Cherenkov Light Imaging
Fundamentals and recent Developments

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7th International Workshop on
Ring Imaging Cherenkov detectors
May 2-7, 2010, Cassis, France


http://RICH2010.in2p3.fr
RICH 2010
7th International Workshop
on Ring Imaging Cherenkov Detectors
Cassis, Provence, France
May 3rd – 7th 2010
Topics
• Cherenkov light imaging in particle and nuclear physics experiments
• Cherenkov detectors in astroparticle physics
• Novel Cherenkov imaging techniques
• Photon detection for Cherenkov counters
• Technological aspects of Cherenkov detectors
• Pattern recognition and data analysis
• Research & Development for future experiments
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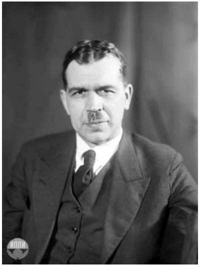
Introduction

A charged particle with a velocity *v* larger than the velocity of light in a medium emits light.
(Pavel A. Cherenkov, Ilja M. Frank, Igor Y. Tamm Nobel Price 1958)




Basic Formulas

Threshold:

$$\beta_{\text{thres}} = \frac{v_{\text{thres}}}{c} = \frac{1}{n} \qquad \gamma_{\text{thres}} = \frac{n}{\sqrt{n^2 - 1}}$$

Angle of emission:

$$\cos\theta_c = \frac{1}{\beta\, n} = \frac{1}{\frac{v}{c}\, n}$$

Number of photons:

$$\frac{d^2N}{dE\, dl} = \frac{\alpha z^2}{\hbar c}\left(1 - \frac{1}{(\beta n)^2}\right) = \frac{\alpha z^2}{\hbar c}\sin^2\theta_c$$

$$\frac{d^2N}{d\lambda\, dl} = \frac{2\pi\alpha z^2}{\lambda^2}\sin^2\theta_c$$

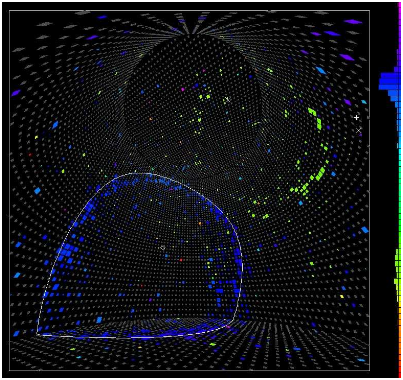
Outline

Basic Components of Cherenkov Detectors

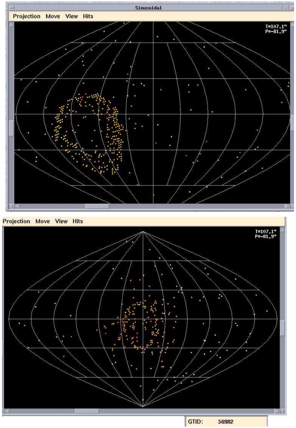
- Cherenkov Radiator(s)
- Photon Detection System
- Optional: Focusing Element(s) (mirrors/lenses)

- Some Examples. . .

Water Cherenkov

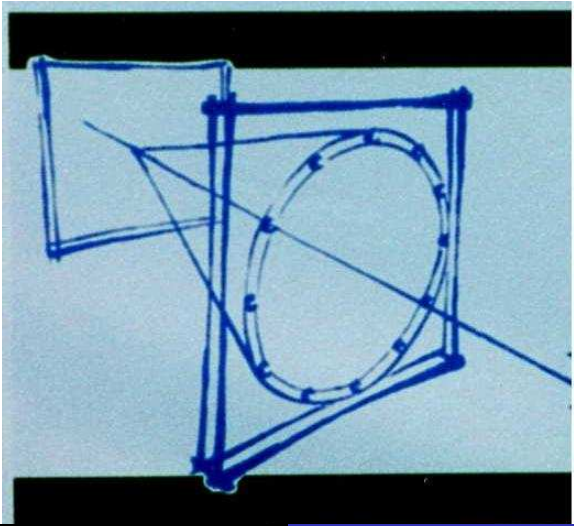


neutrino induced muon in SuperKamiokande

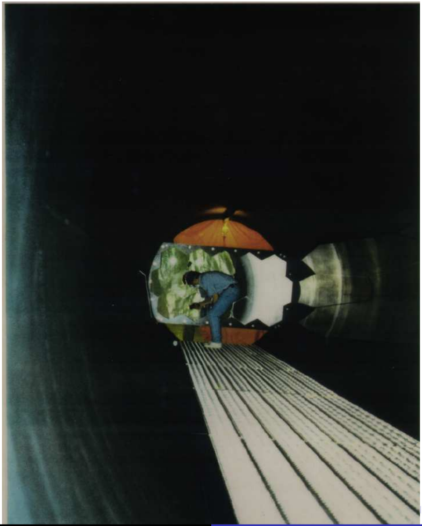


neutrino induced muon (top) and electron (bottom) in SNO

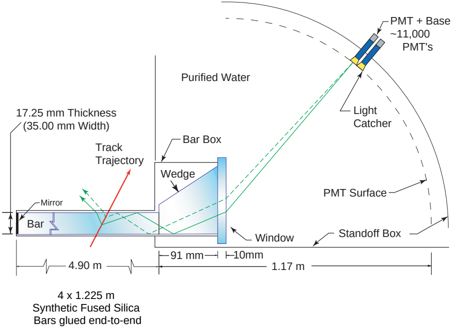
Proximity Focusing

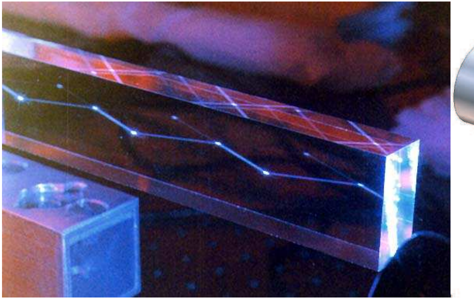


RICH with Radiator and Mirrors

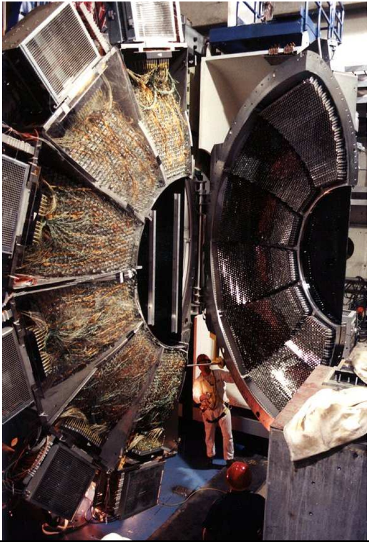


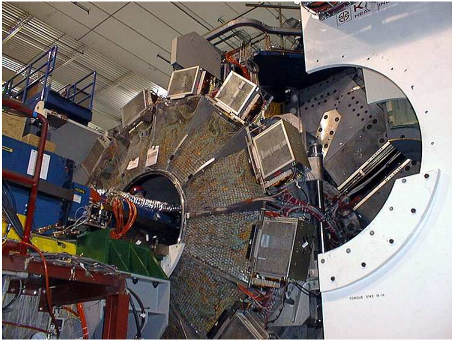
Detection of internally reflected Cherenkov light





DIRC at BaBar





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 ± 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

1. Introduction

The Čerenkov light emitted by a fast-moving particle consists of rays parallel to the elements of a right circular cone. As observed by a detector,

photography of single particles. However, existing image-intensifier tubes, as now used in cascade for scintillation track-imaging, can record such ring images. Fig. 3 shows such a

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.

1. Introduction

The Cherenkov radiation effect in an optical medium allows a precise determination of the velocity β[or $\gamma = (1-\beta^2)^{-\frac{1}{2}}$] of a charged particle passing through the medium. From the Cherenkov relation[1])

$$\cos\theta = 1/\beta n, \tag{1}$$

where θ is the emission angle of the Cherenkov light and n the refractive index of the optical medium, we find

$$\frac{\Delta\beta}{\beta} = \left[\tan^2\theta\,(\Delta\theta)^2 + \left(\frac{\Delta n}{n}\right)^2\right]^{\frac{1}{2}}, \tag{2}$$

with $\Delta\beta$, $\Delta\theta$ and Δn the r.m.s. error in the mea-

the emitted photons. Obviously a DISC type counter can only be used in collimated beams so that the source of Cherenkov radiation is along the optical axis of the device. Furthermore, the counter is not continuously sensitive in β and responds only to particles having a preset value of β (i.e. Cherenkov light which passes through the annulus). Such counters are suitable for velocity (mass) selection in collimated (momentum analyzed) primary particle beams but completely unsuitable for velocity measurement of secondary particles emerging from an interaction. The phase space occupied by these particles is large whereas the phase space acceptance of DISC is small.

A secondary particle detector may be imagined

190 Nuclear Instruments and Methods in Physics Research A248 (1986) 190–202
North-Holland, Amsterdam

ON THE DETECTION OF CHERENKOV RADIATION RINGS WITH THE HELP OF HODOSCOPES AND SMALL-SIZE PMs

A.I. RONZHIN, V.I. RYKALIN and V.I. SOLYANIK

Institute for High Energy Physics, Serpukhov, USSR

1. Introduction

Identification of particles in magnetic optic beam channels and identification of particles produced in interactions with the target matter, is one of the most important problems in the experiments of high energy physics.

In a great number of cases classical threshold Cherenkov counters (TCC) and differential Cherenkov counters (DCC) turn out not to be efficient enough:

1. Identification of rare particles in intense pion beams with a fixed momentum such as antinuclei ($\bar{d}$, $^3\overline{He}$, $^3\overline{H}$) and heavy nuclei

Unambigous identification of nuclei requires measurements to be carried out not only in the mass range corresponding to their masses, but in the adjacent background intervals as well, which results in an increase of the time needed for measurements by several times.

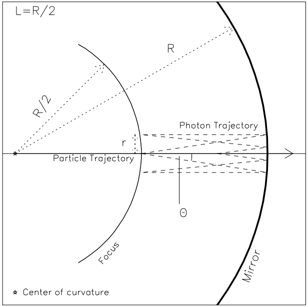
tion rings in this most general but very complicated problem, allows one to identify each particle by its velocity, and particle momentum or total energy being measured independently.

It was Roberts [2] who first proposed a detector of such a type. Nowadays their commonly adopted name is RICH (ring imaging Cherenkov) counters. The optical scheme of a RICH detector similar to that of a differential Cherenkov counter, involves one spherical mirror, which focuses the Cherenkov radiation from a particle into a ring whose radius is unambiguously related to the particle velocity, and the distance from the ring centre to the spherical mirror axis – with the particle slope angle to the mirror axis. In this case a position-sensitive photodetector is installed in the mirror's focal plane.

We shall recall the main relations for a Cherenkov detector with a focusing spherical mirror:

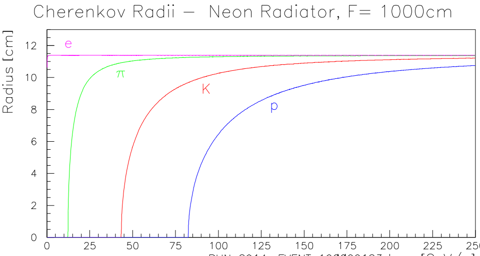
Ring Imaging Cherenkov – The Basics

$$\cos\theta_c = \frac{1}{\beta \cdot n} \qquad r = F \cdot \tan\theta_c = \frac{R}{2} \cdot \tan\theta_c \qquad N_{ph} = N_0 \cdot L \cdot \sin^2\theta_c$$



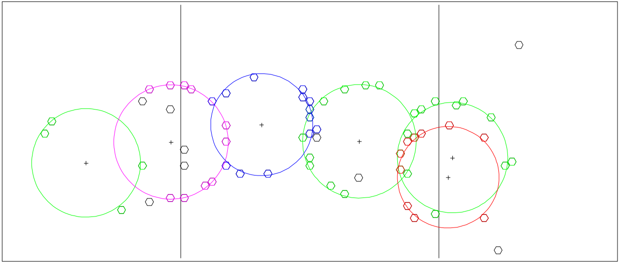
θ_c: Cherenkov angle
β: velocity
n: refractive index
r: Radius of ring on focal surface
R: Radius of curvature of
spherical mirror(s)
F: Focal length ($F = R/2$)
L: Radiator length (usually $L = F$)

Parallel particles have the same ring image

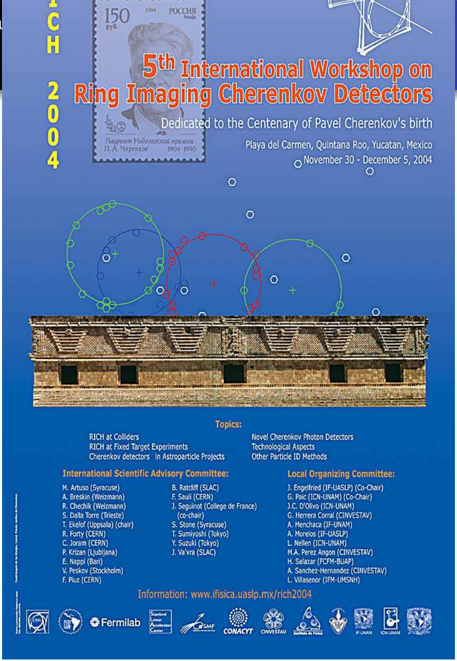


small angle approximation:

$$r = \frac{R}{2}\sqrt{2 - \frac{2}{n}\sqrt{1 + \frac{m^2c^2}{p^2}}}$$



Fu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Лауреат Нобелевской премии П. А. Черенков 1904-1990
5th International Workshop on
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Dedicated to the Centenary of Pavel Cherenkov's birth
Playa del Carmen, Quintana Roo, Yucatan, Mexico
November 30 - December 5, 2004
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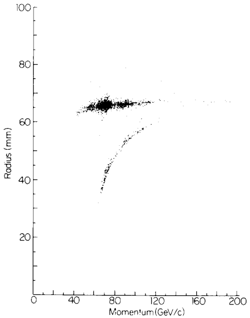
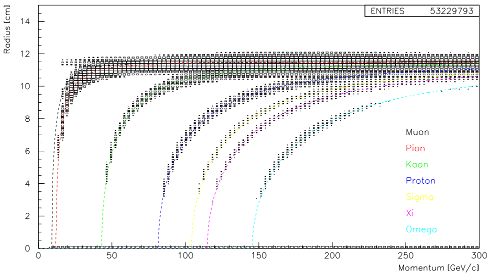


Fig. 5. Scatter plot of radius versus momentum for events having at least two photons. Curves showing the expected radii for π, K and p are superimposed.

E605, NIM 217 (1983) 237



SELEX, NIMA 502 (2003) 285

$$r = F \tan \Theta_c \approx \frac{R}{2}\sqrt{2 - \frac{2}{n}\sqrt{1 + \frac{m^2c^2}{p^2}}}$$

Knowing R and n, and measuring r, we can identify a particle of mass m.

$$\Theta_c \Delta\Theta_c = \frac{m_1^2 - m_2^2}{2p^2}$$

Usually (production experiments):
Most difficult to separate pions and kaons
μ and e are identiffied by other means

But really: Most difficult is μ-π, key features of Velocity Spectrometer (CKM, NA62)

A RICH Detector is as simple as

- a box
- some mirrors
- and a few phototubes?

NO!

Short History of RICHes in Experiments

First Generation: Beginning of 1980's.
Examples: E605, Omega (WA69, WA82), E665.

Second Generation: End-of 80's beginning of 90's.
Examples: Upgraded Omega (WA89, WA94), Delphi, SLD–GRID, CERES, SPHINX.

Third Generation: Mid-End 90's.
Examples: SELEX, Hermes, Hera-B.

Fourth Generation: BaBar–DIRC, PHENIX, CLEO–III, COMPASS, . . .

New Generation: LHCb, ALICE, *BTeV, CKM*, . . .

Future: BELLE II, NA62, Panda, WASA, CBM, . . .

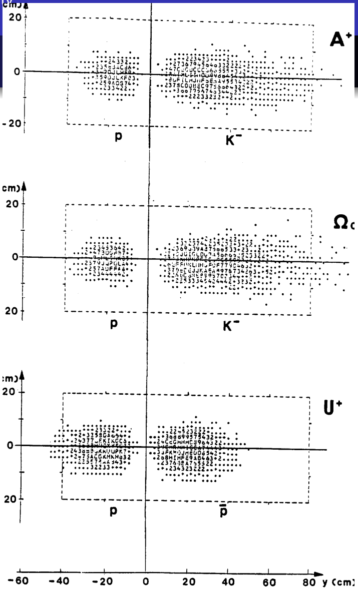
RICH – The Reality

- Center of ring depends on track angle
  $\Longrightarrow$ large detector surface (up to square meters)
- good resolution of photon position
  $\Longrightarrow$ large number of "pixels" (up to 100000 or more)
- Number of Cherenkov photons $\propto 1/\lambda^2 \Longrightarrow$ Ultraviolet
- refractive index $n = n(\lambda) \Longrightarrow$ Chromatic dispersion
- Mirrors
- Detection of UV-photons: convert photon in electron (photoeffect)
- Tracks passing through photon detector
- All pieces have to work together!

Distribution of Ring Centers

WA89 Proposal (1987)

$$
\begin{aligned}
(\Xi_c^+)A^+ &\rightarrow \Lambda K^- \pi^+ \pi^+ \\
\Omega_c^0 &\rightarrow \Xi^- K^- \pi^+ \pi^+ \\
U^+ &\rightarrow \Lambda \bar{p} \pi^+ \pi^+ \\
\Xi^- &\rightarrow \Lambda \pi^- \\
\Lambda &\rightarrow p \pi^-
\end{aligned}
$$



RICH – The Reality

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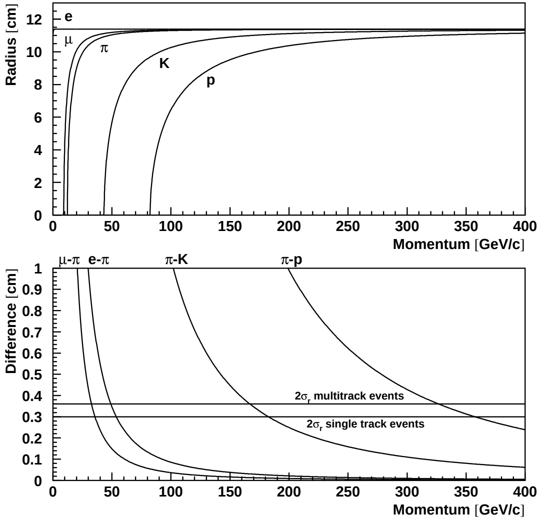
Ring Radii Differences



$$n - 1 = 66ppm$$
$$R = 20m$$

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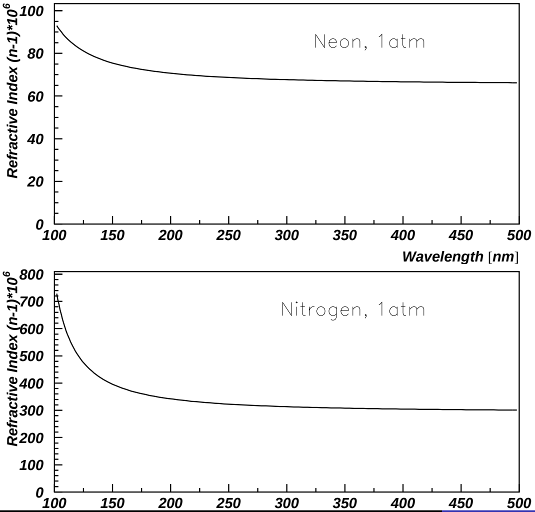
How to select n?

- Usually: RICH after magnetic field
  $\Rightarrow$ Minimum Momentum is $\pi^{\pm}$ Threshold
- But also reverse: CERES RICH
- Use pressure or mixture
- Carefull with sensitive range: Chromatic Dispersion and absorption.

Material	$n-1$	γ_{thres}
Diamond	1.42	1.10
ZnS (Ag)	1.37	1.10
Lead Fluoride	0.80	1.20
Glass	0.46-0.75	1.22-1
Water	0.33	1.52
Aerogel	0.025-0.075	4.5-2.
CO_2 (STP)	430×10^{-6}	34.1
N_2 (STP)	300×10^{-6}	45
Ne (STP)	65×10^{-6}	90
He (STP)	33×10^{-6}	123

Refractive Index as function of Wavelength

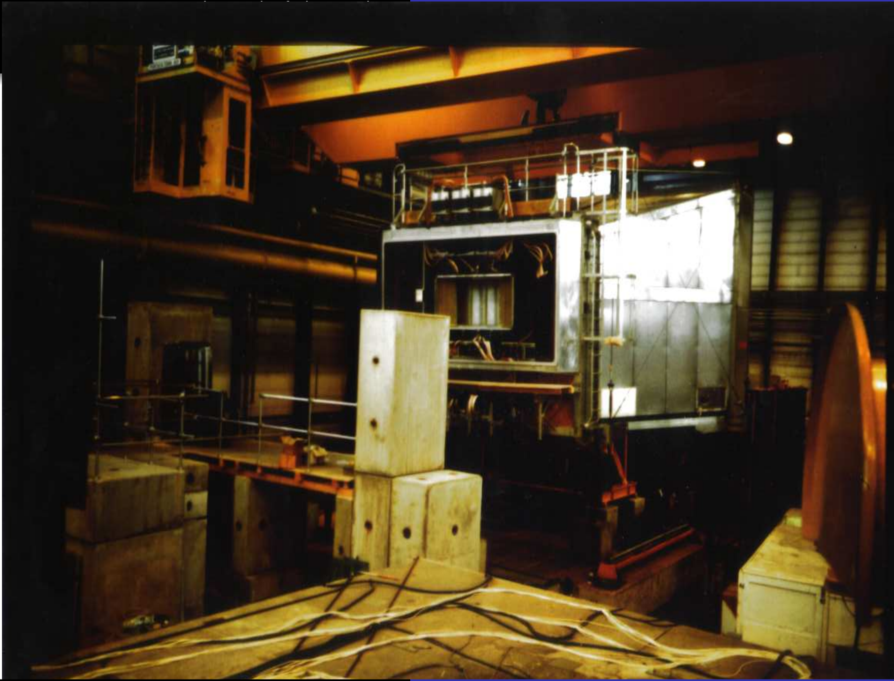


smaller λ

- $\Rightarrow$ More Photons
- $\Rightarrow$ Larger Dispersion
- Do you want more photons?

More on Refractive Index

- If n selected, curves are fixed
- Is resolution at high momentum good enough?
- If not:
  - more (smaller) pixels (if resolution limit)
  - larger Mirror radius R, (larger Photon Detector)
  - More than one radiator
    (Examples: Delphi, SLD, Hermes, LHCb)
- If possible: make radiator system gas tight
  no change of refractive index over time



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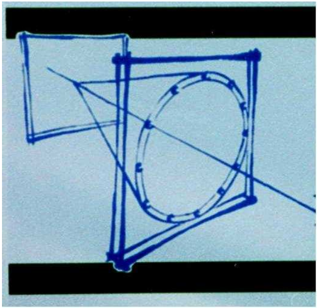
Proximity Focusing



- If n "large" (glas, liquid): radiator is "thin"
  $N_{\mathrm{ph}} \propto \sin^2 \Theta_c$
- If width of ring image thin compared to needed separation
  Proximity Focusing is enough
- Otherwise: Focusing necessary

Mirrors

- Mirror Radius usually 2 $\times$ the Radiator Length but also folding with flat mirror(s)
- Mirrors have to be “thin” to avoid interactions and γ conversion
- Surface quality “good enough” (not to be resolution limit) correct geometrical form (usually spherical)
  - Typically surface quality $\times$10 worse than astronomical (1 λ)
  - Need to measure properties $<R>$, quality: Ronchi
- Reflectivity high, covering full range of photon detection (VUV).
- Best would be one mirror only, but usually not possible (size, thickness, surface quality, coating)
- Optimum size: radius of $\beta = 1$ ring to facilitate alignment.

RICH – The Reality

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  $\Longrightarrow$ large detector surface (up to square meters)
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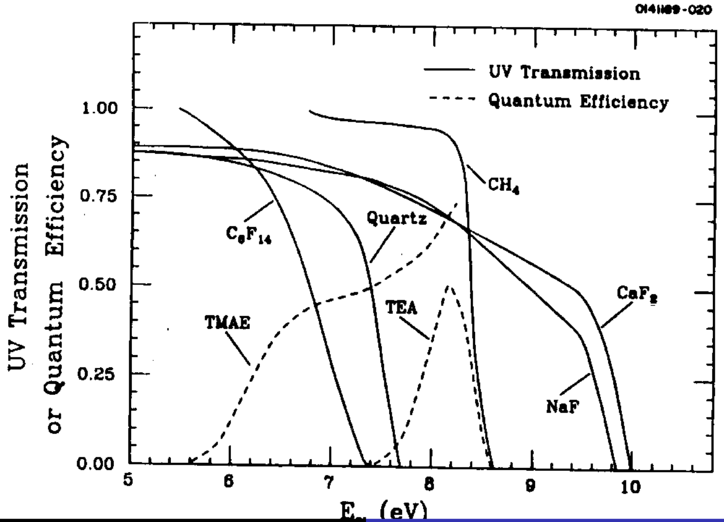
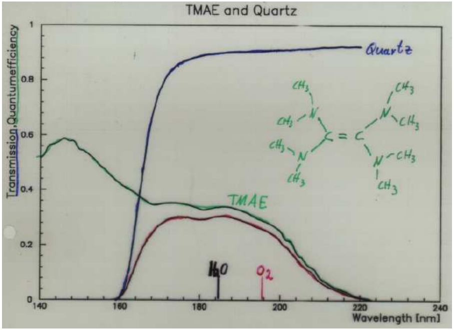
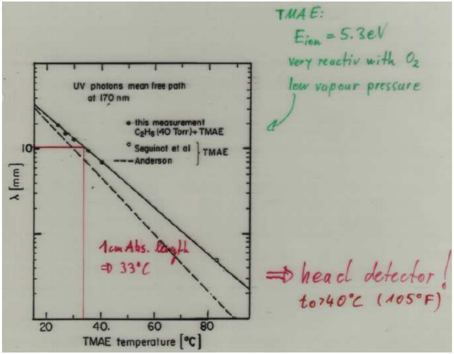
  $\Longrightarrow$ large number of “pixels” (up to 100000 or more)
- Number of Cherenkov photons $\propto 1/\lambda^2 \Longrightarrow$ Ultraviolet
- refractive index $n = n(\lambda) \Longrightarrow$ Chromatic dispersion
- Mirrors
- Detection of UV-photons: convert photon in electron (photoeffect)
  - small (up to a few thousand) number of pixels: PMTs
  - large number of pixels or area: some chamber
- Tracks passing through photon detector
- All pieces have to work together!

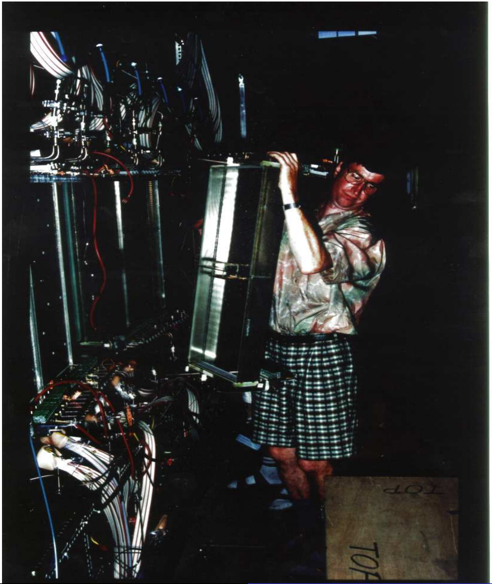
Photon Sensitive Gas Vapors and Windows



TMAE: Upgraded Omega RICH



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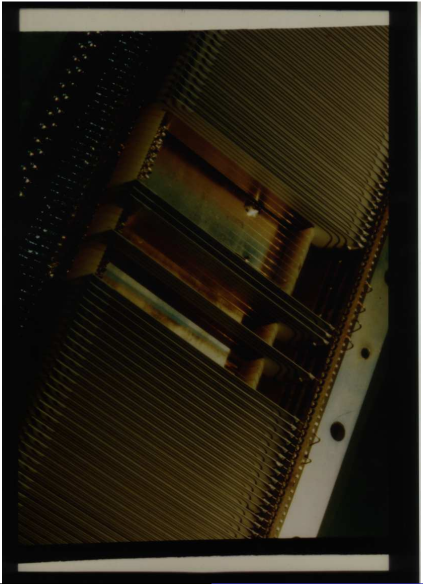
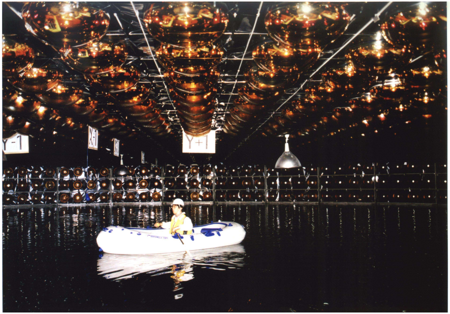


Photomultipliers

Photomultipliers



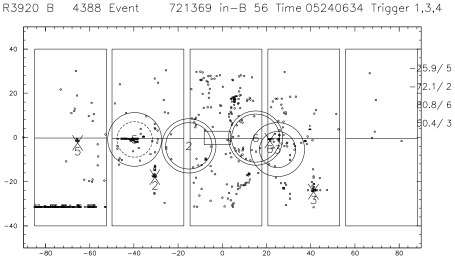
More on Photon Detection

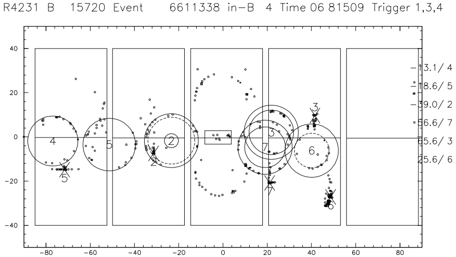
- Cherenkov photons are single photons!
- Other detectors:
  - Multi-Anode PMTs
  - Microchannel Plates
  - Hybrids (Photocathode, Silicon Strip/Pixel Detector)
  - CsI photocathode, “GEM” to detect photon
  - Solid state (silicon) devices
- talks on all of them at this conference!

RICH – The Reality

- Center of ring depends on track angle
  $\Longrightarrow$ large detector surface (up to square meters)
- good resolution of photon position (ring radius)
  $\Longrightarrow$ large number of "pixels" (up to 100000 or more)
- Number of Cherenkov photons $\propto 1/\lambda^2 \Longrightarrow$ Ultraviolet
- refractive index $n = n(\lambda) \Longrightarrow$ Chromatic dispersion
- Mirrors
- Detection of UV-photons: convert photon in electron (photoeffect)
- Tracks passing through photon detector
- All pieces have to work together!

Upraded Omega RICH – Time Projection Chambers with TMAE





$n - 1$ plot (Nitrogen radiator)

Take distance d of signals to predicted ring center(s)
assume pion mass

$$n-1 = \frac{m^2R^2 + 4p^2d^2}{2p^2(R^2 - 2d^2)}$$

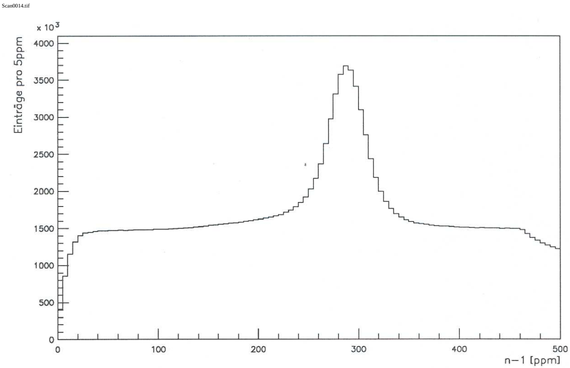


Abbildung 6.2: Verteilung der (n-1)–Werte

RICH – The Reality

- Center of ring depends on track angle
  $\Longrightarrow$ large detector surface (up to square meters)
- good resolution of photon position (ring radius)
  $\Longrightarrow$ large number of “pixels” (up to 100000 or more)
- Number of Cherenkov photons $\propto 1/\lambda^2 \Longrightarrow$ Ultraviolet
- refractive index $n = n(\lambda) \Longrightarrow$ Chromatic dispersion
- Mirrors
- Detection of UV-photons: convert photon in electron (photoeffect)
- Tracks passing through photon detector
- All pieces have to work together!

Contributions to total resolution

WA89 (Omega): $n-1$ plot for $42.5 \pm 2.5\,\text{GeV}/c$

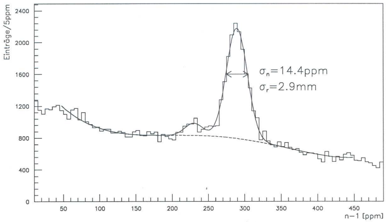


Abbildung 8.19: (n-1)–Plot für das Impulsintervall $(42.5 \pm 2.5)\,\text{GeV}/c$. *Halbkammer 2, Run 2208*

Source	Value [mm]
Pixel Size (Spacing/4)	4.03
Mirror Alignment (σ_m)	2.06
PWC Resolution (σ_t)	3.0
Dispersion in Neon	1.2
Total expected (σ_h)	5.54
Total measured (σ_h)	5.5 ± 0.1

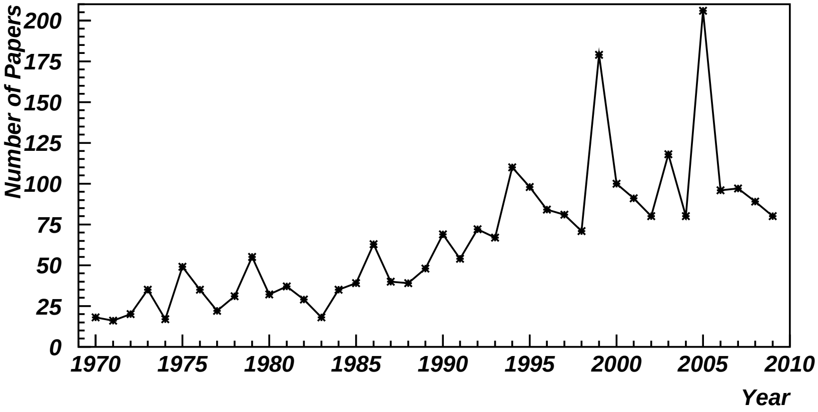
Single Hit Resolution
SELEX RICH

Are there new developments?
Or are there just extensions of what was done before?

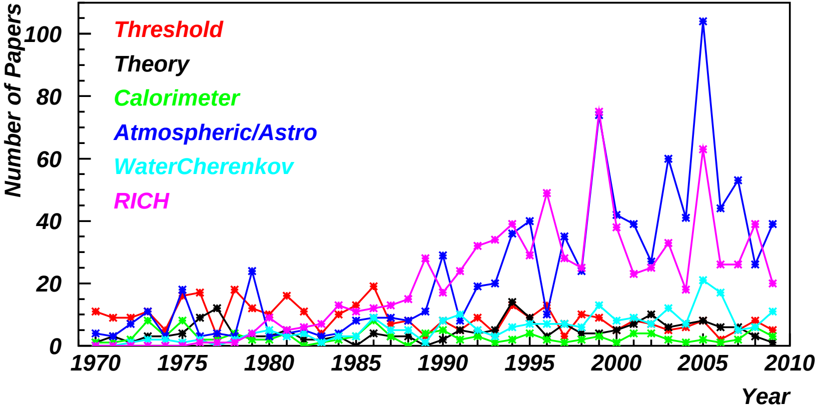
Are there new developments?

- Made a SPIRES search on title containing:
  “RICH” or “Ring Imaging” or “cherenkov” or “tscherenkov” or “cerenkov”
  for every year since 1970.
- Divide (by hand) into the following Categories:
  - Water/Ice Cherenkov
  - Threshold (and similar) Counters
  - Atmospheric Cherenkov and Astronomy
  - Calorimeters (lead glass and similar)
  - Physics Results from Cherenkov detectors
  - Cherenkov Theory
  - RICH
- Not counting Accelerator techniques etc.

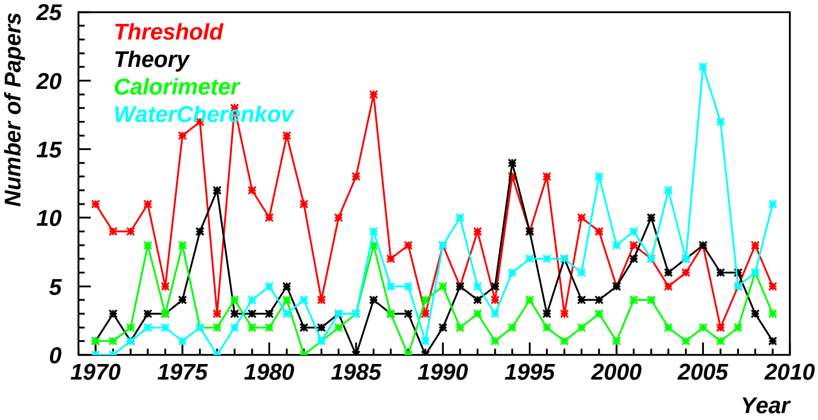
Total Number of Papers



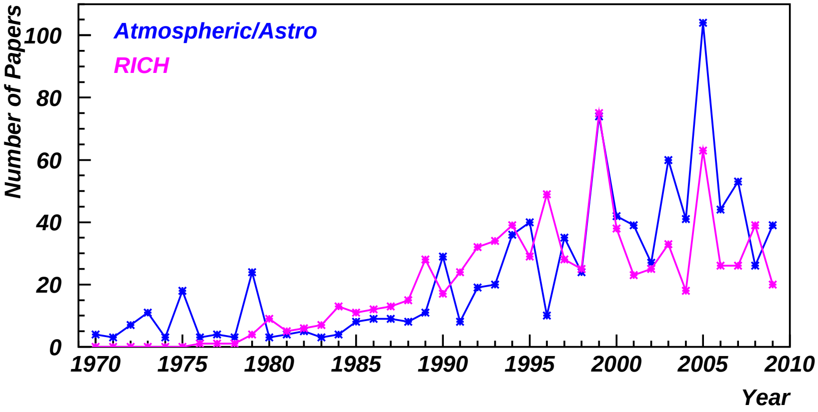
Separated By Category



Separated By Category



Separated By Category



Paper Search Summary

- Number of papers increasing, so there are new interesting things!
- Number of paper treating "conventional" (old) detectors, like Threshold Counters, is constant.
- Most (but not all!) are (highly sophisticated!) "optimizations" of the "basics" discussed before.
- So, what are the "new developments"?
- Easy for me: All of them will be discussed at the conference!
- Lets go in pieces: Mirrors, Radiators, Photon Detectors...
- ...and full detector systems.

News on Mirrors

- Main problem with Mirrors: have to be thin (small λ_{int}, X_0)
- But: 20 years ago CERES had (one!) mirror made of Carbon Fibres!
- Later in the conference (Thursday): LHCb Mirrors

News on Radiators

- Gases: nothing new (nearly)
- Liquids: not much new, but see talk by Greg Hallwell on Thursday about Freons.
- Aerogels: some new developments in Novosibirsk and Japan, see posters.
  also posters on LHCb, Belle II
- Solids: New DIRCs (talks, posters)

News on Photon Detectors

There are a lot of new and exciting developments!!

4 summary talks: (in order of appearance. . .)

- Samor Korpar: Solid State Detectors
- Leszek Ropelewski: MPGDs
- Silvia Dalla Torre: Gaseous detectors
- Toru Iijima: Vaccum-based detectors

and 7 talks all Wednesday. . . and several posters. . .

Extremely fast detectors with high quantum efficiency

News on Detector Systems

- Lot of talks here at the conference
- RICH systems are really well understood
- New photon detectors allow different optimizations of design parameters

Summary

- RICHes were extensively studied and used in the last ~ 30 years
- RICHes are very well understood devices
- Use and sophistication is still incrementing
- New Photon Detectors open new possibilities in RICHes

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http://RICH2010.in2p3.fr
RICH 2010
7th International Workshop
on Ring Imaging Cherenkov Detectors
Cassis, Provence, France
May 3rd – 7th 2010
Topics
• Cherenkov light imaging in particle and nuclear physics experiments
• Cherenkov detectors in astroparticle physics
• Novel Cherenkov imaging techniques
• Photon detection for Cherenkov counters
• Technological aspects of Cherenkov detectors
• Pattern recognition and data analysis
• Research & Development for future experiments
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