Techniques for Hadronic Particle ID and Their Evolution

- A view from Outer Space. Jerry Vavra’s talk is much more grounded.
- Focus on Hadronic PID. (No discussion of range or shower detectors for lepton ID, or Transition Radiation detectors, for example)
- Explore characteristics, limitations, and evolution of known experimental techniques
  - Cherenkov Detectors
    - Threshold Cherenkov Counters
    - Imaging Cherenkov Counters
      - Classic RICH (Ring Imaging CHerenkov counters)
      - DIRC (Detection of Internally Reflecting Cherenkov light)
  - dE/dx in tracking chambers
  - Time of Flight devices (TOF)

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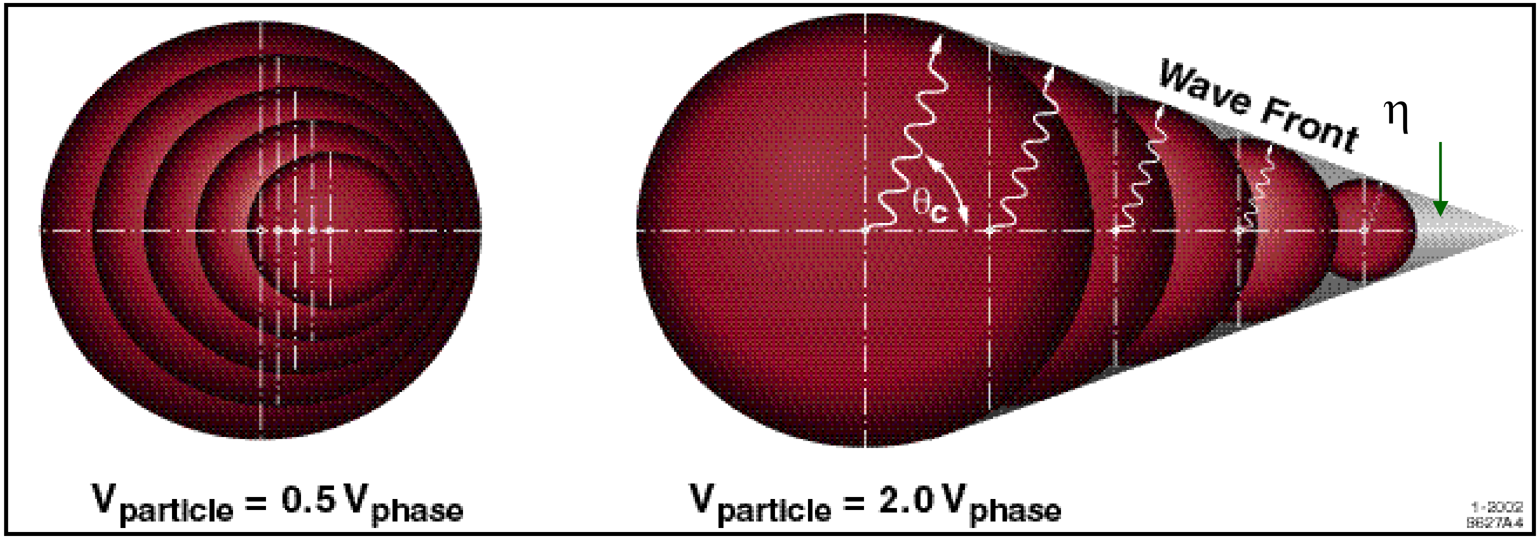
A brief look at Cherenkov devices



Cherenkov radiation is (a) prompt; (b) has a velocity threshold; (c) is polarized; (d) is proportional in intensity to particle path length; (e) is "white" in energy; and (f) radiation of wavelength λ is emitted at polar angle (θ_c), uniformly in azimuthal angle (φ_c), with respect to the particle path,

$$\cos\theta_c = \frac{1}{\beta n(\lambda)}$$

→ This implies a fundamental intrinsic "chromaticity" dispersion limit for a finite photon detection bandwidth.

Fundamentals- Basic Cherenkov Equations-II

- The number of photo-electrons N_{pe} is usually “challenging”.

$$N_{pe} = 370 L \int \varepsilon \sin^2 \theta_c dE = L N_0 \sin^2 \theta_c$$

For z=1

- N_o typically ranges between ~ 20 and 150

- Broad Range of available radiators. N_{pe} very small for radiators with small refractive indices

E.g., for No = 100, β = 1;

		n	N_{pe}/cm
Solid	SiO_2	1.47	54
Liquid	H_2O	1.34	44
Gas	C_5F_{12}	1.0017	0.34
Gas	He	0.00004	0.008

Fundamentals- Basic Cherenkov Equations-II

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

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

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.

Typically, $\mathbf{t_{measured} = t_{stop}-t_{start}= t_p+TOF}$;
where $\mathbf{t_{measured}}$ is the calibrated measured time,
$\mathbf{t_p}$ is the photon travel time in propagating to the detector,
and **TOF** is the time of flight of the particle from the common start…usually the event time in an accelerator.

➔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).

Cherenkov Counters Contain 2 Crucial Elements:

1. **A radiator through which the charged particle passes.**
2. **A photo-detector (camera) (which may contain an optical collection or focusing scheme plus detectors to transform photons into photo-electrons)**

Cherenkov counters utilize one or more of the fundamental attributes of the Cherenkov effect:

1. **Prompt emission of a light pulse.**
2. **The existence of a velocity threshold for radiation.**
3. **The dependence of the Cherenkov cone half-angle θ_c and the number of emitted photons on the particle velocity.**

Counter Types

- **Threshold Counters**

  1. **Yes/No decision based on whether particle species is above or below threshold .**
  2. **Separation usually depends on not seeing a signal for the below threshold particle**

  ➔ **electronic, non-Cherenkov light production, and physics background noise sources (such as interactions, decays, and delta rays) often limit separation attainable.**

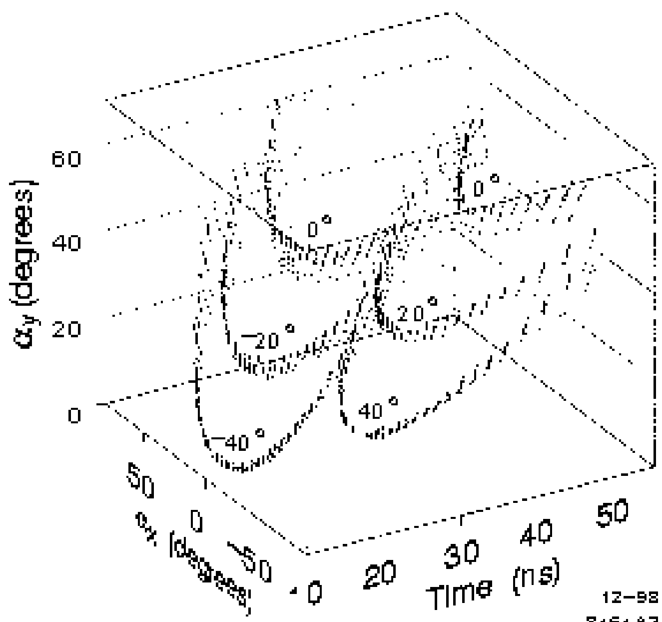
- **Imaging Counters**

  1. **Based on combined measurement of ring-correlated angles or times of emission of individual Cherenkov photons from each track.**
  2. **Since low energy photon detectors can measure only the position (or/plus perhaps a precise time) and not the angles directly, the photons must be "imaged" onto the detector.**
  3. **Lots of different imaging techniques are available (see below)**
  4. **Since both wanted and unwanted particles are usually imaged, these devices usually have good Mis-id/ID ratios, and behave well in high backgrounds and luminosities**

Cherenkov Fundamentals-Comments

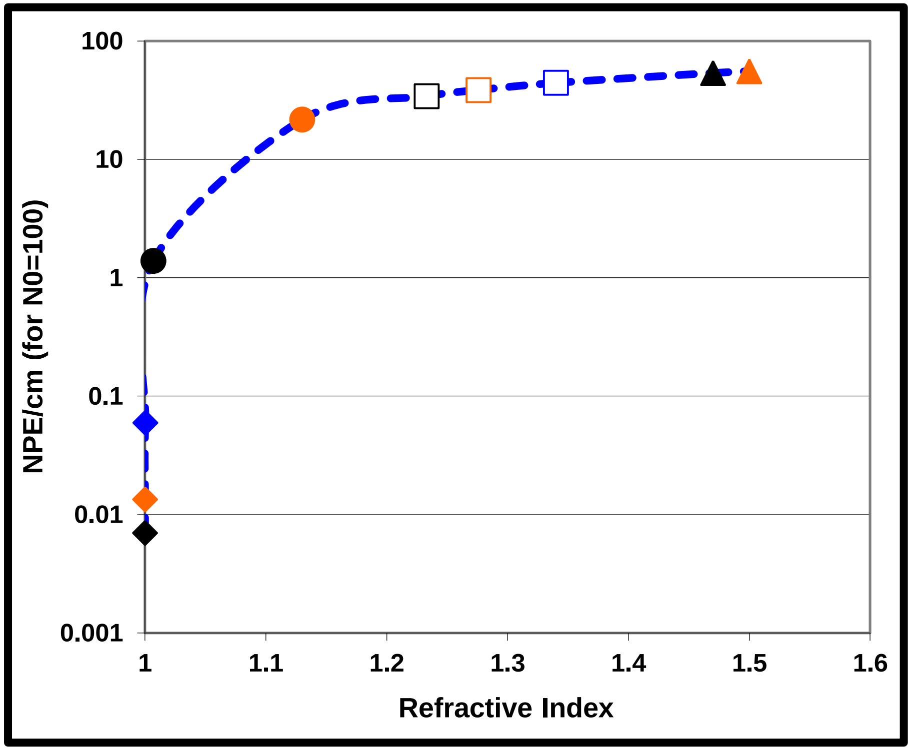
- In general, up to 3 measurements (α_x, α_y, t_p) are available to measure the 2 Cherenkov angles (θ_c, φ_c) with respect to a known track => nominal over-constraint at the single p.e. level.
- Powerful Ring correlation => can reduce "dimensionality" required of each photon measurement.
- Caveats:
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

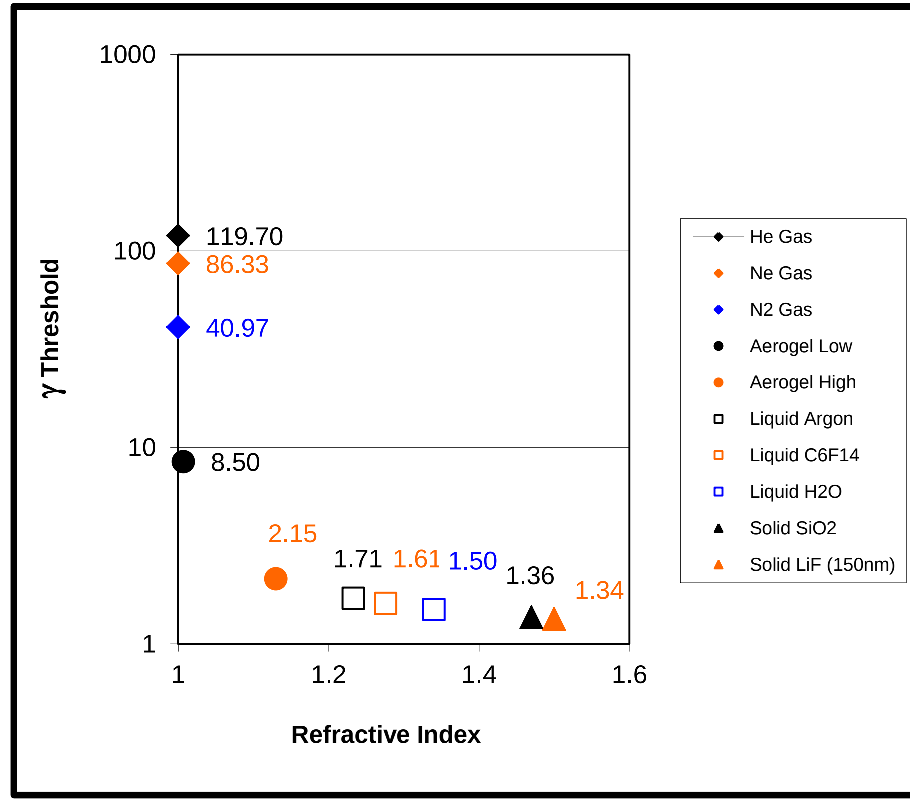


Radiators-Momentum Coverage

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



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



- "Hole" between Gas & Liquid/Solids partially filled by Aerogel in last few decades. Transparency crucial. Progress in materials helps.
- Practical upper limit on γ_{max} ~ 10-20x $\gamma_{threshold}$. (From dispersion & angle res.)

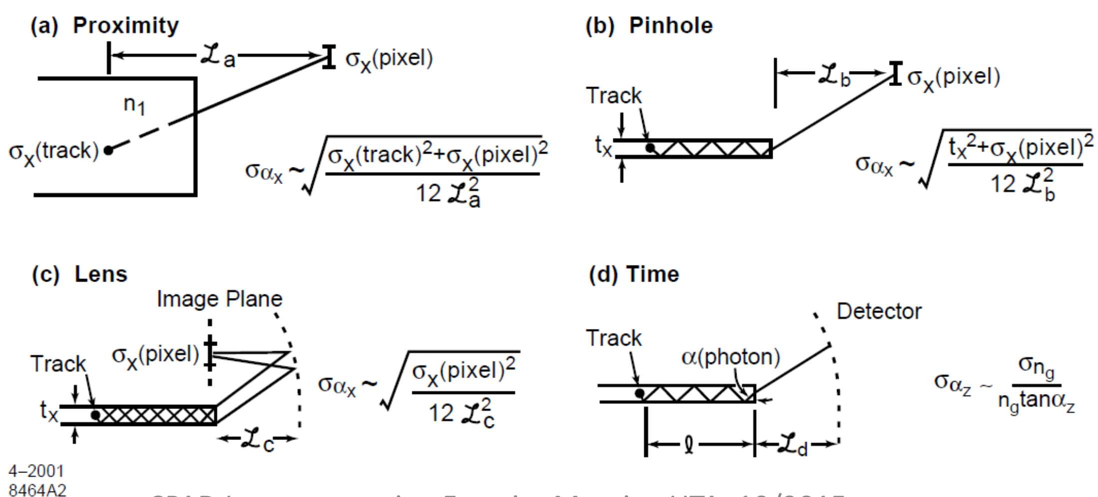
- # Imaging

The photons must be "imaged" (or focused) onto the detector. There are a wide variety of optical techniques.

"Standard" Optical techniques

a) Focusing by a lens.
b) Focusing through a pinhole.
c) Proximity focusing (i.e., focusing by limiting the size of the radiating region).
d) Time focusing with very fast timing detectors. (is usually convolved with the particle TOF (as described earlier)
e) Correlated (constrained) focusing (e.g., as in Kamiokande)

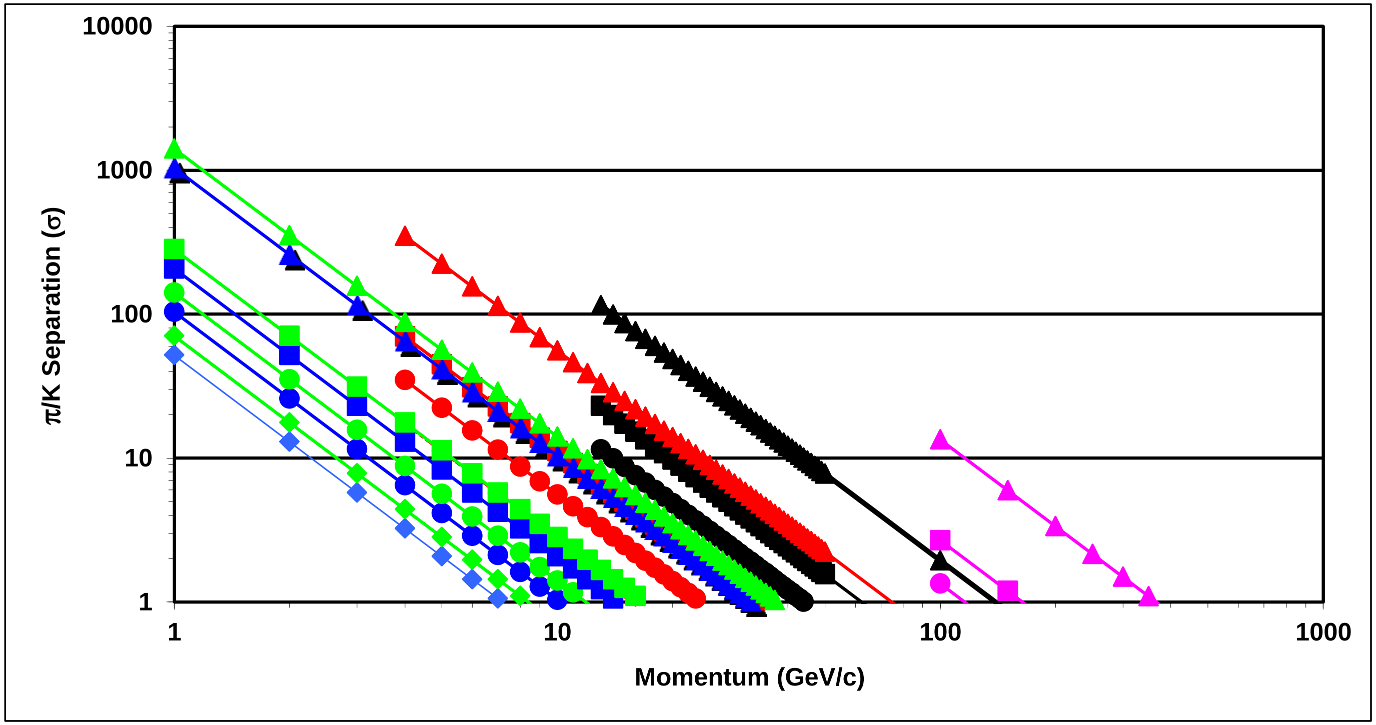
Examples given for DIRCs using (a-d) above. Techniques (a and c) are typically used for conventional RICH geometries, and variants of a, d, and e in the large water Cherenkovs.



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

For momenta well above threshold

π/K separation-limiting case



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)

N=1.0000349 (He)

$\sigma[\theta_c(tot)]$

◆ 2 mrad

● 1 mrad

■ 0.5 mrad

▲ 0.1 mrad

A central challenge:

- Need high efficiency for detecting single photons with very low noise.
- Very fast timing resolution essential if timing used for angular measurement or TOF and useful to reject background and resolve ambiguities.
- High segmentation (small pixels) needed for good resolution and background rejection.

Basic Types:

1. Vacuum-based
   a) Many different types (e.g, photomultipliers (PMTs); MCP-PMTs, HPMTs, HAPDs)
   b) Sensitive, versatile, and robust. Some are very fast, low noise, high gain. Some types are rather rate sensitive
   c) Variety of different photocathodes sensitive to wavelengths from the UV cutoff of the window material (LiF cuts off around 100nm) up to the near IR.
   d) Illustrious History. Most successful Cherenkov counters used PMTs until the 1980's, and they are still very widely used, and remain under active development
   e) Commercially available (good!). Difficult to produce without a large investment in equipment and understanding (bad!).
   f) Usual types are quite sensitive to magnetic fields, but new types (like MCPs) work in high fields in some field directions.
   g) Development continues. Several pixelated types in use. Smaller pixel sizes being developed. Single PE space and timing resolution continue to improve, and new higher efficiency photocathodes are being developed.

Basic Types-II:

2. Gaseous Detectors:

   a) Gaseous (e.g., TMAE,TEA) and Solid (CsI) Photocathodes. Moderate efficiency.

   b) Work in UV near window cutoff. Large radiator dispersion per unit bandwidth. Modest number of P.E.

   c) P.E. Readout usually with proportional chambers, TPCs, (R&D devices have used GEMS Micromegas, etc. as well). Inexpensive coverage of large photon collection area with good point resolution.

   d) Performance at high luminosity depends on photocathode and readout. Slow with TMAE, but can be faster with TEA or CsI. Difficult at the highest luminosities

   e) Too slow for time dimension focusing.

   f) Challenging operational characteristics.

   g) Can be used in magnetic fields.

3. Solid State Detectors…little used to date maybe but for the future?

   a) Need PMT like gain and photon detection efficiency ➔ SiPM is likely the most plausible candidate at present.

   b) Achieve 10^6 gain with low bias voltage. Well resolved NPE counting. Noise mostly single PE. Compact and insensitive to magnetic fields. Small pixels and quite fast (~100 ps).

   c) High dark count rate (~100kHz/mm^2) at room temperature. May gain > two orders of magnitude by cooling.

   d) Challenging (expensive) to cover large areas, as is usually required in RICH (to a lesser extent in DIRCs). Radiation sensitivity

Comparison of different PID devices

Generic properties of PID devices

1. Geometry
   - Space taken (Thickness)
   - Is space used for another function?
   - Hermeticity
   - Flexibility of layout and P range
2. Susceptibility to backgrounds
   - Speed
   - Segmentation
   - Positive versus veto ID
   - Low Mass
3. Simplicity (Complexity) of Technology
4. Performance
   - Quality
   - Momentum Range
   - Physics Limits

One Page Synopsis of Pros and Cons

	PRO	CON
TOF	• Scintillation devices are simple, rather thin. • Fast! Cherenkov devices particularly so! • May use "free" space (from tracking) for TOF	• Low (or modest) P only unless track lengths long • Track Overlap unless channel count large
dE/dx	• Best acceptance • Uses "free" (tracking) space • Excellent PID at very low P	• Cross-over region where no ID • ID performance modest at higher momentum
C(threshold)	• Simple • Can be fast • Choice of radiators to cover wide P range	• Limited P range for each radiator type • Substantial space needed at higher momenta • Asymmetric ID. Veto versus positive id region. Higher Mis-ID and sensitive to backgrounds
RICH/DIRC	• Can be very fast. Wide P range • Can be excellent TOF counters • Many techniques available • Positive ID for both particles. Low Mis-ID • Can be very thin in low P region	• Complexity • Cost • Rather thick for separation at high P (but much better than threshold devices)

Simplified Comparison of High Momentum Performance of Imaging and Threshold Counters

Threshold Counters ➔

$$\delta_\beta = \frac{\sigma_\beta}{\beta} \approx \frac{\tan^2\theta_c}{(2\times\sqrt{N_{pe}})}$$

Imaging Counters ➔

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

Ratio (Imaging Counter /Threshold Counter)➔

$$R \approx \frac{\tan^2\theta_c}{(2\times\sigma_{\theta_c})}$$

E.g. For DIRC-like angular resolution with fused silica radiator

$$R \approx 200$$

Considerations-TOF Counters

- Need both a good **start** (usually the event) and a **stop** time (when the Cherenkov photon is converted in the PID photon detector).
- Knowledge of particle path is usually not a limiting factor. However, in collider detectors, track length is often shorter for PID than one would like, except in very forward geometries.
- Obtaining adequate segmentation can be a substantial issue in high luminosity environments
- Using Imaging Cherenkov detectors, rather than scintillation counters as is traditional, has several advantages:
  - Very prompt Cherenkov light emission
  - Intrinsically good track to track separation
  - Rather precisely known light path in radiator on a photon by photon basis

    ➔ total timing resolution can improve ~ like $1/\sqrt{(N_{pe})}$
  - However, number of photons in Cherenkov TOFs is usually rather small, there is a velocity threshold, the photon detectors must have extremely good single PE properties, and the analysis is more complex

TOF Counters

- TOF Fundamentals: Consider a particle with velocity v, momentum p, and energy E traveling a distance L. Then the time of flight (TOF) t is…….

$$t = \frac{L}{v} = \frac{LE}{pc^2}$$

- The separation in time (t_1-t_2) between two particles of the same momentum with Energies (masses) E_1 (m_1) and E_2 (m_2).

$$t_1 - t_2 = \frac{L}{c^2 p}\left[E_1 - E_2\right]$$

- So, for p>> m with a time resolution σ(t) , the separation N_σ is

➔ Same separation dependence vs. momentum as a RICH (and no threshold in a scintillating device) but with a very different and less flexible scale!

$$N_\sigma \approx \frac{Lc}{2p^2}\frac{\left[m_1^{\,2} - m_2^{\,2}\right]}{\sigma(t)}$$

Comparing RICH and TOF Performance-A question of the Separation Scale

- TOF "scale" is the fractional timing resolution on the TOF (t_0) for a β=1 particle

$$= \frac{t_0}{\sigma(t)}$$

- RICH "scale" is more widely tunable

$$= \frac{1}{\left(\sqrt{n^2-1}\,\sigma[\theta_c(tot)]\right)}$$

RICH

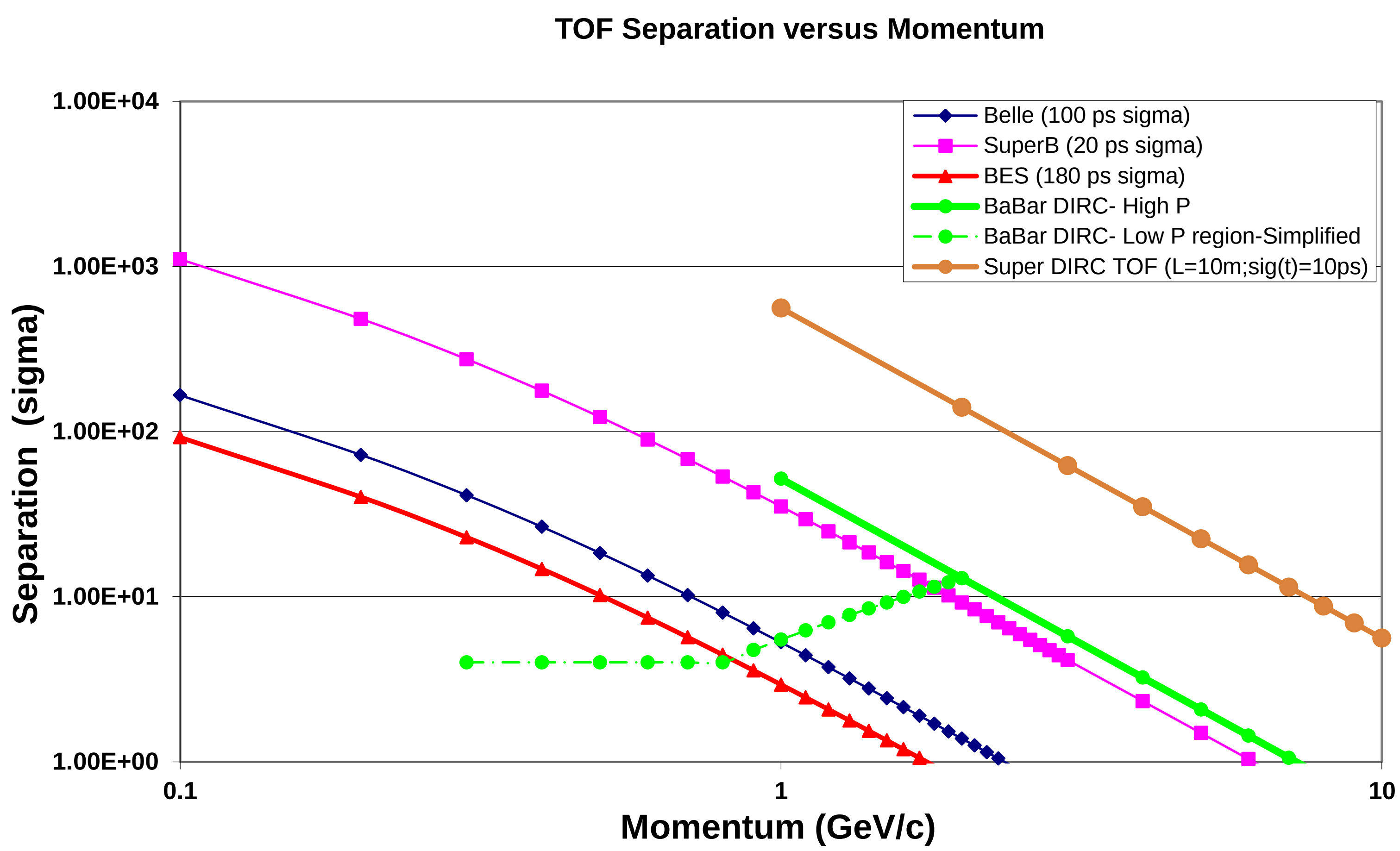
n ($pK_{thres\text{-}Gev/c}$)	$\sigma(\theta)$ **mrad**	Scale
1.474 (0.7)	2	462
1.0017 (3.5)	1	17140
1.000035 (84)	0.1	1.2E6

TOF

t_0(ns)/L(m)	σ(t) **ps**	Scale
5/1.5	200	25
5/1.5	100	50
5/1.5	10	500
50/10	10	5000

RICH PID spans much broader range….but very fast Imaging Cherenkov TOF (e.g. a DIRC TOF) may be attractive in some detectors for P of a few GeV.

Examples of TOF vs RICH (DIRC) Performance at low P



- Geometrical (P_T) Cutoffs ignored

→ TOF provides fine separation at low P, but coverage of higher P range is quite limited unless track lengths are very long, or timing resolution is extraordinary

Comparing RICH and dE/dX

- dE/dX Fundamentals: The mean energy loss for a heavy particle of mass ($m \gg m_e$) with charge 1 is given by the Bethe-Bloch equation.

$$dE/dX = D_e \beta^{-2} n_e \left[\ln \frac{2mc^2 \beta^2 \gamma^2}{I} - \beta^2 - \frac{\delta(\gamma)}{2} \right]$$

where $De = 2\pi r_e^2 m_e c^2$, n_e is the number of atomic electrons per unit volume, r_e is the classical electron radius, m_e is the electron rest mass, I is the mean ionization potential of the material, and $\delta(\gamma)$ is the so-called "density effect".

Features→

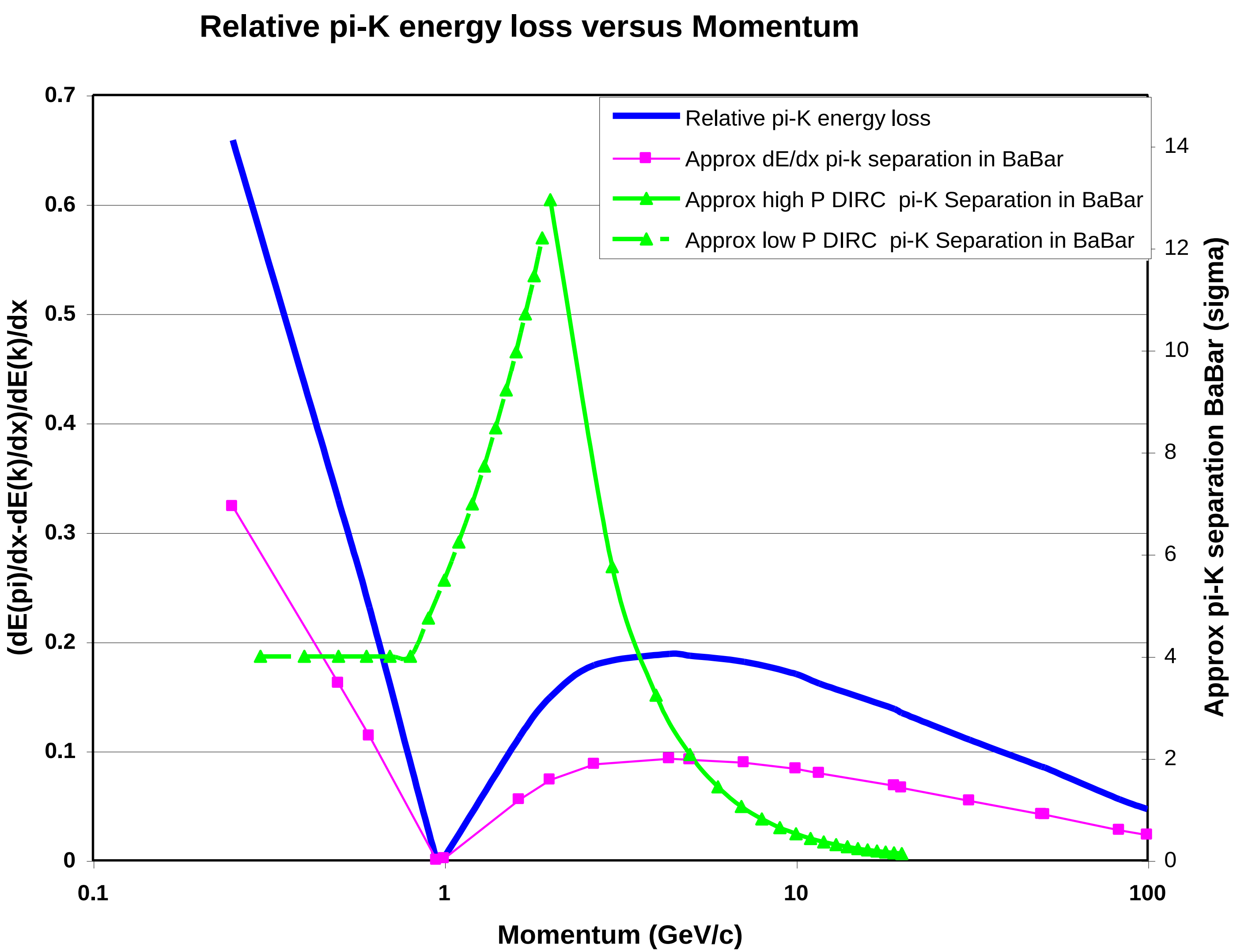
(1) $1/\beta^2$ region at low p

(2) minimum at $\beta\gamma \sim 4$ ➔ "cross over region"

(3) "relativistic rise" region

(4) Fermi plateau due to "density effect"

E.g., Comparing RICH and dE/dX



Future Evolution of PID techniques and R&D Directions

TOF	• Improved Photon Detectors (is ~1-5 ps res. possible?) better magnetic field properties; better photocathodes; more rate and radiation resistant; etc?) • More non-conventional Photon Detector choices (Solid State/MCP/Etc.) • Cherenkov based TOF vs. scintillator • Photon by Photon Timing • Very long track lengths with small acceptance
dE/dx	• Cluster counting…. ~ 2x resolution? (may be feasible with modern electronics) ➔ Might get better PID in relativistic rise region
C(threshold)	• Better photodetectors. • Improved radiators especially aerogels
RICH/DIRC	• Better Photon Detectors (Solid State/MCP/Etc) • Faster Photon detectors with smaller pixels • Use of timing to measure angle, and/or correct chromaticity, and particle separation via TOF. • Clever Optics • Continued improvement in radiators (especially 3d materials, transparent aerogels, and radiation resistant materials) • Wave form sampling electronics and sophisticated software.

A PID Reprise

• There are several powerful PID techniques available with applications across many areas of HEP. Each could benefit from further R&D.

•Scientific Bases for these PID techniques are well understood, but instruments continue to develop and evolve using newly available components being developed mostly by industry, using new ideas and instrumental innovation from members of our field.

➔ Imaging Cherenkov techniques are an evolving "standard" for PID instruments in general purpose detectors, although dE/dx in tracking systems often provides some PID "for free".

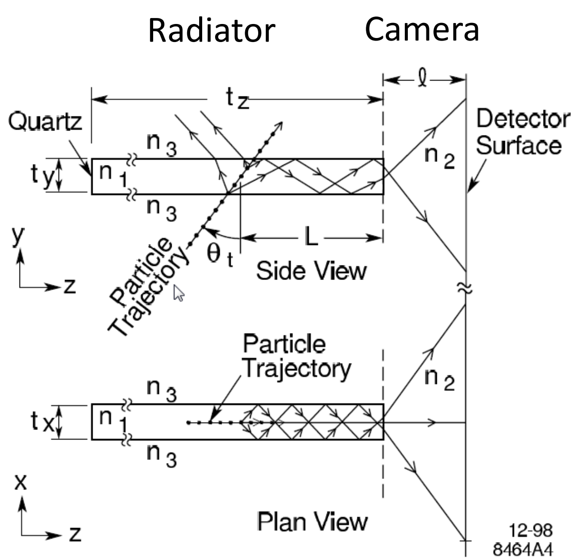
- "Tunable". Provide positive ID. Can deal with a very wide range of momenta, luminosities, geometries, and backgrounds.
- Usually the technique of choice at accelerators when very high quality hadronic (pi/K/P) PID (and low Mis-id) is required.
- With the very fast photon detectors now becoming available, they may become superior TOF detectors.
- Many choices commercially available for optics, photon detectors and radiators; there are a wide variety of possible geometrical configurations.
- New photon detectors (faster, smaller pixels, magnetic field resistant, etc.) are still being developed (mostly commercially) and open new opportunities for innovation in design. It is usually very challenging for a smaller HEP research effort to compete with these commercial developments.
- Principle limitations are geometrical and costs, the physics need for new designs, and the designers' imagination.

Additional Slides

- The generic name for Imaging Cherenkov counters in HEP has become RICH. Not so much true in the astrophysics community.

- DIRC counters are a distinct type of RICH that uses the radiator in two ways simultaneously…first as the Cherenkov radiator and second as a precision light guide to transport the photons down to the end, maintaining the magnitude of the angles in the radiator. At the radiator end, images are formed by a camera.

Typical DIRC Geometry

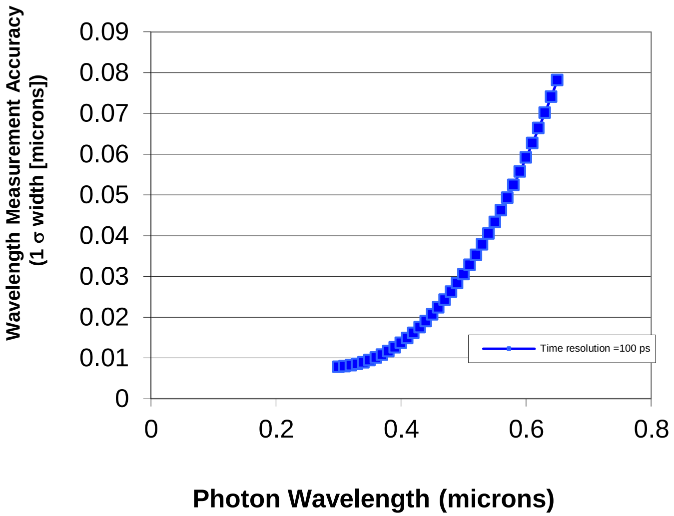


Physics Limits to Imaging Counter Performance-Chromaticity

Measuring the Chromatic Smearing via timing?

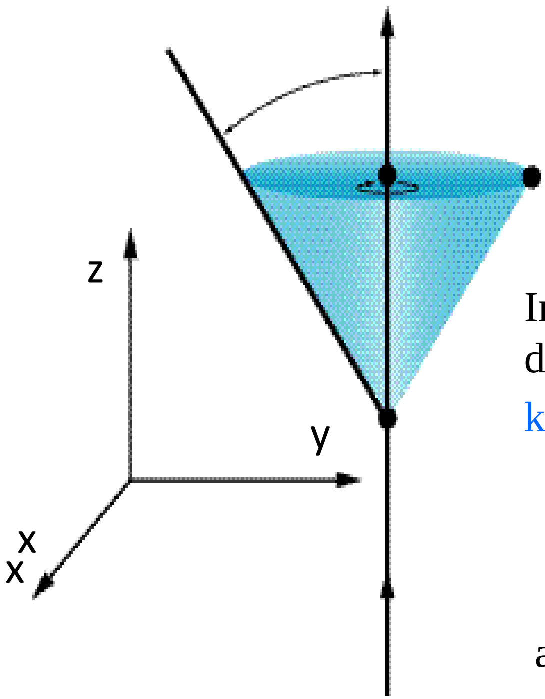
- Use the large dispersion in n_g in a 3-D DIRC to measure the photon wavelength….(I.e., compare the individual photon flight time with its measured angle)

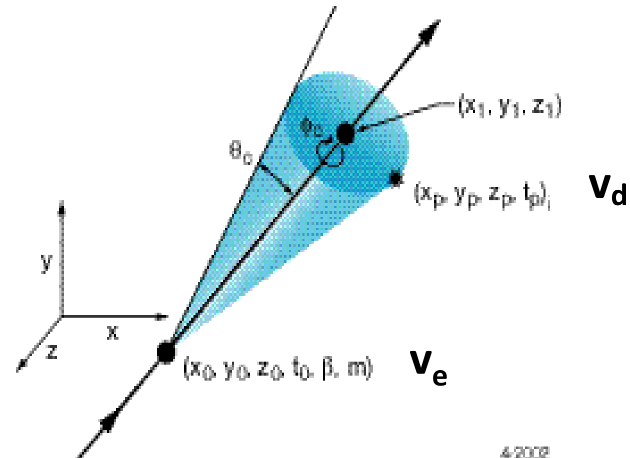
→ can improve chromatic limit by ~5x with 100 ps detector time resolution at 6m propagation length. Scales with time resolution.



Has been demonstrated in the FDIRC device...see JV talk .

For Reference- Cherenkov Coordinate System





In frame (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 $\mathbf{v_e}$ and detection point $\mathbf{v_d}$

$$t_p = \frac{L_p n_g}{c} = \frac{\left|(\vec{v}_d - \vec{v}_e)\right| n_g}{c}$$