Ring Imaging Cherenkov (RICH) Detectors

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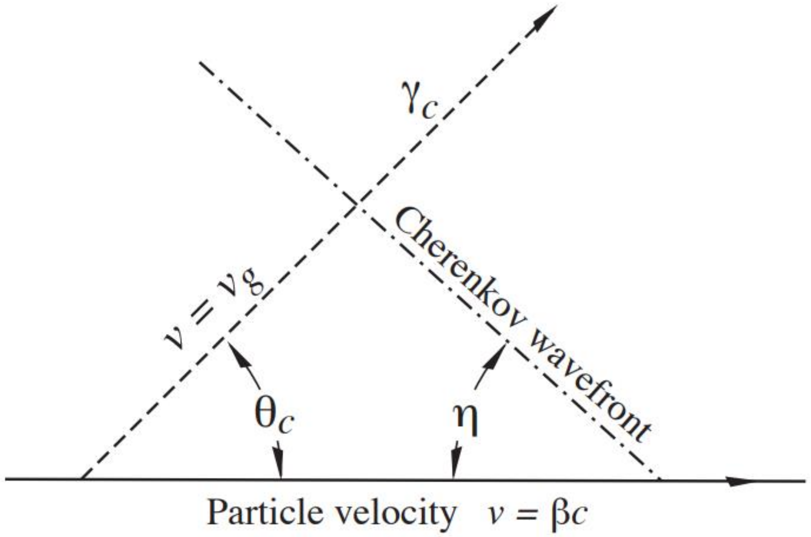
Cherenkov Radiation Reminders

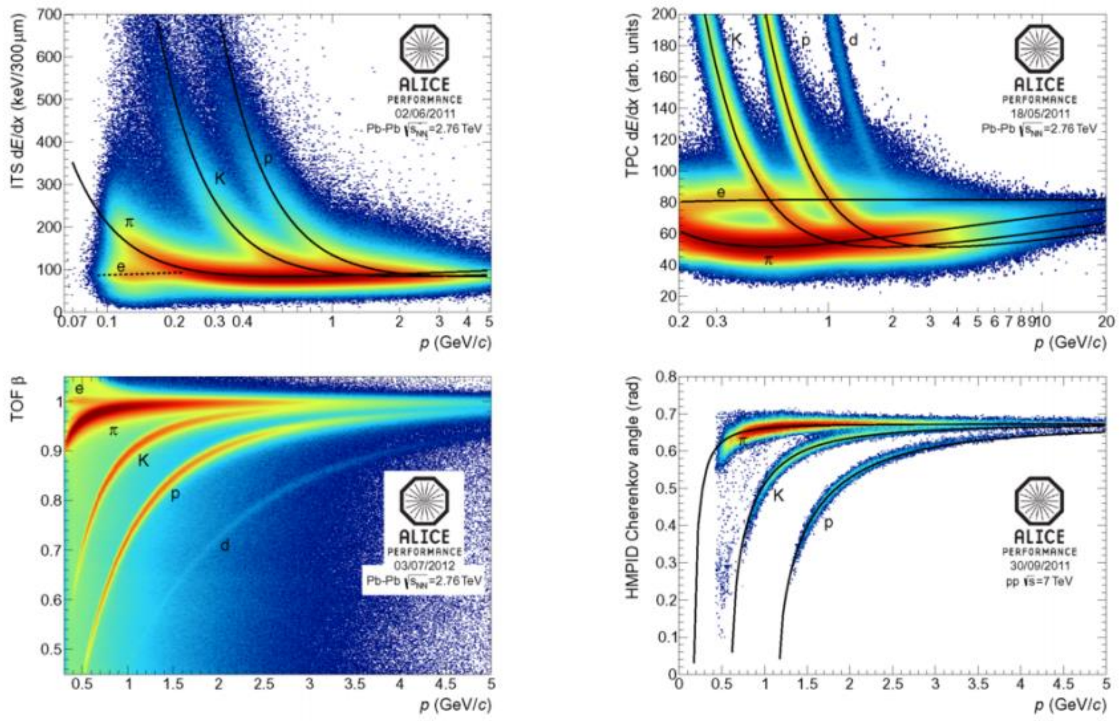
- Radiation emitted by a charged particle moving in a medium with $\beta > \frac{1}{n}$ or passing between materials of different refractive indices.
- Radiation profile peaked very sharply at the Cherenkov angle $\cos\theta_c = \frac{1}{n\beta}$
- Number of photons emitted at energy E to E+dE in length dx

$$\frac{d^2N}{dxdE} = \frac{\alpha}{\hbar c}\sin^2\theta_c = \frac{\alpha}{\hbar c}\left(1 - \frac{1}{n(E)^2\beta^2}\right)$$



Fundamentals of Cherenkov Detectors

- Most Cherenkov detectors are primarily PID detectors
  - Measure β, p, calculate $m = \frac{p}{\beta\gamma} = p\sqrt{\beta^{-2} - 1} = p\sqrt{\sin^{-2}\theta_c - 1}$
- Cherenkov radiation also used in TOF detectors and some calorimeters
- The strong velocity dependence of the radiation profile and the specific geometrical pattern are usually taken advantage of
- The low number of photons produced is a consistent challenge
- Typical detectors consist of 3 stages
  - A radiator with tunable parameters L, n in which particles emit light
  - Optionally, a focusing apparatus to direct the Cherenkov light to a photodetector
  - Light collection and detection

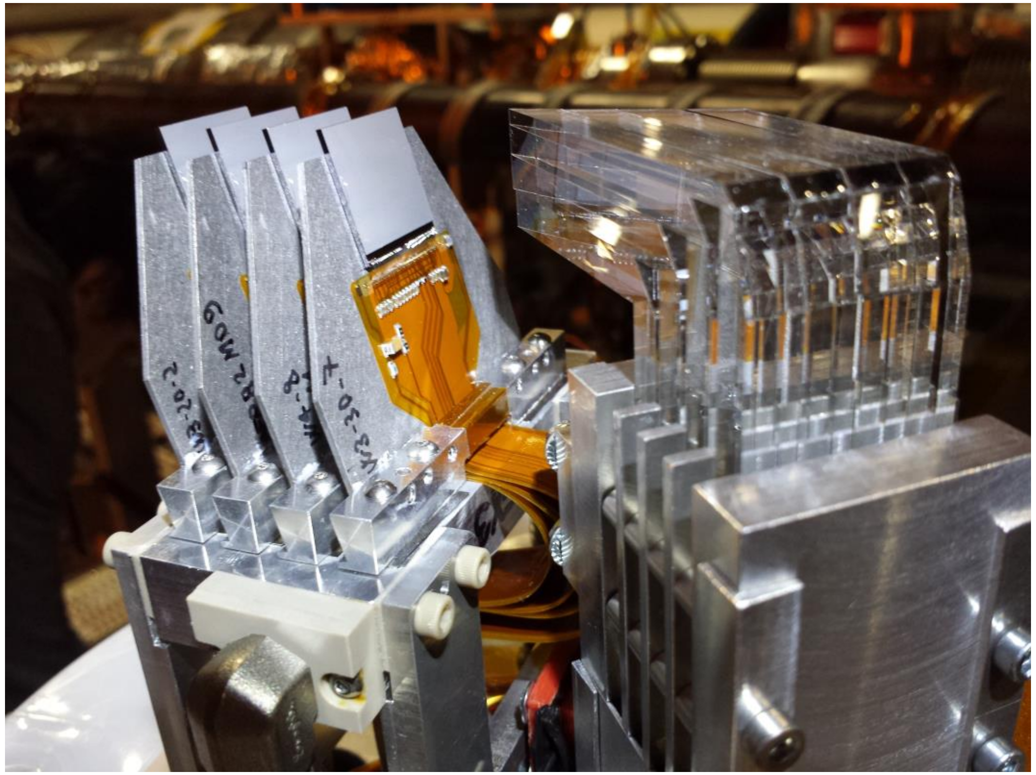


Resolution Considerations

- For a typical PMT, $\int \epsilon dE \approx 0.27 \text{ eV}$, which with an acceptance of 90%, gives
$$N_{p.e.} = L \times 90 \text{ cm}^{-1} \times \sin^2 \theta_c$$
- For a PID detector measuring the Cherenkov angle, the velocity resolution goes as
$$\frac{\sigma_\beta}{\beta} = \tan \theta_c \, \sigma_{\theta_c} = \tan \theta_c \sqrt{\frac{\sigma_{\theta_i}^2}{N_{p.e.}} + \sigma_{det}^2}$$
- In the relativistic limit, the separation power for two species becomes
$$S \approx \frac{\left|m_1^2 - m_2^2\right|}{2p^2 \sigma_{\theta_c} \sqrt{n^2 - 1}}$$

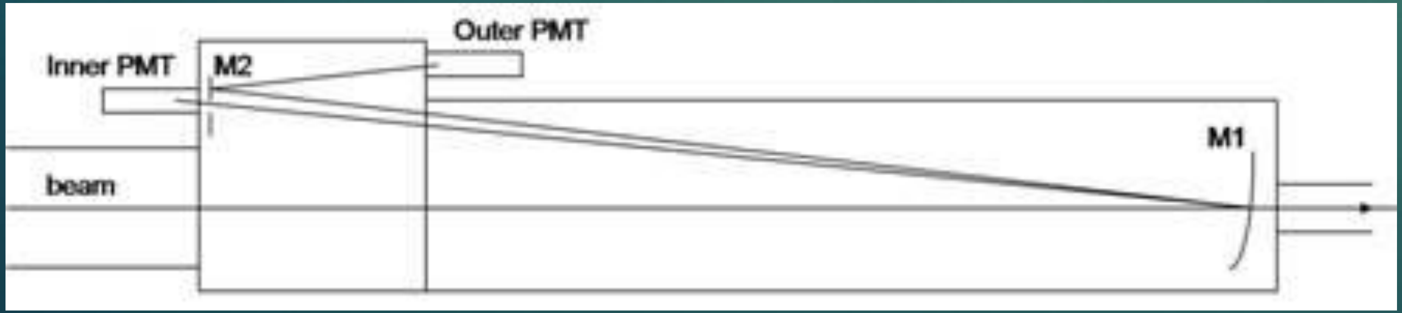
Non-Imaging Cherenkov Detectors

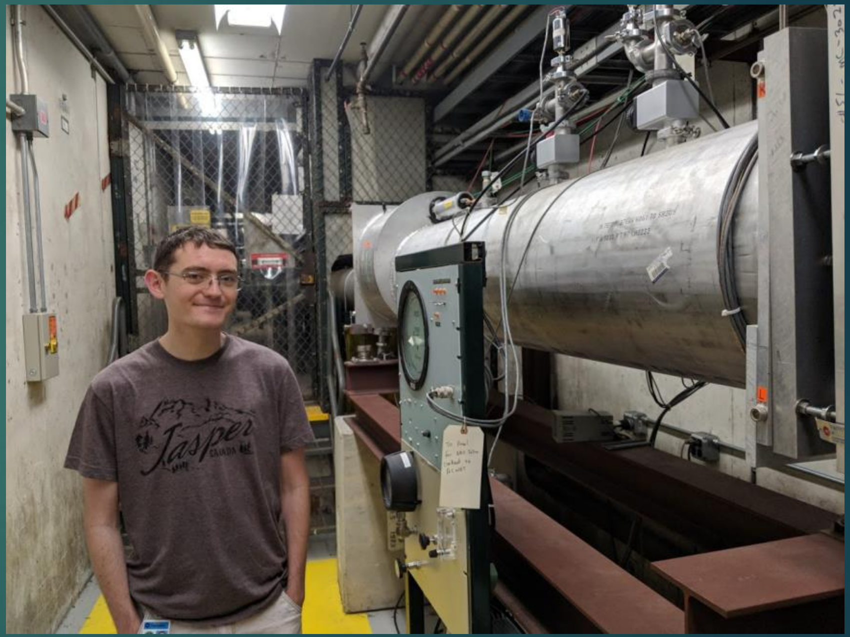
- The first Cherenkov detectors were of a binary nature, only able to identify the presence of a particle traveling above the threshold velocity !cite!
- The next improvement was to measure the number of photons emitted $N_{p.e.}$
  - $N_{p.e.} = LN_0\langle\sin^2\theta_c\rangle, \quad N_0 = \frac{\alpha}{\hbar c}\int dE\epsilon(E)$
  - Photon detection efficiency is a product of an energy dependent efficiency and a geometry dependent acceptance
- This allows some PID for particles above threshold



Differential Cherenkov Detectors

- Simplest detector based on measuring θ_c
- Can achieve very good separation between two species in a beam

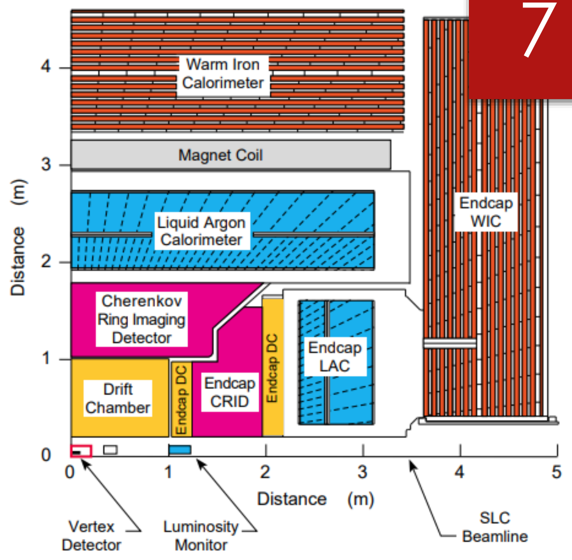




Summer 2018 – Differential Cherenkov Detector at Fermilab's FTBF

Ring Imaging Cherenkov Detectors

- RICH counters are distinguished by imaging the whole Cherenkov ring in order to measure θ_c
- The goal of such a detector is usually to distinguish e/p/K/π over some momentum range
- The first RICH detectors date to the LEP era (DELPHI, SLD)
- Example SLD – 2 radiators, light reflected into drift chamber doped with TMAE to detect photons
- Gas (liquid) detector typically detects 12.8 (9.2) photons with angular resolution 16 (4.5) mrad
- π/K/p separation achieved in the range 0.25-45 GeV



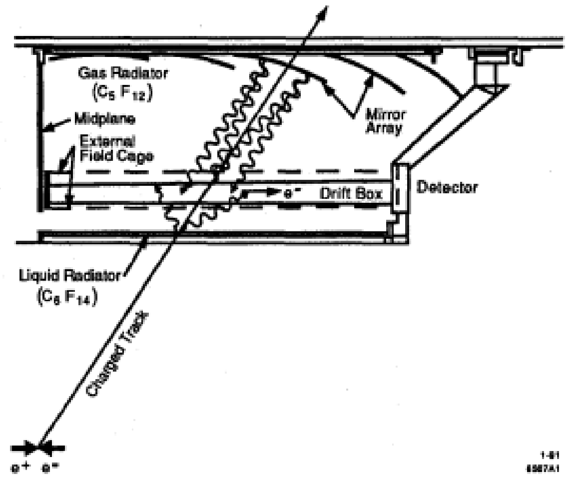
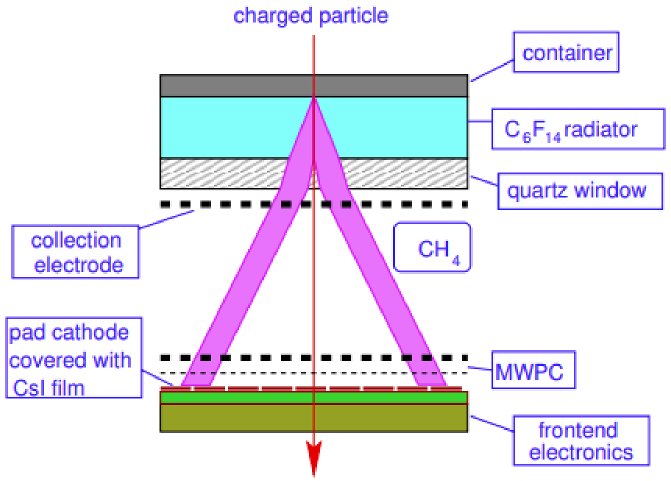


Figure 1: Quarter section of the SLD barrel CRID showing its principal components.

Survey of Modern RICH types

- RICH detectors vary in their choices of radiator, focusing mechanism, and photodetection
- The most significant design decision for integration with a larger detector system is the geometry/focusing
- The SLD layout – known as mirror focused – is used in ABC
- Proximity Focused RICH's simply have the photodetectors in line with the radiator without intervening optical elements
- The most exotic of these configurations is the DIRC



Schematic of proximity focused RICH used in ALICE

Detection of Internally Reflected Cherenkov Light (DIRC)

- Subclass of RICH detectors first used at BaBar
- Fused silica radiator is also used as a light pipe to direct light via total internal reflection
- Reduces material particle must pass through after the radiator
- Allows light detection outside the main detector environment

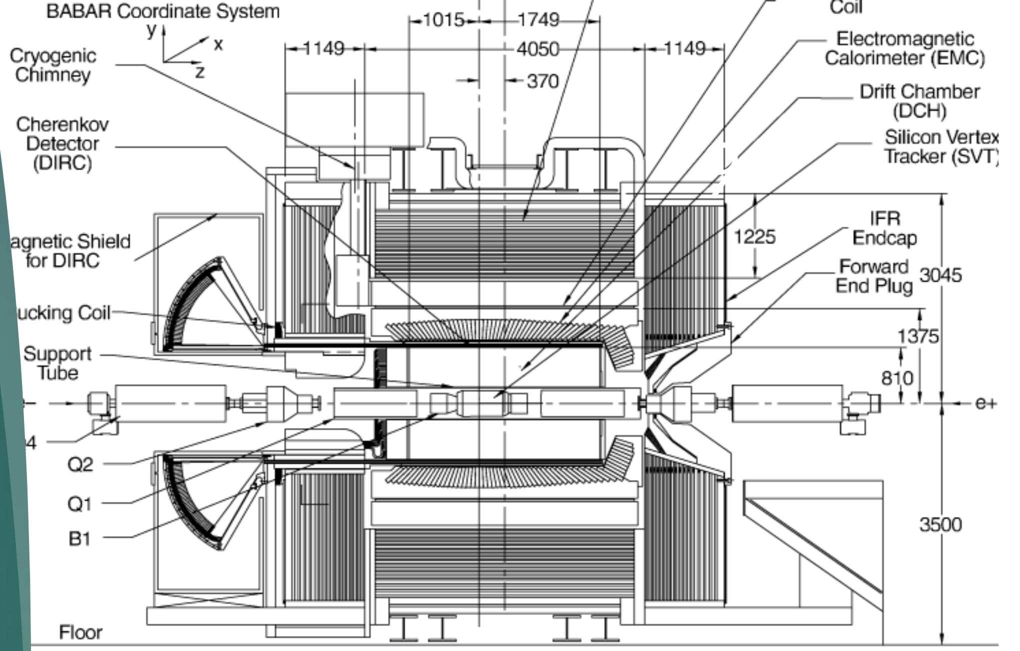


Fig. 1. Elevation schematic of the BaBar detector. All dimensions are given in millimeters.

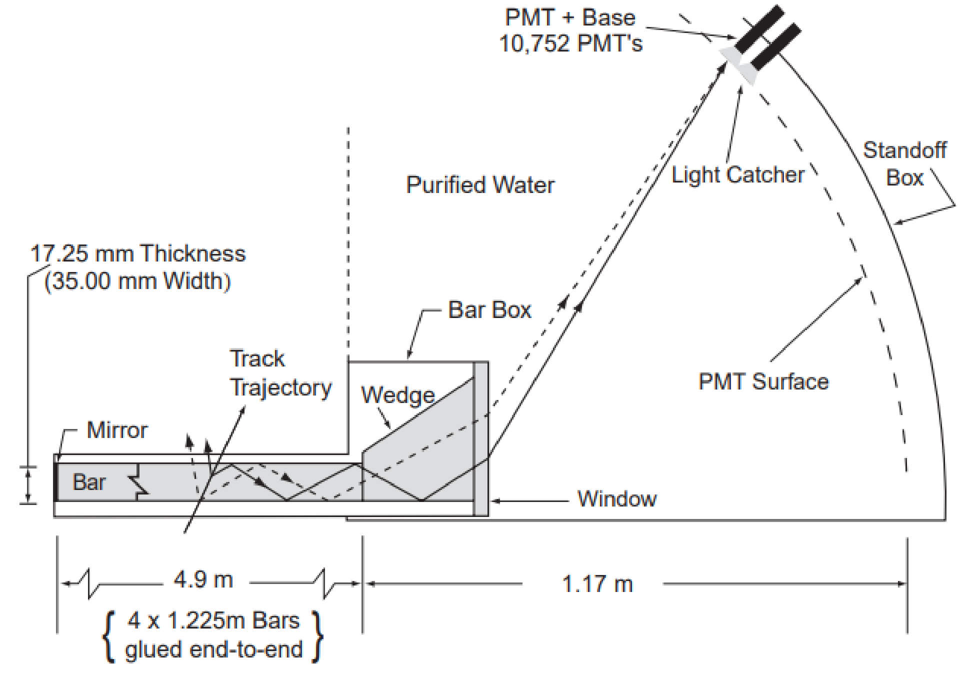


Fig. 3. Schematic of the DIRC fused silica radiator bar and imaging region.

Radiator Choice

- The most crucial parameter is the refractive index
  - At low momenta, need large n to lower threshold and increase separation
  - At high momenta, use dilute gases for $n \approx 1$
- Other optical properties, including dispersion and absorption are important considerations for detector performance
- Radiation length, radiation hardness, and cost are practical factors in the larger context of detector design
- Advent of aerogels with large bandwidth and tunable n has added a lot of flexibility
  - Indices from 1.007 to 1.13 achievable

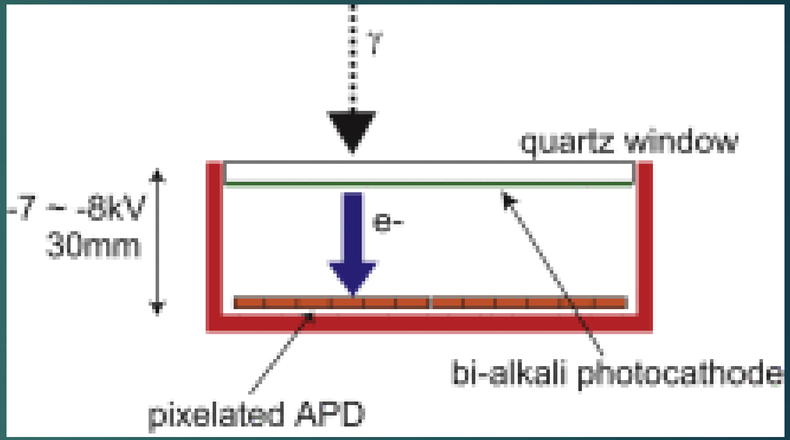
Table 2

Liquid refractive index $n = a + bE$

Molecule	a	b (eV^{-1})	ρ (g/cm^3)	M (g/mol)	b.p. (K)
CF_4	1.2039	0.00475	1.603	88	146
C_2F_6	1.1956	0.00746	1.608	138	195
C_4F_{10}	1.2037	0.01025	1.594	238	265
C_5F_{12}	1.2109	0.00785	1.63	288	303
C_6F_{14}	1.2177	0.00928	1.68	338	329

Photodetector Choice

- First RICH's used drift chambers with dopants
- ALICE uses MWPC's with a photocathode
- Increasingly common are PMT's and their derivatives
  - Higher rate
- Multi anode PMT's (MaPMT's)
  - Improved spatial resolution
- Micro channel plate PMT's (MCP-PMT's)
  - 1 mm spatial resolution, 20 ps timing resolution
- Hybrid Avalanche Photon Detectors (HAPD's)
  - Photocathode with silicon sensor
  - ~10 ps timing resolution



HAPD design used by Belle II

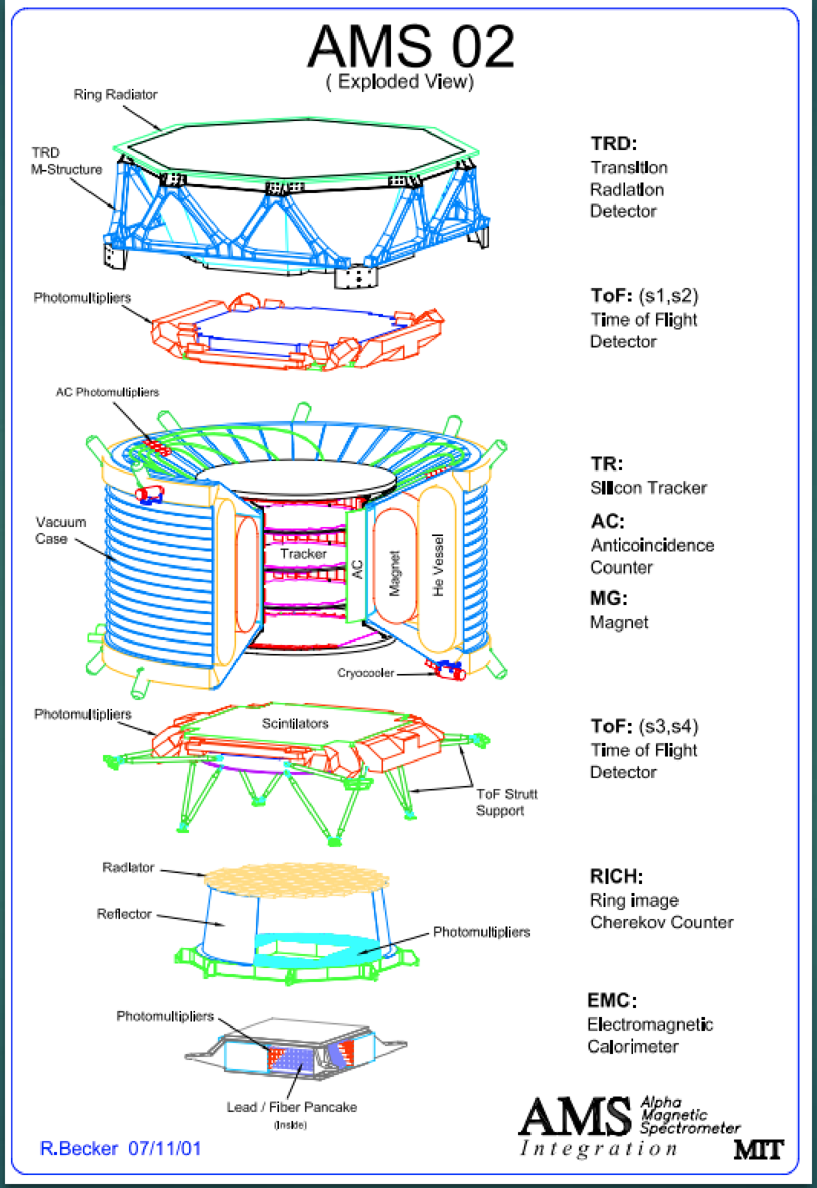
Examples of RICH Detectors in Current Experiments

1. Belle II – ARICH 2019
2. AMS II - 2012
3. LHCb – 2x RICH 2011
4. ALICE – HMPID 2010
5. NA62 – pi/mu 2018
6. COMPASS/NA58 – 2002
7. CLAS12

- Wide variety of detectors and uses currently in use
- Variously use liquid, gas, and aerogel radiators
- Using PMT's and photocathodes
- Proximity focused, mirror focused, and DIRC arrangements
- Fixed target, B factory, LHC, and cosmic applications
- Not even considering neutrino detectors and cosmic ray shower detectors

Example 1 – AMS

- RICH in Space!
- ISS mounted cosmic ray spectrometer
- RICH detector follows tracking and TOF detectors
- Goal is spectrometry and ID of various cosmics 0.5 GeV-2 TeV, especially heavy nuclei



AMS RICH Design

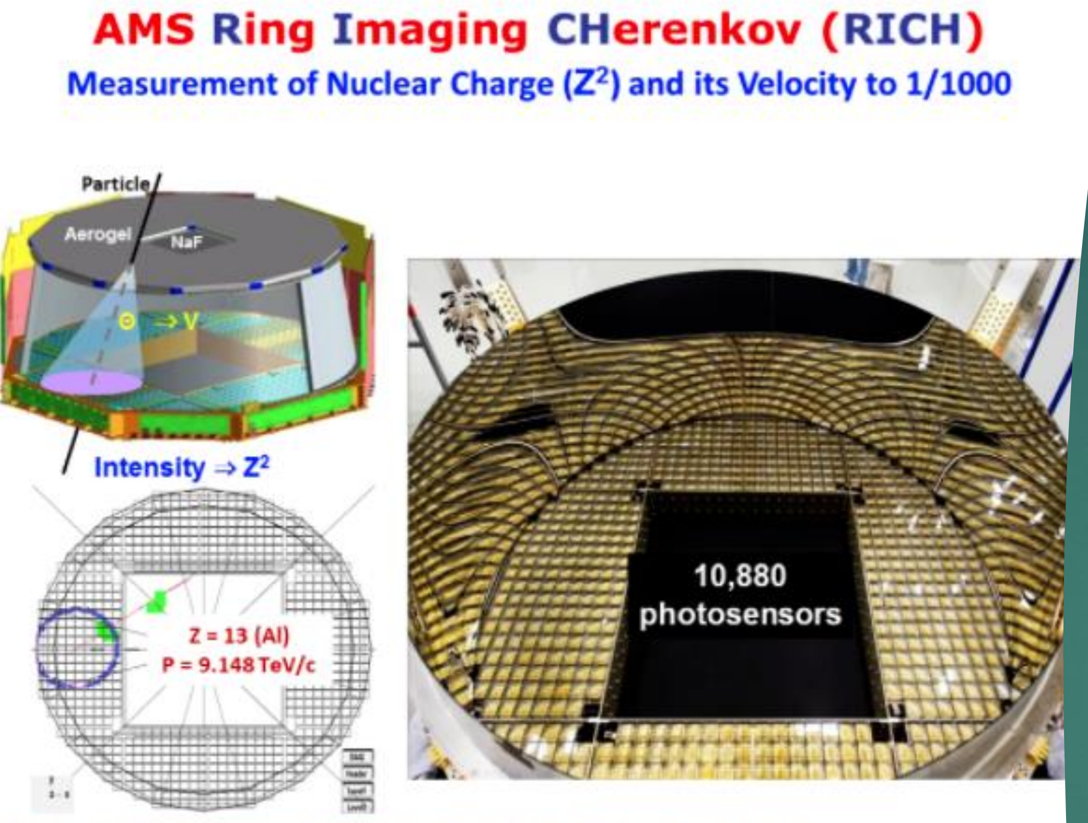


Figure 1. The RICH detector and an event display with $Z = 13$ and $P = 9.148$ TeV/c.

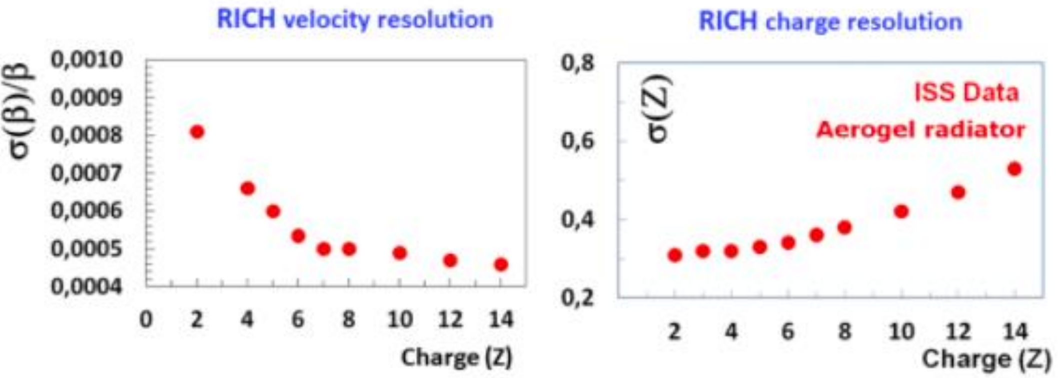
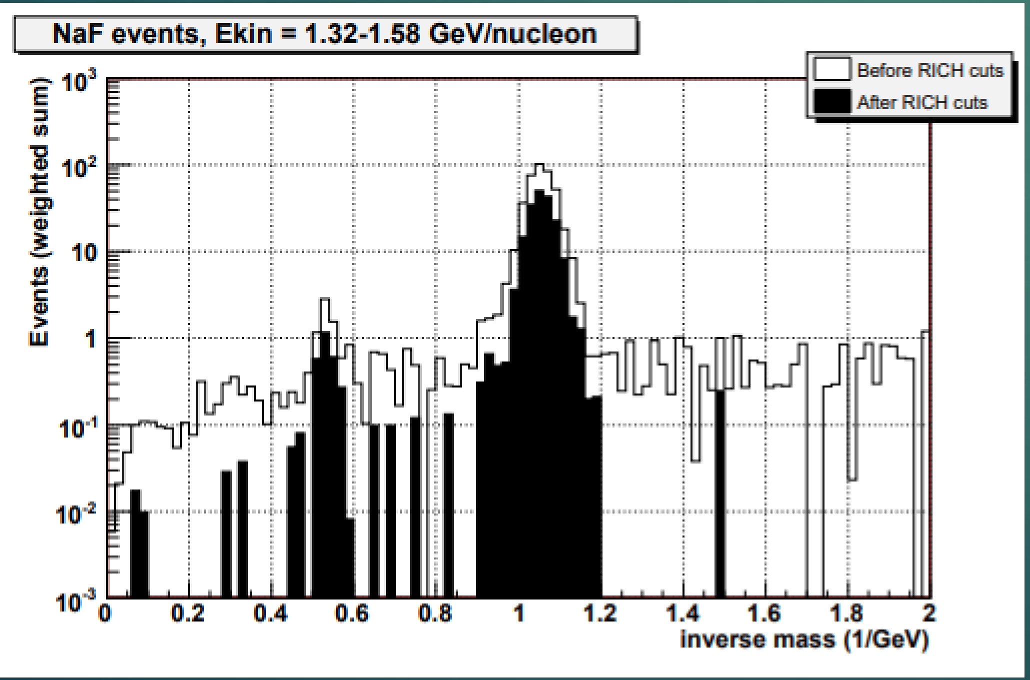


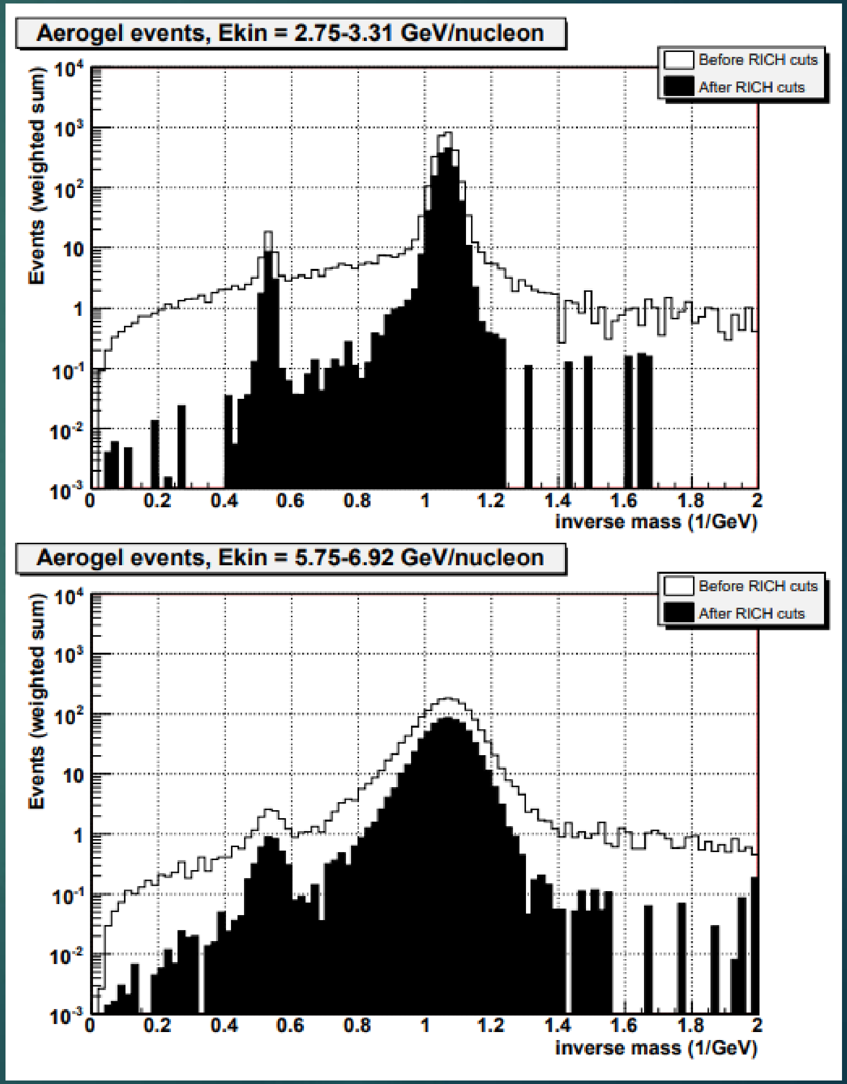
Figure 2. The RICH velocity and charge resolution vs charge Z.

- The AMS RICH uses two radiators
  - Silica aerogel (n=1.050)
  - NaF (n=1.334)
- A large conical mirror directs the light onto a plane of 680 PMT's
- The RICH achieves an expected sensitivity of $\frac{\sigma_\beta}{\beta} \sim \frac{10^{-3}}{Z}$ and charge ID for Z up to 26 (Fe)
  - The expected number of photons goes as Z^2
- In simulated data of protons 0.5-200 GeV, no events recorder >15 hits

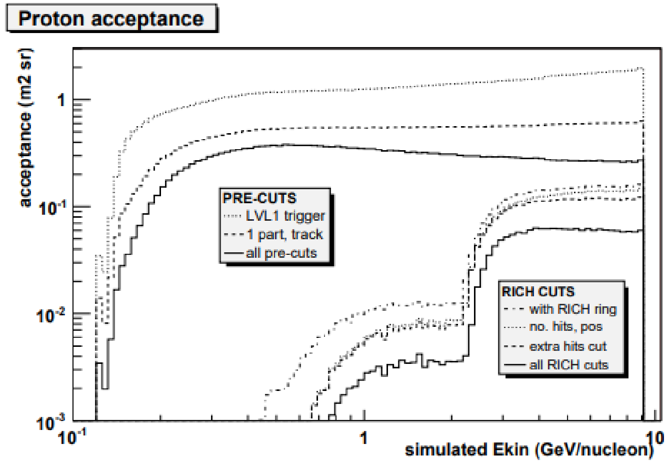
AMS RICH Performance

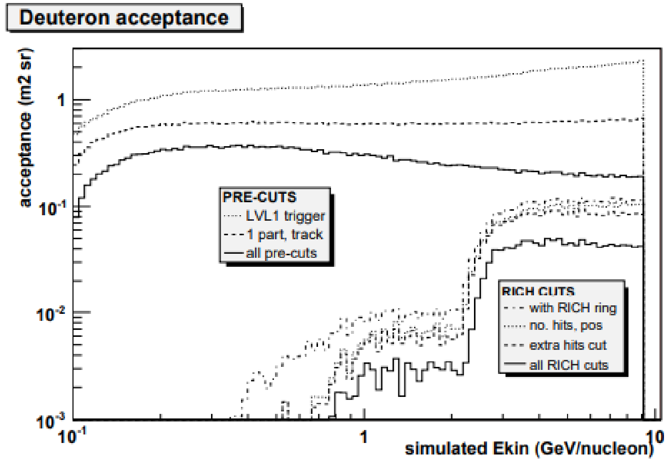
- Simulated samples of proton and deuteron events used to determine separation
- Mass resolution is about 2%

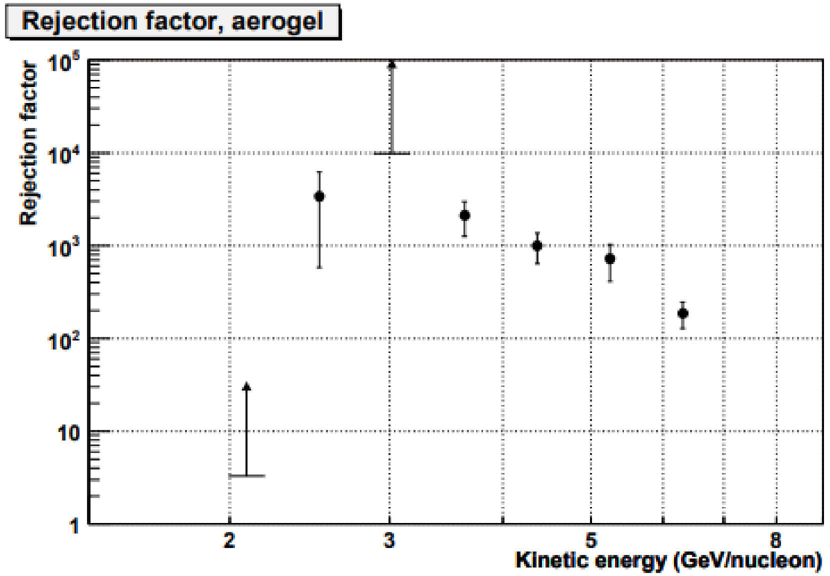


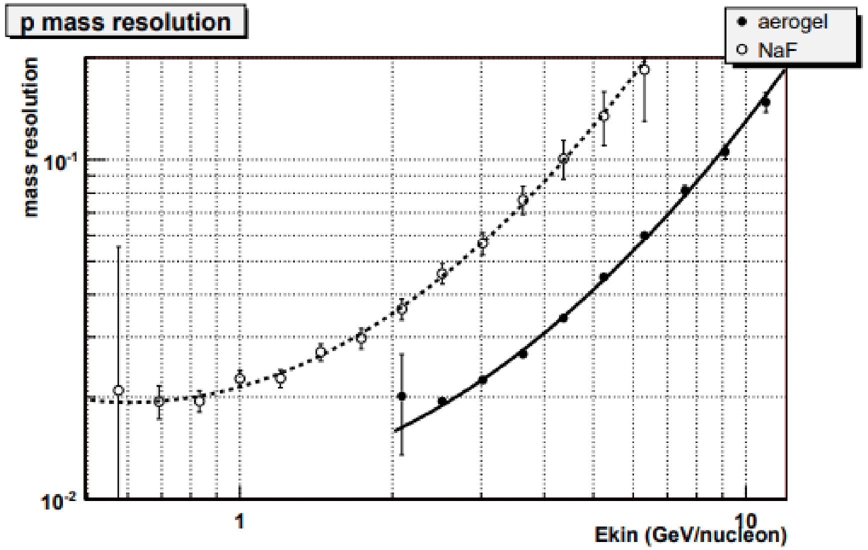


AMS RICH Performance



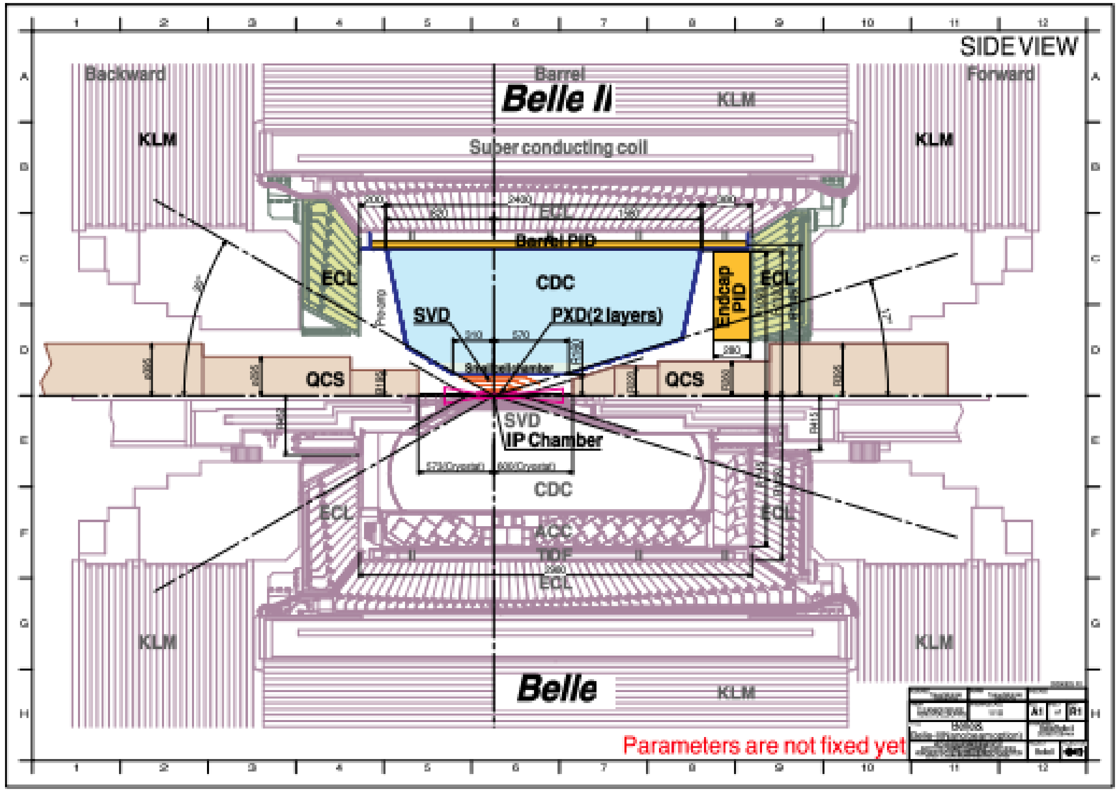






Example 2 – Belle II

- Belle II is a detector at the SuperKEKB B factory
- Main PID goals is K/π
- Barrel and endcap both contain new innovations on a RICH



Belle II Barrel PID: Cherenkov TOP

- In the barrel, they use a Time of Propagation (TOP) detector to image Cherenkov rings in x,y,t
- Layout is similar to a DIRC
- Radiator is 10 mm fused silica
- Photon detection comes from MCP-PMT's
- 8k total channels

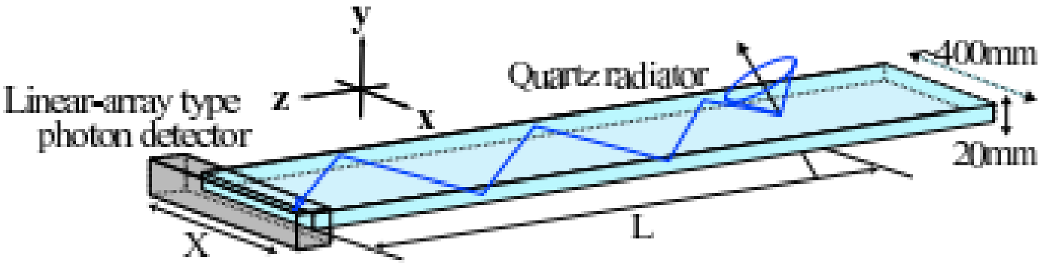
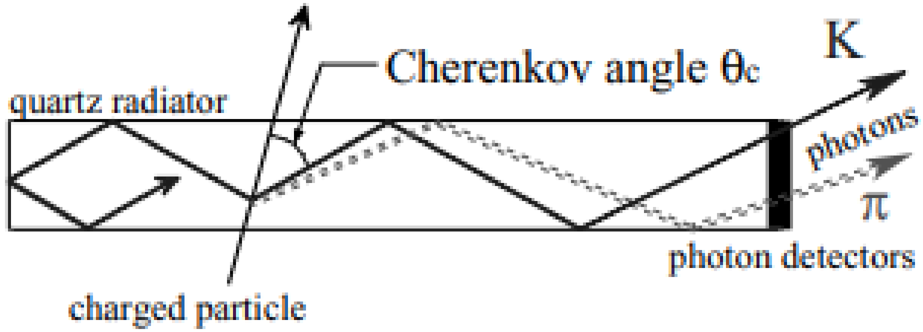
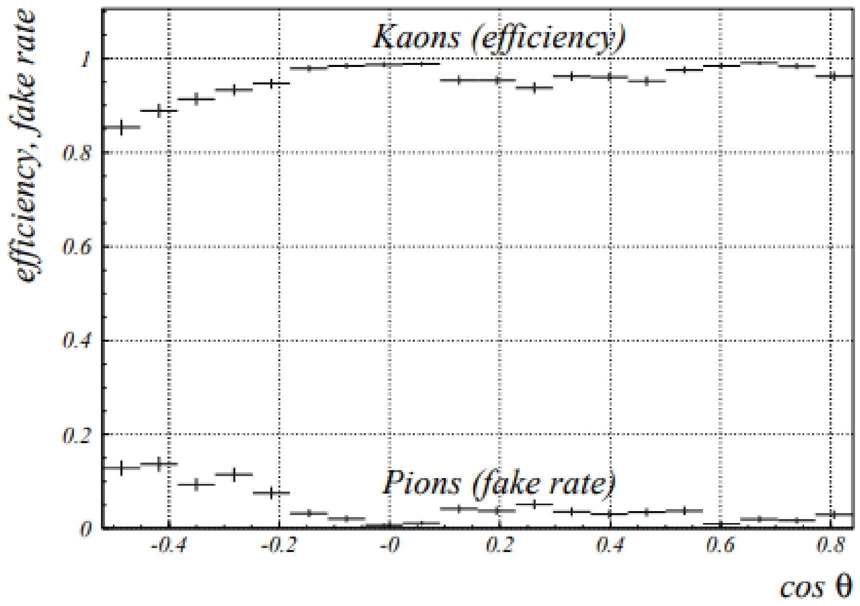


Figure 7.1: Conceptual overview of TOP counter.





Belle II Endcap PID: ARICH

- Explicitly target 4 GeV – determined by kinematics of B decays in lab frame
- The endcaps use a proximity focusing RICH with an aerogel radiator
- Radiator has inhomogeneous n to allow larger radiator length without sacrificing resolution
  - Two 20 mm layers, $n_1 = 1.046, n_2 = 1.056$
  - Configured to focus Cherenkov rings together
- Photons detected in HAPD
- 80k readout channels

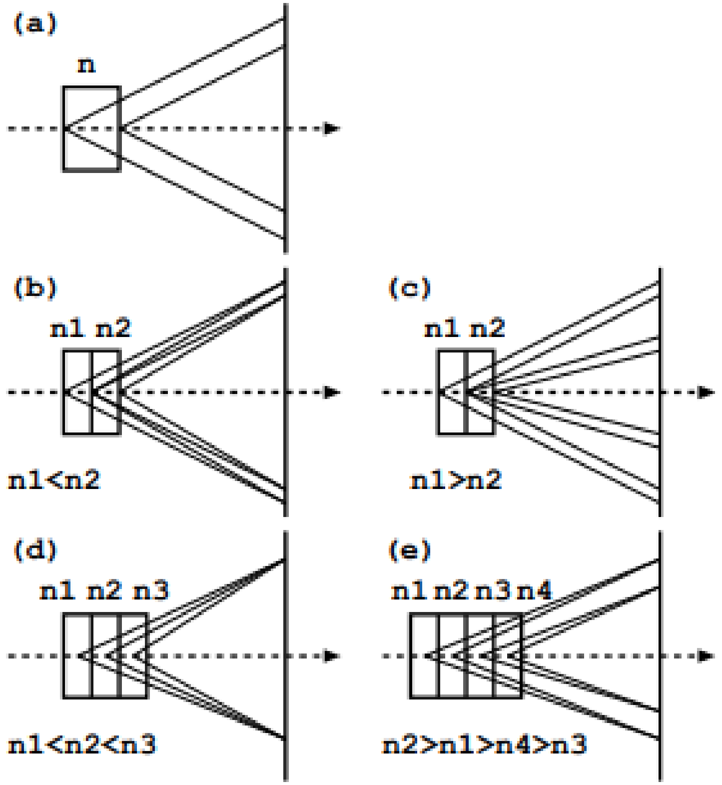
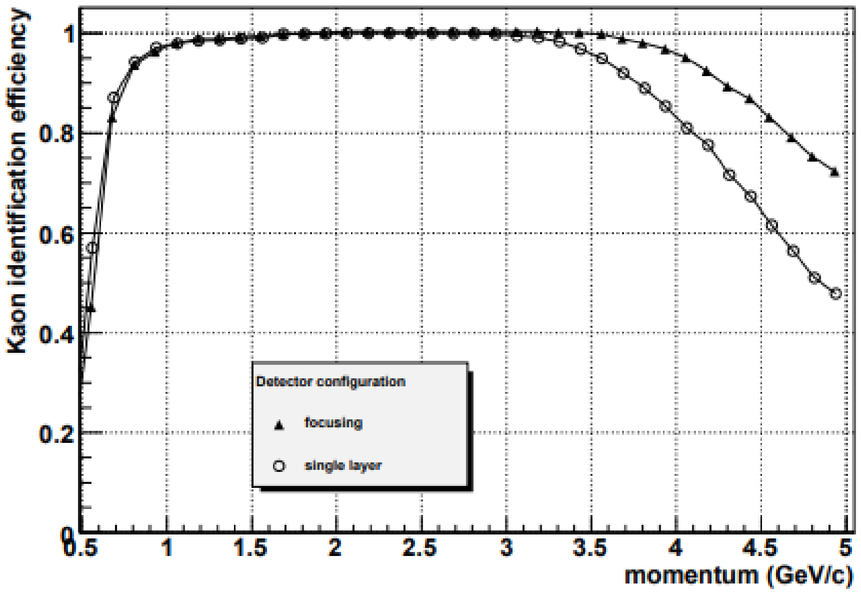


Figure 2. Principle of dual radiator and multiple radiator ring imaging Cherenkov counter: (a) single radiator, (b) focusing dual radiator, (c) defocusing dual radiator, (d) focusing multiple radiator and (e) defocusing multiple radiator RICH. Only photons from the middle of the radiator are shown in (d) and (e).

Belle II Endcap PID Performance

- Expect 20 photons per ring
- Expected angular resolution 3.1 mrad
- Focusing configuration gives large improvement in the important 4 GeV region



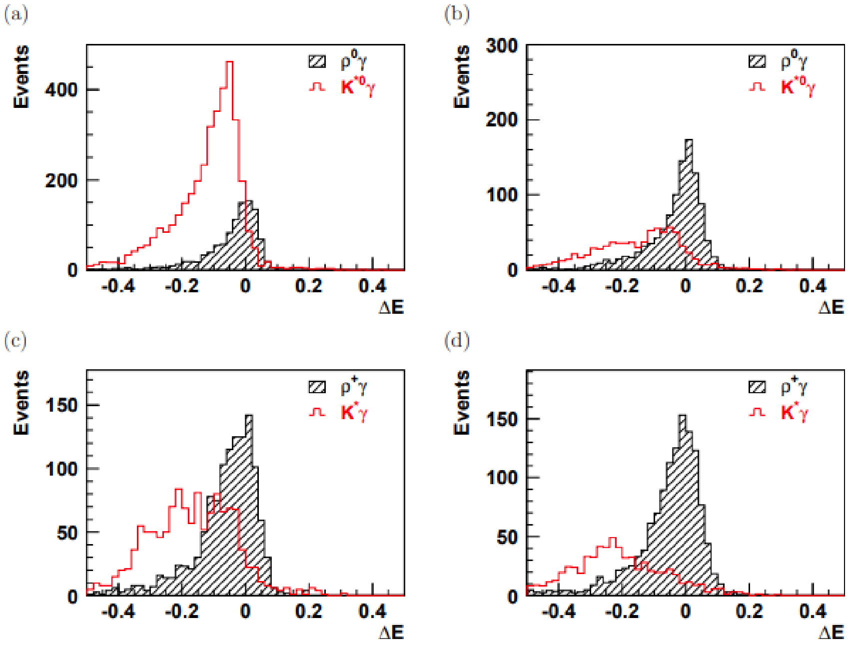


Figure 8.41: Expected ΔE distribution at $7.5\,\mathrm{ab}^{-1}$ for (a) $B^0 \to \rho^0\gamma$ with Belle PID configuration (B1+F1), (b) $B^0 \to \rho^0\gamma$ with TOP and ARICH (B2+F2), (c) $B^+ \to \rho^+\gamma$ with Belle PID configuration (B1+F1), (d) $B^+ \to \rho^+\gamma$ with TOP and ARICH (B2+F2).

Future RICH Detectors

- CBM/FAIR – e ID
- PANDA/FAIR – DIRC in barrel, RICH forward
- ePHENIX
- LHCb – TORCH
- General trends
  - Taking advantage of DIRC's
  - More crossover with TOF detectors
  - Quartz radiators and MCP-PMT's favored in most applications

Conclusions

- RICH counters are a sophisticated subclass of Cherenkov detectors which perform PID by measuring the Cherenkov opening angle associated with a charged particle track
- Performance is controlled by angular resolution and efficiency of photodetectors as well as refractive index and length of the radiator
- Modern advancements include the DIRC, allowing different detector configurations
- Silica aerogels with tunable refractive index allow focusing inhomogeneous radiators
- Advancements in photodetection, especially MCP-PMT's, have allowed better time resolution, allowing integration with TOF detectors and the use of photon timing in ring reconstruction

Sources

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