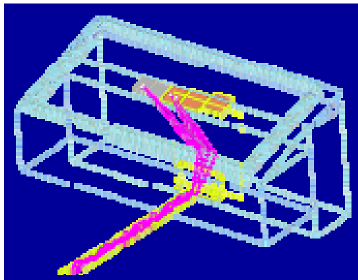
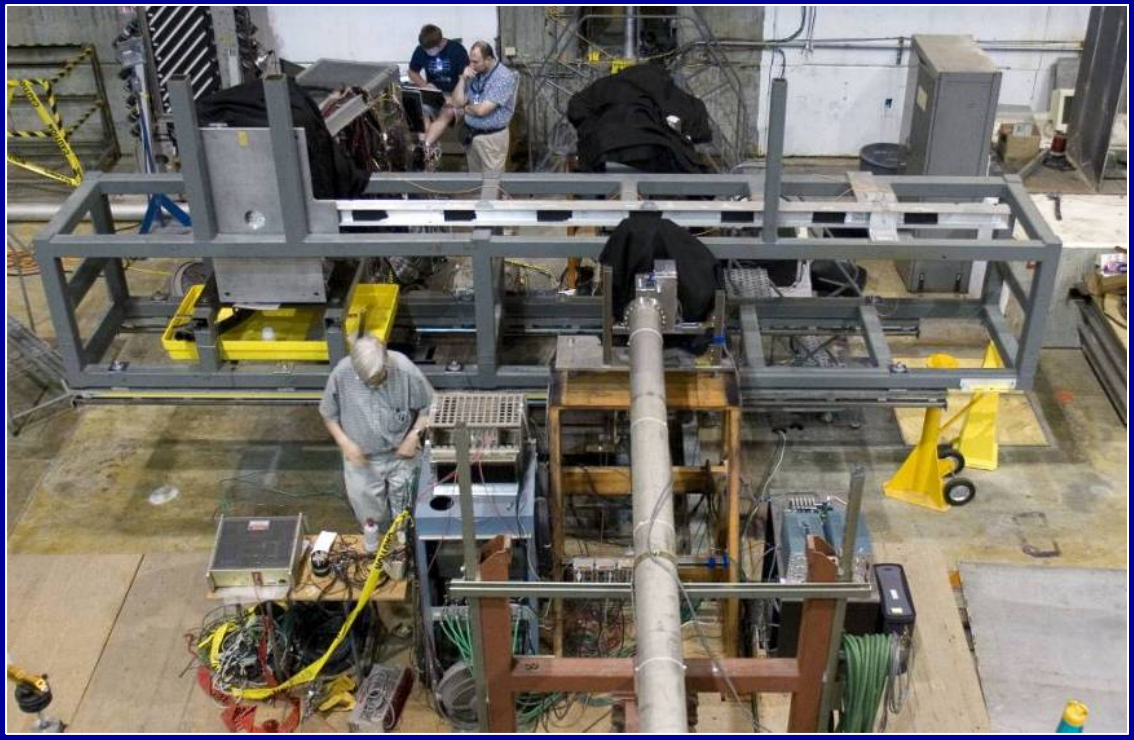


Status of the Focusing DIRC

Focusing DIRC R&D effort at SLAC:

Jose Benitez #
Gholam Mazaheri #
Larry L. Ruckman +
Gary S. Varner +
David W.G.S. Leith #
Blair N. Ratcliff #
Jochen Schwiening #
Jerry Va'vra #

SLAC   + University of Hawai'i

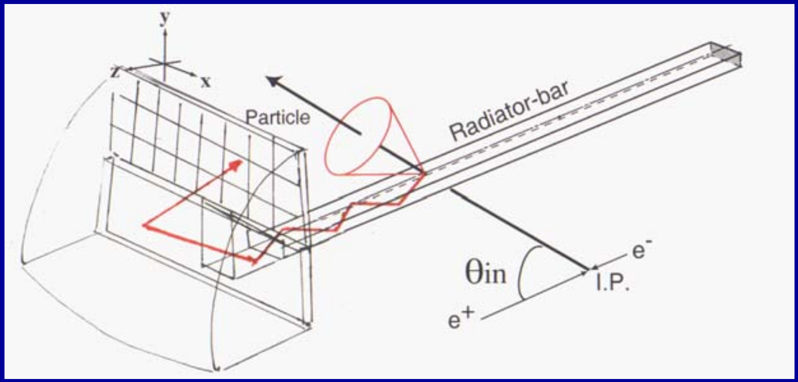


Acknowledgements:

- M. McCulloch and B. Reif (prototype construction)
- I. Bedajanek and J. Uher (software development)
- K. Suzuki (beam test)

Outline

- Motivation
  - DIRC Principle
  - BABAR DIRC Performance Highlights
  - DIRC at future experiments (i.e. SuperB)



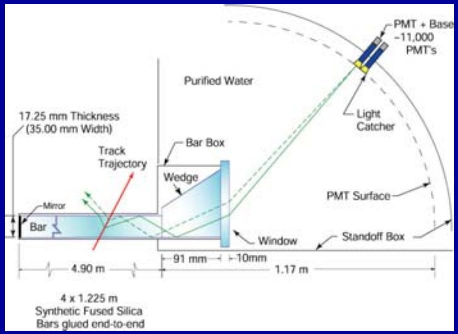
- Focusing DIRC Prototype Design
- Beam Tests 2005/2006
  - Timing resolution, θ_c resolution
  - Chromatic correction of θ_c using precision timing
  - Projected PID performance
- News of Beam Test in 2007
  - ADC readout
  - New U. Hawaii electronics

DIRC Concept

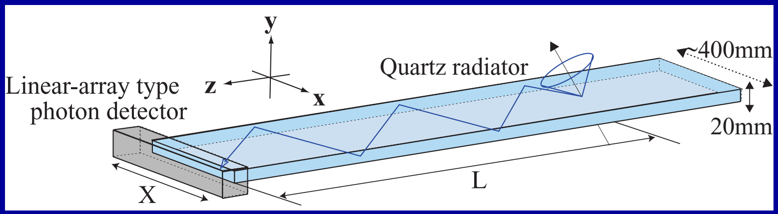
Detection of Internally Reflected Cherenkov Light

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 (SuperB Factory, Panda, GlueX, ILC)

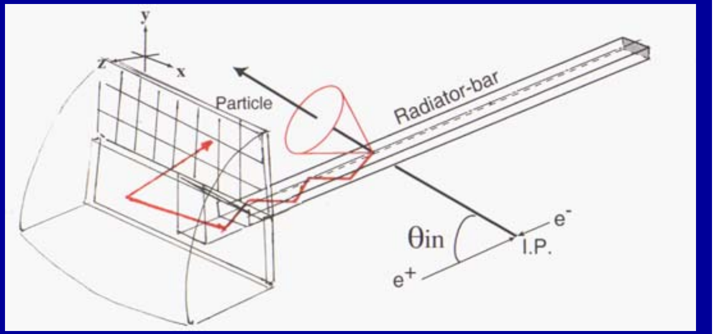


BABAR DIRC



TOP Counter

(see talk earlier today)



Focusing DIRC

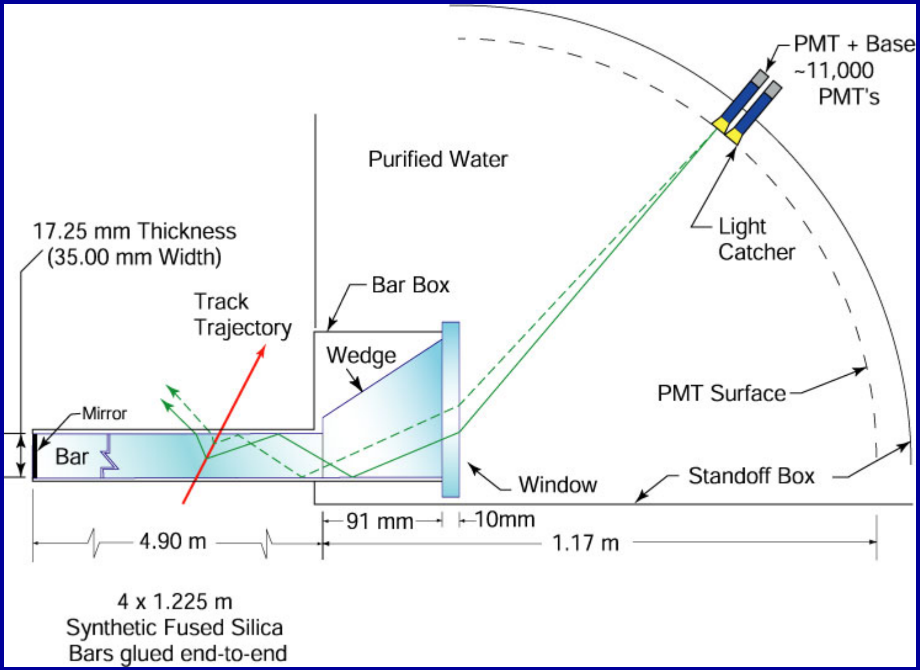
§ *B.N. Ratcliff, SLAC-PUB-6047 (Jan. 1993)*

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)

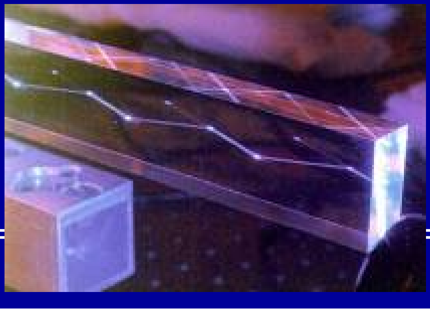


- Photons exit via wedge into expansion region (filled with $6m^3$ pure, de-ionized water).

- 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)



Almost eight 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.
- 97% of channels fully functional after 9+ 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

(typical PMT rates: 200-300kHz, primarily a DAQ issue, not a PID problem)

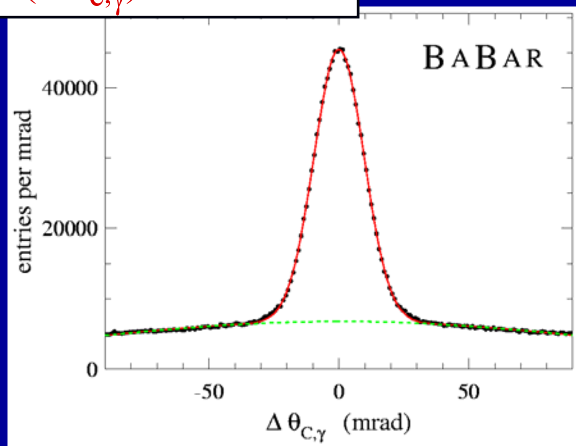
→ Added additional shielding; upgraded TDCs in 2002.

→ Time measurement essential in dealing with backgrounds.

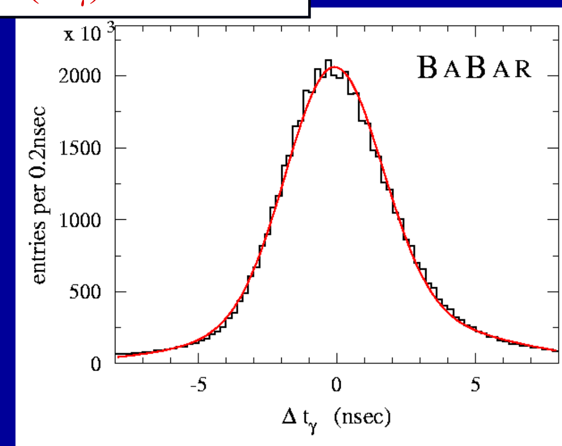
§ *J.S. talk at RICH 2004 and Nucl. Instrum. Meth. A502 (2003) 67*

Single Photon resolution

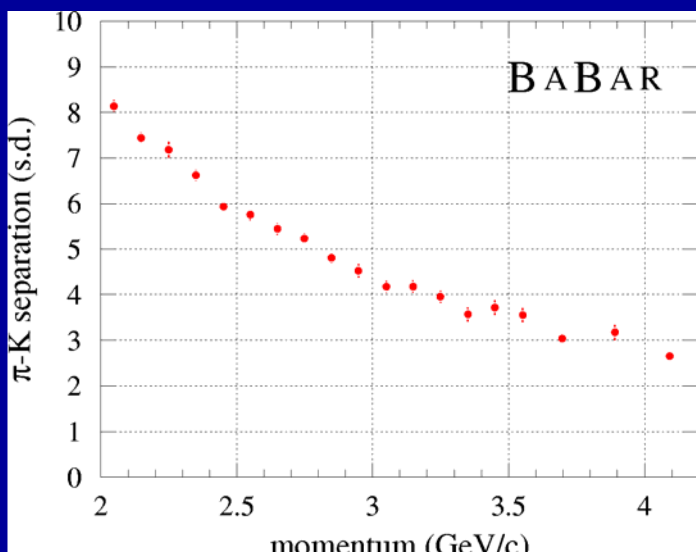
$\sigma(\Delta\theta_{c,\gamma}) = 9.6$ mrad



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



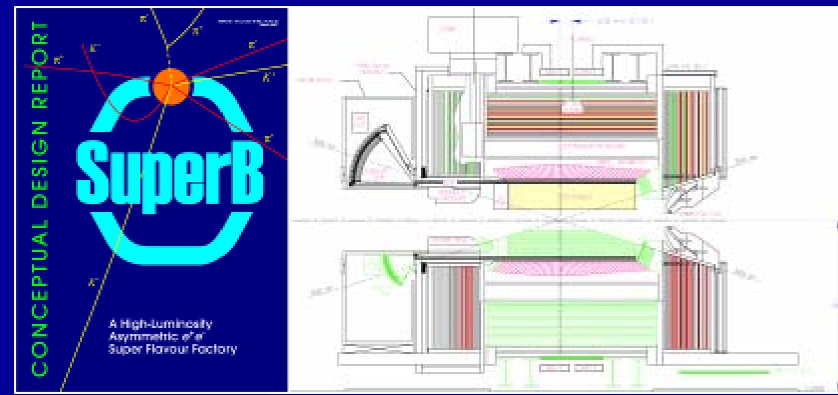
π/K separation power:



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

Nucl. Instrum. Meth. A502 (2003) 67

Motivation



Goal:

- Super-B will have 100x higher luminosity
- Backgrounds are not yet understood, but they would scale with the luminosity if they are driven by the radiative Bhabhas

→ Future DIRC needs to be smaller and faster:

Focusing and smaller pixels can reduce the expansion volume by a factor of 7-10

Faster PMTs reduce sensitivity to background.

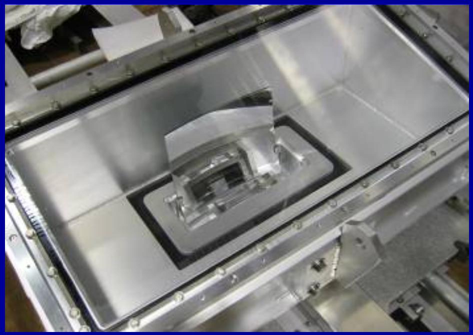
Additional benefit of the faster photon detectors:

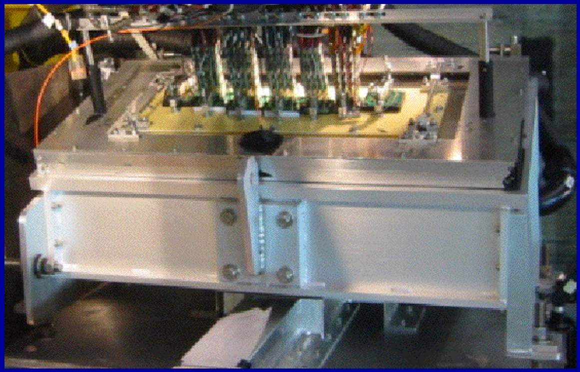
- Timing resolution improvement: σ ~1.7ns (BABAR DIRC) → $\sigma \leq$150ps (~10x better) which allows measurement of photon color to correct the chromatic error of θ_c (contributes σ ~ 5.4 mrads in BABAR DIRC)

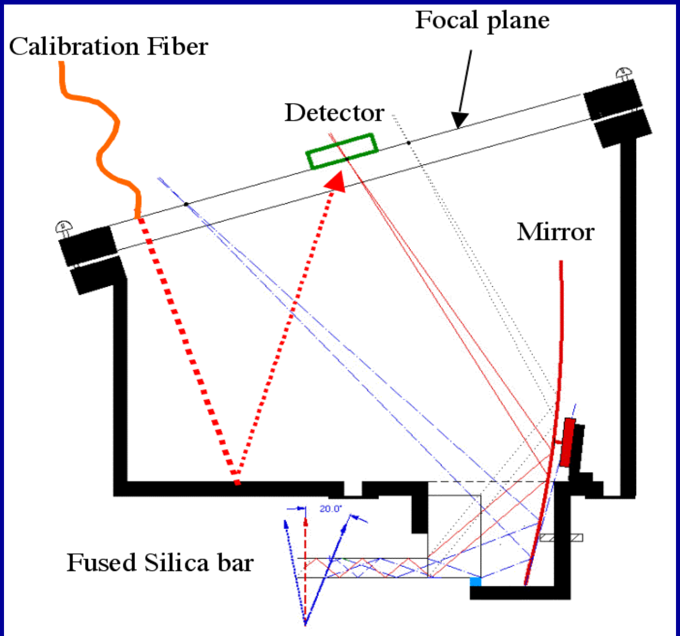
Focusing mirror effect:

- Focusing eliminates effect of the bar thickness (contributes σ ~ 4 mrads in BABAR DIRC)
- However, the spherical mirror introduces an aberration, so its benefit is smaller.

Focusing DIRC Prototype Optics



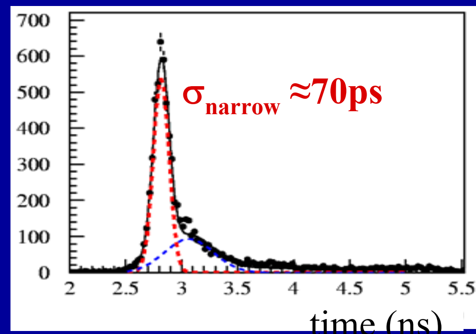


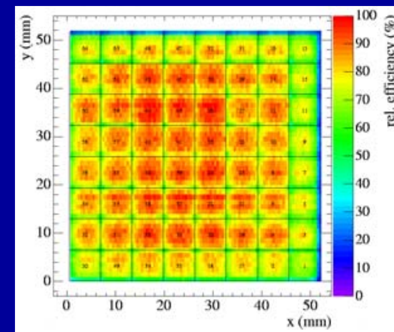


- Radiator:
  - 1.7 cm thick, 3.5 cm wide, 3.7 m long fused silica bar (spares from BABAR DIRC).
- Optical expansion region:
  - filled with a mineral oil to match the fused silica refraction index (KamLand oil).
  - include optical fiber for the electronics calibration (PiLas laser diode).
- Focusing optics:
  - a spherical mirror with 49cm focal length focuses photons onto a detector plane.

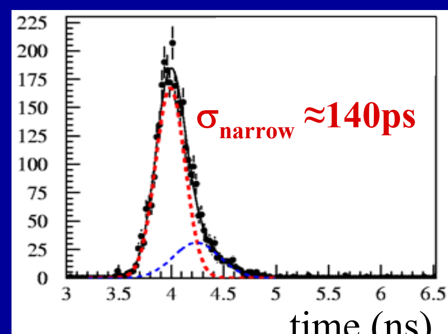
Focusing DIRC Prototype Photon Detectors

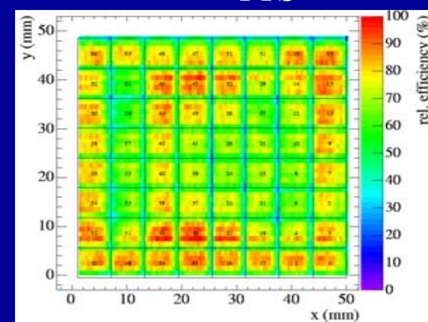
1) Burle 85011-501 MCP-PMT (64 pixels, 6x6mm pad, σ_{TTS} ~50-70ps)





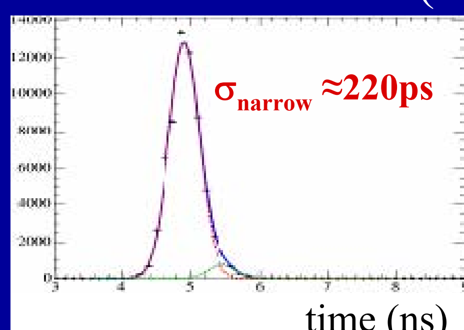
2) Hamamatsu H-8500 MaPMT (64 pixels, 6x6mm pad, σ_{TTS} ~140ps)

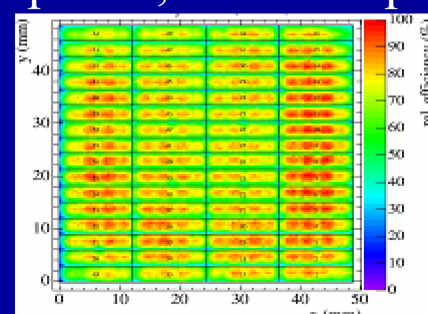




Timing resolutions were obtained using a fast laser diode (PiLas) in bench tests with single photons on pad center.

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





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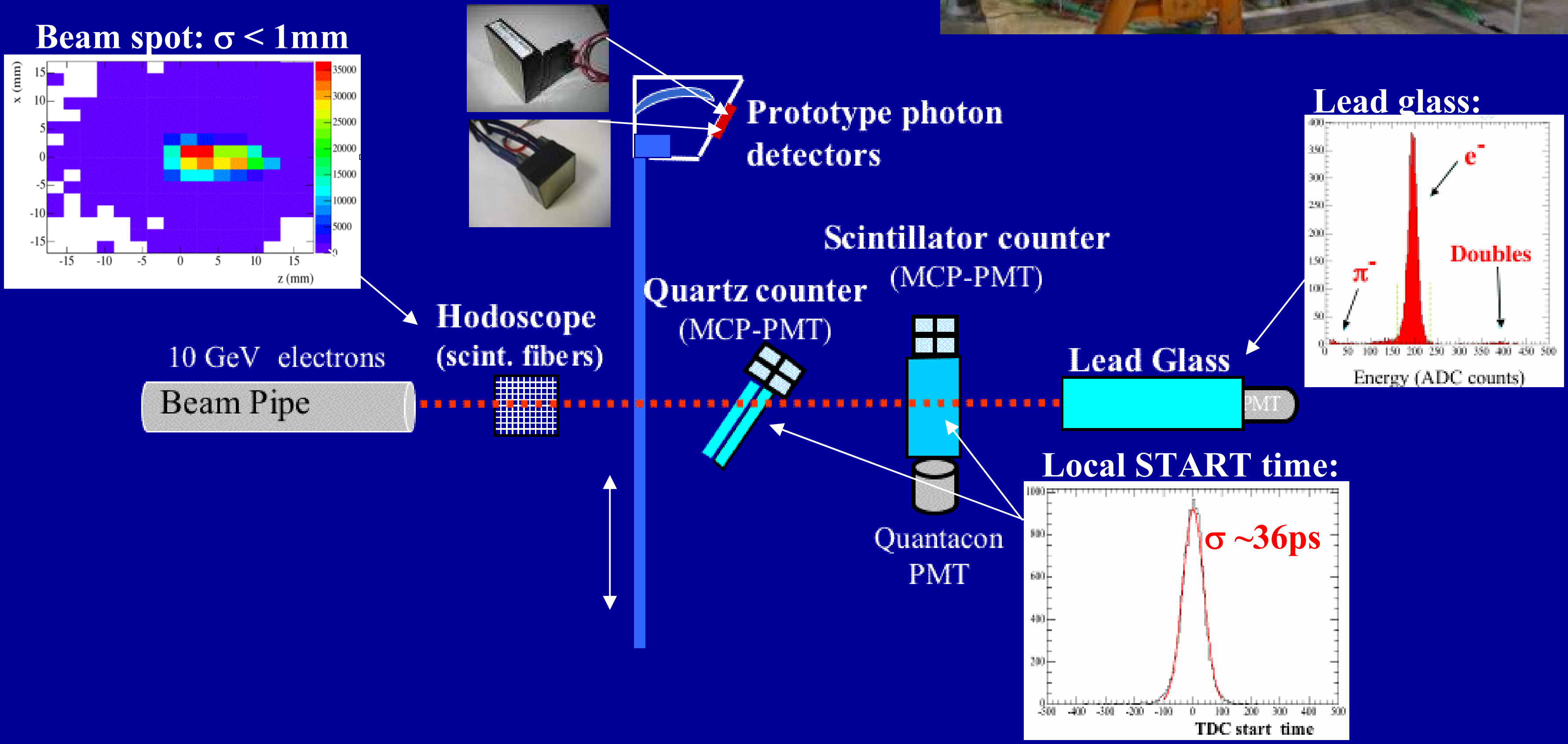
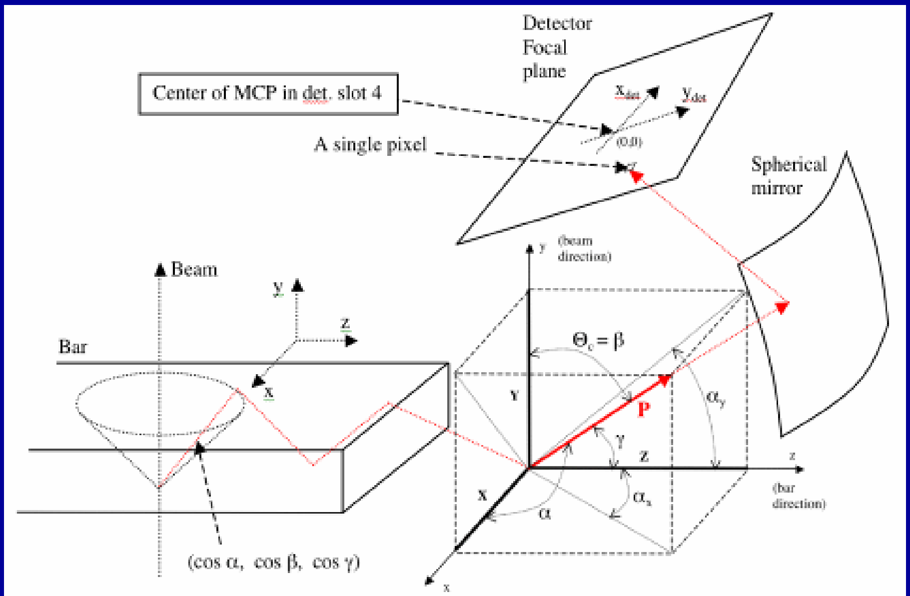
Beam Test Setup in 2006

- SLAC 10 GeV/c electron beam in End Station A
- Beam enters bar at 90º angle
- Prototype is movable to 7 beam positions along bar
- Time start from the LINAC RF signal, but correctable with a local START counter
- SLAC-built amplifier and constant fraction discriminator
- TDC is Phillips 7186 (25ps/count), CAMAC readout

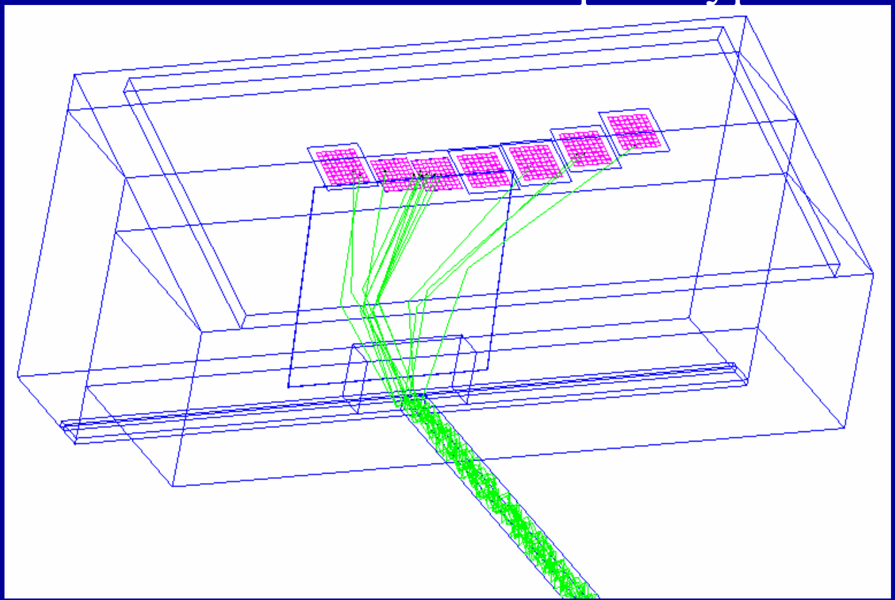


FOCUSING DIRC PROTOTYPE RECONSTRUCTION

Prototype coordinate systems:



Geant 4 simulation of the prototype:

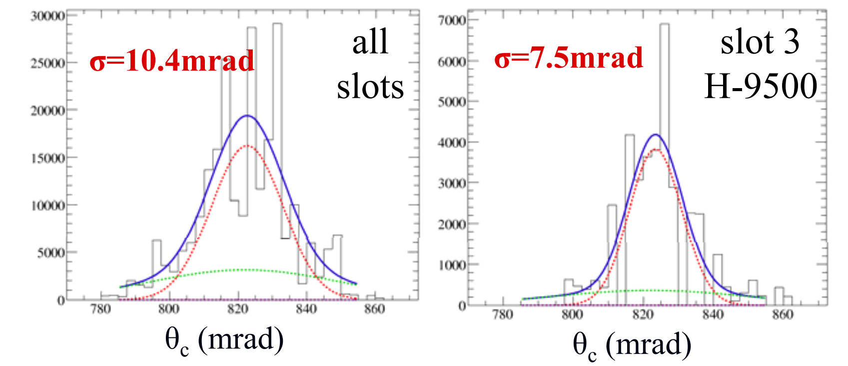


- Each detector pixel determines these photon parameters for average λ :
  θ_c, cos α, cos β, cos γ, Photon path length, time-of-propagation, number of photon bounces.
- We use full GEANT4 simulation to obtain the photon track parameters for each pixel.
  (it is checked by a ray-tracing software)

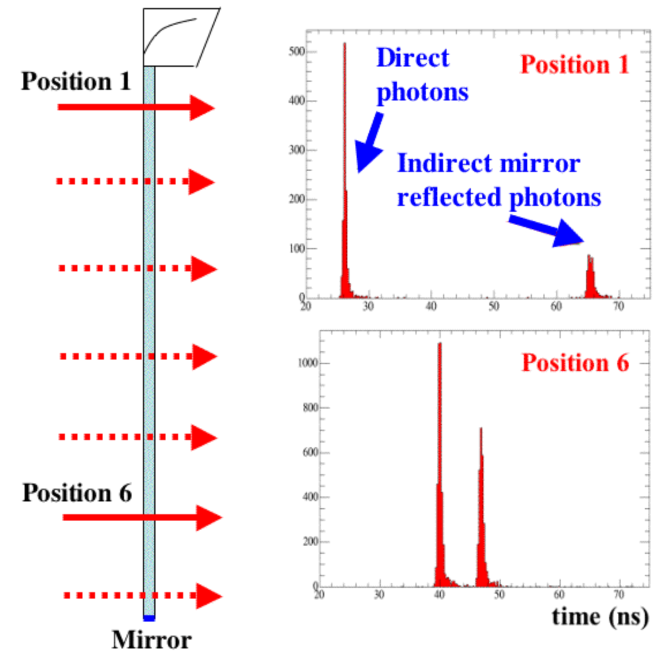
CHERENKOV PHOTON SIGNAL (2006)

- 10 GeV/c electron beam data
- approx. 7.7M triggers, 560k good single e^- events
- ~ 200 pixels instrumented
- Ring image is most narrow in the 3 x 12 mm pixel detector (H-9500 in slot 3)

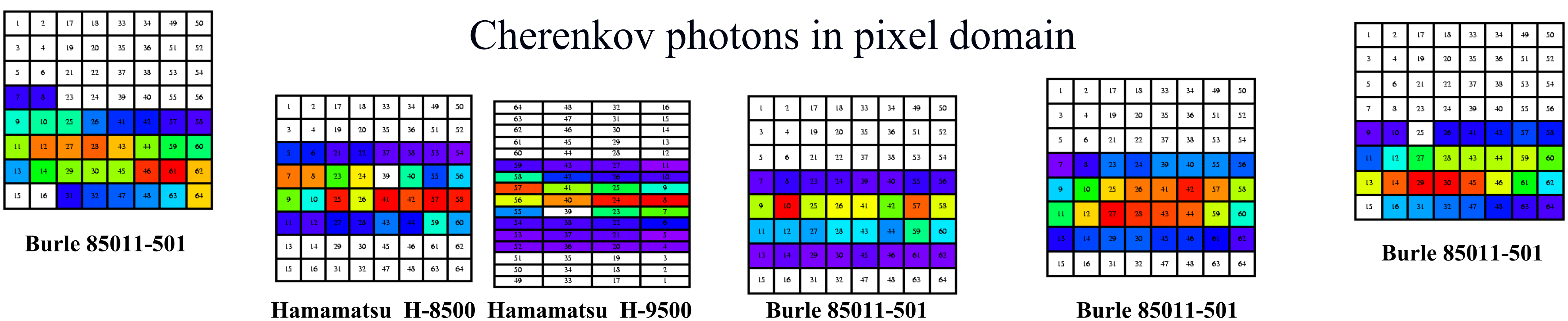
Cherenkov photons in θ_c domain



Cherenkov photons in time domain



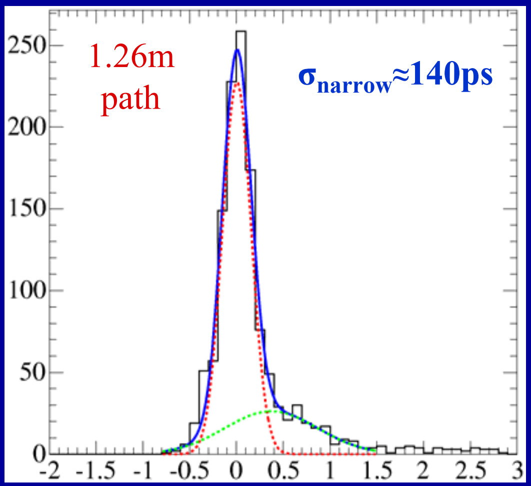
Cherenkov photons in pixel domain

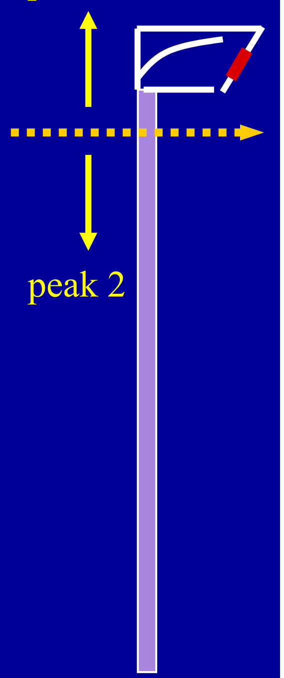


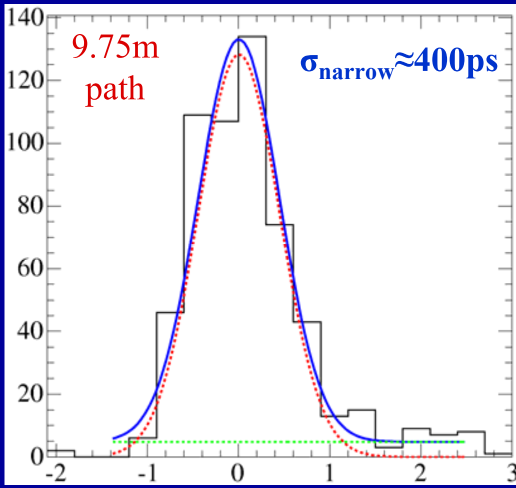
Chromatic Broadening

Example for one detector pixel in position 1

- First peak ~1.3m photon path length
- Second peak ~9.8m photon path length
- Measure time of propagation (TOP)
- Calculate expected TOP
  assuming average <λ>≈410nm
- Plot ΔTOP: measured minus expected
  time of propagation
- Observe clear broadening of timing peak for
  long path length (mirror-reflected photons)





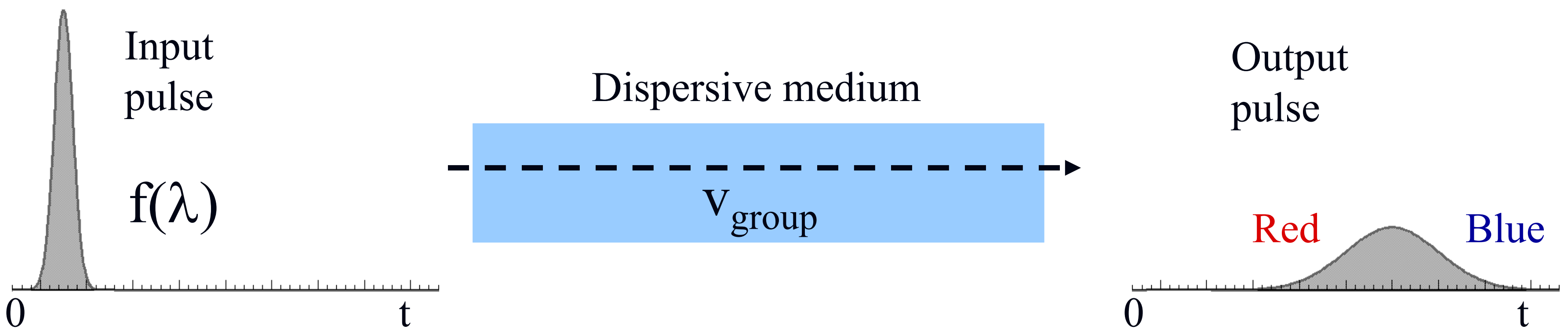


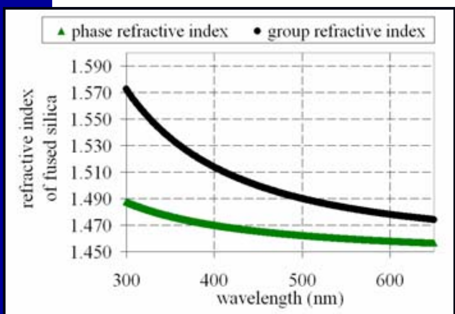
Two chromatic effects

- time dispersion during propagation in the bar
  (group velocity is function of wavelength)
- dispersion of the Cherenkov angle
  (refractive index is function of wavelength)

→ Use time dispersion to correct Cherenkov angle

Color tagging using of photon propagation time





fused silica: n_{phase}(red) < n_{phase}(blue) → v_{group}(red) > v_{group}(blue)

red photons arrive before blue photons

$$v_{group} = c_0 \,/\, n_{group} = c_0 \,/\, [n_{phase} - \lambda \cdot dn_{phase} \,/\, d\lambda]$$

$$t = TOP = L \,/\, v_{group} = L\,[n_{phase} - \lambda \cdot dn_{phase} \cdot d\lambda\,] \,/\, c_0$$ Time-of-Propagation

$$dt/L = dTOP/L = \lambda \cdot d\lambda \cdot |- d^2 n_{phase}/d\lambda^2| \,/\, c_0$$

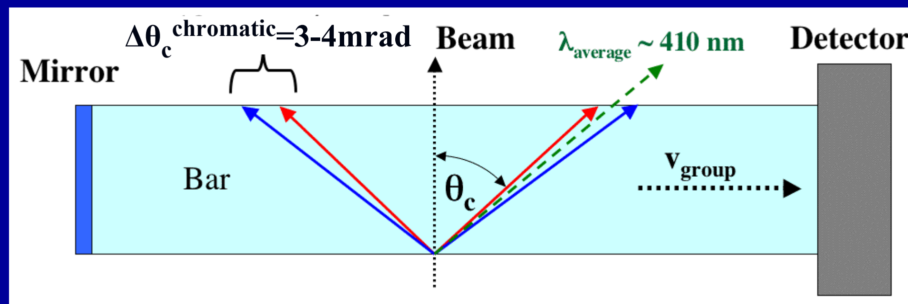
dt is pulse dispersion in time, length L, wavelength bandwidth dλ, refraction index n(λ)

- We have determined in Fused Silica: dt/L = dTOP/L ~ 40ps/meter.
- Our goal is to measure the color of the Cherenkov photon by timing

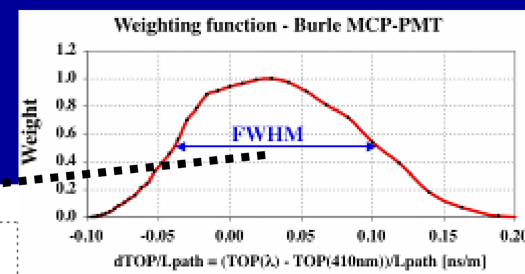
Correcting the Chromatic Error on θ_c

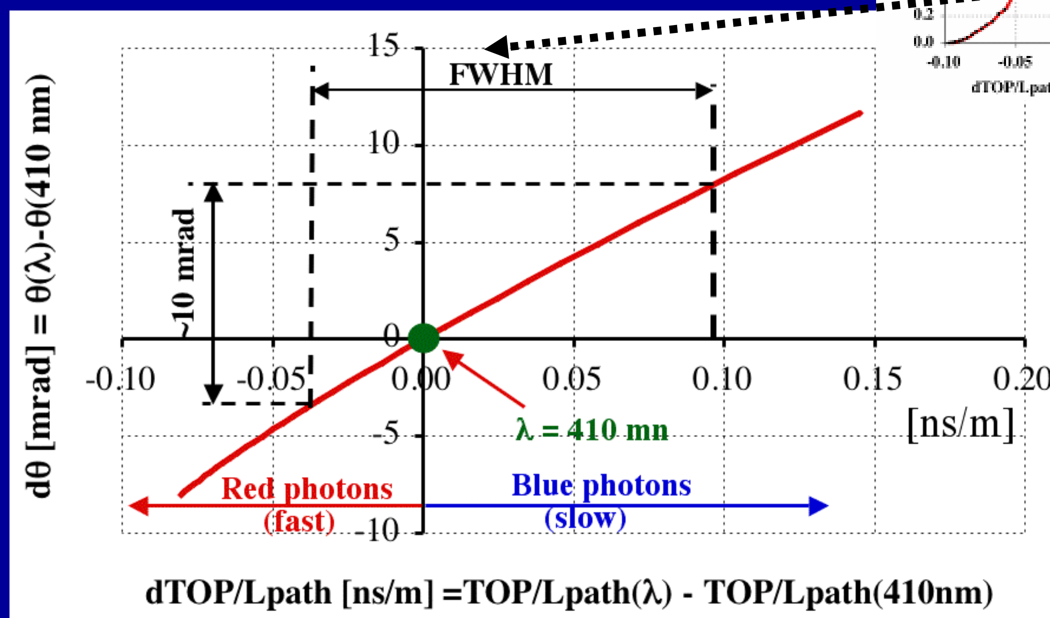
Cherenkov angle production controlled by n_{phase} $(\cos\theta_c = 1/(n_{phase}\beta))$: $\theta_c\,(\text{red}) < \theta_c\,(\text{blue})$

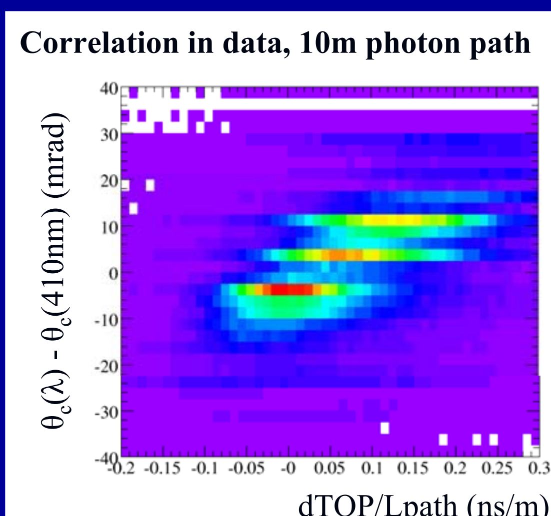
Propagation of photons is controlled by n_{group} $(v_{group} = c_0/n_{group} = c_0/[n_{phase} - \lambda \cdot dn_{phase} \cdot d\lambda\,])$: $v_{group}(\text{red}) > v_{group}\,(\text{blue})$



Principle of chromatic correction by timing:







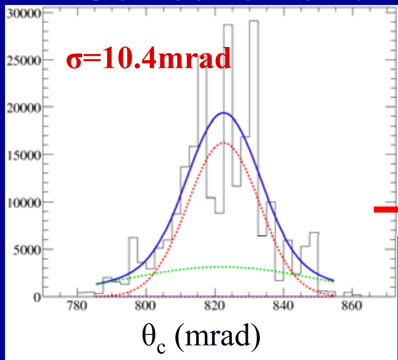
TOP = time of propagation of photon in the bar

$TOP/Lpath = 1/v_{group}(\lambda)$

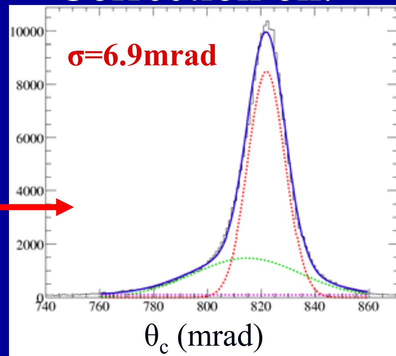
θ_c resolution and Chromatic correction

All pixels:

Correction off:



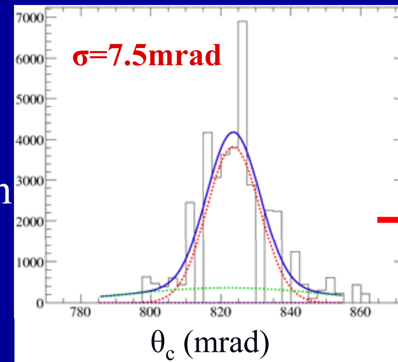
Correction on:



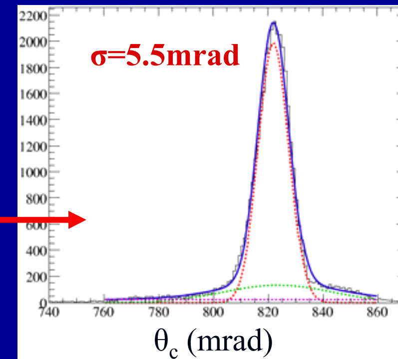
Position 1
Lpath≈10m

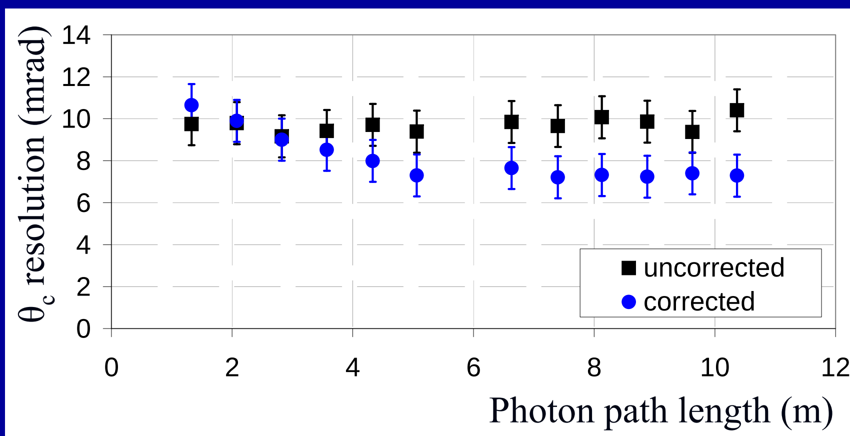
3mm pixels only:

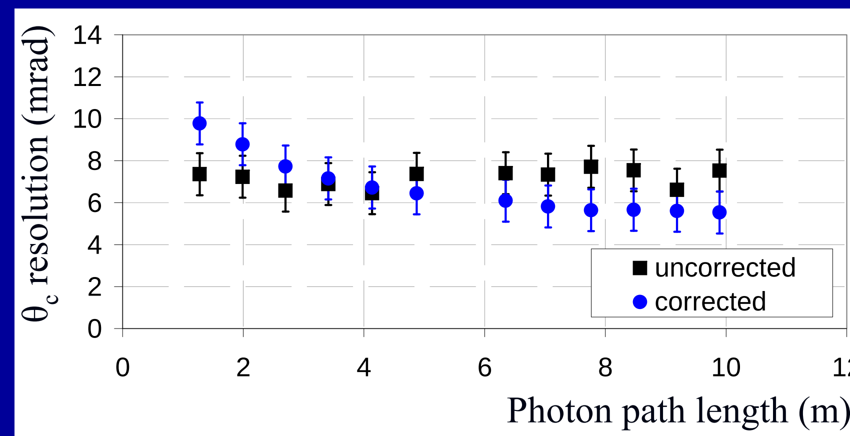
Correction off:



Correction on:



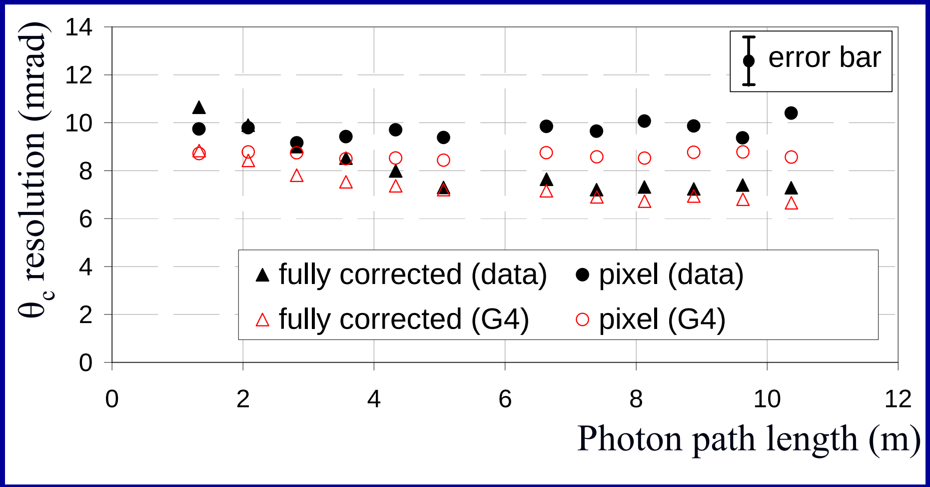




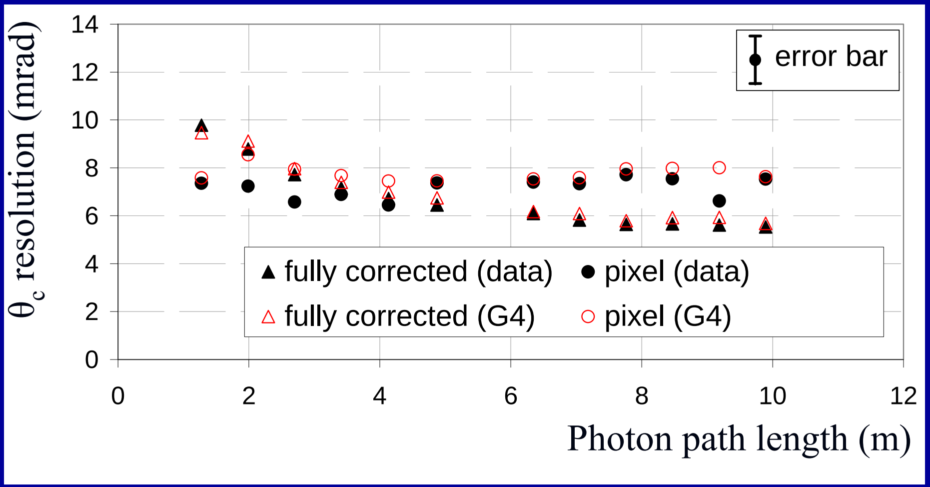
- The chromatic correction starts working for Lpath > 2-3 meters due to a limited timing resolution of the present photon detectors.
- Holes in the uncorrected distributions are caused by the coarse pixelization, which also tends to worsen the resolution. In the corrected distributions this effect is removed because of the time correction.
- Smaller pixel size (3mm) helps to improve the Cherenkov angle resolution; it is our preferred choice.

θ_c resolution and Geant 4 MC simulation

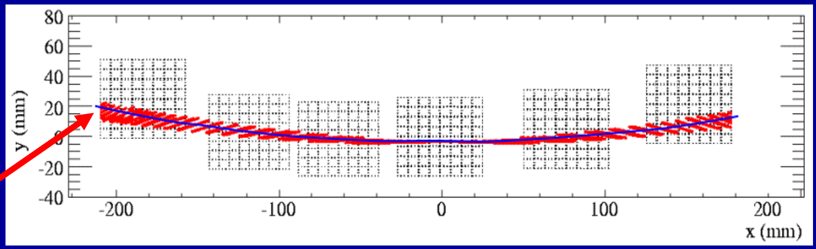
θ_c resolution - all pixels:



θ_c resolution - 3mm pixels only:



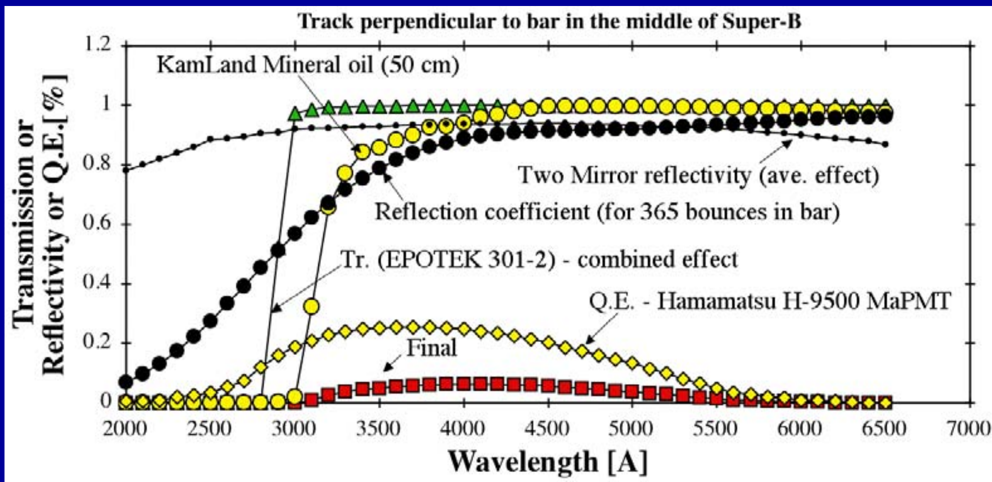
- Main contributions to the θ_c resolution:
  - chromatic smearing: ~ 3-4 mrad
  - 6mm pixel size: ~5.5 mrad
  - optical aberrations of this particular design:



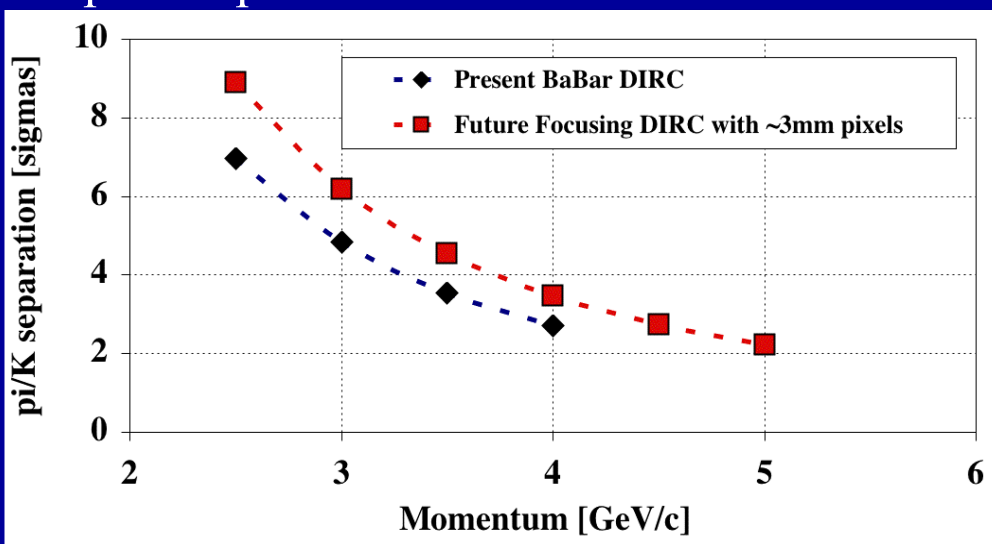
grows from 0 mrad at ring center to 9 mrad in outer wings of Cherenkov ring

(this effect is caused by the spherical focusing mirror in the present design)

Focusing DIRC prototype bandwidth:



Expected performance of a final device:



- Prototype $N_{pe\_measured}$ and $N_{pe\_expected}$ are consistent within ~20%.
- Hamamatsu H-9500 MaPMTs:

  We expect $N_0 \sim 31\ cm^{-1}$, which in turn gives $N_{pe} \sim 28$ for 1.7 cm fused silica bar thickness, and somewhat better performance in pi/K separation than the present BABAR DIRC.
- Burle-Photonis MCP-PMT:

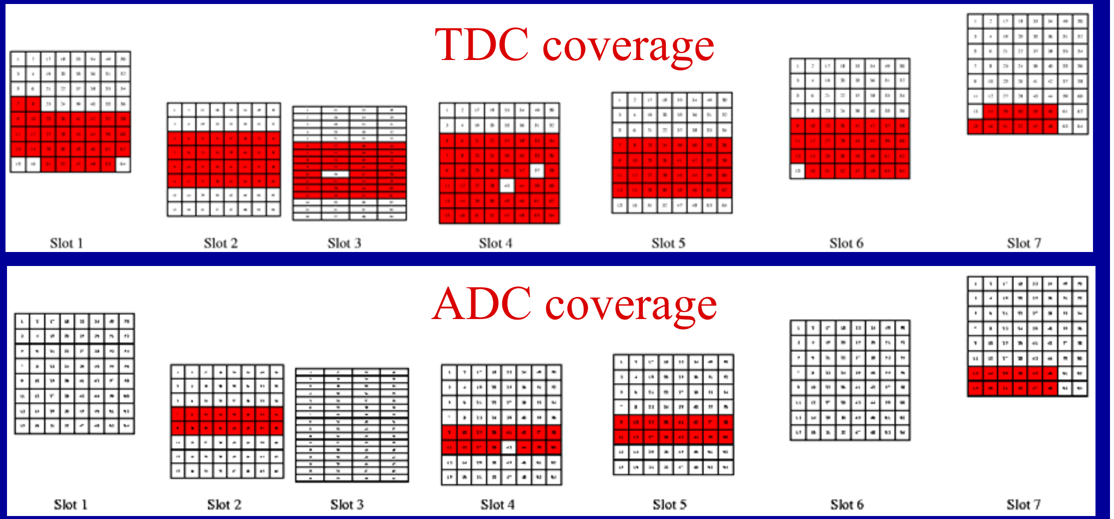
  We expect $N_0 \sim 22\ cm^{-1}$ and $N_{pe} \sim 20$ for B = 0kG.
- BABAR DIRC design:

  $N_0 \sim 30\ cm^{-1}$ and $N_{pe} \sim 27$.

Beam Test in August 2007

For the beam test in 2007 we added:

- (partial) readout for 7 PMT slots
  - one H-8500 MaPMT
  - one H-9500 MaPMT
  - five 85011-501 MCP PMT
- second fiber hodoscope behind bar
- U. Hawai'i ASIC electronics for time and charge measurement
- time-of-flight system (see Jerry's talk tomorrow)
- ~220 pixels, ~350 electronics channels



Photodetector and TDC/ADC coverage in 2007 runs

- Phillips ADC charge measurement for charge-sharing treatment

  2006 data demonstrated that best θ_c resolution obtained with 3 mm pixels

  (hit location error due to assignment of pixel center is smaller than for 6 mm pixels)

  However, choice of 3 mm pixels quadruples number of electronics channels per surface unit

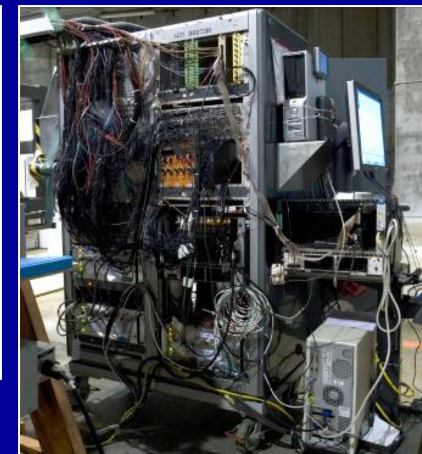
  Could obtain better hit location information for 6 mm pixels by exploiting charge sharing

  when hit location can be interpolated between pads based on ADC information

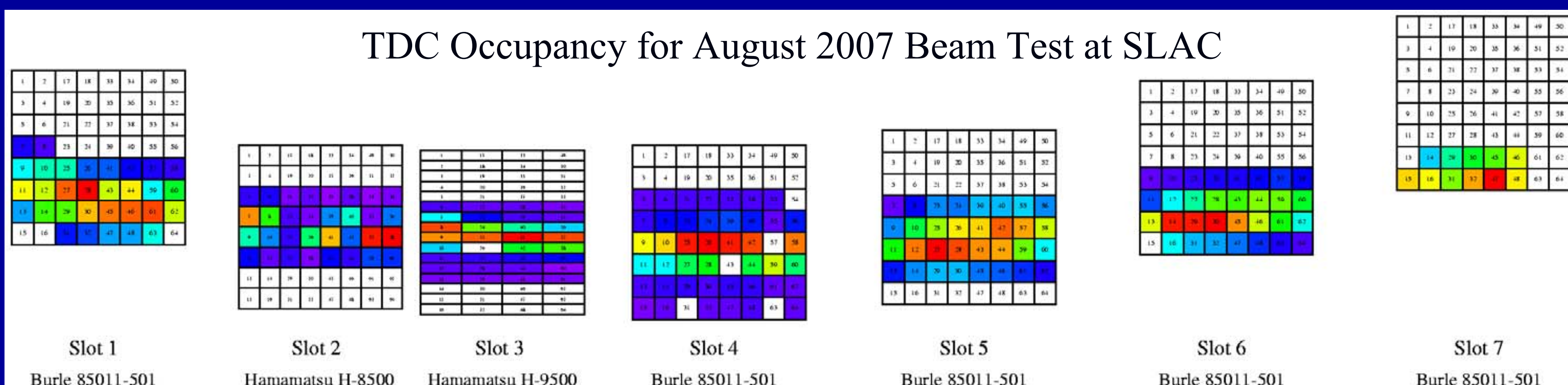
Beam Test in August 2007

Six days of 10 GeV electron beam in End Station A at SLAC

Recorded some 10M triggers, 800k good single-track events.



Still working on detector calibration and data analysis.



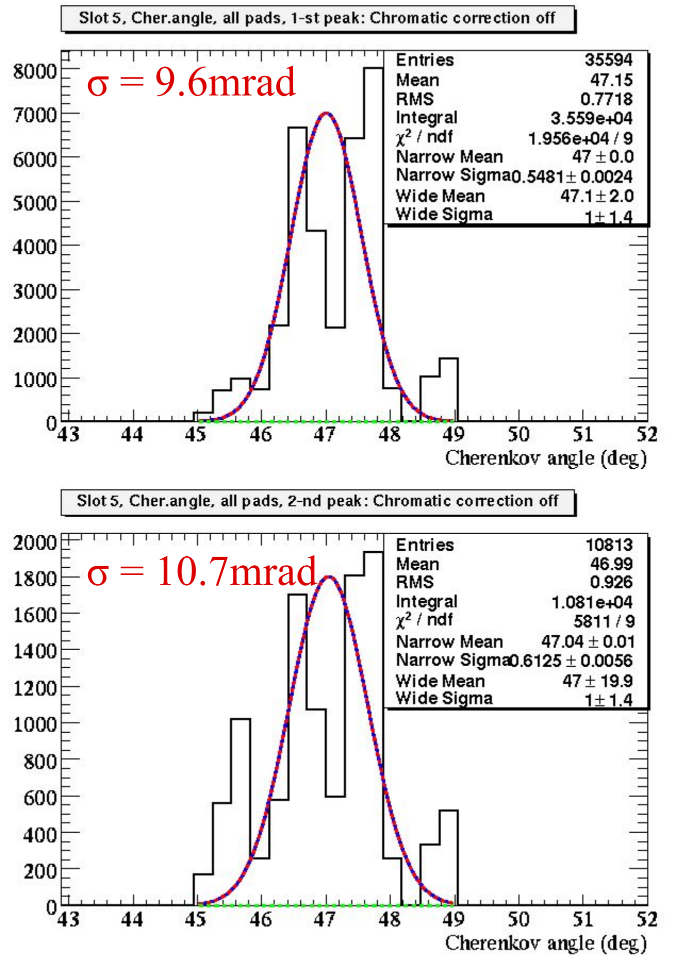
Charge Sharing

First, very preliminary look at charge sharing treatment for slot 5 (position 1)

- look for ADC hit in (vertical) neighbor pad
- use average pixel θ_c of the two pads if ADC hit is found

→ significant improvement of θ_c resolution for both peak 1 and peak 2

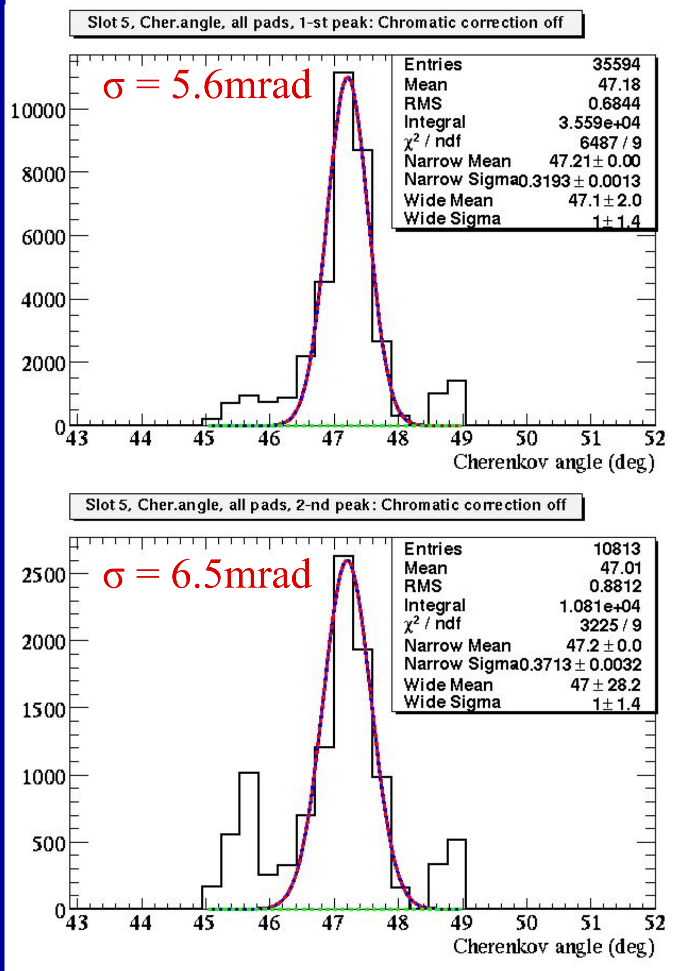
slot 5 before correction



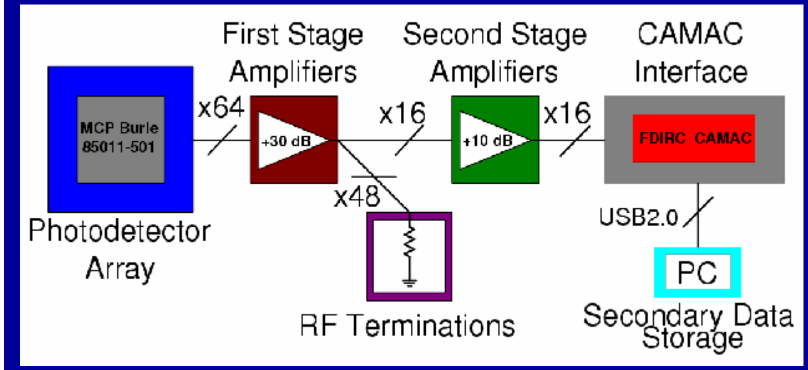
direct photons
(path ~1.3m)

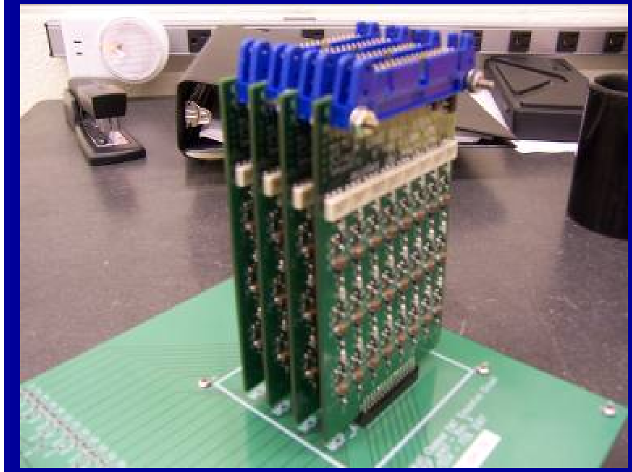
mirror-reflected photons
(path ~10m)

slot 5 after correction



UH Prototype Readout Chain

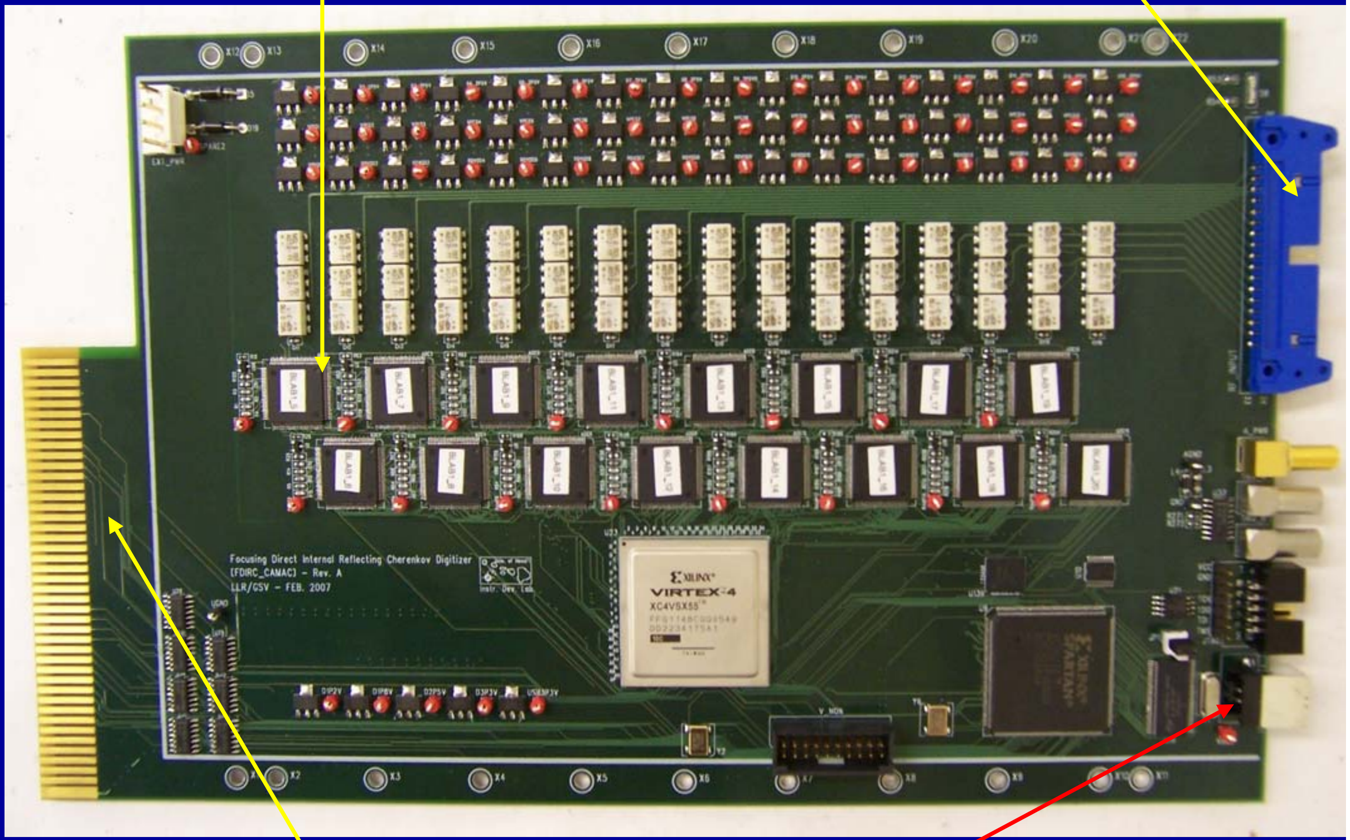




Amplifiers mounted on MCP backplane

Differential inputs from amp boards

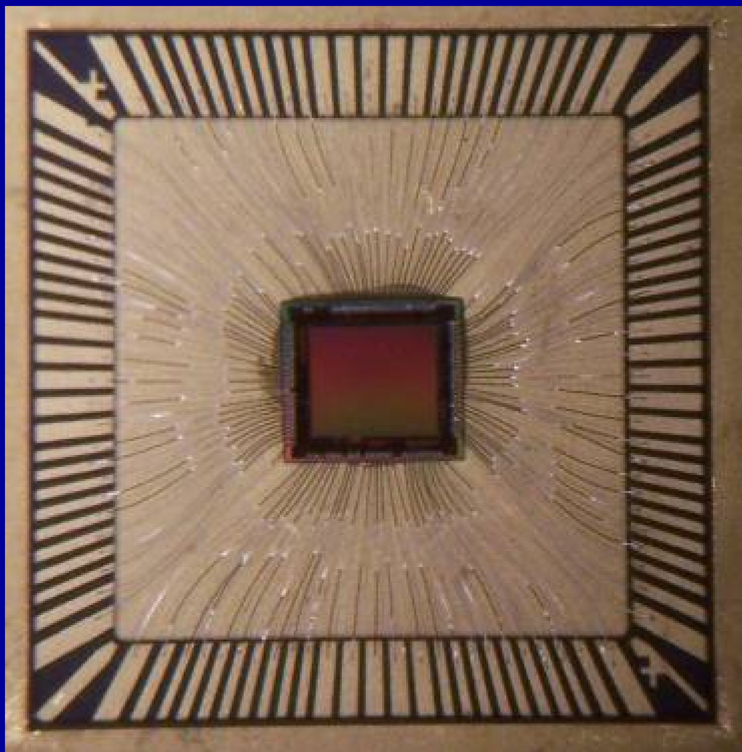
16 BLAB1 ASICs



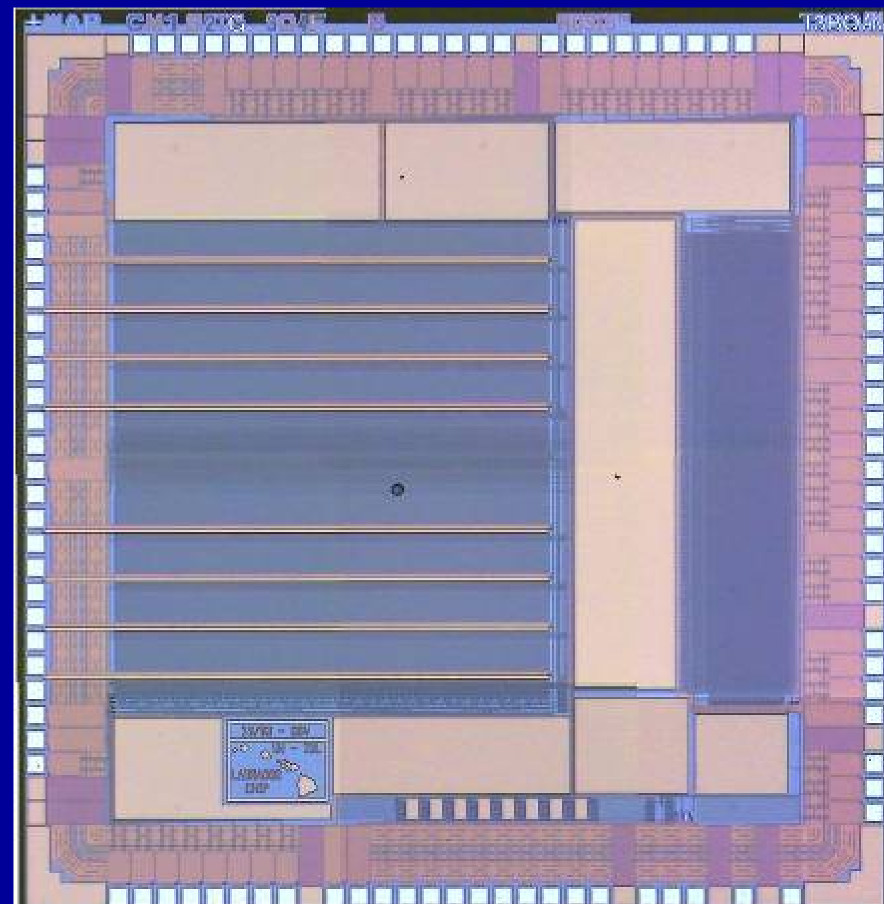
Processed hit times via CAMAC

Full waveforms over USB2

Buffered LABRADOR (BLAB1) ASIC



Variant of the LABRADOR 3



3mm x 2.8mm, TSMC 0.25um

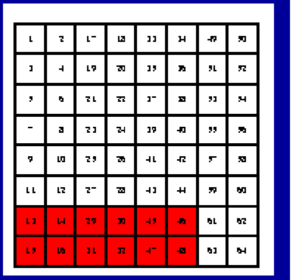
- 64k samples deep
- Multi-MSa/s to Multi-GSa/s
- 12-64us to form Global trigger

Successfully flew on ANITA in Dec 06/Jan 07 (<= 50ps timing)

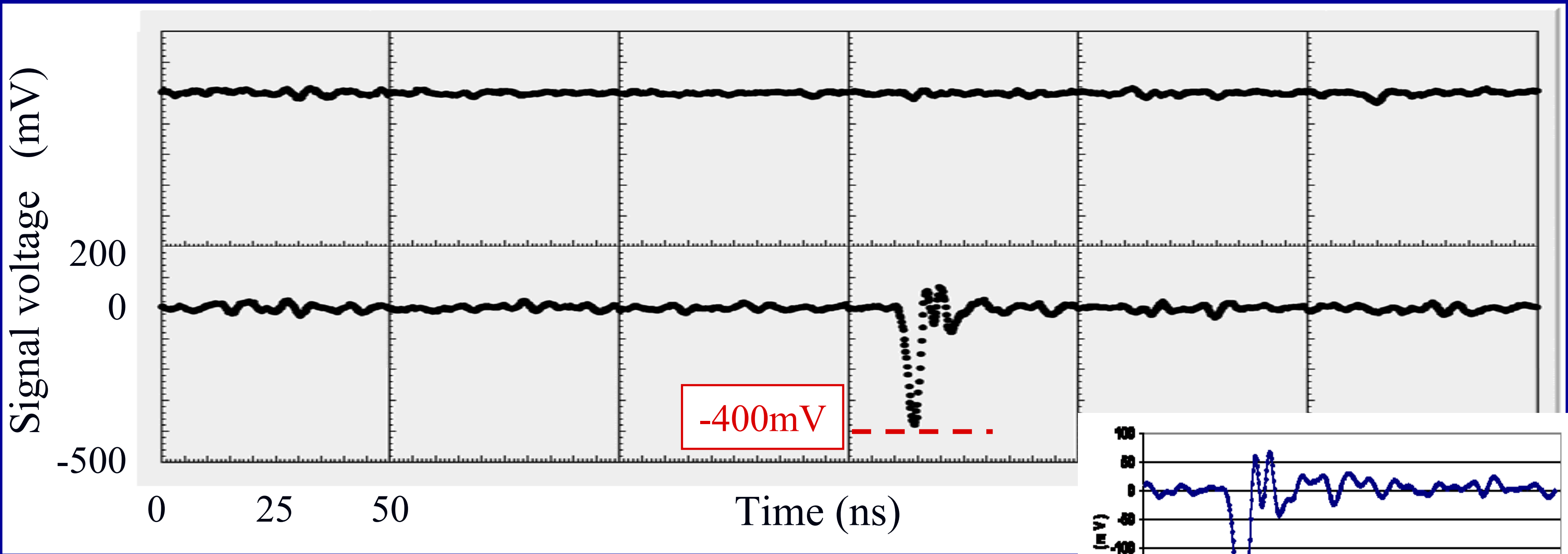
Sample Event in 2007 Beam Test

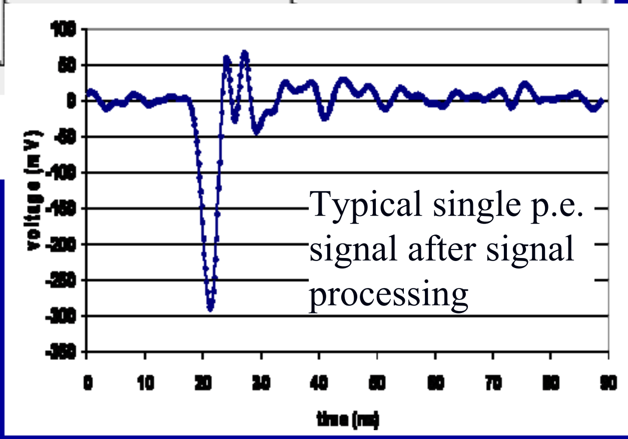
12 channel waveforms from slot 7 in a typical event with one hit on pad 32 sampled at approx. 5.8 GSa/s

slot 7



analysis of waveform, extraction of hit time ongoing





during beam test

- single p.e. signal typically -300-400mV
- RMS noise typically -10mV

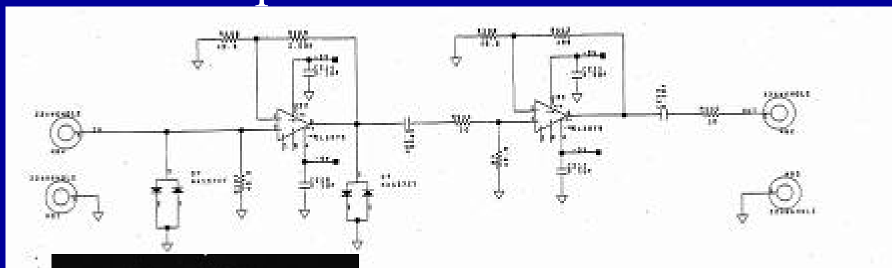
Conclusions

- We have demonstrated that we can correct the chromatic error of θ_C
  This is the first RICH detector which has been able to do this.
- Single-photon θ_C resolution 5.5 – 7 mrad after chromatic correction for long paths (consistent with G4 simulation).
- Expected N_0 and N_{pe} is comparable to BABAR DIRC for MaPMT H-9500.
- Expected improvement of the PID performance with 3x3mm pixels: ~20-30% compared to BABAR DIRC for pi/K separation, if we use H-9500 MaPMT.
- The main defense against the background at SuperB is to make (a) the expansion volume much smaller, which is possible only with highly pixilated photon detectors, and (b) use of faster detectors.
  SuperB Conceptual Design Report includes (Focusing) DIRC as barrel PID system.
- 2007 test beam run: Added (a) ADC-based pixel interpolation, (b) 2-nd hodoscope after a bar, (c) ASIC-based readout on one MCP-PMT allowing a measurement of time and pulse height, (d) test of the TOF detector.
  Data analysis just starting; first ADC pixel interpolation looks promising, stay tuned…

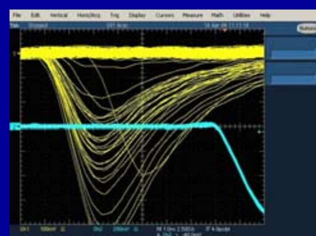
Extra Material

Focusing DIRC electronics

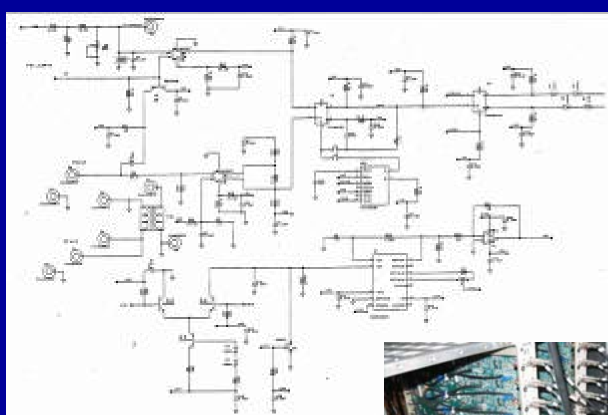
SLAC Amplifier:



Amplifier output from MCP-PMT (trigger on PiLas), 100mV/div, 1ns/div



SLAC CFD:



- Amplifier, based on two Elantek 2075EL chips, has a voltage gain of ~130x, and a rise time of ~1.5ns.
- Constant-fraction-discriminator (32 channels/board).
- Phillips 7186 TDC with 25ps/count.

Nucl.Inst.&Meth., A 553 (2005) 96

Charge Sharing

Single photo-electron may result
in multiple anode pads with hits
if hit location close to pad boundary and
both charges above discriminator threshold

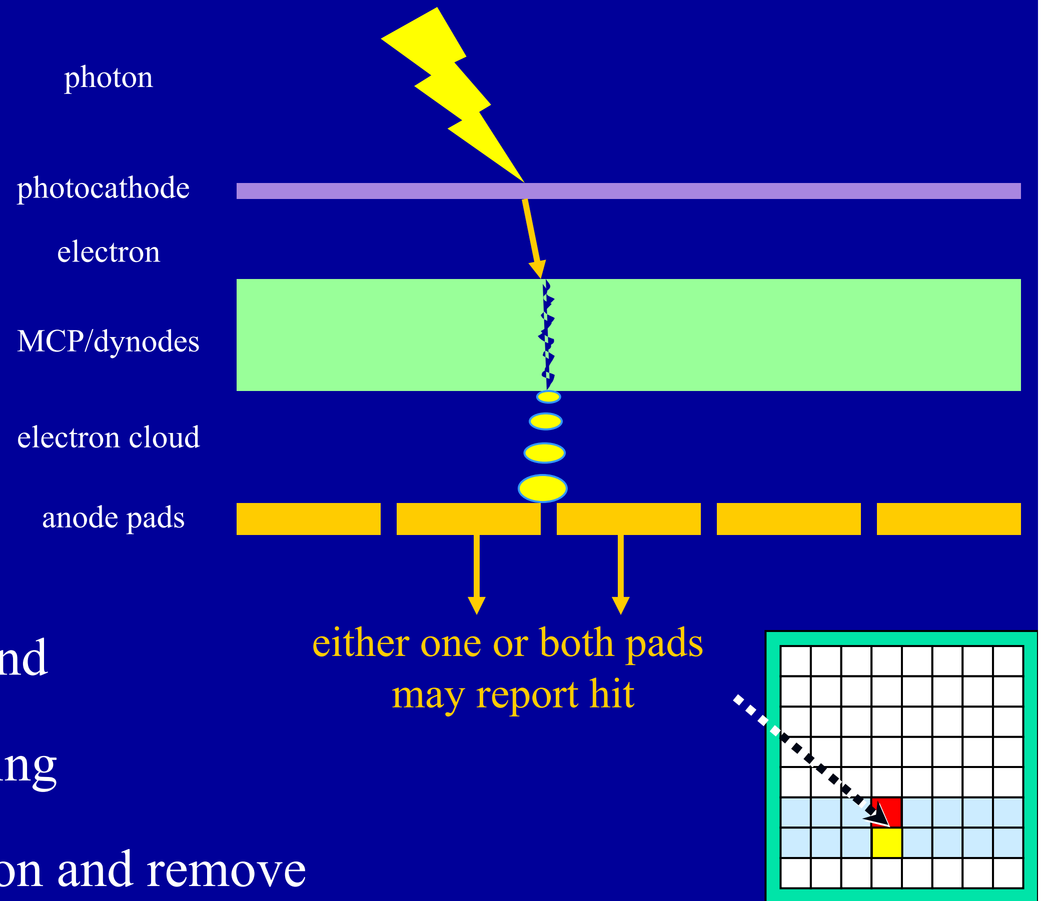
Fake extra hit will broaden θ_c resolution

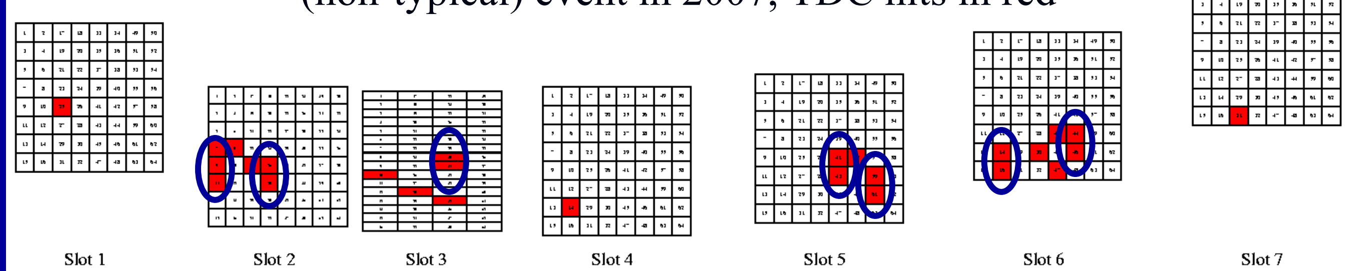
Identify charge sharing hits using ADC

→ measure charge as well as hit time

- if neighbor pads have same hit time and
- if hit charges are consistent with sharing

→ assign charge-weighted average location and remove
extra hit, improve θ_c resolution and N_0 measurement

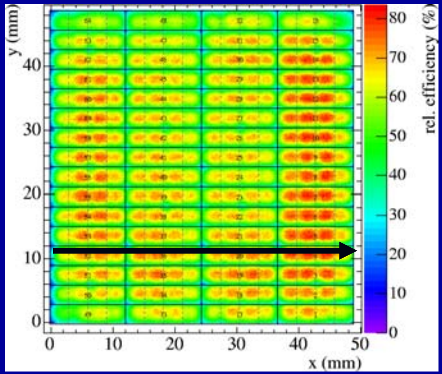




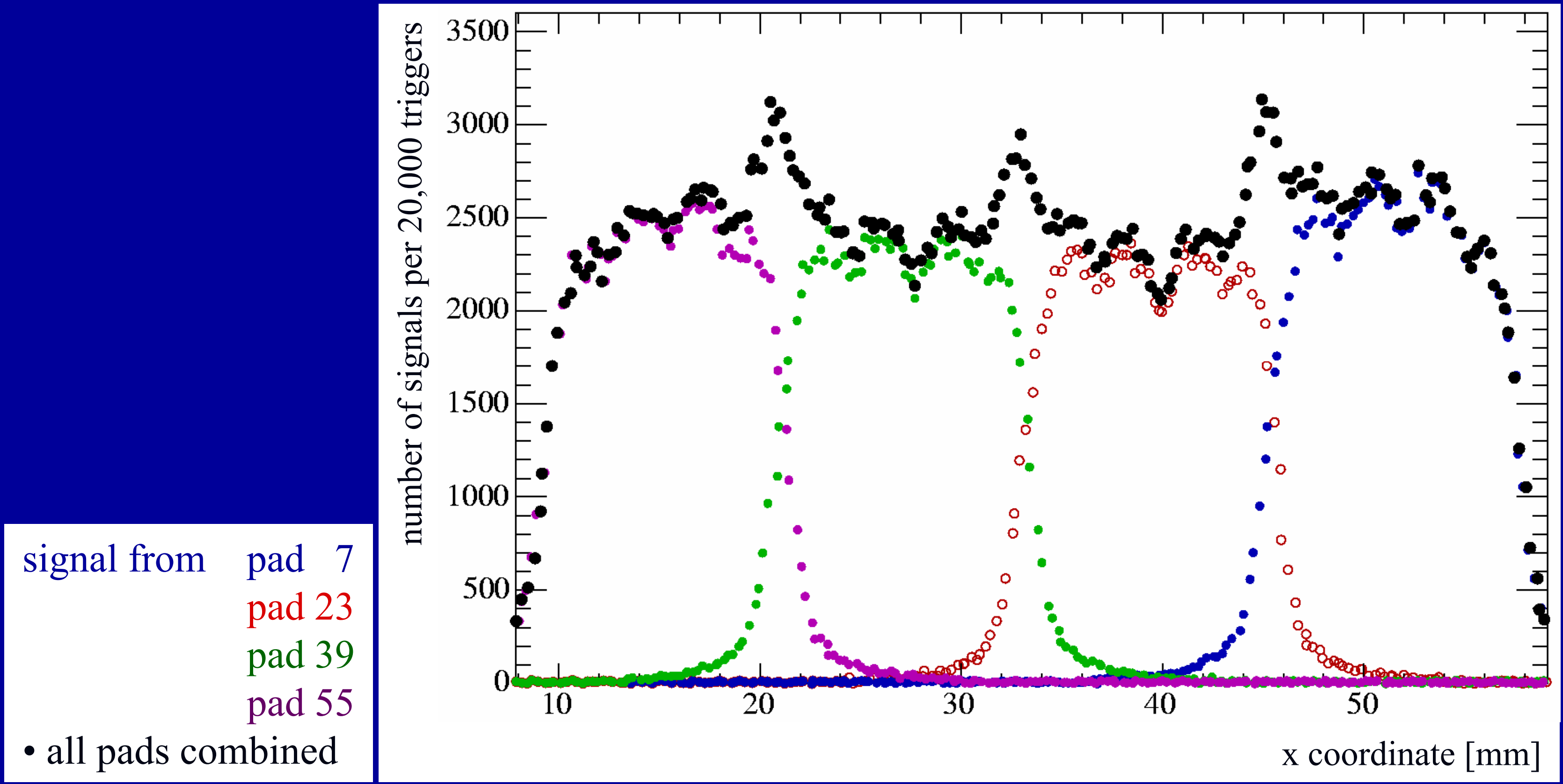
(non-typical) event in 2007, TDC hits in red

Charge Sharing

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

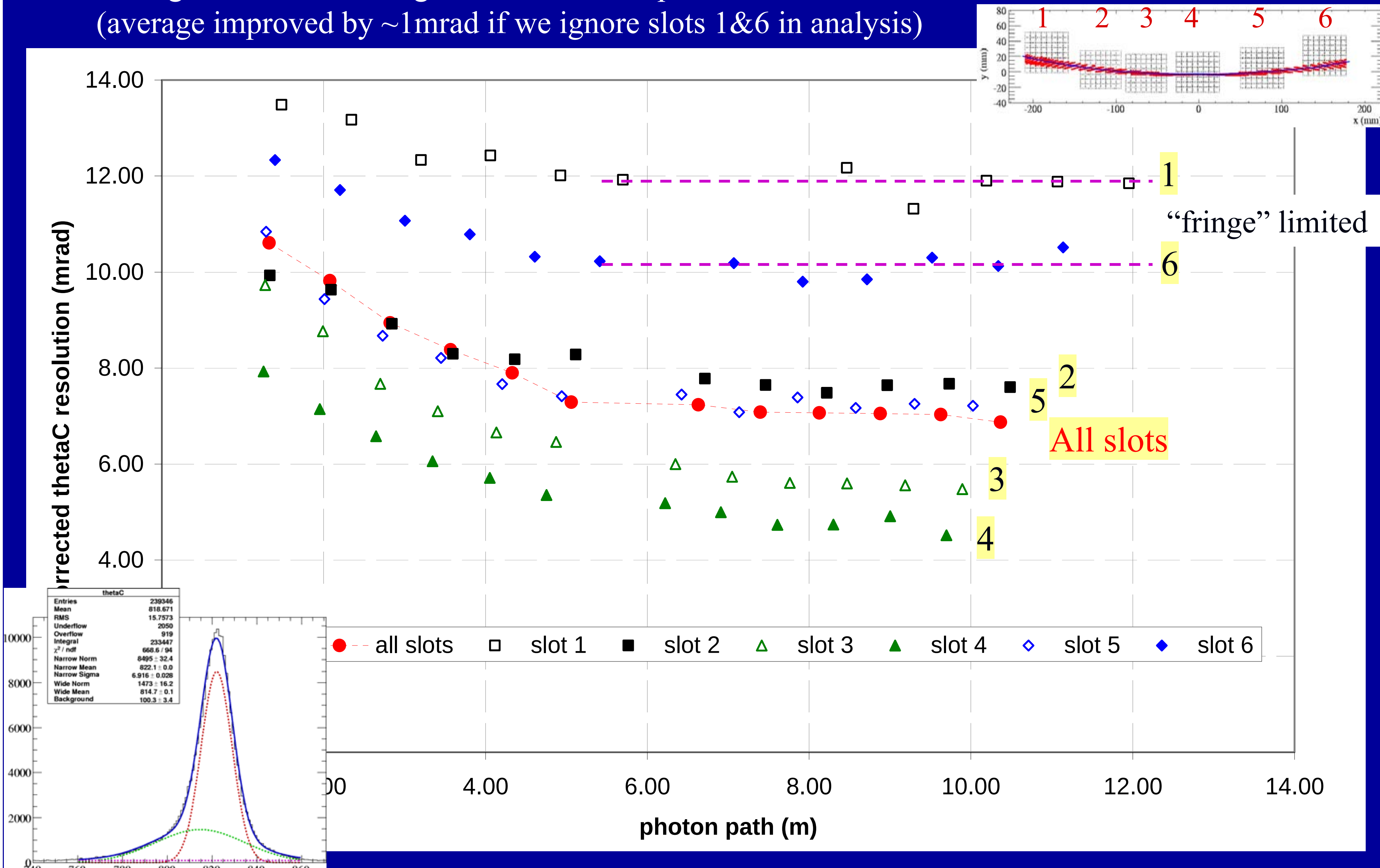


If signals are detected simultaneously on two or more neighboring pads this signature can be used to constrain the photon hit position more precisely and improve thetaC resolution.



Fully corrected thetaC as function of photon path for each slot

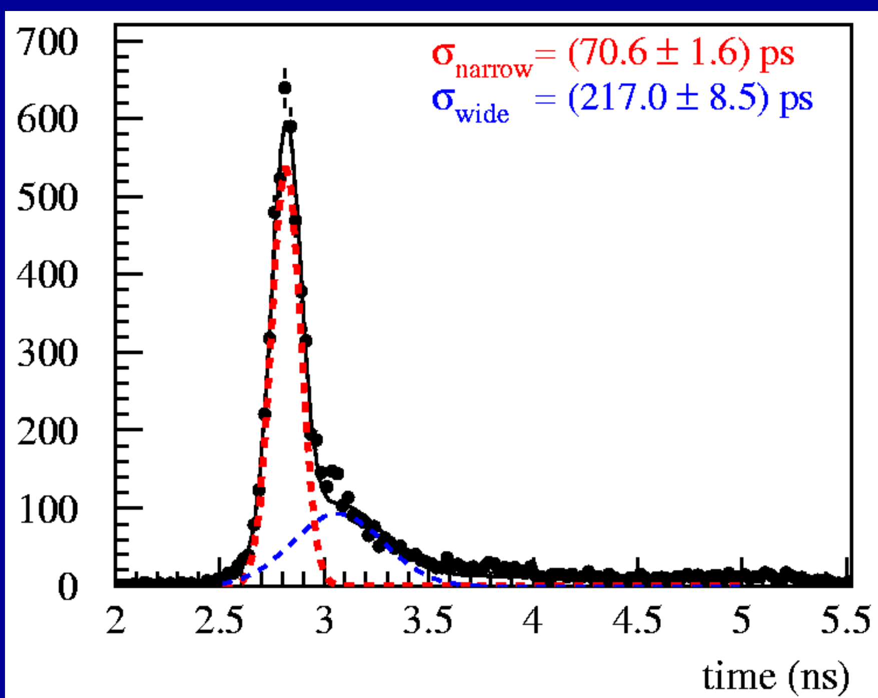
→ if we get a handle on fringe issue we will improve overall resolution (average improved by ~1mrad if we ignore slots 1&6 in analysis)



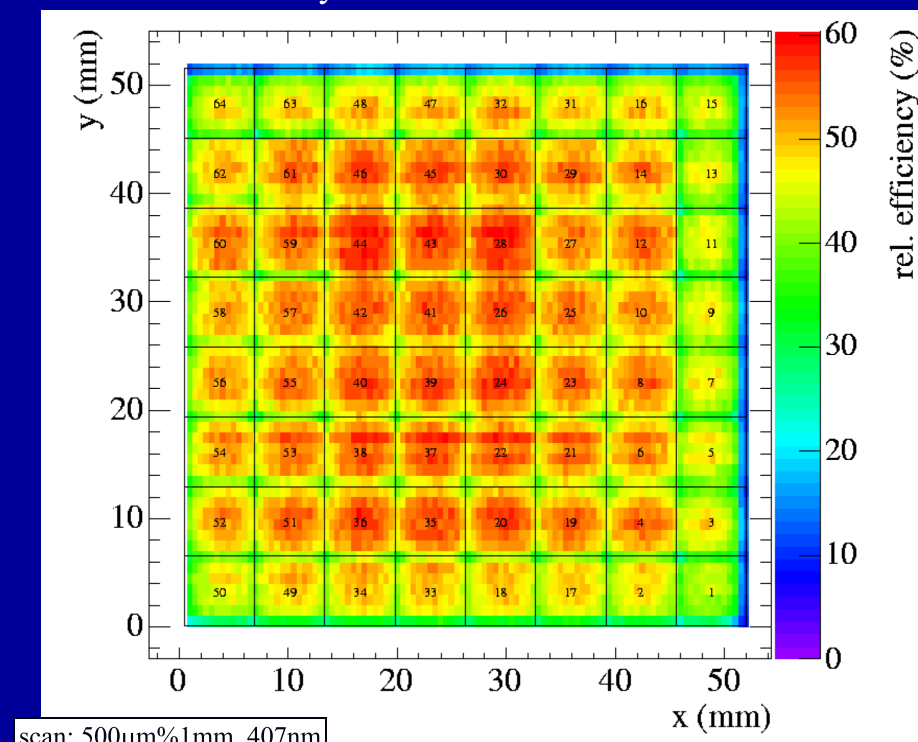
Burle 85011-501 MCP-PMT

- 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

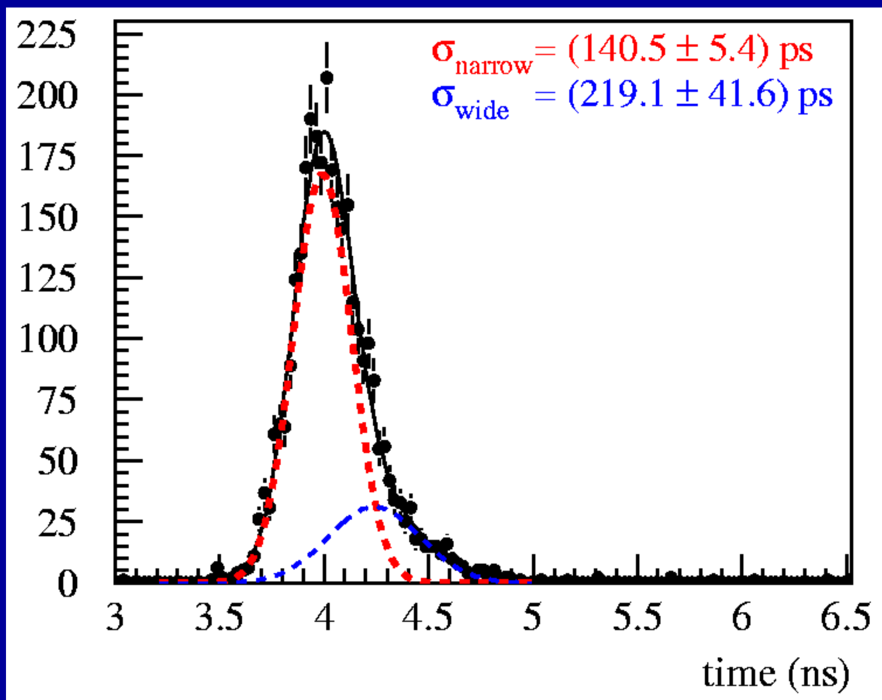


Hamamatsu H-8500

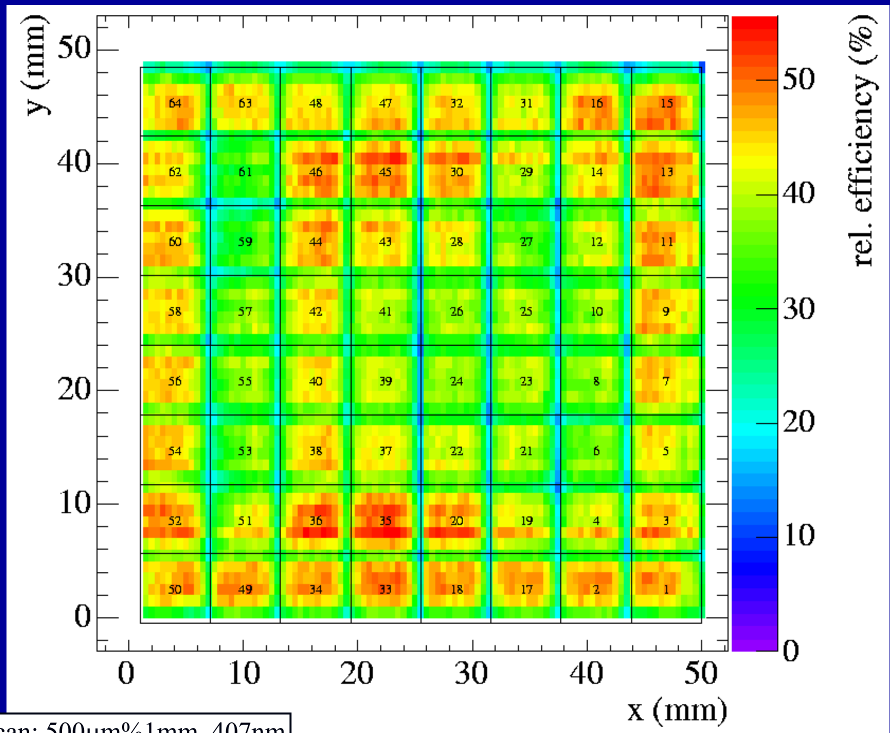
Hamamatsu H-8500 Flat Panel Multianode PMT

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

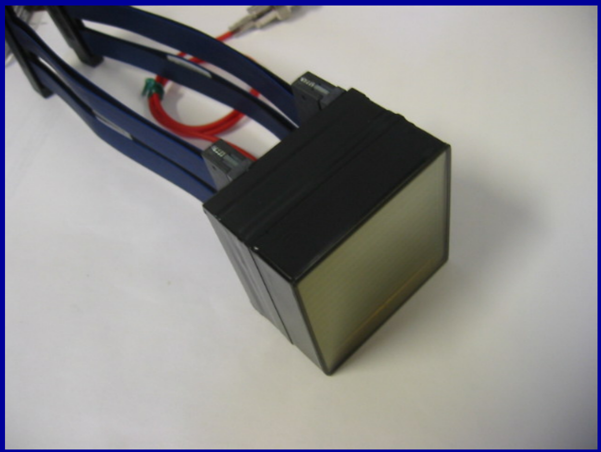
→ IEEE NSS 2003



Efficiency relative to Photonis PMT

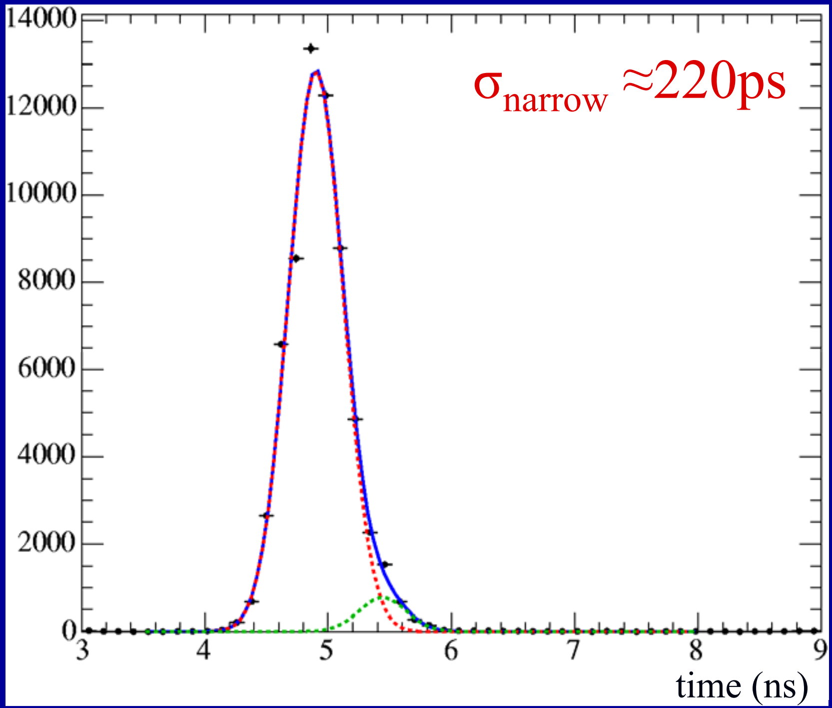


scan: 500μm%1mm, 407nm

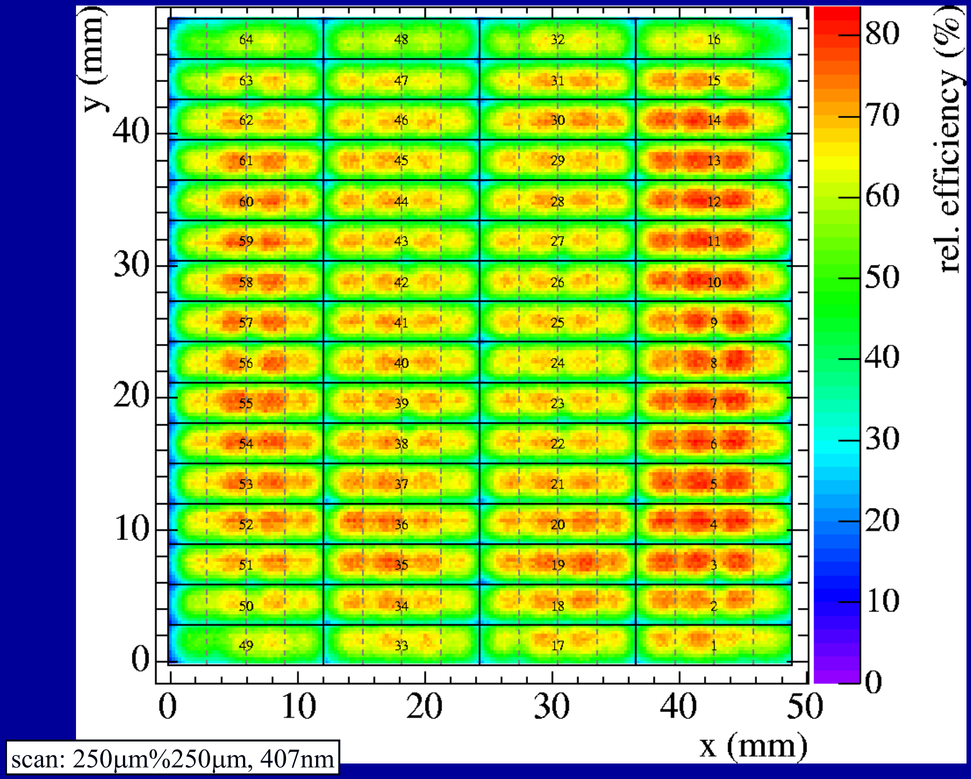


Hamamatsu H-9500 Flat Panel Multianode PMT

- 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



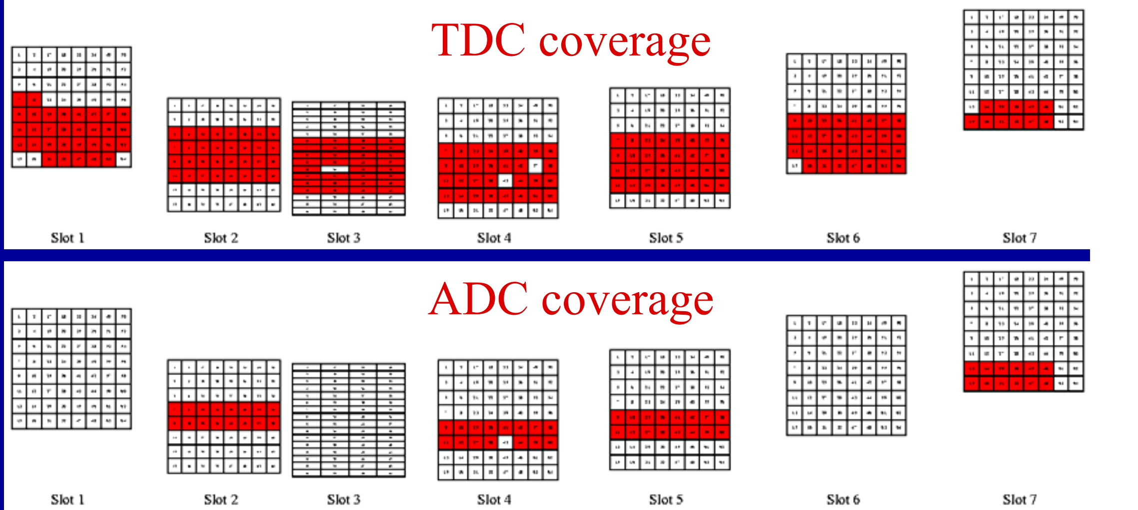
Efficiency relative to Photonis PMT



Prototype Readout

For 2005-2007 beam tests read out two Hamamatsu MaPMTs (H-8500 and H-9500) and up to four Burle 85011-501 MCP-PMTs (total of up to 384 pixels)

- Elantec 2075EL amplifier (130x) on detector backplane
- SLAC-built constant fraction discriminator
- Twelve Phillips 7186 TDCs (25ps/count) for 192 channels
- Three Phillips 7166 ADCs for 48 channels
- Twelve channels read out via U. Hawaii ASIC
- Read out only pixels close to expected hit pattern of Cherenkov photons
  (155 pixels used in analysis shown today)



Photodetector and TDC/ADC coverage in 2007 runs

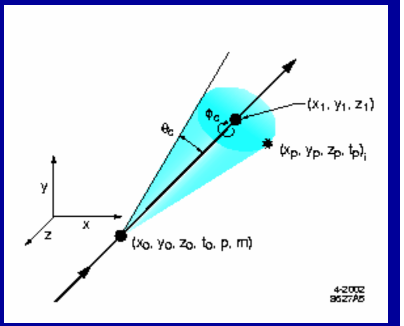
- Calibration with PiLas laser diode (~35ps FWHM) to determine and monitor TDC channel delays and ps/count calibration

Reconstruction:

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

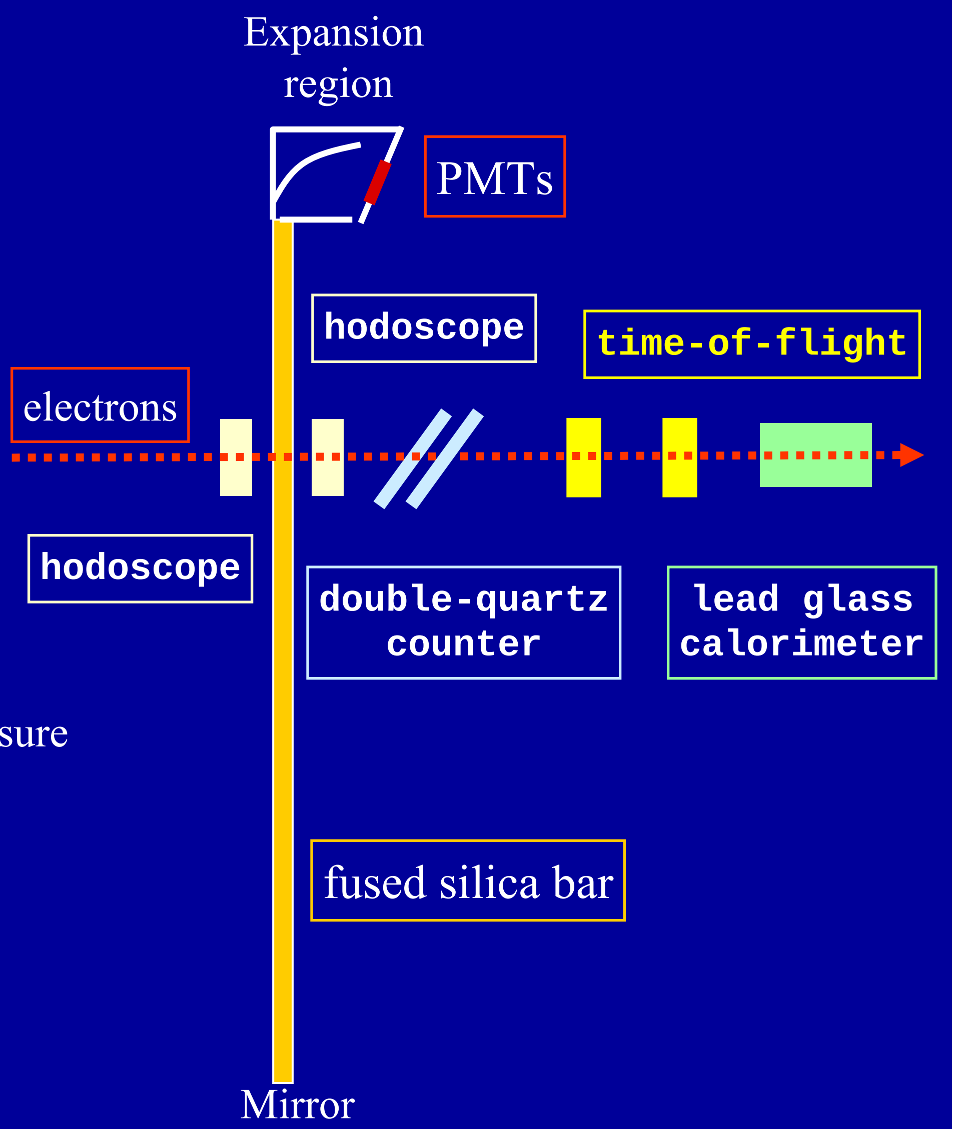
→ Pixel with hit (x_{det}, y_{det}, t_{hit}) defines 3D photon propagation vector in bar and Cherenkov photon properties *(assuming 90° track, β=1, <λ>=410nm)*

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



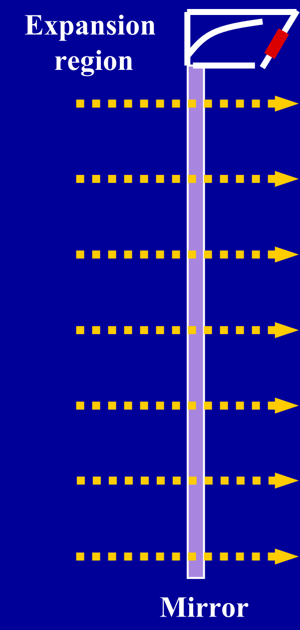
Beam Test Setup

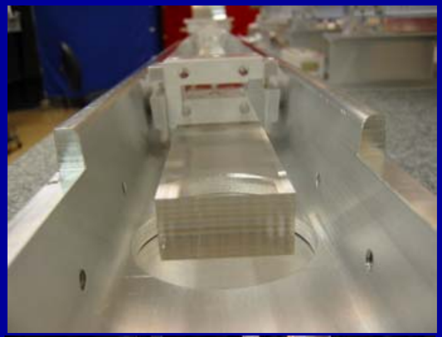
- Prototype located in beam line in End Station A at SLAC
- Accelerator delivers 10 GeV/c electron beam (e^-)
- Beam enters bar at 90º angle.
- 10 Hz – 30 Hz pulse rate, approx. 0.2 particles per pulse
- Bar contained in aluminum support structure
- Beam enters through thin aluminum foil windows
- Bar can be moved along long bar axis to measure photon propagation time for various track positions
- Trigger signal provided by accelerator
- Two fiber hodoscopes (16+16 channels, ~2mm pitch) measure 2D beam position and track multiplicity
- Cherenkov counter monitors event time
- Lead glass calorimeter selects single electrons
- Time of flight system (see Jerry's talk tomorrow)
- All detectors read out via CAMAC to linux system

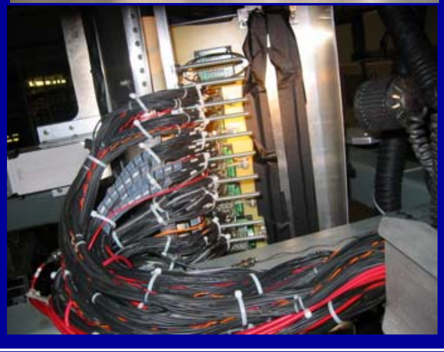


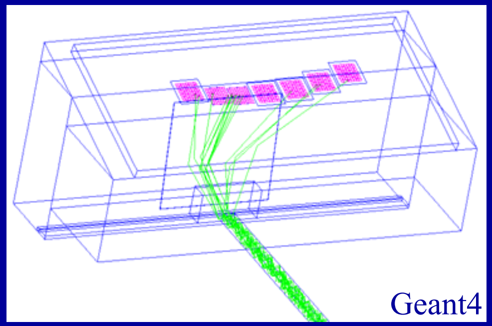
Beam Test Data

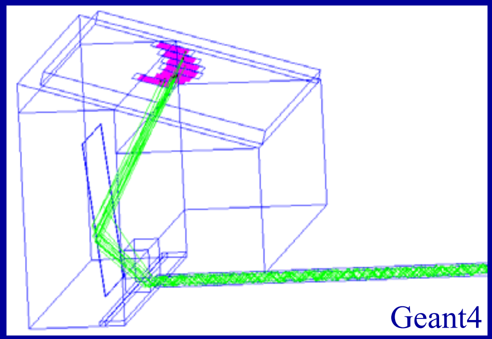
- In 2005, 2006, and 2007 we took beam data for 1-2 weeks each, runs lasting from few hours to several days.
- Total of 22M triggers recorded, 10 GeV/c e^-
- Reconstructed ~1.6M good single-track events
- Beam entered the radiator bar in 7 different locations.
- Photon path length range: 0.75m – 11m.
- Simulated full detector with all efficiencies in Geant4.



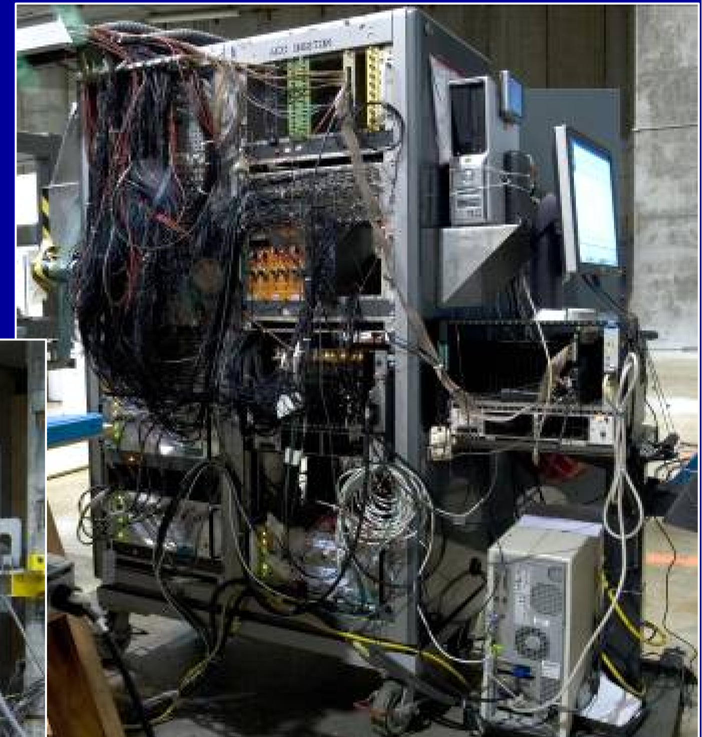




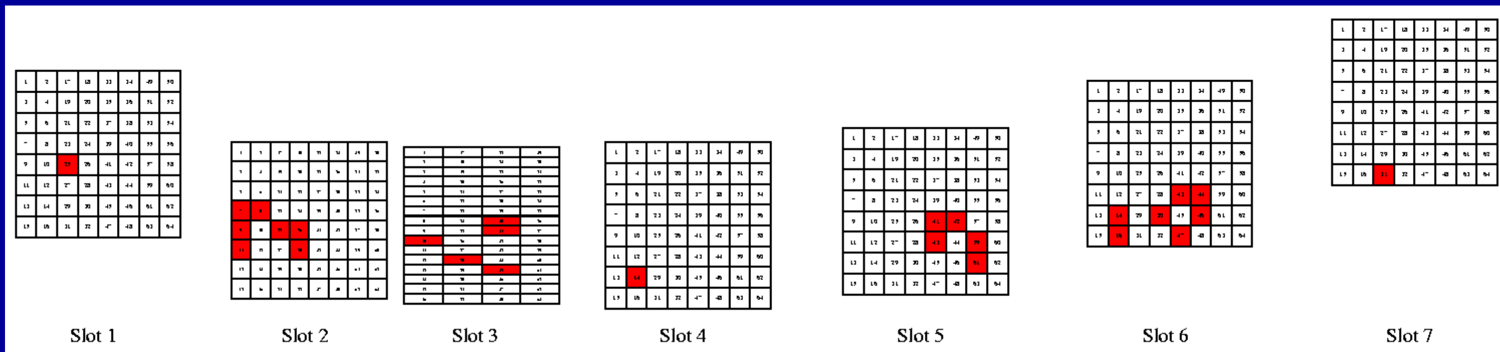




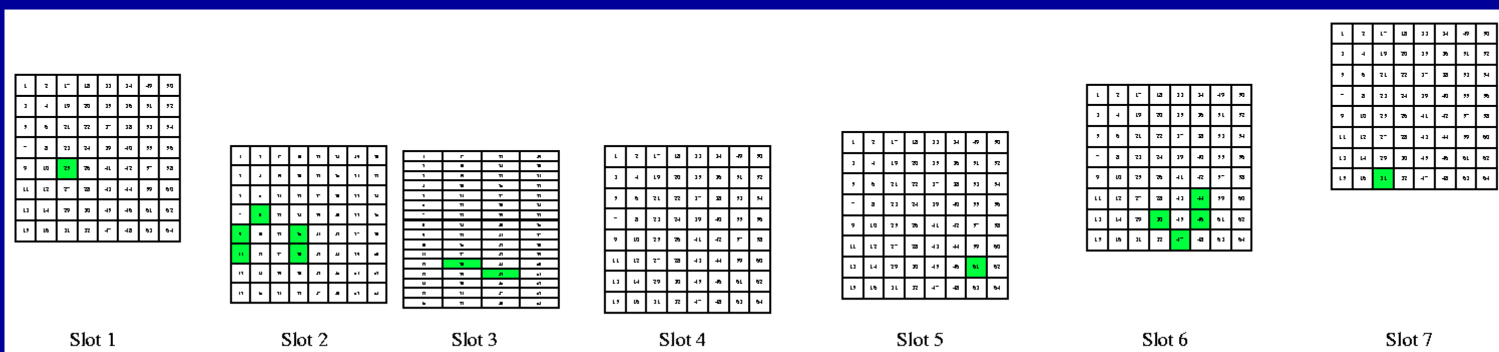
Beam Test Setup in 2007



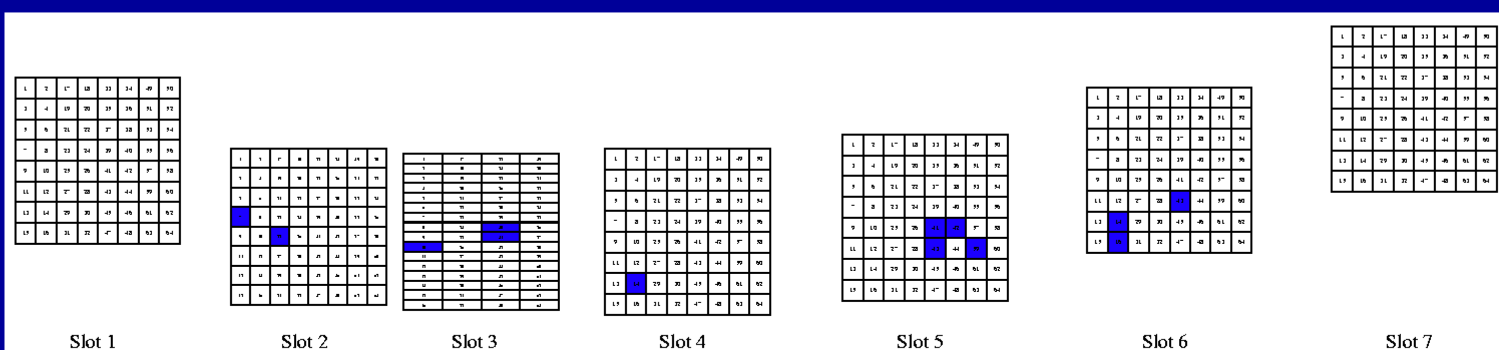
Event in Focusing DIRC 2007



All hits in event



Early hits (peak 1)



Late hits (peak 2)

Beam Detectors

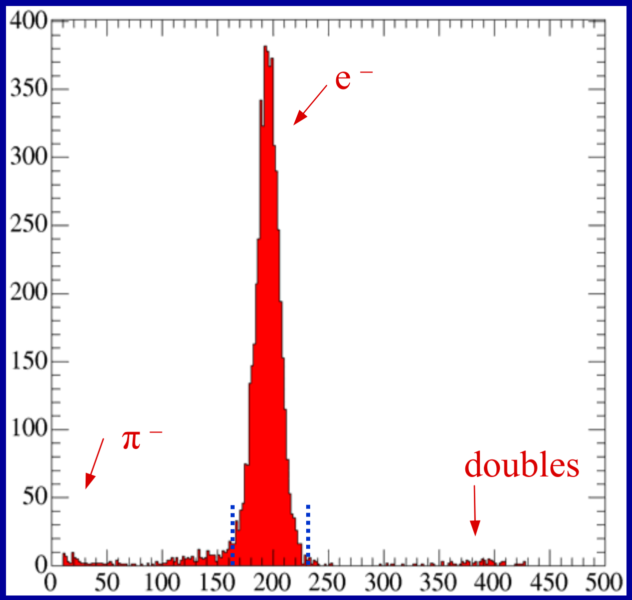
Event selection:

- 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

Data corrections:

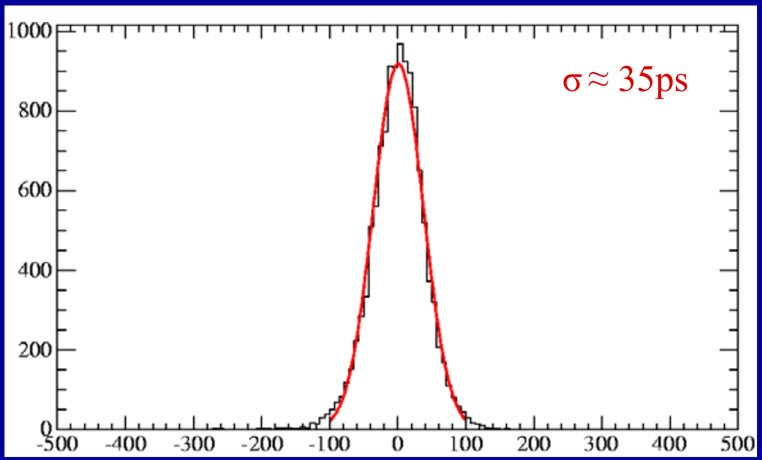
- use hodoscope beam spot to correct the path of photons in bar
- use ADC measurement in start counters to correct TDC value for time walk
  → resulting start counter resolution ~35ps
- use PiLas laser diode to calibrate prototype TDCs and cable delays
  → all pixels aligned in time

Lead glass: single track ADC distribution



Charge (ADC counts)

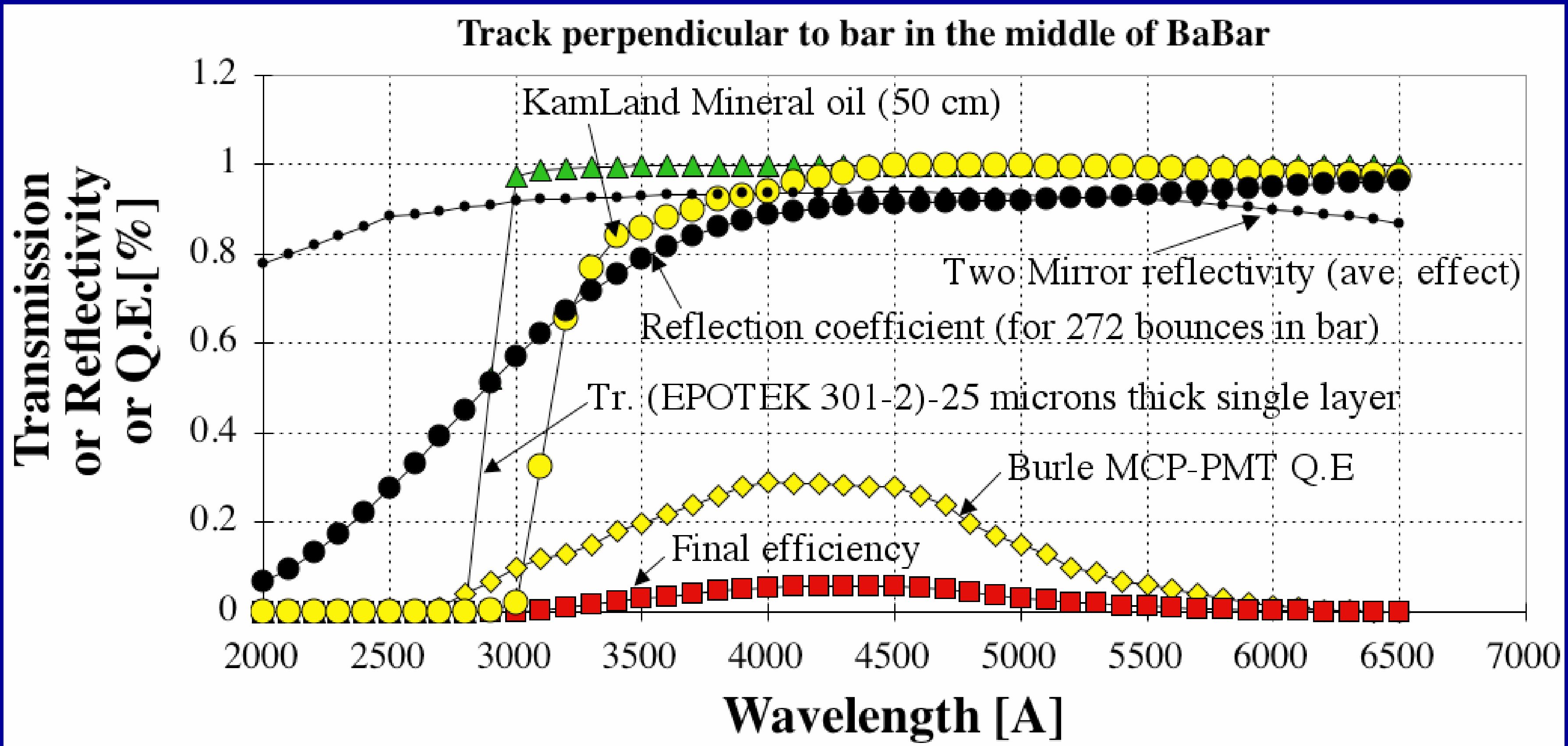
Start counters: corrected event time



Corrected time (ps)

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

SuperB Detector Options

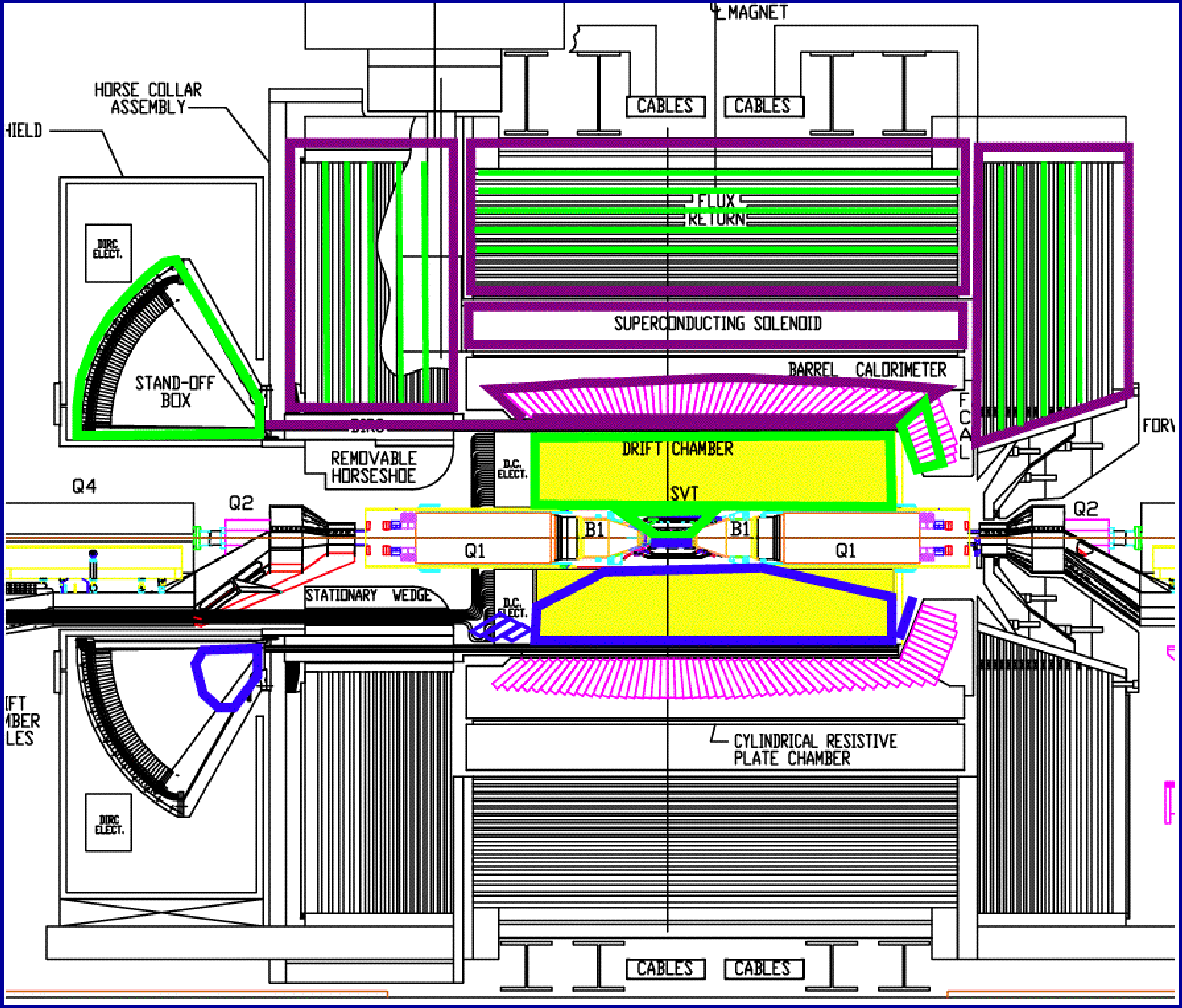
SuperB Conceptual Design Report§ includes DIRC barrel PID options

Reuse BABAR, keep DIRC radiator bars

option A:
- keep stand-off box
- replace PMTs with similar PMTs

option B:
- keep stand-off box
- replace PMTs with fast MaPMT/MCP

option C:
- add focusing optics
- use smaller stand-off and fast MaPMTs



§arXiv:0709.0451, INFN/AE - 07/2, SLAC-R-856, LAL 07-15