Practical message from recently developed PID detectors ?

Jerry Vavra

Content

- **DIRC in BaBar**
  - Pin hole focusing optics and lessons we learned from it.

- **DIRC devices with full imaging**
  a) FDIRC with with cylindrical lens focusing for SuperB,
  b) FDIRC with with cylindrical lens focusing for GLUEX,
  c) DIRC with a spherical lens focusing for Panda and EIC.
  b) GLUEX FDIRC

- **DIRC devices which are hybrid between imaging and TOF**
  - TOP counter for Belle-II.

- **DIRC TOF devices**
  - LHCb TORCH DIRC using BaBar bar boxes.

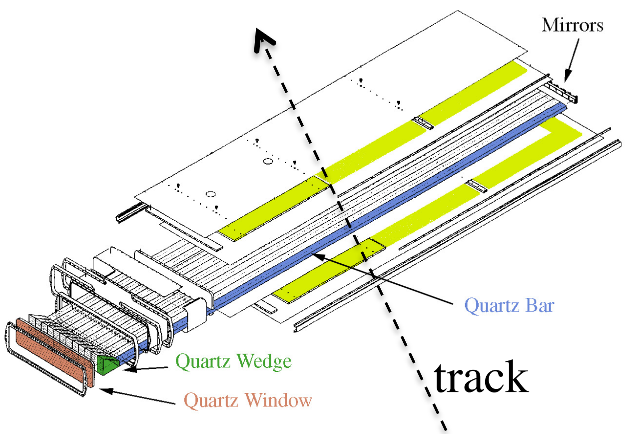
- **Forward RICH with Aerogel radiator**
  - Belle-II FARICH.

- **“Pixilated” TOF devices**
  - “Pixilated” TOF devices.

Invention of DIRC

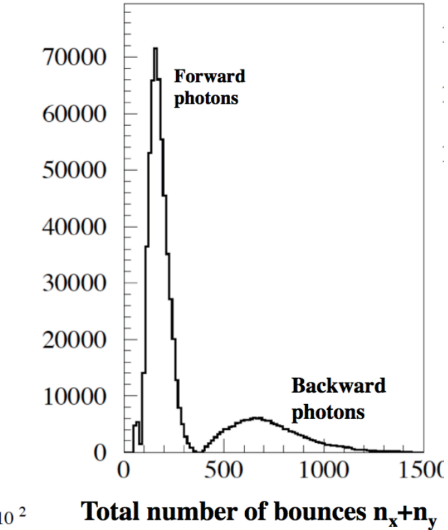
SLAC-PUB-5946 and NIMA 538(2005)281

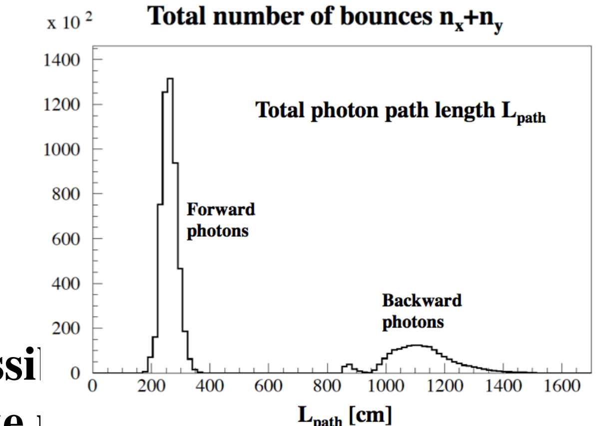
DIRC radiator:



144 bars, ~5m long:

FDIRC data analysis:



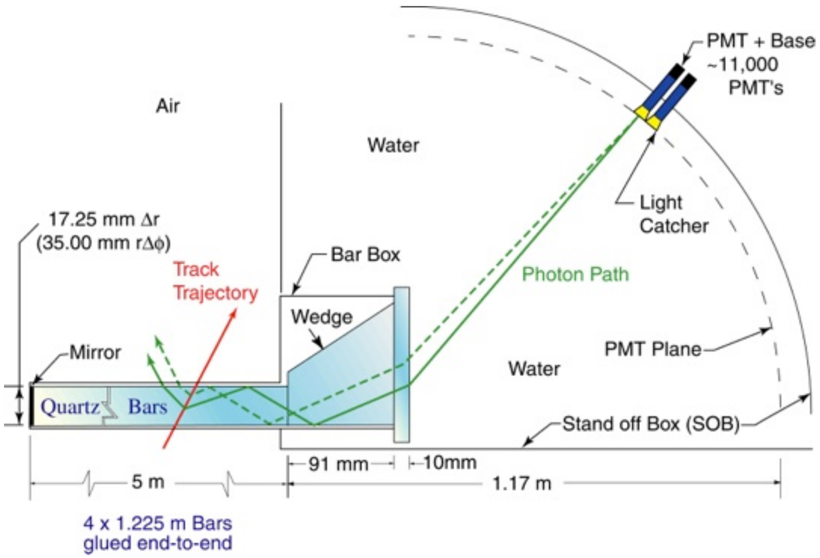


- **DIRC concept was invented by Blair Ratcliff.**
- **Ingenius part of Blair's idea was that he saw that it is possi quartz radiator bars, where Cherenkov photons can make photon path of up to ~15 meters, and preserve the Cherenkov angle infomation.**
- **He managed to convince BaBar to allow the bar penetration of magnet iron, so that the photon detector can be located outside, which made it practical at that time.**
- **To me DIRC is basically a photon TPC. If one measures a photon position, time, and track entry, one can reconstruct the photon path.**

BaBar DIRC

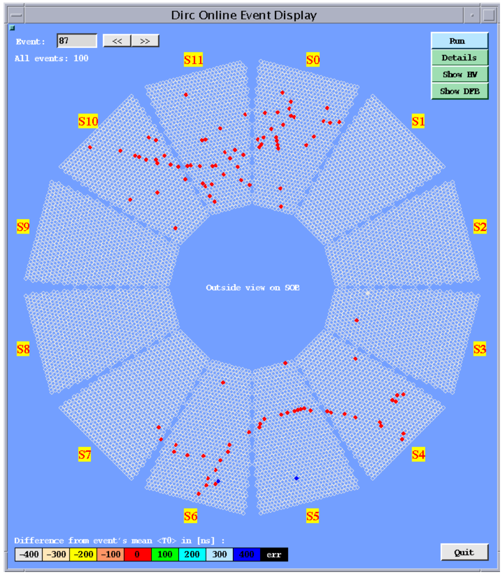
SLAC-PUB-5946 and NIMA 538(2005)281

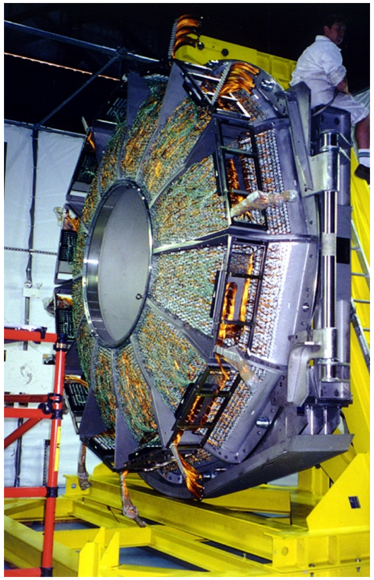
Pin hole focusing:



$$\cos\theta_c = \mathbf{k}_{track} \cdot \mathbf{k}^{pixel}$$

Photon detector: ~11,000 PMTs, 6000 *l* of water

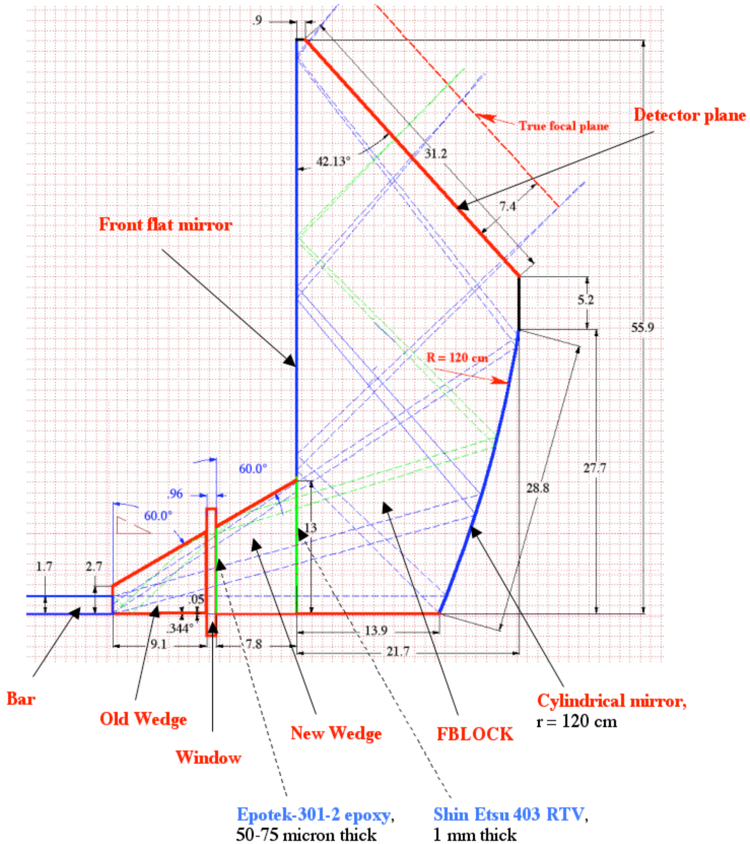


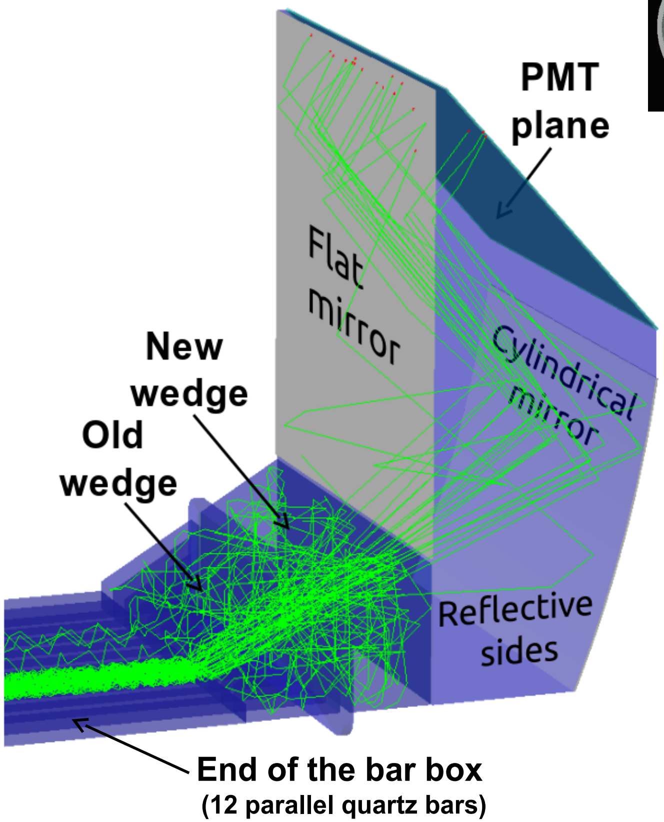


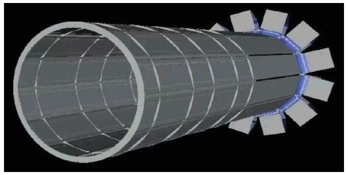
- **DIRC detector proved to be very successful for BaBar.**
- **However, many questions/puzzles had to be answered. To name a few R&D examples: (a) internal reflection coefficient, (b) transmission, (c) background issues, (d) radiation damage, (e) issues around how to build it and maintain quality control, (f) etc…**
- **Message for next step: make photon camera small and use smaller pixels.**

FDIRC photon camera for SuperB

NIMA 775(2015)112-131







- Optical design: Focus only in y-direction using a single cylindrical lens, which "corrects out" the bar thickness, in x-direction it is a pin hole focusing. No focusing in x-direction, i.e., it remains the pin hole focusing.
- Improve timing compard to BaBar DIRC.
- A full coverage would require 48 H-8500 MaPMTs; or only 4 LAPPD MCP-PMTs !

Cherenkov angle resolution in DIRC

Cherenkov angle resolution per track:

$$\sigma_C^{track} \sim \sqrt{[(\sigma_C^{single\ photon}/\sqrt{(N_{pe})})^2 + (\sigma_C^{track\ resolution})^2 + \ldots]}$$

Single photon Cherenkov angle resolution:

$$\sigma_C^{single\ photon} \sim \sqrt{[(\sigma_C^{pixel\ in\ y\text{-}direction})^2 + (\sigma_C^{bar\ imperfections})^2 + (\sigma_C^{chromatic\ error})^2 + (\sigma_C^{optical\ aberration})^2 + \ldots]}$$

Examples:

Item	Cherenkov resolution per single photon	[mrad]
1	Chromatic error	5.5
2	Pixel contribution (6 / 3 mm pixels)	5.5 / 2.8
3	Optical aberration	1 - 9
4	Transport along the bar	2 - 3
5	Bar thickness	~ 1
6	Old wedge bottom inclined surface	3.5
	Final error (no chromatic correction)	10 / 8.8
	Final error (with chromatic correction)	8.4 / 7.0

Item	Cherenkov resolution per track	[mrad]
1	BaBar DIRC	2.5
2	FDIRC with 6 mm pixels, no chromatic correction and H-8500 with QE ~ 24%	2.4
3	FDIRC with 6 mm pixels, chromatic correction and H-8500 with QE ~ 24%	2.2
4	FDIRC with 3 mm pixels, chromatic correction and R11256-M64 with QE ~ 36%	1.9

- **A good tracking resolution is very critical to good performance.**

Optical aberration in DIRC detectors

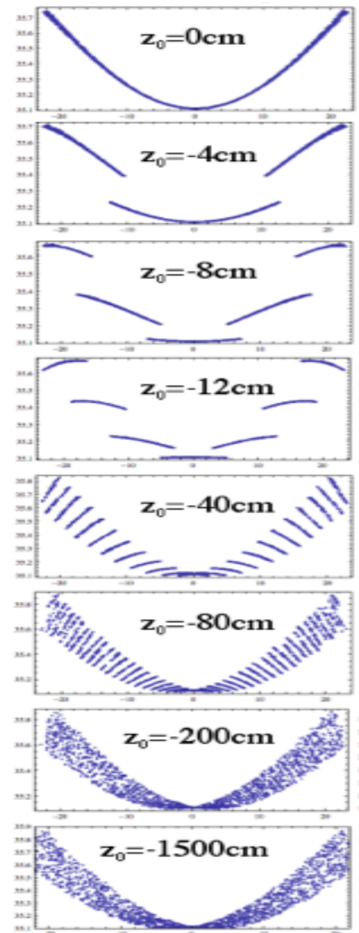
NIMA 766(2014)189

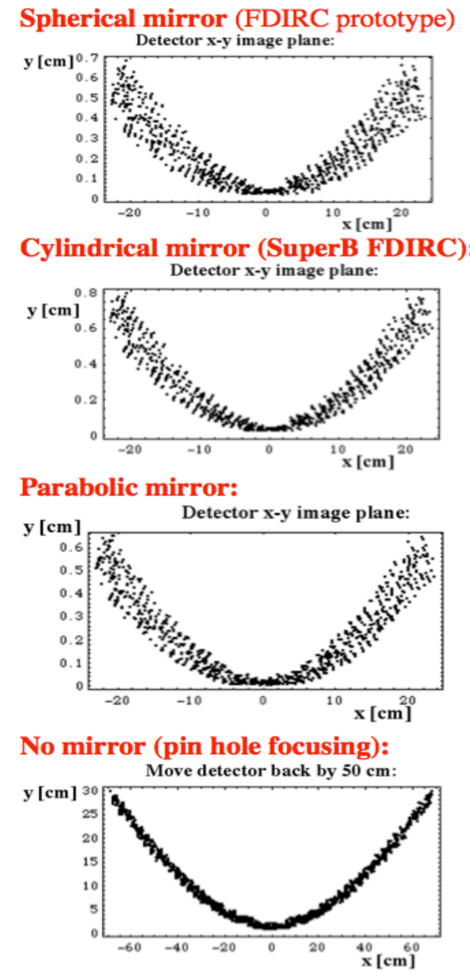
Kaleidoscopic effect:

$\sigma_C^{\text{optical aberration}}$ **~ 1 - 9 mrads**

~ 4.5 mrads

(on average)





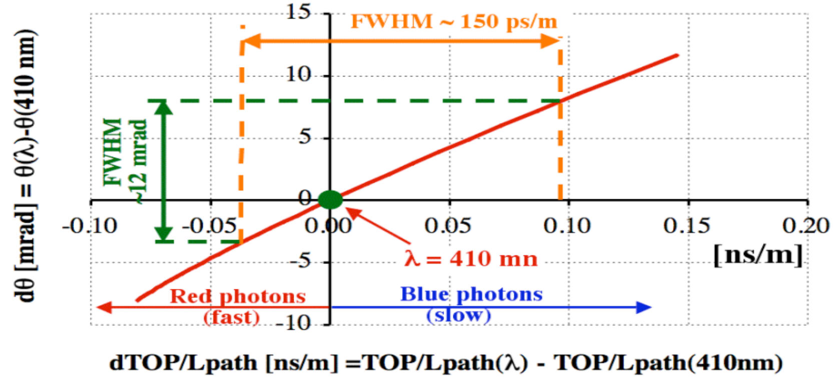
- **To correct optical aberration is hard; it needs a high degree of pixelization.**
- **None of the existing detectors are correcting this effect.**

FDIRC prototype was the 1-st RICH detector to correct the chromatic error

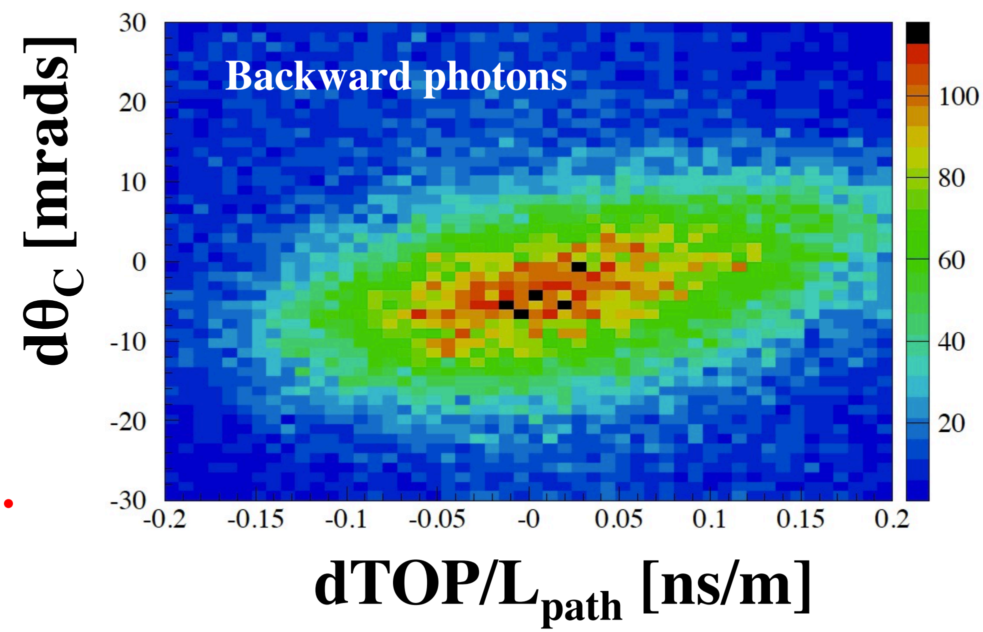
NIMA 775(2015)112 and NIMA 766(2014)114

Expect:

$\sigma_C^{\text{chromatic effect}} \sim$ **4-5 mrads**

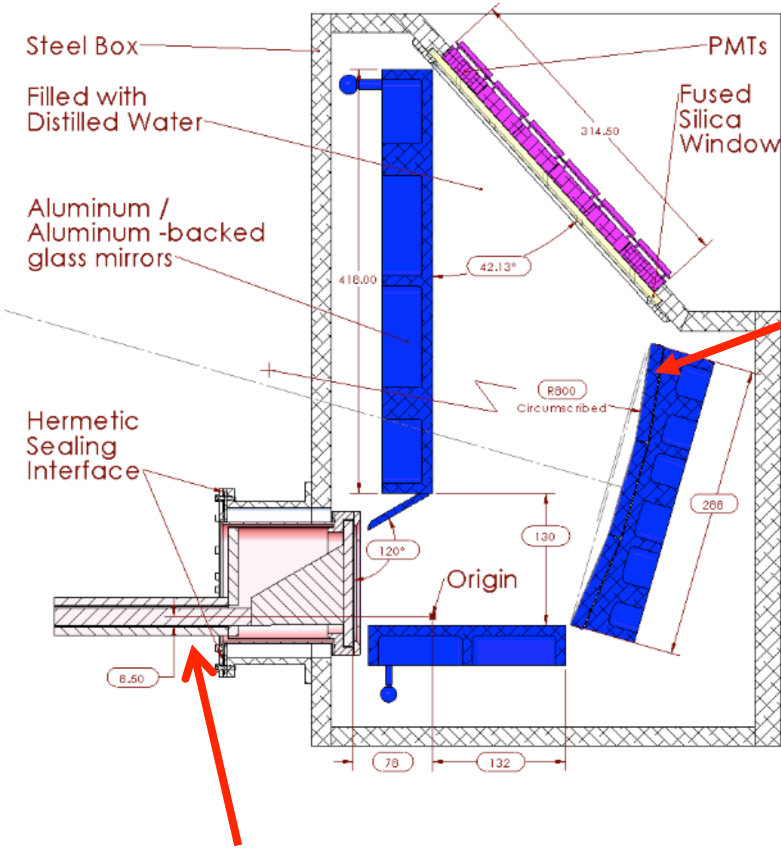


FDIRC data:



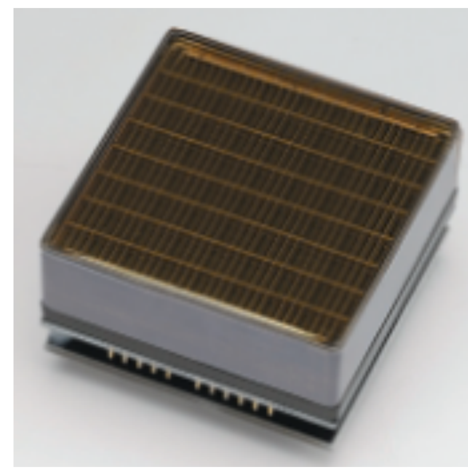
- **The chromatic correction is possible if: $\sigma_{\text{single photon}} \leq$ 200ps.**

GLUEX FDIRC



Cylindrical mirror approximated by three-segment flat mirrors:

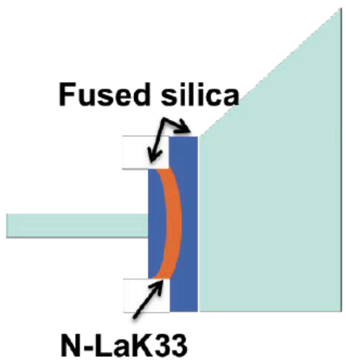
H-12700 MaPMT (6mm x 6mm pixels):

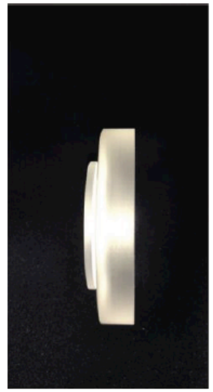


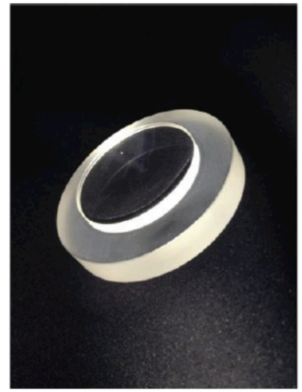
- **GLUEX will re-use BaBar DIRC bar boxes.**
- **It is a ring imaging detector a'la FDIRC camera, but it will be simplified because tracks are nearly perpendicular to bars. The cylindrical mirror will be replaced by three-segment flat mirrors. For their conditions, they seem to achieve a good enough resolution.**
- **A full coverage would requires 48 H-17200 MaPMTs; or only 4 LAPPD MCP-PMTs !**

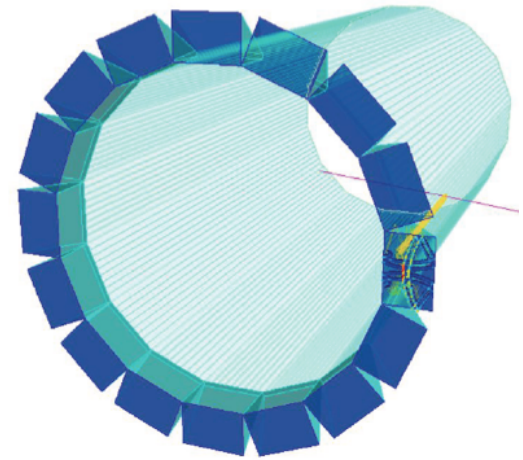
Panda/EIC DIRC

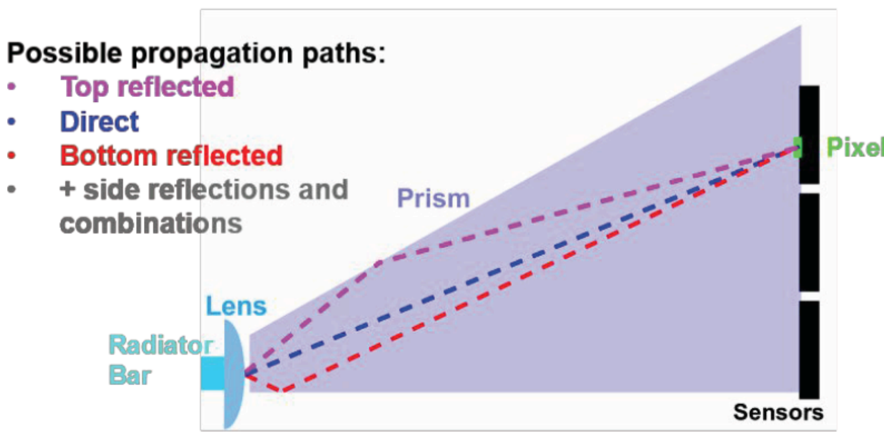
EIC R&D review, BNL, 2015









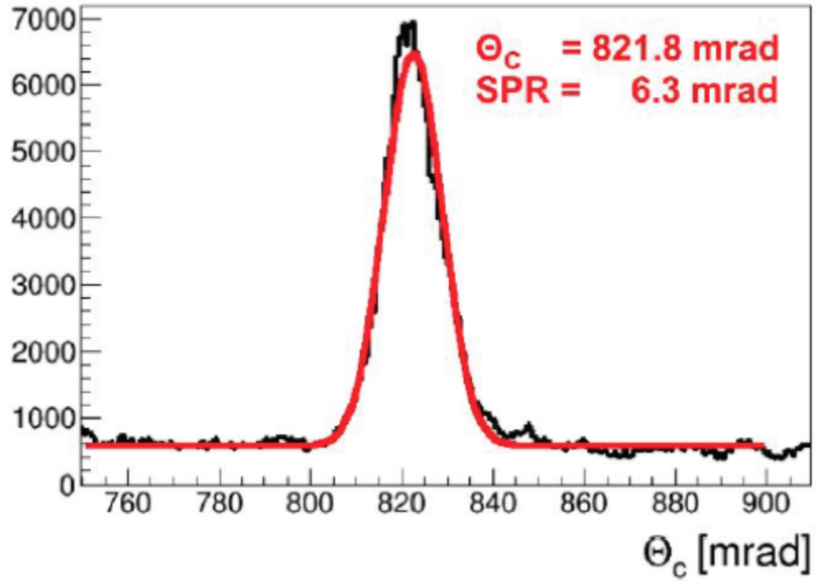


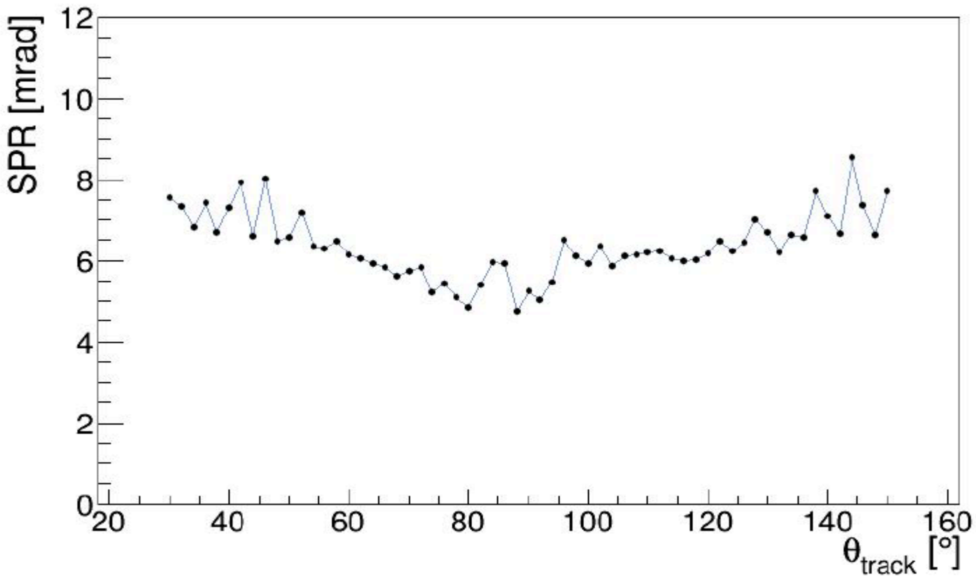
- Elegant solution yielding somewhat smaller photon camera size.
- One needs a Pb-based glass for lens with high refraction index. It needs to be radiation hard.
- It is not clear yet to me if there are some photon losses or some abberation due to lens optics.
- Since the camera will be inside magnetic field, one needs the MCP-PMT based photon detector.

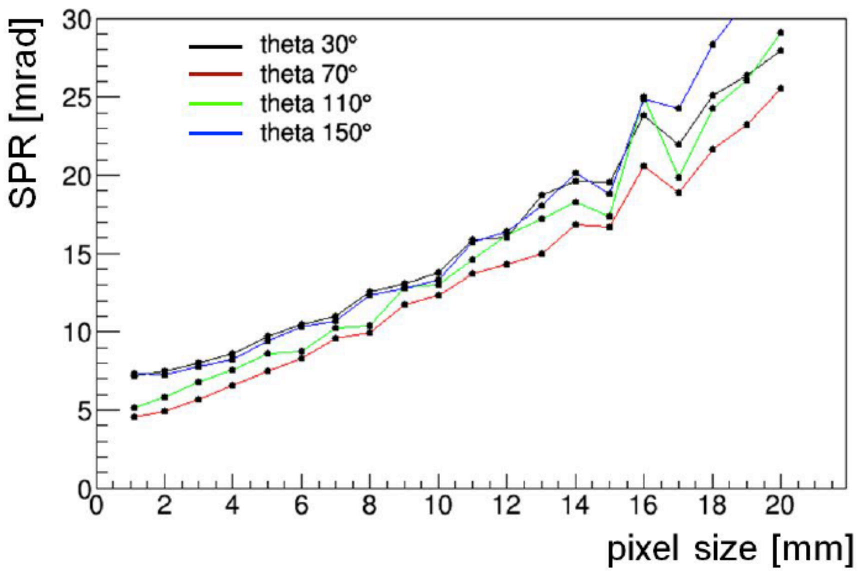
Panda/EIC DIRC – single photon resolution (SPR)

EIC R&D review, BNL, 2015

MC simulation



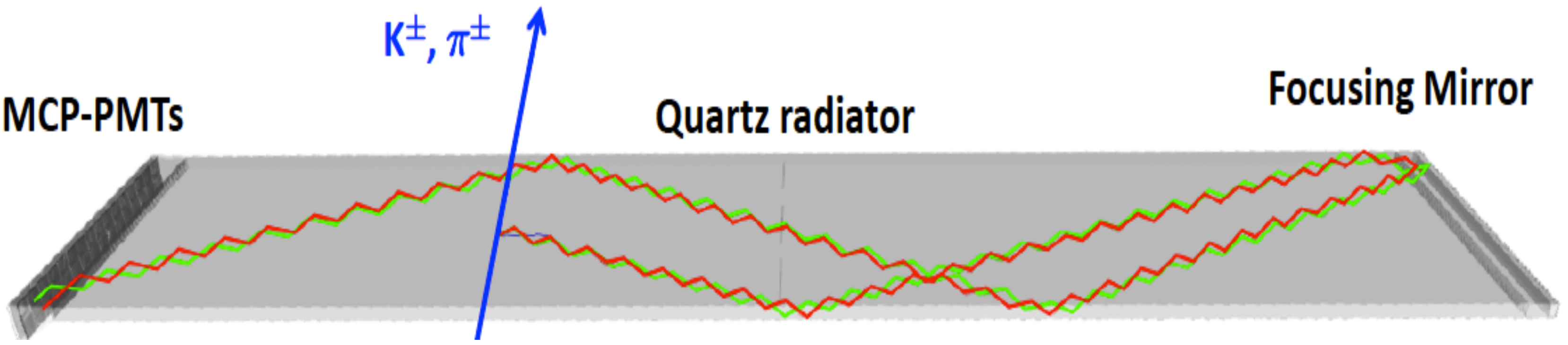




Belle-II TOP counter

Belle-II Technical design report, 2010 and later updates

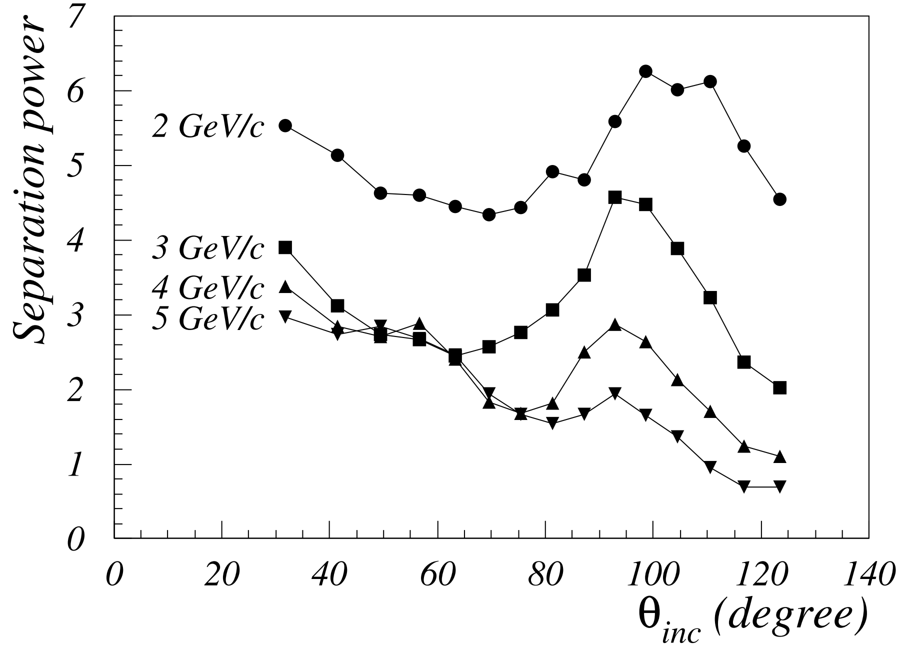
TOP counter measure "x , y and time":



- **It is a hybrid of an imaging and a simple TOF detector.**
- **Single photon timing resolution of σ ~ 40 ps / photon is essential.**

Belle-II TOP counter performance

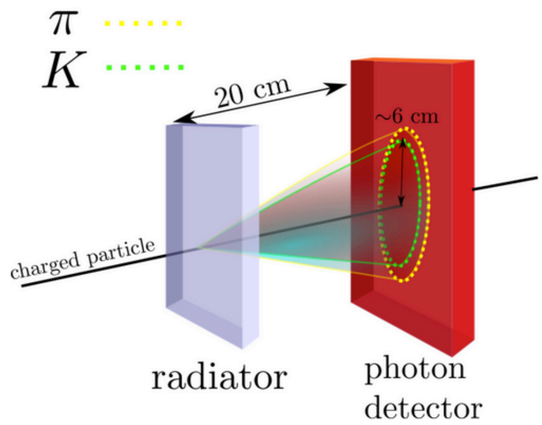
Plot produced by Marko Staric, Belle-II collaboration



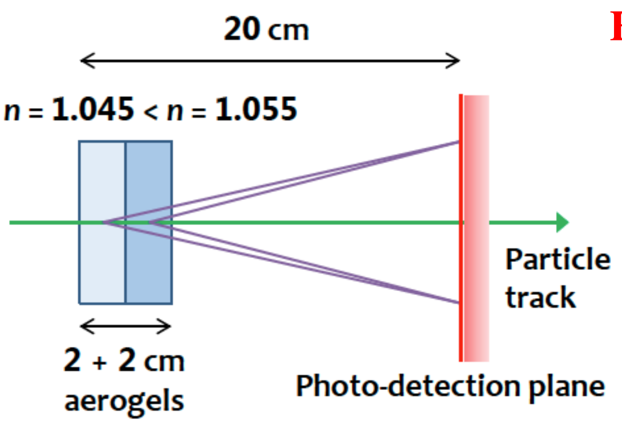
- **Performance dependes critically on track angle of incidence.**
- **Best resolution is in the region around track angle of ~90-100^o.**
- **The main reason for track dip angles near 50-60^o is that too many photons go almost straight towards the photon detector and have a poor measurement of the Cherenkov angle, and what remains is the TOF part, which is also not that good because of the short path.**
- **Near 120^o (the end of the bar) and the measurement is purely TOF.**

Belle-II Forward RICH

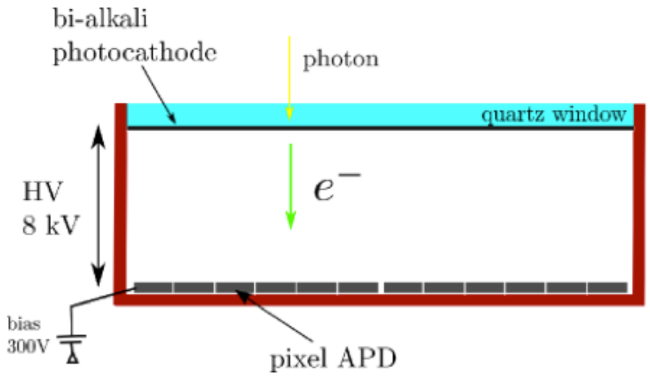
Principle:



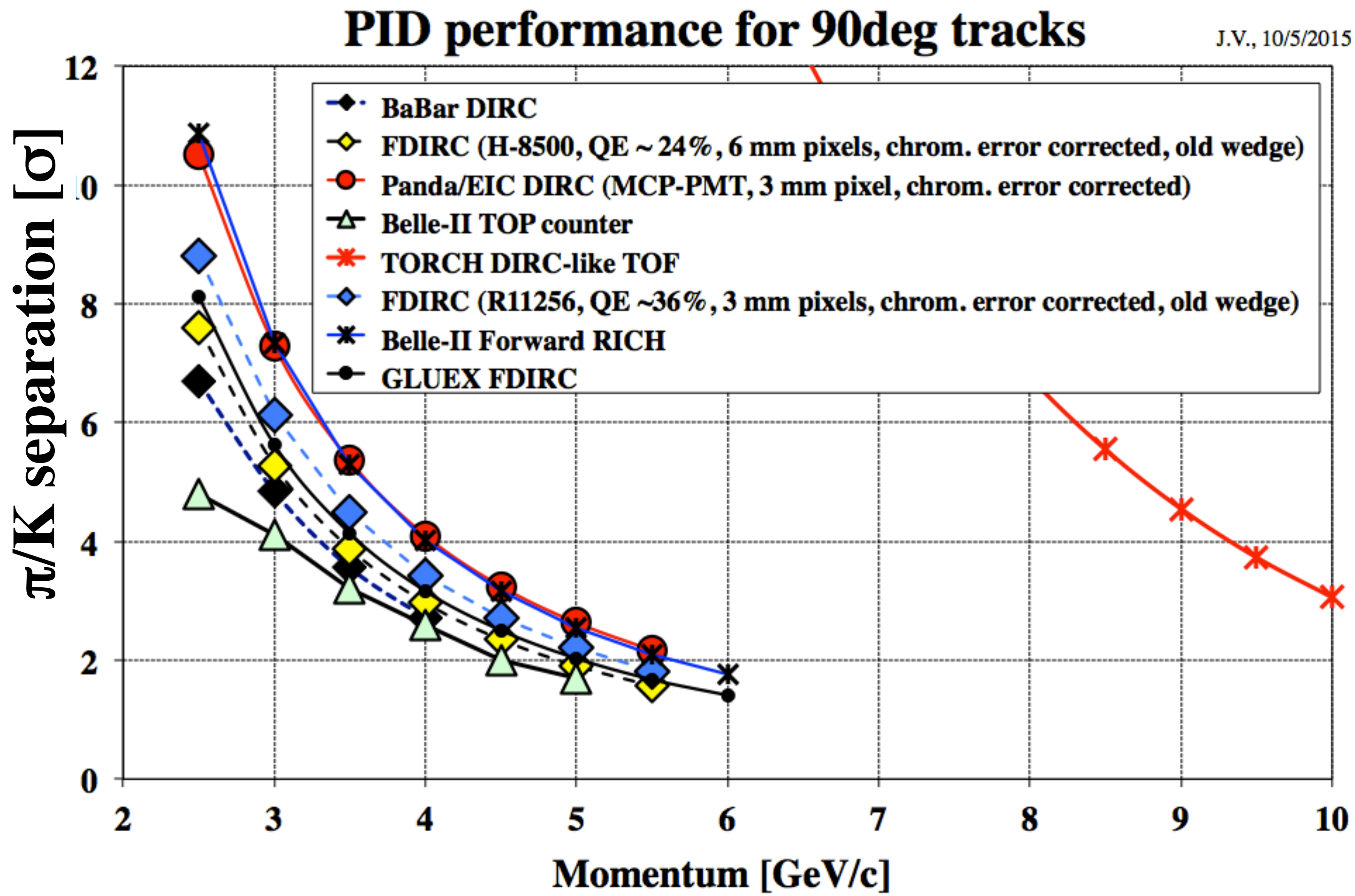
Focusing with two Aerogel tiles:



HAPD:



- **Challenges: (a) Aerogel with good transmission (limitation is the Rayleigh scattering), (b) reliable photon detector working at 1.5 T with ~5x5mm² pixels, (c) number of photoelectrons, (d) high QE.**
- **LAPPD MCP-PMT detector would find a great application in this type of detector.**



- This is my personal plot with as much experimental input as possible. Plots assume Gaussian θ_C resolution for simplicity. I take a responsibility for any error.
- Mis-id rates are important (see appendix for BaBar DIRC for one such example).

TOF counters

- **LHCb TORCH DIRC TOF detector.**

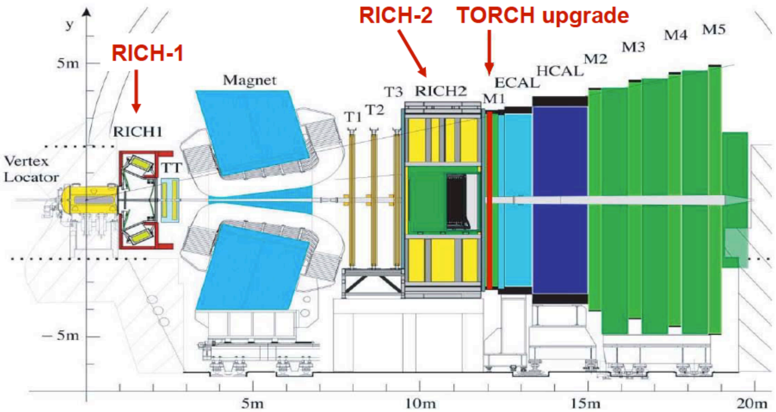
- **Pixilated TOF detectors:**

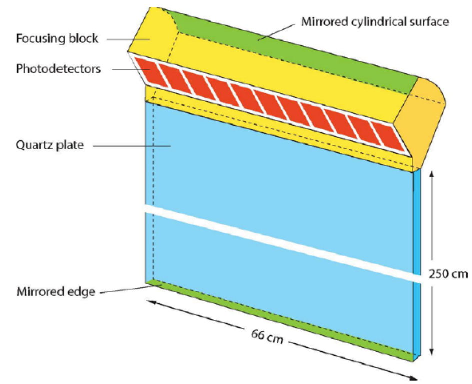
  a) Best result so far: σ ~ 6.2 ps. Is this result really understood ? Why our effort yielded only σ ~ 14 ps ?

  b) How to get consistently below ~ 10ps ?

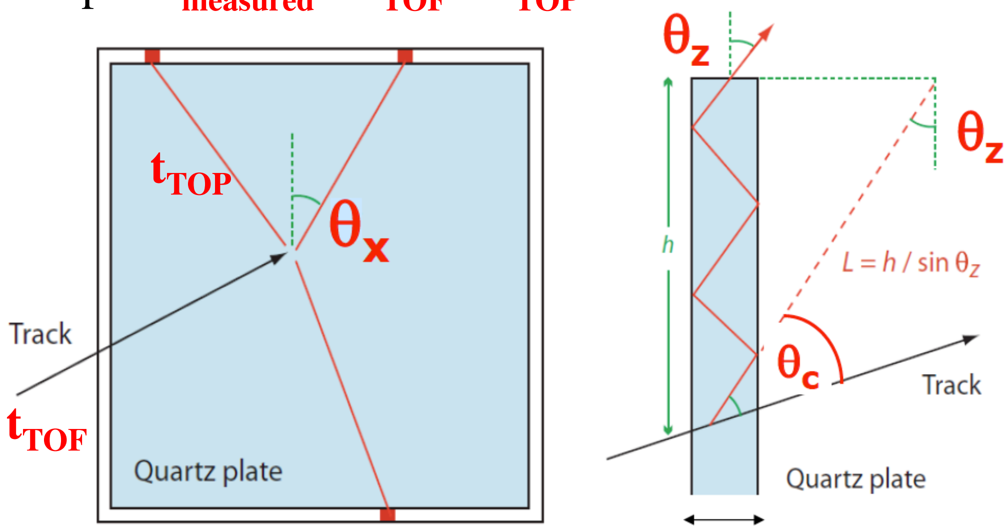
LHCb TORCH TOF detector principle

N. Harnew for TORCH collaboration, TIPP 2011

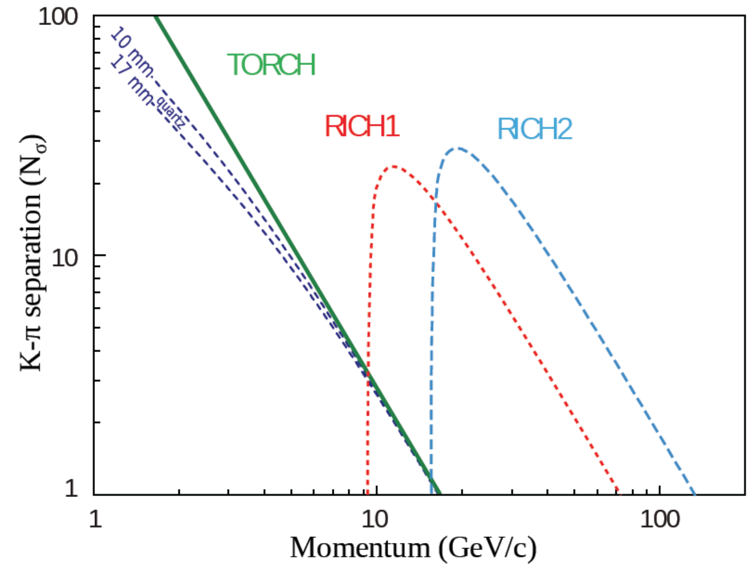




Principle: $t_{measured} = t_{TOF} + t_{TOP} + \dots$



Expected performance:

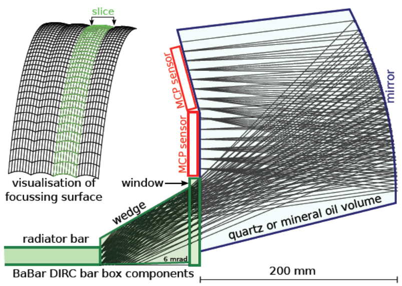


- **Goal for timing resolution: σ ~ 70 ps / photon (dominated by chromatic error).**
- **ΔTOF (π-K) = 35 ps at 10 GeV over ~10 m flight path => aim for σ ~15 ps / track.**

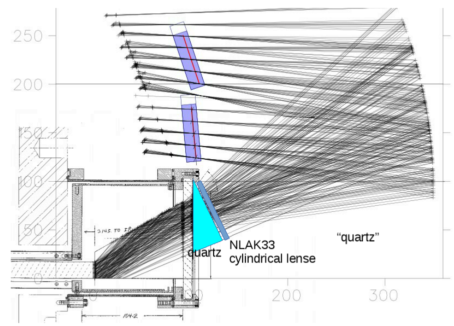
LHCb TORCH with BaBar bar boxes

TORCH collaboration

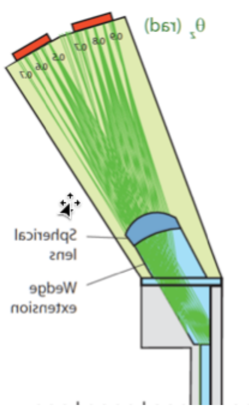
Solution #1:



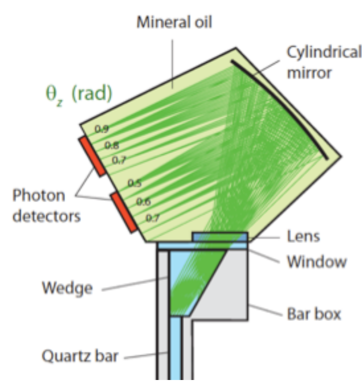
Solution #2:



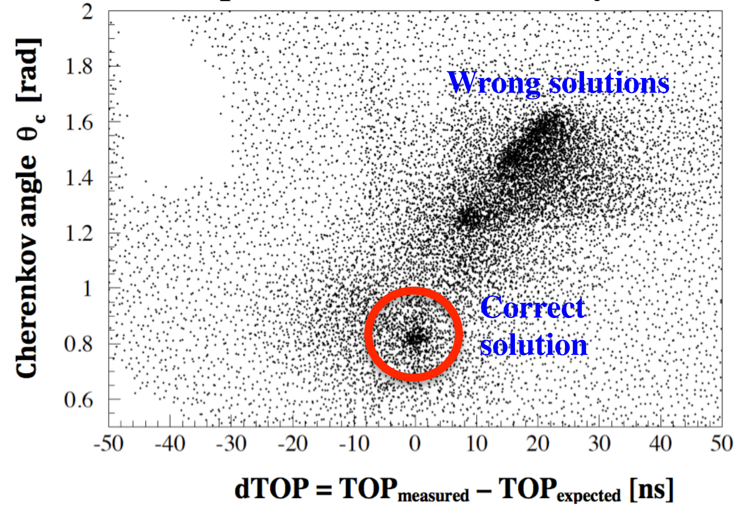
Solution #3:



Solution #4:



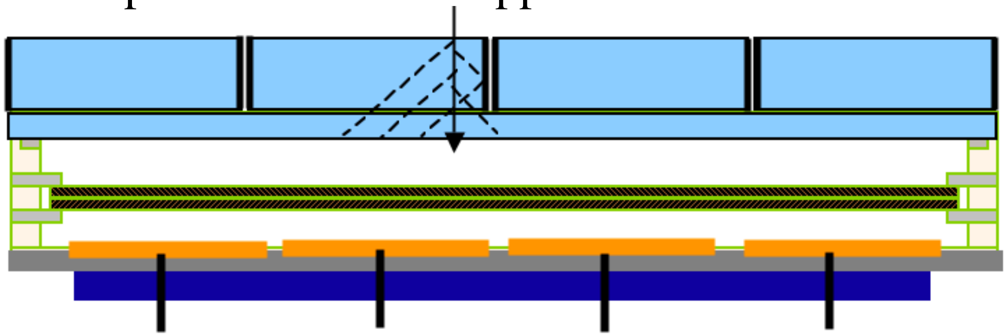
Example of FDIRC data analysis:



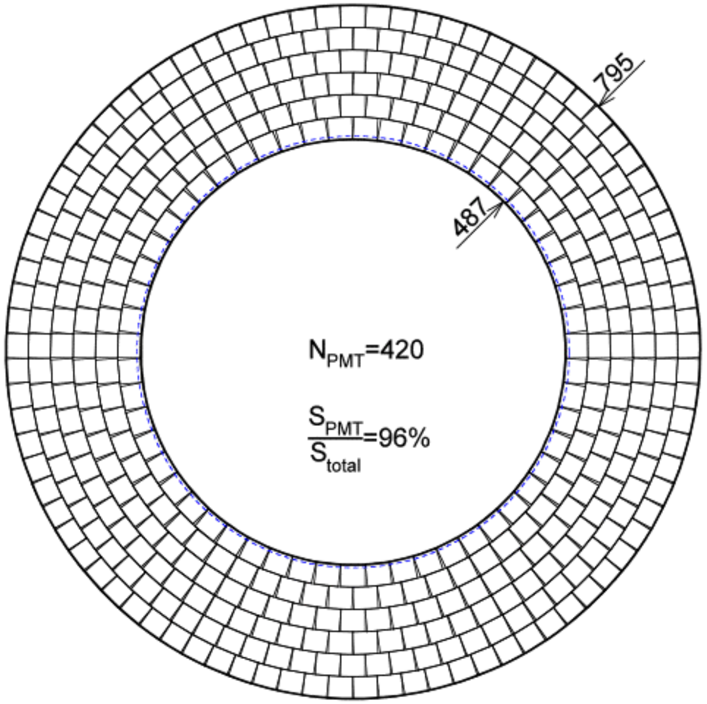
- **One needs to measure not only time with very high resolution, but also the Cherenkov angle θ_C with enough resolution to eliminate wrong solutions for TOP.**
- **One needs 1-2mm pixels and very fast MCP-PMT detectors.**

Pixilated TOF concept

Example of MCP-PMT application:



Proposal forward TOF for SuperB:



Would need ~550 Planacon MCP-PMTs

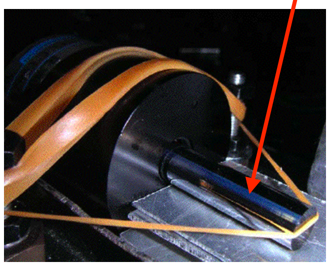
- **This is a possible concept for many detectors, both TOF and Forward Aerogel RICH, if the LAPPD detectors are available.**

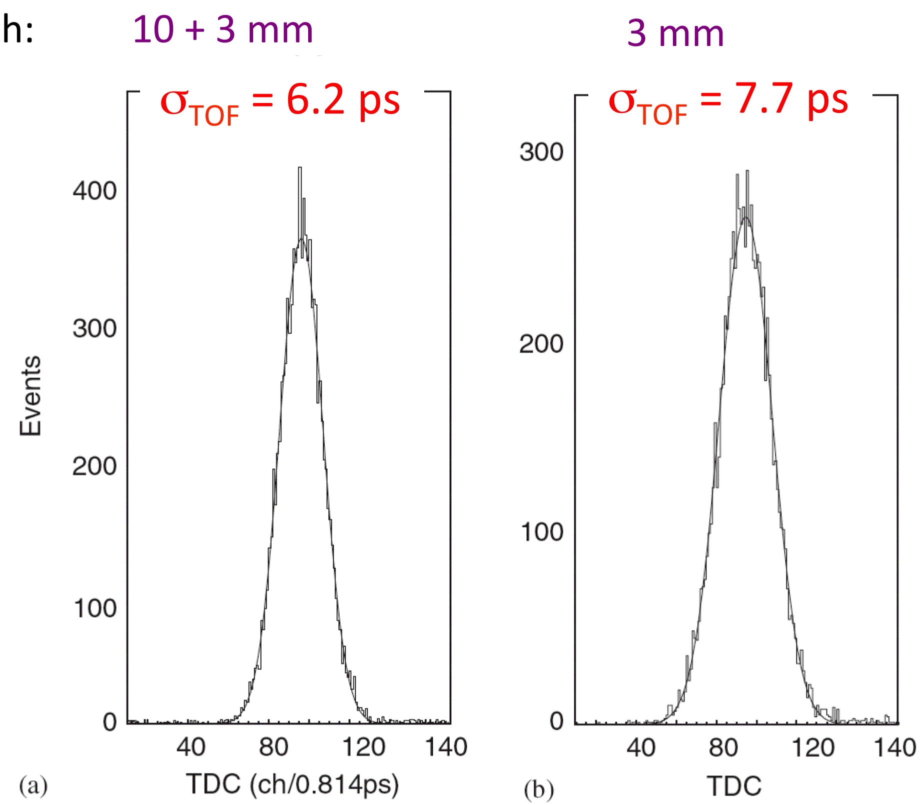
The best beam results so far

NIM A560(2006)303-308.

Quartz radiator length:

Vary the length





$$\sigma_{TOF} = \sigma_{measure}/\sqrt{2}$$

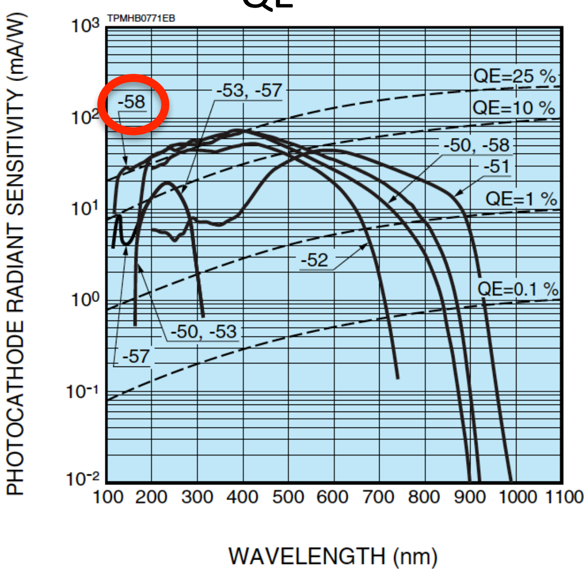
- **Two identical HPK MCP-PMT R3809U-59-11 with 6 μm holes.**
- **MCP-PMT operated at a very high gain of ~ 2 x 10^6.**
- **No amplifier to avoid saturation effects in CFD timing.**

How well do we understand it with MC ?

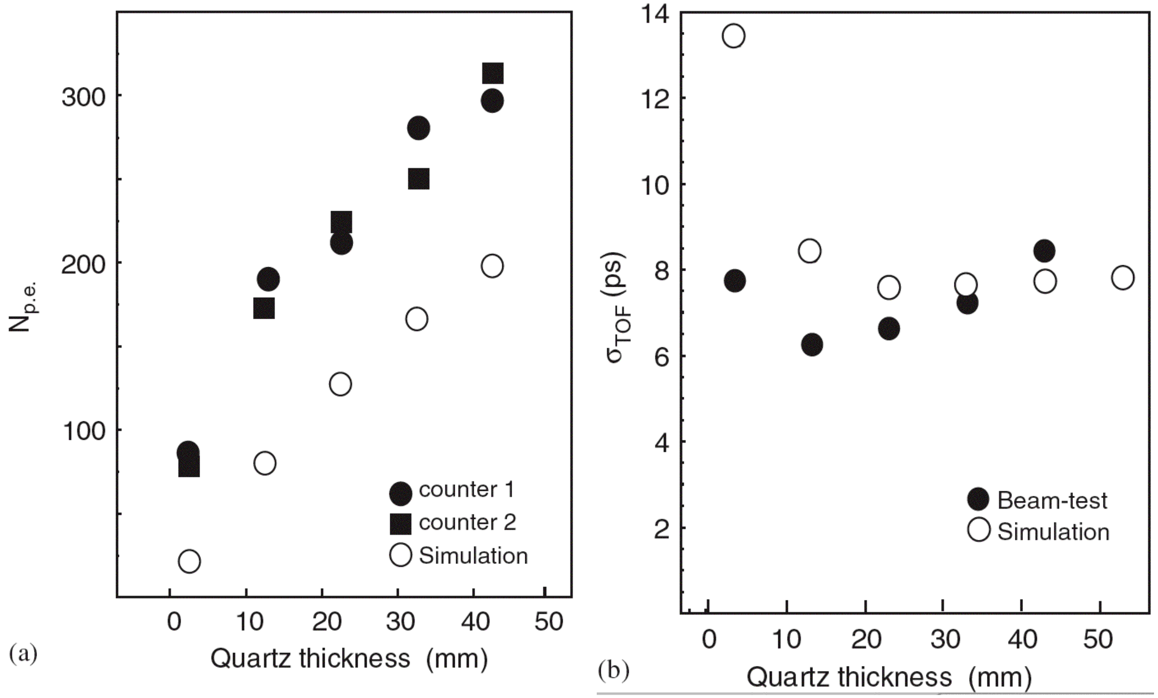
NIM A560(2006)303-308.

MCP-PMT R3809U-50 with quartz window:

QE



Data & MC

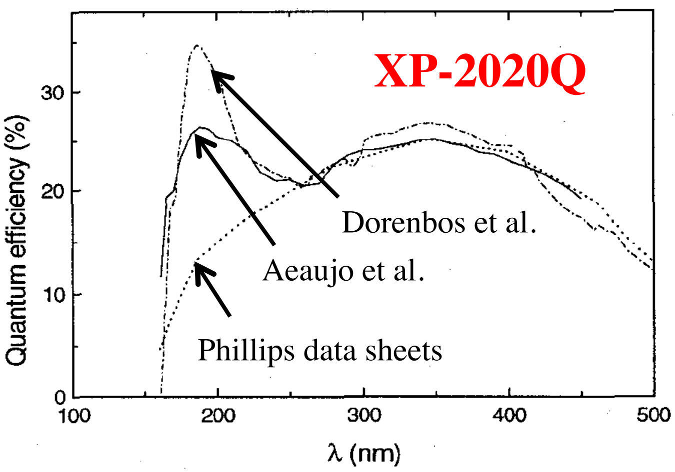


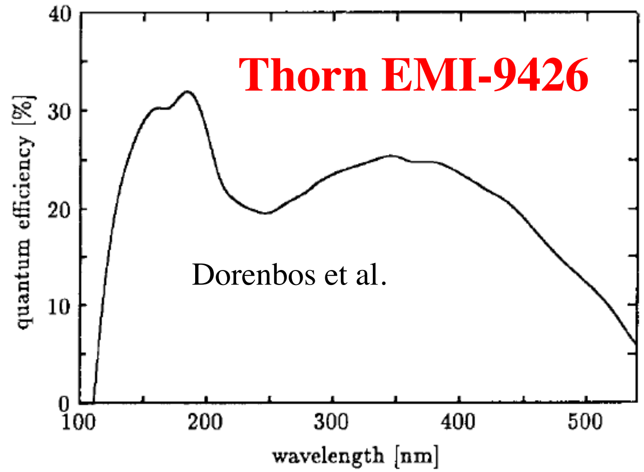
- **Measured Npe is SIGNIFICANTLY larger than expected.**
- **MC does not reproduce data well.**

New idea: improve QE in VUV region

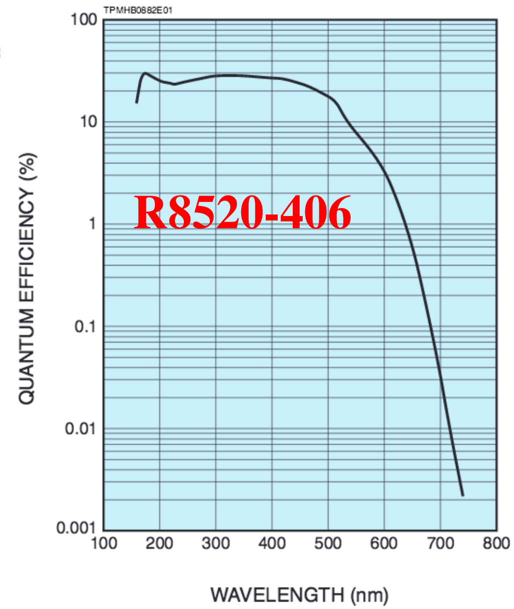
Thanks to pointing this out to me: Mickey Chew, BNL EIC R&D review, 2015

P. Dorenbos et al, NIM A A325(1993)367 and H.M. Araujo et al., IEEE, Vol.45, No 3, 1998:





Hamamatsu data sheets:

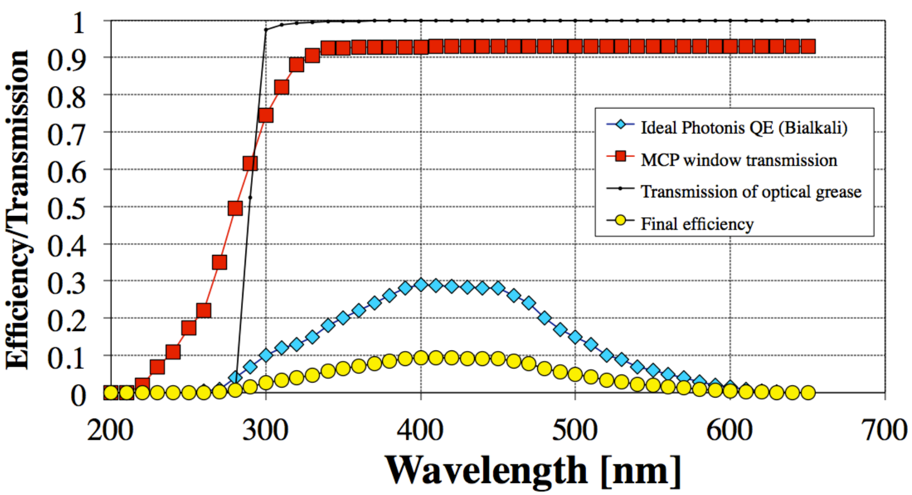


- **Some Bialkali PMTs do show a peak near 180 nm; manufacture may not quote it.**
- **Mickey's point: Nagoya's tubes had QE with the peak and they did not know it.**
- **He works with BNL photocathode group (Triveni Rao and Thomas Tsang).**
- **Triveni's comment: the effect strongly depends on the crystalline structure of the cathode material.**
- **Their idea is to study the effect and feed this information to LAPPD group.**

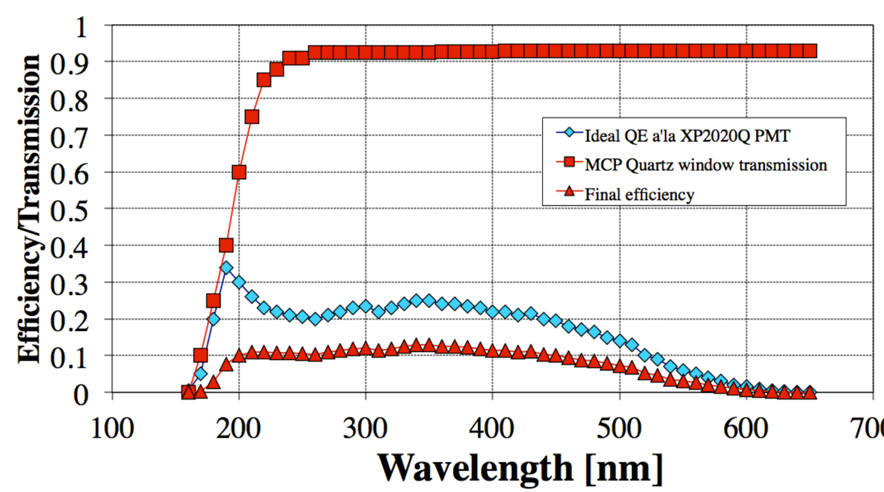
Impact of QE peak at ~180nm on Npe

a) Our Fermilab beam test with Burle MCP-PMT

(NIM A606(2009)404)



b) With QE peak:



Npe ~ 50, $\sigma_{measured}$ ~ 14ps /cm of quartz

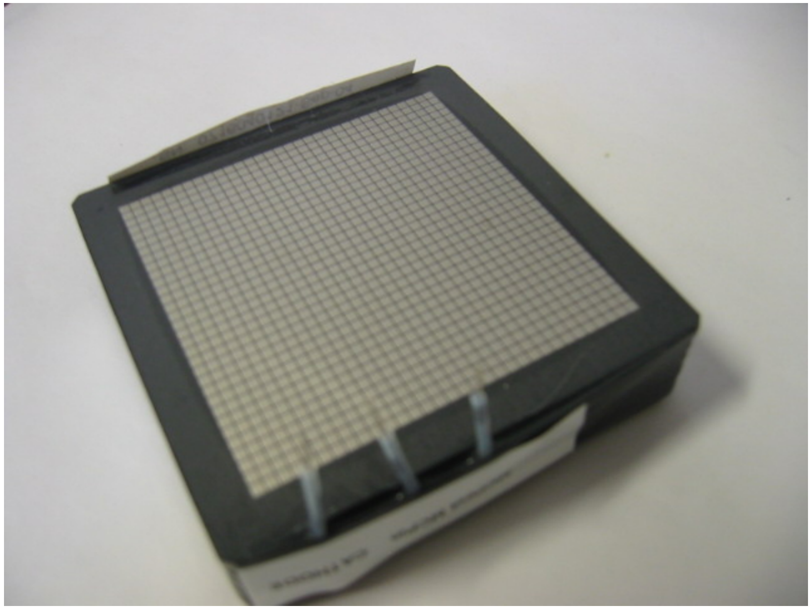
Npe ~ 120, $\sigma_{estimated}$ < 10ps /cm of quartz

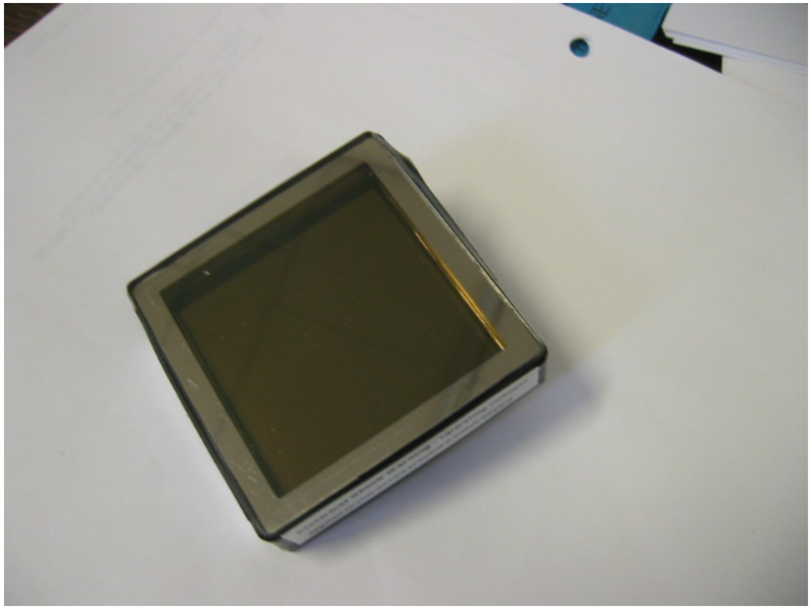
- **The peak is right where the quartz window starts cutting into transmission.**
- **Perhaps, one should use MgF_2 windows for LAPPD detectors ? Point: if one achieves >120 pe's, one will measure consistently σ_{TOF} < 10ps.**
- **To do all this, one needs a very good start time, good tracking (1ps ⇔ 300µm), and highly pixilated MCP-PMT detector.**

Just to remind you, Burle had a 1024 pixel MCP-PMT detector almost 10 years ago

SLAC-PUB-12236, 2006

Burle 32 x 32 = 1024 pixel MCP-PMT available in 2005 !!





- **This level pixilization is needed for the future Cherenkov and TOF detectors.**
- Paul Hinks from Burle: The 1024 anode tube has metal pad anodes inside the ceramic plate that are connected to the external pads via conductive vias.

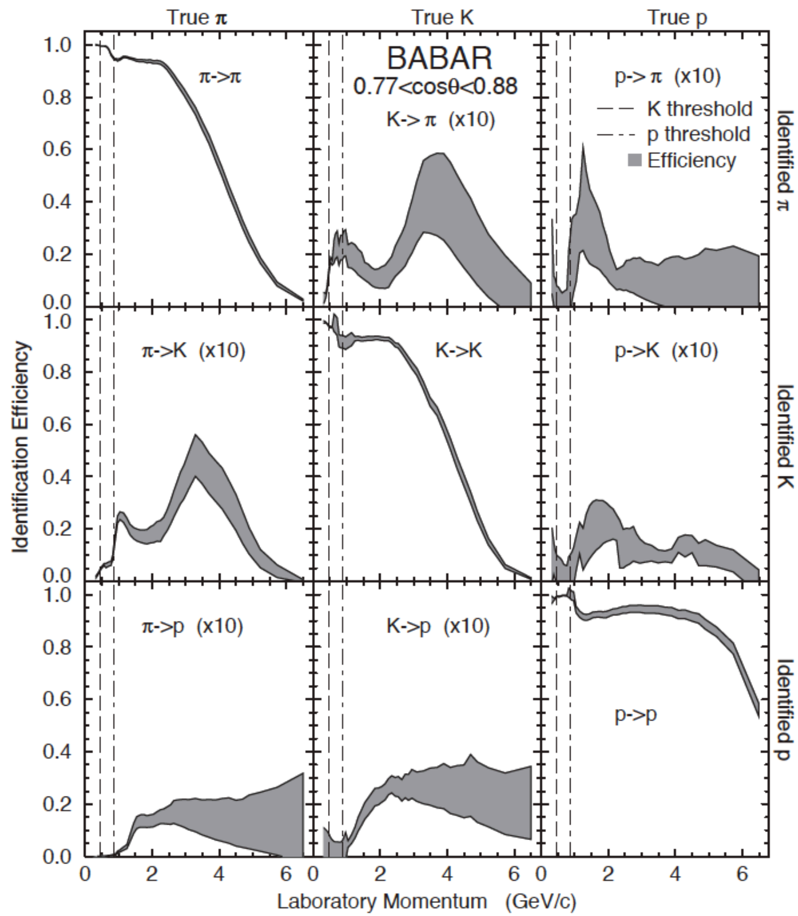
Conclusions

- **DIRC technique has number of followers. The reason is that it can cover a large solid angle, and it can be used either as a RICH or TOF devices.**
- **For pixilated TOF one needs to develop MCP-PMTs with QE peak near 180nm. This requires a better understanding of photocathodes and, perhaps, use of MgF_2 windows, which could be also radiators.**
- **One needs highly pixilated MCP-PMTs to develop new RICH and TOF detectors. LAPPD project has a good chance to make a substantial breakthrough in this area.**
- **But we need to transfer the know how to private companies and then collaborate with them, provide them long term feedback. We used to do that with Burle.**

Appendix

Babar DIRC PID performance

NIMA 538(2005)281



- **This is a correct way to present a PID performance.**
- **This was not yet done for other PID methods presented in this talk.**

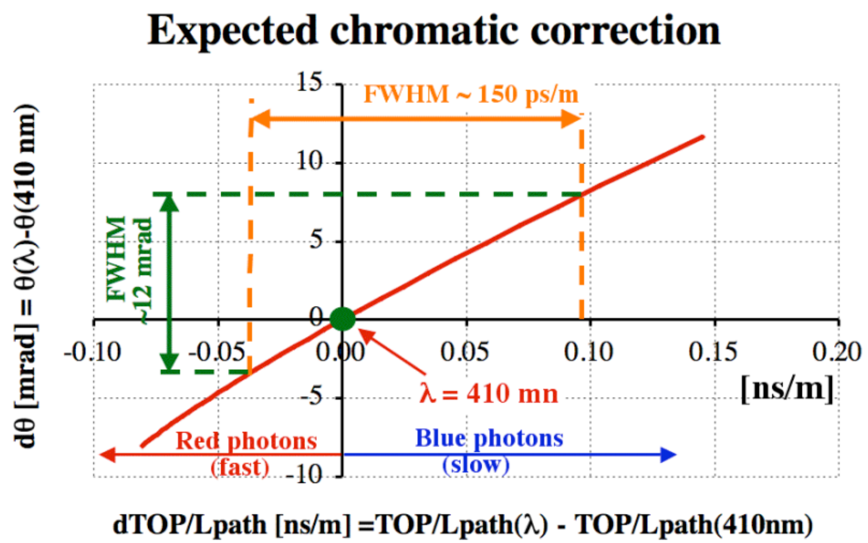
Two dominating contributions for FDIRC

NIMA 775(2015)112, NIMA 766(2014)114 and NIMA 766(2014)189

- **Chromatic error:**

$\sigma_C^{\text{chromatic effect}} \sim$ **4-5 mrads**

Can be corrected if a single photon timing resolution of ~200ps is used.



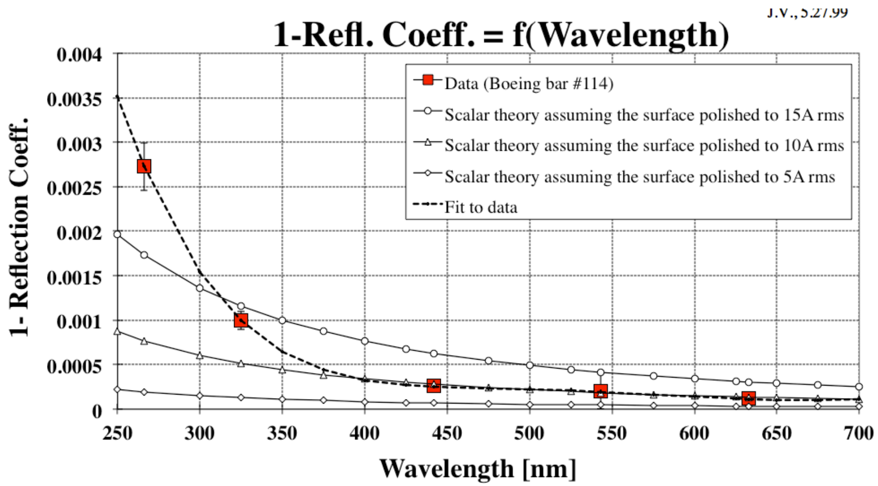
$TOP = L_{path}/v_{group} = L_{path}\,[n_{phase} - \lambda\, dn_{phase}/d\lambda]/c, \quad v_{group} = c/n_{group} = c/[n_{phase} - \lambda\, dn_{phase}/d\lambda],$

$\sigma_{dTOP} \sim \sqrt{(\sigma_{TTS}^2 + \sigma_{Chromatic}^2 + \sigma_{Electronics}^2 + \sigma_{Pixel\_contribution}^2 + \sigma_{Tracking\_contribution}^2 + \sigma_{propagation\ in\ bar}^2)}$

Two examples of major issues for BaBar DIRC

NIMA 538(2005)281

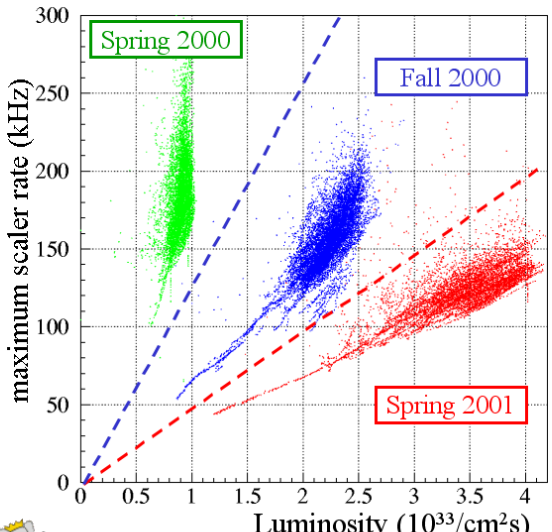
- **Can a single photon propagate over a distance of ~5-10 m ?**



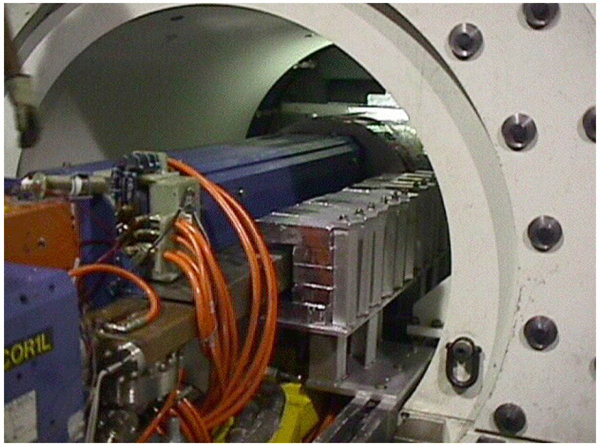
R ~ 0.9997 @ 450nm

Measurement result is consistent with ~5-10Å rms surface polish

- **Can DIRC handle background in BaBar ?**



Temporary lead brick shielding:



Final lead shielding: