Lecture I:
Super-B Particle Identification Systems - <u>basic design concepts</u>

J. Va'vra, SLAC

Content of these lectures

- ## Lecture I: Basic Design Concepts
    - Basic PID concepts: Cherenkov detectors, dE/dx, TOF
    - Photocathodes and Photon detection efficiency (PDE)
    - Photon propagation in dispersive media: transmission, chromaticity, internal reflection, etc.
    - DIRC-like detectors, 1-st DIRC-like detector: BaBar DIRC

- ## Lecture II: Photon detectors
    - MaPMTs, MCP-PMTs, GAPDs or SiPMTs, HAPDs, APDs
    - Timing performance, quantum efficiency
    - Aging, rate capability, effects of magnetic field
    - Readout schemes: pixels, strip lines, charge sharing
    - New trends: photocathodes, new MCP-PMT construction methods

- ## Lecture III: Detector systems for SuperB and Belle 2
    - Focusing DIRC (FDIRC) concept,
    - TOP counters
    - Aerogel RICH,
    - TOF detectors
    - Comparison of various methods.

Privilege to meet many people in my life. Each person taught me something.

- It takes a village to develop a certain knowledge, including the PID technique.

- Thanks to people in the RICH community I had a privilege to know and learn from during the past ~30 years:

T. Ypsilantis, J. Sequinot, B. Ratcliff, D. Leith, Ch. Joram, T. Eckeloff, R. Stone, T. Sumiyoshi, T. Iijima, K. Inami, S. Dalla Torre, E. Nappi, G. Hallewell, M. Cavalli Sforza, D. Coyne, J. Schwiening, A. Hoeker, G. Wormser, S. Spanier, P. Krizan, S. Korpar, M. Staric, V. Shelkov, B. Donwoodie, R. Forty, A. Di Mauro, J. Engelfried, F. Sauli, G. Charpak, D. Andersdon, A. Breskin, R. Chechik, C. Williams, O. Ullaland, V. Titov, E. Kravchenko, V. Peskov, E. Lorenz, G. Varner, D. Ferenc, and many others, including students and technicians.

PID devices covered in this lecture

- **DIRC**-like detectors
  - BaBar DIRC
  - Focusing DIRC (FDIRC)
  - TOP counter

- **Aerogel Focusing RICH**

- **TOF detectors**

- **dE/dx**

All of them use the Cherenkov light and all of them are considered for the SuperB or Super Belle PID detectors

- uses ionization deposit in gas

Basic PID concepts

Cherenkov light

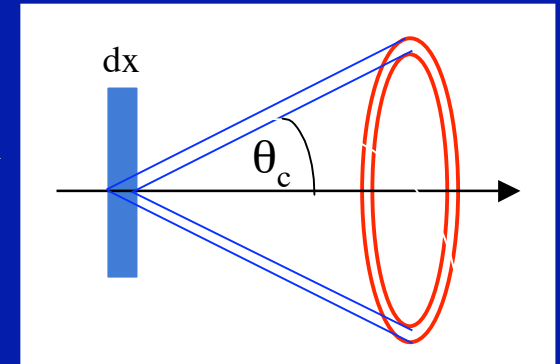P.A. Cherenkov, I. M. Frank, and I. Y. Tamm, Nobel prize in 1958

$$\cos \theta_c = 1 / \beta \, n(\lambda)$$

$\beta = v/c$, $n = n(\lambda)$ is a refraction index, also called "phase" index, λ - wavelength
c - velocity of light in vacuum, v - velocity of particle
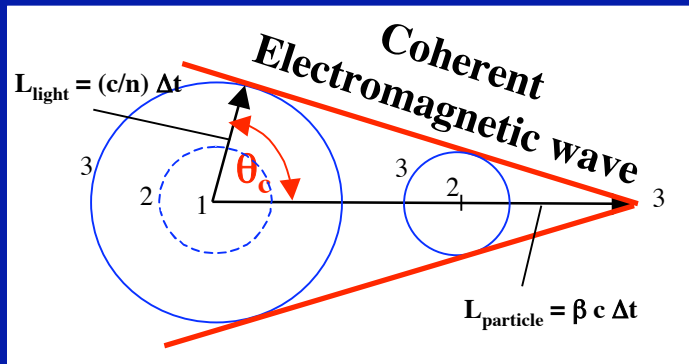Light is emitted at polar angle θ_c, and uniformly in azimutal angle ϕ_c
When $\beta_{thr} = 1/n$ -> $\theta_c = 0$ - threshold occurs for $\beta = \beta_{thr}$
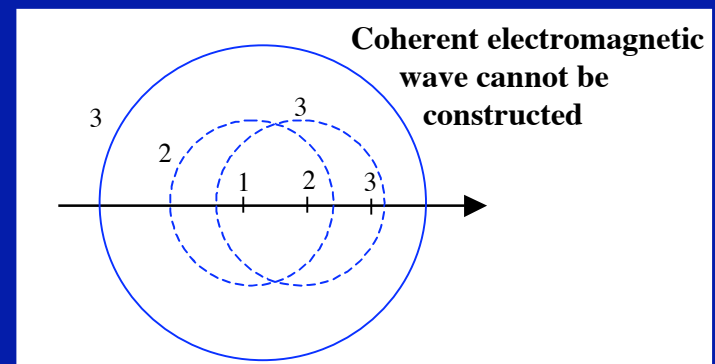$\theta_c(max) = \arccos(1/n(\lambda))$ - saturated angle for $\beta = 1$

dx

θ_c

For $\beta > \beta_{thr} = 1/n$ ($v_{particle} > c/n$):

For $\beta < \beta_{thr} = 1/n$:

Expanding the spherical wavefront at three instances of time 1, 2, 3:

Coherent Electromagnetic wave

$L_{light} = (c/n) \, \Delta t$

θ_c

$L_{particle} = \beta \, c \, \Delta t$

Coherent waveform can form

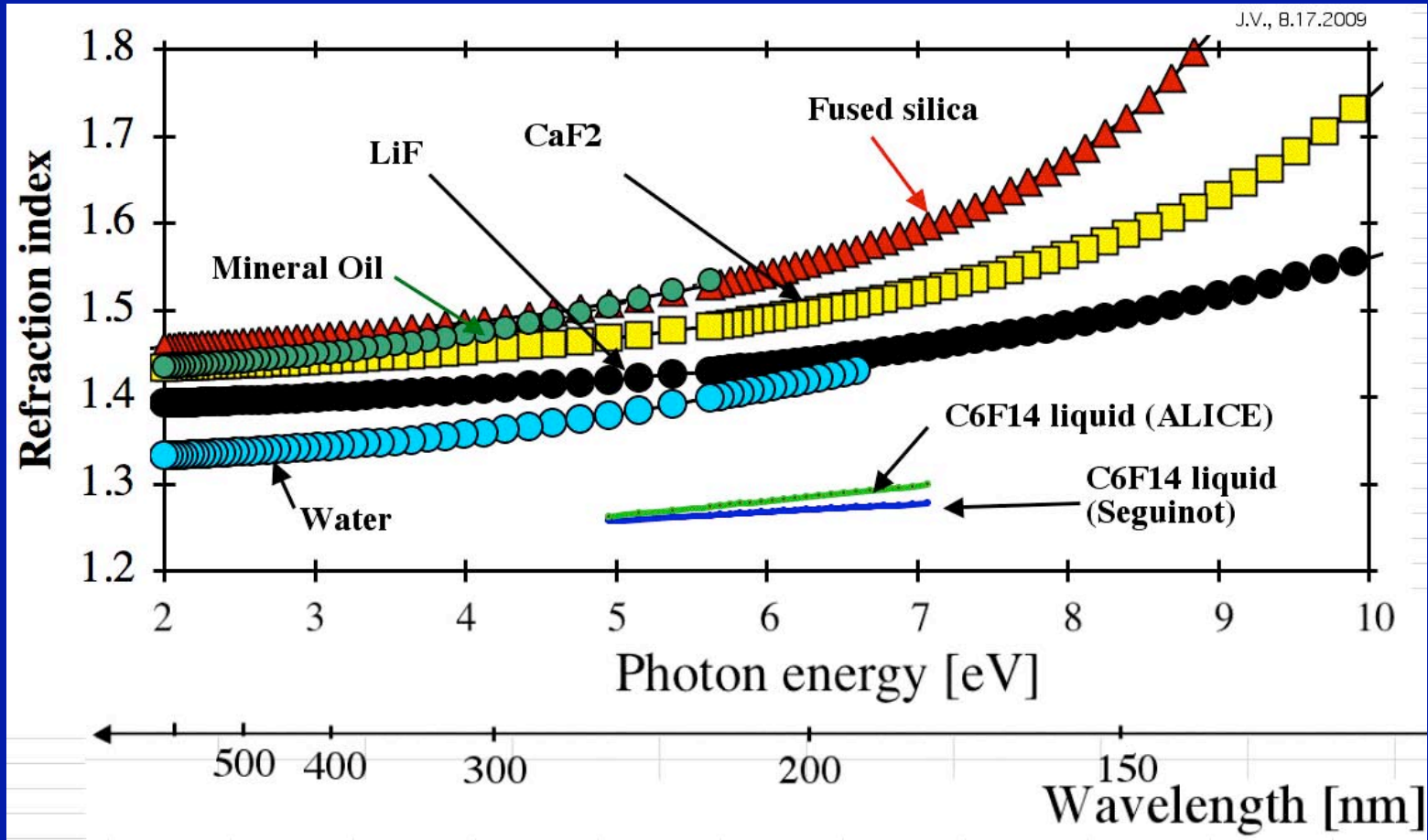Coherent electromagnetic wave cannot be constructed

Coherent waveform cannot form

- **Cherenkov radiation is emitted when a charged particle passes a dielectric medium with velocity $\beta > \beta_{thr} = 1/n$.**

- **Coherent electromagnetic wave is extremely fast.**

Refraction index

J. Va'vra, The 42-nd workshop on Supercolliders, Erice, Sicily, Italy, 2003, SLAC-PUB-11019

$E \sim 1/\lambda$

- **Amazing thing about the Cherenkov light theory is that it can be described by only one constant: n = n(E).**

Number of photons

P.A. Cherenkov, I. M. Frank, and I. Y. Tamm, Nobel prize in 1958

Number of generated Cherenkov photons per unit of dx & dλ :

$$d^2N_\gamma /dxd\lambda = [2\pi\, Z^2\, \alpha\, / \lambda^2] * [1 - 1/(\beta\, n)^2] = [2\pi\, Z^2\, \alpha\, / \lambda^2] * \sin^2 \theta_c$$

$$d^2N_\gamma /dxd\lambda \sim 1/\lambda^2$$

Because $E \sim 1/\lambda \Rightarrow d^2N_\gamma /dxdE \sim$ constant (E)

Number of detected photoelectrons per unit of energy $\Delta E = E_2 - E_1$:

$$Npe \sim L\, (\alpha\, / \hbar c) \int_{E_1}^{E_2} \sin^2 \theta_c(E) \prod_i \varepsilon_i\, (E)\, dE$$

ε_i - various detection efficiencies

- **Energy loss by Cherenkov radiation is small compared to ionization (1%).**
- **Furthermore, because our photon detectors are rather inefficient at present, we detect typically only 10-20% of these photons.**
- **Therefore, to design a good Cherenkov detectors is always a "battle" to get as many Npe as possible. Any mistake is paid for very dearly.**
- **Npe is typically 15-25 in a typical RICH detector.**

Examples of Cherenkov angles and Npe

$$\cos \theta_c = 1 / \beta \, n(\lambda)$$

$$Npe = 370 \, L \int \sin^2\theta_c (E) \, \Pi_i \varepsilon_i (E) \, dE$$
$$\sim L \, N_o \sin^2 \theta_c$$

Npe - number of photoelectrons, L - radiator thickness, ε_i - various detection efficiencies

Radiator type	Refraction index n	θ_c (max) ($\beta = 1$)	$\Delta\theta_c = \theta_c(\pi) - \theta_c(K)$ [mrad]	Npe/cm (No = 50 & β = 1)
Aerogel (SiO_2)	1.05	309 mrad	22.8 @ 4 GeV/c	4.6
Solid Quartz (SiO_2)	1.47	823 mrad	6.5 @ 4 GeV/c	27
H_2O	1.34	728 mrad	7.9 @ 4 GeV/c	22
C_5F_{12} gas at 1 bar	1.0017	58.3 mrad	2.6 @ 10 GeV/c	0.17
He gas at 1 bar	1.00004	8.9 mrad	1.4 @ 100 GeV/c	0.004

- N_o is a measure of quality of the optical system and a detector performance.
- $N_o \sim 20 - 100 \ cm^{-1}$ typically.

Total number of generated Cherenkov photons is large ! But most of them are not detected !!
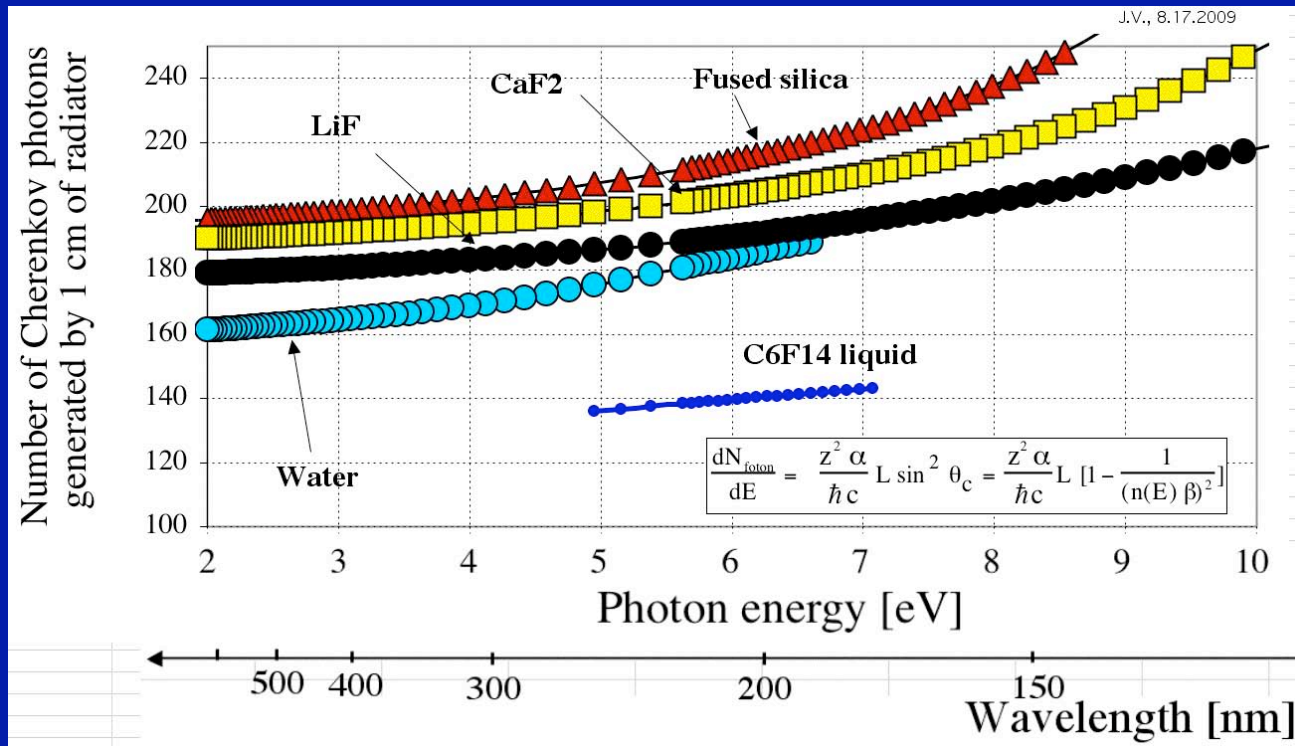
- **The overall detection efficiency is typically very low; we detect only 10-20% of what is available.**
- **Clearly, a search for new detectors with high PDE is important.**

Threshold Cherenkov counters

T. Ypsilantis and J. Seguinot, Theory of RICH detectors, Nucl. Instr. & Meth. A343(1994)30-51

Detectors measure Npe, but not θ_c angle

$d^2N_{pe}/dxd\lambda \sim 1 - 1/(n\,\beta)^2 = 1 - (1/n^2) * (1 + m^2/p^2)$

$\Rightarrow$ **For a given n, a particle of mass m will produce light if p > p_{thr}**

From equations $\beta = 1/(n\cos\theta_c)$, Npe $\sim \sin^2\theta_c$, $\sigma_\beta/\beta = \tan\theta_c\,(d\theta_c/dN)\,dN$, one can derive:

The threshold counter scaling:

$$(\sigma_\beta/\beta)_{thr} = \tan^2\theta_c /(2\sqrt{Npe})$$

Example how a threshold counter: Two aerogel radiators, R_1 and R_2, with $n_1 = 1.055$ and $n_2 = 1.0065$

Example
of threshold
counter is
Belle Aerogel
detector
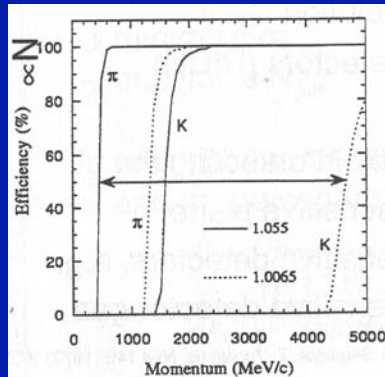
for p > 0.4 GeV/c: detect π in R_1

    p > 1.2 GeV/c: detect π in R_1 & R_2

    p > 1.4 GeV/c: detect K in R_1

    p > 4.2 GeV/c: detect K in R_1 & R_2

=> **p/K separation between 0.4 and 4.3 GeV/c**

RICH ≡ Ring Imaging Cherenkov counters

T. Ypsilantis and J. Seguinot, Theory of RICH detectors, Nucl. Instr. & Meth. A343(1994)1-29 and
T. Ypsilantis and J. Seguinot, Theory of RICH detectors, Nucl. Instr. & Meth. A343(1994)30-51

Detectors measure $\theta_c = \arccos(1/n\beta)$

From equations $\beta = 1/(n \cos \theta_c)$, Npe $\sim \sin^2\theta_c$, one can derive:

The imaging RICH counters scaling:

$$(\sigma_\beta/\beta)_{RICH} = \sigma_{\theta c}(tot) * \tan \theta_c ~ \sim [\sigma_{\theta c}(single~pe)/\sqrt{Npe}] * \tan \theta_c$$

$$\Rightarrow (\sigma_\beta/\beta)_{thr} / (\sigma_\beta/\beta)_{RICH} = \tan \theta_c/(2~\sigma_{\theta c}(tot)) > 200 \text{ for DIRC-like RICH.}$$

RICH detectors are much more powerful PID instruments than the threshold detectors.

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Example of RICH imaging:
(SLD & DELPHI RICH detectors)
See, for example:
K. Abe et al., Performance of the CRID at SLD,
Nucl. Instr. & Meth., A343(1994)74-86
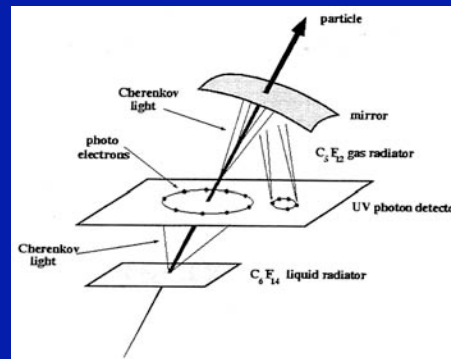
Resolution of RICH detectors: $\sigma_{\theta c}(\text{tot})$

B. Ratcliff, Trieste RICH conference, 2008, Nucl. Instr. & Meth. A595(2000)1-7

$$\sigma_{\theta c}(\text{tot}) \sim \sigma_{\theta c}(\textbf{single photoelectron}) / \sqrt{N_{pe}} \quad \oplus \quad \sigma_{\theta c} \, (\textbf{track systematics})$$

$$\sigma_{\theta c}(\text{single photoelectron}) = \sqrt{[\sigma_{\theta c}{}^2(\text{chromatic}) + \sigma_{\theta c}{}^2\,(\text{pixel}) + \sigma_{\theta c}{}^2\,(\text{imaging})}$$
$$+ \sigma_{\theta c}{}^2\,(\text{transport})\dots]$$

$$\sigma_{\theta c}\,(\text{track systematics}) \sim \sqrt{[\,\sigma_{\theta c}{}^2(\text{external tracking}) + \sigma_{\theta c}{}^2(\text{multiple scatt.})}$$
$$+ \sigma_{\theta c}{}^2(\text{alignment errors})]$$

where

N_{pe} - number of photoelectrons detected in a wavelength bandwidth $\Delta\lambda$
$\sigma_{\theta c}(\text{chromatic})$ - resolution broadening because of color dispersion: $n = n(\lambda)$
$\sigma_{\theta c}(\text{pixel})$ - broadening due to finite detector pixel size
$\sigma_{\theta c}(\text{imaging})$ - effect of the imaging method (lens, mirrors, etc.)
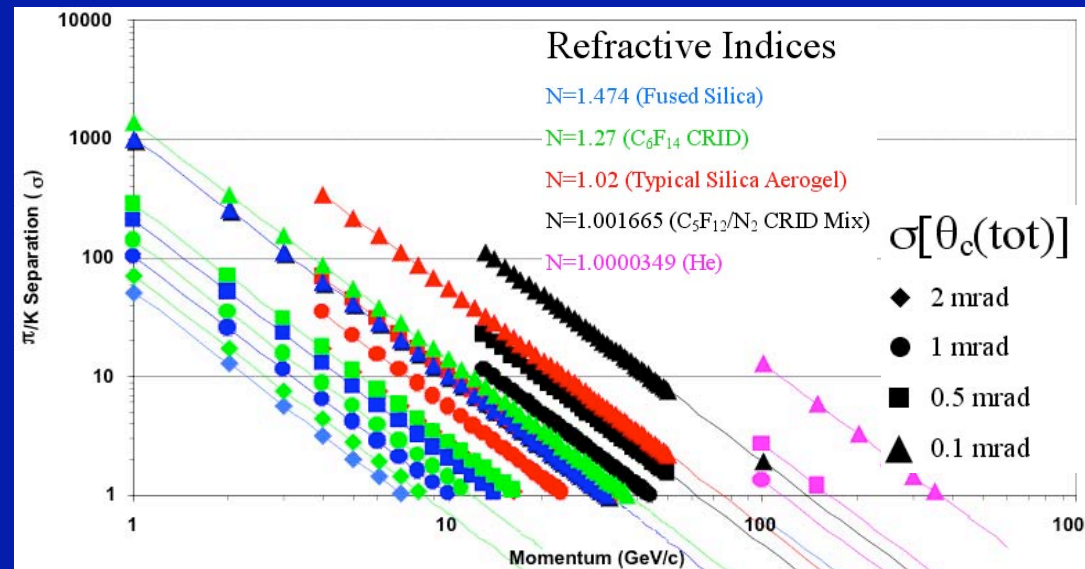$\sigma_{\theta c}(\text{transport})$ - applicable only to DIRC-like counters (otherwise negligible)

- **To get smallest possible $\sigma_{\theta c}(\text{tot})$, one should maximize N_{pe} and minimize all error contributions.**

- **In practical counters $\sigma_{\theta c}(\text{tot})$ is typically between 0.1 and 2 mrads.**

"Ideal" PID separation in sigmas

$$N_\sigma = [\theta_c (m_1) - \theta_c (m_2)] / \sigma_{\theta c}(tot) \text{ - separation in number of sigmas}$$
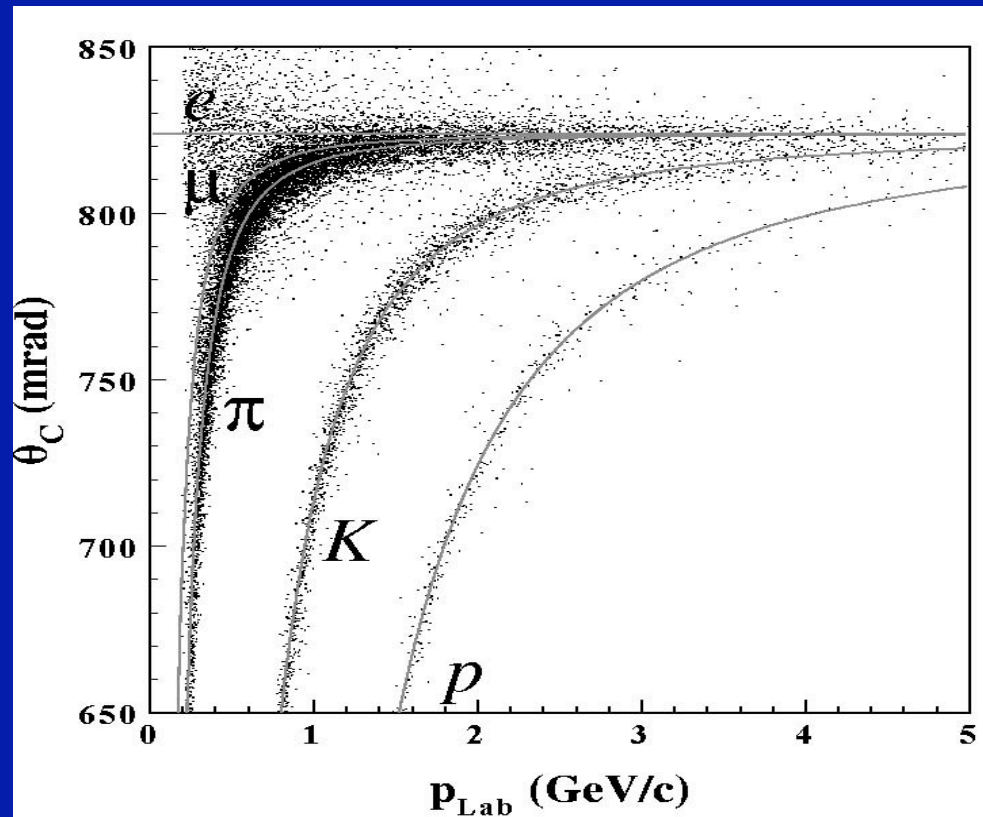
$$\sim (m_1^2 - m_2^2) / [2p^2 \sigma_{\theta c}(tot) \sqrt{(n^2 -1)}] \text{ for a limiting case of } \beta = 1$$

- **In practical counters $\sigma_{\theta c}(tot)$ is typically between 0.1 and 2 mrads.**
- **Refraction index n choice:**
  - low index is required for a high momentum range. Counters become very long in order to get a large enough Npe.
  - high index is required for a low momentum range

BaBar DIRC PID

I. Adam et al., Nucl. Instr. & Meth. A538(2005)281-357

- **Typical PID performance in BaBar DIRC.**

Other useful RICH equations

T. Ypsilantis and J. Seguinot, Theory of RICH detectors, Nucl. Instr. & Meth. A343(1994)30-51

θ_c = arccos[1/(n β)] = arccos(1/n * E/p) = arccos[1/n * √(p²+m²/p)]

$m = p \sqrt{(n^2 \cos^2\theta_c - 1)}$ - RICH counters measure mass, if you know p & θ_c

$\sigma_p/p = \gamma^2 * \sigma_\beta/\beta = \gamma^2 * \sigma_{\theta c}(tot) * tg\ \theta_c$ - fractional error in momentum p

=> RICH counters can measure the momentum !!

dE/dx PID technique

R.Fernow "Introduction to experimental particle physics", or W.Blum&L.Ronaldi "Particle detection with drift chambers"

$$N_\sigma = [dE/dx(m_1) - dE/dx(m_2)] / \sigma(dE/dx)$$

Bethe-Bloch were first to calculate it in 1930's

Average energy loss for e, μ, π, K, p in 80/20 Ar/CH_4 (NTP)
(J.N. Marx, Physics today, Oct.78)

π/K separation (2σ) requires a dE/dx resolution of < 2.5%
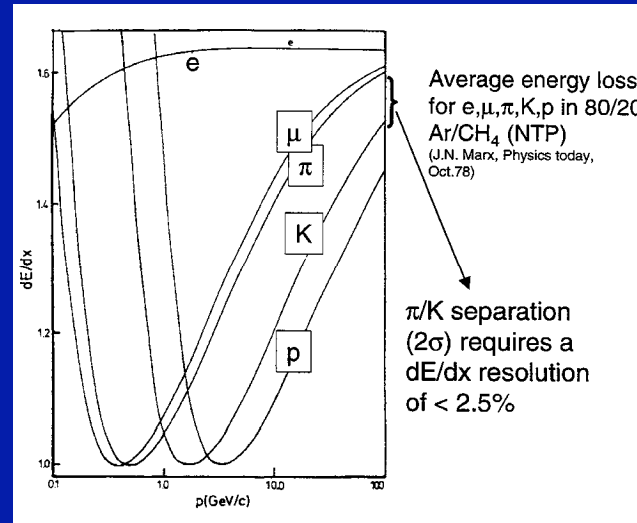
- **To predict dE/dx, one can use:**
  - <u>Bethe</u> - Bloch - Sternheimer calculation, or
  - Landau - Sternheimer calculation, or
  - Allison - Cobb Monte Carlo simulation, or
  - Empirical fits to data, such as in the book of Ronaldi-Bloom.
  - Bischel program

- **To predict σ(dE/dx), one can use:**
  - Allison - Cobb Monte Carlo simulation, or
  - Empirical fits to data.

Which model works best and is most useful ?

Prediction of dE/dx

J. Va'vra, Nucl. Instr. & Meth., A453(2000)262, and SLAC-PUB-8356, Jan. 2000, and dE_dx = f(beta_gamma) study.xls

Bethe-Bloch formula for dE/dx with Sternheimer parameterization of the density function:

$$\frac{dE}{dx} = -0.3071 \frac{Z}{A} \rho\, t\, \frac{1}{\beta^2} \left[\frac{1}{2} \ell n \frac{2 m_e c^2 \beta^2 \gamma^2 E_{cut}}{I^2} - \frac{\beta^2}{2} - \frac{\delta}{2} \right]$$

where

Z	is atomic number of medium,
A	is atomic mass of the medium,
ρ	is density of the medium,
t	is sample thickness,
m_e	is mass of electron,
I	**is mean excitation energy of the medium,**
E_{cut}	is maximum kinetic energy which can be given to a free electron in a single collision,
δ	is density correction due to polarization of the medium.

Sternheimer parametrization of density function δ:

$$\delta = 0 \qquad \text{for} \quad X = \ln \beta\gamma < X_0$$

$$\delta = 4.606(X - X_a) + \frac{4.606(X_a - X_0)}{(X_1 - X_0)^3}(X_1 - X)^3 \quad \text{for} \quad X_0 \leq X < X_1$$

$$\delta = 4.606(X - X_a) \qquad \text{for} \quad X > X_1$$

Electron density:
$n_{el} = N_A * Z * \rho / A$

Bloch found that the mean ionization potential can be approximated by:
$I \sim (10 eV) * Z$

One of many examples in the paper:

LEHRAUS - 95%Ar+5%CH4, 1bar, 4 cm sample

Ecut (Bethe) = 1.5 keV

Landau+Sternheimer

Bethe&Bloch+Sternheimer
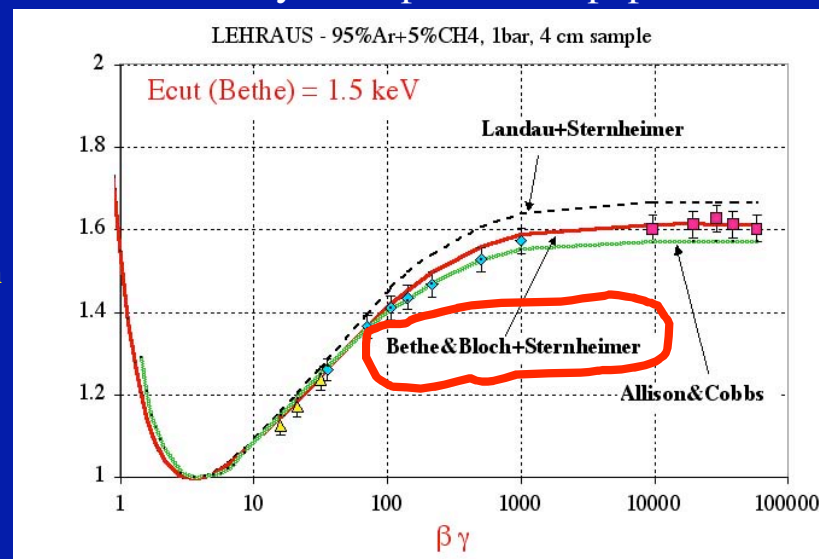
Allison&Cobbs

- **The density function parameterization is important to get an agreement in the relativistic part of the curve.**
- **Although Allison-Cobb MC method is a correct way to do it, I find that the Bethe-Bloch-Sternheimer parameterization is simple, practical and it works.**

Prediction of dE/dx resolution

J. Va'vra, Nucl. Instr. & Meth., A453(2000)262, and SLAC-PUB-8356, Jan. 2000, and dE_dx = f(beta_gamma) study.xls

Empirical formula for dE/dx resolution, i.e.,
$\sigma(dE/dx) = $ **f(electron density in the medium):**
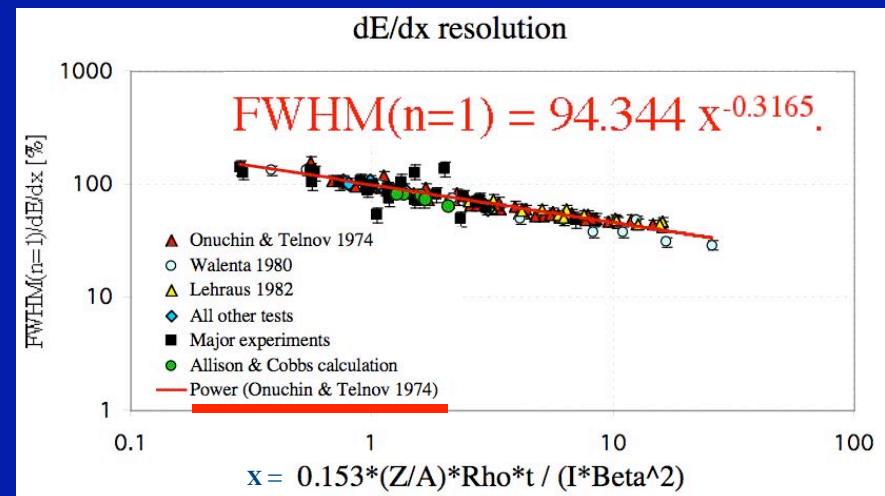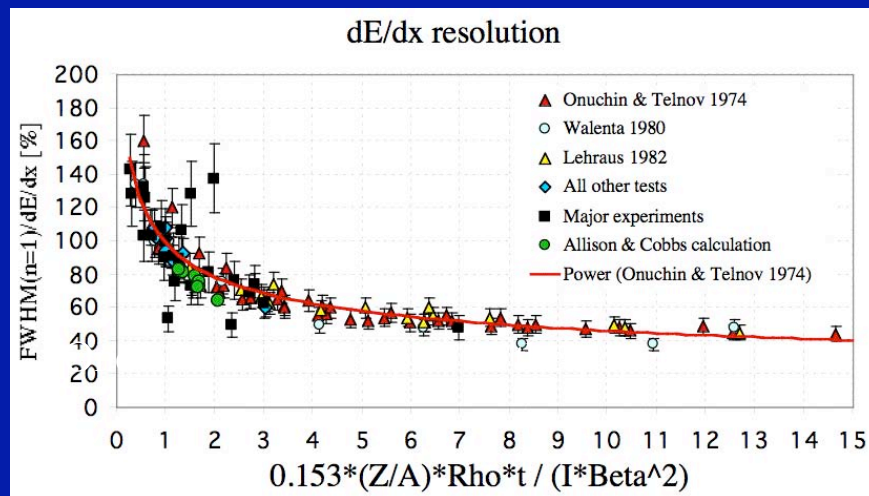
n - number of samples

Electron density:
$n_{el} = N_A * Z * \rho / A$

- **Conclusion of the paper:**

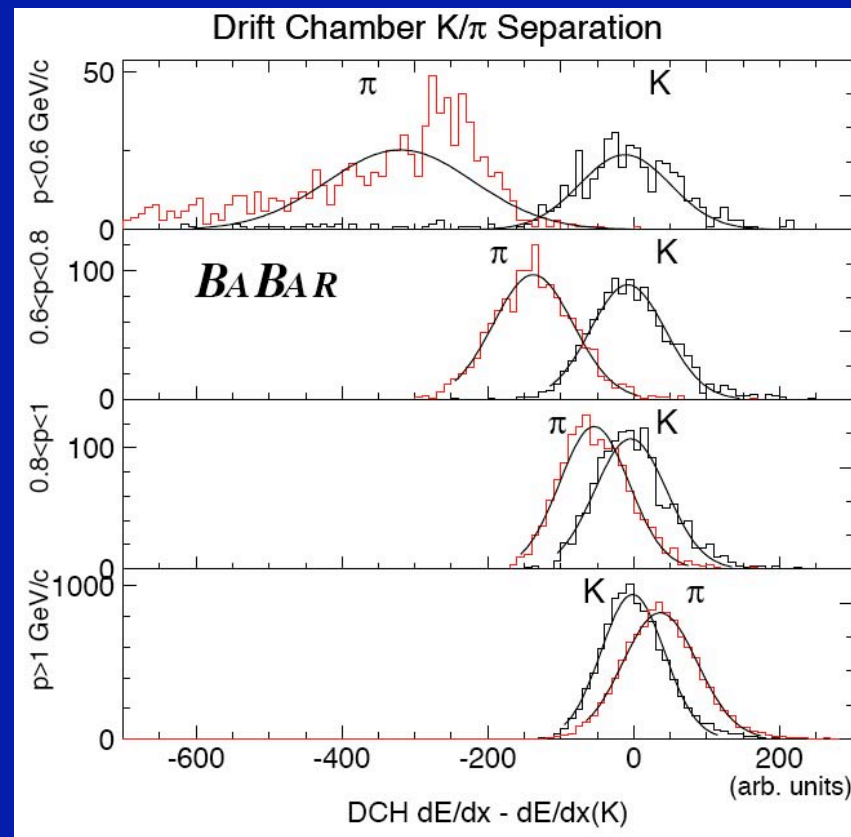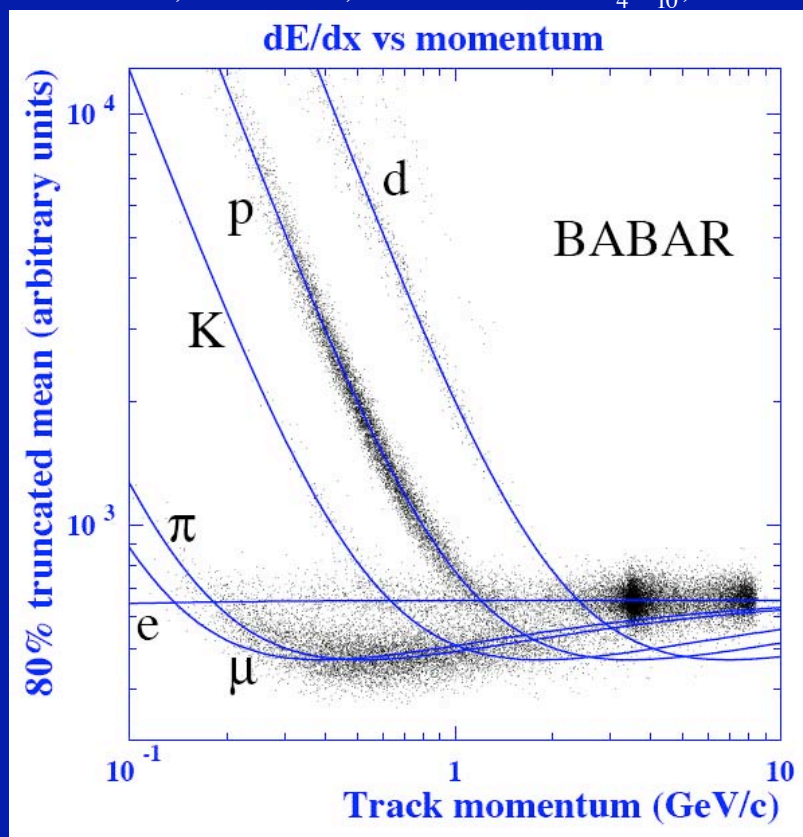 dE/dx: a) **Bethe-Bloch-Sternheimer formula works best.**

           b) **Allison - Cobb Monte Carlo agrees with data within ~3%.**

  $\sigma(dE/dx)$: **Allison - Cobb prediction works well. However, I have found that the empirical fit is a fast and equally correct way to do it.**

BaBar DCH dE/dx performance

M.Kelsey, SuperB workshop, Hawaii, Jan. 2004

$n = 30$, $t = 1.2$ cm, $80\%He + 20\%iC_4H_{10}$, 1 bar

- **A good p/K performance up to ~ 0.7 GeV/c.**
- **Can this be improved in the forward direction by the cluster counting at SuperB ?**

Cluster counting

Original idea to use cluster counting for PID: A.Walenta, IEEE NS-26, 73(1979)

Typical dE/dx resolution in typical drift chambers for 1cm in Ar gas at 1 bar:

FWHM/dE/dx$_{\text{most probable}}$ ~ 100%

dE/dx resolution
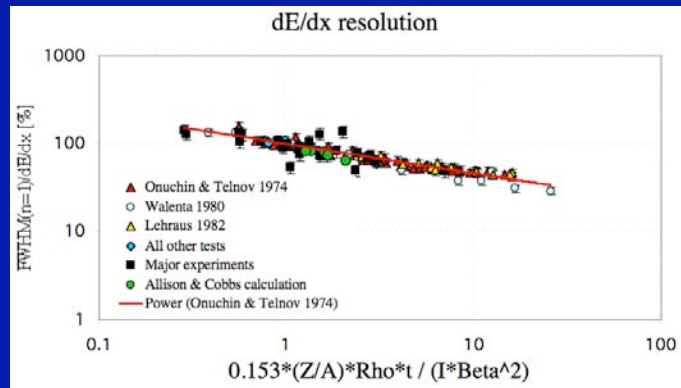
What do we expect from cluster counting ?

N_{primary} ~ 28/cm at 1 bar in Ar gas

FWHM/ dE/dx$_{\text{most probable}}$ =

= 2.35 $\sqrt{(N_{\text{primary}})}$/ N_{primary} ~ 44%

- **So far nobody has succeeded to do this in a large experiment.**
- **The clusters are 300-400 μm apart, which corresponds to a few ns separation.**
- **Hard to do with a conventional TDC electronics. However, a new waveform digitizers are coming to market, and one could think about it again.**
- **A new SuperB DCH plans to try it.**

TOF PID technique

Principle is simple:

$$\Delta t = (L_{path}/c) *(1/\beta_1 - 1/\beta_2) = (L_{path}/c) *[\sqrt{(1+(m_1 c/p)^2)} - \sqrt{(1+(m_2 c/p)^2}] =$$

$$\sim (L_{path}c/2p^2) *(m_1^2 - m_2^2)$$

Therefore expected particle separation: $N_\sigma = [(L_{path}c/2p^2) *(m_1^2 - m_2^2)]/ \sigma_{Total}$

where

$$\sigma_{Total} \sim \sqrt{[(\sigma_{TTS}/\sqrt{N_{pe}})^2 + (\sigma_{Chromatic}/\sqrt{N_{pe}})^2 + \sigma^2_{Electronics} + \sigma^2_{Track} + \sigma^2_{T0}]}$$

$\sigma_{Electronics}$ - electronics contribution ~ 10 ps
$\sigma_{Chromatic}$ - chromatic term = f (photon path length) ~ 5-45 ps for path lengths 10-50 cm long
σ_{TTS} - transit time spread ~ 35 ps for the best MCP-PMT detectors
σ_{Track} - timing error due to track length L_{path} (poor tracking in the forward direction) ~ 5-10 ps
σ_{T0} - start time dominated by the SuperB crossing bunch length ~ 20-25 ps (?)

- **SuperB TOF in the forward direction:**

  For L_{path} = 1.8 meters and $\sigma_{Total} \sim$ 25ps, one obtains $N_\sigma \sim$ 3 sigmas for π/K separation at 3 GeV/c. Clearly worse than the RICH techniques, such as DIRC or Aerogel. Useful, however, if it can be made more simple and less expensive, and if physics requires PID at low momentum.

dE/dx vs. TOF vs. DIRC - SuperB geometry

Ideal
PID
separation:

Expected π/K separation

- dE/dx (n=30, t=1.2cm, 1 bar, 80%He+20%C4H10)
- TOF (1.8 m path, sigma = 50 ps)
- TOF (1.8 m path, sigma = 25 ps)
- BaBar DIRC

y-axis: # of sigmas

x-axis: Momentum [GeV/c]
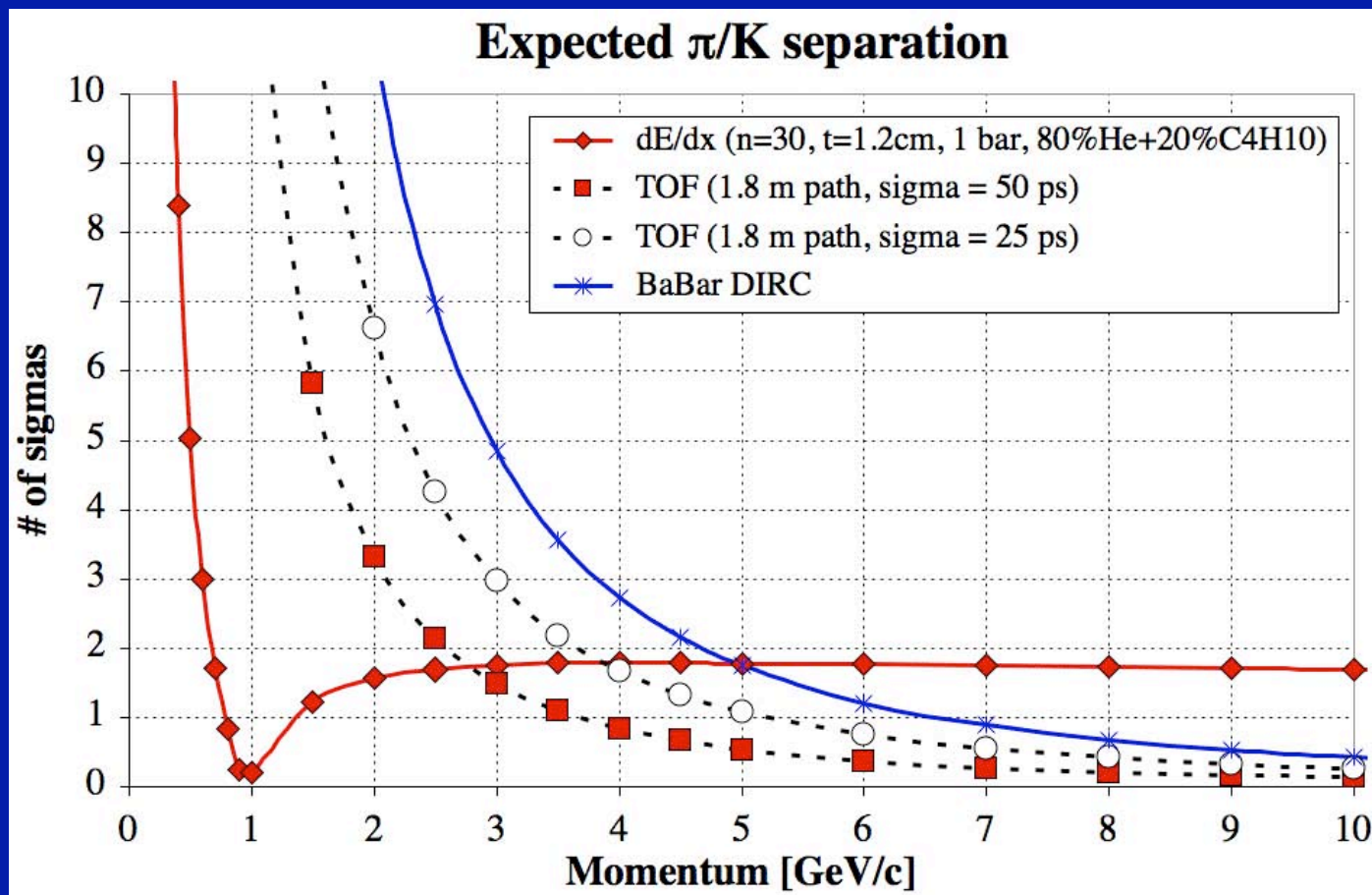
- **A practical TOF technique is competitive only below ~2-3 GeV/c. But it is useful if one wants to suplement a dE/dx dip ~1 GeV/c.**

Photocathodes

Compilation of various Photocathodes

J. Va'vra, The 42-nd workshop on Supercolliders, Erice, Sicily, Italy, 2003, SLAC-PUB-11019, and Q.E.&Tr&n - overall.xls
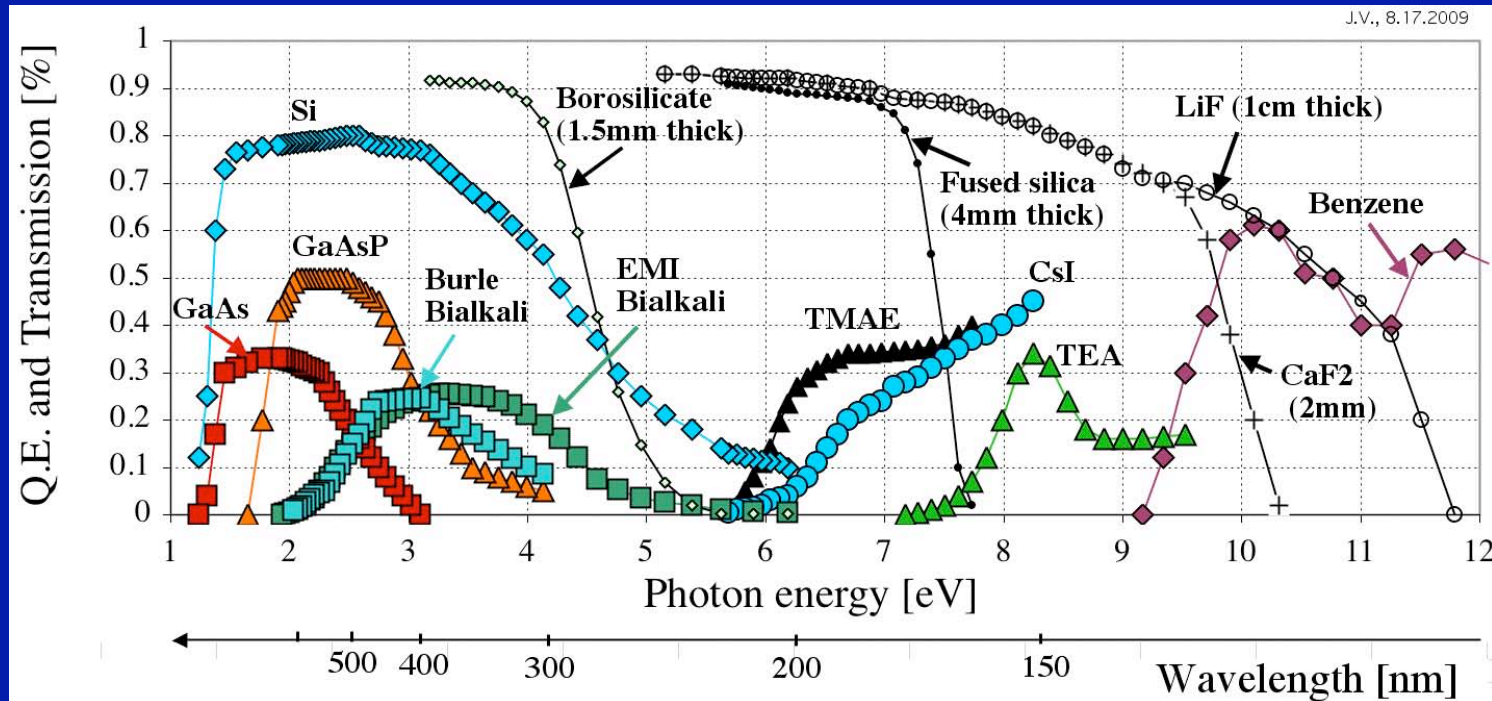
- **In the past 40 years, there was a steady push to develop photocathodes operating in the visible wavelength range.** The main reasons: (a) The radiators are very chromatic in the UV region, (b) Materials are less transparent, expensive, (c) Mirrors are difficult to make, expensive, (d) The far UV region is difficult to work in (cleanliness, outgasing pollution, etc).
- **Benzene** was used by HRS, **TMAE** by DELPHI, SLD, OMEGA, CERES, JETSET and CAPRICE; **TEA** by CLEO, **CsI** by ALICE, COMPASS, HADES; **Bialkali** by HERA-B, DIRC, HERMES, Belle, CELEX, **Multi-alkali** by LHC-b, and **GaAsP, GaAs or Si** will be pushed by new detectors.
- **QE in TMAE, TEA and Benzene measured in the gas.**

Photon Detection Efficiency

$$PDE = QE \times \varepsilon_{\text{pe collection}} \times \varepsilon_{\text{detection}} \times \varepsilon_{\text{packing geometry}}$$

Edge effects

Not all pe convert into a signal.

Watch out for after pulsing.
Do not include them in PDE !

Examples of typical PDE values at present:

1. PMT: > 15%

2. Multi-pixel G-APD (SiPMTs): 30-40%

3. MaPMT such as H-8500: ~ 14%

4. MCP-PMT: 9-12 %

Photon propagation through optical dispersive medium
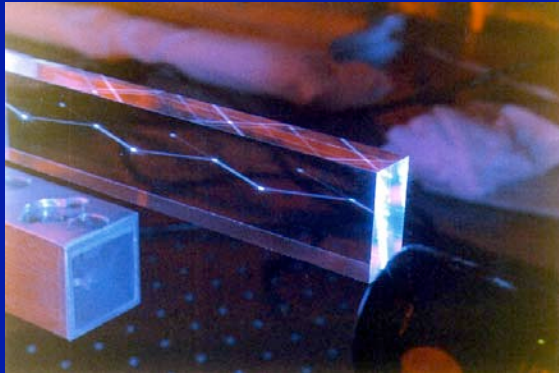
- Transmission
- Chromaticity effects
- Internal reflection
- Fresnel reflections on glues
- Bar orthogonality

Transmission in quartz

3M Co. fiber data sheets

- **In the region of interest, between 300 and 650nm, DIRC quartz has excellent transmission.**
- **Our measurements with 1.2 m long bars confirm this.**

Rayleigh scattering

$$I \sim 1/\lambda^4$$

- A portion of the light lost in the bar is due to this component, which represents scattering on small objects.

- That is why we see a 325nm laser in the bar.

- This component acts as a filter to suppress a UV component of the light, which tends to help the chromatic effects

Chromatic effects

Refraction index $n_{phase} = f(\lambda)$

J. Va'vra, The 42-nd workshop on Supercolliders, Erice, Sicily, Italy, 2003, SLAC-PUB-11019, and Q.E.&Tr&n - overall.xls
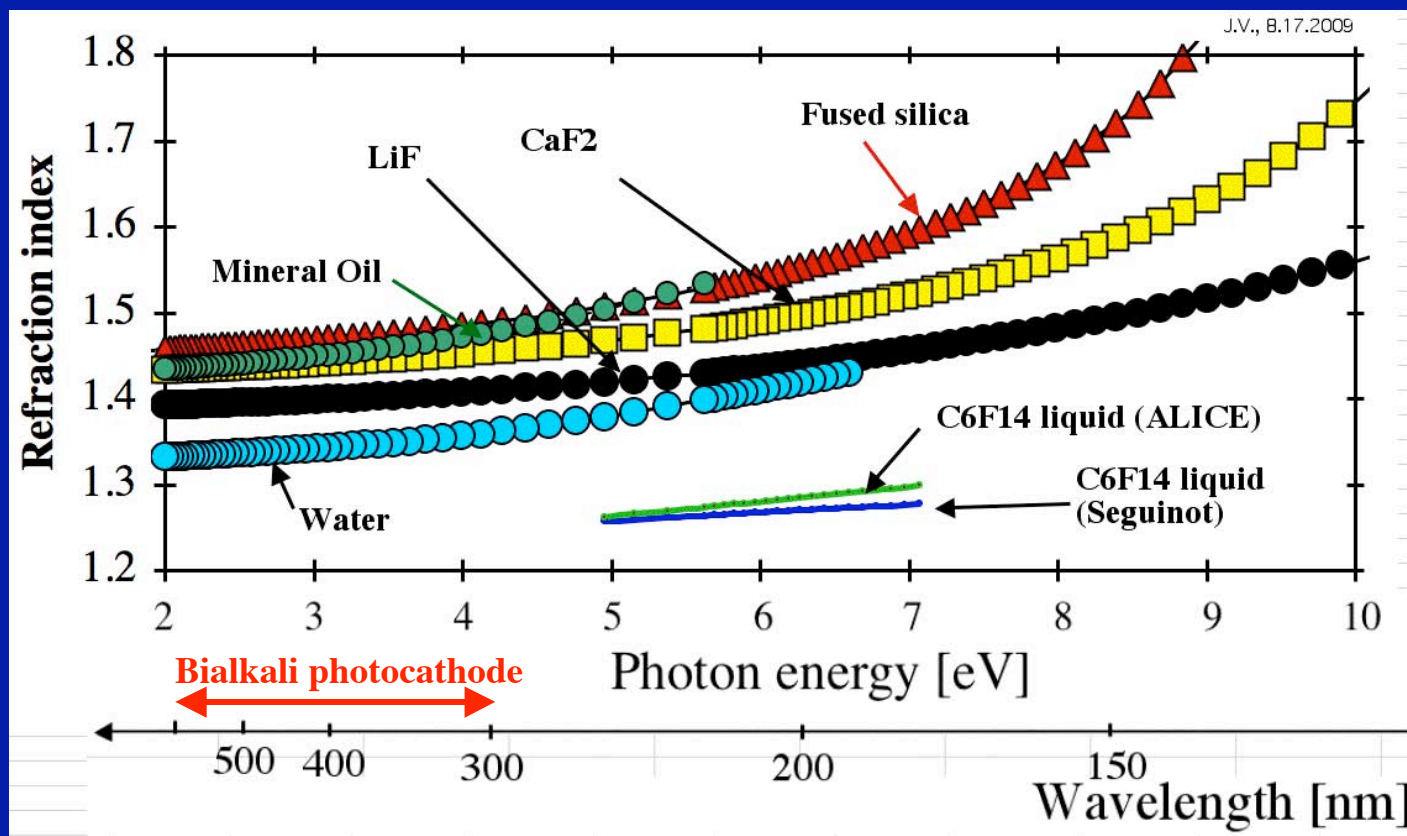
- **This index is also called phase refraction index.**
- **All detectors sensitive below ~300 nm have rapidly varying refraction index if they use these radiators.**

Chromatic dispersion of light impulse

Dispersive medium

Input pulse

Output pulse

Assume:
Pulse has also a certain a spectral distribution = f(λ)

n_{phase}

Red gets ahead of blue

$n_{phase}(red) < n_{phase}(blue) => v_{group}(red) > v_{group}(blue)$
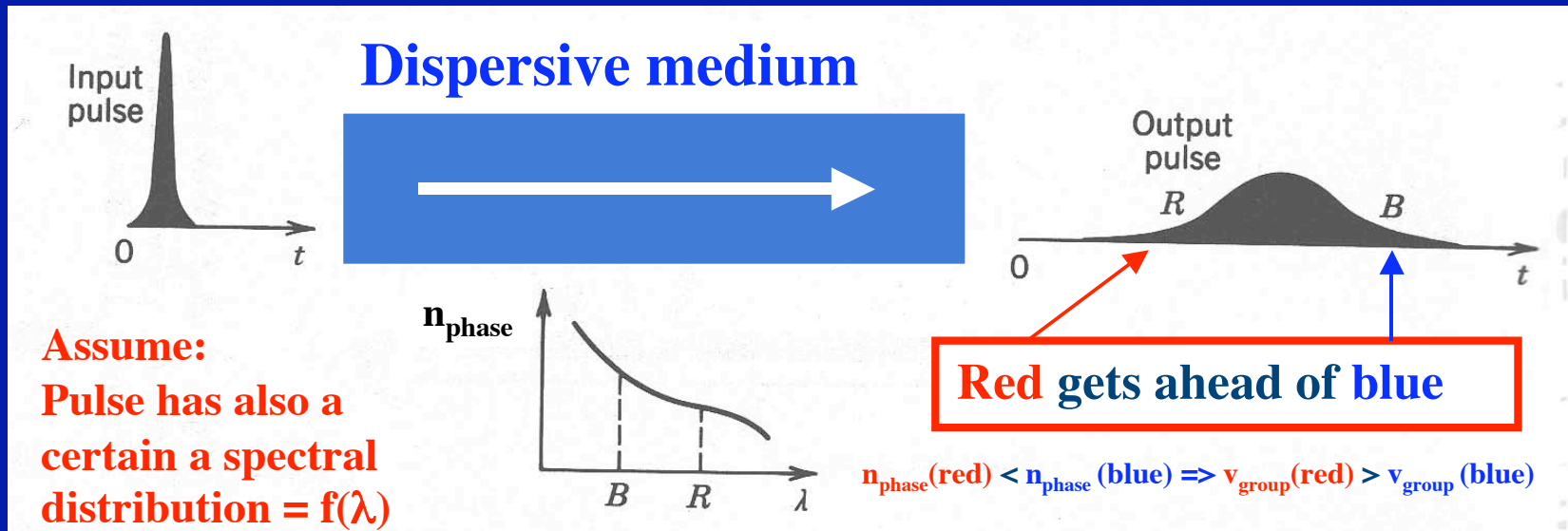
$$v_{group} = c / n_{group} = c / [n_{phase} - \lambda * dn_{phase}/d\lambda]$$

$$t \equiv TOP = L_{path} / v_{group} = L_{path} [n_{phase} - \lambda * dn_{phase}/d\lambda] / c = \text{time-of-propagation}$$

$$dt = L \ \lambda \ d\lambda / c * |- d^2 n_{phase}/d\lambda^2|$$

dt is pulse dispersion, fiber length L, wavelength bandwidth $d\lambda$, refraction index $n(\lambda)$,
n_g is typically a few % larger than n for photons in a Bialkali photocathode wavelength range

- **Chromaticity of the medium can easily dominate the timing resolution.**

Chromatic behavior of the Cherenkov light

Quartz at ~ 420 nm:

n_{phase}	n_{group}
~1.4681	~1.5065

$$\cos \theta_c = 1 / \beta\, n(\lambda)$$

$\Delta\theta_{chromatic} \sim 4\ mrad$ **Beam** $\lambda_{average} \sim 410\ nm$ **Detector**

Mirror

Bar θ_c v_{group}
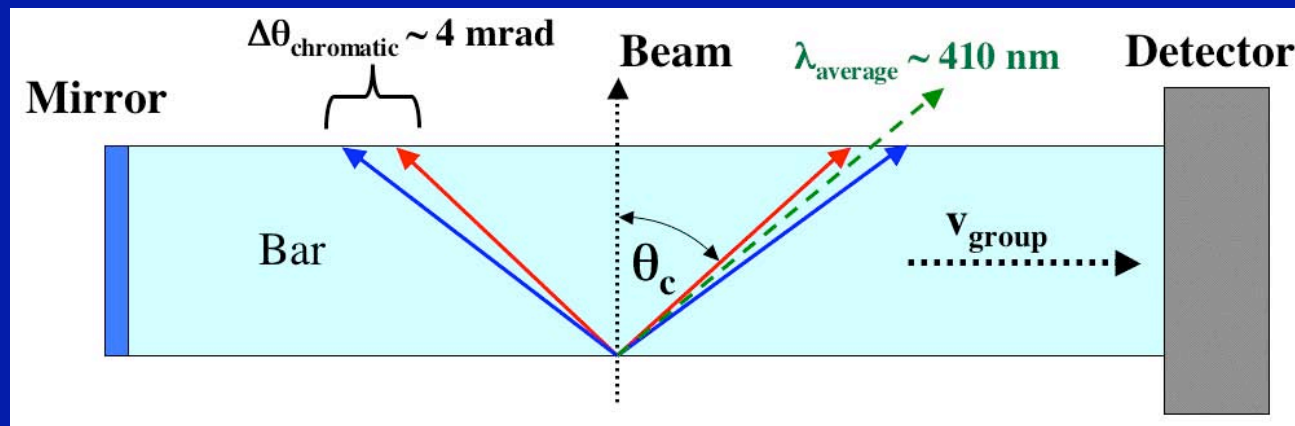
Cherenkov angle production controlled by n_{phase} ($\cos \theta_c = 1/(n_{phase}\beta)$): $\qquad$ θ_c **(red)** $< \theta_c$ **(blue)**

Propagation of photons is controlled by n_{group} ($v_{group} = c_0/n_{group} = c_0/[n_{phase} - \lambda*dn_{phase}/d\lambda]$): $\quad$ v_{group}**(red)** $> v_{group}$ **(blue)**

- **Chromaticity of the medium typically dominates the Cherenkov angle θ_c error in all Cherenkov detectors. Can we use time to correct it ? <u>Answer:</u> yes (see the 3-rd lecture). One can also use red-sensitive photocathodes or UV filters.**

Chromatic errors and type of photocathode

K. Inami, RICH workshop, Giessen, Germany, 2009

$$v_g = c/n_g(\lambda)$$
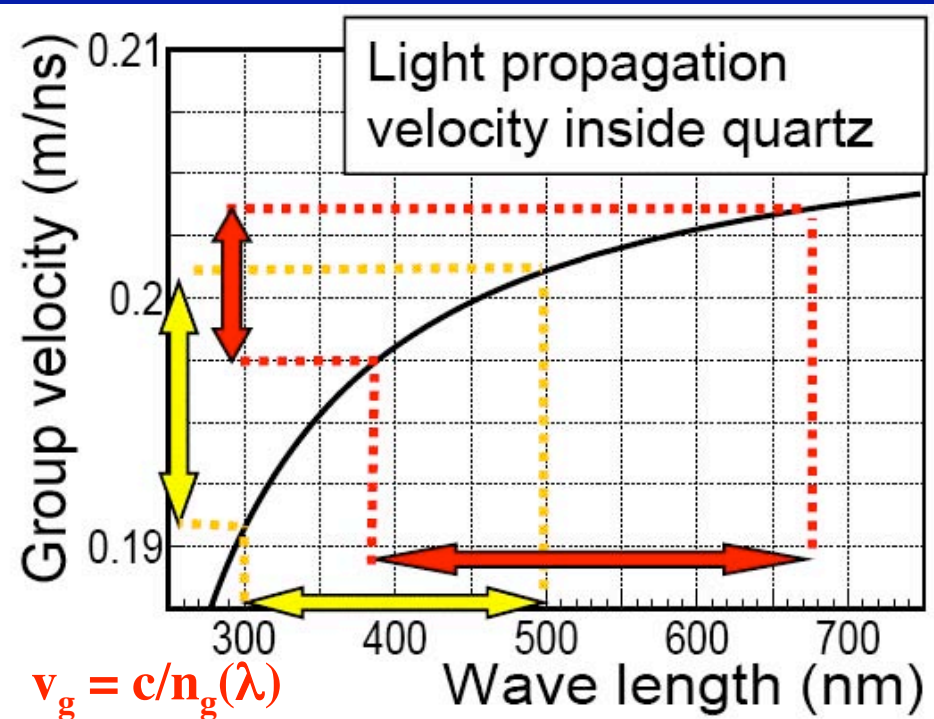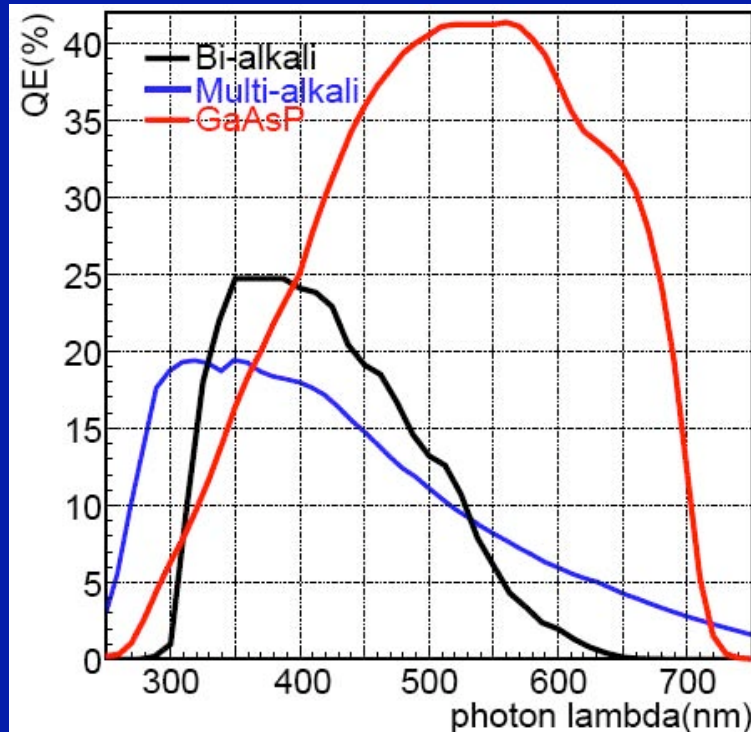
- **Operation at longer wavelength yields smaller chromatic error.**
- **The chromatic error with GaAsP photocathode may be reduced further by adding a filter to block the light below 400 nm.**

PID detectors
(all are based on detection of the Cherenkov light)

- DIRC-like RICH detectors:
  - BaBar DIRC
  - FDIRC prototype
  - FDIRC for SuperB
  - TOP counter
- Aerogel RICH detectors
- TOF detectors

DIRC-like RICH detectors

DIRC-like detector concept

DIRC ≡ **D**etection of **I**nternally **R**eflected **C**herenkov light)

DIRC was invented by B. Ratcliff, SLAC-PUB-5946, 1992
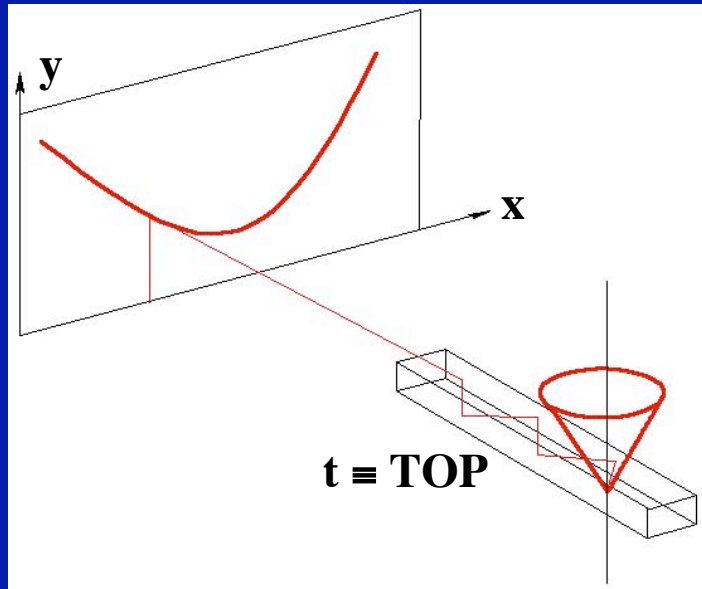
DIRC is intrinsically a **3D device**, i.e. it measures x, y, and time for each photon
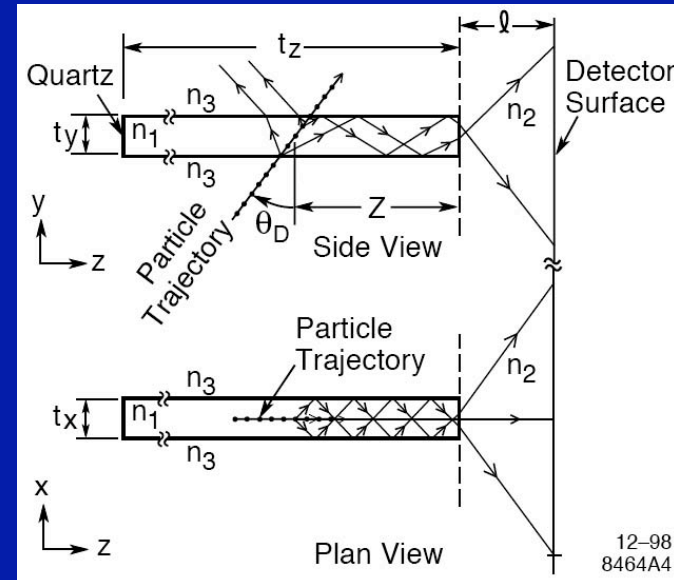
If the bar's refraction index (n_1) substantially exceeds $\sqrt{2}$, and the index of the surrounding material (n3) is ~1, then for a particle close to $\beta = 1$, some portion of the light will always be transported down the bar to the end.

- **A typical Cherenkov photon in BaBar DIRC has a wavelength of ~ 380 nm (driven by QE of the ETL PMT), bounces 350 times and travels through 6 -10 m of quartz. Even so the original photon direction is preserved by the bar's symmetry, <u>except the chromatic broadening</u>.**

DIRC-like detectors - 3D aspect

Definition of angles for $\theta_{dip} = 90^o$:
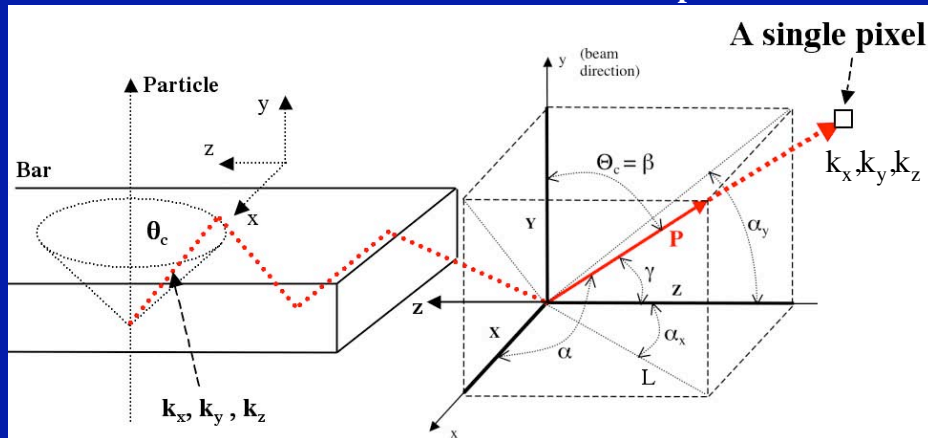
$$\tan \alpha_x = k_x/k_z$$
$$\sin \theta_c = k_z \sqrt{(\tan^2\alpha_x+1)}$$
$$\cos \theta_c = k_y$$

3D ring images in BaBar DIRC:

B. Ratcliff, ICFA Instrumentation Bulletin, 2001,
http://www.slac.stanford.edu/pubs/icfa/spring01/paper2/paper2a.html
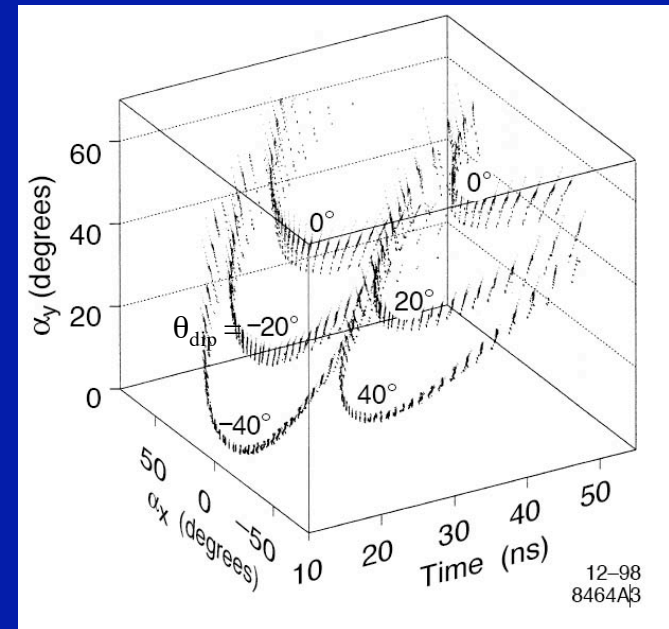
- **For a general track direction:**

$$\cos \theta_c = < \overline{k}.\overline{k}\_track > = k_x*k\_track_x+ k_y*k\_track_y+ k_z*k\_track_z$$

DIRC-like concept

$\Delta\theta_{chromatic} \sim 4$ mrad **Beam** $\lambda_{average} \sim 410$ nm **Detector**

Mirror

Bar θ_c v_{group}
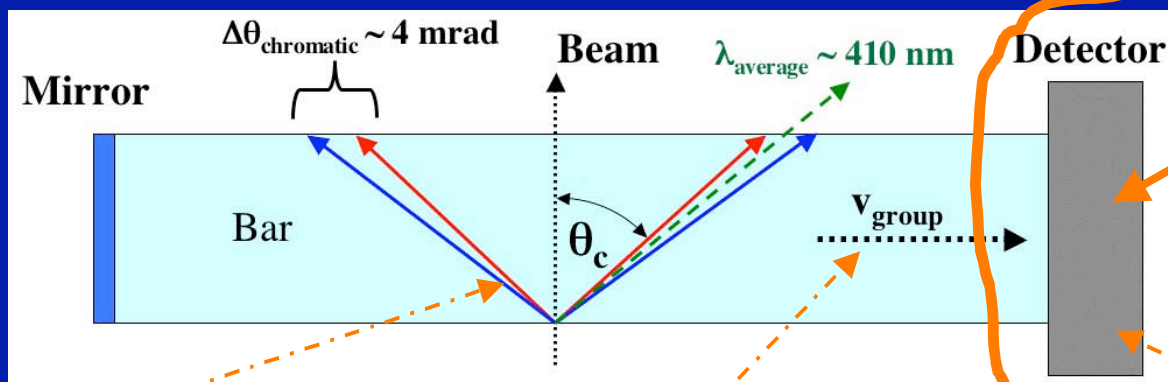
There are many detector schemes as we will see in the following lectures.

γ - creation part:	**γ - propagation part:**	**Detection part:**
$\cos\theta_c = 1/\beta\, n(\lambda)$ (uniformly in ϕ_c)	$v_{group}(\lambda) = c / n_{group}(\lambda) =$ $= c / [n_{phase}(\lambda) - \lambda * dn_{phase}/d\lambda]$	For each photon: **x, y, z & time**

where $\beta = v_{particle}/c$, c = velocity of light in vacuum, v_{group} - photon velocity in dispersive medium, $n(\lambda) \equiv n_{phase}(\lambda)$ = refraction index of radiator material, $n_{group}(\lambda)$ - group refraction index

Differences in imaging methods:

BaBar DIRC: x & y & "poorly" time (time is used to reduce bckg and remove z-ambiguities)

FDIRC prototype: x & y & "good" time (time: reduce bckg + ambiguities + chromatic correction)

TOP counter (in the latest incarnation): x & "poorly" y & "very good" time

Latest addition

Examples of DIRC-like detectors

BaBar DIRC:

Pin hole imaging with x, y, time

Approximate "pin hole imaging" is accomplished since bar end (pinhole) has dimension small compared with PMT "stand off" distance from bar. => PMT hit position (Δz; Δr) determines the photon direction. Far end has a simple flat mirror.

$$c \cdot TOP = \sqrt{\Delta z^2 + \Delta r^2}$$
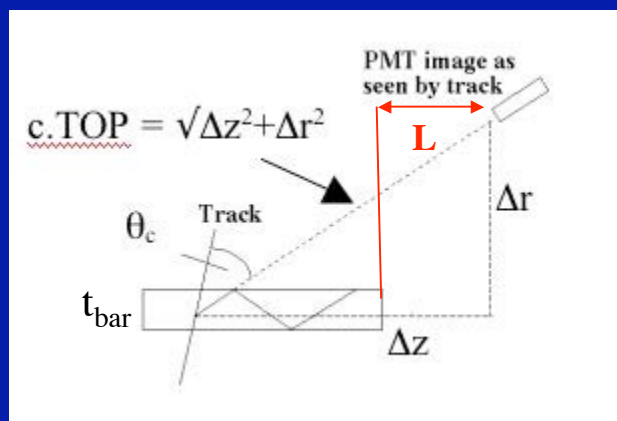
$$\sigma_{imaging} \sim \sqrt{[(t_{bar}^2 + pixel^2)/(12\,L^2)]}$$
$$\sim 5.5 \text{ mrads}$$

Pixel size: ~1 inch dia.
L ~ 1.1 m
TTS Time resolution ~ 1.7 ns

FDIRC prototype:

Imaging with a mirror & x,y,time

Mirror removes the bar thickness.contribution to the Cherenkov error. One also demagnifies the image to match smaller pixel size, and therefore detector can be 2-3x smaller. The far end end has a simple flat mirror, as BaBar DIRC. The same type of imaging as DIRC, but better time measurement allows a correction of the chromatic error by timing.
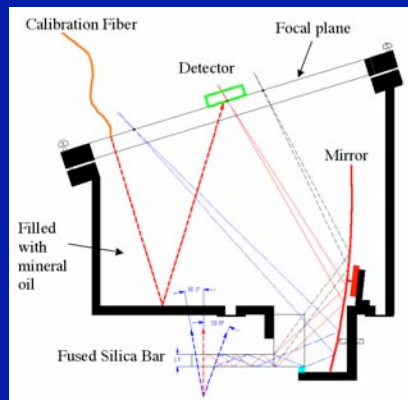
$$\sigma_{imaging} \sim (pixel/\sqrt{12})\,/L_{ave.\ optical\ path}$$
$$\sim 4 \text{ mrads}$$

Pixel size: ~6mm x 6mm
$L_{ave.\ optical\ path}$ ~ 45 cm
TTS Time resolution ~ 200 ps

TOP counter:

Imaging with x & time

Each photon is measured with a very high time resolution. In addition, one measures a photon position in x-direction. There is no stand-off box. In the later incarnation of this scheme they added a segmented spherical mirror at far end of the bar, which will measure y roughly for photons going toward the mirror. Needs timing to work.
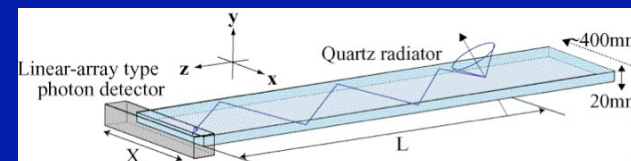
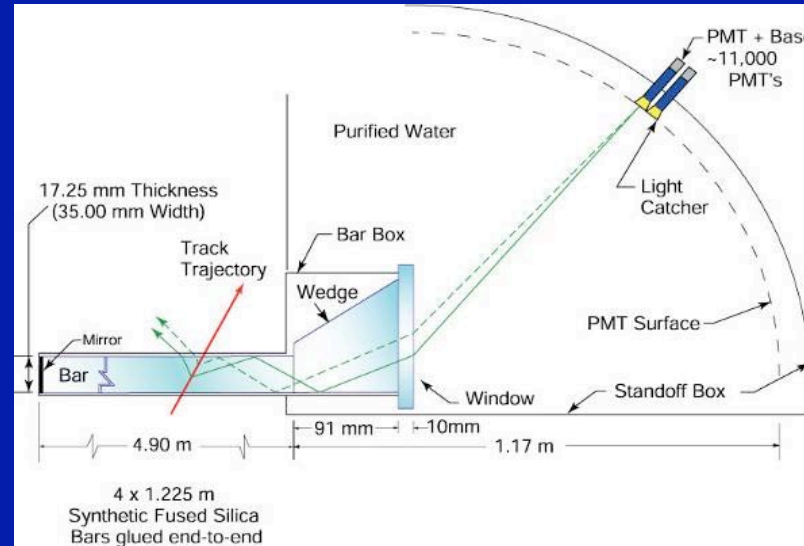$$\sigma_{imaging} \sim \tan\theta_c \sqrt{[(\sigma_{ng}/ng)^2 + (\sigma_{TOP}/TOP)^2 + \sigma^2_{\alpha x}\tan^2\alpha_x]}$$

Pixel size in x-direction: 1mm
TTS Time resolution ~ 40 ps

BaBar DIRC

A simple estimate of DIRC performance

I. Adam et al., Nucl.Inst.&Meth., A 538 (2005) 281-357

Assume:
**4 GeV/c, n = 1.47, radiator thickness = 1.7cm, ETL PMT (~2.5 cm dia.), θ_{dip} = 90°**

$\theta_c(\pi)$ [mrad]	$\Delta\theta_c = \theta_c(\pi) - \theta_c(K)$ [mrad]	$\sigma(\theta_c)_{single\ photon}$ measured	Npe measured	$\sigma(\theta_c)_{track} = \sigma(\theta_c)_{single\ photon}/\sqrt{Npe}$	Separation at θ_{dip} = 90° $[\theta_c(\pi) - \theta_c(K)]/\sigma(\theta_c)_{track}$
822	6.5 mrad	~ 9.6 mrad	~ 25	~ 1.9	~ 3.5 sigmas

- **Internally reflected photons bounce off polished surfaces towards a photon detector.**
- **Wedge was added to direct the photons to the photon detector and limit its size.**
- **Water was used as a coupling medium between PMTs & bar box.**

BaBar DIRC RICH = Detection of Internally Reflected Cherenkov light

I. Adam et al., Nucl.Inst.&Meth., A 538 (2005) 281-357

Photon detector:

~11,000 PMTs

Cherenkov radiator:

~5 m long Fused silica bars
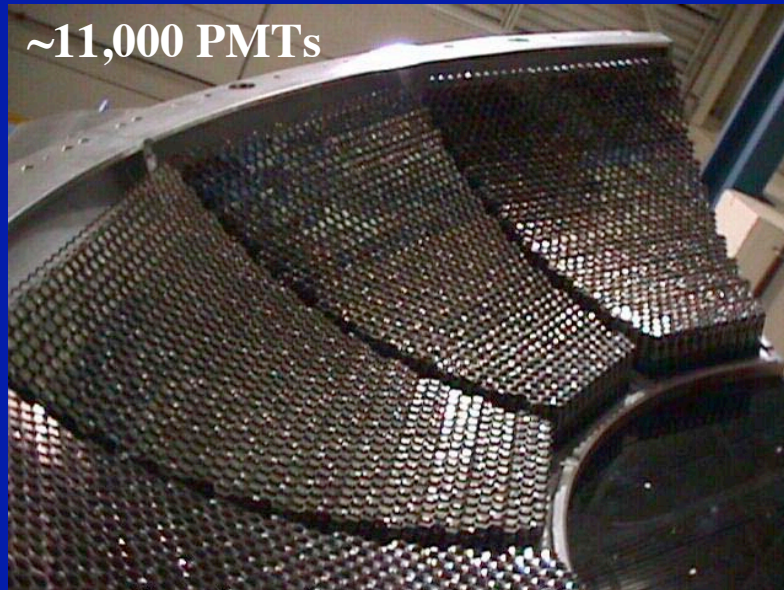
- **Bar dimensions (glued out of 4 segments): 488 cm x 3.5 cm x 1.7 cm**
- **~11,000 1 inch dia. ETL PMTs, sitting in water to minimize the photon loss.**
- **Measurements are made at only one bar end.**
- **Mirror at the other bar end.**

Efficiency response = f (wavelength)

J.Va'vra, DIRC internal note #129, April 12, 2000
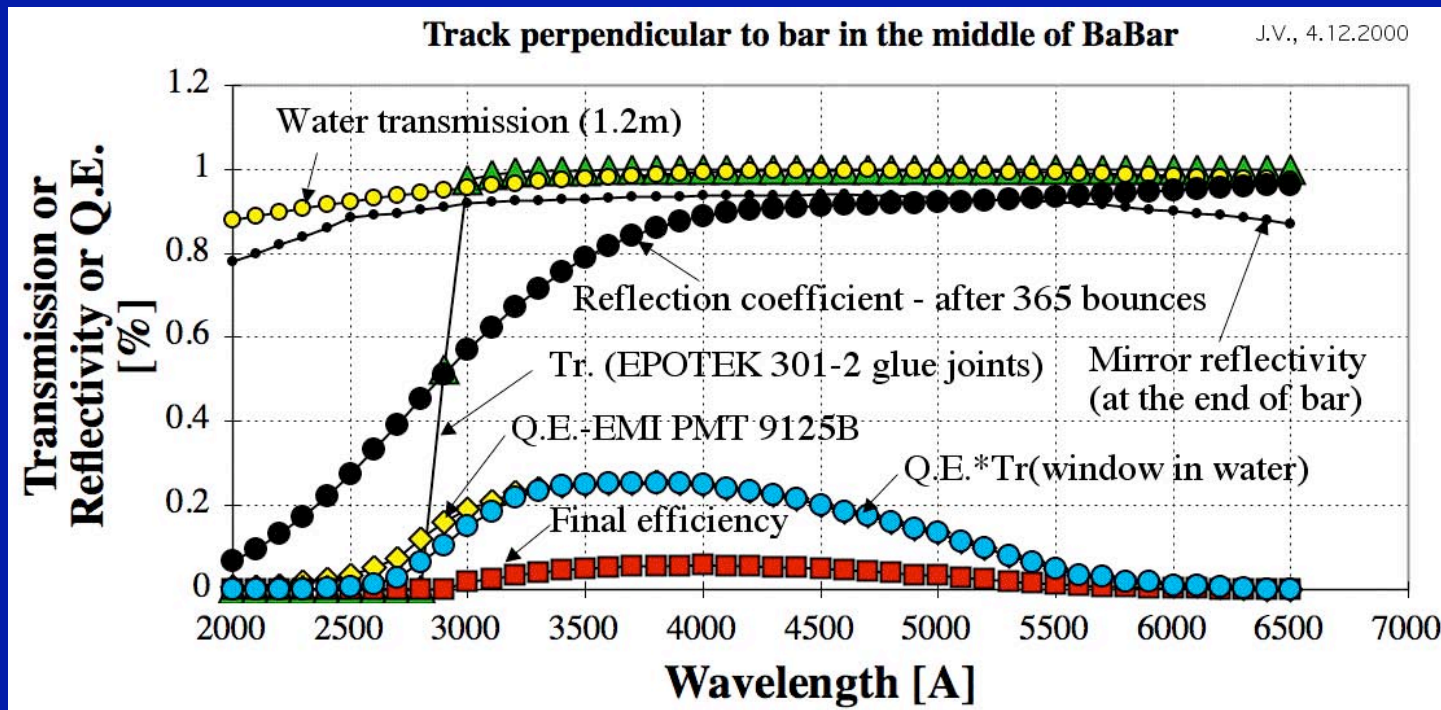
- **Epotek glue, which is used to glue bars together, cuts the DIRC response at low wavelengths, QE cuts it at high wavelengths. Bar reflections also play a role for a large number of bounces at low wavelengths.**
- $N_o \sim 30$ cm^{-1}, L = 1.7 cm, θ_{dip} = 90°, middle of bar.
- Npe $\sim$ 370 L $\int \epsilon$(E) sin$^2 \theta_c$ dE $\sim$ 28 photoelectrons, θ_{dip} = 90°, middle of bar.

DIRC performance at BaBar

Single photon resolution: **Resolution per track:**
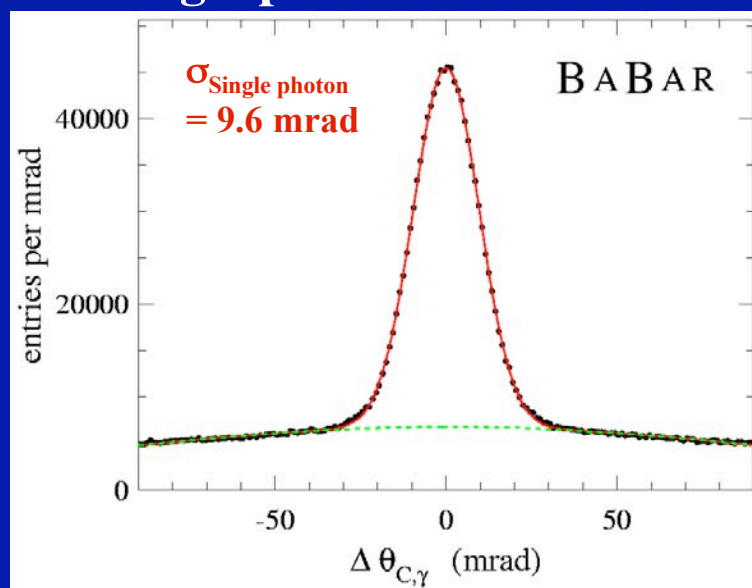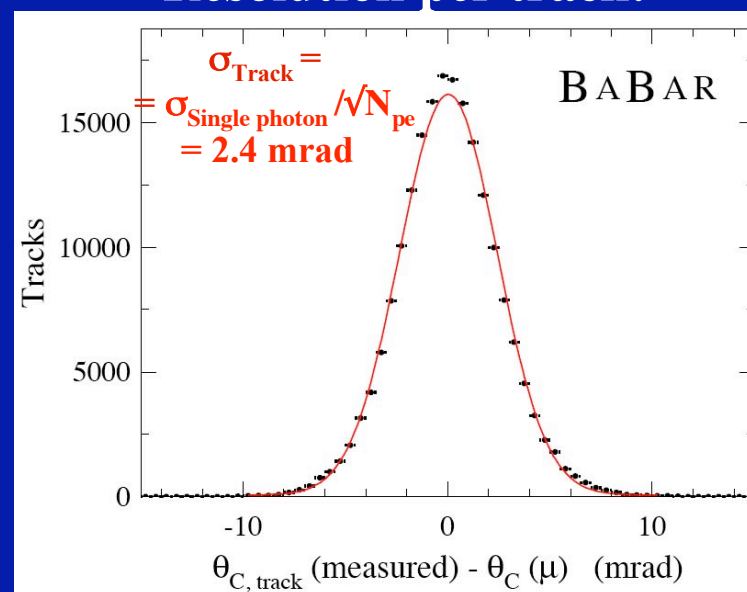
$$\sigma_{\theta c}^{\text{tot}} = \sqrt{[(\sigma_{\theta c}^{\text{ext. track}})^2 + (\sigma_{\theta c}^{\text{prod}})^2 + (\sigma_{\theta c}^{\text{trans}})^2 + (\sigma_{\theta c}^{\text{imaging}})^2 + (\sigma_{\theta c}^{\text{align}})^2]} \sim 9.6 \text{ mrad}$$

$\sim$ f(θ_{track}) ~1mrad

$\sim$ f[chromatic error, multiple scatt.~$1/(\beta p)$] ~5-6 mrad

$\sim$ f(bar imperfections) ~2-3 mrad

$\sim$ f(bar size, pixel size) ~6-7 mrad

$\sim$ f(alignment) <1 mrad

- **Imaging error (pixels and bar size) and the Chromatic errors dominate.**

Timing window on Δt in BaBar DIRC

Δt: difference between measured and expected time

$\sigma_{\Delta t} \sim 1.7$ ns — BABAR
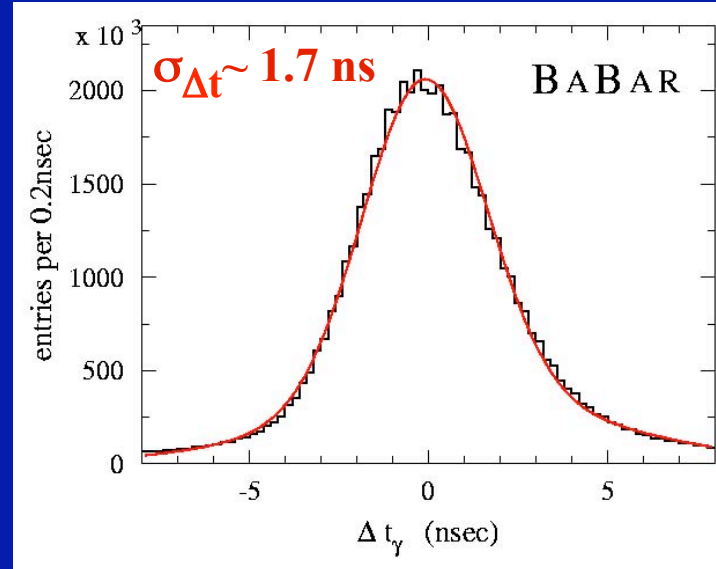
$$\Delta t = t_{measured} - t_{expected} = TDC_{Start:\,bunch\_to} - (TOF_{track} + TOP_{bar\_expected} + t_{offsets})$$

$$\sigma_{\Delta t}{}^{tot} = \sqrt{[(\sigma_{\Delta t}{}^{ext.\,trigger})^2 + (\sigma_{\Delta t}{}^{TDC})^2 + (\sigma_{\Delta t}{}^{det\,TTS})^2 + (\sigma_{\Delta t}{}^{TOF})^2 + (\sigma_{\Delta t}{}^{TOP})^2]} \sim 1.7\ ns$$

TDC resolution ~0.5/$\sqrt{12}$ ns

PMT TTS ~1.5 ns

~ f(bar imperfections, alignment) ~1ns

~ f(ref. time for TDC) ~1ns

~ f(track TOF) - small

- **Time resolution of BaBar DIRC was sufficient to eliminate the background, but not good enough to do the chromatic corrections.**
- **At SuperB we hope to improve the timing by a factor of 5-10.**

Elimination of background by timing cut

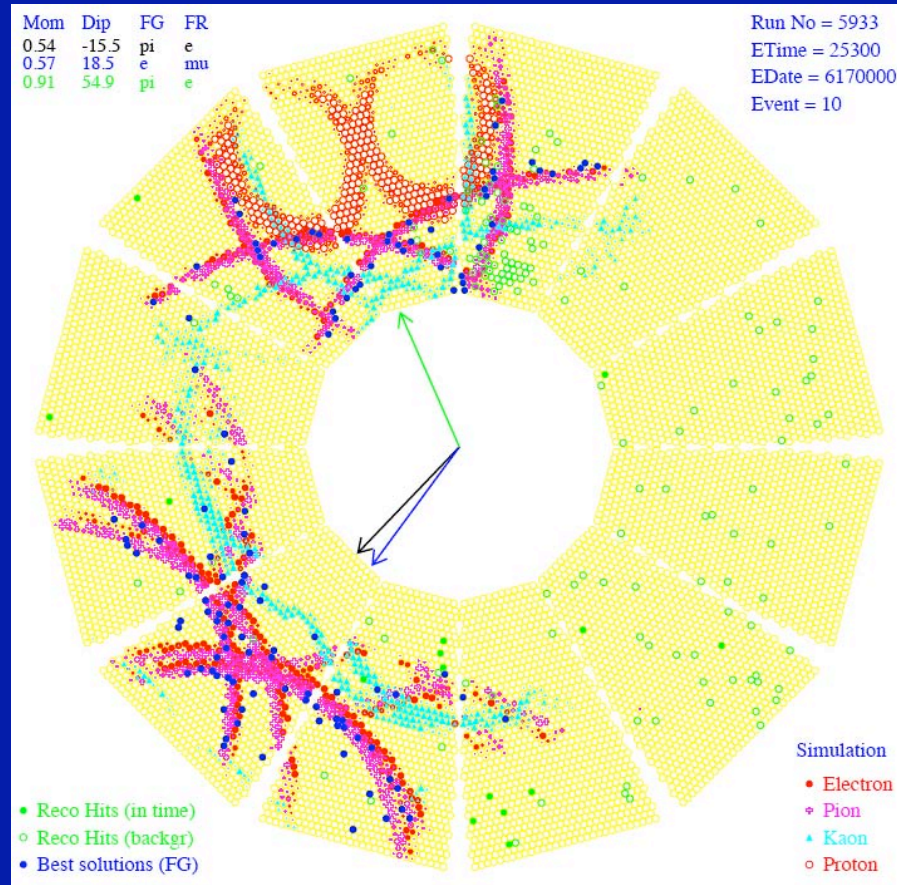I. Adam et al., Nucl.Inst.&Meth., A 538 (2005) 281-357

Δt window = ±300 nsec → Δt window = ±8 nse

(~500-1300 background hits/event)   (1-2 background hits/sector/event)
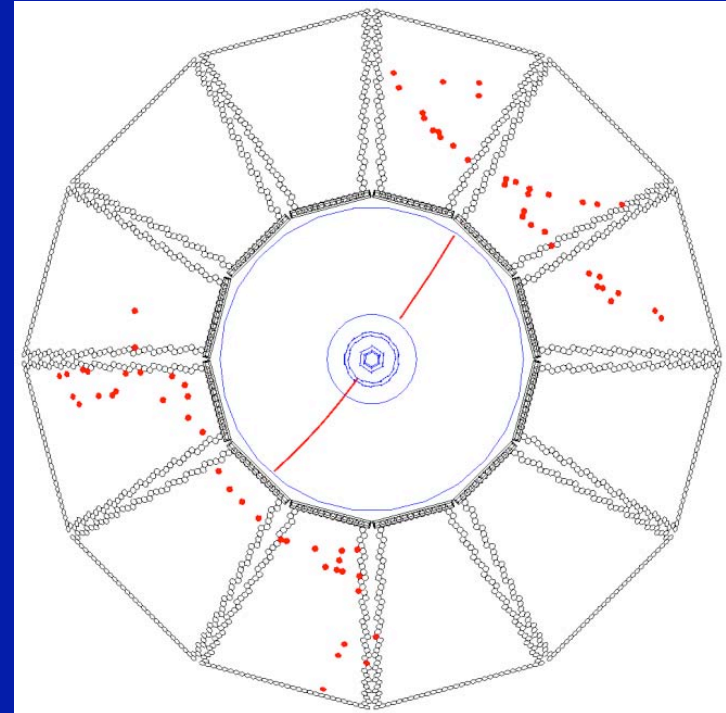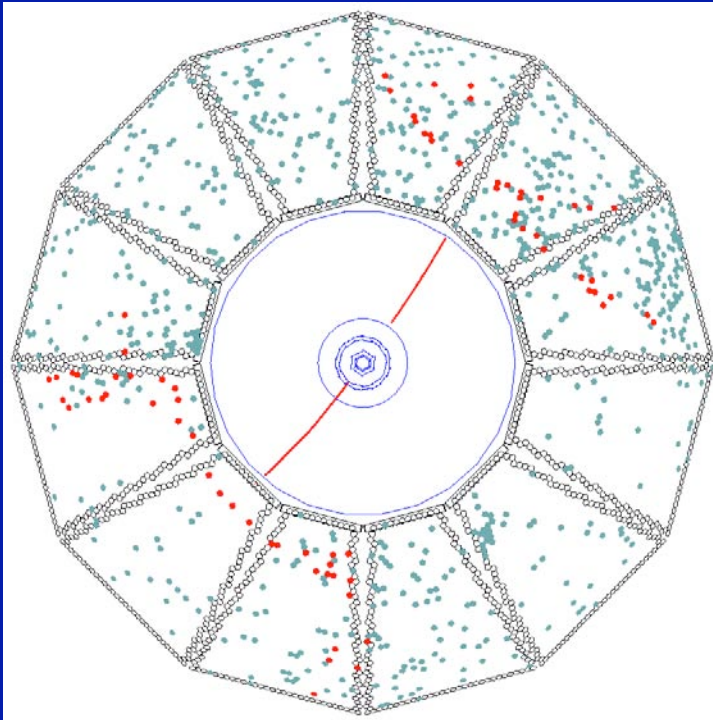
- **Timing cut is crucial for the background reduction and also for resolving the forward-backward ambiguity.**
- **At SuperB we hope to improve the timing by a factor of 5-10.**

DIRC single event in BaBar

I. Adam et al., Nucl.Inst.&Meth., A 538 (2005) 281-357

- **DIRC event (solid dots) and simulated ring probability densities for e, K and p. The arrows give the azimuthal position of the bar hit by a track.**

BaBar DIRC PID performance

PID is decided among 5 hypothesis (π,K,p,e,μ) on the basis of the maximum likelihood $L^{(h)}$,

assuming a Gaussian distribution of $<\theta_c>$: $L^{(h)} = \exp[-(\theta_c^{(h)} - <\theta_c>)/\sqrt{2}\sigma_{\theta c}]^2$

$\ln[L^{(h1)}/L^{(h2)}] = 0.5$ (1σ separation between hypothesis h1 & h2), $\ln[L^{(h1)}/L^{(h2)}] = 2$ (2 σ), and 4.5 (3σ)
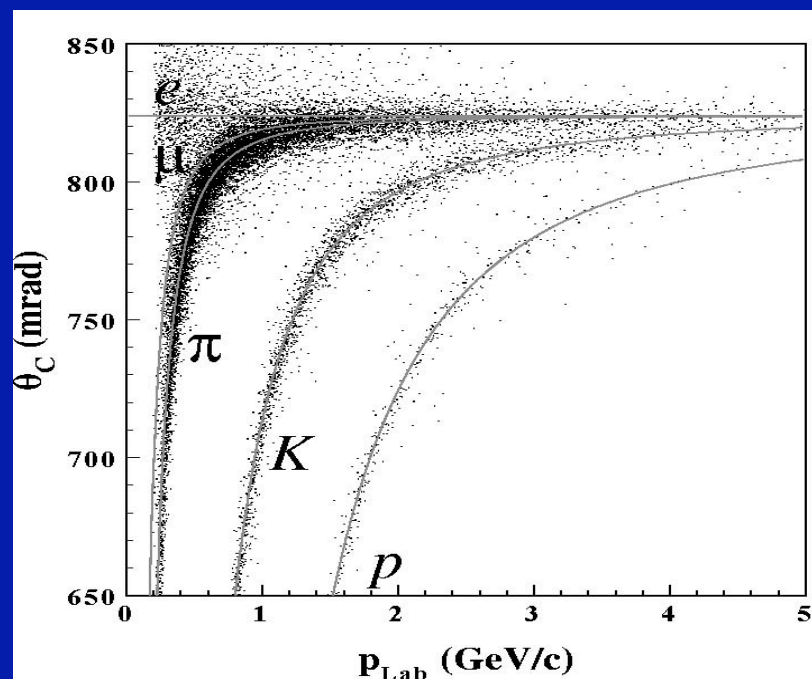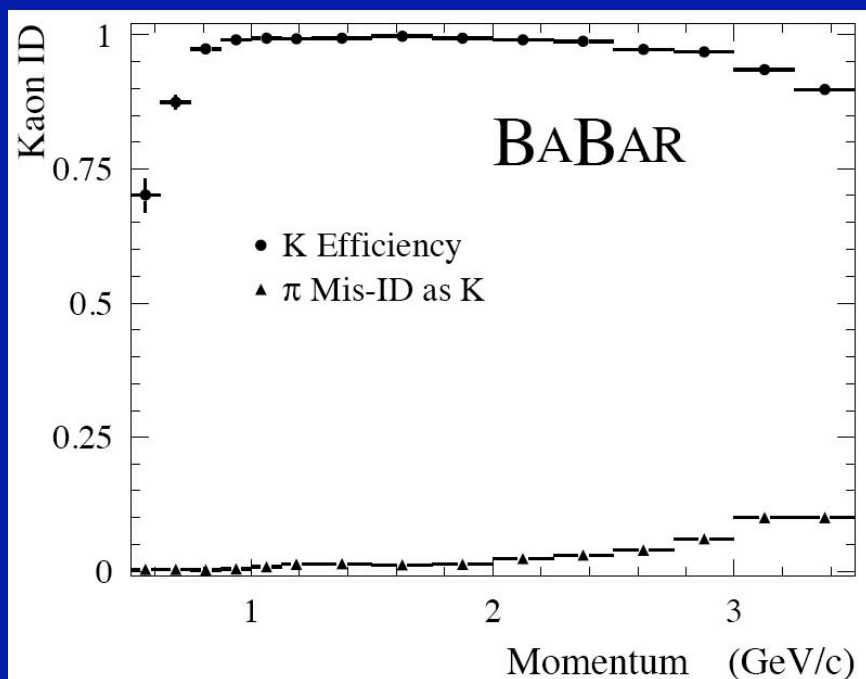
- **Very successful PID detector (a degree of success can be measured by the fact that many people want to copy DIRC in various forms).**
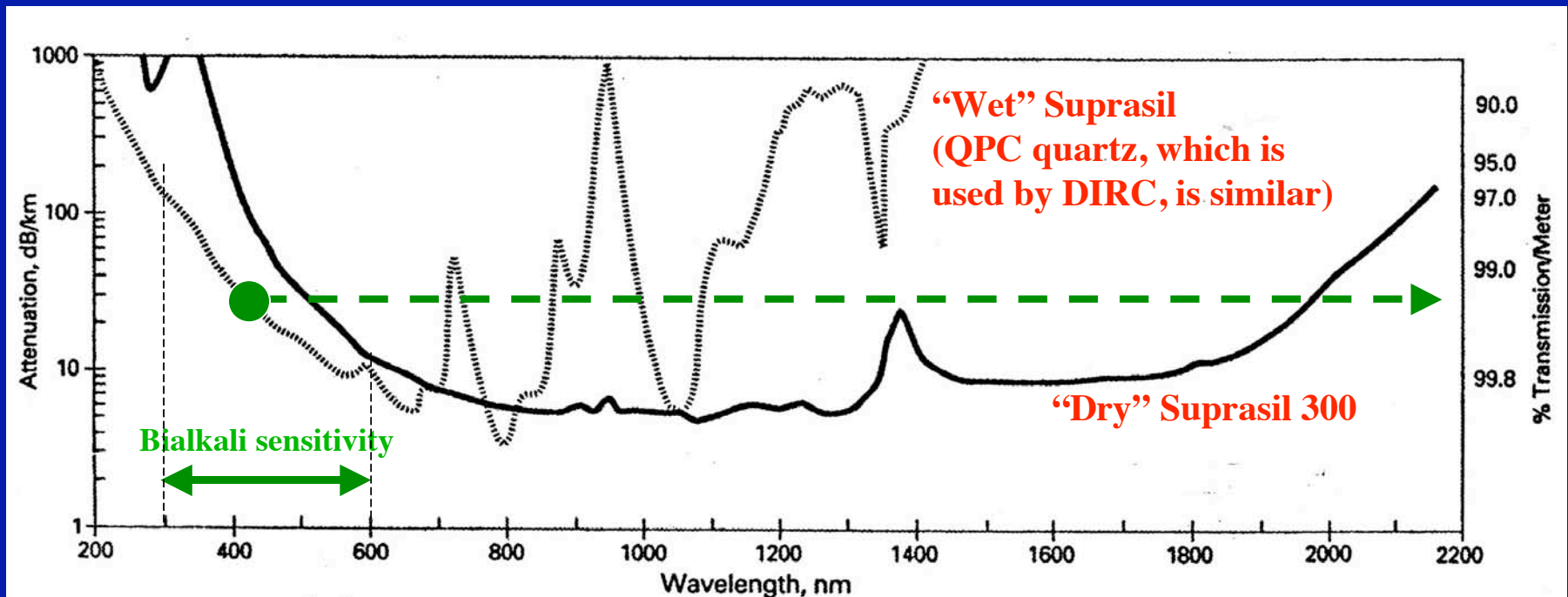
Appendix

Photon propagation through optical dispersive medium
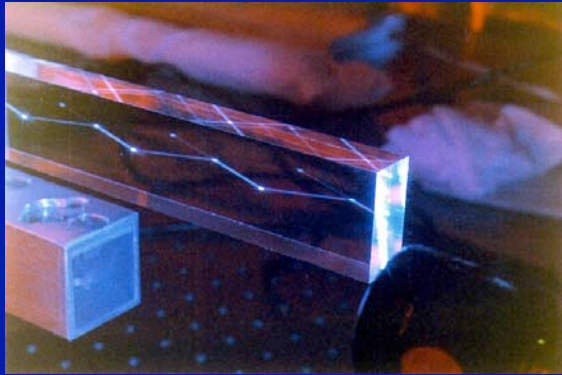
- Transmission
- Chromaticity effects
- Internal reflection
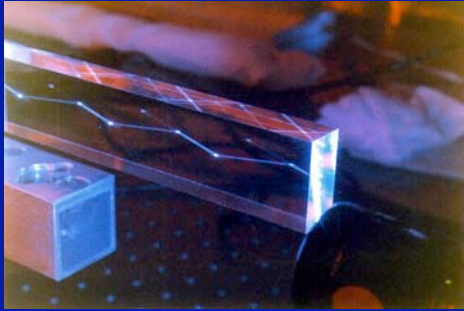- Fresnel reflections on glues
- Bar orthogonality

Transmission in quartz

3M Co. fiber data sheets

- **In the region of interest, between 300 and 650nm, DIRC quartz has excellent transmission.**

- **Our measurements with 1.2 m long bars confirm this.**

Rayleigh scattering

$$I \sim 1/\lambda^4$$

- A portion of the light lost in the bar is due to this component, which represents scattering on small objects.

- That is why we see a 325nm laser in the bar.

- This component acts as a filter to suppress a UV component of the light, which tends to help the chromatic effects

Internal reflection

Scattering from optical surfaces

J. Melson, H.E. Bennet and J.M. Bennet, Appl.Otics&Otptical Engineering, Vol VII, 1979

Total integrated scatter (TIS) by micro-regularities on the surface is described by simple scattering theory:

$$\text{TIS} = 1 - \text{Refl. Coeff.} = 1 - (R/R_o) =$$

$$1 - \exp[-(4\,\pi\,\delta\,\cos(\theta_o/\lambda))^2] \sim (4\,\pi\,\delta\,\cos(\theta_o/\lambda))^2$$
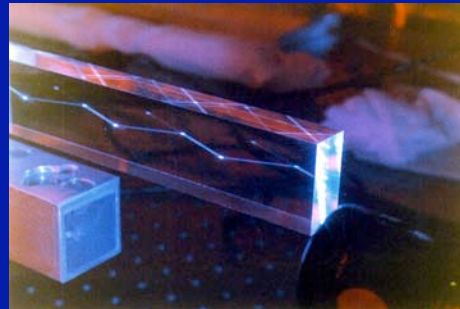
where R_o -   fraction of the incident light reflected into all angles

R - fraction which is speculary reflected at an angle θ_o

θ_o - angle of incidence

δ - surface micro-regularities (rms error in Angstroems)

Laser light in the DIRC bars:
(polished to 5-10 A rms)

Measurement of internal reflection = f (λ)

J.Va'vra, DIRC internal note #129, April 12, 2000

The starting equation is:

$$(((I_0 - I_1)r^N - I_2)r^N - I_3)r^N = I_4$$

which leads to:

$$I_0 = I_1 + I_2 * x + I_3 * x^2 + I_4 * x^3$$

Its solution **X** is related to the coefficient of internal reflection **r** through the following equation:

$$x^{-1} = r^N * \exp\left\{-\frac{L}{\lambda} * \sqrt{[1 + (\frac{bN}{L})^2]}\right\} \,,$$
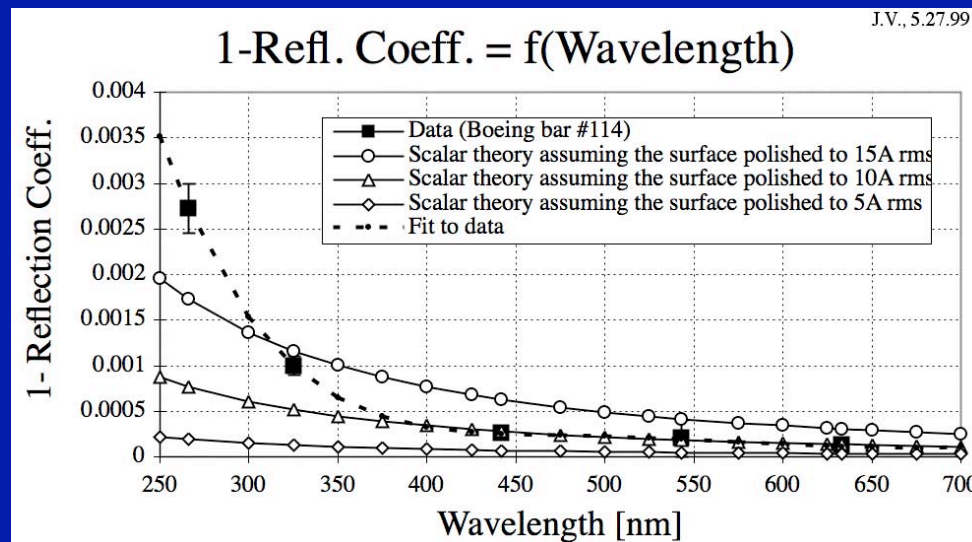
$$= (Reflection\_coeff.)^N * Transmission\_coeff.,$$

where N is the number of bounces, L is the length of the quartz bar, b is the width of the quartz bar, λ is the quartz attenuation length, and I_i the laser intensities.
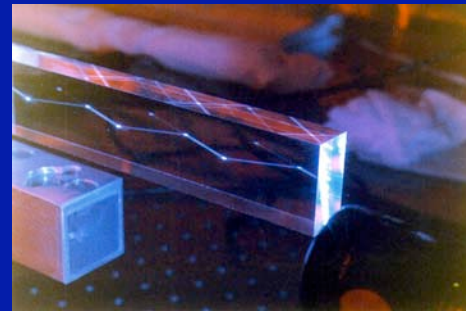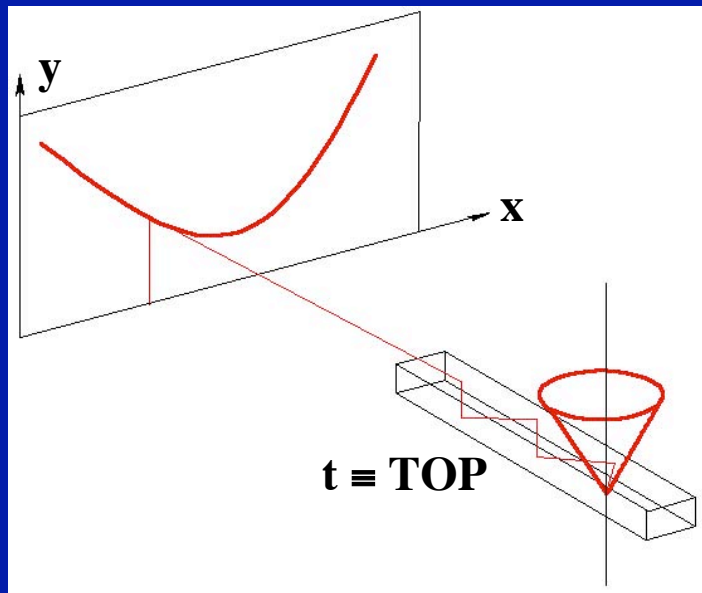

$r_{DIRC} < 0.9995$

$(350 < \lambda < 650nm)$

1-Refl. Coeff. = f(Wavelength)
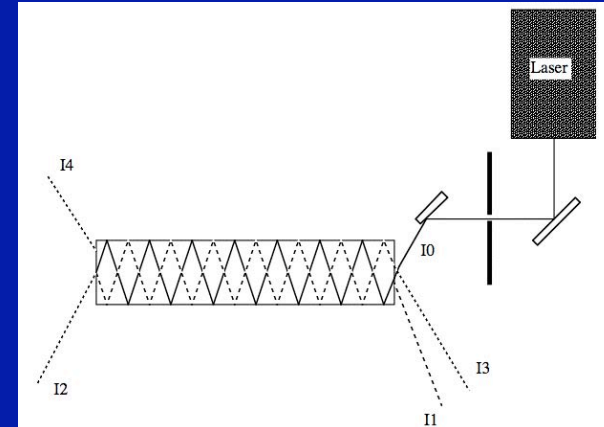
**Measurement done with five different laser wavelengths**

- **Above ~ 350 nm, the scattering theory agrees with the data; below 350nm there is a disagreement (Pollution ? Moisture ? Not sure).**

How orthogonal optical bar must be to preserve the image quality of many meters ?

How precise bar has to be to preserve the image ?

BaBar DIRC specs: I. Adam et al., "The DIRC PID for BaBar experiment", Nucl. Instr. & Meth. A538(2005)281-357

face

side

Measurements of face-to-side squareness:
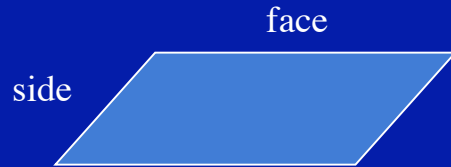
DIRC bar specifications:

| Parameter	Tolerance
Side parallelism	< 0.025 mm
Face parallelism	< 0.025 mm
Flatness	< 0.1 mm
Side-to-face squareness	< 0.25 mrad
End-to-face squareness	< 0.5 mrad
Bar polish quality	5-10 A rms

$$RMS = (\Sigma \, (angle)^2/8)^{1/2}$$
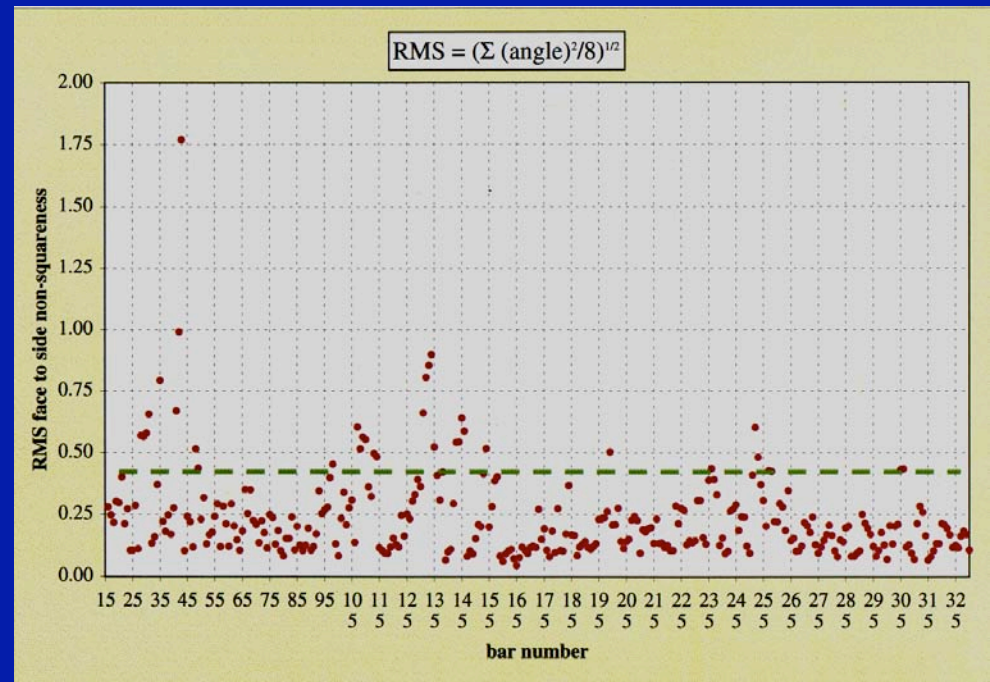
- **BaBar goal: $\Delta\theta_{Photon\ transport\ in\ bar} \sim 1$ mrad.**
- **In practice it was probably 2-3x worse**

Fresnel reflections on glue/quartz joints

# Reflection at glue/quartz and water/quartz interfaces

See much more detail on this issue in J. Va'vra, DIRC note 140, 2000

Fresnel reflection at n_1/n_2 boundary:
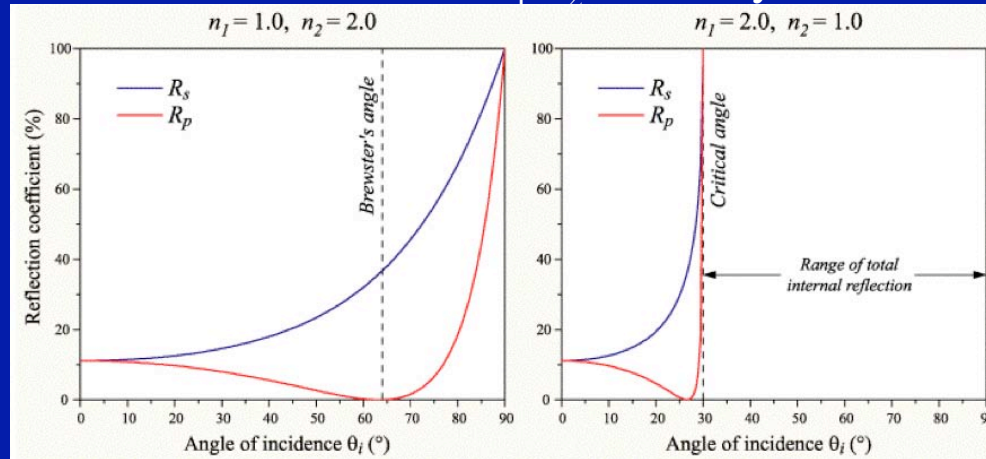
- **Fresnel reflection/refraction occurs every time light goes through an interface of two different refraction indicies.**
- **It is an effect depending on the incident a angle and light polarization.**
- **It is a small reflection, except at grazing angles $\theta_{inc} > 40^o$.**
- **This effect is important to consider in the DIRC/FDIRC design in a number of places.**

Refraction indicies involved in DIRC:
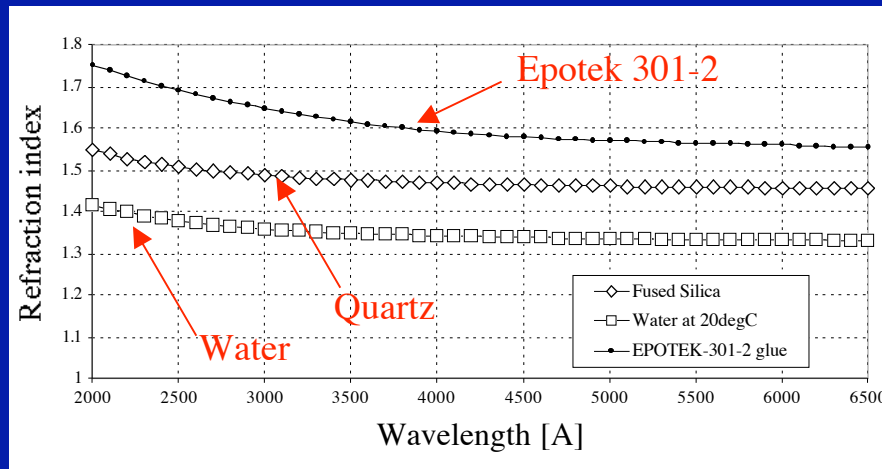
Fresnel reflection for glue/quartz boundary:
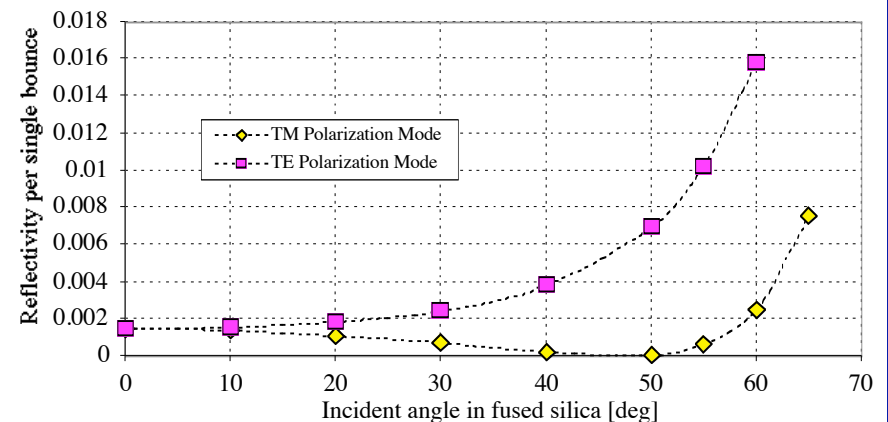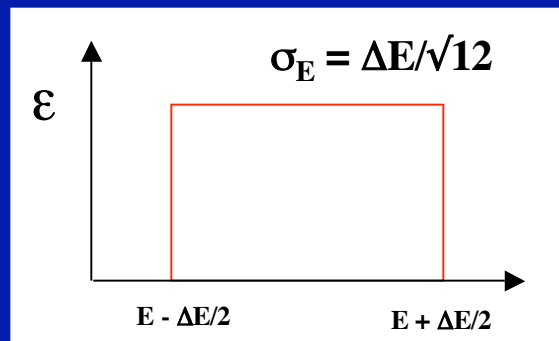
Chromatic part of the Cherenkov angle error

T. Ypsilantis and J. Seguinot, Theory of RICH detectors, Nucl. Instr. & Meth. A343(1994)30-51

The chromatic error "$\sigma_{\theta c}$ (chromatic)" in θ_c is caused by $n = n(\lambda)$ or $n(E)$ dependence.

Differentiating "cos $\theta_c = 1/\beta\, n(E)$" one gets $\partial\theta/\partial n = 1/(n \tan \theta_c)$, and then it follows:

$$\sigma_{\theta c} \text{ (chromatic)} = (\partial\theta/\partial n)\,(dn/dE)\,\sigma_E = [1/(n \tan \theta_c)] * dn/dE * \sigma_E$$

Typical overall efficiency:

$$\sigma_E = \Delta E/\sqrt{12}$$

ε

E - ΔE/2   E + ΔE/2

- **The chromatic error can only be reduced by reducing ΔE. However, this reduces number of photoelectrons Npe. A compromise has to be found.**
- **Cherenkov angle resolution of a typical detector is dominated by the chromatic error.**
- **However, we will show that <u>time</u> can be used for the color tagging, and in this way one can reduce the chromatic error effect - see <u>Focusing DIRC prototype</u> in lecture III.**