Advantages and Limitations of the RICH Technique for Particle ID

Outline:

- **Introduction**
- **RICH**
  - ❑ **Fundamentals**
  - ❑ **Performance Metrics**
  - ❑ **Limits to Performance**
- **Comparing Other PID Devices with RICH**
- **Summary**

6th International Workshop on Ring Imaging Cherenkov Counters

Blair Ratcliff
Stanford Linear Accelerator Center

Introduction & Disclaimer

- **Venerable RICH Conference Tradition:** At past meetings one or two speakers have been invited to elucidate and summarize some basic properties of RICH devices, their common properties, and limitations. Examples include:
  - "A historical survey of ring imaging Cherenkov counters", Seguinot and Ypsilantis. RICH93.
  - "Theory of ring imaging Cherenkov Counters", Ypsilantis and Seguinot, RICH93.
  - "Photon Detectors", Va'vra, RICH95.
  - " The evolution of the RICH technique", Ypsilantis and Sequinot, RICH98.
  - "The limits of the RICH technique", Glassel, RICH98.
  - "Imaging rings in ring imaging counters", Ratcliff, RICH2002.
  - "New Perspectives with RICH", Nappi, RICH2004.
- Several wonderful papers providing overviews of the field, its physical foundations, its history, and its experimental properties, detector capabilities, and limitations.
- But is there more to be said now?
  - Carrying Coals to Newcastle?
  - Selling ice to Eskimos?
  - Bringing Owls to Athens?

Shakespeare

- Paint the Lily?
- Gild refined gold?
- Throw perfume on the violet?

Introduction

- **Concentrate today on RICH PID as used in detectors at particle accelerators.**
- **Focus on Hadronic PID. (No discussion of range or shower dectectors for lepton ID, or Transition Radiation detectors, for example).**
- **Discuss characteristics and limitations of RICH Technique & Compare with other classic PID techniques:**
  - **Threshold Cherenkov Counters**
  - **DE/dx techniques in tracking chambers**
  - **Time of Flight devices (TOF)**

I apologize that several examples are taken from BaBar!

Early History-At the Curies' for Dinner

"We had an especial joy in observing that our products containing concentrated radium were all spontaneously luminous. My husband, who had hoped to see them show beautiful colorations, had to agree that this unhoped-for characteristic gave him even greater satisfaction."

Sometimes, after dinner, the Curies would walk the five blocks from their apartment to the famous shed "for another survey of our domain. Our precious products, for which we had no shelter, were arranged on tables and boards; from all sides we could see their slightly luminous silhouettes, and all these gleamings, which seemed suspended in the darkness, stirred us with ever new emotion and enchantment."

Marie Curie, 1899 Paris

Early History of the Cherenkov Effect

- ~1900: Eerie blue glow see in fluids containing concentrated radium (Marie & Pierre Curie)
- ~1926-1929: Continuous light spectrum. No discrete spectral lines that are characteristic of fluorescent radiation. (Mallet)
- 1934: (Vavilov) concluded that the observed glow could not be luminescence of the liquid, and the light seemed due to Compton electrons.
- ~1934-1944: Classic studies (P. Cherenkov) with simple apparatus demonstrated that:
    1. Light intensity is proportional to electron path length in medium.
    2. Light comes only from *fast* electrons. It has a velocity threshold.
    3. Emission is very prompt.
    4. It is polarized.
    5. The spectrum is continuous ➔ emission is not fluorescence.
    6. Angular distribution of the radiation, its intensity, wavelength spectrum, velocity and refractive index dependence agree with the explanation proposed by colleagues……..
- ~1936-1939: Proposed explanation in classical “EM” theory (Frank & Tamm).
- 1958: Nobel Prize (Cherenkov, Frank, Tamm).

Early History-The Nobel Prize

The Nobel Prize in Physics 1958

"for the discovery and the interpretation of the Cherenkov effect"

Pavel Alekseyevich Cherenkov

1/3 of the prize

USSR

P.N. Lebedev Physical Institute
Moscow, USSR

b. 1904
d. 1990

Il´ja Mikhailovich Frank

1/3 of the prize

USSR

University of Moscow; P.N. Lebedev Physical Institute
Moscow, USSR

b. 1908
d. 1990

Igor Yevgenyevich Tamm

1/3 of the prize

USSR

University of Moscow; P.N. Lebedev Physical Institute
Moscow, USSR

b. 1895
d. 1971

History-Nim Paper I-The Invention of RICH

NUCLEAR INSTRUMENTS AND METHODS 9 (1960) 55–66; NORTH-HOLLAND PUBLISHING CO.

A NEW TYPE OF ČERENKOV DETECTOR FOR THE ACCURATE MEASUREMENT OF PARTICLE VELOCITY AND DIRECTION†

ARTHUR ROBERTS

Department of Physics††, *University of Rochester*

Received 22 June 1960

A new type of Čerenkov radiation detector is proposed, in which the light emitted by a single particle traversing a radiator is imaged, by means of a lens or mirror focused at infinity, on the cathode of an image-intensifier tube. The image is a ring, whose diameter measures accurately the Čerenkov cone angle, and thus the particle velocity. In addition the coordinates of the center of the circular image accurately indicate the orientation of the particle trajectory (though not its position). The sensitivity of presently available systems of cascaded image-intensifier tubes allows the photographic recording of the image produced by a single particle. The system is inherently insensitive to background noise. It can observe simultaneously several incident particles whose directions span a wide angle. It may be gated with microsecond coincidence resolving times. It can use condensed of gaseous radiators; with the former, chromatic dispersion is likely to limit the accuracy. For gas radiators, the attainable accuracy of velocity determination is estimated as $\Delta\beta = \pm 0.0002$ or better; the accuracy of track orientation $\pm$ 0.001 radians. The range of velocity and orientation simultaneously observable depends on the angular field of view of the objective. Sources of error, the precision attainable, the design of practical systems and some possible applications are discussed.

Arthur Roberts-The Inventor of the RICH- A Visionary Approach

- Ring image from a single particle recorded from cascaded image-intensifiers onto film.
- Recognized the importance of chromatic dispersion limits to ultimate performance in imaging counts
- Recognized the virtues of positive ID....that having an image meant that important physics limits to threshold counter performance would no longer be so important (e.g. knock-on electrons and scintillation light)
- Proposed a plausible detection system with ~ 20-30 p.e.
- Analyzed sources of β measurement error in a reasonable system, including dispersion and particle multiple scattering and concluded that it was reasonable to expect a precision in $\delta\beta \sim 0.0002$.
- But.... he never built a practical device

History-Nim Paper II-The Development of RICH

NUCLEAR INSTRUMENTS AND METHODS 142 (1977) 377-391 ; © NORTH-HOLLAND PUBLISHING CO.

PHOTO-IONIZATION AND CHERENKOV RING IMAGING

J. SEGUINOT* and T. YPSILANTIS†

CERN, Geneva, Switzerland

Received 17 December 1976

We have investigated the photo-ionization process in gases and shown that single photon pulse counting in multiwire proportional chambers (MWPC) is possible with about 50% quantum efficiency for photons above 9.5 eV. An application of this technique in imaging the Cherenkov ultra-violet (UV) radiation is presented.

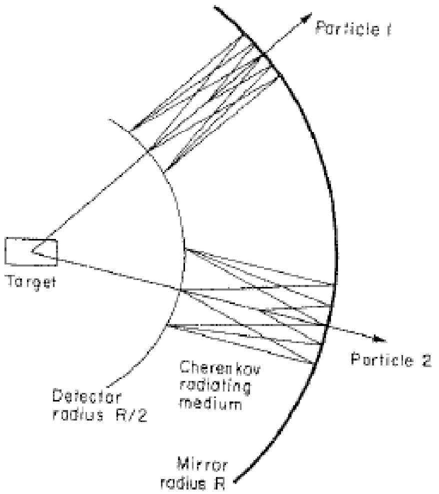
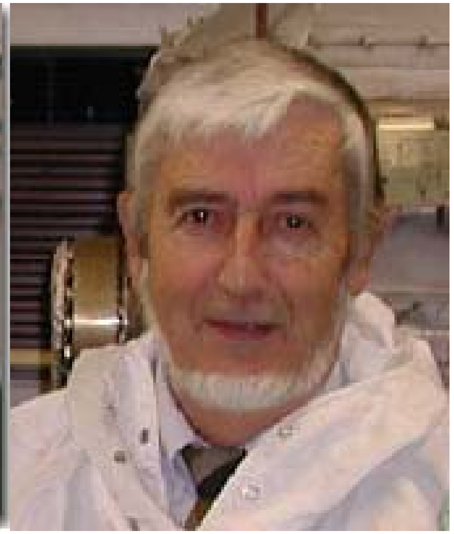


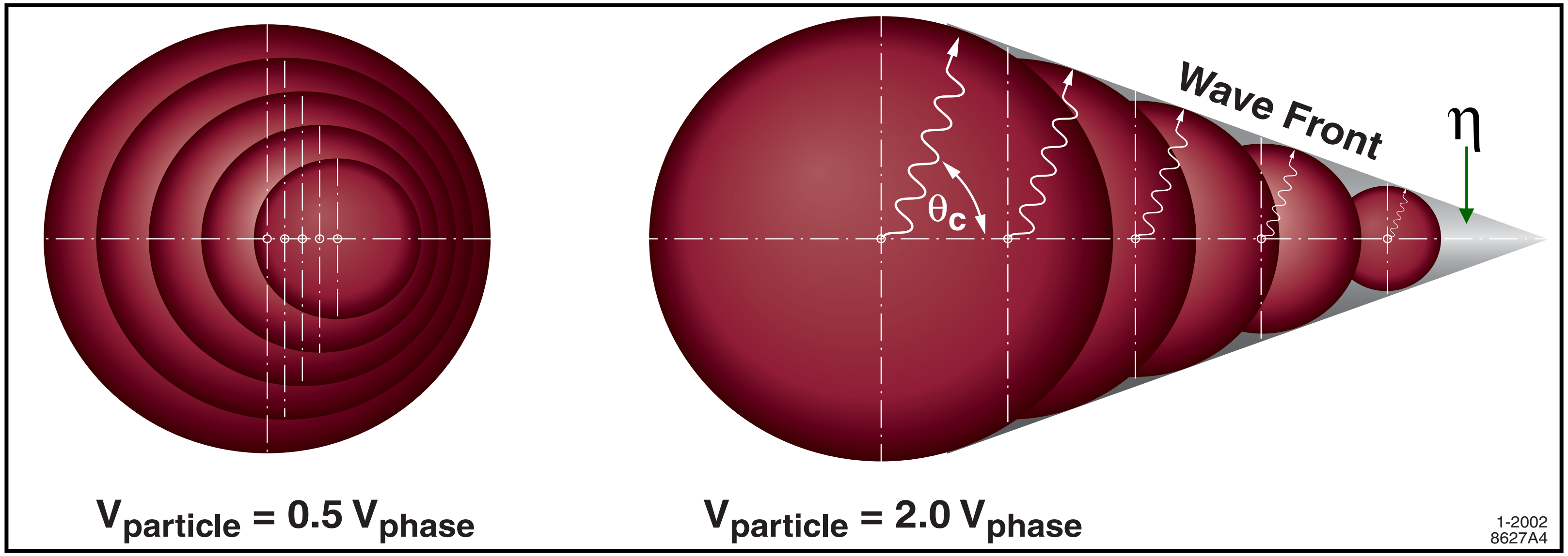
Fig. 1. Schematic large phase space acceptance Cherenkov ring imaging detector.

Seguinot & Ypsilantis-The Developers of RICH- A Practical Beginning

- Seminal Paper
- Analyzed the basic requirements for detectors and the resolution expected from all experimentally important sources.
- Motivated the development of single photon detectors.
- Investigated Photo-Ionization in gases. Demonstrated that single photon counting was feasible in wire chambers.
- Opened a new field of detector science
- Several practical detectors from multiple investigators followed within a few years.



Cherenkov Fundamentals

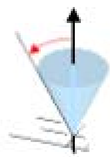


Basic Cherenkov Equations-I

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

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

➔ Fundamental intrinsic "chromaticity" dispersion limit.



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

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

For z=1

Usually N_o ranges between ~ 20 and 100

E.g., for No = 50, β = 1;

		n	N_{pe}/cm
Solid	SiO_2	1.47	27
Liquid	H_2O	1.34	22
Gas	C_5F_{12}	1.0017	0.17
Gas	He	0.00004	0.004

Fundamentals- Basic Cherenkov Equations-II

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

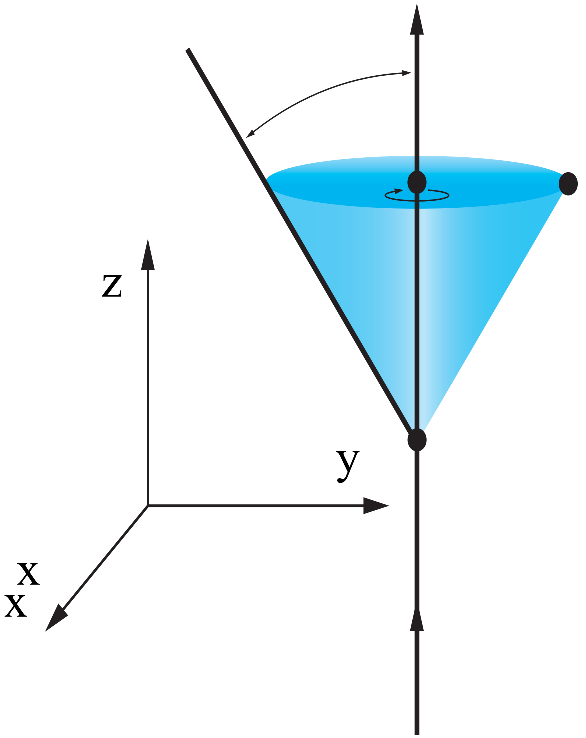
➔Conical Cherenkov radiation shell (the Mach cone) is not quite perpendicular to the photon propagation angle.

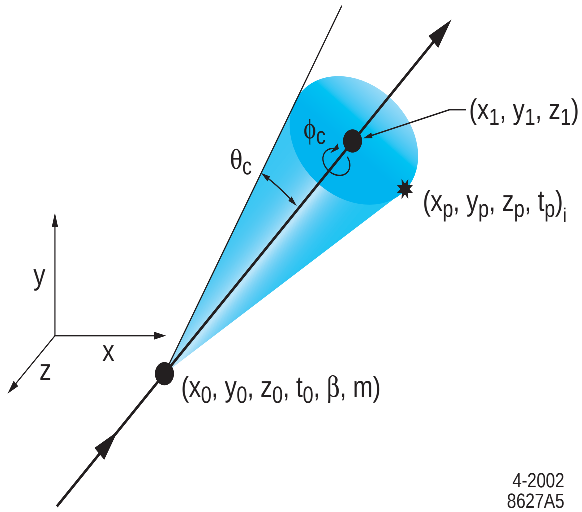
The half-angle of the cone opening (η) is given by,

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

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

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 z_e and detection point z_d

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

Cherenkov Fundamentals-Comments

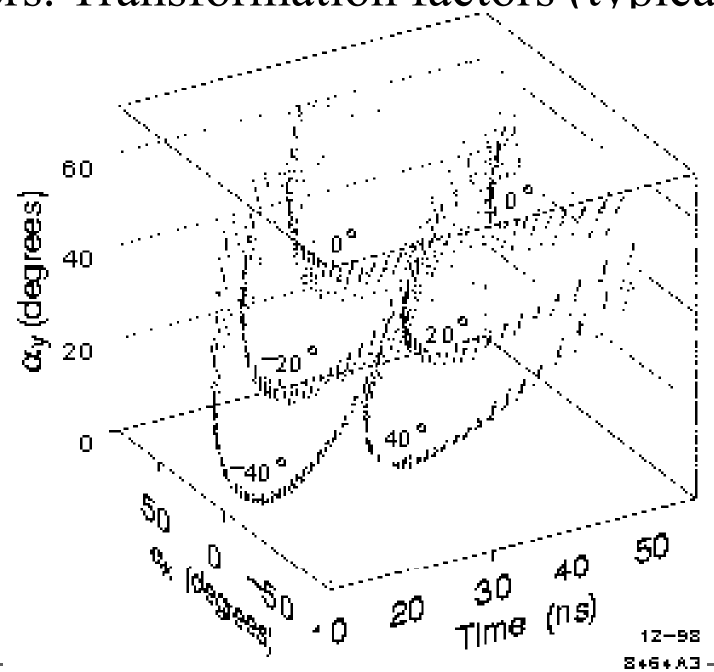
- In general, up to 3 measurements (α_x, α_y, t_p) are available to measure the 2 Cherenkov angles (θ_c, φ_c) with respect to a known track => nominal over-constraint at the single p.e. level.
- Powerful Ring correlation => can reduce "dimensionality" required of each photon measurement.
- Caveats:

  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

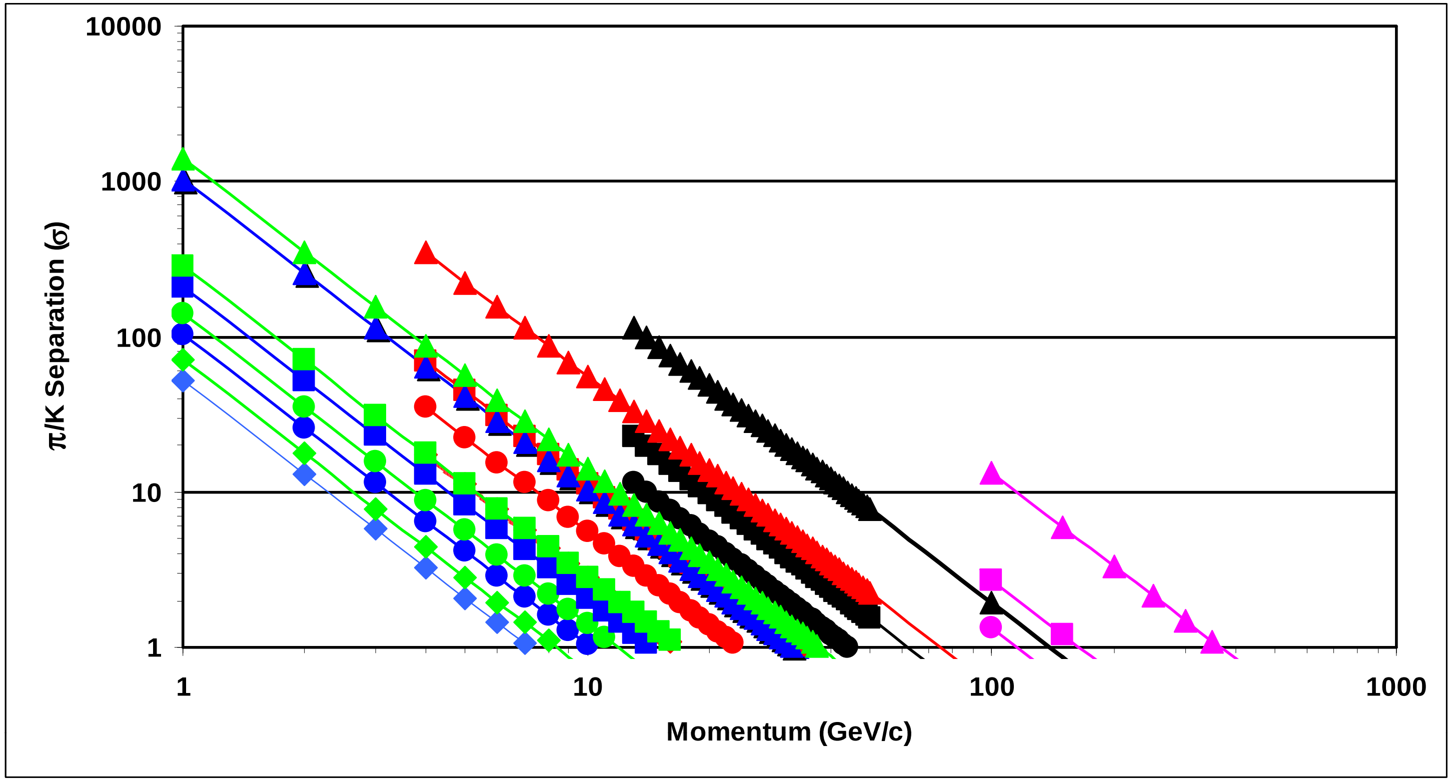


Fundamentals-Separation of Imaging Counters

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

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)

σ[θ$_c$(tot)]

◆ 2 mrad

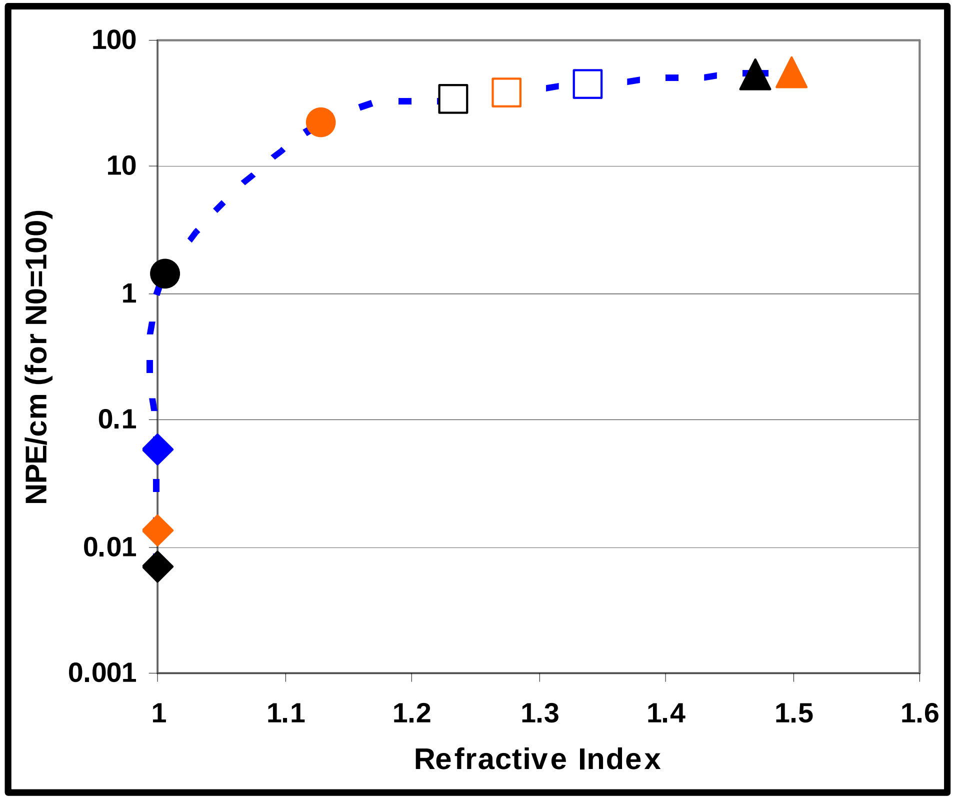
● 1 mrad

■ 0.5 mrad

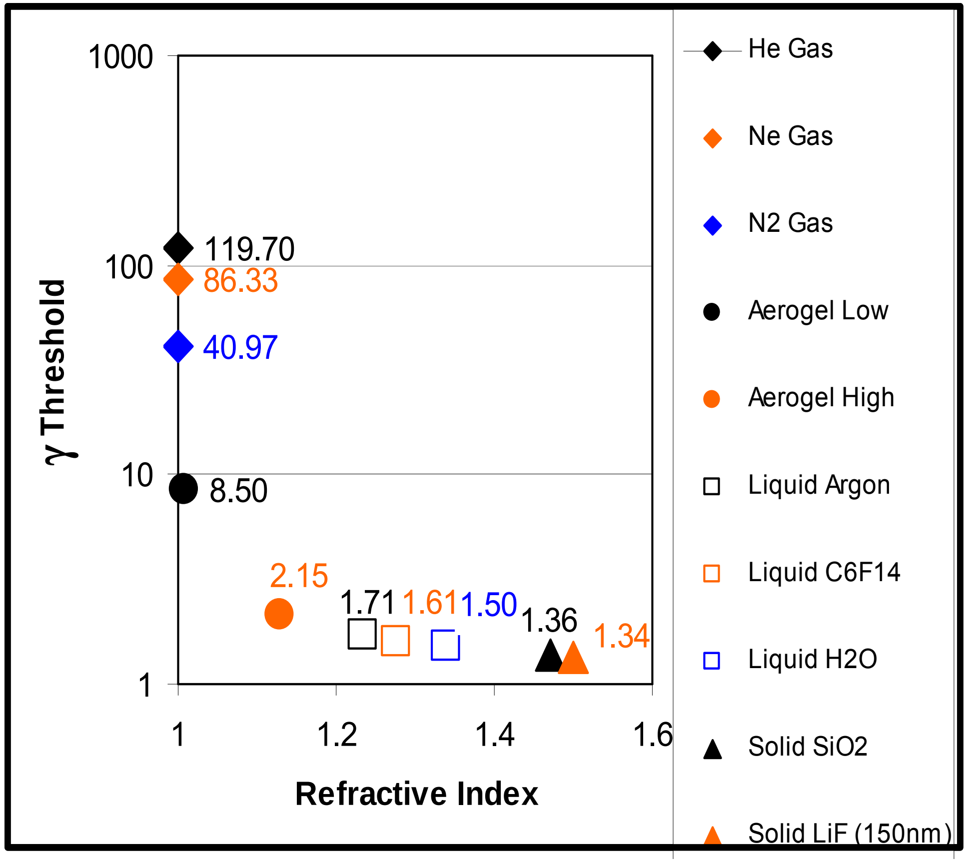
▲ 0.1 mrad

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. Transparency crucial.
- 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 wide variety of 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.**
e) **Correlated (constrained) focusing.**

"Standard" Optical techniques

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 and useful to reject background.
- High segmentation needed for resolution and background rejection.

Basic Types:

1. Vacuum-based
   a) Many different types (e.g, photomultipliers (PMTs); MCPs, HPMTs)
   b) Very sensitive, versatile, and robust. Very fast, low noise, high gain.
   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 work in some field directions.
   g) Development continues. Several pixelated types in use. Single PE resolution and timing resolution continue to improve.

Photon Detectors for Cherenkov Counters-II

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.

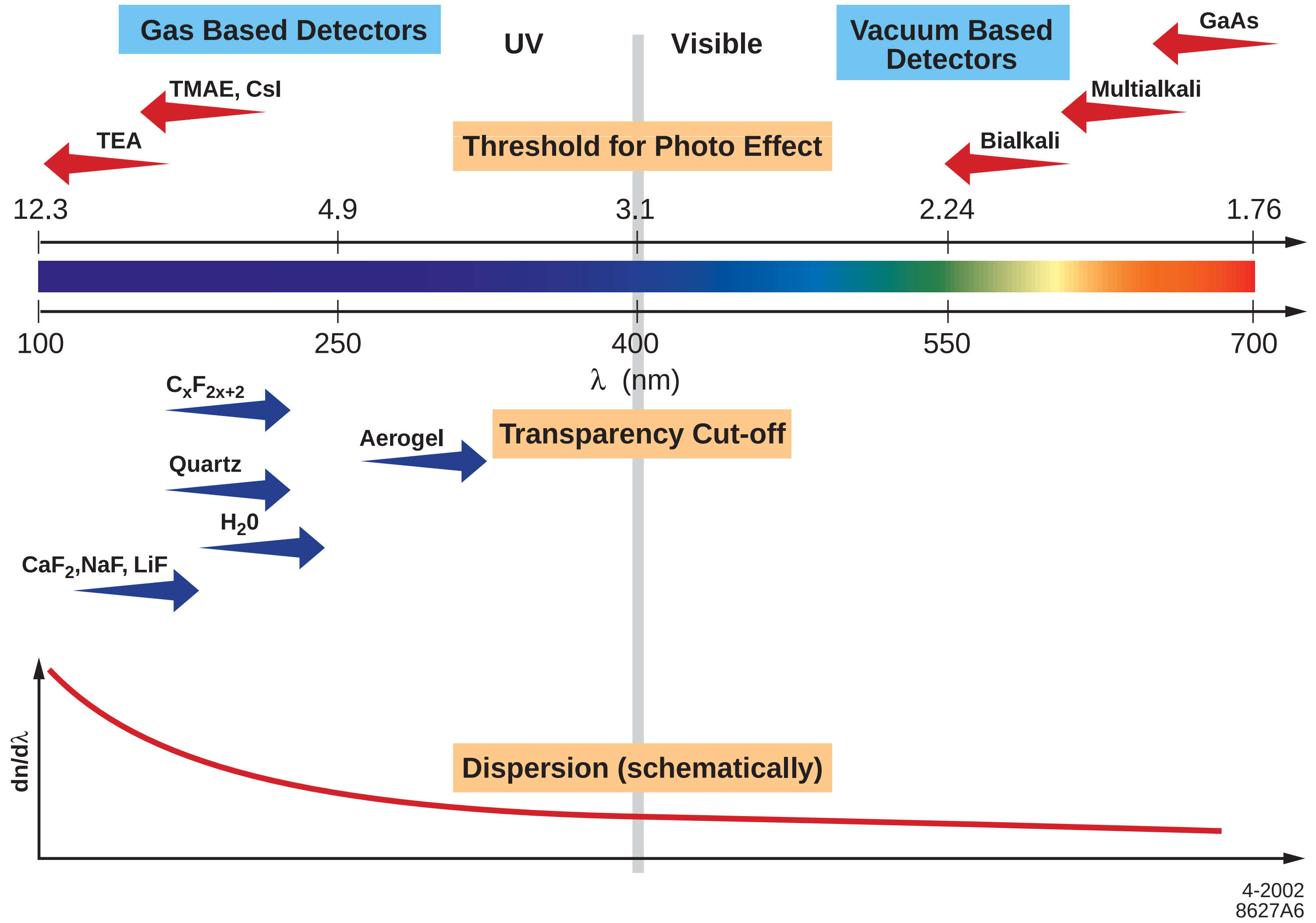
   d) Performance at high luminosity depends on photocathode and readout. Slow with TMAE, but can be faster with TEA or CsI. Difficult at the highest luminosities

   e) Too slow for time dimension focusing.

   f) Challenging operational characteristics.

   g) Can be used in magnetic fields.

Detectors-Photon Detection and Radiator Thresholds



An Aside- Think about PID Performance Metrics (N_σ)

Defining a PID Performance Metric (N_σ)

- Gaussian N_σ is far from the whole story. One wants to minimized Mis-ID (for unwanted particles) versus a maximized Eff. (for wanted particle).

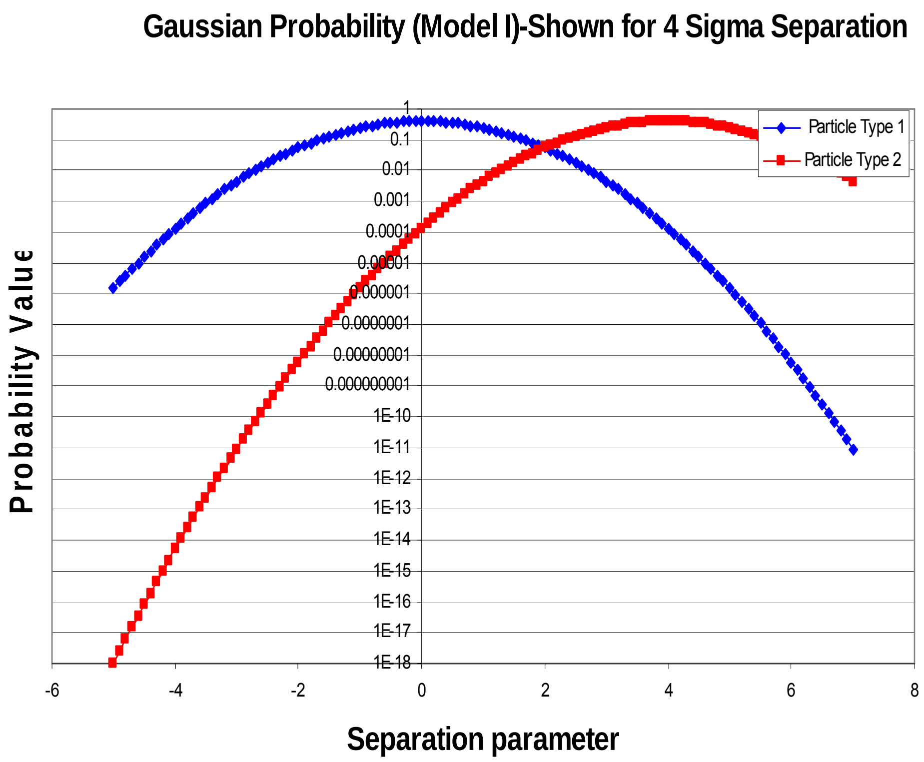
- Sources of Mis-ID include not only separation cuts (N_σ) but also physics effects (knock-ons, interactions, particle decays) as well as mis-tracking, backgrounds, etc. Many physics effects are asymmetric so that, e.g., π-k Mis-ID rates may be quite different than k-π rates.

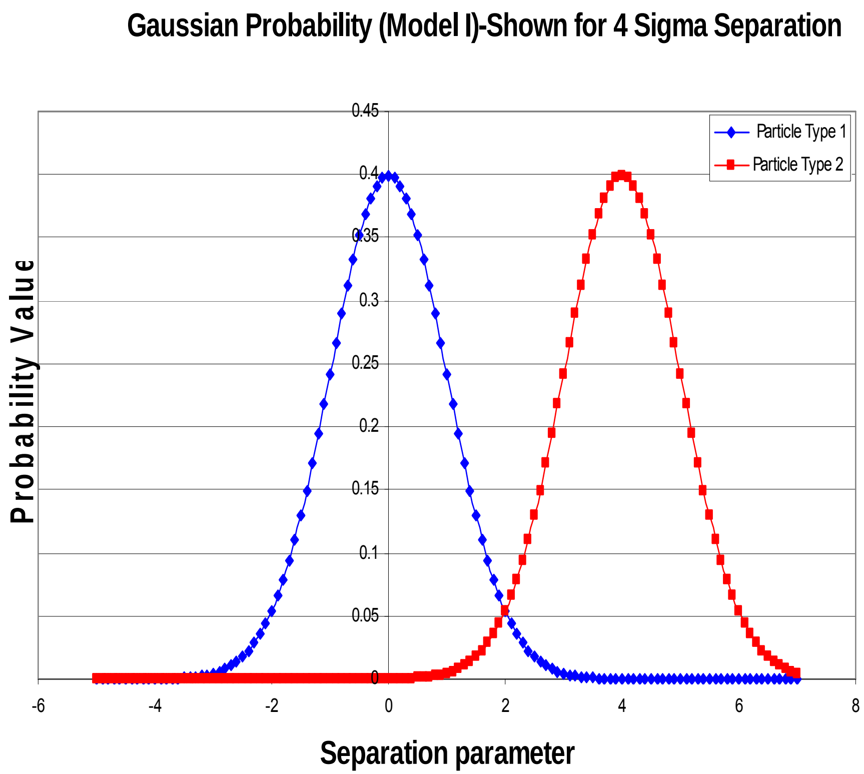
- Positive ID reduces but does not eliminate Mis-ID.

- Comment: Some sources of Mis-ID can be reduced by ~x10 with post RICH tracking. However, in realistic cases (at least at BaBar energies), the dominant effects on the physics come from physics effects in other parts of the detector. i.e, since physics "happens" as the particle travels through the detector, even perfect PID at the RICH leads to significant Mis-ID at the event vertex.

A pedagogical example

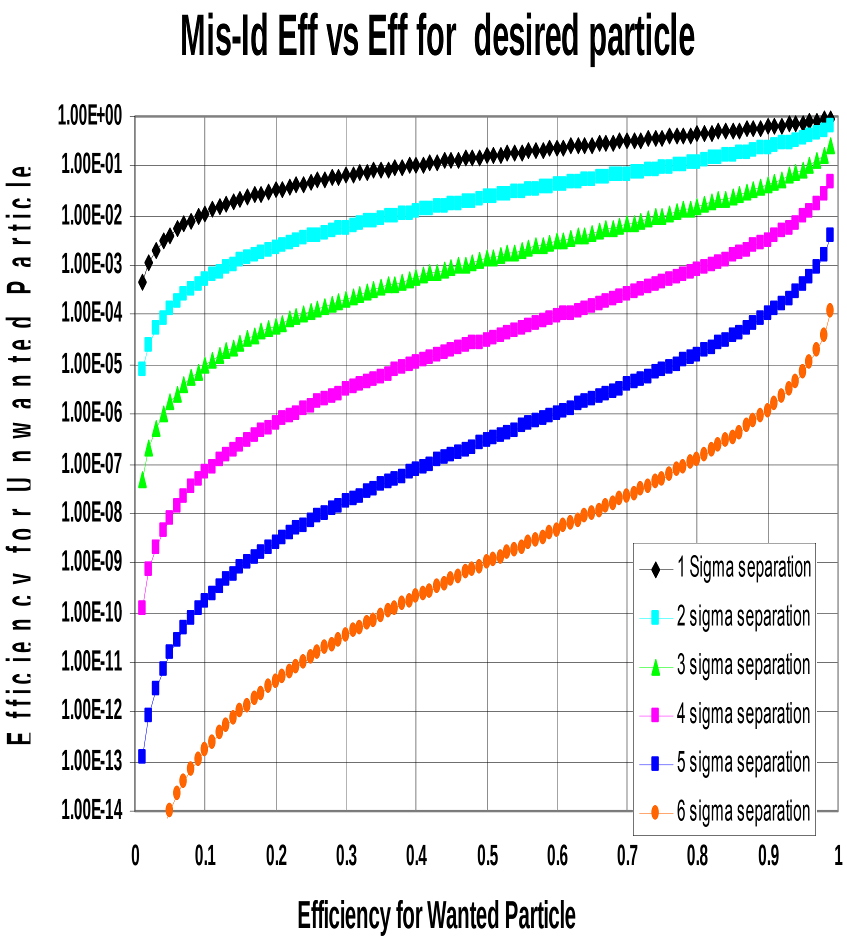
Consider single Gaussian PDFs for Two Particles with Equal Populations

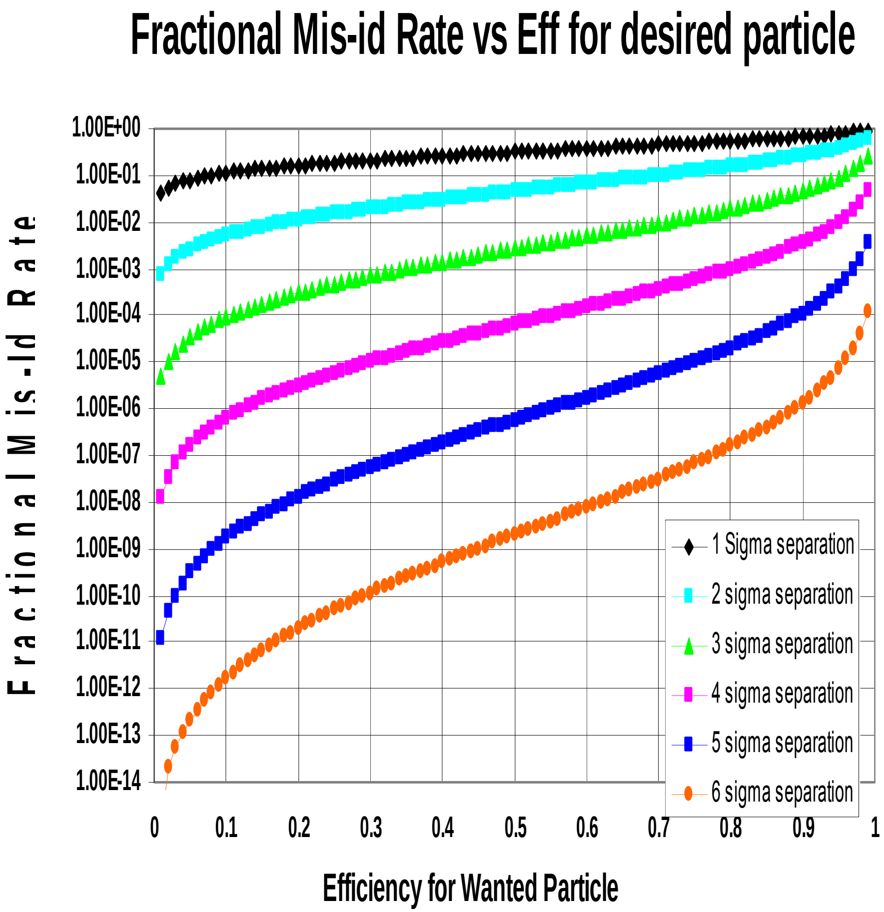




Mis-id vs Eff Performance-Gaussian Model

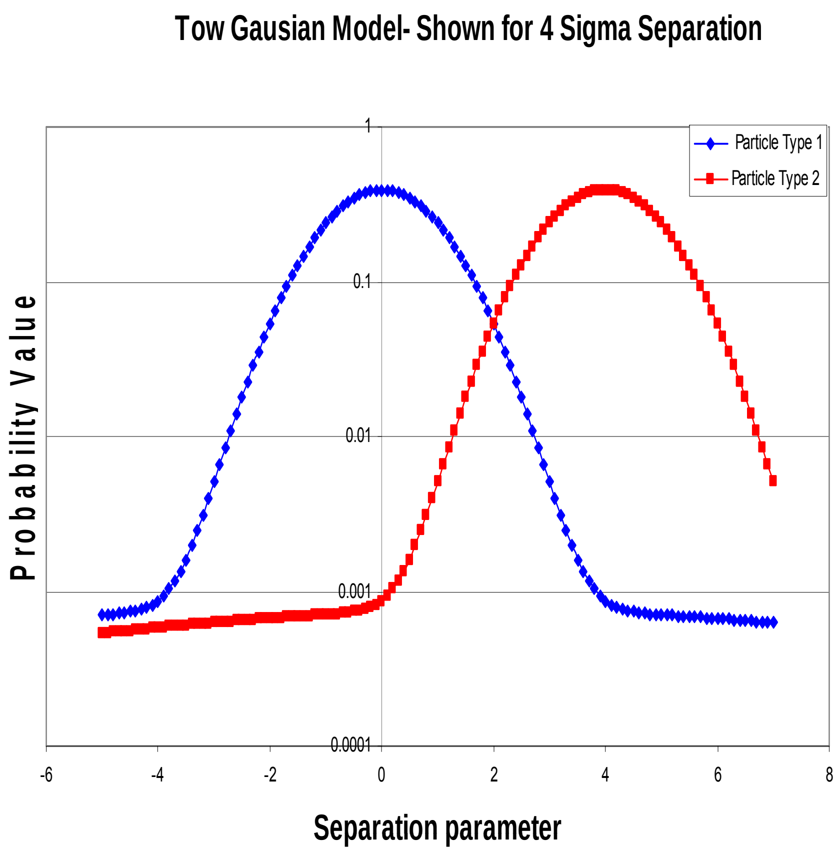
Pure Gaussian PDFs for Two Particles with Equal Populations

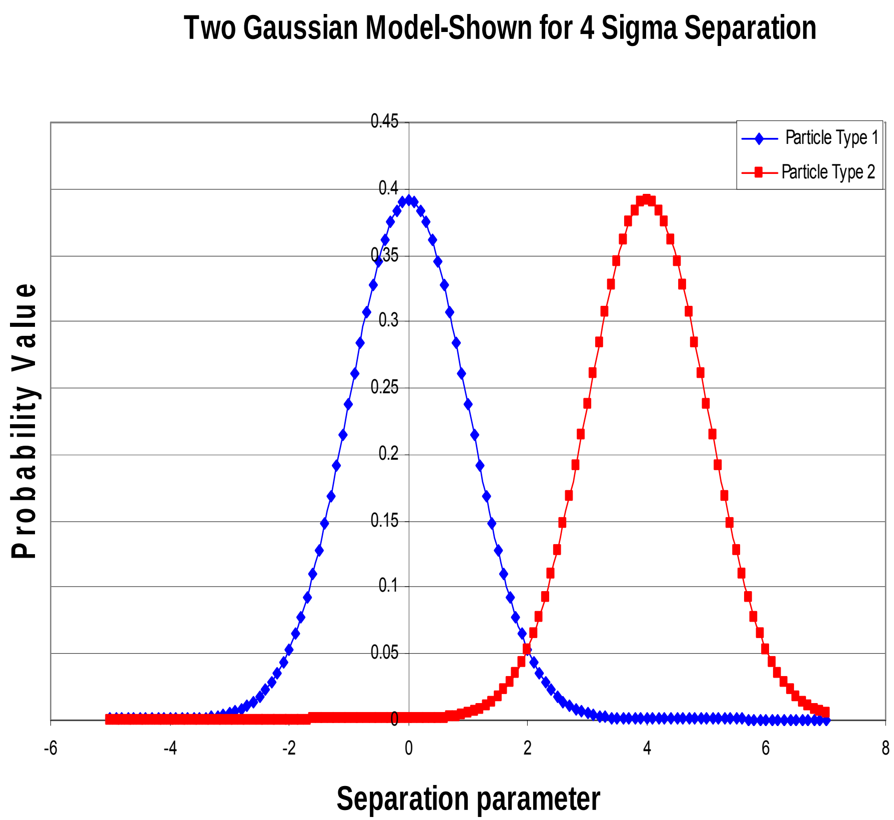




A bit more realistic model

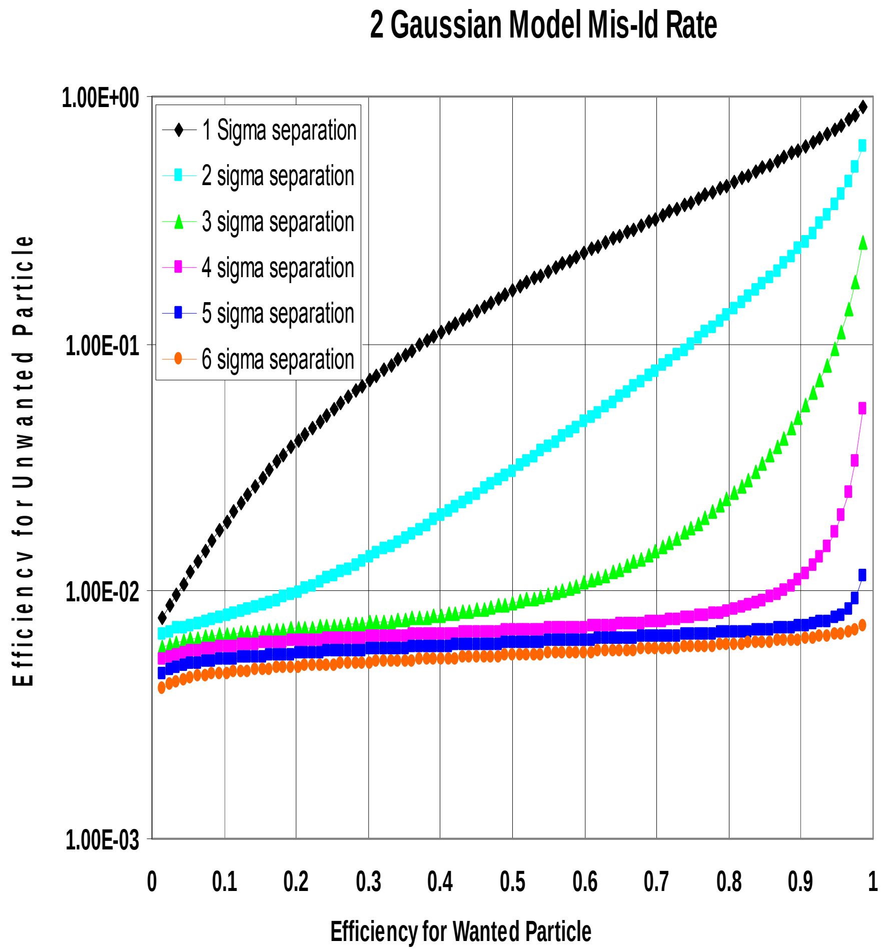
Now consider a separation model where the PDF for each particle comprises one Gaussian of width "1" contains 98% of the particles and the other of width "10" contains the other 2% of the particles.

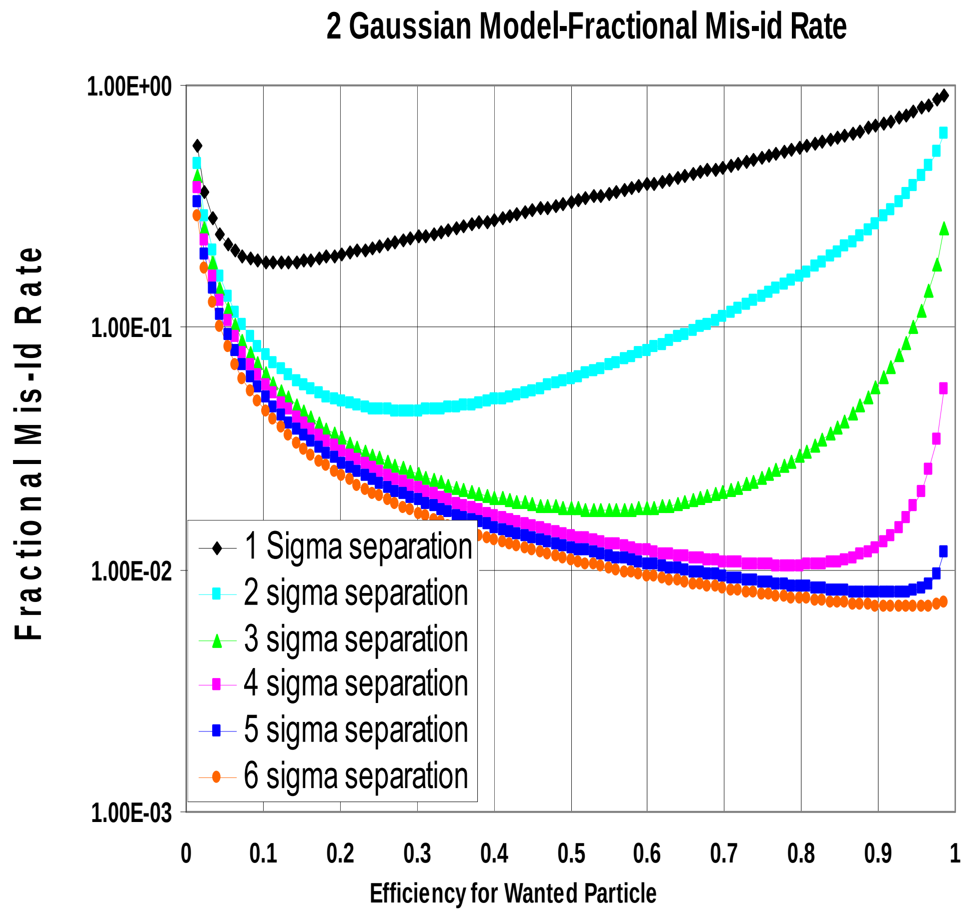




Mis-id vs Eff Performance-"More Realistic" Model

2 Gaussian PDFs for each of Two Particles with Equal Populations





- **For a fixed P range, "diminishing returns" as sigma separation improves.**

•~ constant Mis-ID rate-independent of eff (for "good enough" separation)
→ a minimum in Mis-ID rate.

Limits to RICH Performance

RICH Imaging-Limits to Performance

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

a) **Single photon resolution (see below)**

b) **N_{pe} : More photons are better, but number is constrained by photon detection technology available**

- **Larger detector bandwidth ➔ rapid increase in chromatic term**
- **Slow (Sqrt (Npe)) dependence in any case)**

c) **C (correlated term): Need excellent tracking and control of alignment systematics.**

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

➔ c) and d) are helped with a post PID tracking detector, but overall performance for the event is often limited by decays and interactions. (see discussion below)

RICH Imaging-Limits to Performance-Single Photon Resolution

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

1. $(\sigma[\theta_{\mathrm{Imaging}}]^2 + \sigma[\theta_{\mathrm{Detection}}]^2)$ …….. In principle, can make this combination almost arbitrarily good, but cost of pixels and high quality optics enforces limits.

➔ Must balance with other resolution components.

2. $\sigma[\theta_{\mathrm{Transport}}]^2$ is usually small except for DIRC type counters

e.g, in BaBar DIRC the side-to-face orthogonality of the bars gives ~1-4 mrad per photon.

➔ To improve

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

-1-D (plate) transport design.

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

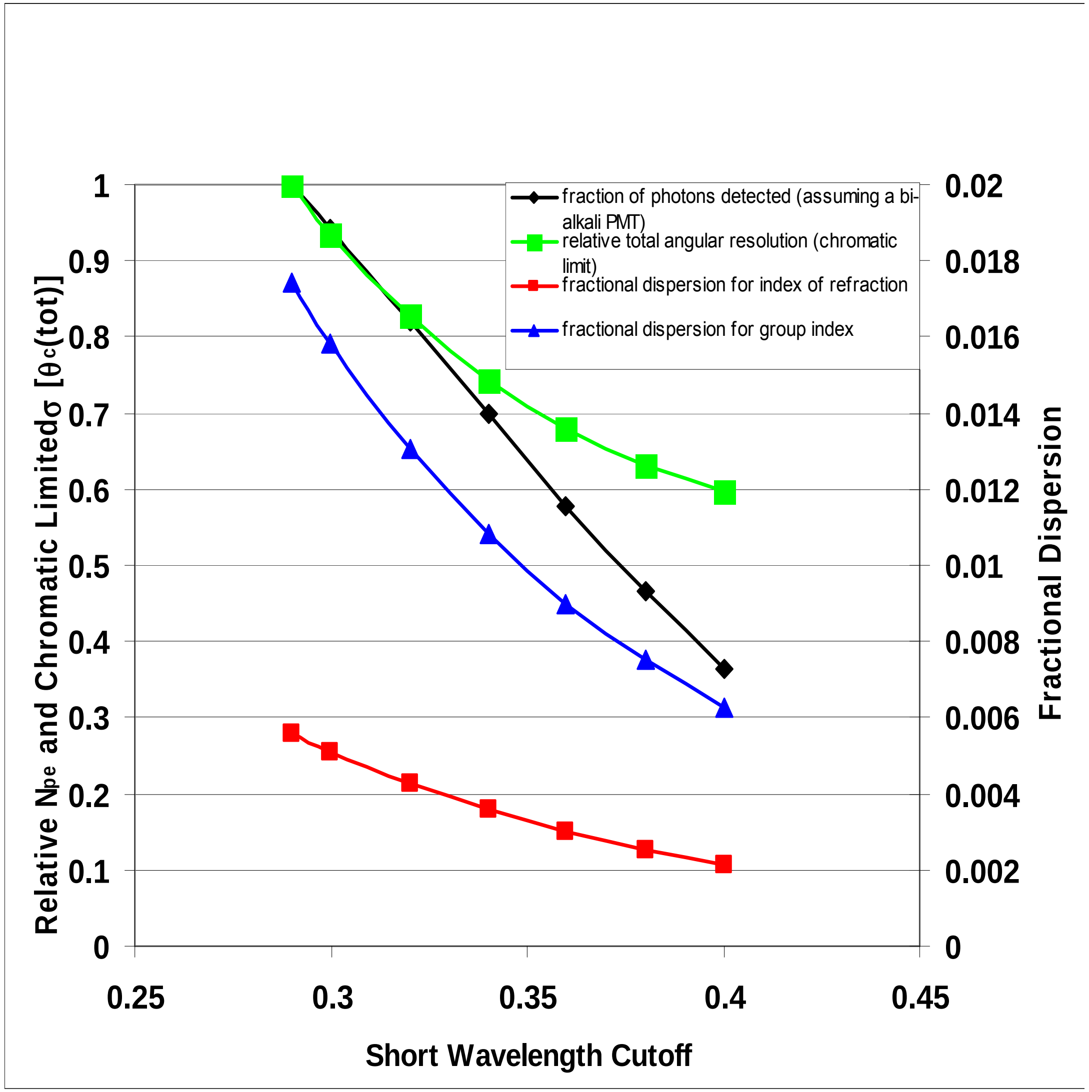
RICH Imaging-Limits to Performance-Chromaticity

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".

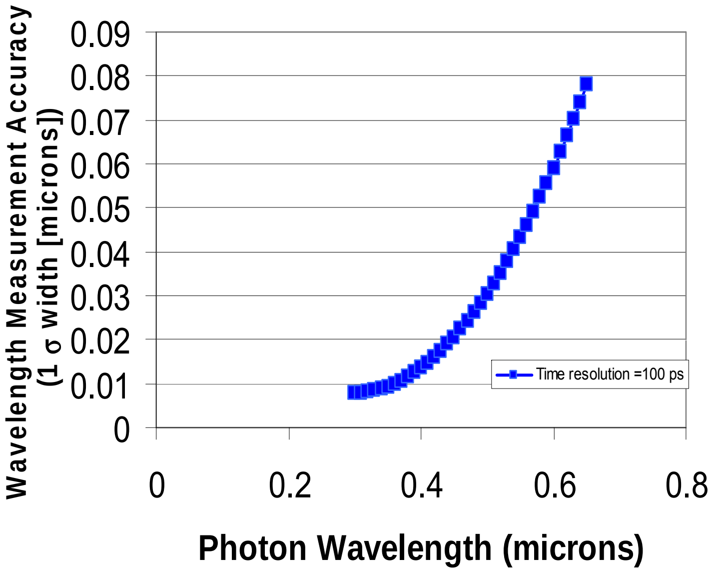
➔Big potential advantage for a detector response curve (~solid state devices) which is >> 50% in the visible (400-600 nm) with limited banwidth.



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 resolution at 6m. Scales with resolution.



Has been demonstrated…see talks at this workshop

Comparison of different PID devices

Generic properties of PID devices

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

One Page Synopsis of Pros and Cons

	PRO	CON
TOF	•Simple, rather thin •Fast •May use "free" space (from tracking) for TOF	•Low P only • Track Overlap unless channel count large
dE/dx	• Best acceptance • Uses "free" (tracking) space • Excellent ID at very low P	•Cross-over region where no ID •ID very modest at high momentum
C(threshold)	• Simple • Can be fast • With choice of radiators can cover wide P range	•Limited P range for each radiator • substantial space needed • veto ID
RICH	•Can be very fast •Wide technical choices •Widest P range •Positive ID. Lowest Mis-ID •Thin at low P	• Complexity • Cost • Very thick for high P

Threshold Cherenkov Counters

- **Threshold Counters**

  Separation usually depends on not seeing a signal for the below threshold particle("Yes/No or veto mode"). (A straightforward enhancement of this techniques uses the number of observed photoelectrons to discriminate between species).

  ➔ **Electronics, non-Cherenkov light production, extra tracks, and physics background noise sources (such as interactions, decays, and δ-rays) limit separation attainable.**

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

$$R \approx 200$$

Comparing RICH and 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**

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

➔ **Same separation dependence vs. momentum as a RICH (and no threshold) but with a very different scale!**

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 tunable**

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

RICH

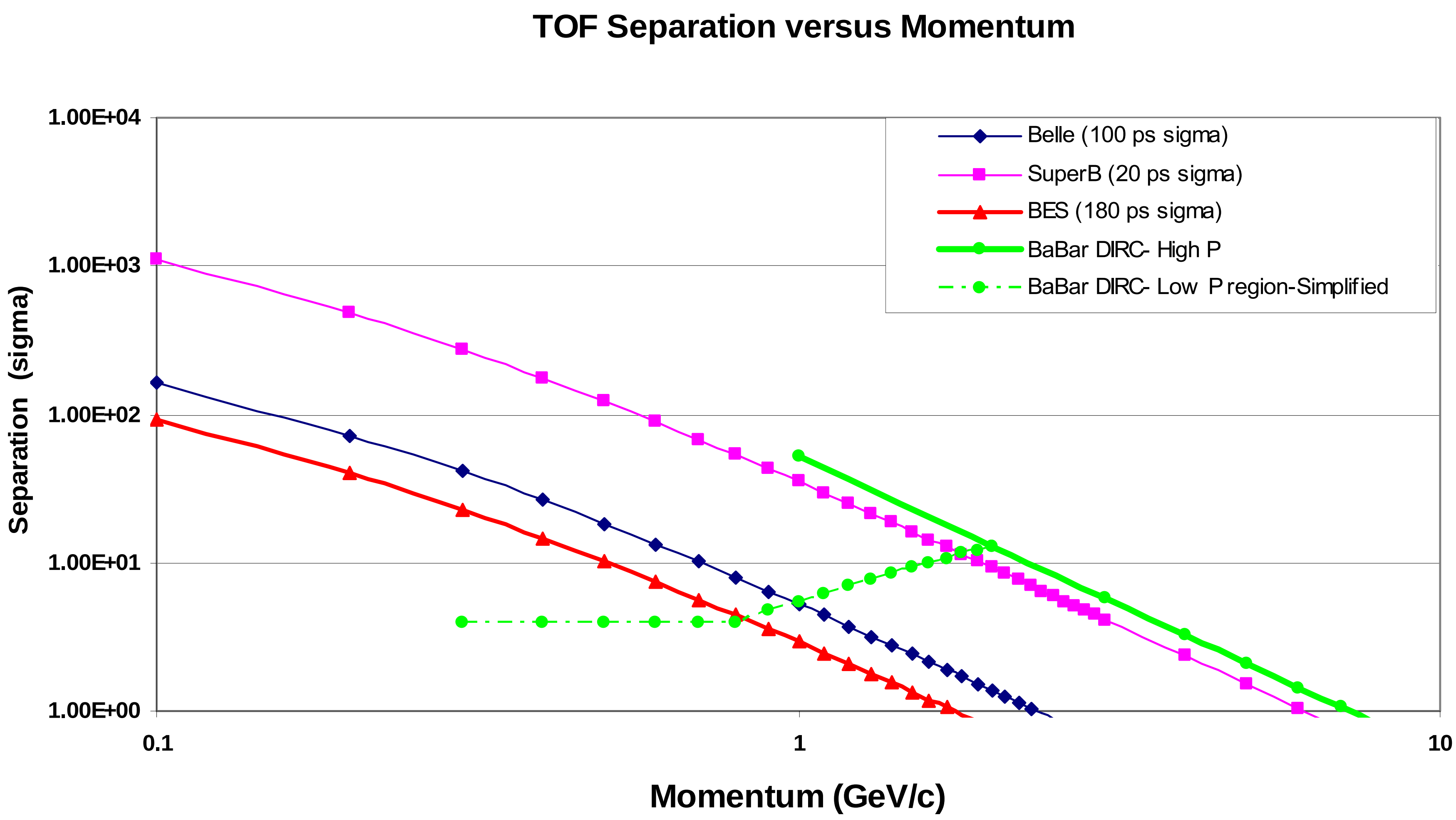
n ($pK_{thres\text{-}Gev/c}$)	σ(θ) **mrad**	Scale
1.474 (0.7)	2	462
1.0017 (3.5)	1	17140
1.000035 (84)	0.1	1.2E6

TOF

t_0 (ns)	σ(t) **ns**	Scale
5	0.2	25
5	0.1	50
5	0.01	500

RICH spans much broader range….but very fast Cherenkov TOF may be becoming feasible (see talks later at this conference).

TOF vs RICH Performance



- **Geometrical (P_T) Cutoffs ignored**

→ TOF provides fine separation at low P, but range is limited

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".

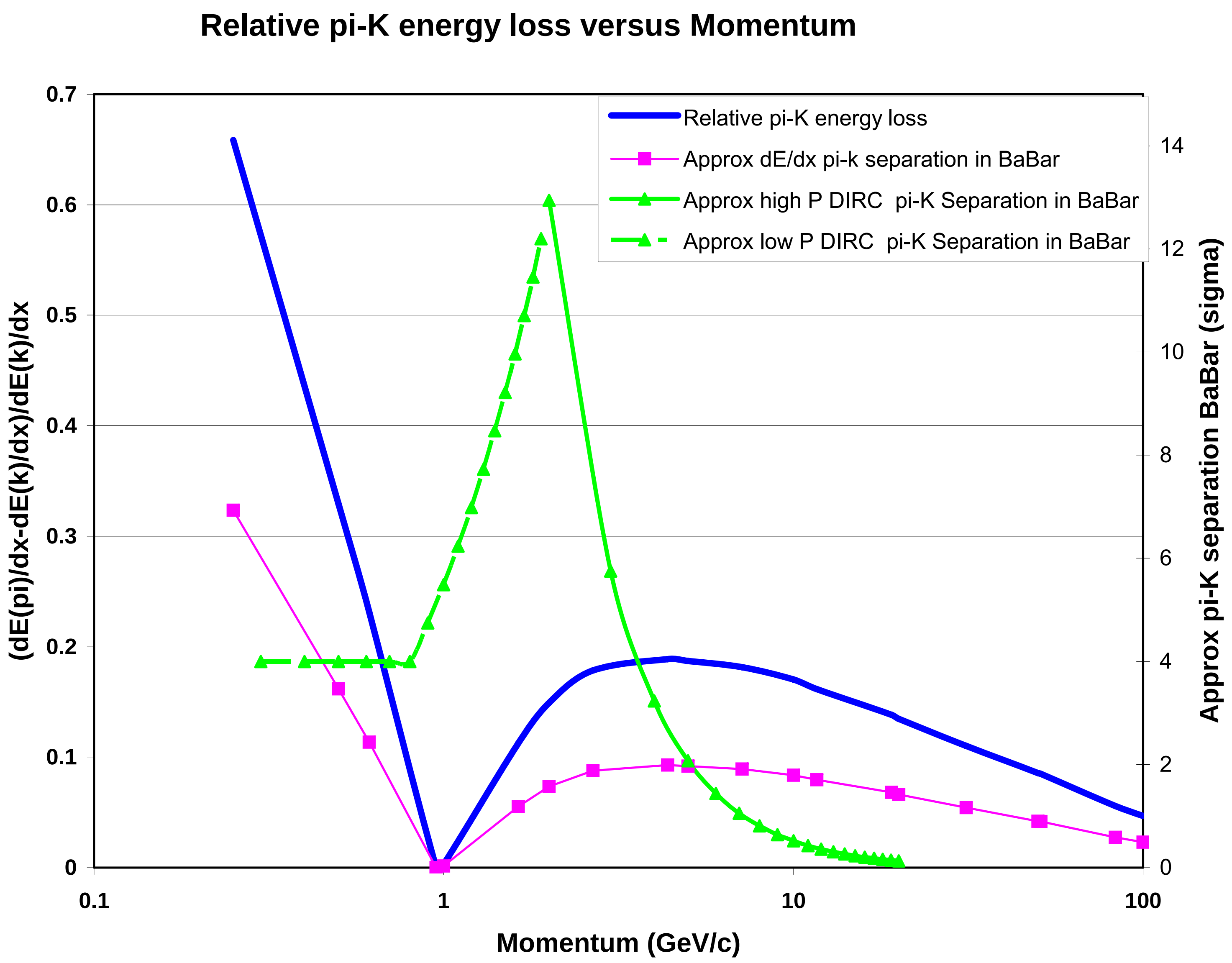
Features→ **(1) $1/\beta^2$ region at low p**

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

(3) "relativistic rise" region

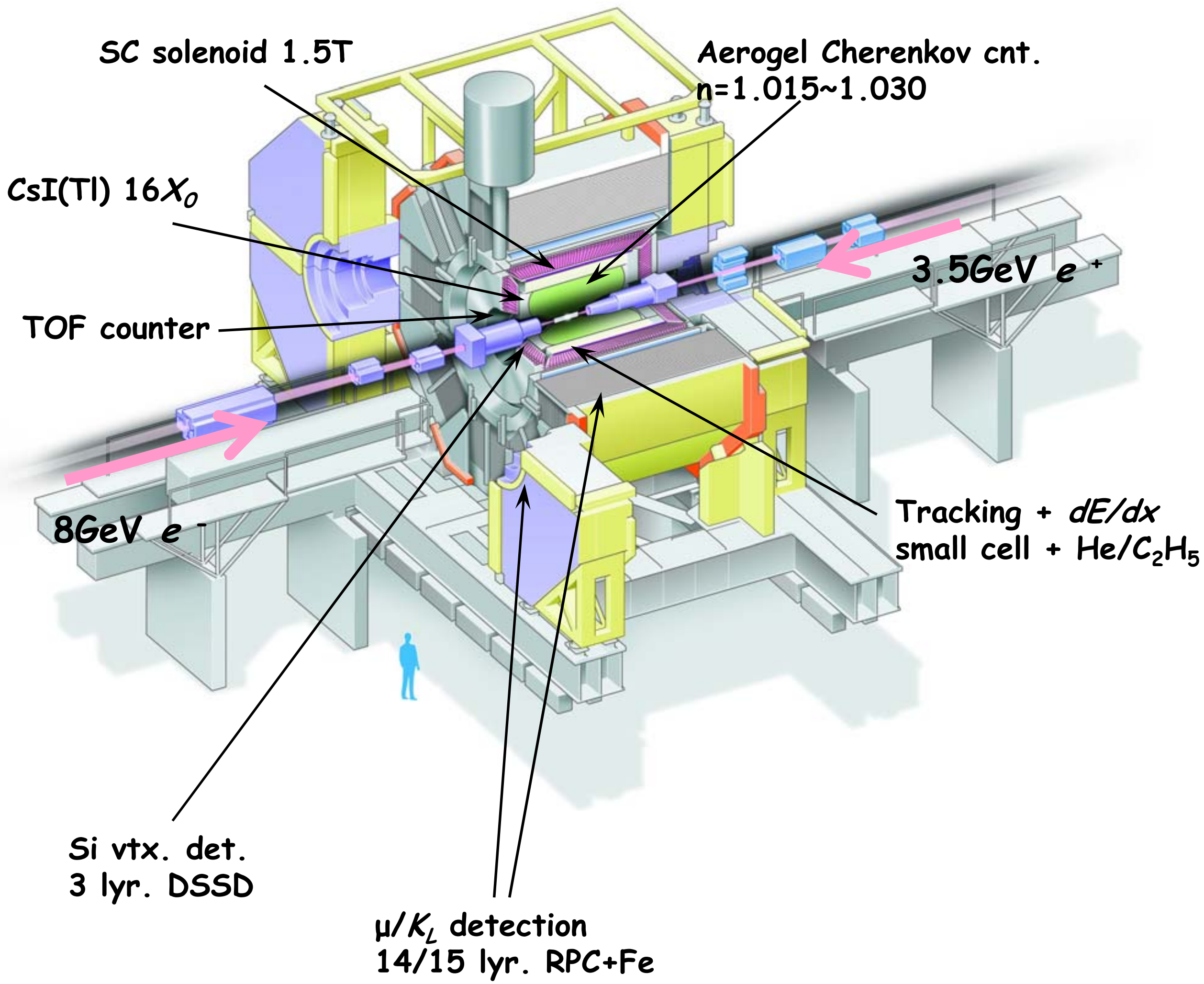
(4) Fermi plateau due to "density effect"

Comparing RICH and dE/dX

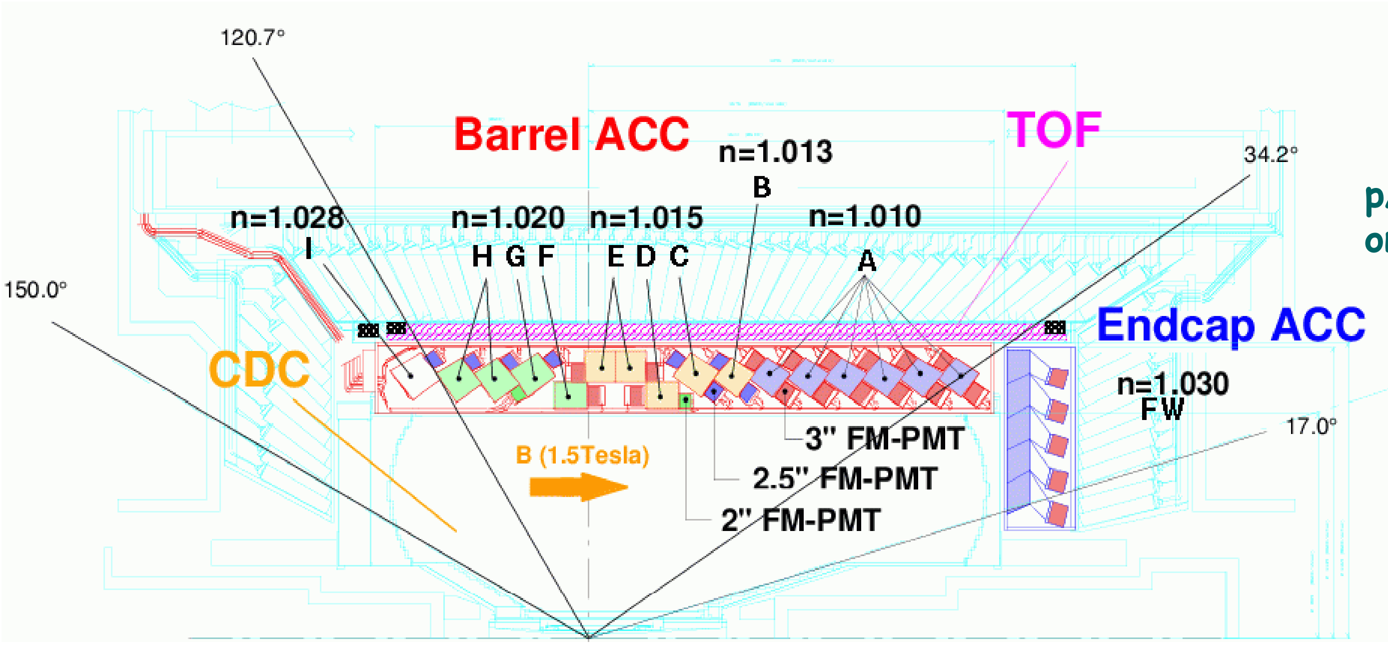


System comparison from the B Factories- Low Momentum Case

Belle Detector

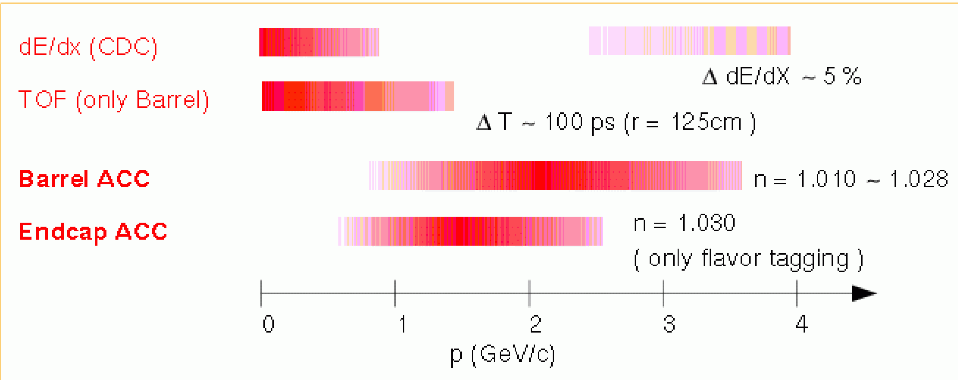


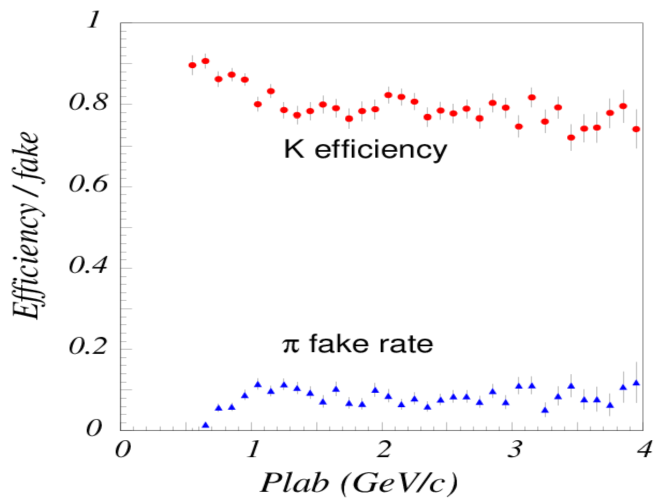
Particle Identification at Belle



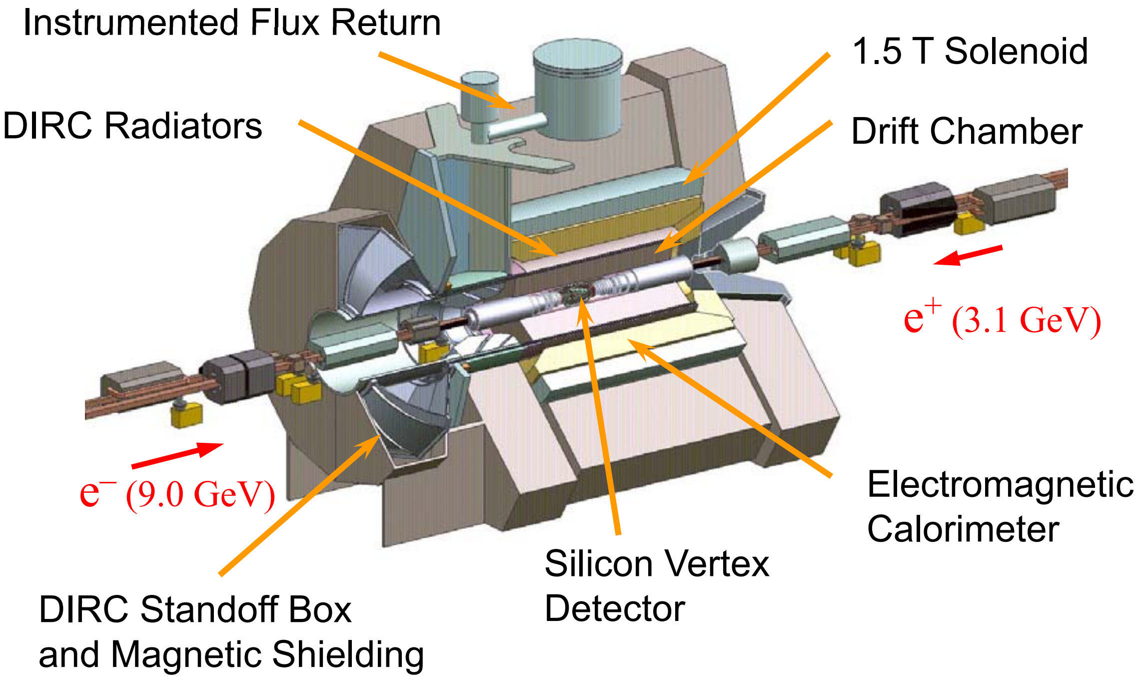
p/K/π separation is based on Likelihood ratio:

$$LR(K) = \frac{L(K)}{L(K)+L(\pi)}$$



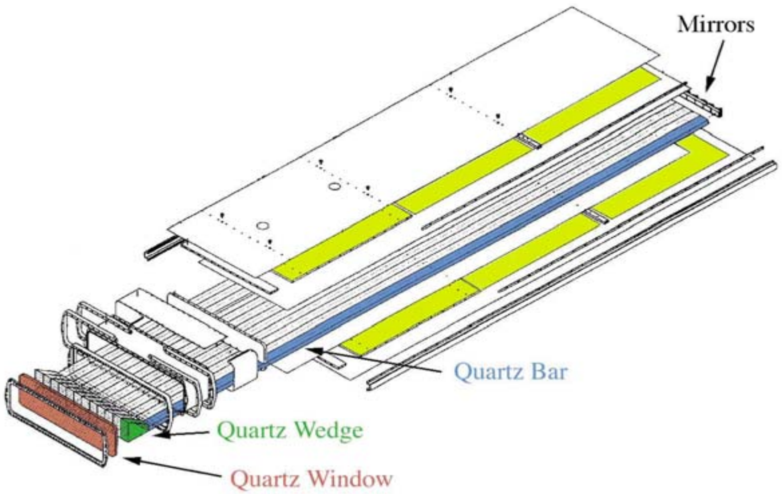


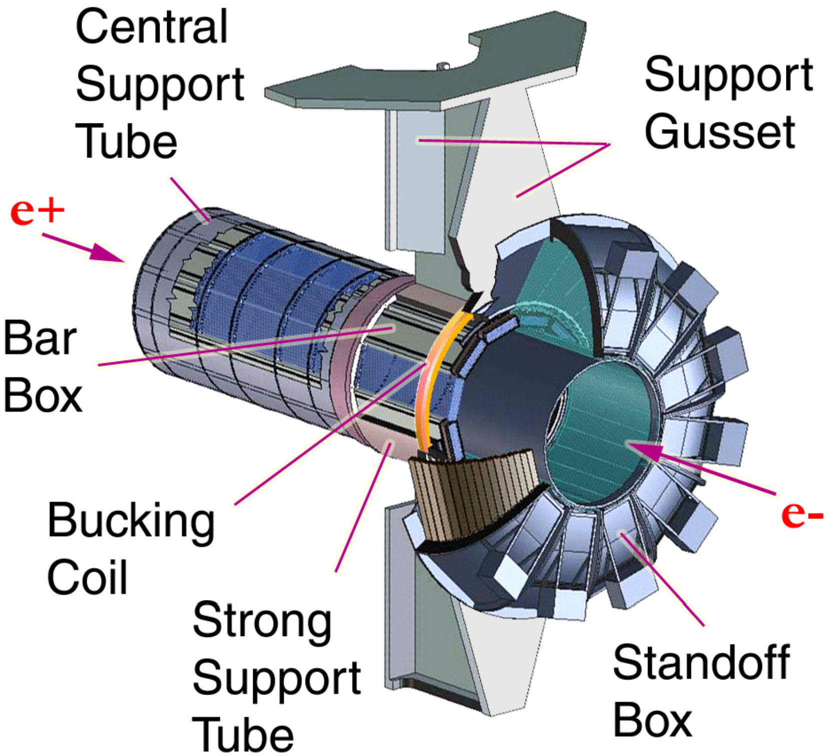
BaBar Detector



DIRC thickness:
- 8 cm radial incl. supports
- 19% radiation length at normal incidence

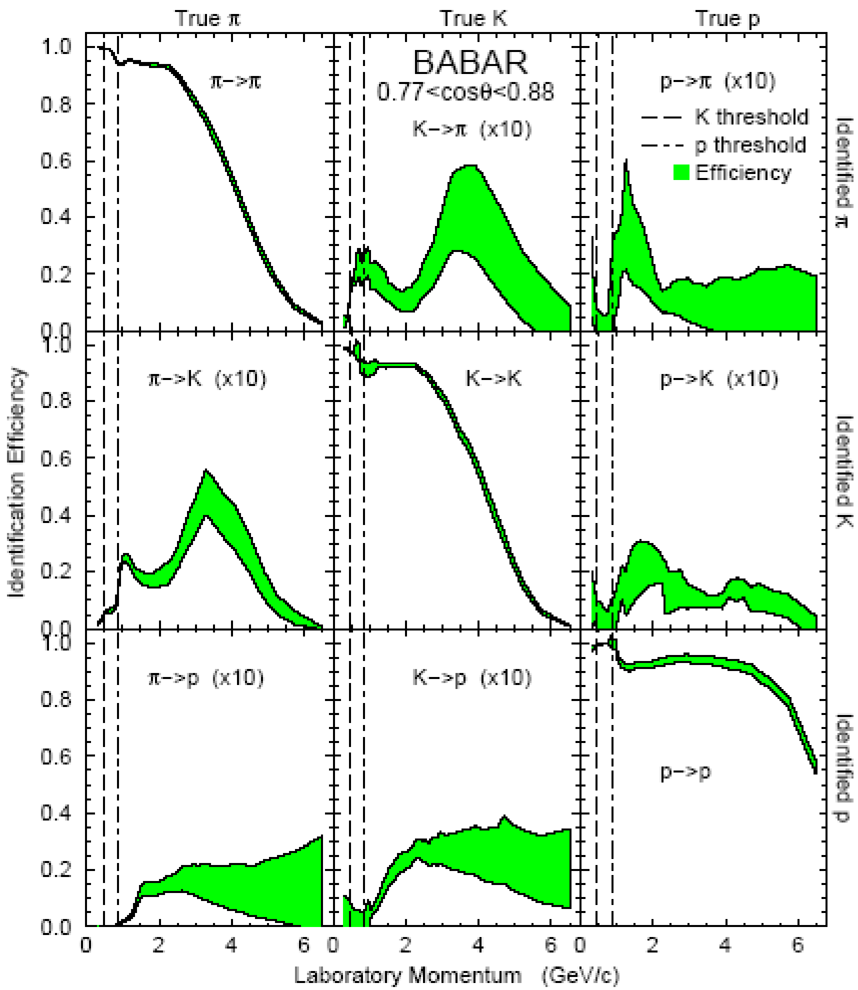
DIRC radiators cover:
- 94% azimuth,
- 83% c.m. polar angle



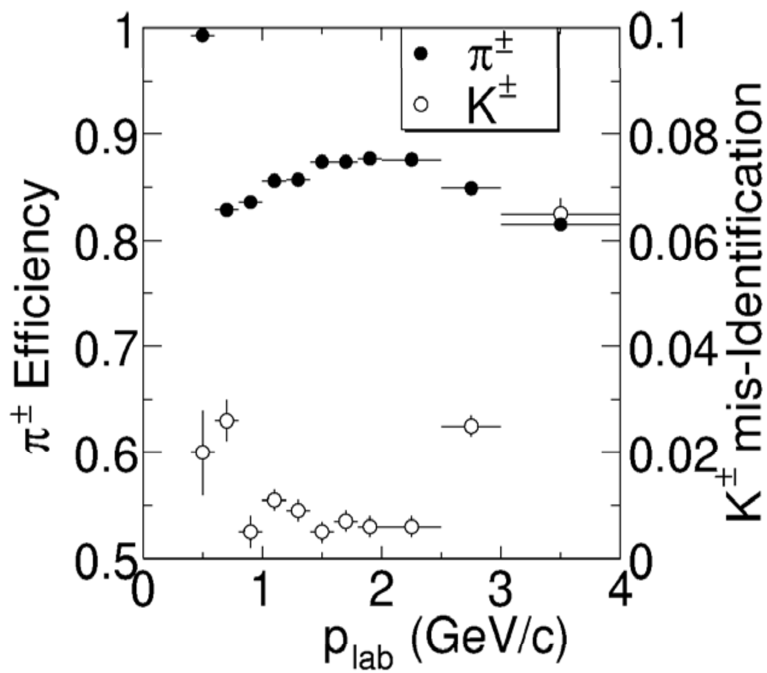


Hadronic PID at BaBar

Fully corrected efficiency/mis-id matrix for a standard selector. Bands represent uncertainties from control samples. Mis-id rates can be tuned down to ~1% over most of momentum space if needed



B to ργ



- B to ργ topology identical to $K^*\gamma$, which is expected to have ~20x the BF. Need to reject Kaons by positive pion ID.
- Optimized cuts give ~1/2-1 percent K mis-id for most of the events.

Future Evolution of PID techniques?

TOF	• Very fast PMTs (~1 ps possible?) • Cherenkov light vs. scintillator light • Very long path lengths with small acceptance
dE/dx	• Cluster counting…. could get ~ 2x resolution (may be feasible with modern electronics) ➔ Could get usable PID in relativistic rise region
C(threshold)	• Faster photodetectors insensitive to magnetic fields? • Improved aerogels
RICH	• Very fast PMTs. Small pixels • Use of timing to measure angle, TOF, and/or correct chromaticity. • Clever Optics • Improved aerogel radiators • Very large natural radiators

A RICH reprise

• RICH technique is extremely broad and powerful technique that has applications in an extremely wide range of fields.

→ The gold standard for PID

- "Tunable". Can deal with a very wide range of momentum. Provides positive ID.
- Many choices available for optics, detectors, geometrical configurations, and radiators. Developments continue.
- Technique of choice at accelerators when very high quality hadronic (pi/K/P) PID is required.
- Moreover, the use of water tanks or natural media (ice/water/atmosphere) as radiators allows the construction of massive instruments with excellent performance for neutrino and astroparticle physics, and also provides excellent π/e separation in Heavy Ion physics

• Primary limitations are geometry and costs.

→ A final advantage of RICH is the community of builders and this great series of conferences. I am looking forward to an enjoyable and productive week!