# STATUS OF THE FOCUSING DIRC

**Focusing DIRC R&D effort at SLAC:**

| | |
|---|---|
| Jose Benitez [#] | David W.G.S. Leith [#] |
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| Larry L. Ruckman [+] | Jochen Schwiening [#] |
| Gary S. Varner [+] | Jerry Va'vra [#] |

[#] SLAC     [+] University of Hawai'i
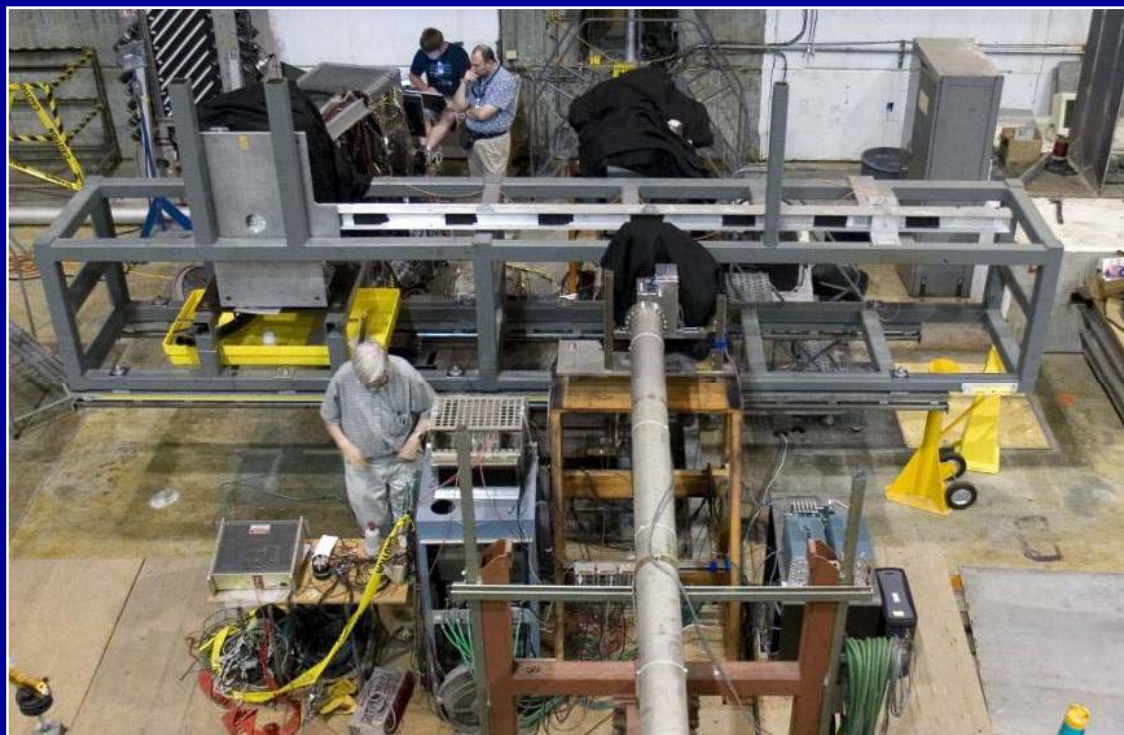
- Motivation
  - DIRC Principle
  - BABAR DIRC Performance Highlights
  - DIRC at future experiments (i.e. SuperB)

- Focusing DIRC Prototype Design

- Beam Tests 2005/2006
  - Timing resolution, $\theta_c$ resolution
  - Chromatic correction of $\theta_c$ using precision timing
  - Projected PID performance

- News of Beam Test in 2007
  - ADC readout
  - New U. Hawaii electronics
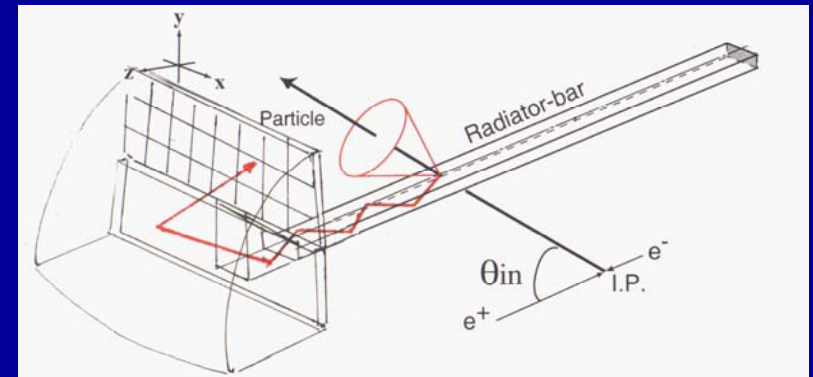
## Detection of Internally Reflected Cherenkov Light
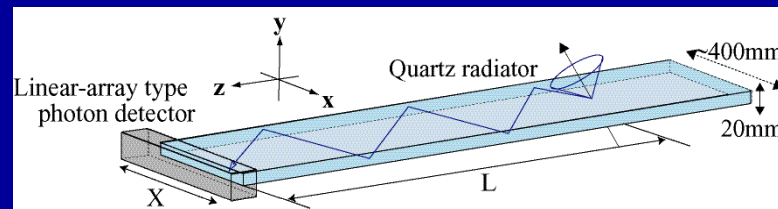
Novel Ring Imaging CHerenkov detector [§]
  based on total internal reflection of Cherenkov light
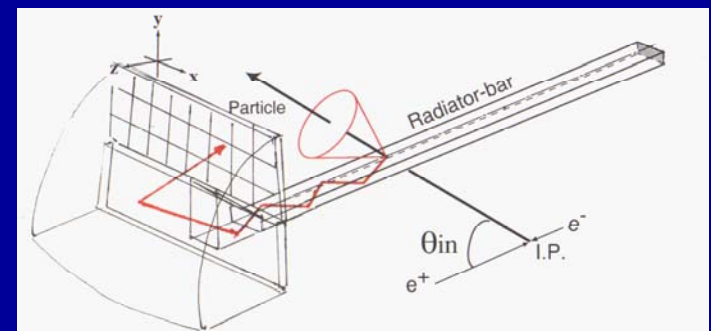  used for the first time in BABAR for hadronic particle identification

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)
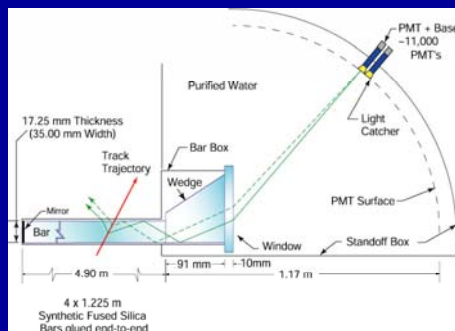
BABAR DIRC          TOP Counter          Focusing DIRC
                  *(see talk earlier today)*

[§]*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 $\langle n(\lambda) \rangle \approx 1.473$, radiation hard, homogenous, low chromatic dispersion)
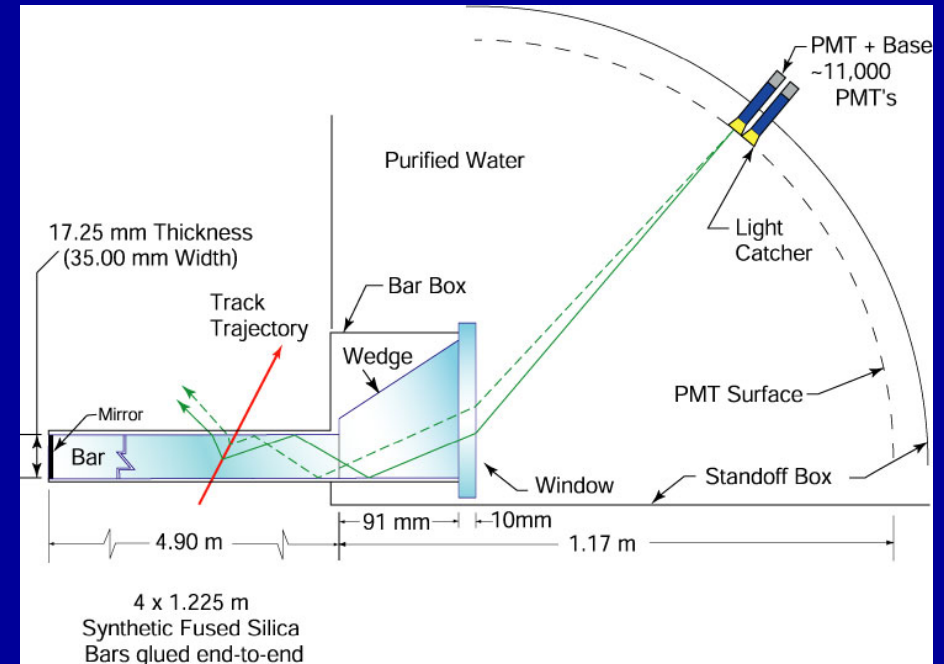


- Photons exit via wedge into expansion region (filled with 6m³ pure, de-ionized water).

- 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 <u>time</u> of Cherenkov photons, defining $\theta_c, \phi_c, t_{propagation}$ of photon.

  (time measurement used primarily for rejecting accelerator background and resolving ambiguities)
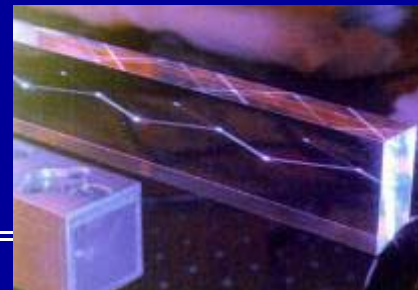
Almost eight years of experience in PEP-II/BABAR B-factory mode [§]:

## 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.

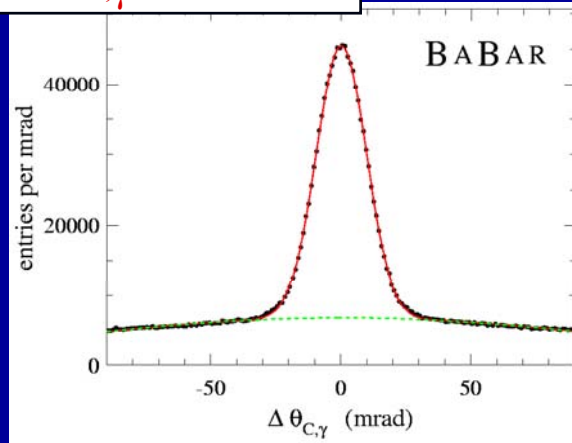→ Time measurement essential in dealing with backgrounds.

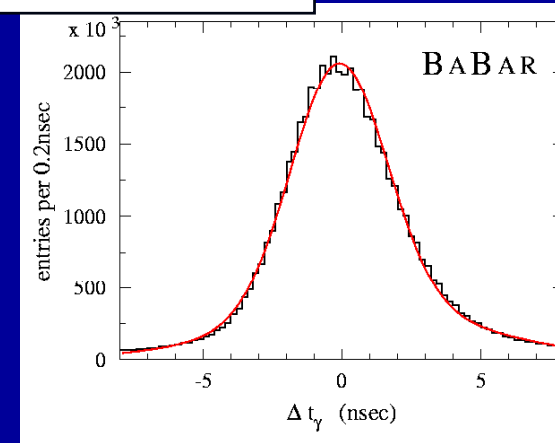[§]*J.S. talk at RICH 2004 and*
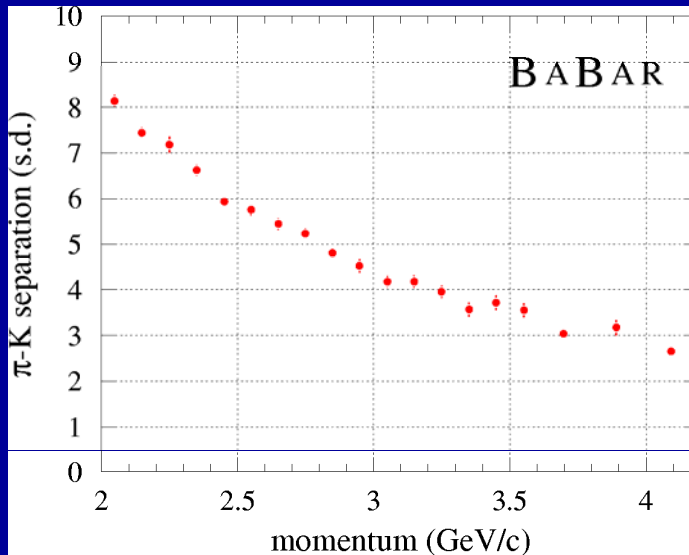*Nucl. Instrum. Meth. A502 (2003) 67*

## Single Photon resolution

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

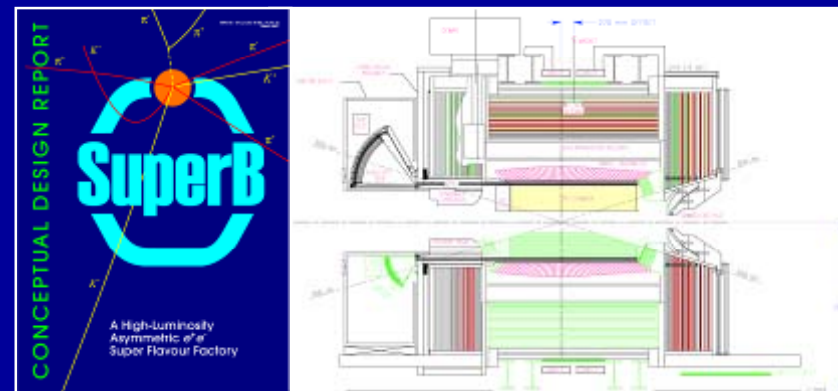$\sigma(\Delta t_\gamma) = 1.7$ nsec



## π/K separation power:



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

*Nucl. Instrum. Meth. A502 (2003) 67*

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

Focusing mirror effect:
- Focusing eliminates effect of the bar thickness (contributes $\sigma \sim 4$ mrads in BABAR DIRC)
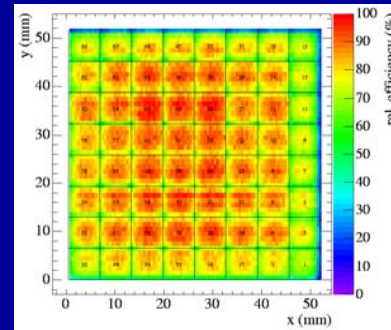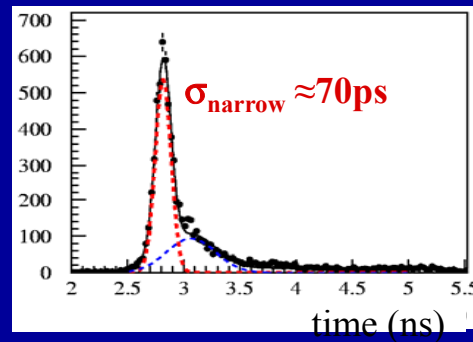- However, the spherical mirror introduces an aberration, so its benefit is smaller.
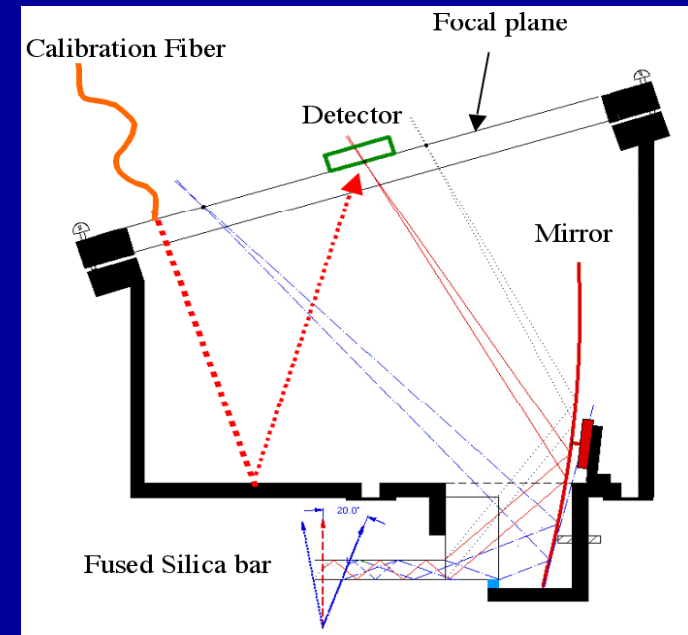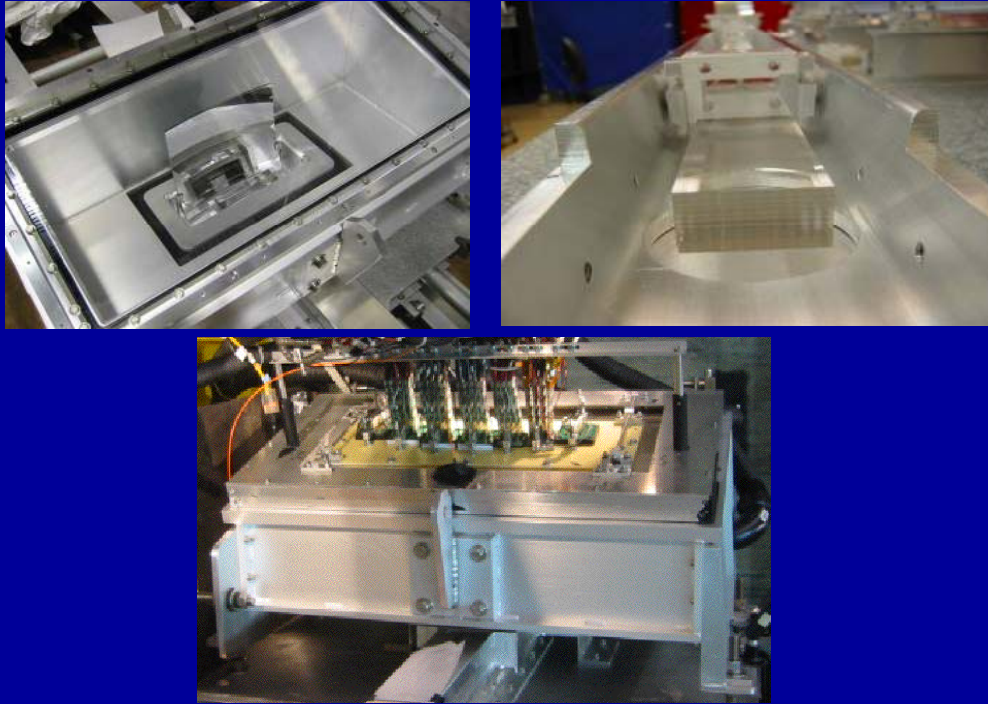
- Radiator:
  - 1.7 cm thick, 3.5 cm wide,  3.7 m long fused silica bar (spares from BABAR DIRC).
- Optical expansion region:
  - filled with a mineral oil to match the fused silica refraction index (KamLand oil).
  - include optical fiber for the electronics calibration (PiLas laser diode).
- Focusing optics:
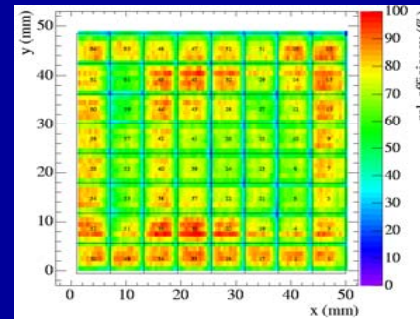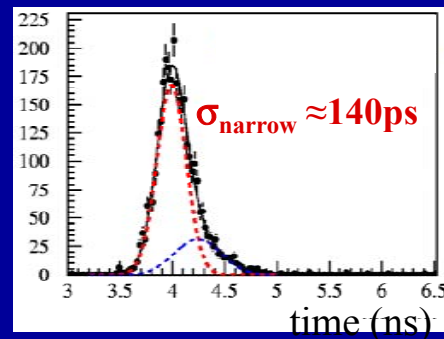  - a spherical mirror with 49cm focal length focuses photons onto a detector plane.

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

$\sigma_{narrow} \approx 70ps$

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

$\sigma_{narrow} \approx 140ps$

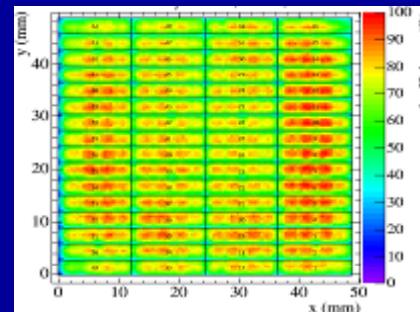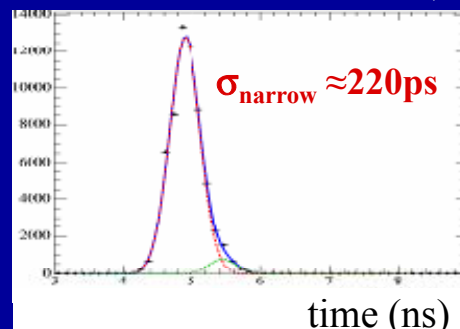3) Hamamatsu H-9500 Flat Panel MaPMT (256 pixels, 3x12mm pad, $\sigma_{TTS}$ ~220ps)

$\sigma_{narrow} \approx 220ps$

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

*Nucl.Inst.&Meth., A 553 (2005) 96*
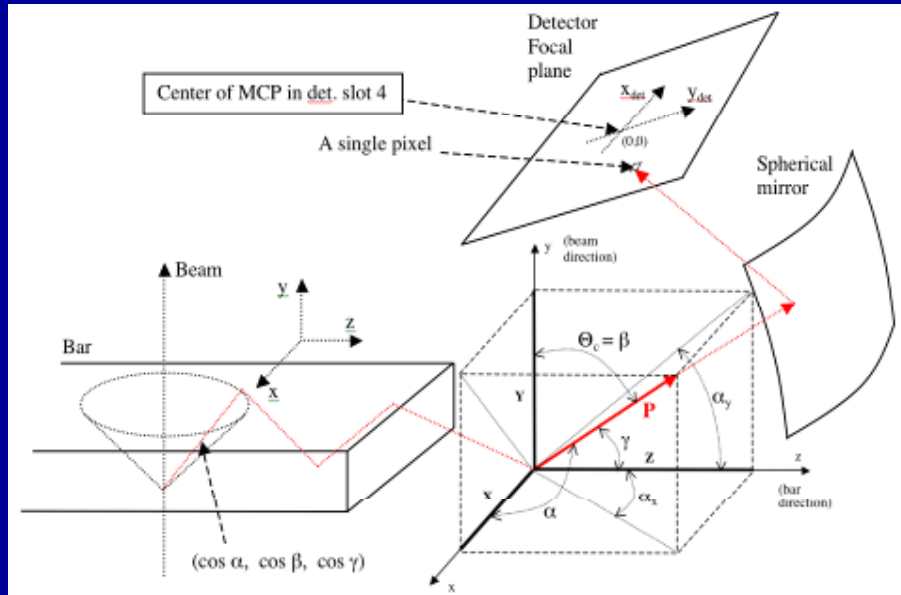
- SLAC 10 GeV/c electron beam in End Station A
- Beam enters bar at 90º angle
- Prototype is movable to 7 beam positions along bar
- Time start from the LINAC RF signal, but correctable with a local START counter
- SLAC-built amplifier and constant fraction discriminator
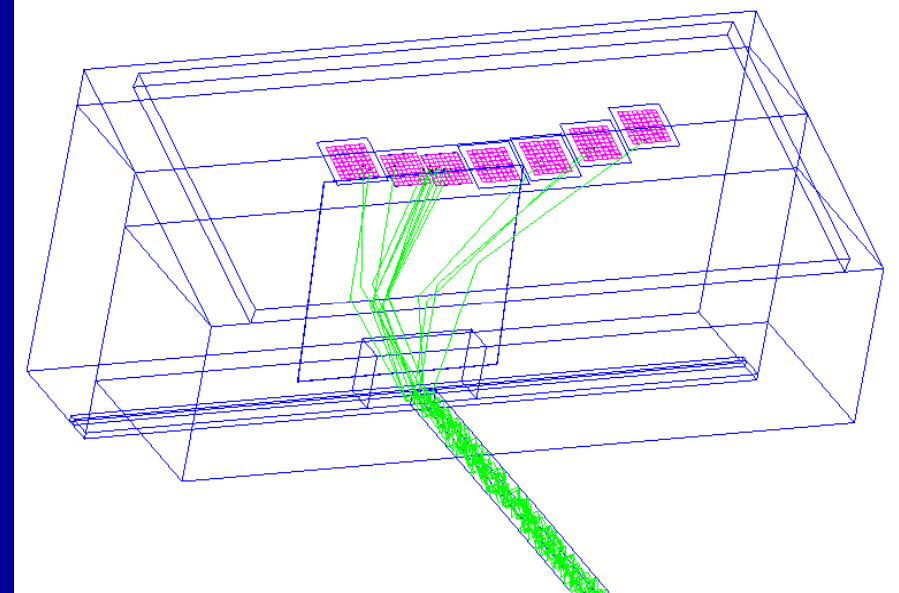- TDC is Phillips 7186 (25ps/count), CAMAC readout



**Beam spot: $\sigma$ < 1mm**

**Prototype photon detectors**

**Scintillator counter** (MCP-PMT)

**Quartz counter** (MCP-PMT)

**Lead glass:**

e⁻

π⁻

**Doubles**

Energy (ADC counts)

10 GeV electrons

**Hodoscope** (scint. fibers)

Beam Pipe

**Lead Glass**

PMT

Quantacon PMT

**Local START time:**

$\sigma$ ~36ps

TDC start time
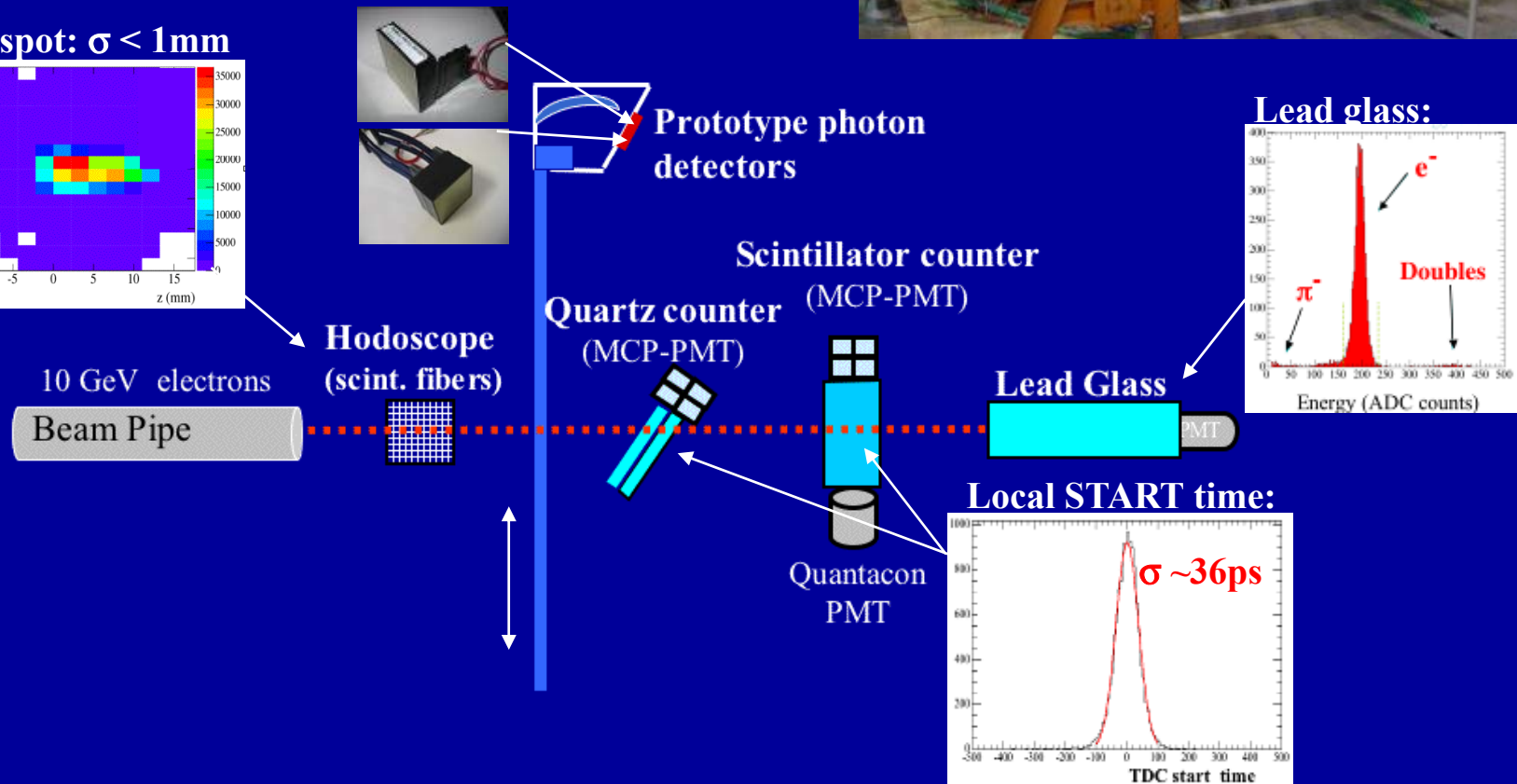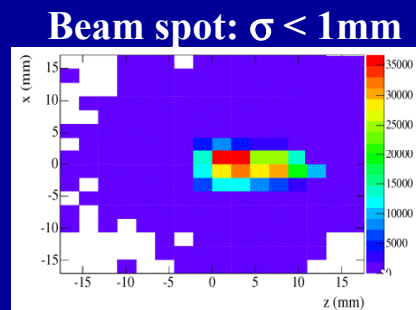
Prototype coordinate systems:

Geant 4 simulation of the prototype:
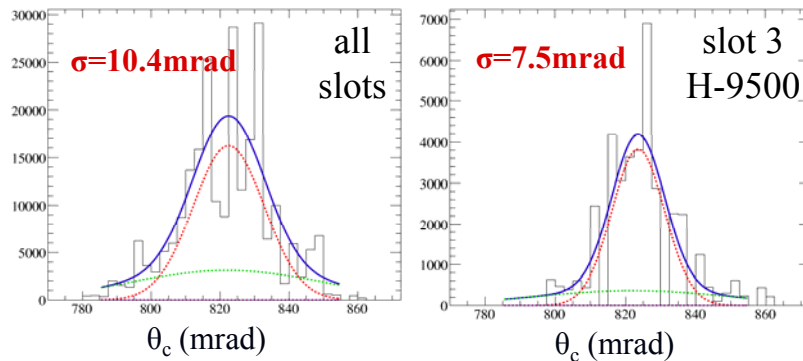


- Each detector pixel determines these photon parameters for average $\lambda$ :

  $\theta_c$, cos $\alpha$, cos $\beta$, cos $\gamma$, Photon path length, time-of-propagation, number of photon bounces.

- We use full GEANT4 simulation to obtain the photon track parameters for each pixel.
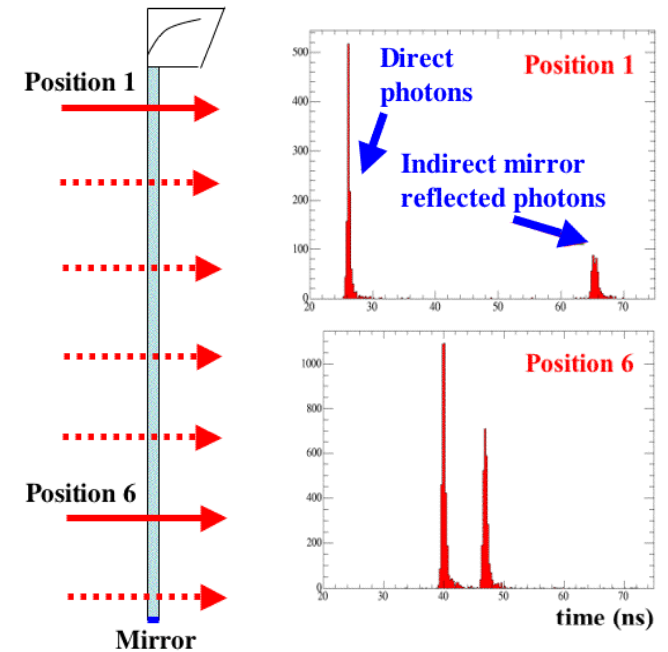  (it is checked by a ray-tracing software)

# 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)

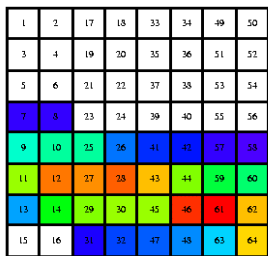Cherenkov photons in time domain

Cherenkov photons in $\theta_c$ domain

σ=10.4mrad — all slots

$\theta_c$ (mrad)

σ=7.5mrad — slot 3 H-9500

$\theta_c$ (mrad)

Position 1

Direct photons — Position 1

Indirect mirror reflected photons

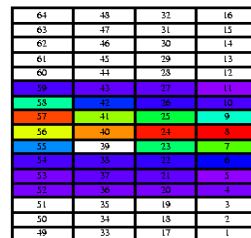Position 6
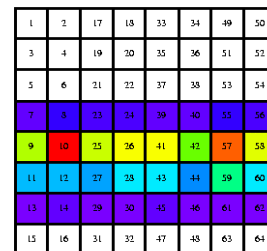
Position 6

time (ns)

Mirror

Cherenkov photons in pixel domain

Burle 85011-501
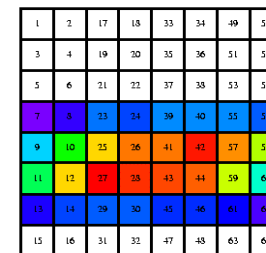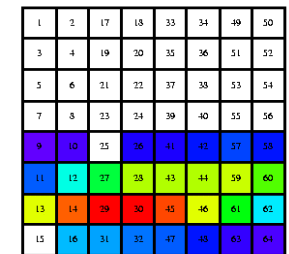
Hamamatsu H-8500

Hamamatsu H-9500

Burle 85011-501

Burle 85011-501

Burle 85011-501
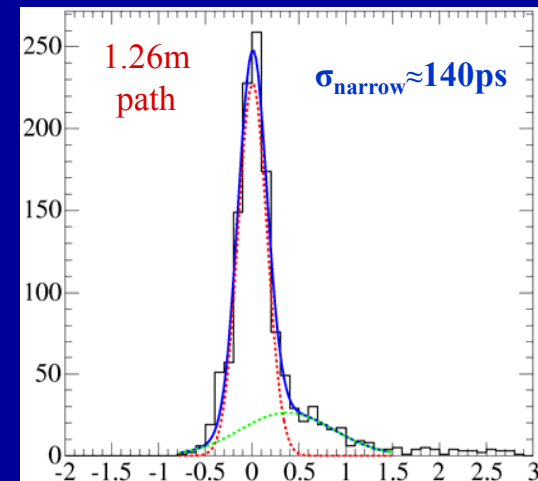
## Example for one detector pixel in position 1

- First peak ~1.3m photon path length

- Second peak ~9.8m photon path length

- Measure time of propagation (TOP)

- Calculate expected TOP
  assuming average $\langle\lambda\rangle\approx410$nm

- Plot $\Delta$TOP: measured minus expected
  time of propagation

- Observe clear broadening of timing peak for
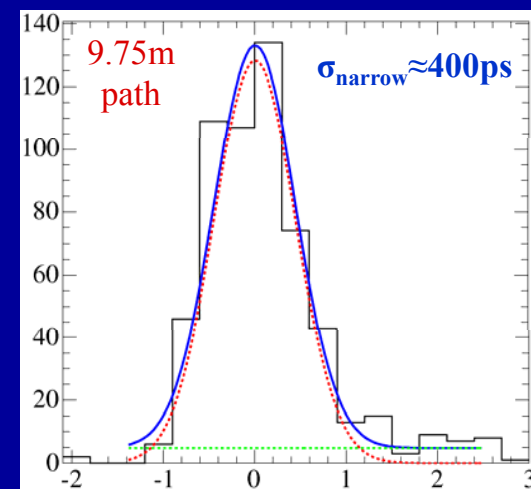  long path length (mirror-reflected photons)

## Two chromatic effects

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

- dispersion of the Cherenkov angle
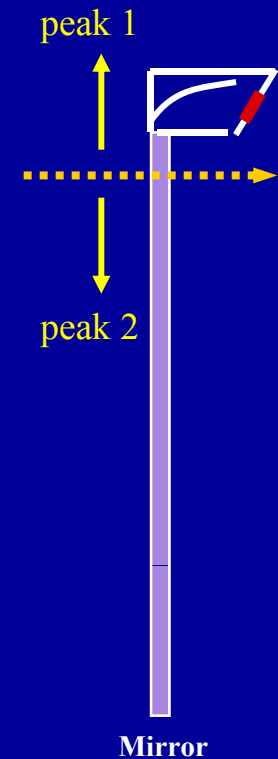  (refractive index is function of wavelength)

→ Use time dispersion to correct Cherenkov angle



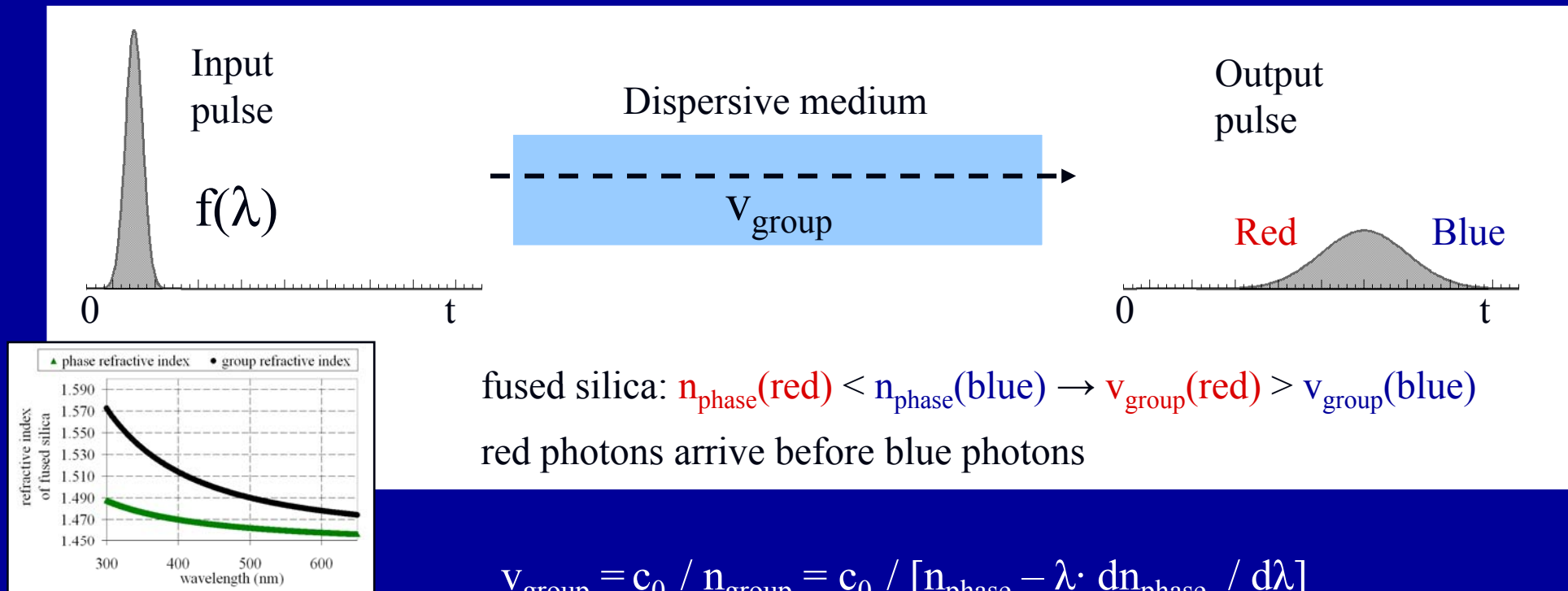1.26m path  $\sigma_{narrow}\approx140$ps

$\Delta$TOP (ns)



9.75m path  $\sigma_{narrow}\approx400$ps

$\Delta$TOP (ns)

peak 1

peak 2

Mirror

Input pulse

$f(\lambda)$

Dispersive medium

$v_{group}$

Output pulse

Red    Blue

0    t    0    t

fused silica: $n_{phase}(red) < n_{phase}(blue) \rightarrow v_{group}(red) > v_{group}(blue)$

red photons arrive before blue photons

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

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

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

dt is pulse dispersion in time, length L, wavelength bandwidth $d\lambda$, refraction index $n(\lambda)$

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

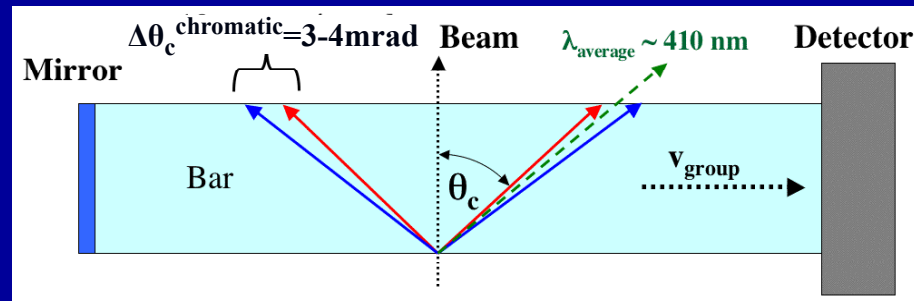Cherenkov angle production controlled by $n_{phase}$ ($\cos \theta_c = 1/(n_{phase}\beta)$:
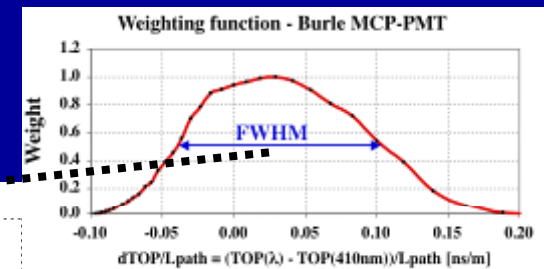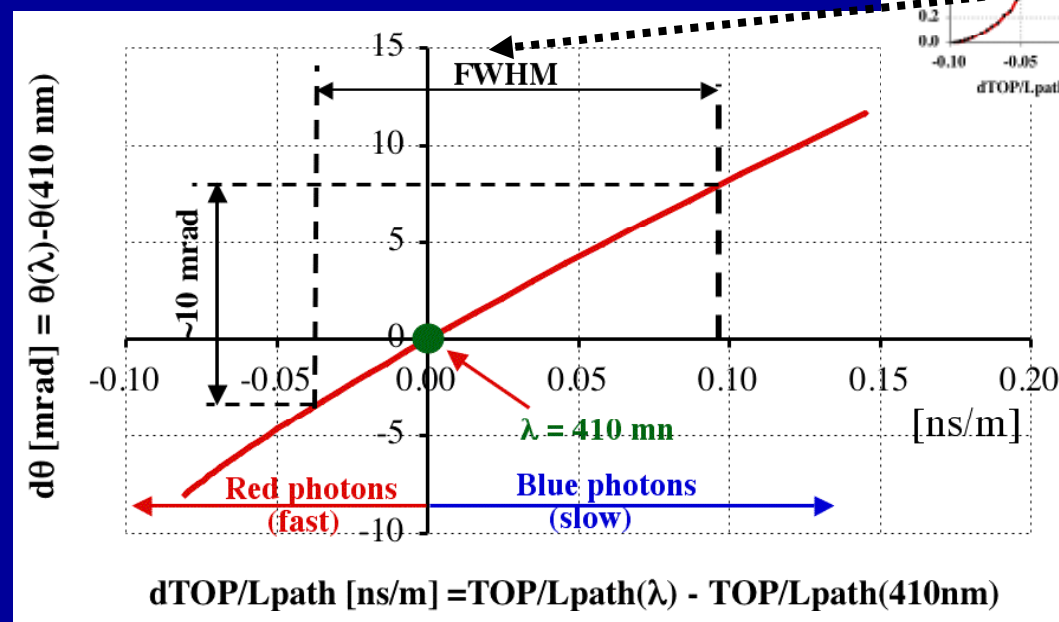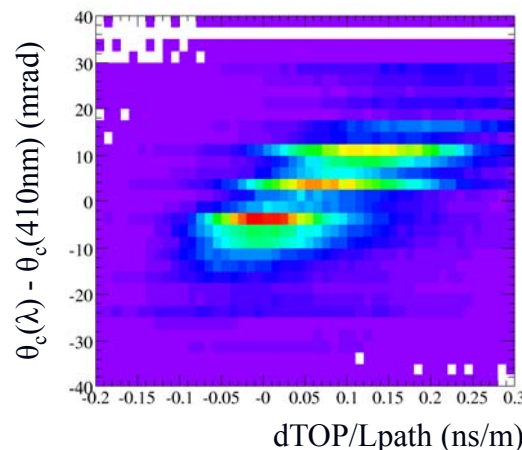
Propagation of photons is controlled by $n_{group}$ ($v_{group} = c_0/n_{group} = c_0/[n_{phase} - \lambda \cdot dn_{phase} \cdot d\lambda$ ):

$\theta_c$ (red) $< \theta_c$ (blue)

$v_{group}$(red) $> v_{group}$ (blue)

Principle of chromatic correction by timing:

Correlation in data, 10m photon path

TOP =
time of
propagation
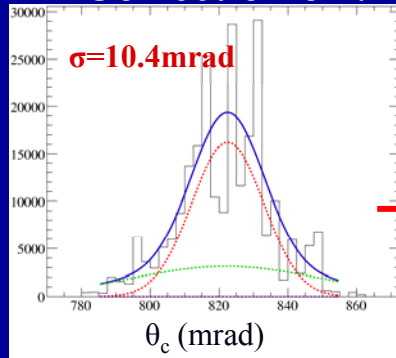of photon
in the bar

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

## All pixels:

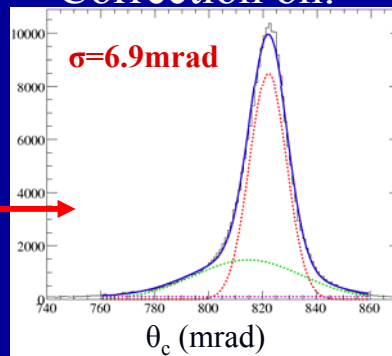### Correction off:

$\sigma=10.4\text{mrad}$

$\theta_c$ (mrad)

### Correction on:

$\sigma=6.9\text{mrad}$

$\theta_c$ (mrad)

## 3mm pixels only:

### Correction off:

$\sigma=7.5\text{mrad}$

$\theta_c$ (mrad)

### Correction on:

$\sigma=5.5\text{mrad}$

$\theta_c$ (mrad)

Position 1
Lpath≈10m

$\theta_c$ resolution (mrad)

Photon path length (m)

■ uncorrected
● corrected

$\theta_c$ resolution (mrad)

Photon path length (m)
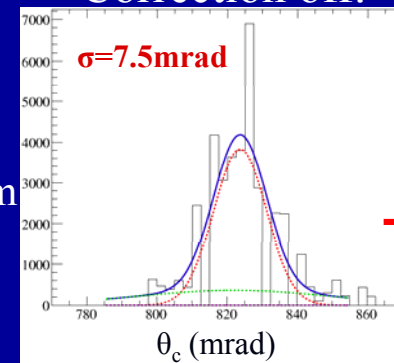
■ uncorrected
● corrected
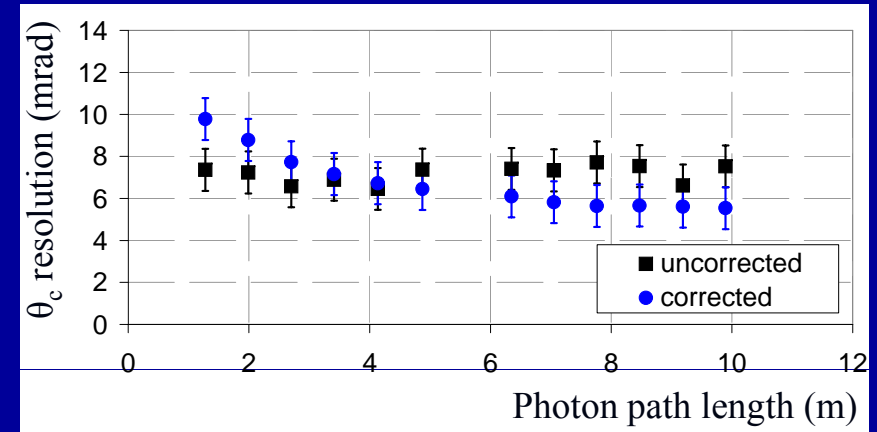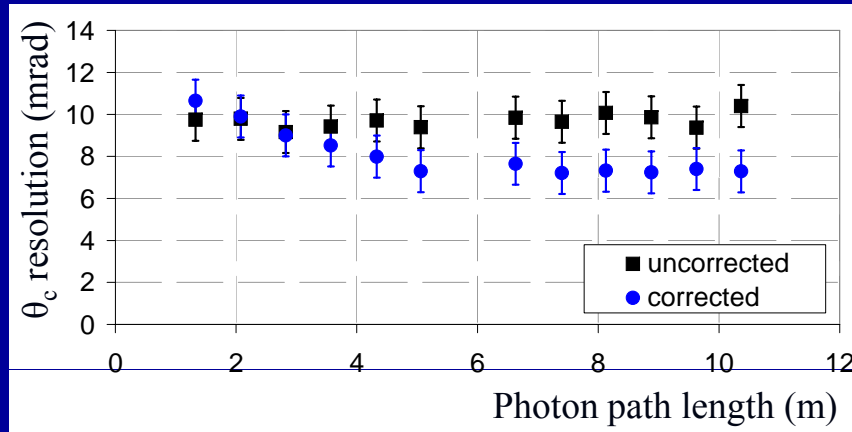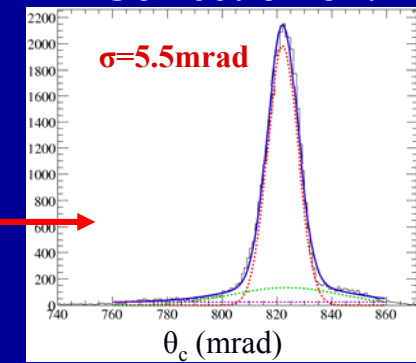
- The chromatic correction starts working for Lpath > 2-3 meters due to a limited timing resolution of the present photon detectors.

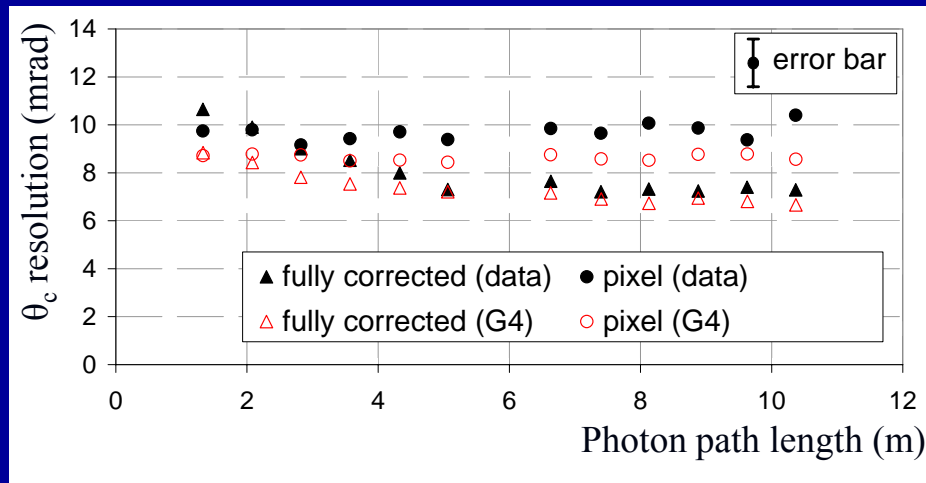- Holes in the <u>uncorrected</u> distributions are caused by the coarse <u>pixelization</u>, which also tends to worsen the resolution. In the corrected distributions this effect is removed because of the time correction.

- Smaller pixel size (3mm) helps to improve the Cherenkov angle resolution; it is our preferred choice.
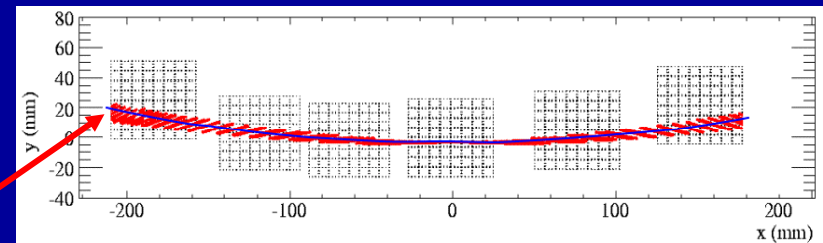
θ$_c$ resolution - all pixels:

θ$_c$ resolution - 3mm pixels only:
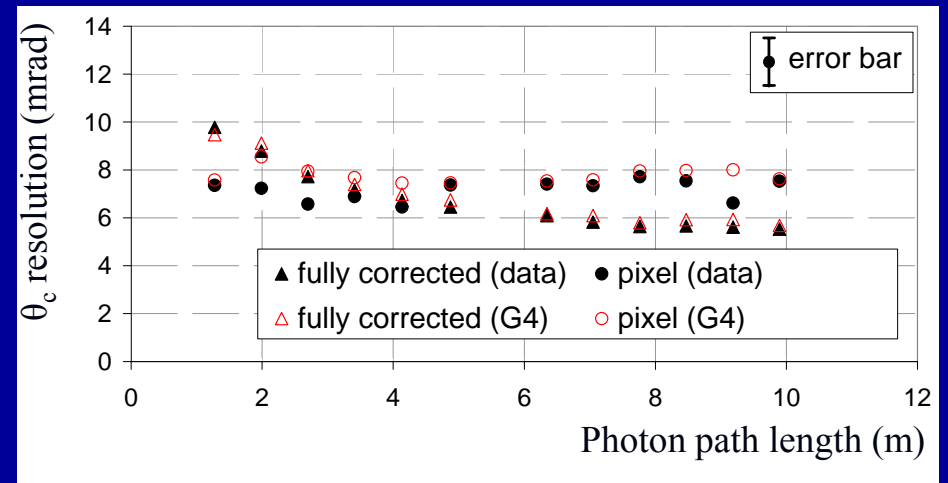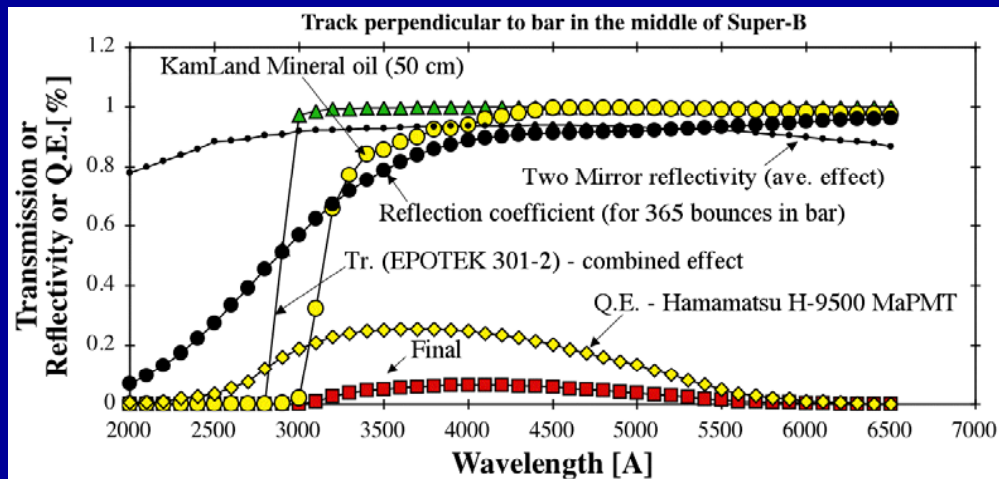




■ Main contributions to the $\theta_c$ resolution:

– 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)
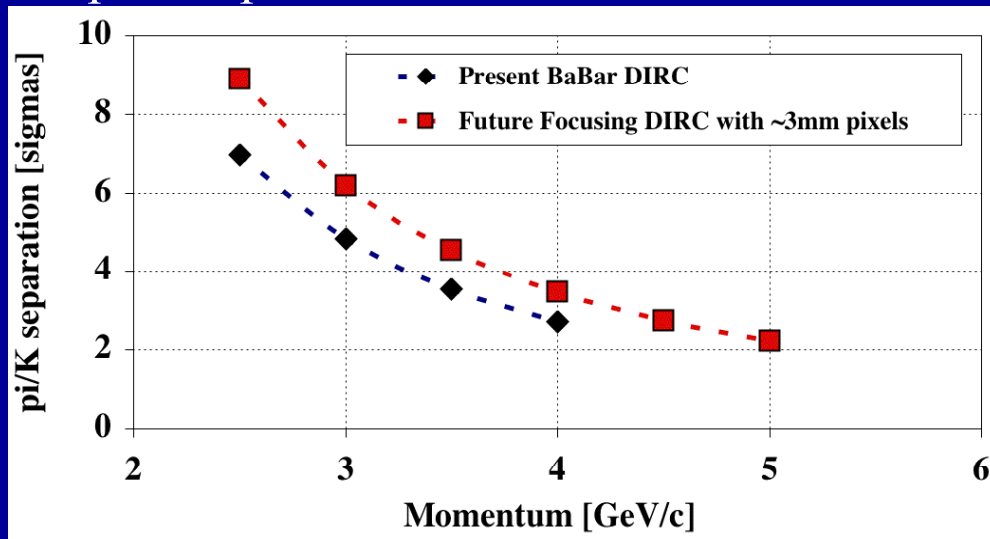
## Focusing DIRC prototype bandwidth:



- 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.

## Expected performance of a final device:



- 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 $N_{pe} \sim 27$.

## 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

- Phillips ADC charge measurement for charge-sharing treatment
  - 2006 data demonstrated that best $\theta_c$ 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
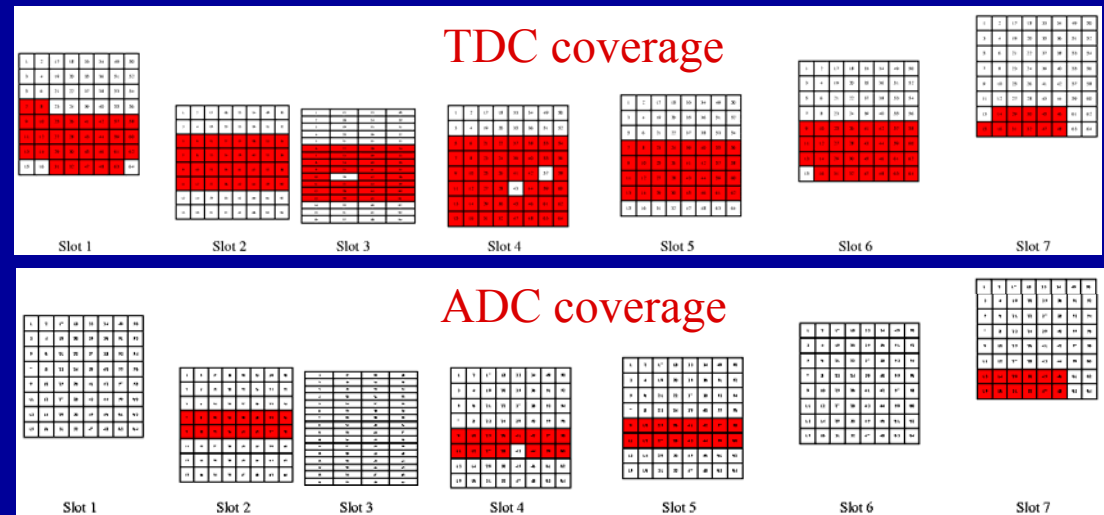


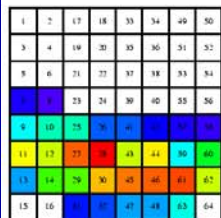Photodetector and TDC/ADC coverage in 2007 runs

Six days of 10 GeV electron beam in End Station A at SLAC
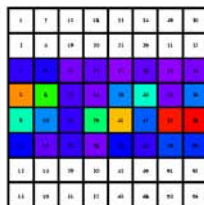
Recorded some 10M triggers, 800k good single-track events.

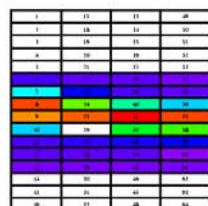Still working on detector calibration and data analysis.



TDC Occupancy for August 2007 Beam Test at SLAC
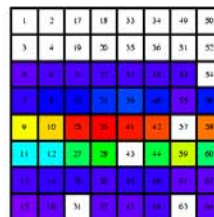
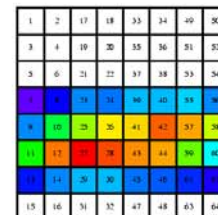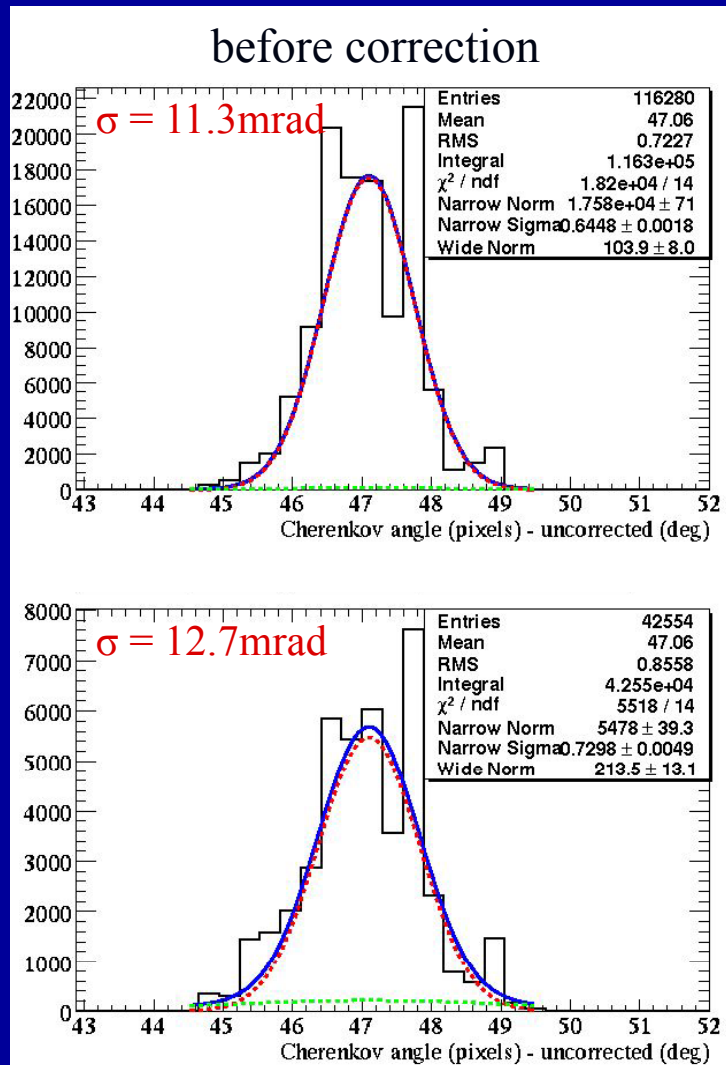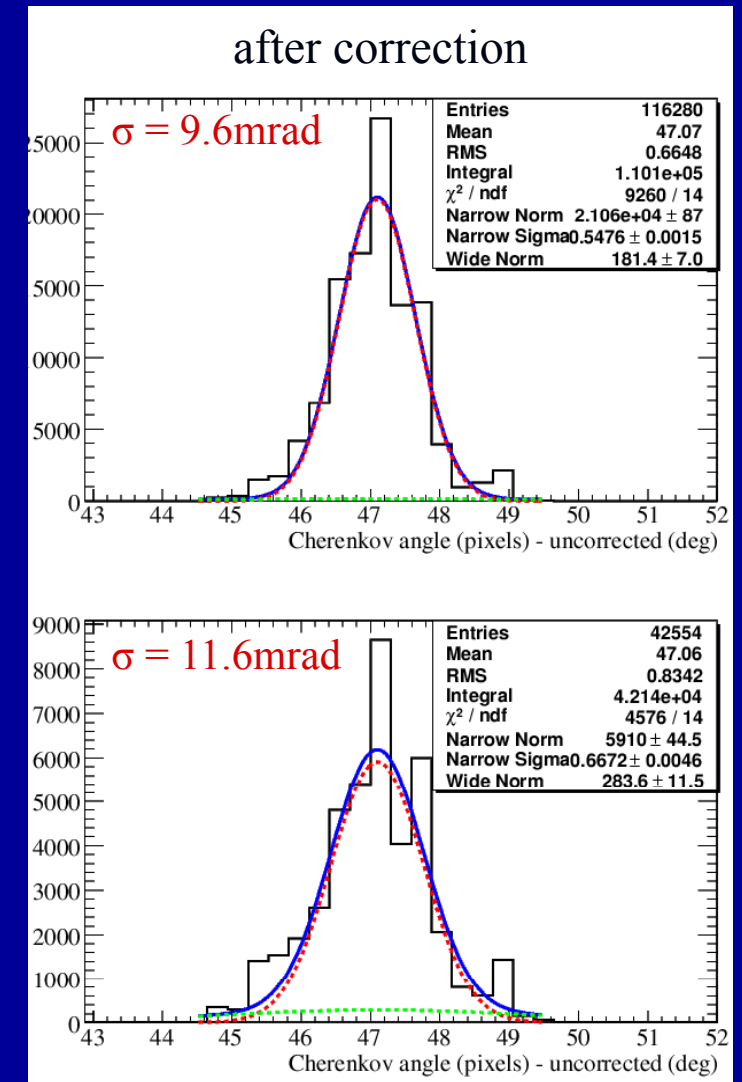| Slot 1 | Slot 2 | Slot 3 | Slot 4 | Slot 5 | Slot 6 | Slot 7 |
|---|---|---|---|---|---|---|
| Burle 85011-501 | Hamamatsu H-8500 | Hamamatsu H-9500 | Burle 85011-501 | Burle 85011-501 | Burle 85011-501 | Burle 85011-501 |
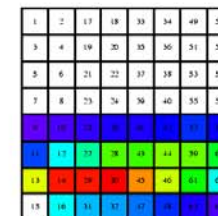
First, very preliminary look at charge sharing treatment for all slots combined, position 1

- look for ADC or TDC hit in (vertical) neighbor pad
- use average pixel $\theta_c$ of the two pads if hit is found
→ significant improvement of $\theta_c$ resolution for both peak 1 and peak 2

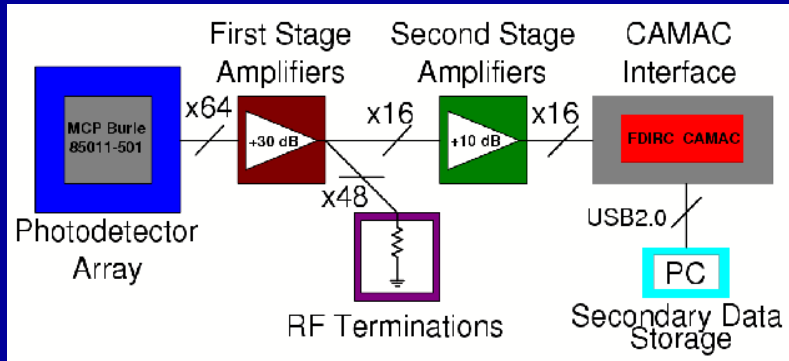before correction

after correction

σ = 11.3mrad

| Entries | 116280 |
|---|---|
| Mean | 47.06 |
| RMS | 0.7227 |
| Integral | 1.163e+05 |
| $\chi^2$ / ndf | 1.82e+04 / 14 |
| Narrow Norm | 1.758e+04 ± 71 |
| Narrow Sigma | 0.6448 ± 0.0018 |
| Wide Norm | 103.9 ± 8.0 |

σ = 9.6mrad

| Entries | 116280 |
|---|---|
| Mean | 47.07 |
| RMS | 0.6648 |
| Integral | 1.101e+05 |
| $\chi^2$ / ndf | 9260 / 14 |
| Narrow Norm | 2.106e+04 ± 87 |
| Narrow Sigma | 0.5476 ± 0.0015 |
| Wide Norm | 181.4 ± 7.0 |

direct photons
(<path> ~1.3m)

σ = 12.7mrad

| Entries | 42554 |
|---|---|
| Mean | 47.06 |
| RMS | 0.8558 |
| Integral | 4.255e+04 |
| $\chi^2$ / ndf | 5518 / 14 |
| Narrow Norm | 5478 ± 39.3 |
| Narrow Sigma | 0.7298 ± 0.0049 |
| Wide Norm | 213.5 ± 13.1 |

σ = 11.6mrad

| Entries | 42554 |
|---|---|
| Mean | 47.06 |
| RMS | 0.8342 |
| Integral | 4.214e+04 |
| $\chi^2$ / ndf | 4576 / 14 |
| Narrow Norm | 5910 ± 44.5 |
| Narrow Sigma | 0.6672 ± 0.0046 |
| Wide Norm | 283.6 ± 11.5 |

mirror-reflected
photons
(<path> ~10.5m)

Cherenkov angle (pixels) - uncorrected (deg)
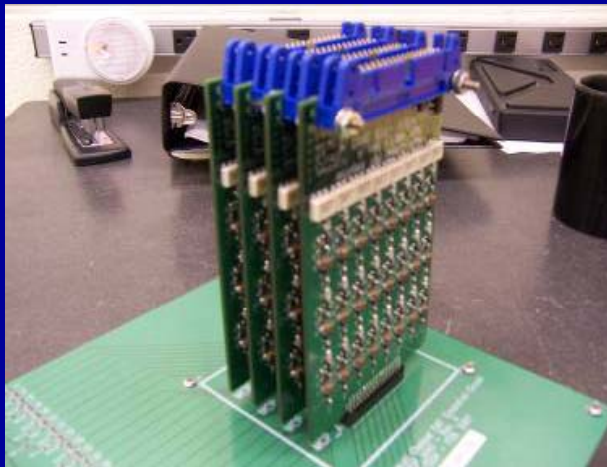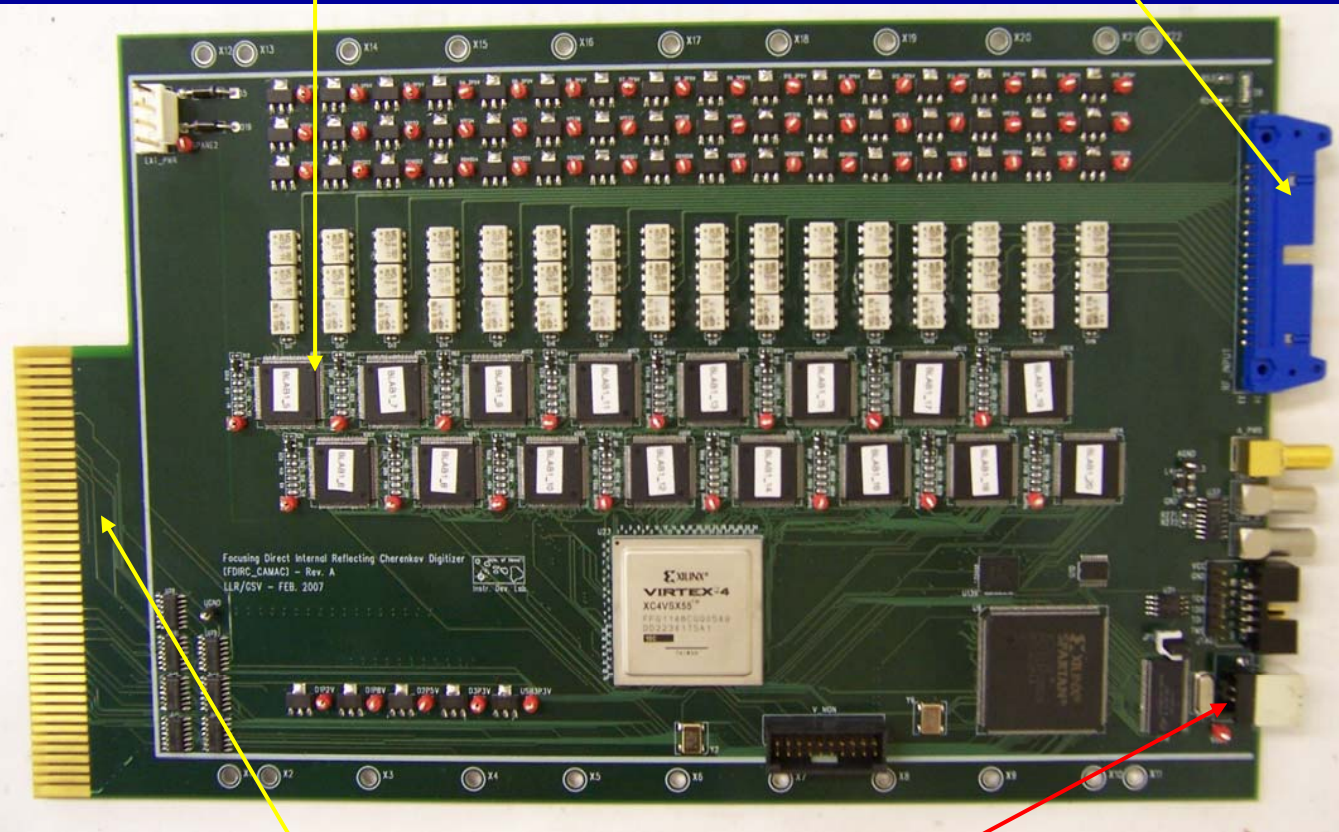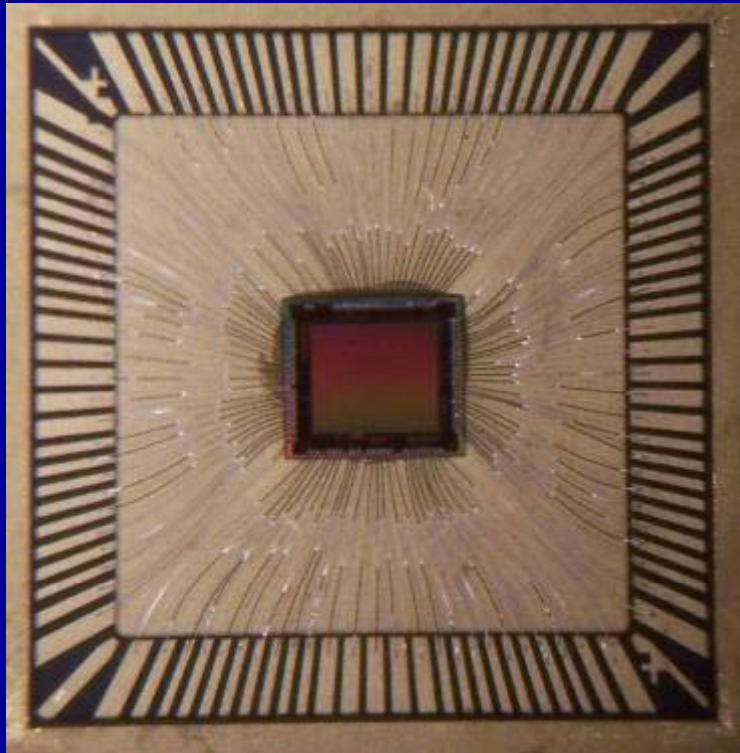
Differential inputs from amp boards

16 BLAB1 ASICs

Amplifiers mounted on MCP backplane
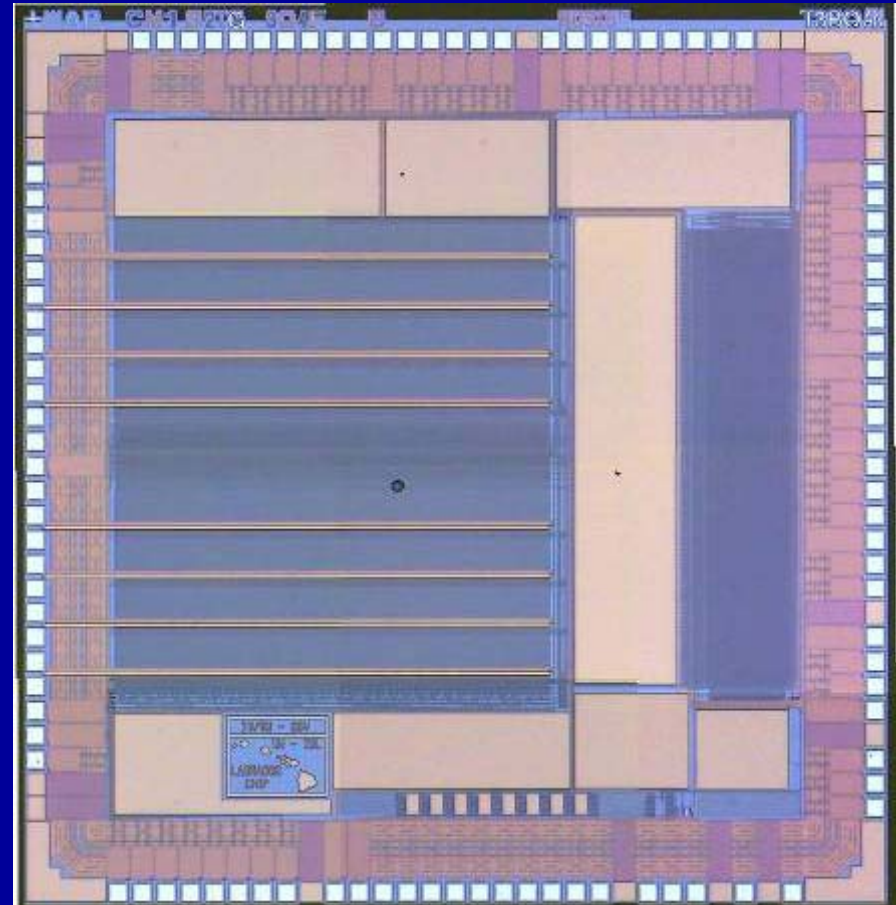
Processed hit times via CAMAC

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)

slot 7

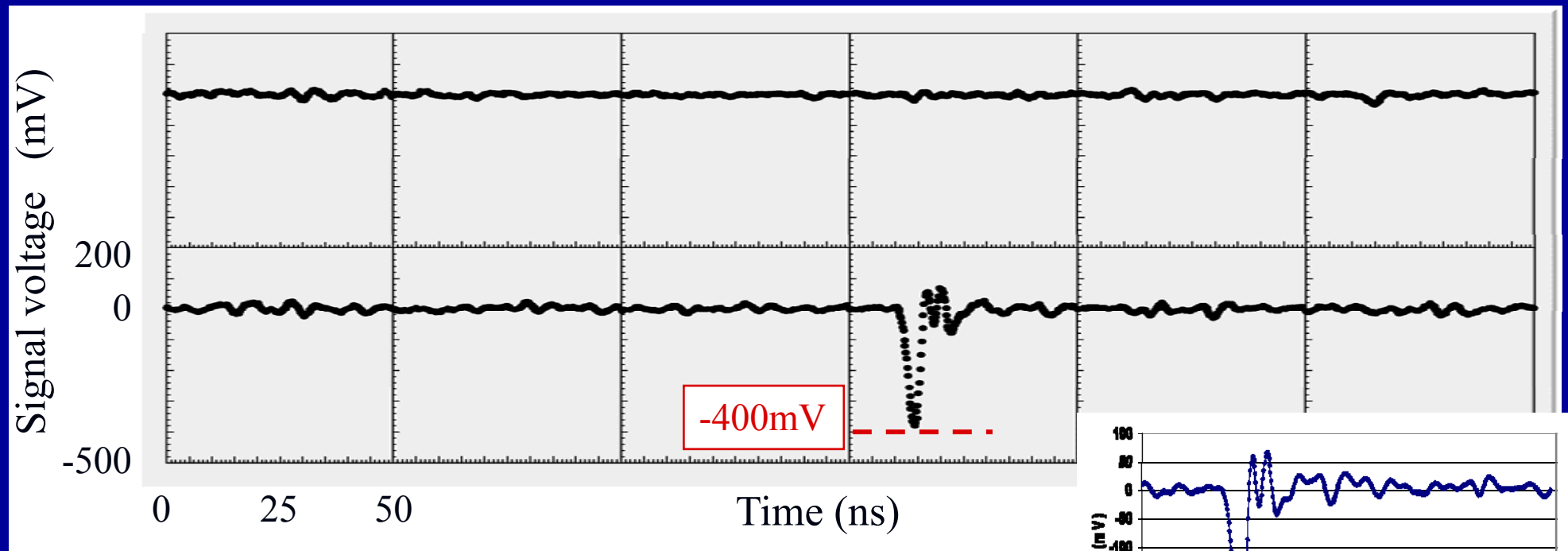12 channel waveforms from slot 7 in a typical event with one hit on pad 32 sampled at approx. 5.8 GSa/s

analysis of waveform, extraction of hit time ongoing
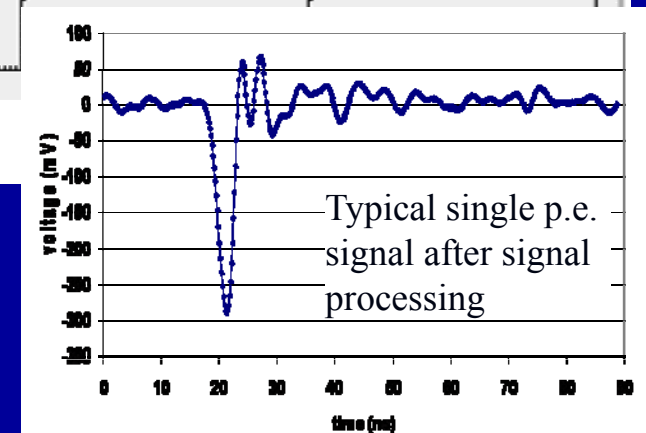


-400mV

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

Typical single p.e. signal after signal processing

- <u>We have demonstrated that we can correct the chromatic error of $\theta_C$</u>
  This is the first RICH detector which has been able to do this.

- Single-photon $\theta_C$ 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.
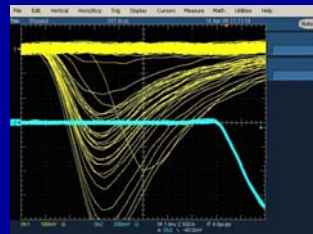  Data analysis just starting; first ADC pixel interpolation looks promising, stay tuned…
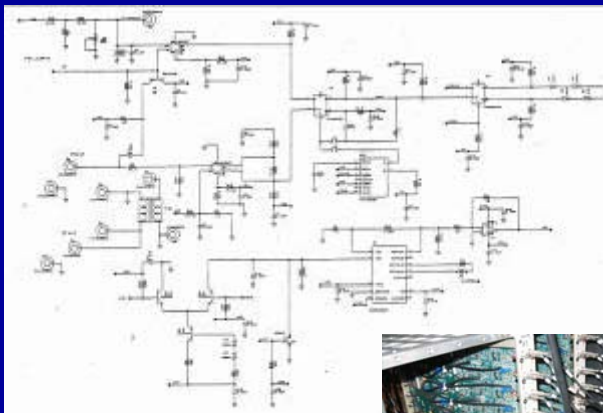
# Extra Material
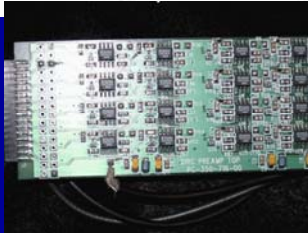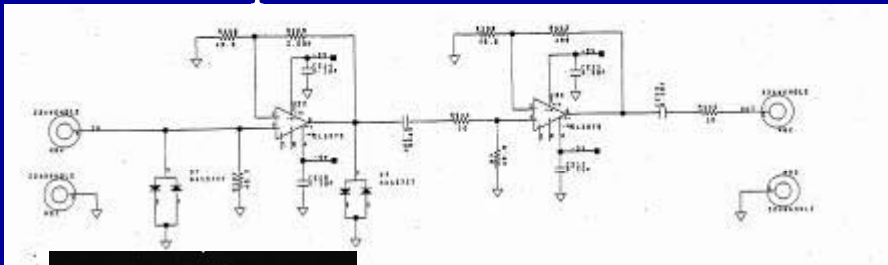
SLAC Amplifier:





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*

Single photo-electron may result
in multiple anode pads with hits

if hit location close to pad boundary and
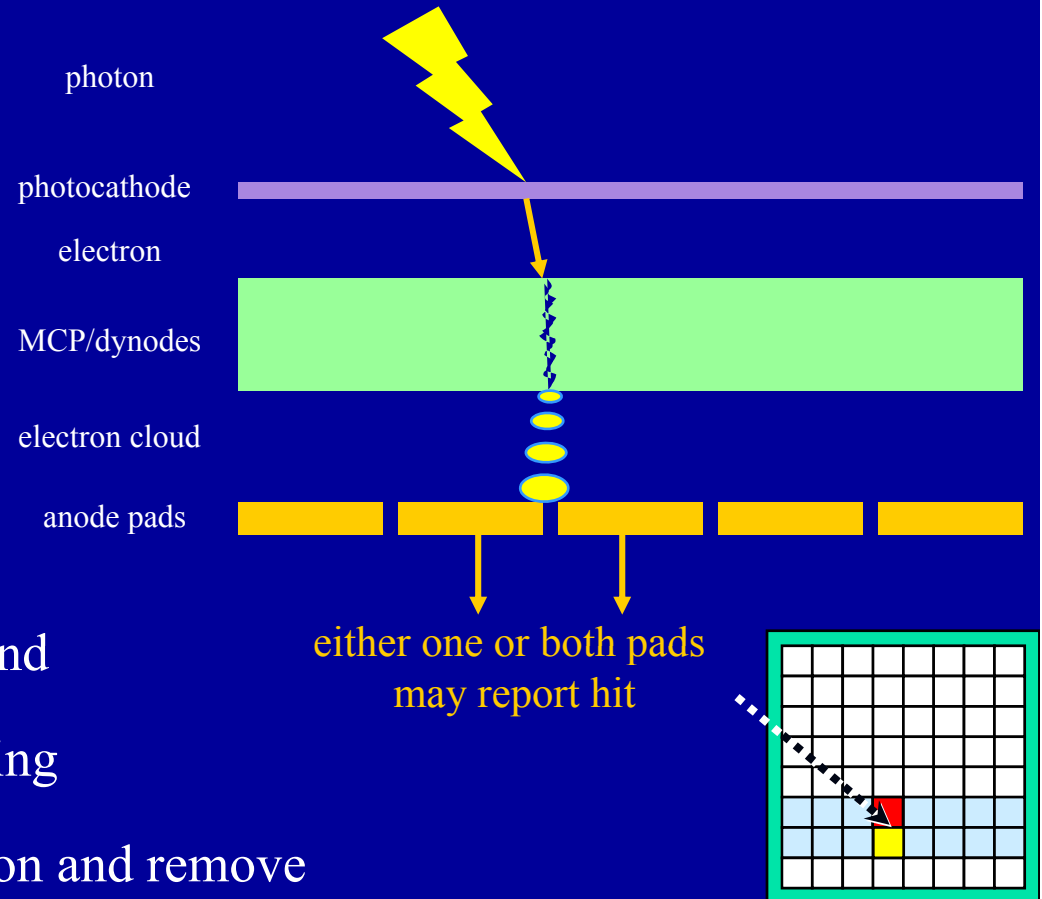both charges above discriminator threshold

Fake extra hit will broaden $\theta_c$ resolution
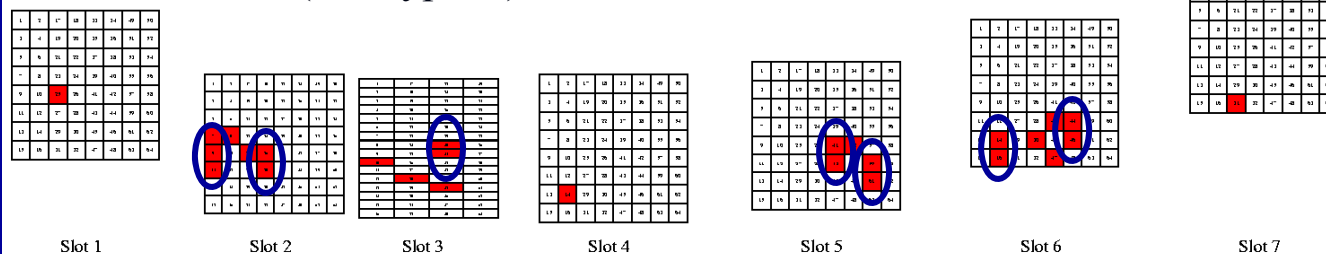
Identify charge sharing hits using ADC

→ 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 $\theta_c$ resolution and $N_0$ measurement

photon

photocathode

electron

MCP/dynodes

electron cloud

anode pads

either one or both pads
may report hit

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

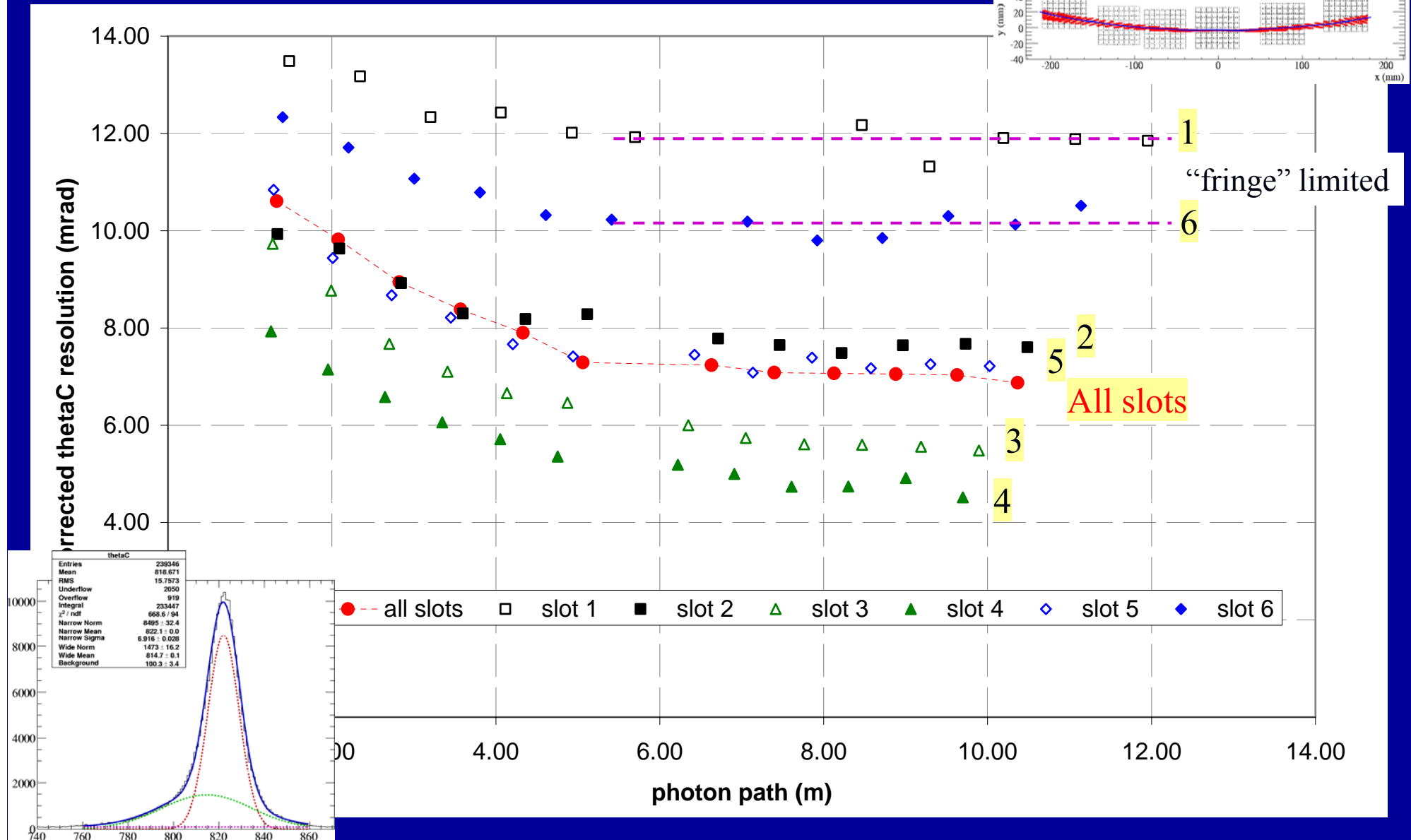Slot 1     Slot 2     Slot 3     Slot 4     Slot 5     Slot 6     Slot 7

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.



signal from   pad   7
              pad 23
              pad 39
              pad 55
• all pads combined
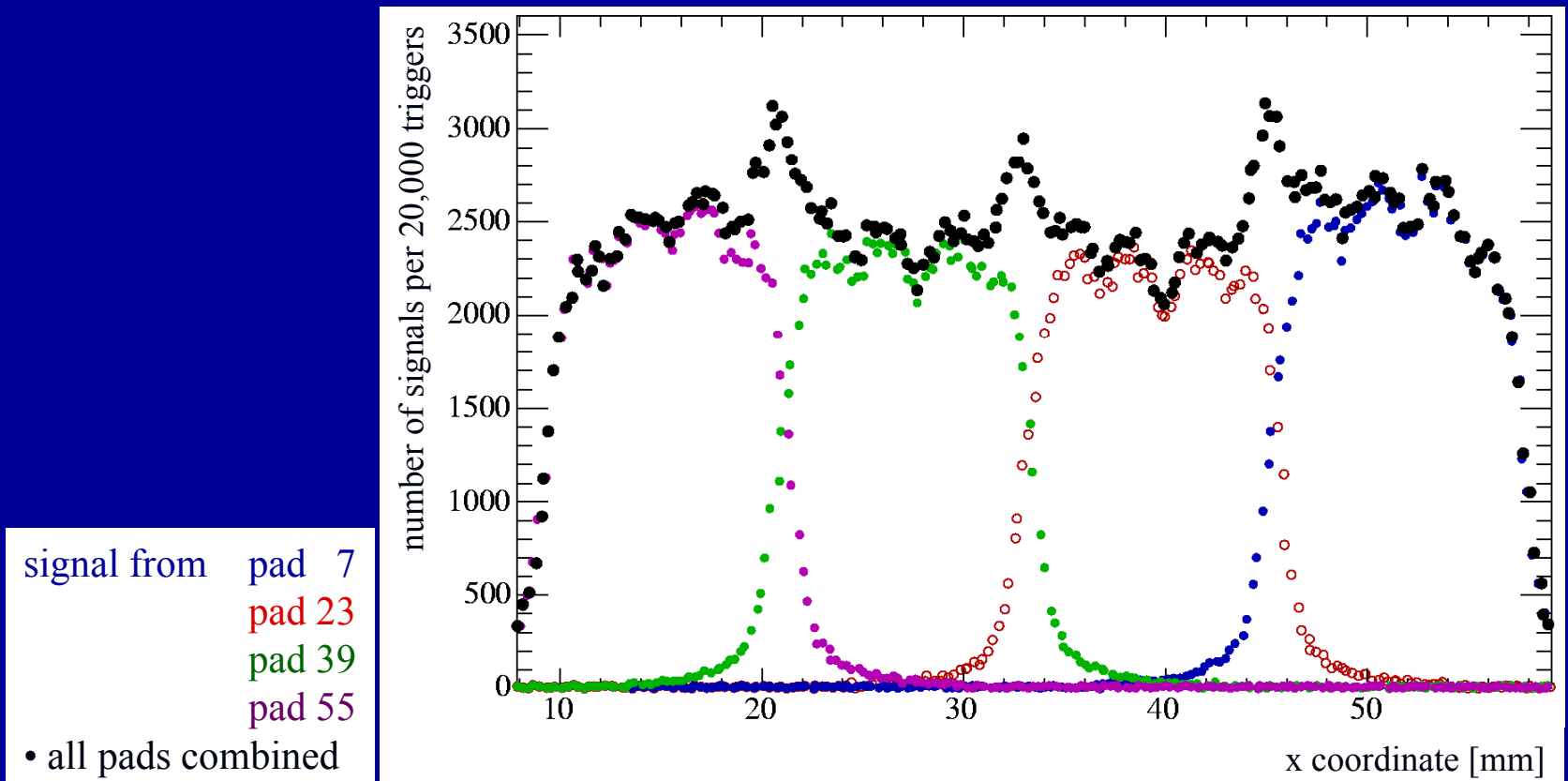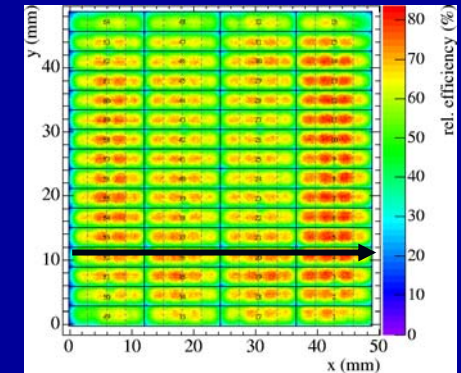
# Fully corrected thetaC as function of photon path for each slot

→ 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)
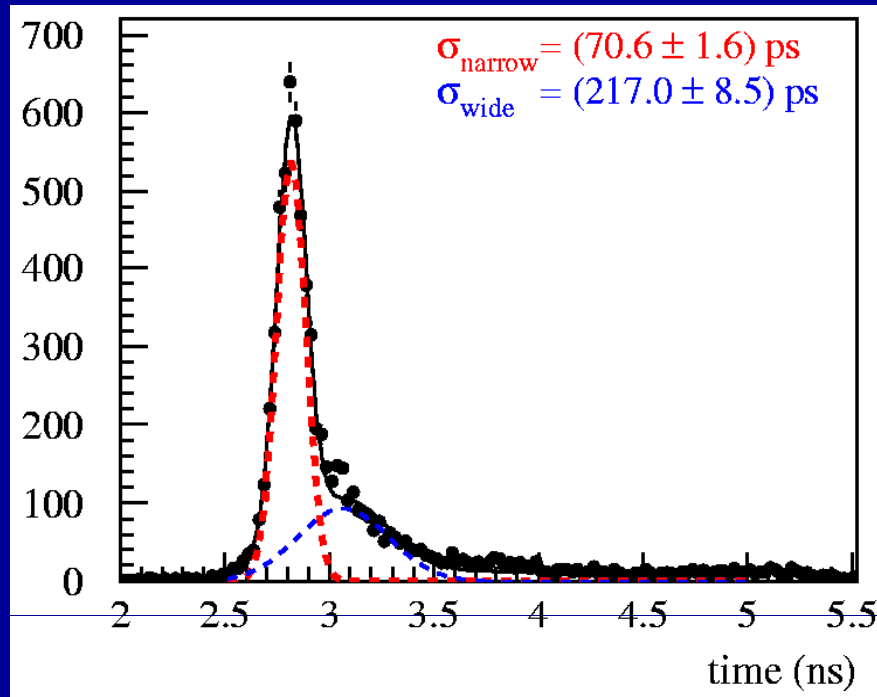


"fringe" limited

All slots

Legend: all slots · slot 1 □ · slot 2 ■ · slot 3 △ · slot 4 ▲ · slot 5 ◇ · slot 6 ◆

Y-axis: corrected thetaC resolution (mrad)
X-axis: photon path (m)

**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

$\sigma_{narrow}$ = (70.6 ± 1.6) ps
$\sigma_{wide}$ = (217.0 ± 8.5) ps
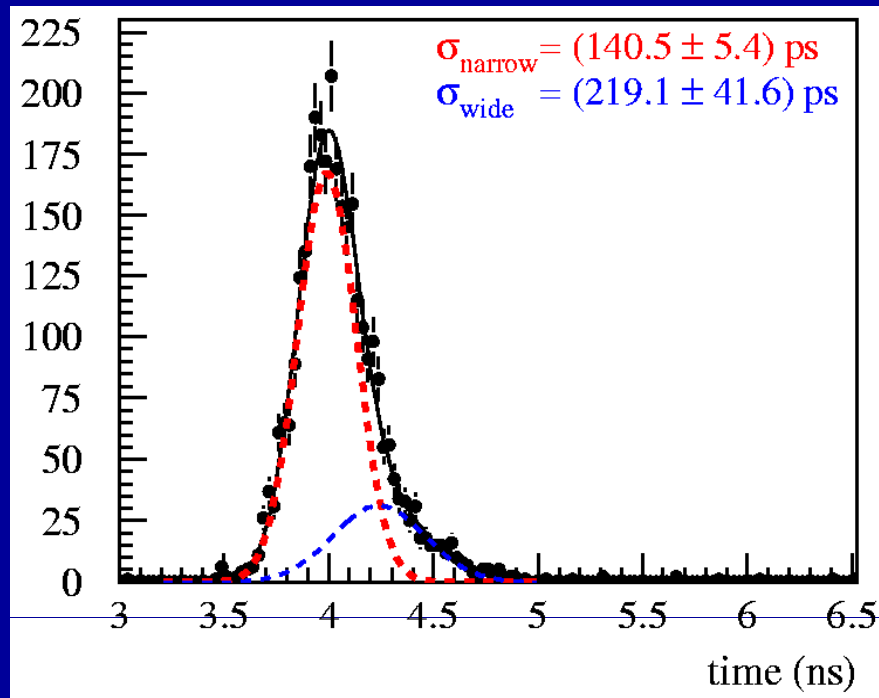
time (ns)

Efficiency relative to Photonis PMT

scan: 500µm%1mm, 407nm
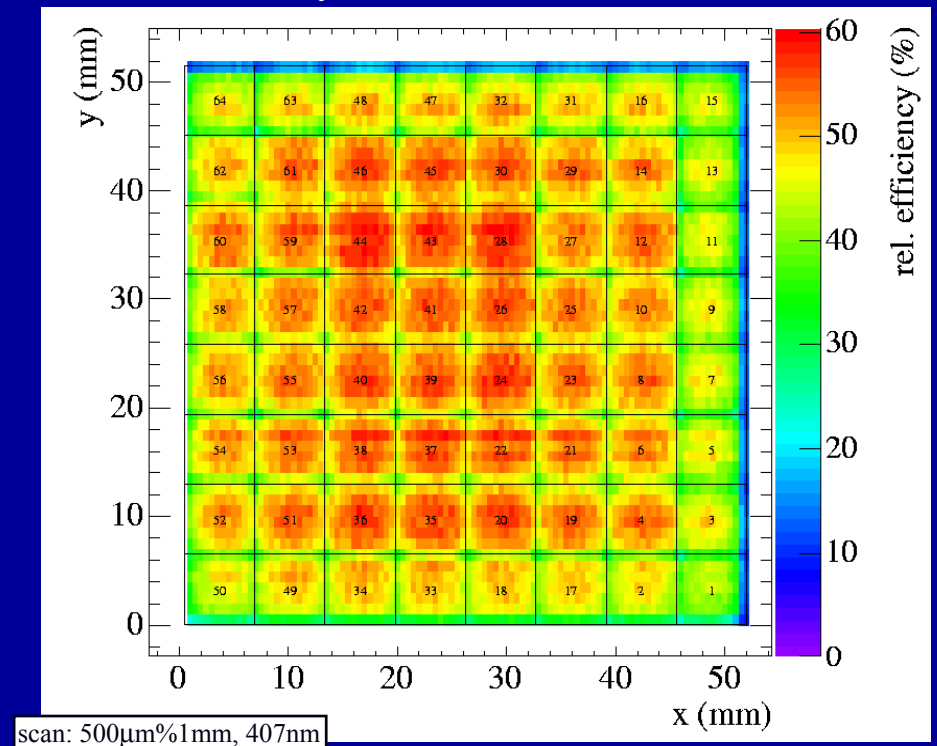
**Hamamatsu H-8500 Flat Panel Multianode PMT**

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

→ IEEE NSS 2003

$\sigma_{narrow} = (140.5 \pm 5.4)$ ps
$\sigma_{wide} = (219.1 \pm 41.6)$ ps

time (ns)

Efficiency relative to Photonis PMT

y (mm)

rel. efficiency (%)
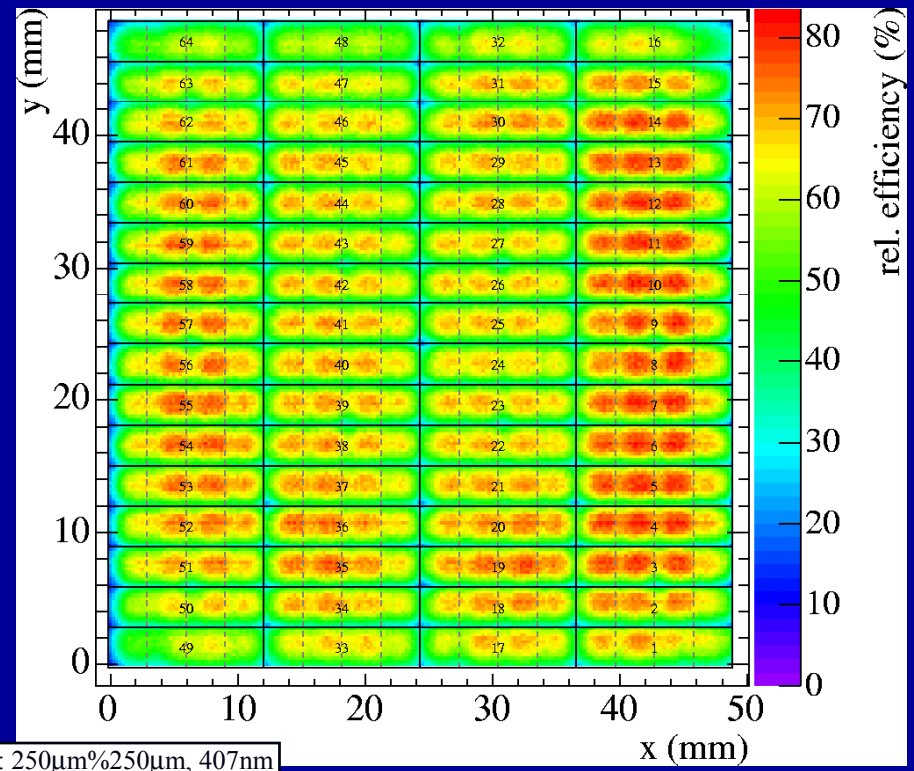
x (mm)

scan: 500µm%1mm, 407nm
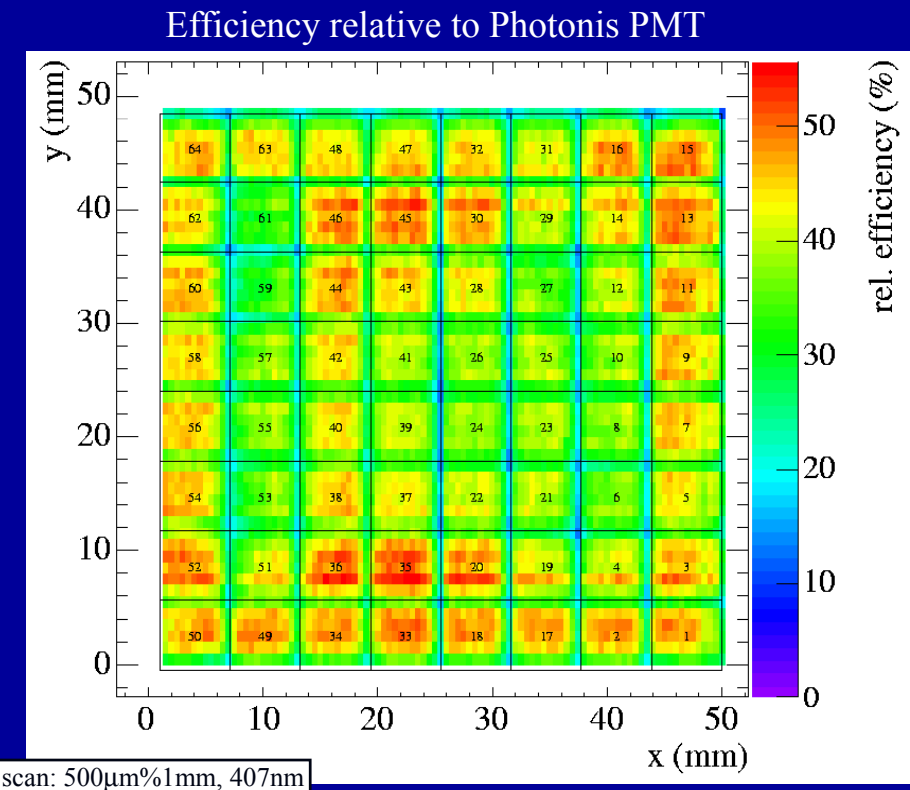
# Hamamatsu H-9500

**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
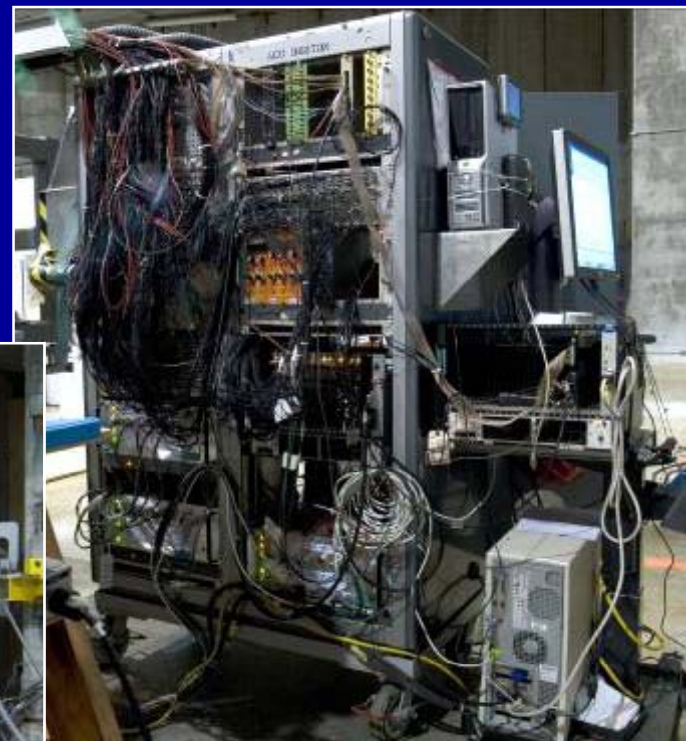- custom readout board – read out as 4×16 channels
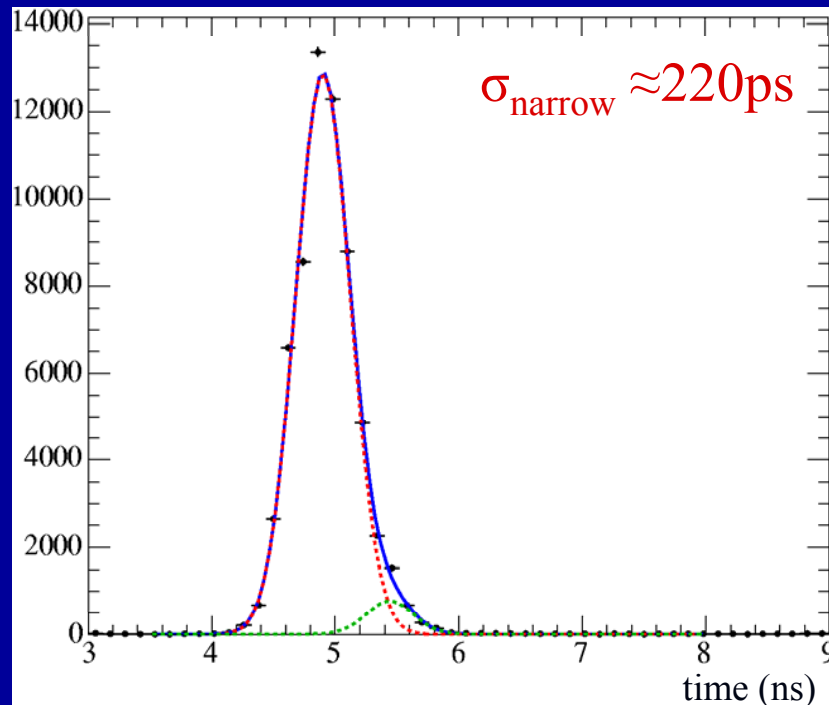
$\sigma_{narrow} \approx 220ps$

Efficiency relative to Photonis PMT

scan: 250μm%250μm, 407nm

34

Joe Schwiening, SLAC
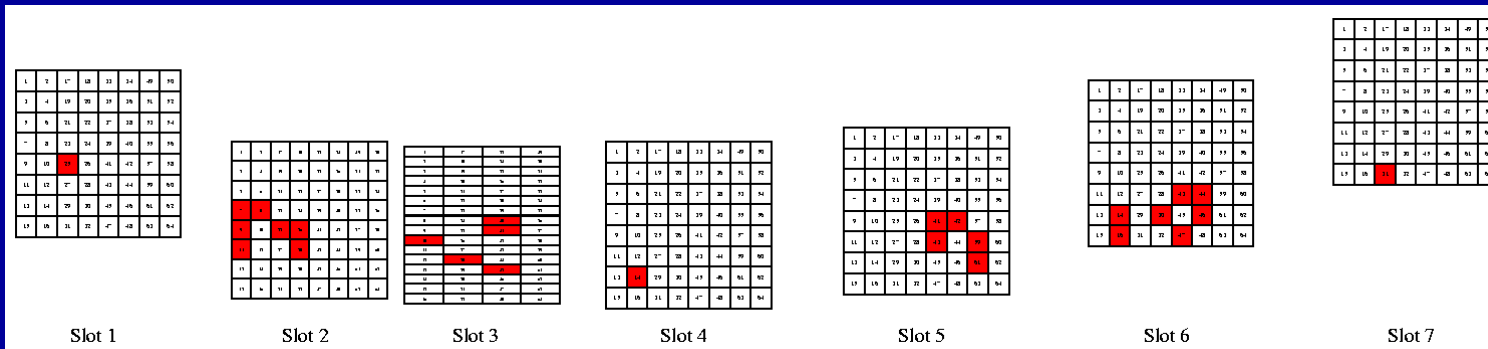
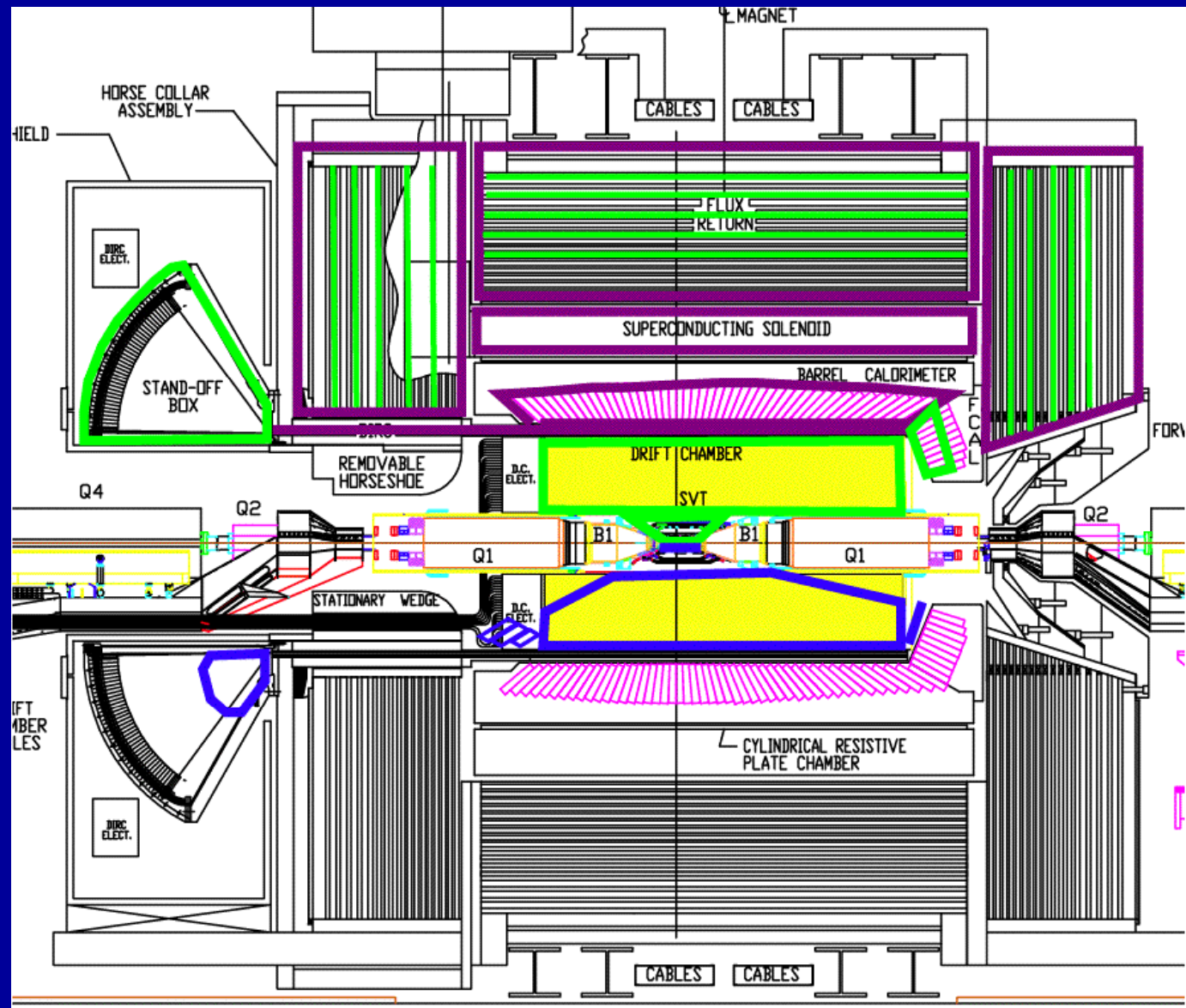All hits in event
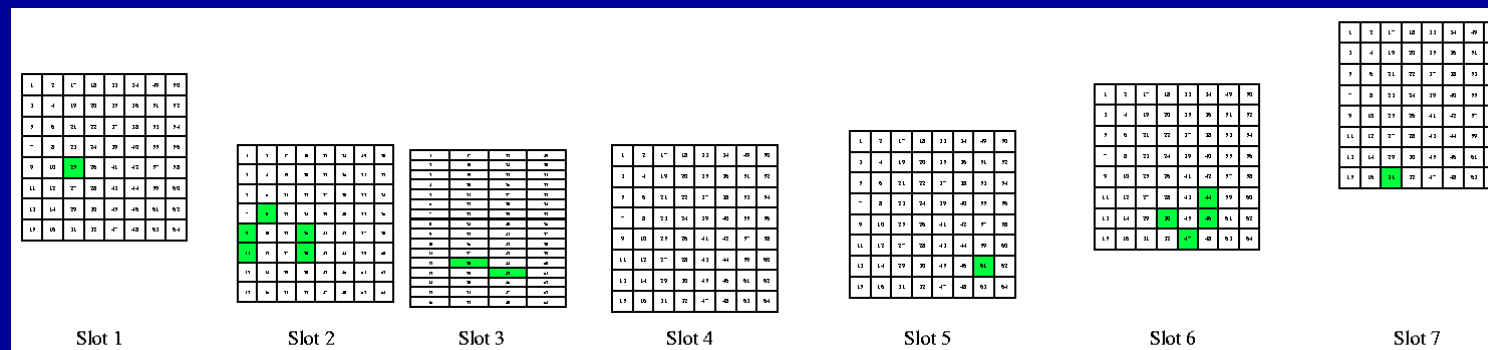
Early hits (peak 1)
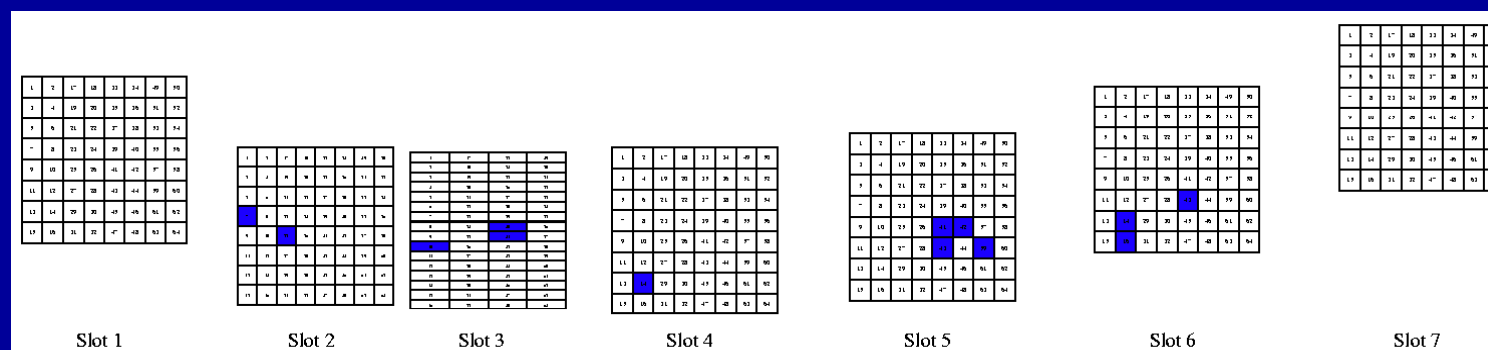
Late hits (peak 2)

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*