Focusing DIRC R&D

J. Va'vra, SLAC

Collaboration to develop the Focusing DIRC:

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Content

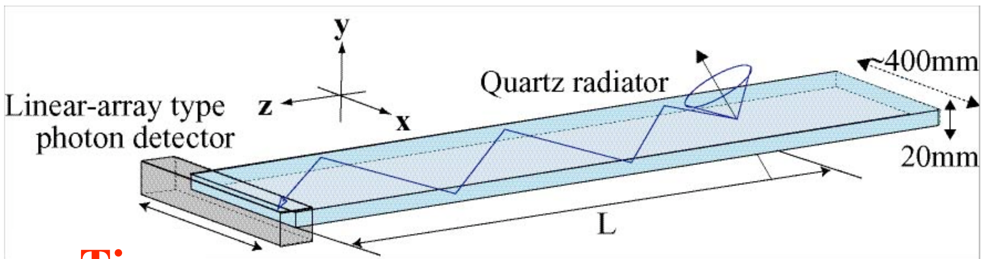
- Prototype design
- Test beam results
- Future steps

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

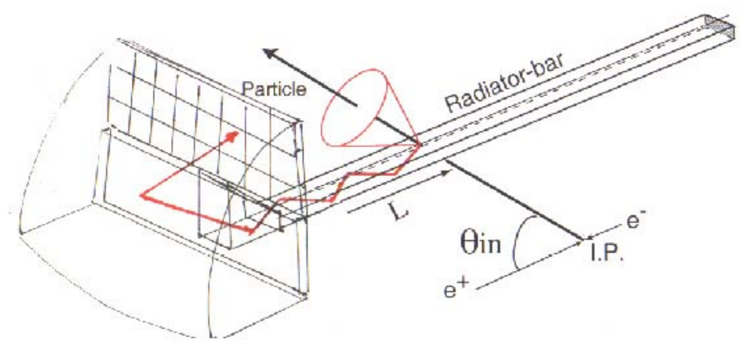
TOP counter (Nagoya):



x, Time

- **2D imaging:**
  a) x-coordinate
  b) TOP ($\sigma \leq$ 70ps).

Focusing DIRC prototype (SLAC):

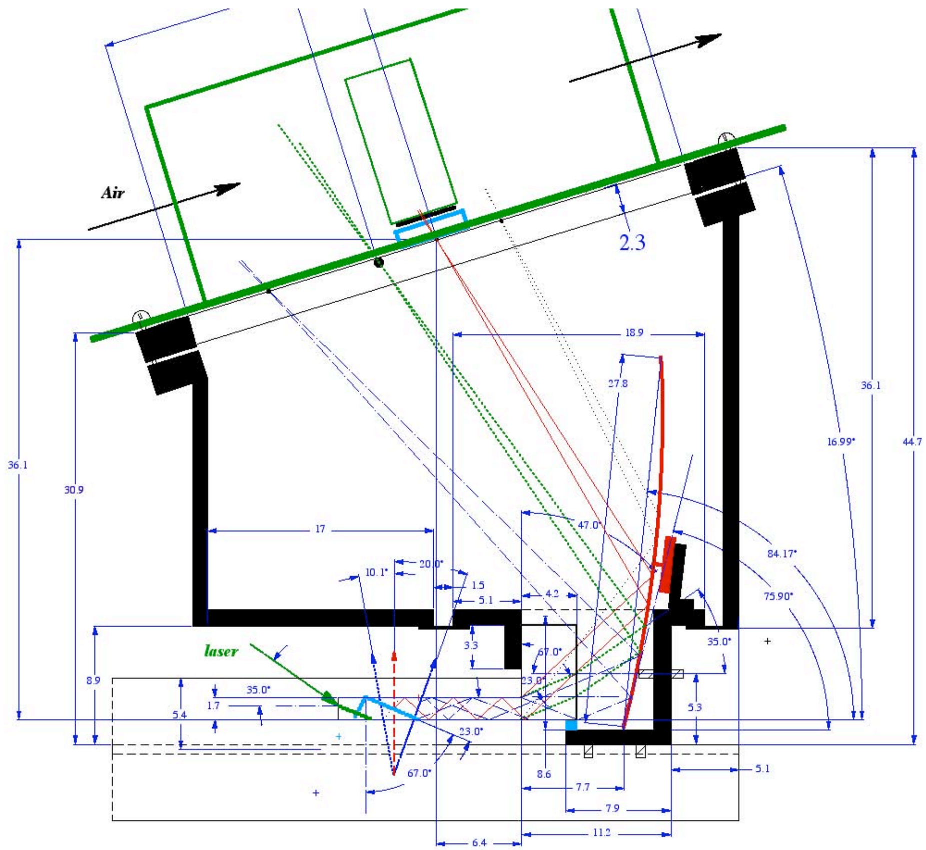


x, y, Time

- **3D imaging:**
  a) x-coordinate
  b) y-coordinate
  c) TOP ($\sigma \leq$ 150ps).

Focusing DIRC prototype design

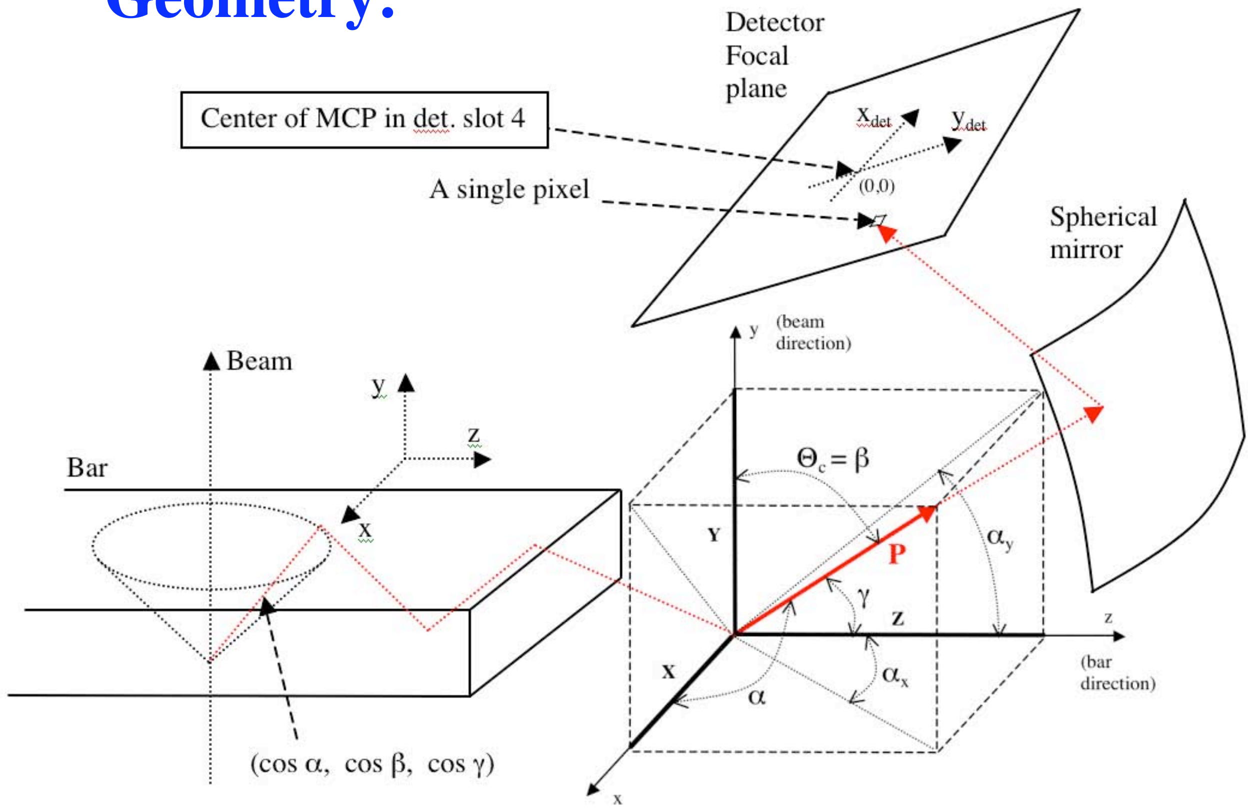
Design by ray tracing:

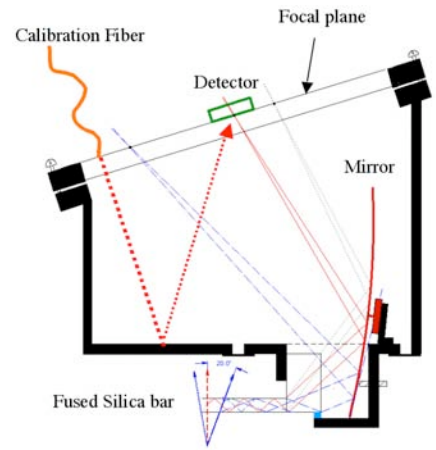


- The Focusing DIRC prototype optics was designed using the ray tracing method with a help of the mechanical design program (no Monte Carlo available in early stages !!).
- The focal plane adjusted to an angle convenient for easy work
- Space filled with oil.
- **Red line** (with oil) - running in the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

Photon path reconstruction

Geometry:

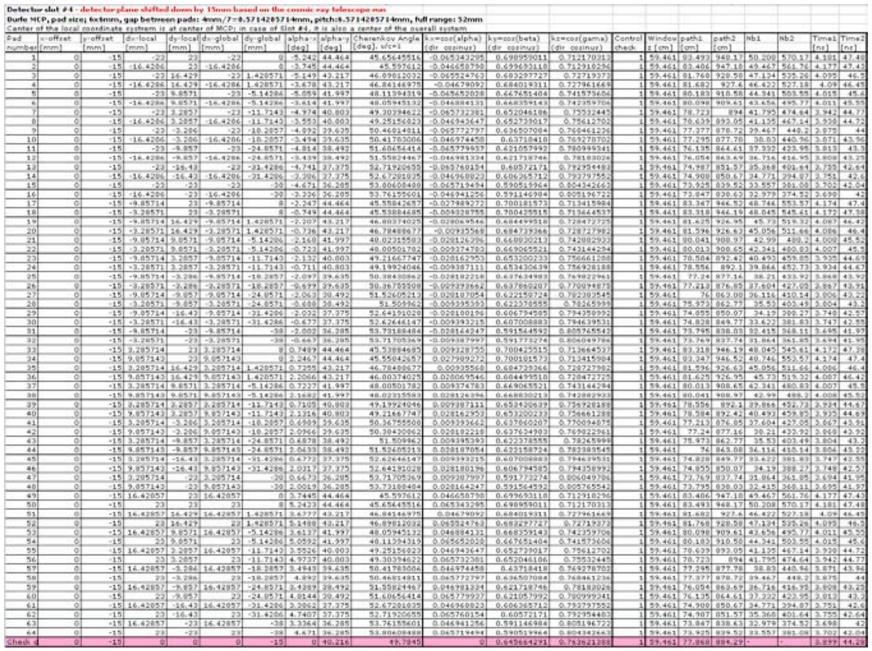




- **Each detector pixel determines these photon parameters:**
  θ_c, α_x, α_y, cos α, cos β, cos γ, L_{path}, $t_{propagation}$, $n_{bounces}$ – for aveerage λ

($t_{propagation}$= TOP)

Initial edsign with a spreadsheet calculation



Pad number	x-offset [mm]	y-offset [mm]	dx-local [mm]	dy-local [mm]	dx-global [mm]	dy-global [mm]	alpha-x [deg]	alpha-y [deg]	Cherenkov Angle [deg], v/c=1	kx=cos(alpha) (dir cosinus)	ky=cos(beta) (dir cosinus)	kz=cos(gama) (dir cosinus)	Control check	Window z [cm]	path1 [cm]	path2 [cm]	Nb1	Nb2	Time1 [ns]	Time2 [ns]
1	0	-15	-23	23	-23	0	-5.242	44.464	45.65645516	-0.065343295	0.690959011	0.712170313	1	59.461	83.493	948.17	50.208	570.17	4.181	47.48
2	0	-15	-16.4286	23	-16.4286	0	-3.745	44.464	45.597612	-0.046650798	0.699693118	0.712910296	1	59.461	83.406	947.18	49.467	561.76	4.177	47.43
3	0	-15	-23	16.429	-23	1.428571	-5.149	43.217	46.09012032	-0.065524763	0.683297727	0.7271937	1	59.461	81.768	928.58	47.134	535.26	4.095	46.5
4	0	-15	-16.4286	16.429	-16.4286	1.428571	-3.678	43.217	46.84146975	-0.04679092	0.684019311	0.727961669	1	59.461	81.682	927.6	46.422	527.18	4.09	46.45
5	0	-15	-23	9.8571	-23	-5.14286	-5.059	41.997	48.11394319	-0.065652038	0.667651404	0.741573606	1	59.461	80.183	910.58	44.341	503.55	4.015	45.6
6	0	-15	-16.4286	9.8571	-16.4286	-5.14286	-3.614	41.997	48.05945132	-0.046884131	0.668359143	0.742359706	1	59.461	80.098	909.61	43.656	495.77	4.011	45.55
7	0	-15	-23	3.2857	-23	-11.7143	-4.974	40.803	49.30394622	-0.065732381	0.652046186	0.75532445	1	59.461	78.723	894	41.795	474.64	3.942	44.77
8	0	-15	-16.4286	3.2857	-16.4286	-11.7143	-3.553	40.803	49.25156823	-0.046943647	0.652739017	0.75612702	1	59.461	78.639	893.05	41.135	467.14	3.938	44.72
9	0	-15	-23	-3.286	-23	-18.2857	-4.892	39.635	50.46814811	-0.065772797	0.636507004	0.768461236	1	59.461	77.377	878.72	39.467	448.2	3.875	44

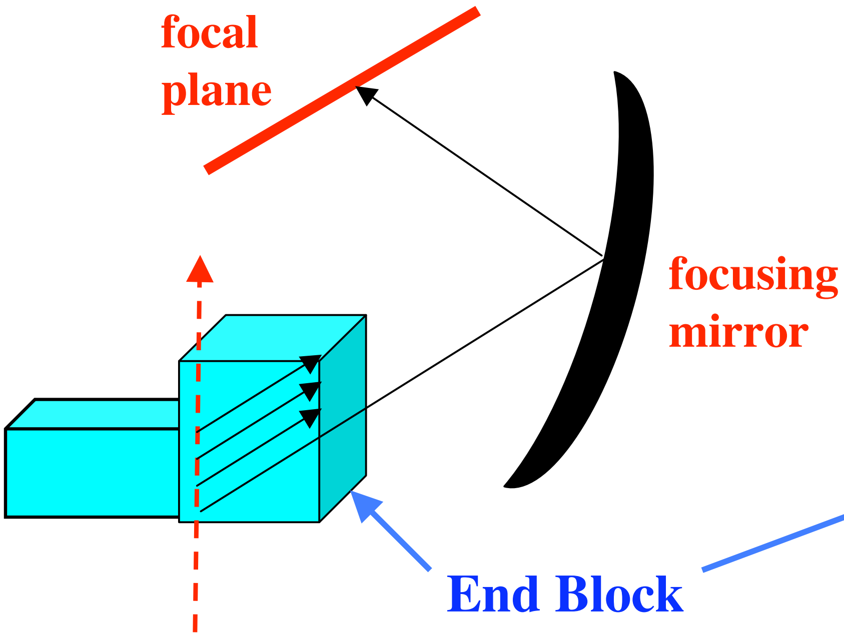
- **Each pad predicts the photon propagation history** **for average λ of ~ 410nm**.
- **Example - detector slot #4, pad #26, beam in position #1**:

  $\theta_c = 47.662^o$, $L_{path\ 1} = 80.447$ 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
- **Error in detector plane of 1mm in y-direction will cause this systematic shift:**

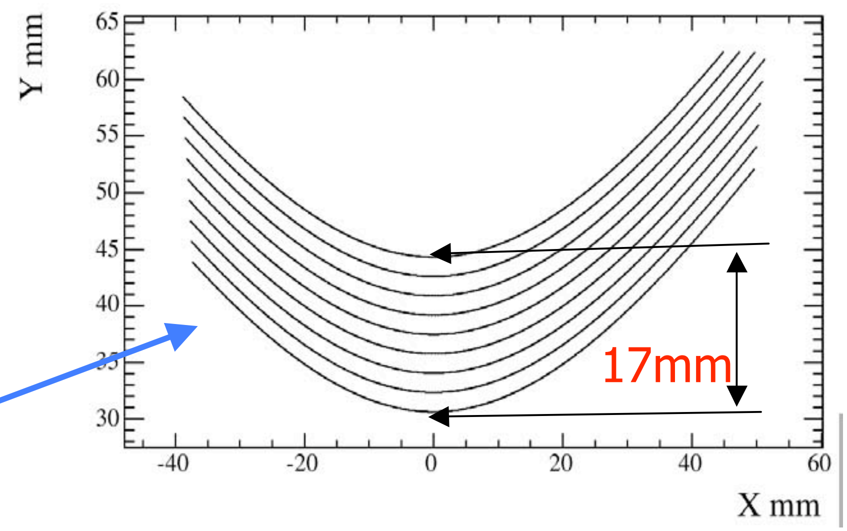
  $\Delta\theta_c$ ~3mrad, $\Delta L_{path\ 1}$ ~2.2mm, $\Delta t_{path\ 1}$ ~11ps, $\Delta L_{path\ 2}$ ~24.5mm, $\Delta t_{path\ 2}$ ~123ps, ΔT (|Peak2-Peak1|) ~112ps

Rings from outside bar are well focused

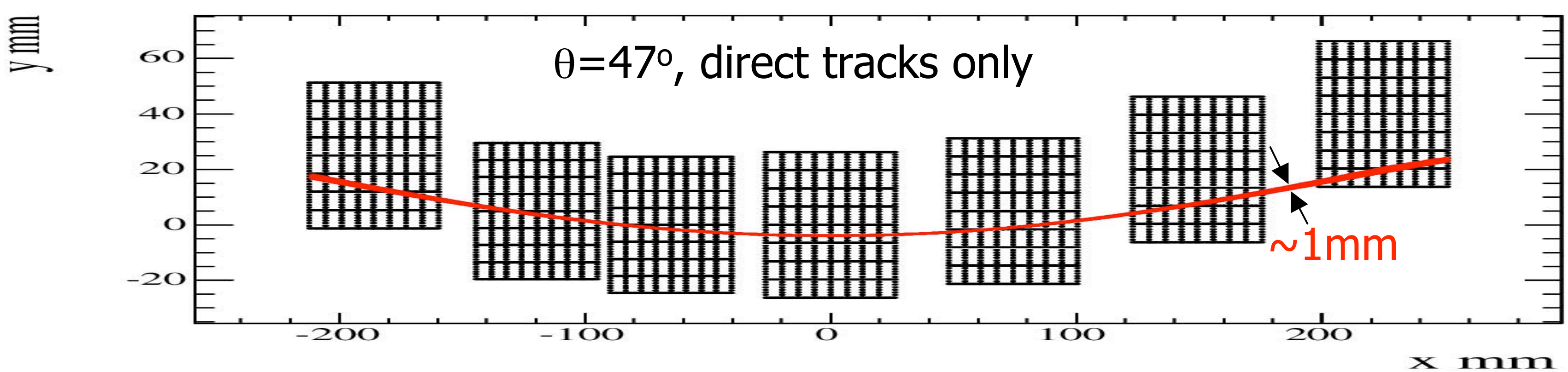
(Jose Benitez independent check of the focusing design)



Ring images at the End Block:

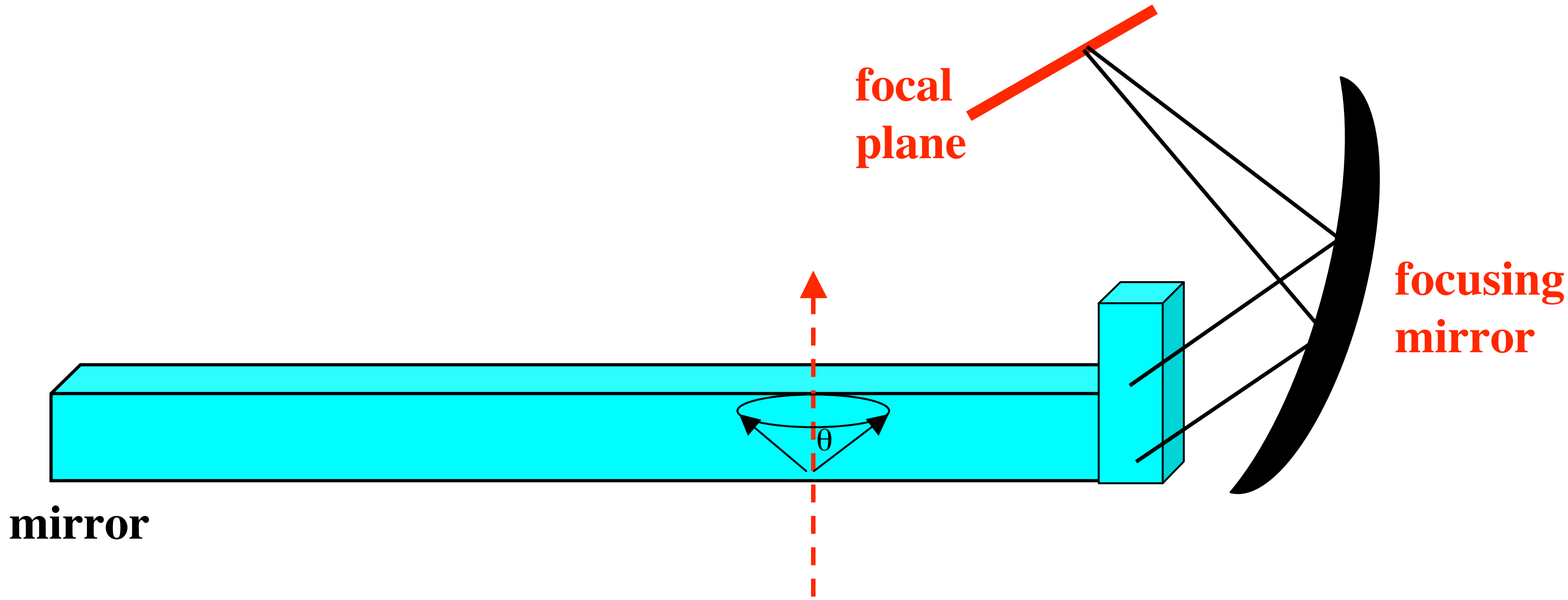


Cherenkov rings in the detector focal plane:

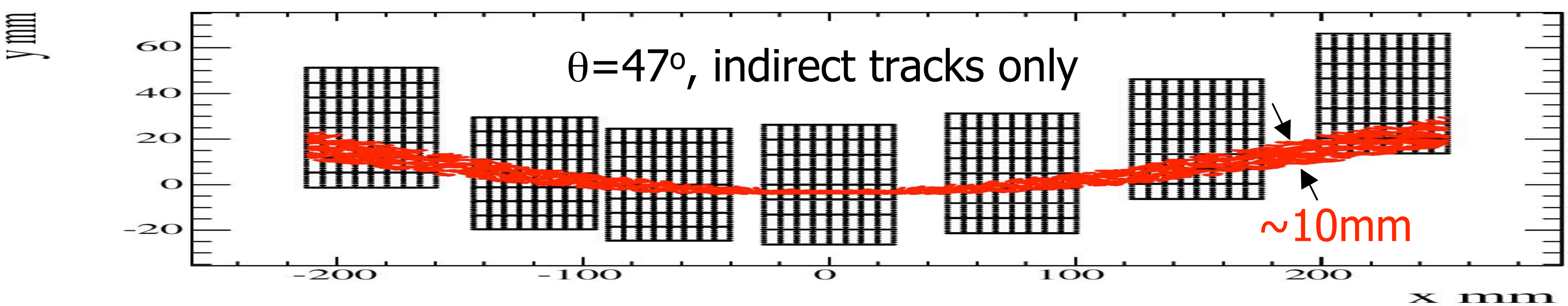


Rings from bar are blurred in outer slots

(Jose Benitez)

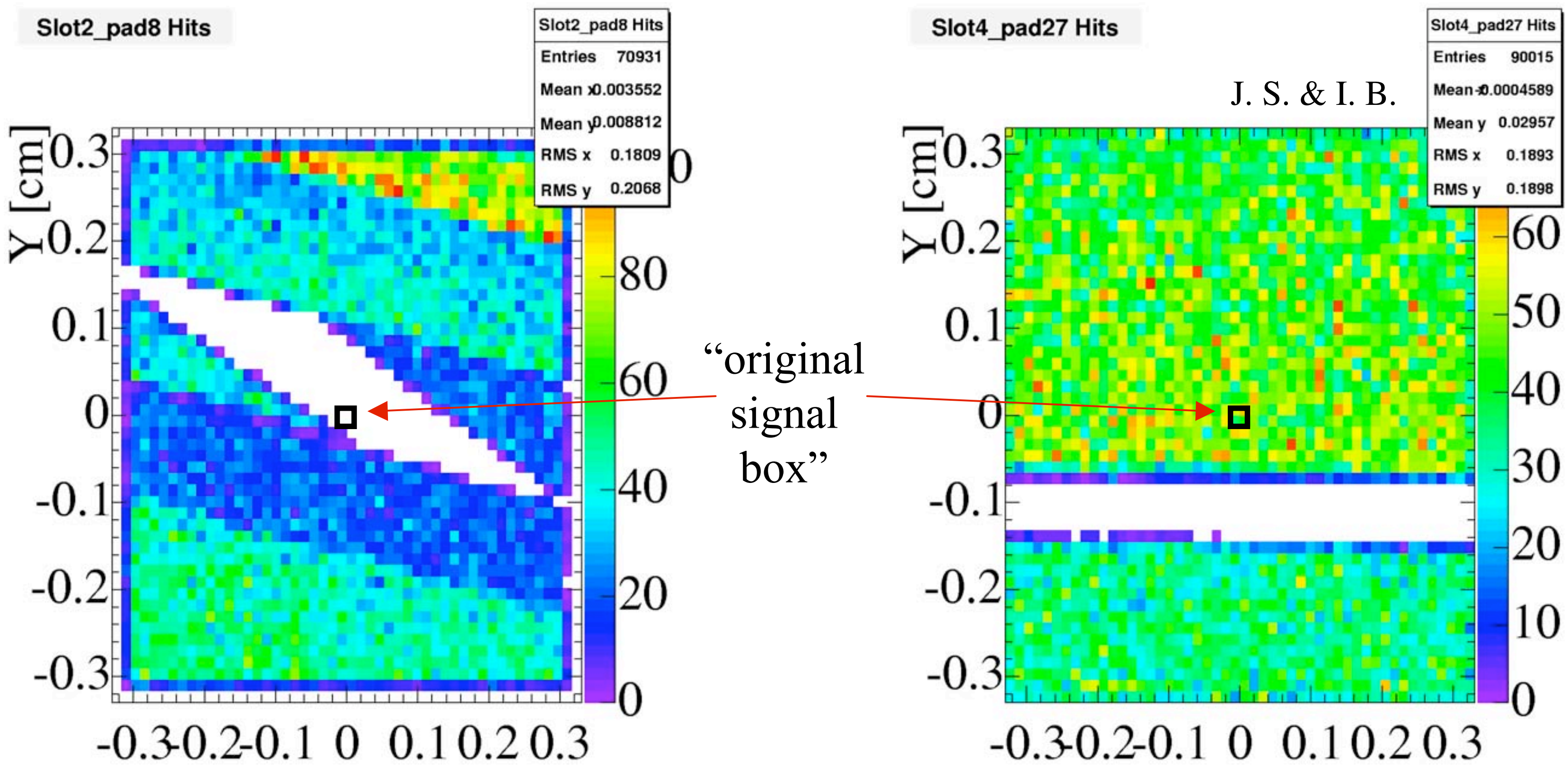


Cherenkov ring image ray traced from inside the bar is blurred in the outer slots - this is a bar effect.



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

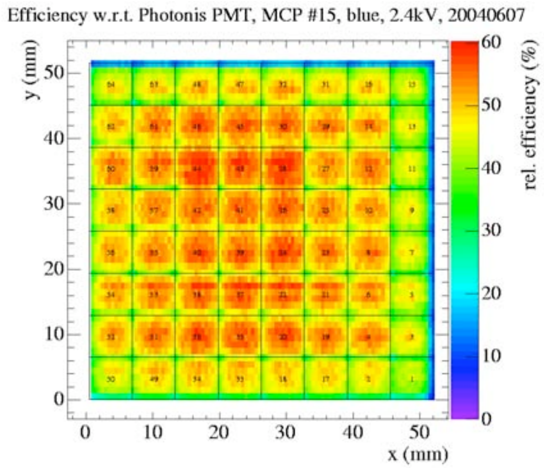
- **Bar introduces kaleidoscopic images on the pads**
- **This effect shows up only in the test beam (in BaBar, one would integrate it out)**
- **One needs a MC to understand effects like this.**



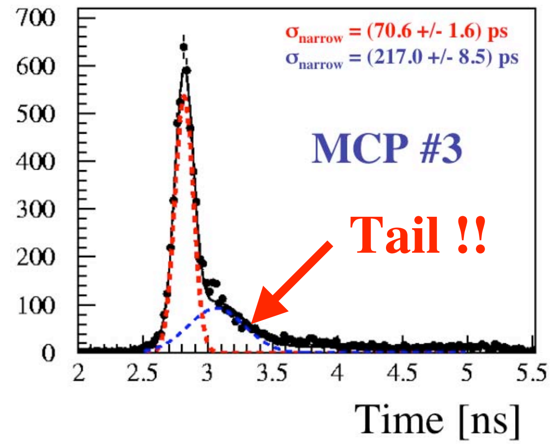
Photon detectors in the prototype (σ~70-150ps)

Burle MCP PMT (64 pixels):

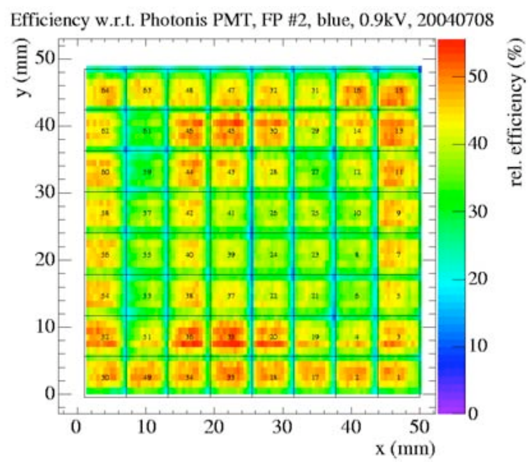
PiLas single pe calibration:



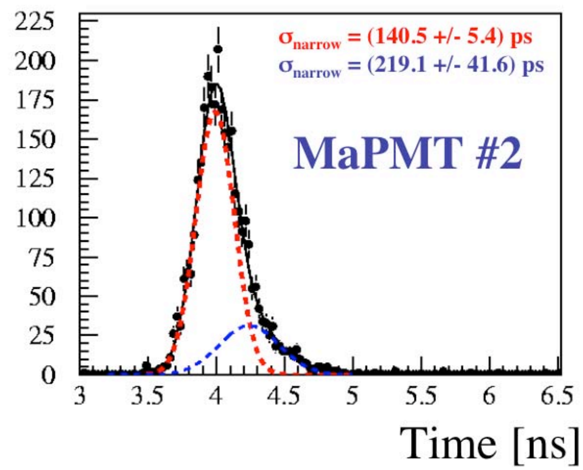
Burle 85011-501 MCP-PMT:



Hamamatsu MaPMT (64 pixels):



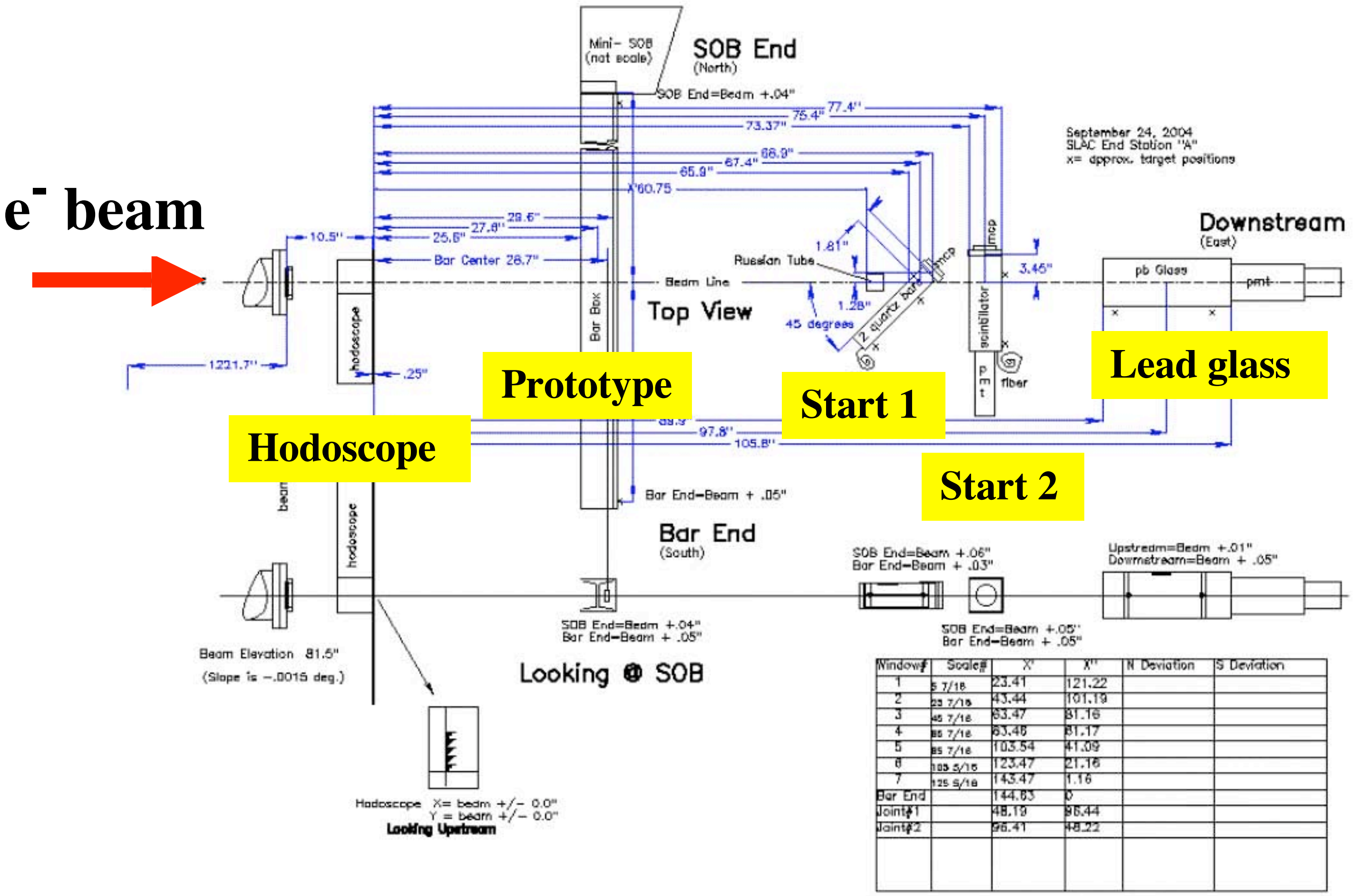
Hamamatsu Flat Panel H8500 PMT:



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



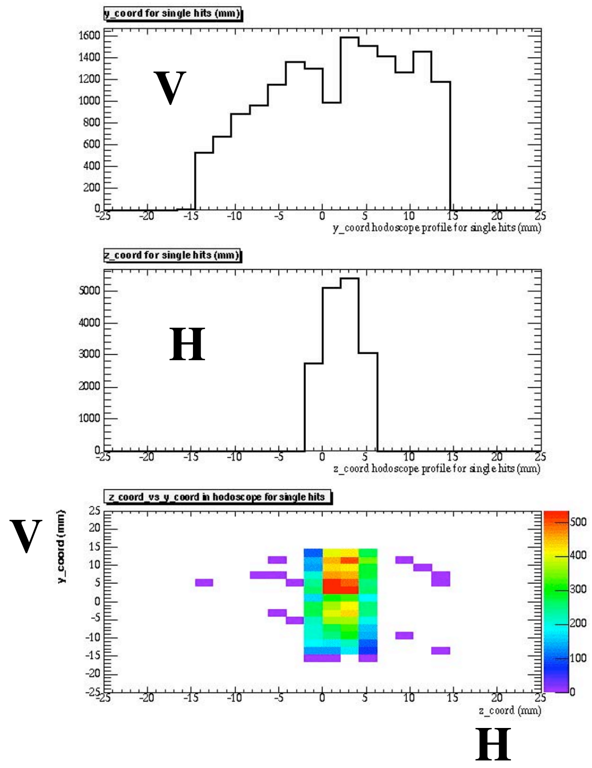
Window#	Scale#	X'	X''	N Deviation	S Deviation
1	5 7/16	23.41	121.22		
2	25 7/16	43.44	101.19		
3	45 7/16	63.47	81.16		
4	65 7/16	63.46	81.17		
5	85 7/16	103.54	41.09		
6	105 5/16	123.47	21.16		
7	125 5/16	143.47	1.16		
Bar End		144.63	0		
Joint#1		48.19	96.44		
Joint#2		96.41	48.22		

- 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

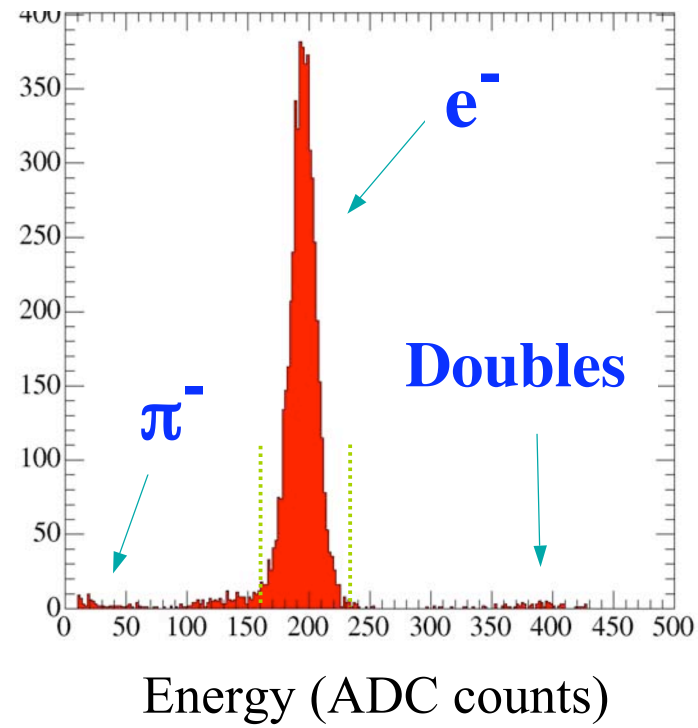
Definition of a good beam trigger

Run 2

Single hodoscope hits only:



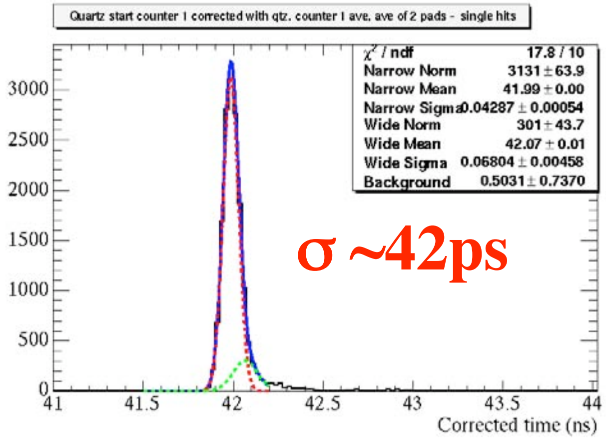
Lead glass:



- **<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.**

1. Start counter 1 - Double-quartz counter

Average of 2 pads:

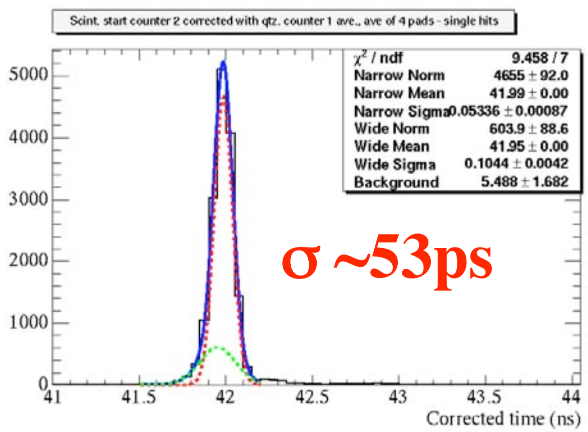


4-pad Burle MCP-PMT:

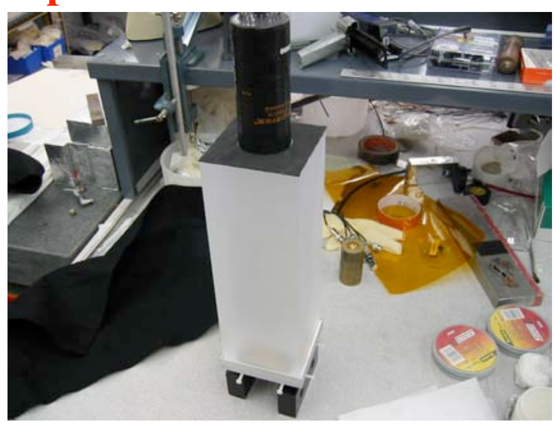
Local START Counters:

2. Start counter 2 - Scintillator counter

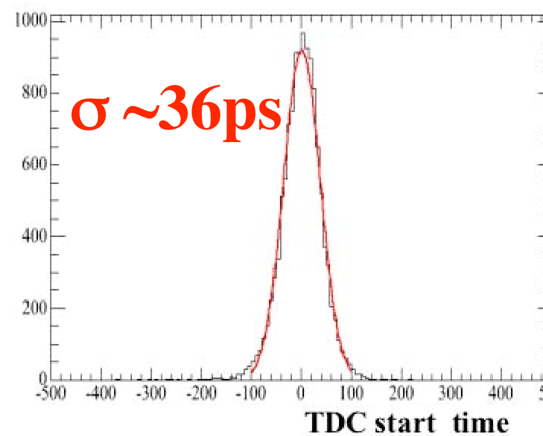
Average of 4 pads:



4-pad Burle MCP-PMT :



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



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

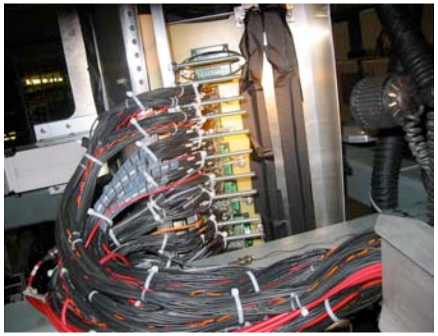
Focusing DIRC prototype

Setup in End Station A: movable bar support and hodoscope

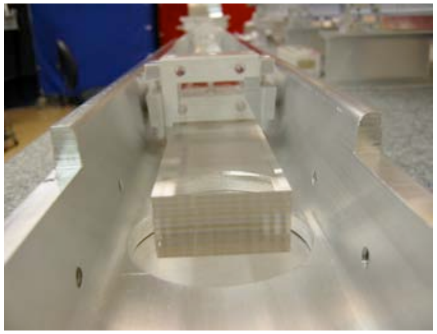
Setup in End Station A

Electronics and cables

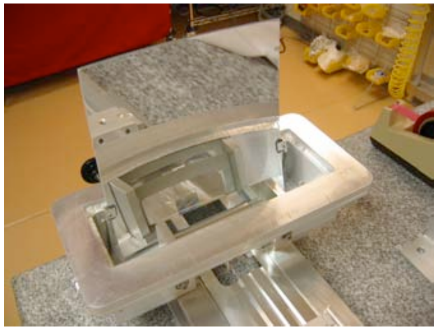
Photodetector backplane



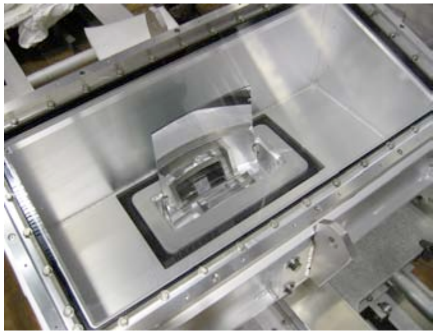
Radiator bar



Mirror



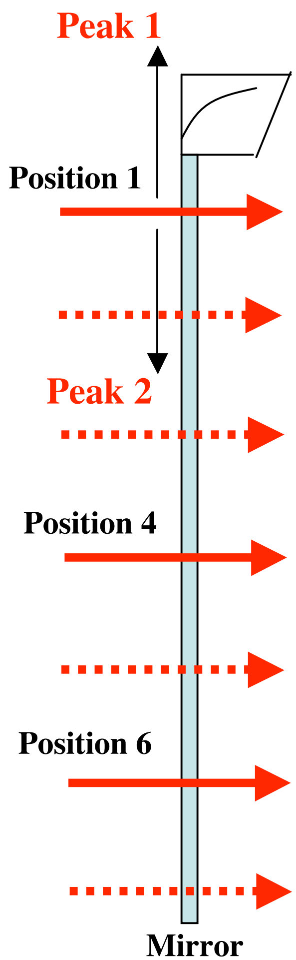
Oil-filled detector box:

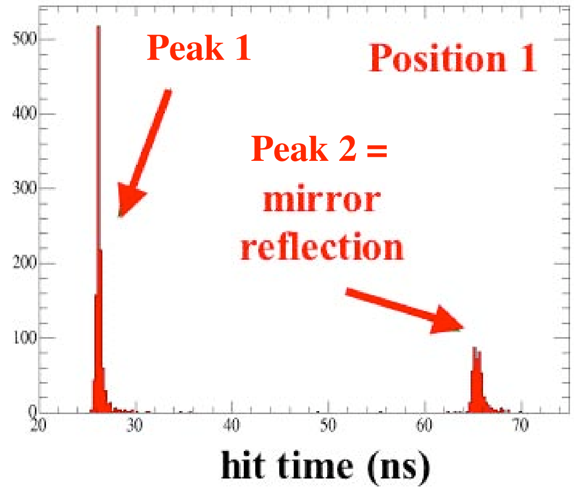


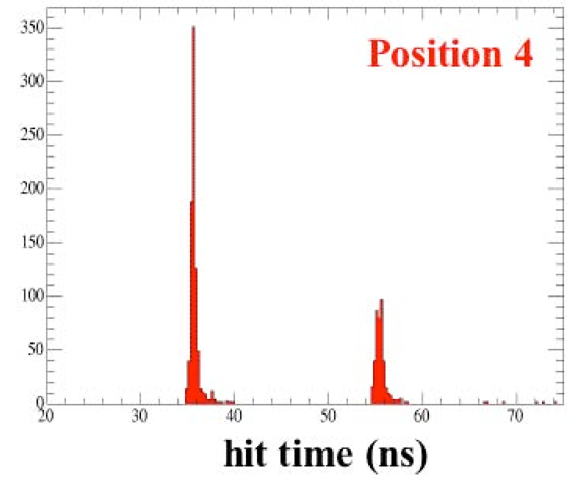
Start counters, lead glass

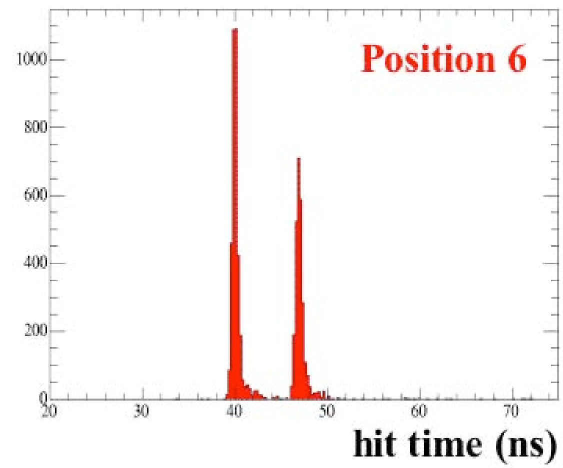
Cherenkov ring in the time domain

Pixel #25, Slot #4



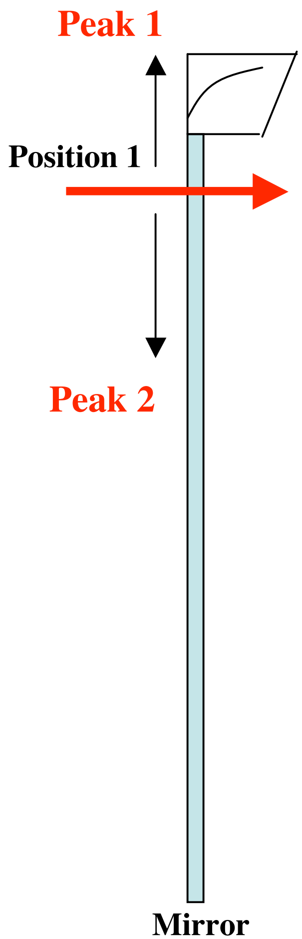


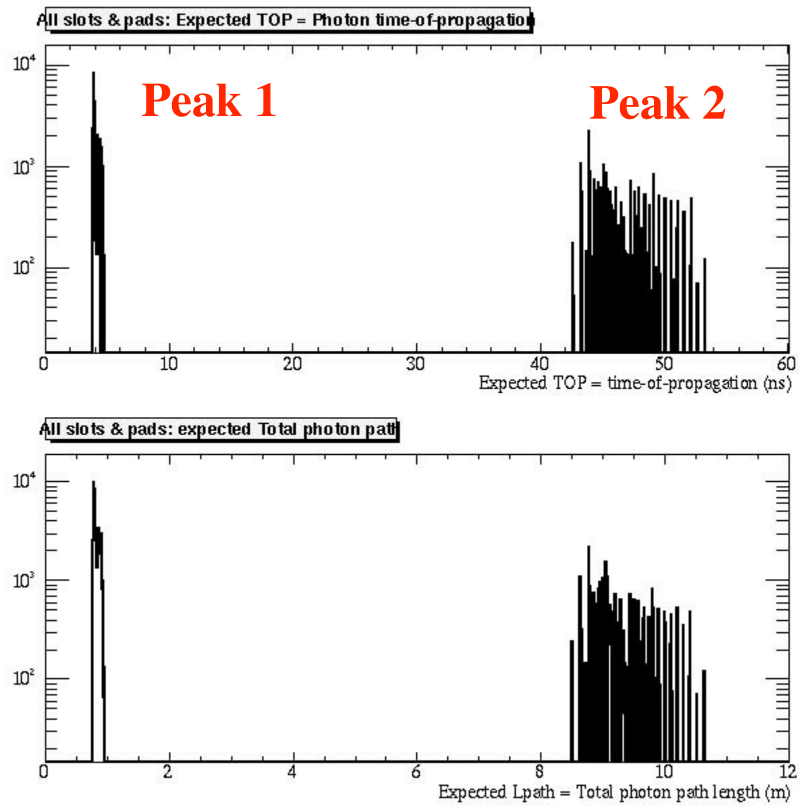




- Two peaks correspond to forward and backward part of the Cherenkov ring.

Typical distribution of TOP and Lpath





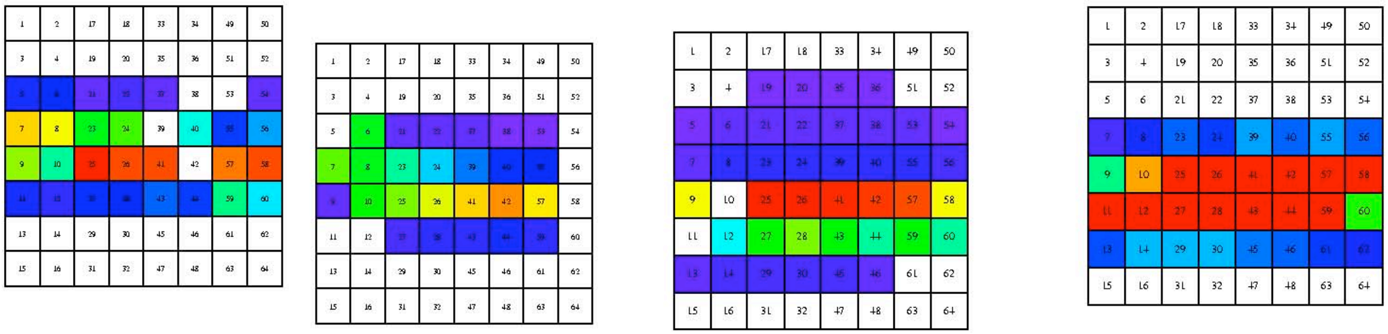
TOP [ns]

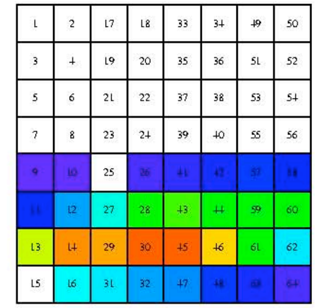
Lpath [m]

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

Cherenkov Angle resolution in the pixel domain

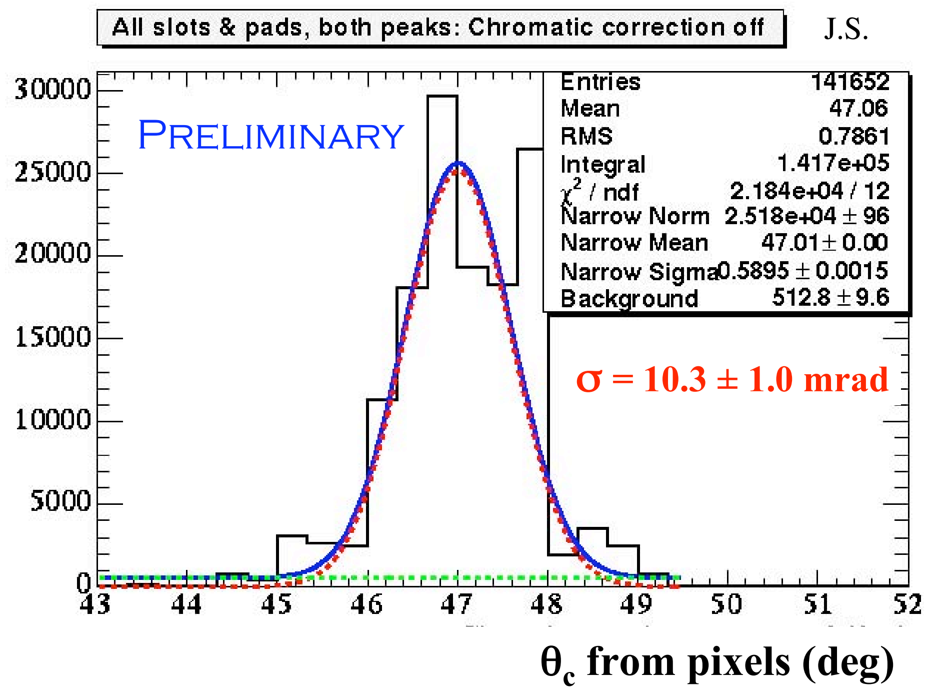
Occupancy for accepted events in one run, 400k triggers, 28k events





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

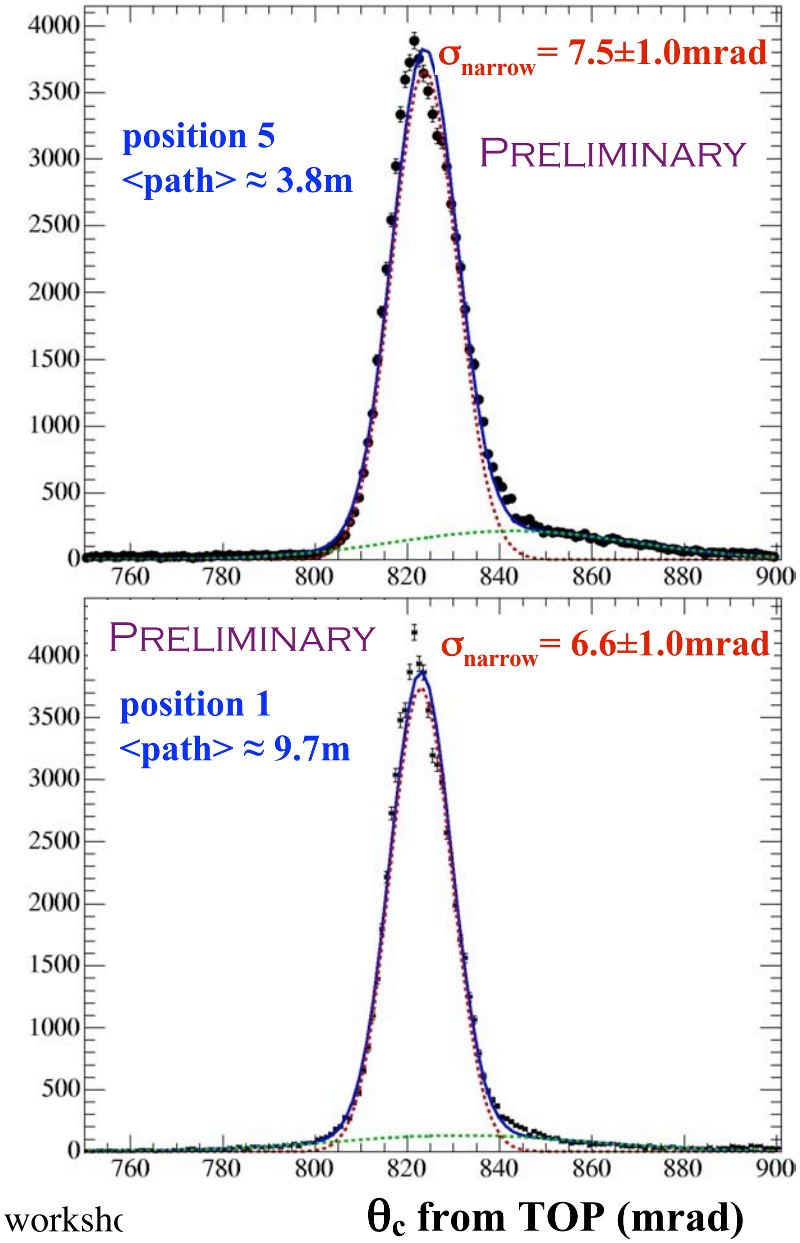


Cherenkov Angle resolution in the time domain

J.S.

Method:

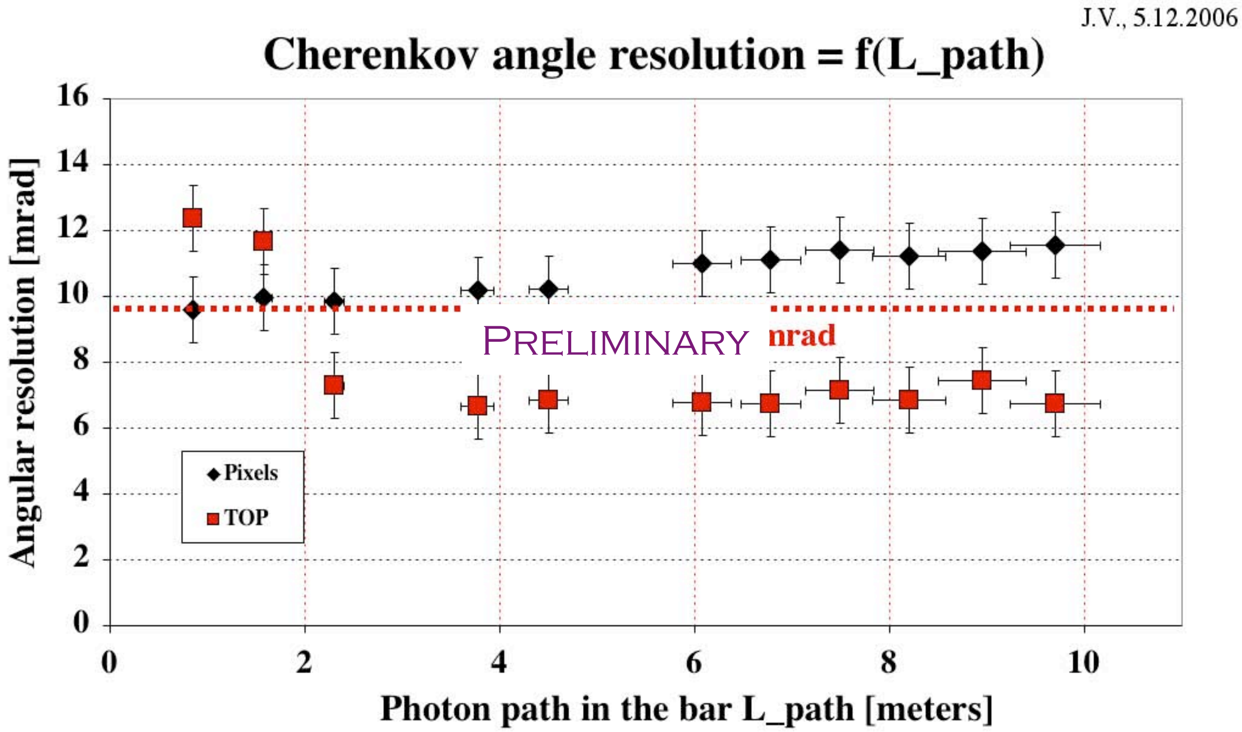
- Use measured **TOP** for each pixel
- Combine with calculated photon path in radiator bar - **Lpath**
- Calculate group index: $n_G(\lambda) = c_o \cdot$ **TOP / Lpath**
- Calculate phase refractive index $n_F(\lambda)$ from group index $n_G(\lambda)$
- Calculate photon Cherenkov angle Θ_c (assuming $\underline{\beta = 1}$): $\theta_c(\lambda) = \cos^{-1}(1/n_F(\lambda))$
- **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.

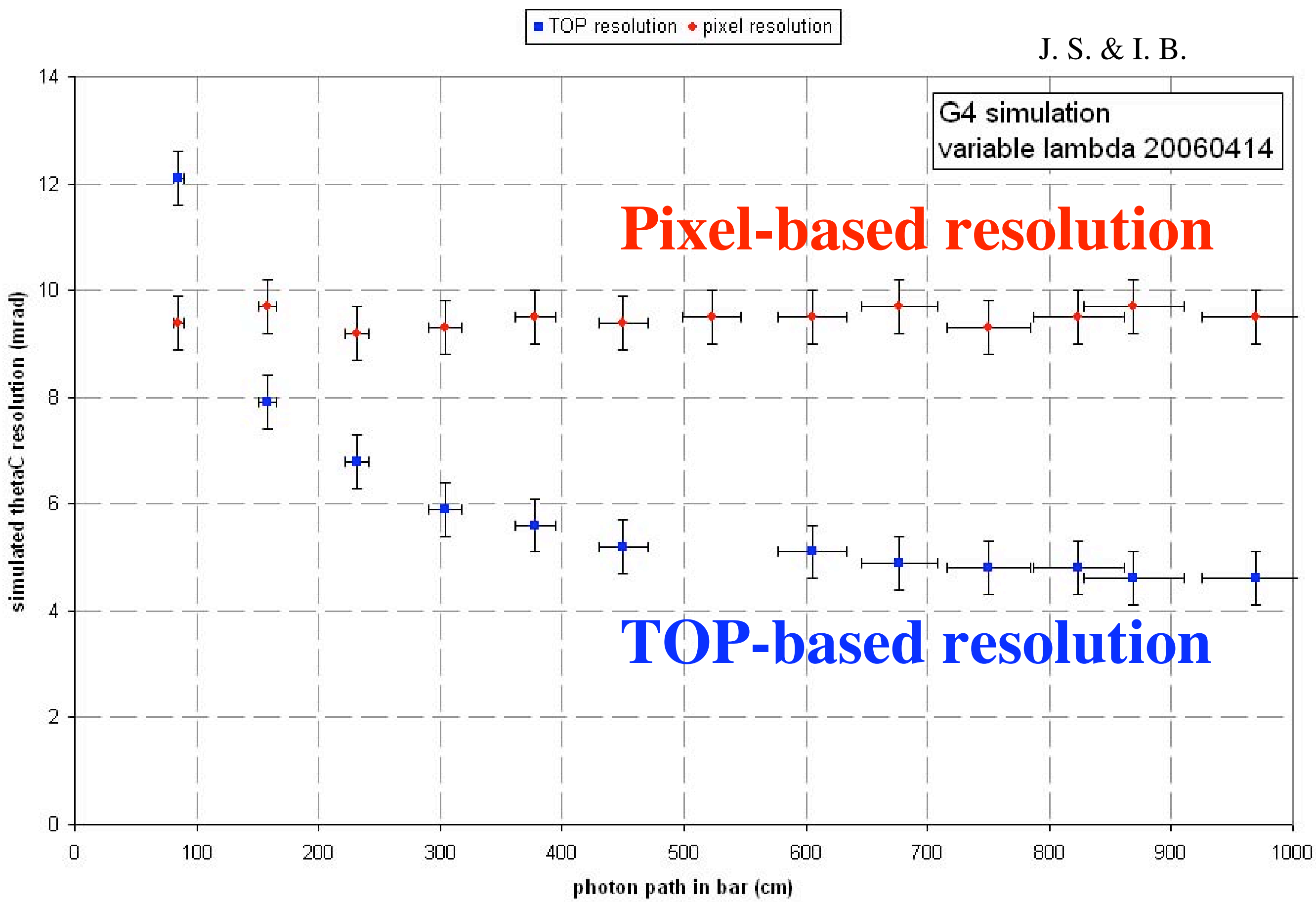
Θ_c resolution from time of propagation (TOP) improves rapidly with path length, reaches plateau at ~7mrad after 3-4 meters photon path in bar.



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.

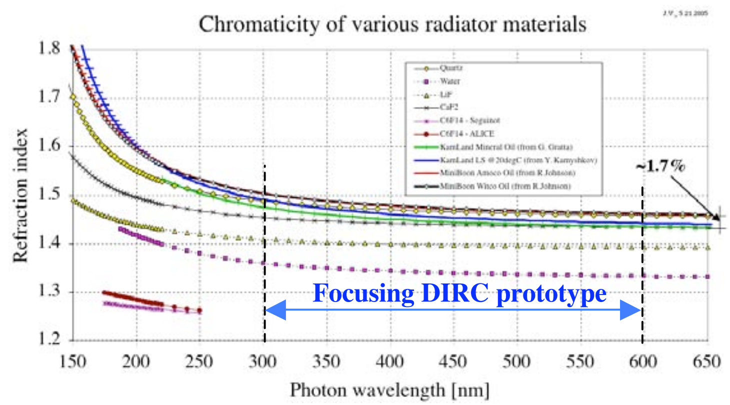
Geant 4 MC simulation of the prototype

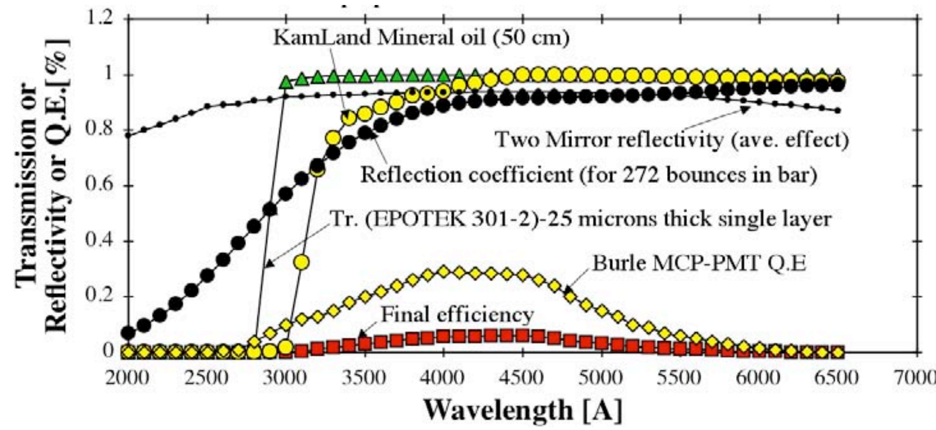


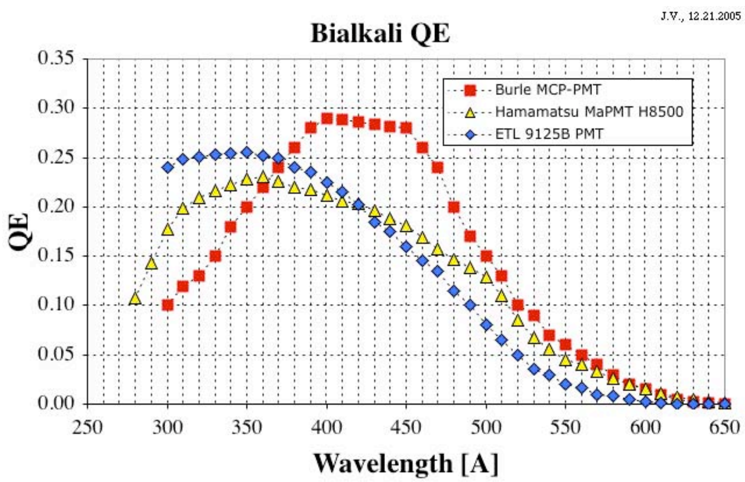
- **Data and MC almost agree; still some work needed for pixel-based data analysis**

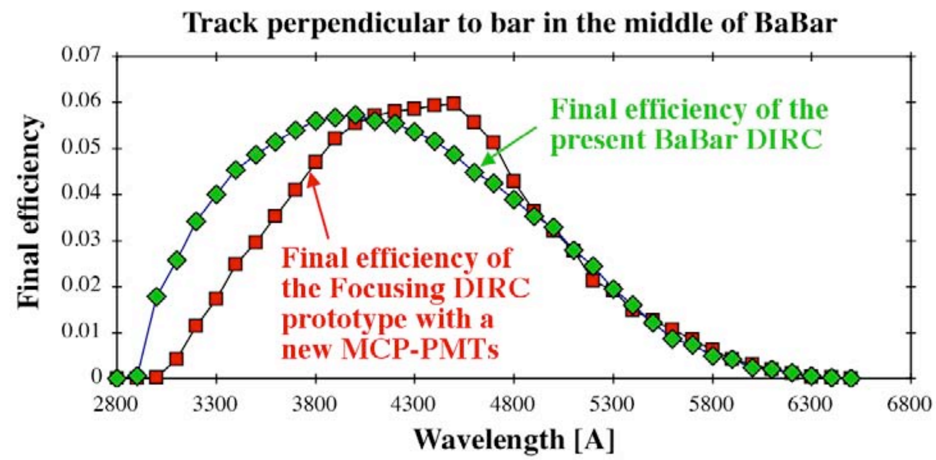
Chromatic behavior of the prototype

J.V.









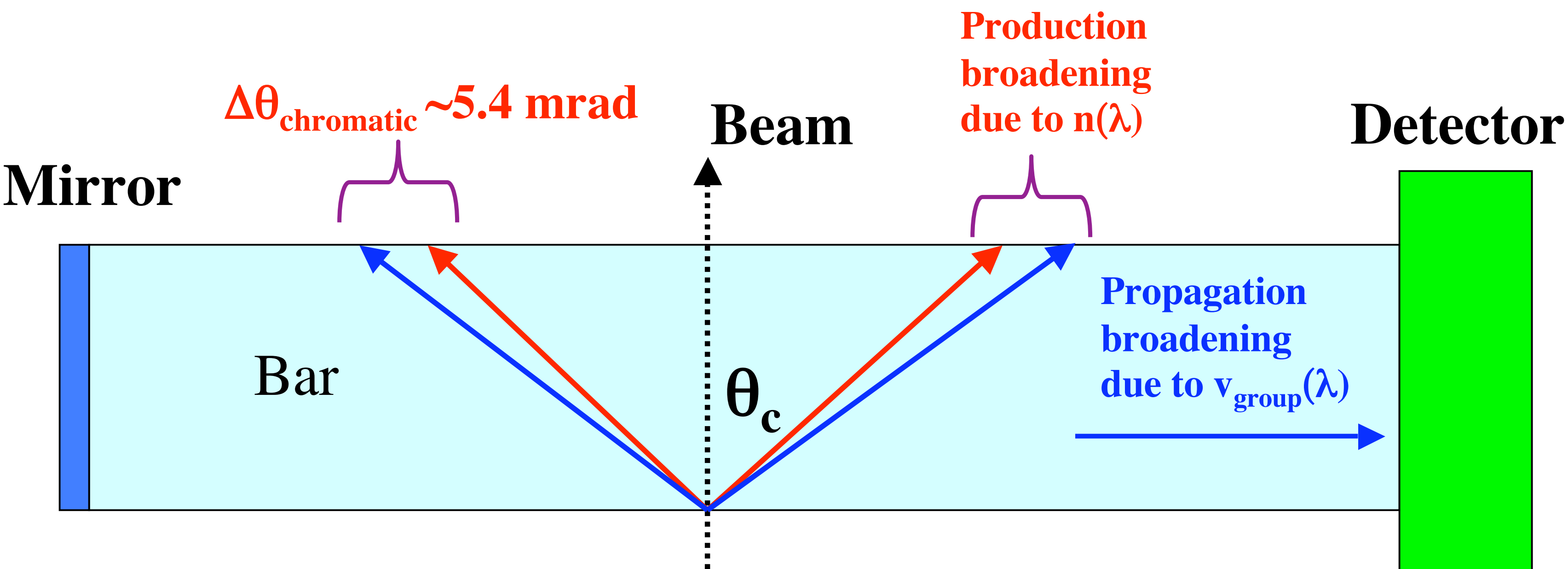
- **The prototype has a better response towards the red wavelengths, which reduces the Cherenkov angle chromatic contribution to 3-4 mrads (BaBar DIRC has 5.4mrads).**

Chromatic effects on the Cherenkov light

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

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

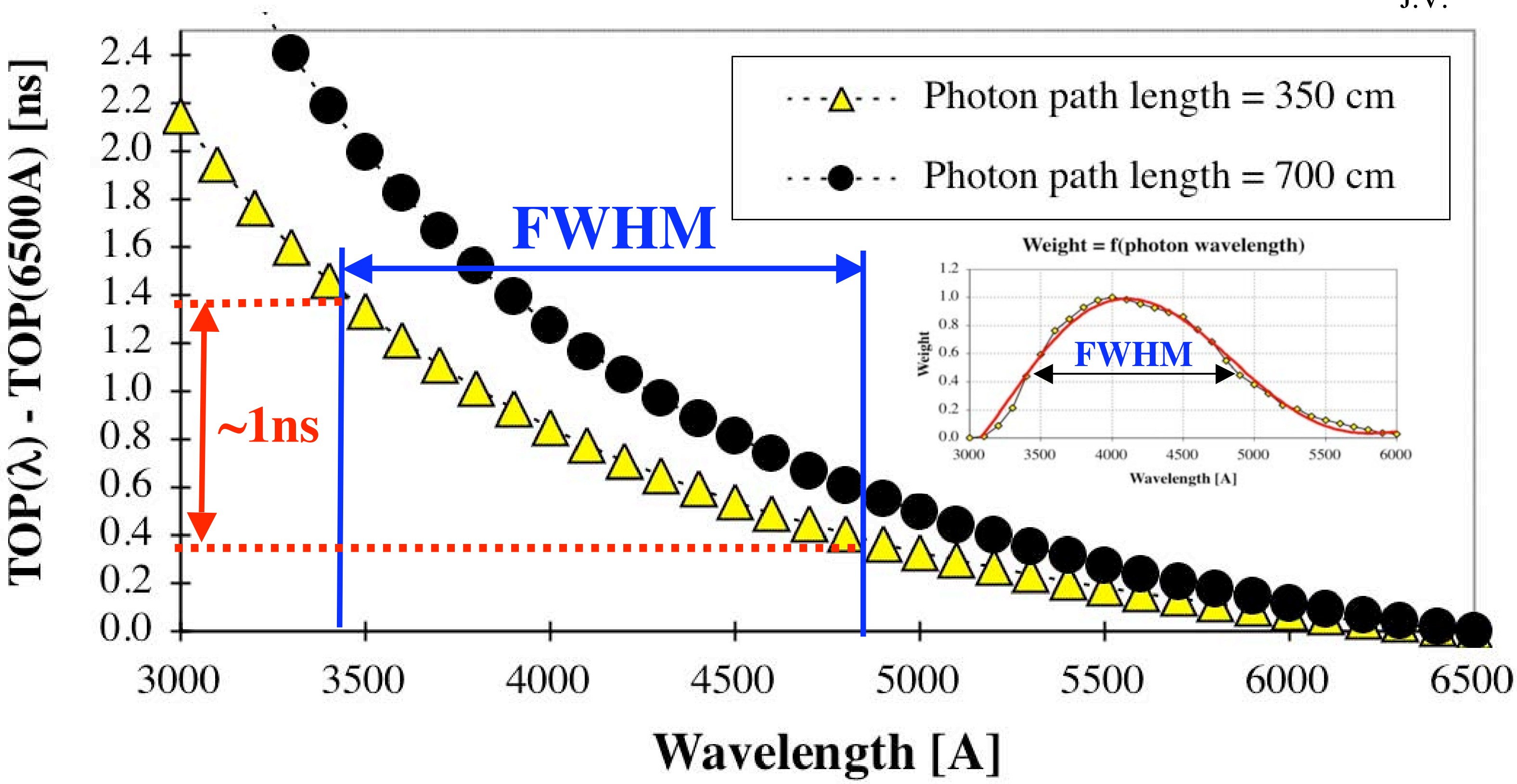
n_{phase}(red) < n_{phase} (blue) => v_{group}(red) > v_{group} (blue)



- **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.

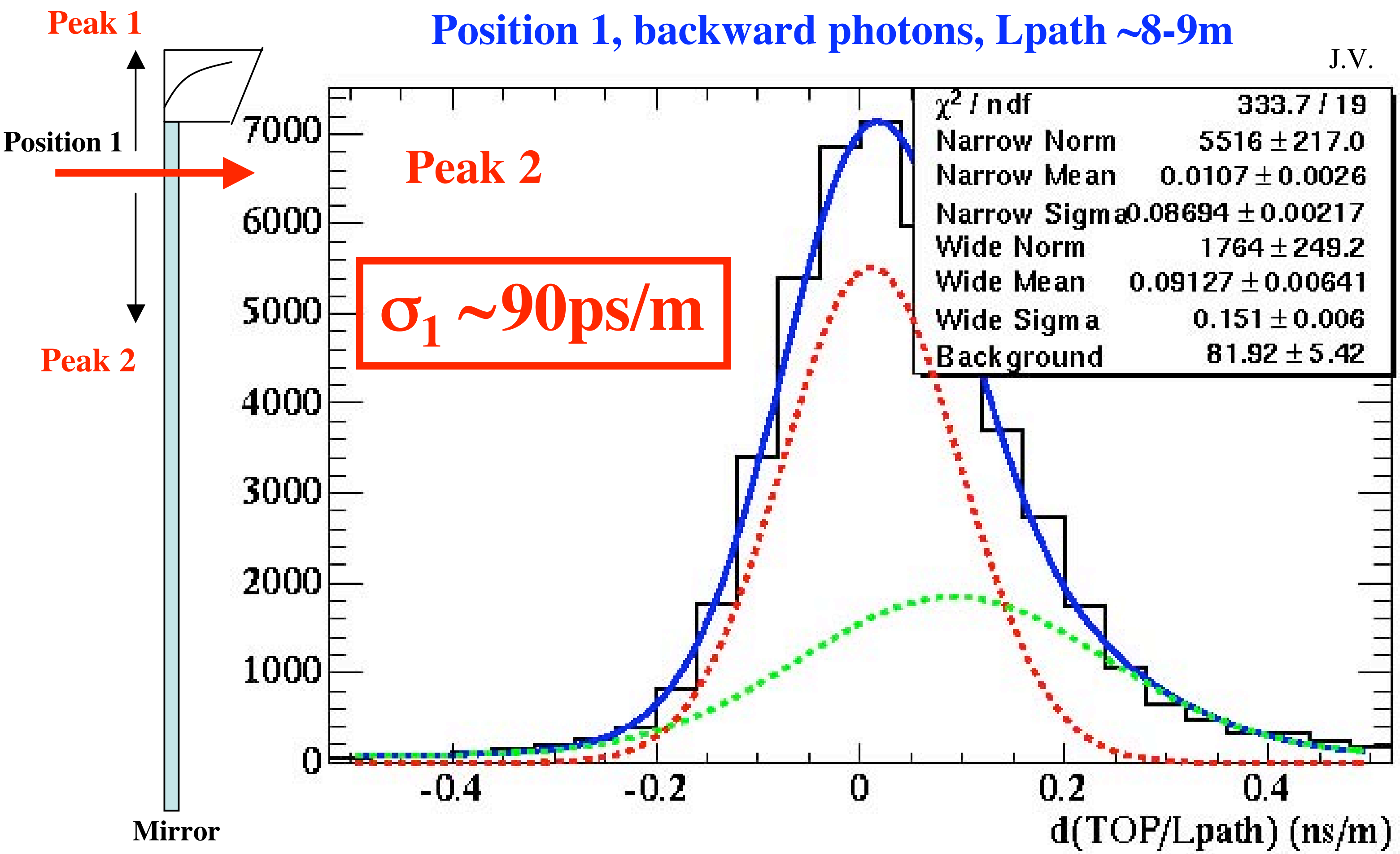
Expected size of the chromatic effect in time domain

J.V.



- **Θ_{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.**

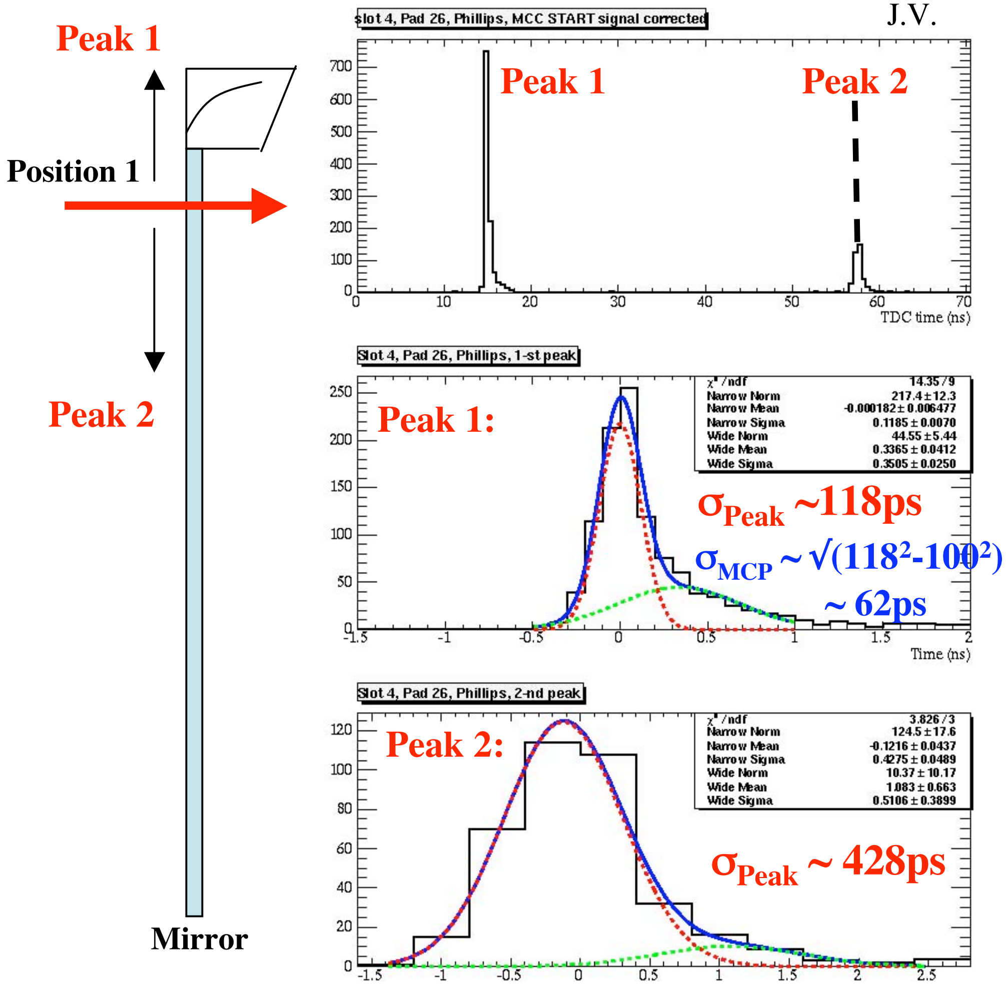
Time spread growth due to chromaticity



- **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,



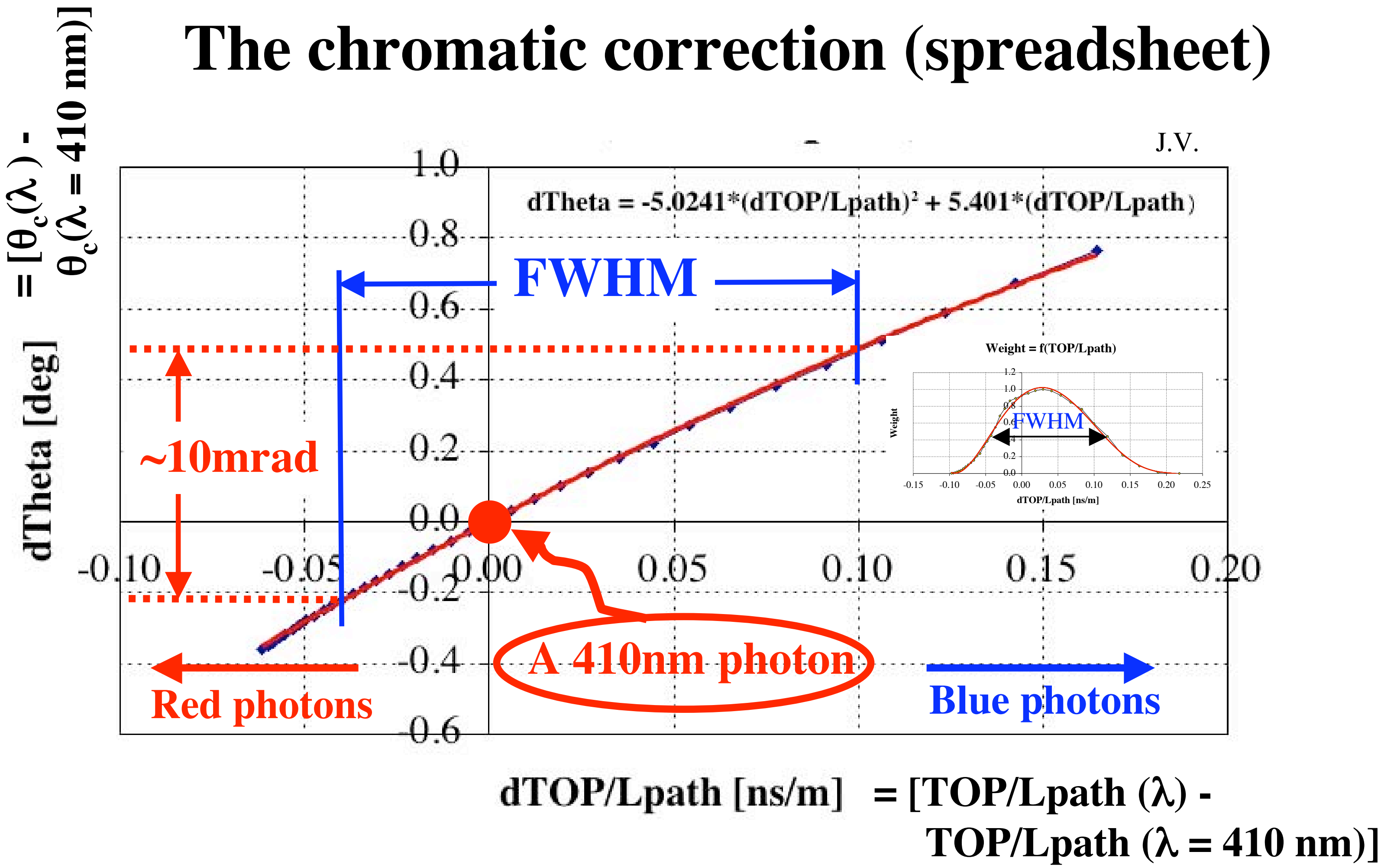
ΔTOP = TOP_measured (λ) - TOP_expected (λ = 410 nm) [ns]

- **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**

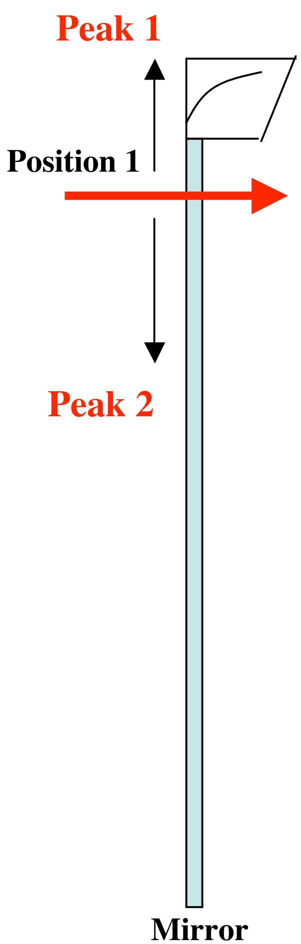
The chromatic correction (spreadsheet)

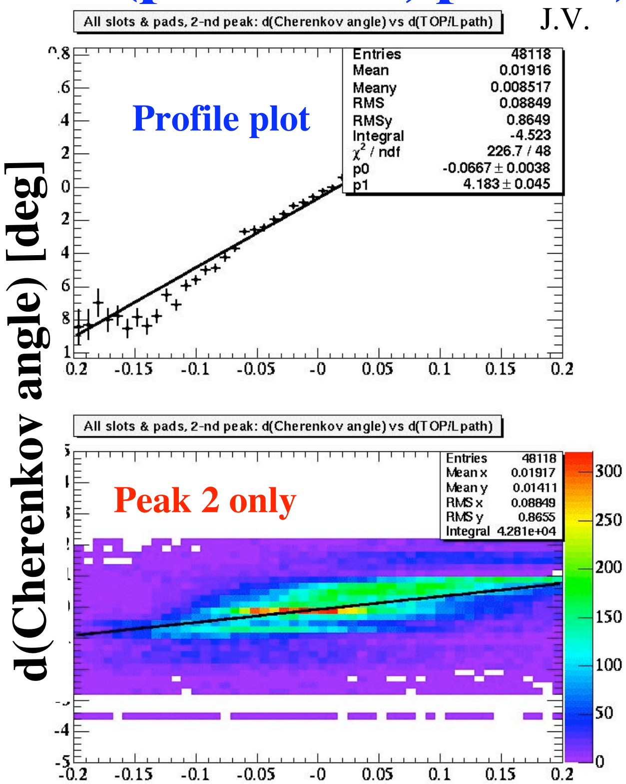


- An average photon with a color of λ ~410 nm arrives at "0 ns offset" in dTOP/Lpath space. A photon of different color, arrives either early or late.
- The overall expected effect is small, only FWHM ~10mrad, or σ ~ 4 mrads.

Do we see this effect in the data ?

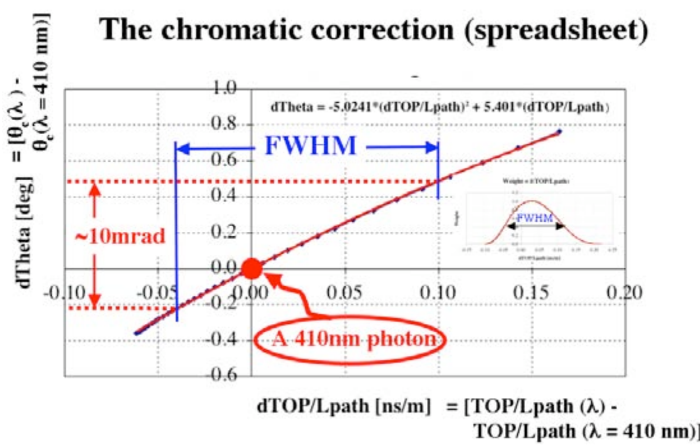
Data (position 1, peak 2):





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

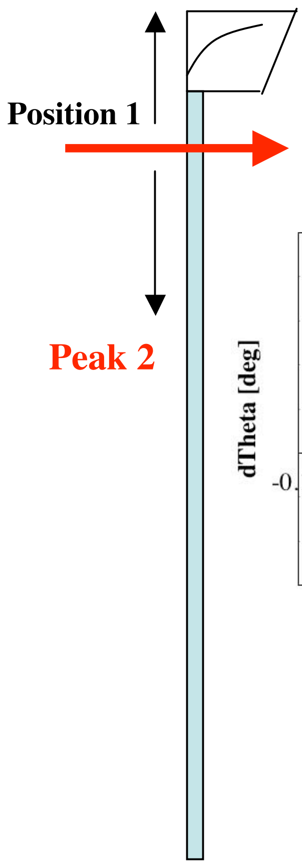
Spreadsheet calculation:



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

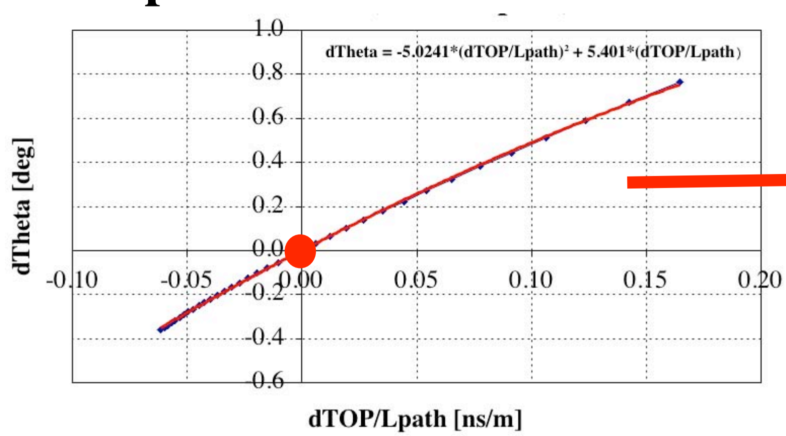
Method #1: Spreadsheet calculation of $d\theta_c$ vs d(TOP/Lpath).

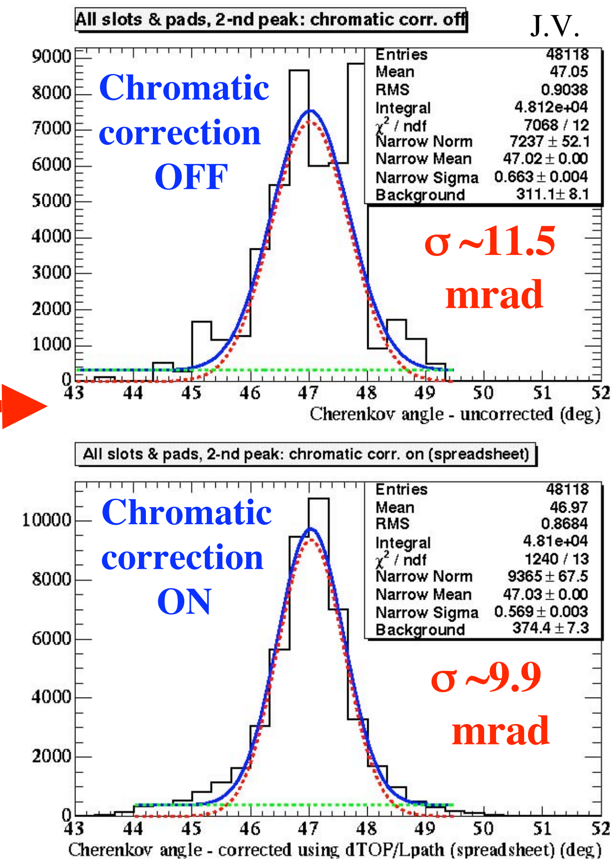
All slots, all pads, position 1, Peak 2 only:



PRELIMINARY

Spreadsheet:

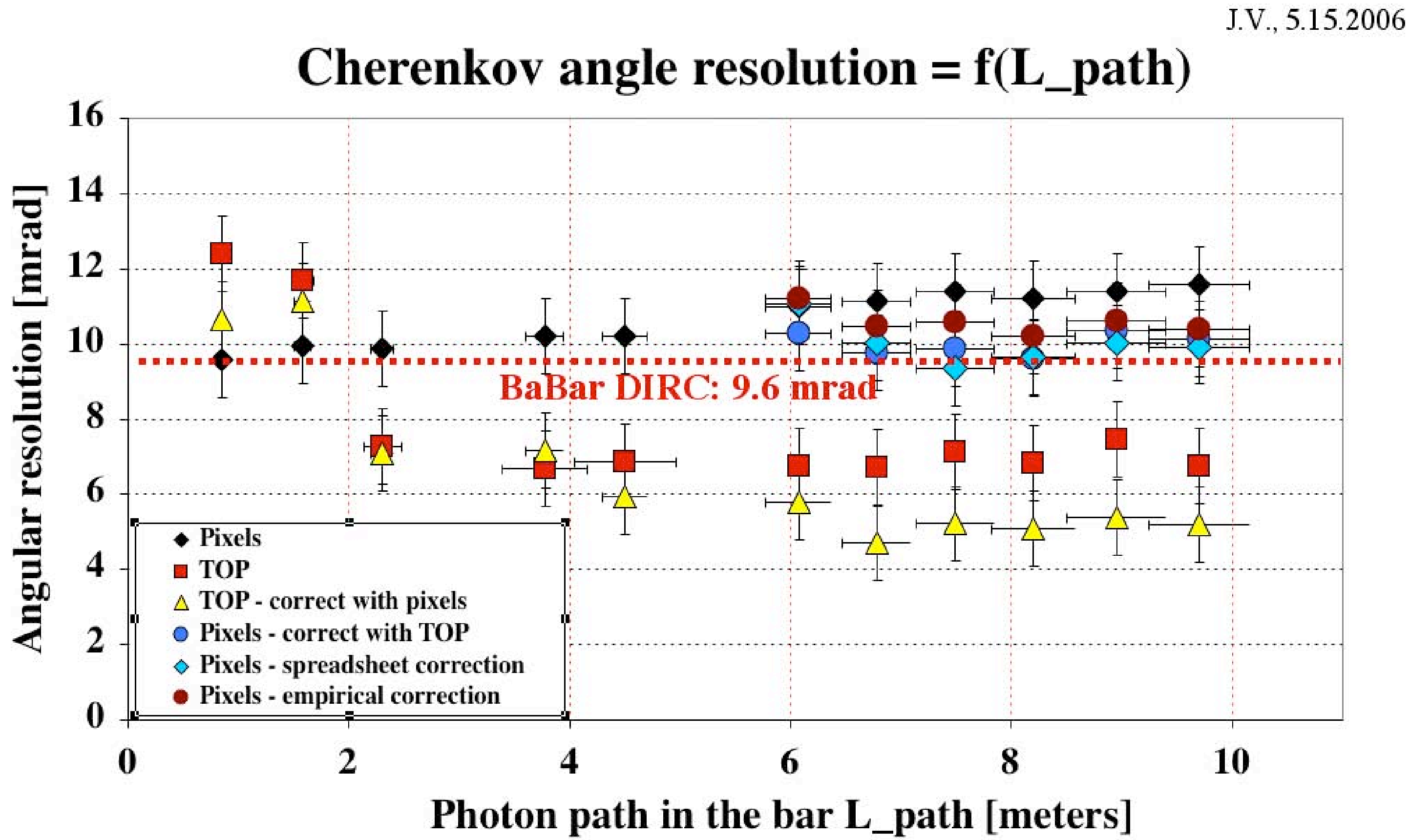




Cher. Angle (pixel) [deg]

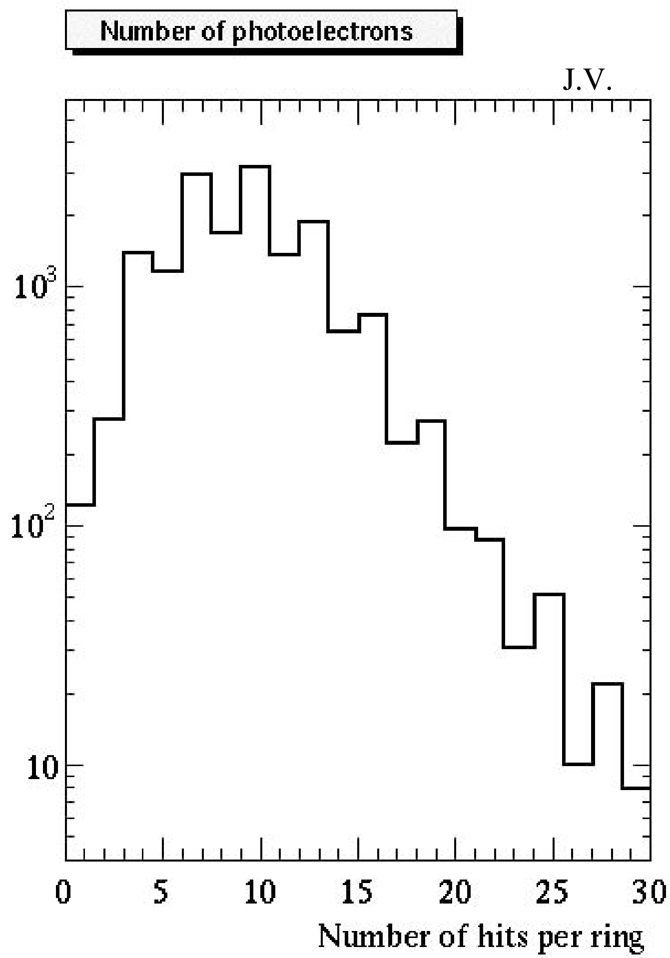
- **An improvement of ~1.5 mrads.**

Status of chromatic corrections - preliminary



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

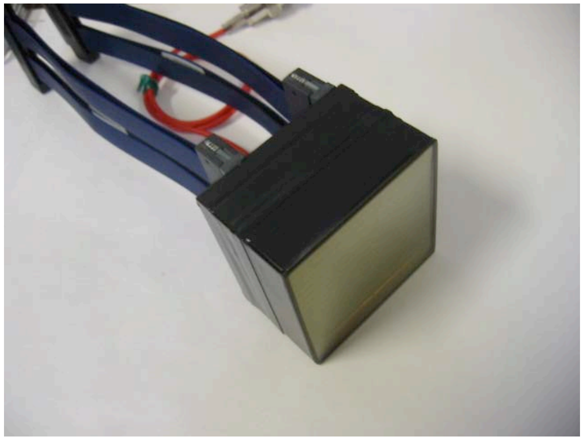
How many photoelectrons per ring ?

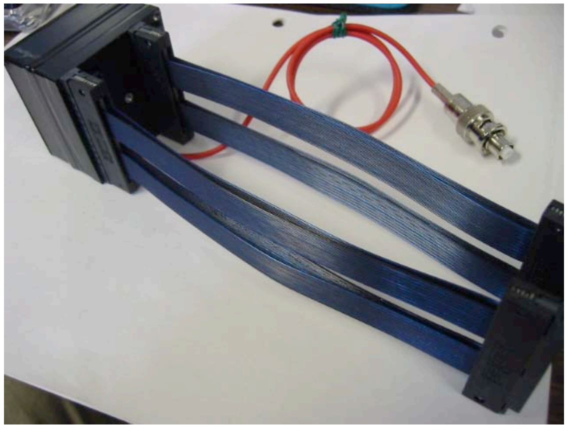


- **<N$_{pe}$> ~ 8-10 for 90^o inc. angle**
- With a hermetic configuration and other Burle improvements in the MCP-PMT design, we could achieve a factor of 1.5-2 improvement, perhaps.
- BaBar DIRC has N_{pe}~20 at a track incident angle of 90^o

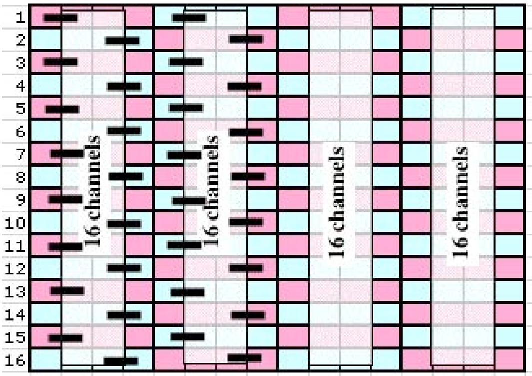
Upgrades for the next run in July

New 256-pixel Hamamatsu MaPMT H-9500

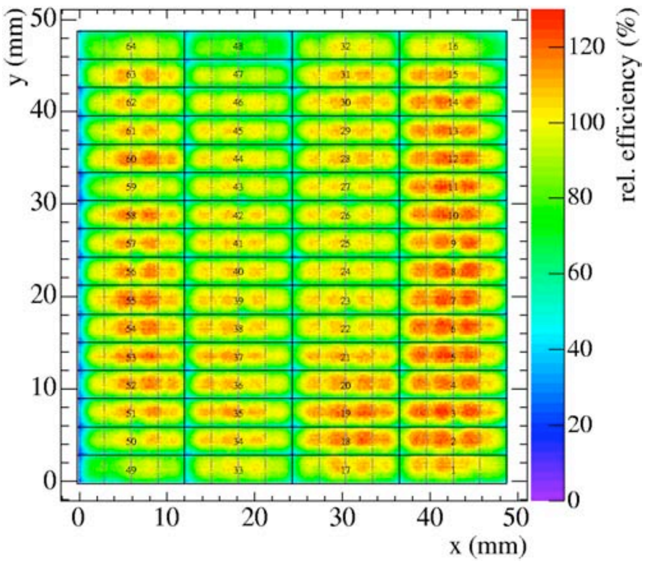




We made a small adaptor board to connect pads in the following way:



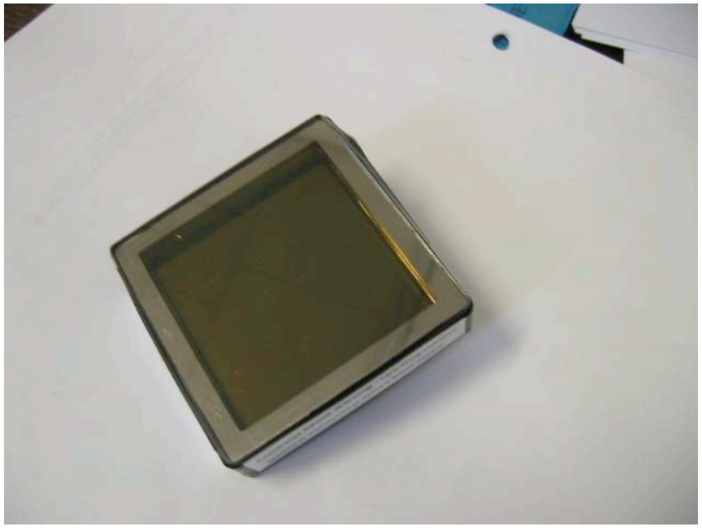
2D scan:

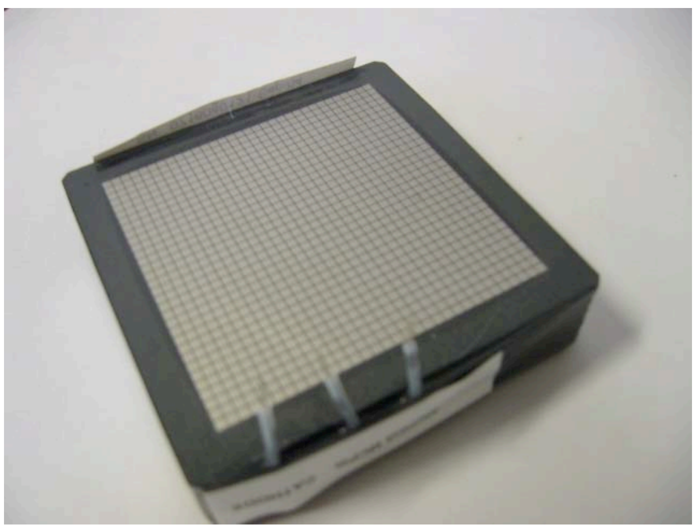


- 256 pixels (16 x 16 pattern).
- Pixel size: 2.8 mmx2.8 mm; pitch 3.04 mm
- 12 stage MaPMT, gain ~10^6, bialkali QE.
- Typical timing resolution σ ~ 220 ps.
- Charge sharing important

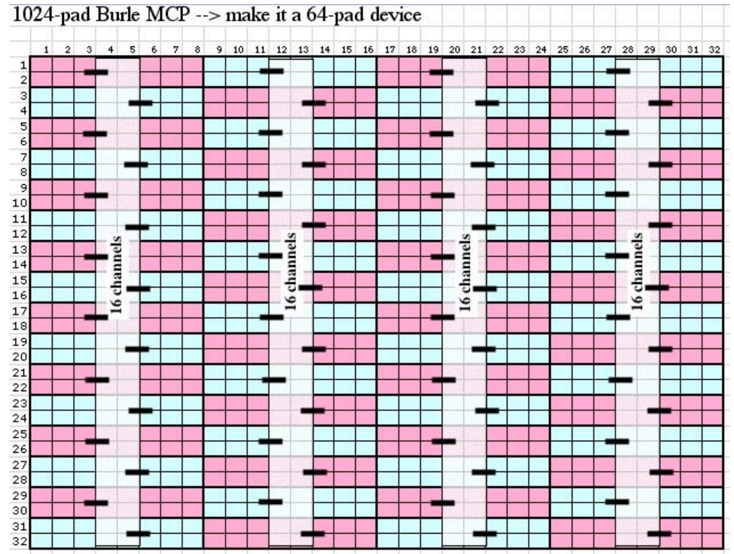
- **Large rectangular pad: 1x4 little ones**
- **This tube was now installed to slot 3**

“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

#111

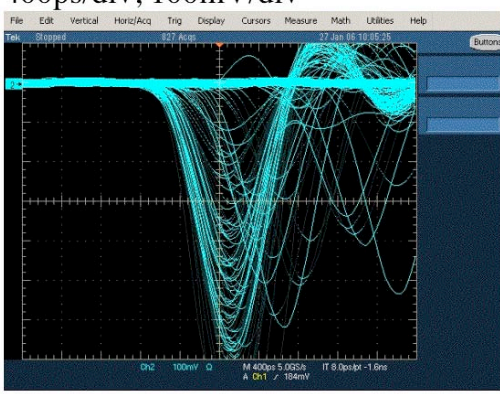
Single-photon timing resolution

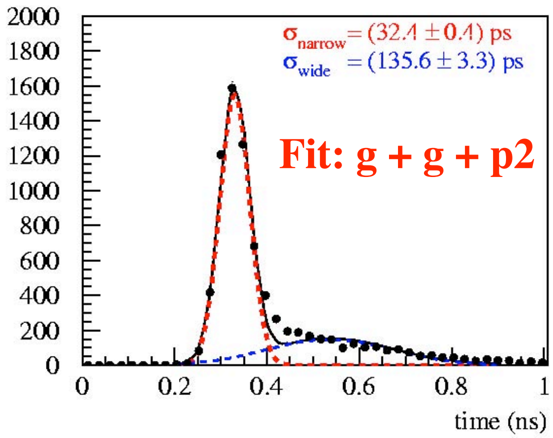
- Burle MCP-PMT 85012-501 (open area)
- 10 μm MCP hole diameter
- 64 pixel devices, pad size: 6 mm x 6 mm.
- Small margin around the boundary
- Use Phillips CFD discriminator
- All tests performed with PiLas red laser diode operating in single photoelectron mode by adding filters.

Hamamatsu C5594-44

1.5 GHz BW, 63x gain

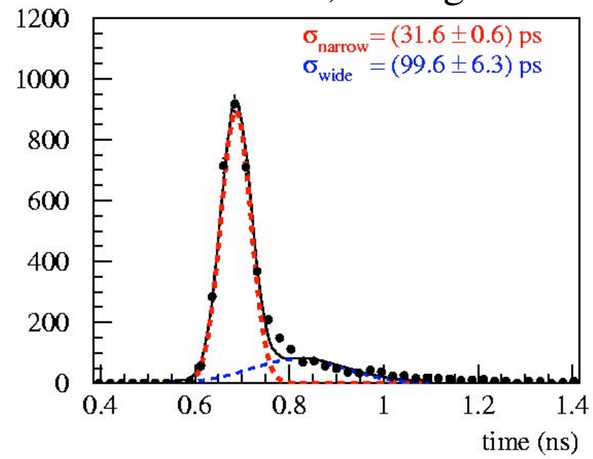
400ps/div, 100mV/div





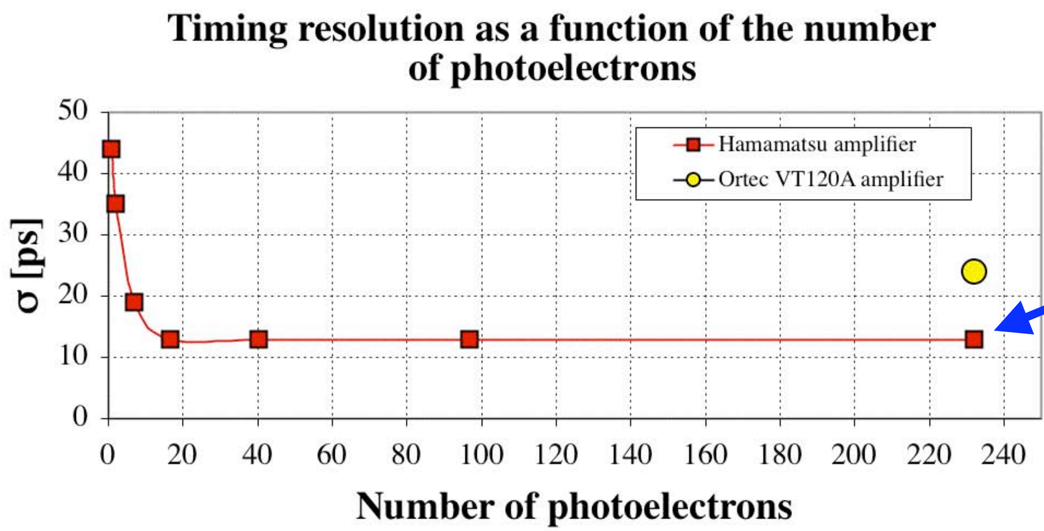
Ortec VT120A with a 6dB att.

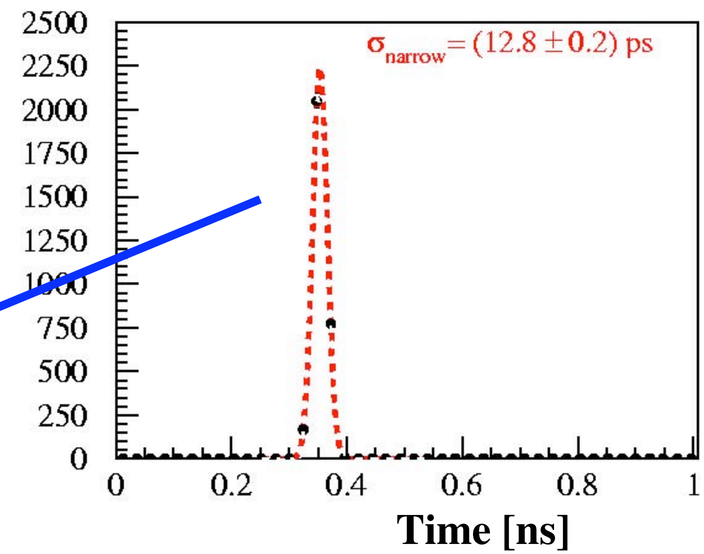
~0.4 GHz BW, 200x gain



#111

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



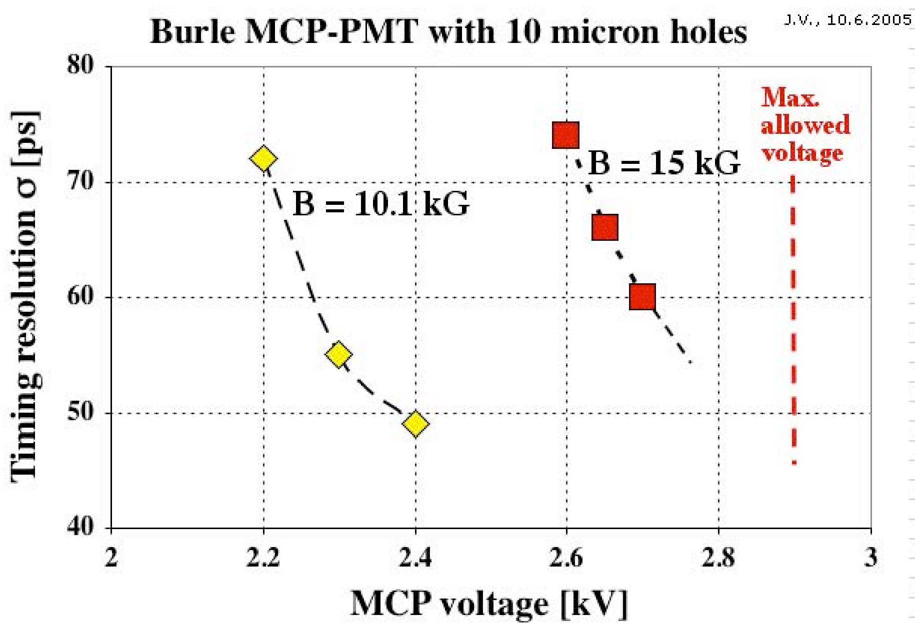


- **Achieved σ ~12 ps for N_{pe} >20 with the Hamamatsu C5594-44 amplifier, while the amplifier is operating in a saturated mode. Very similar results achieved with Ortec 9306 amp. Did not investigate the linear mode yet (att. before amplifier). Can use the saturated mode only if Npe is constant.**
-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

#111

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.

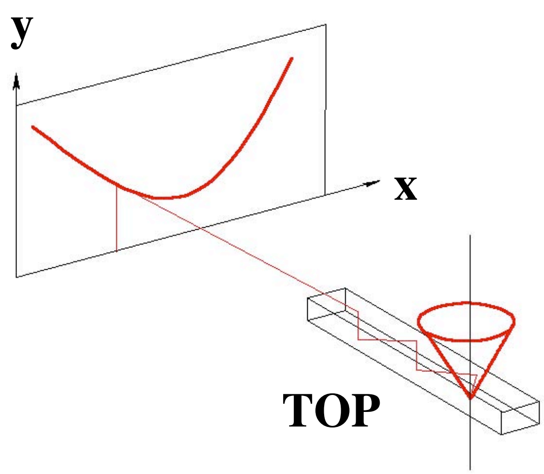
Conclusions

- **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

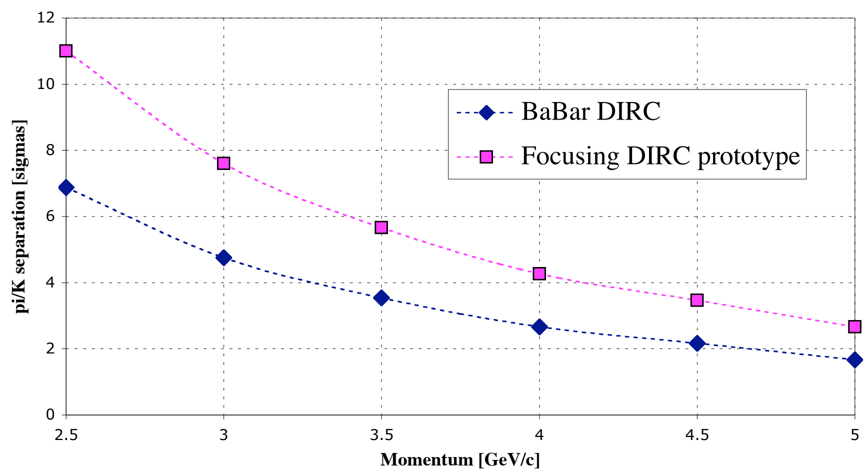
Focusing DIRC prototype: x & y & TOP

- 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

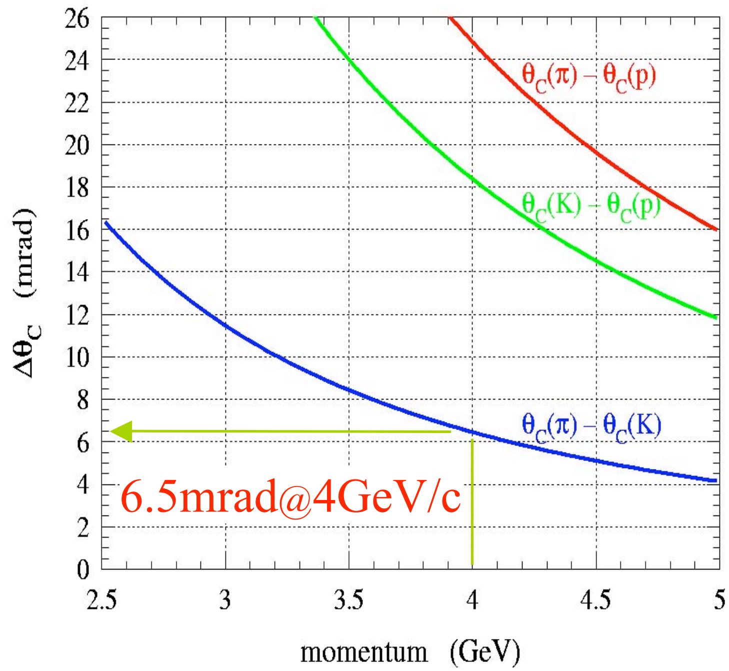
Expected performance of the prototype



- **<u>Present BaBar DIRC:</u>**
  - 2.7σ π/K separation at 4GeV/c
- **<u>Focusing DIRC prototype:</u>**
  - 2.7σ π/K separation at 5GeV/c
- **<u>Focusing DIRC assumptions:</u>**
  - 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

Nucl.Instr.&Meth., A502(2003)67



- **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

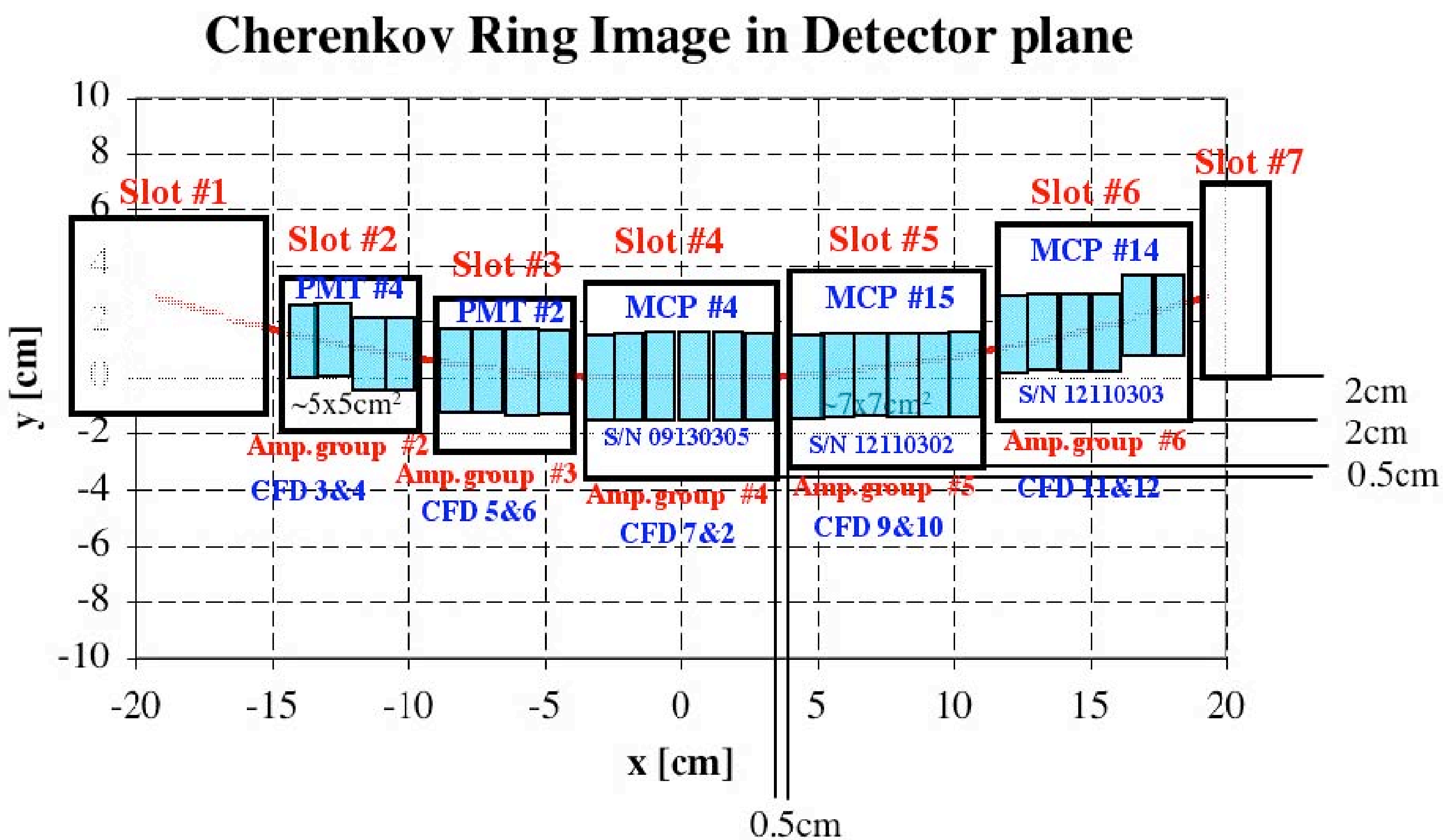
- Total: $\Delta\theta_c^{photon}$ ~ 9.6 mrad

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

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

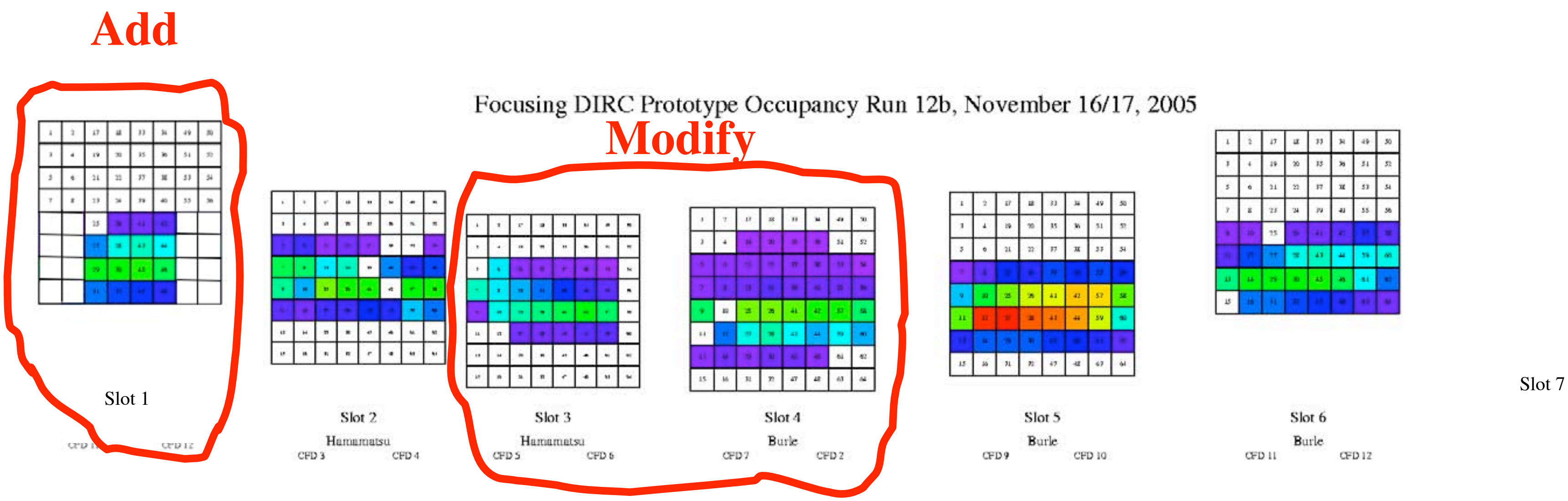
~ 2.4 mrad on average

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).**

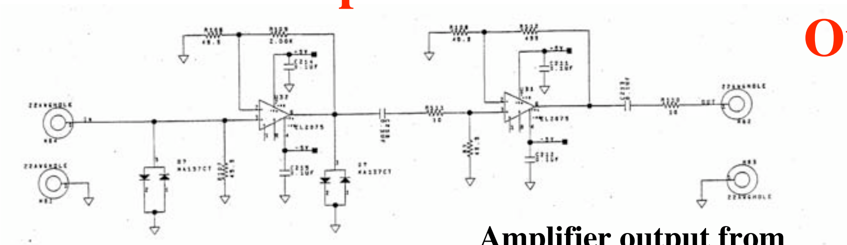
Modifications for the next run in July

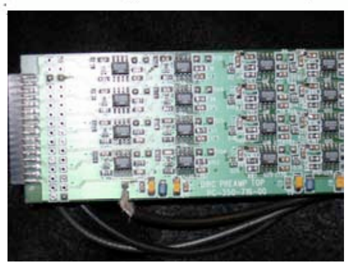


- **Add 32 new channels in slot 1**
- **Slot 1 will have Burle MCP-PMT with 6 mm x 6 mm pads**
- **Slot 3 will have a new Hamamatsu MaPMT with rectangular pads**
- **Slot 4 will have a new Burle MCP-PMT with rectangular pads**
- **Better TDC calibration over larger TDC range**
- **Some improvements in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

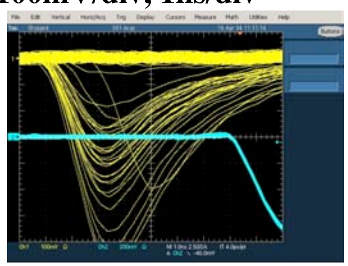
Focusing DIRC electronics

SLAC Amplifier:





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



Overall chain:

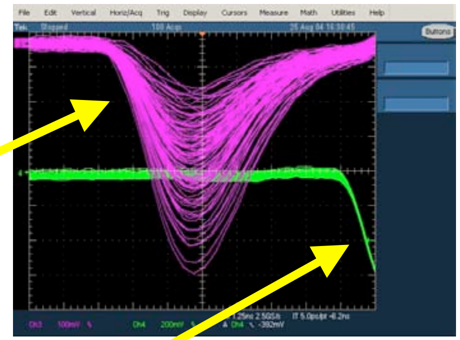
Detector

Amplifier

CFD

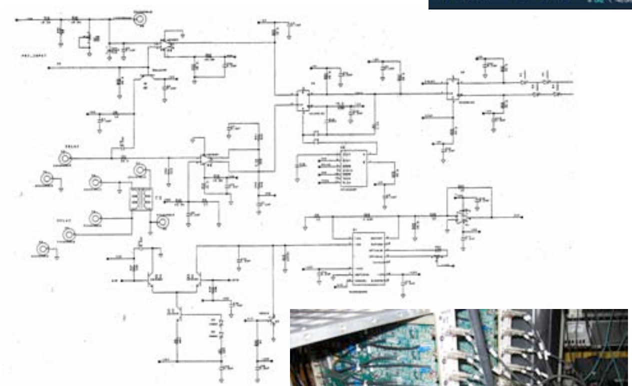
TDC

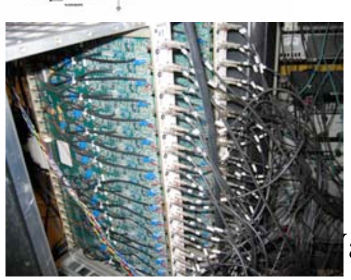
Amplifier outputs from MCP-PMT (trigger scope on CFD analog output), 100mV/div, 1ns/div



CFD analog pulse out

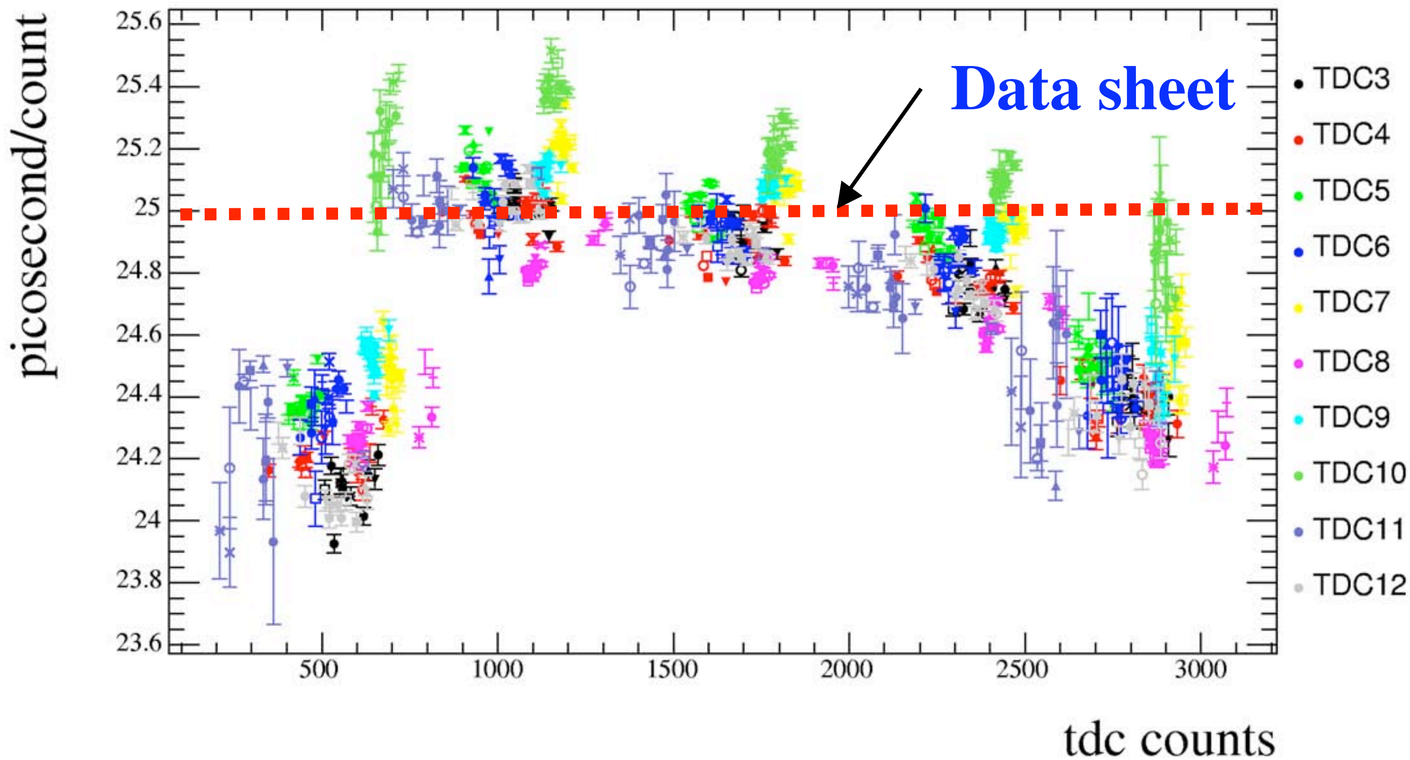
SLAC CFD & TAC:





- 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.

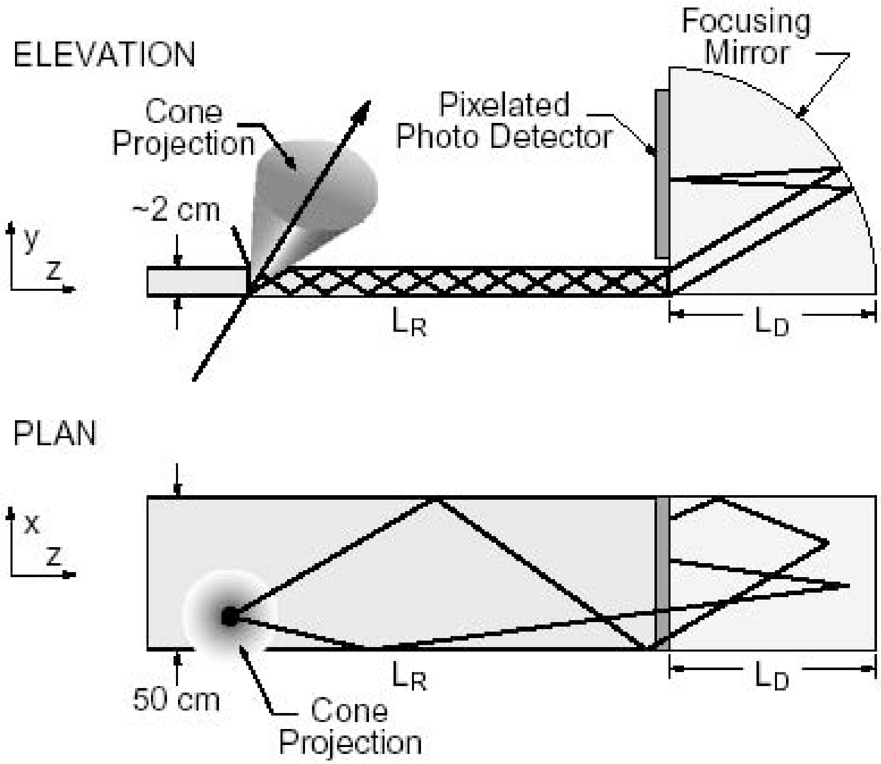
Phillips TDC calibration



- **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

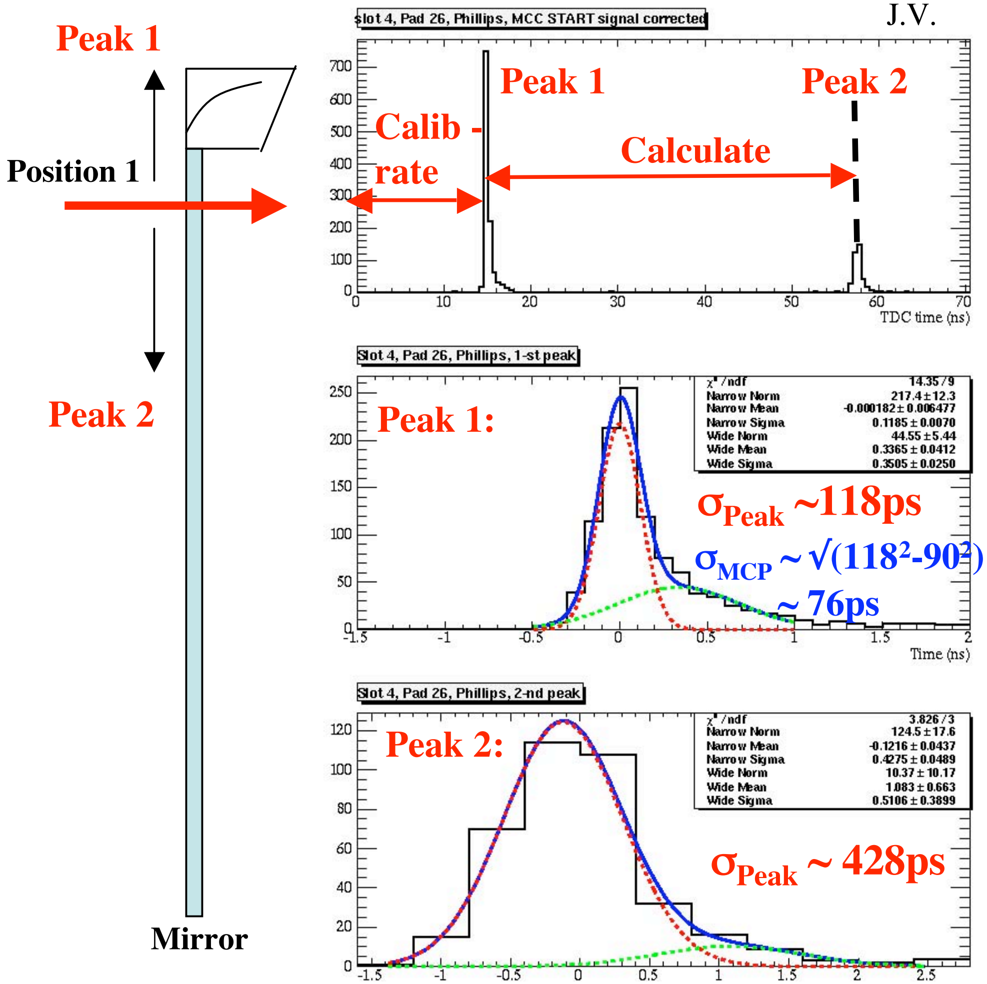


- **Goal: 3D imaging using x,y and TOP, and wide bars.**
- **The detector is located in the magnetic field of 15 kG.**

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.**