Focusing DIRC R&D

J. Va'vra, SLAC

Collaboration to develop the Focusing DIRC:

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Content

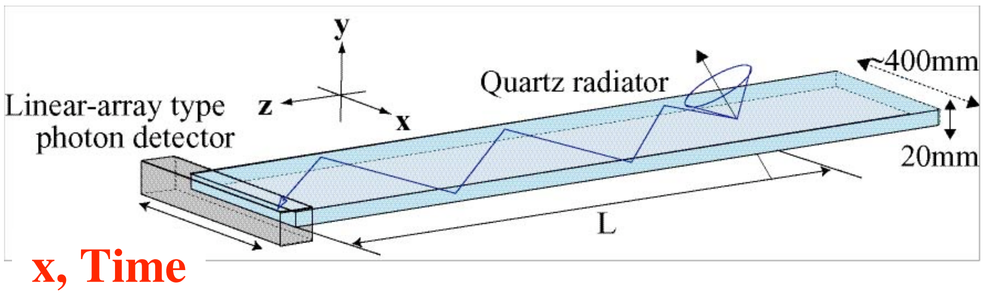
- Prototype design
- Test beam results
- Future steps

Improvements compared to BaBar DIRC

- Timing resolution improved from $\sigma \sim 1.7$ns -> $\sigma \leq 150$ps
- Time resolution at this level can help the Cherenkov angle determination for photon path lengths Lpath ≥ 2-3m
- Time can be used to correct the chromatic broadening
- Better timing improves the background rejection
- Smaller pixel sizes allow smaller detector design, which also reduces sensitivity to the background
- Mirror eliminates effect of the bar thickness

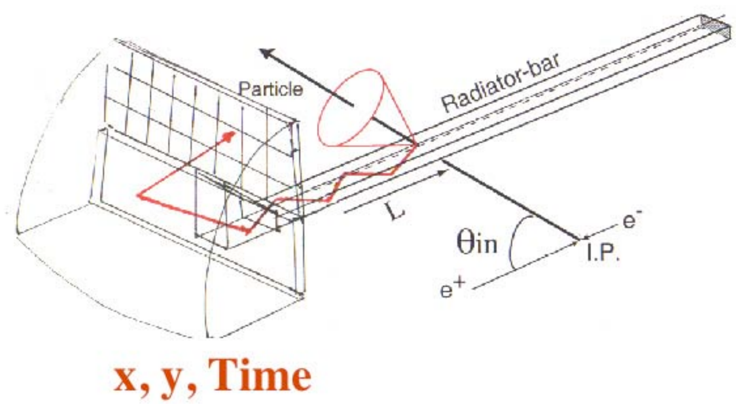
Examples of two "DIRC-like" detectors

TOP counter (Nagoya):



- **2D imaging:**
  a) x-coordinate
  b) TOP (σ ≤ 70ps).

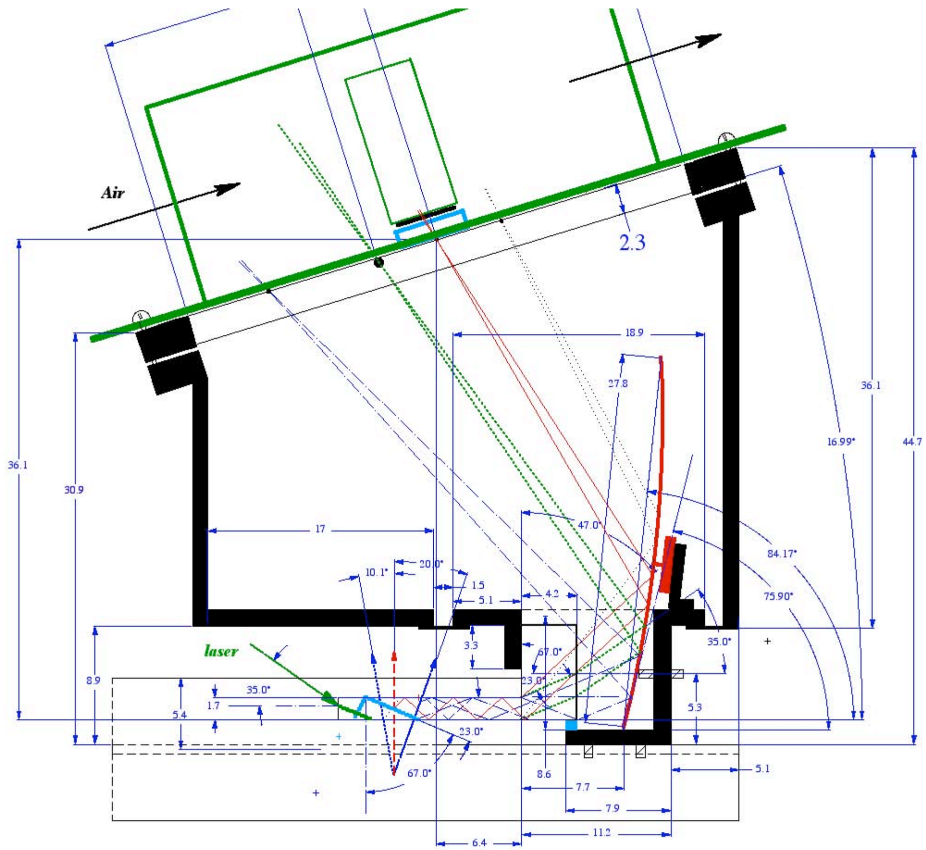
Focusing DIRC prototype (SLAC):



- **3D imaging:**
  a) x-coordinate
  b) y-coordinate
  c) TOP (σ ≤ 150ps).

Focusing DIRC prototype design

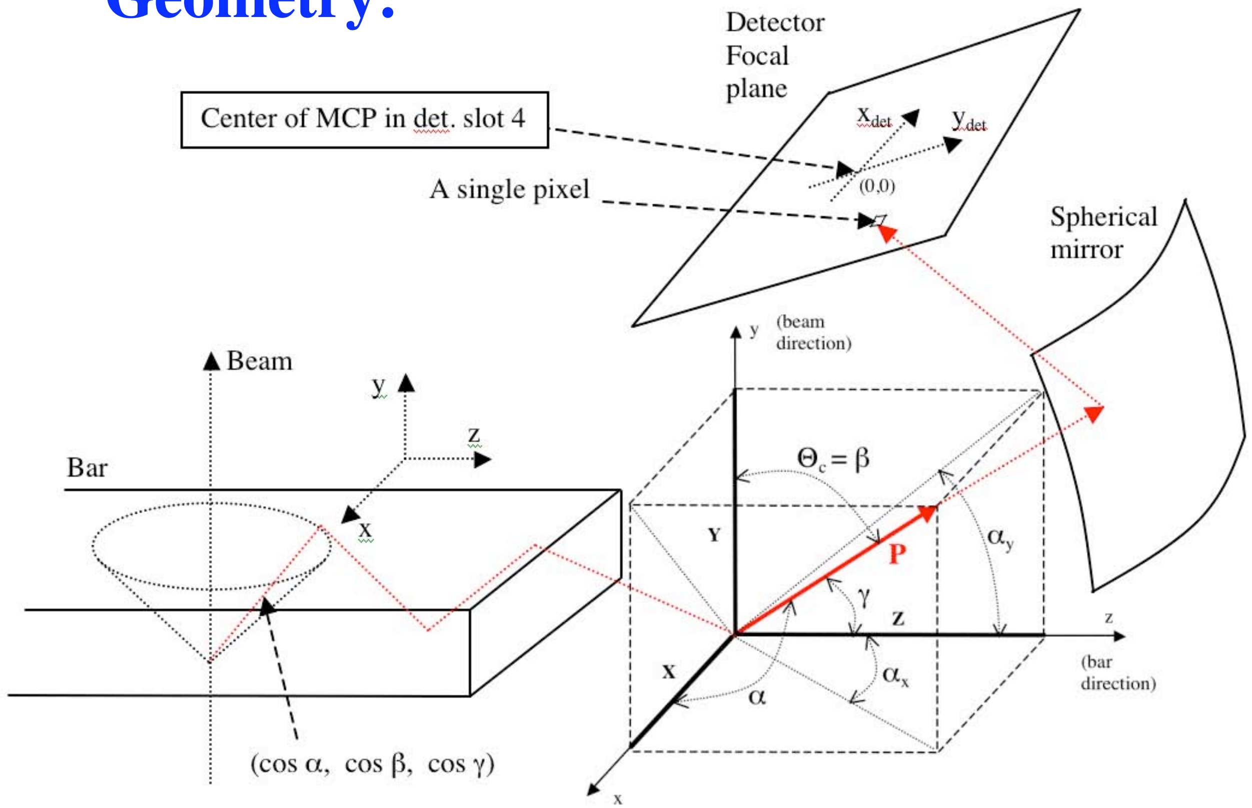
Design by ray tracing:

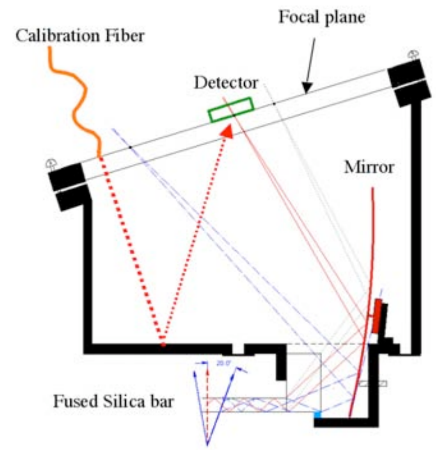


- The Focusing DIRC prototype optics was designed using the ray tracing method with a help of the mechanical design program (no Monte Carlo available in early stages !!).
- The focal plane adjusted to an angle convenient for easy work
- Space filled with oil.
- **Red line** (with oil) - running in the beam
- **Green line** (no oil) - laser check in the clean room
- Spherical mirror R= 49.1cm

Photon path reconstruction

Geometry:

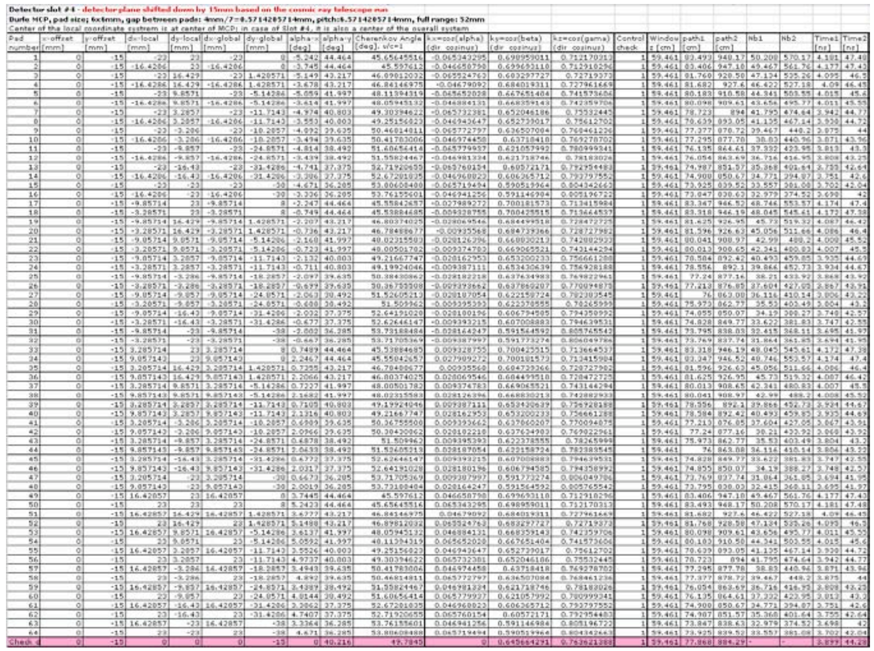




- **Each detector pixel determines these photon parameters:**
  θ_c, α_x, α_y, cos α, cos β, cos γ, L_{path}, $t_{propagation}$, $n_{bounces}$ – for aveerage λ

 ($t_{propagation}$= TOP)

Initial edsign with a spreadsheet calculation



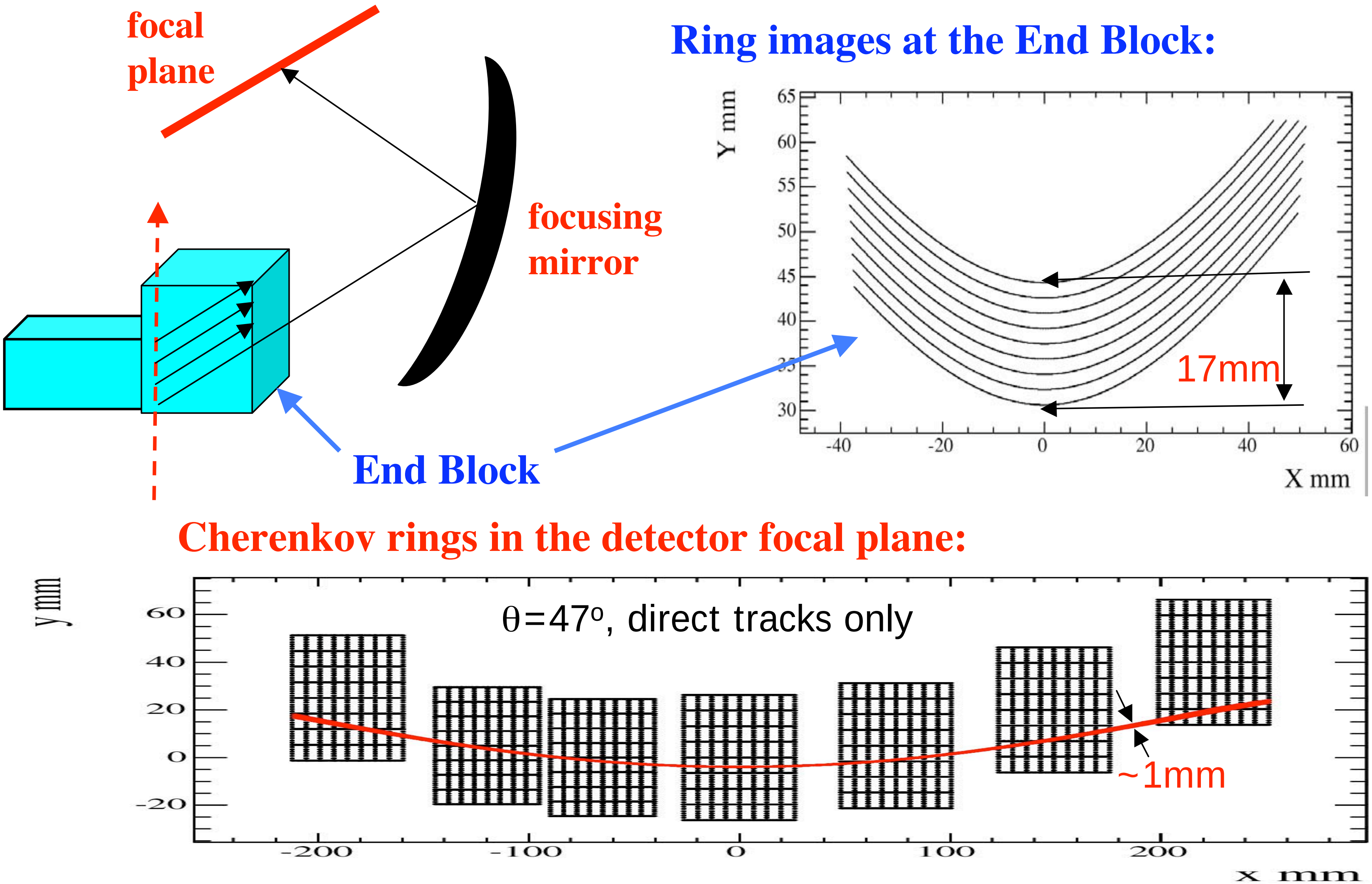
- **Each pad predicts the photon propagation history <u>for average λ of ~ 410nm</u>.**
- **<u>Example - detector slot #4, pad #26, beam in position #1</u>:**

  $\theta_c = 47.662^o$, $L_{path\ 1} = 80.447$ cm, $n_{bounces\ 1} = 43$, $t_{path\ 1} = 4.028$ ns, $L_{path\ 2} = 913.58$ cm, $n_{bounces\ 2} = 489$, $t_{path\ 2} = 45.75$ ns, dT(|Peak2 - Peak1|) = 41.722 ns
- **<u>Error in detector plane of 1mm in y-direction will cause this systematic shift:</u>**

  $\Delta\theta_c$ ~3mrad, $\Delta L_{path\ 1}$ ~2.2mm, $\Delta t_{path\ 1}$ ~11ps, $\Delta L_{path\ 2}$ ~24.5mm, $\Delta t_{path\ 2}$ ~123ps, ΔT (|Peak2-Peak1|) ~112ps

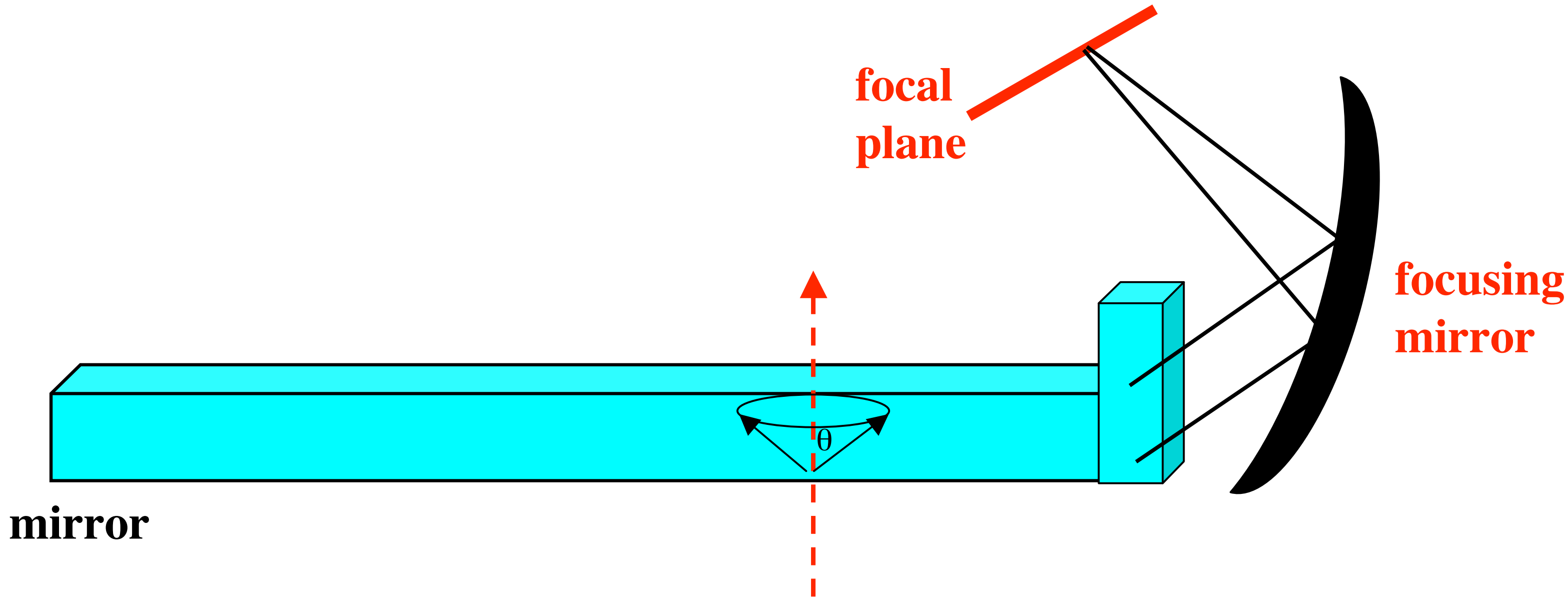
Rings from outside bar are well focused

(Jose Benitez independent check of the focusing design)

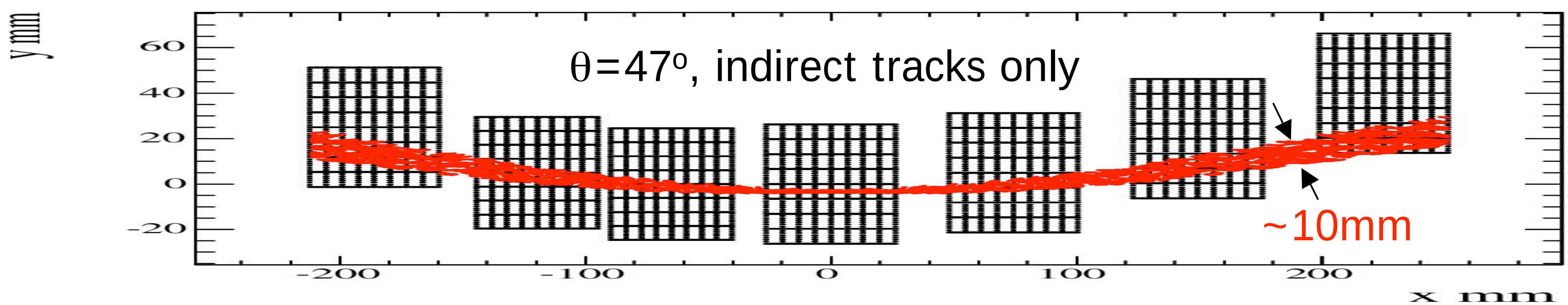


Rings from bar are blurred in outer slots

(Jose Benitez)

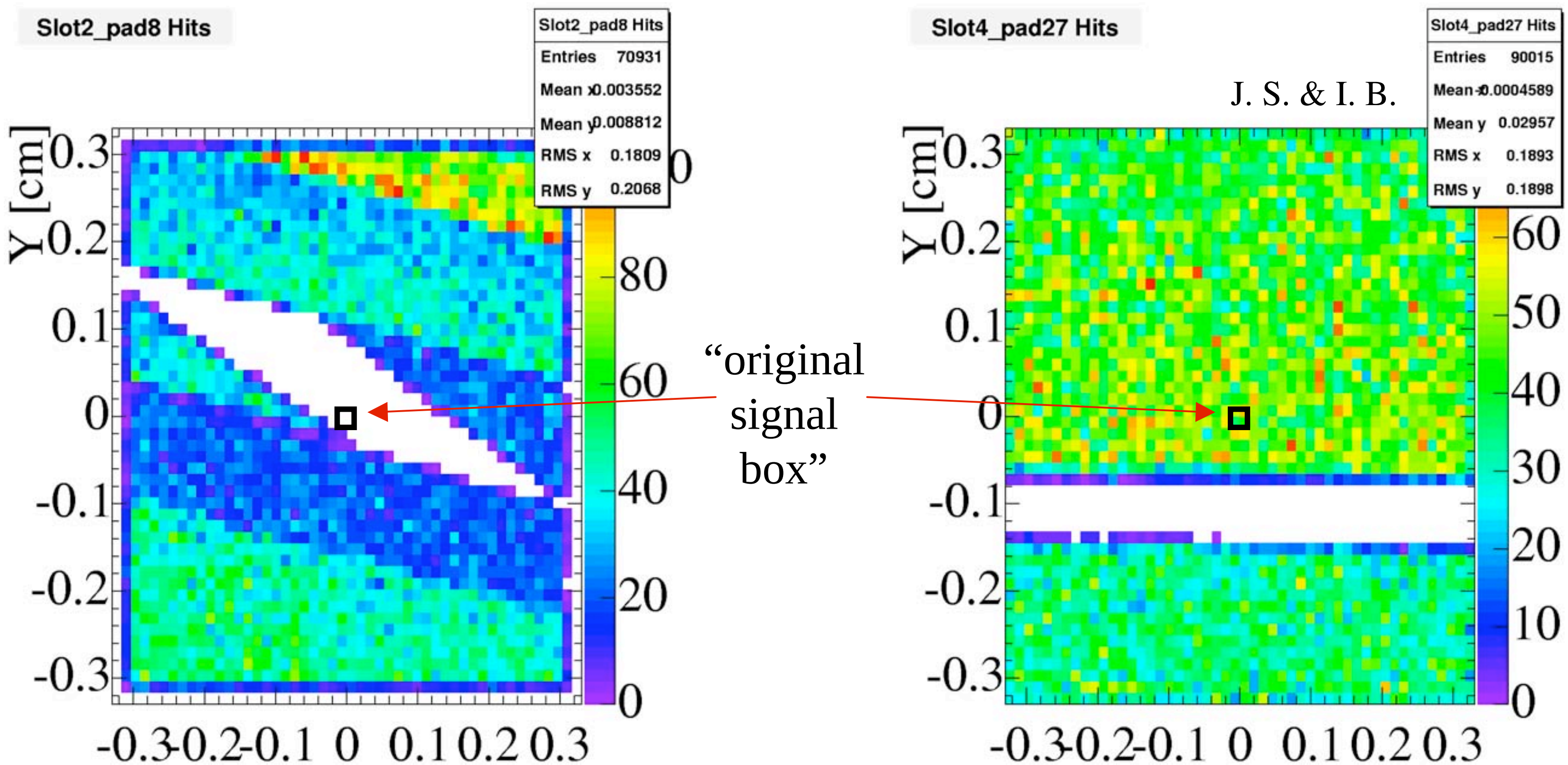


Cherenkov ring image ray traced from inside the bar is blurred in the outer slots - this is a bar effect.



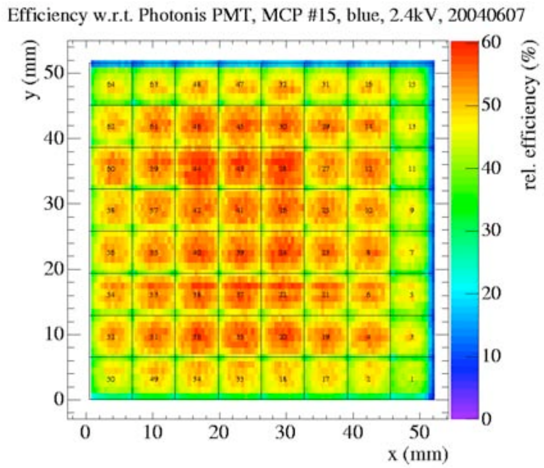
When assigning the parameters, such as θ_c & direction cosines, to each pad, it is necessary to average over entire pad

- Bar introduces kaleidoscopic images on the pads
- This effect shows up only in the test beam (in BaBar, one would integrate it out)
- One needs a MC to understand effects like this.



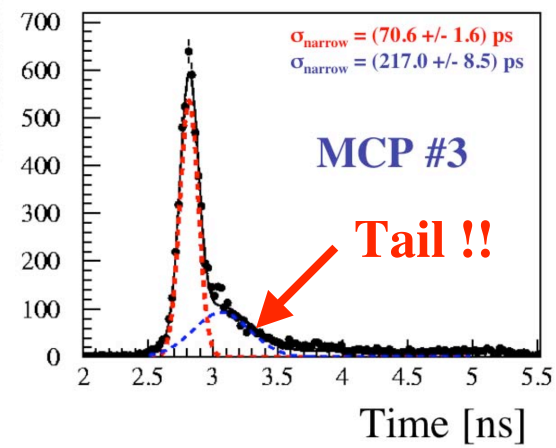
Photon detectors in the prototype (σ~70-150ps)

Burle MCP PMT (64 pixels):

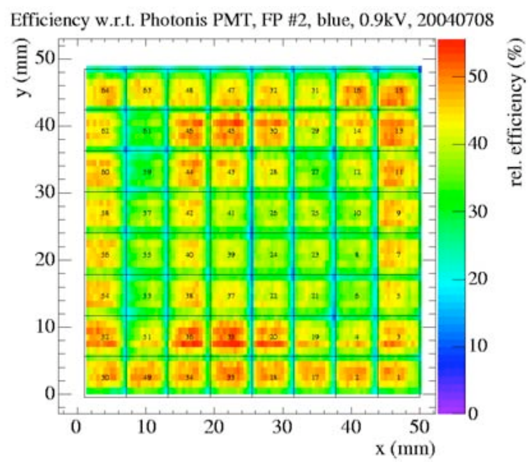


PiLas single pe calibration:

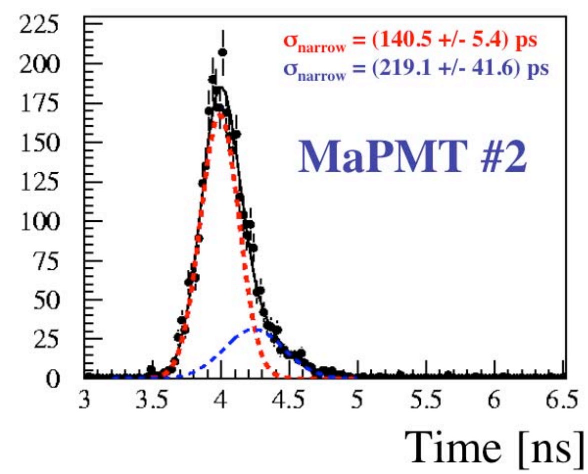
Burle 85011-501 MCP-PMT:



Hamamatsu MaPMT (64 pixels):



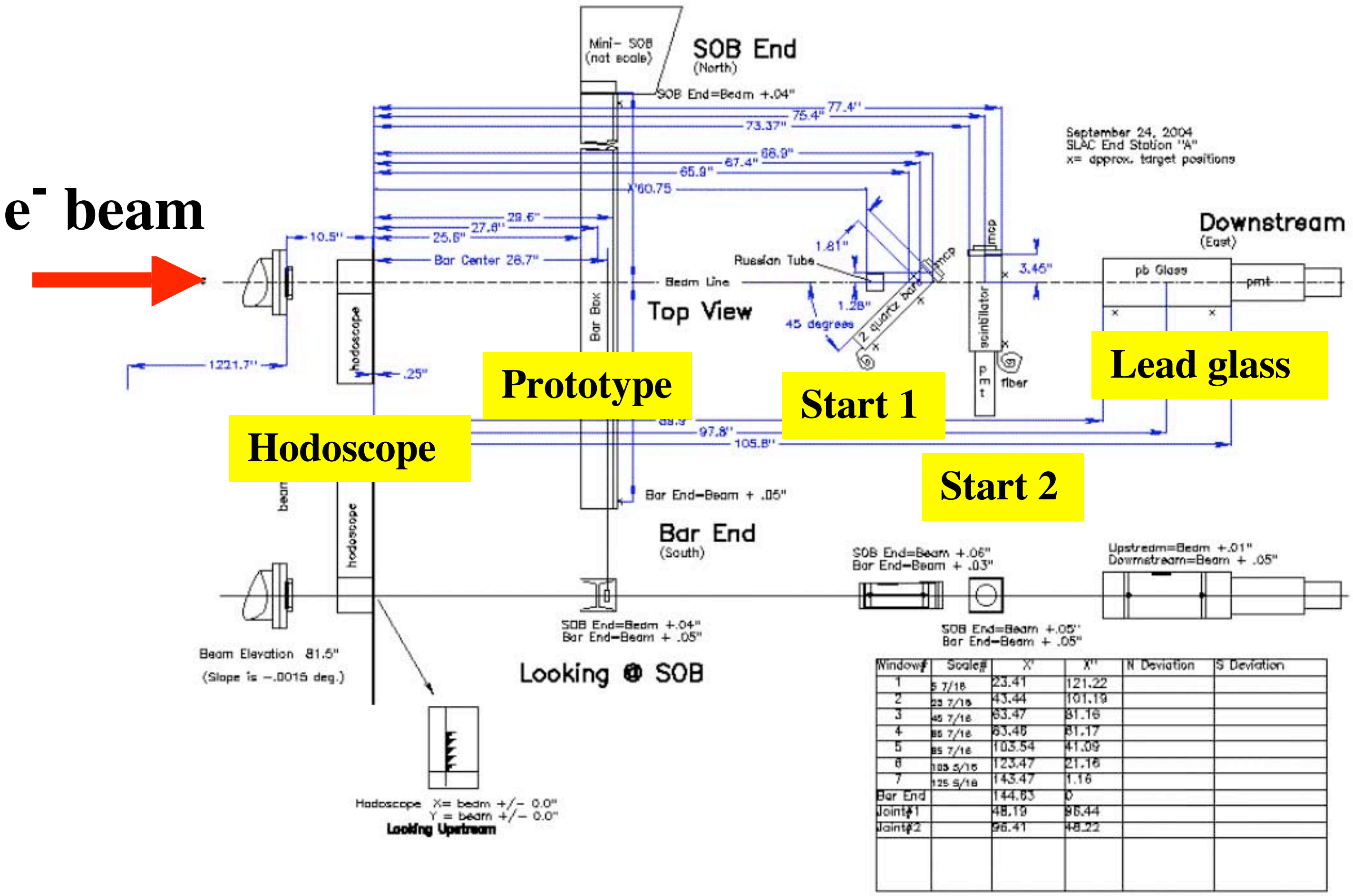
Hamamatsu Flat Panel H8500 PMT:



Need a good start signal

- **We start TDCs with a pulse from the LINAC RF.** However, this pulse travels on a cable several hundred feet long, and therefore it is a subject to possible thermal effects.
- To protect against thermal effects, we have several local Start time counters providing an average timing resolution of σ ~35ps per beam crossing. In addition, averaging over 100 consequtive events, we can correct slow drifts to 10-20ps level.
- **However, in practice, the analysis of the prototype data shows that the LINAC RF pulse is the best start, i.e., no local correction is needed.**

Test beam setup



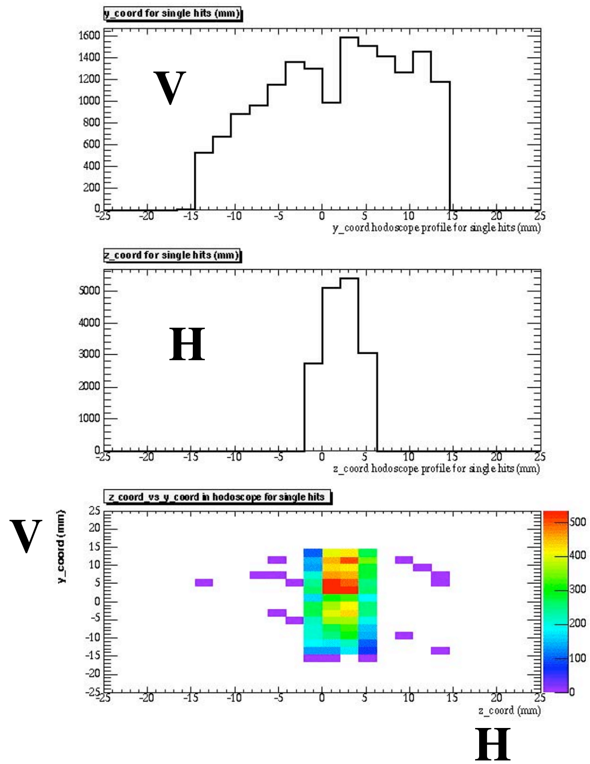
Window#	Scale#	X'	X''	N Deviation	S Deviation
1	5 7/16	23.41	121.22		
2	25 7/16	43.44	101.19		
3	45 7/16	63.47	81.16		
4	65 7/16	63.46	81.17		
5	85 7/16	103.54	41.09		
6	105 5/16	123.47	21.16		
7	125 5/16	143.47	1.16		
Bar End		144.63	0		
Joint#1		48.19	96.44		
Joint#2		96.41	48.22		

- Beam enters bar at 90 degrees.
- Bar can be moved along the bar axis
- Trigger and time ref: accelerator pulse
- Hodoscope measures beam's 2D profile

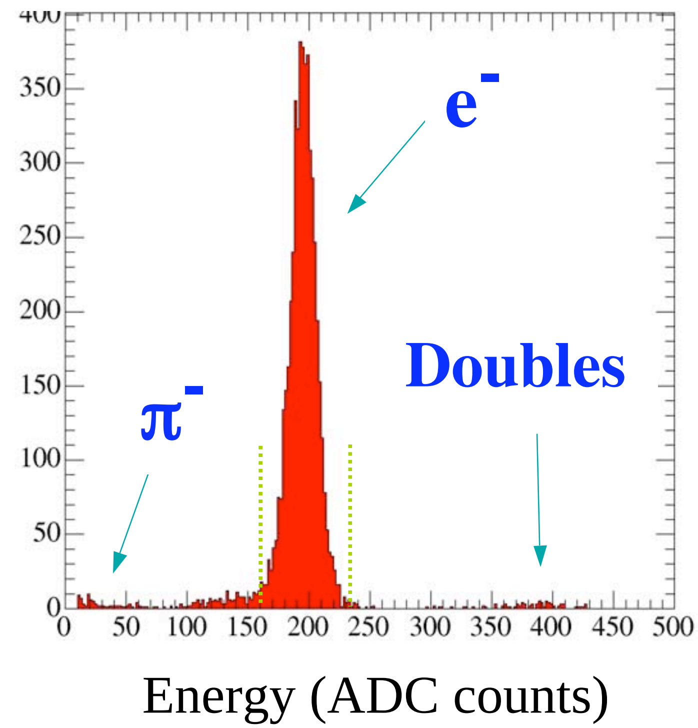
Definition of a good beam trigger

Run 2

Single hodoscope hits only:



Lead glass:

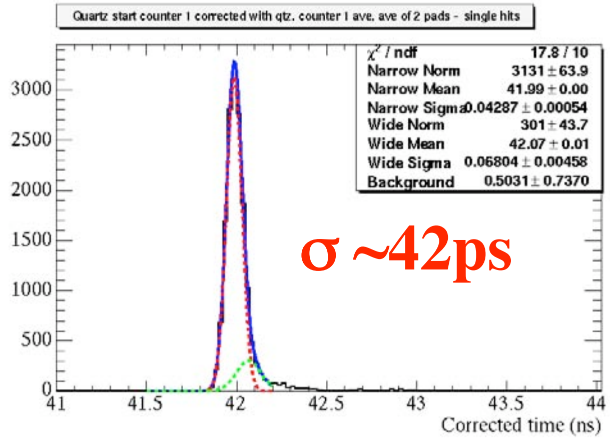


- **<u>Good beam trigger definition</u>: single hit in the hodoscope, good energy deposition in the lead glass, and good quality local start time hit.**

Local START Counters:

1. Start counter 1 - Double-quartz counter

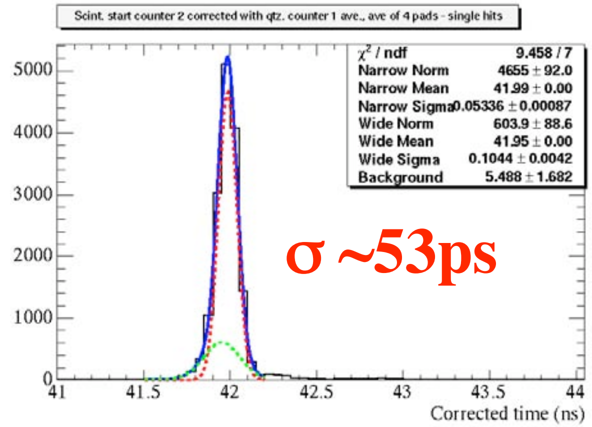
Average of 2 pads:



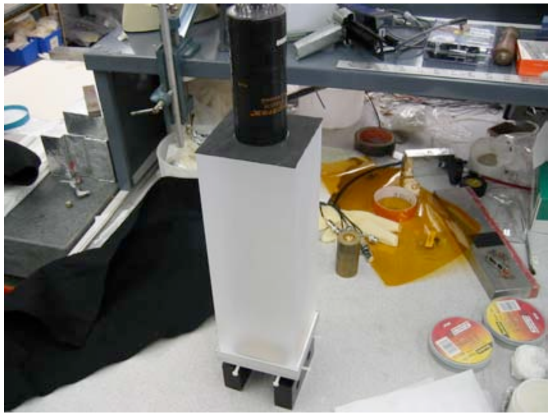
4-pad Burle MCP-PMT:

2. Start counter 2 - Scintillator counter

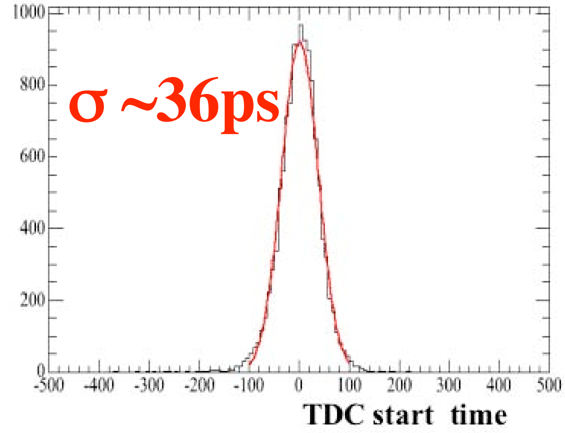
Average of 4 pads:



4-pad Burle MCP-PMT :



3. Overall average of Start 1, Start 2 and Quantacon counters:



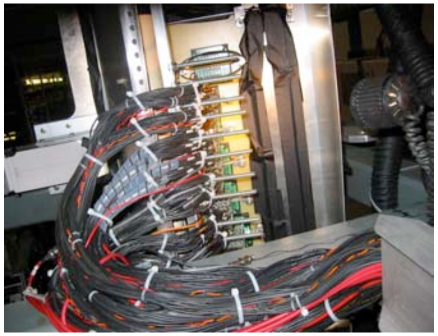
- **Corrections: ADC, hodoscope position and timing drifts.**

Focusing DIRC prototype

Setup in End Station A: movable bar support and hodoscope

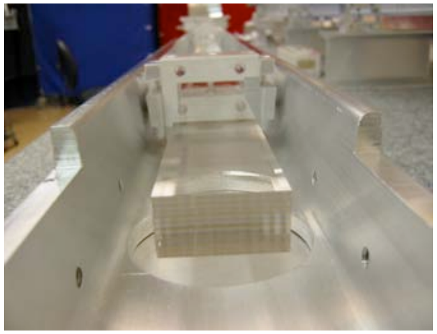
Setup in End Station A

Photodetector backplane

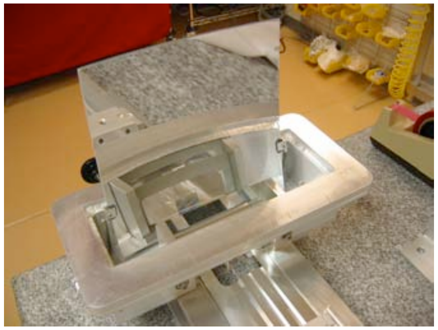


Electronics and cables

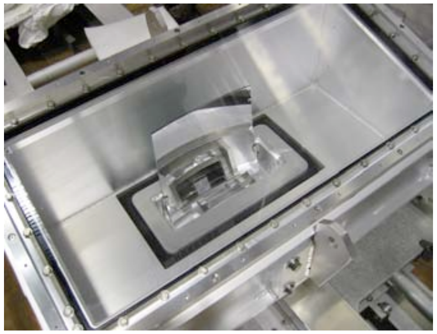
Radiator bar



Mirror



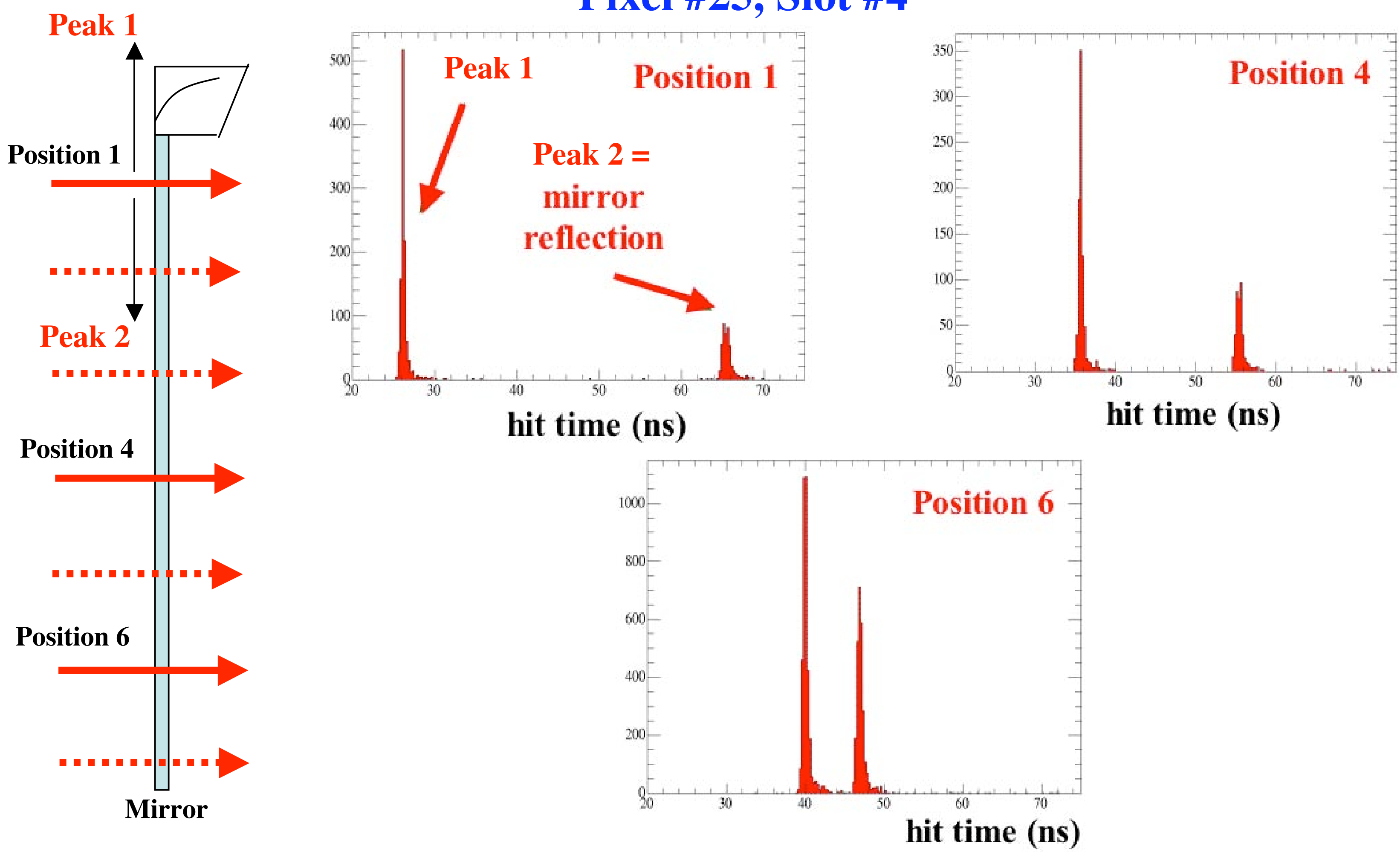
Oil-filled detector box:



Start counters, lead glass

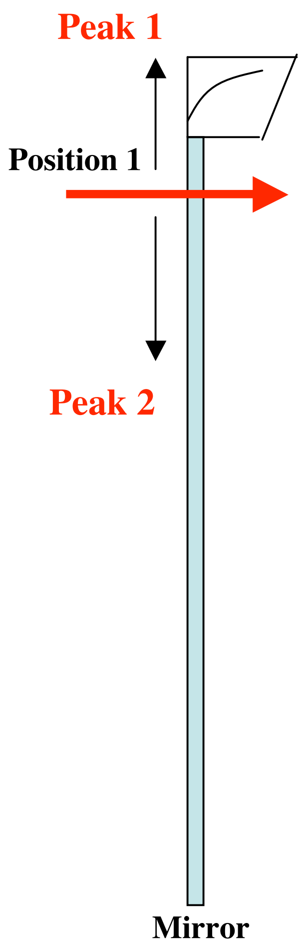
Cherenkov ring in the time domain

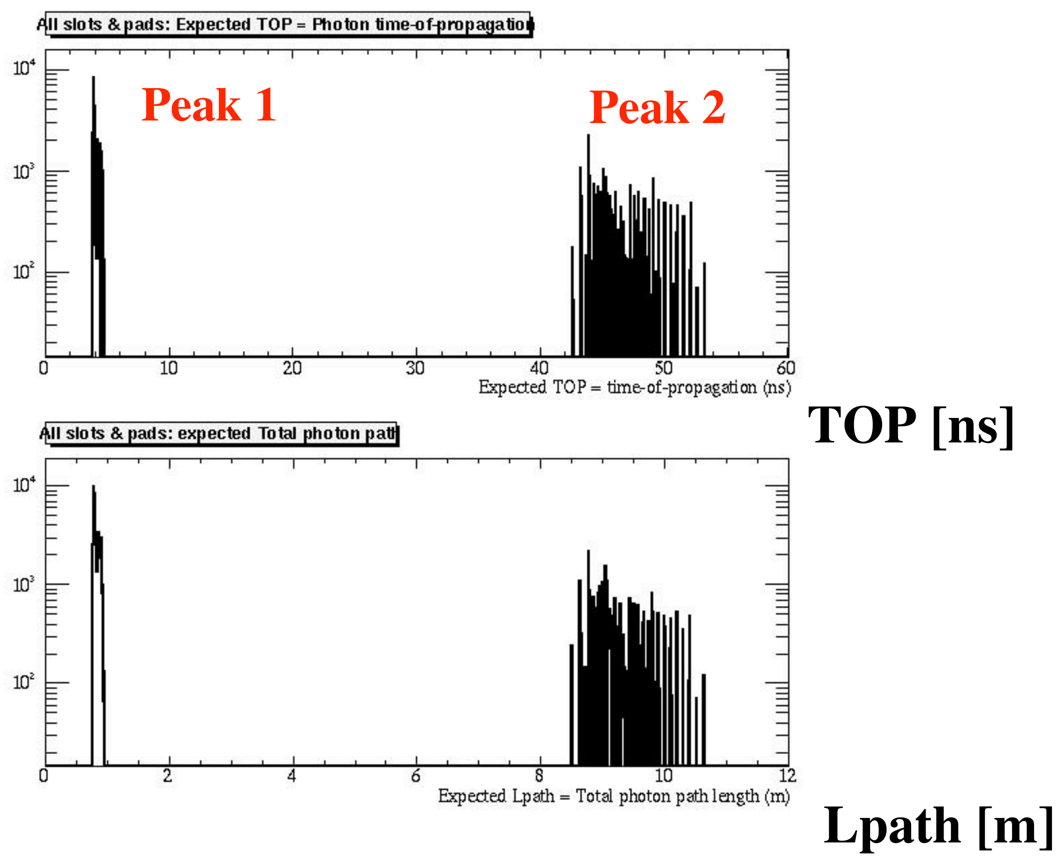
Pixel #25, Slot #4



- Two peaks correspond to forward and backward part of the Cherenkov ring.

Typical distribution of TOP and Lpath

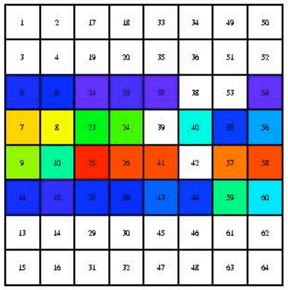
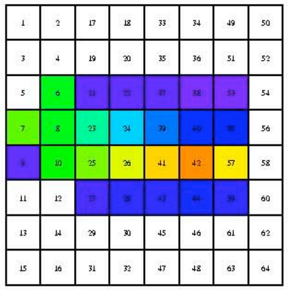
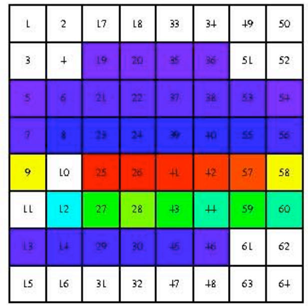
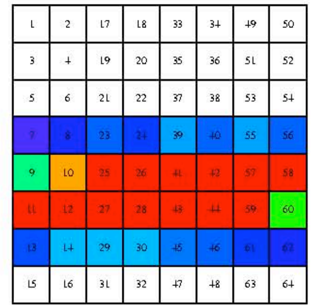
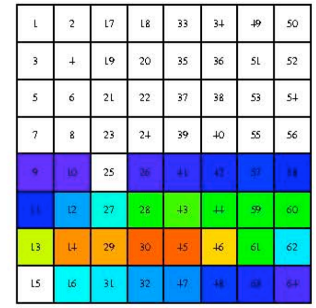




- **Measured TOP and calculated photon path length Lpath**
- **Integrate over all slots & pixels**

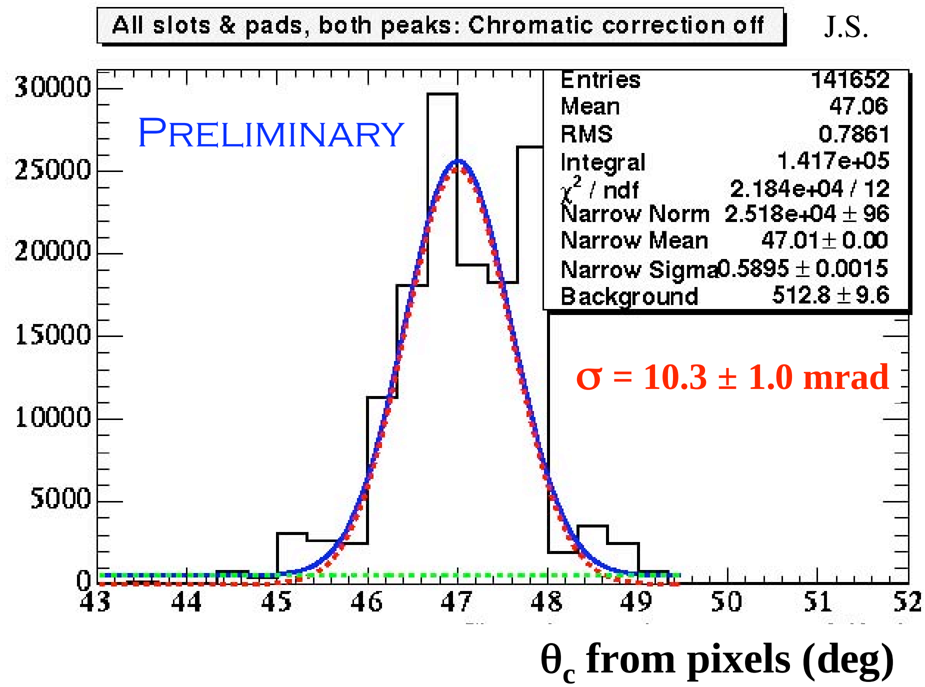
Cherenkov Angle resolution in the pixel domain

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

Cherenkov angle from pixels:

- **θ_c resolution ≈ 10-12mrad**
- **Assign angles to each pads averaging over the entire pad for λ = 410 nm.**
- Clear pixelization effect visible; this would go away if we integrate over variable incident angles or use smaller pixel size
- θ_c resolution should still improve with better alignment & better MC simulation

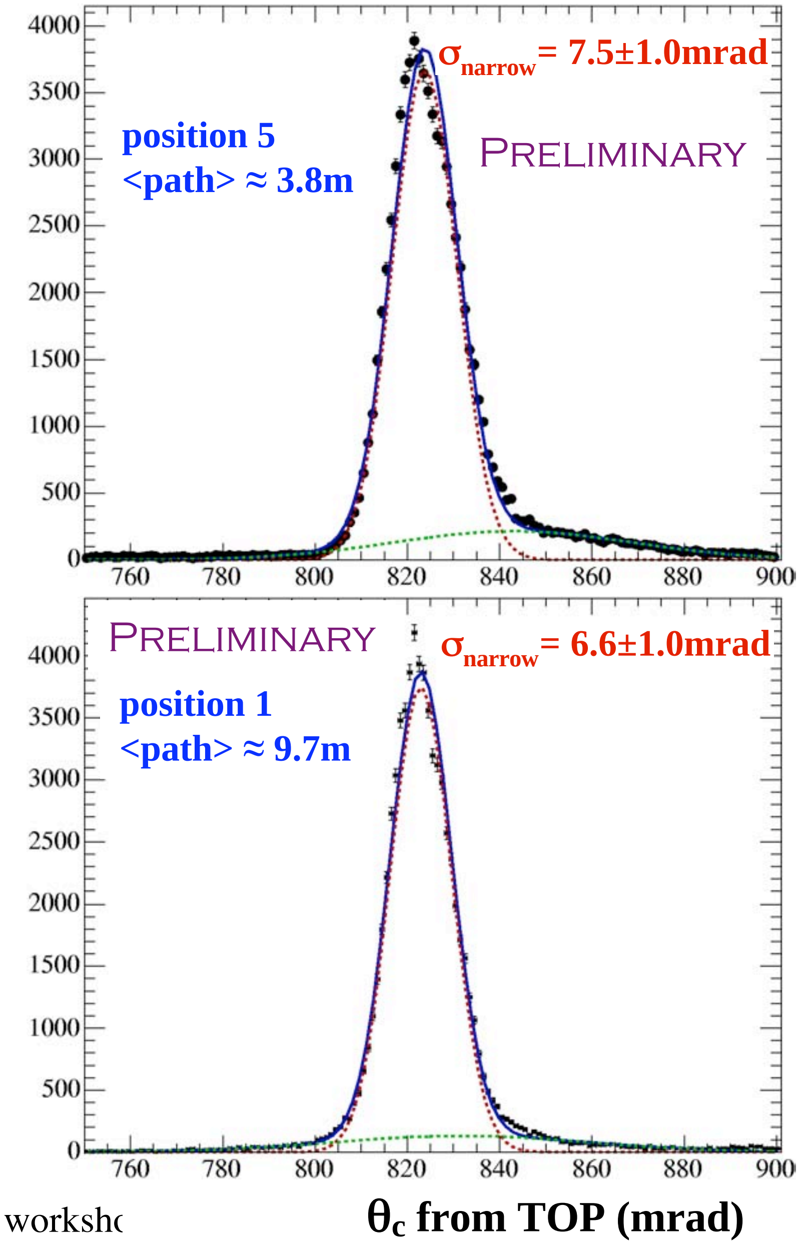


Cherenkov Angle resolution in the time domain

J.S.

Method:

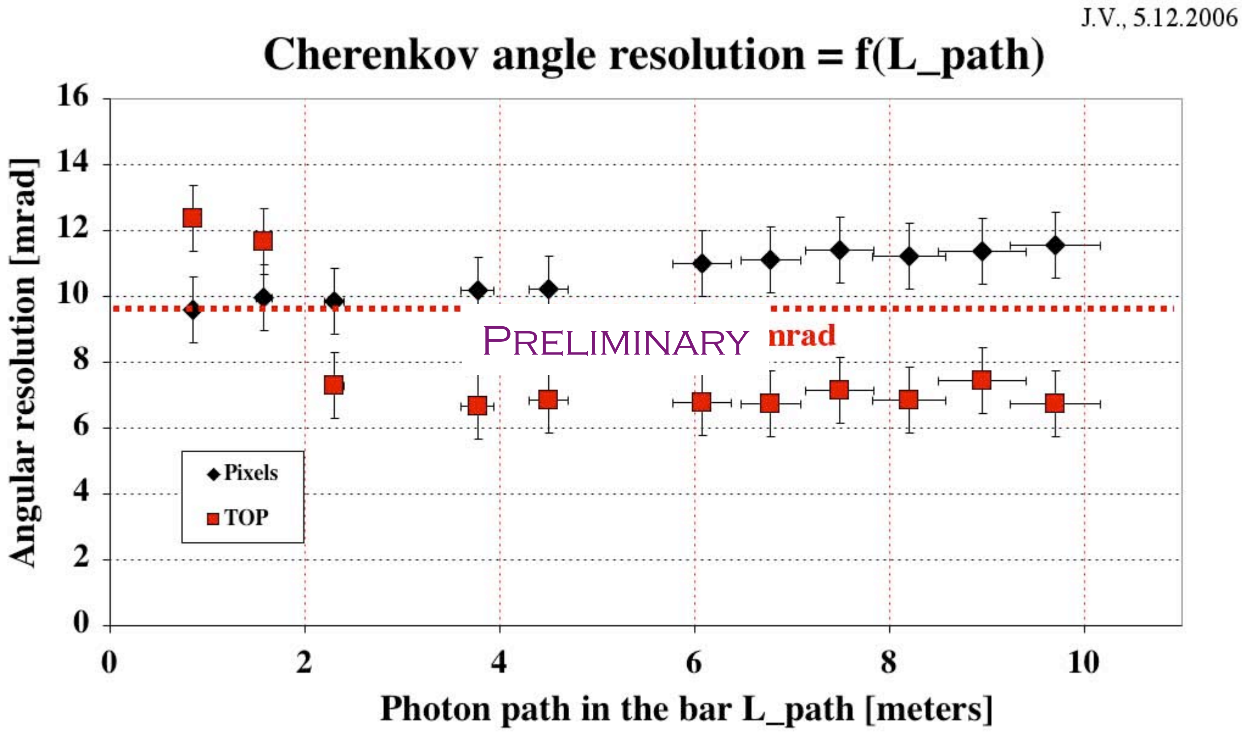
- Use measured **TOP** for each pixel
- Combine with calculated photon path in radiator bar **- Lpath**
- Calculate group index:
  $n_G(\lambda)$ = $c_o \cdot$ **TOP / Lpath**
- Calculate phase refractive index $n_F(\lambda)$ from group index $n_G(\lambda)$
- Calculate photon Cherenkov angle Θ_c (assuming $\underline{\beta = 1}$): $\theta_c(\lambda) = \cos^{-1}(1/n_F(\lambda))$
- **Resolution of Θ_c from TOP is 6-7mrad for photon path length above 3 m.**
- Expected to improve with better calibration.



Summary of preliminary results:

Θ_c resolution from pixels is 10-12 mrad.

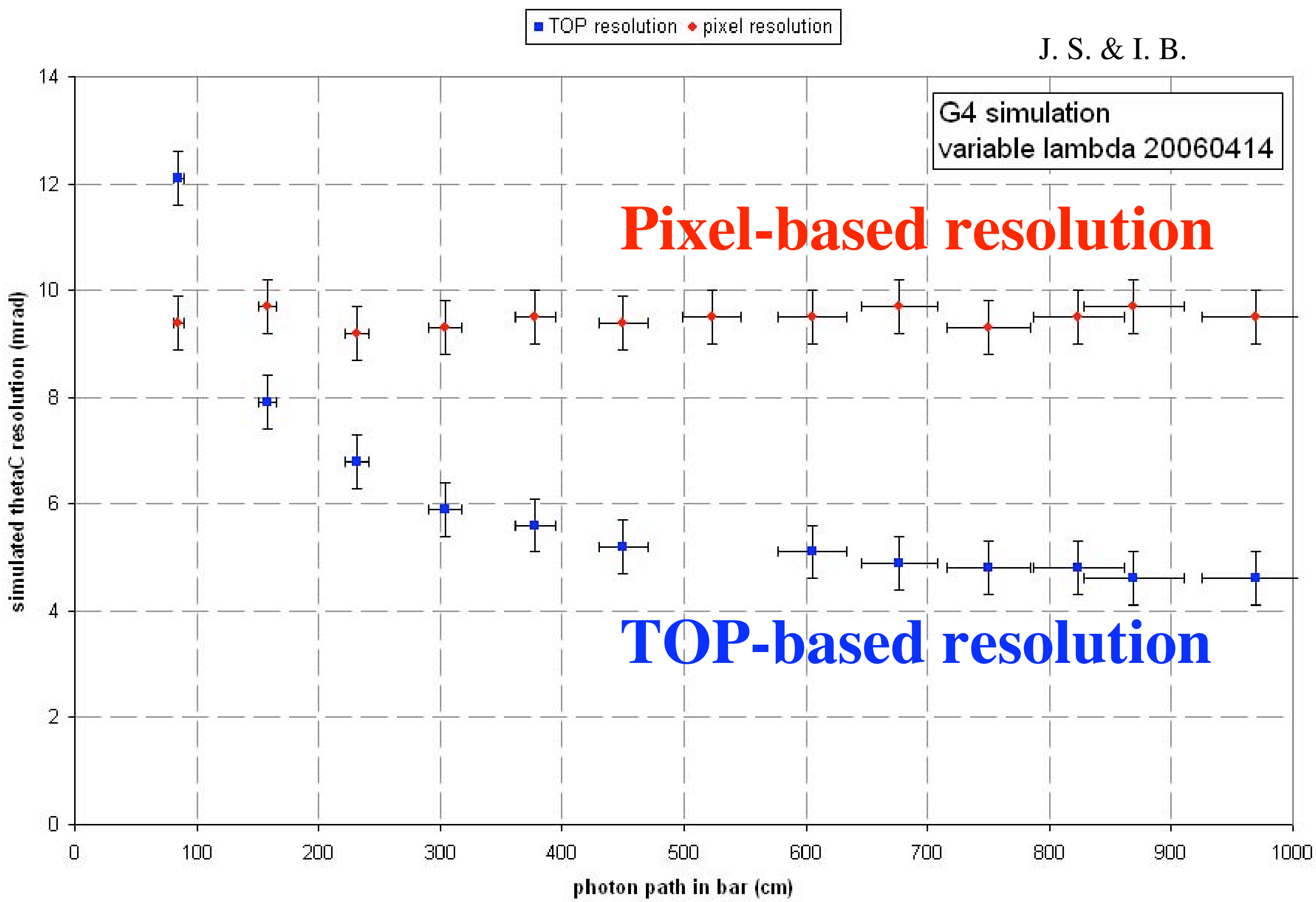
Θ_c resolution from time of propagation (TOP) improves rapidly with path length, reaches plateau at ~7mrad after 3-4 meters photon path in bar.



Comments: a) The present TOP-based analysis assumes $\beta = 1$,

b) In the final analysis we will combine pixels & time into a maximum likelihood analysis.

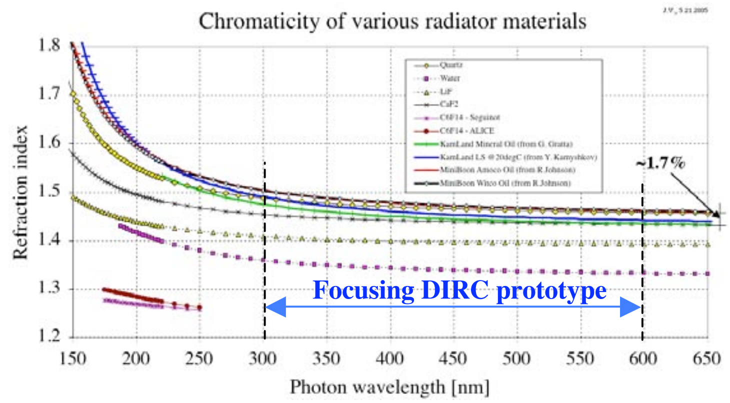
Geant 4 MC simulation of the prototype

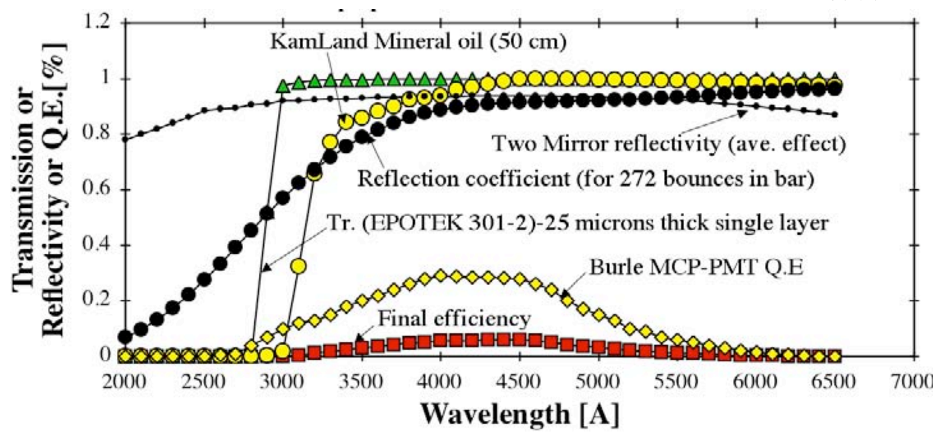


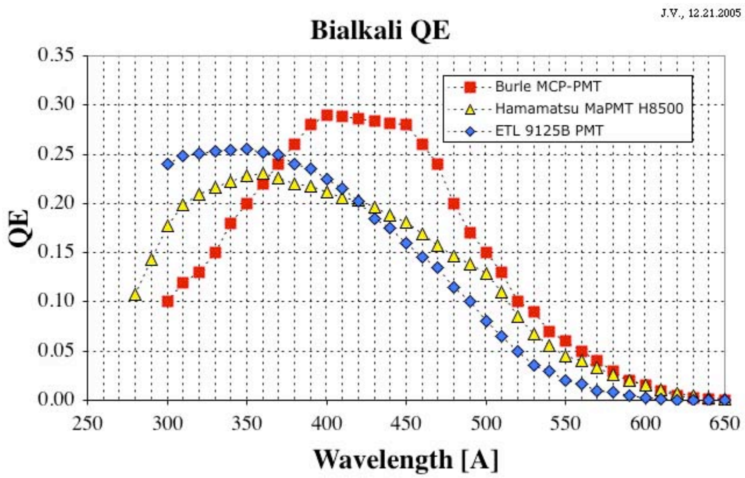
- **Data and MC almost agree; still some work needed for pixel-based data analysis**

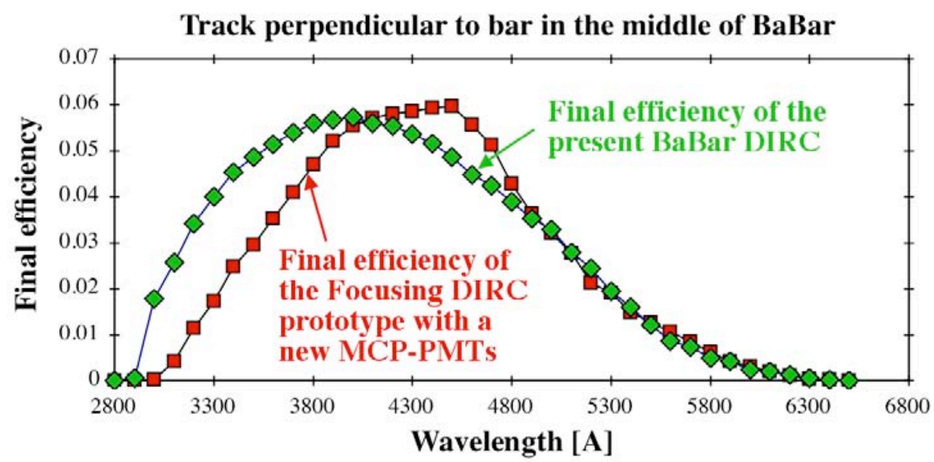
Chromatic behavior of the prototype

J.V.









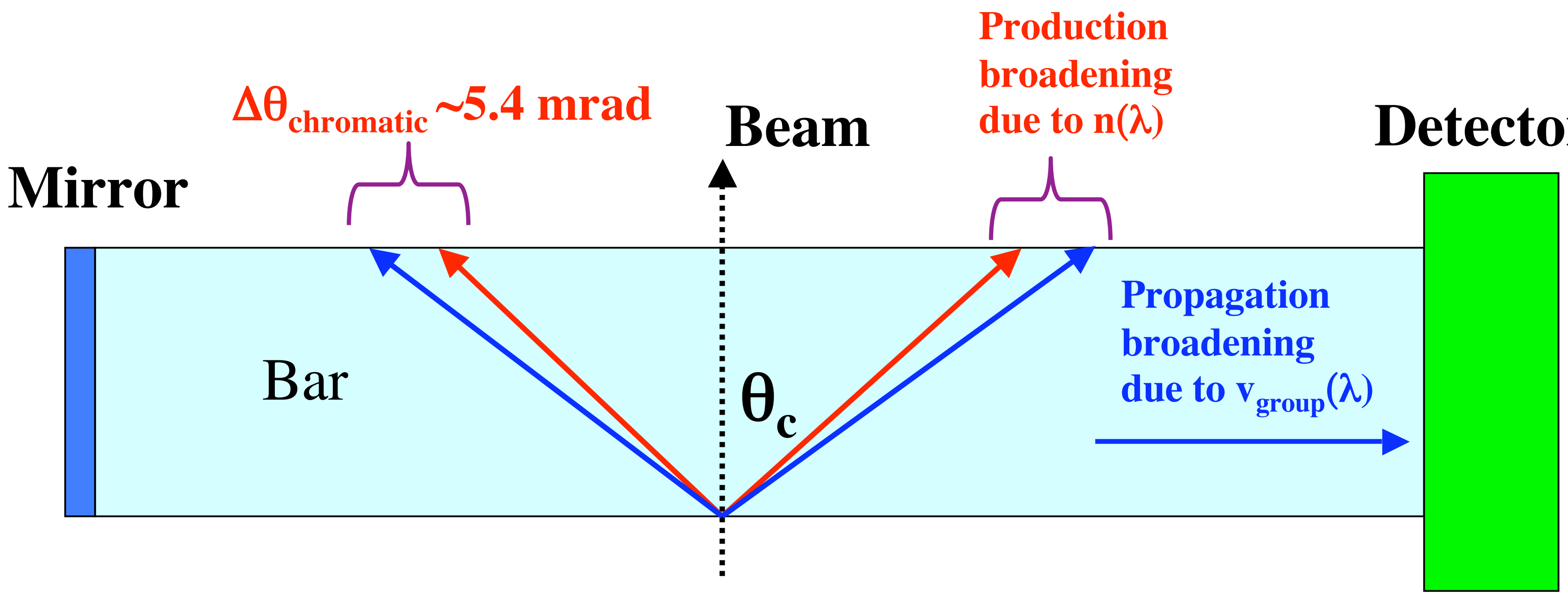
- **The prototype has a better response towards the red wavelengths, which reduces the Cherenkov angle chromatic contribution to 3-4 mrads (BaBar DIRC has 5.4mrads).**

Chromatic effects on the Cherenkov light

1) **Production part:** $\cos\theta_c = 1 / (n_{phase}\,\beta)$, $n_{phase} = f(\lambda)$

2) **Propagation part:** $v_{group} = c_0 / n_{group} = c_0 / [n_{phase} - \lambda * dn_{phase}/d\lambda]$

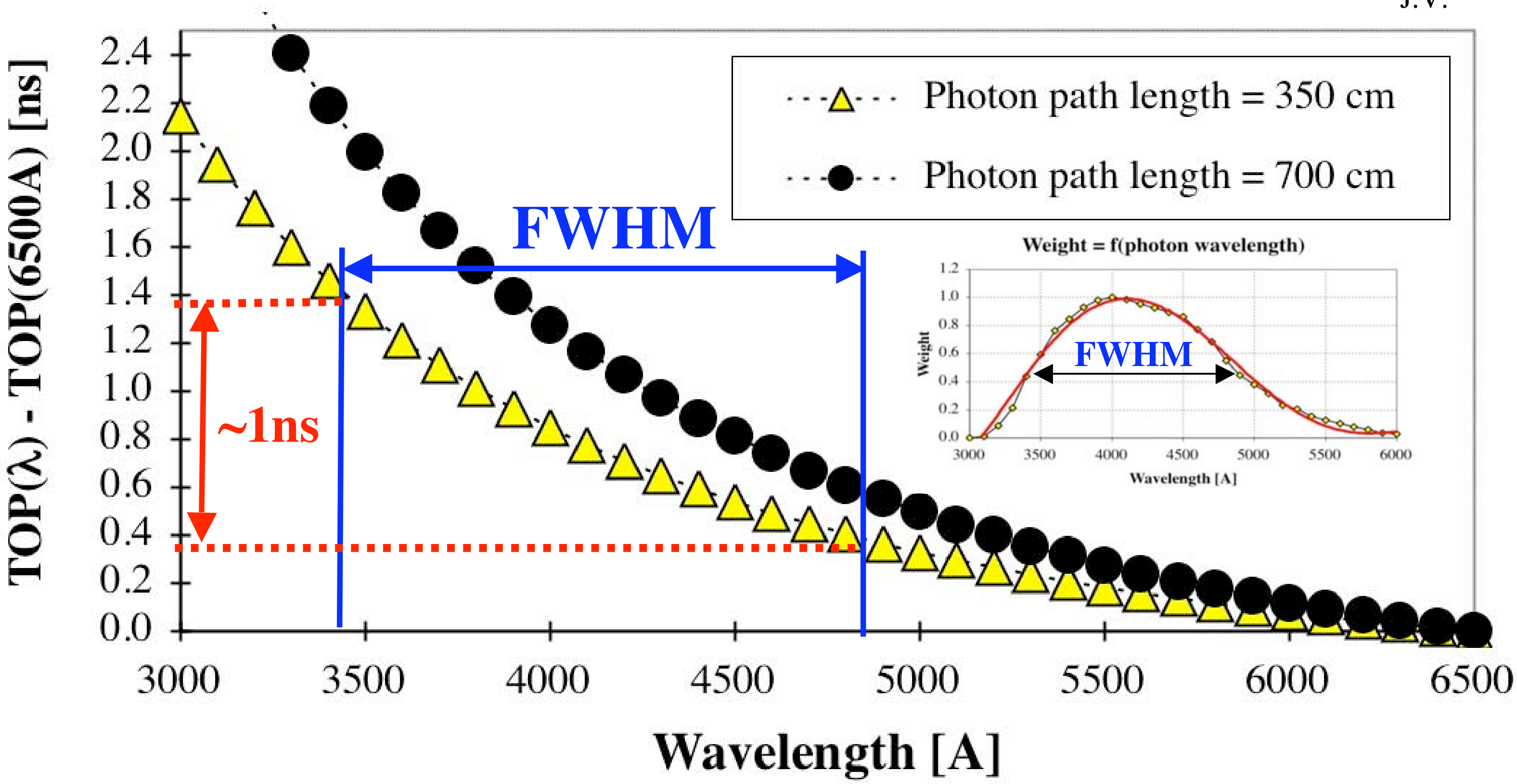
n_{phase}(red) < n_{phase} (blue) => v_{group}(red) > v_{group} (blue)



- **Two parts of the chromatic effects:**
  - **Production part** (due to $n_{phase} = f(\lambda)$) - Red photons "handicaped"by ~200 fsec initially.
  - **Propagation part** - Red photons go faster than blue photons; color can be tagged by time.

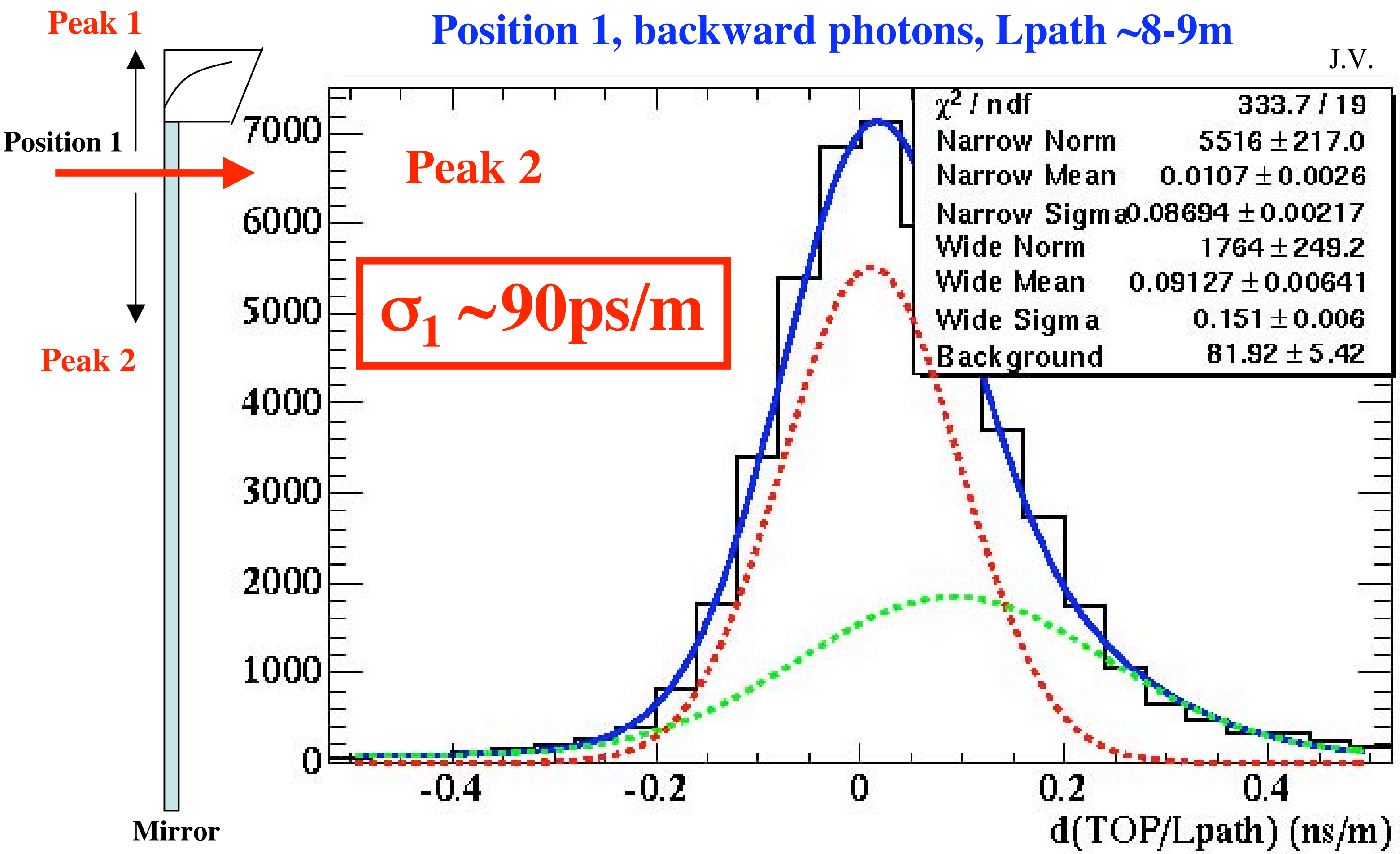
Expected size of the chromatic effect in time domain

J.V.



- $\Theta_{track} = 90^o$ **(perpendicular to bar);** photons propagate in y-z plane only.
- **~1 ns overall total range typically.**
- **Need a timing resolution of 150-200ps to parameterize it.**

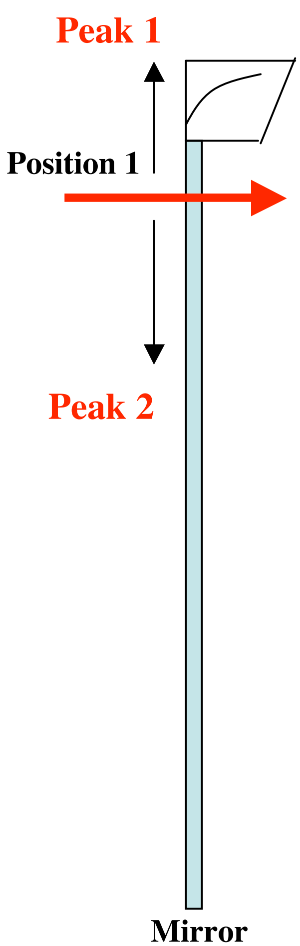
Time spread growth due to chromaticity

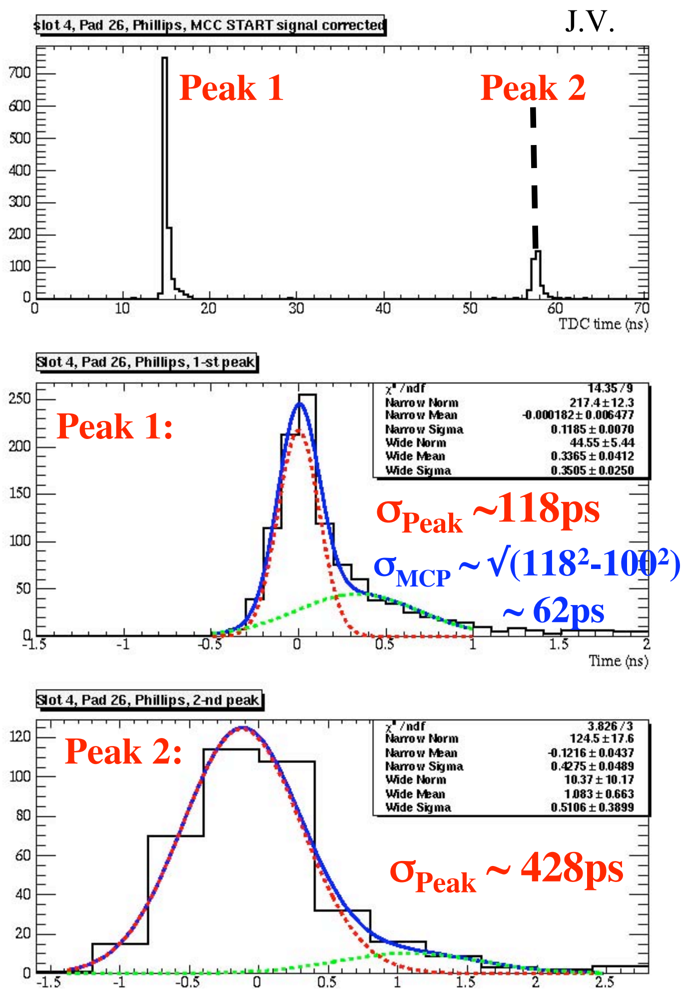


- **The width increases at a rate of σ ~90 ps/meter of photon path length; the growth is "fueled" by different group velocity of various colors.**

Chromatic broadening of a single pixel

Slot 4, single pixel #26,





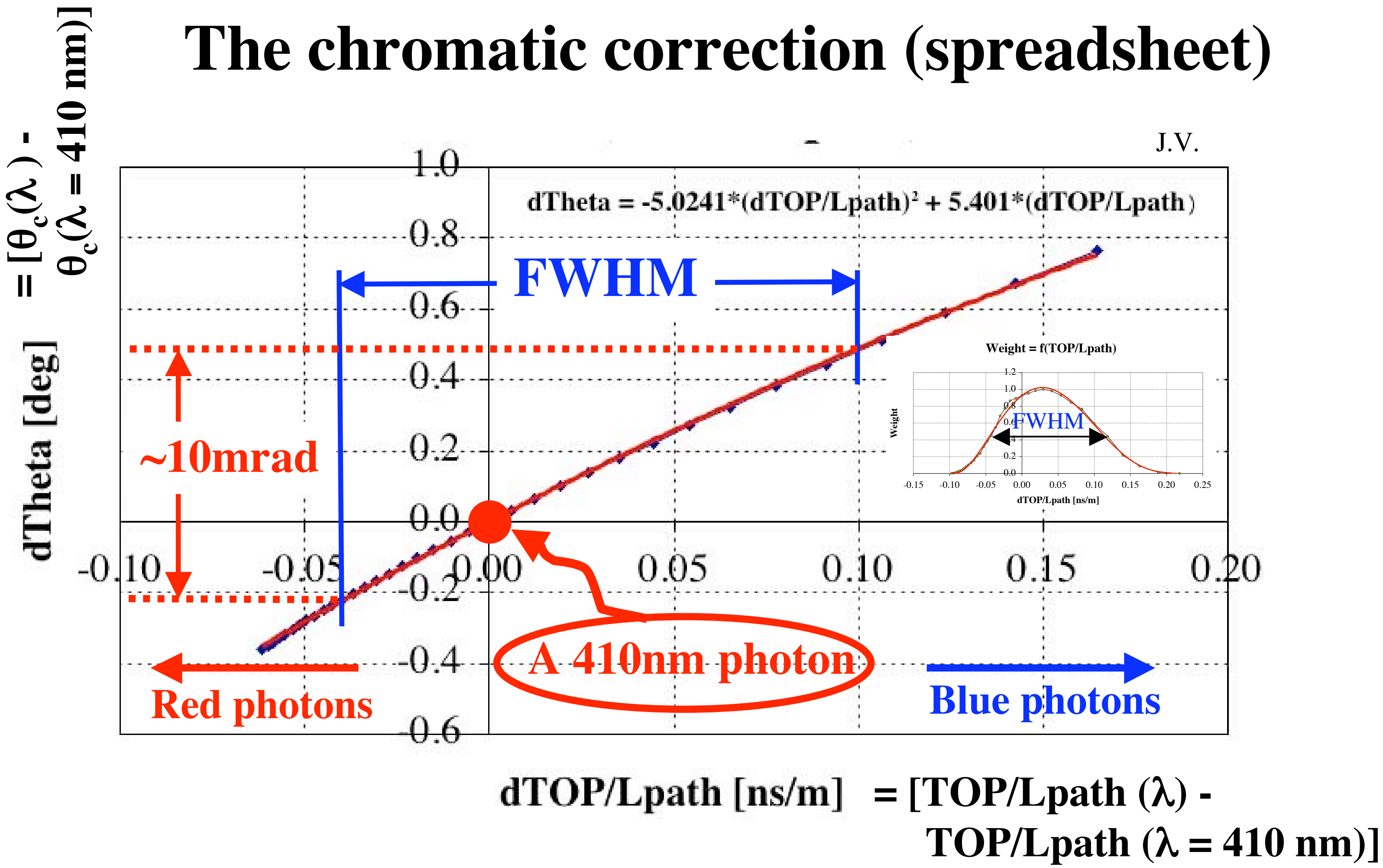
ΔTOP = TOP_measured (λ) - TOP_expected (λ = 410 nm) [ns]

- **Total photon path lengths:**
  Peak 1:
  - **Lpath ~1.25 m in bar**

  Peak 2:
  - **Lpath ~9.70 m in bar**

- **When one substracts the chromatic broadening from peak 1, one gets expected MCP-PMT resolution**

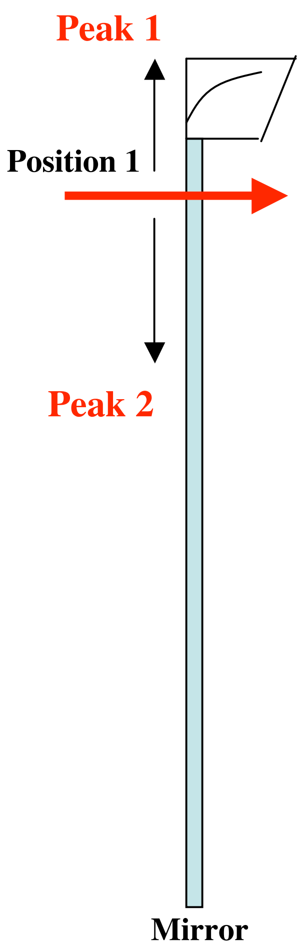
The chromatic correction (spreadsheet)

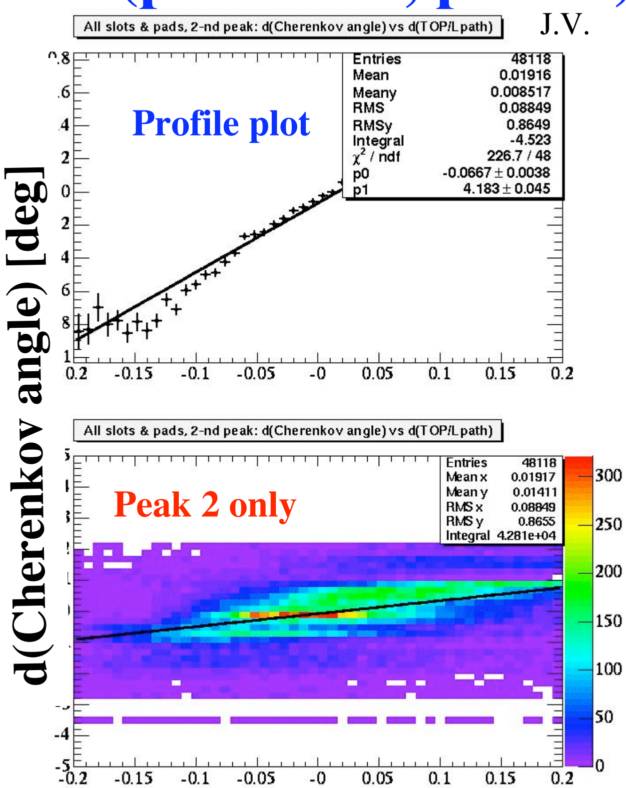


- An average photon with a color of λ ~410 nm arrives at "0 ns offset" in dTOP/Lpath space. A photon of different color, arrives either early or late.
- The overall expected effect is small, only FWHM ~10mrad, or σ ~ 4 mrads.

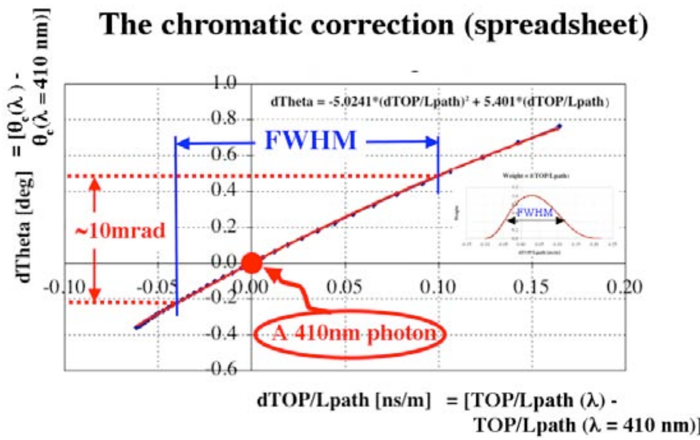
Do we see this effect in the data ?

Data (position 1, peak 2):





Spreadsheet calculation:

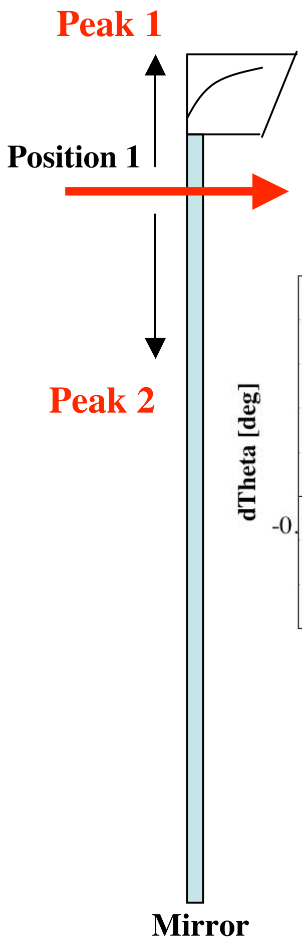


d(TOP/Lpath) [ns/m] = [TOP/Lpath (λ) - TOP/Lpath (λ = 410 nm)]

- One can see expected size in the data, approximately.

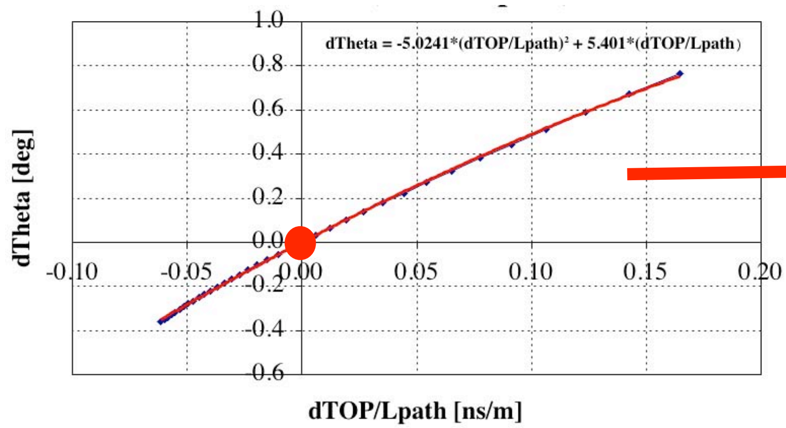
Method #1: Spreadsheet calculation of $d\theta_c$ vs d(TOP/Lpath).

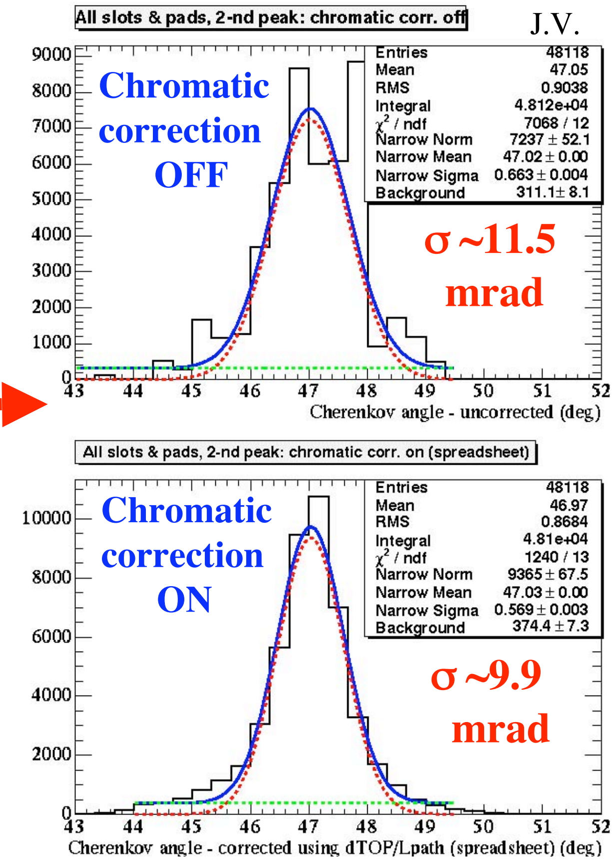
All slots, all pads, position 1, Peak 2 only:



PRELIMINARY

Spreadsheet:

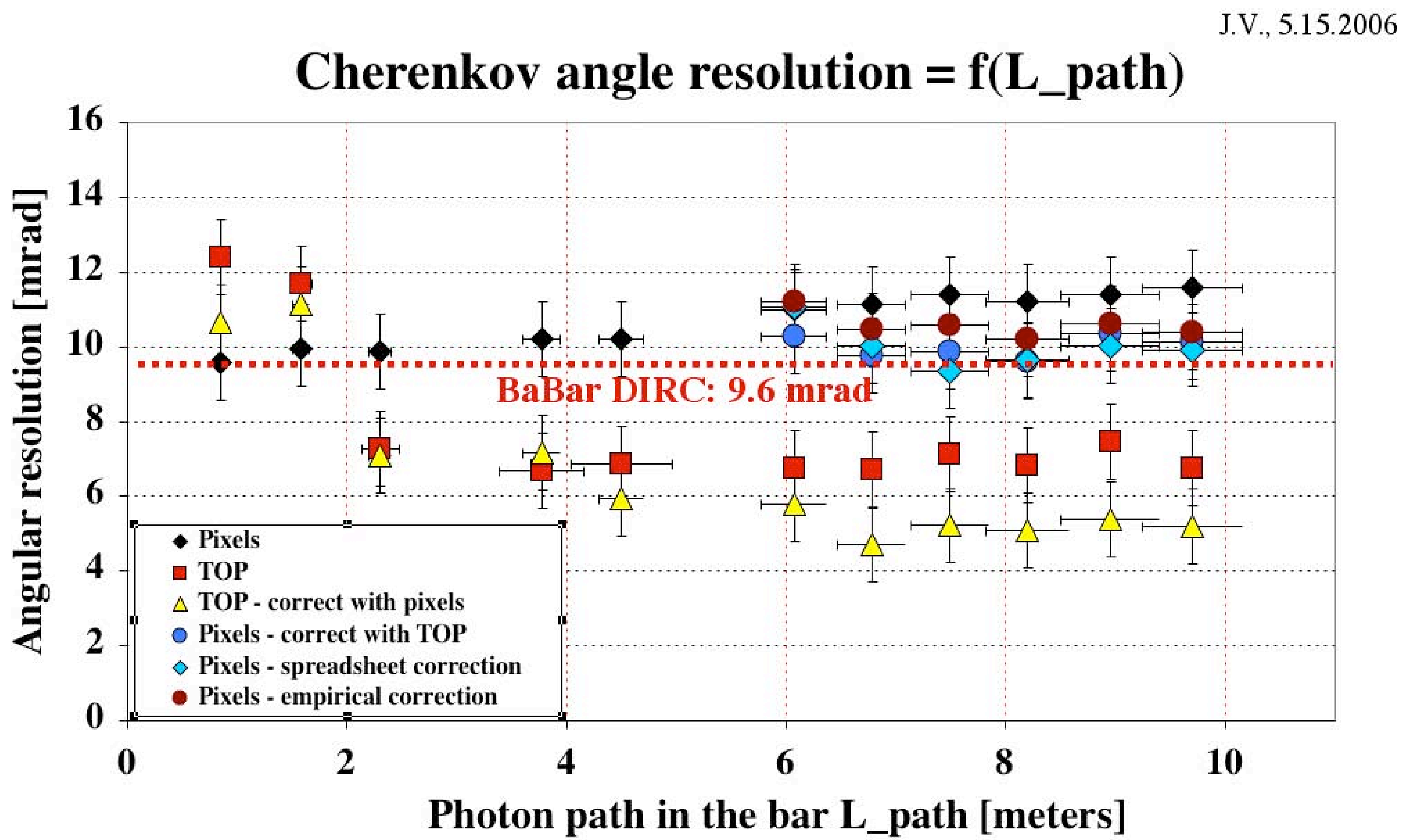




Cher. Angle (pixel) [deg]

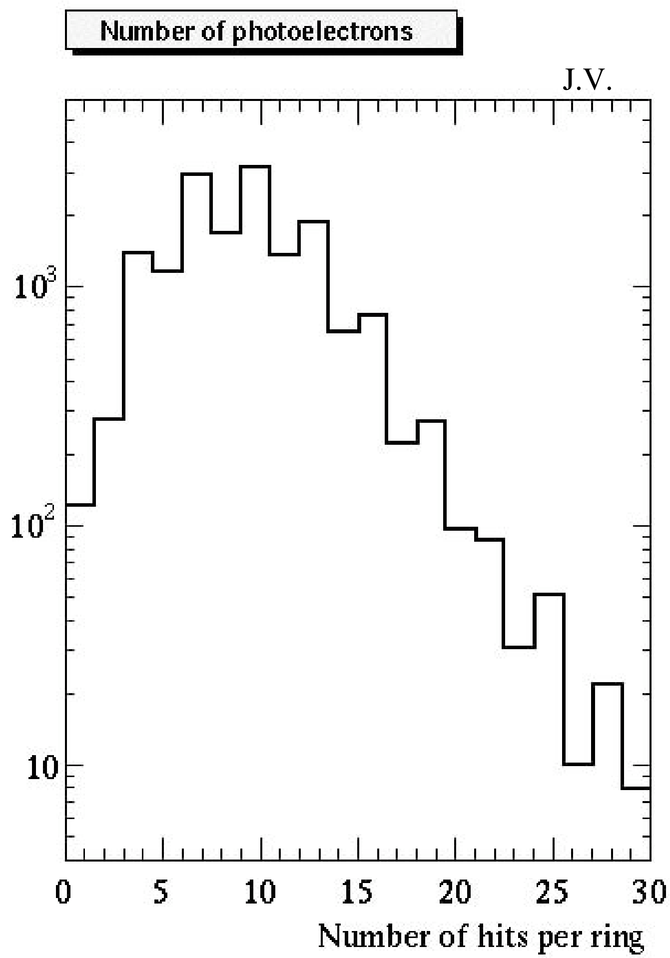
- **An improvement of ~1.5 mrads.**

Status of chromatic corrections - preliminary



- **A slight improvement of ~1-2 mrads for long Lpath.**
- **Apply the chromatic correction to longer photon paths only**

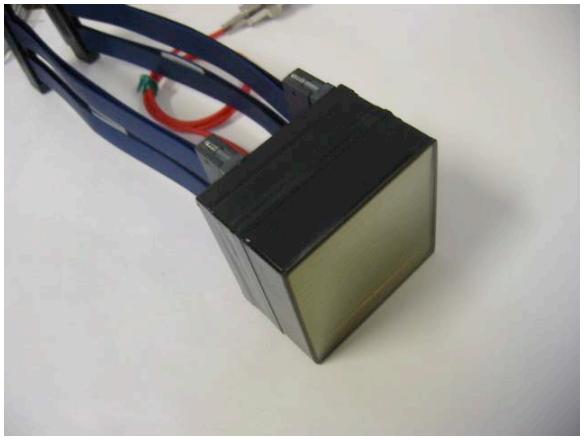
How many photoelectrons per ring ?

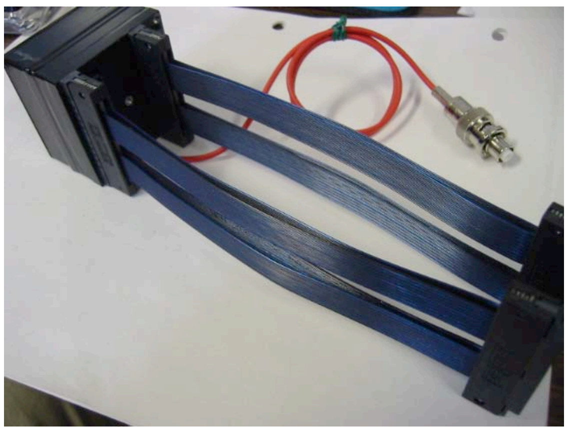


- **$\langle N_{pe} \rangle$ ~ 8-10 for 90^o inc. angle**
- With a hermetic configuration and other Burle improvements in the MCP-PMT design, we could achieve a factor of 1.5-2 improvement, perhaps.
- BaBar DIRC has N_{pe}~20 at a track incident angle of 90^o

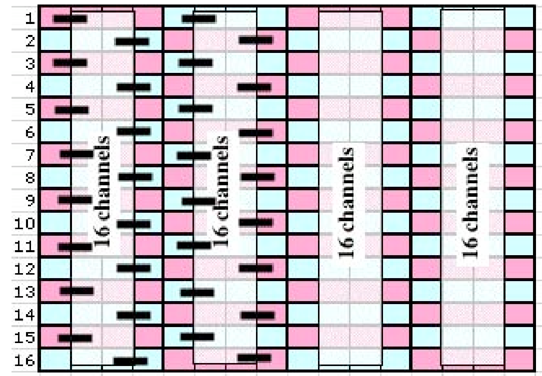
Upgrades for the next run in July

New 256-pixel Hamamatsu MaPMT H-9500

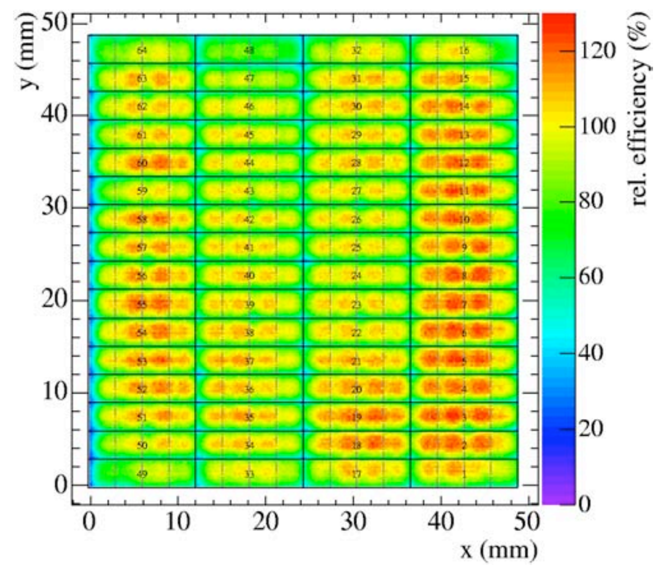




We made a small adaptor board to connect pads in the following way:



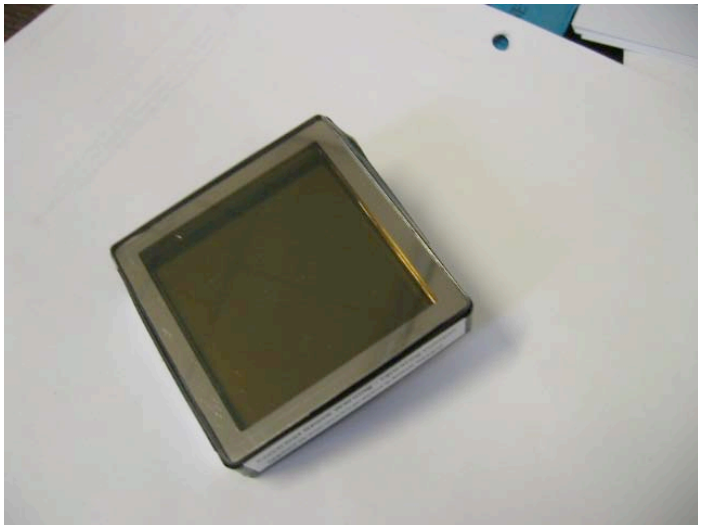
2D scan:

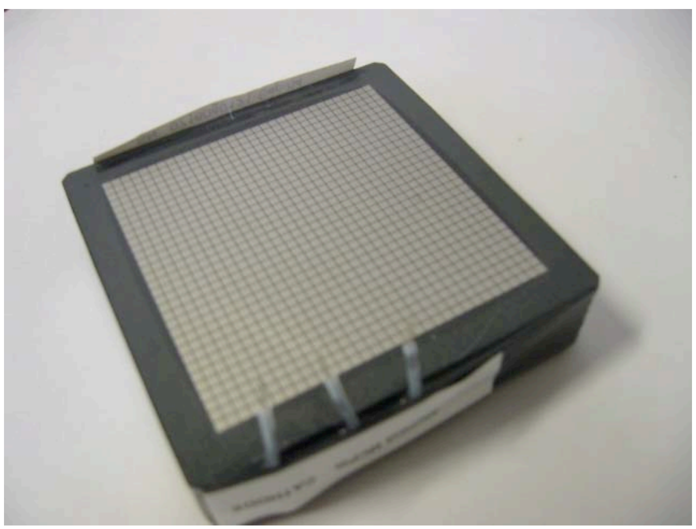


- 256 pixels (16 x 16 pattern).
- Pixel size: 2.8 mmx2.8 mm; pitch 3.04 mm
- 12 stage MaPMT, gain ~10^6, bialkali QE.
- Typical timing resolution σ ~ 220 ps.
- Charge sharing important

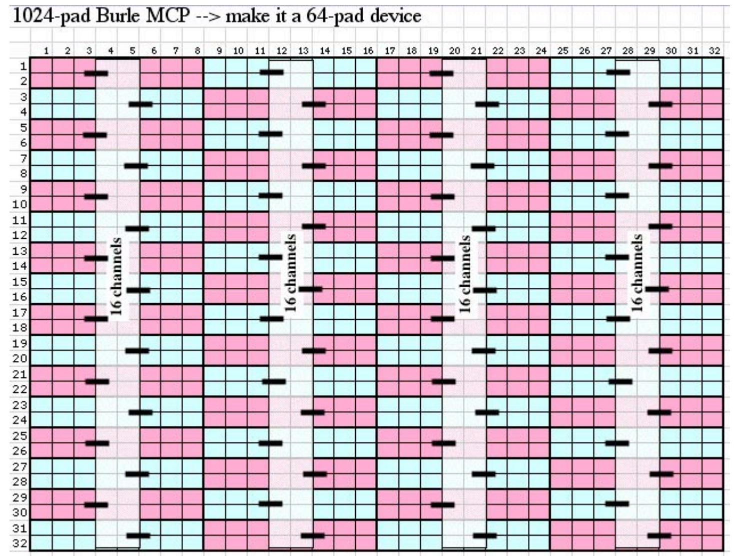
- **Large rectangular pad: 1x4 little ones**
- **This tube was now installed to slot 3**

“Open area” 1024-pixel Burle MCP 85021-600





Burle will connect pads as follows:



- **Large rectangular pad: 2x8 little ones**
- **Small margin around boundary**
- Nominally 1024 pixels (32 x 32 pattern)
- Pixel size: ~1.4mm x 1.4mm
- Pitch: 1.6 mm
- **This tube will be in slot 4 in next run**

A future if Super B-factory exists

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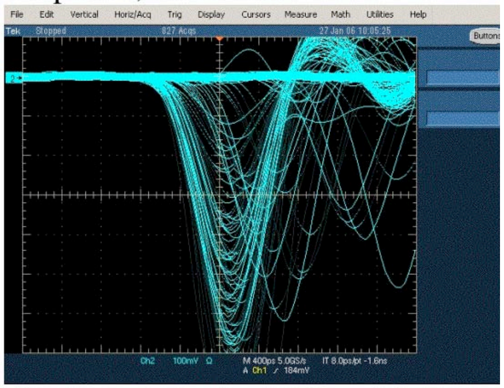
Single-photon timing resolution

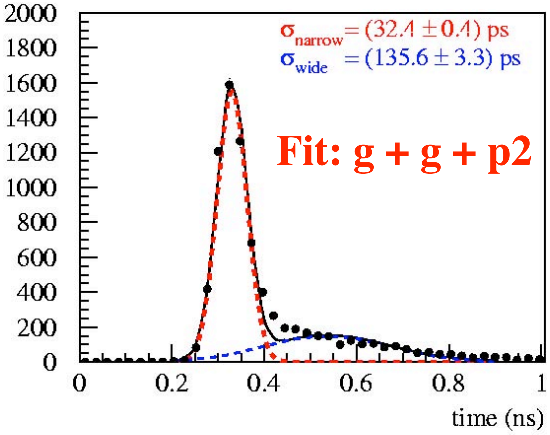
- Burle MCP-PMT 85012-501 (open area)
- 10 μm MCP hole diameter
- 64 pixel devices, pad size: 6 mm x 6 mm.
- Small margin around the boundary
- Use Phillips CFD discriminator
- All tests performed with PiLas red laser diode operating in single photoelectron mode by adding filters.

Hamamatsu C5594-44

1.5 GHz BW, 63x gain

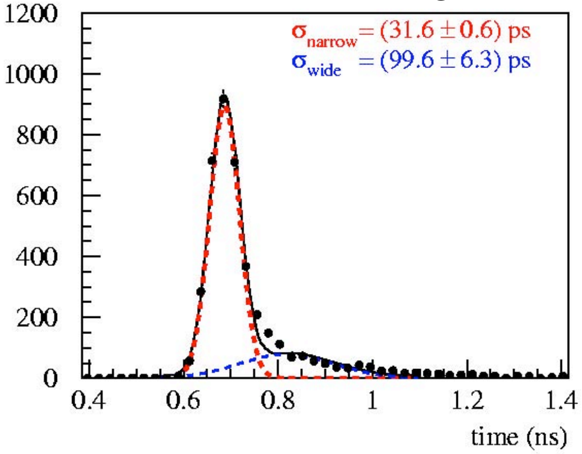
400ps/div, 100mV/div





Ortec VT120A with a 6dB att.

~0.4 GHz BW, 200x gain



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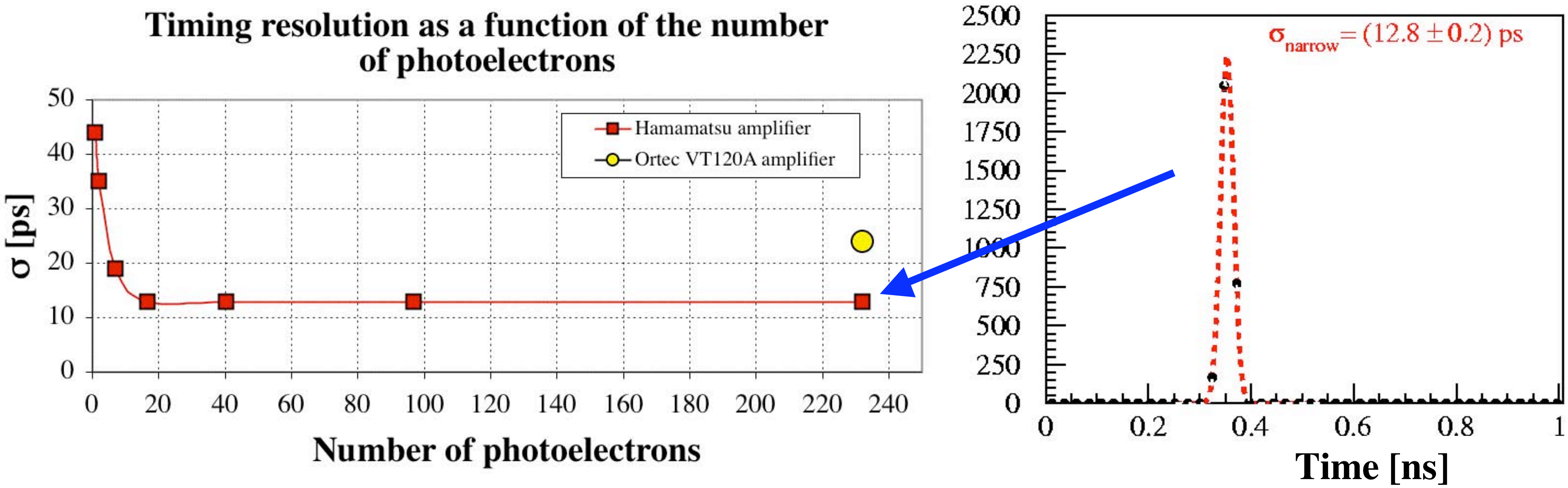
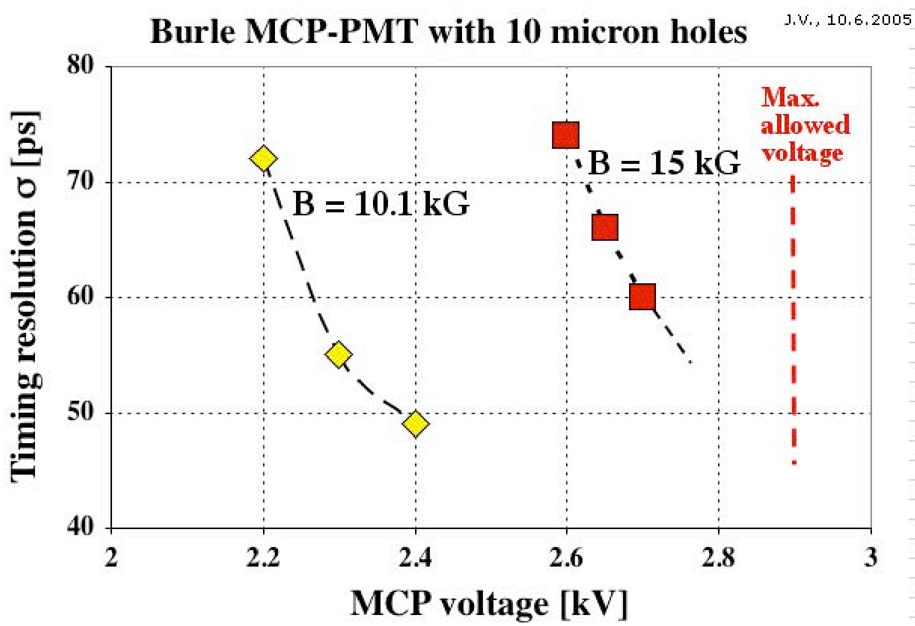
Timing resolution = f($N_{photoelectrons}$)



- **Achieved σ ~12 ps for N_{pe} >20 with the Hamamatsu C5594-44 amplifier, while the amplifier is operating in a saturated mode. Very similar results achieved with Ortec 9306 amp. Did not investigate the linear mode yet (att. before amplifier). Can use the saturated mode only if Npe is constant.**
- **However, with a slower VT120A, get worse result: σ ~ 23 ps for N_{pe} >20**

- **Resolution is** $\sigma_t \sim \sigma_A/(ds_o/dt)_{t=0}$, where σ_A is the noise, and $(ds_o/dt)_{t=0}$ is the slope at the zero-crossing point of CFD
- **In the "10ps timing resolution domain," the amplifier speed is crucial.**

Timing results at B = 15 kG



- **Single photoelectrons**
- **10μm hole 4-pad MCP-PMT**
- **Ortec VT-120A amp**

- **It is possible to reach a resolution of σ ~50ps at 15kG.**

Conclusions

- **New R&D on the Focusing DIRC shows promising results.**
- **I believe, the final results will be better than I presented.**
- **We have a new photon detector solution working at 15kG yielding a very impressive timing resolution.**

- **More running in July:**

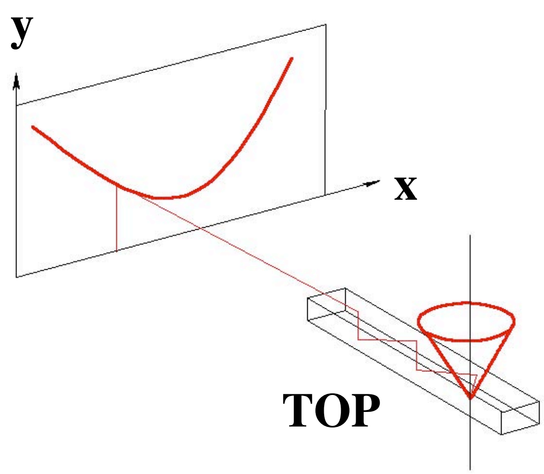
  - rectangular pixel geometry to minimize the pixilization effects
  - add more pixels

- **More running next year:**

  - push QE to red wavelengths via multi-alkali photocathodes.
  - test new electronics schemes (TDC & ADC vs. CFD &TDC)

Backup slides

Various approaches to imaging methods



BaBar DIRC: x & y & TOP

- x & y is used to determine the Cherenkov angle
- TOP iw used to reduce background only

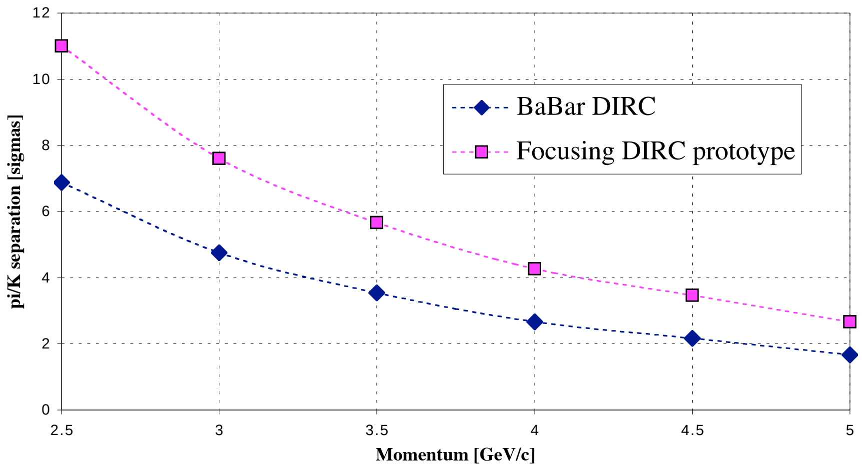
Focusing DIRC prototype: x & y & TOP

- x & y is used as in BaBar DIRC
- TOP can be used to determine the Cherenkov angle for longer photon paths (gives a better result)
- Requires large number of pixels

TOP counter: x & TOP

- x & TOP is used to determine the Cherenkov angle
- TOP could be used for an ordinary TOF
- In principle, more simple, however, one must prove that it will work in a high background environment

Expected performance of the prototype



- **Present BaBar DIRC:**
  - 2.7σ π/K separation at 4GeV/c
- **Focusing DIRC prototype:**
  - 2.7σ π/K separation at 5GeV/c
- **Focusing DIRC assumptions:**
  - optics to remove the bar thickness
  - similar efficiency as BaBar DIRC
  - improvements in the tracking accuracy
  - x&y pixels are used for Lpath <3-4 m.
  - TOP is used for Lpath > 3-4m.
  - The chromatic error is not improved by timing -1-2mrads effect.
  - Change a pixel size from the present 6 x 6 mm to 3 x 12 mm

Present BaBar DIRC : Error in θ_c

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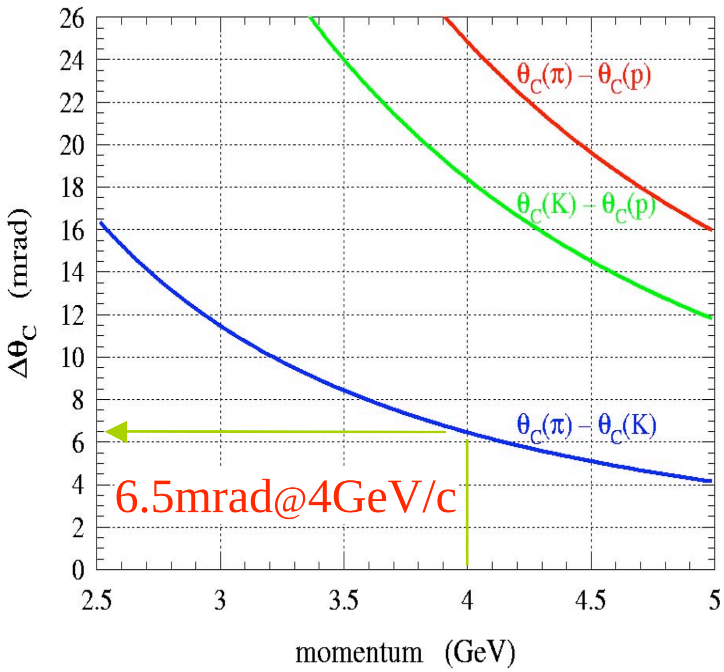


- **Per photon:**

- $\Delta\theta_{track}$ ~1 mrad
- $\Delta\theta_{chromatic}$ ~5.4 mrad
- $\Delta\theta_{transport\ along\ the\ bar}$ ~2-3 mrad
- $\Delta\theta_{bar\ thickness}$ ~4.1 mrad
- $\Delta\theta_{PMT\ pixel\ size}$ ~5.5 mrad

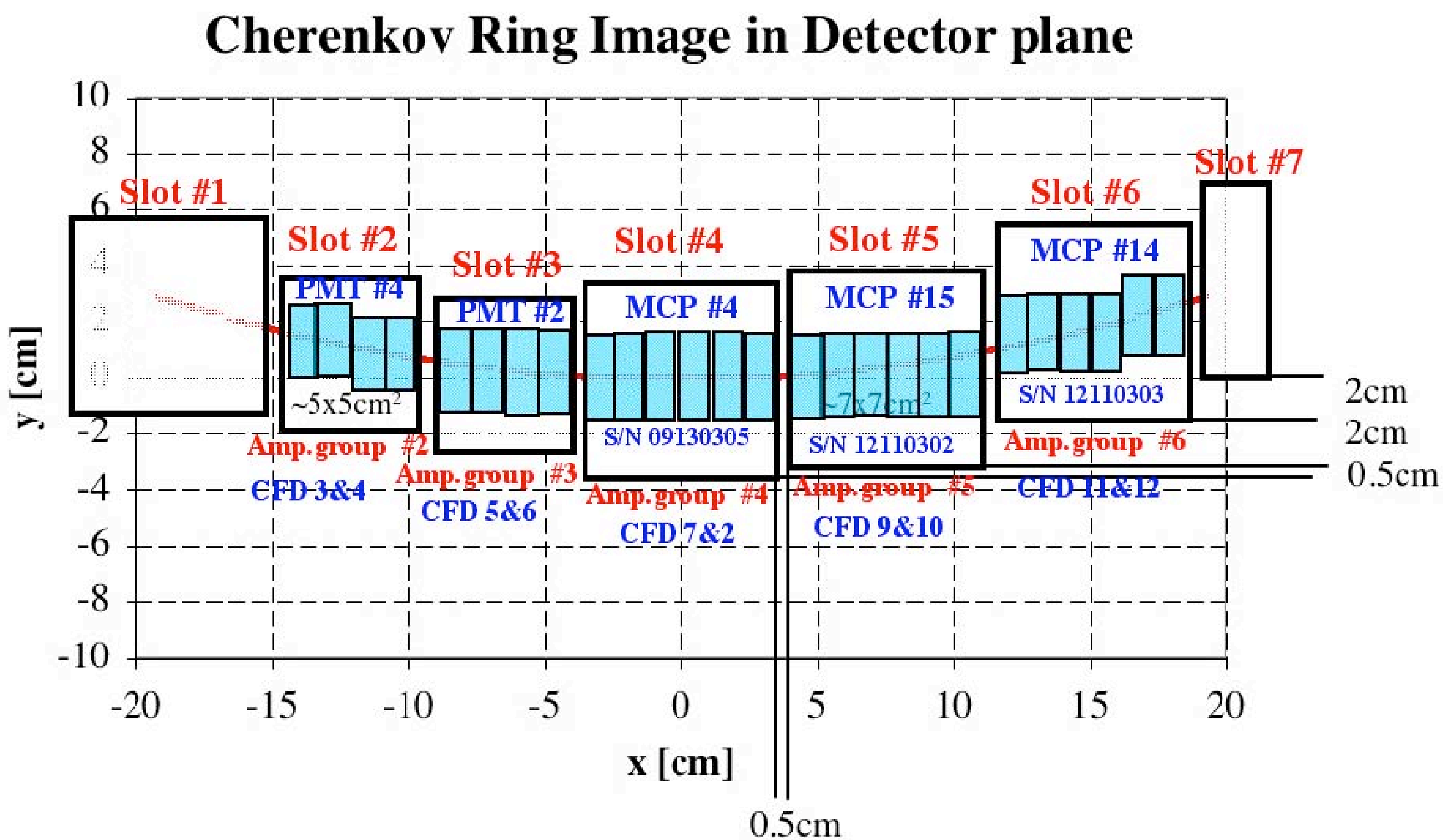
- Total: $\Delta\theta_c^{photon}$ ~ 9.6 mrad

- **Per track (N_{photon}~20-60/track):**

$$\Delta\theta_c^{track} = \Delta\theta_c^{photon}/\sqrt{N_{photon}} \otimes \Delta\theta_{track}$$

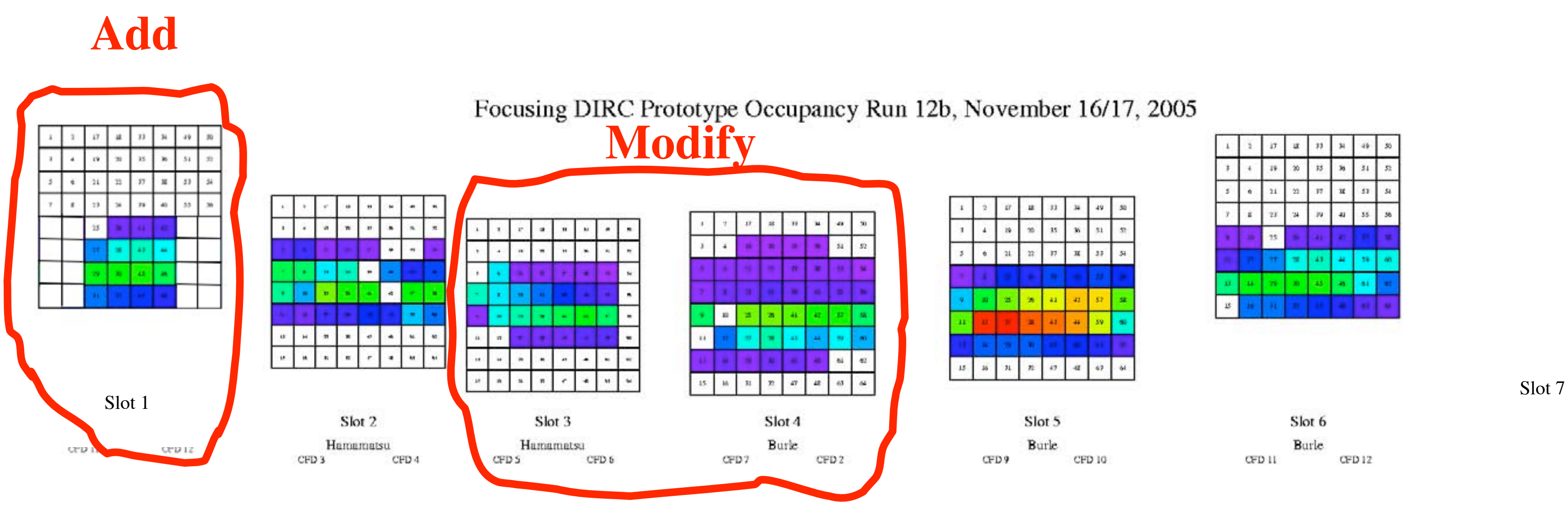
~ 2.4 mrad on average

Distribution of detectors on the prototype



- **3 Burle MCP-PMT and 2 Hamamatsu MaPMT detectors (~320 pixels active).**
- **Only pads around the Cherenkov ring are instrumented (~200 channels).**

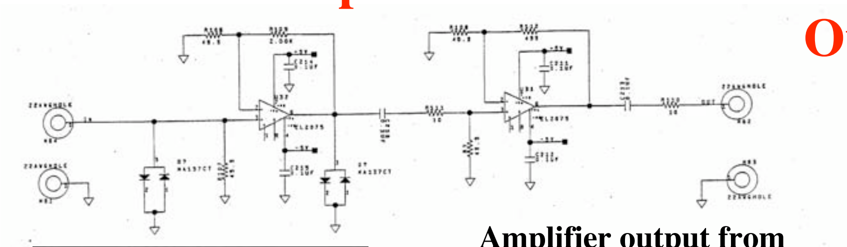
Modifications for the next run in July

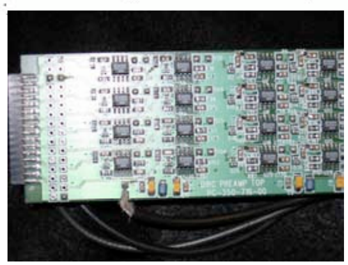


- **Add 32 new channels in slot 1**
- **Slot 1 will have Burle MCP-PMT with 6 mm x 6 mm pads**
- **Slot 3 will have a new Hamamatsu MaPMT with rectangular pads**
- **Slot 4 will have a new Burle MCP-PMT with rectangular pads**
- **Better TDC calibration over larger TDC range**
- **Some improvements in timing of Hamamatsu MaPMTs**

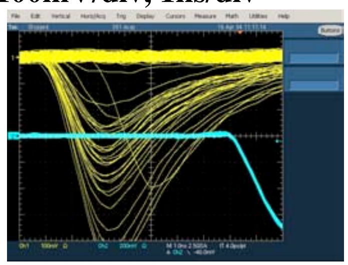
Focusing DIRC electronics

SLAC Amplifier:

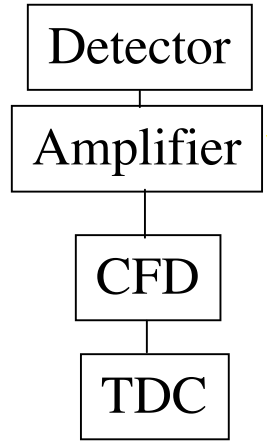




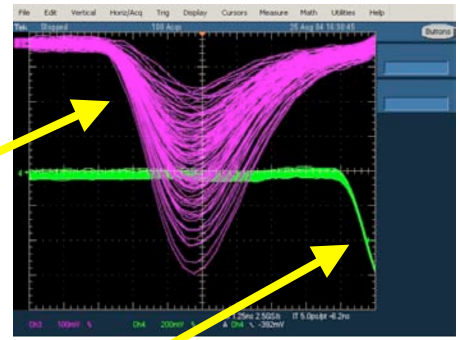
Amplifier output from MCP-PMT (trigger on PiLas), 100mV/div, 1ns/div



Overall chain:

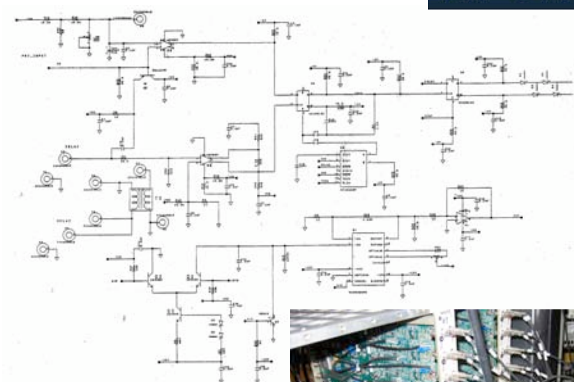


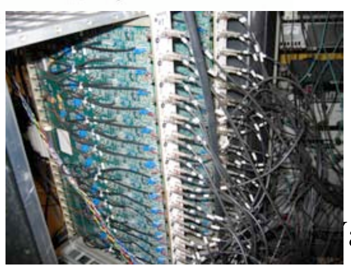
Amplifier outputs from MCP-PMT (trigger scope on CFD analog output), 100mV/div, 1ns/div



CFD analog pulse out

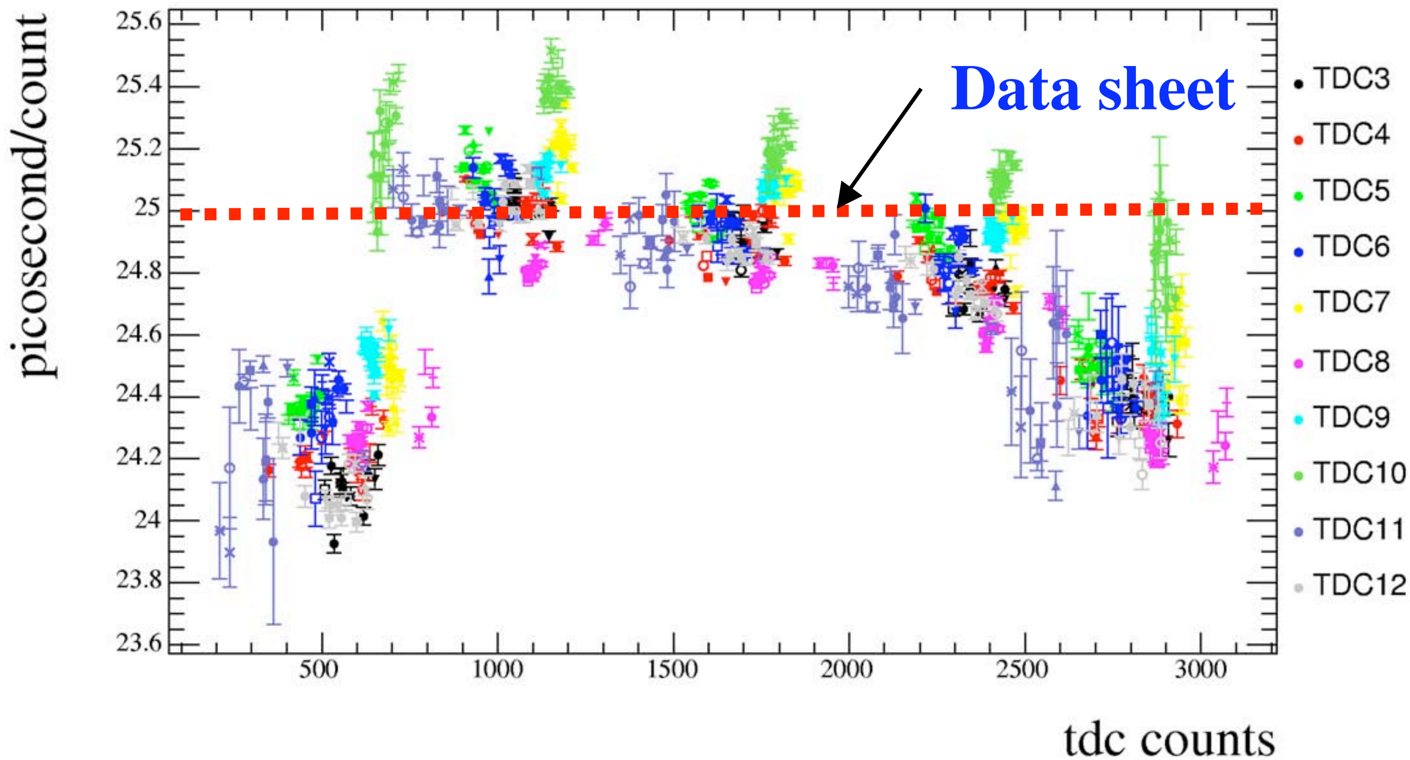
SLAC CFD & TAC:





- **Signals from Burle MCP-PMT #16, P/N 85011-430. PiLas laser diode is used as a light source, and as a TDC start/stop.**
- **Amplifier is based on two Elantek 2075EL chips with the overall voltage gain: ~130x, and a rise time of ~1.5ns.**
- **Constant-fraction-discriminator (CFD) analog output is available for each channel (32 channels/board), and can be used with any TDC for testing purposes (proved to be the essential feature for our R&D effort).**
- **Phillips TDC 7186, 25ps/count.**

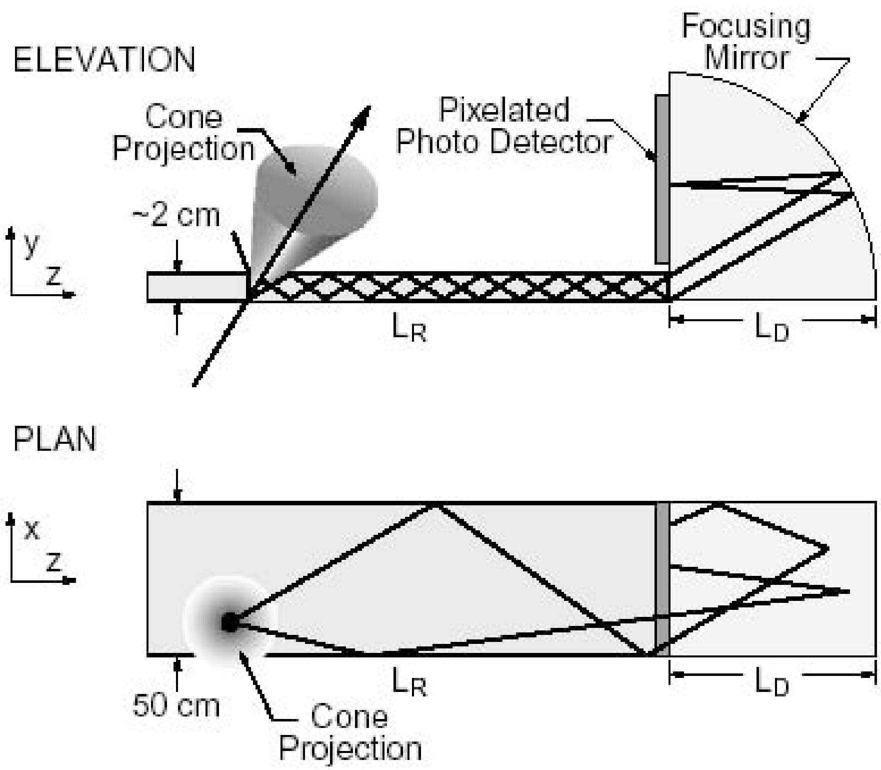
Phillips TDC calibration



- **Is it stable in time ? How often we have to measure this ?**
- The differential linearity measured with the calibrated cables. May have to automatize process with a precision digital delay generator if we get convinced.

Focusing DIRC detector - "ultimate" design

B. Ratcliff, Nucl.Instr.&Meth., A502(2003)211

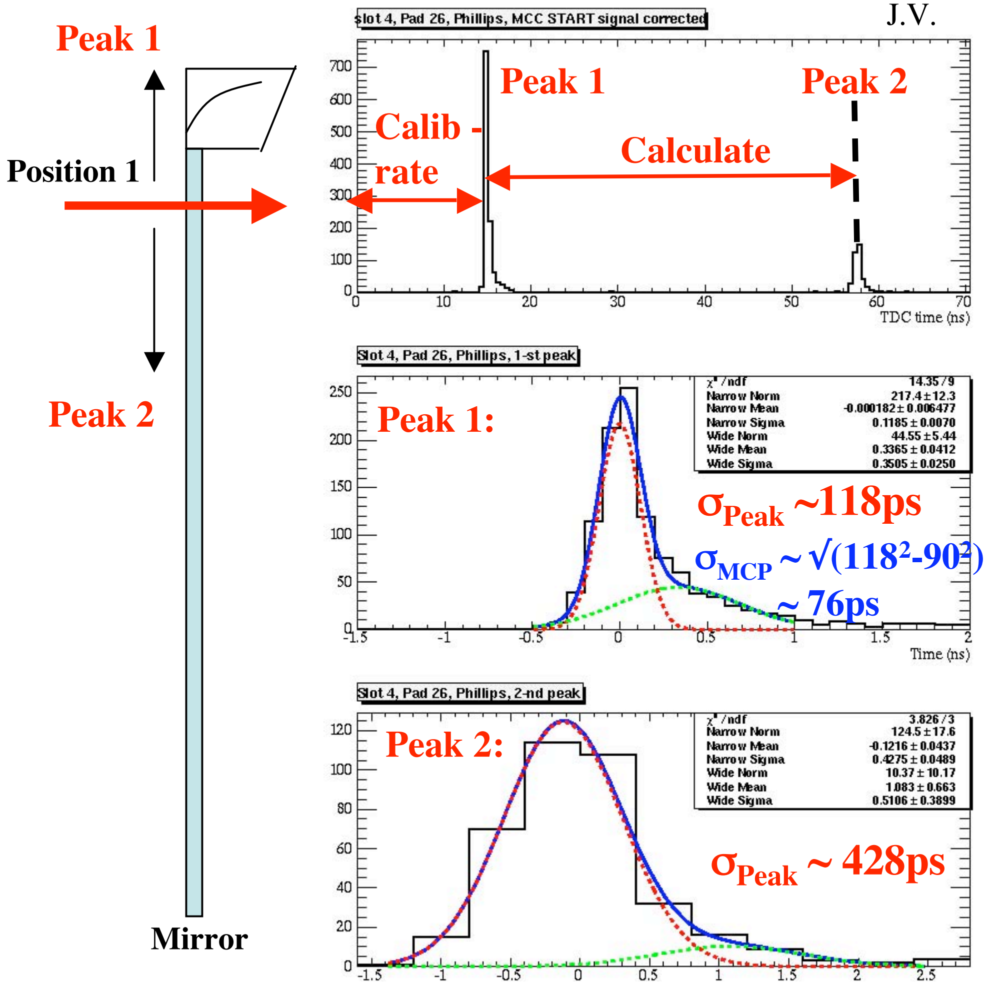


- **Goal: 3D imaging using x,y and TOP, and wide bars.**
- **The detector is located in the magnetic field of 15 kG.**

Chromatic broadening on the level of one pixel

Cherenkov photons:

Slot 4, single pixel #26,



ΔTOP = TOP_measured (λ) - TOP_expected (λ = 410 nm) [ns]

- **The largest chromatic effect is in the position 1**
- **Peak 1: ~81cm photon path length**
  Peak 2: ~930cm photon path length
- Measure time-of-propagation (TOP)
- Calculate expected TOP using average λ = 410nm.
- Plot $\Delta TOP = TOP_{measured} - TOP_{expected}$
- **Many corrections needed:**
  - MCP cross-talk
  - thermal time drifts
  - cable offsets (PiLas)
  - TDC calibration(PiLas)
  - geometry tweaks
- **Observe a clear chromatic broadening of the Peak 2 photons.**