The Focusing DIRC – the first RICH detector to correct the chromatic error by timing, and the development of a new TOF detector concept

(High resolution timing in the photon detection - a new frontier in physics ?)

J. Va’vra, SLAC

Representing:

Collaboration to develop the Focusing DIRC:

I. Bedajanek, J. Benitez, D.W.G.S. Leith, G. Mazaheri, B. Ratcliff, J. Schwiening,
K. Suzuki, J. Uher, J. Va’vra

Content

- **Focusing DIRC prototype**
- The very 1-st first RICH detector, which tags the photon color by timing to correct the chromatic error

- **TOF detector**

- Progress on a road to reach σ ~10-15ps per track.

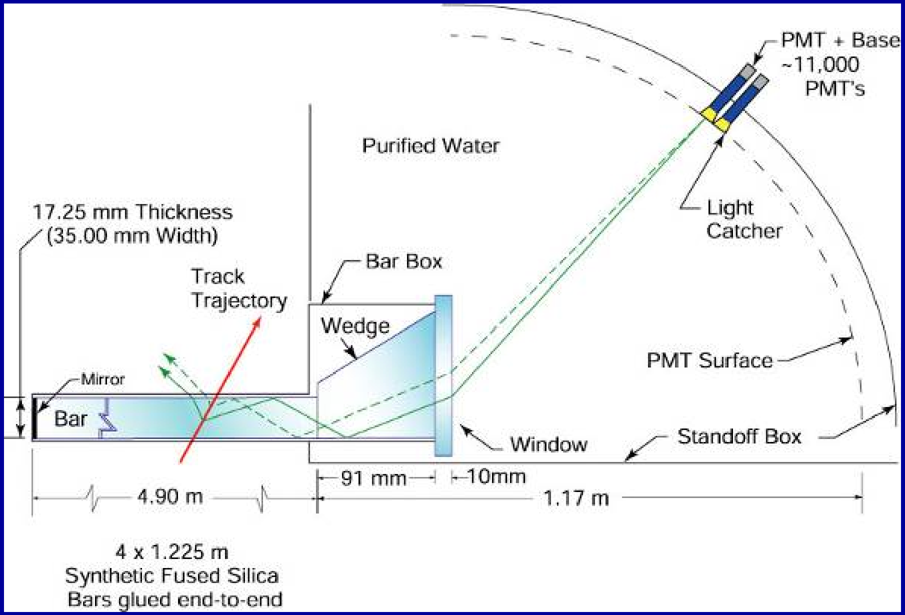
- **Both developments are for possible for Super-B**

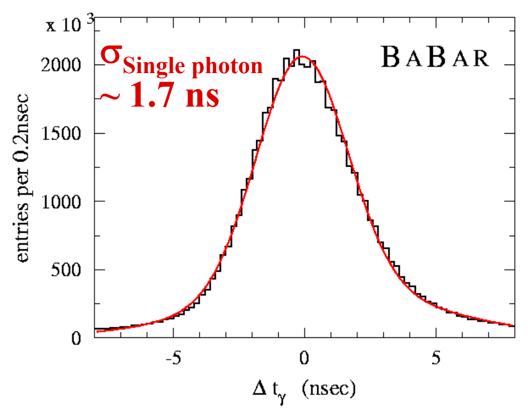
BaBar DIRC RICH = Detection of Internally Reflected Cherenkov light

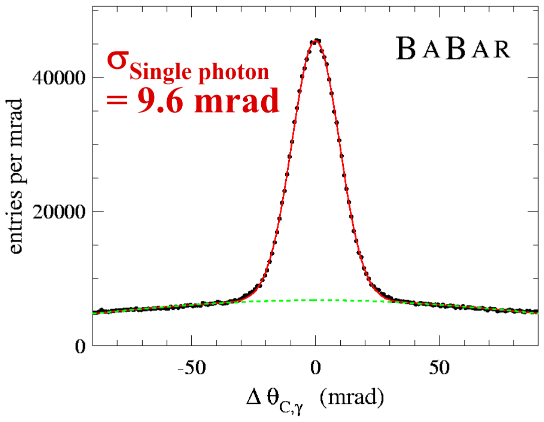
Nucl.Inst.&Meth., A 538 (2005) 281

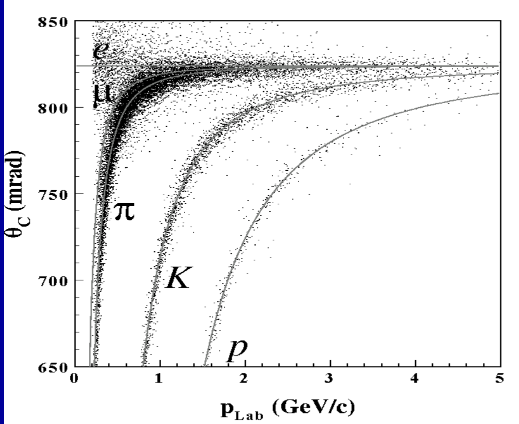
- **Very successful** in hadronic particle identification, with ~ 3σ π-K separation at 4 GeV/c.
- **3D imaging of photons: θ_c ,ϕ_c & time**

Principle of BaBar DIRC RICH:

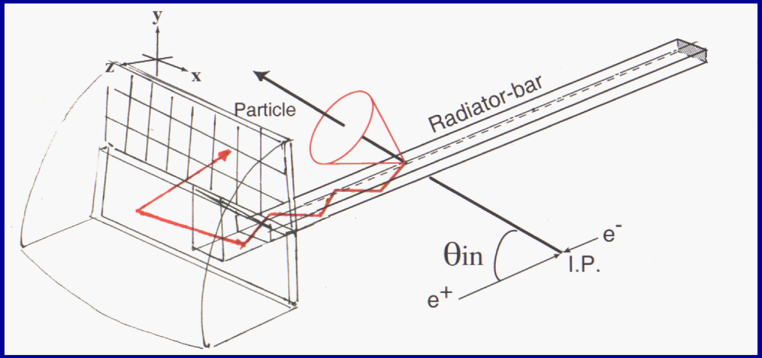








Motivation to develop a new DIRC at Super-B



Goal:

- Super-B will have 100x higher luminosity

- Backgrounds are not yet understood, but they would scale with the luminosity if they are driven by the radiative Bhabhas

⇒ **DIRC needs to be smaller and faster:**

- Focusing and smaller pixels can **reduce the expansion volume by a factor of 7-10 !**
- Faster PMTs reduce a sensitivity to background.

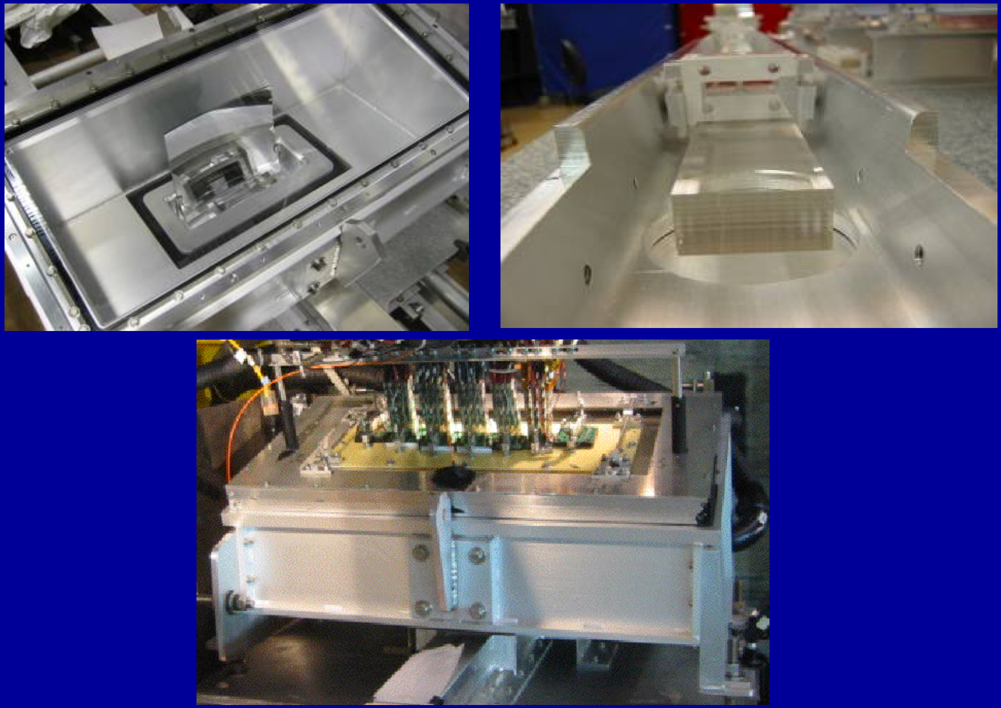
Additional benefit of the faster photon detectors:

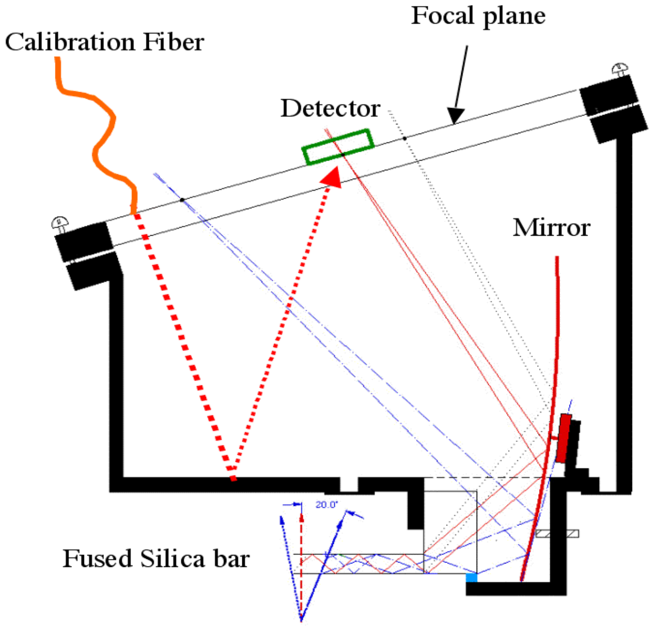
- Timing resolution improvement: **σ ~1.7ns (BaBar DIRC) -> $\sigma \leq$150ps (~10x better)** which allows a measurement of a **photon color** to correct the chromatic error of θ_c.

Focusing mirror effect:

- Focusing eliminates effect of the bar thickness (contributes σ ~ 4 mrads in BaBar DIRC)
- However, the spherical mirror introduces an aberration, so its benefit is smaller.

Focusing DIRC prototype optics



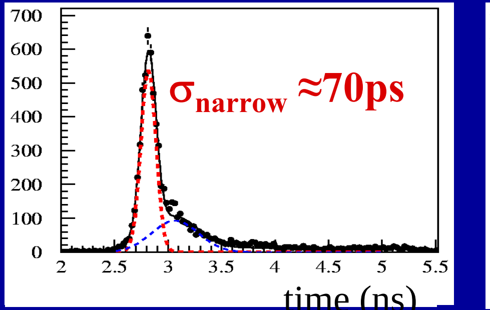


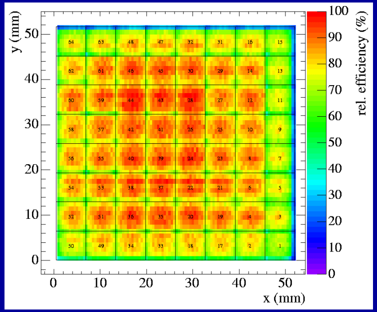
- **Radiator:**
  - 1.7 cm thick, 3.5 cm wide, 3.7 m long fused silica bar (the same as for BaBar DIRC).
- **Optical expansion region:**
  - filled with a mineral oil to match the fused silica refraction index (KamLand oil).
  - include optical fiber for the electronics calibration.
- **Focusing optics:**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

Focusing DIRC prototype photon detectors

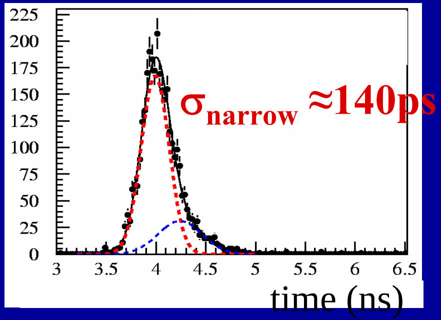
Nucl.Inst.&Meth., A 553 (2005) 96

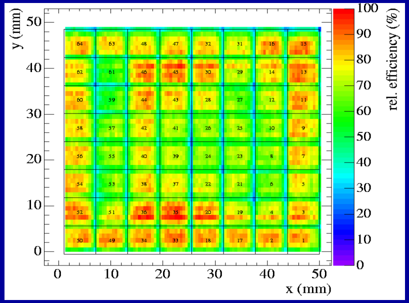
1) Burle 85011-501 MCP-PMT (64 pixels, 6x6mm pad, σ_{TTS} ~50-70ps)



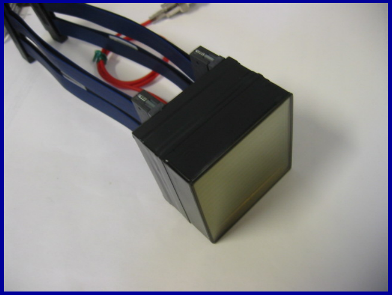


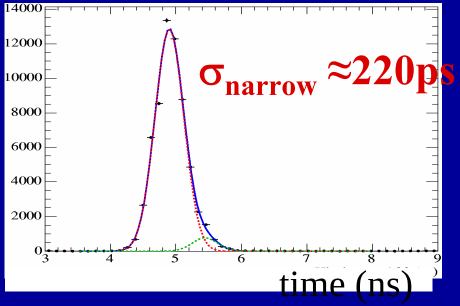
2) Hamamatsu H-8500 MaPMT (64 pixels, 6x6mm pad, σ_{TTS} ~140ps)

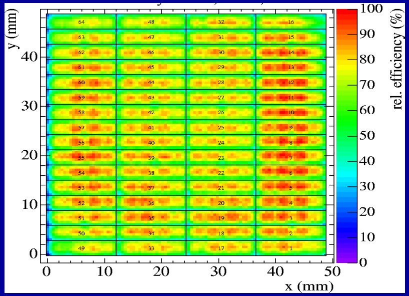




3) Hamamatsu H-9500 Flat Panel MaPMT (256 pixels, 3x12mm pad, σ_{TTS} ~220ps)





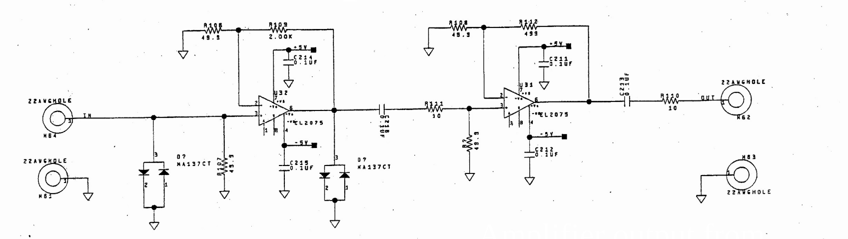


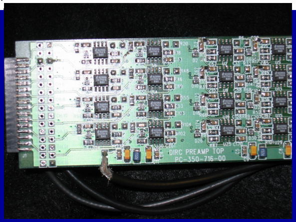
- **Timing resolutions were obtained using a fast laser diode in bench tests with single photons on pad center.**

Focusing DIRC electronics

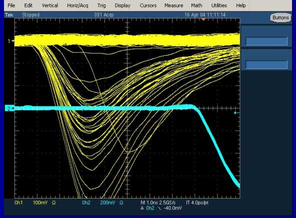
Nucl.Inst.&Meth., A 553 (2005) 96

SLAC Amplifier:

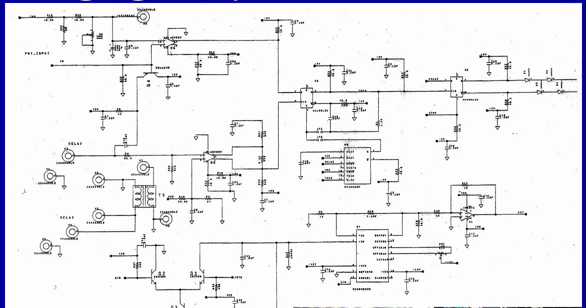


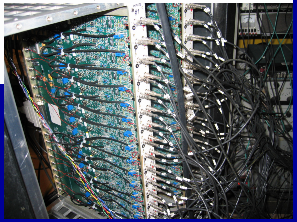


Amplifier output from MCP-PMT (trigger on PiLas), 100mV/div, 1ns/div



SLAC CFD:

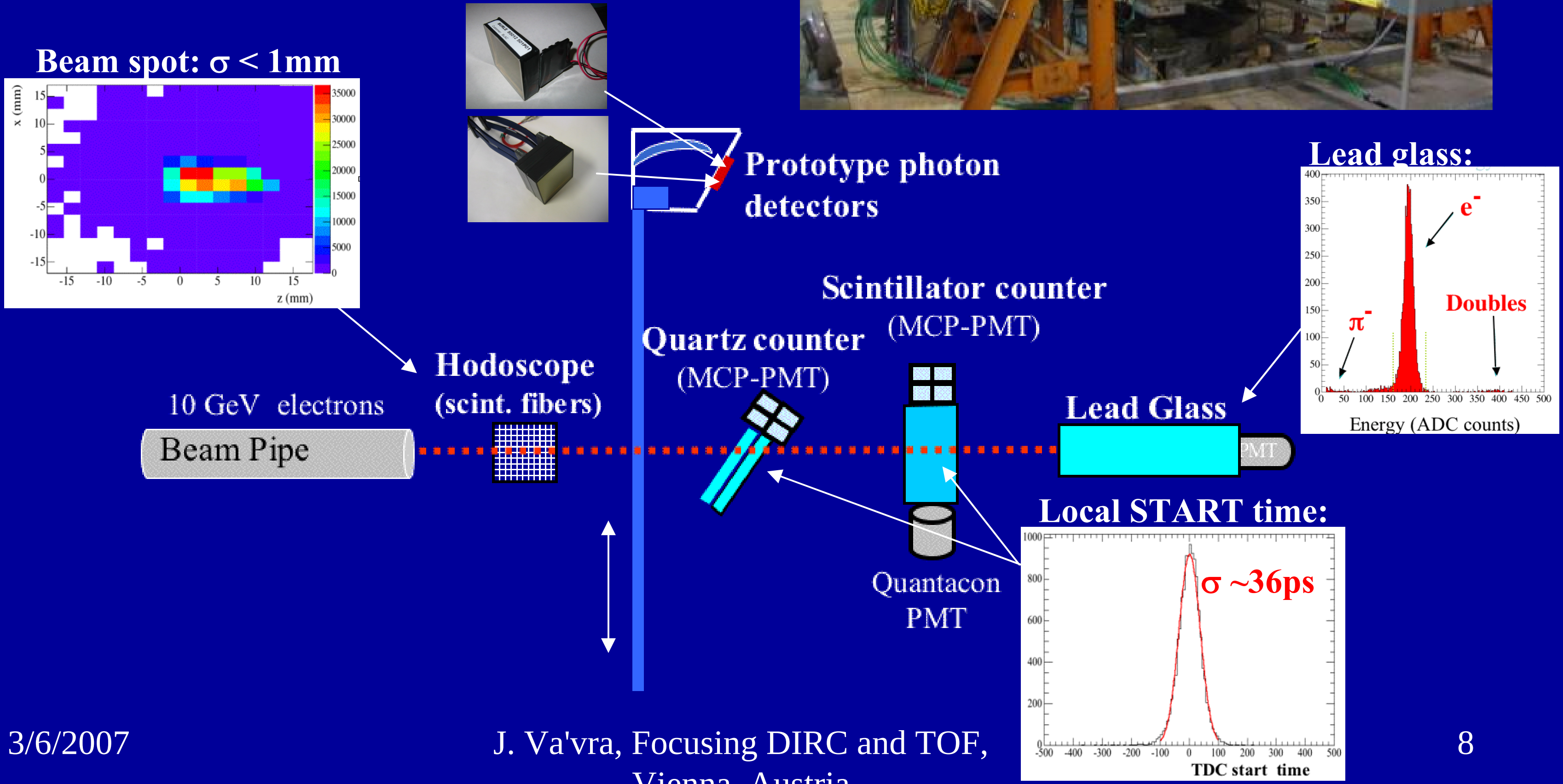




- **Amplifier**, based on two Elantek 2075EL chips, has a voltage gain of ~130x, and a rise time of ~1.5ns.
- **Constant-fraction-discriminator** (32 channels/board).
- **Phillips TDC** with 25ps/count.

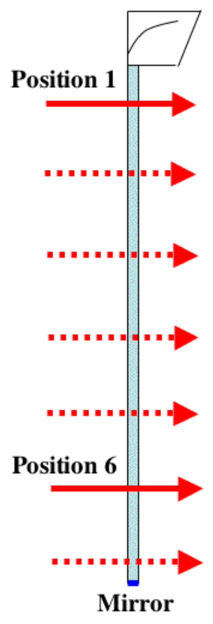
Beam Test Setup

- SLAC 10 GeV/c electron beam
- Beam enters bar at 90º angle.
- Prototype is movable to 7 beam positions along bar.
- Time start from the LINAC RF signal, but correctable with a local START counter

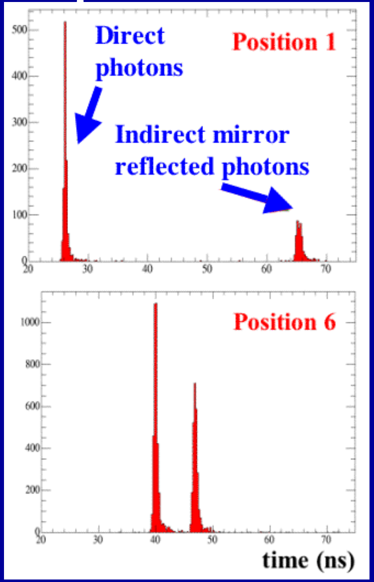


Cherenkov Photons in Time and Pixel domains

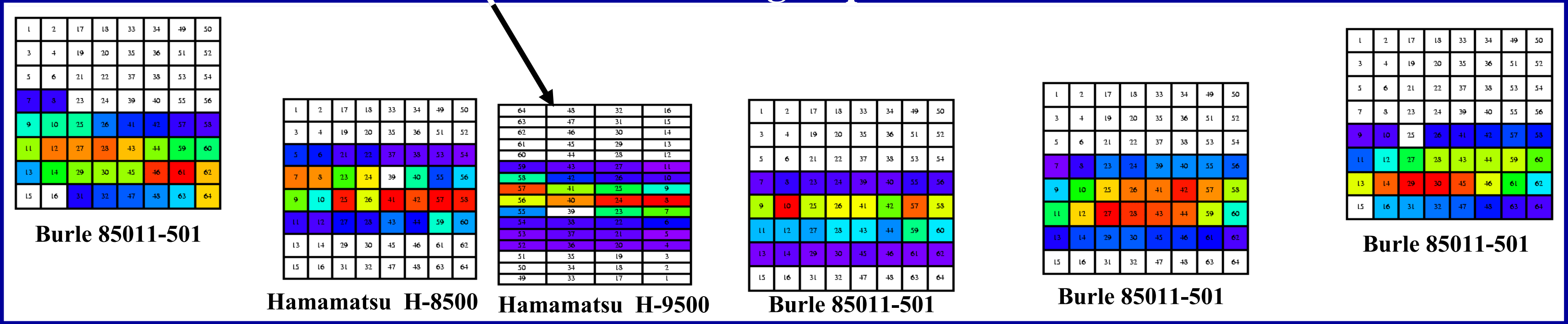
- 10 GeV/c electron beam data.
- ~ 200 pixels instrumented.
- Ring image is most narrow in the 3 x 12 mm pixel detector.



Cherenkov photons in time domain:



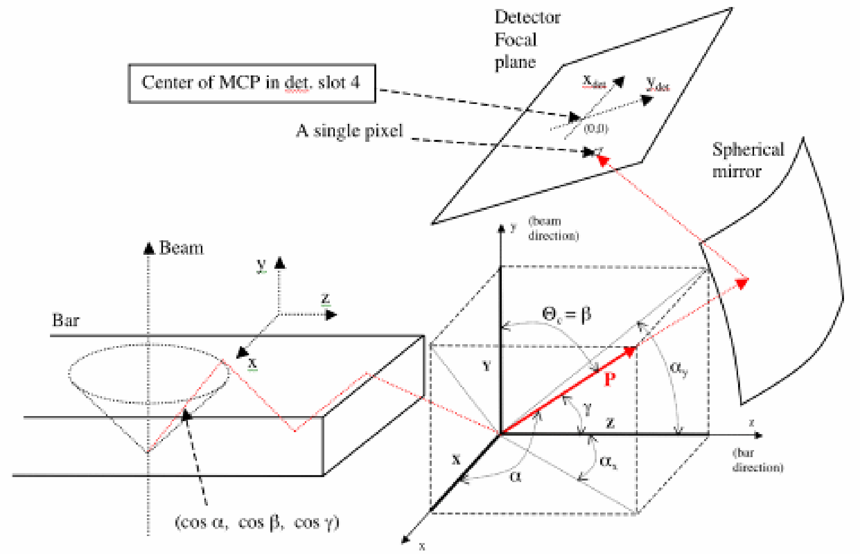
Cherenkov ring in pixel domain:



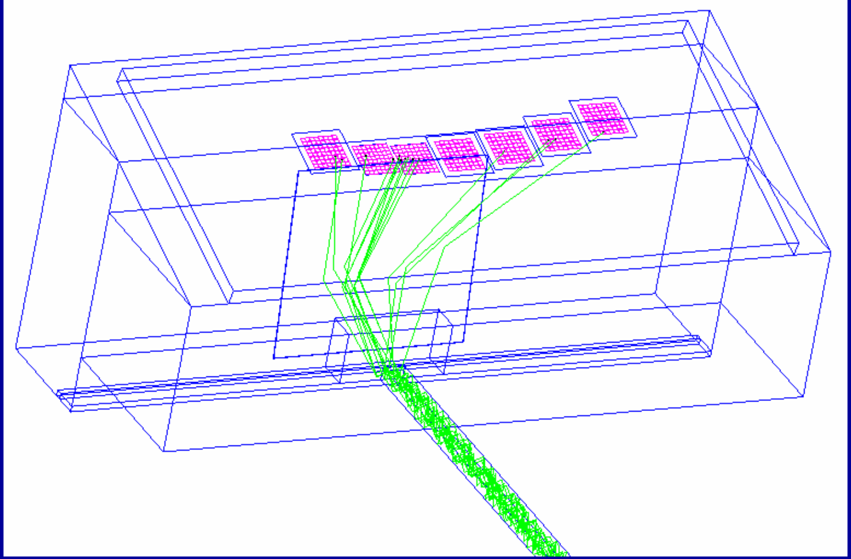
Burle 85011-501 | Hamamatsu H-8500 | Hamamatsu H-9500 | Burle 85011-501 | Burle 85011-501 | Burle 85011-501

Focusing DIRC prototype reconstruction

Prototype coordinate systems:



Geant 4 simulation of the prototype:



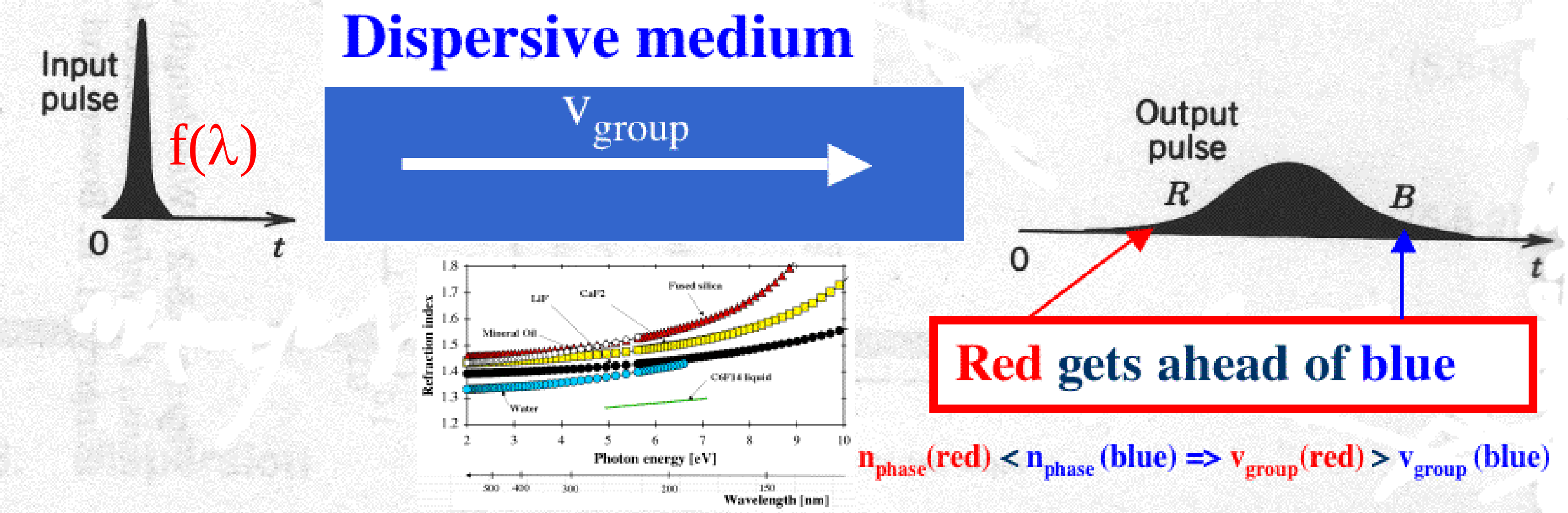
- **Each detector pixel determines these photon parameters for average λ :**

  θ_c, cos α, cos β, cos γ, Photon path length, time-of-propagation, number of photon bounces.

- **We use GEANT4 simulation to obtain the photon track parameters for each pixel.**

  (it is checked by a ray-tracing software)

Color tagging by measurement of photon propagation time



Red gets ahead of blue

$n_{phase}(red) < n_{phase}(blue) \Rightarrow v_{group}(red) > v_{group}(blue)$

$$v_{group} = c_0 / n_{group} = c_0 / [n_{phase} - \lambda \square\square\tilde{}_{phase} \square\lambda\square$$

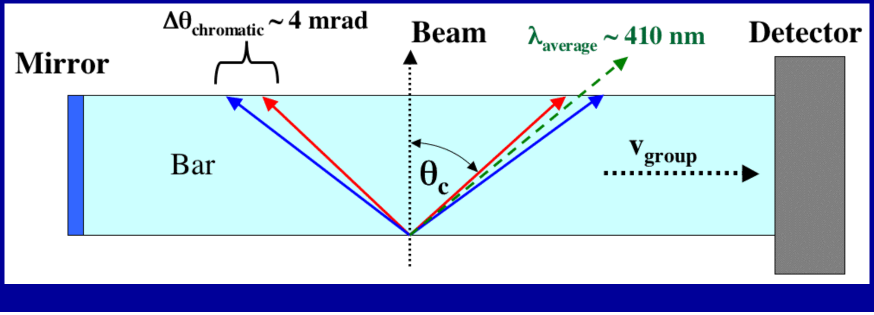
$$t = TOP = L / v_{group} = L\,[n_{phase} - \lambda \square\square\tilde{}_{phase} \square\lambda\square / c_0$$ = Time-Of-Propagation

$$dt/L = dTOP/L = \lambda \; d\lambda * |-d^2n/d\lambda^2| / c_0$$

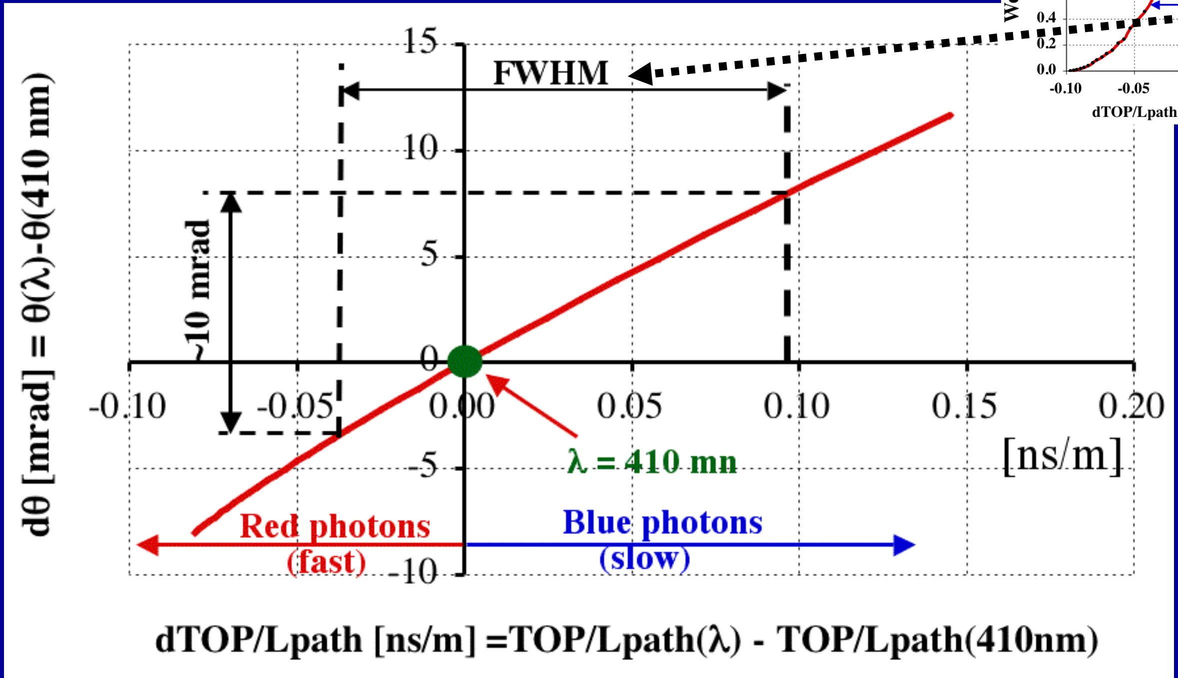
dt is pulse dispersion in time, length **L**, wavelength bandwidth **dλ**, refraction index **n(λ)**

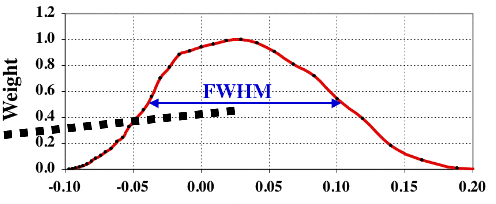
- We have determined in Fused Silica: **dt/L = dTOP/L ~ 40ps/meter**.
- **Our goal is to measure the color of the Cherenkov photon by timing !**

Cherenkov light: tagging color of photon by time



Principle of chromatic correction by timing:





TOP = time of propagation of photon in the bar

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

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

Propagation of photons is controlled by n_{group} ($v_{group} = c_0/n_{group} = c_0/[n_{phase} - \lambda\square\square_{phase}\tilde{}\square\lambda\square]$):

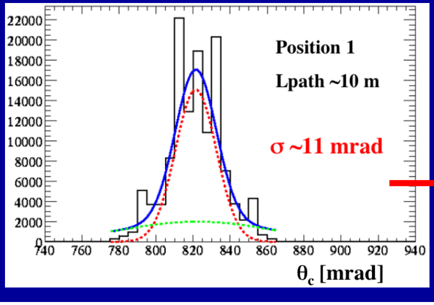
θ_c (red) < θ_c (blue)

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

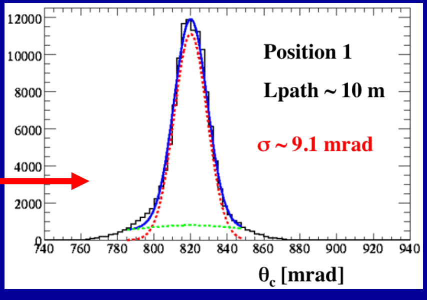
θ_C resolution and Chromatic correction

All pixels:

Correction off:

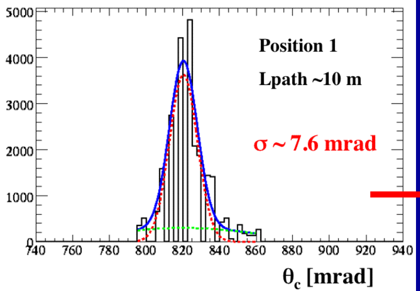


Correction on:

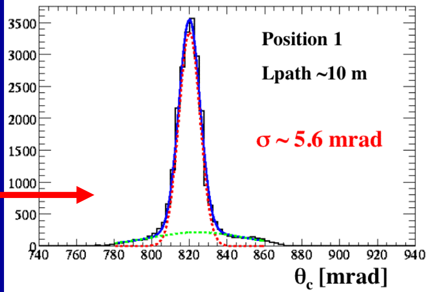


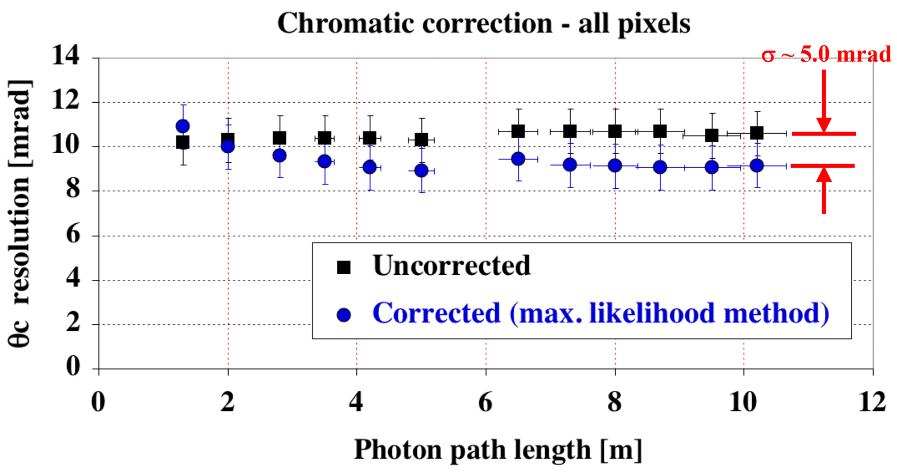
3mm pixels only:

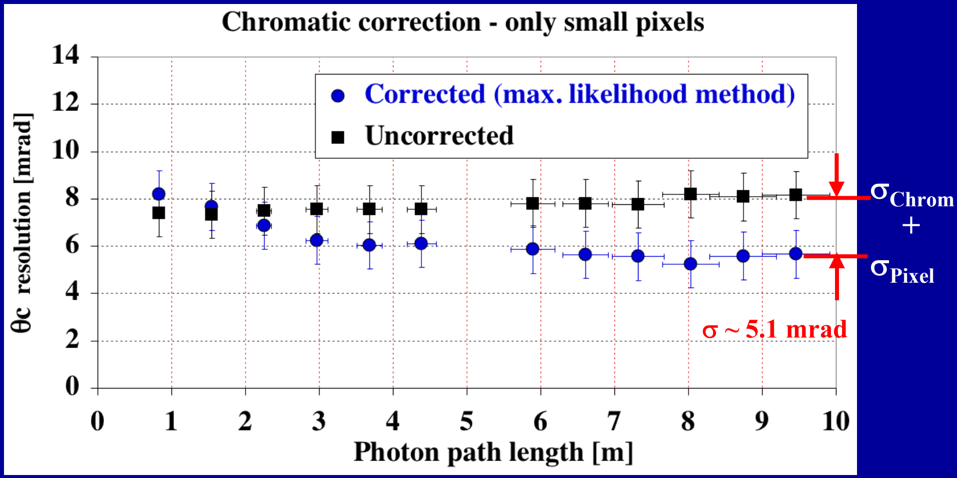
Correction off:



Correction on:



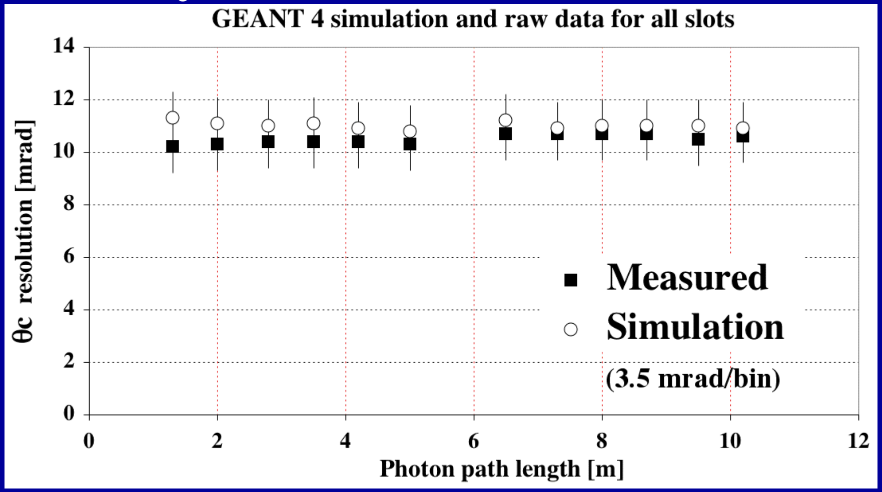




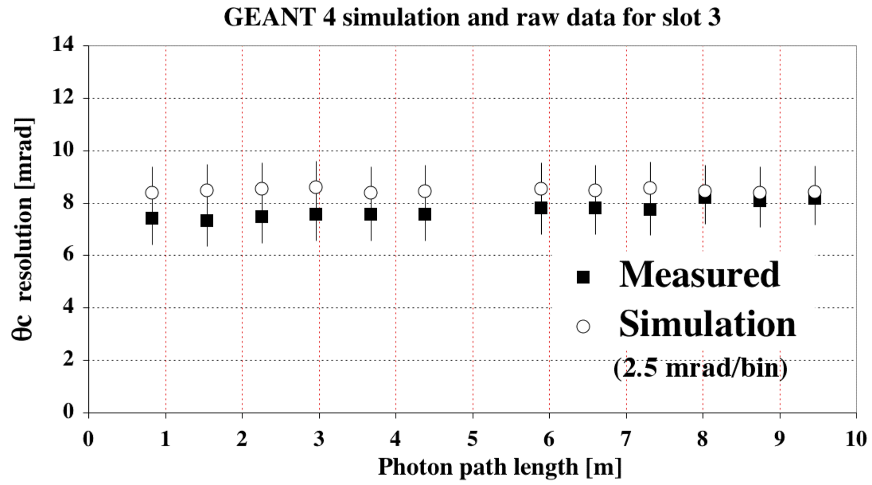
- The chromatic correction starts working for Lpath > 2-3 meters due to a limited timing resolution of the present photon detectors. The maximum likelihood technique does better for short Lpath than other methods
- Holes in the uncorrected distributions are caused by the coarse pixilization, which also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

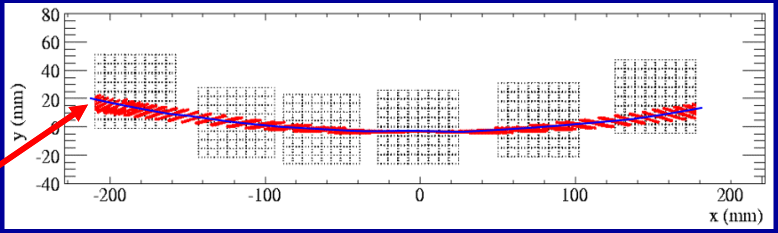
θ_C resolution and Geant 4 MC simulation

θ_c resolution - all pixels:



θ_c resolution - 3mm pixels only:





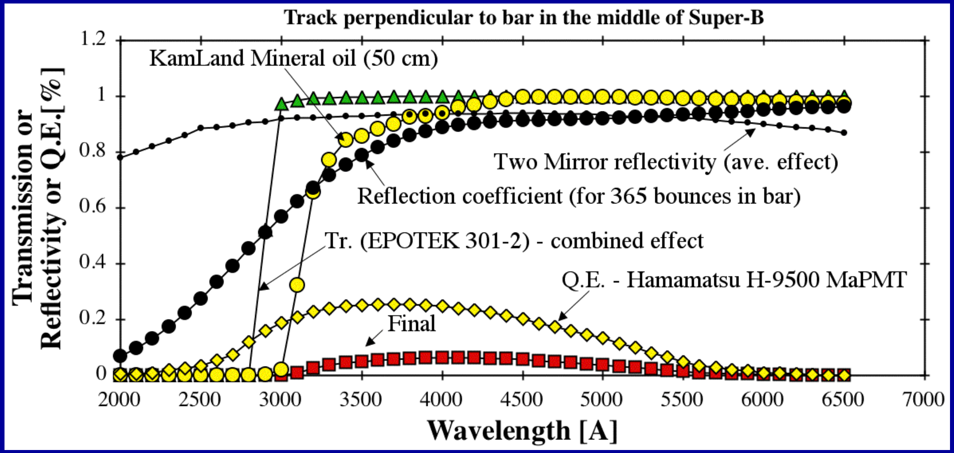
- **Main contributions to the θ_c resolution:**
  - **chromatic smearing: ~ 3-4 mrad**
  - **6mm pixel size: ~5.5 mrad**
  - **optical aberrations of this particular design:**

grows from 0 mrad at ring center to 9 mrad in outer wings of Cherenkov ring

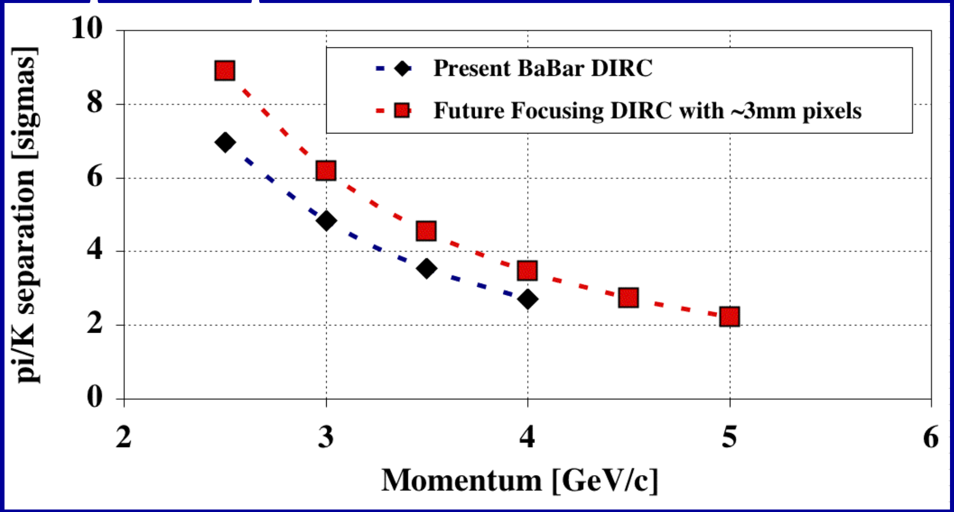
(this effect is caused by the spherical focusing mirror in the present design)

Expected final performance at incidence angle of 90°

Focusing DIRC prototype bandwidth:



Expected performance of a final device:



- Prototype’s **Npe_measured** and **Npe_expected** are consistent within **~20%.**

- **Hamamatsu H-9500 MaPMTs**:

  We expect **No ~ 31 cm^{-1}**, which in turn gives **Npe ~ 28** for 1.7 cm fused silica bar thickness, and somewhat better performance in **pi/K** separation than the present BaBar DIRC.

- **Burle-Photonis MCP-PMT:**

  We expect **No ~ 22 cm^{-1}** and **Npe ~ 20** for B = 0kG.

- **BaBar DIRC design**:

  No ~ 30 cm^{-1}, and **Npe ~ 27**.

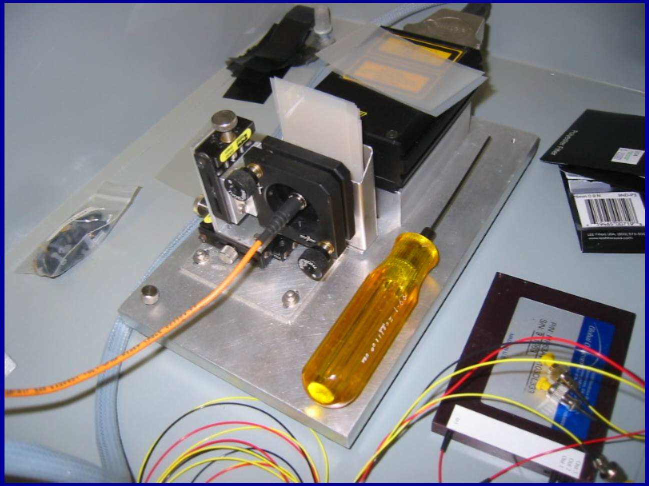
New trends in timing

- Goal: to reach a timing resolution of ~15 ps

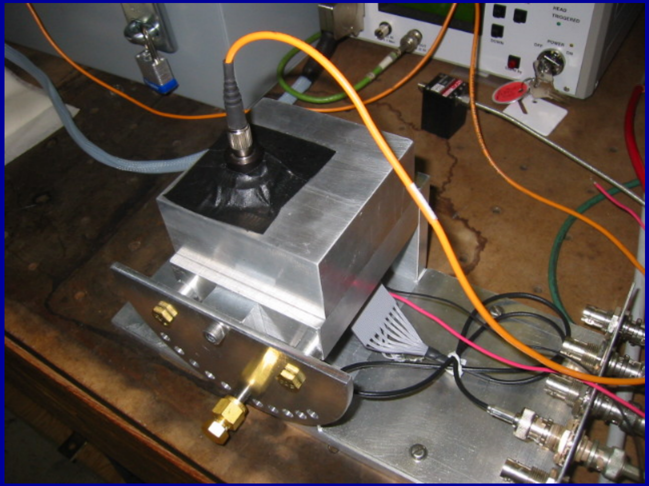
New laser-based testing methods

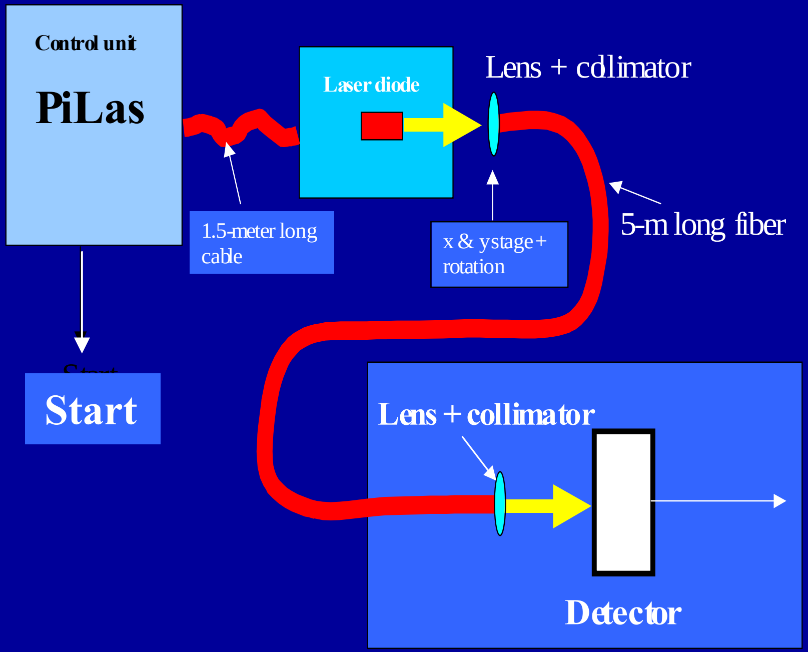
J.Va’vra, log book

PiLas laser head:



Calibration of a fast detector:





Parameter	SLAC tests
Laser diode source	PiLas
Wavelength	635 nm
TTS light spread (FWHM)	~ 35 ps
Fiber size	62.5 µm

Limit of the Single-photon timing resolution - σ_{TTS}

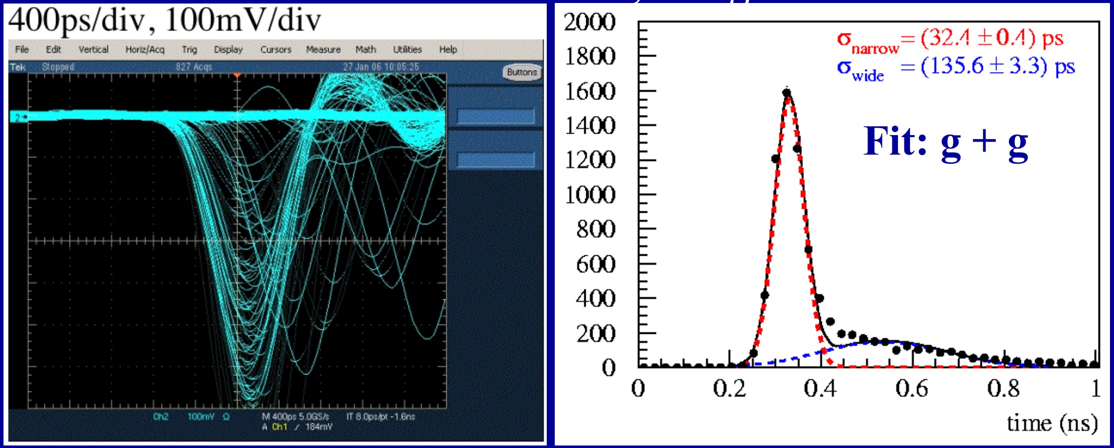
Timing measurement setup in trailer 233 at SLAC

Burle/Photonis MCP-PMT 85012-501 (ground all pads except one)

- **10 μm MCP hole diameter**
- **B = 0 kG**
- **64 pixel devices, pad size: 6 mm x 6 mm.**
- **Phillips CFD**
- **PiLas red laser diode operating in the single photoelectron mode (635 nm).**
- **$\sigma_{TTS} < \sqrt{(32^2-15^2-11^2)} = 26$ ps (Npe = 1)**

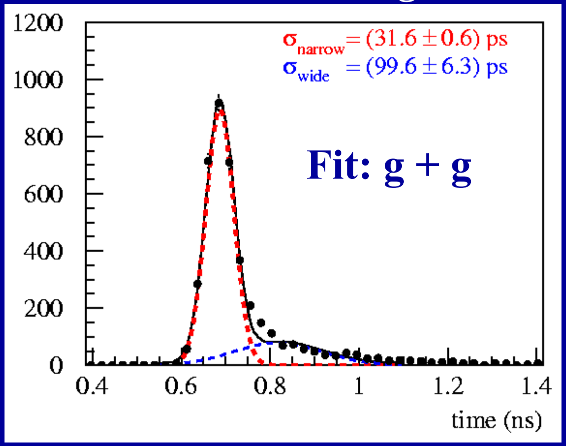
Hamamatsu C5594-44 amplifier

1.5 GHz BW, 63x gain



Ortec VT120A amplifier

~0.4 GHz BW, 200x gain + 6dB



Timing resolution with TAC & ADC

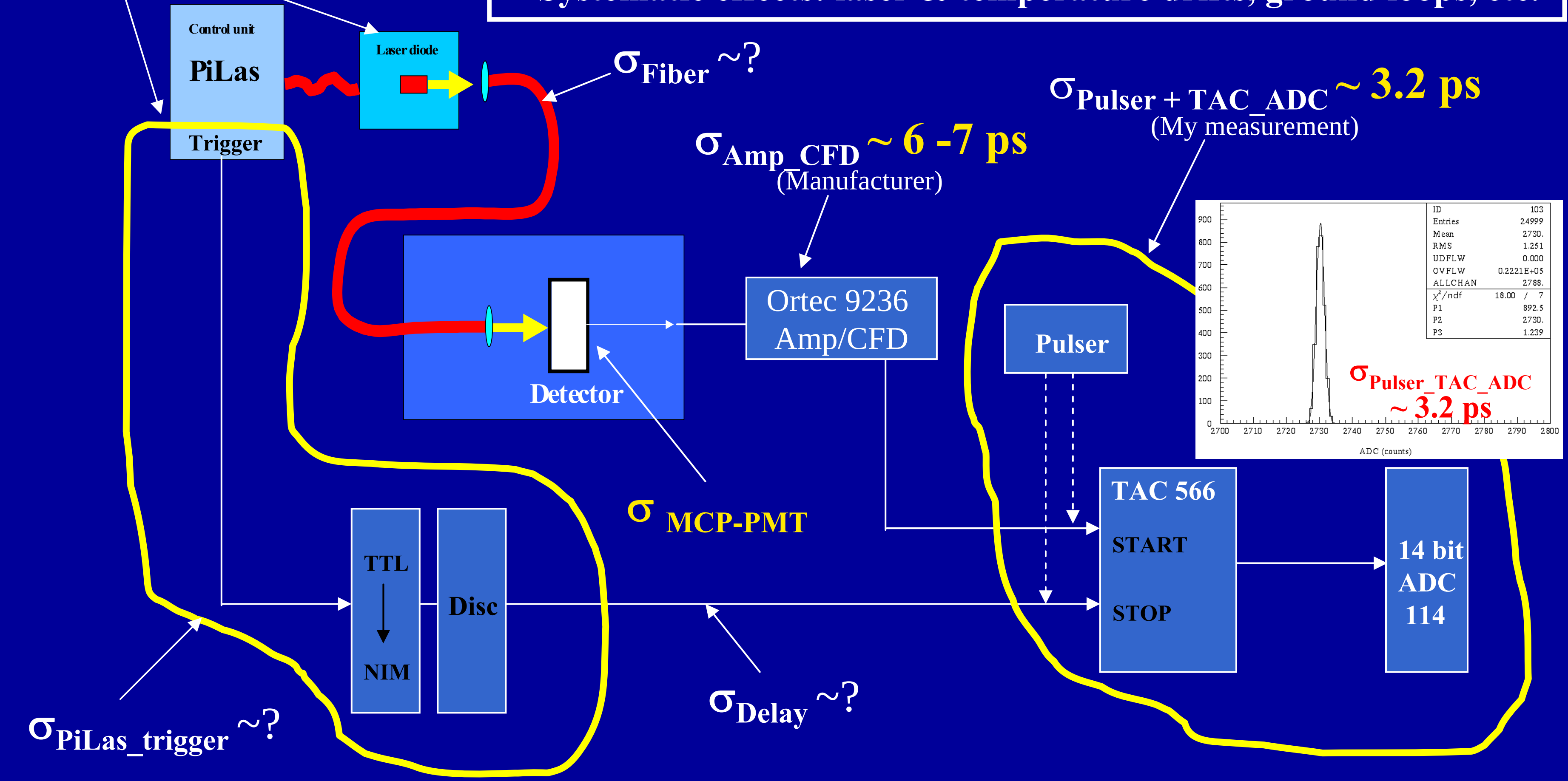
Timing measurement setup in trailer 233 at SLAC

$$\sigma = \sqrt{\{\sigma^2_{\text{MCP-PMT}} + \sigma^2_{\text{Fiber}} + \sigma^2_{\text{Amp\_CFD}} + \sigma^2_{\text{Delay}} + \sigma^2_{\text{PiLas}} + \sigma^2_{\text{Pulser+TAC\_ADC}} + \sigma^2_{\text{PiLas\_trigger}}\}}$$

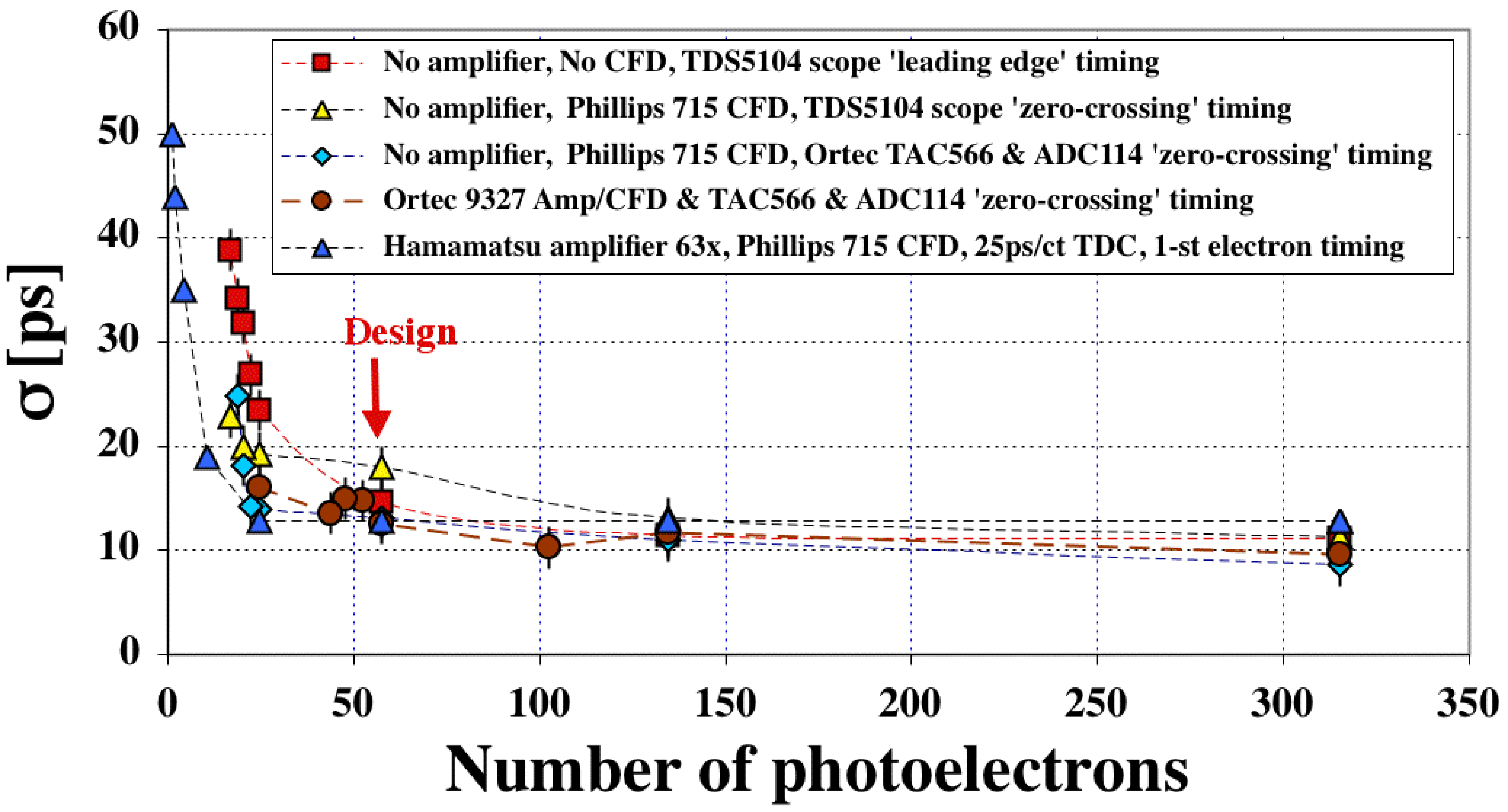
+ Systematic effects: laser & temperature drifts, ground loops, etc.

Manufacturer My measurement

σ_{PiLas} ~15 ps/$\sqrt{N_{pe}}$

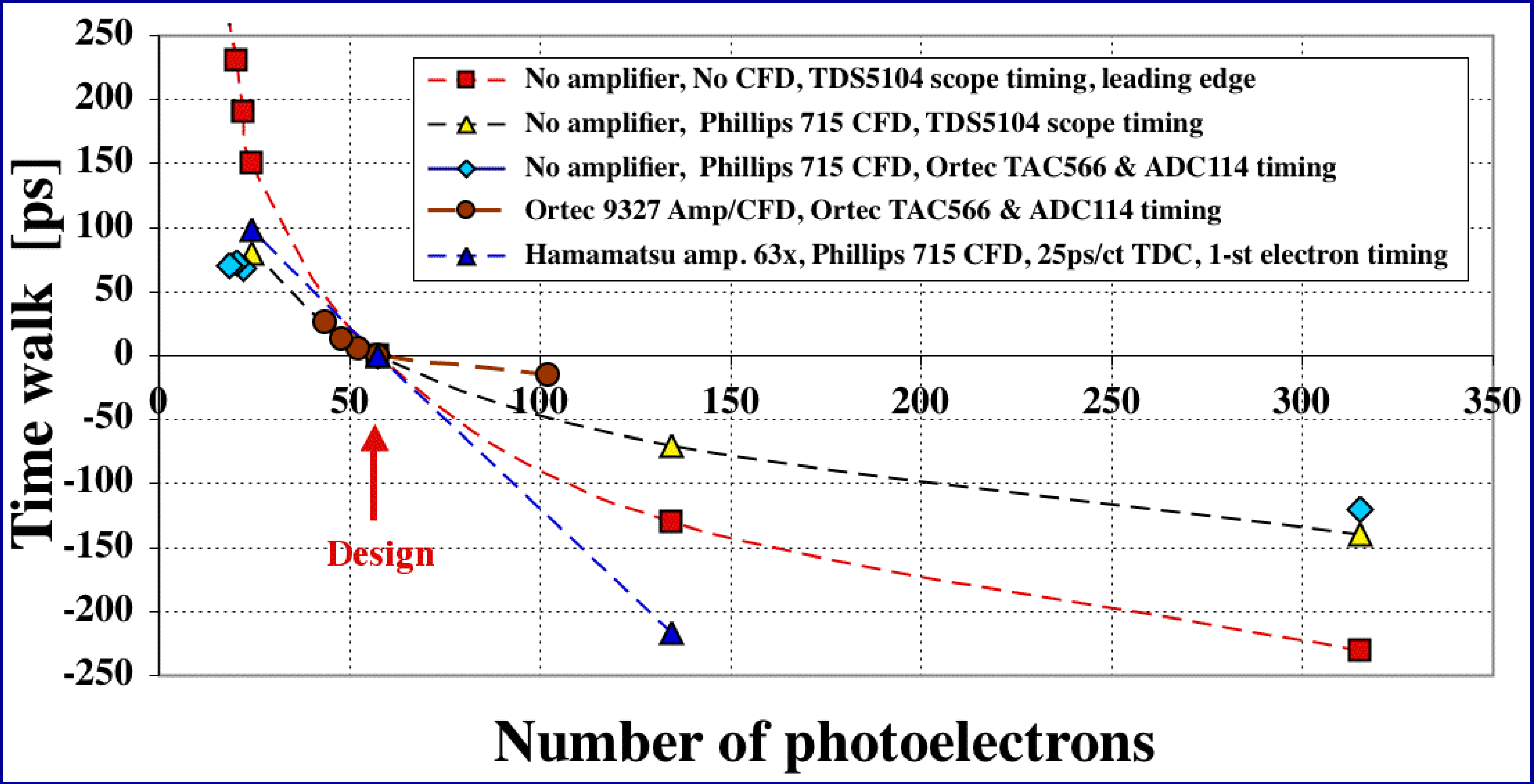


Timing resolution σ = f(Npe)



- Npe = 50-60 for 1cm-thick Quartz radiator + window & with Burle Bialkali QE.
- A goal to reach σ < 15 ps seems possible.
- The Ortec 9327-like performance is good.

Time-walk = f(Npe)

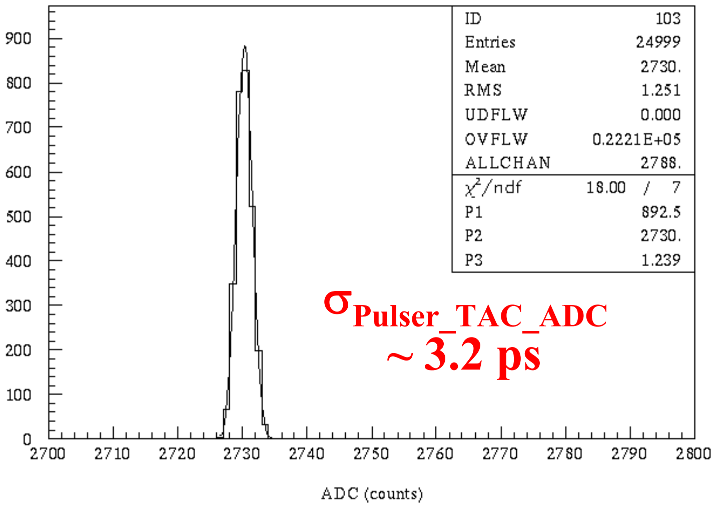


- **Time-walk <u>needs</u> to be corrected for any variation of Npe, <u>for all methods</u> !**
- **Ortec 9327 time-walk is smallest, but still significant.**

Determine upper limit on $\sigma_{\text{MCP-PMT}}$

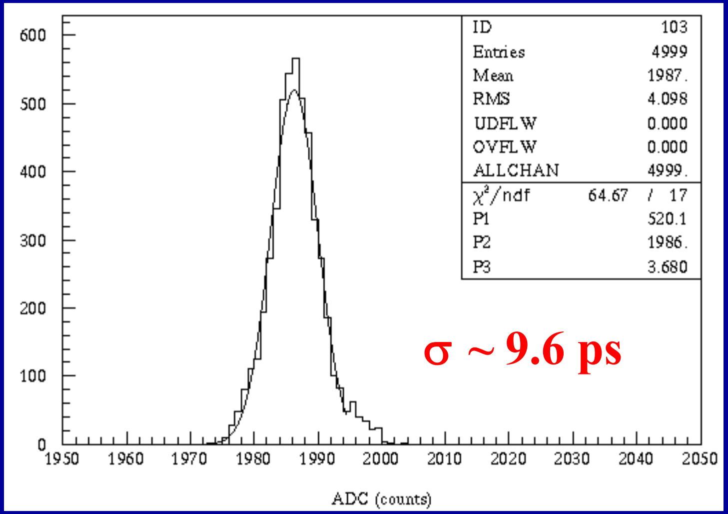
- MCP-PMT with 10 μm holes, 64 pads, ground all pads except one being used
- 2.33 kV with Ortec 9327 Amp/CFD (max. allowed voltage is 2.8kV => plenty of margin available for a future magnetic field operation.

Calibrate $\sigma_{\text{Pulser + TAC\_ADC}}$:



$\sigma_{\text{Pulser\_TAC\_ADC}}$ ~ 3.2 ps

Determine σ for Npe ~ 300:



σ ~ 9.6 ps

(Note: σ ~ 8.6 ps with Phillips CFD 715)

Upper limit on MCP-PMT contribution to the resolution:

$$\boxed{\sigma_{\text{MCP-PMT}} < \sqrt{\{\sigma^2 - \sigma^2_{\text{PiLas}}(N_{pe}) - \sigma^2_{\text{Amp\_CFD}} - [\sigma^2_{\text{Pulser+TAC\_ADC}} - \sigma^2_{\text{Pulser}}]\}} < 6.5\text{ ps}}$$

9.6 ps

< 1 ps (PiLas & measure)

6-7 ps (Ortec)

3.2 ps

< 2 ps (manufacturer)

Conclusions

- **We have demonstrated that we can correct the chromatic error of θ_C. This is the first RICH detector which has been able to do this.**
- **Expected N_o and Npe is comparable to BaBar DIRC for MaPMT H-9500.**
- **Expected improvement of the PID performance with 3x3mm pixels: ~20-30% compared to BaBar DIRC for pi/K separation, if we use H-9500 MaPMT.**
- The main defense against the background at Super-B is to make (a) the expansion volume much smaller, which is possible only with highly pixilated photon detectors, and (b) use of faster detectors.

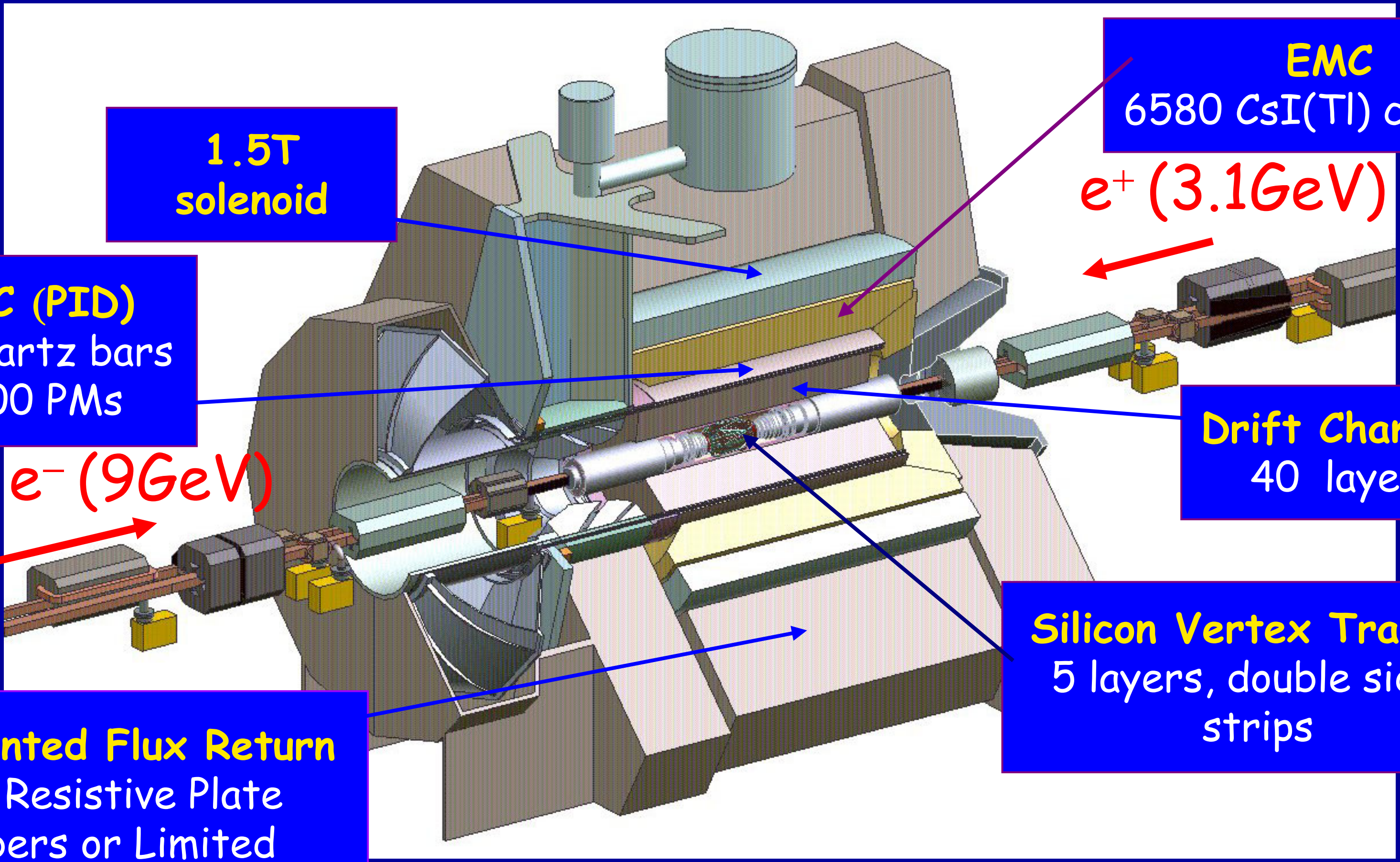
- **Our present best results with the laser diode:**
  - **$\sigma \sim 12$ ps for Npe = 50-60 (expected from 1cm thick Cherenkov radiator).**
  - **$\sigma_{TTS} < 26$ ps for Npe ~ 1.**
  - **Upper limit on the MCP-PMT contribution: $\sigma_{MCP\text{-}PMT} < 6.5$ ps.**
  - **TAC/ADC contribution to timing: $\sigma_{TAC\_ADC} < 3.2$ ps.**
  - **Total electronics contribution at present: $\sigma_{Total\_electronics} \sim 7.2$ ps.**

    (One has to be aware that the time-walk, due to variation of Npe, has to be corrected).

- **Next test beam run:** Add (a) ADC-based pixel interpolation, (b) 2-nd hodoscope after a bar, (c) ASIC-based readout on one MCP-PMT allowing a measurement of time and pulse height, (d) test of the TOF detector.

Backup slides

BaBar detector at SLAC



1.5T solenoid

EMC
6580 CsI(Tl) crystals

e^{+} (3.1GeV)

DIRC (PID)
144 quartz bars
11000 PMs

e^{-} (9GeV)

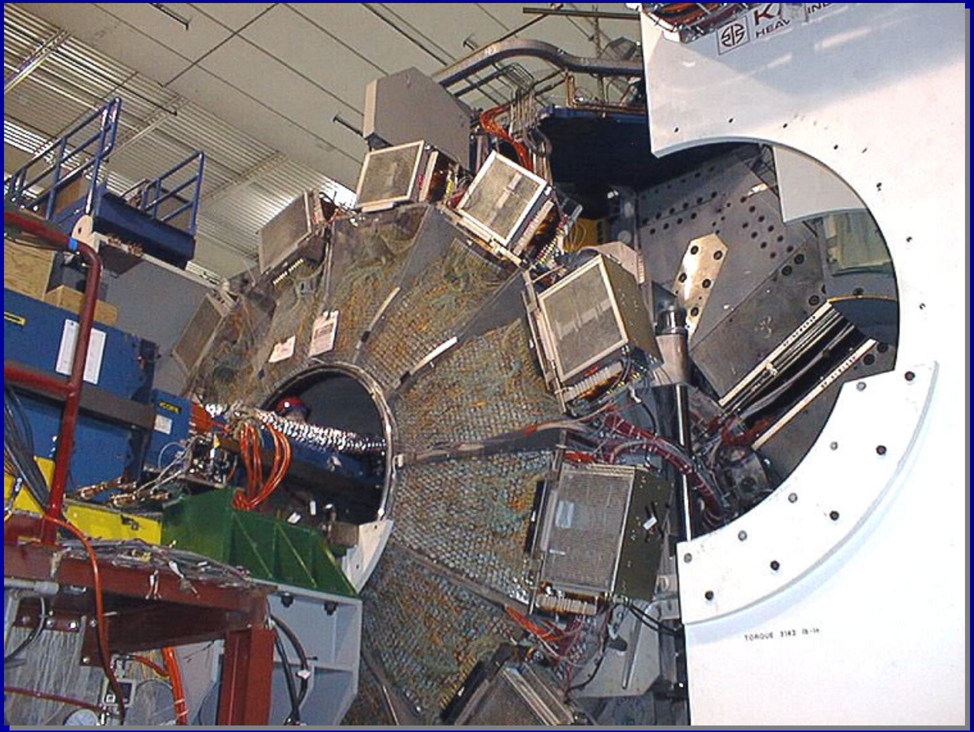
Drift Chamber
40 layers

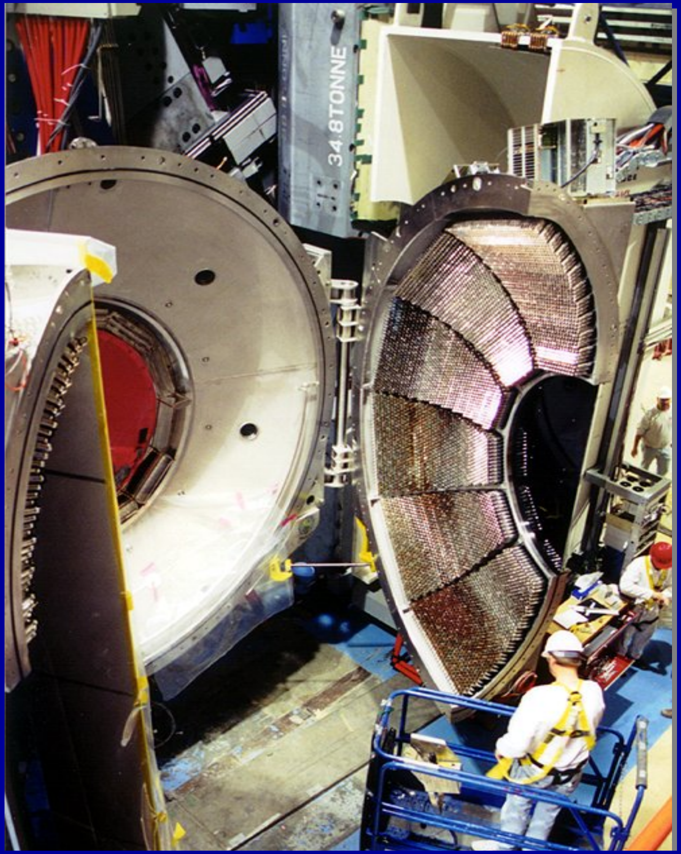
Silicon Vertex Tracker
5 layers, double sided strips

Instrumented Flux Return
Iron / Resistive Plate Chambers or Limited Streamer Tubes (muon / neutral hadrons)

Detector commissioned in 1999

BaBar DIRC photon detector

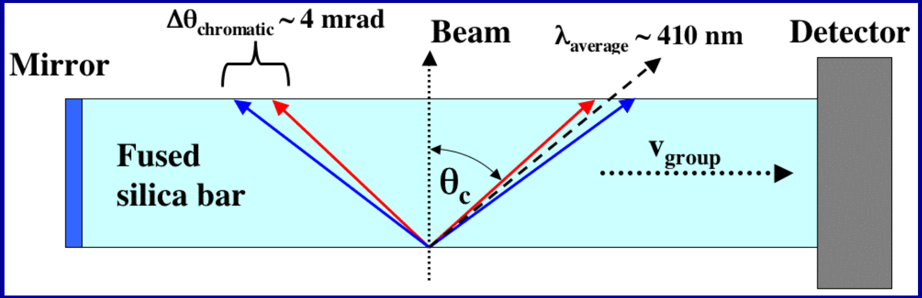


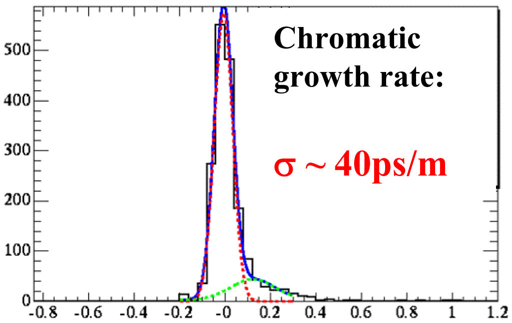


- *10752 ETL 9125 PMTs, 1 inch dia.*
- *TDC: 0.5 ns/count*
- *No dead time up to rate of ~500 kHz/PMT*
- *Serial data link: 1.2 Gbits optical fibers*

Comparison of various methods to determine the chromatic correction

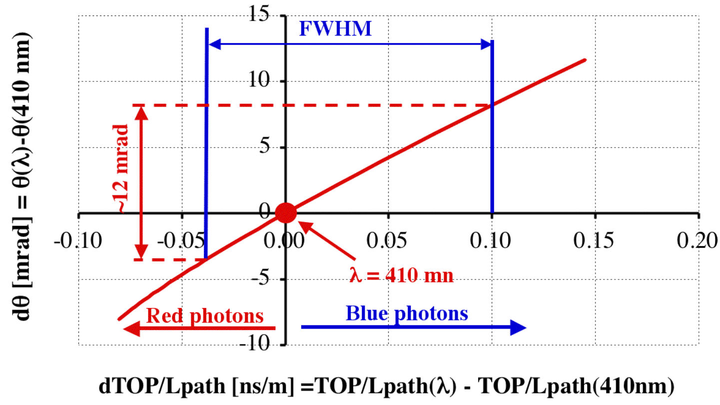
Cherenkov light: tagging color by time





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

Analytical calculation:



Cherenkov angle production controlled by n_{phase}:

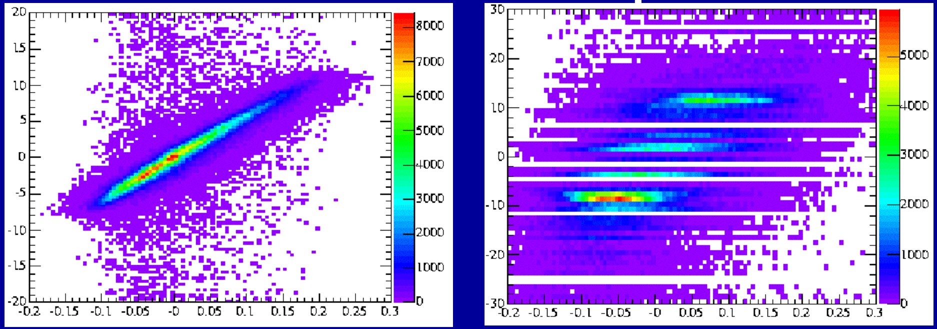
$\cos\theta_c = 1/(n_{phase}\beta)$, n_{phase}(red) < n_{phase}(blue) => $\theta_c < \theta_c$

Propagation of photons is controlled by n_{group} ($\neq n_{phase}$) :

$$v_{group} = c_0/n_{group} = c_0/[n_{phase} - \lambda □□_{phase} □\lambda□]$$

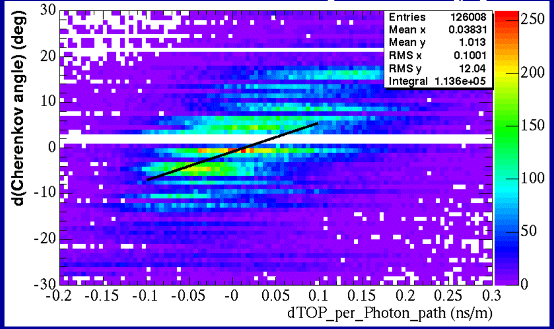
$$v_{group}(\text{red}) > v_{group}(\text{blue})$$

Geant 4 - without and with pixilization:



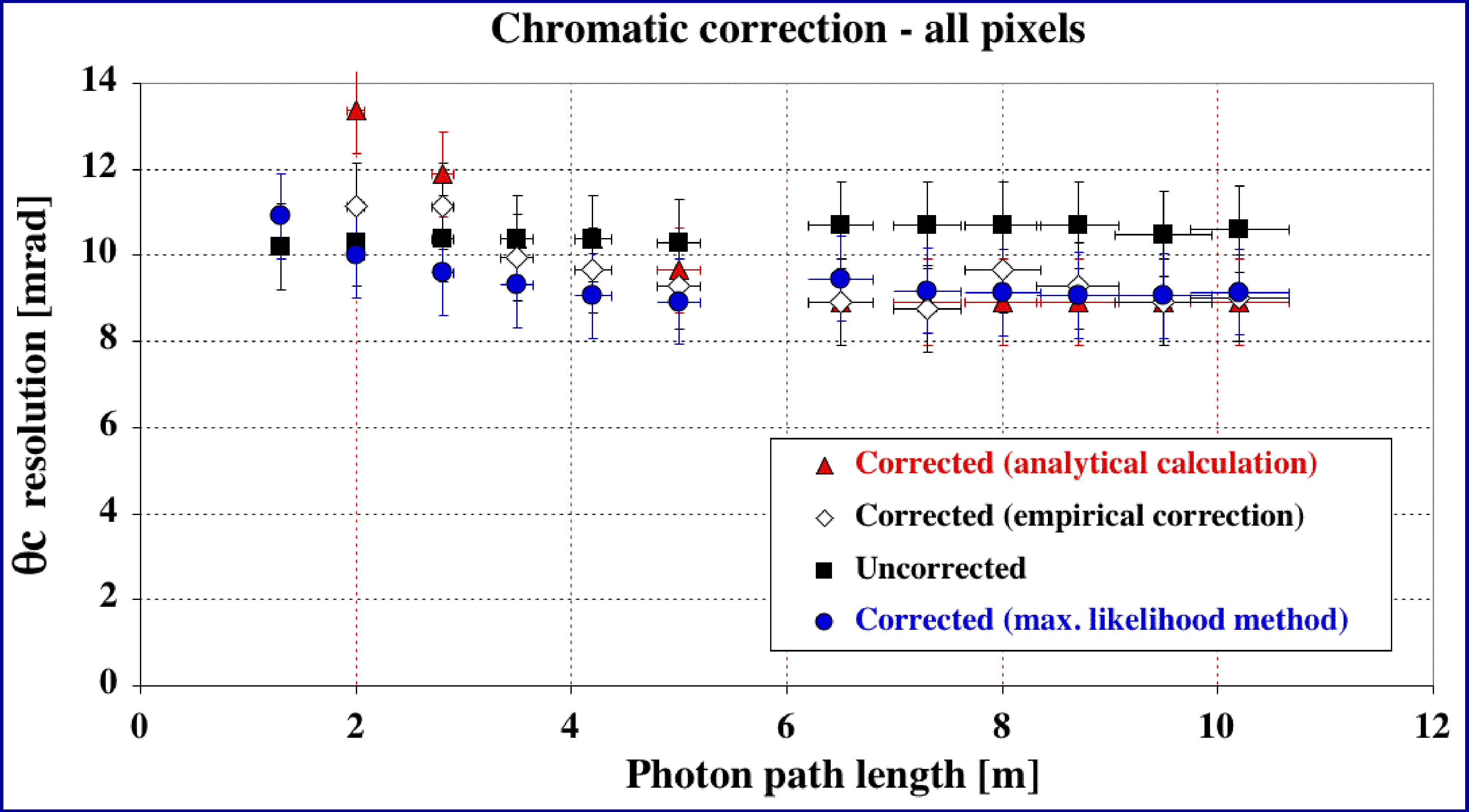
dTOP/Lpath [ns/m]

Data from the prototype:



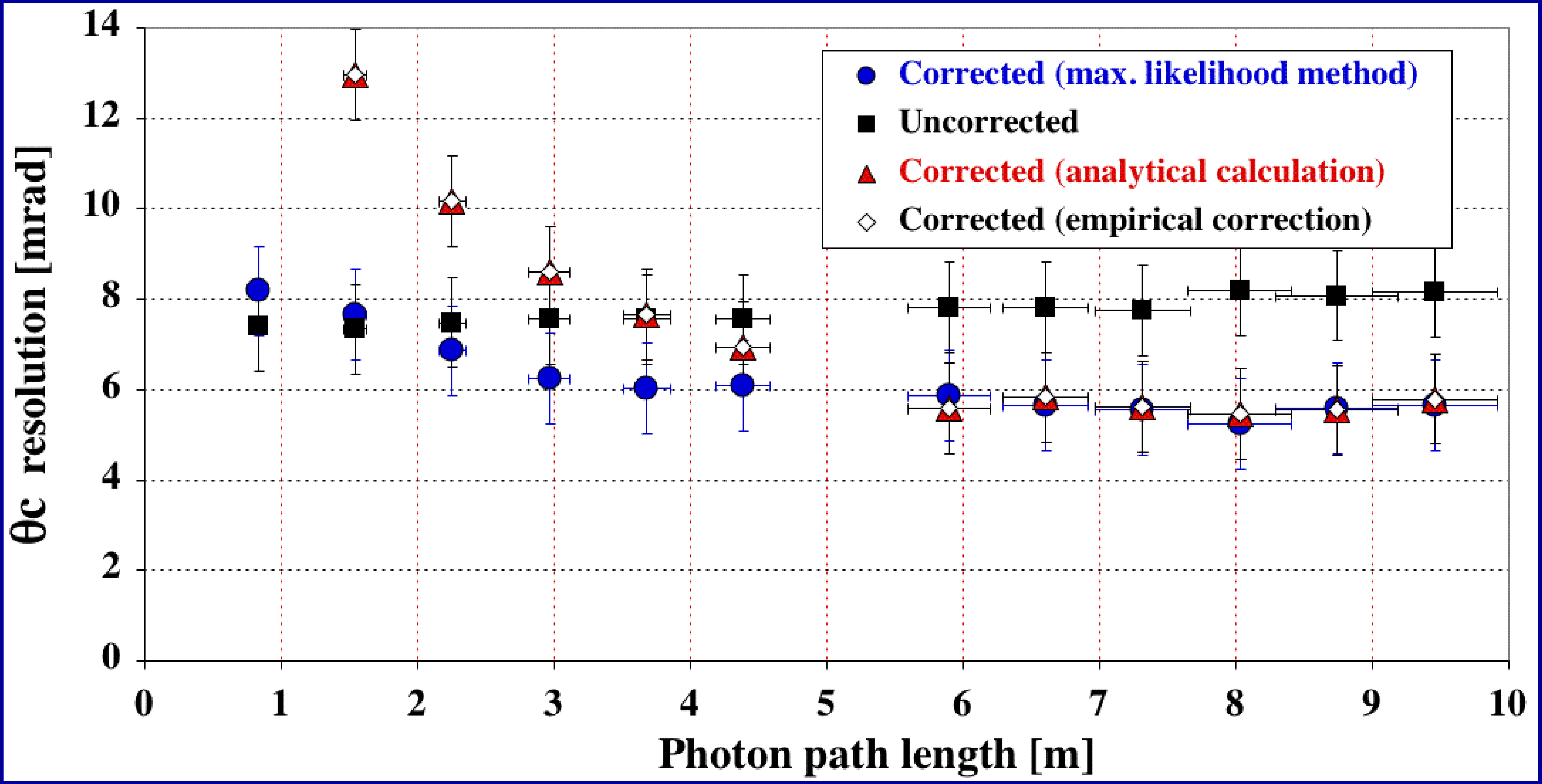
dTOP/Lpath [ns/m]

Chromatic correction - all methods



- There is a good agreement among various methods for Lpath > 4 meters. For smaller Lpath values the max. likelihood has a best performance.

Chromatic correction - small pixels only



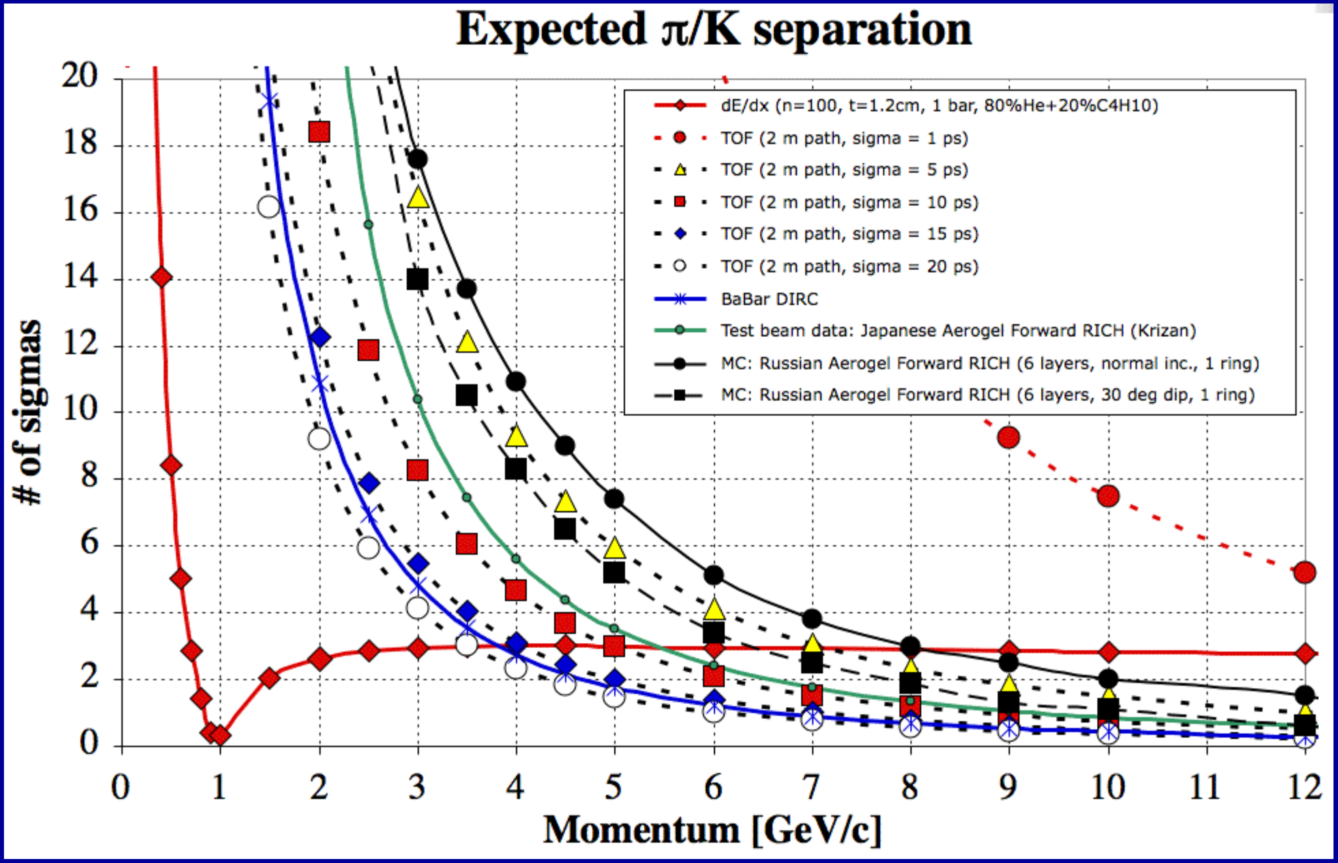
- There is a good agreement among various methods for Lpath > 5-6 meters. For smaller Lpath values the max. likelihood performs best.

TOF detector

Timing at a level of σ <15ps can start competing with the RICH techniques

Example of various Super-B factory PID designs:

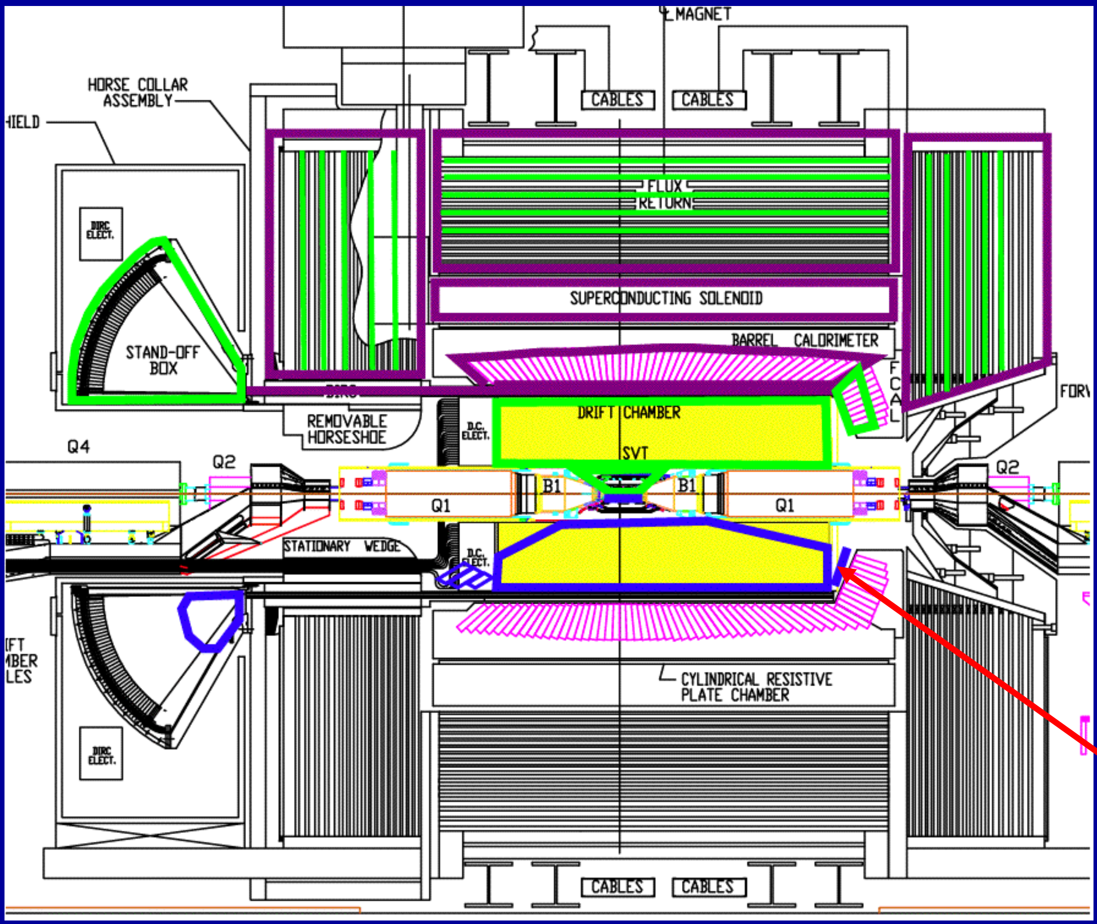
Calculation done for Flight Path Length = 2m



- **Recent progress in the TOF technique is driven by these advances:**

  (a) a fast Cherenkov light rather than a scintillation, (b) new detectors with small transit time spread σ_{TTS}, (c) fast electronics, and (d) new fast laser diodes for testing.

Super-B detector options



- **Forward TOF detector with σ ~ 15ps is one option**