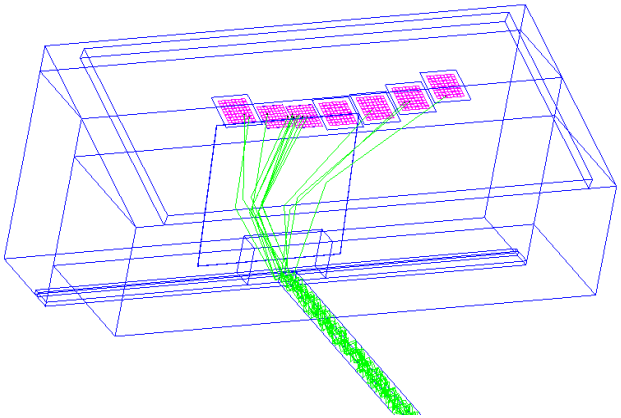
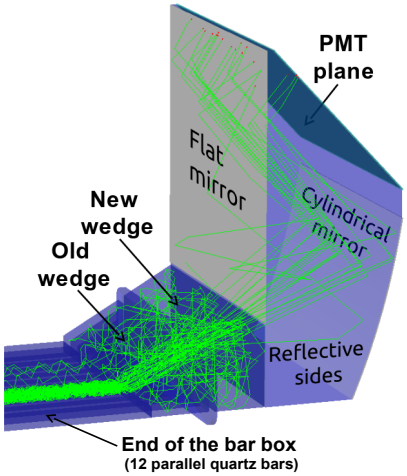
Development of Focusing DIRC detectors

J. Va'vra, SLAC





Abstract

- **It is not easy to achieve a 4p-PID coverage in solenoid-based experiments. DIRC technology solved this problem very elegantly. BaBar DIRC was very successful PID detector.**
- **Since then there was a large effort by several groups to develop the Focusing DIRC technology based on smaller, faster and highly pixilated photon detector camera. This effort has started by developments at SLAC, followed by Panda, GLUEX and Electron-ion-collider (EIC) groups.**
- **These pixel-based technologies are compared to time-based concepts, as used in TOP and TORCH detectors.**
- **In this talk we will discuss mainly the SLAC FDIRC results, show performance of photon detectors and compare them with results of other people. We will also mention remaining questions to be answered by future R&D.**

Blair Ratcliff

SLAC-PUB-5946(1992), and SLACPUB-6047(1993).

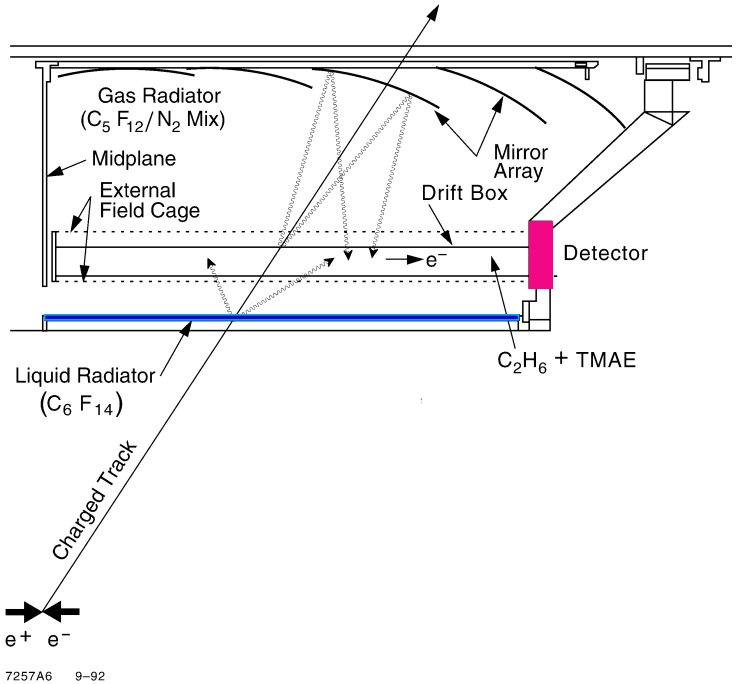
BaBar DIRC

DIRC = Detector of Internally Reflected Cherenkov light

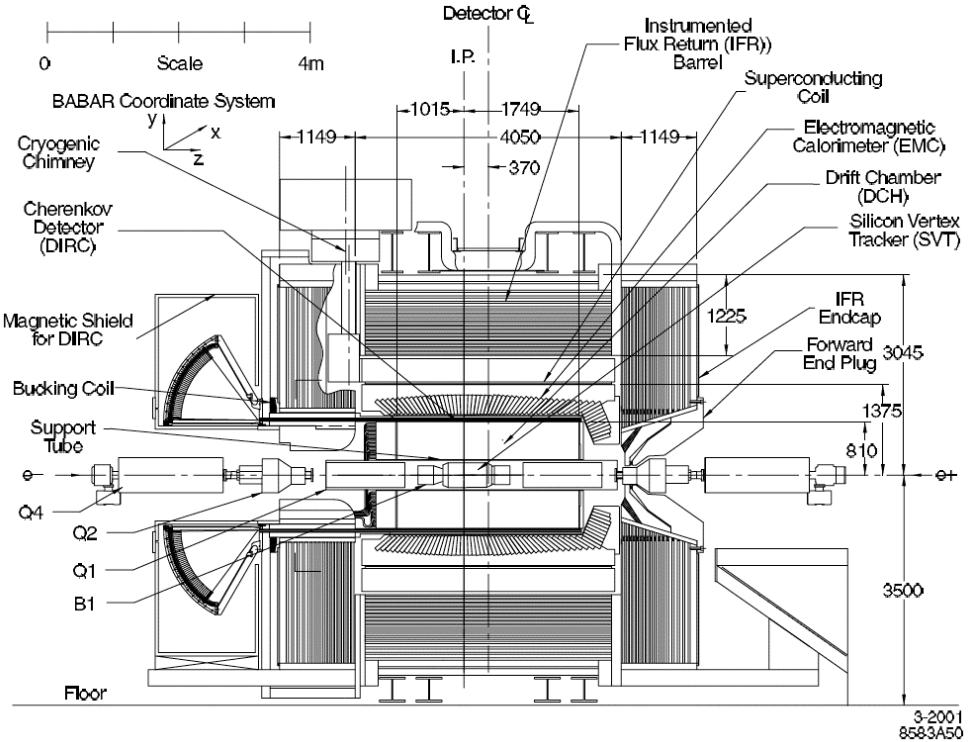
- DIRC proved to be a very successful PID detector
- π/K separation up to 3-4 GeV/c
- Many similar efforts are under way

Challenges of 4π-detection in PID detectors

SLD CRID:



BaBar DIRC:

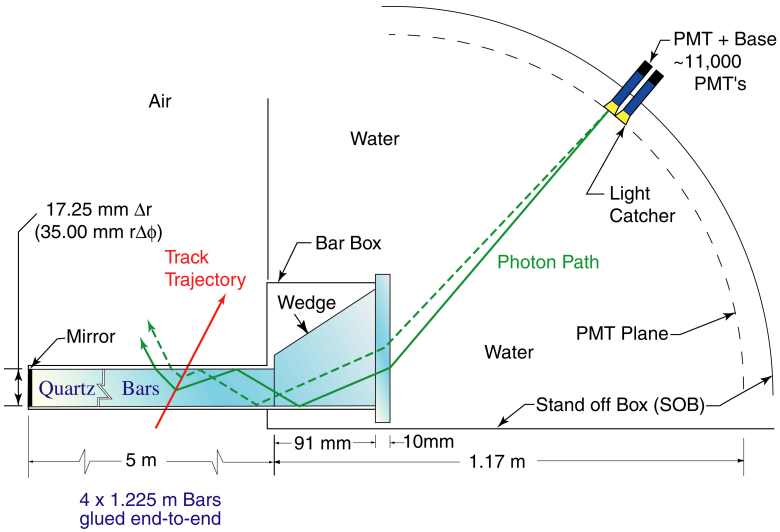


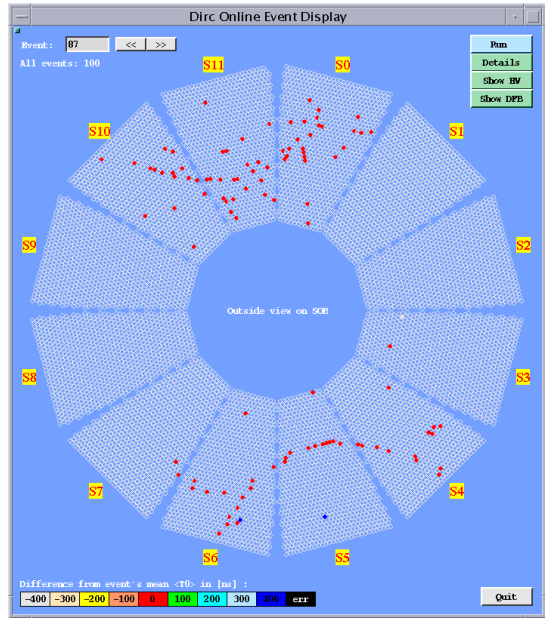
- **<u>CRID challenge</u>: Drift single electrons for over 1.2 meters, without distortions, and detect them with a good efficiency.**
- **<u>DIRC challenge</u>: Propagate single photons over path length of 2-15 meters in Fused silica, preserve the Cherenkov angle while bouncing up to ~2000 times, and then detect them with a good efficiency.**

BaBar DIRC

SLAC-PUB-5946 and NIM A583 (2007) 281.

Photon pin hole camera:





Resolution per photon:

- σ_{time} ~1.7ns
- $\sigma_{\Theta c}$ (total) ~9.6 mrad
- $\sigma_{chromatic}$ ~5.4 mrad

Resolution per track:

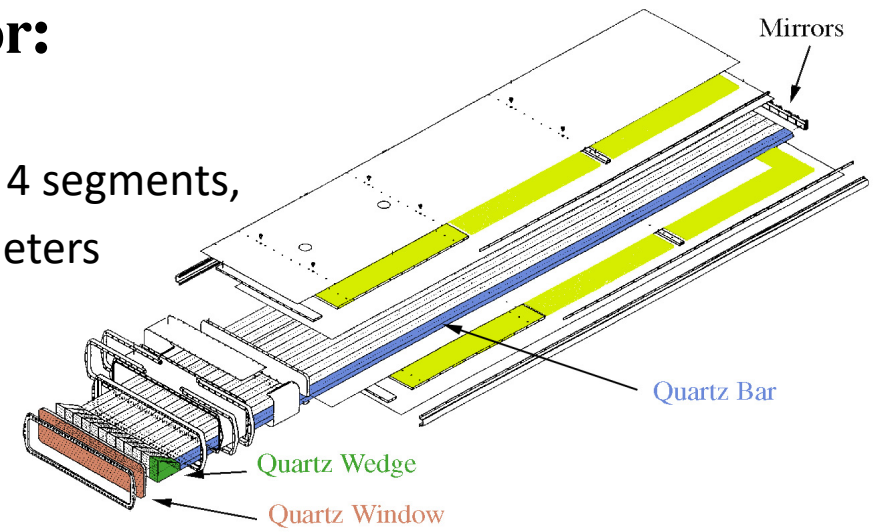
- $\sigma_{\Theta c}$ ~2.5 mrad ($\mu^+\mu^-$)
- $\sigma_{\Theta c}$ ~3.0 mrad (Bhabhas)

Quartz Radiator:

144 bars,

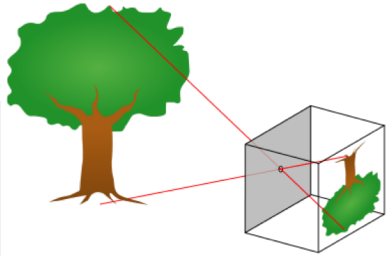
each bar made out of 4 segments,

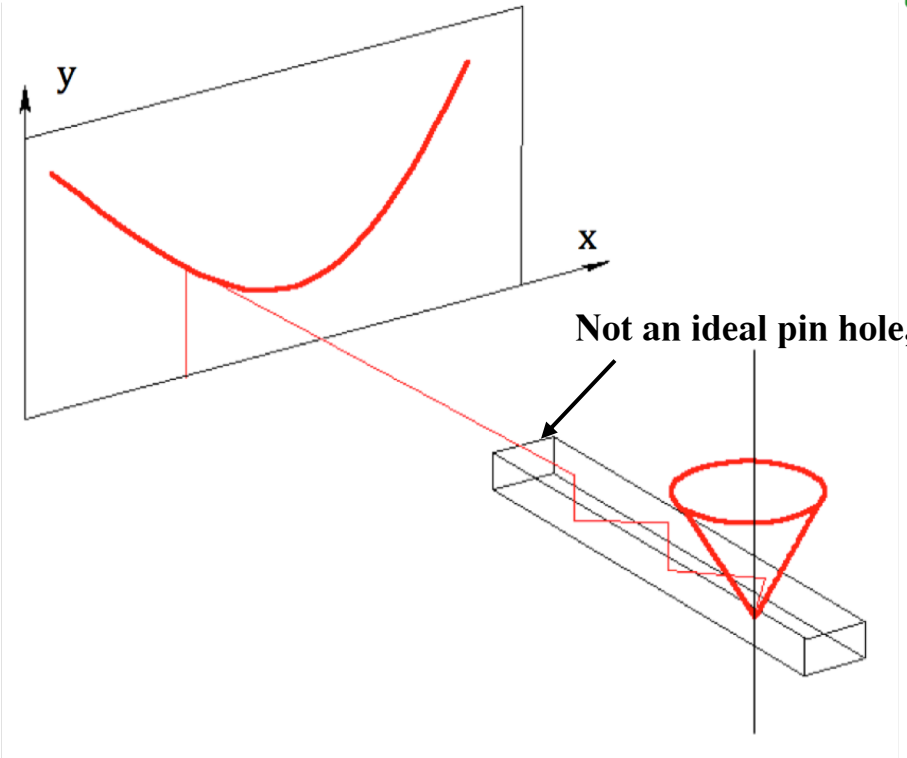
total bar length is 5 meters



DIRC imaging principle

Pin hole camera without focusing:



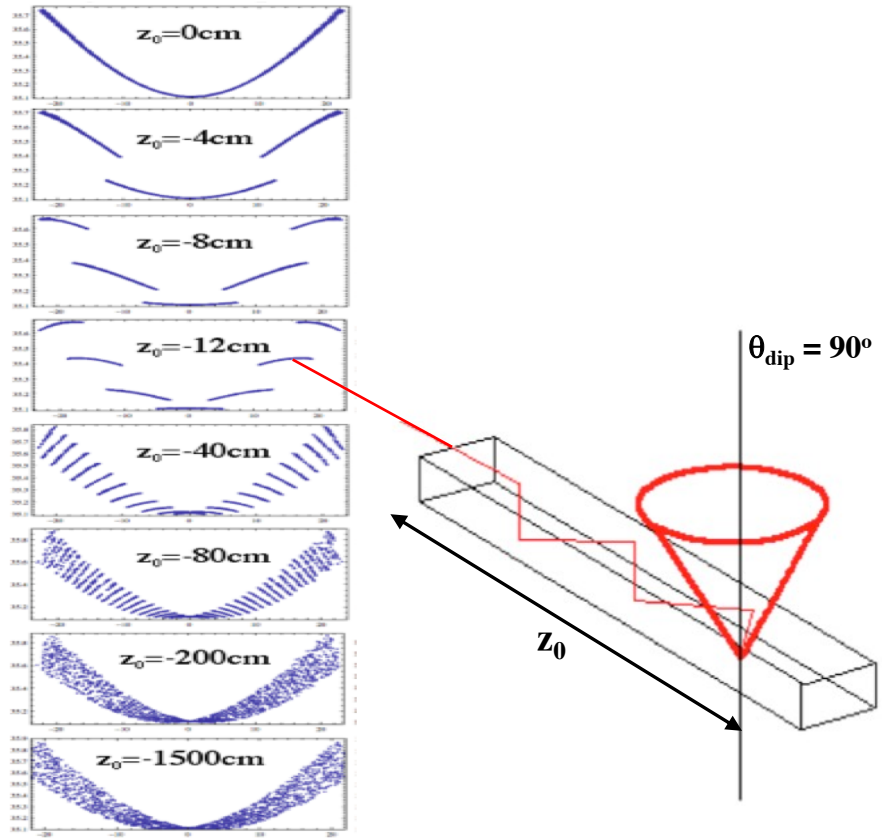


- Cherenkov photons are generated in fused silica bar, propagate to the end of the bar, and then imaged in a photon camera.
- In this talk you will see several solution how to minimize the effect of the finite pin hole size in FDIRC (BaBar DIRC has chosen a very large photon detector size).

Cherenkov ring image is more complicated in DIRC

J.Va'vra, Images generated by Mathematica code, SLAC-PUB-13464, 2008:

Vary z_0:

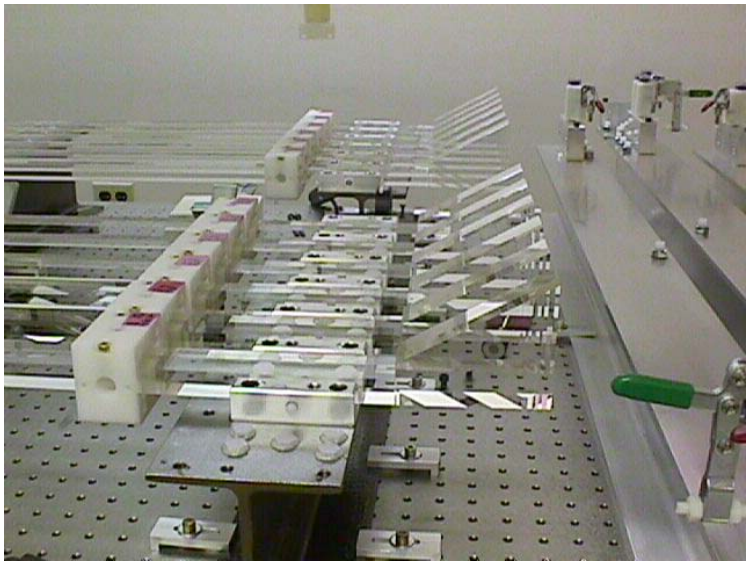


- **The optical aberration (kaleidoscopic pattern)** is due to a bar squareness, creating Cherenkov ring segments. **The effect adds ~4-5 mrads to the θ_c resolution.** (In practice, we do not have a pixel resolution to see this ring micro-structure).
- In addition, the final camera optics adds additional rotations – see later.

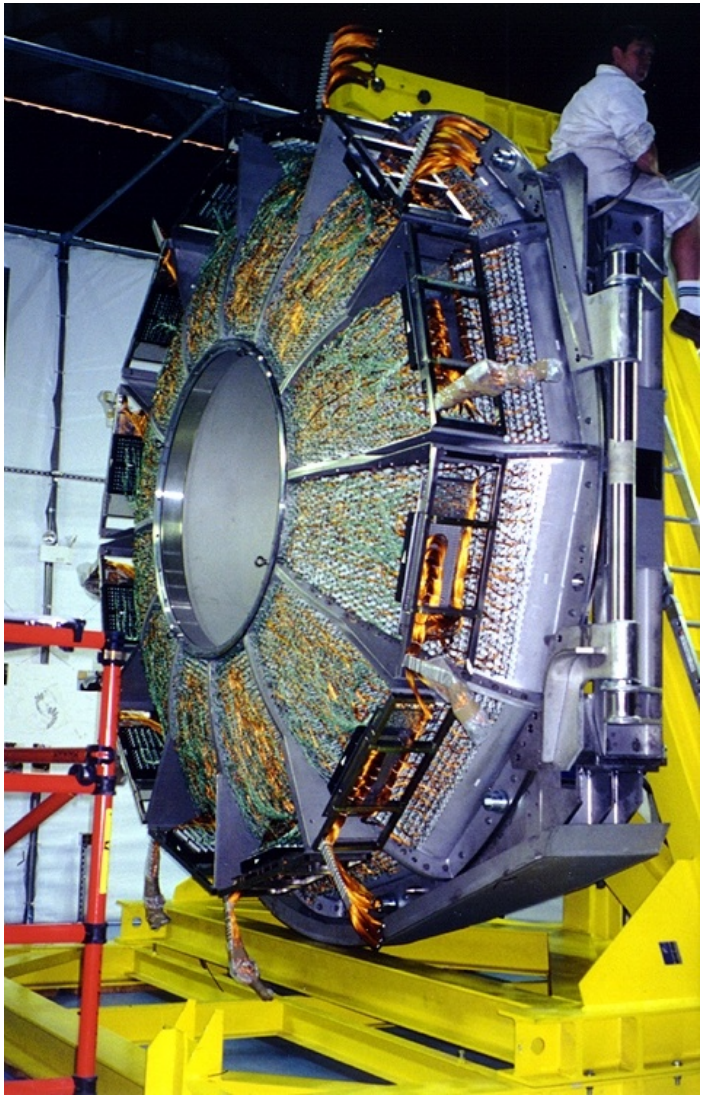
A lot of R&D steps were needed to go from the proof of the principle to a final DIRC detector

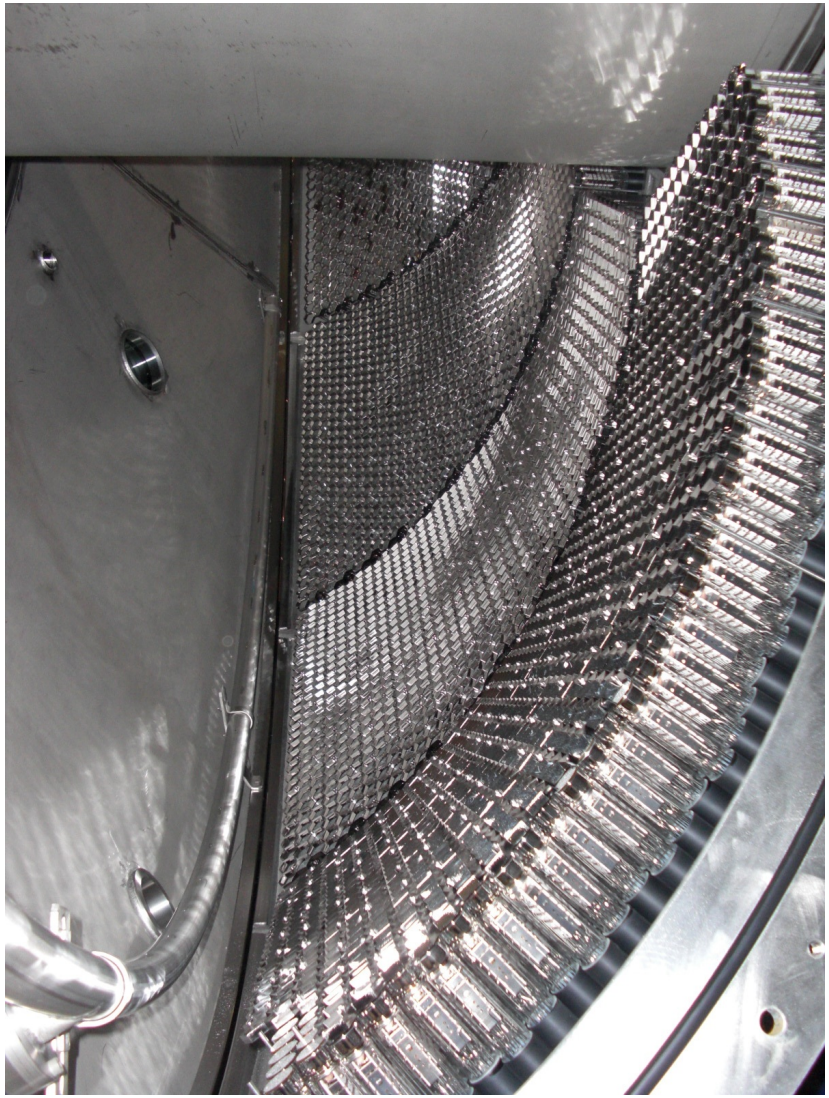
1. Penetrate iron or not ? A crucial decision contributing to DIRC success.
2. Define pin hole camera optics, and select photon detector.
3. Electronics development.
4. Transmission through Fused silica bars and optical glues.
5. Radiation hardness studies of Fused silica and various other materials.
6. Effect of pollution from various materials on the internal reflection coefficient.
7. Transmission study of water.
8. Water corrosion study of PMT glass and other materials sitting in highly purified water.
9. Effect of large photon fluxes over many years on optical epoxies.
10. Does Fused silica scintillates ?
11. Periodic variation of refraction index within Fused silica.
12. Water tightness of bar boxes.
13. Study of mechanical precision of bars.
14. Study of edge quality of bars.
15. Develop a procedure to minimize mechanical stresses on bars when in bar boxes in various positions.
16. Software: (a) data analysis and (b) MC codes.
17. DIRC background studies in BaBar.
18. How to keep bars in a clean environment for many years ?

Building DIRC for BaBar



Babar DIRC Photon detector





- **~11,000 1”-dia. PMTs; 6,000 liters of water.**

Bar boxes shine like new after the final opening

- **They can be reused:** 4 will go to GLUEX at JLAB, 8 may go to TORCH at LHCb

What camera design to choose for the SuperB detector ?

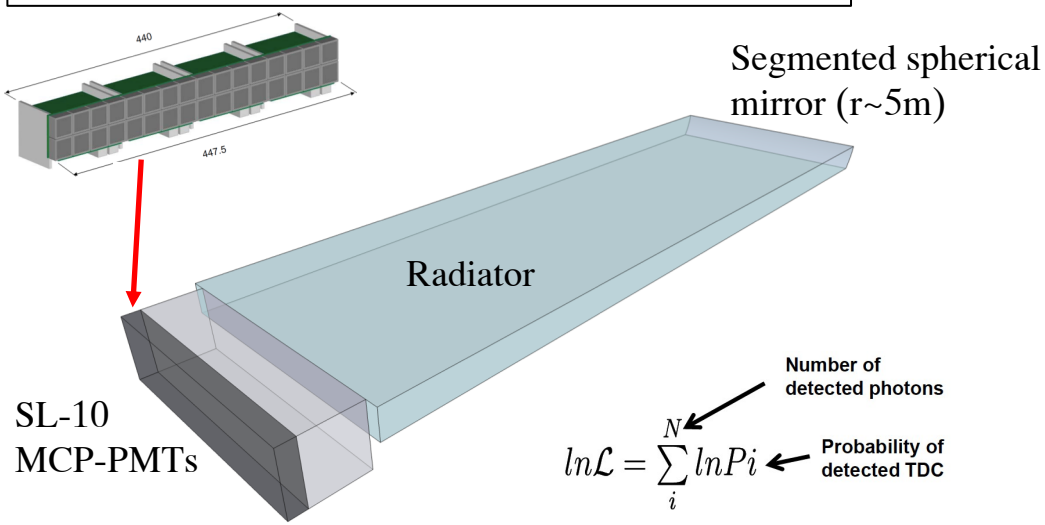
Two major directions in 3D imaging in DIRCs

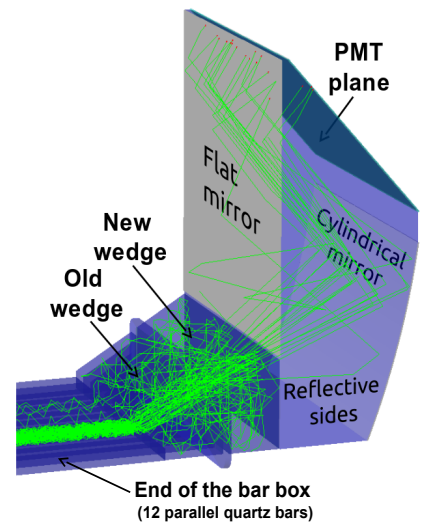
Belle-II TOP: time, and x & y

The outcome is a <u>very complicated</u> max. likelihood requiring measurements of the arrival times and positions of each photon; it cannot determine θ_c angle easily.

SLAC FDIRC: x & y, and time

Uses pin-hole camera concept with look-up tables for each pixel with k_x,k_y,k_z and time; it can determine θ_c angle easily.





- **Belle-II TOP counter:** Relies on **time-based analysis**, which requires σ_{TTS}~40 ps; **pixels** are used, but one cannot determine the Cherenkov angle independently. For tracks pointing to photon detectors, it is essentially a TOF counter.
- **SLAC FDIRC:** Relies on **pixel-based analysis**; it does determine the Cherenkov angle; **time** is used to (a) reject wrong solutions, (b) do chromatic corrections, (c) reject background, and (d) help the likelihood analysis (σ_{TTS}~200 ps is sufficient).

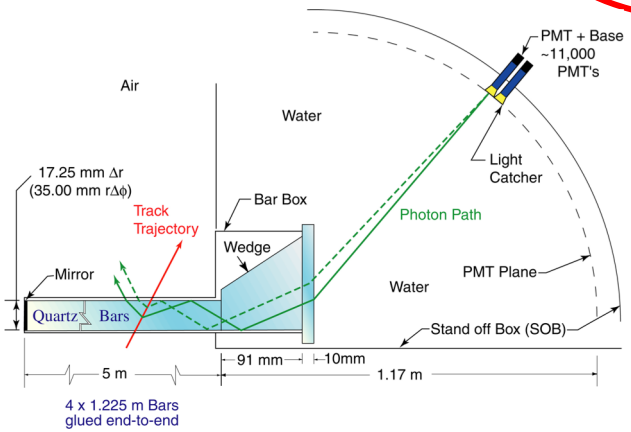
We built two FDIRC prototypes

- 1-st FDIRC prototype with a single-bar.
- Final prototype for SuperB with a real bar box and a final optics.

BaBar DIRC ---> SuperB FDIRC

BaBar DIRC

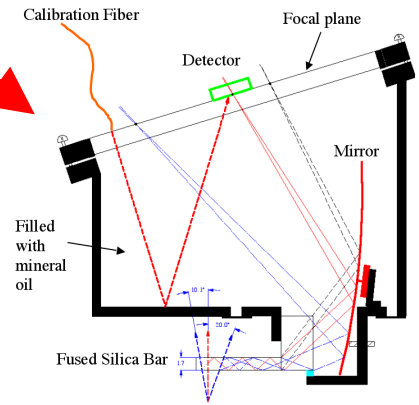
100x higher luminosity



3D imaging (x, y & time):

- No. of (x,y)-pixels: ~11,000
- σ_{time}~1.7ns /photon
- $\sigma_{\theta c}$ ~ 9.6 mrads/photon

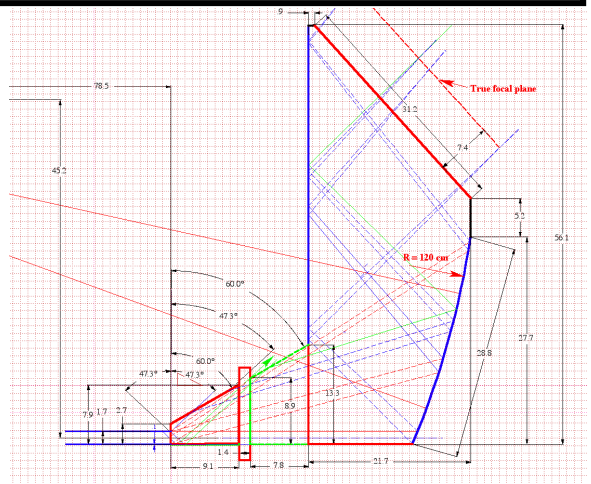
1-st FDIRC prototype (oil filled)

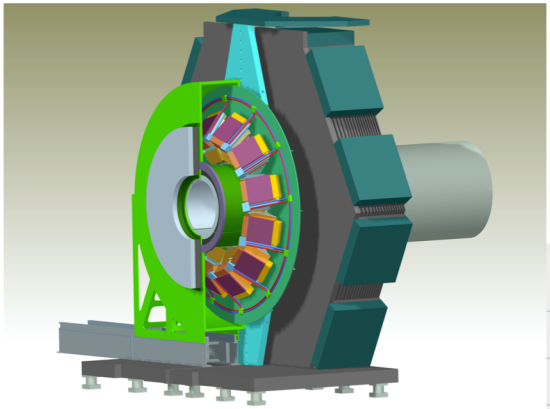


- Learn the FDIRC concept
- Do many detector studies

Final FDIRC prototype (solid Fused Silica)

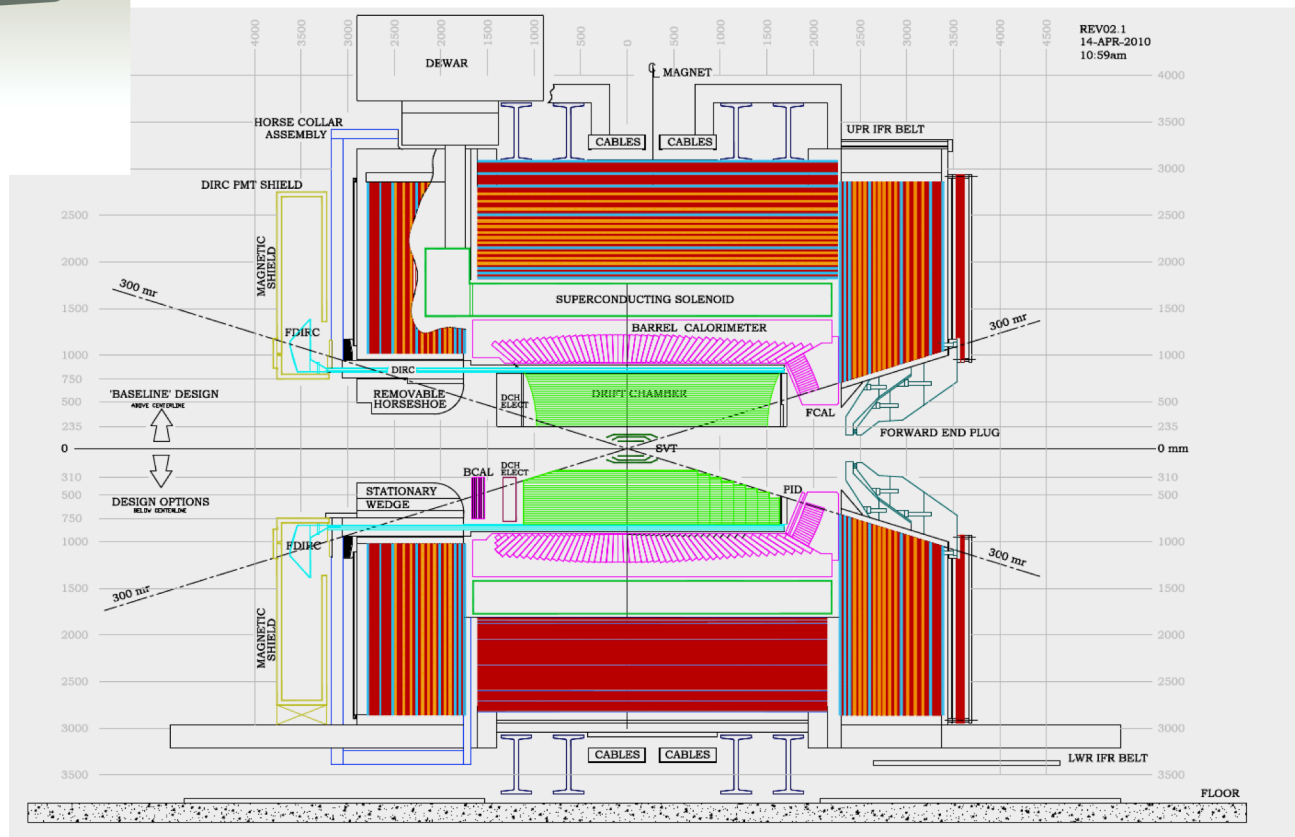
- No. of (x,y)-pixels: ~18,432
- σ_{time}~200-300 ps /photon
- 25x smaller volume
- 10x faster than BaBar DIRC
- $\sigma_{\theta c}$ ~ 9.6 mrads/photon





SuperB FDIRC TDR

ArXiv:1306.5655v1 [physics.ins-det] 24 Jun 2013



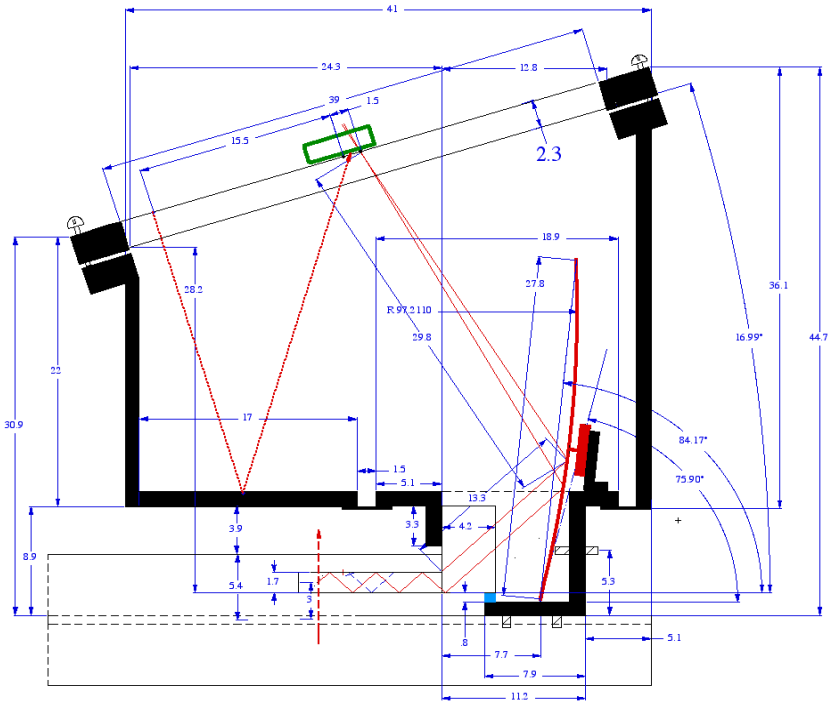
- **100x larger luminosity than BaBar.**
- **25x smaller volume compared to BaBar DIRC.**
- **10x faster highly-pixilated photodetectors compared to BaBar DIRC.**

SLAC 1-st FDIRC prototype design

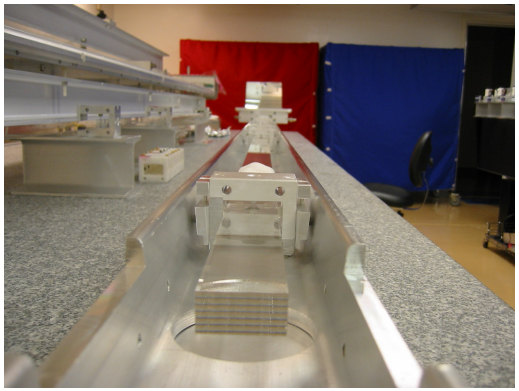
Design concept:

- **Cherenkov angle is determined by x-y pixel location**
- **Time is used to reduce background and to make chromatic corrections**
- **Spherical mirror removes bar thickness contribution to resolution in y-direction**
- **Expansion volume filled with a mineral oil to match the fused silica refraction index**

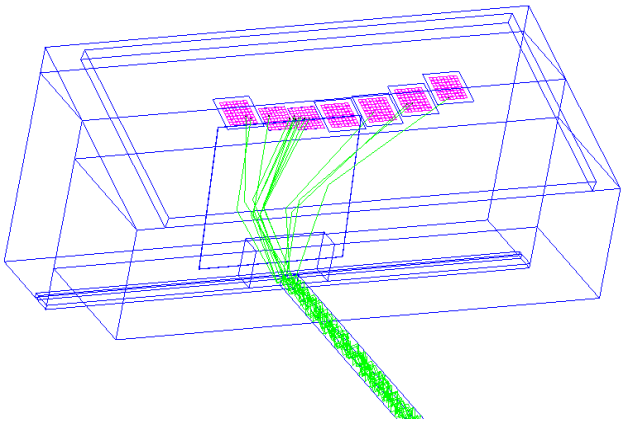
Ray tracing design (J.V.):



Single DIRC bar:

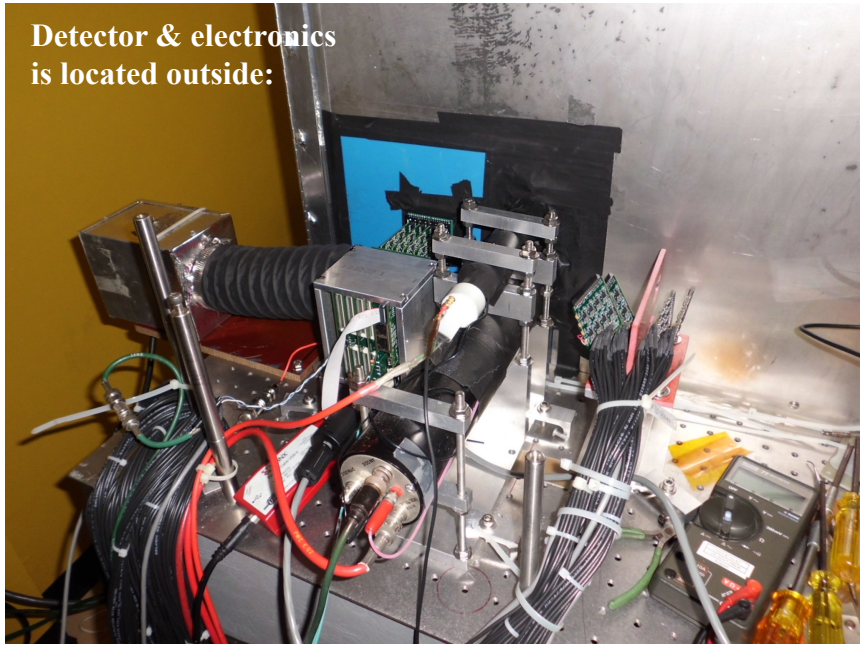


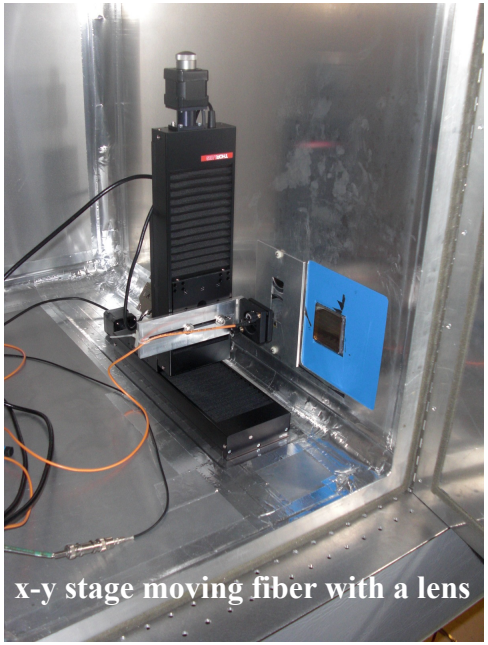
Photon detector choice

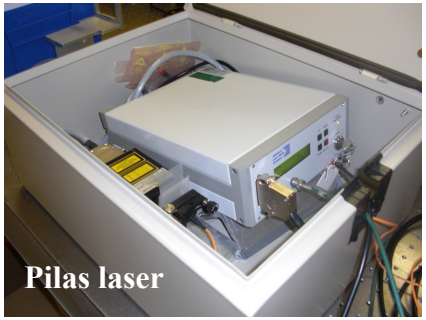


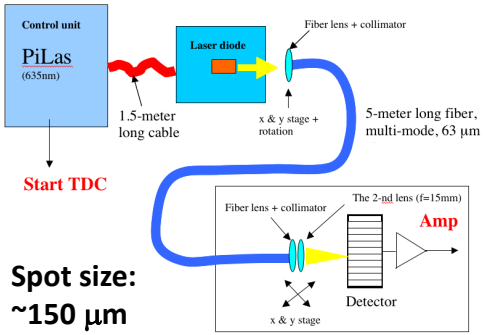
Scanning setup to test detectors

C. Field, T. Hadig, David W.G.S. Leith, G. Mazaheri, B. Ratcliff, J. Schwiening, J. Uher, J. Va'vra, NIMA 553 (2005) 96



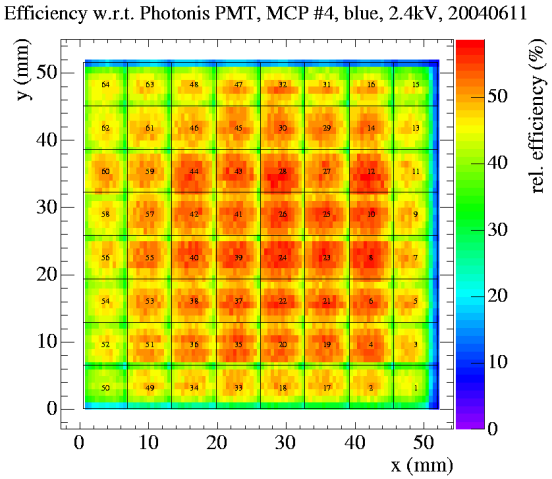




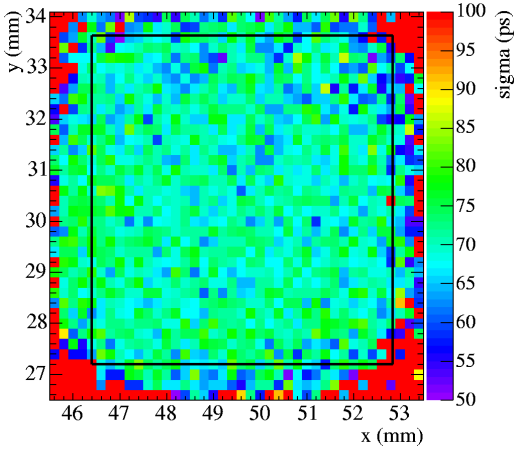


Spot size: ~150 μm

Single photon efficiency:



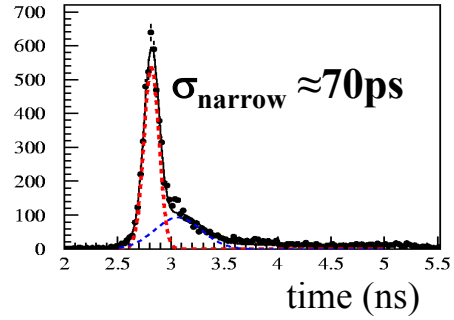
TTS resolution of one pad:

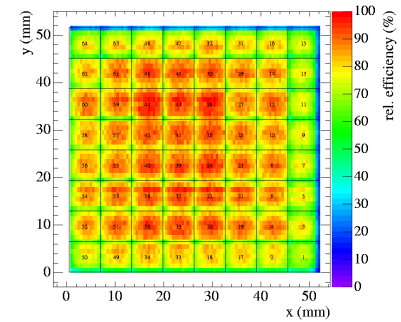


SLAC 1-st FDIRC prototype detector study

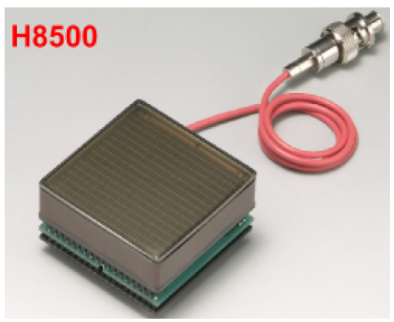
Field, T. Hadig, David W.G.S. Leith, G. Mazaheri, B. Ratcliff, J. Schwiening, J. Uher, J. Va'vra, NIMA 553 (2005) 96

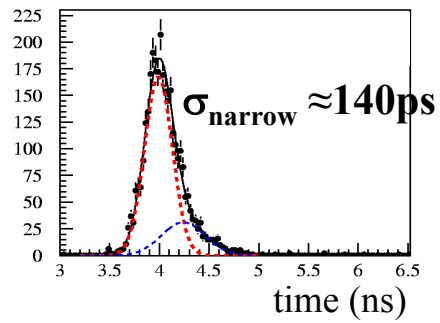
1) Burle 85011-501 Planacon MCP-PMT (64 pixels, 6x6mm pad, σ_{TTS} ~**50-70ps**)

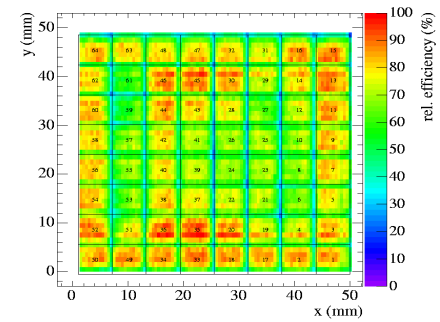




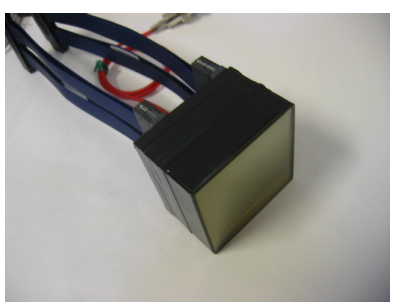
2) Hamamatsu H-8500 MaPMT (64 pixels, 6x6mm pad, σ_{TTS} ~**140ps**)

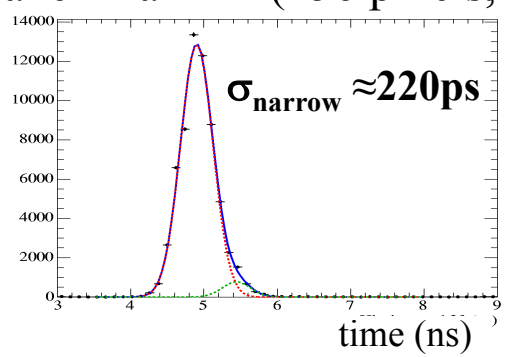


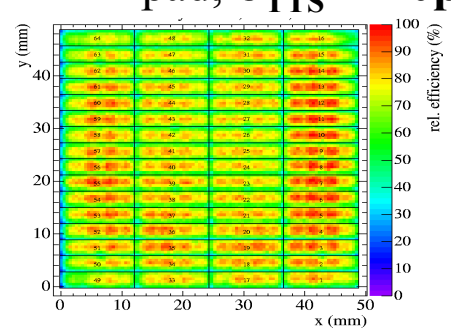




3) Hamamatsu H-9500 Flat Panel MaPMT (256 pixels, 3x12mm pad, σ_{TTS} ~**220ps**)



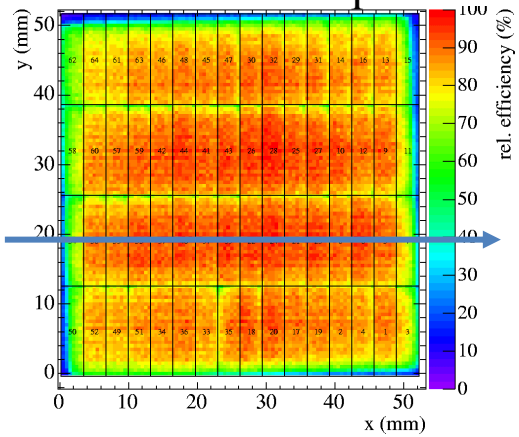




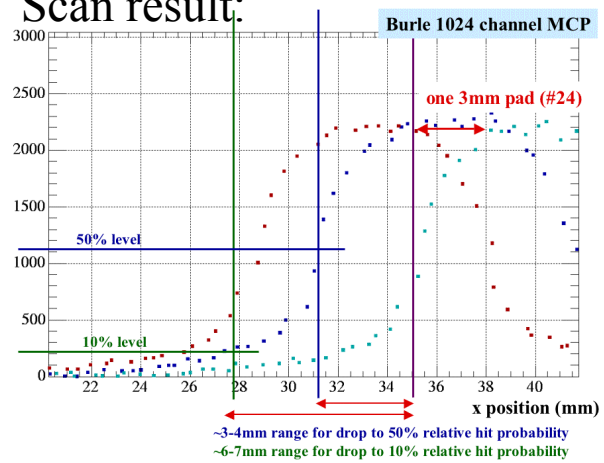
Charge spread in Burle 1024-pad MCP-PMT

Scanning setup in bldg 403 at SLAC

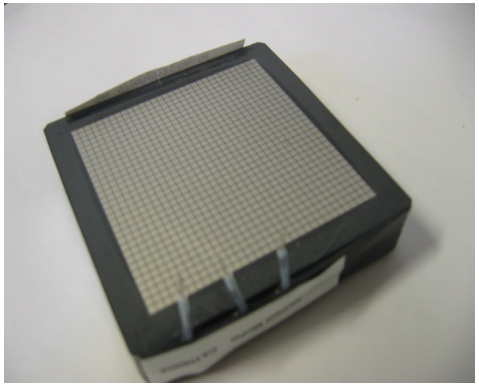
3 mm x 12 mm pixels:



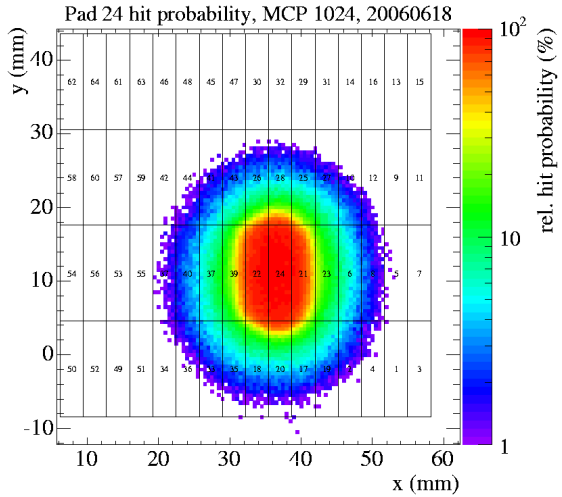
Scan result:



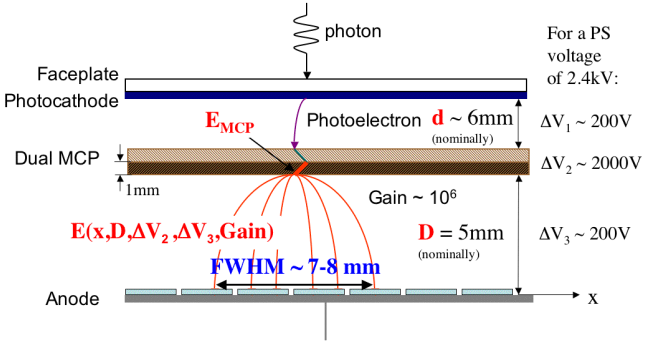
1024-pixel Burle MCP-PMT:



Response to a light spot of ~150μm size:



Burle Planacon MCP-PMT:

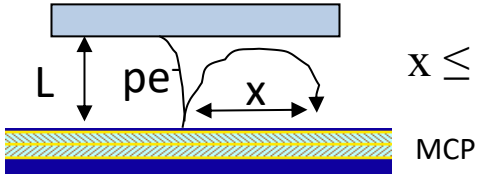


- **FWHM of the charge spread ~7-8 mm due to large MCP-to-anode gap.**
- Attempt to make 3x12 mm pixels out of a 1024-pixel Burle tube **failed.**

Timing tails in various MCP-PMTs

J.Va'vra, MCP log book #3, pages 27-40, & SLAC-PUB-11934, 2006 & NIMA 572(2007)459, and Inami's talk, Nagoya

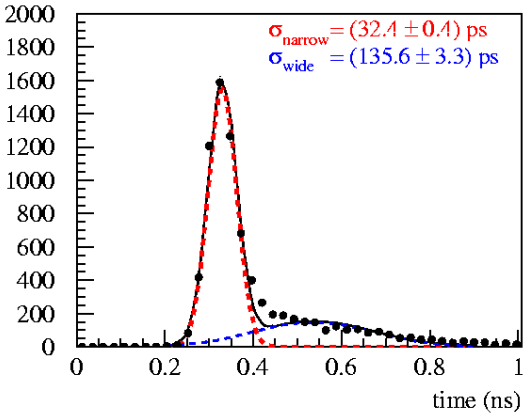
L should be small:



$x \leq 2\,L$

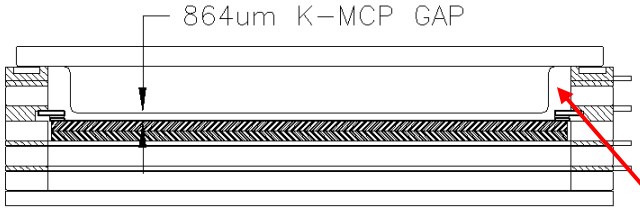
MCP-to-Cathode distance: ~ 6 mm

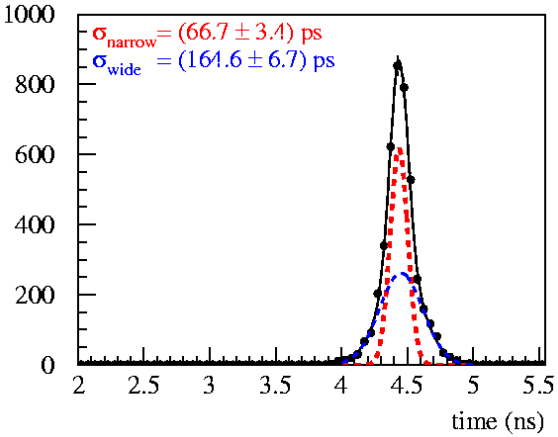
Burle Planacon (10μm holes):

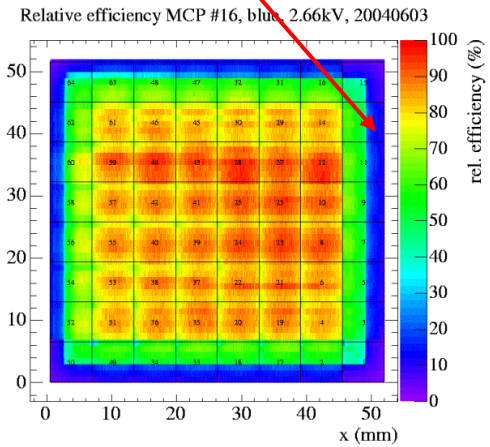


MCP-to-Cathode distance: ~0.85 mm

Burle Stepped Faceplate (25μm holes):



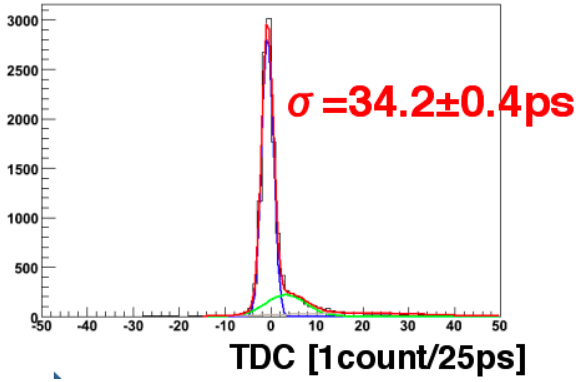




MCP-to-Cathode distance: ~ 2 mm

Hamamatsu SL-10 (10μm holes):

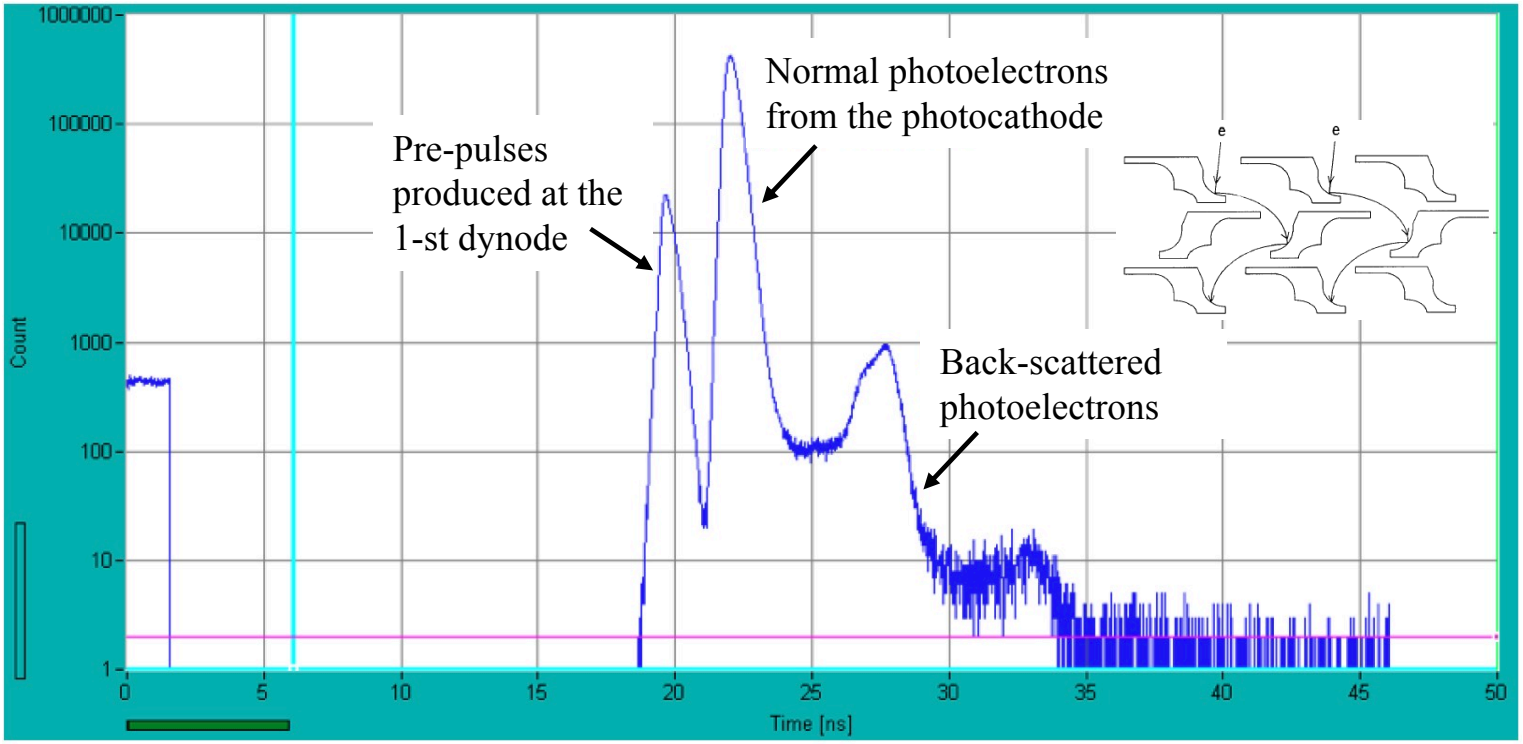
Belle-II TOP DIRC:



- **Stepped faceplate eliminates the tail.**

Timing tail in H-8500 MaPMT

G. Simi, SuperB TDR, arXiv:1306.5655v1 [physics.ins-det] 24 Jun 2013

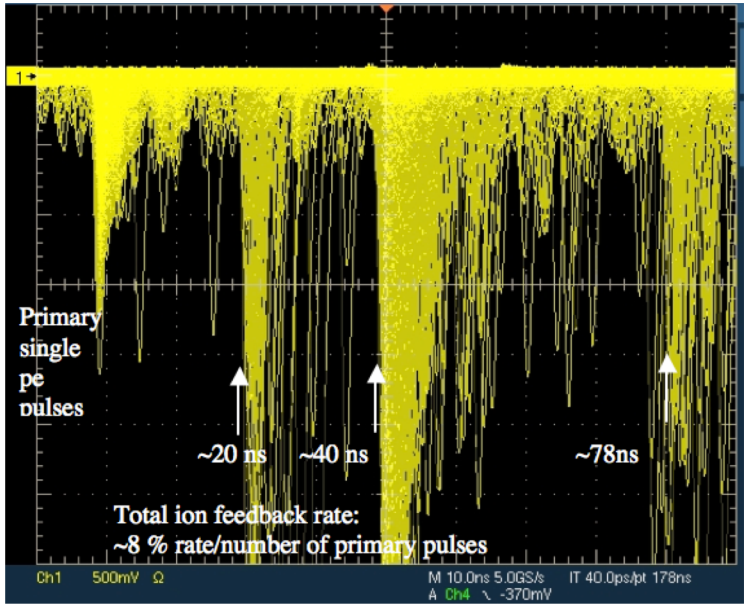


- H-8500 MaPMT has a significant fraction of **pre-pulses**, produced at the first dynode and arriving ~2.5 ns earlier.
- **Back-scattered** photoelectrons are arriving ~6 ns later. The fraction is similar to the MCP rate mentioned earlier.
- Our MC does not have this in the H-8500 time response.

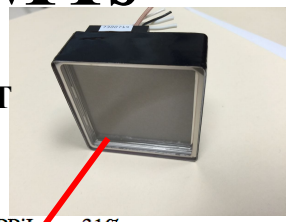
Ion-induced timing tail in Burle MCP-PMTs

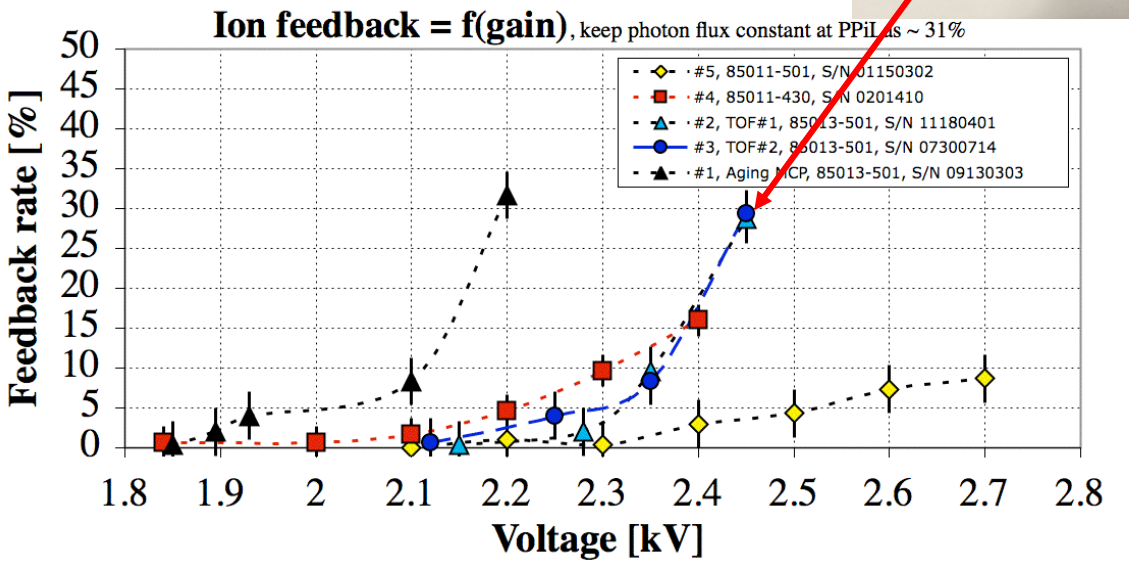
J. Va'vra, MCP logbook #6, page 122, 2008. and NIM A876(2017)185–193

Peaks on storage scope correspond to various ions (H^+, He^+…) **:**



This MCP-PMT died at the end:



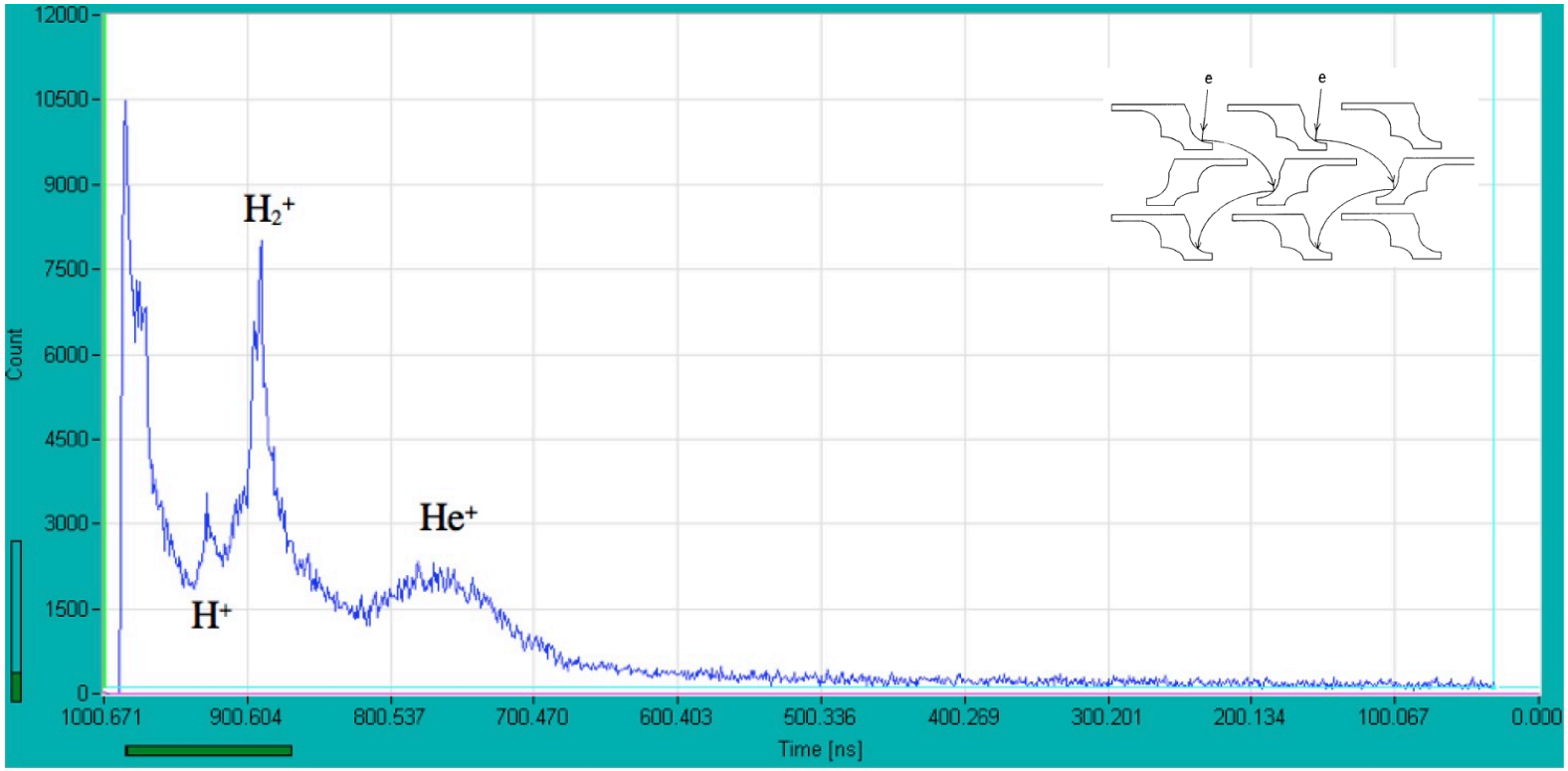


- **The ion feedback was the reason why I did not want to select the Burle MCP-PMT for the final version of SuperB FDIRC.**
- The ion feedback was worse at higher gain. Therefore we kept the MCP-PMT gain below ~5×10^5 and run the amplifier at gain of ~140x.
- Solution for Belle-II TOP counter: use a foil between top & bottom MCPs.
- Solution for Panda: ALD coating helps – see discussion later.

Ion-induced timing tail in H-8500 MaPMT

G. Simi, SuperB TDR, arXiv:1306.5655v1 [physics.ins-det] 24 Jun 2013

Peaks on storage scope correspond to various ions (H^+, He^+…) **:**



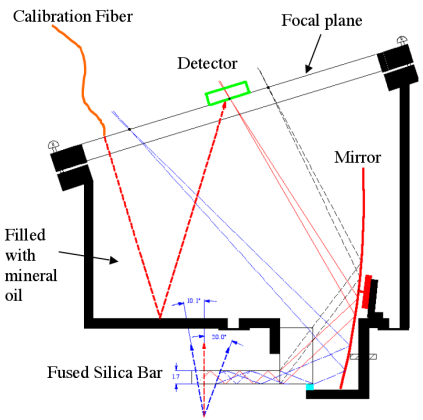
- The total measured rate of after pulses was **<u>less than 1% rate</u>** for this tube.
- This measurement should be part of QC procedure, and it should be repeated periodically during data taking.
- Our MC does not have this in the H-8500 time response.

Cross-talk causing coherent excitations

J.V., MCP-PMT log book #1, p.18, 2005, and FDIRC#1 beam test log book #3, p. 34, 2005

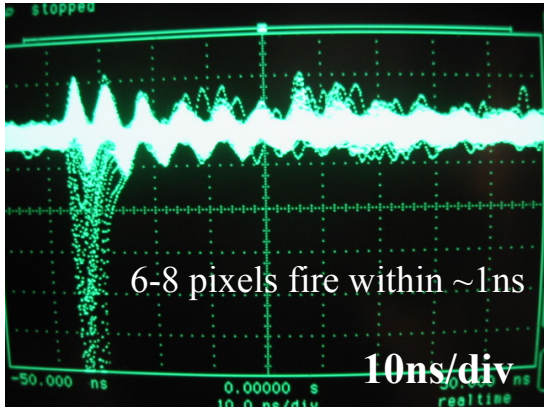
Planacon Burle MCP-PMT (85001, S/N 09130305):

Illuminate the entire photocathode:



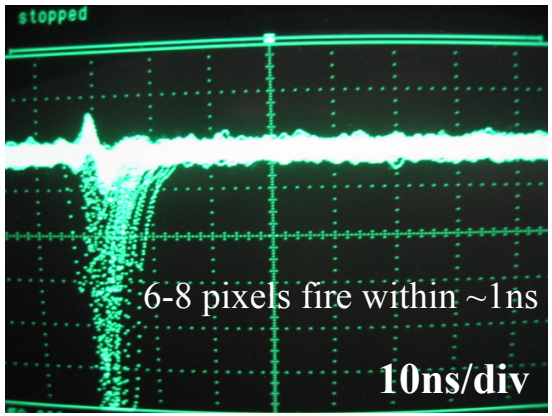
(Etched aluminum surface acts as a diffuser)

100mV/div

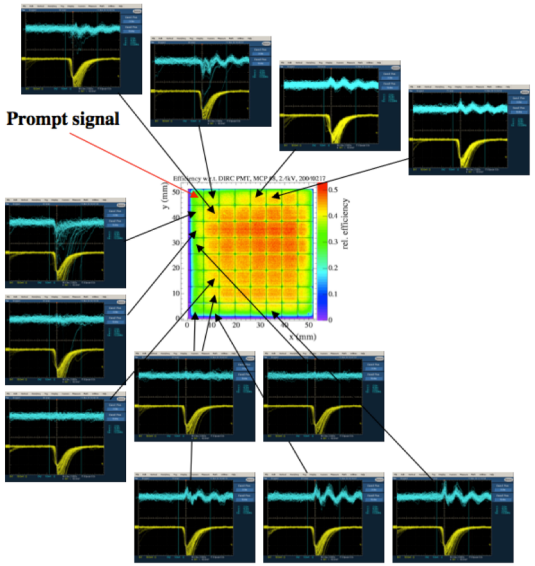


Hamamatsu H-8500 MaPMT:

100mV/div



Reason: A cross-talk in the old Burle Planacon was complicated



Scope trigger: Pilas

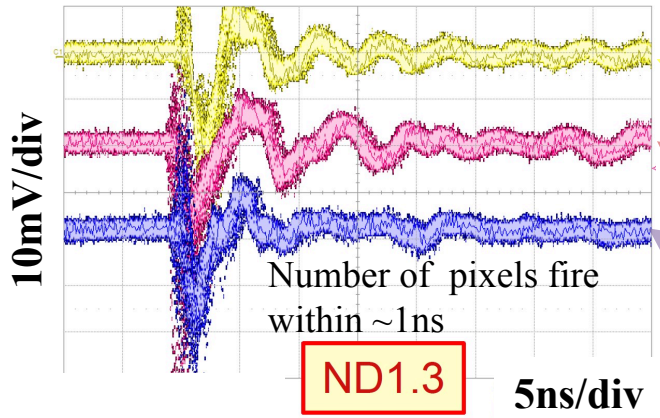
- **The cross-talk in the Planacon MCP-PMT was related to MCP backplane issues. This problem affected the timing resolution. H-8500 MaPMT was OK.**
- I pressed Albert Lehman to do the same measurement with a new Photonis Planacon.

Cross-talk causing coherent excitations in new tubes

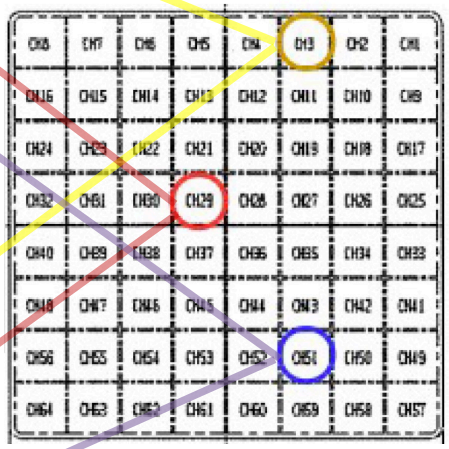
Albert Lehman, private communication before this talk, 5.20.2018

New Photonis Planacon 64-pixel MCP-PMT (XP85112-Q-HA**):**

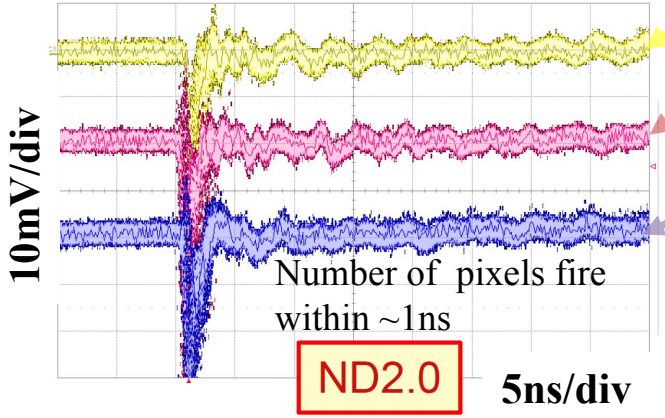
Illuminate the entire photocathode:



Pixel's read out



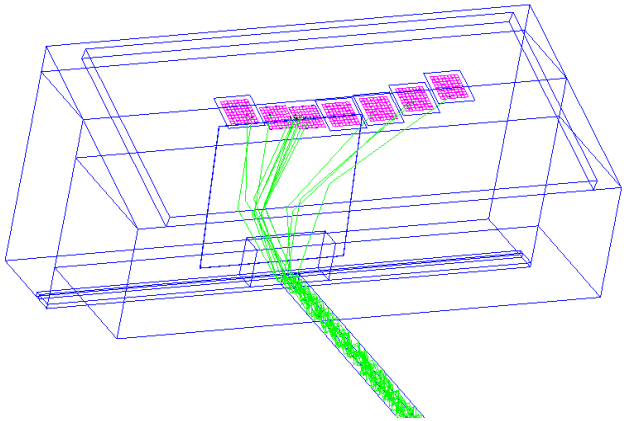
Hamamatsu MCP-PMT 64-pixel (R13266-07-M64M**):**



Scope trigger: ch.29

- **The cross-talk in the new Photonis Planacon MCP-PMT seems to be still there.**
- **Quantitative studies are in progress.**

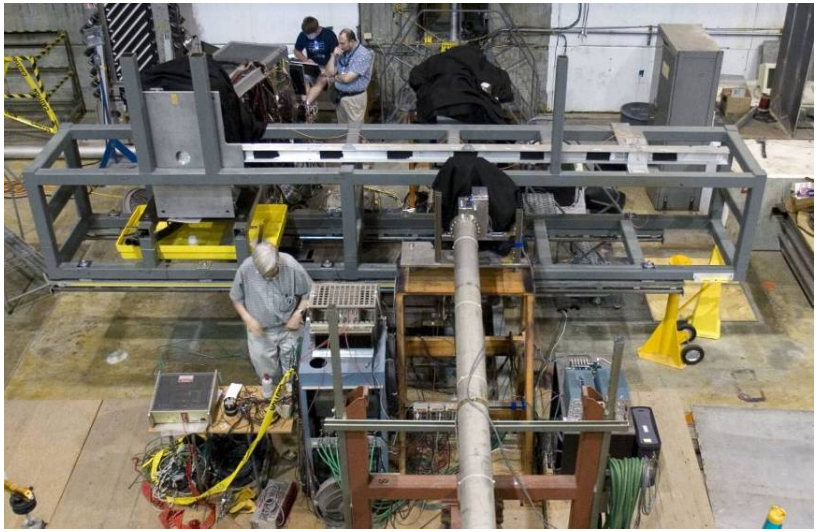
A few important results from the 1-st FDIRC prototype

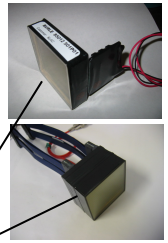


The 1-st FDIRC prototype

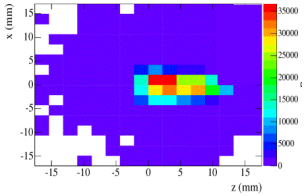
J. Benitez, I. Bedajanek, D.W.G.S. Leith, G. Mazaheri, B. Ratcliff, K. Suzuki, J. Schwiening, J. Uher, L.L. Ruckman, G. Varner, and J. Va'vra,
SLAC-PUB-12236 & NIMA 595 (2008) 104

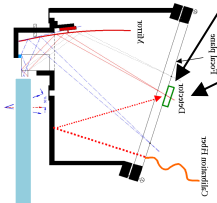
- **Beam test instrumentation:**
  - Two x-y scintillating fiber hodoscopes (σ<1mm)
  - START Quartz counter (σ ~40-45ps)
  - Time start from the LINAC RF signal
  - Lead glass to monitor beam multiplicity (very important in the SLAC's beam)
  - A tandem of two TOF counters
  - Run ~0.2 particles/pulse (need lead glass)





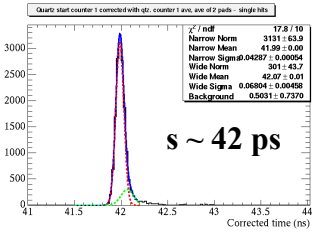
Beam spot: s < 1mm





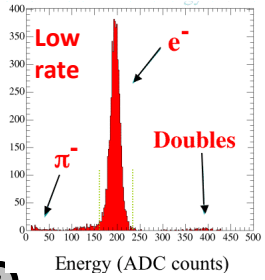
Start Quartz counter
(4-pad MCP-PMT)

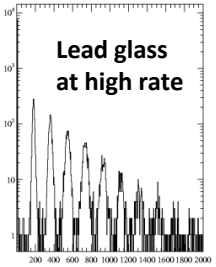
Timing relative to machine:



s ~ 42 ps

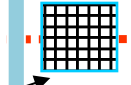
Lead glass:

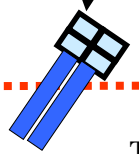


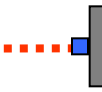


10 GeV electrons

Beam Pipe





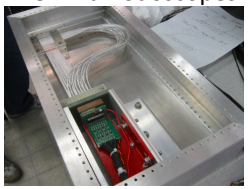


Lead Glass

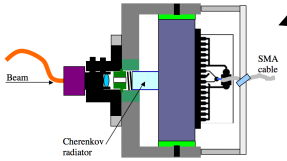
PMT

TOF #1 **TOF #2**

The 2-nd hodoscopes:

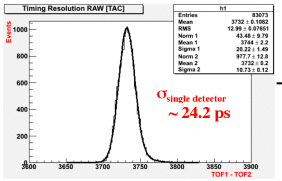


Hodoscopes #1&2
(2mm scint. fibers)

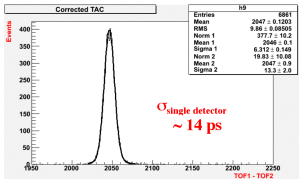


TOF counter result:

Initial result at SLAC:



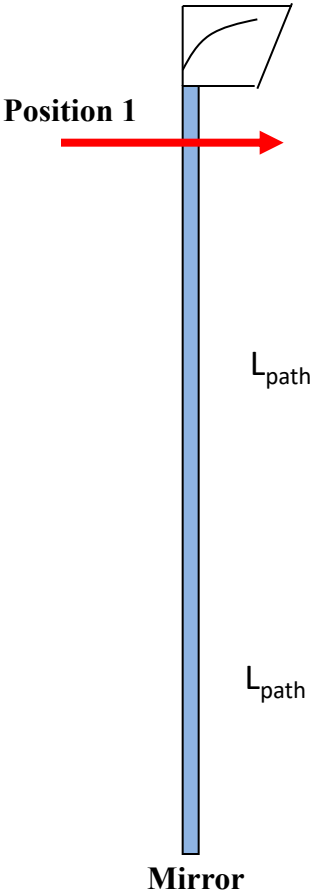
Final Result in Fermilab test beam:

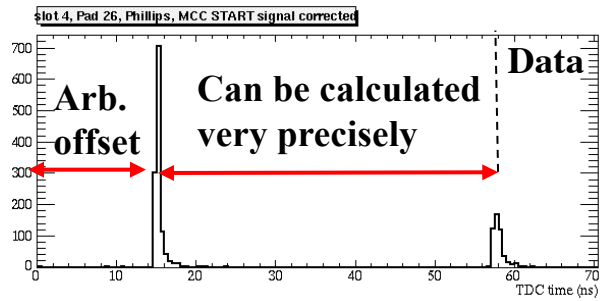


Chromatic broadening

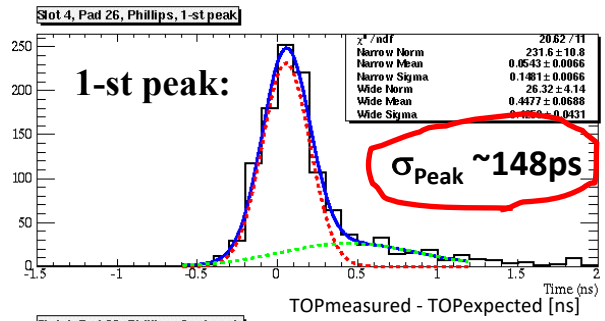
J.V., "Beam test FDIRC" log book #5, page 19-33, 2008, Run 4, position 1, 10GeV e^-

Slot 4, **single pixel** time distribution:

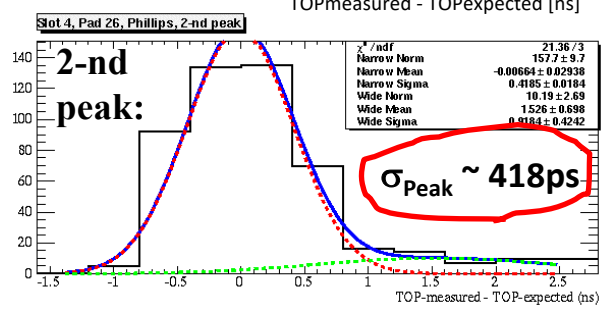




L_{path} ~ 1-1.5 m:



L_{path} ~ 10-12 m:



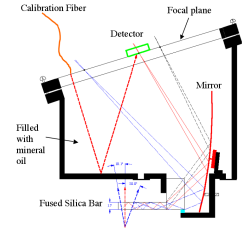
TOP = Time-of-progation of photon in the bar

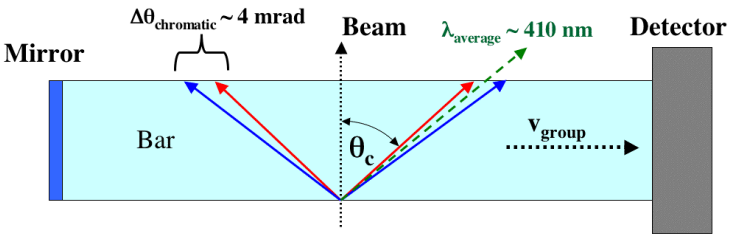
dTOP = TOP_measured - TOP_expected (410nm) [ns]

- The **chromatic dispersion of time** is significant in all DIRCs. However, FDIRC takes advantage of it to measure a color of each photon.

The 1-st FDIRC test: chromatic error correction

SLAC-PUB-12803, 2007 & NIMA595(2008)104





Time of propagation is controlled by n_{group} : $TOP = L_{path}\, n_{group}/c$ $TOP/L_{path} = 1/v_{group}$

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

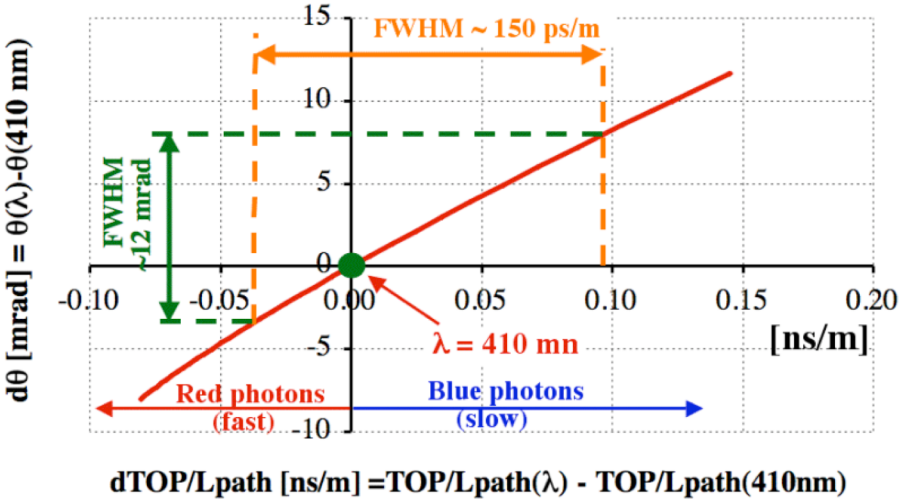
n_{phase} and n_{group} are of course related: $v_{group} = c/n_{group} = c/[n_{phase} - \lambda*(dn_{phase}/d\lambda)]$

θ_c correlates with TOP/L_{path}

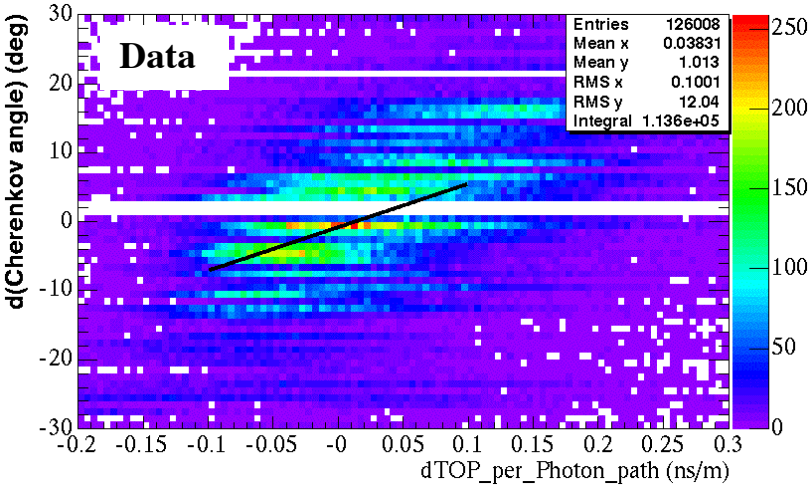
θ_c (red) < θ_c (blue)

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

Expected chromatic correction



Data from the 1-st FDIRC prototype:

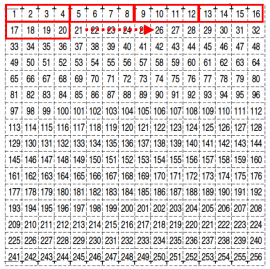


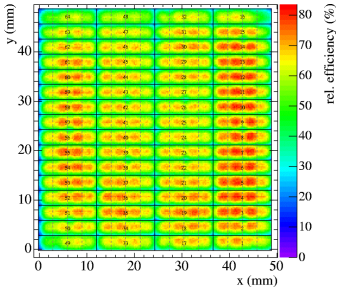
One can either correct Cherenkov angle θ_c by dTOP, or correct dTOP by θ_c.

The 1-st FDIRC prototype performance with 3mm pixels

J. Benitez, I. Bedajanek, D.W.G.S. Leith, G. Mazaheri, B. Ratcliff, K. Suzuki, J. Schwiening, J. Uher, and J. Va'vra, SLAC-PUB-12236, 2006

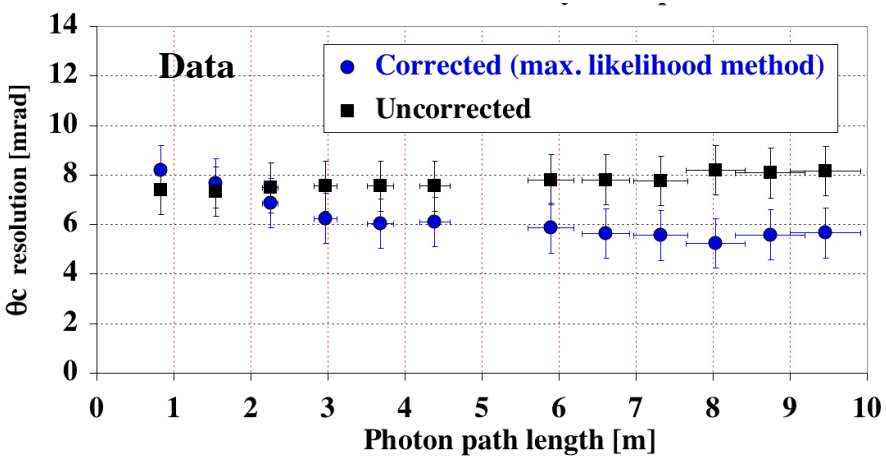
H-9500 MaPMT:



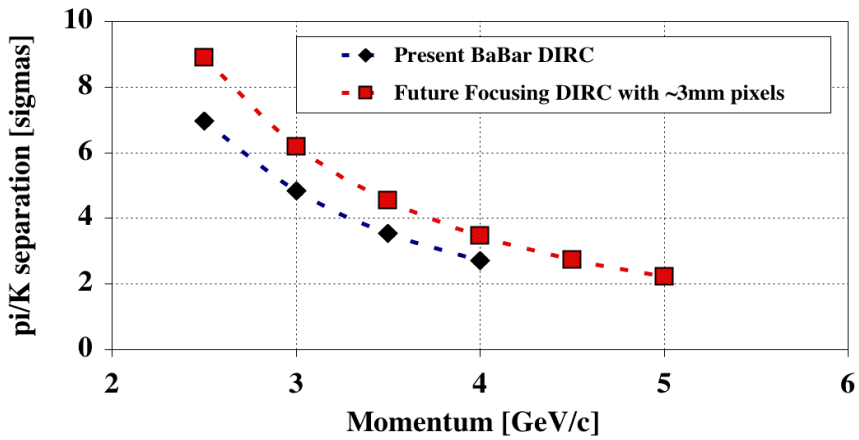


Pixel size: **~3 mm x 12 mm**

Beam test result for 3 mm pixels:



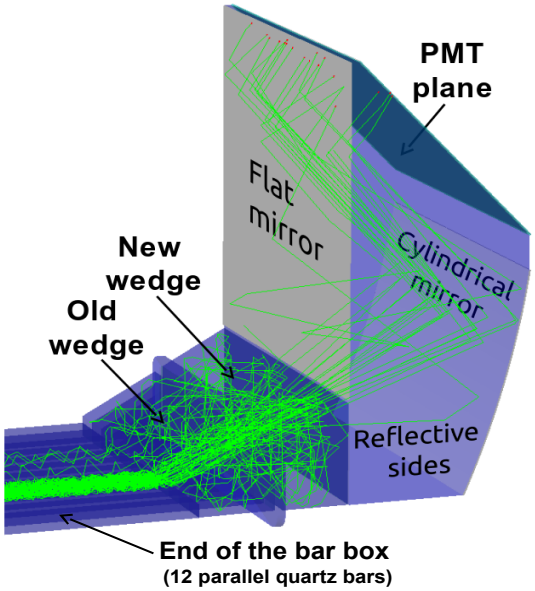
Expected performance in a final detector:



- **The first Cherenkov detector to correct the chromatic error.**
- **To do this, one needs a pixel-based θ_c analysis, and σ_{TTS} ~150 ps.**
- Note: BaBar DIRC θ_c resolution was ~9.6 mrads.

Final FDIRC prototype

Photon camera:



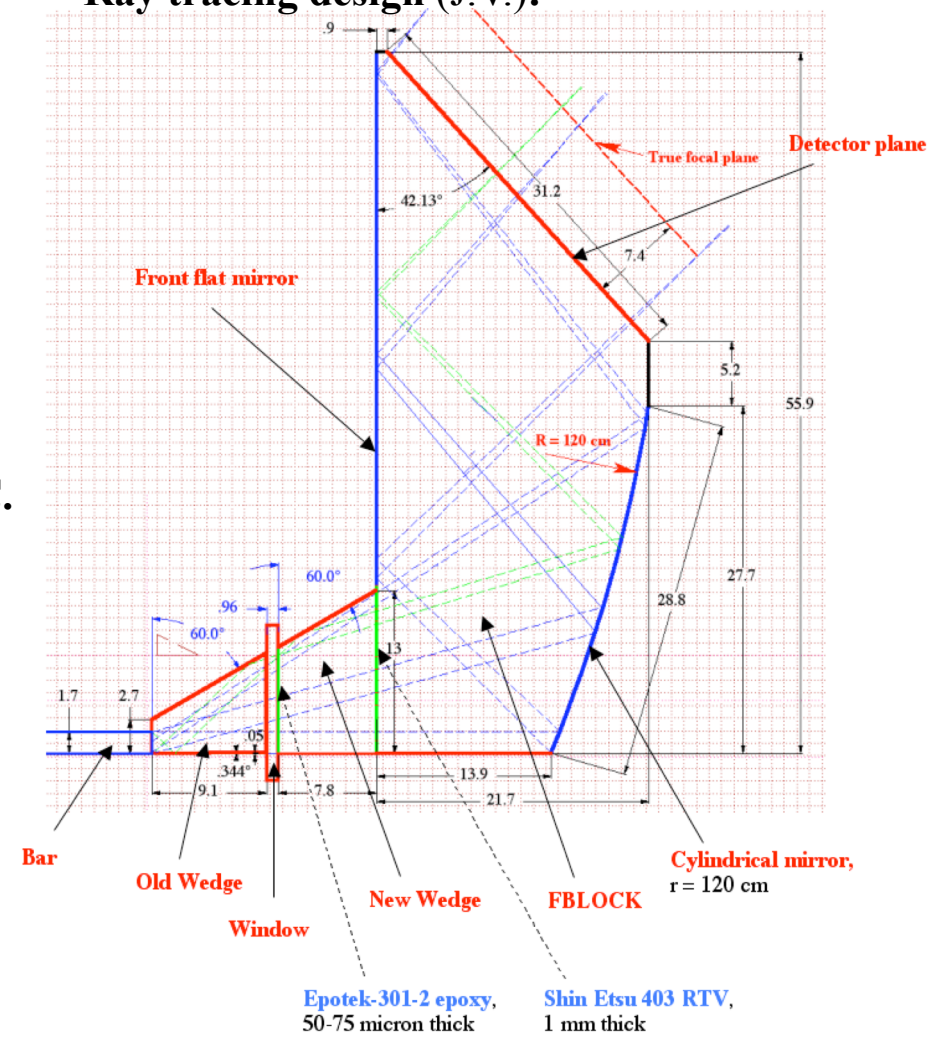
SuperB FDIRC design

J. Va'vra, D. Roberts and B. Ratcliff, SLAC-PUB-14282, Oct. 15, 2010

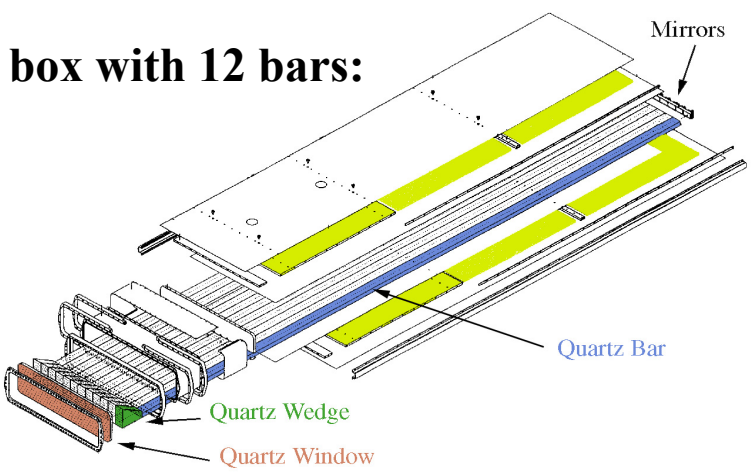
Design concept:

- Cherenkov angle is determined from x-y pixels
- Time is used to reduce background, reduce ambiguities and make chromatic corrections
- Cylindrical mirror removes the bar thickness contribution to resolution in y-direction
- FBLOCK designed to be used with 6mm x 6mm pixels (H-8500)
- Double-folded mirror optics provides easy access
- Use the early "practice" bar box for BaBar DIRC.

Ray tracing design (J.V.):

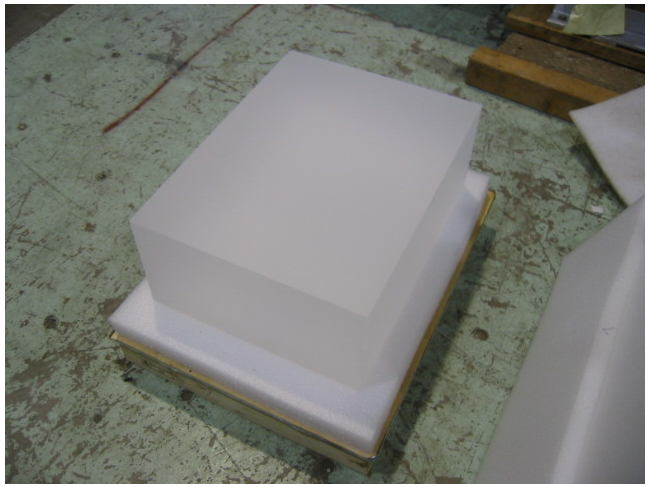


BaBar bar box with 12 bars:



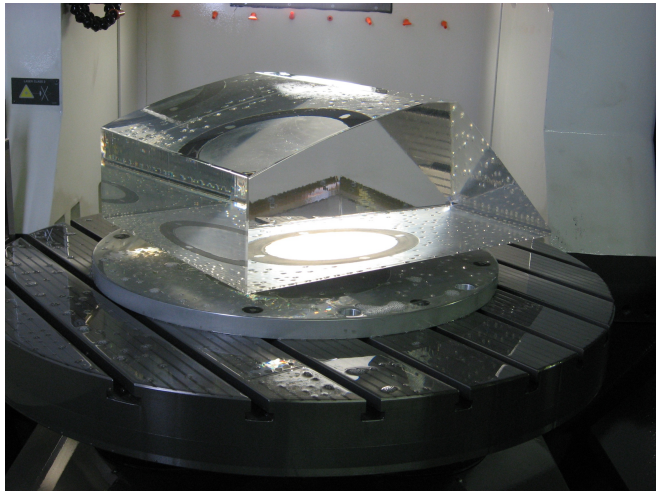
Production of FBLOCK optics

Raw 7980 Fused silica block from Corning:



Machining on NC machine at AGI:

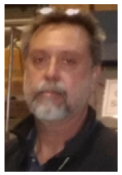
Finished machining at AGI:



Polishing at Cosmo:

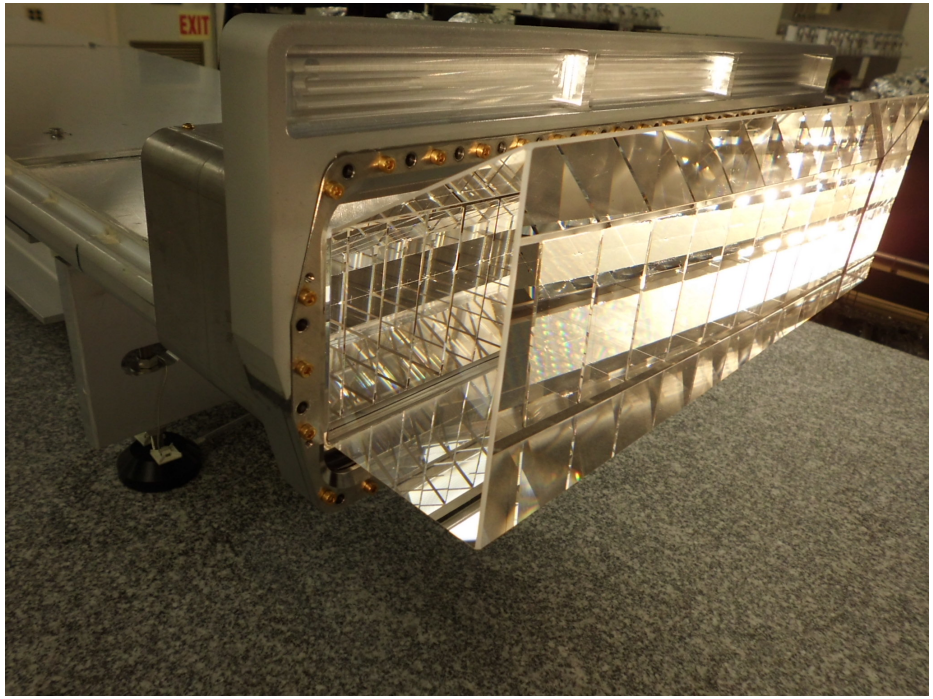
- **We proved that his kind of camera is buildable at an acceptable cost.**

Finished new Wedge and Fblock



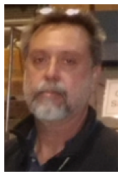
Finished Focusing Block:

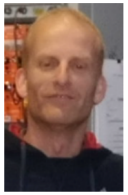
New Wedge glued to the bar box:



- **Optical coupling between bar box window and new Wedge is 50-75 μm-thick Epotek 301-2 epoxy.**

Coupling of Fblock to New Wedge in situ





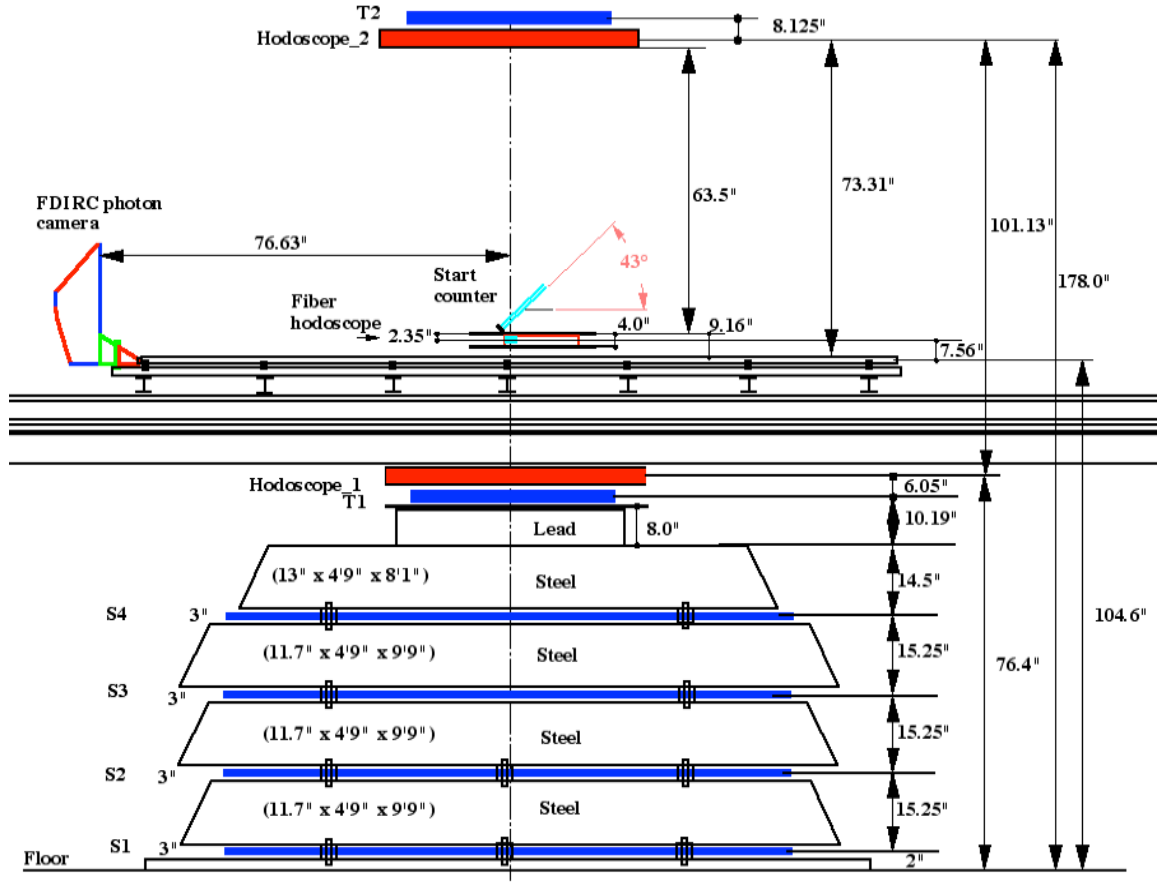
- **Optical coupling between FBLOCK and New Wedge is 1 mm-thick Shin-Etsu 403 RTV. One can decouple Fblock in case of a problem.**

FDIRC test in cosmic ray telescope (CRT)

SLAC-PUB-13873 (2010)

Cosmic Ray Telescope (CRT):

FDIRC prototype located in CRT:



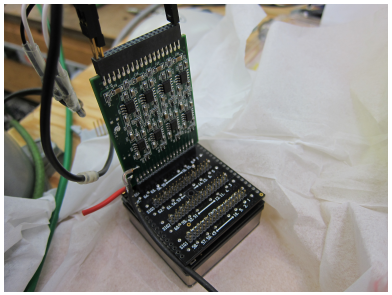
- σ_{track} ~ 1.5 mrads track resolution
- $\sigma_{x\text{-}y\ tracking}$ ~ 5-6 mm
- $\sigma_{start\ time}$ < 90 ps
- E_{muon} > 2.0 GeV muon energy lower limit
- 3D tracking using scintillator counter hodoscopes
- ~70”- thick iron & lead absorber, 55” x 90” x-y size

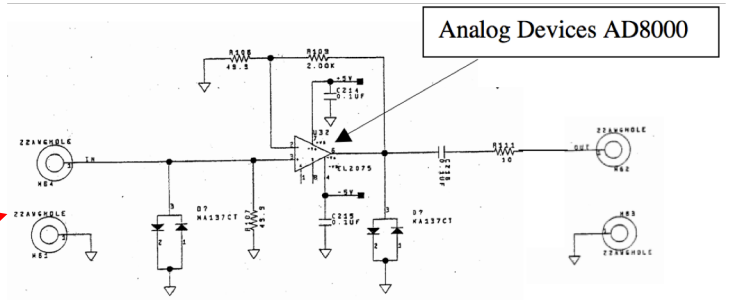
FDIRC prototype electronics in CRT

N. Arnaud, M. Borsato, B. Dey, D.W.G.S. Leith, K. Nishimura, B.N. Ratcliff, D. Roberts, G. Varner, J. Va'vra , NIMA 775(2015)112

Photodetectors:

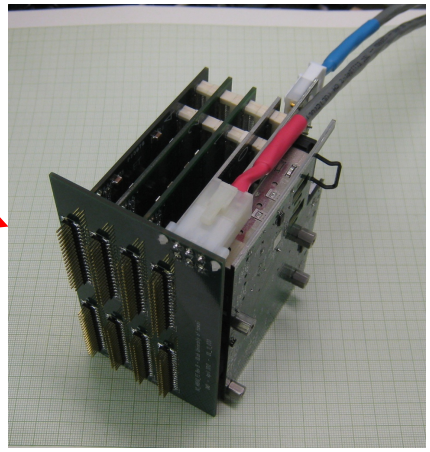
- 12 Hamamatsu H8500 MaPMTs placed in the region most hit by cosmic rays
- H-8500 MaPMTs have 64 channels each
- H8500 Pixel size: 6mm x 6mm
- H8500 σ_{TTS}~140ps





Electronics:

- SLAC amplifiers with ~40x gain
- IRS-2 waveform digitizing electronics (Hawaii)
- 2.7 GHz sampling rate
- Digitized waveforms analyzed offline
- The IRS-2 electronics was an early version of the Belle-II electronics.

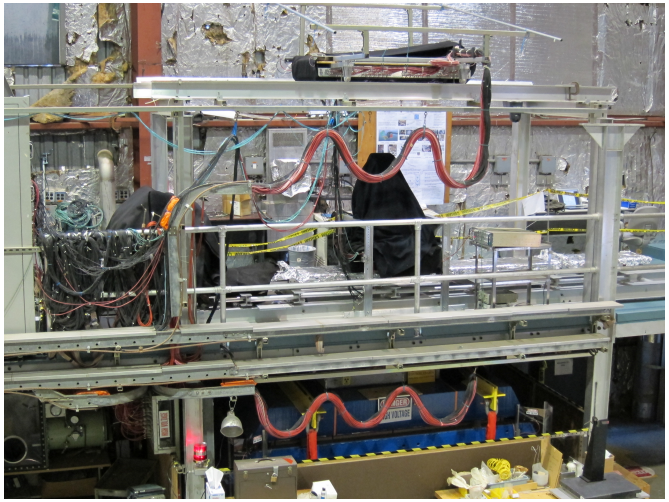


- **IRS-2 electronics was early version of the Belle-II electronics; our version had timing resolution of only σ ~600 ps.**

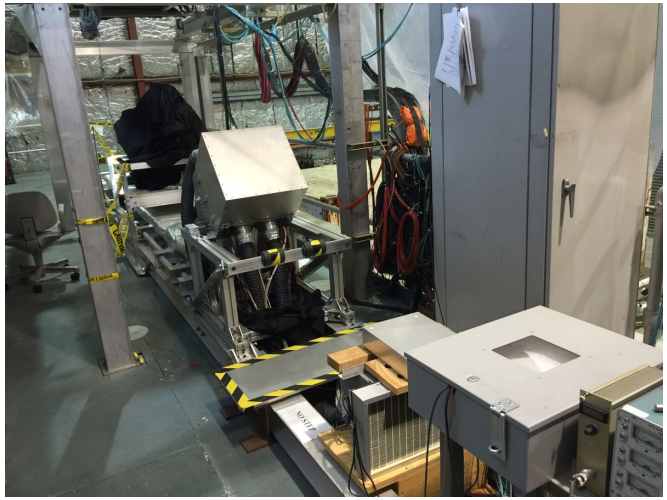
FDIRC prototype test in CRT

B. Dey, M.Borsato, N.Arnaud, D.W.G.S.Leith, K.Nishimura, D.A.Roberts, B.N. Ratcliff, G.Varner, J.Va'vra NIMA 775(2015)112

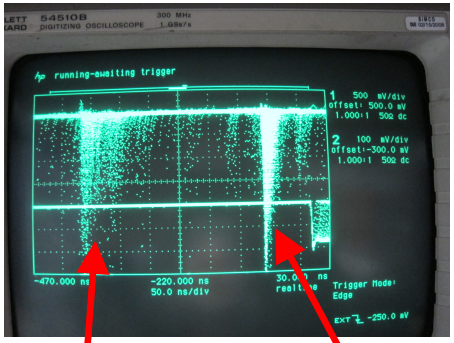
CRT:



FDIRC in CRT:



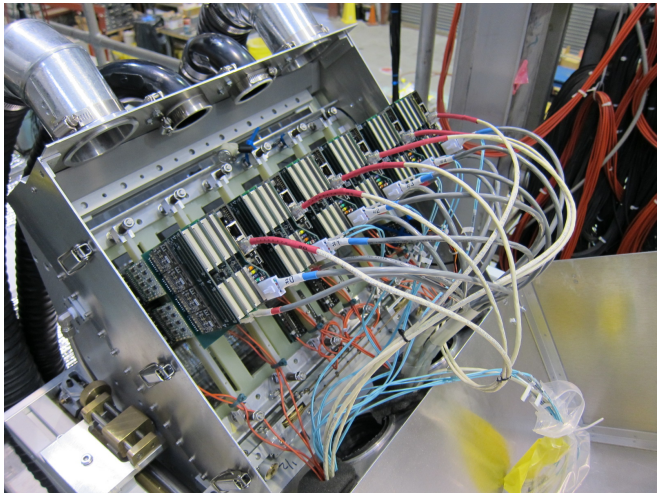
One pixel connected to scope:



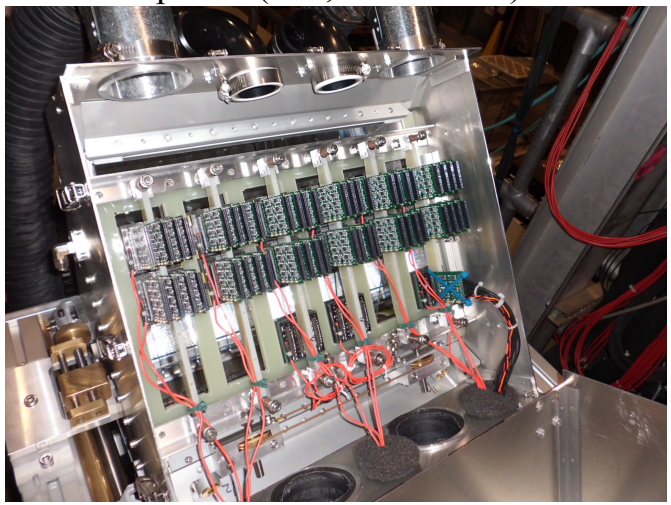
Cherenkov photons

Laser

Hawaii IRS-2 electronics:



SLAC amplifier (40x, 16 ch./card):



- **Very successful test with excellent results proving that FDIRC works.**

Reconstruction in FDIRC using a dictionary

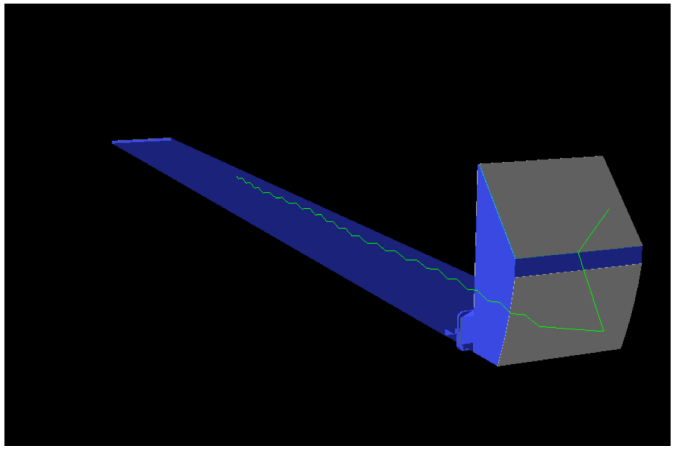
N. Arnaud, M. Borsato, B. Dey, D.W.G.S. Leith, K. Nishimura, B.N. Ratcliff, D. Roberts, G. Varner, J. Va'vra, NIMA 775(2015)112.

Principle of θ_c reconstruction in FDIRC:

- Tracking system measures **p**, FDIRC measures **k**.
- FDIRC task: translate a hit in PMT into **k**-vector.

$$\cos\theta_C = \vec{p}\cdot\vec{k} = p_x k_x + p_y k_y + p_z k_z$$

Photon path to a given pixel:



Procedure to generate pixel dictionary:

- Possible **k** solutions from a given pixel are determined via a dictionary compiled from single photon simulations with fixed wavelength.
- Photons generated isotropically.
- For each pixel/bar combination, store $\mathbf{k_x}$, $\mathbf{k_y}$ and **time**.
- Multivalued due to multiple paths into a given pixel.

dTOP:

- It is the primary variable to reject the background, resolve ambiguities and correct chromatic dispersion.

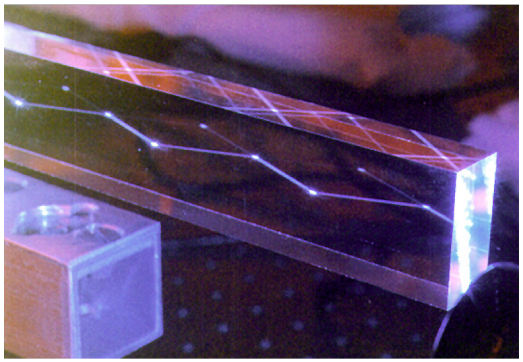
$$\mathrm{dTOP} = \mathrm{TOP}_{\mathrm{Measured}} - \mathrm{TOP}_{\mathrm{Expected}}$$

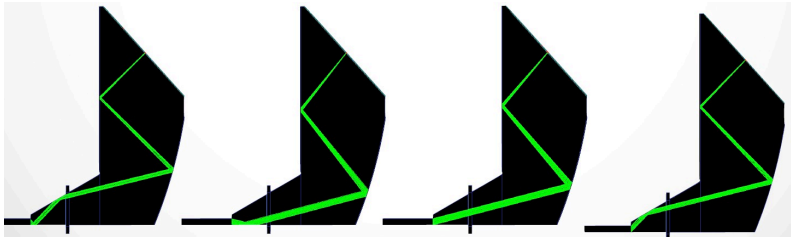
Ambiguities in FDIRC

N. Arnaud, M. Borsato, B. Dey, D.W.G.S. Leith, K. Nishimura, B.N. Ratcliff, D. Roberts, G. Varner, J. Va'vra, NIMA 775(2015)112.

Bar ambiguities:

- Each bounce in the horizontal direction changes the sign of kx. Similar for vertical bounces and ky. And backward-going photons that hit the end mirror change sign of kz. This creates a potential **8-fold ambiguity** between the photon's original direction and it's direction as it leaves a quartz bar. **We treat these ambiguities as possible solutions.**





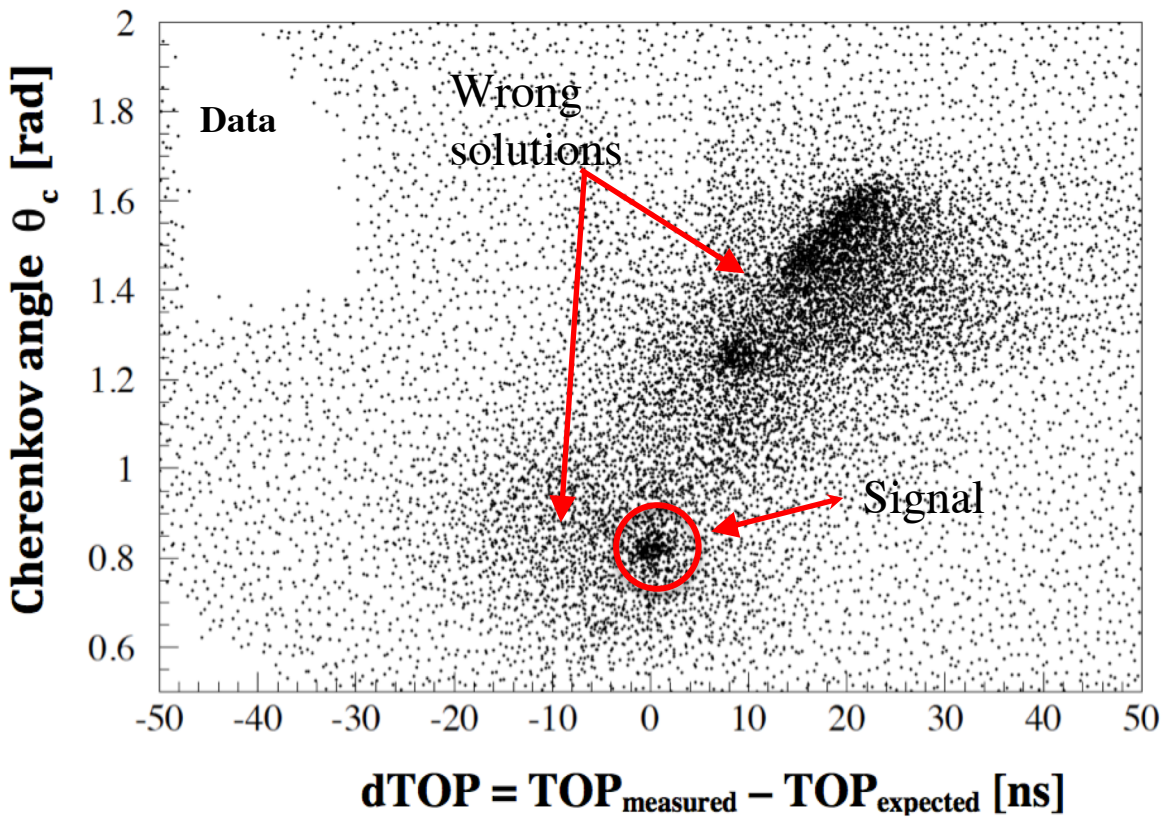
Focusing optics ambiguities:

- After a photon leaves a quartz bar, it propagates through wedges and the FBLOCK before being detected by the PMT.
- Reflections off the surfaces of the wedges and sides of the FBLOCK can lead to further ambiguities, as there is more than one path, with different k, that can bring a photon from a quartz bar to a given pixel.

- **Time is important variable to resolve some ambiguities.**

Elimination of wrong solutions

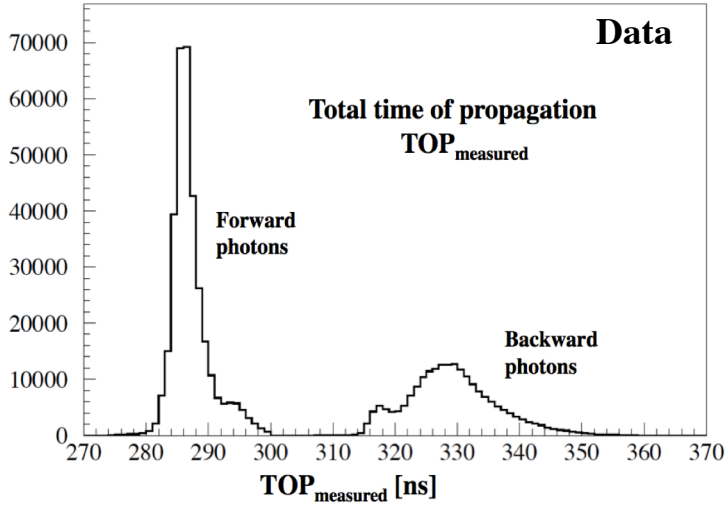
N. Arnaud, M. Borsato, B. Dey, D.W.G.S. Leith, K. Nishimura, B.N. Ratcliff, D. Roberts, G. Varner, J. Va'vra , NIMA 775(2015)112

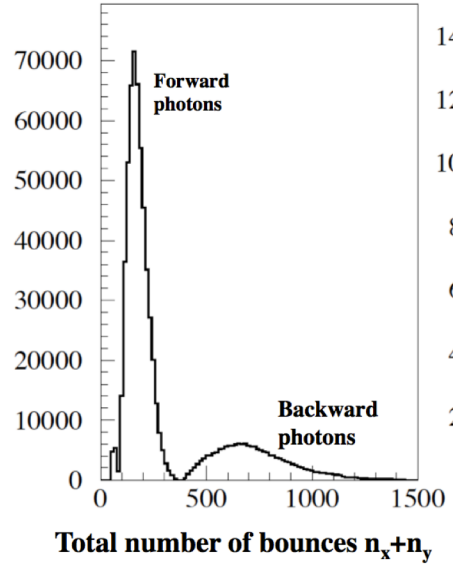


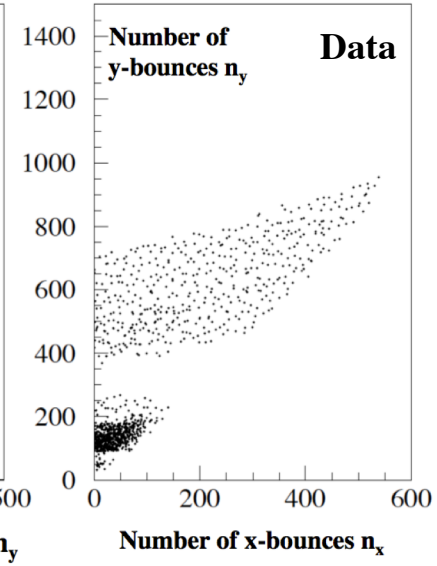
- **A combination of pixels and time is crucial to eliminate wrong solutions.**

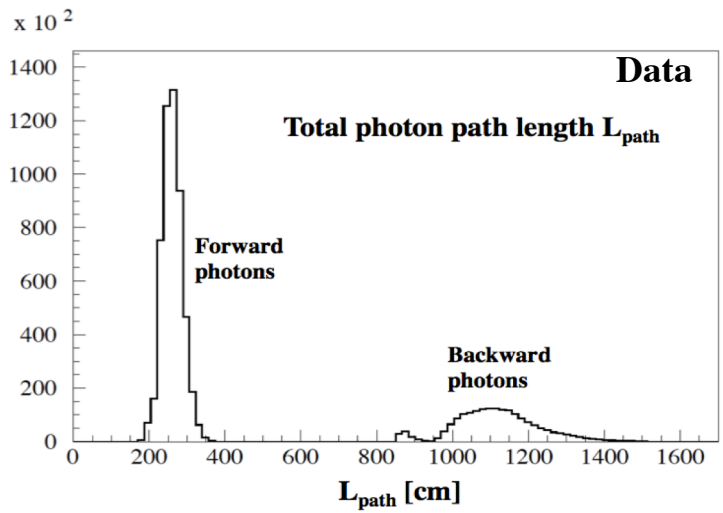
Measured TOP, dTOP, n_x, n_y, L_{path} distributions

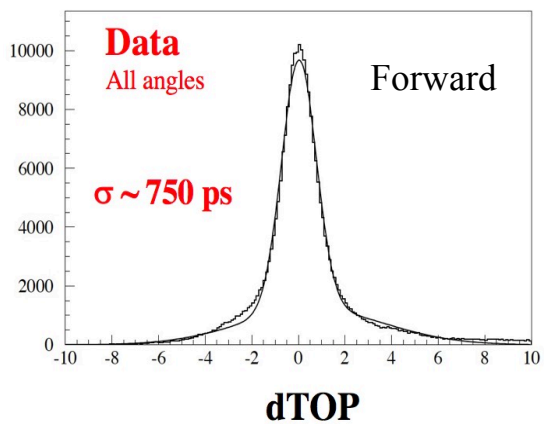
N. Arnaud, M. Borsato, B. Dey, D.W.G.S. Leith, K. Nishimura, B.N. Ratcliff, D. Roberts, G. Varner, J. Va'vra , NIMA 775(2015)112

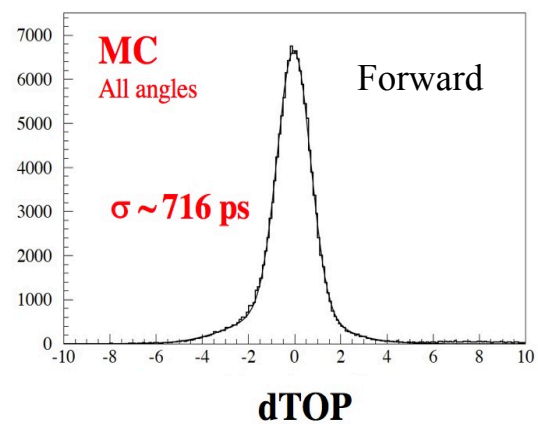










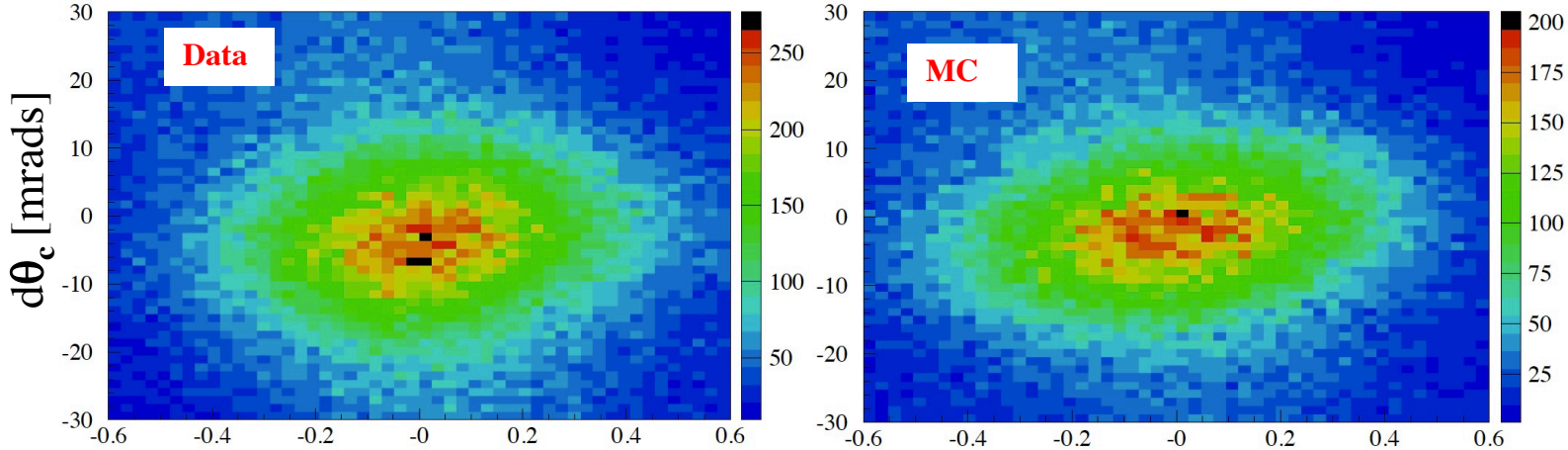


- **FDIRC has tremendeous capability to self-monitor its performance.**
- IRS-2 electronics was an early version of the Belle-II electronics (it added σ_{time}~600ps).

$dTOP/L_{path}$ vs. θ_c: Data vs. MC simulation

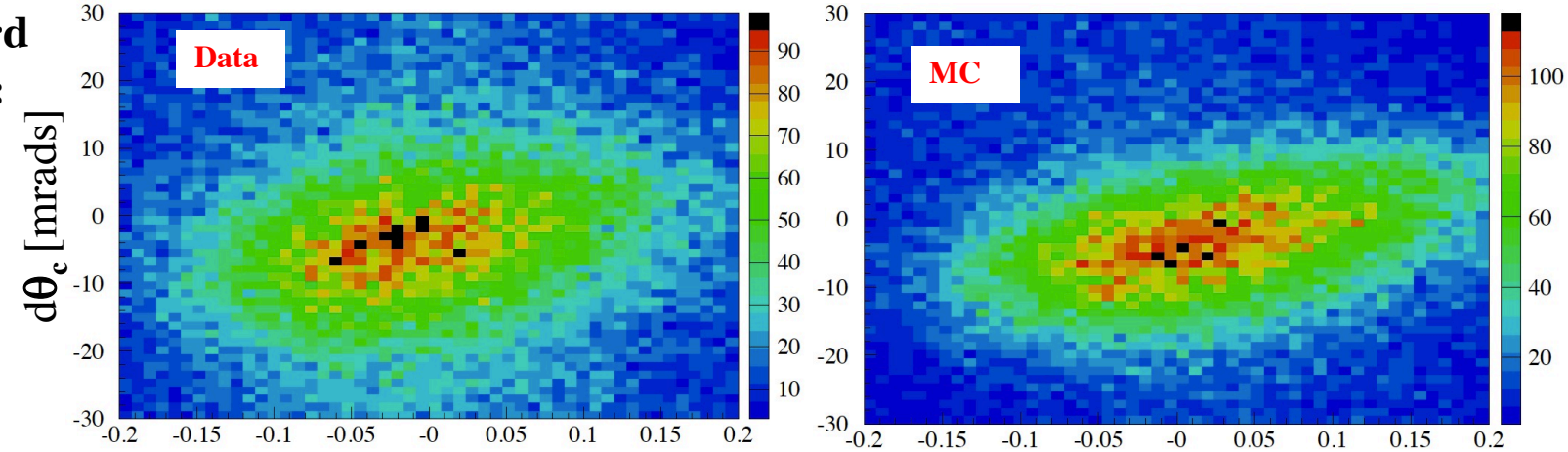
N. Arnaud, M. Borsato,, B. Dey, D.W.G.S. Leith, K. Nishimura, B.N. Ratcliff, D. Roberts, G. Varner, J. Va'vra , NIMA 775(2015)112

1) Forward photons:



$dTOP/L_{path} = (TOP_{measured}-TOP_{expected})/L_{path}$

2) Backward photons:

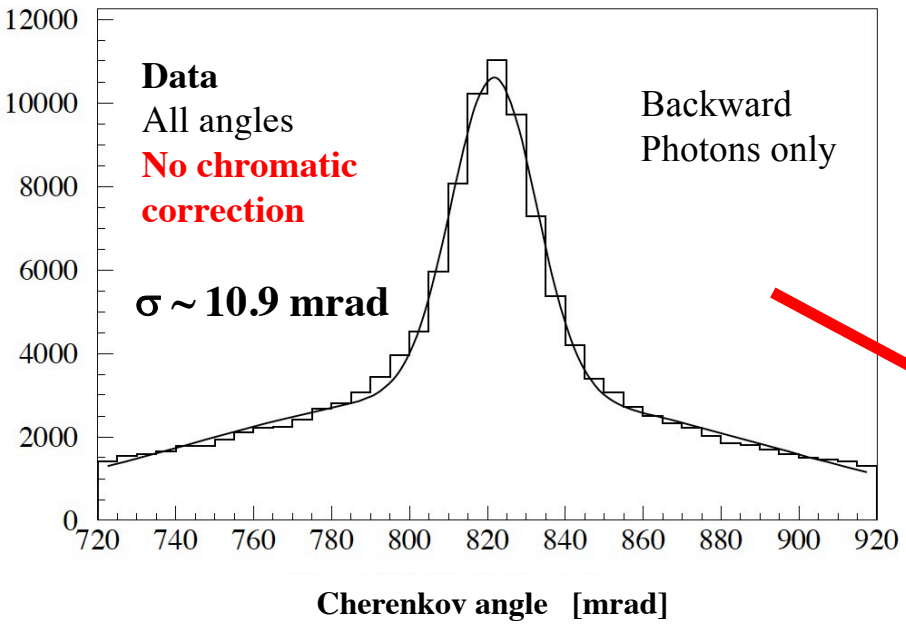


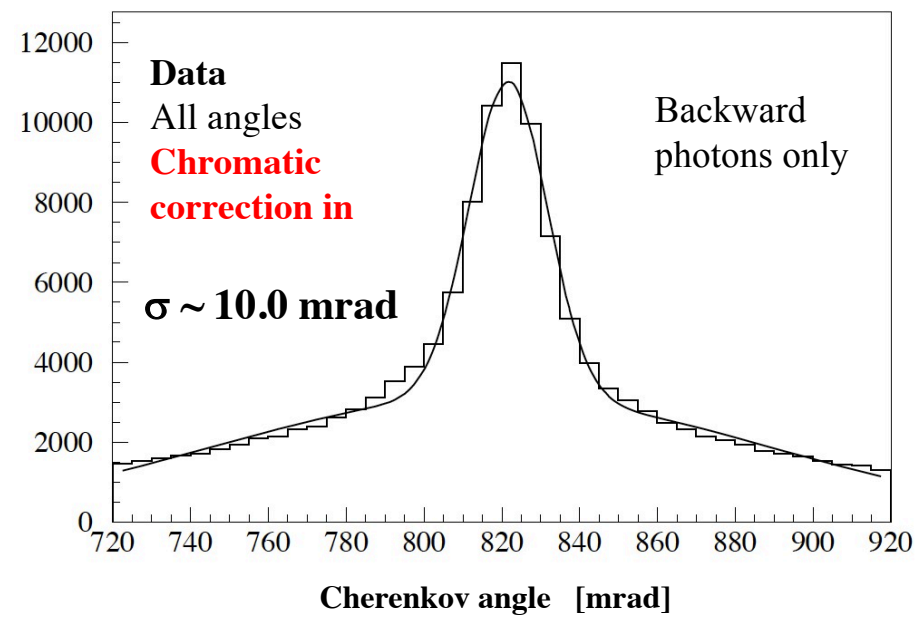
$dTOP/L_{path} = (TOP_{measured}-TOP_{expected})/L_{path}$

- **Use this correlation to correct θ_c by time.**

FDIRC chromatic correction

N. Arnaud, M. Borsato, B. Dey, D.W.G.S. Leith, K. Nishimura, B.N. Ratcliff, D. Roberts, G. Varner, J. Va'vra, NIMA 775(2015)112

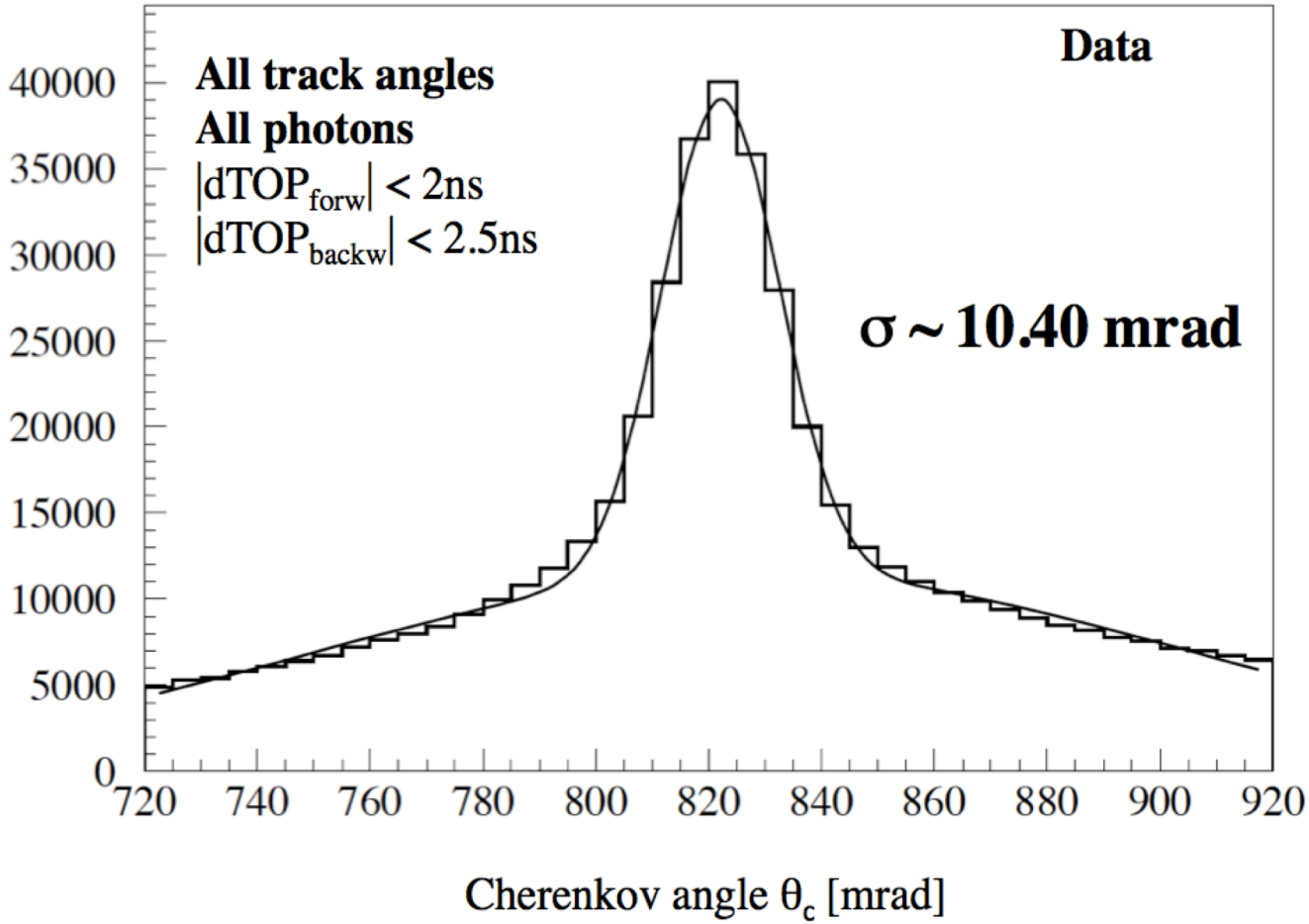




- **We gain about ~0.8 mrads by doing this correction.**

FDIRC final result in CRT: θ_C resolution

N. Arnaud, M. Borsato, B. Dey, D.W.G.S. Leith, K. Nishimura, B.N. Ratcliff, D. Roberts, G. Varner, J. Va'vra , NIMA 775(2015)112



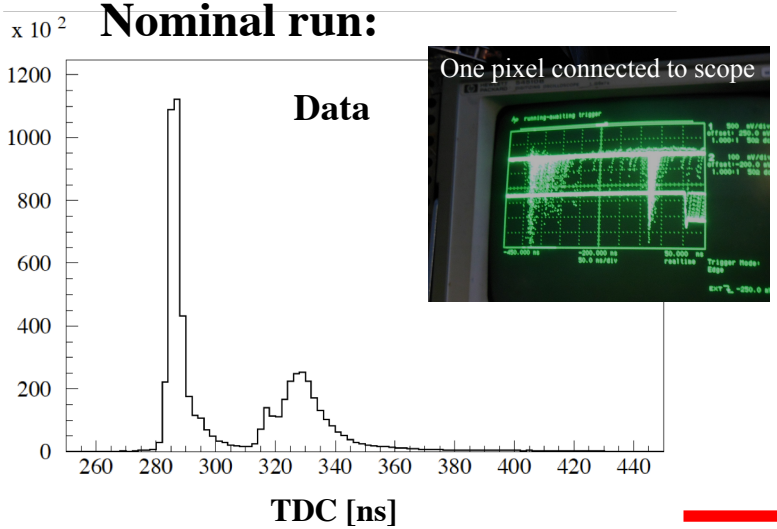
- **The measured Cherenkov angle resolution (10.4 mrads) is somewhat worse than MC resolution (9.1 mrads).**

Background studies

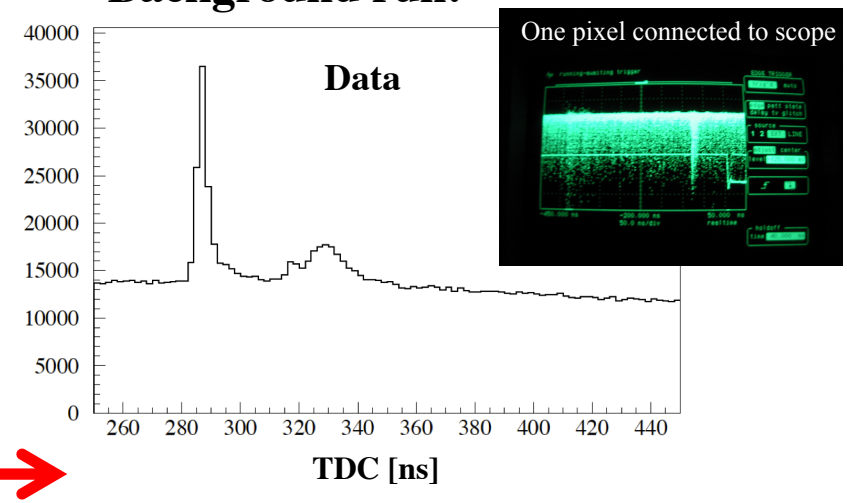
~250MHz/bar box, i.e., ~3x than what Belle-II TOP counter expects

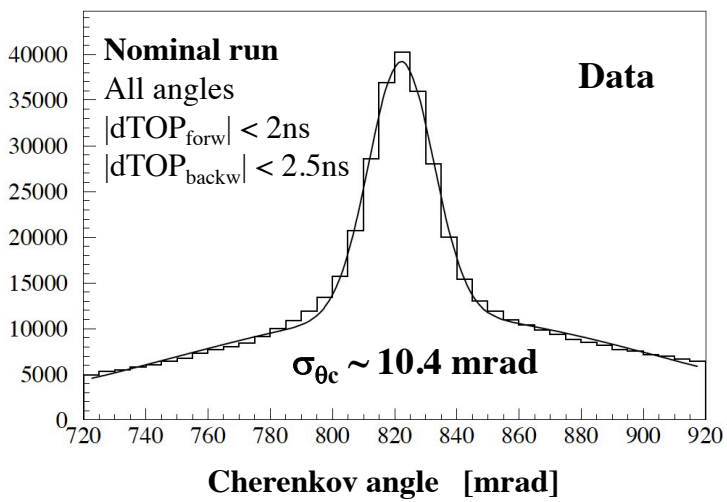
NIMA 775(2015)112.

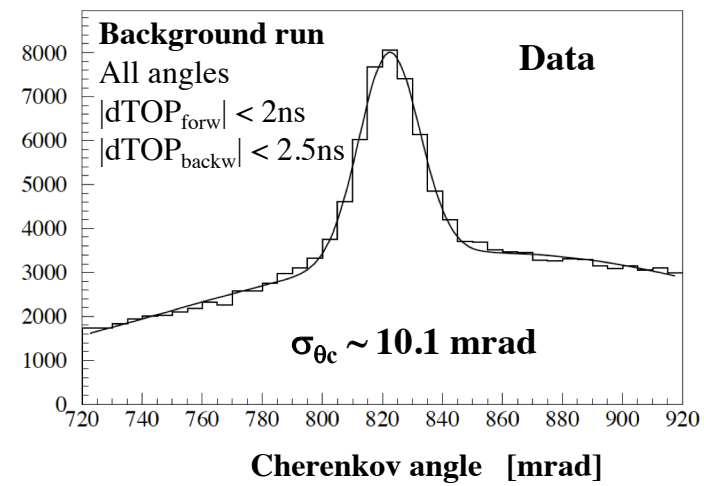
Nominal run:



Background run:





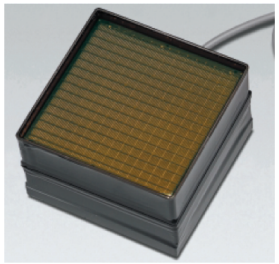


- **One can still reconstruct the Cherenkov angle. With a better dTOP resolution, say |dTOP| < 1 ns, one would restore the S/N ratio fully.**

New SLAC FDIRC designs

- #1: The same as SuperB design but smaller 3mm pixels
- #2: New smaller FBLOCK design with 3mm pixels
- #3: New smaller FBLOCK with a plate with 3mm pixels

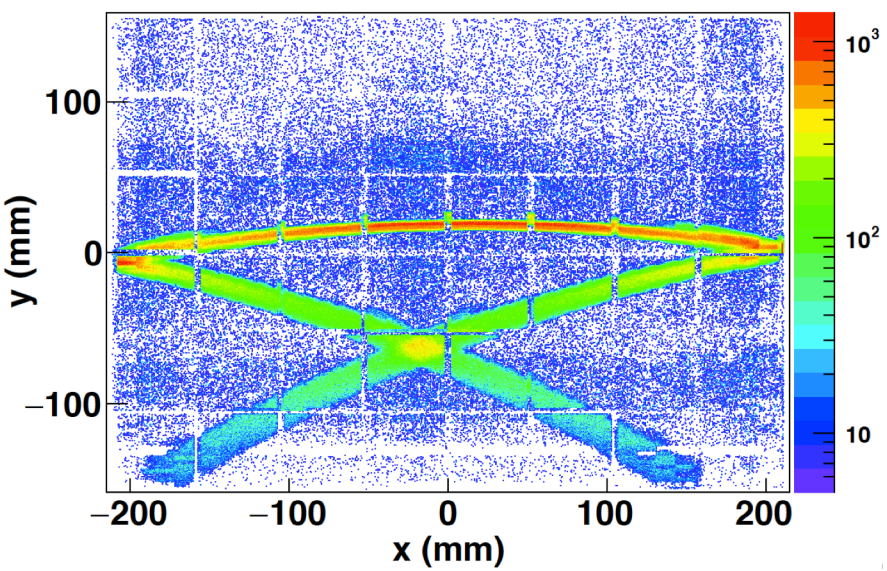
H-9500 MaPMT
3mm x 12 mm



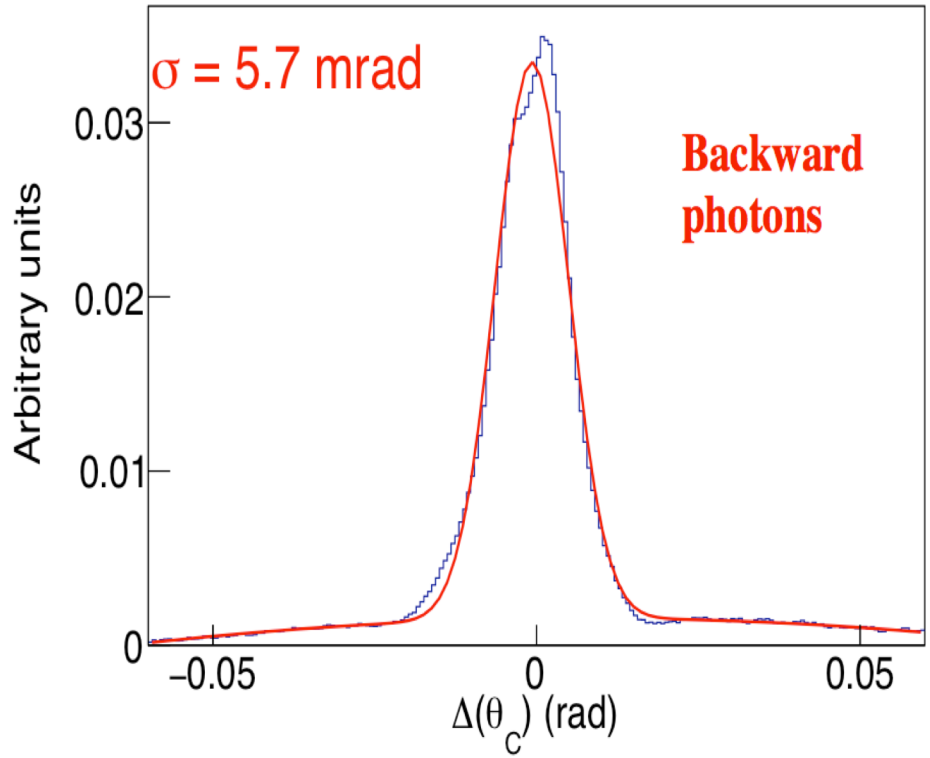
#1: SuperB design with 3 mm pixels

B. Dey, B.N. Ratcliffc, J. Va'vra , NIMA 775(2015)112.NIM A 876 (2017) 141

Cherenkov ring x-y image in FDIRC:
(show individual hits)



10 GeV muons:

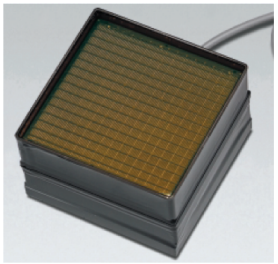


- Single photon resolutions for <u>backward</u> going photons: $\sigma_{\theta c} \sim$ **5.7mrads.**
- BaBar bar box without any changes.

#2: New smaller FBLOCK

B. Dey, B.N. Ratcliffc, J. Va'vra , NIMA 775(2015)112.NIM A 876 (2017) 141

H-9500 MaPMT
3mm x 12 mm



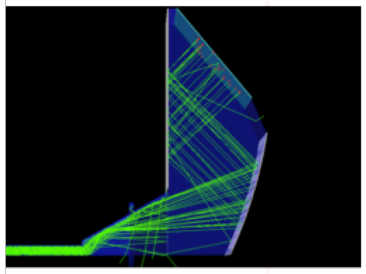
Ray tracing design:

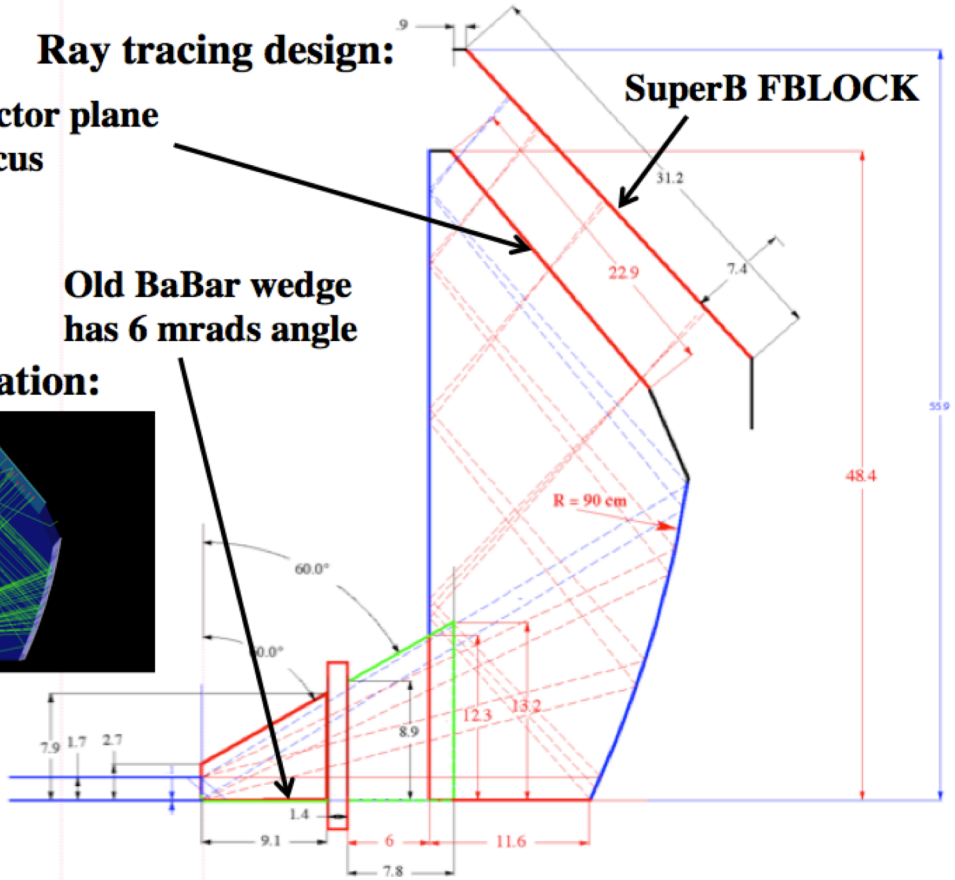
The detector plane is in a focus

SuperB FBLOCK

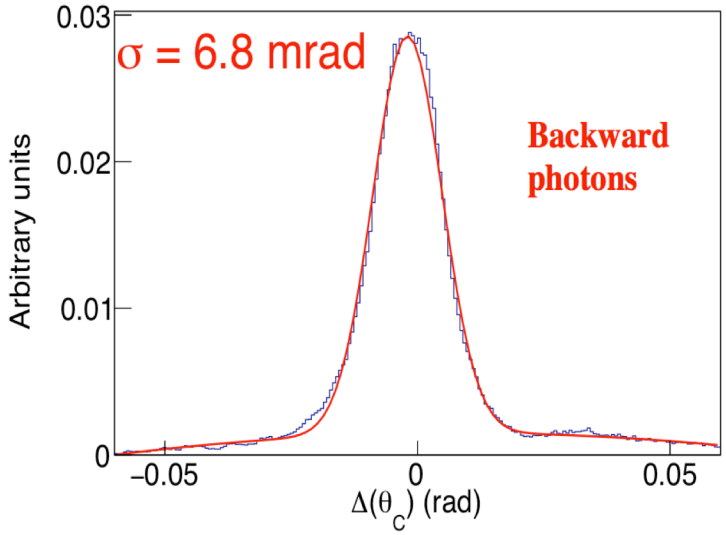
Old BaBar wedge has 6 mrads angle

MC simulation:



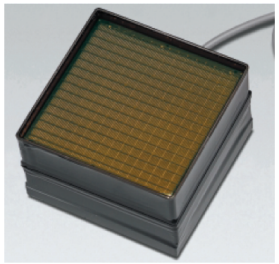


10 GeV muons:



- Smaller FBLOCK: $\sigma_{\theta c}$ **~ 6.8 mrads.**
- BaBar bar box without any changes.

H-9500 MaPMT
3mm x 12 mm

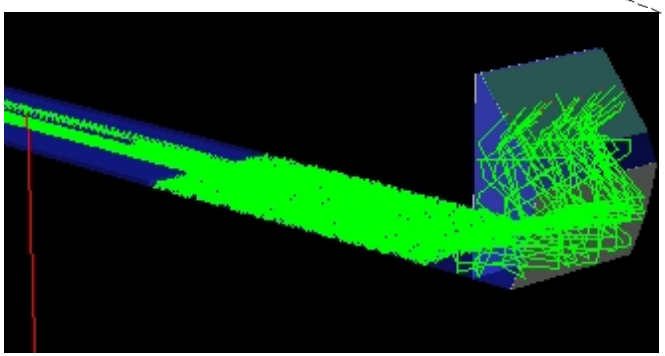


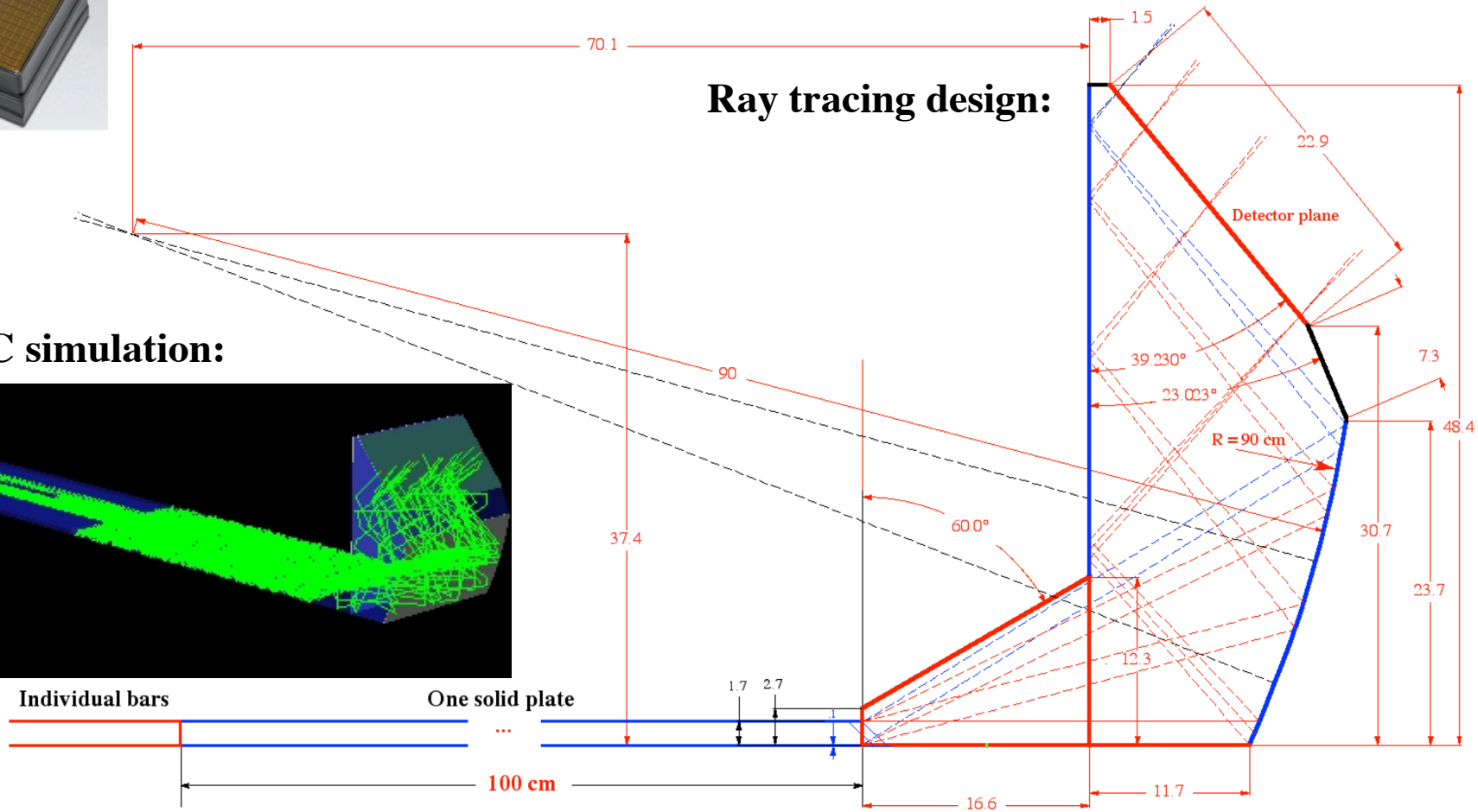
#3: New smaller FDIRC with a plate

B. Dey, B.N. Ratcliffc, J. Va'vra , NIMA 775(2015)112.NIM A 876 (2017) 141

Ray tracing design:

MC simulation:



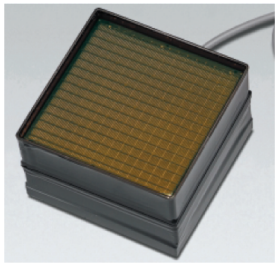


- **This solution improves the pinhole optics in the x-direction**.
- Babar bar box is modified: the last group of bars is replaced by a 1m-long wide plate.
- Remove BaBar DIRC wedge and add a new wedge.

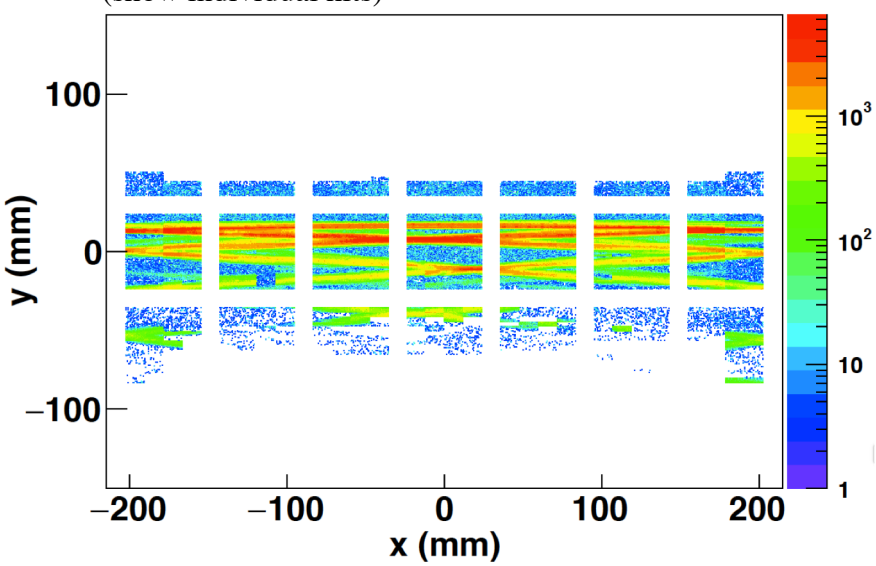
#3: New smaller FDIRC with a plate

B. Dey, B.N. Ratcliffc, J. Va'vra , NIMA 775(2015)112.NIM A 876 (2017) 141

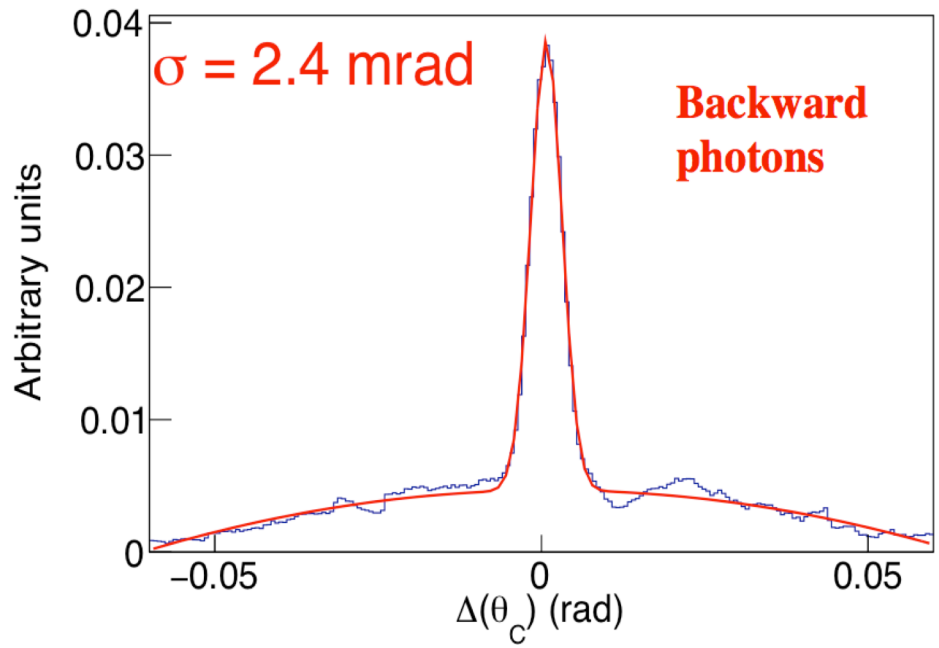
H-9500 MaPMT
3mm x 12 mm



Cherenkov ring x-y image in FDIRC:
(show individual hits)



10 GeV muons:



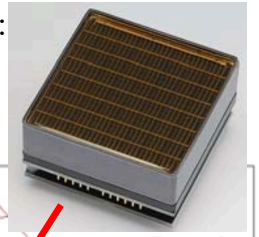
- This design provides the best θ_c resolution: $\sigma_{\theta c} \sim$ **2.4 mrads.**
- We have not tried the time-based analysis, so, one could do even better.
- **I think this is the best FDIRC design.**

GLUEX design

- The design is based on the SLAC FDIRC prototype for SuperB.

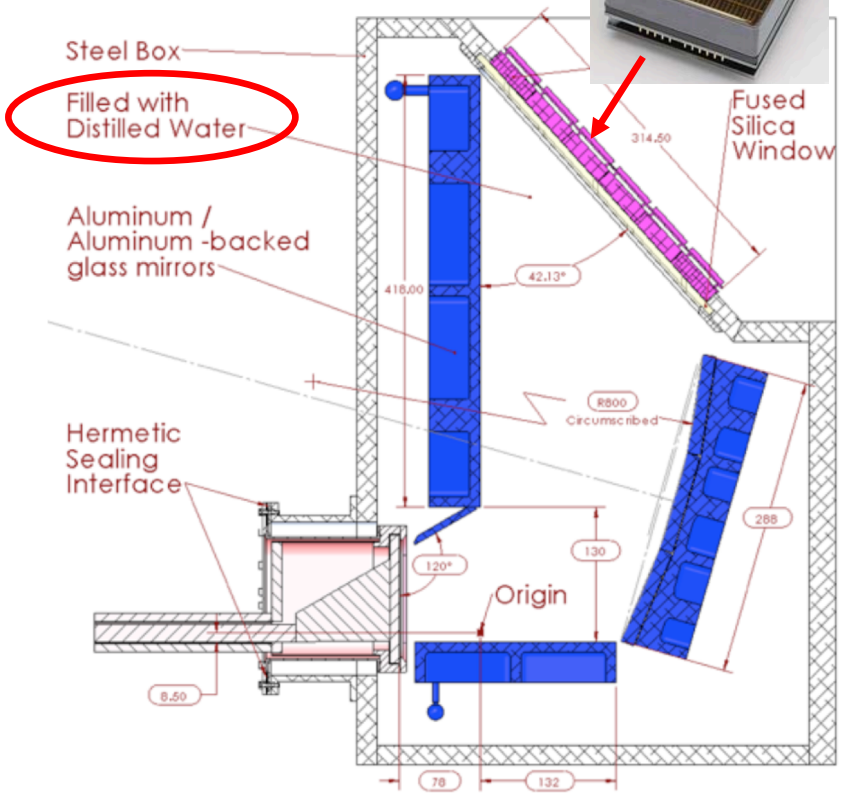
GLUEX FDIRC at JLAB

H12700 MaPMT:
(6mm x 6 mm)

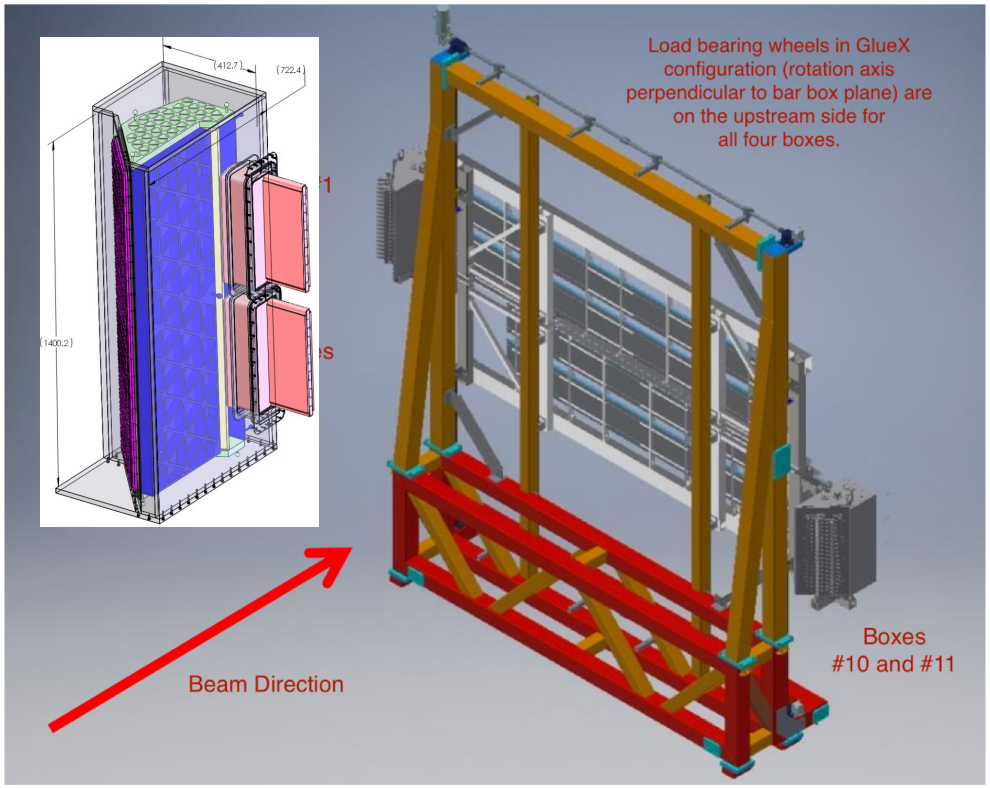


GLUEX TDR, Sept. 30, 2015

Photon camera:



Setup in the collider hall with 4 bar boxes:



- **Very similar geometry to SLAC FDIRC prototype for SuperB.**
- **Because there is no magnetic field, they can use Hamamatsu H12700 MaPMTs, 6mm x 6mm pixels, goal is to get ~1ns timing resolution.**
- **Goal is to do π/K separation up to 4 GeV/c.**

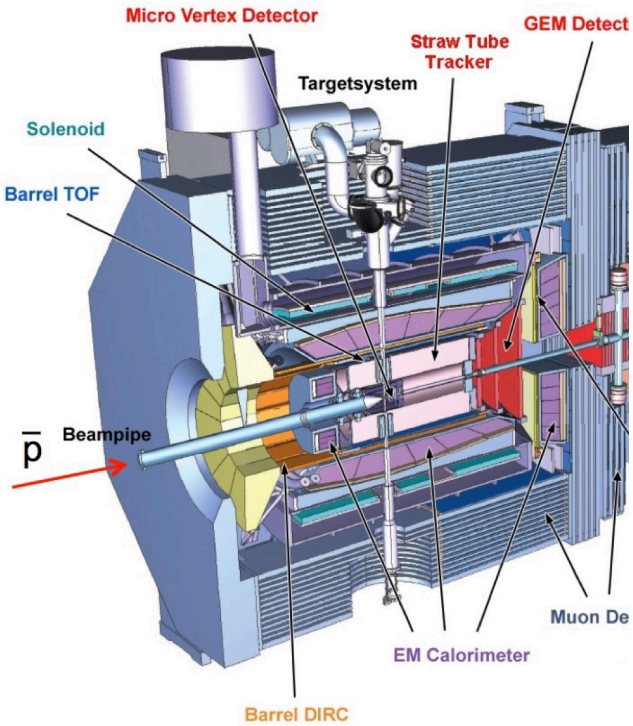
Panda design

- Still Focusing DIRC, but focusing is different.
- Detectors operate at 1 Tesla.

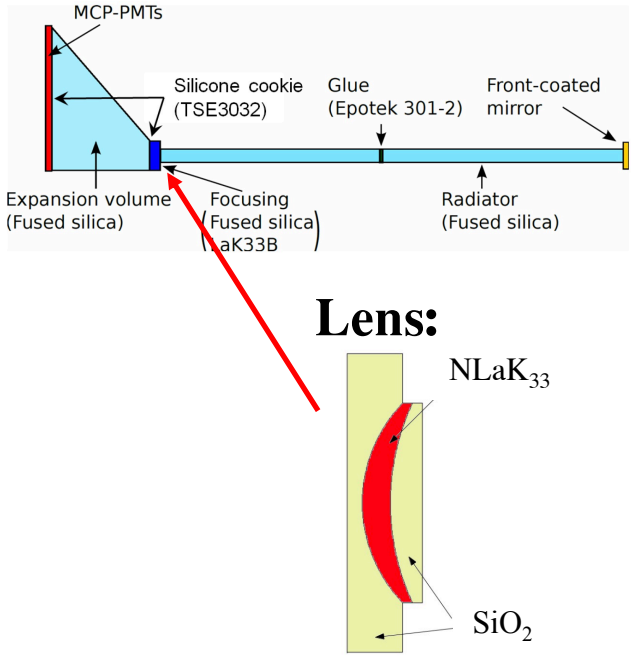
Panda Barrel Focusing DIRC detector

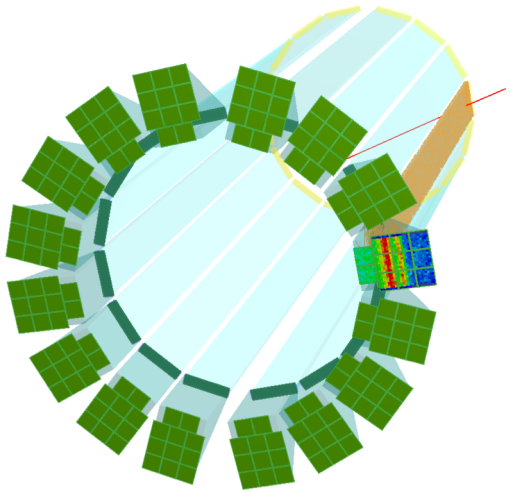
Panda TDR, April 12, 2017, and ArXiv1803.10642, 2017

Panda experiment:



Panda barrel Focusing DIRC:



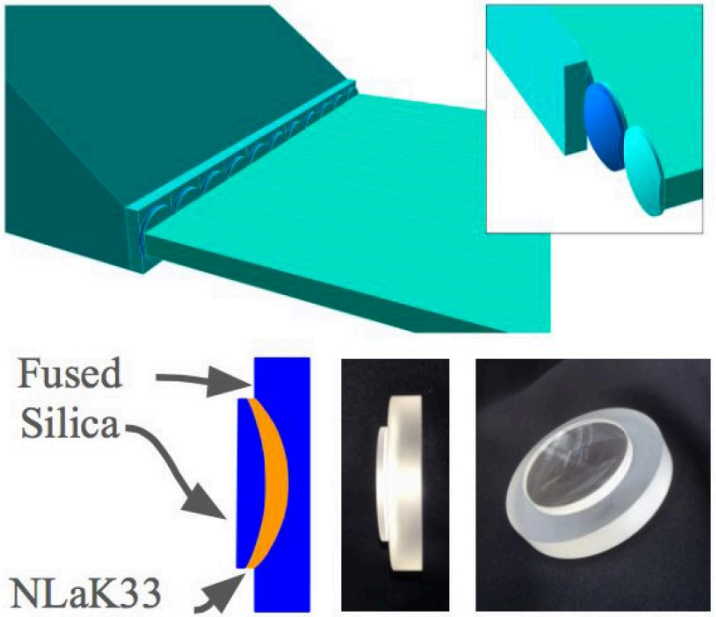


- Spherical triplet lens made from one layer of lanthanum crown glass ($NLaK_{33}$ with refractive index n=1.786 at ~380 nm) between two layers of synthetic fused silica (n=1.473 at ~380 nm). Other types of glass materials studied.
- **Panda wants to use the Photonis MCP-PMTs (6 mm x 6 mm pixels) and operate in 1T field; time-over-threshold timing delivers σ ~100ps resolution.**

Panda Barrel Focusing DIRC has two choices

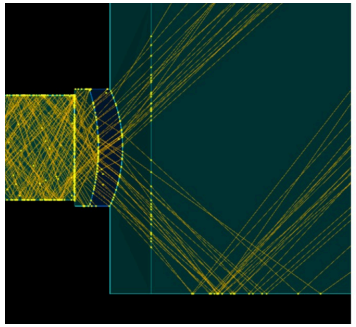
Panda TDR, April 12, 2017, and ArXiv1803.10642, 2017

a) Narrow bar option:

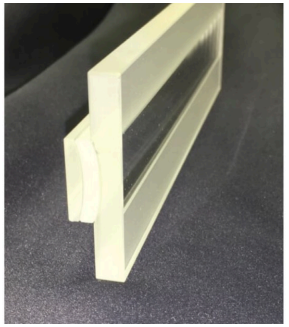


b) Wide bar option:

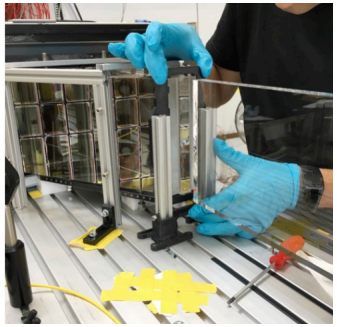
Some photons are lost:



Long cylindrical lens:



Wide bar:

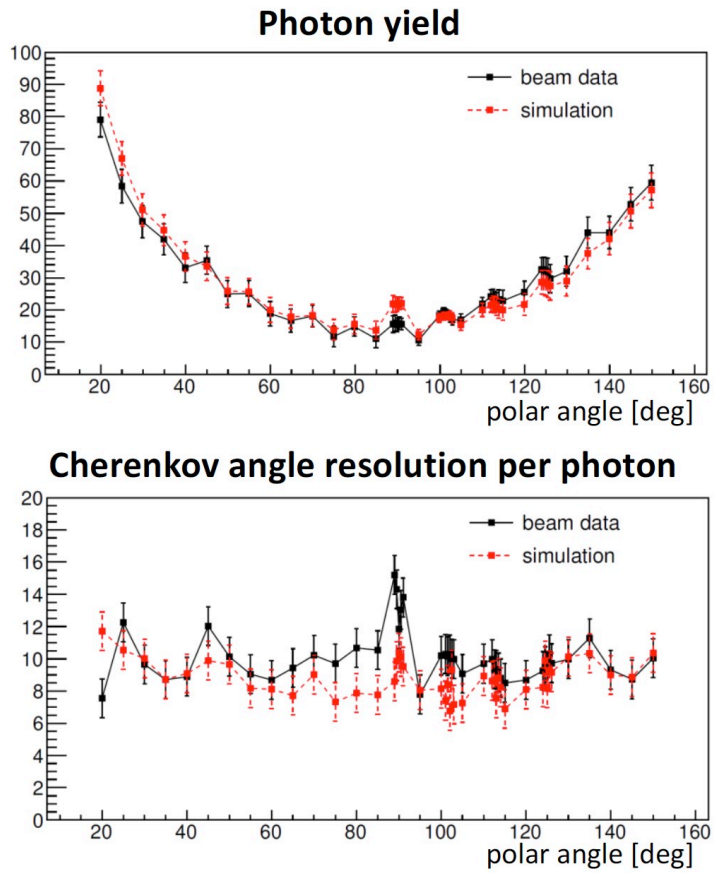


- **Narrow bar option is more resistant to background.**
- **Wide bar option is cheaper, but requires to rely more on the time-based analysis, precise calibration and more strict control of bar dimensions. It becomes more like the Belle-II TOP counter.**

Panda Barrel DIRC detector beam test with narrow bars

Panda TDR, April 12, 2017, and ArXiv1803.10642, 2017

Test beam results:
(no magnetic field)



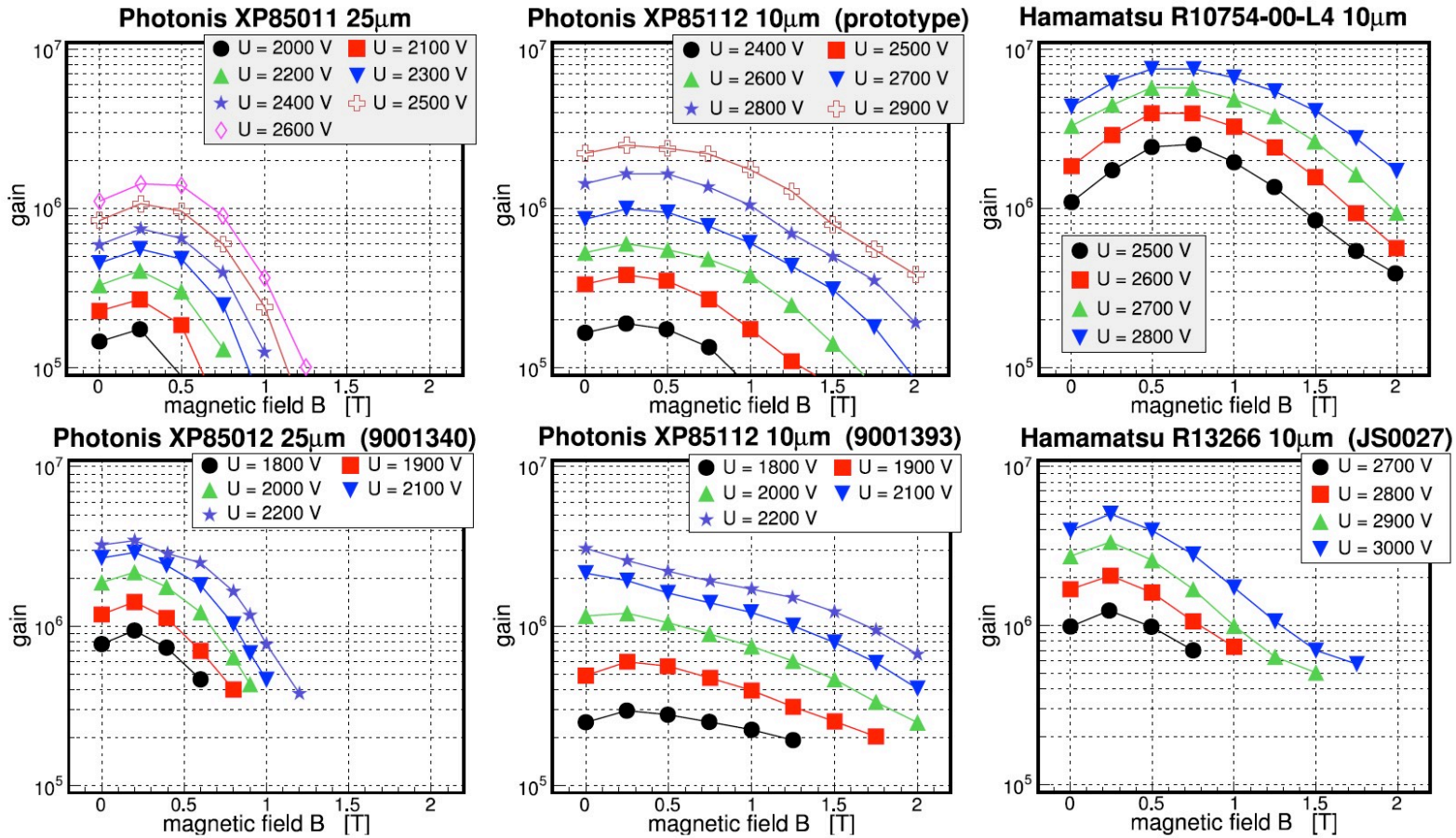
- **The single photon Cherenkov angle resolution is comparable to that of BaBar DIRC, i.e., worse than what one can get from the best FDIRC designs.**
- **Number of photons is somewhat smaller than what the BaBar DIRC obtained.**
- **Goal is to do π/K separation up to ~3.5 GeV/c, comparable to BaBar DIRC.**

Magnetic field sensitivity

A. Lehmann, talk at RICH 2016, Bled, Slovenia, and Panda TDR, 2017

Non-ALD

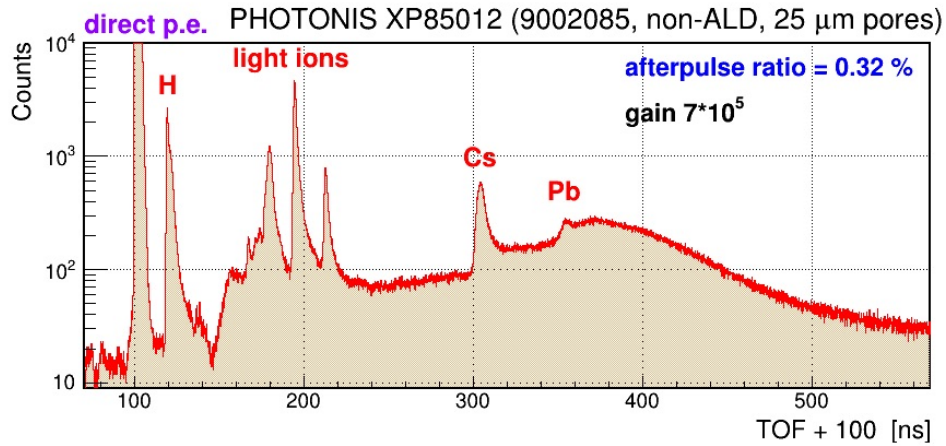
ALD

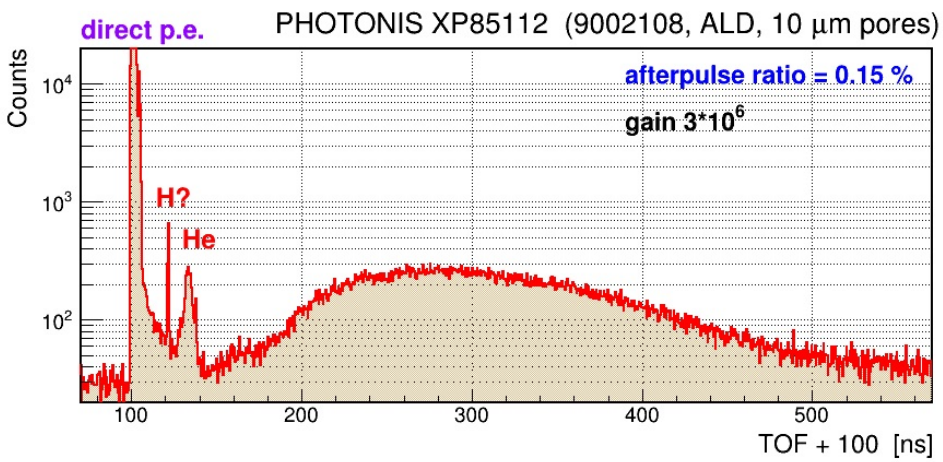


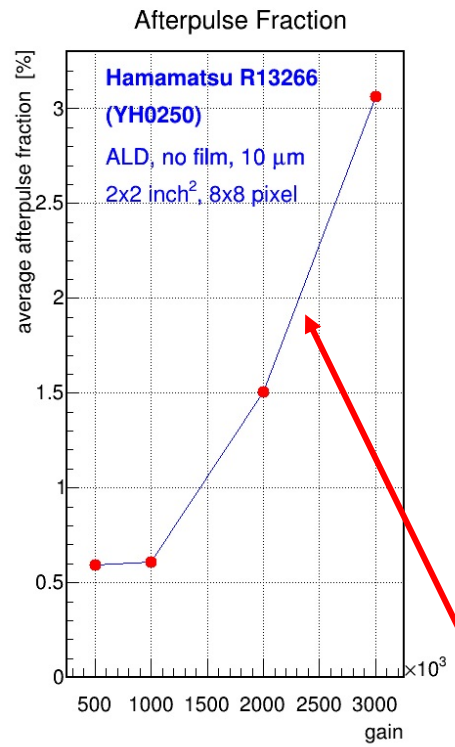
- **The gain for a tube with 25 μm pores collapses almost completely at around 1 Tesla, and a 10 μm tube is just sufficient for 2 Tesla.**
- **ALD coating does affect this response, probably due to saturation effects.**

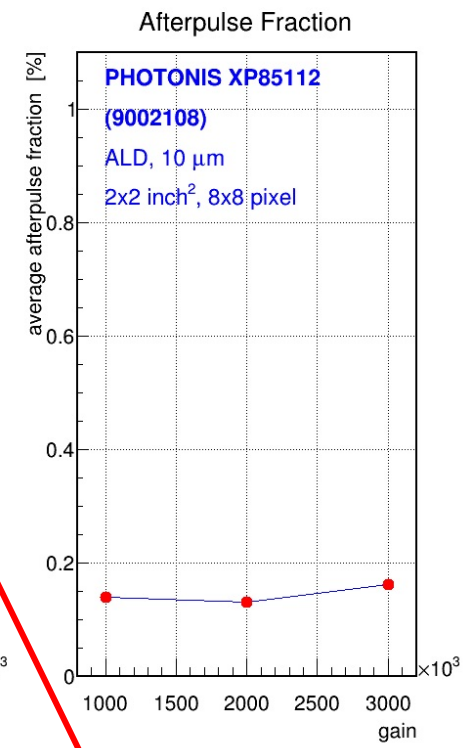
Ion feedback in new MCP-PMTs with ALD coating

A. Lehmann, private communication, April 22, 2018





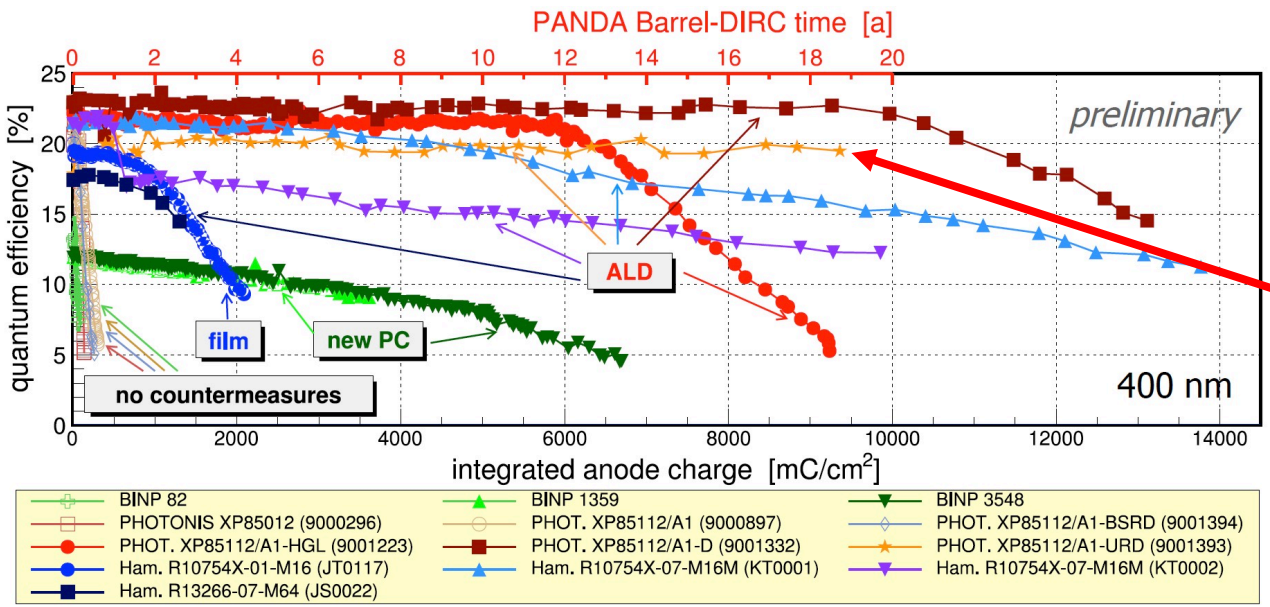


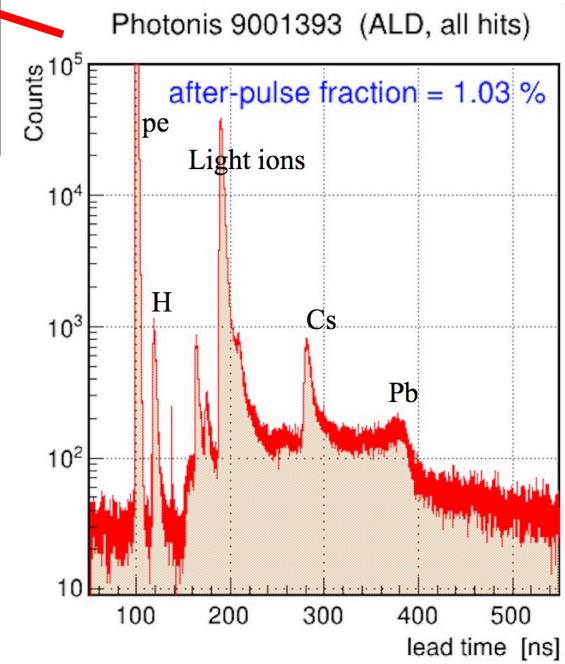


- **A. Lehmann conclusion: Photonis XP85112 MCP-PMT with 10µm performs well all the way up to large gains. Hamamatsu tube has similar problems as the old Burle tube.**
- **Next step for them: Repeat this in magnetic field at planned operating point.**

MCP-PMTs aging with ALD coating

A. Lehmann, talk at RICH 2016, Bled, Slovenia, and private communication





- Hamamatsu film MCP-PMT: Q.E. drops beyond 1 C/cm^2
- Photonis 9001393: no Q.E degrading observed up to ~10 C/cm^2

- **The ion feedback on the tube, which has succesfully completed ~10 C/cm^2 aging run, is ~1%. They did not measure this effect before aging test.**

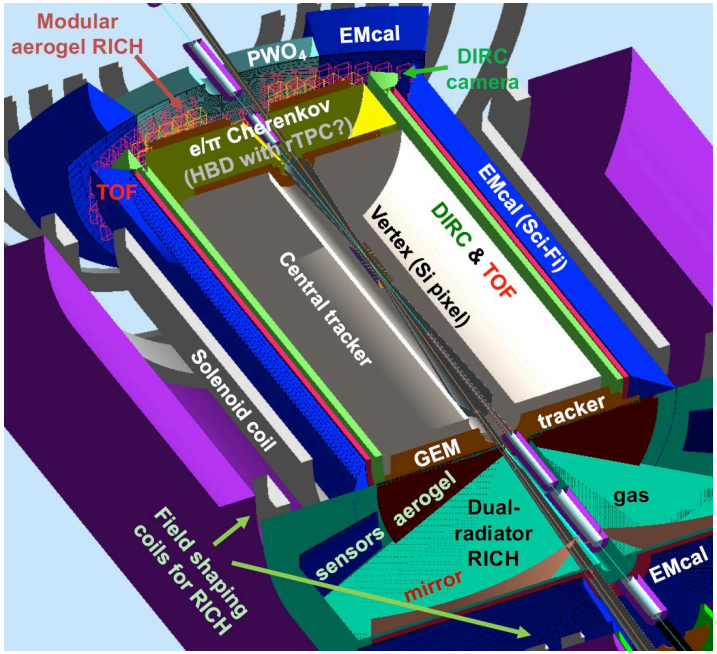
EIC design

- At present, the design follows the Panda design closely.
- Detectors operate at 1 or 2 Tesla.

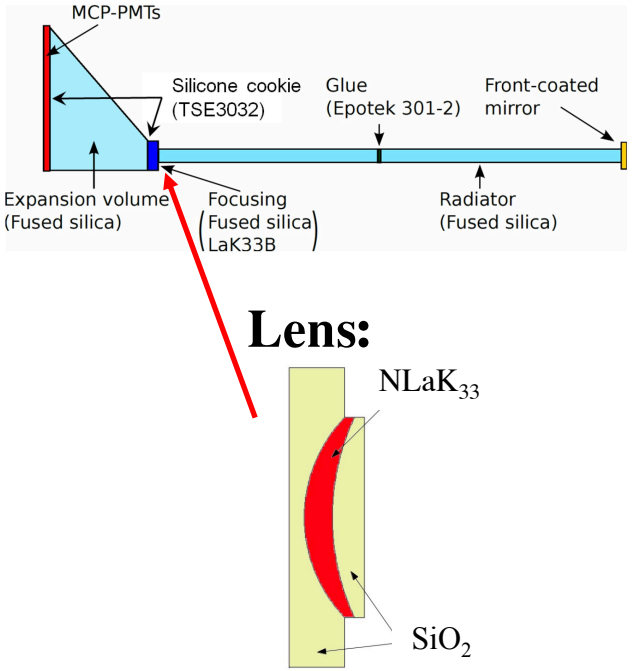
EIC Barrel Focusing DIRC detector R&D

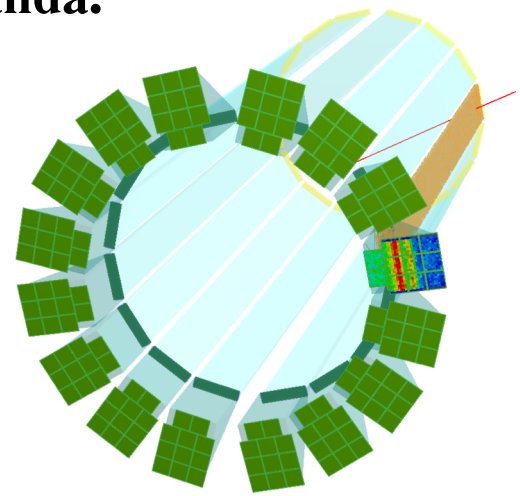
Panda TDR, April 12, 2017, and ArXiv1803.10642, 2017

JLAB EIC detector concept:



Focusing DIRC a'la Panda:



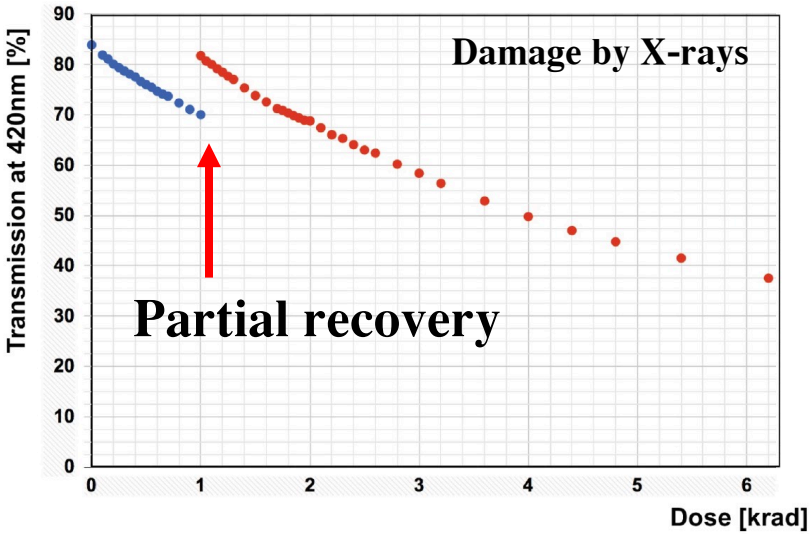


- So far, EIC group follows closely the Panda DIRC design, assuming that the photon camera operates at~1-2 T field. This requires a development of MCP-PMT detectors, and a radiation hard new optics.

EIC Barrel Focusing DIRC detector R&D

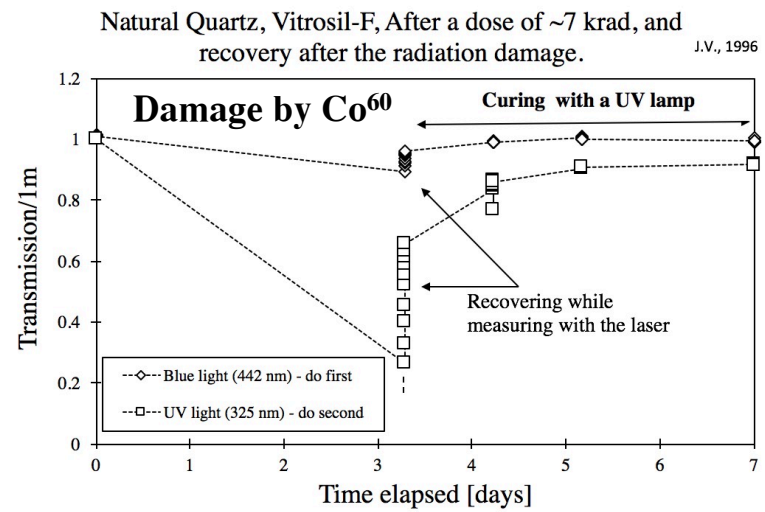
EIC review, Jan. 2018

Radiation damage of the lens:

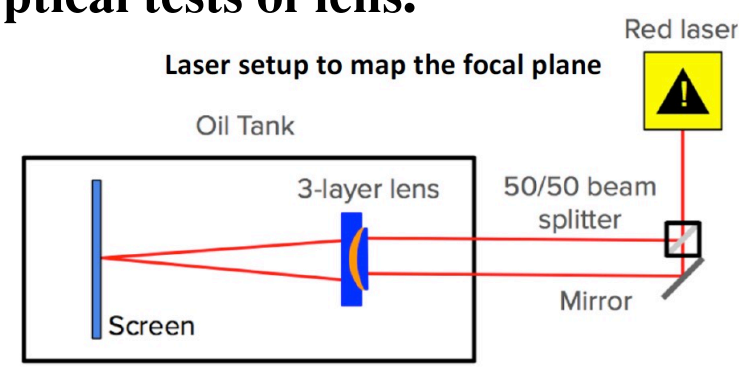


BaBar DIRC – observed a similar effect:

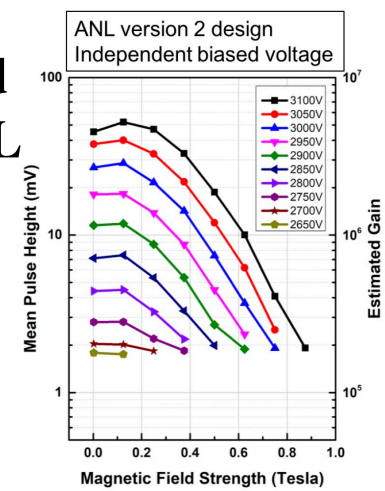
(This type of quartz was rejected)



Optical tests of lens:



Magnetic field studies of ANL MCP-PMTs:



- Radiation hard lens material, and MCP magnetic field studies are under way.

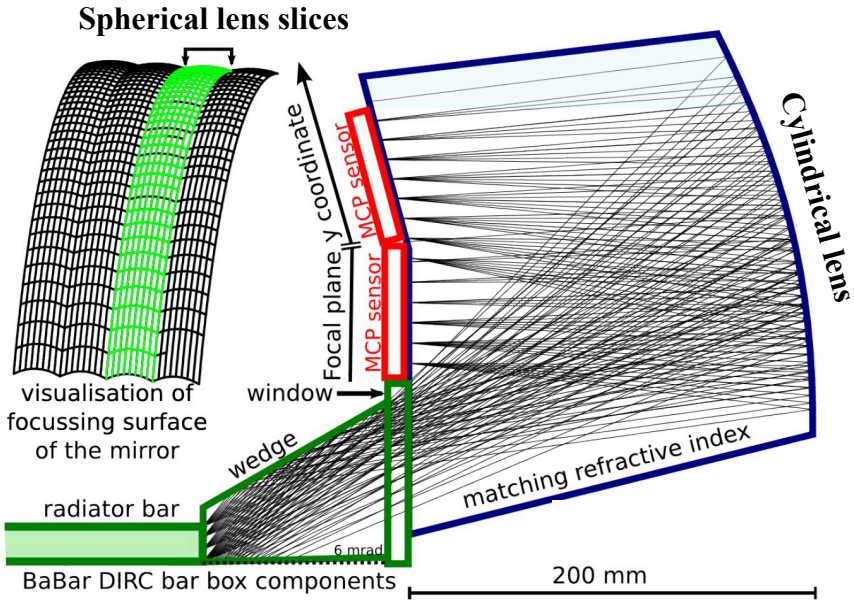
TORCH for LHCb

- No magnetic field.

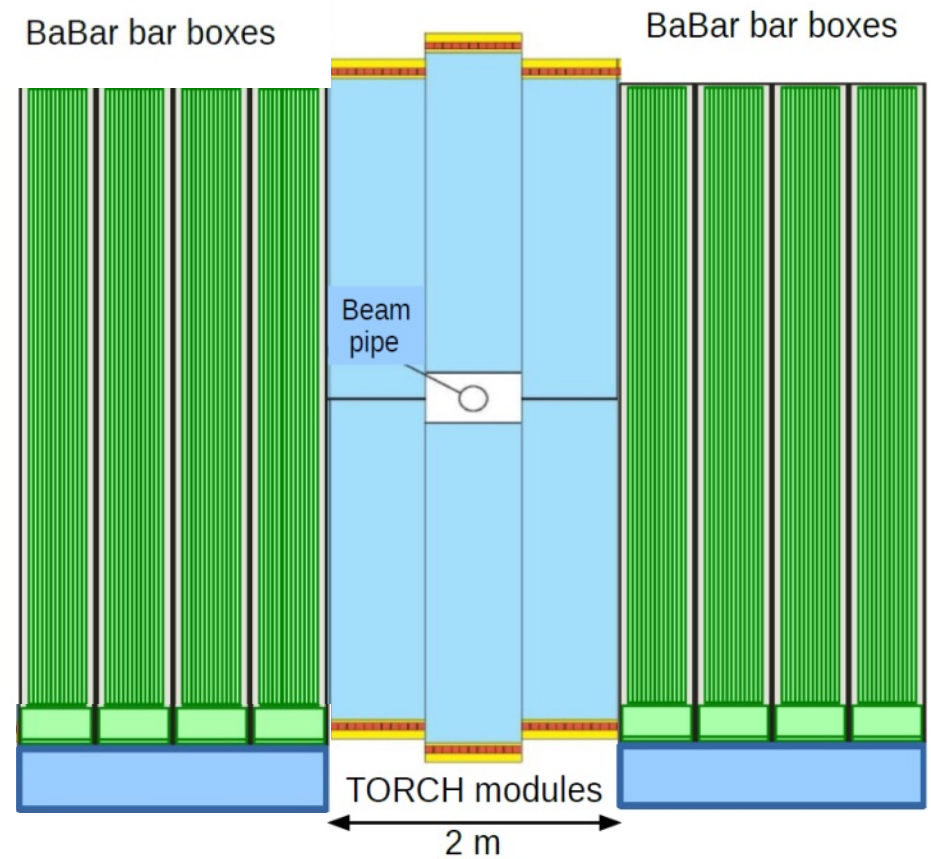
TORCH design for LHCb

Private communication with Neville Harnew, and Klaus Fohl et al., IEEE, N41-7, 2014

Photon camera example:



Arrangement in LHCb experiment:



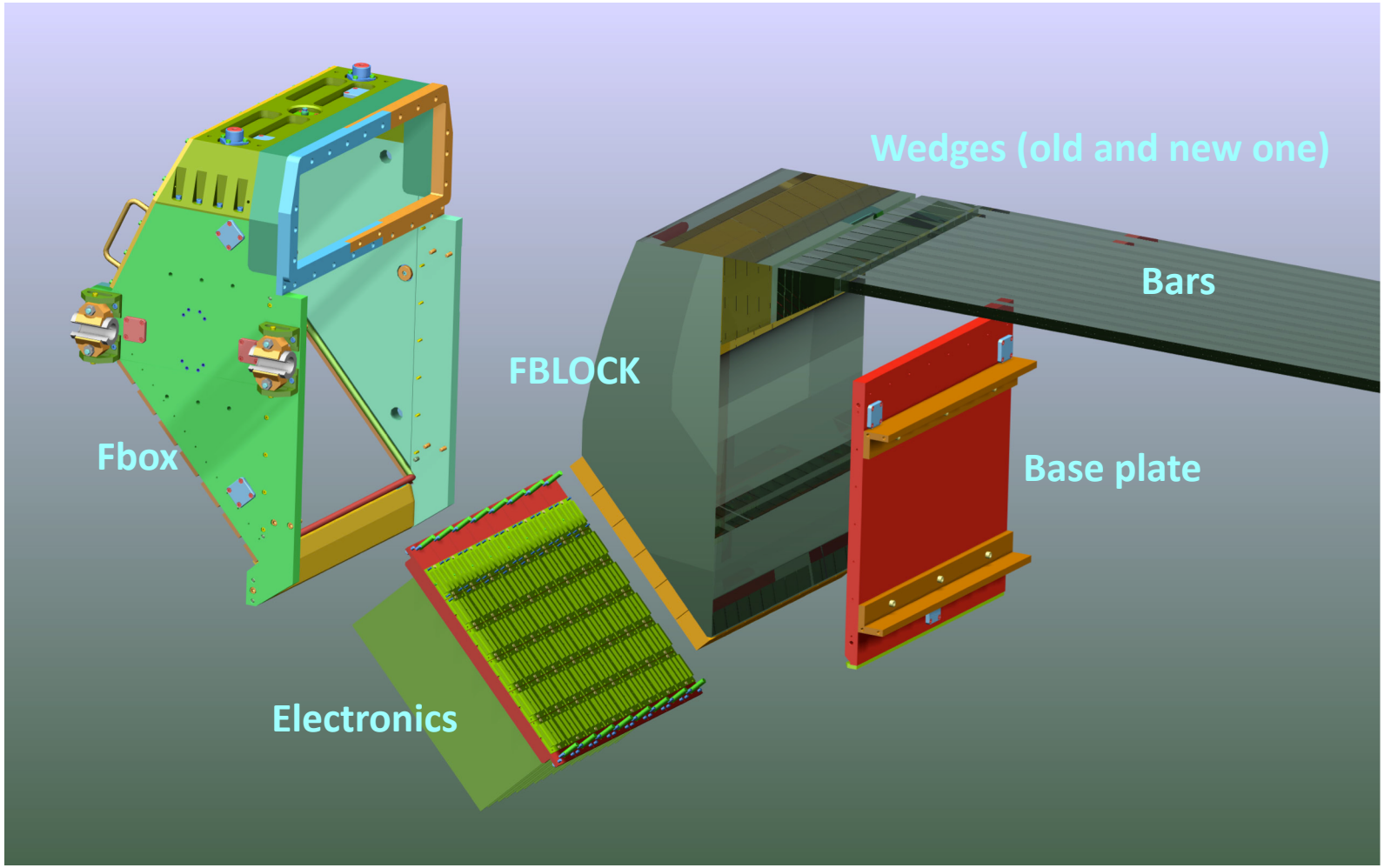
- **Detector area 30m^2, L_{path} ~ 9.5 m, σ_{TOF} ~10-15 ps, σ_{TTS} ~50 ps, and ~3σ π/K @ 10 GeV/c.**
- Detectors: Photek or Photonis MCP-PMTs.
- **My comment: To eliminate time chromatic broadening, you have to measure θ_c well.**

Conclusion

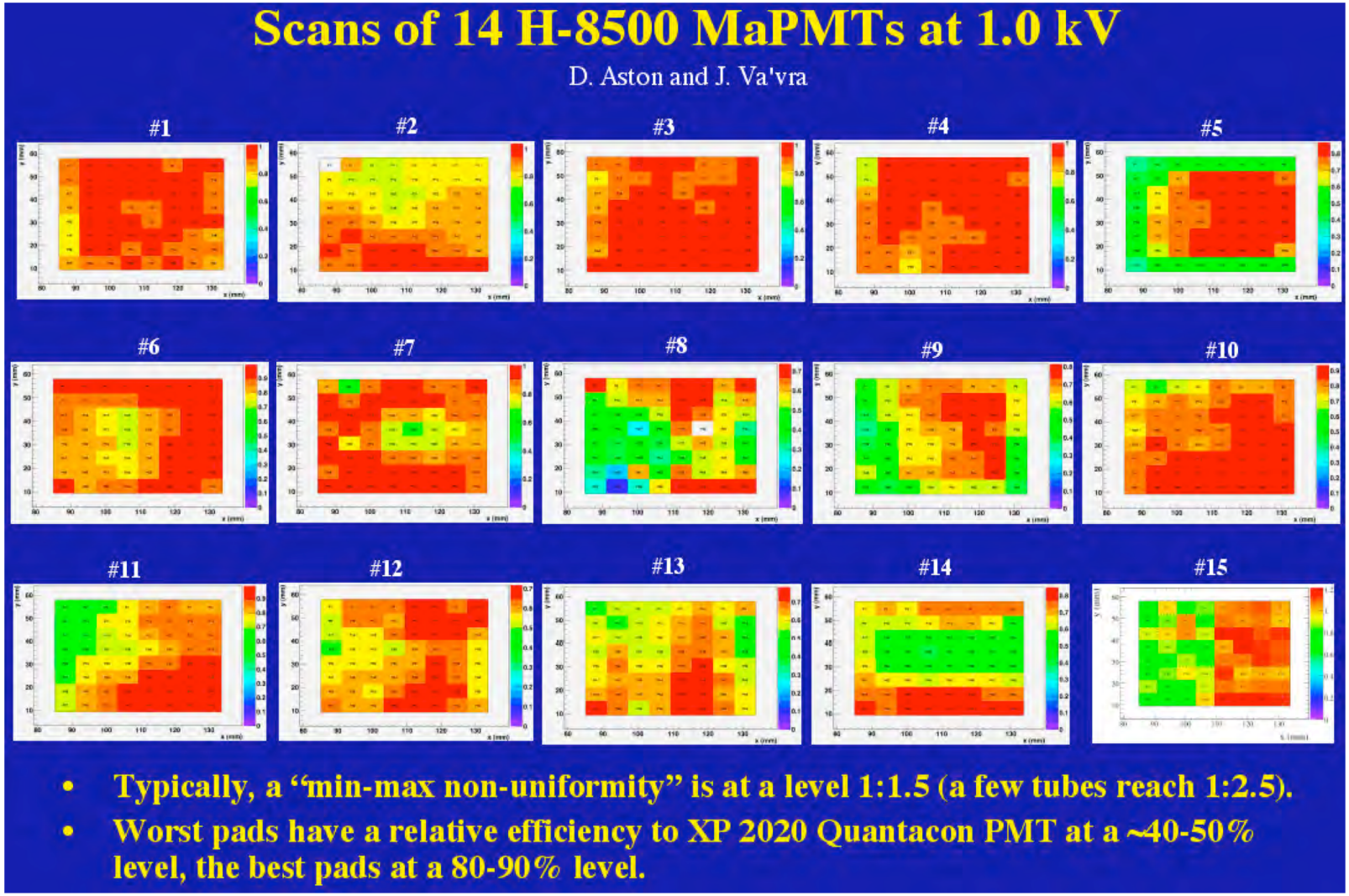
- **FDIRC, solution with no magnetic field, is now a mature technology.**
- **For example, FDIRC with H-9500 MaPMTs, with 3 mm x 12 mm pixels, and ~250ps timing resolution, would create an <u>excellent RICH detector</u>.**
- **GLUEX FDIRC solution at JLAB should work very well.**
- **Panda and EIC Focusing DIRCs require MCP-PMTs to work at 1-2T field, which in turn requires MCPs with 10μm holes. This solution still needs some R&D effort to solve several remaining issues.**
- **Time-based TOP counter is now installed, Belle-II is starting to take data, and we are interested to see results. TORCH is still in R&D phase.**
- **MCP-PMT detectors have improved tremendeously in the past 10 years, but I would still worry about some details.**
- **I consider "pixel-based" designs safer/better than "time-based" designs.**

Appendix

How it goes together ?



Uniformity of H-8500 MaPMTs in FDIRC



- **These tubes were not very uniform. But it was measured and used in MC.**

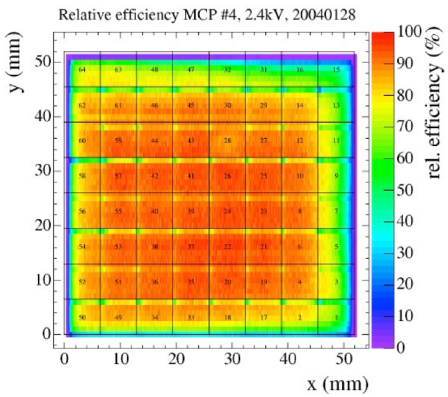
Burle MCP-PMTs: blue vs. red laser response

3. MCP #4 (S/N 09130305)

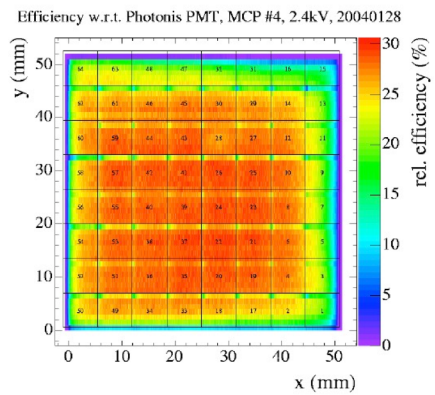
a) Red PiLas Laser (635nm)

(quite uniform)

a) Normalize to best spot in the tube:



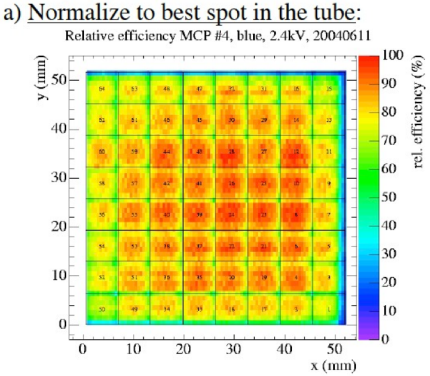
b) Normalize to Photonis PMT at 635nm:



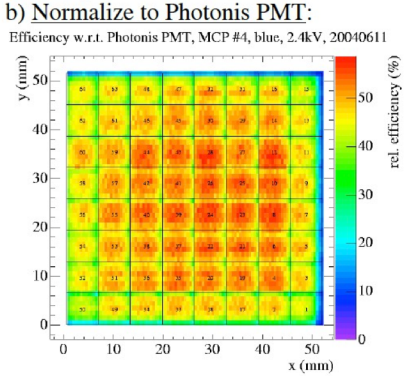
b) Blue PiLas Laser (430nm)

(quite uniform, ~50-60% of the Photonis PMT efficiency at 430nm)

a) Normalize to best spot in the tube:



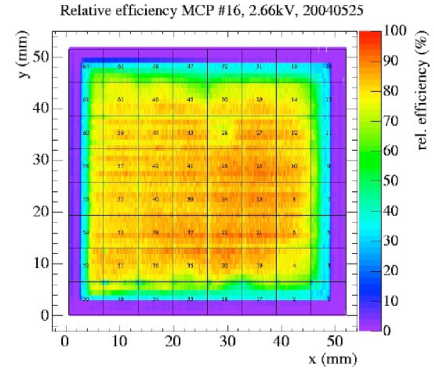
b) Normalize to Photonis PMT:



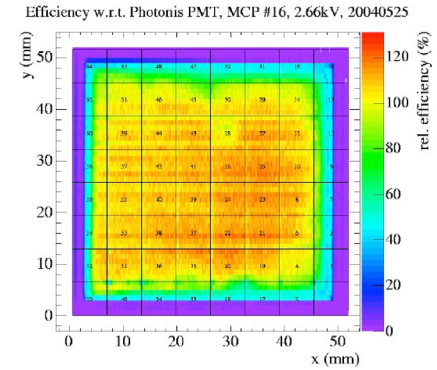
15.MCP #16 (S/N 02010410) – stepped face MCP (expect edge effects)

a) Red PiLas Laser (635nm) (relatively uniform, except the edge pads)

a) Normalize to best spot in the tube:



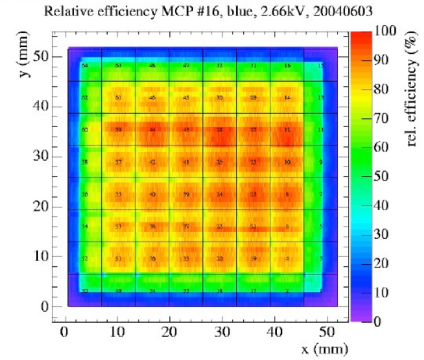
b) Normalize to Photonis PMT at 635nm:



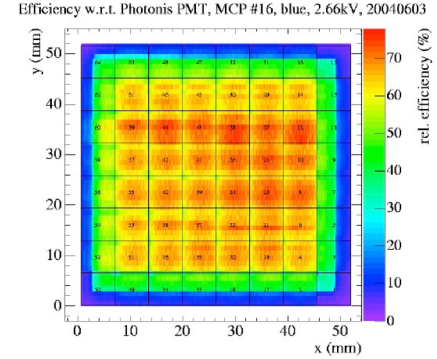
b) Blue PiLas Laser (430nm)

(relatively uniform, except the boundary pads, ~70% of the Photonis PMT efficiency at 430nm)

a) Normalize to best spot in the tube:



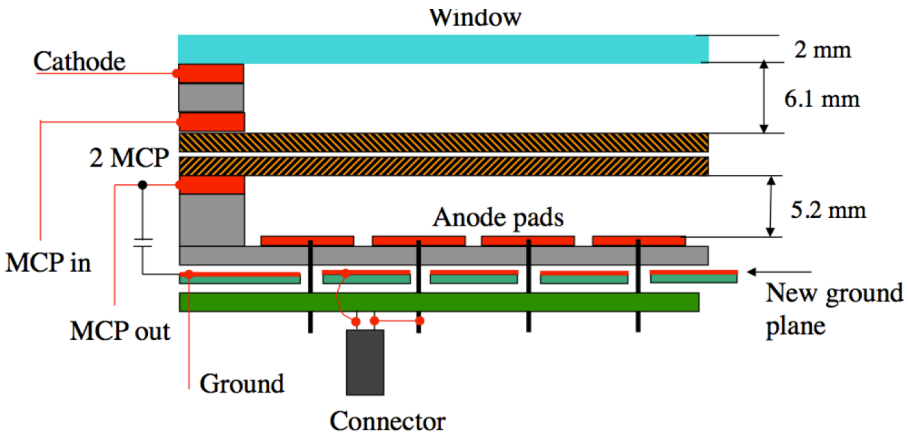
b) Normalize to Photonis PMT:



- **There seems to be some difference.**

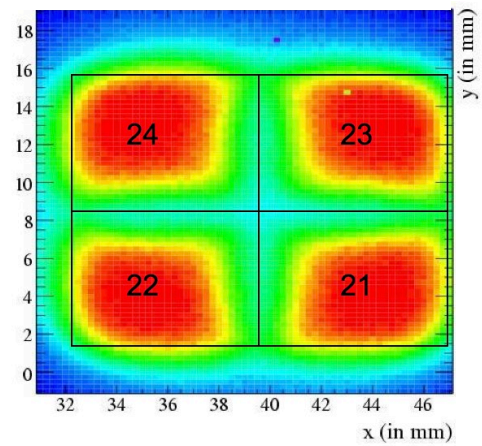
MCP-PMT pad charge sharing

Burle Planacon MCP-PMT 85011:

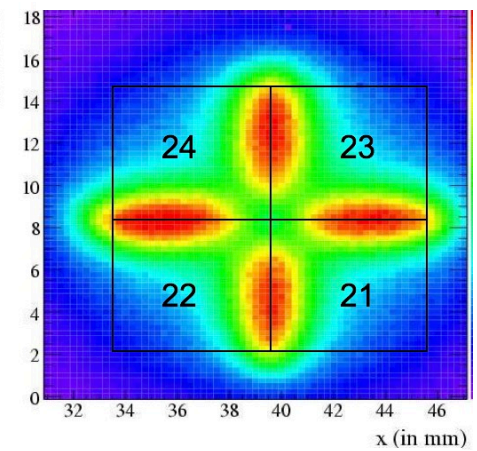


Analysis was done using ADCs:

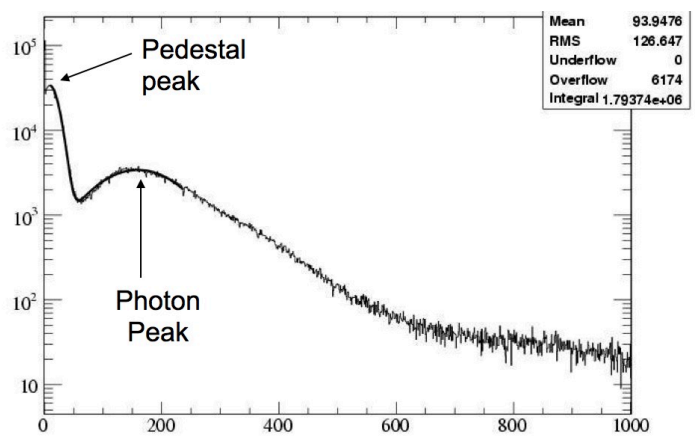
Single pad required:



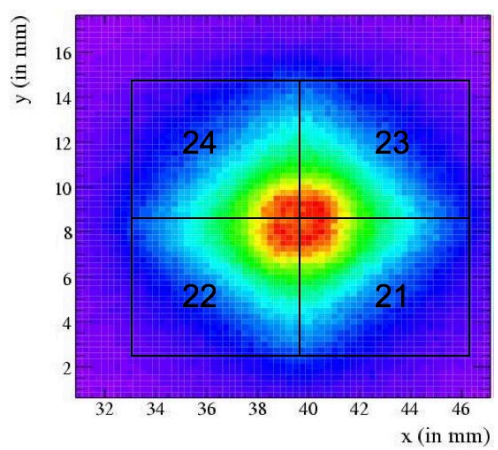
2 pads required:



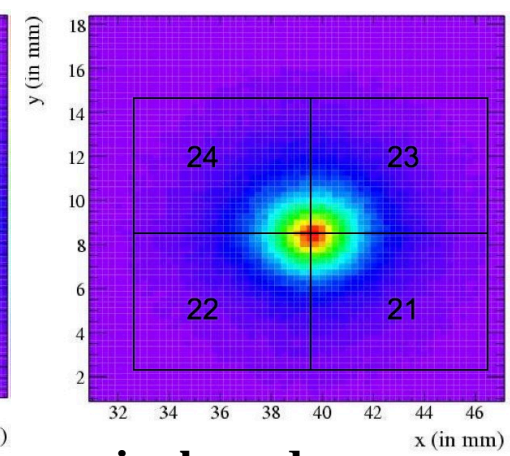
Single electron PH spectrum using 1 pad only:



3 out of 4 pads required:



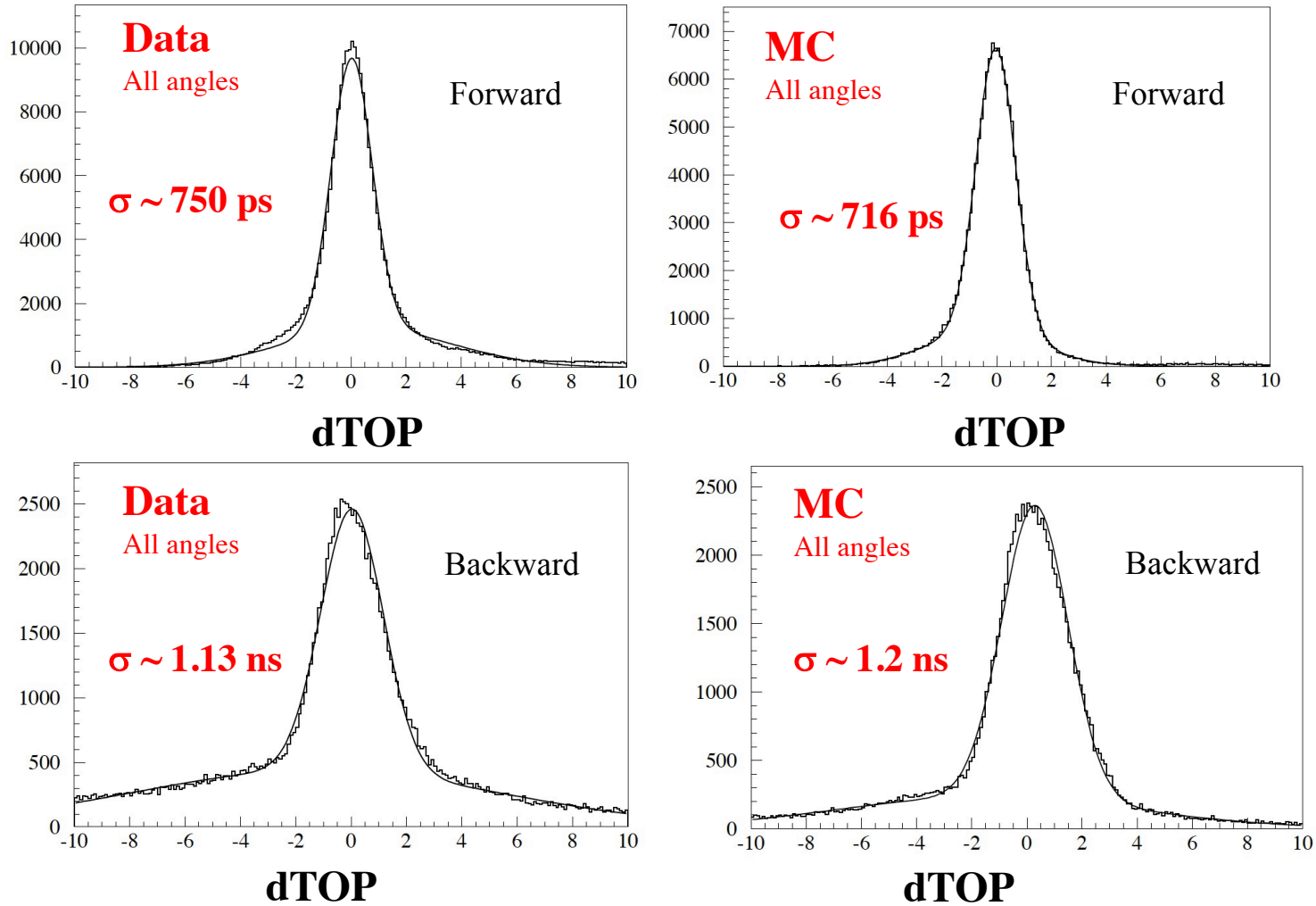
All 4 pads required:



- **One gets a good pulse height distribution only if one requires a single pad.**

dTOP: Data vs. MC simulation

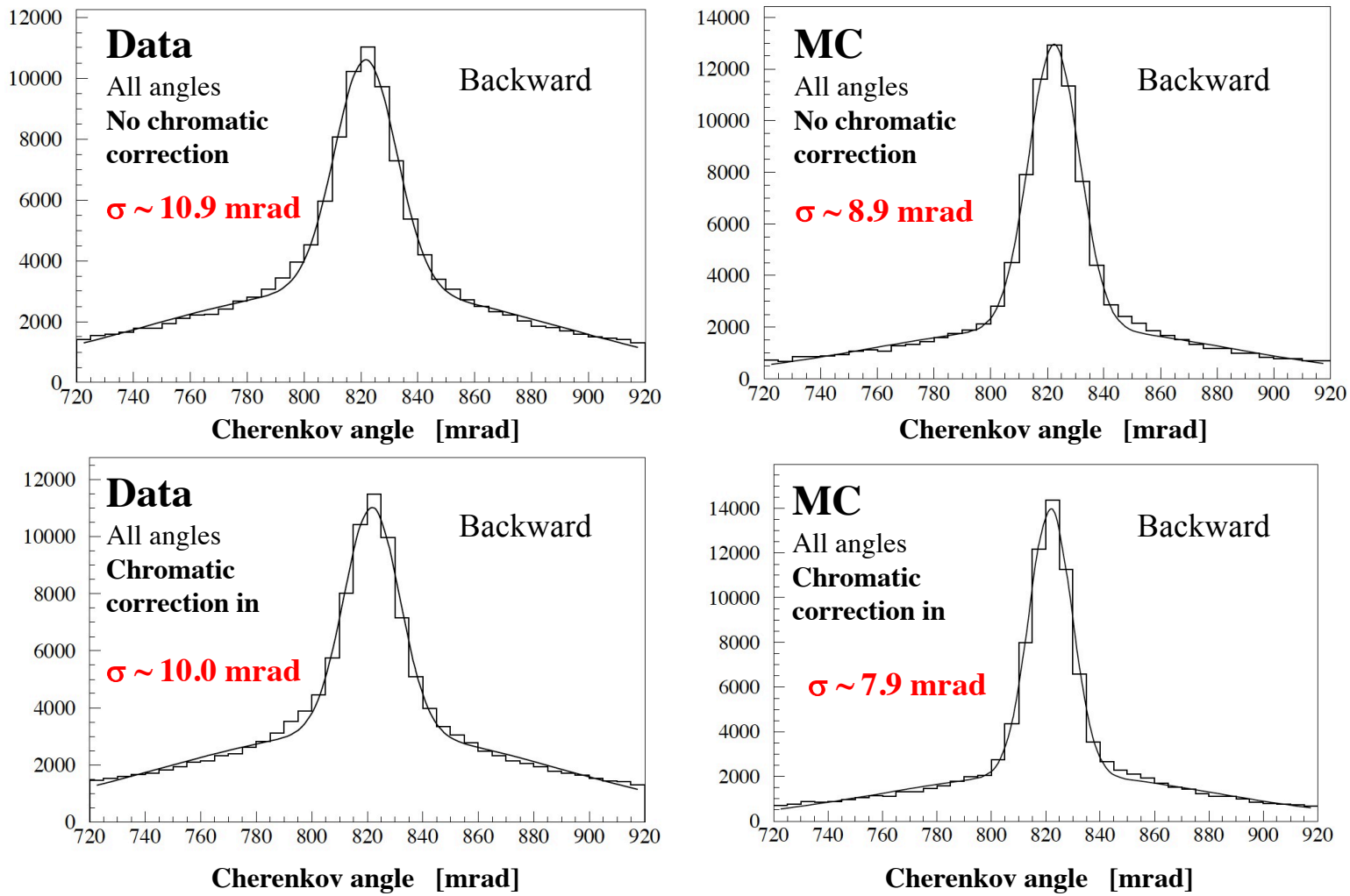
N. Arnaud, M. Borsato, B. Dey, D.W.G.S. Leith, K. Nishimura, B.N. Ratcliff, D. Roberts, G. Varner, J. Va'vra , NIMA 775(2015)112



- **MC generated dTOP is closer to data after adding a timing resolution of ~600ps. The IRS-2 electronics was an early version of the Belle-II electronics.**
- **MC does not have a tail and per-pulses for the H-8500 time response.**

Cherenkov angle resolution: chromatic correction

N. Arnaud, M. Borsato, B. Dey, D.W.G.S. Leith, K. Nishimura, B.N. Ratcliff, D. Roberts, G. Varner, J. Va'vra, NIMA 775(2015)112



- **We gain about ~0.8 mrads. MC resolution is slightly better.**
- **MC does not have a tail and per-pulses for the H-8500 time response.**