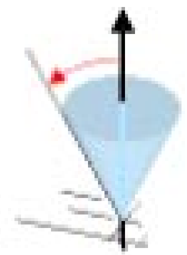

Imaging Rings in Ring Imaging CHerenkov Counters:

Outline:

- Fundamentals
- Radiators
- Imaging
- Time Imaging DIRCs
  - Conceptual issues
  - Limits to performance
  - R&D Examples
- Summary

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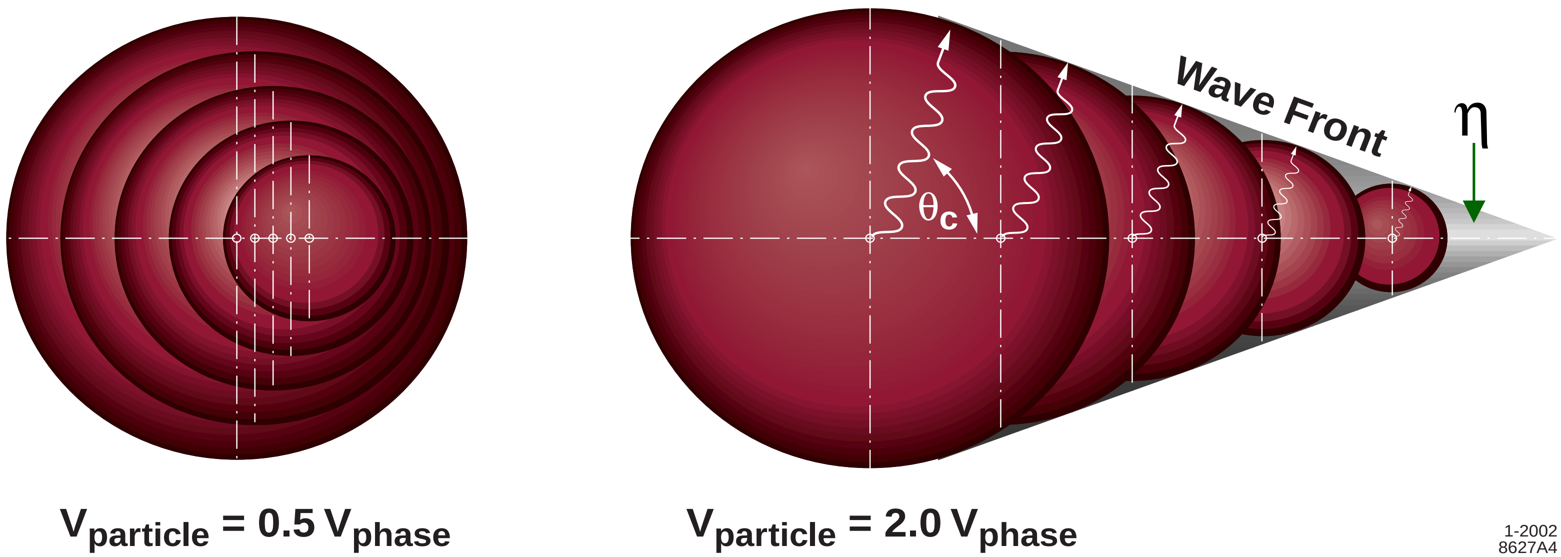
Stanford Linear Accelerator Center

A national laboratory funded by the Department of Energy

RICH2002, Pylos Greece, June 2002

Fundamentals- Basic Cherenkov Equations-I



Basic Cherenkov Equations-I

Cherenkov radiation of wavelength λ emitted at polar angle (θ_c), uniformly in azimuthal angle (φ_c), with respect to the particle path,

➔ **Fundamental intrinsic "chromaticity" dispersion limit.**

Fundamentals- Basic Cherenkov Equations-II

The number of photo-electrons N_{pe} is always "too small".

$$\mathbf{N_{pe}} = 370\,\mathbf{L}\int \boldsymbol{\varepsilon} \sin^2 \boldsymbol{\theta}_c \mathbf{dE} = L\, N_0 \langle \sin^2 \boldsymbol{\theta}_c \rangle$$

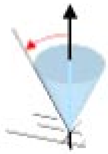
For z=1

Photons propagate a length (L_p) in a time (t_p) in a material with group index n_g,

$$t_p = \frac{L_p n_g}{c}$$

where $n_g(\lambda) = n(\lambda) - \lambda\, dn(\lambda)/d\lambda$.

n_g typically a few % larger than n [i.e., v_g (group velocity) < v(phase velocity)]. It is also substantially more dispersive.



Fundamentals- Basic Cherenkov Equations-III

➔**Conical Cherenkov radiation shell (the Mach cone) is not quite perpendicular to the photon propagation angle.**

The half-angle of the cone opening (η) is given by,

$$\cot\eta = \left[(n(\omega_0)\beta)^2 - 1\right]^{1/2} + \omega_0 n(\omega_0)\beta^2 (dn/d\omega)_0 \left[(n\beta)^2 - 1\right]^{-1/2},$$

Only perpendicular to the direction of photon propagation when the second term = 0 (the non-dispersive case).

Fundamentals- Some Amusing History

- **Tamm (1939) derived expression correctly.**
- **In his new optics book, Sommerfeld (1950) states that the Cherenkov polar angle in a dispersive media is given by the usual formula provided that the group velocity is used.**
- **Motz and Schiff (1952) discuss this disagreement with the usual result, and conclude that the usual formulation is correct, but that the Mach cone is not quite orthogonal to the photon's angle of propagation.**
- **(~>1953) Physicists promptly forget about the group velocity in Cherenkov light production!**

Čerenkov Radiation in a Dispersive Medium

H. Motz and L. I. Schiff

*Microwave Laboratory and Department of Physics, Stanford University, Stanford, California**

(Received October 10, 1952)

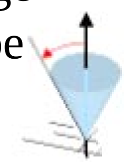
Attention is called to the disagreement between a recent statement of Sommerfeld that the direction of propagation of Čerenkov radiation in a dispersive medium is determined by the group velocity, and the generally accepted result that the phase velocity must be used. The latter is shown to be correct, and the role of the group velocity is discussed in a way similar to that given in Tamm's 1939 paper on the theory of the Čerenkov radiation.

In a recently published book on optics, Sommerfeld[1] states that the direction of propagation of Čerenkov radiation in a dispersive medium is given by the usual formula[2] if the velocity of light in the medium is taken to be the group, not the phase velocity. This is contrary to the generally accepted result, according to which the phase velocity must be used. The difference between these two results can be of considerable physical significance in an experiment like that recently performed by Mather.[3] That the use of the phase velocity is actually correct can readily be seen in the following way. For simplicity, we restrict our attention to an infinitesimal range of radiated frequencies; this might be achieved in practice by use of a narrow-band filter. Then the usual calculation shows that the Poynting vector for each monochro- narrow range of frequencies, the radiation at any instant is concentrated in a thin conical shell whose vertex is at the moving charge, and whose half-angle of opening θ is given by

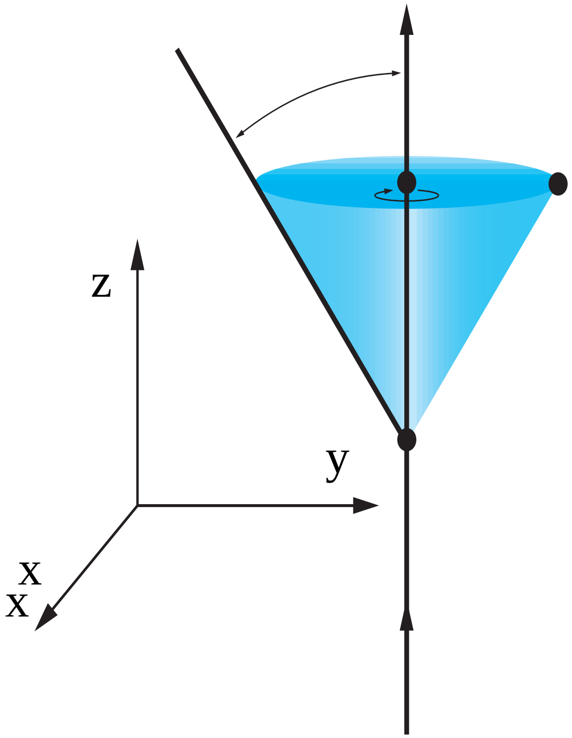
$$\cot\theta = [(n_0 v/c)^2 - 1]^{\frac{1}{2}} + \omega_0 n_0 (v/c)^2 (dn/d\omega)_0 [(n_0 v/c)^2 - 1]^{-\frac{1}{2}}, \quad (1)$$

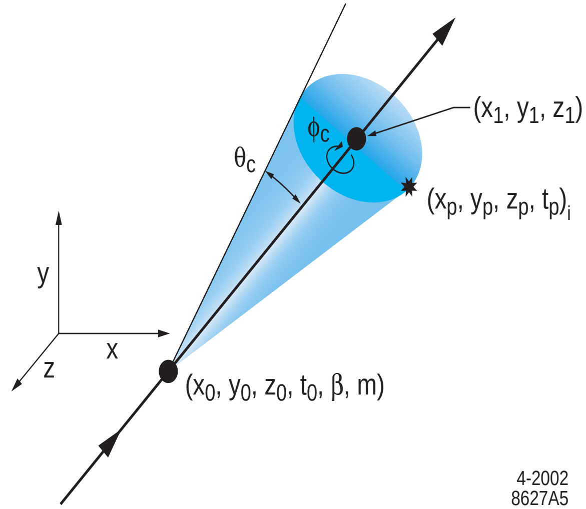
where v is the velocity of the charge, c the velocity of light in vacuum, $n(\omega)$ the refractive index of the medium at angular frequency ω, and the frequency range is centered at ω_0 with $n_0 = n(\omega_0)$. If the radiation were to propagate in directions perpendicular to the planes tangent to the surface of this cone, it would agree with the correct theory only for a nondispersive medium ($dn/d\omega = 0$). Actually, the radiation propagates in directions that make the angle θ_0 with the path of the charge, where

The role of slower group velocity in photon propagation time seems to have been rediscovered independently recently several times from the data, e.g., by DIRC, Super-K, SNO, Amanda (and perhaps others). However, the possible effects of the large dispersion in the group velocity appears to not be widely appreciated.



Fundamentals- Cherenkov Coordinate System





k) where the particle moves along the (**z**) axis, the direction cosines of Cherenkov photon emission (k_x, k_y, and k_z), are related to the Cherenkov angles by,

$$k_x = \cos\varphi_c \sin\theta_c,$$

$$k_y = \sin\varphi_c \sin\theta_c,$$

$$k_z = \cos\theta_c.$$

and, with emission point z_e and detection point z_d

$$t_p = \frac{L_p n_g}{c} = \frac{L n_g}{c\,k_z} = \frac{(z_d - z_e) n_g}{c\,k_z}$$

Fundamentals-Detector Coordinate System

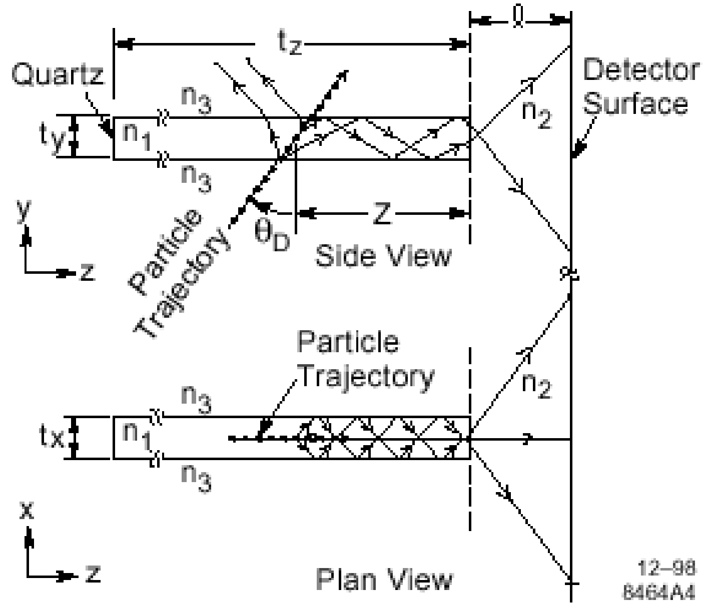
Photon coordinates measured in detector must be transformed back into Cherenkov coordinates.

E.G., for the DIRC:

Consider the right-handed coordinate system attached to the bar frame.

Let track polar and azimuthal angles (θ_t, φ_t).

Align the k frame x-axis such that the direction cosines of the photon emission in the bar frame are:



$$k_x = -k_x \cos\theta_t \cos\varphi_t + k_y \sin\varphi_t + k_z \sin\theta_t \cos\varphi_t,$$
$$k_y = -k_x \cos\theta_t \sin\varphi_t - k_y \cos\varphi_t + k_z \sin\theta_t \sin\varphi_t,$$
$$k_z = k_x \sin\theta_t + k_z \cos\theta_t.$$

Fundamentals-Comments

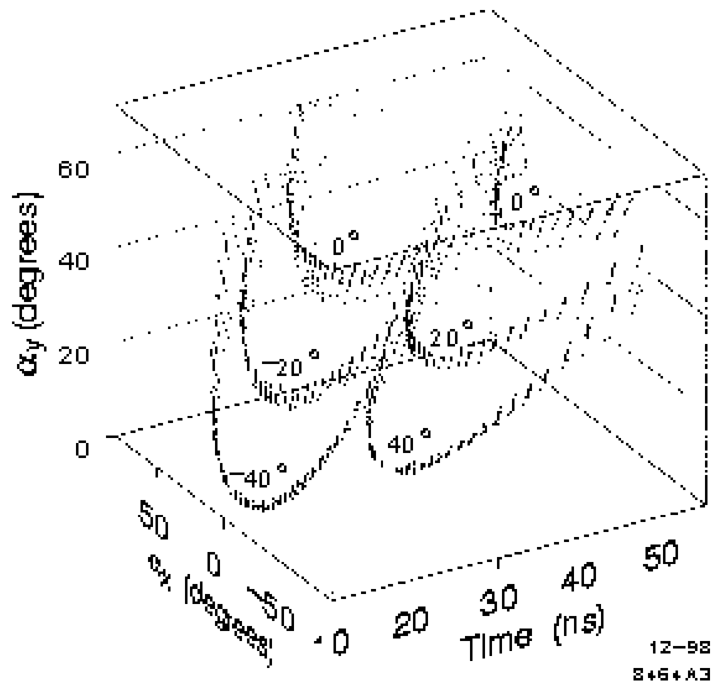
- Thus, up to 3 measurements (α_x, α_y, t_p) are available to measure the 2 Cherenkov angles (θ_c, φ_c) with respect to a known track => nominal over-constraint at the single p.e. level.
- Powerful Ring correlation => can reduce required "dimensonality" of measurement.
- Caveats:

  a) Transforming between Cherenkov and measurement frame often requires/uses externally derived tracking parameters. Transformation factors (typically circular functions) involved can be large and angle dependent.

  b) Solution ambiguities/backgrounds.

  c) Measurement correlations.

E.g. 3-D images in a BaBar DIRC



Fundamentals-Performance Limits

$$\delta_\beta = \frac{\sigma_\beta}{\beta} = \tan\theta_c * \sigma_{\theta_c}$$

where $$\sigma_{\theta_c}(\text{tot}) = \frac{\langle \sigma_{\theta_i} \rangle}{\sqrt{N_{pe}}} \oplus C$$

with $\langle \sigma_{\theta_i} \rangle$ ➔ Average single PE resolution

C ➔ "Correlated" Terms…..
(e.g.,tracking,alignment,scattering)

- **Want to (1) maximize N_{pe},and (2) minimize C and** $\langle \sigma_{\theta_i} \rangle$
- **But…(at fundamental level)**

  (N_{pe} and $\langle \sigma_{\theta_i}$ (Chromaticity)$\rangle$) $\propto \Delta\lambda$ (the detector bandwidth)
- **Meanwhile… many practical limits on detectors, radiators and C**

➔ **For any combination of radiator and detection bandwidth there is**

(1) An intrinsic (chromaticity) performance limit.

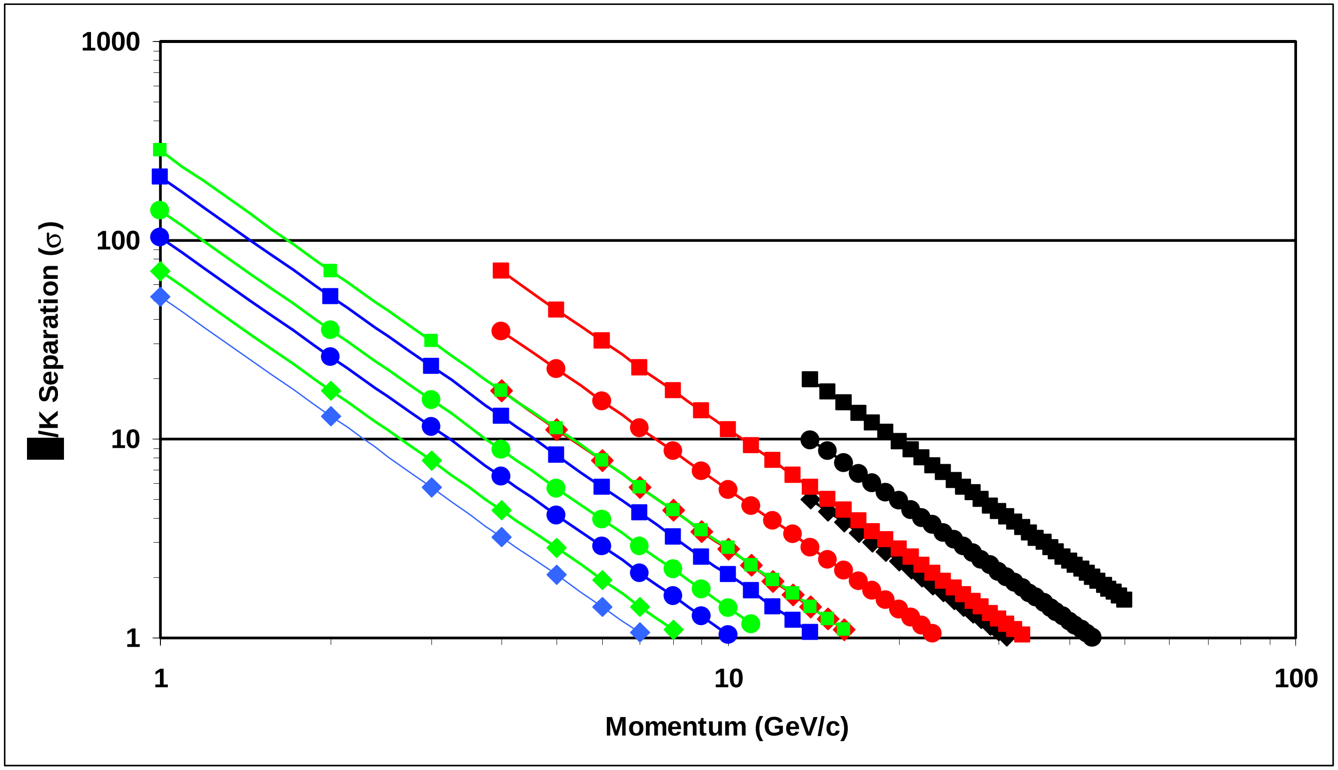
(2) A practical performance limit from single photon angular measurement accuracy and C.

Fundamentals-Separation

$$N_\sigma \approx \frac{\left(m_1^2 - m_2^2\right)}{\left(2p^2\sqrt{n^2-1}\,\sigma[\theta_c(tot)]\right)}.$$

For momenta well above threshold

π/K separation



Refractive Indices

N=1.474 (Fused Silica)

N=1.27 (C_6F_{14} CRID)

N=1.02 (Typical Silica Aerogel)

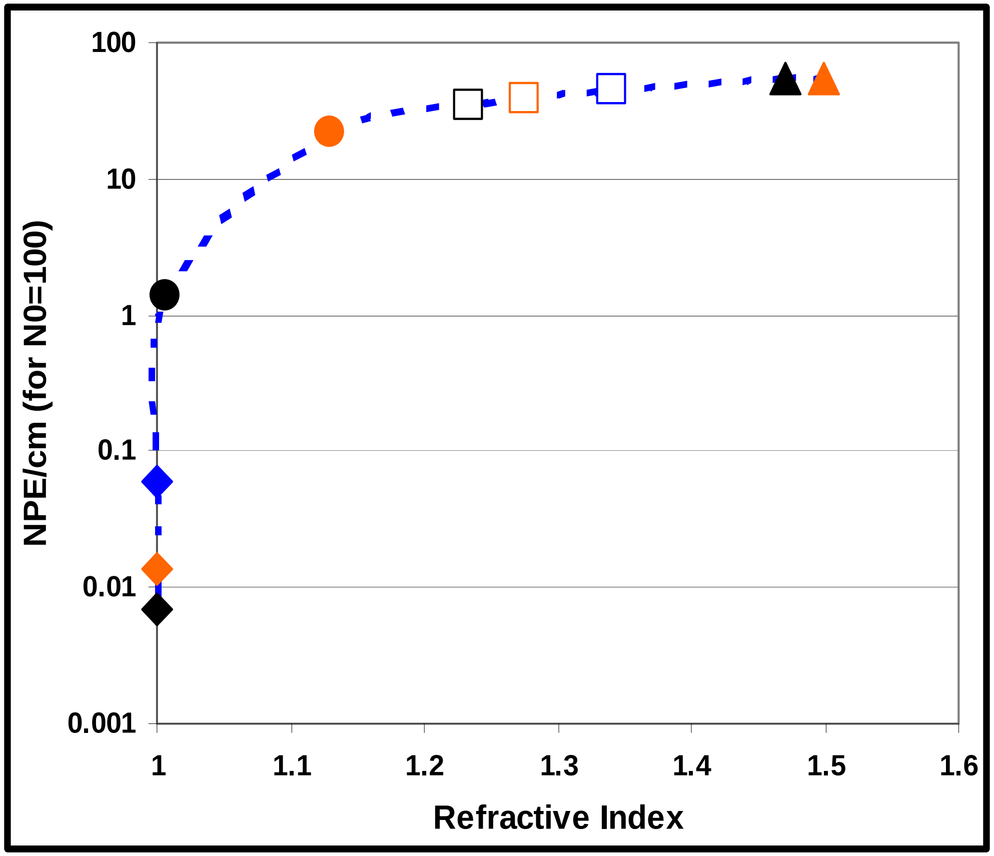
N=1.001665 (C_5F_{12}/N_2 CRID Mix)

$\sigma[\theta_c(tot)]$

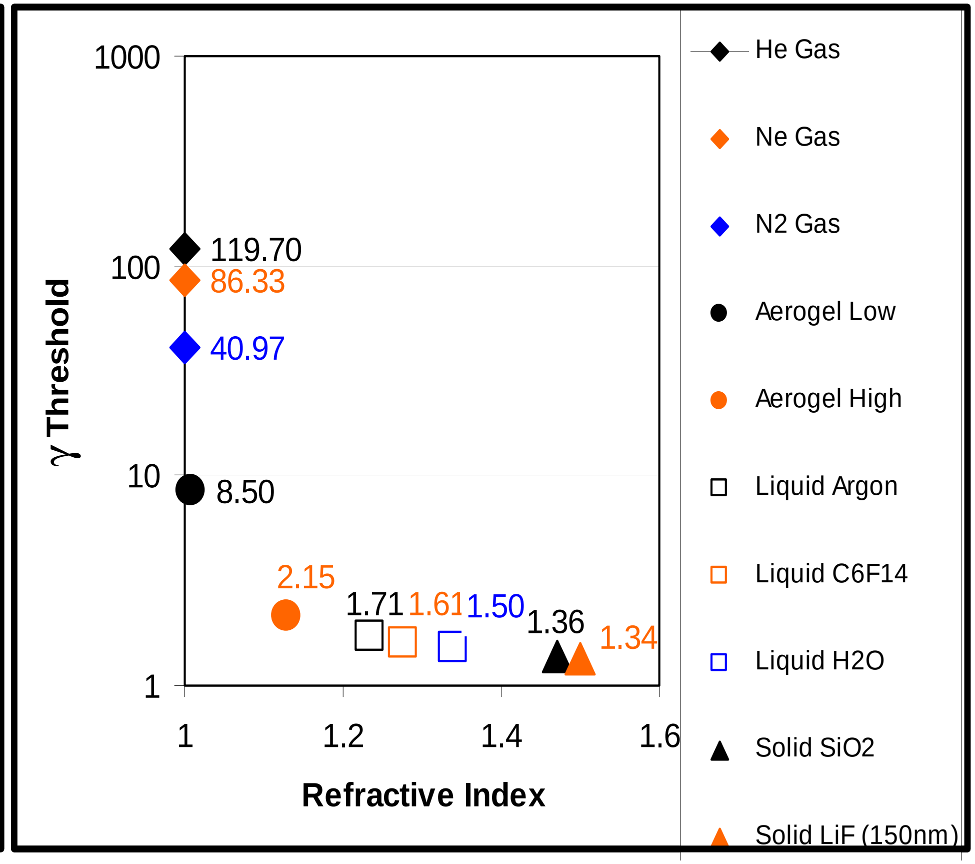
- ◆ 2 mrad
- ● 1 mrad
- ■ 0.5 mrad

Radiators-Momentum Coverage

N_{PE} /cm versus Refractive Index for Various Radiators



$\gamma_{threshold}$ versus Refractive Index for Various Radiators



- •Coverage Hole between Gas & Liquid/Solids partially covered by Aerogel. Transparency crucial.
- Cryo Liquids could cover some of this region…. practical?
- Practical upper limit on γ_{max} ~ 10x $\gamma_{threshold}$.(From dispersion & angle measurement).

Radiators-Dispersion

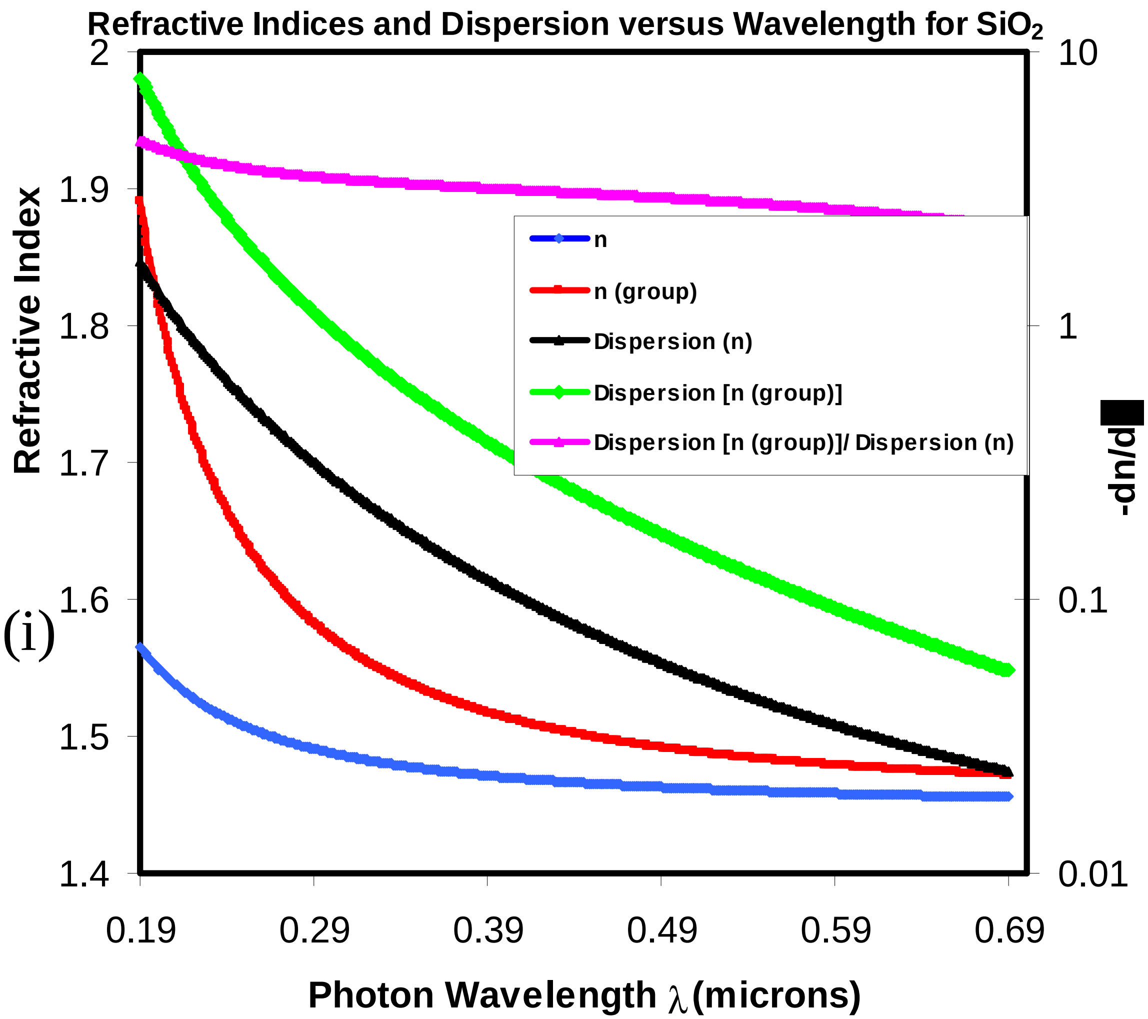
•Chromaticity at Cherenkov Photon Production:

$$\sigma_{\theta_c}(i) = \frac{\delta n}{\tan\theta_c} \quad \text{For } \beta=1$$

•Time Dispersion during photon transport.

$$\delta^2 t_p(i) = \delta^2 L_p(i) + \frac{2C(L_p, n_g)}{L_p(i) n_g(i)} + \delta^2 n_g(i)$$

Example



Typical Weighted Values

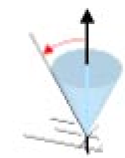
(DIRC EMI 9125 PMT & Fused Silica)

$$\sigma_{\theta_c} = \frac{\delta n}{\tan\theta_c} = \frac{0.0053}{1.08} = 4.9\,\text{mrad}$$

$$\delta t_p \approx \delta n_g * F = 0.016 * F$$

For tracks near 90°

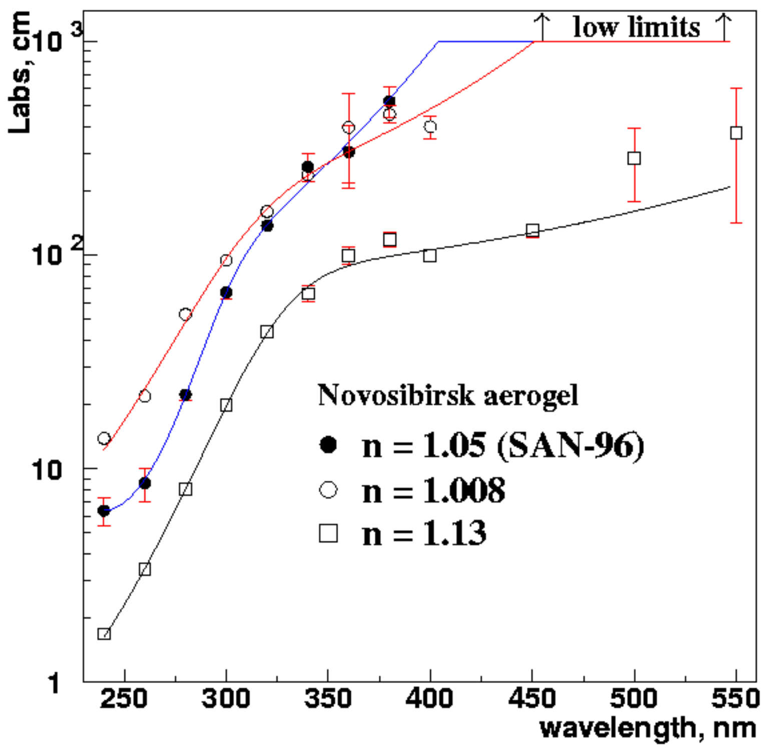
Where **2/3<F< 4/3**, depending on photon dip angle and its measurement accuracy.



Radiators- Aerogel Transparency

Continues to improve. (E.G., Recent Results from Novosibirsk Group)

Absorption Length



Scattering Length (L_{sc}) at 400 nm.

$$T = Ae^{-\left(\frac{d}{L_{sc}\left(\lambda/400\right)^4}\right)}$$

- **T= Transmittance**
- **A=Surface Scattering Coef**
- **d=sample thickness**
- **The n=1.13 sample is prepared from sintered n=1.05 material.**

n	L_{sc}(cm)
1.008	4.2
1.03	5.4
1.05	5.5
1.08	4.4
1.13	1.9

- Many more results in this session!

Radiators-Practical Matters-Availability

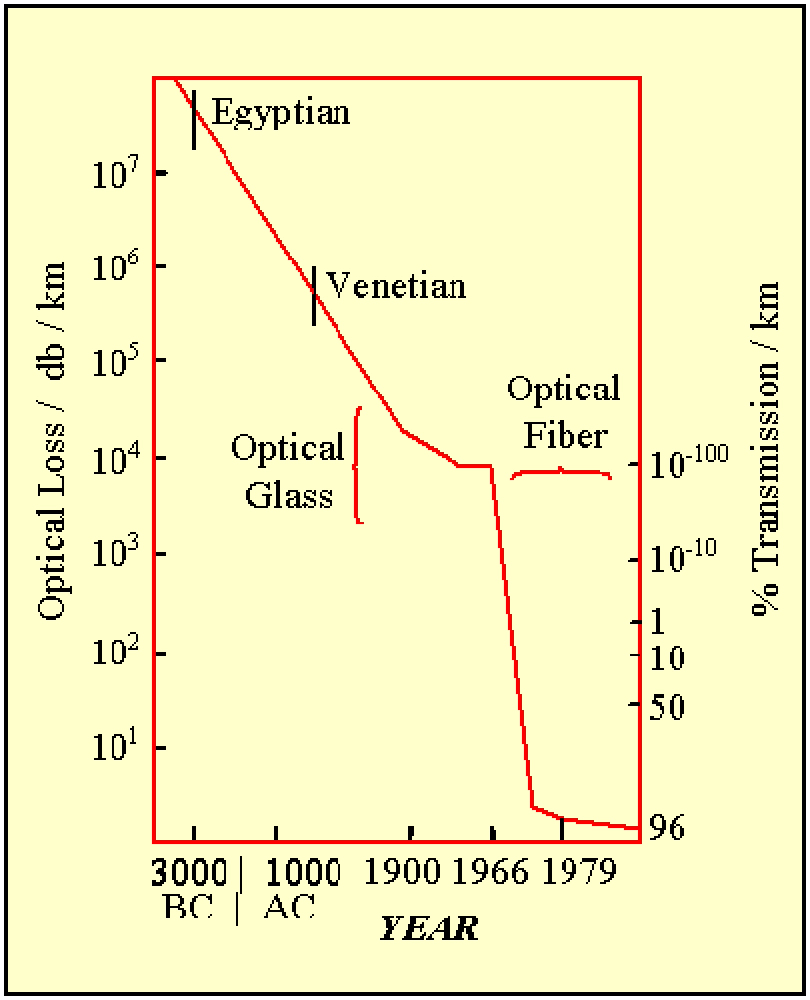
- Many radiators have become available and/or practical in last ~30 years due to need for high purity materials in classic high tech industries. E.G.;

1. Communications
   ➔fiber optics➔fused silica
2. H_2O-free fire suppression & non-chlorinated refrigerants
   ➔ fluoro-inert gases and liquids.
3. High purity materials (and filtration) systems for industry (e.g. chip production)
   ➔availability of inexpensive(?) transparent materials and the technology for cleaning H_2O (and other liquids/gasses in situ).

- However, development in the HEP PID community also fundamental. E.G.,

1. Transparent Aerogels.
2. Cleaning fluoro-carbons at SLD/DELPHI.

History of glass transparency



Radiators-Practical Matters

•Cost => Compare H_2O (~$0/l) with fused quartz (~$200/l) with synthetic fused SiO_2 ($300/kg or ~$650/l) with C_6F_{14}(~$80/l).

•Size => Gases or Liquids: ~ unlimited…except by mechanical considerations radiation length, transparency.etc.

Solids: Practical limit both for raw material and production of finished parts…SiO_2 ~1-1.5m, Crystals(e.g.,CaF_2 LiF) ~ 30 cm.

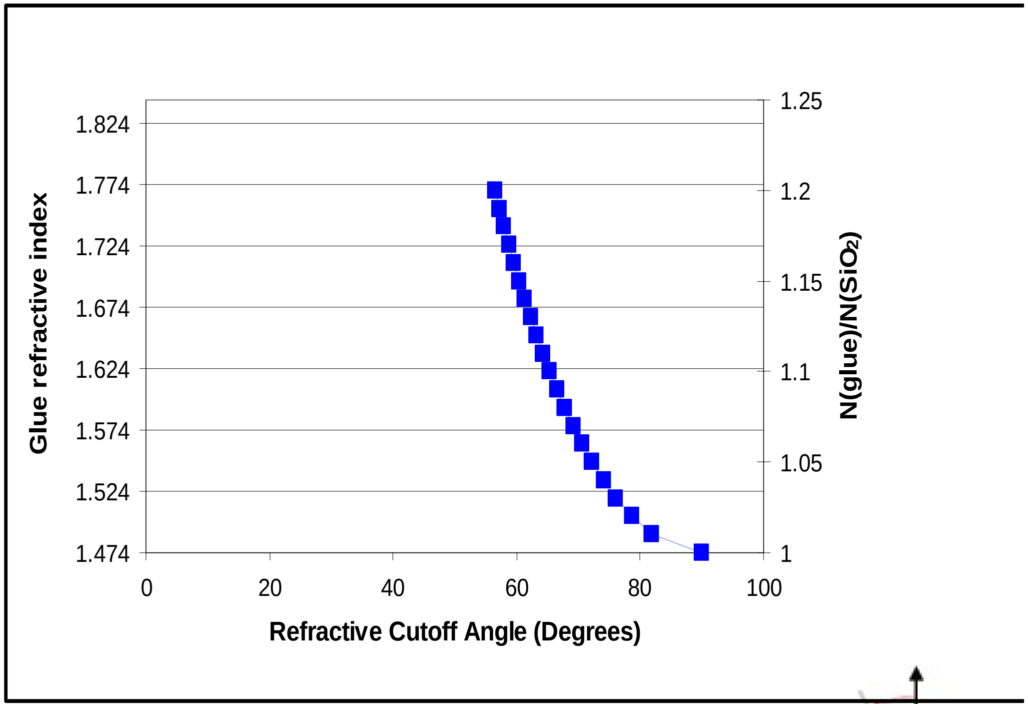
•Glues => Few options much below 300 nm.

•Generally radiation hard.

• Hard to match radiator indices and dispersion.

➔Large transmission loss at steep angles in DIRC radiators.

Transmission Cutoff Angle versus Glue Index in Fused Silica radiator



Radiators-Practical Matters

- Radiation Hardness => Mostly an issue for solid materials and long transmission lengths.
    - Rather pure natural fused quartz not usable in BaBar DIRC due to significant blue and UV transmission loss with exposure of ~5-10 kRad.
    - Glasses and plastics often have significant losses at much smaller dose.
- Radiation Length => For most detectors, a rather weak limit to PID performance, but a concern for any precision calorimetry after the RICH.
    - X_o for Hydrogen containing materials are longer (e.g., compare hydrocarbons versus fluorocarbon gas/liquids, or SiO_2 versus plastic). However, dispersion (and high momentum PID performance) and safety concerns push the other way.
- Material Uniformity => Bulk non-uniformity can limit performance in large gas counters.
    - Periodic structures in index….e.g., as seen by the DIRC group in some kinds of fused silica leads to large diffractive scattering over long distance photon propagation.
- Optical Finish => Solid materials differ greatly in attainable polish, edge quality,etc.
    - Tends to be an inverse relationship between production ease and quality attainable.
    - Can smear measurements significantly in DIRC.

Imaging-Comments

A Brief Pedagogical review of imaging methods follows….

- **Though DIRC is a type of RICH, will consider both for clarity.**
- **"Schematic" drawings/resolutions:**

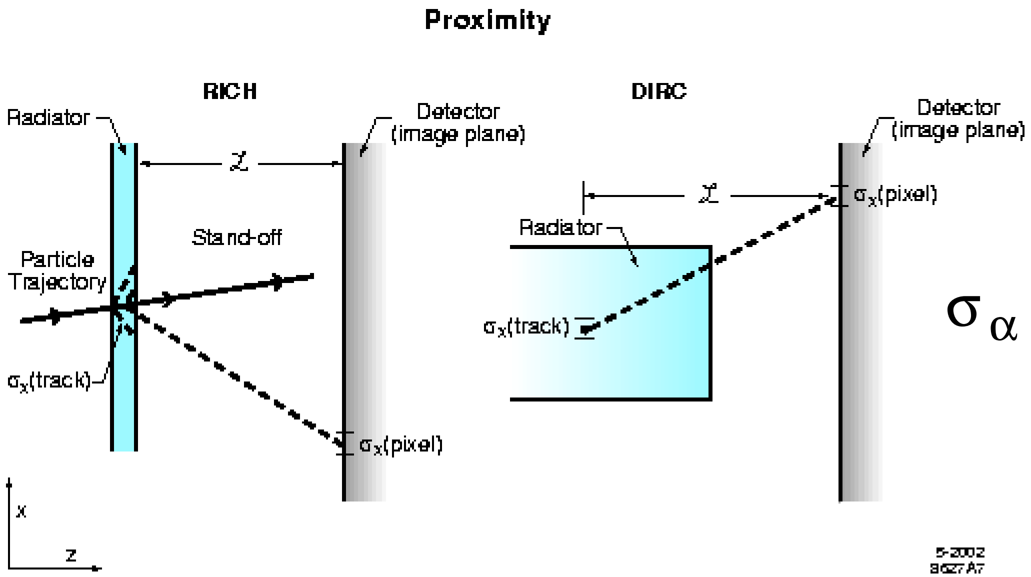
  -In most cases, the drawings assume constant index of refraction for photon propagation. Differing indices in the radiator and imaging (stand-off) regions magnify the image.

  -Angular resolution performance estimates must be transformed back into Cherenkov space to determine the Cherenkov angles. Projection factors involved ~ 1 in some (but not all) cases. "Pixelated" detector and track resolutions

  I.e., $\sigma_x(\text{detector}) = \dfrac{\Delta x(\text{pixel})}{\sqrt{12}}$

- **Imaging methods in each readout dimension can be mixed/matched in a given detector.**
- **Time-dimension imaging practical only when photon propagation lengths are long.**

Imaging-Proximity



$$\sigma_\alpha \approx \sqrt{\frac{\sigma_x^2(\text{track}) + \sigma_x^2(\text{detector})}{L^2}}$$

Nominal propagation-angle resolution performance

RICH

SLD/DELPHI:

For σ_x(track) ~ 2 mm, σ_x(detector) ~ 1mm, L~200 mm

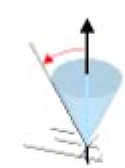
➔ σ_α~ 11 mrad per photon .

DIRC

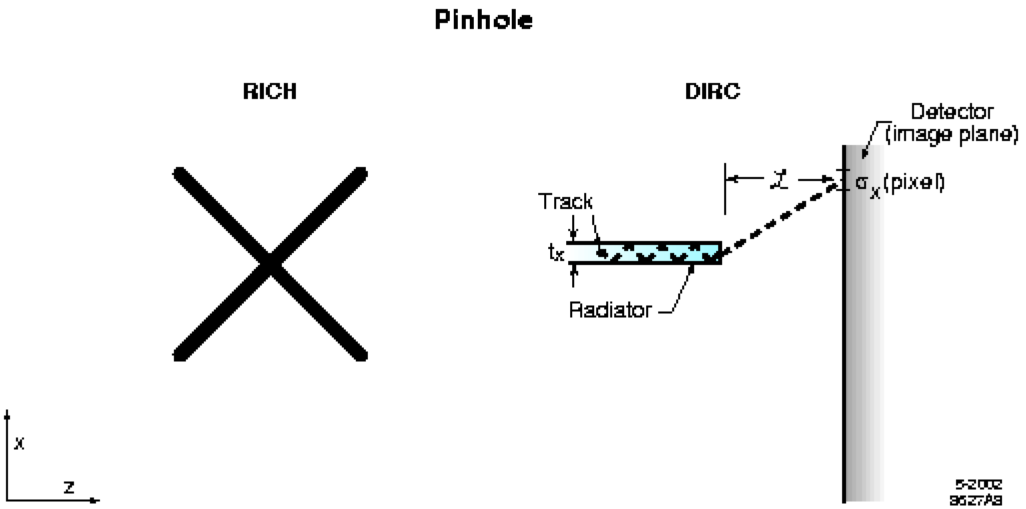
No large device exists: Will discuss an example for a Super-BaBar style device later: Typical Parameters:σ_x(track) ~ 4 mm, σ_x(detector) ~ 6 mm, L=4000 mm

➔ $\sigma(\alpha_x)$~ 2 mrad per photon

But…watch out for ambiguities!



Imaging-Pinhole



$$\sigma_\alpha \approx \sqrt{\frac{\frac{t_x^2}{12} + \sigma_x^2(\text{detector})}{L^2}}$$

Nominal propagation-angle resolution performance

RICH

No equivalent.

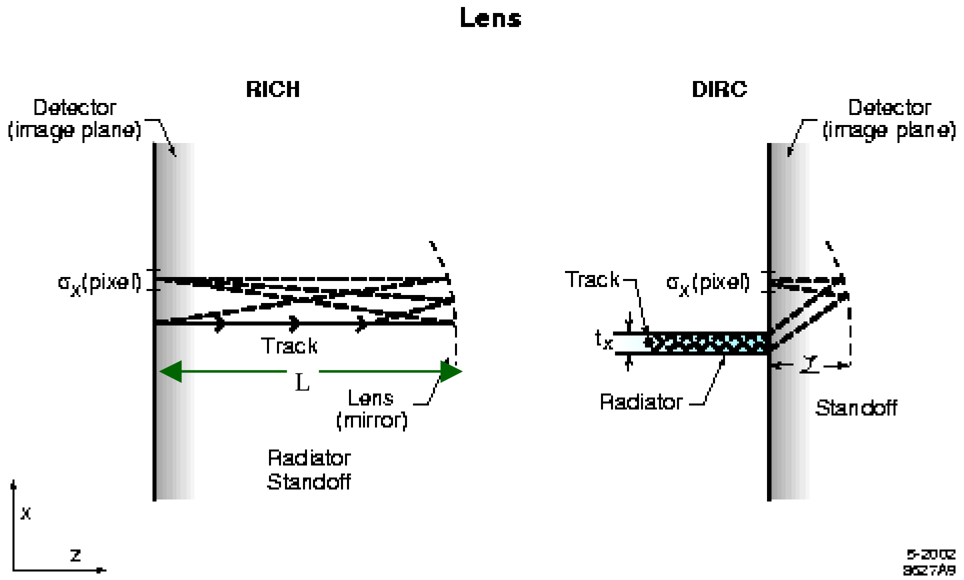
DIRC

For a BaBar like device t_x:t_y (bar) ~ 35:17.5 mm, σ_x:σ_x (detector) ~ 7.5 mm, L=1200 mm:

➔ $\sigma(\alpha_x)$:$\sigma(\alpha_y)$ ~ 10.5:7.5 mrad per photon [with radiator material in stand-off region]

➔ $\sigma(\alpha_x)$:$\sigma(\alpha_y)$ ~ 9.6/6.8 mrad. [with an H_2O standoff …. ~10% magnification].

Imaging-Lens



$$\sigma_\alpha \approx \sqrt{\frac{\sigma_x^2(\text{detector})}{L^2}}$$

Nominal propagation-angle resolution performance

RICH

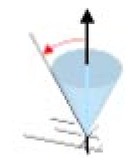
For σ_x(detector) ~ 1 mm, L=400 mm

➔ $\sigma(\alpha_x)$ ~ 2.5 mrad per photon

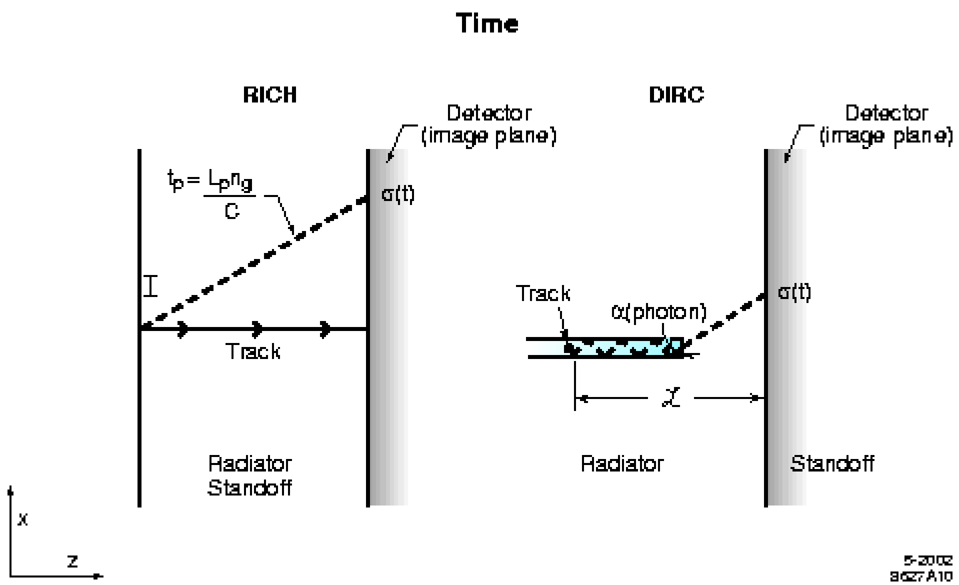
DIRC

Example: For σ_x(pixel) ~ 2 mm, σ_x(detector) ~ 0.6 mm, L=250 mm.

➔ $\sigma(\alpha_x)$ ~ 2.4 mrad per photon.



Imaging-Time



Non-dispersive limit $\sigma_\alpha \approx \frac{c \cos\alpha\, \sigma_t}{N_g L \tan\alpha}$

Non-correlated dispersive limit $\sigma_\alpha \approx \frac{\delta n_g}{\tan\alpha}$

Nominal propagation-angle resolution performance

RICH

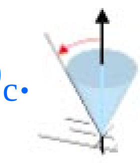
SLD/DELPHI:
Insufficient time resolution to measure an angle.

DIRC

Very angle dependent: For example, in present BaBar DIRC:
Let α_z=45°, L=4 m, σ_t=1.5 ns:
➔ $\sigma(\alpha_z) \sim$ 50 mrad per photon

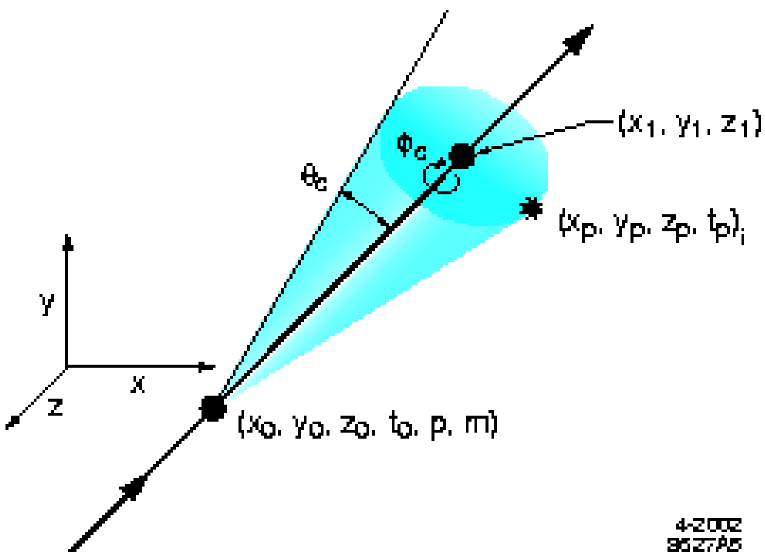
In dispersion limited non-correlated case:
➔ $\sigma(\alpha_z) \sim$ 15 mrad per photon with bi-alkali tube response.

➔ Correlations when using to measure θ_c.



Imaging-Ring Correlated

Ring Correlated



Nominal resolution performance

Different goals than hadron PID RICHes: But as a rough comparison, let L~20 m, 50 cm tubes, σ_t ~2.5 ns

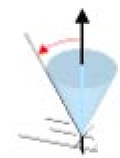
σ_α ~ 6 mrad (space), and ~30 mrad (time)

➔σ (L_p) ~ 0.5 m

•Full track (and event) reconstruction in very large (H_2O) detectors using ring constraints in fit optimization procedure to correlate the "N" Cherenkov photons produced at a constant Cherenkov polar angle from each track and tying them together in an event.

• Determine track and event quantities: Vertex Position; Number of Tracks; Track Momenta; Number of Cherenkov Photons; Particle Type (as e or μ using ring width), and Number of Decay Electrons.

•Fit optimization using ring correlation often done in other RICH/DIRC devices to improve initial track parameters and reduce correlated contribution to Cherenkov angle determination.



Imaging-Some Detector Examples

Proximity

- CLEO-III RICH (2-D)
- DELPHI RICH/SLD CRID Liquid (2-D)

Pinhole

- BaBar DIRC (2-D) (+ time) (3-D overall)

Lens

- DELPHI RICH/SLD CRID Gas (2-D)
- OMEGA RICH Gas(2-D)
- HERMES RICH Gas + Aerogel (2-D)
- HERA-B RICH Gas) (2-D)
- + Many more
- +R&D Devices (e.g., Focusing DIRC for BELLE end-cap combined lens and proximity.)

Time

•BaBar DIRC [Modest time resolution) + 2-d pinhole] (3-D overall)

•Various R&D DIRC Devices

CCT [1-D only]

TOP [Good timing + 1 space dimension-either lens or proximity]

Super-BaBar [Good timing +2 space dimensions-(proximity+lens)] (3-D overall)

Correlated

•Large H_2O Cherenkovs [e.g., Super-Kamiokande, SNO, AMANDA]

Time Imaging In DIRCs-Conceptual Issues

Angle measurement using time. (In non-dispersive Limit)

The fractional propagation time error (δt) is related to the error on propagation angle α_z by

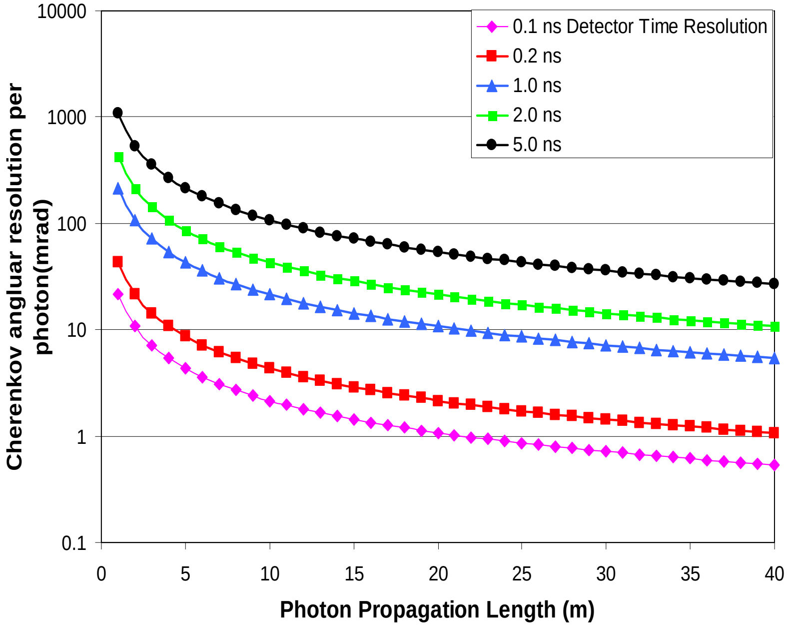
$\delta t = \delta\, k_z = \tan \alpha_z \,\sigma(\alpha_z)$.

➔ $\sigma(\alpha_z)$ blows up as α_z goes to zero.

Examples: For β=1 particle, α_x small and/or very well measured.

1. For particle perpendicular to bar $(\theta_t,\phi_t)=90^o$;
   $\sigma_{\theta c.}$= **tan** $\theta_c\, \delta\, k_z$ =1.08 $\delta\, k_z$

2. For particle at $(\theta_t,\phi_t)=(60^o,90^o)$
   $\sigma_{\theta c.}$= **3.64** $\delta\, k_z$



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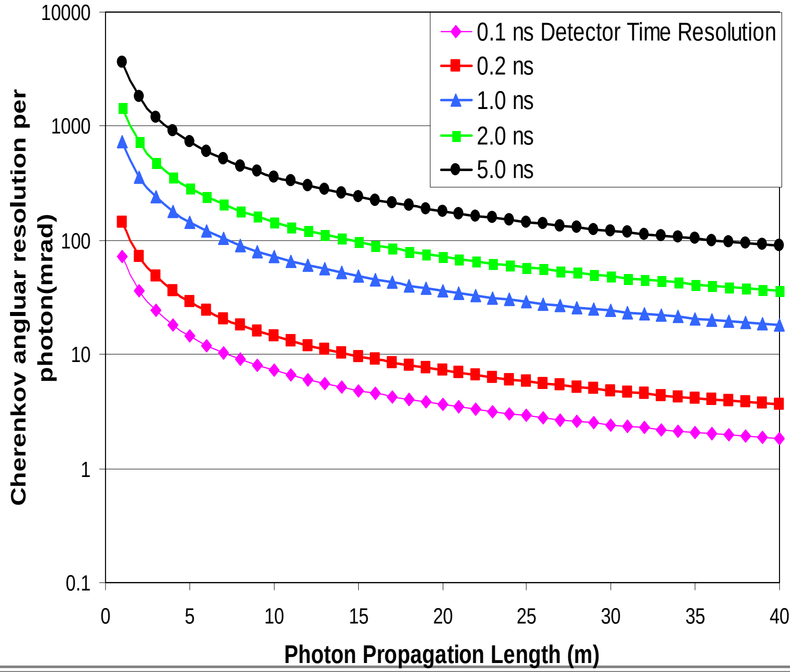


2

Time Imaging In DIRCs-Conceptual Issues

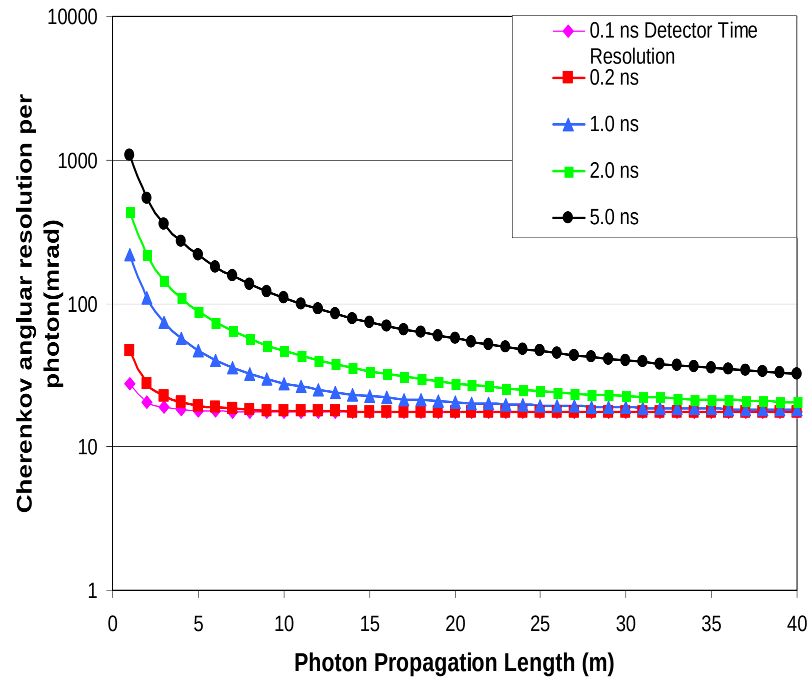
Angle Dependence.
(In Dispersive Limit)

Examples: **For β=1 particle, and α_x very well measured. EMI 9125 Bi-alkali Photodetector response detection curve**

1. $(\theta_t, \phi_t) = (90^o, 90^o)$ **uncorrelated limit**
   $\sigma_{\theta_{c.}}$ **= tan** $\theta_c(\mathrm{sqrt}[\delta^2(n_g) + \delta^2(t_p)])$

2. $(\theta_t, \phi_t) = (90^o, 90^o)$ **correlated limit with**

   $\sigma_{\theta_{c.}}$ **= tan** $\theta_c(\mathrm{sqrt}[\delta^2(n_g) + 2C(n_g, t_p)\, \delta(n_g)\, \delta(t_p)] + \delta^2(t_p)])$



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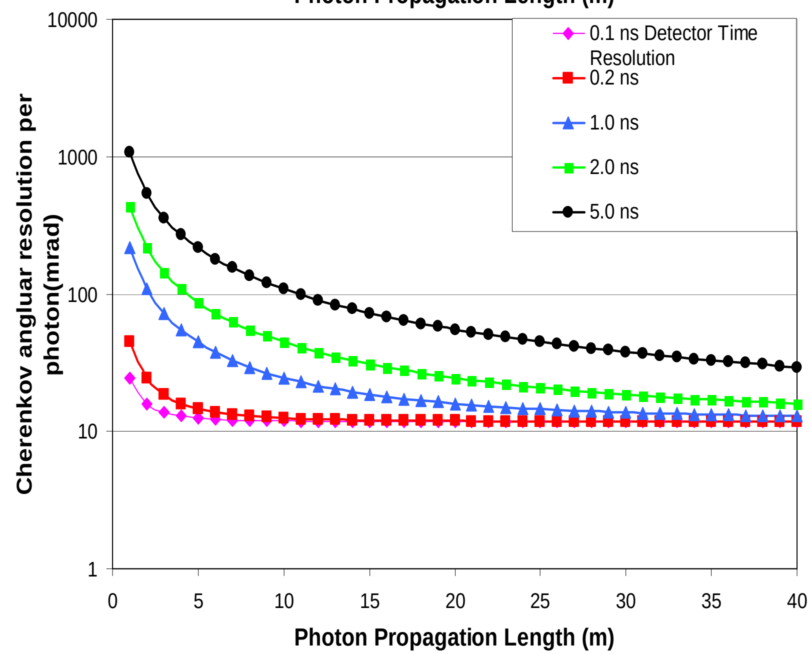

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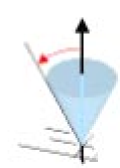
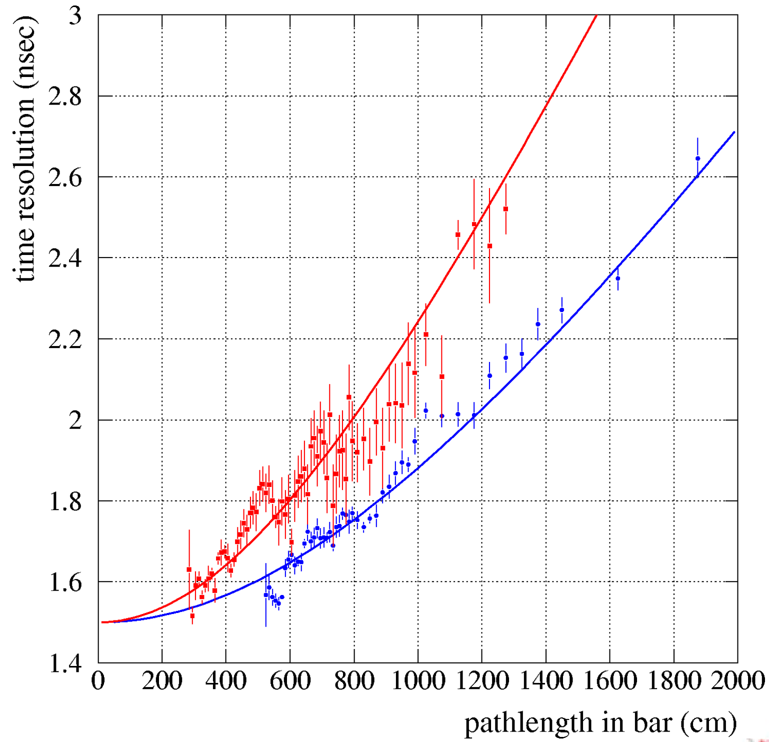


Time Imaging In DIRCs-Conceptual Isssues

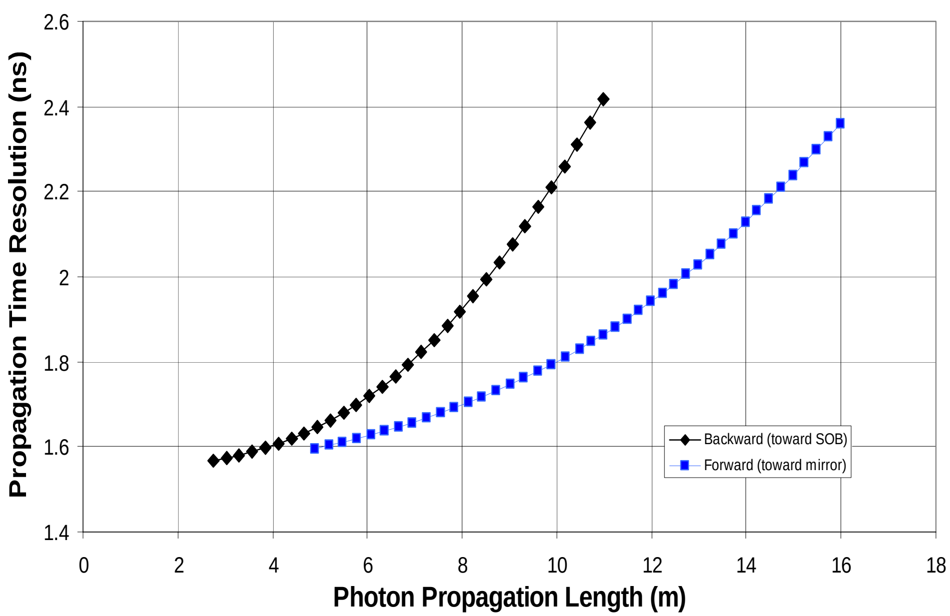
Example:Time Resolution in BaBar DIRC

$$\sigma_t = \sqrt{t_p^2[\delta^2(L_p) + \frac{2C(L_p, n_g)}{L_p n_g} + \delta^2(n_g)] + \sigma_{t_0}^2}$$

Babar Di-muon Sample



Toy Model for DIRC



Imaging In DIRC-Limits to Performance

Single Photon Resolution

$$\sigma[\theta_c]_i = \sqrt{\sigma[\theta_{Production}]^2 + \sigma[\theta_{Transport}]^2 + (\sigma[\theta_{Imaging}]^2 \sigma[\theta_{Detection}]^2)}$$

1. $(\sigma[\theta_{Imaging}]^2 + \sigma[\theta_{Detection}]^2)$ discussed together above. In principle, can make this combination arbitrarily good, but cost enforces limits.
   ➔ Balance with other resolution components.

2. $\sigma[\theta_{Transport}]^2$ due to bar production tolerances. Dominated in BaBar by side-to-face orthogonality that gives ~1-4 mrad per photon.

   ➔To improve

   -Different (more precise) production methods for radiators (more costly?)

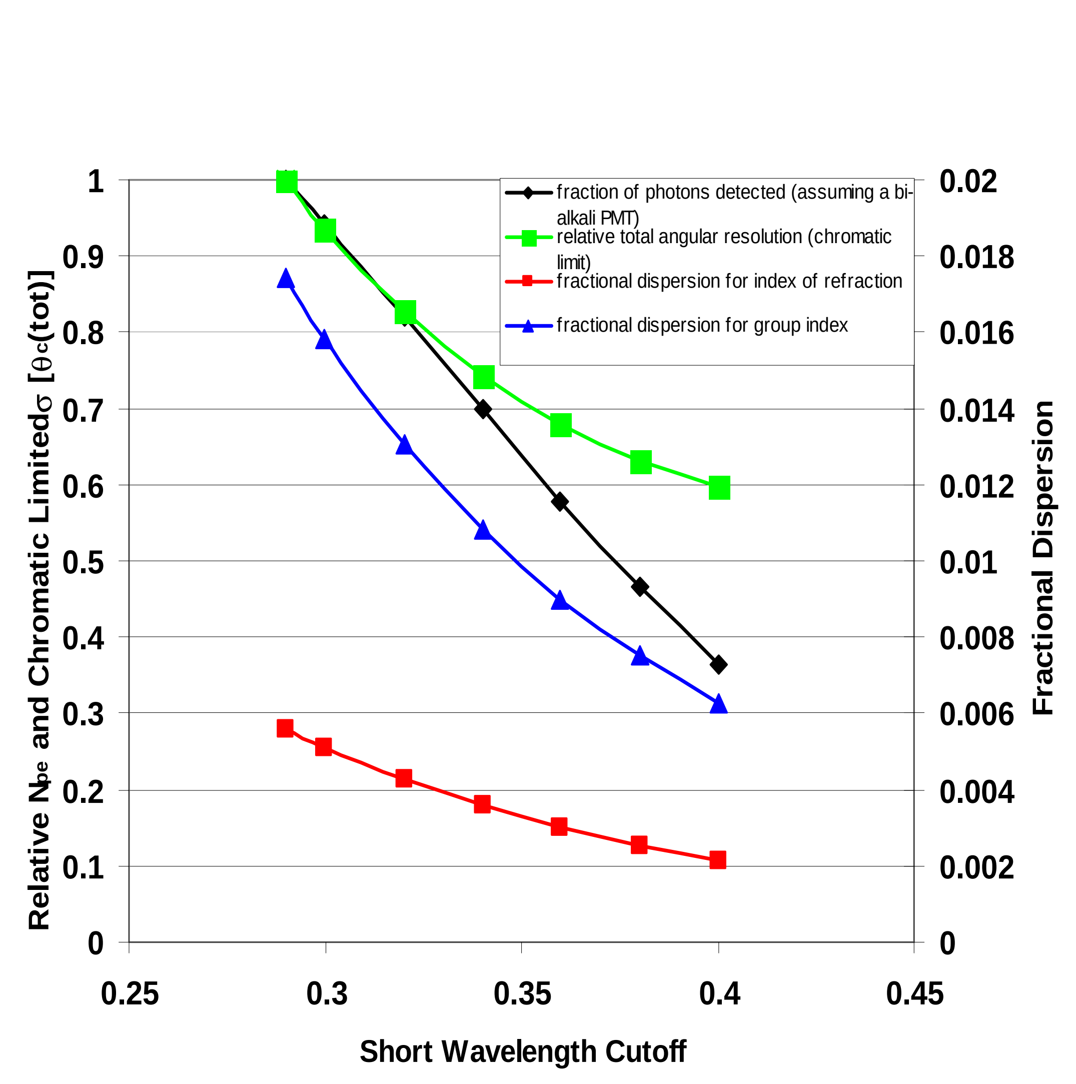
   -1-D (plate) transport design.

3. $\sigma[\theta_{Production}]^2 = \sigma[\theta_{Chromaticity}]^2$ (see below).

Imaging In DIRCs-Limits to performance

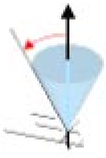
Chromatic Dispersion versus Detector Response and Bandwidth

Relative γ detection efficiency and $\delta(n_g)$
Cherenkov weighted EMI 9125
Spectrum cut at 0.29 microns
(similar to BaBar DIRC which is cut by glue near 0.3 microns)



➔ In dispersion limit, performance actually improves as bandwidth (and N_{pe}) are reduced! Of course this ignores "pattern recognition".

➔ Big potential advantage for a detector response curve (~solid state devices) which is >> 50% in the visible (400-600 nm) with limited banwidth.



Imaging In DIRCs-Conceptual Issues-Resolution

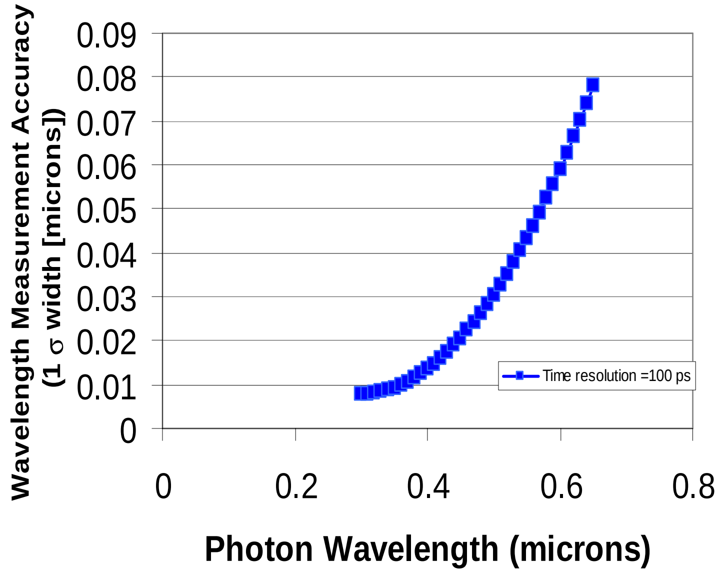
Measuring the Chromatic Smearing?

•Detectors have been proposed that could measure photon wavelength to about 0.15 ev (e.g., the TES (Transition Edge Sensor), but these detectors work at ~40 mk , and are rather slow….

➔impractical?

•Use the large dispersion in n_g in a 3-D DIRC to measure the photon wavelength….(I.e., compare the individual photon flight time with its measured angle.

➔ can improve chromatic limit by ~5x with 100 ps detector resolution at 6m. Scales with resolution.



Time Imaging In DIRCs-Limits to Performance

$$\sigma_{\theta_c}(\mathrm{tot}) = \frac{\langle \sigma_{\theta_i} \rangle}{\sqrt{N_{pe}}} \oplus C$$

1. Separation Resolution

a) Single photon resolution (discussed above)

b) N_{pe} : More are better, but limited technical opportunities to improve…

-1/Sqrt dependence

-Larger detector bandwidth ➔ rapid increase in chromatic term

-Pixelated PMT detectors typically have smaller average detection efficiencies than conventional tubes.

-Wide angle photons:Tend to lose and/or distort. Better material matching between radiator and standoff/glue could retain more. Need well made radiators.

-Are solid state detectors possible?

c) C (correlated terms): Need << 1 mrad tracking and excellent control of alignment systematics to get below 1-1.5 mrad .

d) Physics limits (decays, interactions, δ-rays)

➔ c) and d) could be helped with a post PID tracking detector

2. Backgrounds

a) **Combinatorics and ambiguities:**

b) **Random:**

Other tracks in the event.

Uncorrelated beam background.

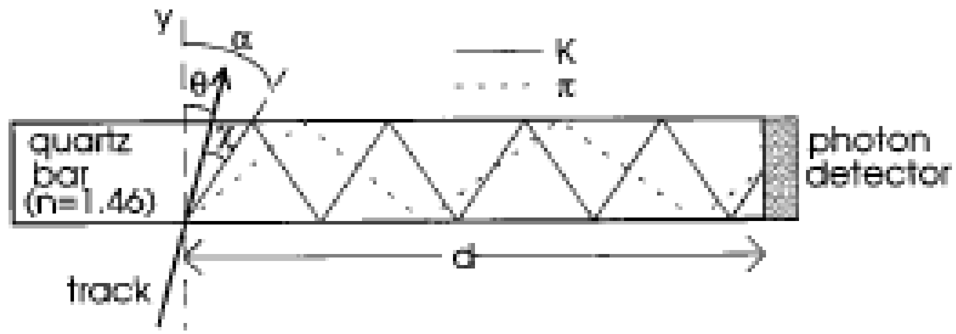
c) **Physics:**

δ-rays, interactions,etc.

➔ **Helped by fast timing, large (resolution limited) pixel count, multiple dimensionality (3-D is best), modular design, good detector shielding from beam line. (Many of these things cost $ so appropriate trade-offs are essential)**

Time Imaging DIRC-R&D Example-CCT

See talks at RICH93 and RICH95 by K. Honscheid, M. Selen, H. Kichimi, et.al.



•Uses 1-D DIRC time imaging, but is it a RICH(DIRC)? (Does not imaging the individual photons.)

• Track δ-rays troublesome. (~10% of events triggered more than 2 σ early).

•Beam tests ➔ at most favorable angles could get ~3 σ p/K separation up to p~1.7 GeV/c.

Beam Test Results

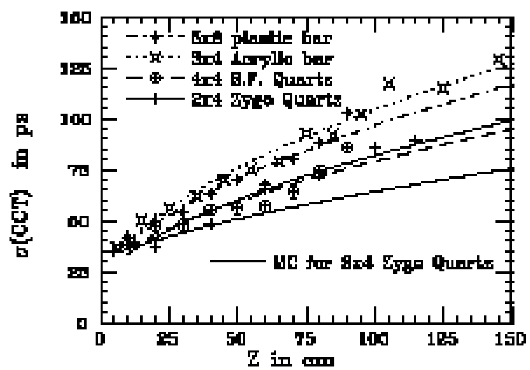


Figure 8: σ_{CCT} vs. Z for quartz and acrylic CCT at θ=20

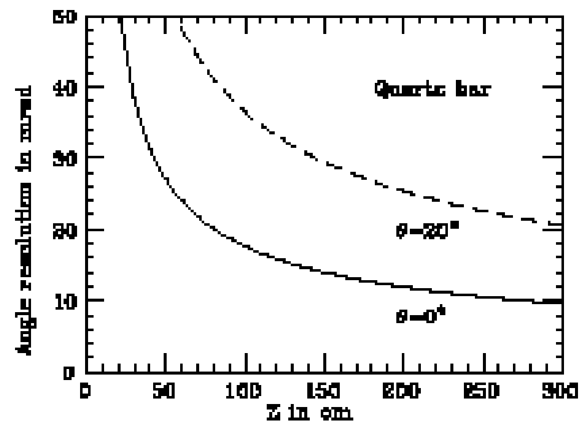
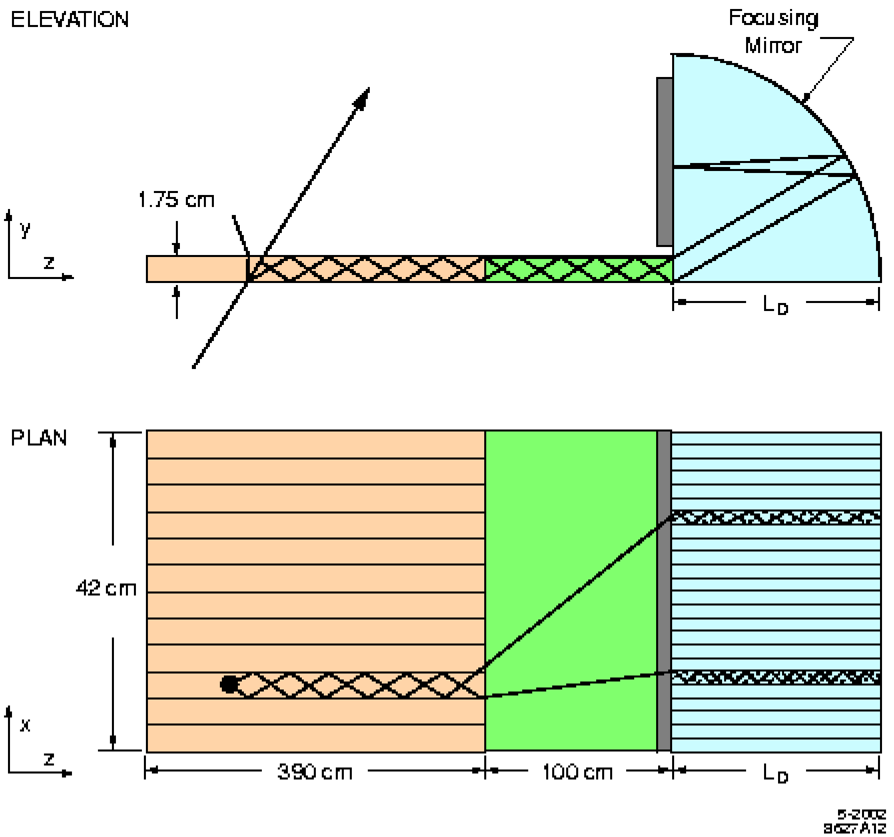
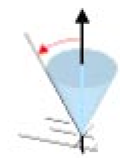


Figure 9: Čerenkov angle resolution vs. Z

Time Imaging DIRC-R&D Example-BaBar DIRC Conceptual Design II

- **Proposed BaBar DIRC group alternative to Pin-hole imaged DIRC with H_2O SOB.**
- **3 D readout: 1-D pinhole, 1-D lens, and fast timing (~100 ps). Sort out ambiguities with timing.**
- **Plausible 64/32 channel PMT to be developed from Hamamatsu Metal Channel R5900 series. (~250/500 tubes). Many concerns [Q.E., uniformity, cross talk, active area ratio (especially in x)]**
- **Nominal Separation performance ~ same or a bit better than with H_2O SOB (if N_{pe} similar)r (α_y ,α_x)~ (6,11) mrad….additional α_z help from < 100ps timing.**
- **Substantial technical risk!!**

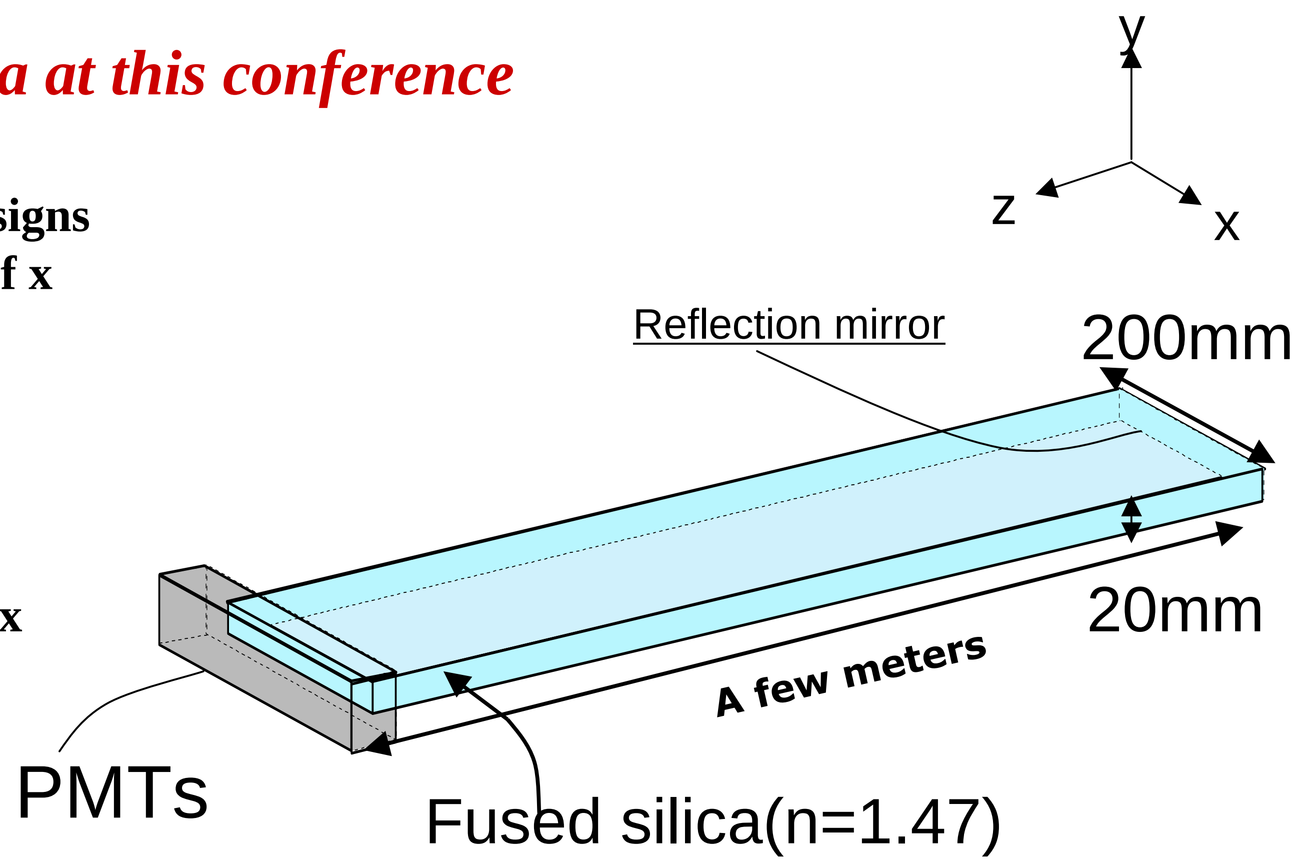




Time Imaging DIRC-R&D Example-TOP

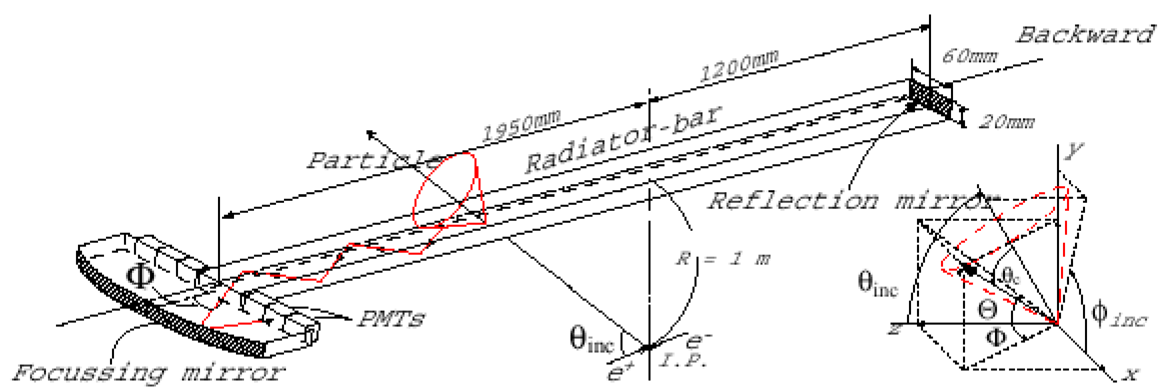
See talk by Ohshima at this conference

Two proposed 2-D designs using a combination of x and time imaging.



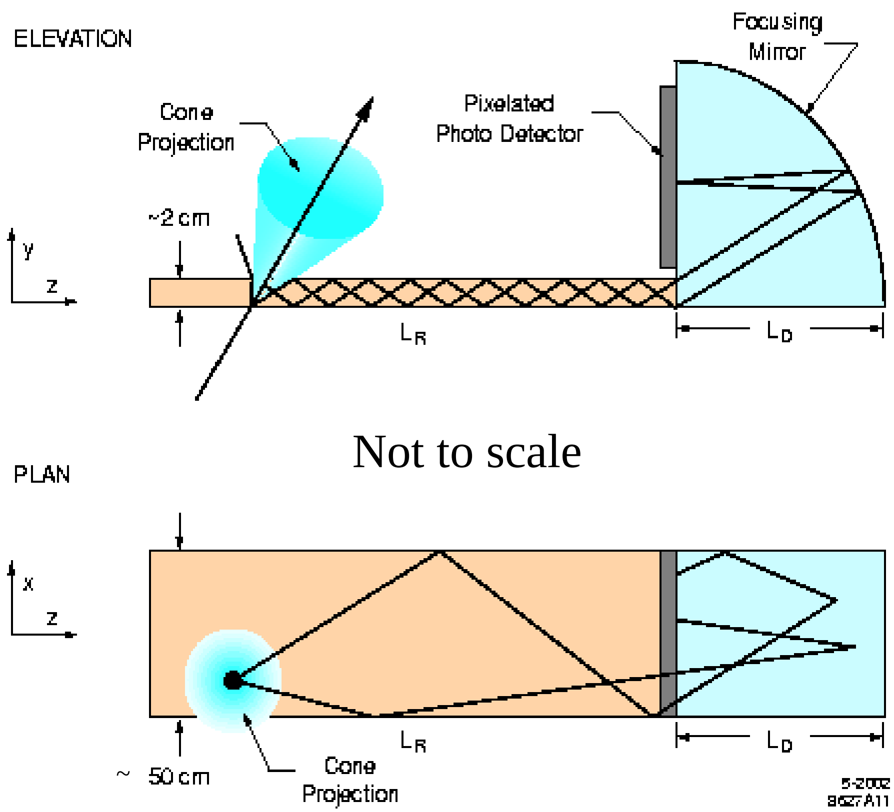
1. Proximity imaging in x and time.

2. Lens imaging in x and time.



Time Imaging DIRC-R&D Example-Super BaBar

BaBar DIRC group R&D for Hadronic PID at a 10^{36} Luminosity Super-PEP . (This is a completely new machine, not an approved upgrade to PEP-II)



Primary Concerns for PID System.

I.Cope with backgrounds;

-Fast Timing. 3-D imaging. Shielded beam.

II. Improve momentum coverage range:

Example: Detector with 120 (y) pixels, ~ 1.2-2 cm x pixels $\sigma(t)$< 150 ps.
➔ >3σ π/K separation up to ~ 6 GeV/c

III. Improve Mis-ID and Correlated terms:

-Post DIRC tracking.

IV. Practical matters:

-Performance of pixelated detectors.

-Cost: ~25000-40000 fast channels.

-Coping with ambiguities.

-Large radiator pieces.

3-D DIRC has good match to P/θ_t correlations of an asymmetric collider.

Design details depend on photon detector.

Summary

The Lord of the Rings

Photons from ice and sea under the sky,
Photons from vast water tanks in halls of stone,
Photons from the atmosphere in an insects eye,
Photons from aerogels, light, clear, blown,
Photons from liquids, gases, crystals flying by,
Photons from fused silica expanding on a cone.
In RICH detectors where PID truths lie.
One Ring to rule them all, One Ring to find them,
One Ring to bring them all, correlate, and bind them
In RICH detectors where PID truths lie.

With apologies to J.R.R. Tolkien,
and appreciation to Tom for his seminal role in this field (and this conference series). He was truly
The Lord of the Rings.