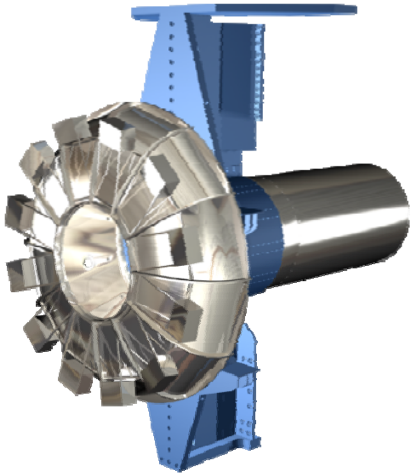
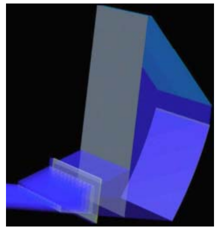
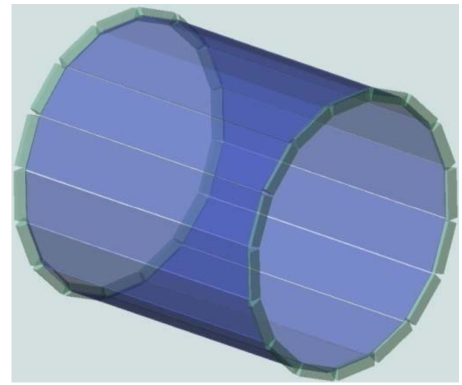
DIRC options: present and future





Blair Ratcliff and
Jerry Va'vra
SLAC

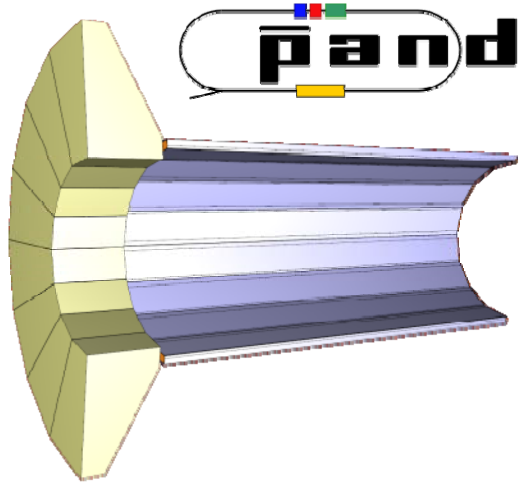


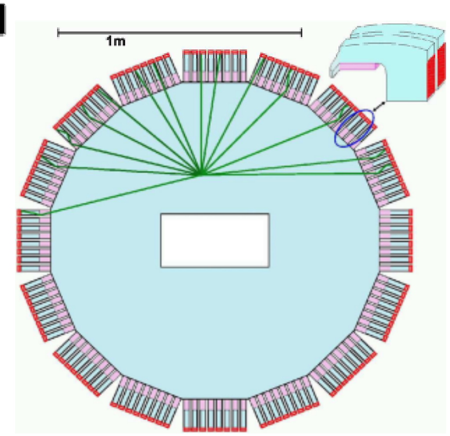
Kurtis Nishimura
and Gary Varner
UNIVERSITY OF HAWAII AT
MANOA

- focusing DIRC (fDIRC)
- imaging TOP (iTOP)

Note: **many** contributors not those listed; only contacts for purposes of this summary!

Please see publications for details.

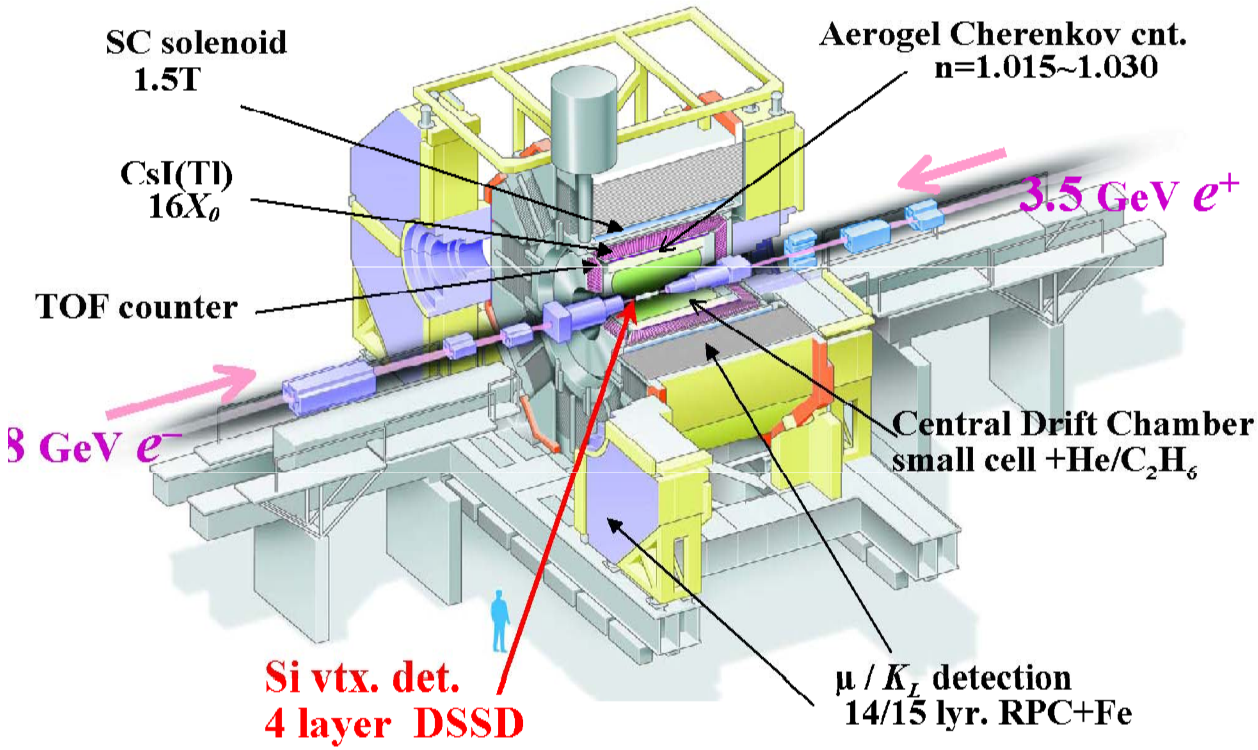




Jochen
Schwiening
GSI

- Panda DIRC/TOP options

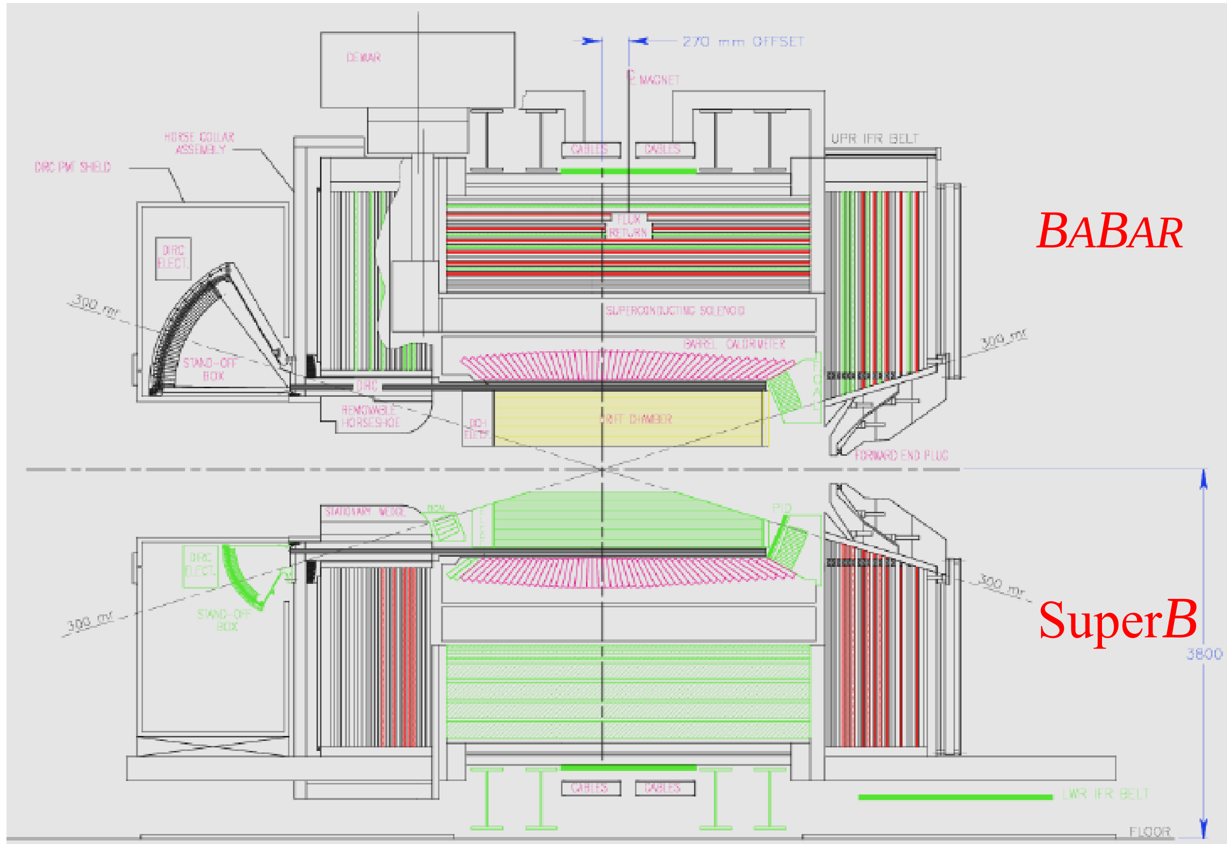
Starting point: upgraded "Super B" Detectors



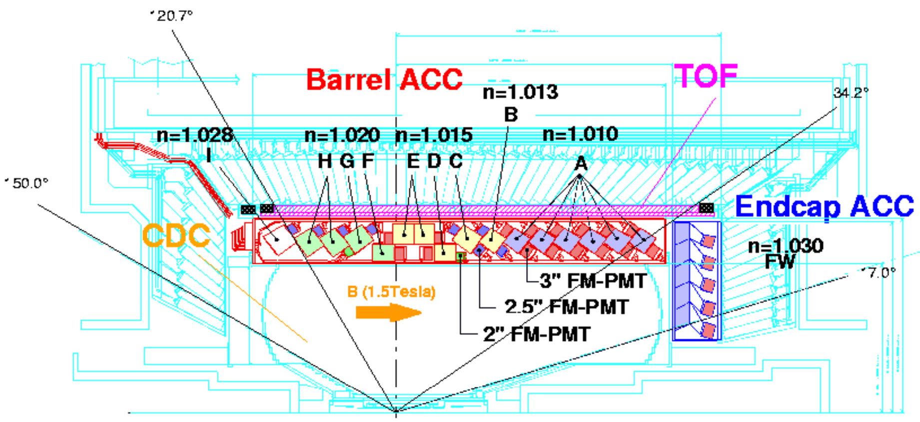
- 3 ways to improve:
  - Pixel detector
  - Hermiticity
  - <u>Particle Identification</u>

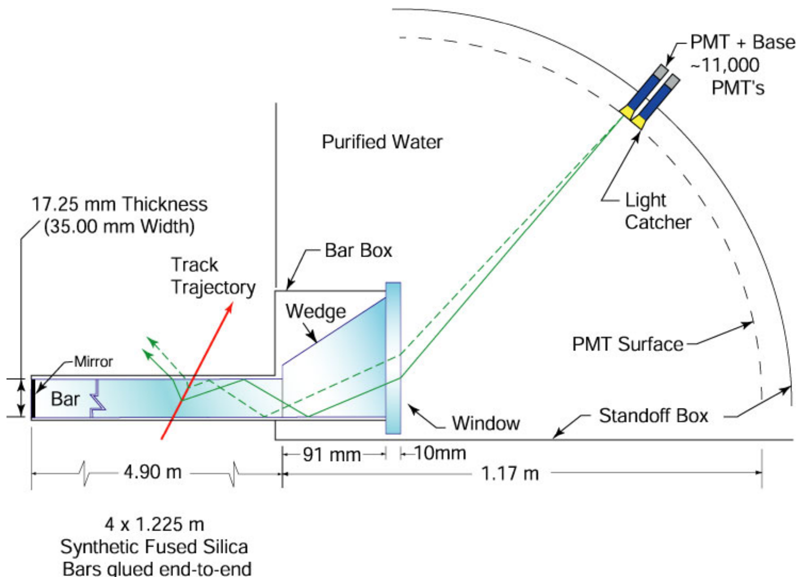
The SuperB detector is an upgrade of BaBar

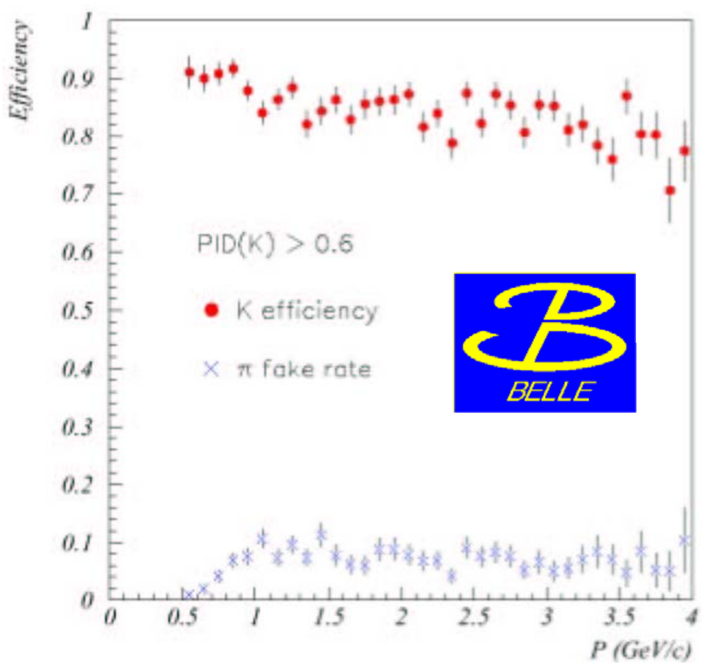
- New SVT with striplet-> pixel Layer 0
- New DCH
- Smaller DIRC SOB
- Possible forward PID
- New EMC forward endcap
- Possible rear endcap calorimeter
- Improved muon ID

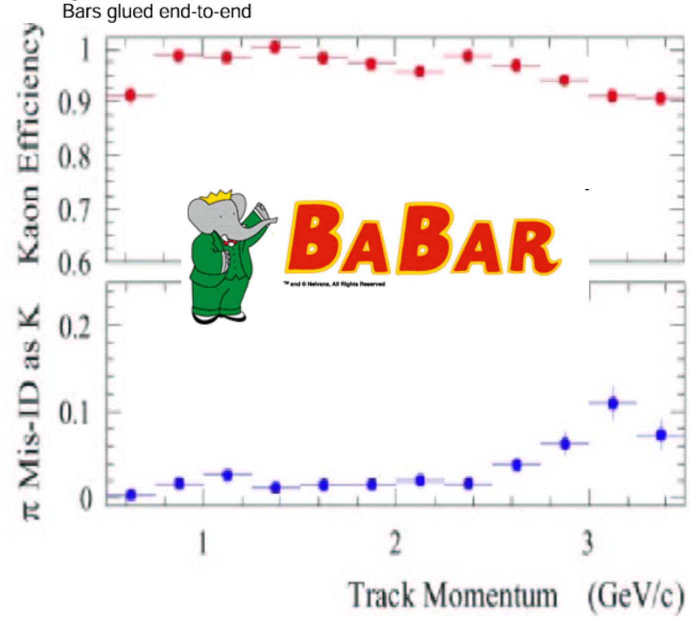


Particle ID at the B Factories



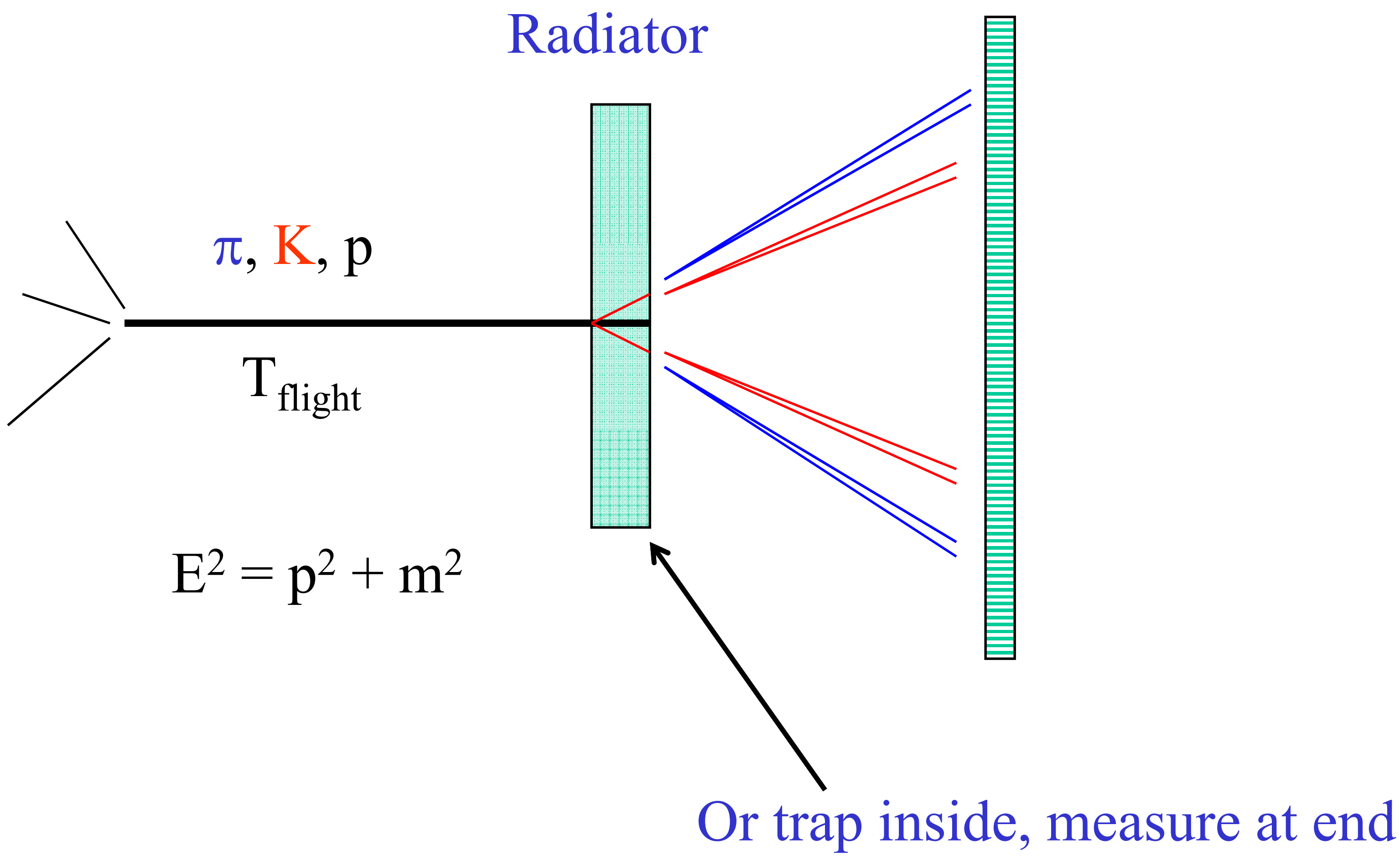






NIM A494 (2002) 402-408. **NIM A553 (2005) 317-322**.

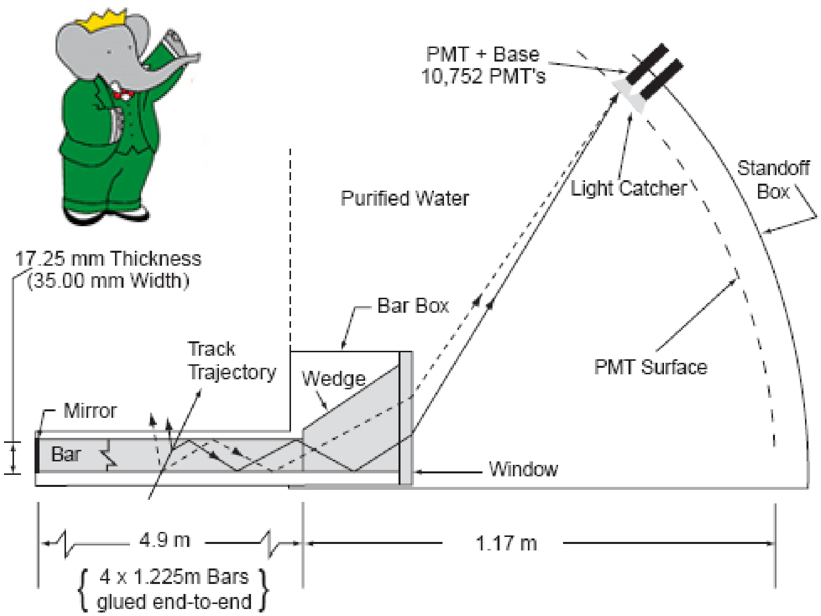
Particle ID observables

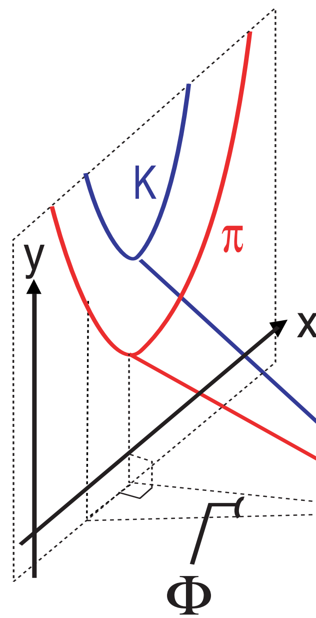


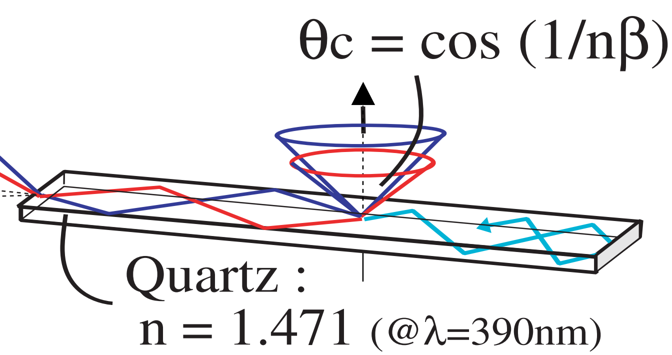
Detection of Internally Reflected Cherenkov (DIRC) Light

- Charged particles of same momentum but different mass (e.g., K and π) emit Cherenkov light at different angles.
- Detect the emitted photons in 2+ dimensions (x,y,t)
- BaBar DIRC as a model:

The larger the expansion region, the better the x-y image...
A **<u>large volume (>1m)</u>** may be required for acceptable performance.



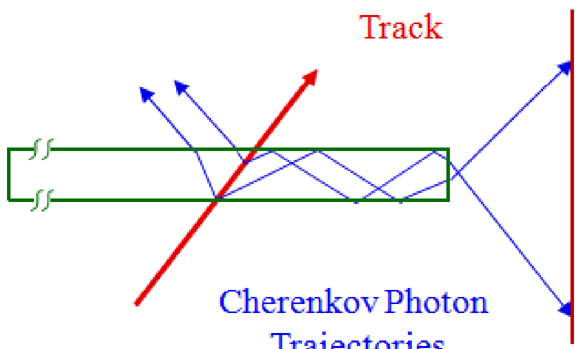




NIM A515 (2003) 680-700.

DIRC Implementation

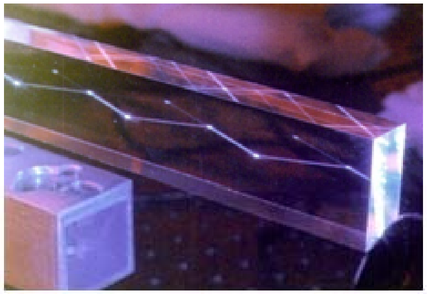
- Charged particle traversing radiator with refractive index n with $\beta = v/c > 1/n$ emits Cherenkov photons on cone with half opening angle $\cos\theta_c = 1/\beta n(\lambda)$.



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

- Radiator and light guide: bar, plate, or disk made from Synthetic Fused Silica (“Quartz”) or fused quartz or acrylic glass or …

- Magnitude of Cherenkov angle conserved during internal reflections (provided optical surfaces are square, parallel, highly polished)

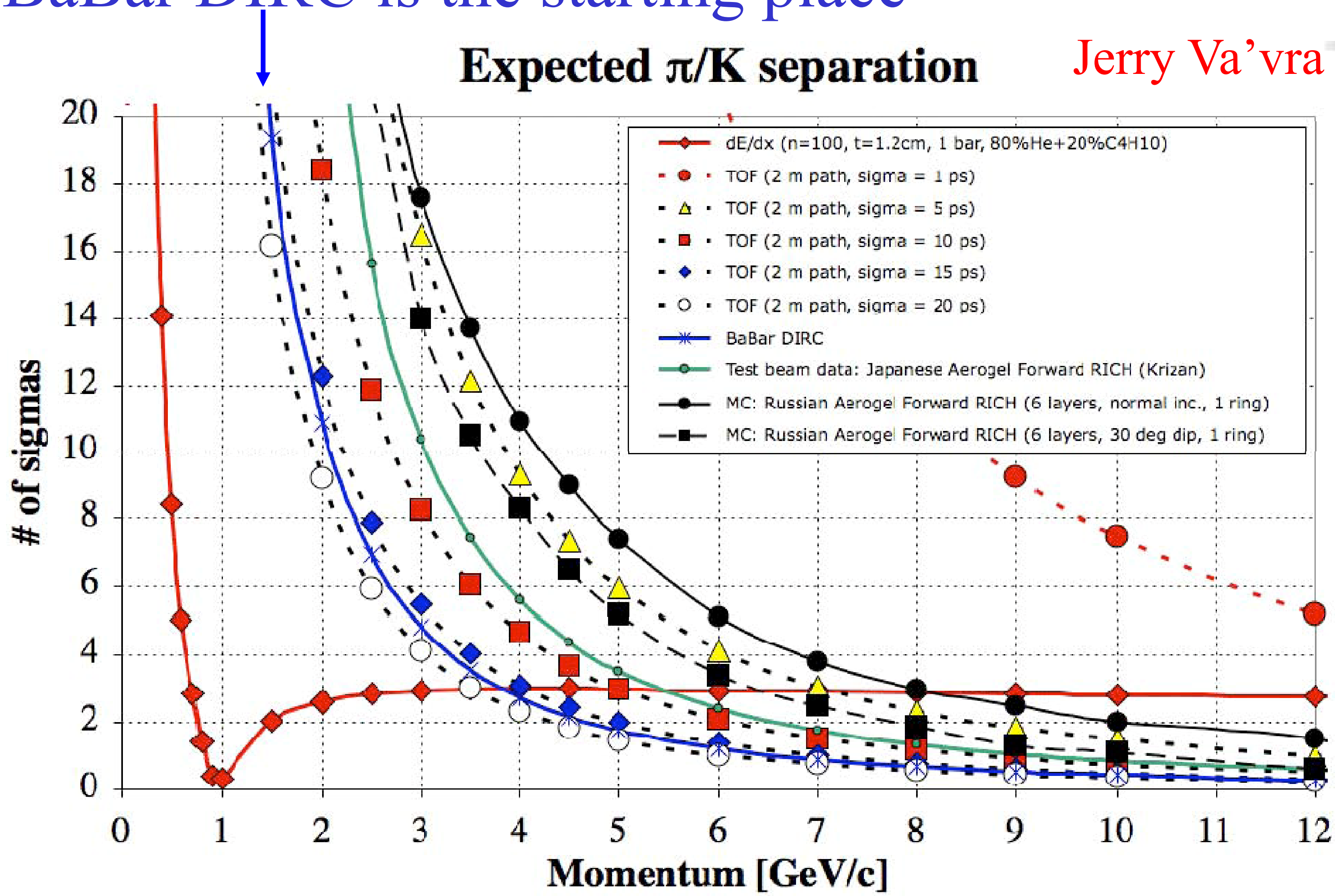


NIM A538 (2005) 281-357.

Particle ID Techniques

- BaBar DIRC is the starting place

Jerry Va'vra



3-D Detector Concept (Blair Ratcliff)

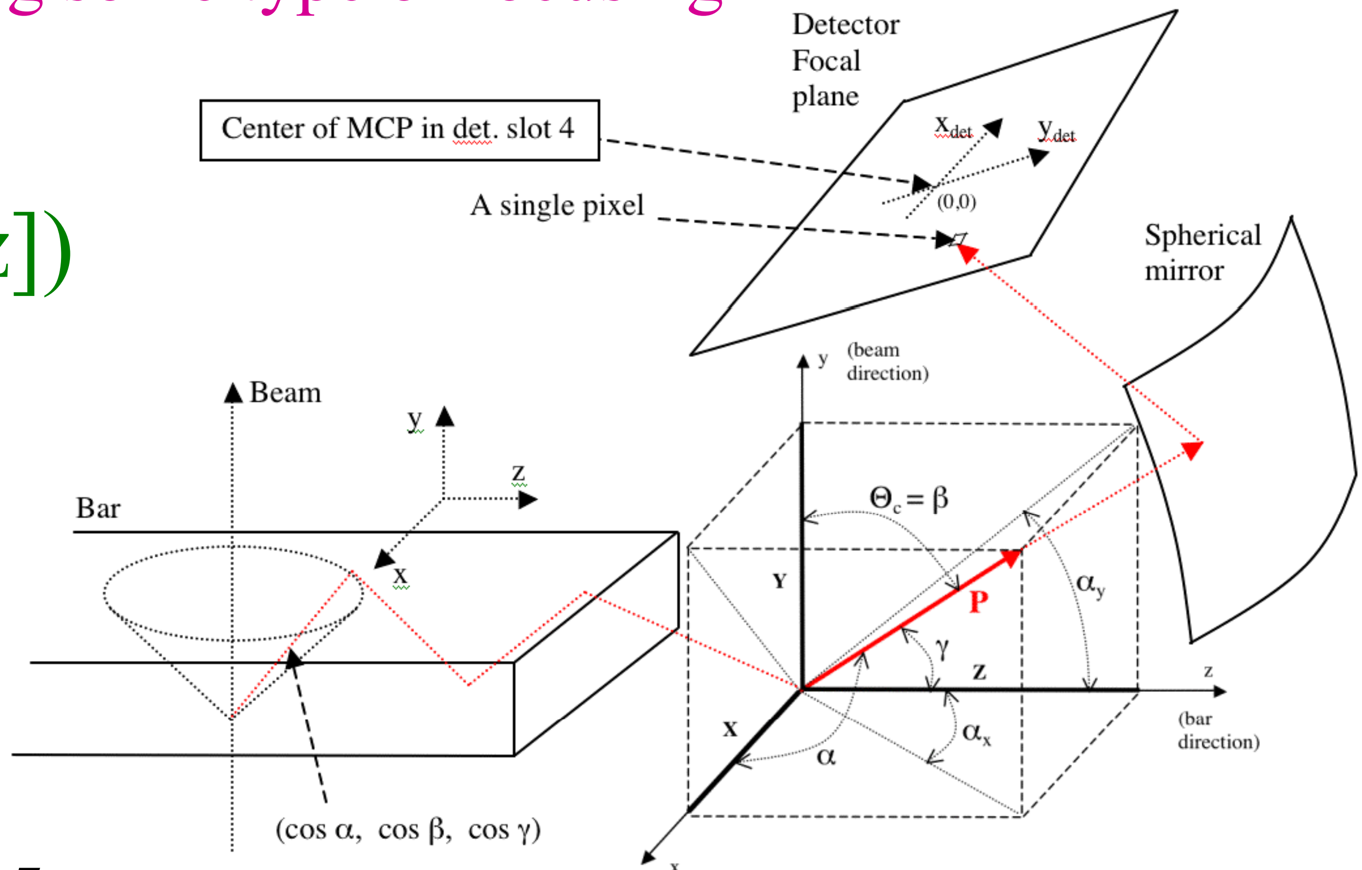
Precisely measured detector pixel coordinates and beam parameters.

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

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

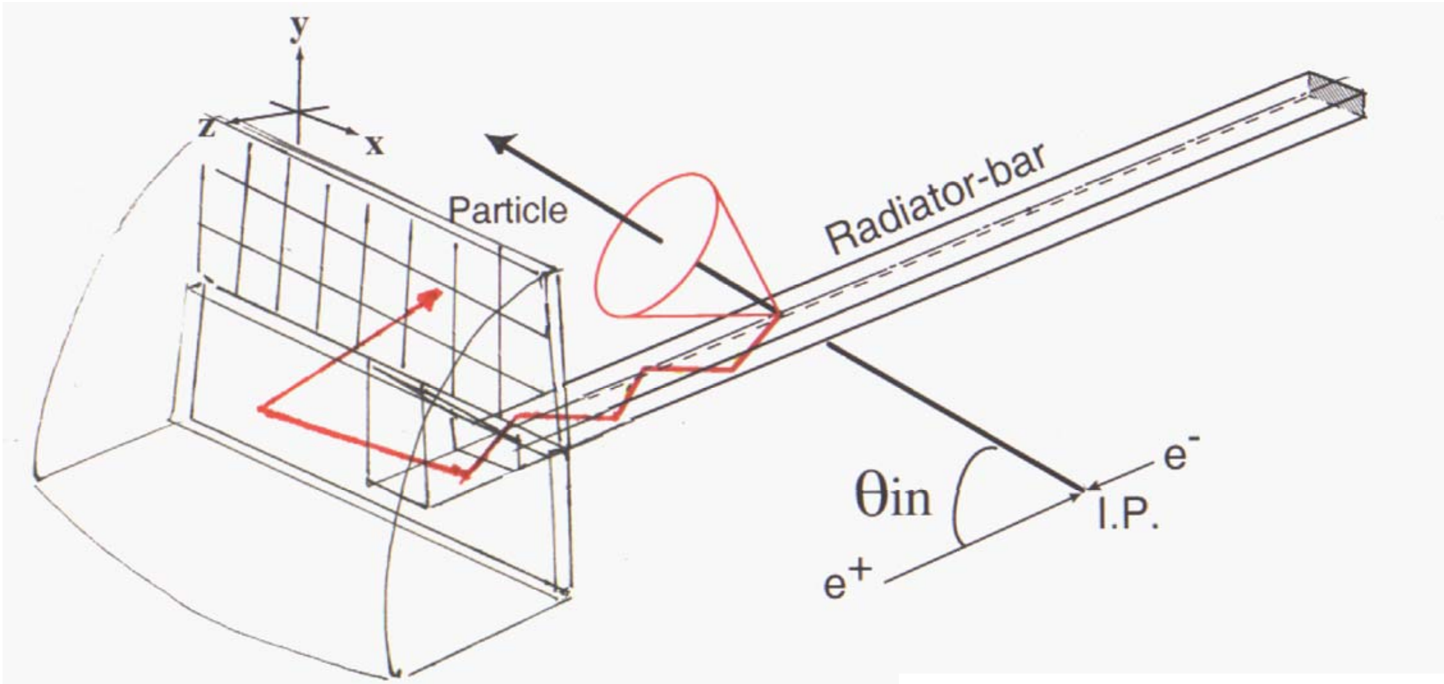
Always doing some type of focusing

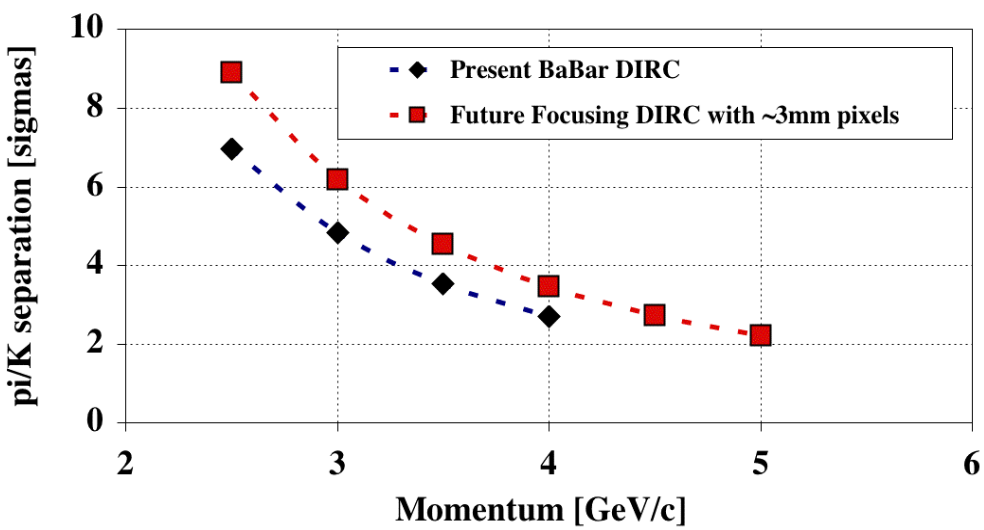
f(x.y.[t-z])

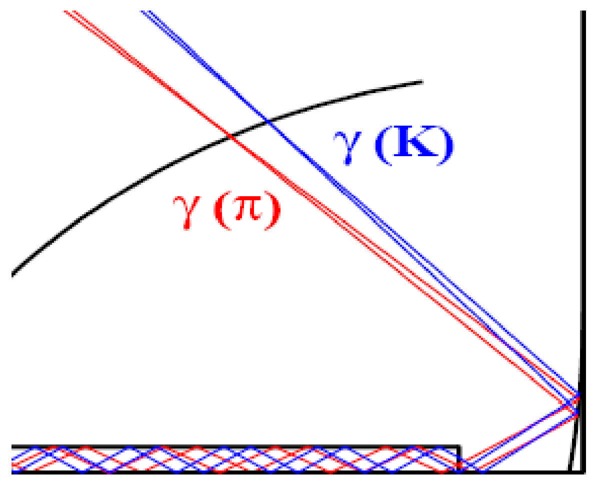


NIM A595 (2008) 1-7.

Fast Focusing DIRC Concept

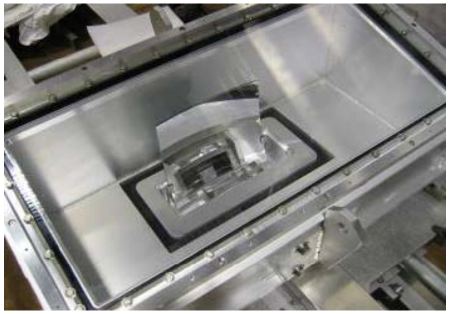


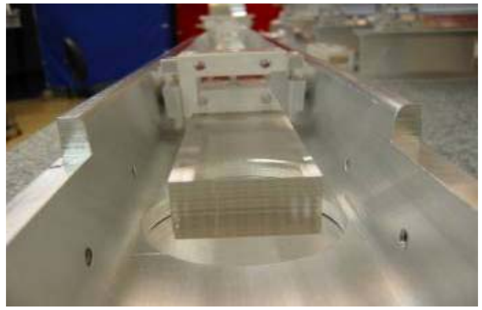


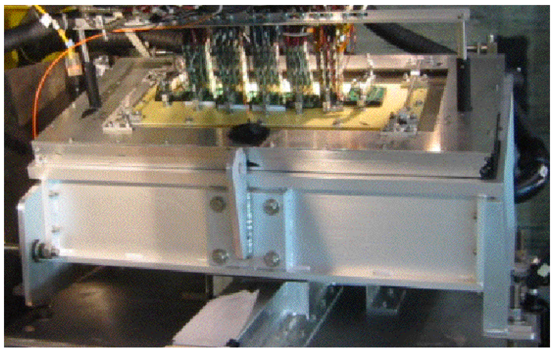


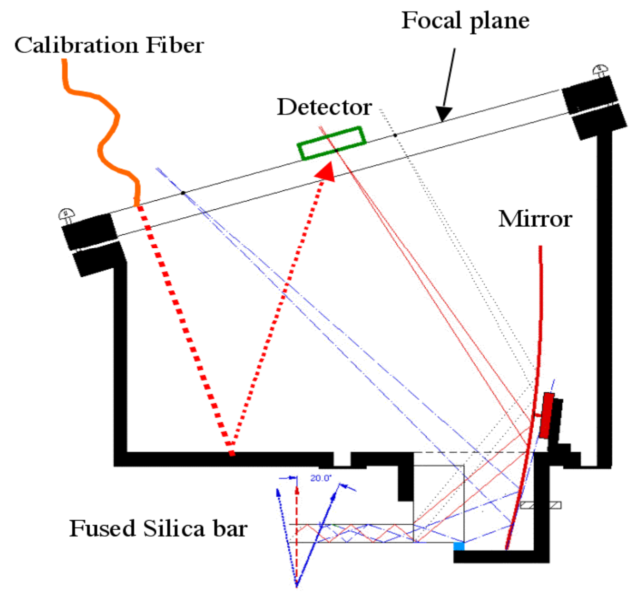
NIM A553 (2005) 96-106.

Focusing DIRC Prototype Optics





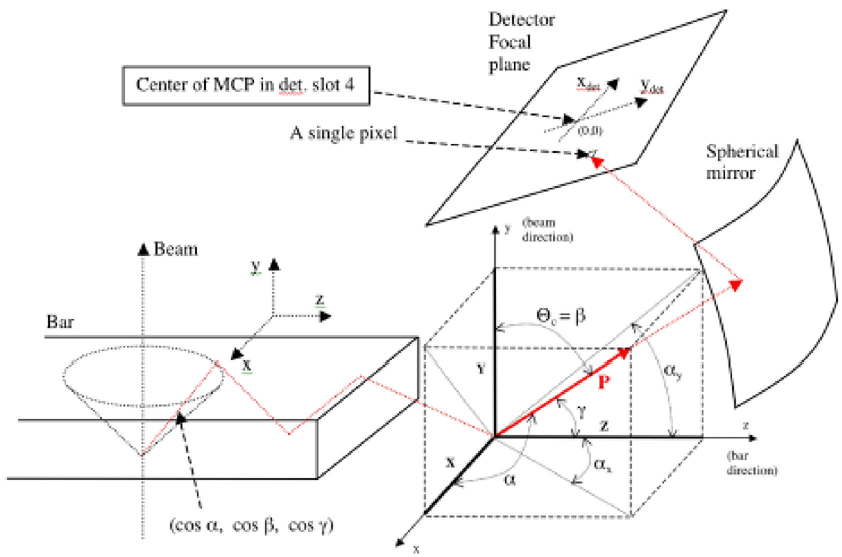




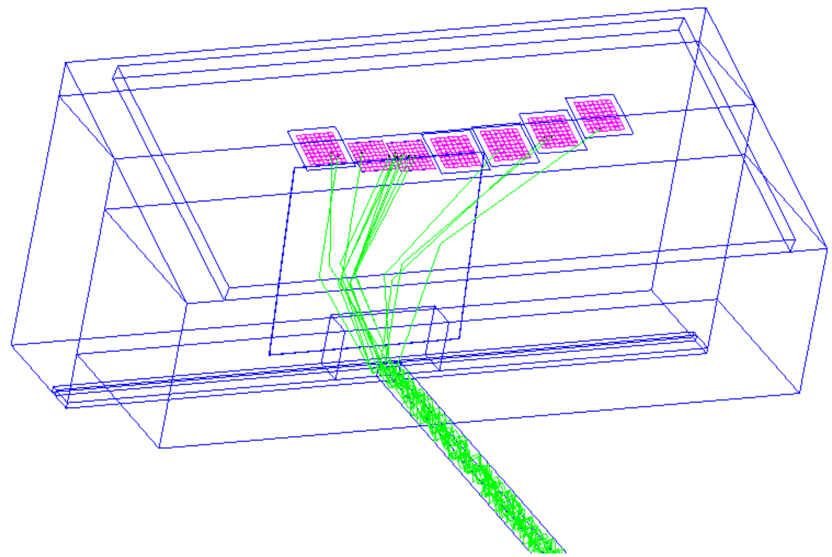
- Radiator:
  - 1.7 cm thick, 3.5 cm wide, 3.7 m long fused silica bar (spares from BABAR DIRC).
- Optical expansion region:
  - filled with a mineral oil to match the fused silica refraction index (KamLand oil).
  - include optical fiber for the electronics calibration (PiLas laser diode).
- Focusing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

Focusing DIRC prototype reconstruction

Prototype coordinate systems:



Geant 4 simulation of the prototype:



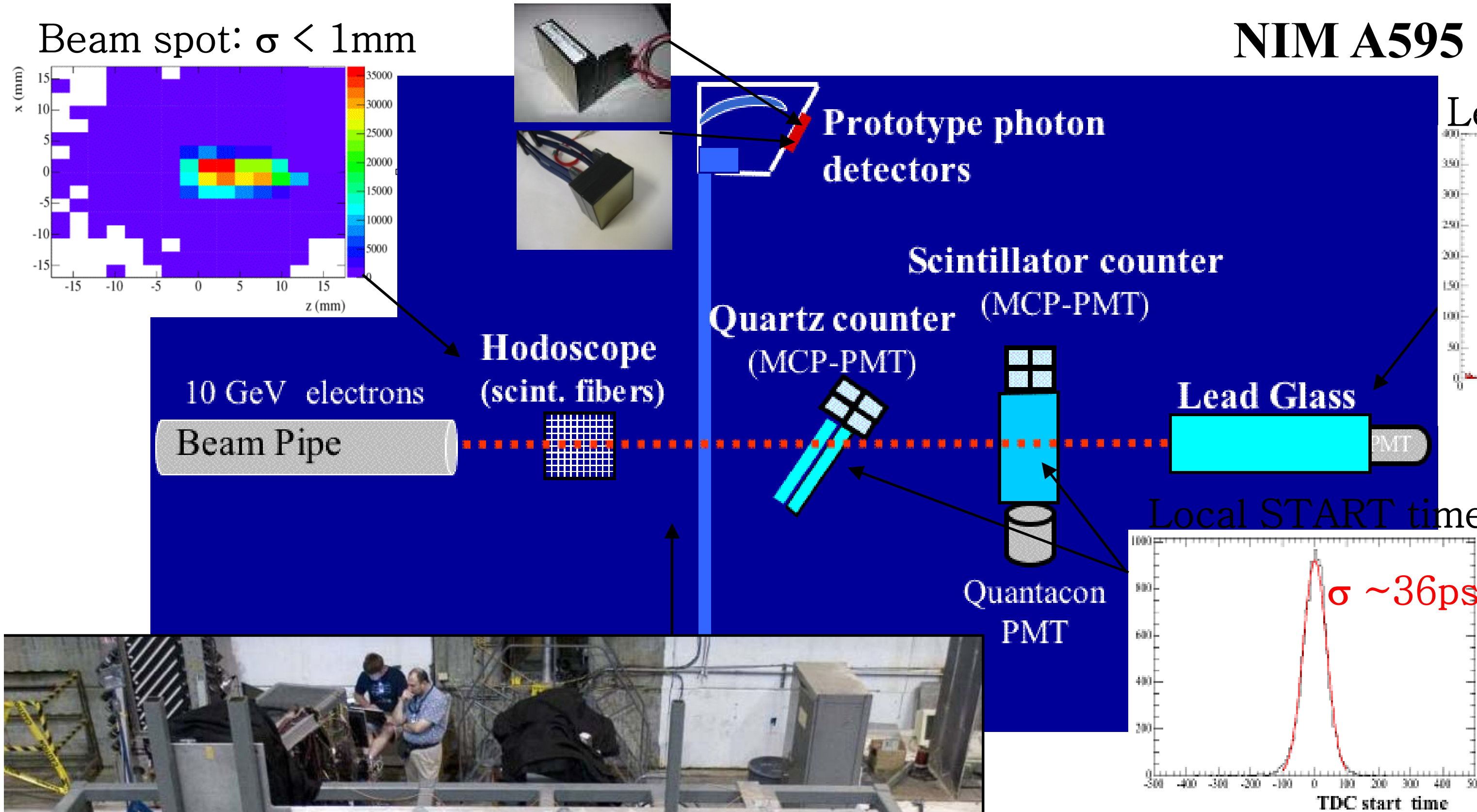
- Each detector pixel determines these photon parameters for average λ :
  θ_c, cos α, cos β, cos γ, Photon path length, time-of-propagation, number of photon bounces.

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

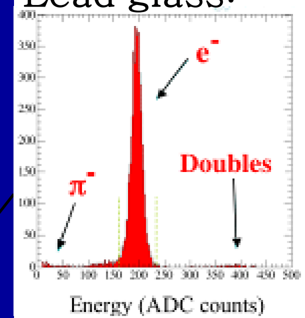
Focusing DIRC Prototype (T-492)

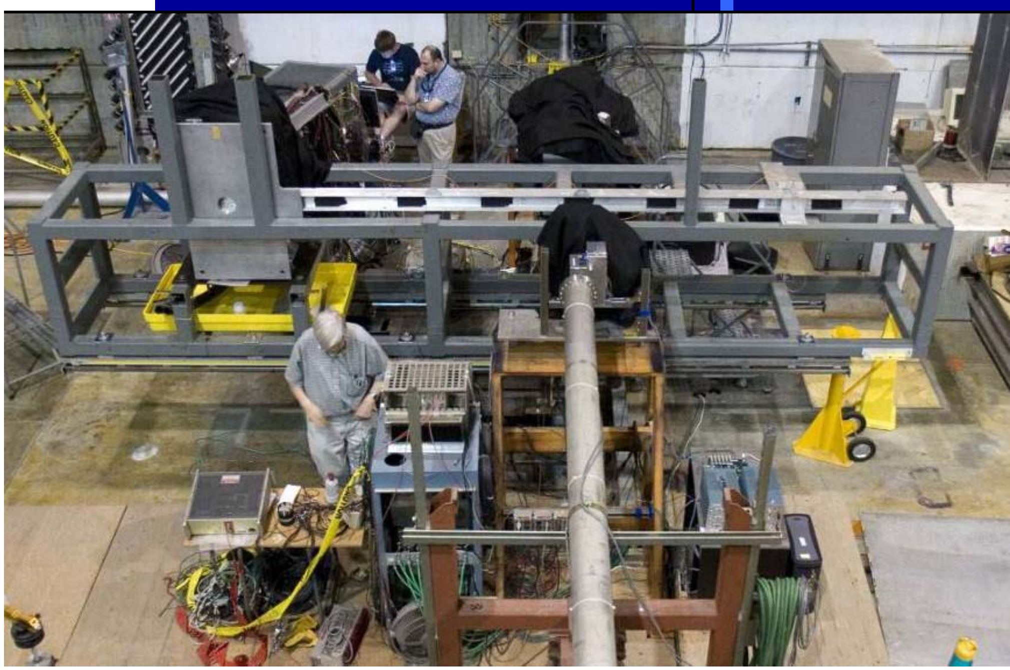
NIM A595 (2008) 104-107.

Beam spot: σ < 1mm



Lead glass:





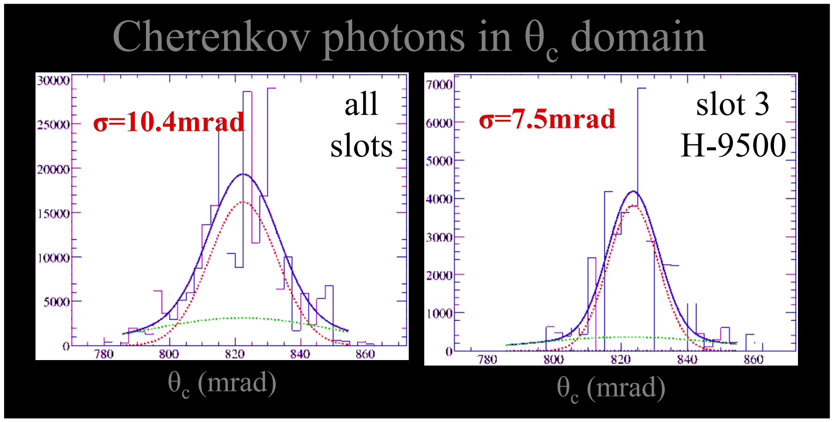
Focusing DIRC R&D effort at SLAC:

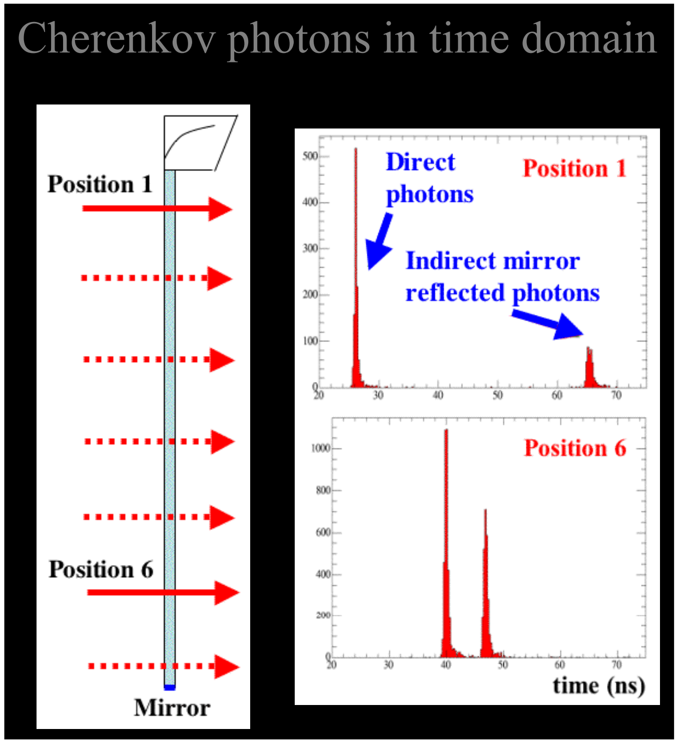
Jose Benitez [#] David W.G.S. Leith [#]
Gholam Mazaheri [#] Blair N. Ratcliff [#]
Larry L. Ruckman [+] Jochen Schwiening [#]
Gary S. Varner [+] Jerry Va'vra [#]

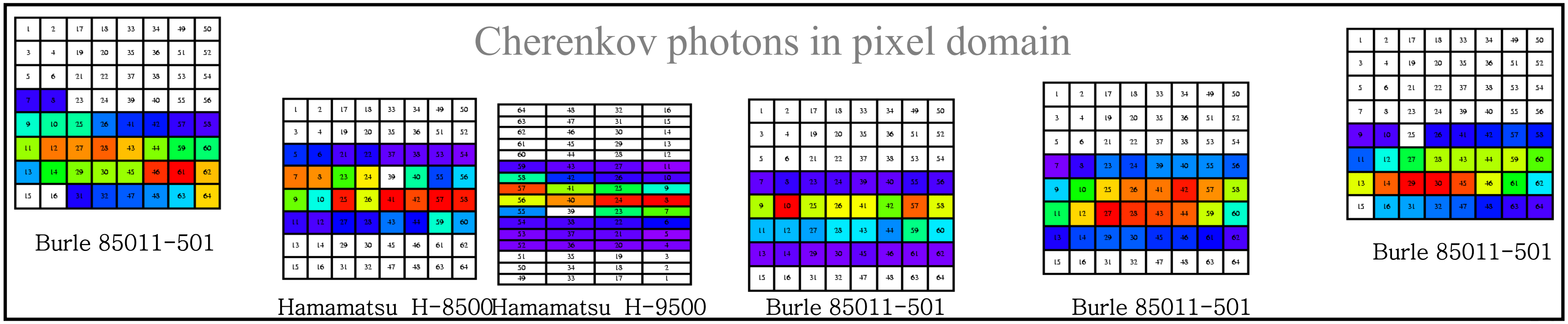
[#] SLAC [+] University of Hawaii

Cherenkov Photon Signal (2006)

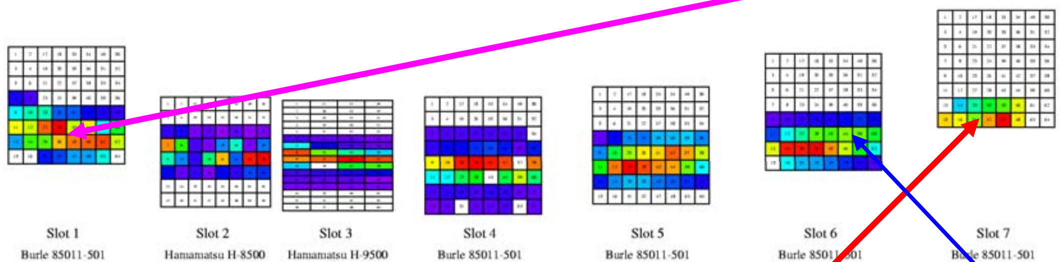
- 10 GeV/c electron beam data
- approx. 7.7M triggers, 560k good single e⁻ events
- ~ 200 pixels instrumented
- Ring image is most narrow in the 3 x 12 mm pixel detector (H-9500 in slot 3)



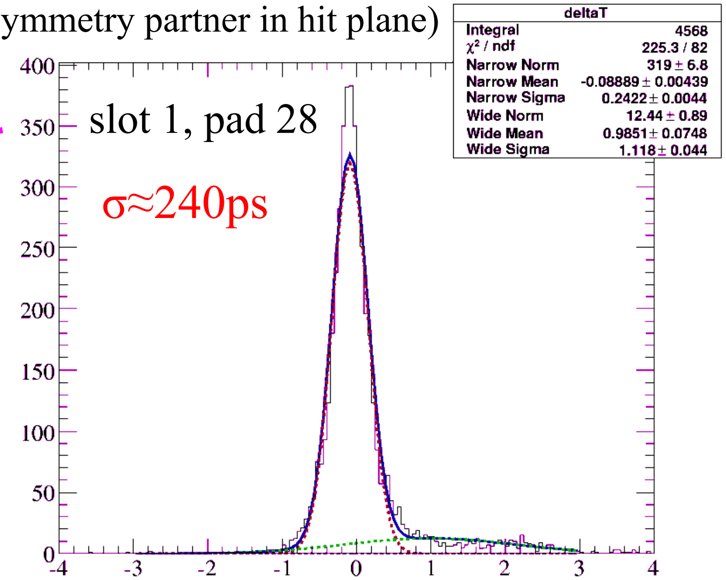




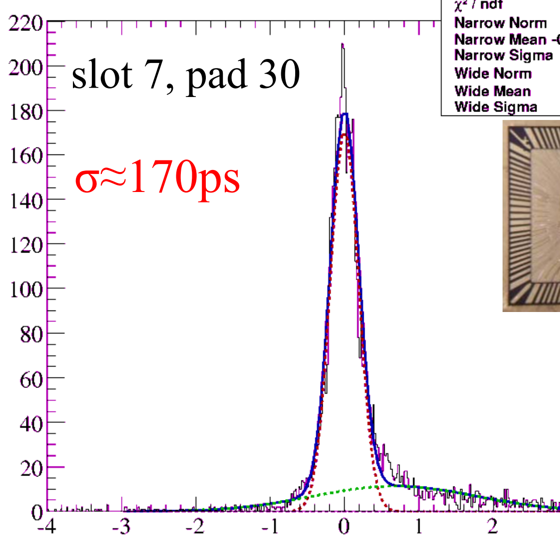
Aug 2007 Run: timing slot 7, pad 15
to Philips slot 1&6
for run 27, pos 1, direct photons

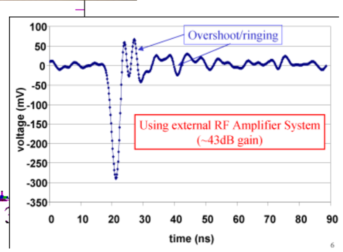


(symmetry partner in hit plane)

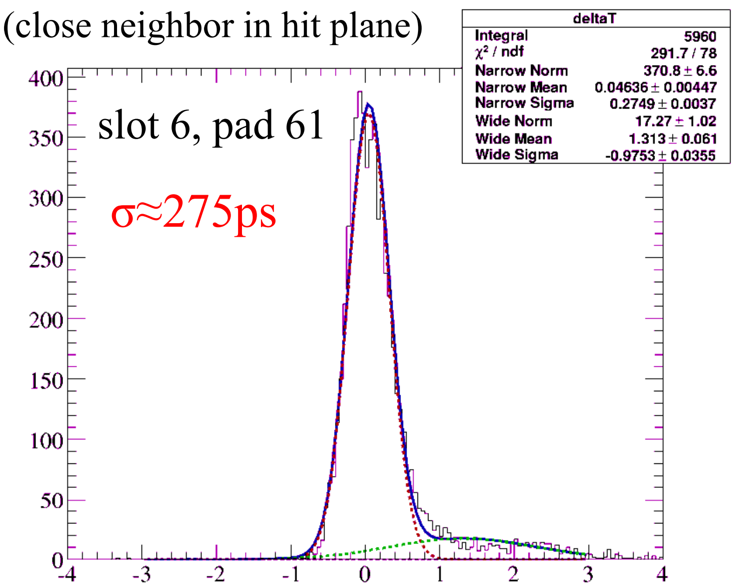


New BLAB-based Readout





(close neighbor in hit plane)



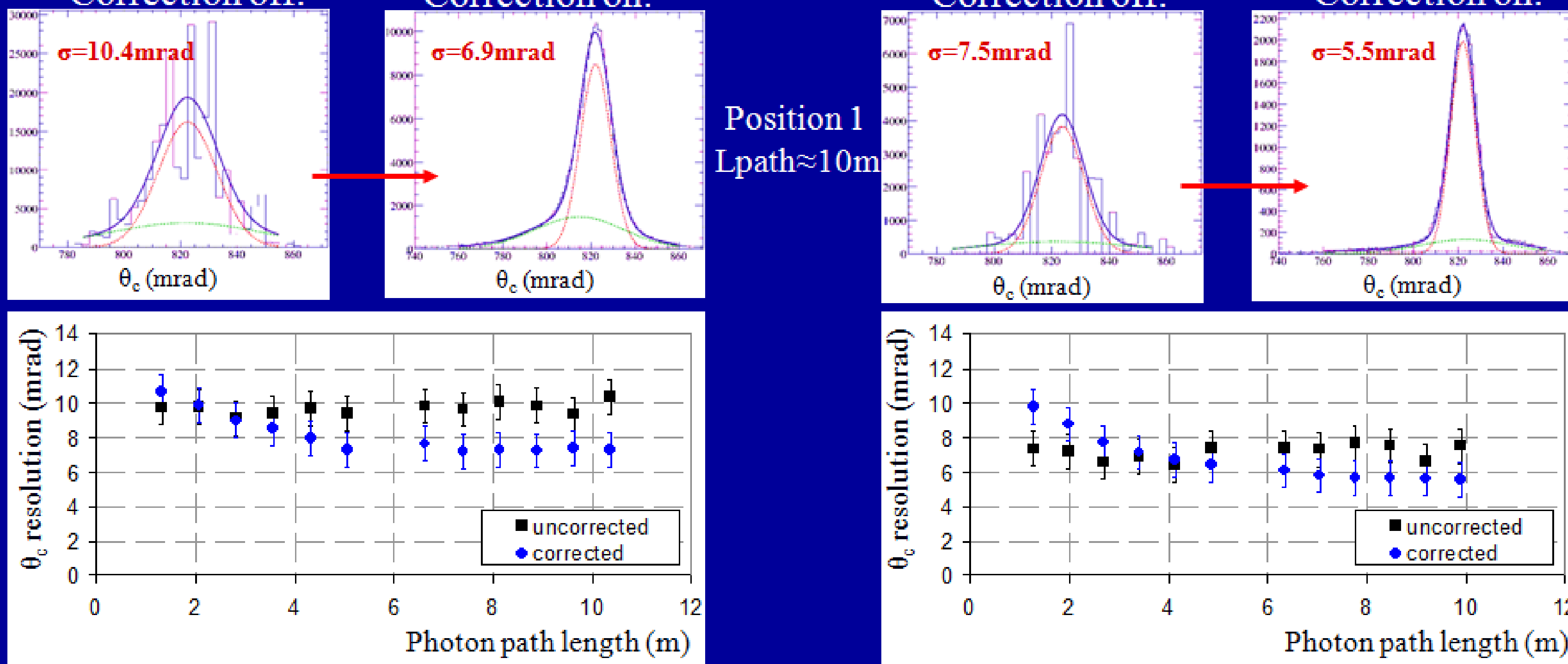
Future readout prototype

delta(time) (ns)

θ_c Resolution and Chromatic Correction

All pixels: 3mm pixels only:

Correction off: Correction on: Correction off: Correction on:

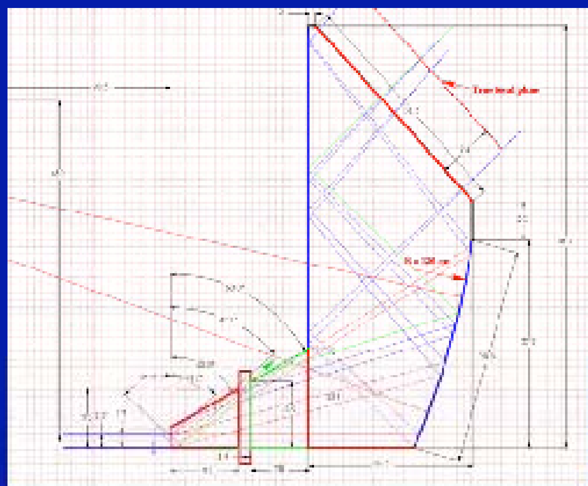


- The chromatic correction starts working for Lpath > 2-3 meters due to a limited timing resolution of the present photon detectors.
- Holes in the uncorrected distributions are caused by the coarse pixelization, which also tends to worsen the resolution. In the corrected distributions this effect is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

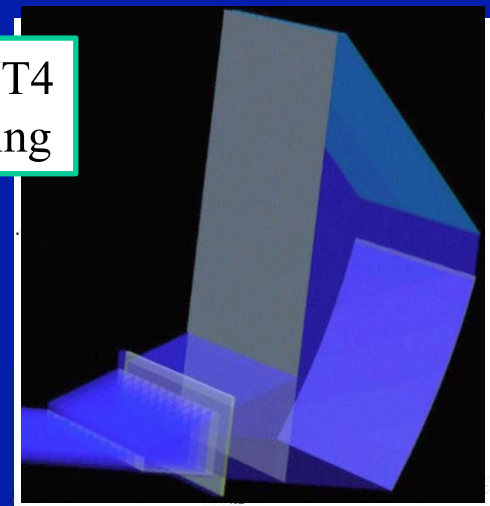
FDIRC for SuperB: optics design

J.Va'vra, SLAC-PUB-13763, 2009

Side view:



GEANT4 rendering



- Optics of the detector camera was designed by ray tracing. Then verified with the Mathematica ray tracing program. Finally, a full check by a MC simulation confirmed the design.
- We have to live with the existing bar box, which includes the Old Wedge, which has two complications: (a) it has a 6 mrad inclined angle at the bottom, intended to do a simple focusing, and (b) it is not long enough to bring all rays onto the cylindrical mirror, thus not all rays would be focused. Adding a New Wedge solves the focusing problem.
- Cylindrical mirror radius is 120 cm.
- Double-folded mirror optics to allow a good access to photon detectors.
- Will measure the timing resolution for a single photon to ~200ps.
- Focusing in y only => would like to use small pixels in y, and large pixels in x-direction.

FDIRC FOR ITALIAN SUPERB

Photodetector:

12 arrays of 6*8 MaPMTs (HPK H8500) → 18,432 pixels.

Readout Electronics:

TDC/ADC information for every photon.

Bottom line:

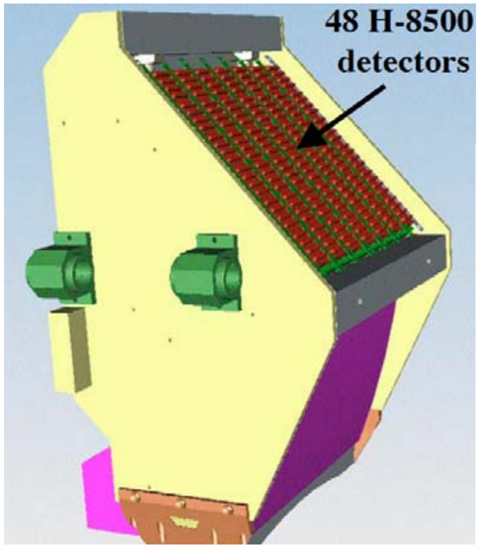
Conservative, robust design;

10x better timing resolution than BABAR DIRC;

25x smaller expansion volume than BABAR DIRC;

Cherenkov angle determined from 2D spatial coordinates;

Time primarily used to correct chromatic dispersion.



camera design model

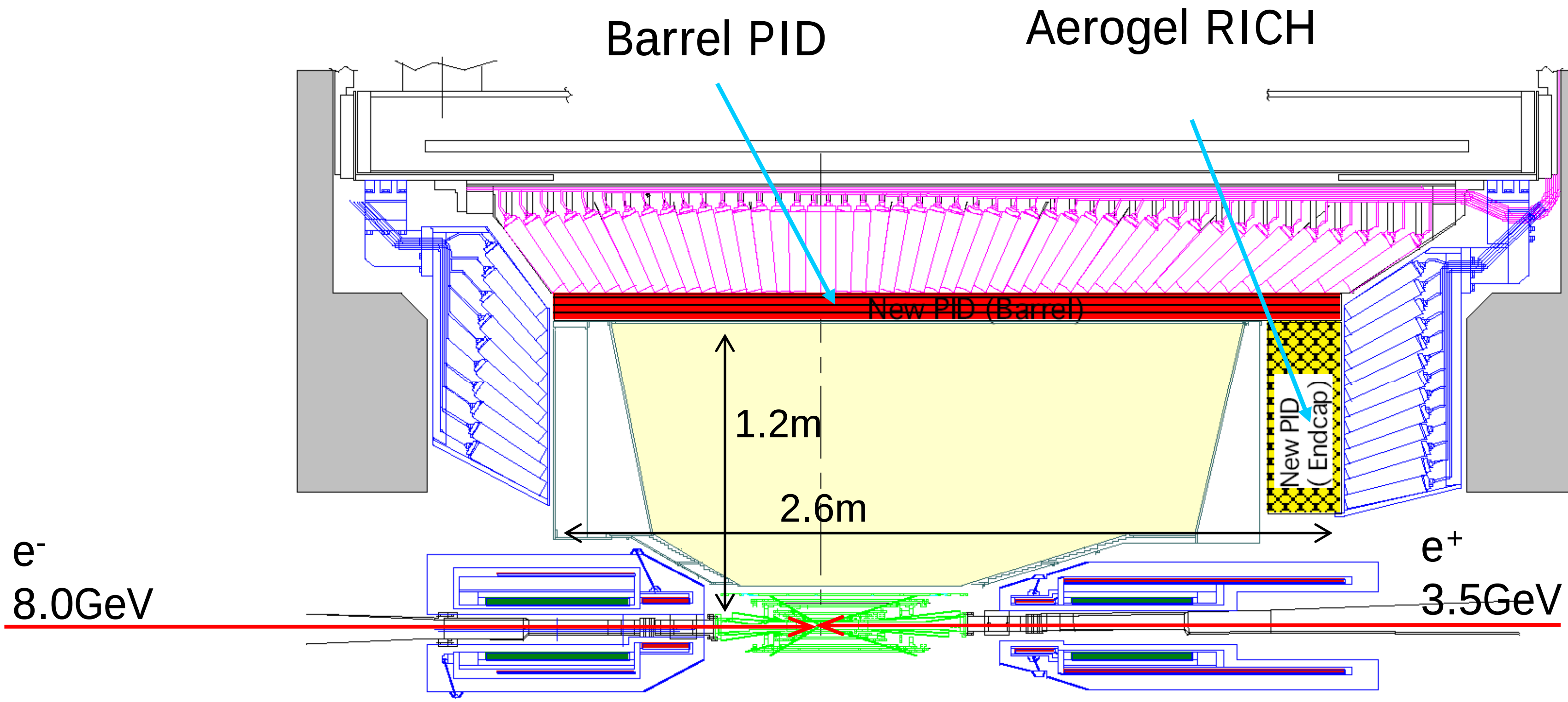
Figure from J. Va'vra RICH2010

Eagerly awaiting project approval to proceed with large prototype.

Collaboration on readout electronics

Upgraded detector

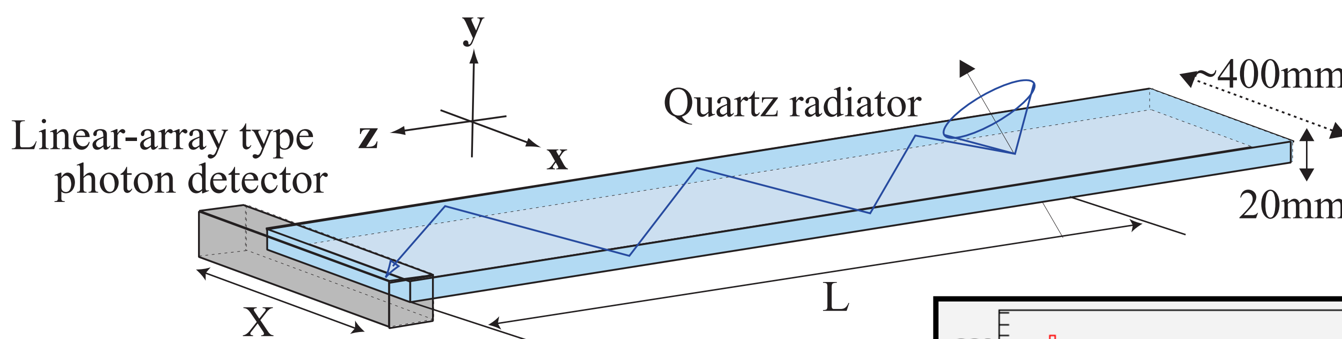
- PID (π/K) detectors
  - Inside current calorimeter
  - Use less material and allow more tracking volume
  - → Available geometry defines form factor
    -

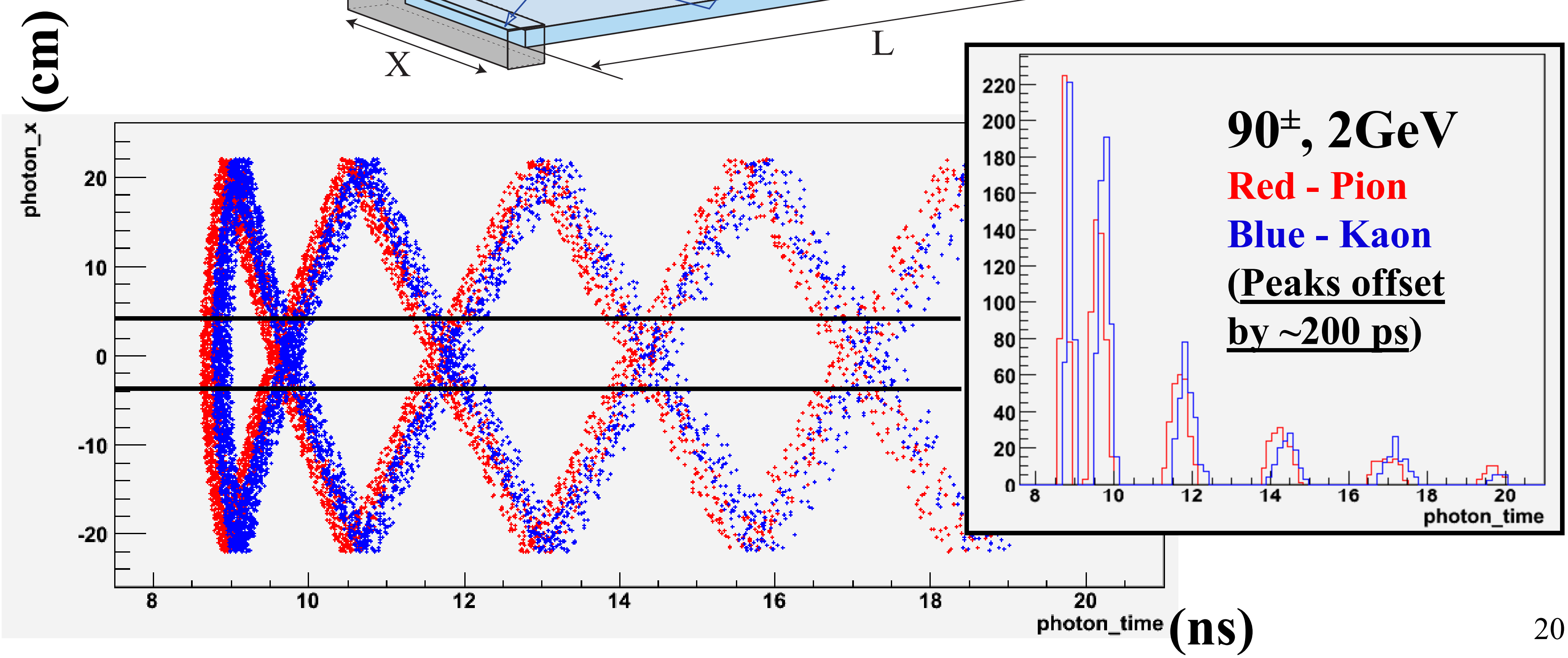


Time-of-Propagation (TOP) Counter

NIM A494 (2002) 430-435. **NIM A595 (2008) 96-99.**

- Work at bar end, measure x,t, not y ➔ compact!

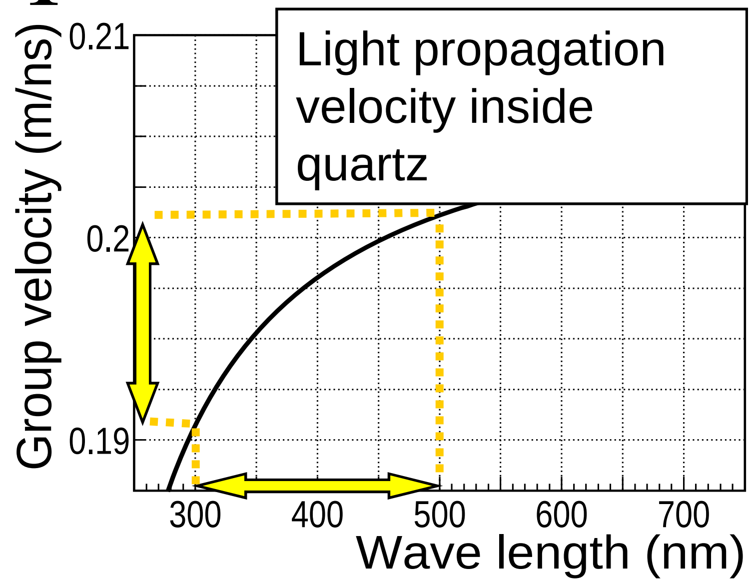




Chromatic dispersion

Variation of propagation velocity depending on the wavelength of Cherenkov photons

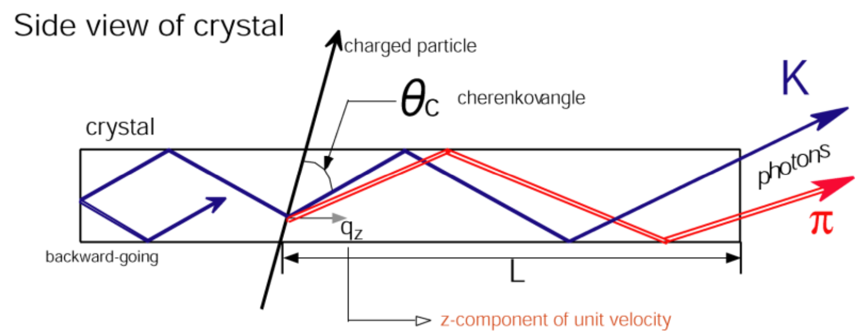
- Due to wavelength spread of detected photons
- → propagation time dispersion



- Longer propagation length

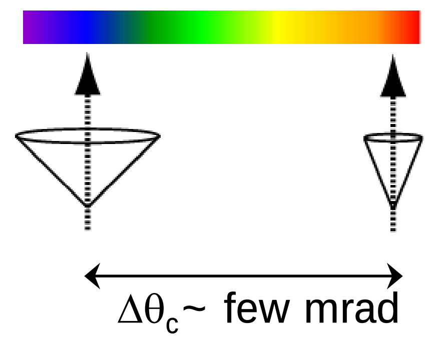
→ Improves ring image difference

But, decreases time resolution.

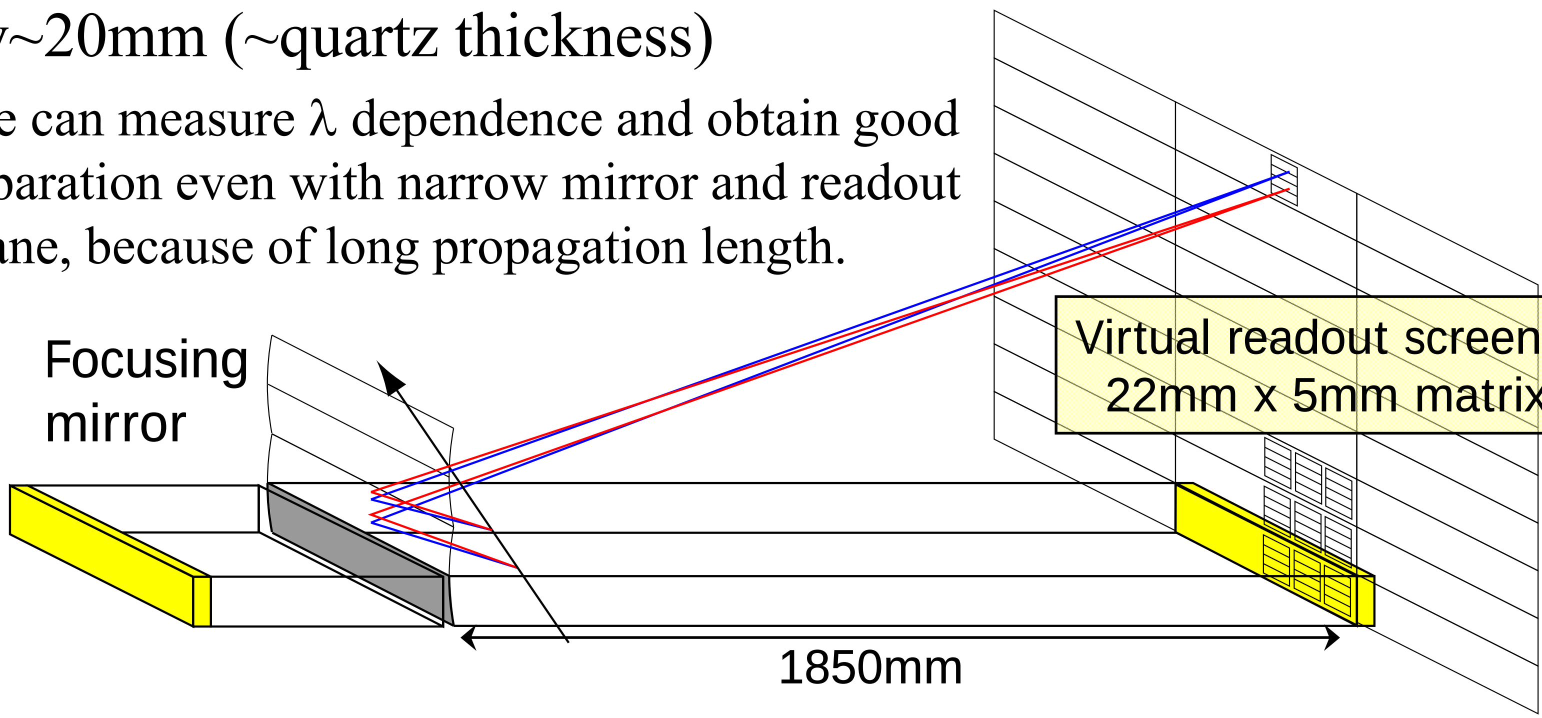


Focusing TOP

- Use λ dependence of Cherenkov angle to correct chromaticity
  - Angle information → y position
  - Reconstruct Ring image from 3D information (time, x and y).



- $\Delta\theta_c$~ few mrad over sensitive λ range
- → Δy~20mm (~quartz thickness)
  - We can measure λ dependence and obtain good separation even with narrow mirror and readout plane, because of long propagation length.



Issues with Belle II PID options

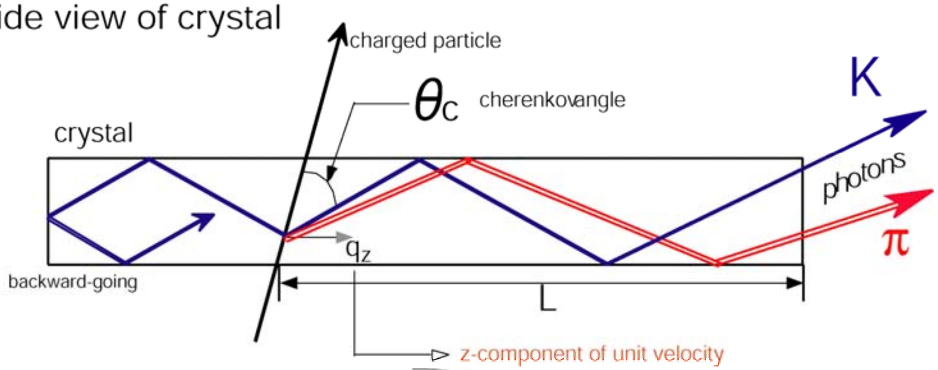
- Basic TOP
  - Performance marginal at best
  - Not robust against multiple particle hits
- Focusing TOP
  - Acceptance gap
  - Complicated image reconstruction
- Fast Focusing-DIRC
  - Works very well
  - Just doesn't fit!
- Some alternative?

imaging TOP (iTOP)

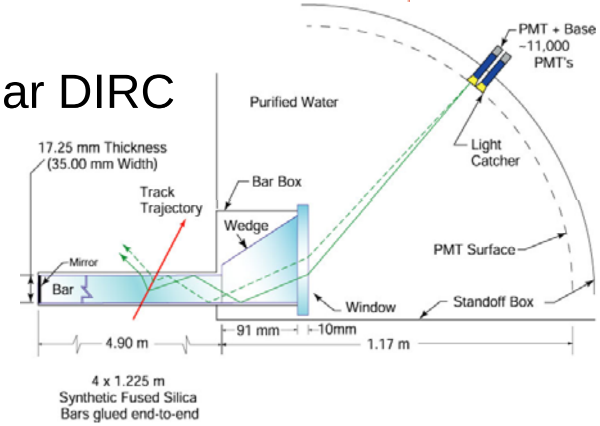
Concept: Use best of both TOP (timing) and DIRC while fit in Belle PID envelope

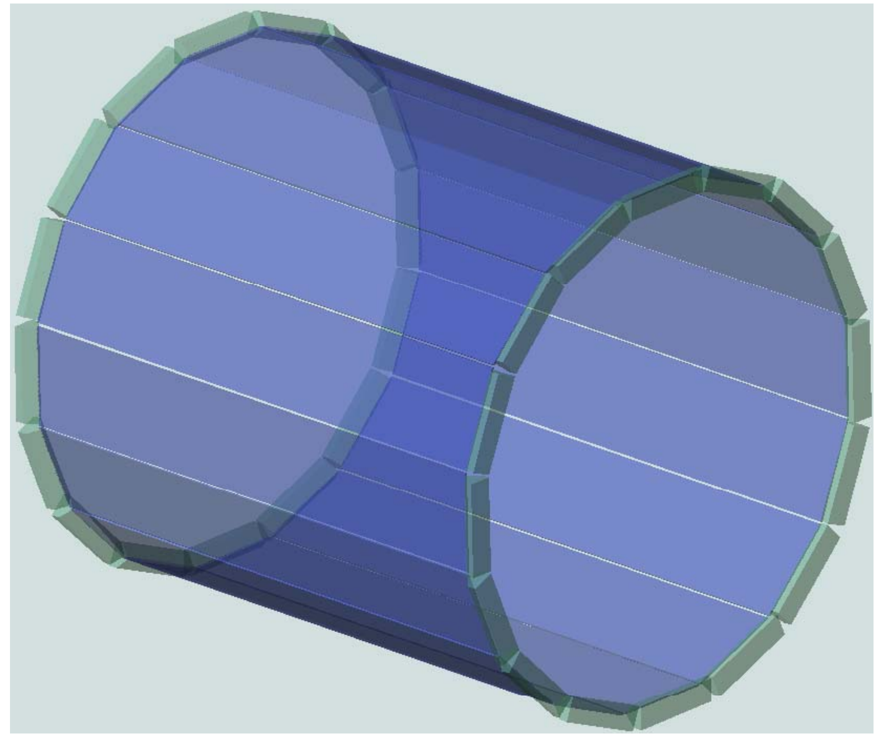
NIM A623 (2010) 297-299.

Side view of crystal



BaBar DIRC



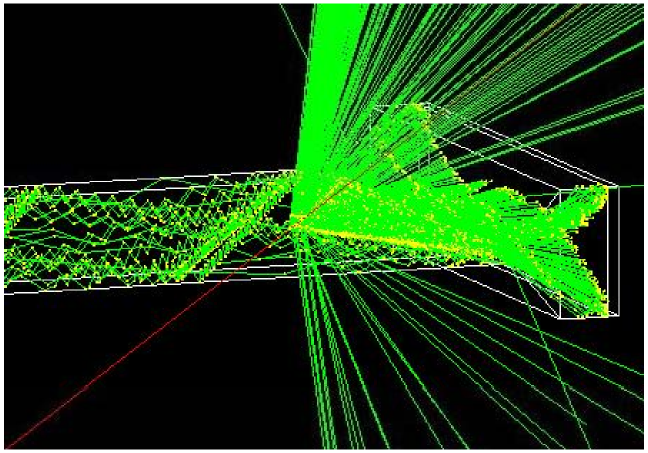


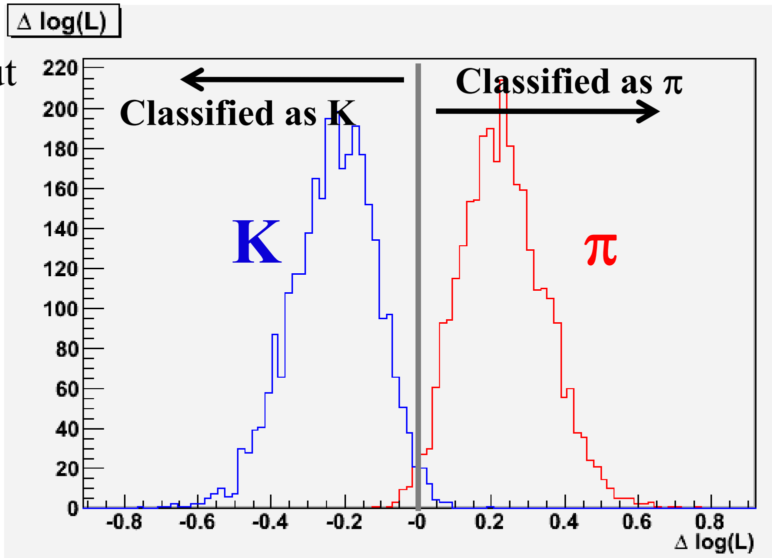
Use wide bars like proposed TOP counter

- Use new, high-performance MCP-PMTs for sub-50ps single p.e. TTS
- Use simultaneous T, θc [measured-predicted] for maximum K/π separation
- Optimize pixel size

Simulation Studies

- Independent simulations:
  - Belle Geant3 + standalone code (Nagoya)
  - Geant4 (Hawaii)
  - Standalone code (Ljubljana)
- All utilize a Log(Likelihood) approach to determine particle classification.
  - PDFs are defined in x,y, and t
  - Geant-based versions take probability distribution functions (PDFs) from simulated events.
    - ➔ Extremely time consuming to generate the PDFs, but can include all the effects (scattering, ionization, delta-rays, etc.) that Geant can provide.
  - Log (Likelihood) in Ljubljana code utilizes analytical expressions for the likelihood functions.
    - ➔ Much faster!
    - ➔ Working to integrate with full simulated data and improve performance.



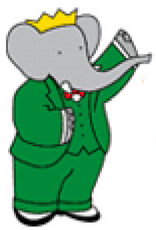


NIM A623 (2010) 297-299.

Quartz Cherenkov Device Landscape

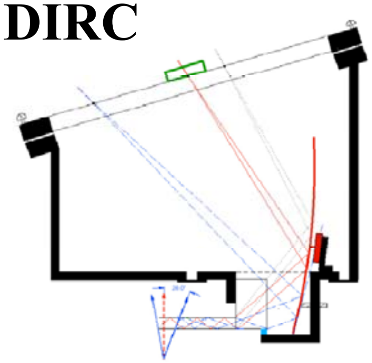
Performance

BaBar DIRC



- **Large (~1m) expansion**
- **Mainly x,y**
- **Very coarse t**

Fast Focusing DIRC



- **Some expansion (~0.5 m)**
- **Focus to correct for finite bar thickness.**
- **Mainly x,y**
- **Order ~200 ps σ_t make chromatic corrections**

More sensitive to tracking uncertainties

Imaging TOP

- **Small expansion (~.1 m)**
- **Mainly x,t**
- **Focusing, coarse y to correct chromatic effects**

More sensitive to t_0 uncertainties

Focusing TOP

- **No expansion**
- **Mainly x,t**
- **Focusing & coarse y to correct chromatic effects**

TOP

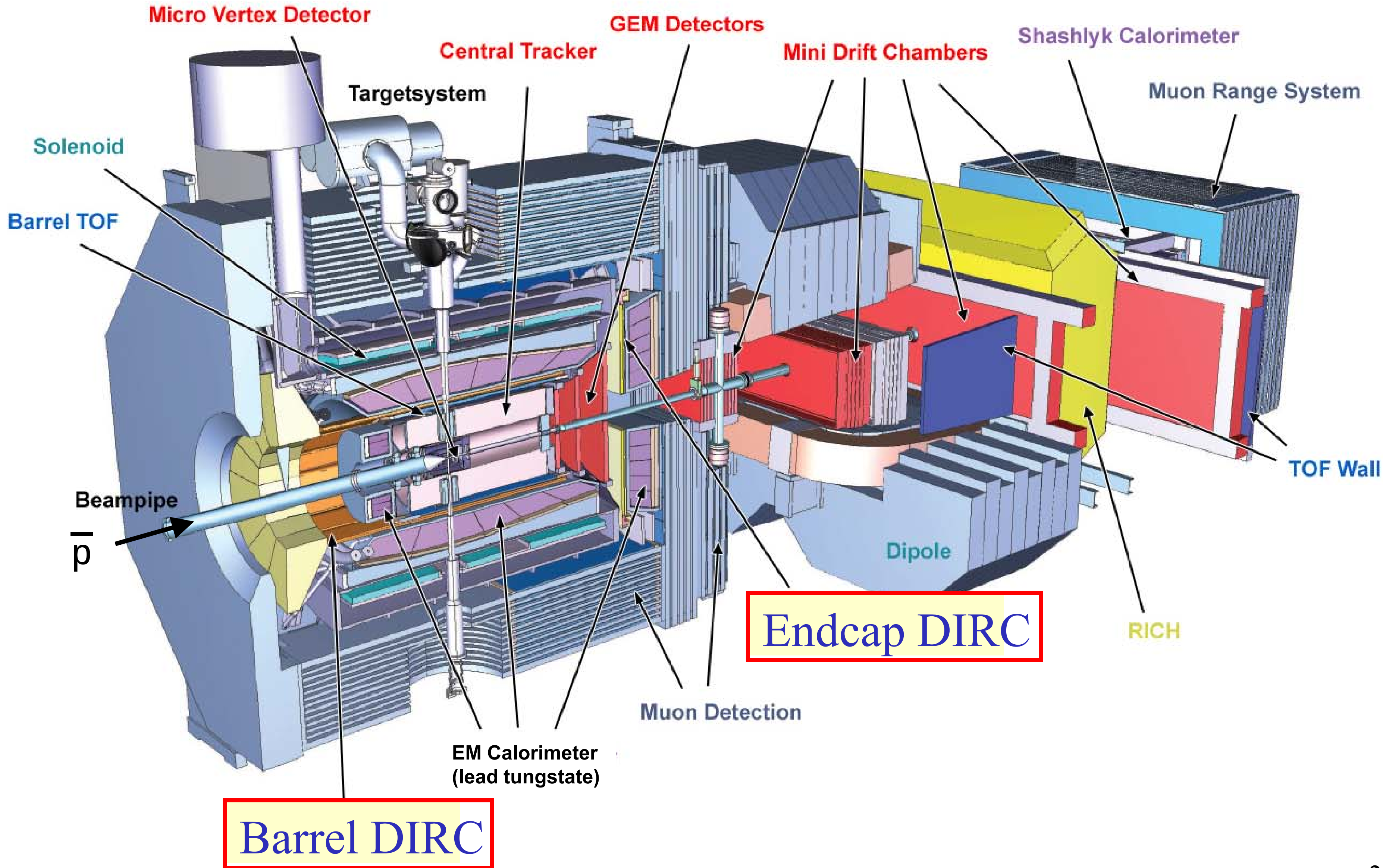
- **No expansion**
- **Only x,t**
- **No focusing ➔ chromatic degradation**

Mostly imaging ←

Mostly timing →

Compactness

For the future: PANDA DETECTOR



DIRC IN PANDA

Most recent review of PANDA DIRCs: C. Schwarz RICH2010

DIRC detector advantages

- Thin in radius and radiation length.
- Moderate and uniform amount of material in front of calorimeter.
- Number of signal photons increases in forward direction *(good match to asymmetric detector at fixed target experiment).*
- Fast and tolerant of background.
- Robust and stable detector operations.

PANDA design includes two DIRC detectors

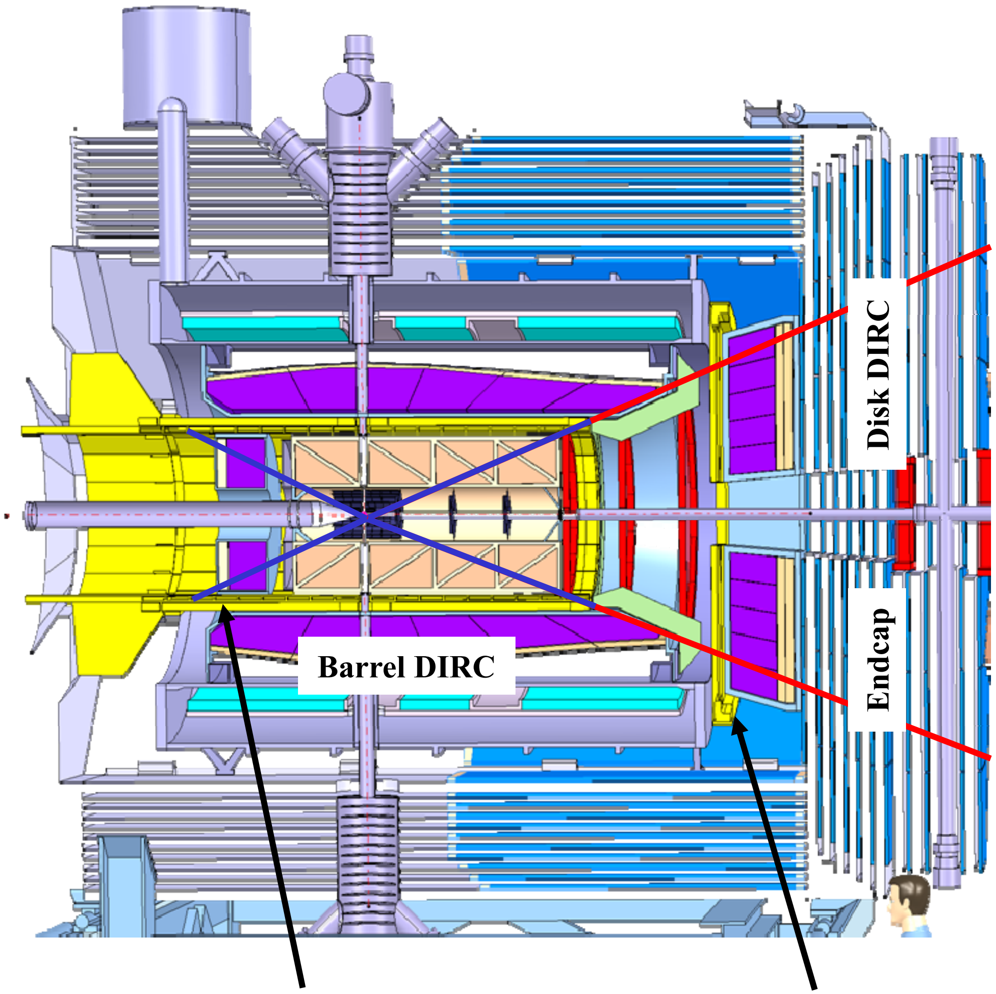
- Barrel DIRC similar to BABAR DIRC.
- Novel endcap Disk DIRC – 2x designs (DIRC & TOP).

Institutions currently involved

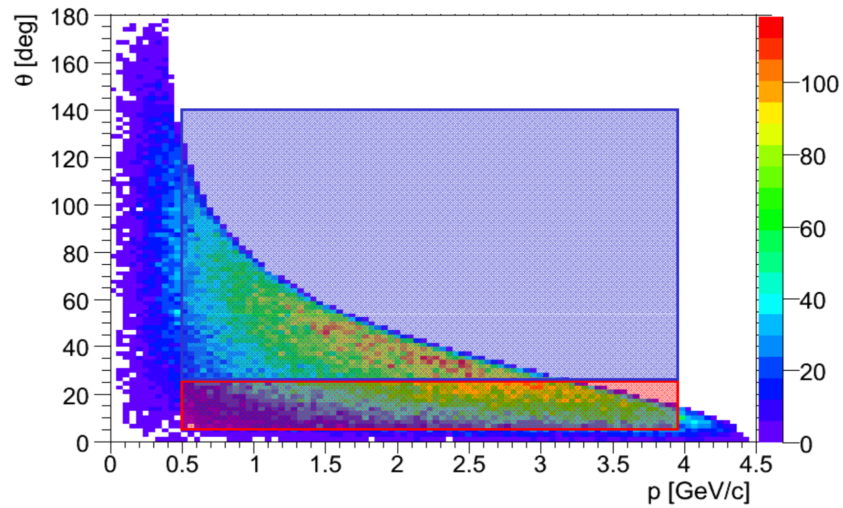
- Edinburgh, Erlangen, Dubna, Ferrara, Gießen, Glasgow, GSI, Vienna.

DIRC IN PANDA

Particle Identification coverage of the two DIRC detectors



Barrel DIRC **Endcap Disk DIRC**



Kaon distribution of the radiative decay

$J/\psi \rightarrow K^+K^-\gamma$

(search of glue balls)

PANDA Barrel DIRC

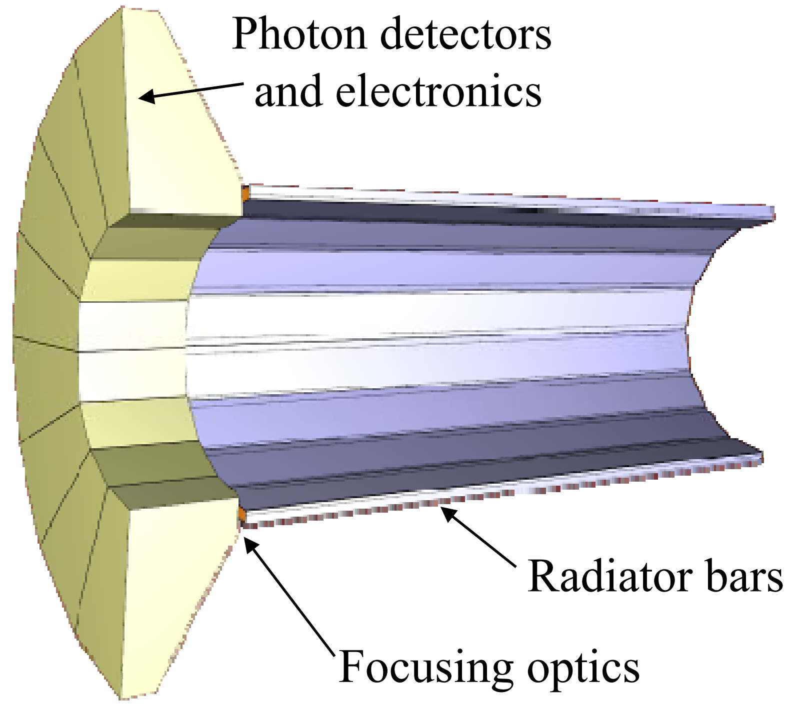
NIM A595 (2008) 112-115.

10.1016/j.nima.2010.10.061

Improved version of proven BABAR-DIRC design

More compact, faster, focusing optics

- 96 radiator bars, synthetic fused silica
  17mm (T) × 33mm (W) × 2500mm (L)
- Focusing optics: lens system
- Compact photon detector: array of
  Burle Planacon MCP-PMT
  or Geiger-mode APD,
  total 7000-10000 channels.
- Fast photon detection: MCP-PMT/gAPD plus
  fast TDC/ADC (ToT) electronics
  → 100-200 ps timing.

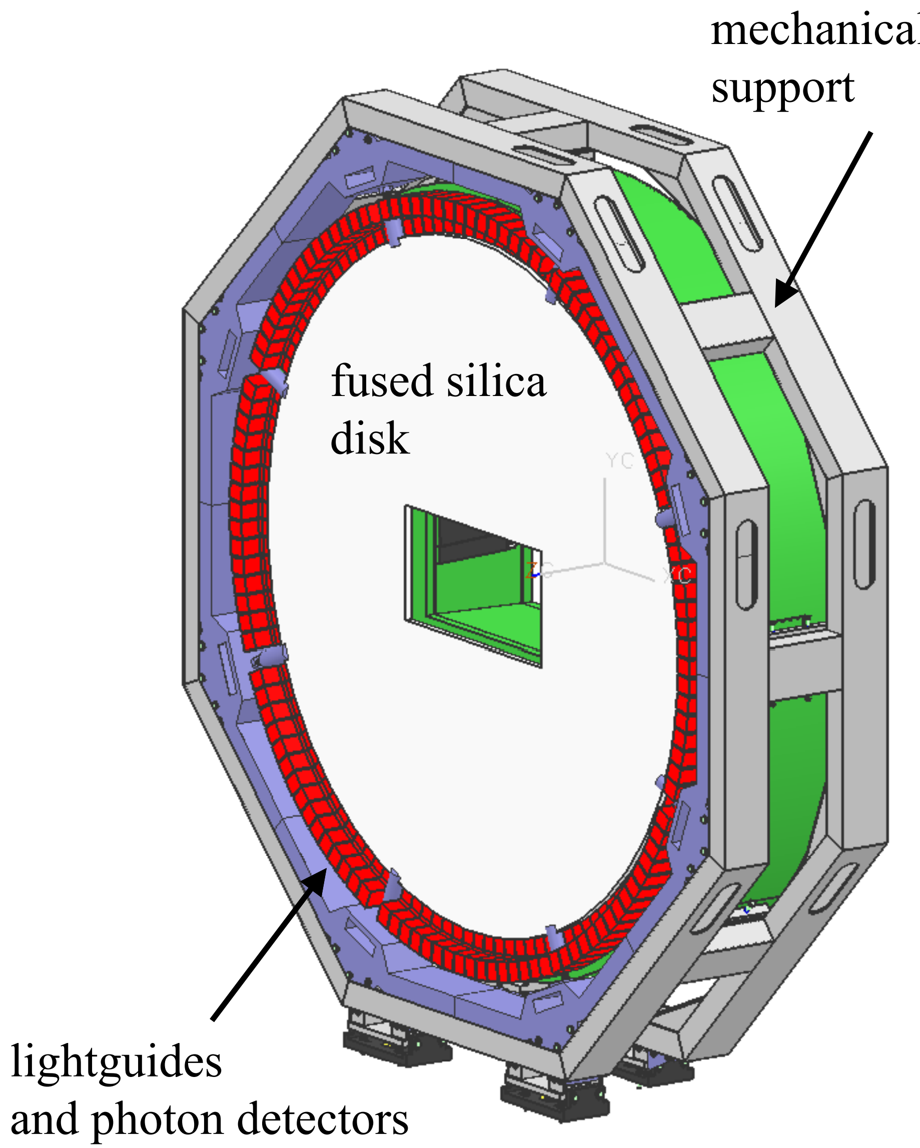


Still investigating several design options:

mirror focusing, radiator plates, photon detection outside magnetic field

PANDA Focusing Disk DIRC

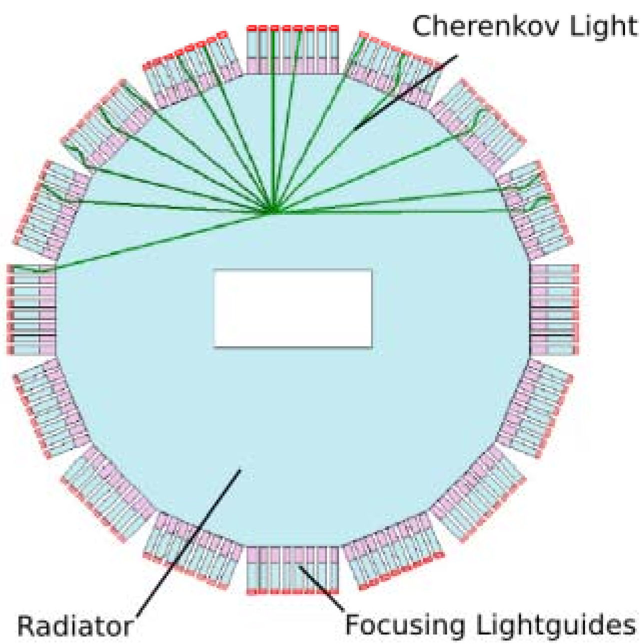
- Image reconstruction in 2D (X, Y)
- Timing used for event correlation and background subtraction
- Radiator: synthetic fused silica, 20 mm thick, 1100 mm radius
- Focusing optics for imaging with dispersion correcting element (LiF)
- Compact detection plane on each light guide (50x50 mm^2)
- 128 light guides, 4096 R/O channels

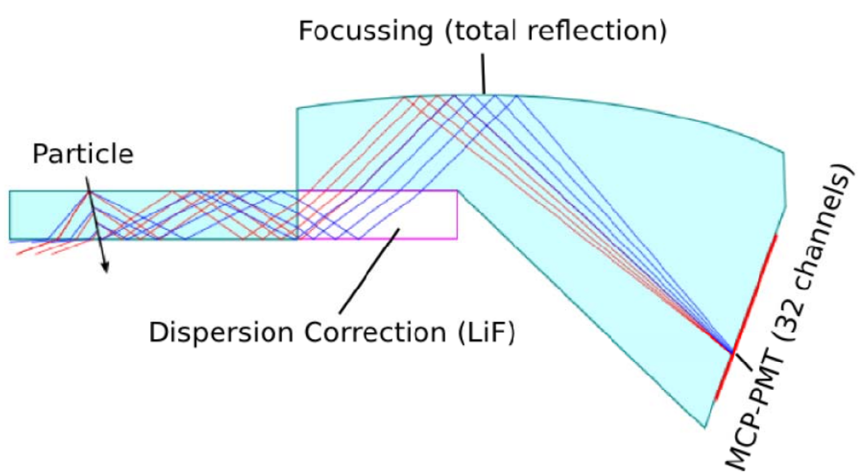


10.1016/j.nima.2010.10.116

Option A: PANDA FOCUSING DISK DIRC

- Direct measurement of Cherenkov angle
  → need expansion region
- Design of expansion region = light guide
  compromise between compact size and
  performance with given MCP-PMT size
- Transition from fused silica
  to LiF and back has two-fold
  prism effect and mitigates dispersion

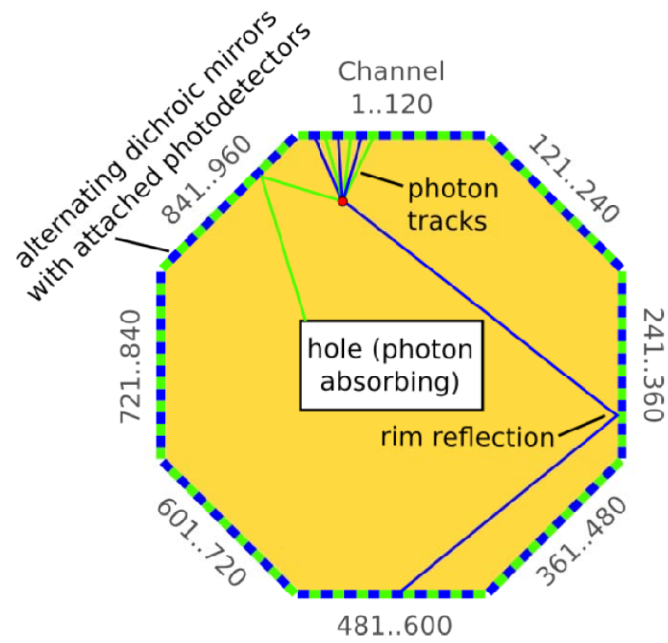


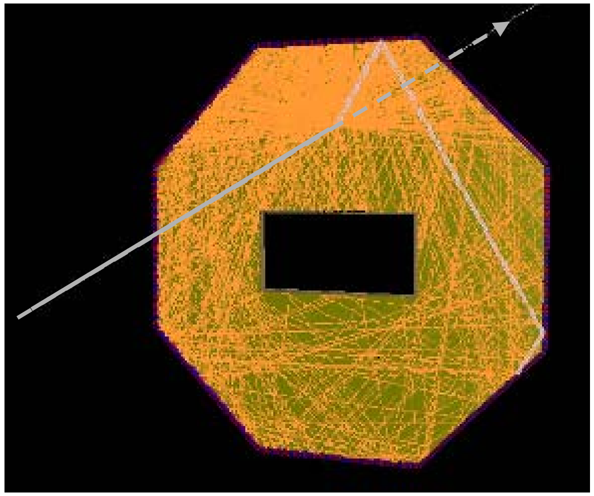


Can also correct dispersion using timing

Option B: PANDA TIME-OF-PROPAGATION DISK DIRC

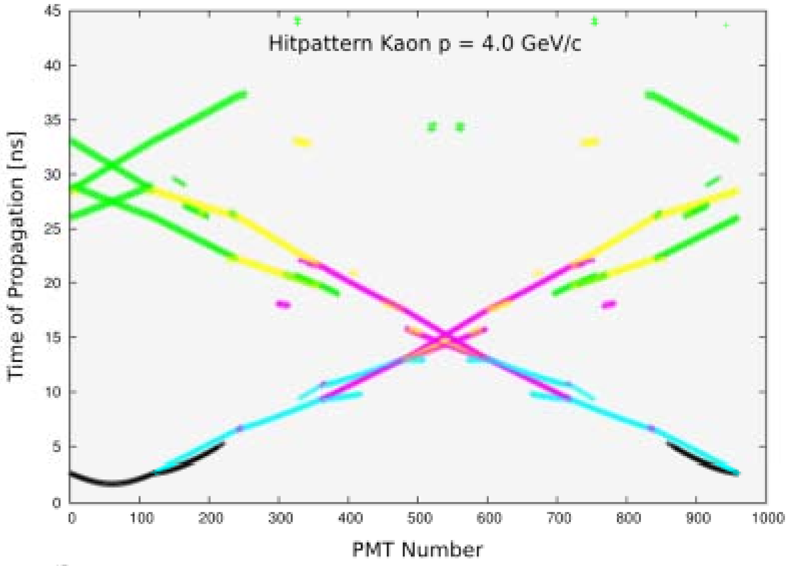
- Reconstruction in 1D+t.
- Indirect measurement of Cherenkov angle using time-of-propagation (TOP) and photon propagation angle in disk.
- Requires photon path reconstruction and fast single-photon timing $\sigma_t < 50$ps
- Dichroic mirrors to select wavelength band and to increase light path
  (relative error drops with increasing path length)
- Approx. 1000 R/O channels.

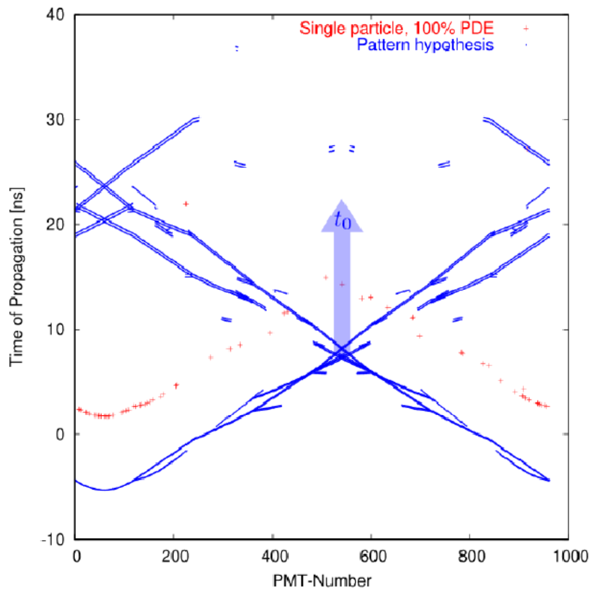


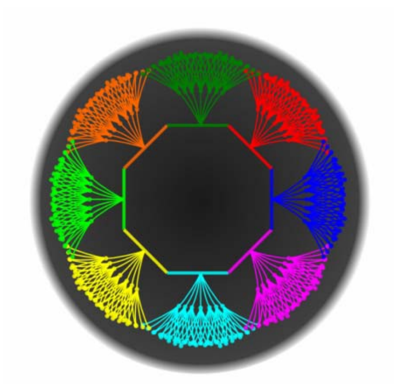


PANDA TIME-OF-PROPAGATION DISK DIRC

- Cherenkov images: pattern in TOP/φ space (φ given by PMT pixel number).
- Use first arriving photons to determine event (start) time t_0.
- Consider all photon paths up to 4 rim reflections for particle hypothesis test.
- Robust reconstruction method required to deal with multiple tracks and backgrounds.







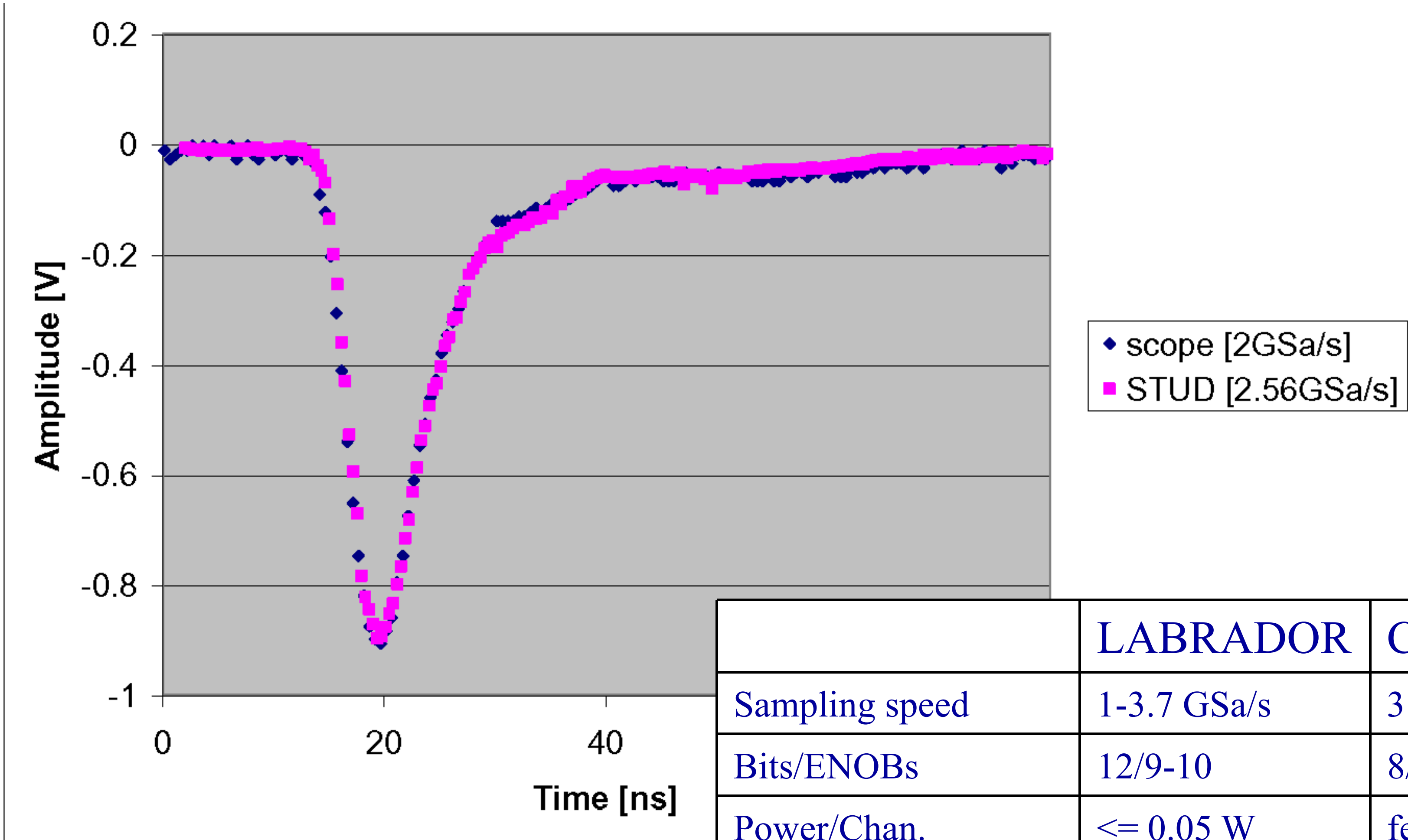
Key (common) PID R&D Items

- Fused silica (quartz) radiator bar production
- High performance Timing readout
- Good single photon timing detector
  - 1.5T field operation
  - >1C/cm^2 integrated charge
  - <50ps Transit-Time Spread
- Triggering possibility?

(not discussed here, but active R&D for Belle II)

Readout Electronics using *"Oscilloscope on a Chip"*

NIM **A583** (2007) 447

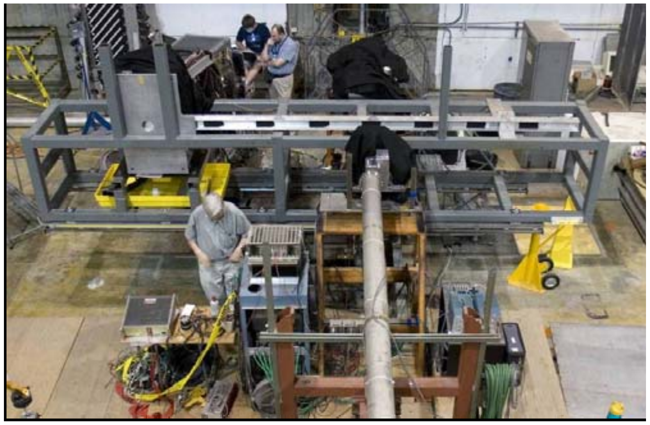


LABRADOR ASIC

	LABRADOR	Commercial
Sampling speed	1-3.7 GSa/s	3 GSa/s
Bits/ENOBs	12/9-10	8/7.4
Power/Chan.	<= 0.05 W	few W
Cost/Ch.	< $10	> 100's $

Summary

Close collaboration between groups has been essential



- Focusing DIRC prototype detector (SuperB)
  - Full prototype test this summer
  - SuperB schedule
- Belle II on very aggressive time scale
  - Quartz production must start 2011
  - Installation in spring 2014
- Panda schedule a bit more relaxed
  - Can explore some interesting new ideas
  - Will learn from the Super-B factory developments
- Joint R&D has been very successful

Source material (page 1)

1. E. Nakano, “Belle PID,” NIM **A494** (2002) 402-408.
2. J. Schwiening *et al.* (BaBar-DIRC Collaboration), “Performance of the BaBar DIRC,” NIM **A553** (2005) 317-322.
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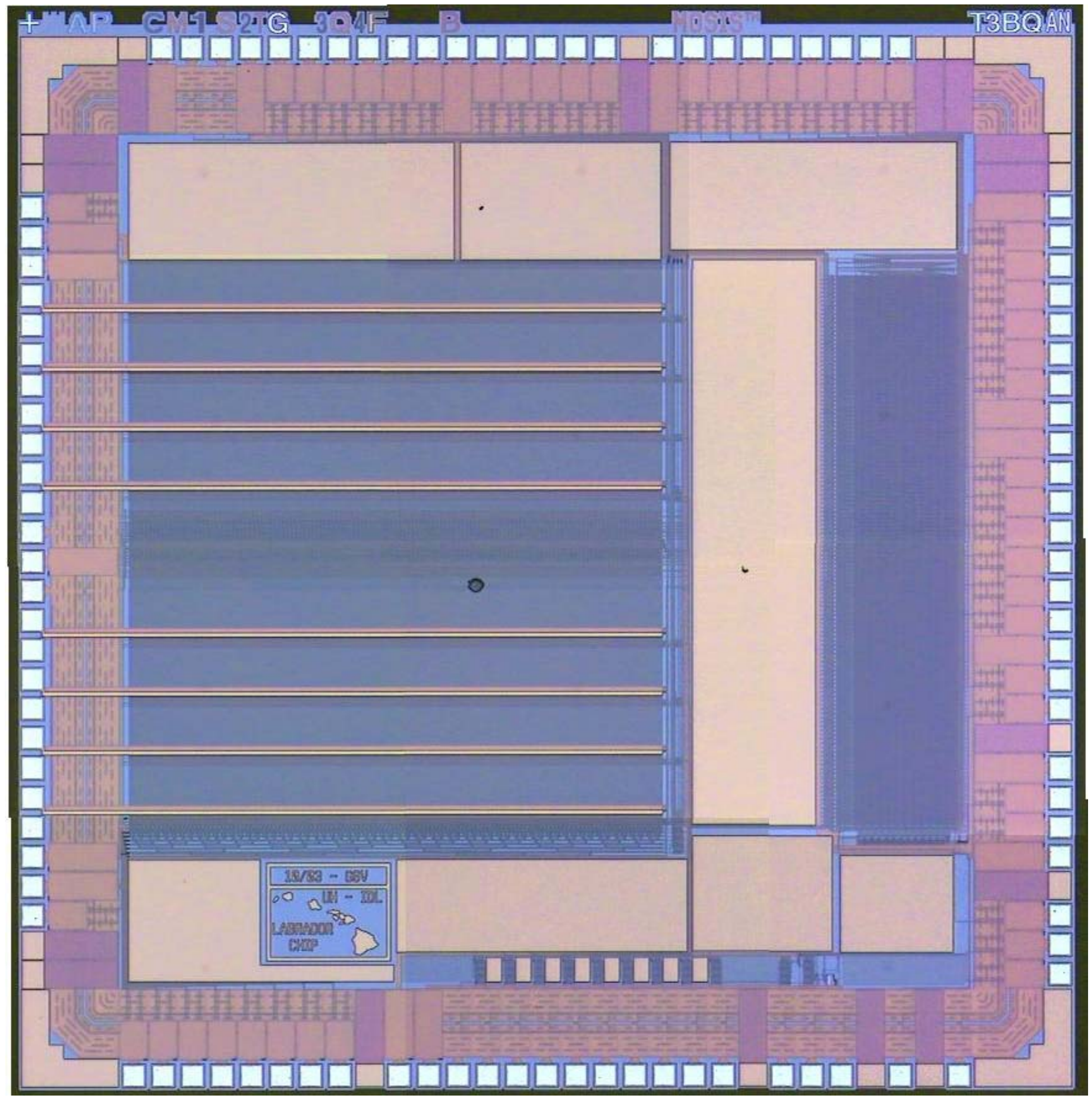
11. C. Schwarz, D. Bettoni, D. Branford, V. Carassiti, A. Cecchi, V.Kh. Dodokhof, M. Dueren, K. Foehl, R. Hohler, R. Kaiser, A. Lehmann, D. Lehmann, H. Marton, K. Peters, G. Schepers, L. Schmitt, P. Schoenmeier, B. Seitz, C. Sfienti, A. Teufel, A.S. Vodopianov, "The barrel DIRC of the PANDA experiment," NIM **A595** (2008) 112-115.
12. J. Schwiening for the PANDA Cherenkov group, "The barrel DIRC detector for the PANDA experiment at FAIR," 10.1016/j.nima.2010.10.061, to appear NIM **A**.
13. C. Schwarz *et al*. (PANDA Cherenkov group), "Particle identification for the PANDA detector," 10.1016/j.nima.2010.10.116, to appear NIM **A**.
14. G.S. Varner, L.L. Ruckman, P.W. Gorham, J.W. Nam, R.J. Nichol, J. Cao, M. Wilcox, "The large analog bandwidth recorder and digitizer with ordered readout (LABRADOR) ASIC," NIM **A583 (**2007) 447-460.
15. L.L. Ruckman, K. Nishimura, G.S. Varner, J. Vavra, D. Aston, D.W.G.S. Leith, B. Ratcliff, "The focusing DIRC with waveform digitizing electronics," NIM **A623** (2010) 303-305.
16. Larry L. Ruckman and Gary S. Varner, "Sub-10ps Monolithic and Low-power Photodetector Readout," NIM **A602** (2009) 438-445.
17. Larry L. Ruckman, Gary S. Varner and Andrew Wong, "The First version Buffered Large Analog Bandwidth (BLAB1) ASIC for high luminosity collider and extensive radio neutrino detectors," NIM **A591** (2008) 534-345.

Back-up slides



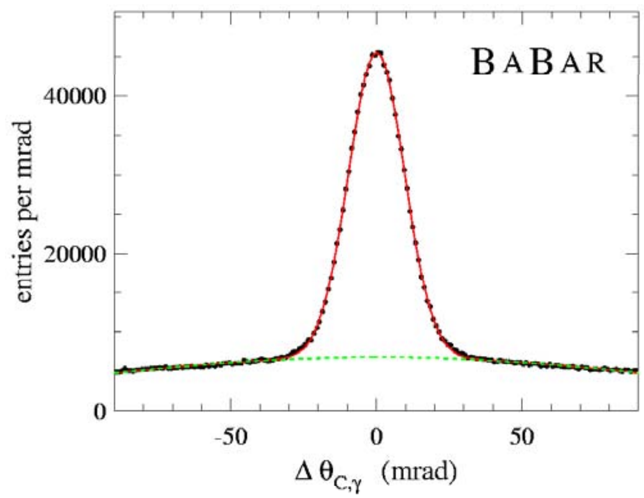
BABAR-DIRC Resolution Limits

Photon yield:	18-60 photoelectrons per track *(depending on track polar angle)*
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)*
Cherenkov angle resolution:	9.6mrad per photon → 2.4mrad per track

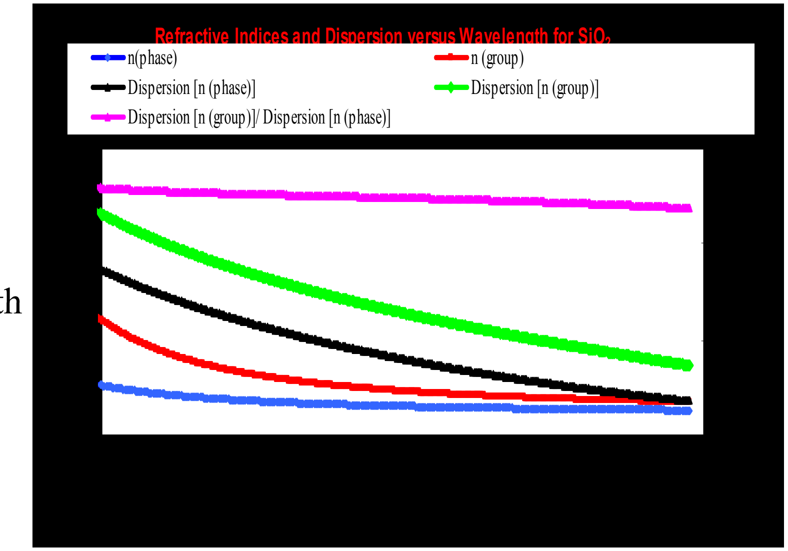
Limited by	*BABAR-DIRC*	*Improvement strategy*
Size of bar image	~ 4.1mrad	Focusing optics
Size of PMT pixel	~ 5.5mrad	Smaller pixel size
Chromaticity ($n=n(\lambda)$)	~ 5.4mrad	Better timing resolution

Focusing DIRC prototype designed to achieve

- 4-5mrad θ_c resolution per photon,
- 3σ π/K separation up to ~ 5GeV/c



Chromatic Effects



Chromatic effect at Cherenkov photon production $\cos\theta_c = 1/n(\lambda)\,\beta$

n(λ) refractive (phase) index of fused silica

n=1.49…1.46 for photons observed in BABAR-DIRC (300…650nm)

→ $\theta_c^\gamma = 835 \ldots 815$mrad

Larger Cherenkov angle at production results in shorter photon path length

→ 10-20cm path effect for BABAR-DIRC *(UV photons shorter path)*

Chromatic time dispersion during photon propagation in radiator bar

Photons propagate in dispersive medium with group index n_g

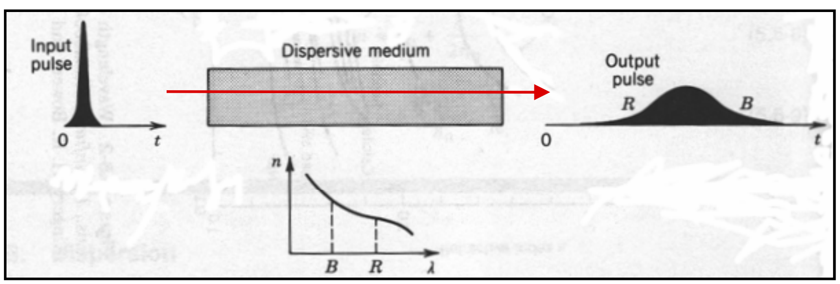
for fused silica: $n / n_g = 0.95 \ldots 0.99$

Chromatic variation of n_g results in time-of-propagation (ΔTOP) variation

$\Delta TOP = | -L\,\lambda\,d\lambda / c_0 \cdot d^2n/d\lambda^2 |$

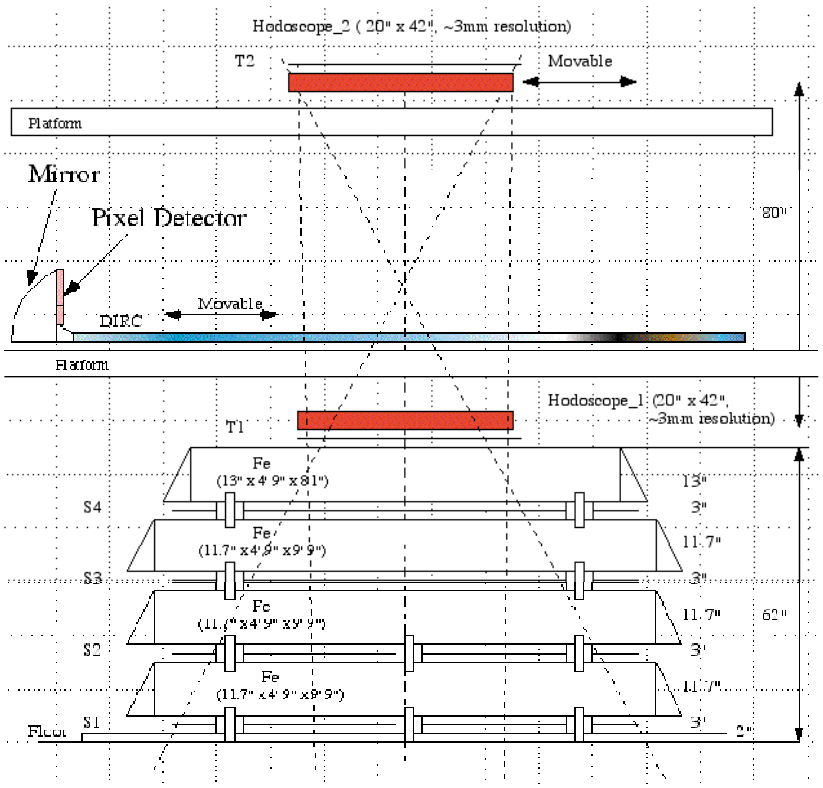
(L: photon path, dλ: wavelength bandwidth)

→ 1-3ns ΔTOP effect for BABAR-DIRC *(net effect: UV photons arrive later)*



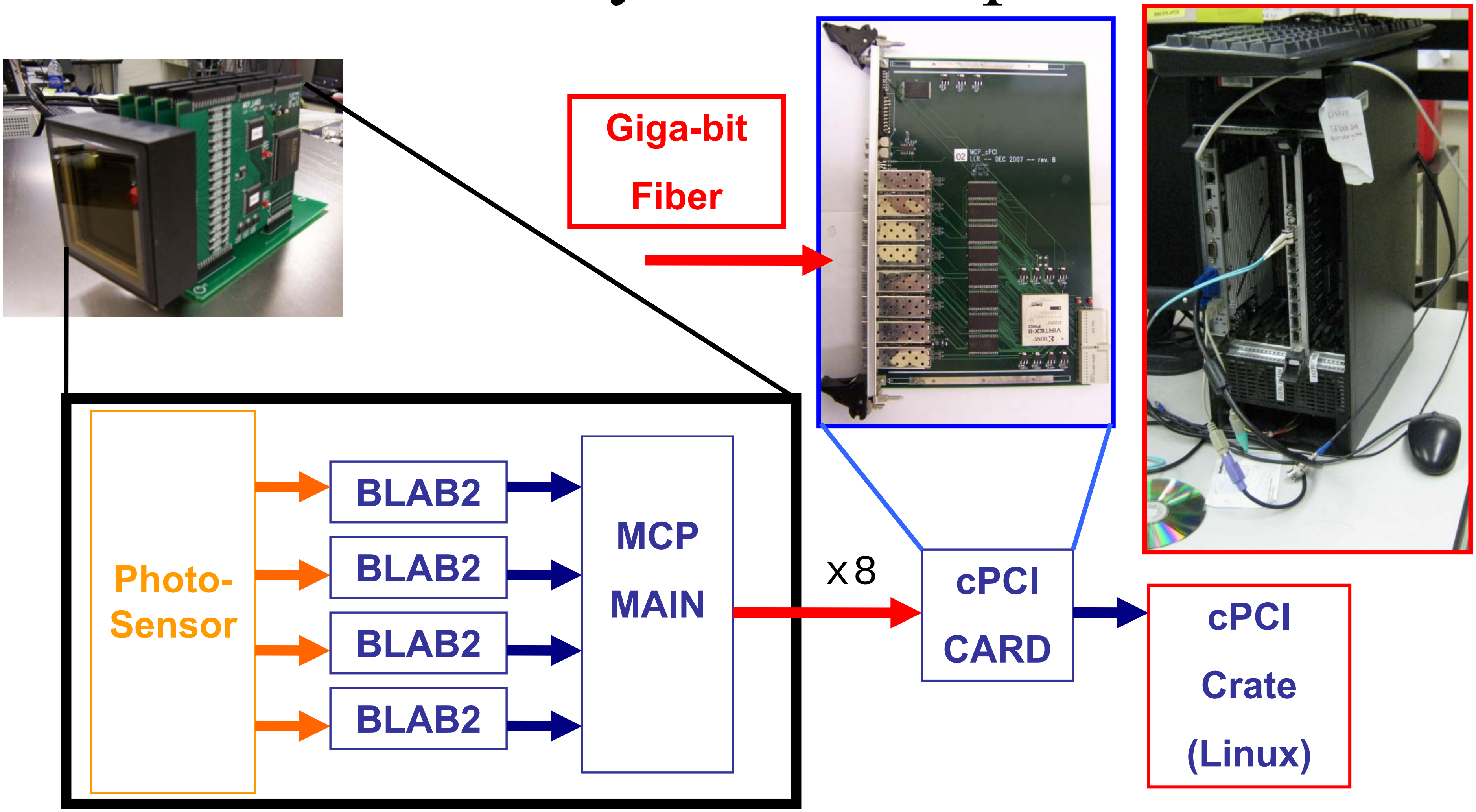
fDIRC: SLAC Cosmic Muon Telescope

- Nice cosmic stand
  - 1 mrad resolution
  - Precision timing and further studies w/ new electronics
- Installed BLAB2-based readout in Jan. 2009
  - Approaching 2 years of experience operating (many TB!!)



~1.5 GeV E_min through range stack

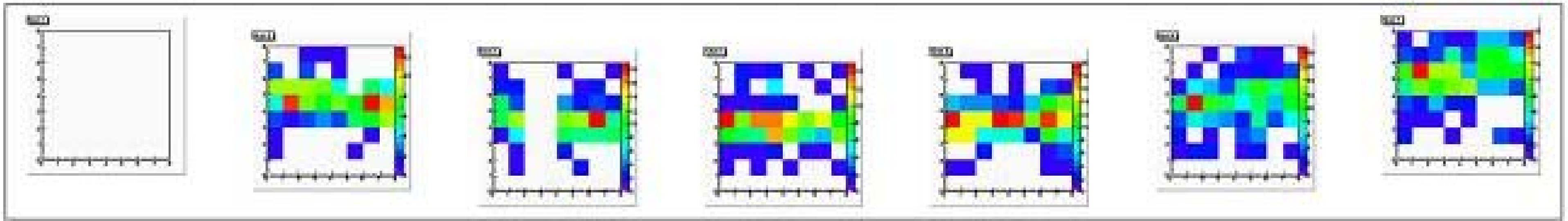
fDIRC Readout System Components

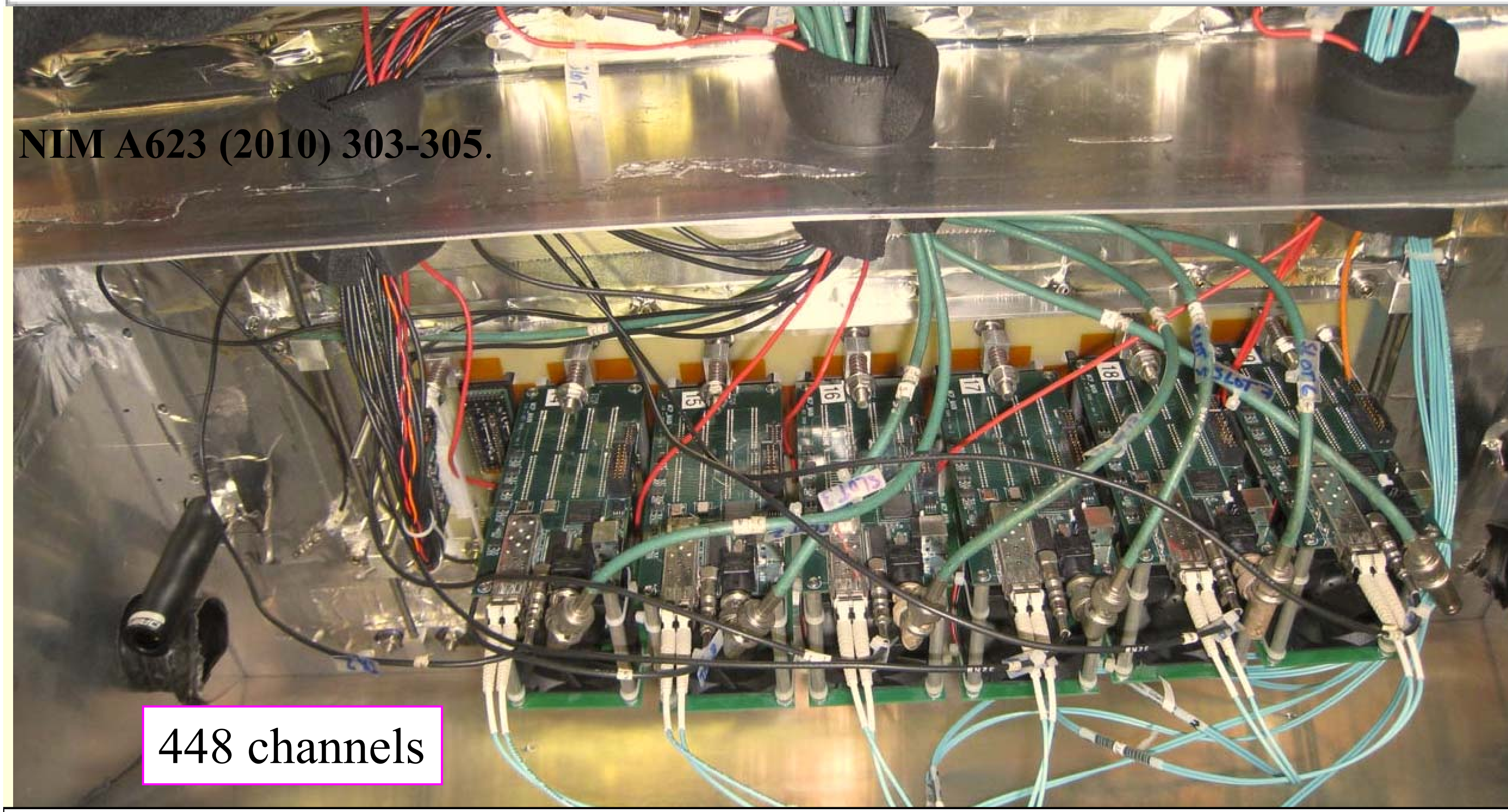


- Up to 8x64 channels per cPCI card
- Very portable DAQ
- Up to 3,584 channels/cPCI crate

Cheap, commodity backend

NIM A623 (2010) 303-305.



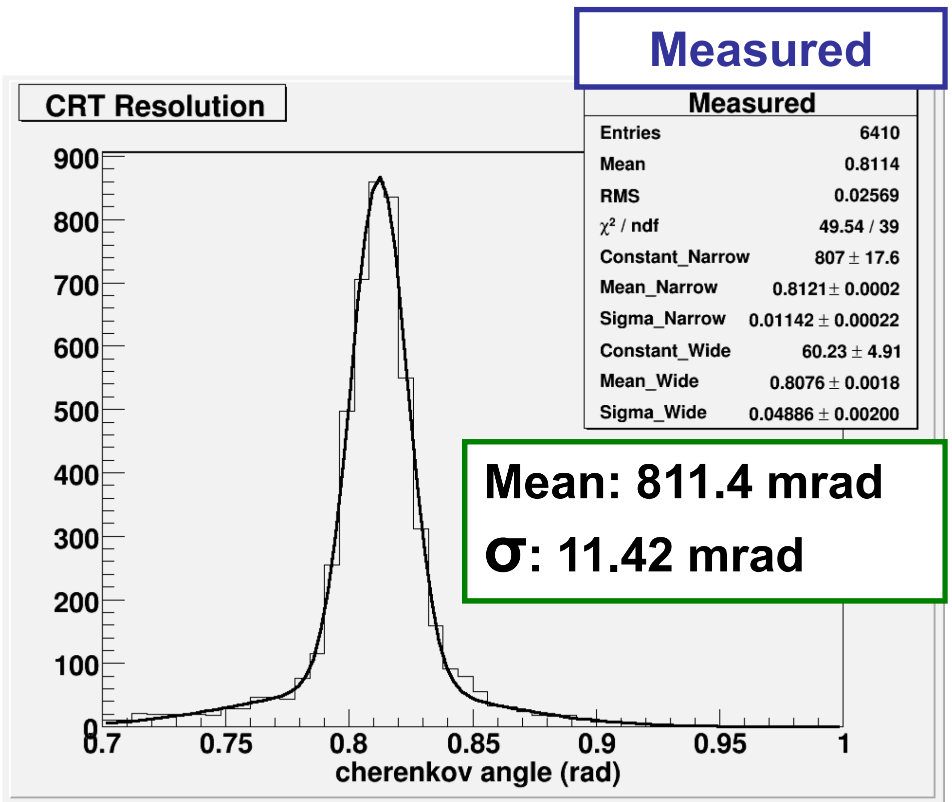


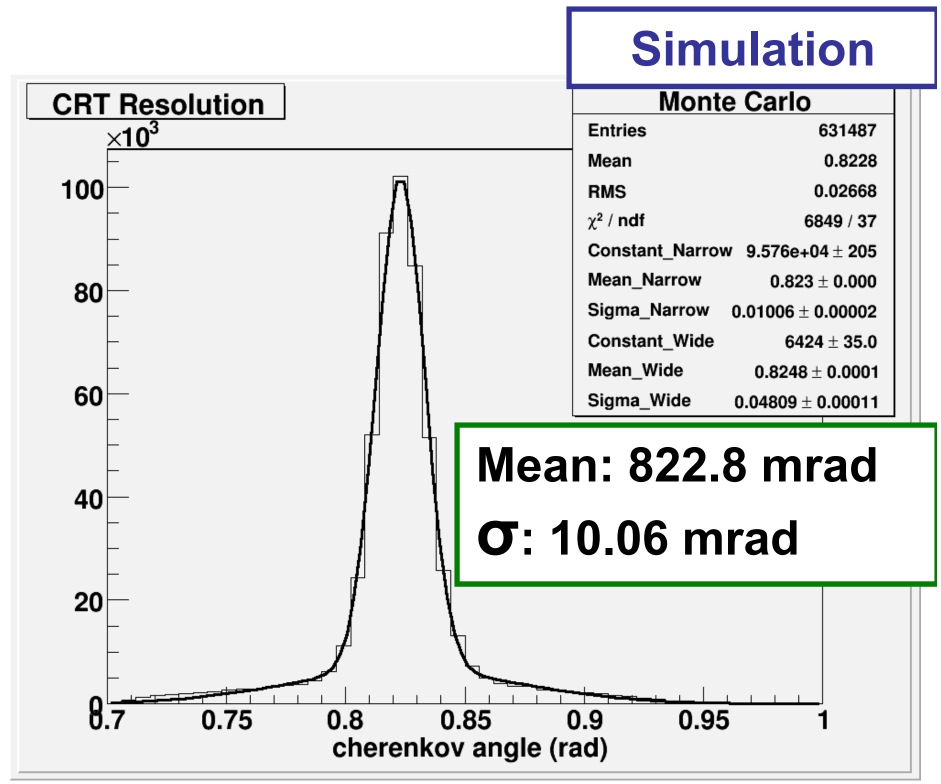
New: Integrated photodetector electronics with waveform sampling

Cosmic Muon Telescope: Cherenkov Angular Resolution

- Shift in mean due to systematic error in PMT holder survey
- Distributions agree with tighter acceptance (near vertical) cuts
- **Chromatic correction next (T0)**

Larry Ruckman thesis

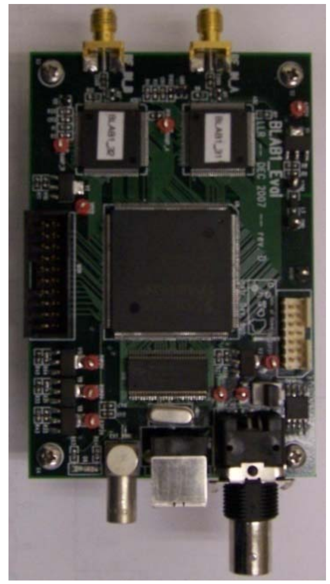


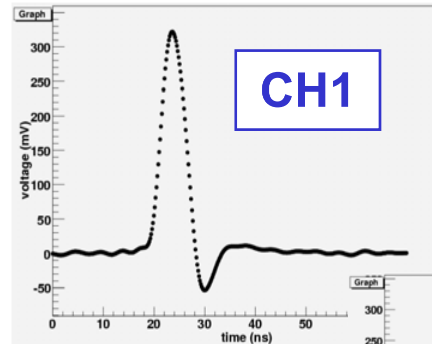


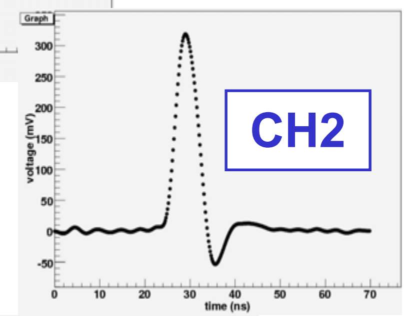
BLAB improved timing performance: Agilent Pulse Cross-Correlation Method

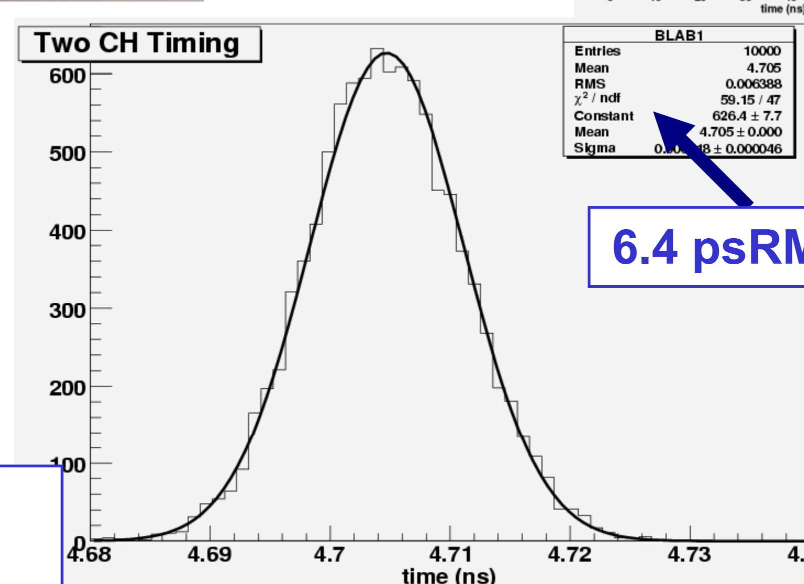
- Comparable performance to best CFD + HPTDC
- MUCH lower power, no need for huge cable plant!
- Using full samples significantly reduces the impact of noise
- Photodetector limited

NIM A602 (2009) 438-445.









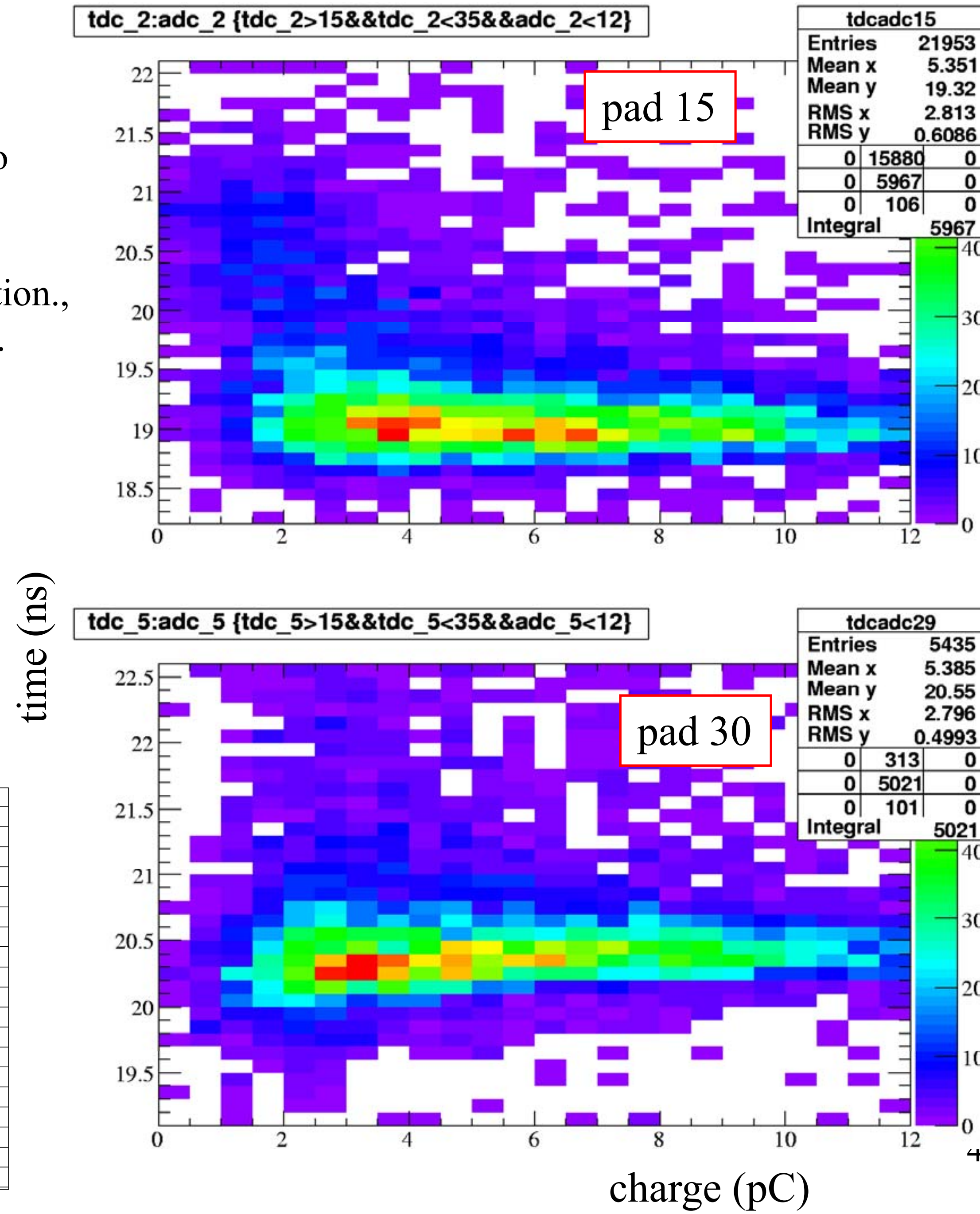
~4.5 ps per waveform

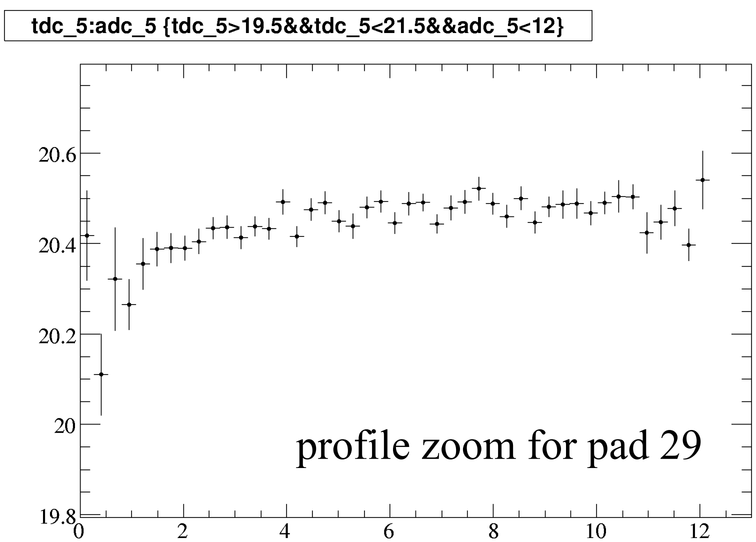
TDC vs. ADC for signal in run 27

Larry’s offline correction method seems to come close to correcting time walk.

Some over-correction, some under-correction., more can be done offline with charge info.

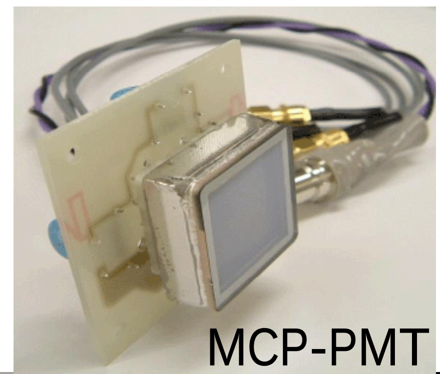
Jochen Schwiening analysis (unpublished)

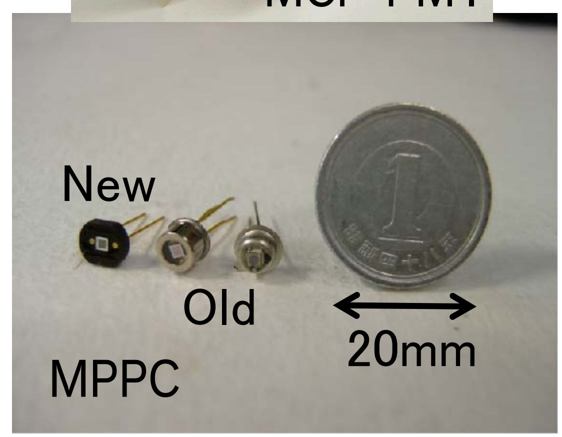




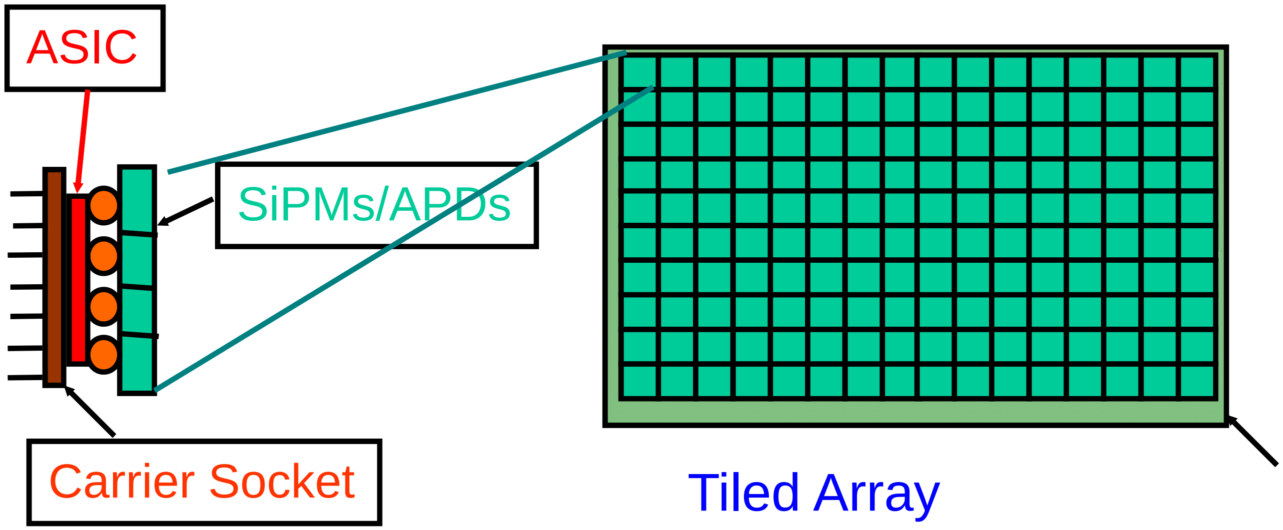
Photon detector options

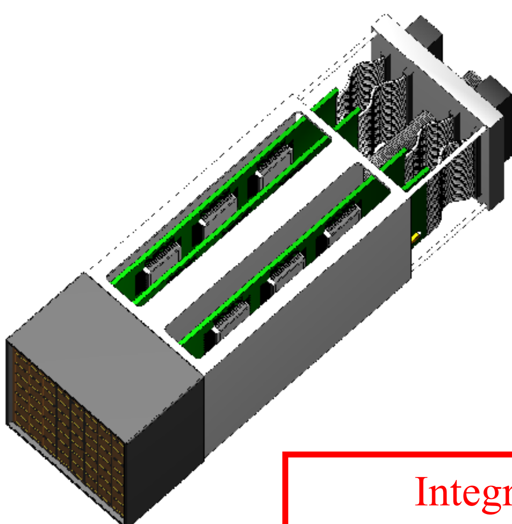
- HAPD
  - Good result from test bench with ASIC readout
  - Need experience with batch production
- MCP-PMT
  - Good TTS for TOF information
    - <20ps TOF resolution
    - Good ability for low momentum PID
  - Improved lifetime – sufficient?
- SiPM/MPPC
  - Good stability, Enough gain but only 100ps TTS
  - Need large effective area or light guide to make ~5x5mm^2 anode
  - High dark count (<~MHz)
  - Radiation hardness → thus far not good enough



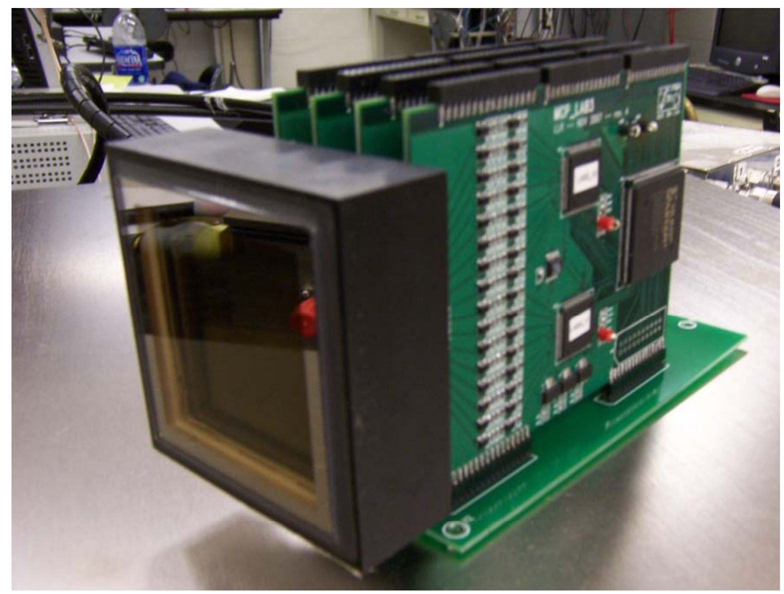


Highly Integrated Readout



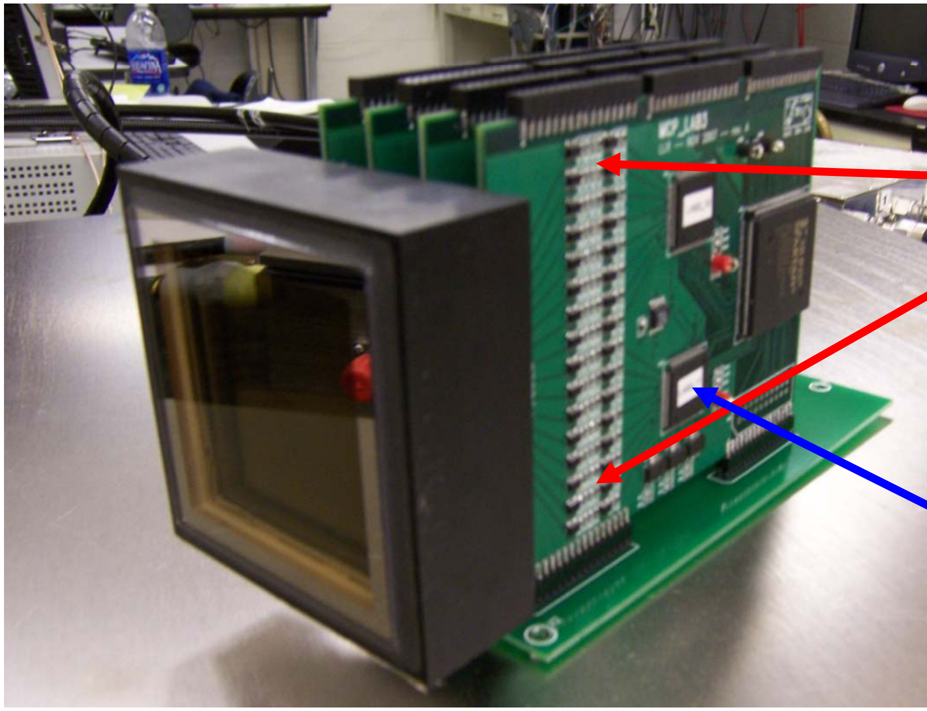


Integrated Photodetector packaging



Gen. 0 Prototype (LAB3-based)

Gain Needed



Amplifiers dominate board space

Readout ASIC tiny (14x14mm for 16 channels)

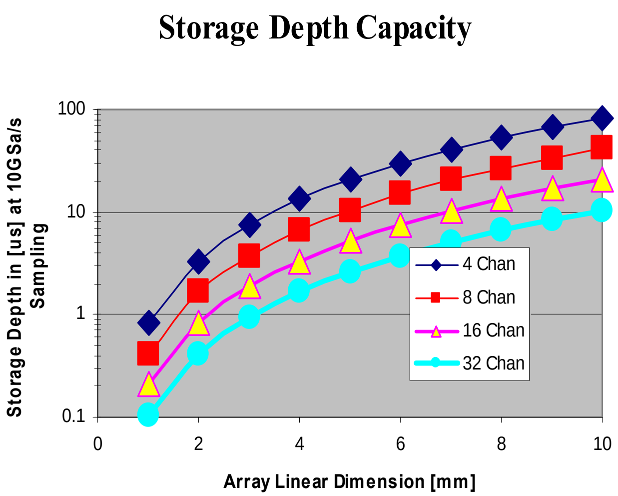
- What gain needed?
  - At 10^6 gain, each p.e. = 160 fC
  - At $2\text{x}10^5$ gain (better for aging), each p.e. = 32 fC
  - In typical ~5ns pulse, Vpeak = dQ/dt * R = 32uA * R = 32mV * R [kΩ] (6.4mV)

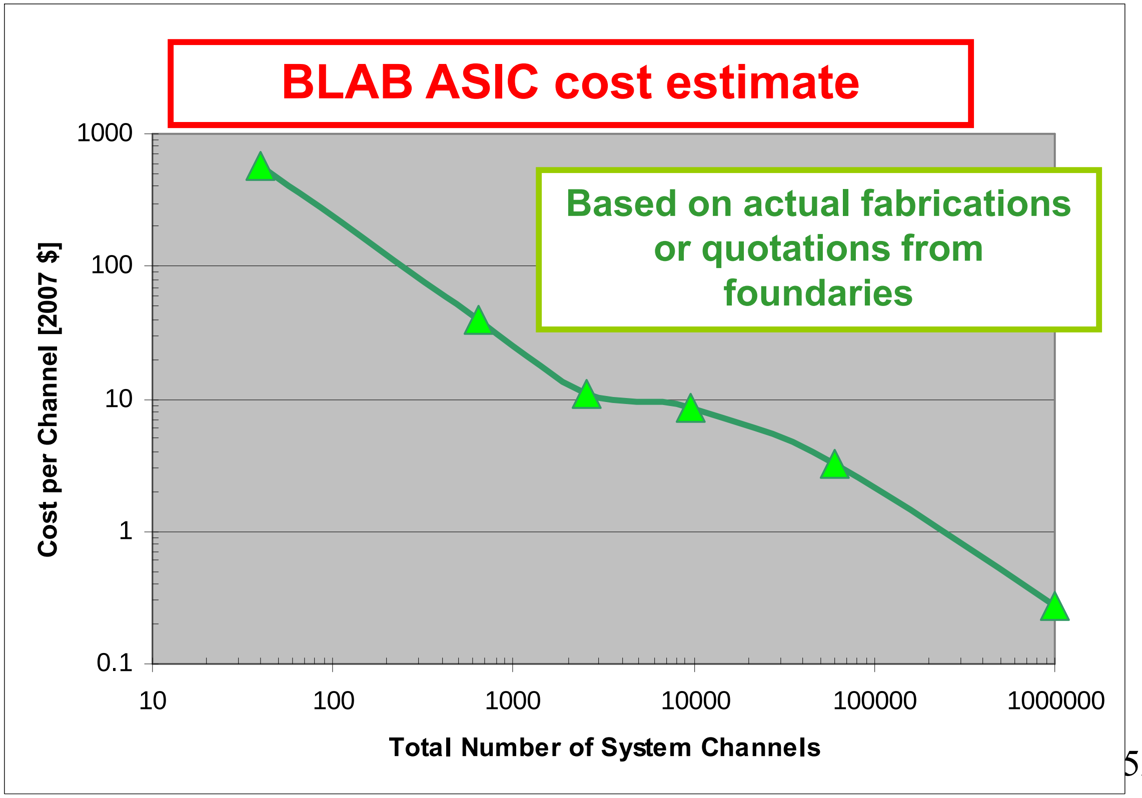
Gain Estimate	
Rterm	**1 p.e. peak**
50	1mV
1k	20mV
20k	400mV

Cost Estimates

- ASIC costing well understood, very competitive!

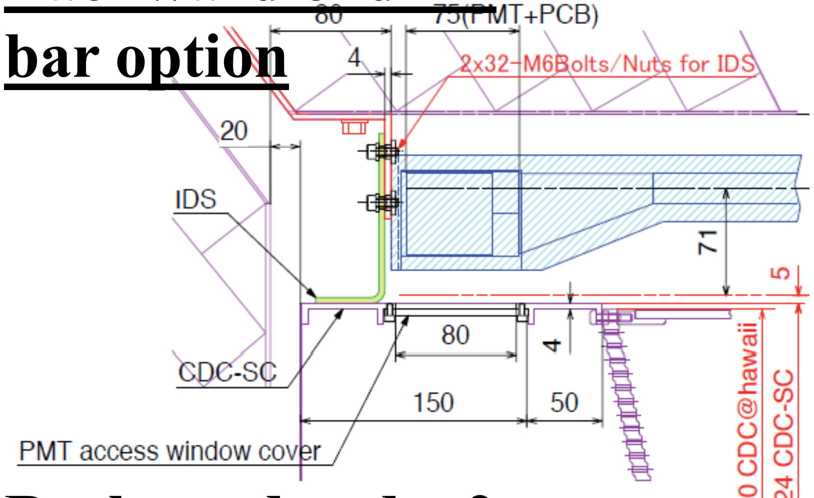
NIM A591 (2008) 534-345.



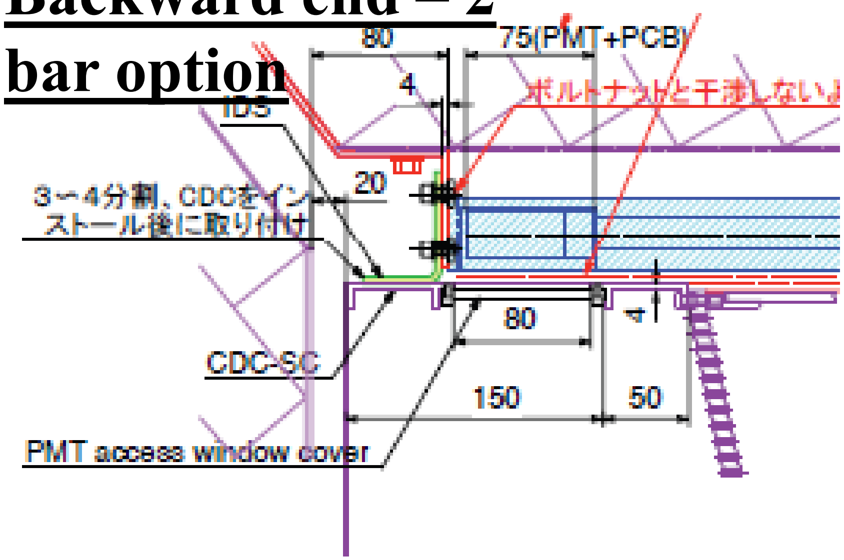


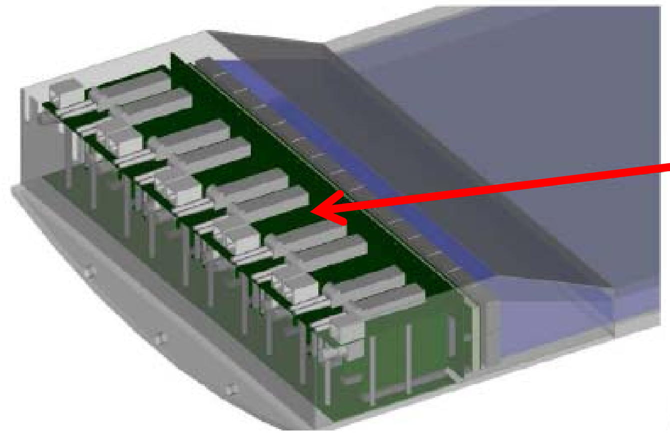
Structural Considerations

Backward end – 1 bar option



Backward end – 2 bar option





PMT & electronics access panel

Important features:

- Both baseline designs are being studied structurally.
- Integrated with existing barrel ECL support structure.
- Provides support for the drift chamber.
- Panels to allow access to PMTs and electronics.