronics calibration
- would ultimately like to used solid fused silica block

Focusing optics

- spherical mirror from SLD-CRID detector (focal length 49.2cm)

Photon detector

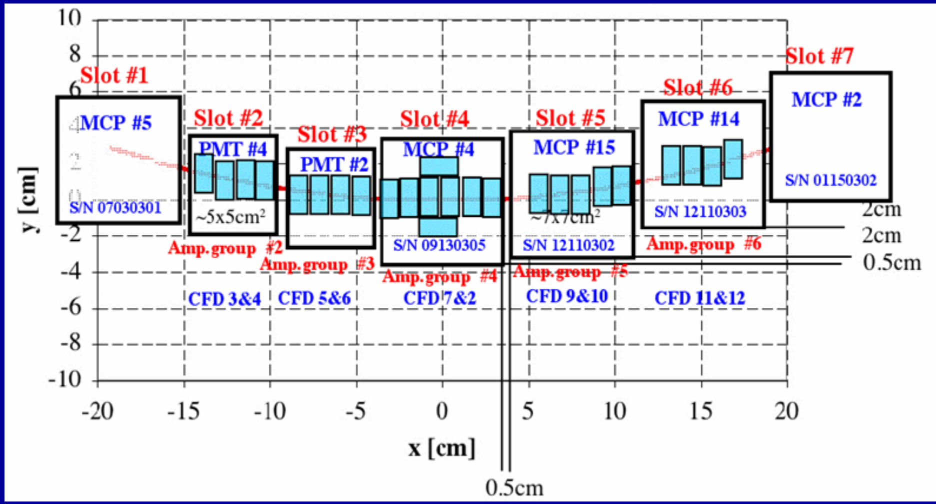
- use array of flat panel PMTs focal plane
- readout to CAMAC/VME electronics



Prototype Readout

For 2005 beam tests read out two Hamamatsu H-8500 MaPMTs and three Burle 85011-501 MCP-PMTs (total of 320 pixels)

- Elantec 2075EL amplifier (130x) on detector backplane
- SLAC-built constant fraction discriminator
- Ten Phillips 7186 TDCs (25ps/count) for 160 channels
- Four SLAC-built TDC boards: TAC & 12 bit ADC (~31ps/count) for 128 channels
- Read out only pixels close to expected hit pattern of Cherenkov photons *(155 pixels used in analysis shown today)*
- Calibration with PiLas laser diode (~35ps FWHM) to determine and monitor TDC channel delays and ps/count calibration



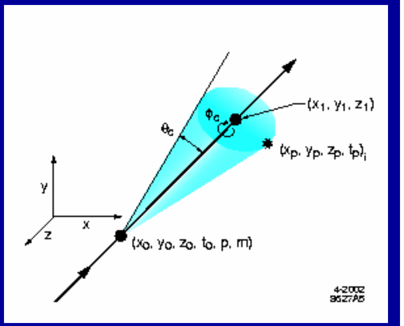
Photodetector coverage in focal plane

Reconstruction:

nice aspect of DIRC: geometry plus simple optics defines many photon properties

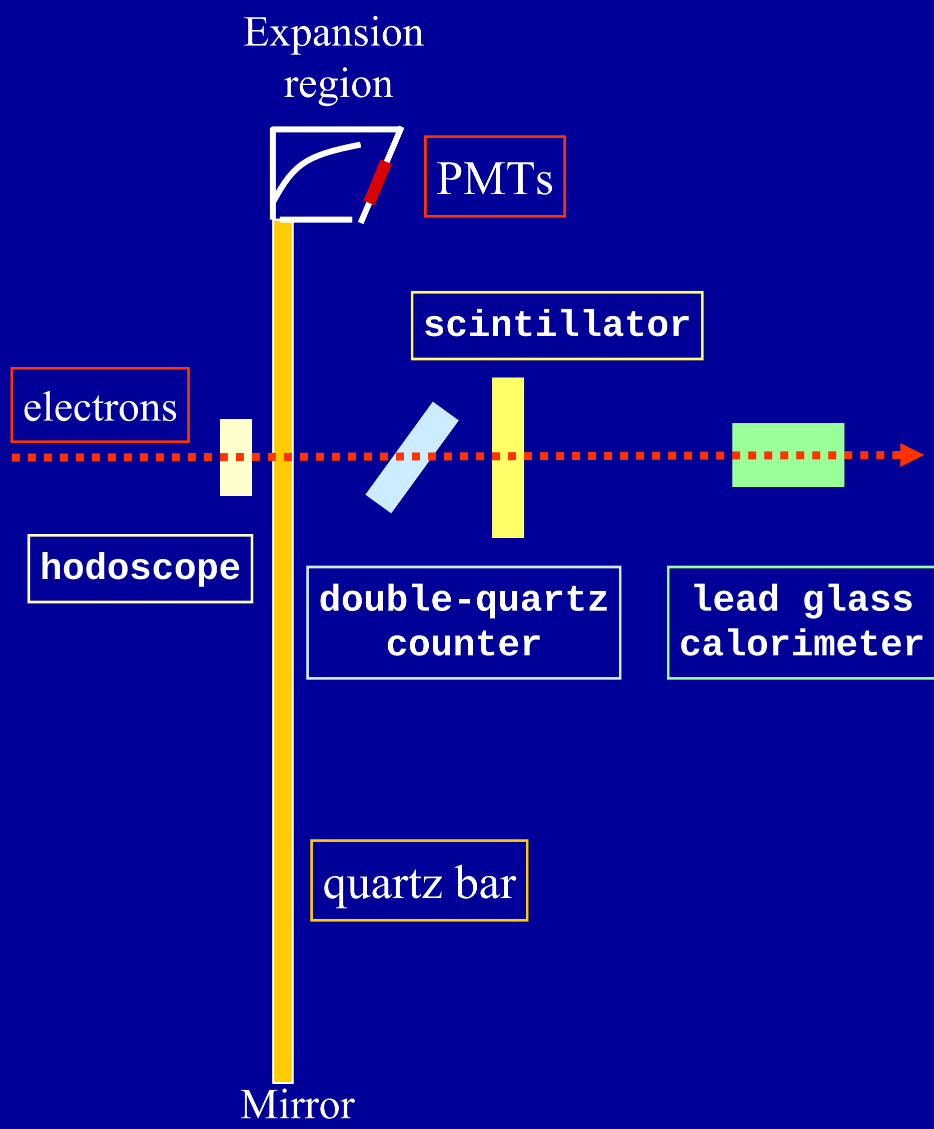
→ Pixel with hit (x_{det}, y_{det}, t_{hit}) defines 3D photon propagation vector in bar and Cherenkov photon properties *(assuming 90° track, β=1, <λ>=410nm)*

α_x, α_y, cos α, cos β, cos γ, L_{path}, $n_{bounces}$, θ_c, ϕ_c, $t_{propagation}$



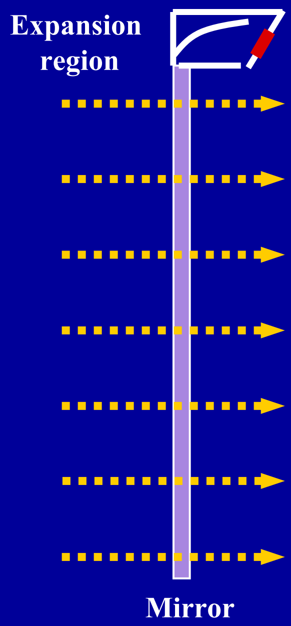
Beam Test Setup

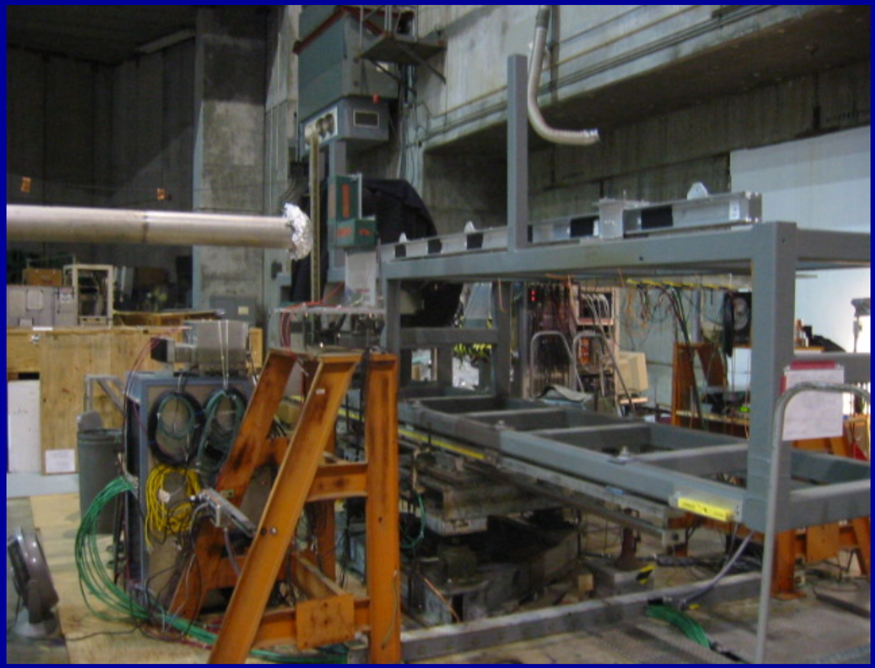
- Prototype located in beam line in End Station A at SLAC
- Accelerator delivers 10 GeV/c electron beam (e^-)
- Beam enters bar at 90º angle.
- 10 Hz pulse rate, approx. 0.1 particle per pulse
- Bar contained in aluminum support structure
- Beam enters through thin aluminum foil windows
- Bar can be moved along long bar axis to measure photon propagation time for various track positions
- Trigger signal provided by accelerator
- Fiber hodoscope (16+16 channels, 2mm pitch) measures 2D beam position and track multiplicity
- Cherenkov counter and scintillator measure event time
- Lead glass calorimeter selects single electrons
- All beam detectors read out via CAMAC (LeCroy ADCs and TDCs, Phillips TDC, 57 channels in total)

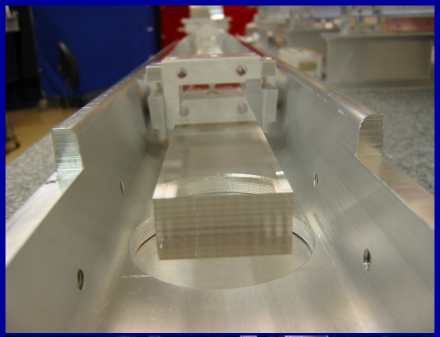


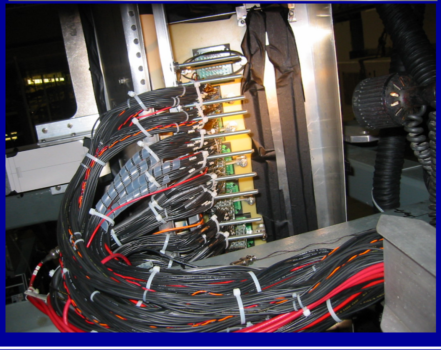
Beam Test Data

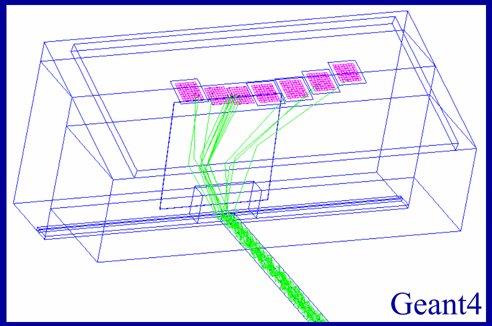
- In July, August, and November 2005 we took beam data during five periods, lasting from few hours to several days.
- Total of 4.1M triggers recorded, 10 GeV/c e^-
- Reconstructed ~200k good single-track events
- Beam entered the radiator bar in 7 different locations.
- Recorded between 100k and 700k triggers in each beam location.
- Photon path length range: 0.75m – 11m.
- Simulated full detector with all efficiencies in Geant4.

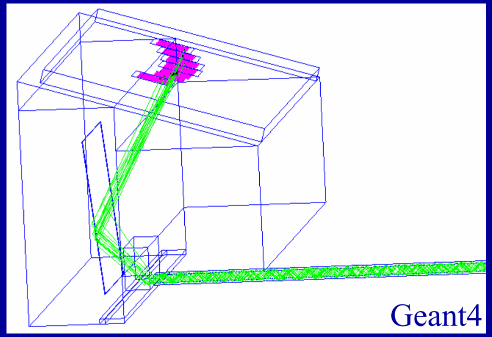










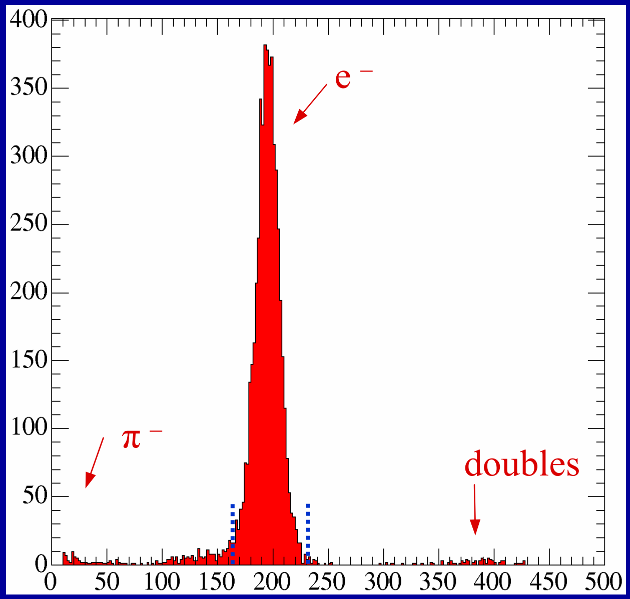


Beam Detectors

Event selection:

- require single track signal in hodoscope
- require charge in lead glass to be consistent with single electron
- require start counter TDC signal in expected time window

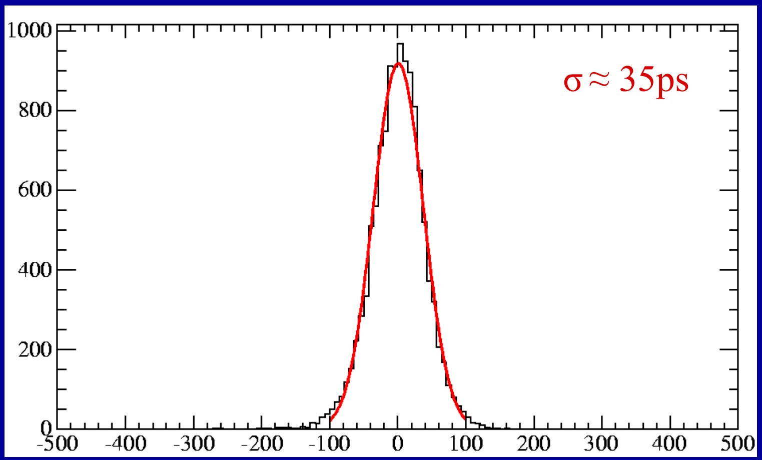
Lead glass: single track ADC distribution



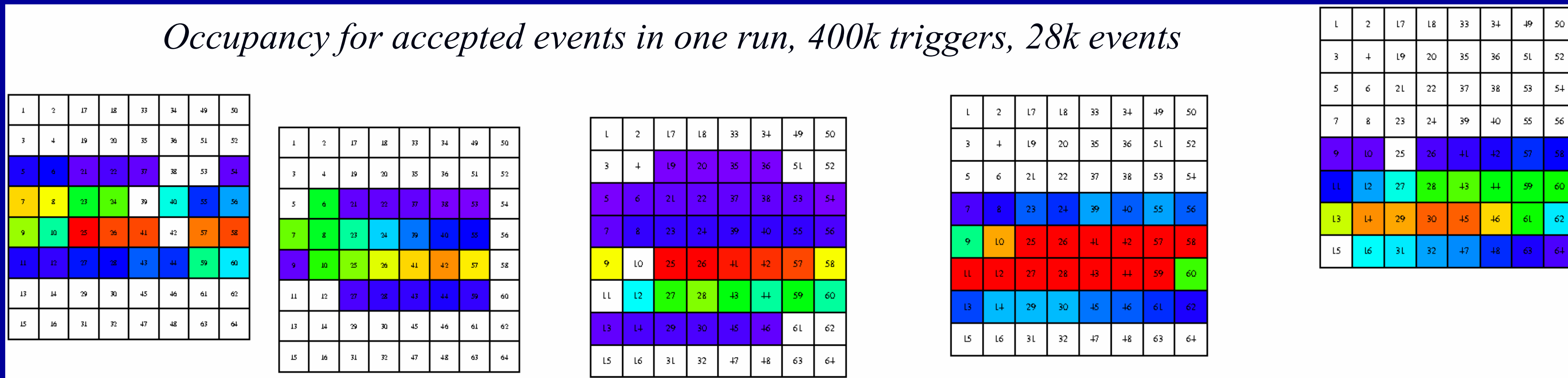
Data corrections:

- use hodoscope beam spot to correct the path of photons in bar
- use ADC measurement in start counters to correct TDC value for time walk
  → resulting start counter resolution ~35ps
- use PiLas laser diode to calibrate prototype TDCs and cable delays
  → all pixels aligned in time

Start counters: corrected event time



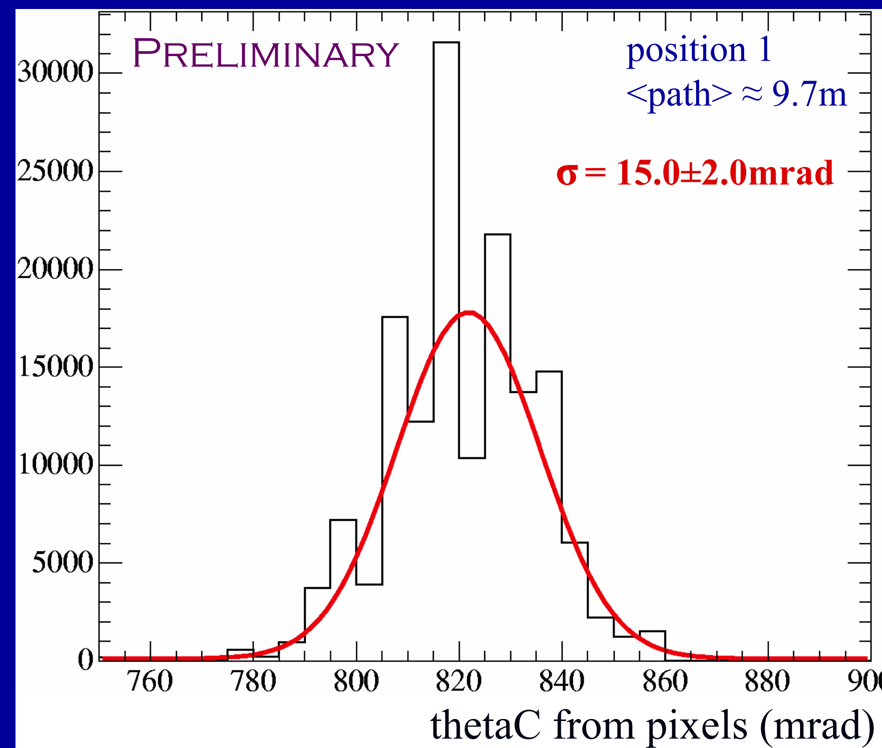
Occupancy and Cherenkov Angle



Occupancy for accepted events in one run, 400k triggers, 28k events

Cherenkov angle for all pixels with signal

- Have to assign angles to pads assuming that photons hit center of pad *(single photons, no center-of-gravity interpolation possible)*
- clear pixelization effect visible, θ_c resolution ≈ 14-16mrad (total pixel size ≈ 21mrad in θ_c space)
- θ_c resolution from pixels worse than expected, should improve with better alignment *(plus systematic checks of hardware, calibration, and software)*



Time Measurement

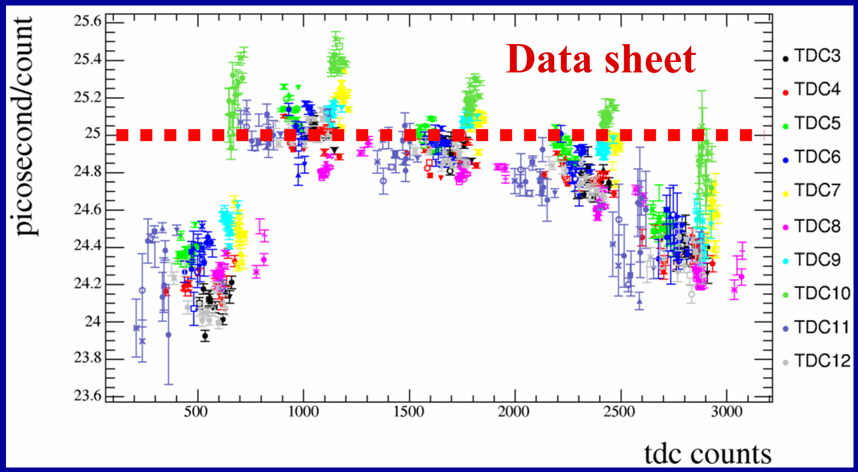
Precise timing at 50ps level requires

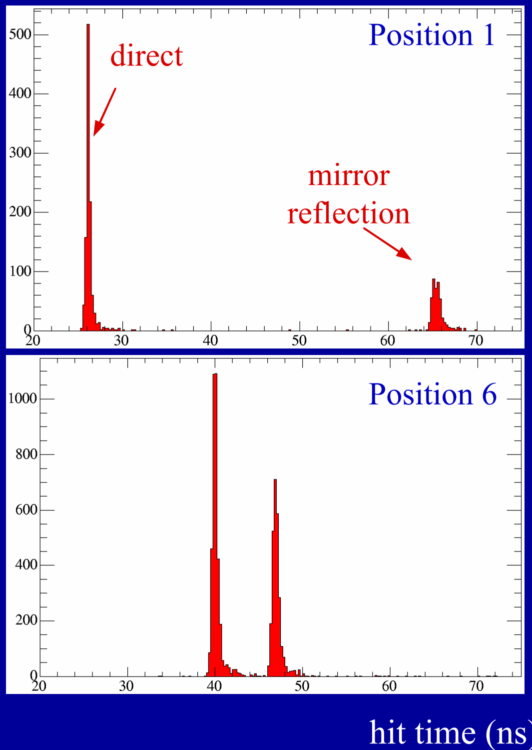
- careful calibration of TDC conversion factor
  Phillips 7186: nominal 25ps/count,
  varies across measurement range
- monitoring of electronics delays
  to correctly align pixels in time space
  temperature variations in hall matter
- use accelerator trigger signal as event time
  and monitor event time using
  start counter (35ps resolution)
- correction for charge-sharing and cross talk

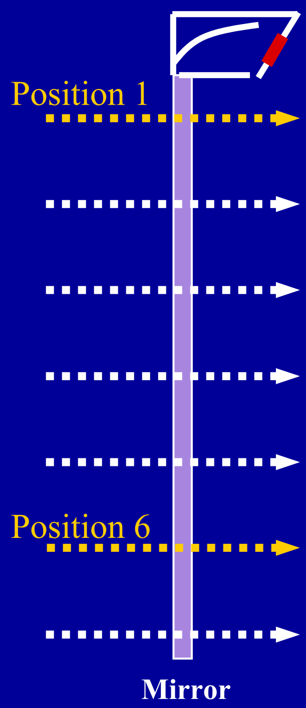
Challenging task, PiLas calibration system
very important

Results shown today do not have
final calibrations and delays yet

PiLas calibration of 10 Phillips 7186 TDCs





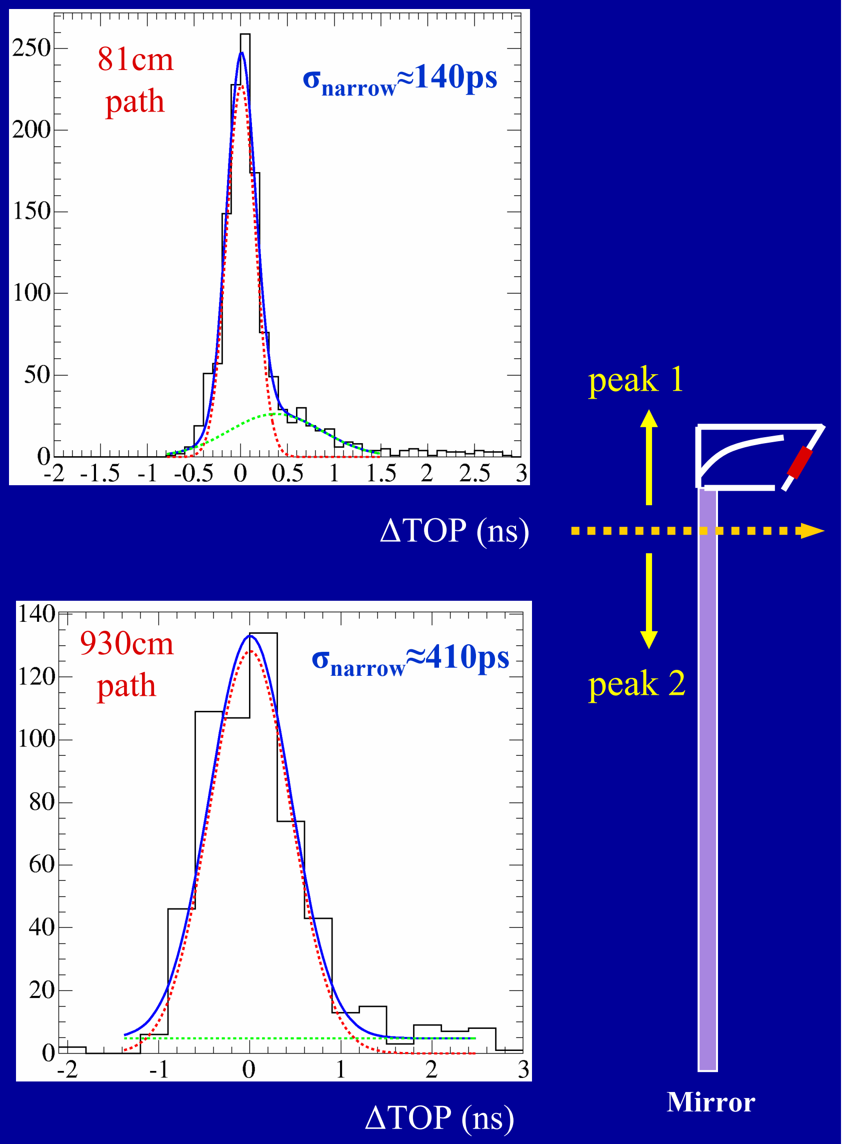


Chromatic Broadening

→ IEEE NSS 2005

Example for one selected detector pixel
in position 1

- First peak ~81cm photon path length
- Second peak ~930cm photon path length
- Measure time of propagation (TOP)
- Calculate expected TOP
  assuming average <λ>≈410nm
- Plot ΔTOP: measured minus expected
  time of propagation
- Fit to double-Gaussian
- Observe clear broadening of timing peak for
  mirror-reflected photons

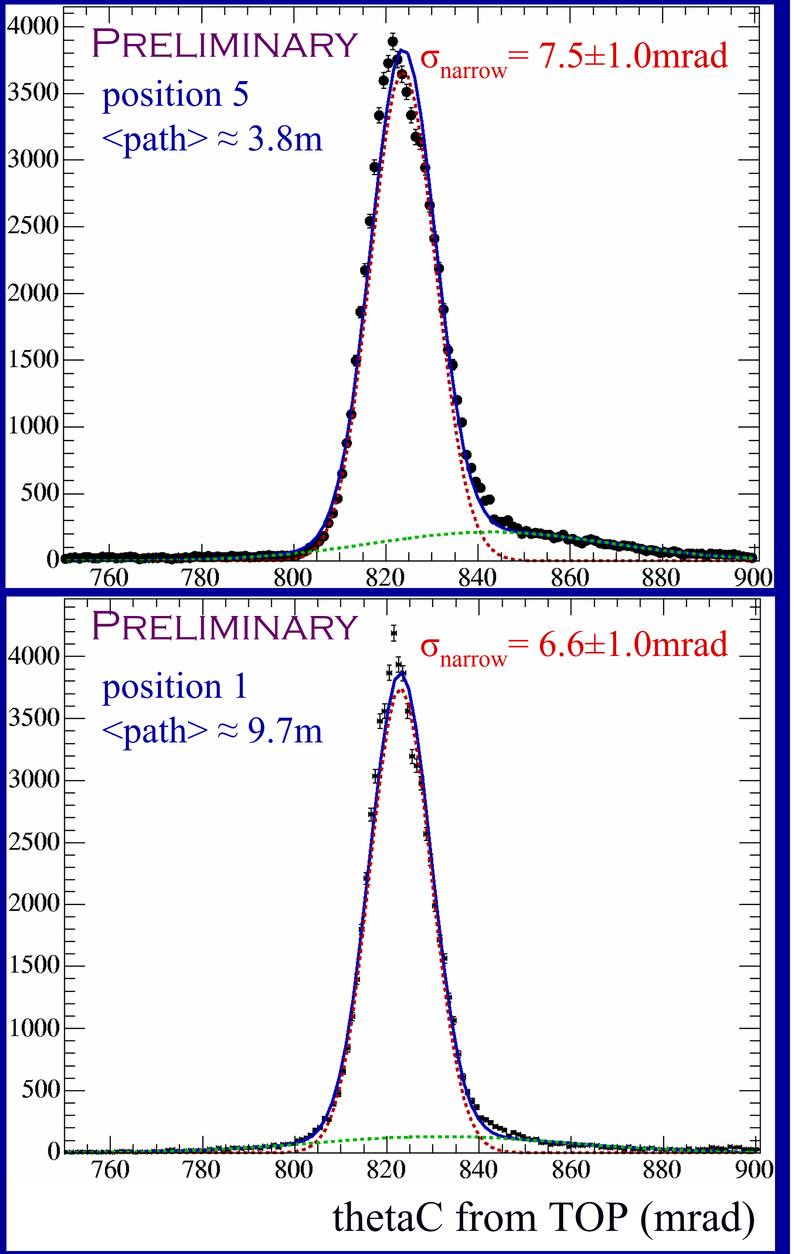


Cherenkov Angle from Time

Cherenkov angle from time of propagation (TOP)

- Use measured TOP for each pixel
- Combine with calculated photon path in radiator bar
- Calculate group index $n_g(\lambda)$ from $n_g(\lambda) = c_0 \cdot \text{TOP} / \text{path}$
- Calculate refractive (phase) index $n(\lambda)$ from group index
- Calculate photon Cherenkov angle θ_c for $\beta=1$ $\theta_c(\lambda) = \cos^{-1}(1/n(\lambda))$

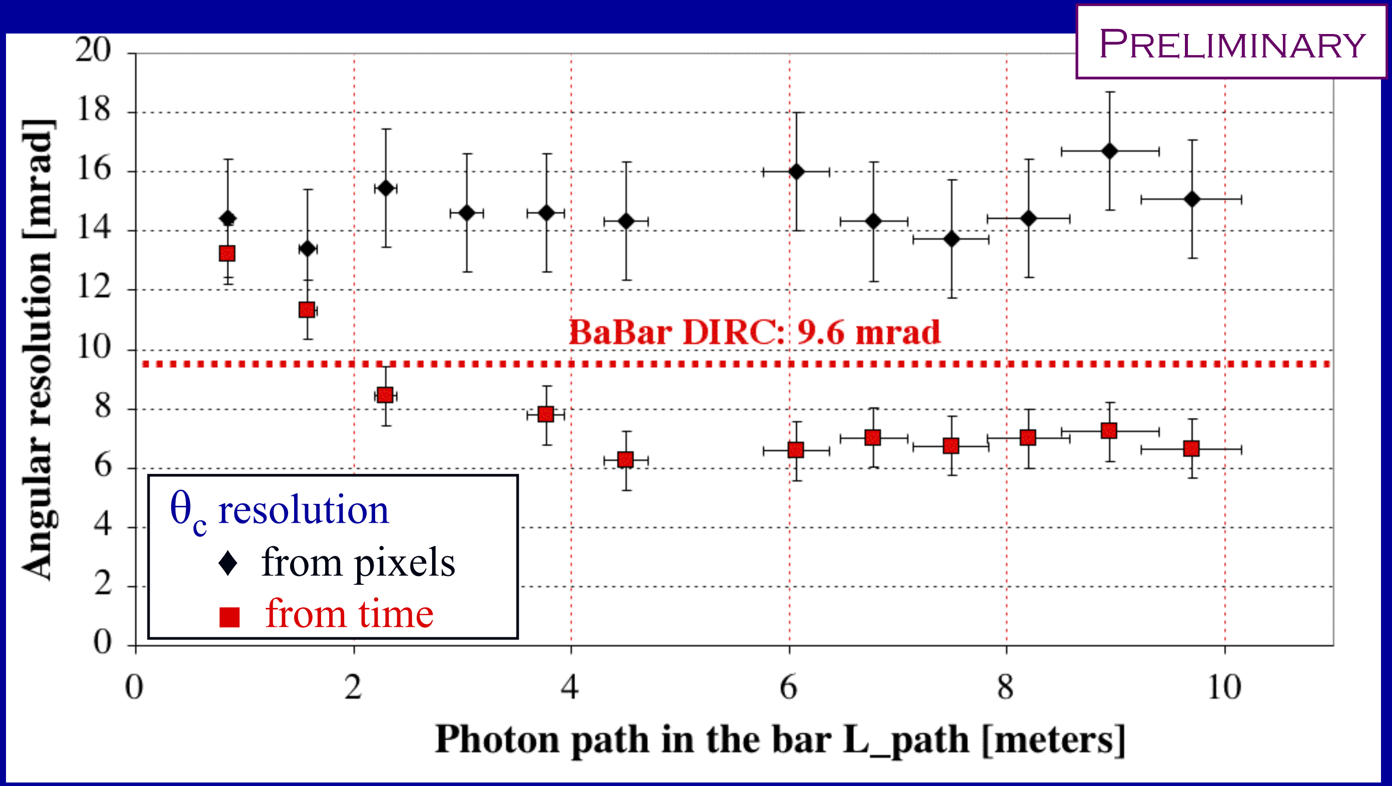
- Resolution of θ_c from TOP is 6-7mrad for photon path length above ~4m.
- Expected to improve with better calibration.



Cherenkov Angle Resolution

Summary of preliminary results

- θ_c resolution from pixels is 14-16mrad for entire range.
- θ_c resolution from time of propagation improves rapidly with path length, reaches plateau at 6-7mrad after approx. 4m photon path in bar.
- Next steps: complete calibration and systematic checks, attempt correction of chromatic production term.



Plan for Future Prototype Tests

Next beam test of prototype is planned for summer 2006

- plan to add new photon detectors:
  - new 1024 pixel Burle MCP-PMT
  - new 256 pixel Hamamatsu Multianode PMT
  - new small cathode-to-MCP gap 64 pixel Burle MCP-PMT

- 256/1024 pixel PMTs will have modified readout
  combining pixels into 4×16 pseudo-pixels, 64 channels
  → provide finer segmentation in vertical direction
  → minimize pixelization effects, provide better
  θ_c resolution from pixels for chromatic correction.

- possibly add a second fiber hodoscope behind prototype
  to reject tracks with large scattering angle in bar

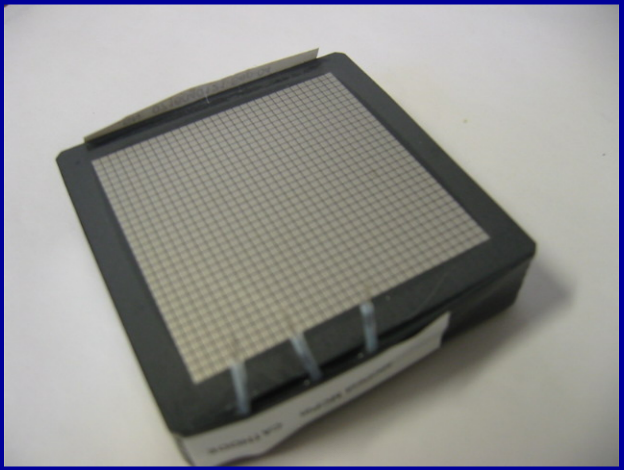
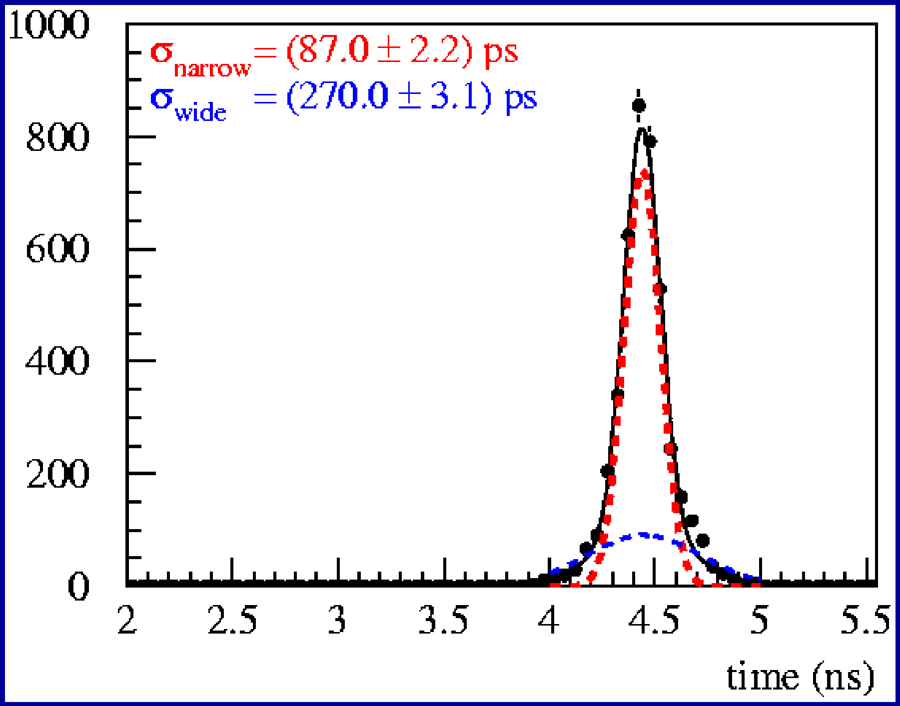


Photo of new 1024 pixel
Burle 85021-600 MCP-PMT

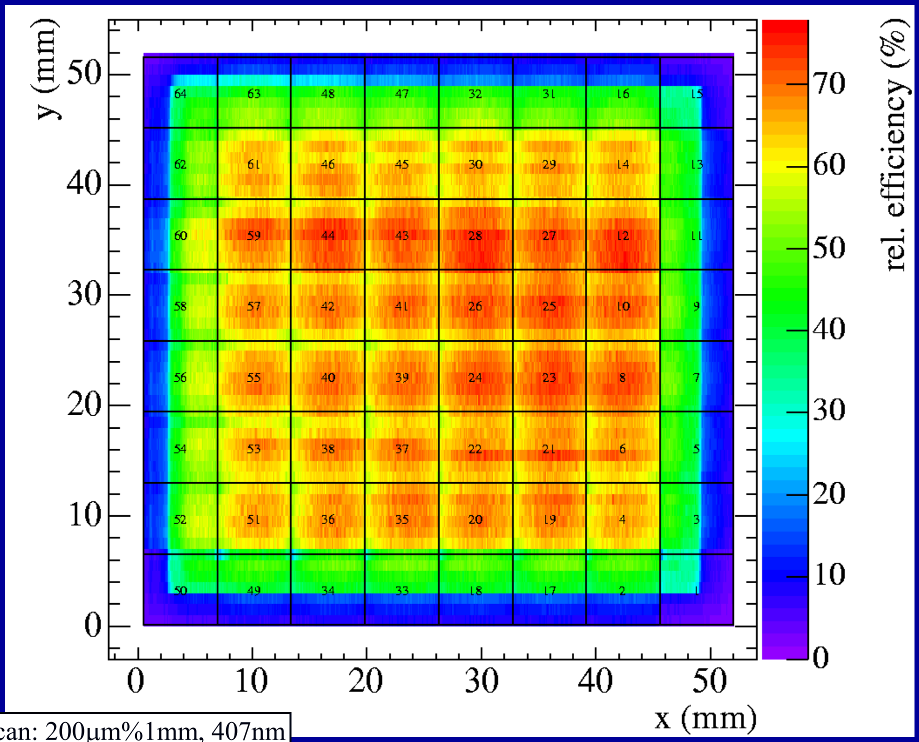
Burle 85011-430 MCP-PMT

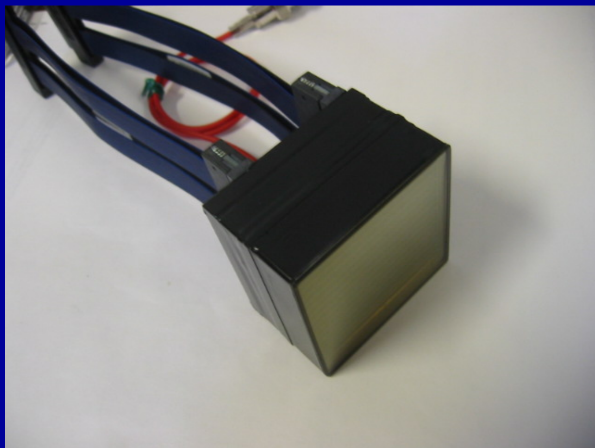
- 64 pixels (8×8), 6.5mm pitch
- bialkali photocathode
- 25µm pore MCP, small 0.75mm MCP-cathode distance
- gain ~5×10^5
- timing resolution ~90ps, much smaller tail
- OK uniformity

→ IEEE NSS 2004



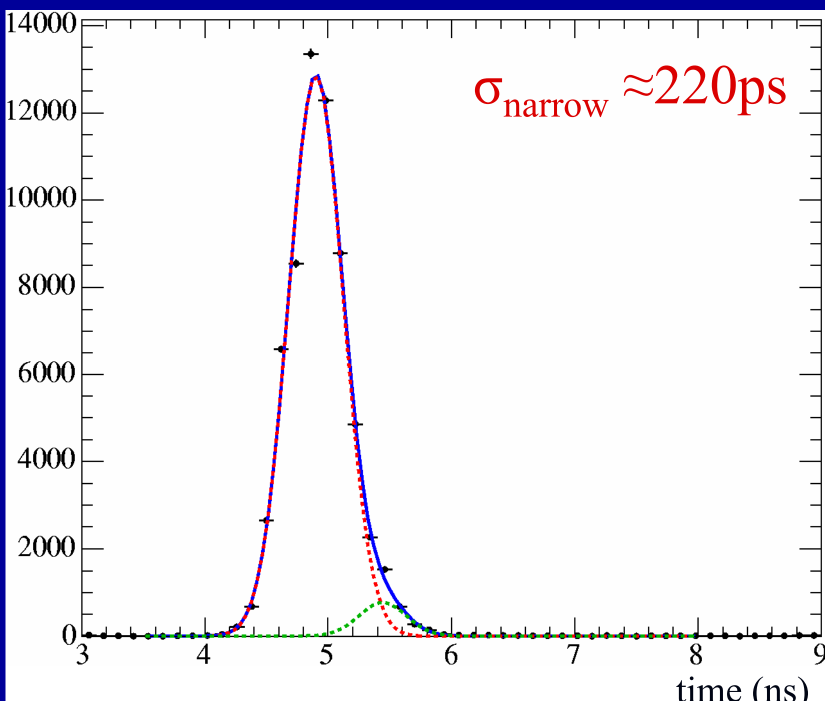
Efficiency relative to Photonis PMT



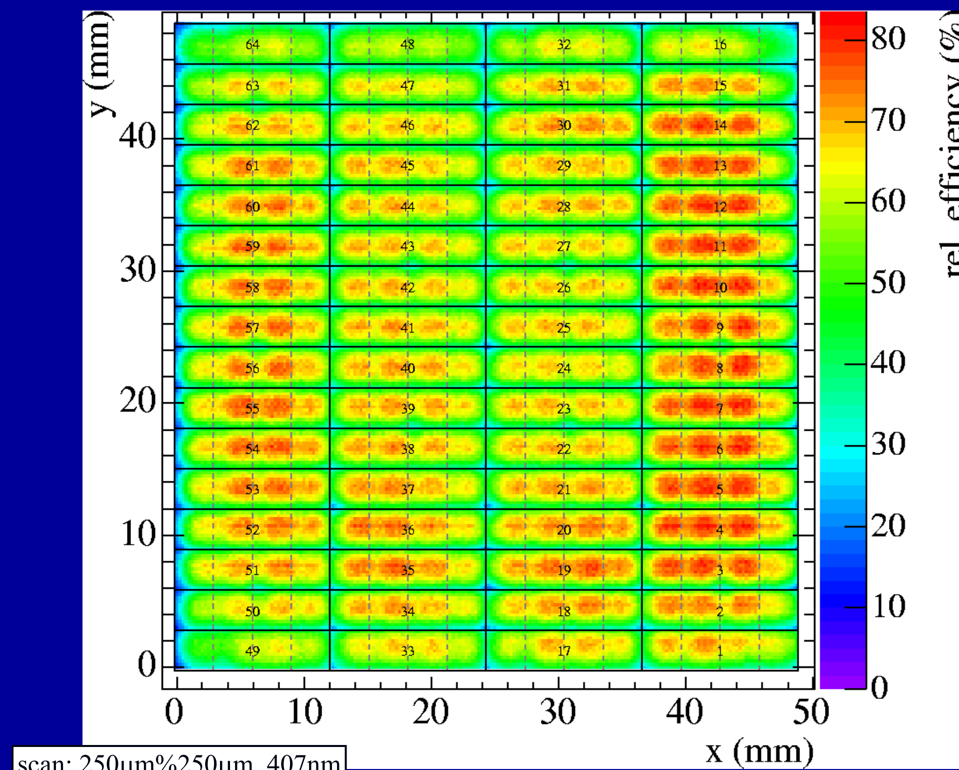


Hamamatsu H-9500 Flat Panel Multianode PMT

- bialkali photocathode
- 12 stage metal channel dynode
- gain ~10^6
- typical timing resolution ~220ps
- 256 pixels (16×16), 3 mm pitch
- custom readout board – read out as 4×16 channels

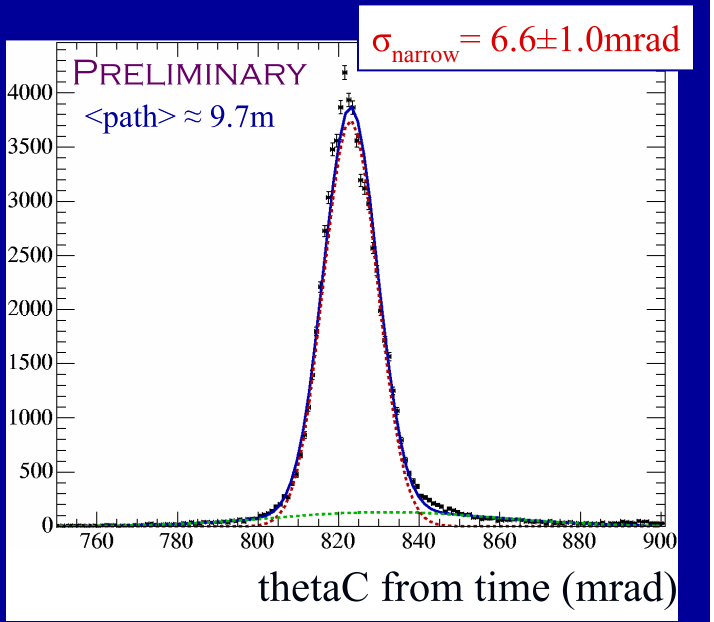


Efficiency relative to Photonis PMT



SUMMARY

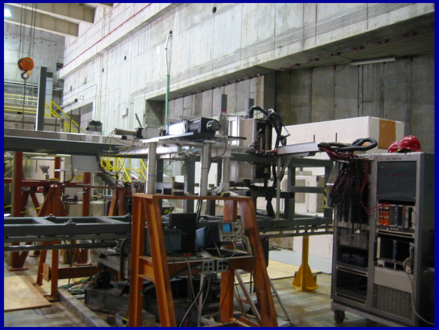
- Six years of experience in PEP-II/BABAR B-factory mode: DIRC successful, very reliable, robust, easy to operate, plays significant role in almost all BABAR physics analyses.
- Focusing DIRC R&D has identified several PMT candidates capable of delivering timing resolution of <140ps with good uniformity and efficiency.
  Remaining questions include: behavior in magnetic fields, aging, rate capability.
- Focusing DIRC prototype is a challenging detector, requiring new approaches to calibration, monitoring, software design, etc.
- 3D readout makes system more complex but also more robust, helps with backgrounds and calibrations. Redundancy makes correction of chromatic production error possible.
- Test beam data for prototype show interesting initial results
  - Timing resolution sufficiently good to determine θ_c with precision better than BABAR-DIRC resolution.
  - $\sigma(\theta_c) \approx 6 - 7$mrad for photon path > 4m
- We are looking forward to the next beam test run with an improved prototype this summer.



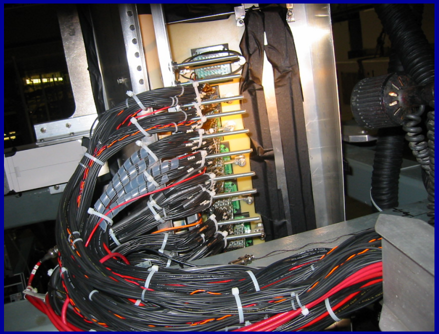
Extra Material

Beam Test Setup

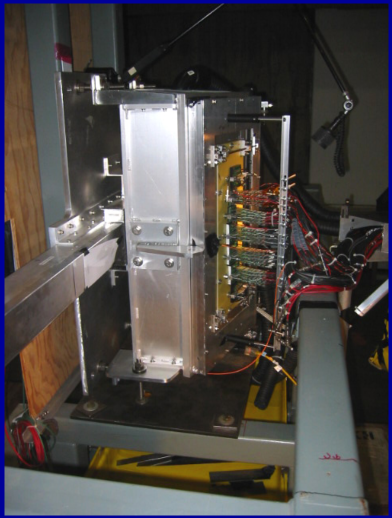
Setup in End Station A: movable bar support and hodoscope



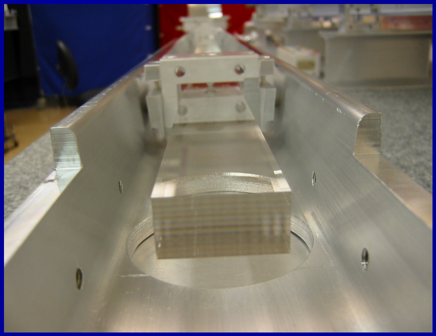
Setup in End Station A



Photodetector backplane

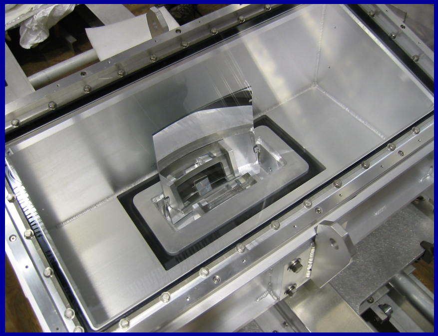


Electronics and cables



Radiator bar

Mirror



Oil-filled detector box:

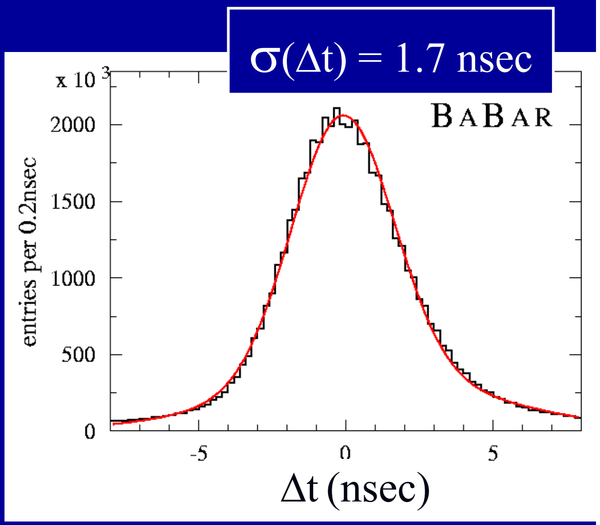
Start counters, lead glass

Time information provides powerful tool to reject accelerator and event related background.

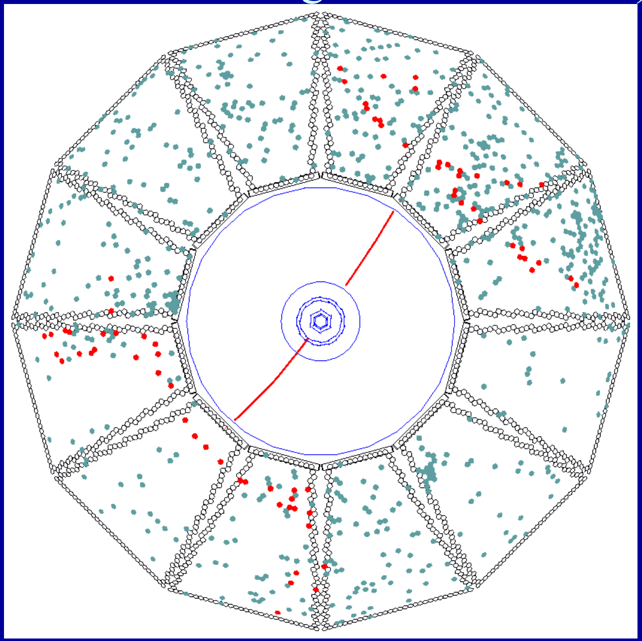
Calculate expected arrival time of Cherenkov photon based on

- track TOF
- photon propagation in radiator bar and in water

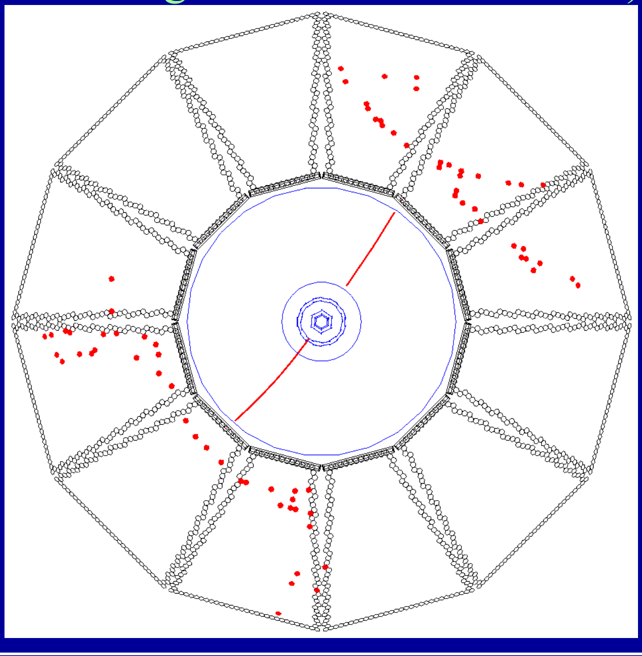
Δt: difference between measured and expected arrival time



± 300 nsec trigger window (~500-1300 background hits/event) → ± 8 nsec Δt window (1-2 background hits/sector/event)



→



Thanks to the BABAR-DIRC group for the plots.

Photon detector Scans

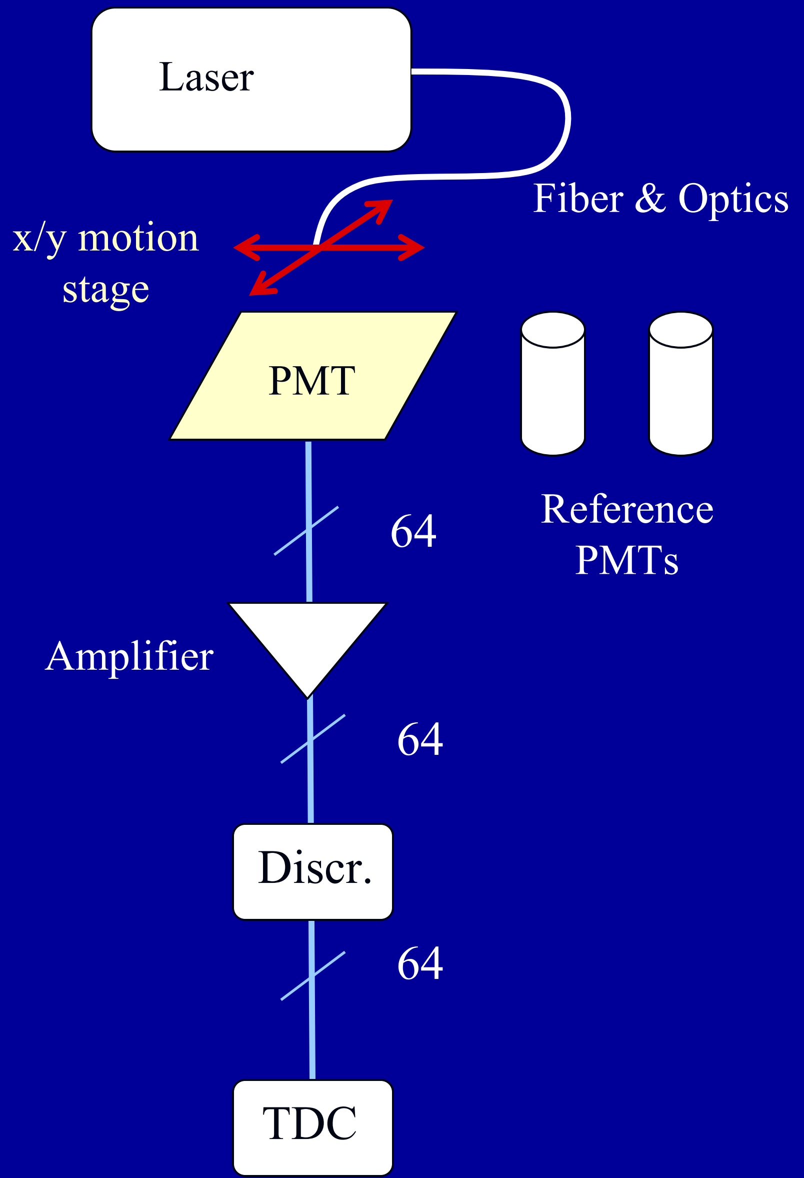
Light source
- PiLas pico-second laser
- λ = 407 nm or λ = 635 nm
- FWHM pulse < 35 ps
- Operated in single photon mode

Motion Controller
- GPIB bus, positioning repeatability <7µm

Laser Intensity Monitoring
- Two conventional PMTs for monitoring
- Photonis XP2262B, ETL 9125FLB17

Amplifiers
- Elantec 130× voltage gain, 2 GHz bandwidth

Readout
- SLAC-built constant fraction discriminator
- Phillips 7186, 25 ps per count TDC
- CAMAC based readout, linux PC



→ IEEE NSS 2003

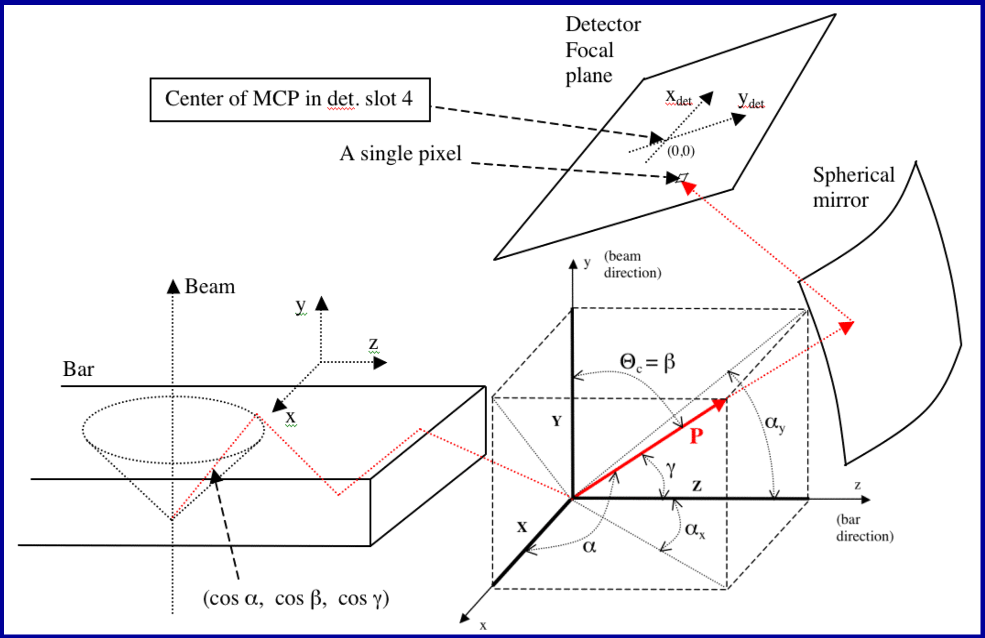
DIRC Reconstruction

Precisely measured detector pixel coordinates and beam/track parameters

→ Pixel with hit (x_{det}, y_{det}, t_{hit}) defines 3D photon propagation vector in bar and Cherenkov photon properties *(assuming average wavelength)*

α_x, α_y, cos α, cos β, cos γ, L_{path}, $n_{bounces}$, θ_c, ϕ_c, $t_{propagation}$

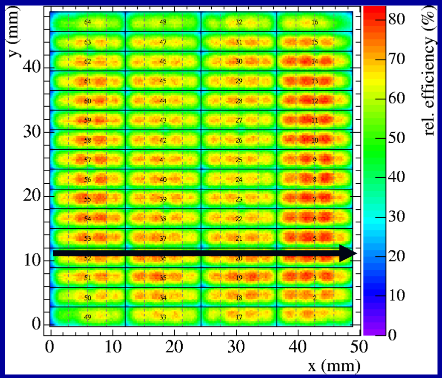
Use GEANT4 simulation and stand-alone ray-tracing software to obtain propagation vector for each pixel.

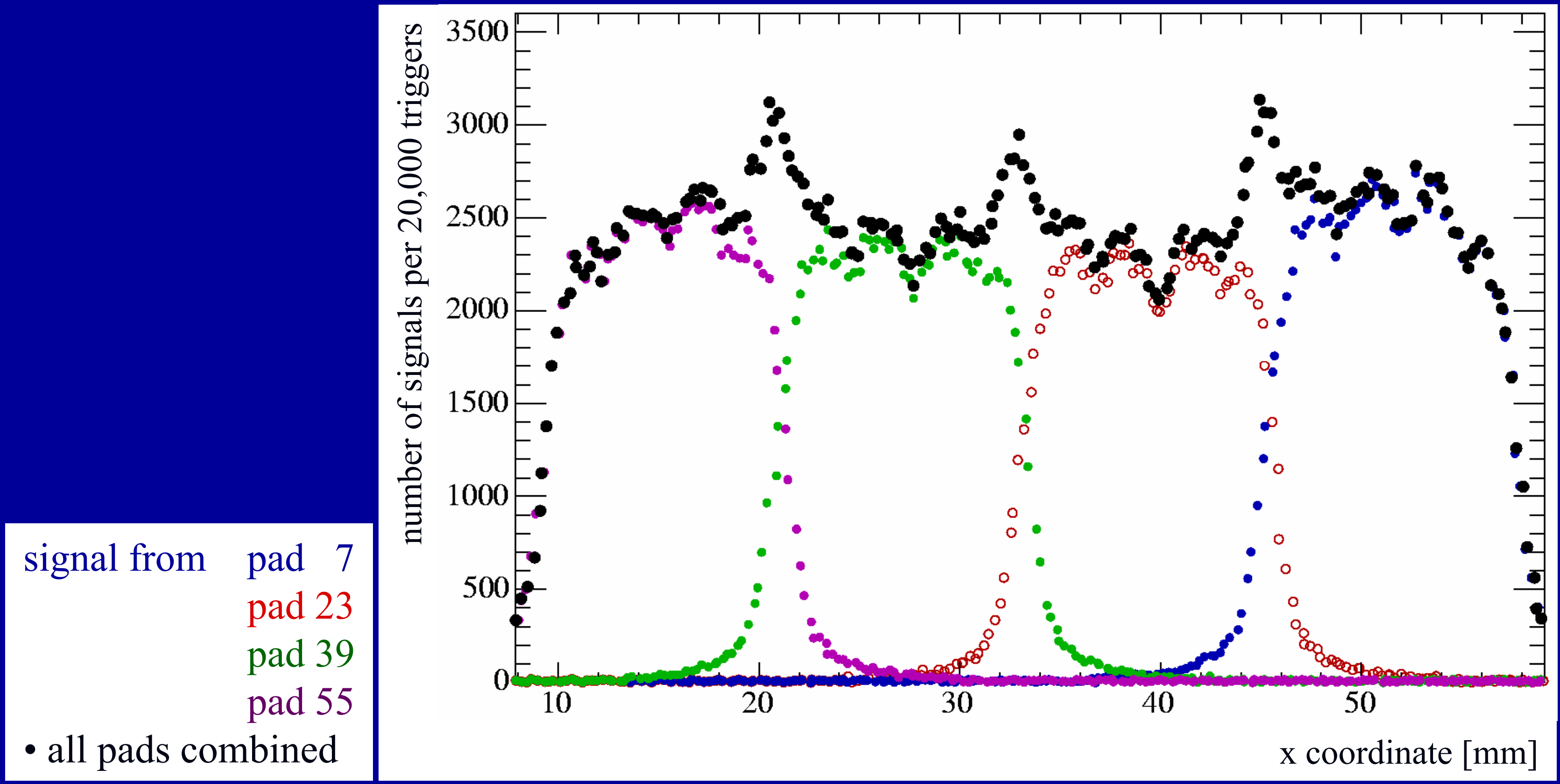


→ IEEE NSS 2005

Charge can be shared between anode pads if the photon hits close to the boundary between pixels.

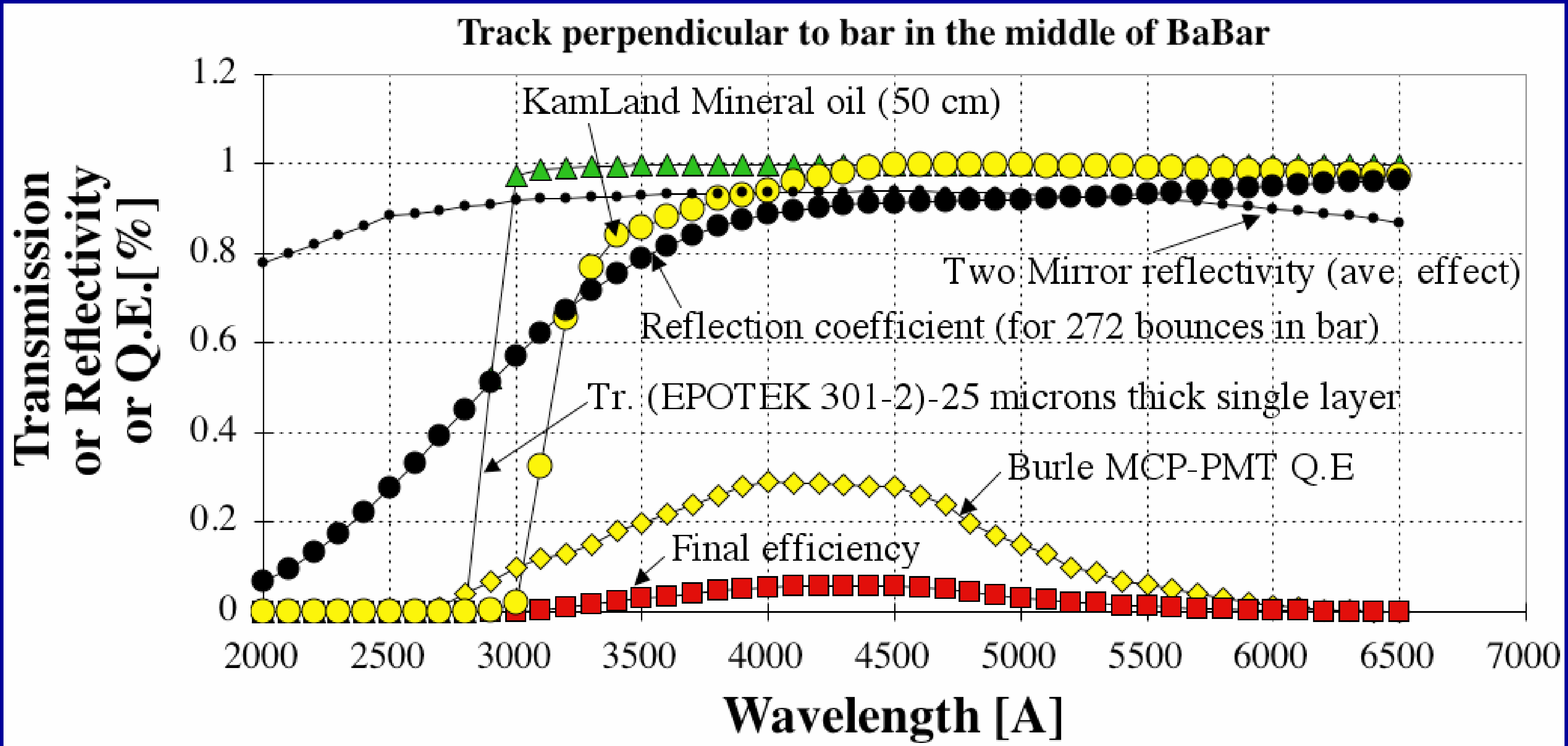
If signals are detected simultaneously on two or more neighboring pads this signature can be used to constrain the photon hit position more precisely and improve thetaC resolution.





Various Efficiencies in the Focusing DIRC

Spreadsheet calculation:



- Assume: "Focusing DIRC prototype-like" DIRC is in the present BaBar.
- Burle QE peaks at higher wavelength than the Hamamatsu MaPMT or ETL PMT.

→ RICH 2004

Chromatic Effects

Compare measured resolution from time of propagation to expected resolution

model assumes 90° track angle and Focusing DIRC bandwidth

→ SLAC-J-ICFA-22-2

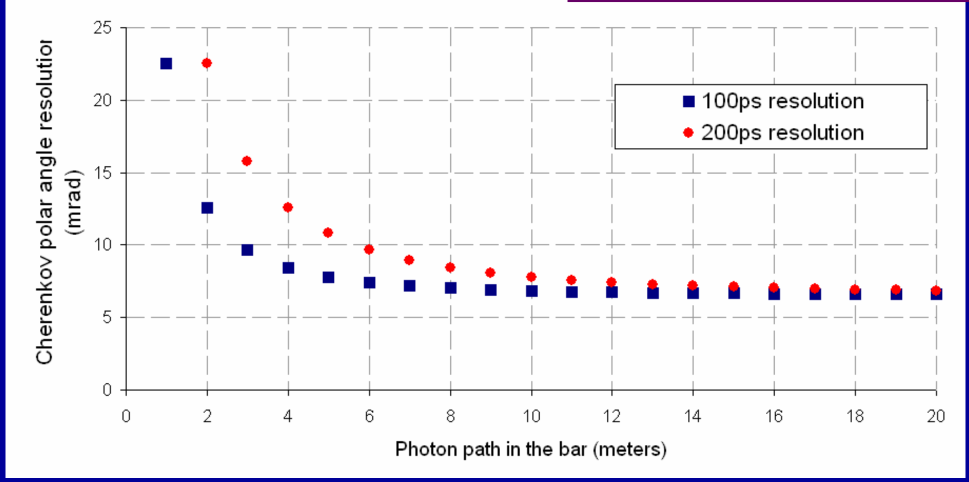
Short path length:

θ_c resolution dominated by timing resolution

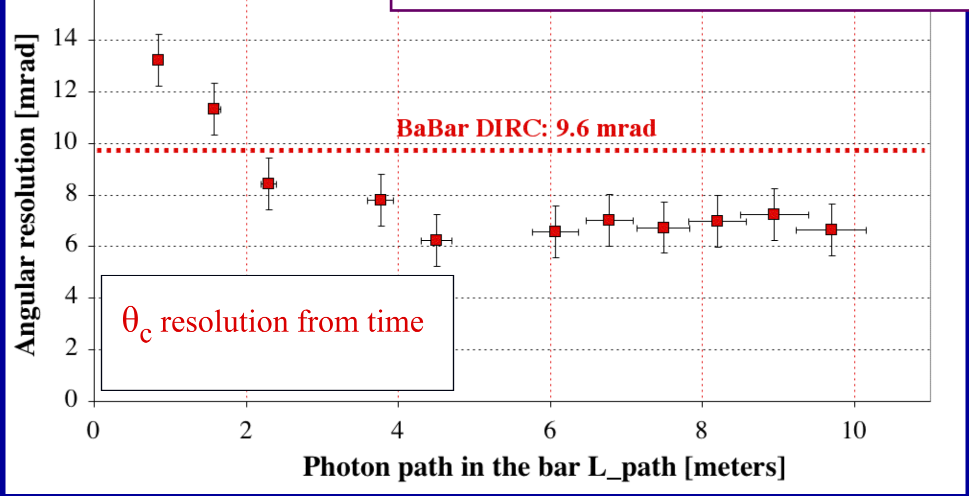
Long path length:

θ_c resolution dominated by chromatic dispersion of group index $n_g(\lambda)$

Model Expectation



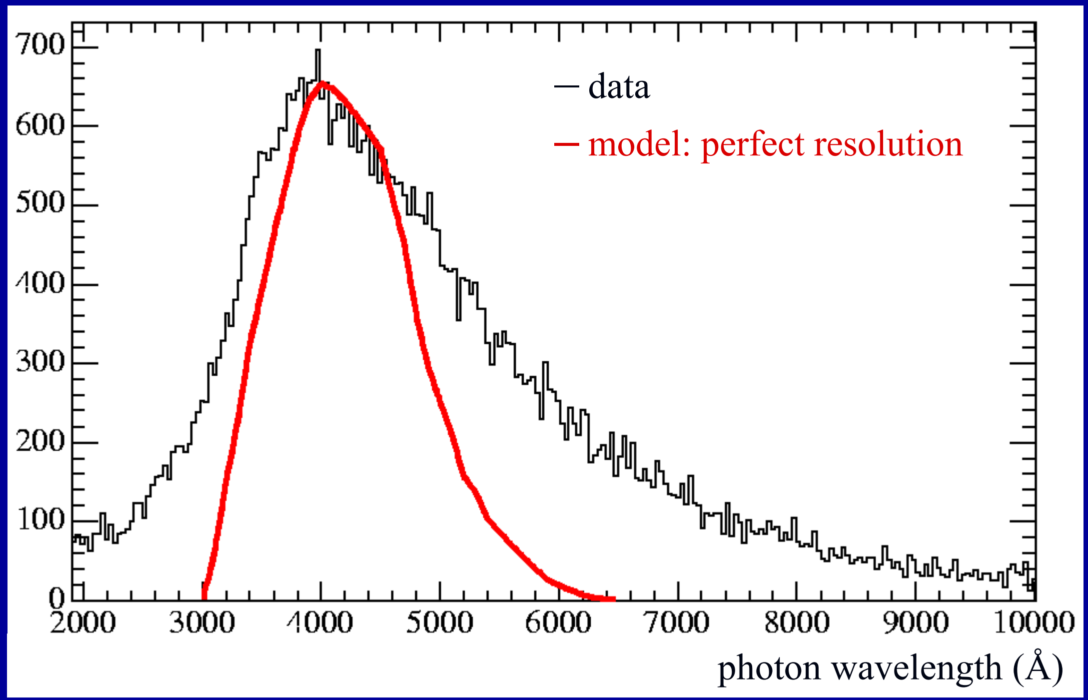
Focusing DIRC , Preliminary



Towards a Correction of the Chromatic Error

θ_c(TOP) measurement is equivalent to determination of photon wavelength

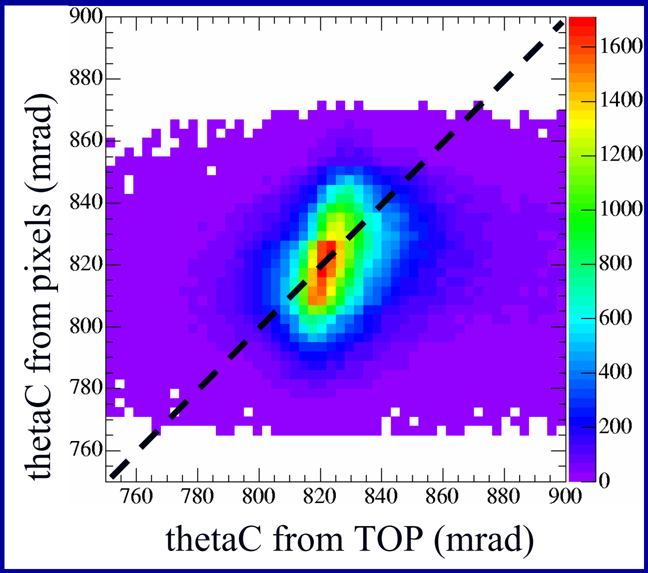
Graph shows measured photon wavelength compared to the expected wavelength spectrum for a device with perfect timing resolution.



Towards a Correction of the Chromatic Error

Simple first approach:

- use θ_c(TOP) as measurement of required correction
- assume full correlation between pixel and TOP measurement
- correction: difference between measured θ_c(TOP)
  and expected average $\theta_c(\lambda=410\text{nm})$
  $\Delta\theta_c = \theta_c(\text{TOP}) - 822.1\text{mrad}$
- $\theta_c(\text{corrected}) = \theta_c(\text{pixel}) - \Delta\theta_c$
- clearly does not combine measurements in optimum way
- this approach slightly improves resolution



Ultimately will want to use full likelihood analysis using all observables.