Particle Identification

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NSS Short Course 1: Radiation Detection and Measurement
Jürgen Engelfried[1]
Instituto de Física, Universidad Autónoma de San Luis Potosí, Mexico

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Outline

- Introduction
- Neutral Particle Identification (fast)
- Time of Flight
- Identification by Energy Loss
- Transition Radiation
- Cherenkov Detectors
- Summary

Please ask questions, be active, do not just consume!

[1]jurgen@ifisica.uaslp.mx, http://www.ifisica.uaslp.mx/˜ jurgen

Introduction

- **Detection and Identification of Particles and Nuclei important in**
  - **high-energy physics**
  - **cosmic ray physics**
  - **nuclear physics**

Basic Idea
Every effect of particles or radiation can be used as a working principle for a detector

Main Purpose of particle detectors:
Detection and identification of particles with mass m and charge z
In particle physics: Usually $z = 0, \pm 1$, but not in nuclear, heavy ion physics, or cosmic rays

Examples

- **Charged particle (charge z) deflected in magnetic field $\longrightarrow$ momentum p**

$$\rho \propto \frac{p}{z} = \frac{\gamma m \beta c}{z}$$

- **Time of flight determines particle velocity**

$$\beta = \frac{v}{c} \propto \frac{1}{t}$$

- **Cherenkov angle determines particle velocity**

$$\theta_C = \frac{1}{\beta n}$$

- **Calorimeter measurement provides energy measurement**

- **Charge measurement: Ionization Energy loss**

$$\frac{dE}{dx} \propto \frac{z^2}{\beta^2} \ln(a\beta\gamma)$$

- **With all the information together one can determine the quadri-vector of the particle.**

- **Basic detection techniques work mostly for charged particles only.**

- **Neutral particles usually detected "indirectly" via production of charged particles.**

Introduction (cont.)

Design of Instrumentation and Detectors requires knowledge of

- **Basic physics for interaction of charged and neutral particles with matter**
- **Mechanical Engineering**
- **Electrical Engineering (high voltage)**
- **Electronic Engineering**
- **Interfaces to Trigger, Data Acquisition and Computing**
- **Software Engineering (calibration)**
- **Operation (stability)**

- **To know any one of them is not sufficient**
- **You have to apply all together to build, operate and use an instrument for your physics measurement**

- **Always keep in mind what you want to measure, and what precision (resolution) you need**

Particle Identification

- **Identification of neutral particles**
- **Identification of charged particles**

Neutral particles

- **Measure total energy (Calorimeter)**
- **If no charged track points to signal in Calorimeter: It's a neutral**
- **Usually not too many possibilities left.**
  Example: Hadron calorimeter, no track: most likely a neutron (or K^0_L)
- **Electromagnetic calorimeter, track, signal: Measure "E/p".**
  $E/p = 1$ for electrons, $E/p < 1$ for pions

- **Long-lived neutral particles (Hyperons), short lived particles (charm, beauty):**
  Measure 4-vector of decay products and calculate invariant mass.

Detection of Neutrons

indirect technique: neutrons interact and produce charged particles

- **Low Energies ($< 20\,\mathrm{MeV}$):**

$n + {}^6\mathrm{Li} \rightarrow \alpha + {}^3\mathrm{H} \quad \Rightarrow$ LiI(Tl) scintillators

$n + {}^{10}\mathrm{B} \rightarrow \alpha + {}^7\mathrm{Li} \quad \Rightarrow$ BF_3 gas counters

$n + {}^3\mathrm{He} \rightarrow p + {}^3\mathrm{H} \quad \Rightarrow$ ^{3}He-filled proportional counters

$n + p \rightarrow n + p \quad \Rightarrow$ proportional chambers with for example CH_4

- **High Energies ($E > 1\,\mathrm{GeV}$)**

$n + {}^{235}\mathrm{U} \rightarrow$ fission products $\Rightarrow$ coated proportional counters

$n +$ nucleus $\rightarrow$ hadron cascade $\Rightarrow$ calorimeters

Identification of Charged Particles

What is Particle Identification?

Two major applications:

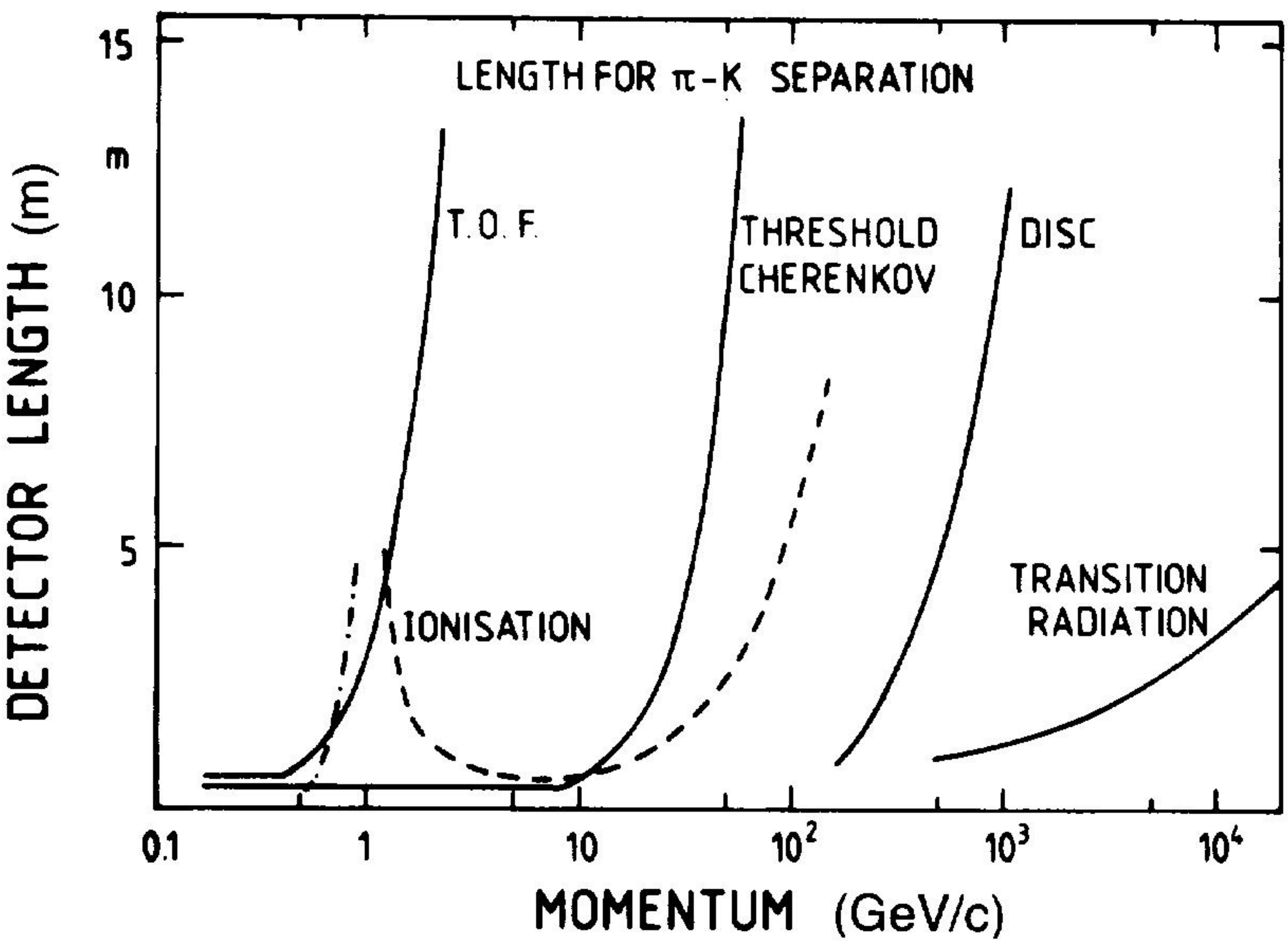
1. **Beam Particle Identification (Fixed Target)**
2. **Identification of decay products**

In both cases the momentum of the particle is known:

1. **By beamline elements (only small momentum bin)**
2. **Measured by a magnetic spectrometer (wire chambers)**

$\Longrightarrow$ Particle Identification reduces to measure the total Energy (calorimeter) or using some velocity-dependent effect (Time of flight, dE/dx, Cherenkov, Transition radiation)

Fig. 5.30. Length of detectors needed for separation of π and K mesons.



First some Physics Example...

Reconstruction of Λ_c^+

- Λ_c^+ baryon consists of (udc) quarks
- Mass $m_0 = 2.284.9\,\mathrm{GeV}/c^2$ (remember: proton $0.938\,\mathrm{GeV}/c^2$)
- Lifetime: $\tau = 2.0 \cdot 10^{-13}\,\mathrm{sec}$
- Decays to $\Lambda_c \rightarrow pK^-\pi^+$ in 5.0 % of the time.
- Only in 1 out of 1000 collisions a charm quark gets produced.

Special Theory of Relativity:

$$
\begin{aligned}
E &= m \cdot c^2 \\
m &= m_0 \cdot \gamma \\
\gamma &= \frac{1}{\sqrt{1-\frac{v^2}{c^2}}} = \frac{E \cdot c^2}{m_0} \\
p &= m \cdot v \approx m_0 \cdot \gamma \cdot c \\
\text{Time dilation:} \quad t &= t_0 \cdot \gamma \\
\text{Mean flight path:} \quad L &= c \cdot \tau \cdot \gamma
\end{aligned}
$$

$\Longrightarrow$ A Λ_c^+ with momentum $200\,\mathrm{GeV}/c$ flies on average 5.4 mm

$\Longrightarrow$ Do a Fixed Target Experiment – But even there we cannot observe a Λ_c directly

What do we do?

- **Measure type, direction, momentum, (the 4-vector) and charge of all decay products**
- **Apply momentum and energy conservation to "interesting" decay vertex and calculate energy and momentum of hypothetical mother particle**
- **Transform into rest system of mother particle to obtain rest mass**
- **Do this for a lot of events, fill histogram with results**

Measuring direction and decay vertex

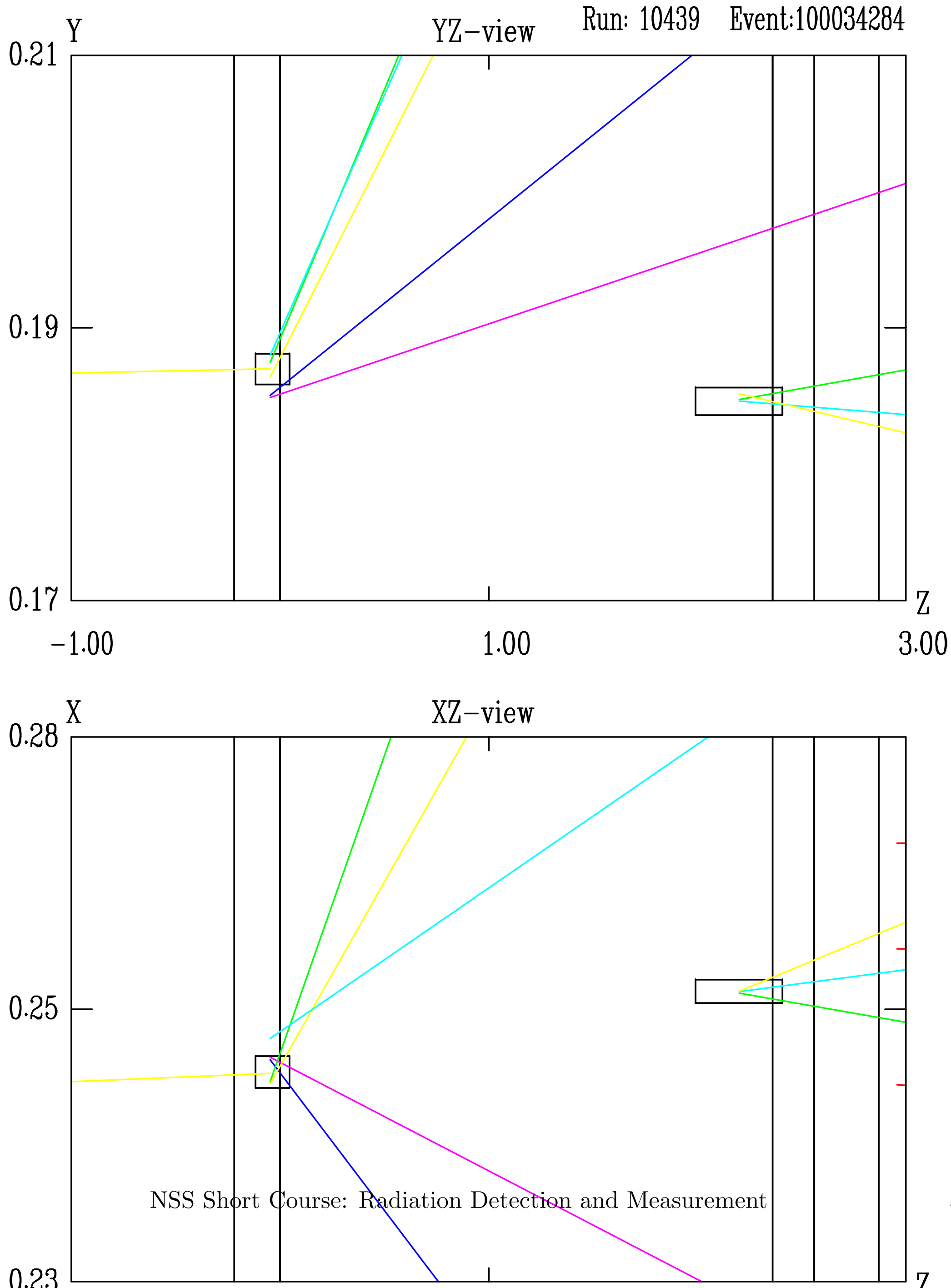
- **Use silicon microstrip detectors**

Measuring momentum and charge

- **Deflection in magnetic field, measure track angles before and after with wire chambers**

Measuring type (is it a proton?)

- **Measure total energy in calorimeter, calculate mass**
- **Measure velocity with Cherenkov effect**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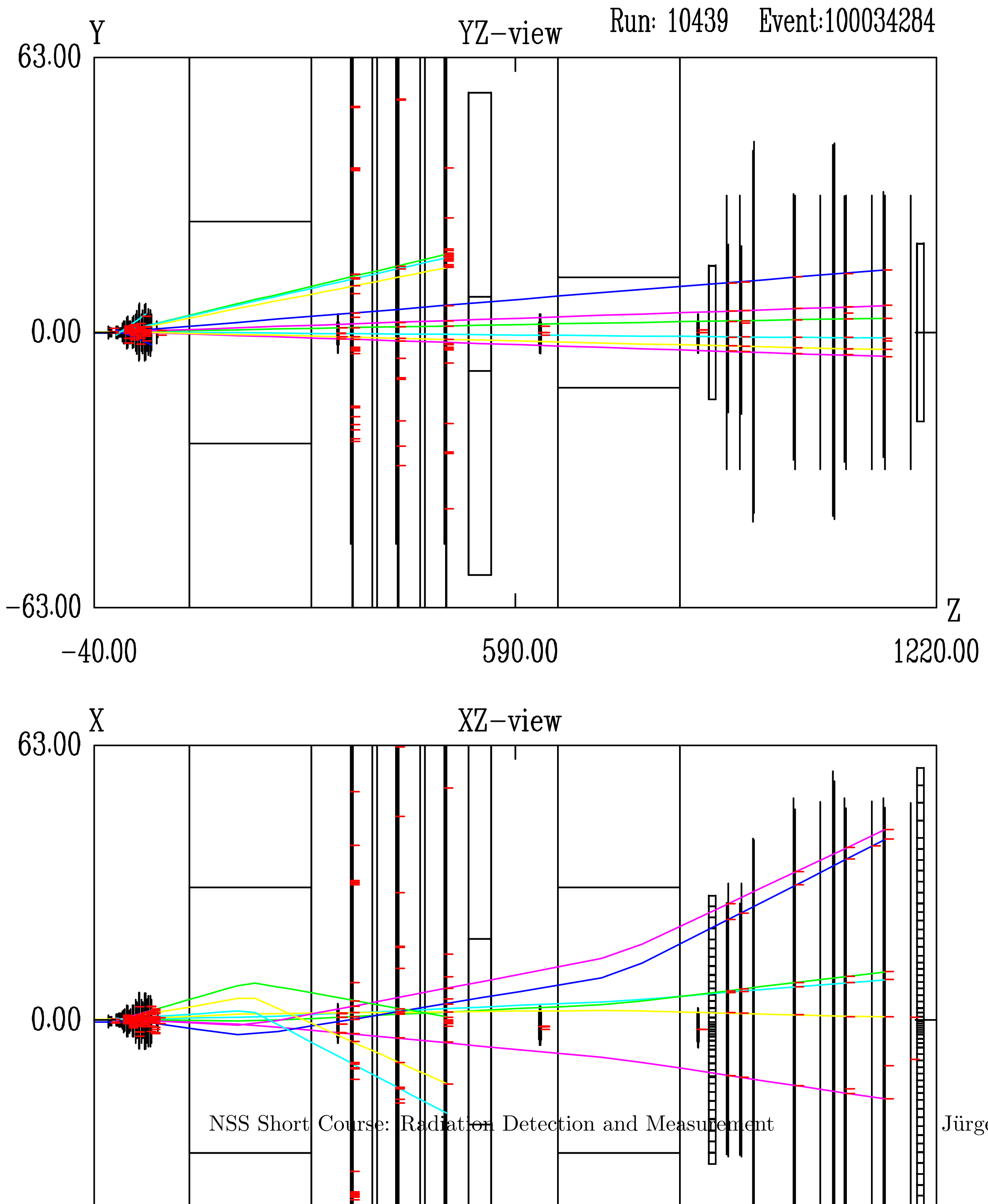
YZ-view
Y
0.21
0.19
0.17
Z
-1.00
1.00
3.00
XZ-view
X
0.28
0.25
0.23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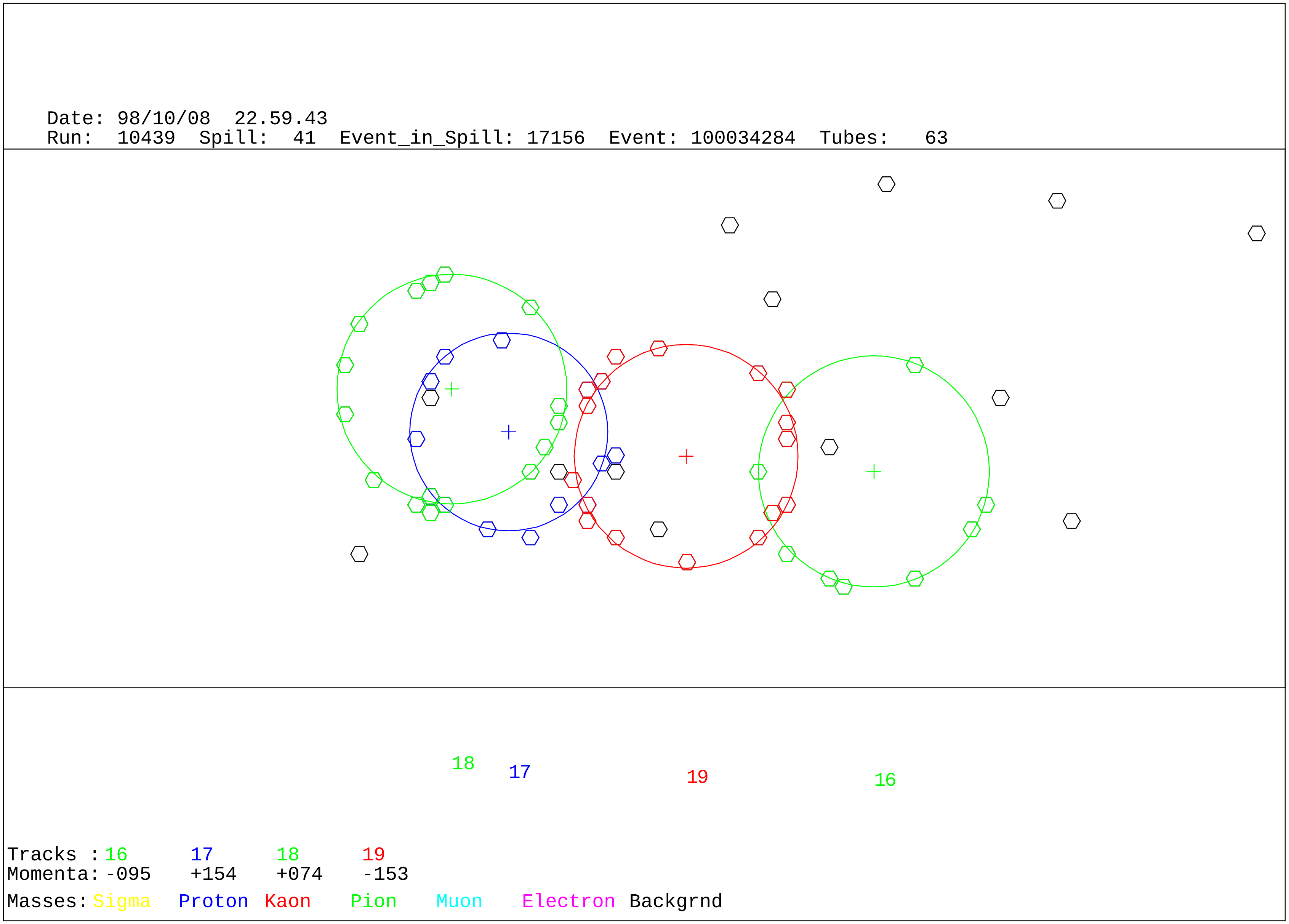
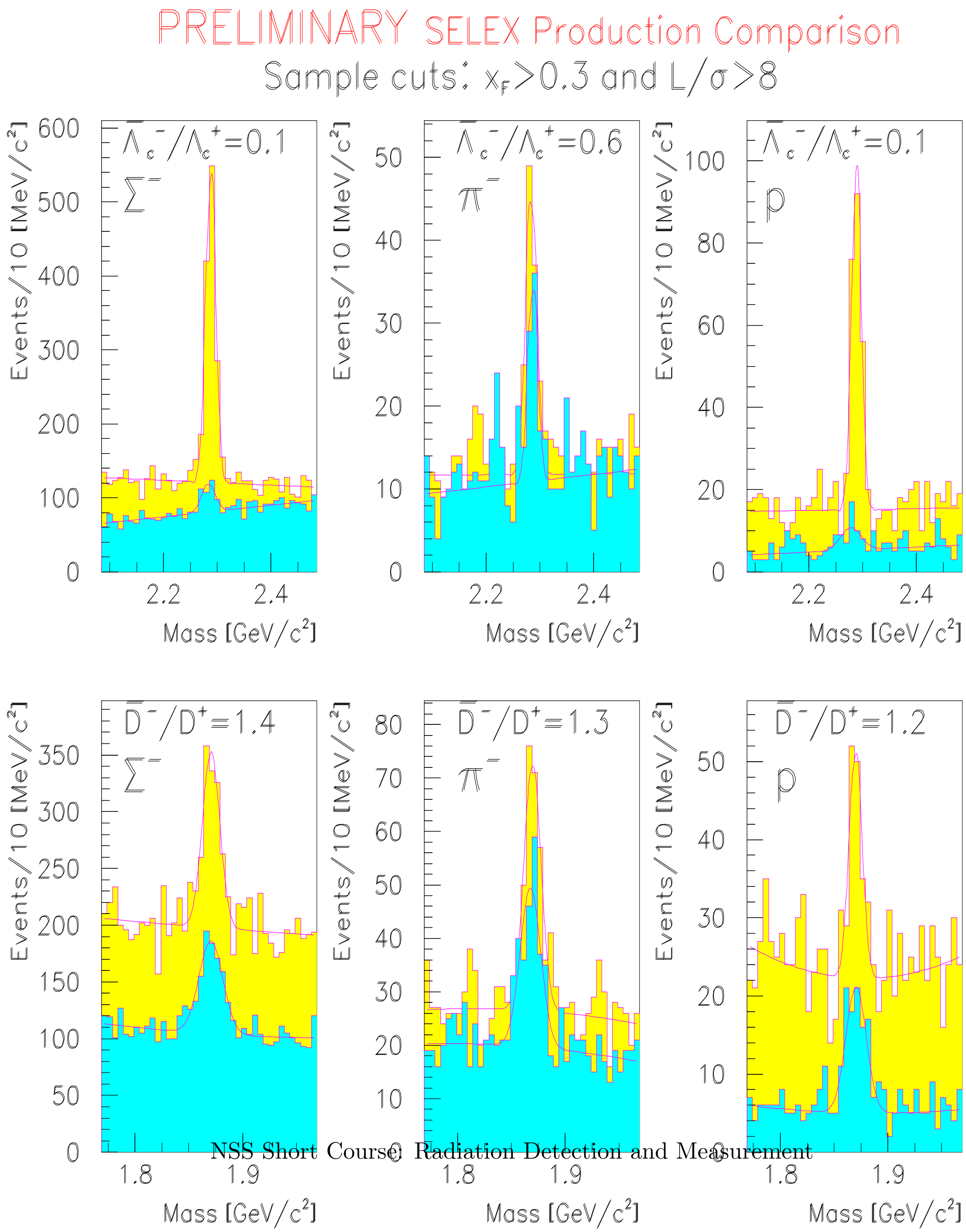
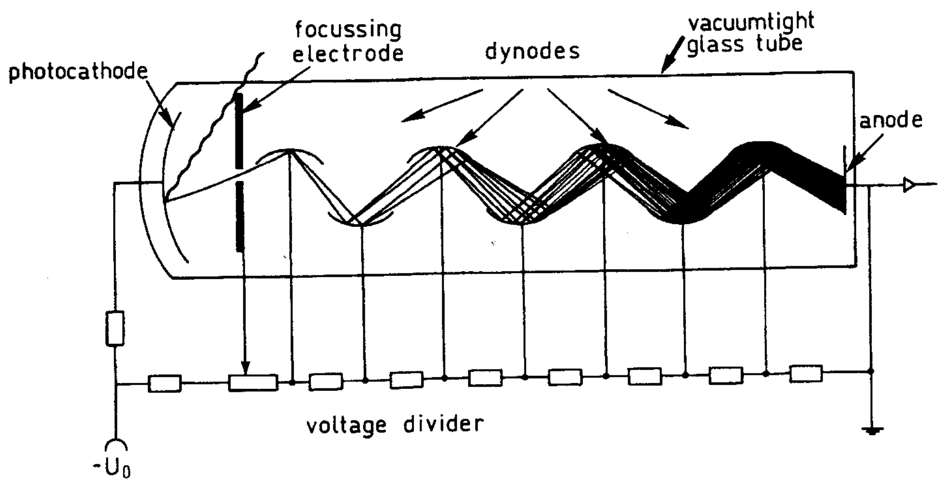
Y
YZ-view
63.00
0.00
-63.00
-40.00
590.00
1220.00
Z
X
XZ-view
63.00
0.00

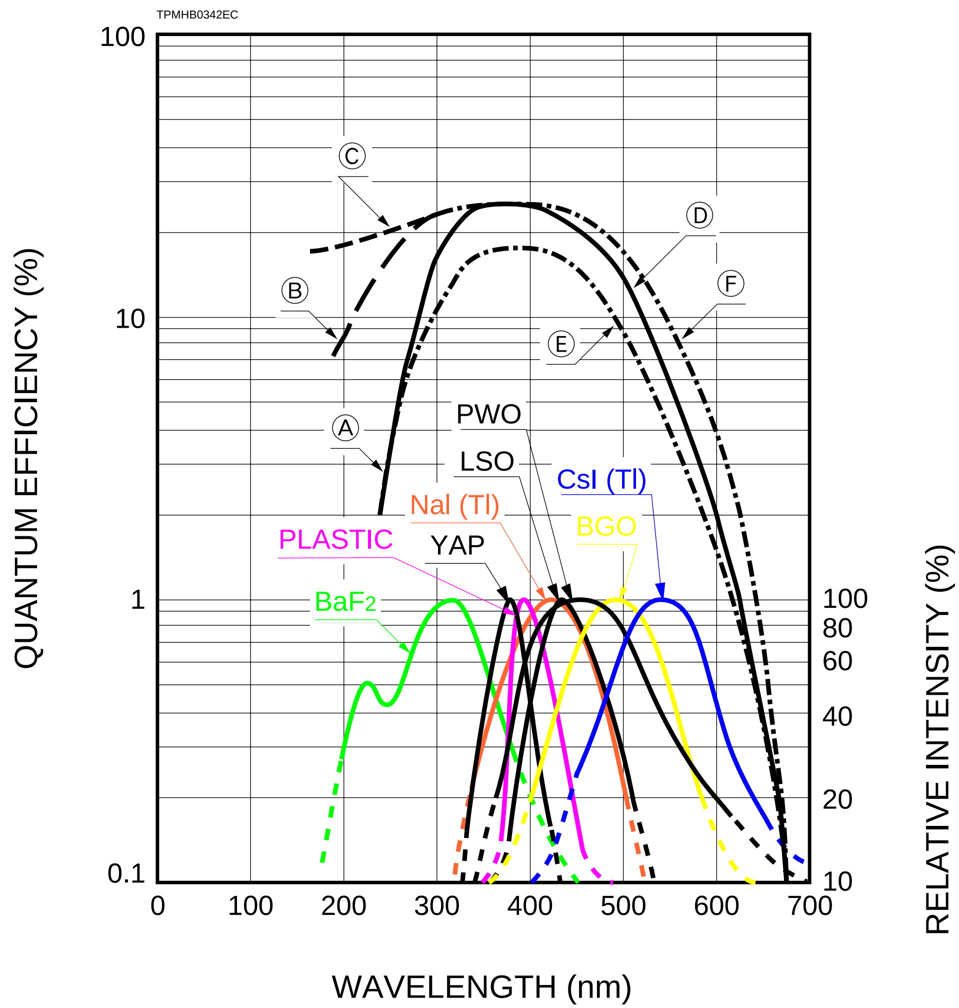


Date: 98/10/08 22.59.43
Run: 10439 Spill: 41 Event_in_Spill: 17156 Event: 100034284 Tubes: 63
18
17
19
16
Tracks : 16 17 18 19
Momenta: -095 +154 +074 -153
Masses: Sigma Proton Kaon Pion Muon Electron Backgrnd


PRELIMINARY SELEX Production Comparison
Sample cuts: x_F>0.3 and L/σ>8
$\bar{\Lambda}_c^-/\Lambda_c^+$=0.1
Σ⁻
$\bar{\Lambda}_c^-/\Lambda_c^+$=0.6
π⁻
$\bar{\Lambda}_c^-/\Lambda_c^+$=0.1
p
$\bar{D}^-/D^+$=1.4
Σ⁻
$\bar{D}^-/D^+$=1.3
π⁻
$\bar{D}^-/D^+$=1.2
p
Events/10 [MeV/c²]
Mass [GeV/c²]

Photomultipliers



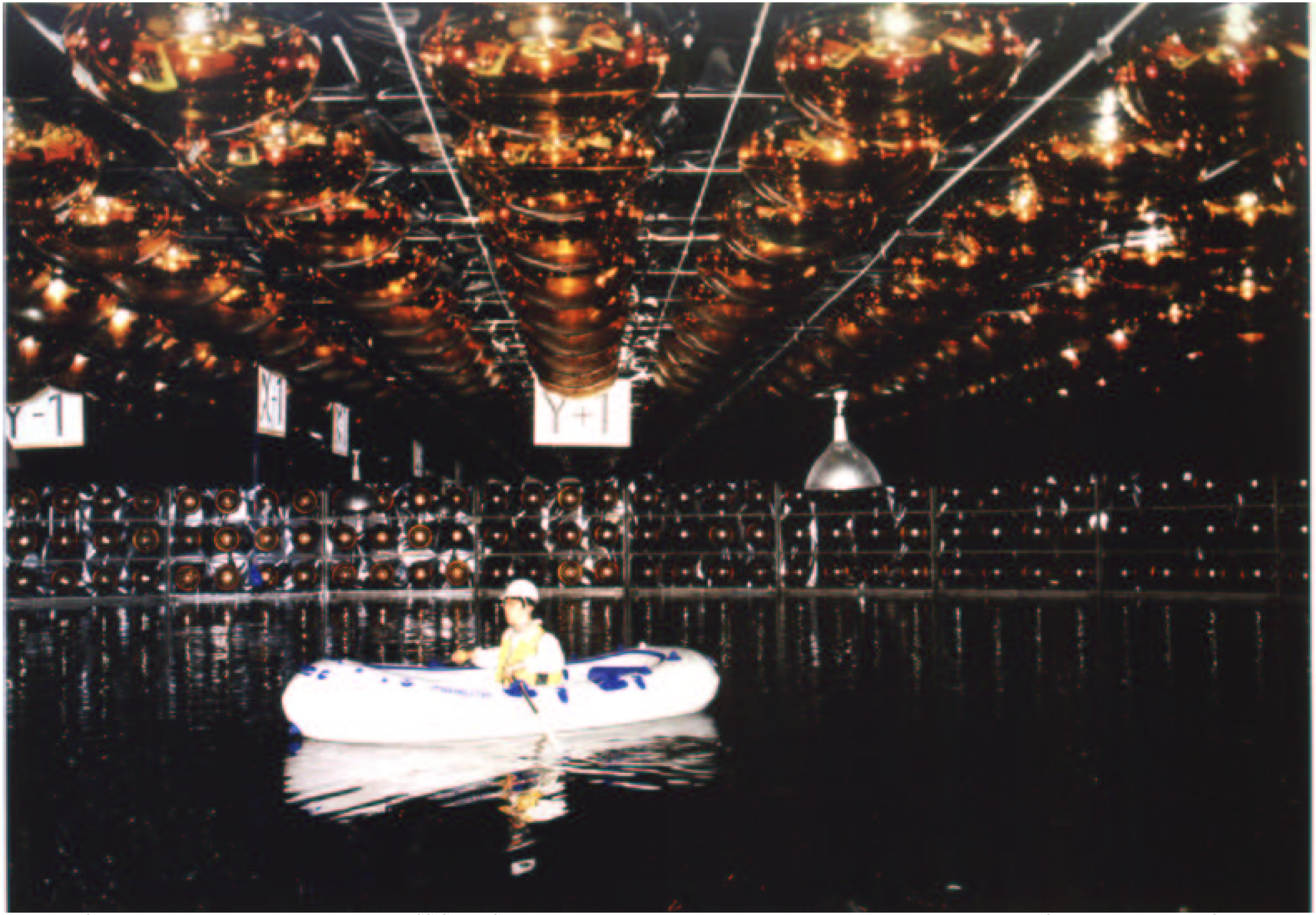


Conversion via photoelectric effect:
One photon to one electron,
electrons multiplied

Typical efficiencies: up to 25%

Photomultipliers (cont.)

Available from 3/8 inch diameters to ≈ 40cm diameter.
Entrance windows on top ("head on") or on sides ("side on")


Y-1
Y+1

“Simple” Method of Particle Identification
Time–of–flight (TOF)

- **Put two Scintillation Counters at a known distance L**
- **Measure time difference Δt between the two signals**

$$\Delta t = \frac{L}{\beta_1 c} - \frac{L}{\beta_2 c} = \frac{L}{c}\left[\sqrt{1 + \frac{m_1^2 c^2}{P^2}} - \sqrt{1 + \frac{m_2^2 c^2}{P^2}}\right]$$

$$P^2 \gg m^2 c^2 : \Delta t \approx (m_1^2 - m_2^2)\frac{Lc}{2P^2}$$

Good time resolution: 150 psec.
Maximum distance: ≈ 10 m (detector), ≈ 100 m (beamline).
⟹ Can measure difference between Kaons and Pions up to a few GeV/c
Also has problem at higher rate and/or multiple particles hitting the same scintillator

Charged Particles Ionisation Loss

Bethe-Bloch formula:

$$-\frac{dE}{dx} = 2\pi \frac{Z\,N_A}{A} \frac{2\,r_e^2\,m_e\,c^2}{\beta^2} z^2 [\frac{1}{2} \ln \frac{2\,m_e\,c^2 \gamma^2 \beta^2}{I^2} \beta^2 - \frac{\delta}{2}]$$

density correction

$$\frac{\delta}{2} = \ln \frac{\hbar\omega_p}{I} + \ln \beta\gamma - \frac{1}{2}$$

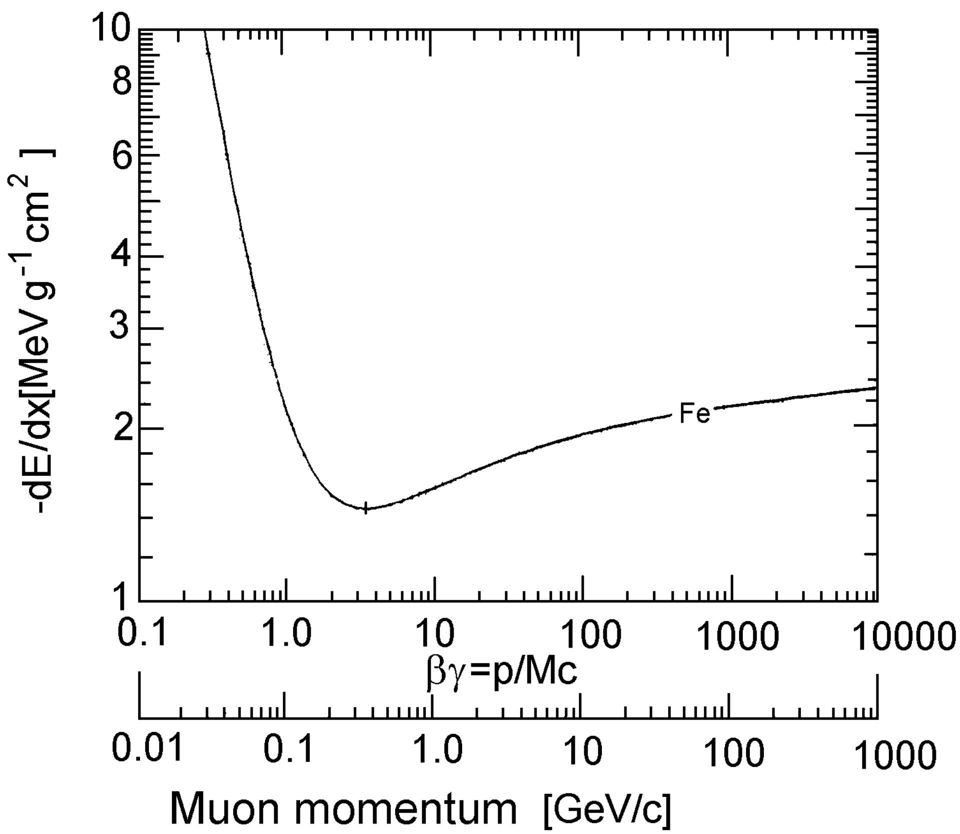
$$\hbar\omega_p = \sqrt{4\pi N_e r_e^2} \frac{m_e\,c^2}{\alpha}$$ **plasma energy**

$\boldsymbol{N_e}$ **electron density of absorbing material**

$\boldsymbol{\alpha}$ **fine structure constant**

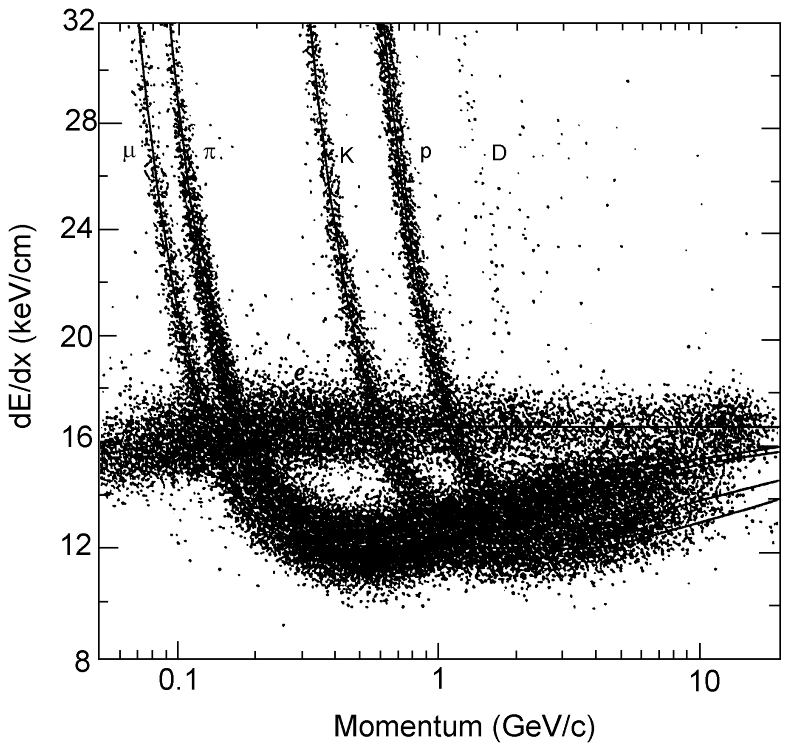
Bethe-Bloch (cont.)

Example:
Energy loss of muons in iron



- Minimum at $3 \leq \beta\gamma \leq 4$
- Minimum ionizing particles:
  - helium: $-dE/dx = 1.94\,\mathrm{MeV/(g/cm^2)}$
  - uranium: $-dE/dx = 1.08\,\mathrm{MeV/(g/cm^2)}$
  - hydrogen: exceptionally large $(Z/A = 1)$
- $\ln\gamma$ term: relativistic (logarithmic) rise
- Fermi-Plateau due to density effect
- in gases: Plateau $\approx 60\,\%$ higher as minimum ionizing.

Energy Loss in Gases



PEP4/9-TPC (185 dE/dx measurements, Ar:CH_4 at 8.5 atm)

Landau Distribution

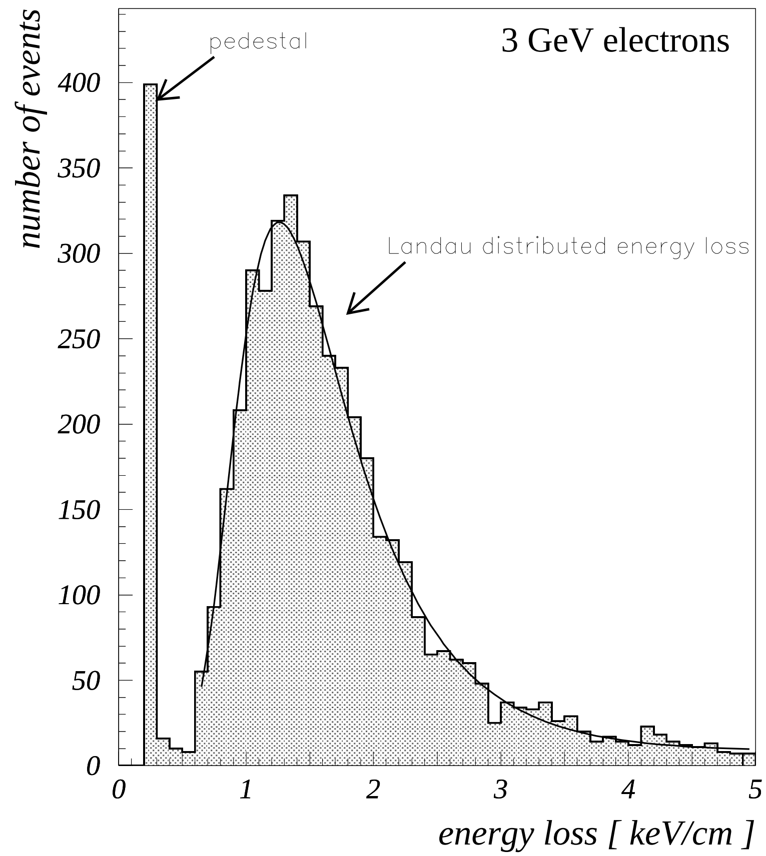
- Bethe-Bloch describes mean energy loss
- Energy loss is distributes asymmetrically
- approximated by

$$\Omega(\lambda) = \frac{1}{\sqrt{2\pi}} e^{-\frac{1}{2}(\lambda + e^{-\lambda})}$$

$$\lambda = \frac{\left(\frac{dE}{dx}\right) - \left(\frac{dE}{dx}\right)^{\text{m.p.}}}{0.123\,\mathbf{keV}}$$

$\left(\frac{dE}{dx}\right)^{\text{m.p.}}$ most probable energy loss

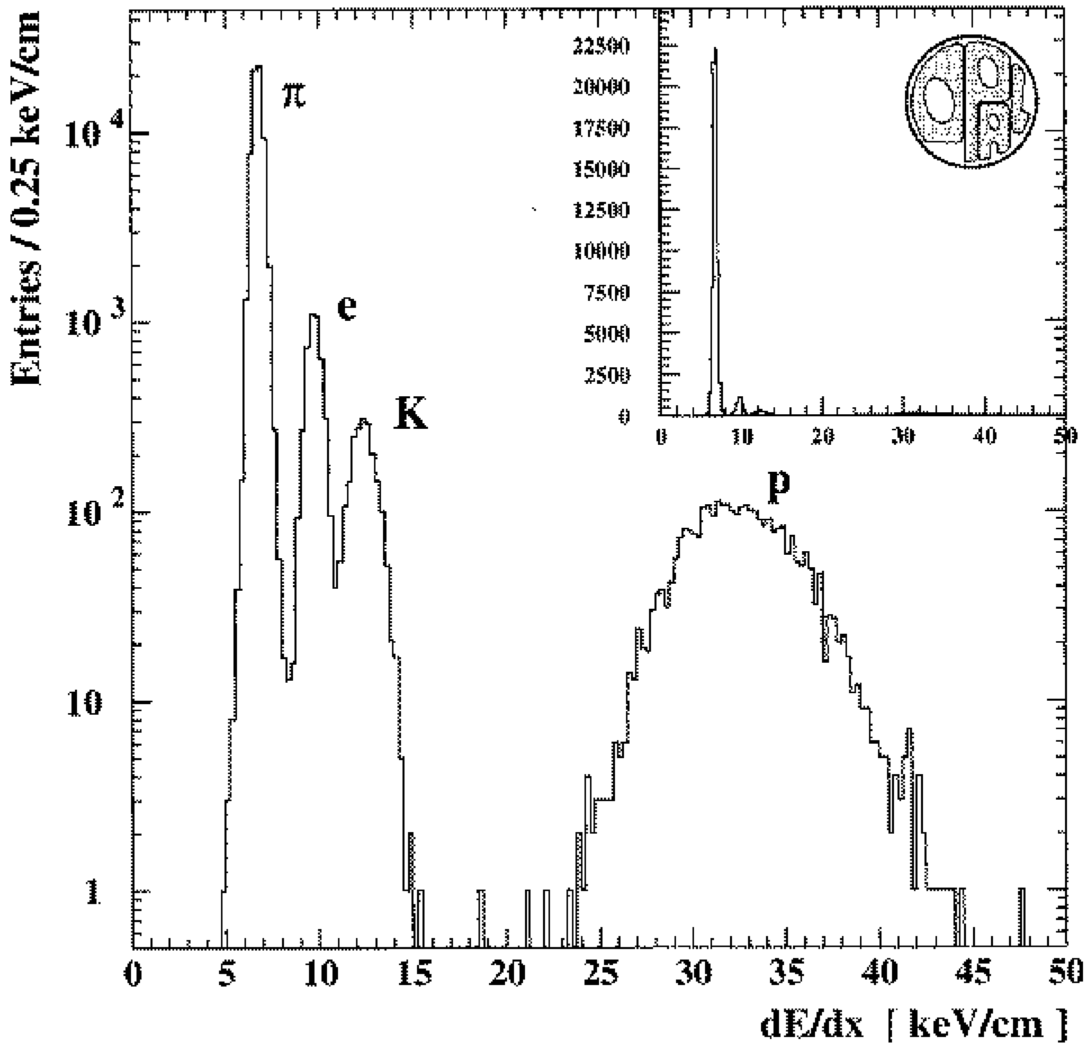
- important in gases, thin absorbers
- Argon, $\beta\gamma = 4$:
  $\left(\frac{dE}{dx}\right)^{\text{m.p.}} = 1.2\,\text{keV/cm}$; $\langle\frac{dE}{dx}\rangle = 2.69\,\text{keV/cm}$
- For Particle Identification:
  - Measure often (typ. 160) to get distribution
  - Use "Truncated Mean"



Electrons in Ar:CH_4 (80:20)

K. Afforlderbach et al., Nucl. Instr. Meth. A410 (1998) 166

Particle Identification via dE/dx



Momentum interval $0.45\,\mathrm{GeV}/c - 0.48\,\mathrm{GeV}/c$

OPAL Collaboration, CERN-PPE-94-49

Radiation by Charged Particles

Radiation is emitted by a charged particle if:

1. $v > c/n$: Cherenkov radiation
2. $\vec{v}/c_{\mathrm{ph}} = \vec{v} \cdot n/c$ changes
   (a) $|\vec{v}|$ changes: Bremsstrahlung
   (b) direction of $\vec{v}$ changes: Synchrotron radiation
   (c) n changes: Transition Radiation

Transition Radiation Detectors (TRD)

Transition Radiation: Reformation of particle field while traveling from medium with $\epsilon = \epsilon_1$ to medium with $\epsilon = \epsilon_2$.

Energy of radiation emitted at a single interface

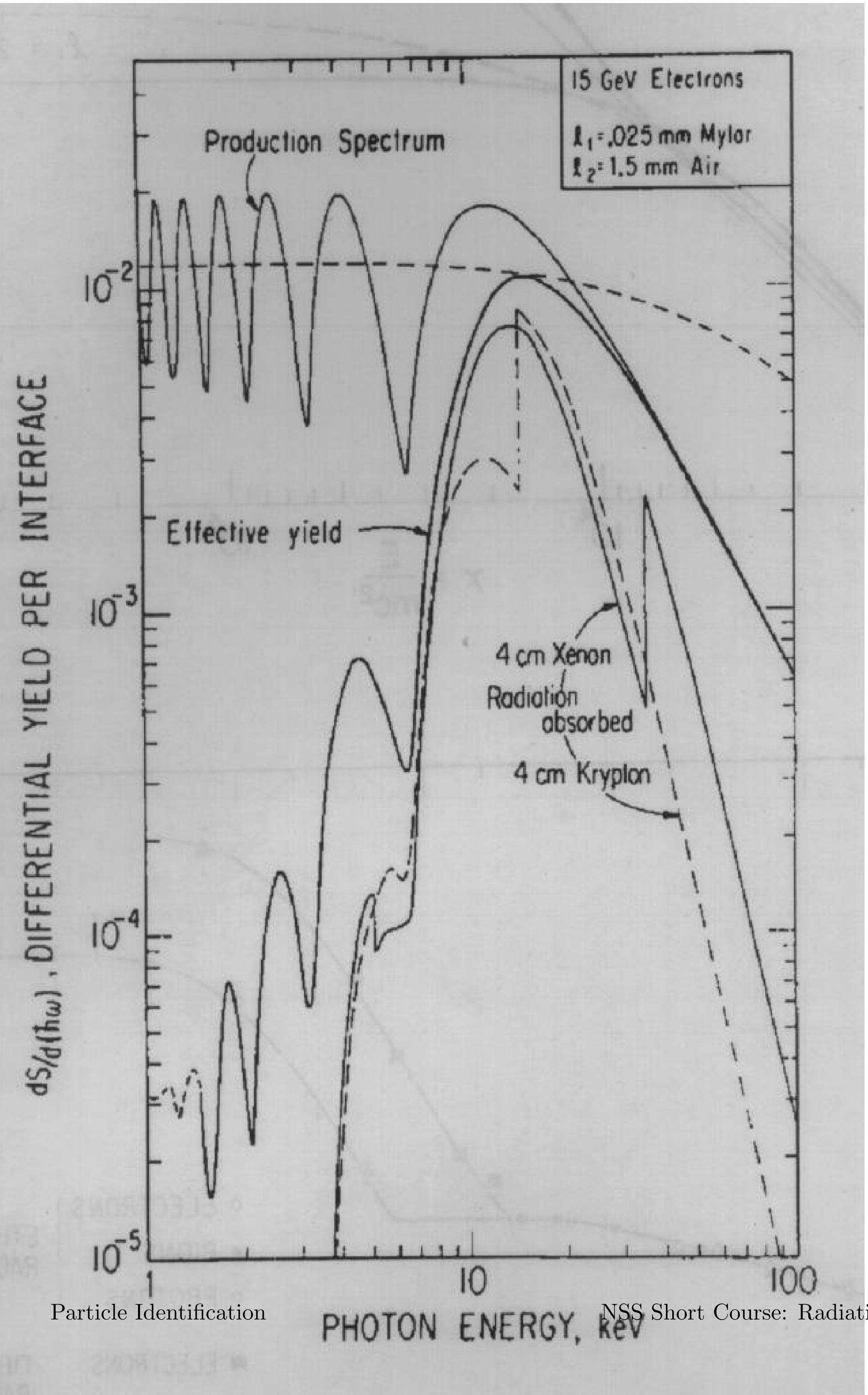
$$S = \frac{\alpha \hbar z^2}{3} \frac{(\omega_1 - \omega_2)^2}{\omega_1 + \omega_2} \gamma$$

$\alpha = 1/137$, ω_1, ω_2 plasma frequencies, $\gamma = E/mc^2$.
Typical values: Air $\omega_1 = 0.7\,\mathrm{eV}$, polypropylene $\omega_2 = 20\,\mathrm{eV}$

Spectral and angular dependence of Transition Radiation:

$$\frac{d^2}{d\vartheta d\omega} = \frac{2e^2}{\pi c} \left(\frac{\vartheta}{\gamma^{-2} + \vartheta^2 + \omega_1^2/\omega^2} - \frac{\vartheta}{\gamma^{-2} + \vartheta^2 + \omega_2^2/\omega^2} \right)^2$$

$\Longrightarrow$ Most of radiation in cone with half angle $1/\gamma$: forward in particle direction.



- Large photon energies $\omega > \gamma\omega_2 \approx 25\,\mathrm{KeV}$: large drop of intensity $\propto \gamma^4/\omega^4$
- Medium energies $\gamma\omega_1 < \omega < \gamma\omega_2$: Logarithmic decrease with ω
- Small energies $\omega < \gamma\omega_1 \approx 1\,\mathrm{KeV}$: intensity almost constant

Probability to emit a KeV photon: $\approx 10^{-2}$
$\Longrightarrow$ Need a lot of interfaces: stack of foils

Consequences:

- Need minimum foil thickness so particle field reaches new equilibrium
- Transition $\omega_1 \rightarrow \omega_2$ and $\omega_2 \rightarrow \omega_1$ equal $\Longrightarrow$ Interference effects
- Equally spaced foils: Interference between amplitude of different foils
- Finite thickness of foils: re-absorption ofradiation ($\propto Z^5$): Low Z materials.

Typical values used in TRDs:
Thickness: $30\,\mu$m, distance: $300\,\mu$m,
materials: mylar, CH_2, carbon fibers, lithium.

Detection of Transition Radiation

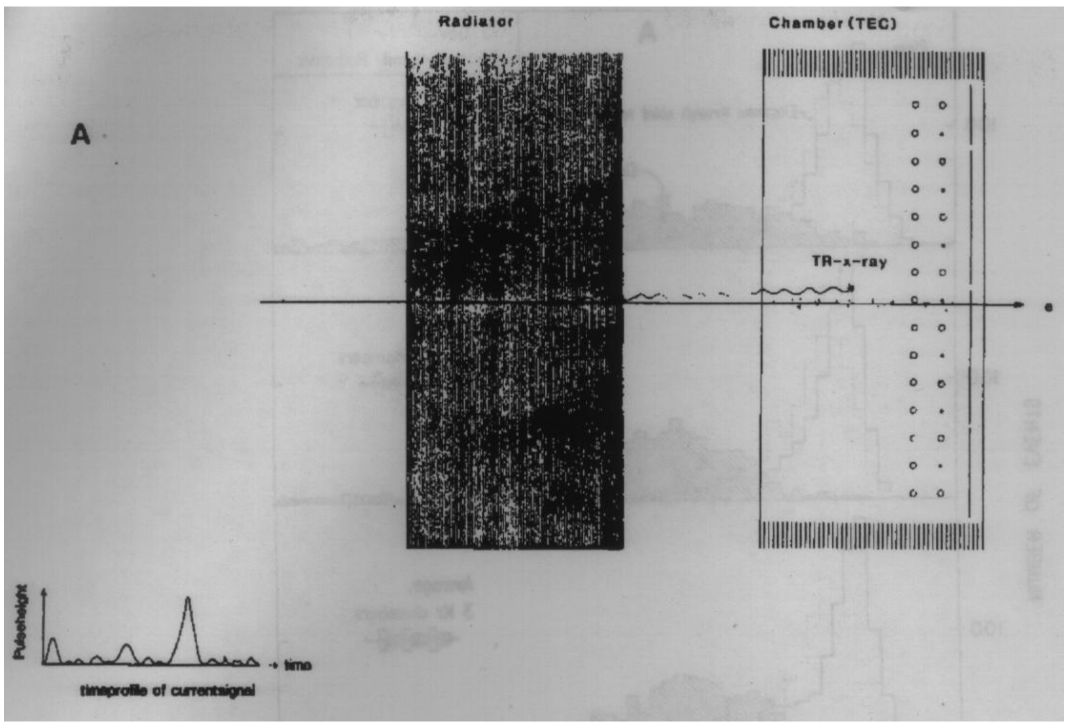
X-rays emitted under small angle to particle track

$\Longrightarrow$ X-ray detector sees X-rays and particle dE/dx together.

Typical dE/dx in gas detectors: some KeV/cm and Landau distributed

$\Longrightarrow$ Signals from dE/dx and X-ray similar

Detector: Use "thin" MWPC, with Xenon or Krypton,
several (10) radiator / chamber units to beat Landau



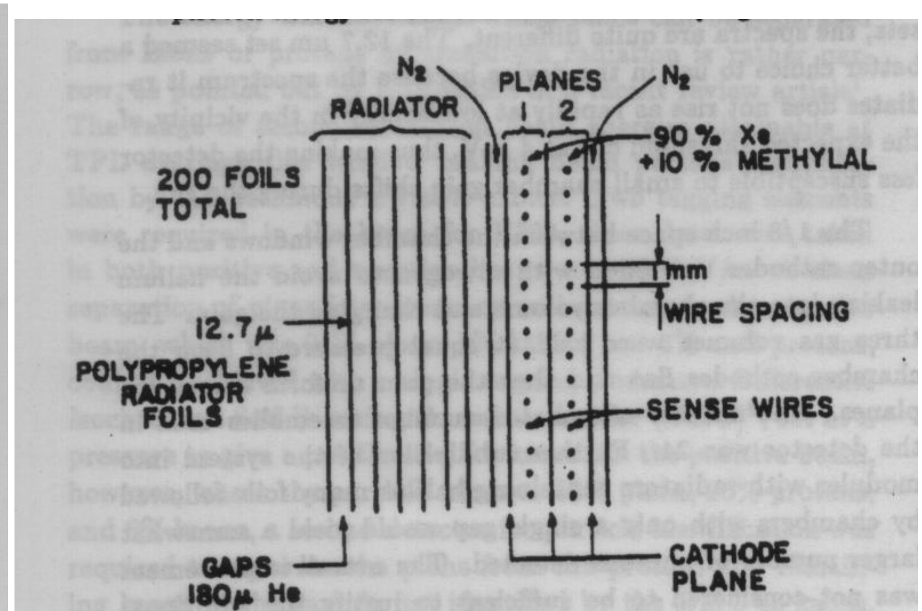
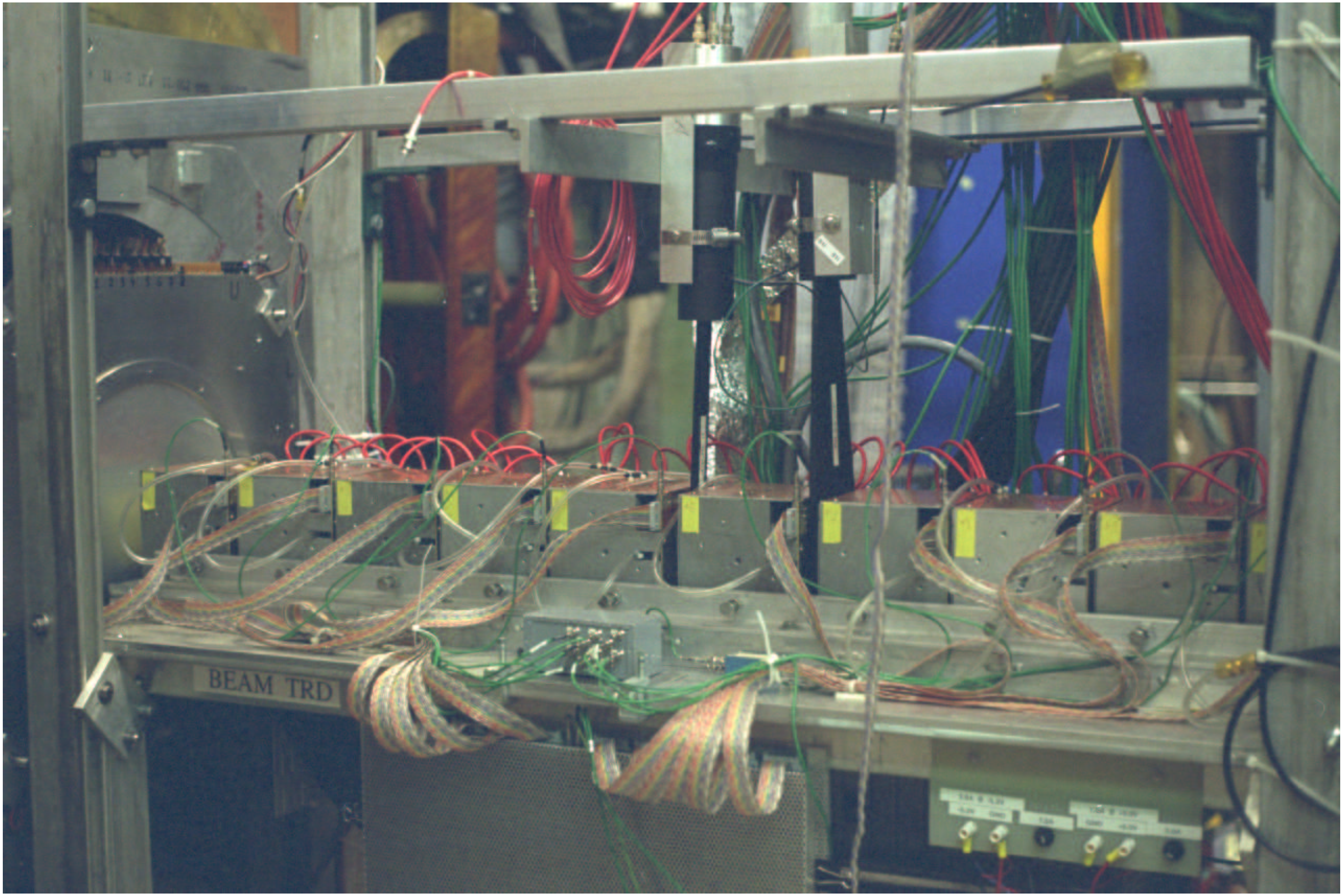
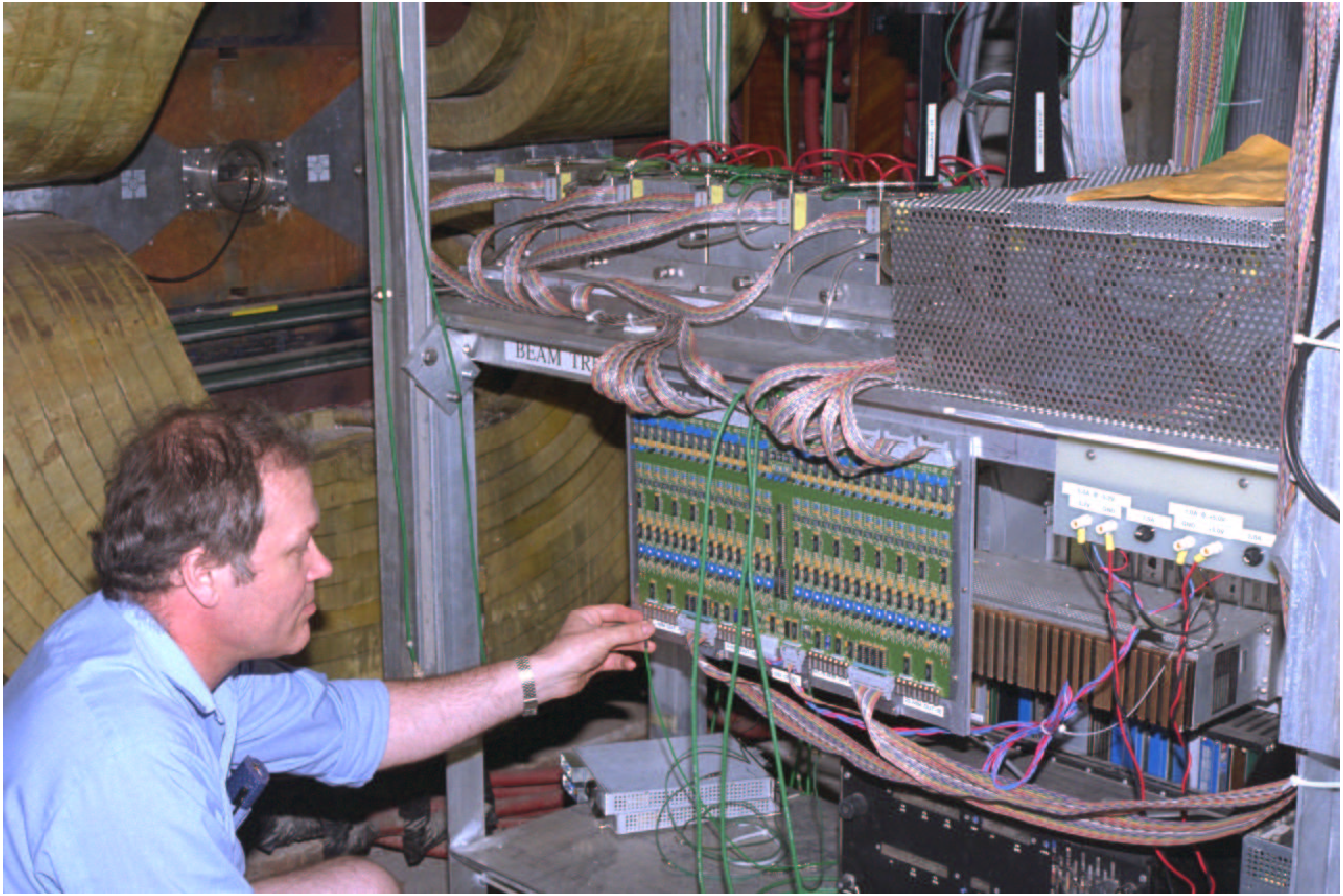
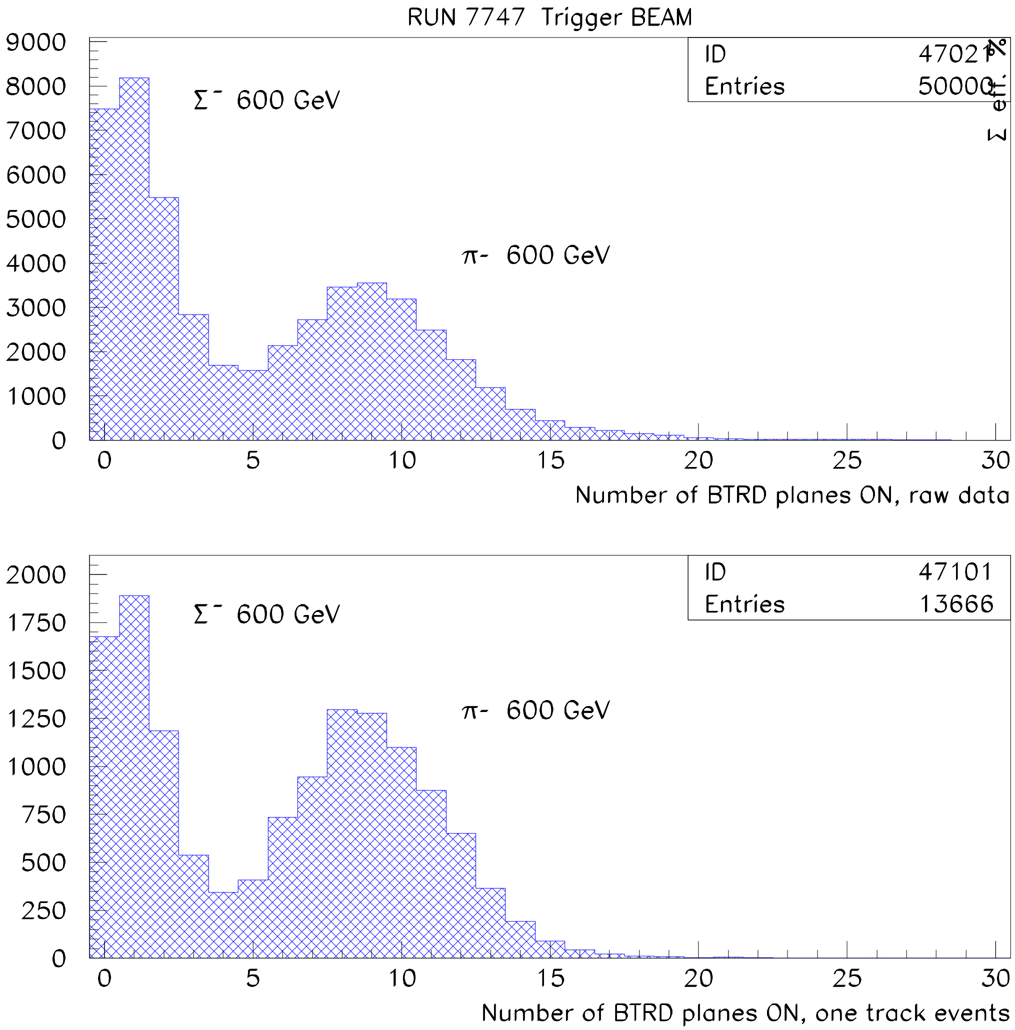


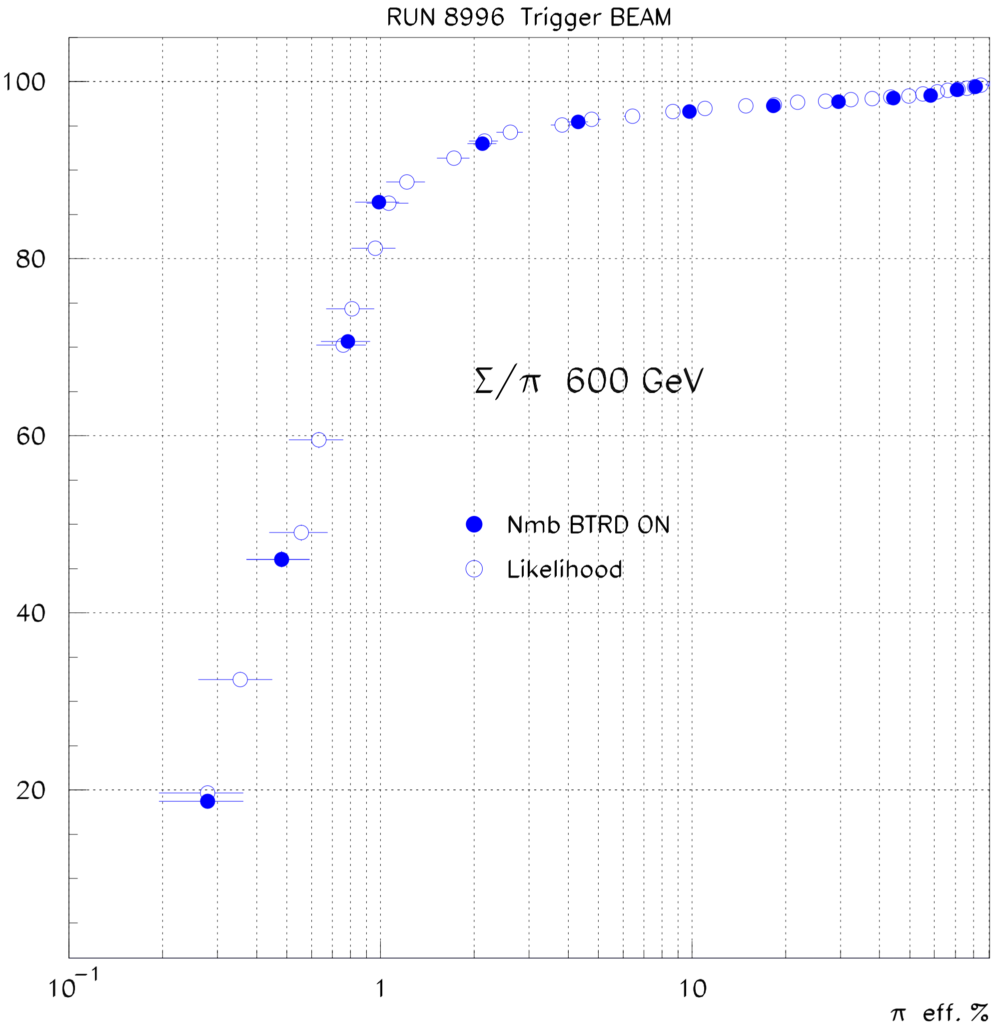
Fig **4. Schematic of a radiator-chamber module showing the final design parameters discussed in the text.**

Two identification methods: Charge integration, Cluster counting

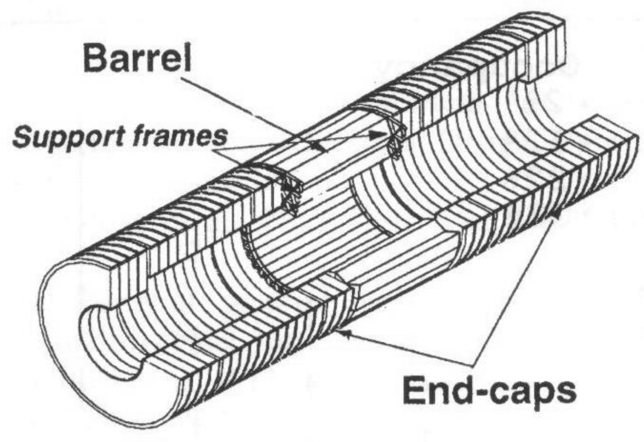

BEAM TRD


BEAM


RUN 7747 Trigger BEAM
ID 47021
Entries 50000
Σ⁻ 600 GeV
π- 600 GeV
Number of BTRD planes ON, raw data
ID 47101
Entries 13666
Σ⁻ 600 GeV
π- 600 GeV
Number of BTRD planes ON, one track events


RUN 8996 Trigger BEAM
Σ eff. %
Σ/π 600 GeV
Nmb BTRD ON
Likelihood
π eff. %

ATLAS Transition Radiation Tracker (TRT)



Length:	Total	6802 cm	N straws:	Total	372032
	Barrel	148 cm		Barrel	52544
	End-cap	257 cm		End-cap	319488
Outer diameter		206 cm	N electronics channels		424576
Inner diameter		96-128 cm	Weight		~ 1500 kg

Fig. 11. ATLAS Transition Radiation Tracker (TRT) conceptual design [2].

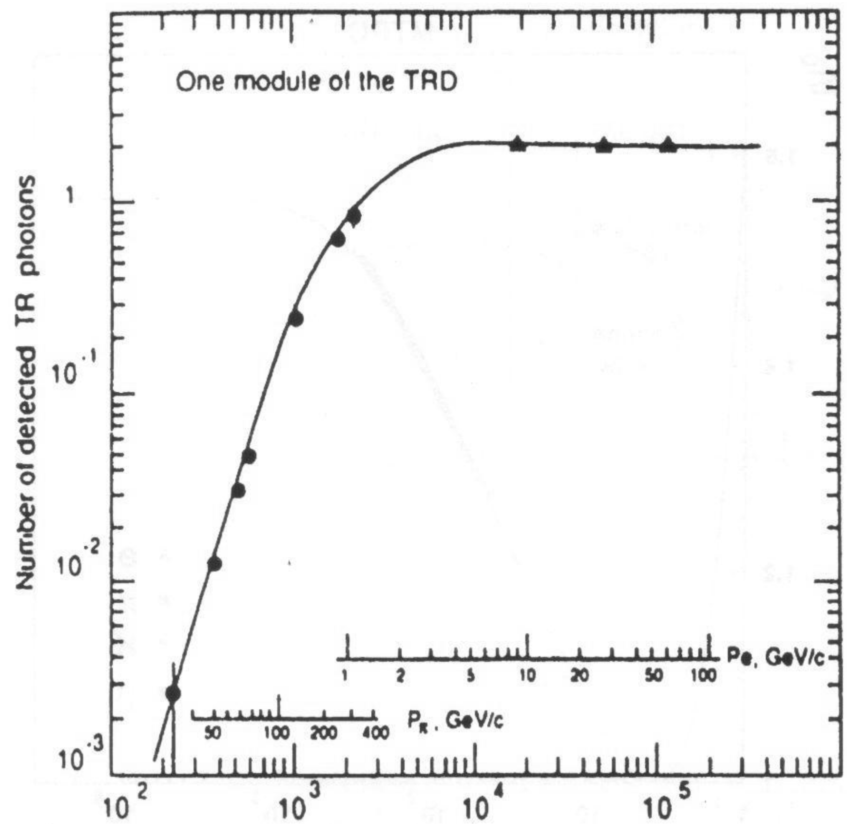


Fig. 8. The detected number of the TR photons for different Lorentz factors [4].

Cherenkov Radiation

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)

Threshold:

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

Angle of emission:

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

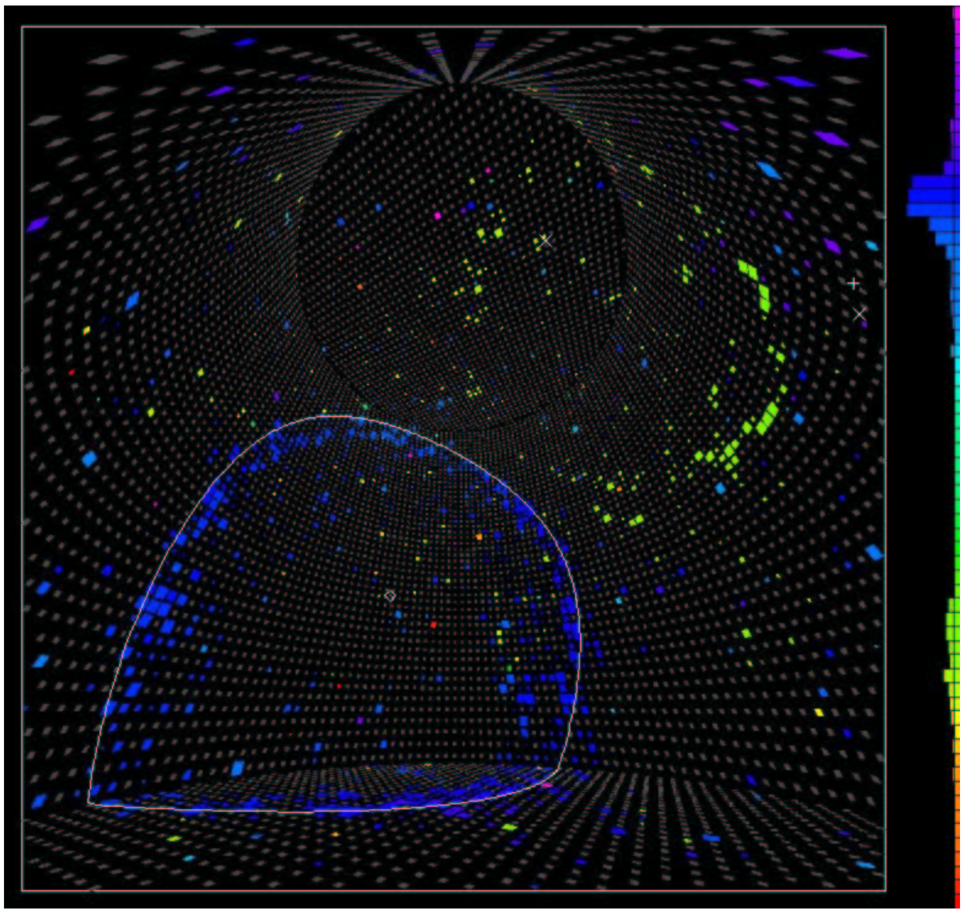
Number of photons:

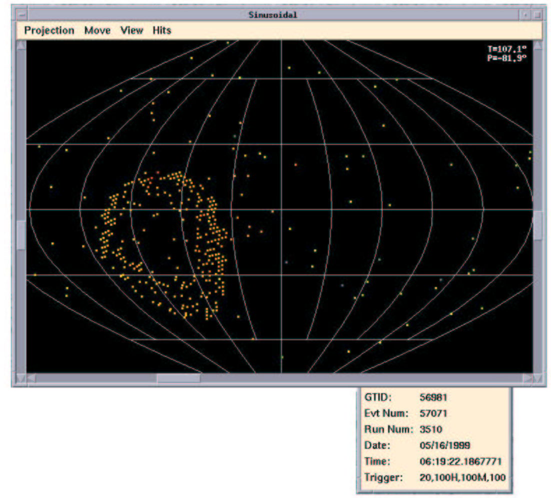
$$\frac{d^2N}{dEdl} = \frac{\alpha z^2}{\hbar c}\left(1 - \frac{1}{(\beta n)^2}\right) = \frac{\alpha z^2}{\hbar c}\sin^2\theta_c$$

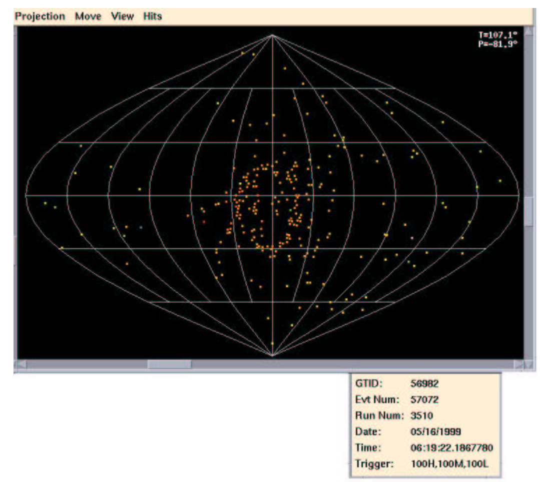
$$\frac{d^2N}{d\lambda dl} = \frac{2\pi\alpha z^2}{\lambda^2}\sin^2\theta_c$$

5th International Workshop on Ring Imaging Cherenkov Counters (RICH2004)
Dedicated to the Centenary of Pavel Cherenkov's Birth
November 30 – December 5, 2004, Playa del Carmen, Mexico

Water Cherenkov



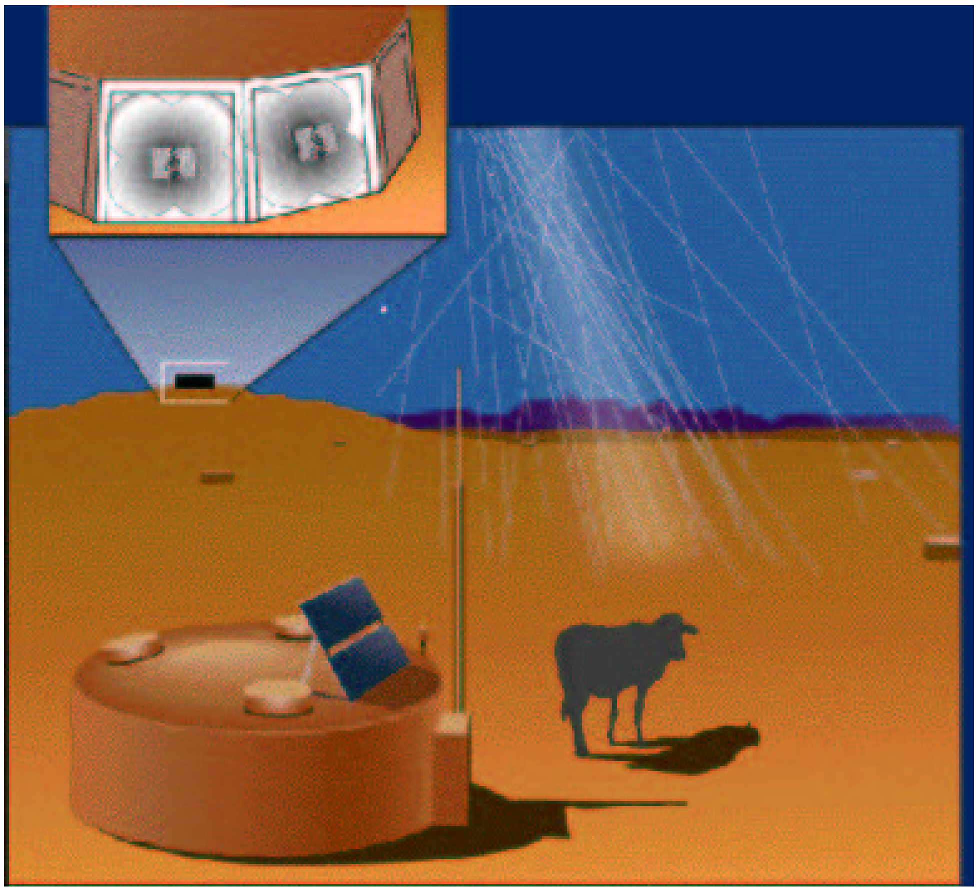


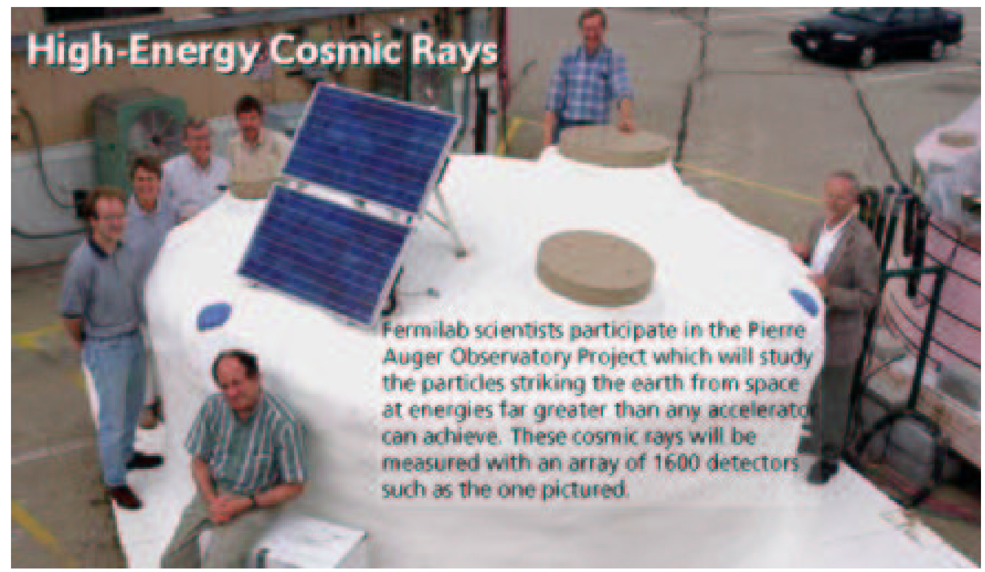


neutrino induced muon in SuperKamiokande

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

Auger Experiment: Water Cherenkov's





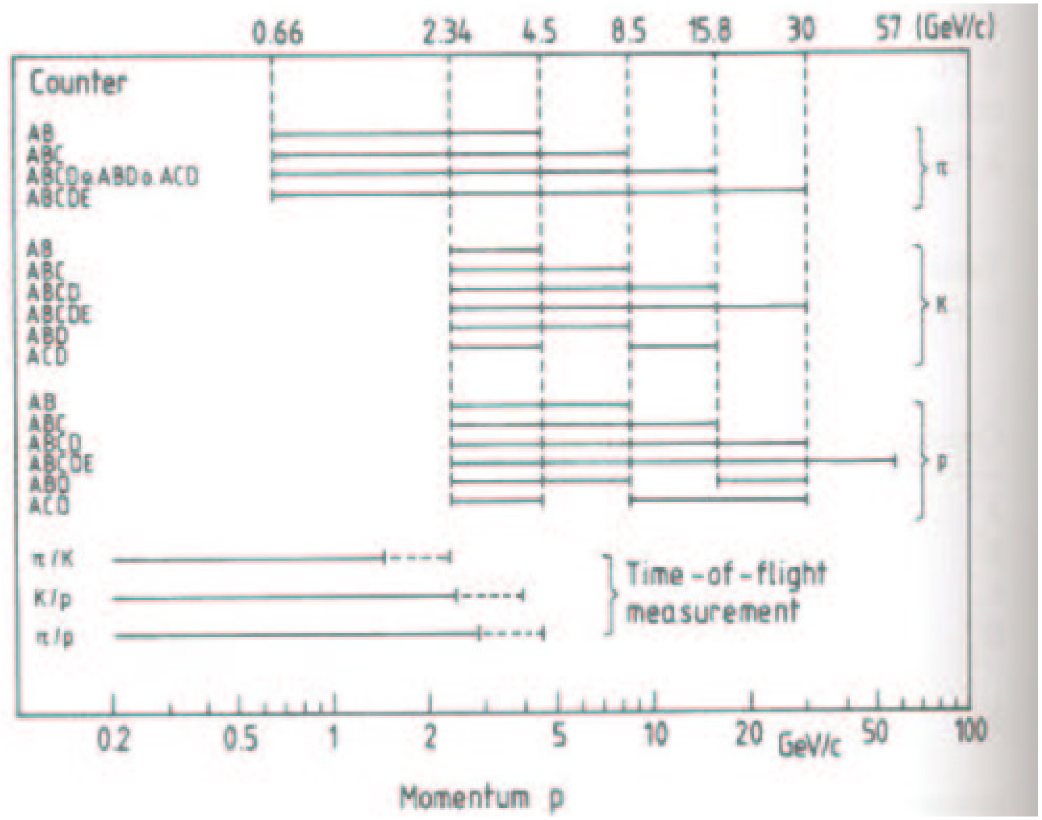
Threshold Cherenkov Detectors

First (obvious) application: Threshold Cherenkov Detectors

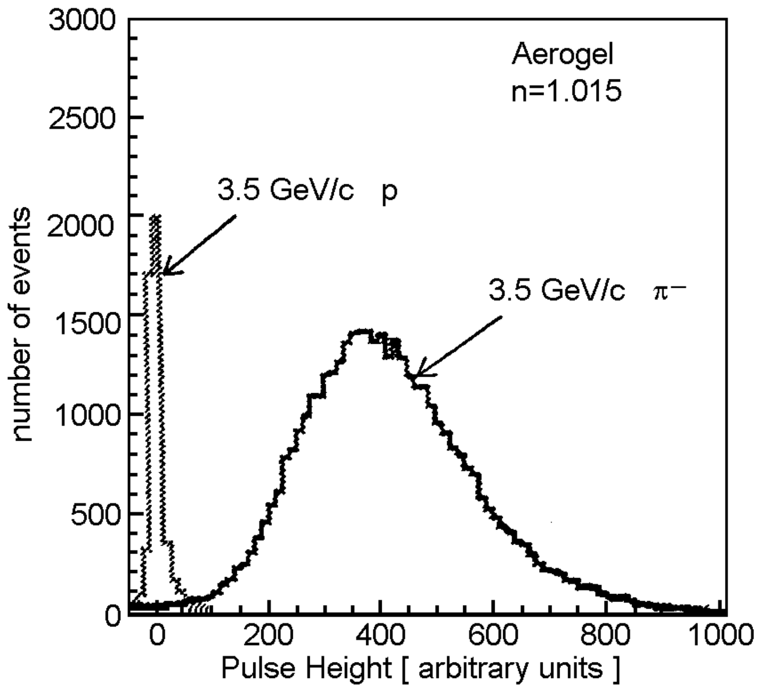
For fixed momentum and only 2 particles to separate (beam line)

More than 2 particles and/or wider momentum range: Several counters at different thresholds

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	1.22-1.37
Water	0.33	1.52
Aerogel	0.025-0.075	4.5-2.7
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



Threshold Cherenkov Detectors



Aerogel: $n = 1.015 \Rightarrow \gamma_{\text{thres}} = 5.84$

$3.5\,\mathbf{GeV/c} \Rightarrow \gamma_\pi = 24.2, \quad \gamma_p = 2.86$

To identify more than 2 particles and/or to cover wider momentum range: Several counters at different thresholds

A. Satpathy et al., BELLE Collaboration, hep-ex/9903045

NUCLEAR INSTRUMENTS AND METHODS 9 (1960) 55–68; 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 or 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, it seems to originate from a ring source at infinity whose angular diameter is that of the cone (fig. 1b). It has justly been likened to the light from a ring of faint stars. If such light is collected by a telescope objective, an image of the ring is formed in the focal plane with a diameter given by

$$d = 2f \tan\theta \qquad (1)$$

where f is the focal length of the objective, and θ the half-angle of the cone of light.

Precisely such an arrangement may be used to collect the Čerenkov radiation from a fast

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 cascade system.

(a) (b)

Fig. 1. (a) [illegible] radiation emitted by a fast particle traversing a radiator [illegible] a circular cone of parallel rays [illegible] The light from a [illegible] which may be [illegible] by a lens or mirror objective.

[illegible] in this way a Čerenkov

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

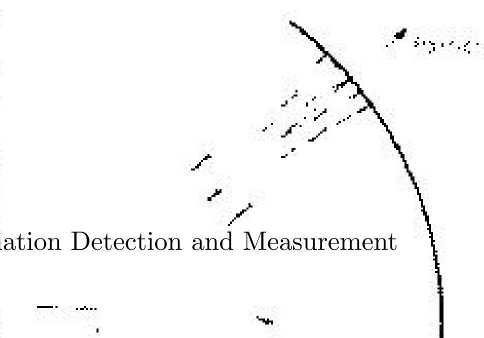
$$\frac{\Delta\beta}{\beta} = \left[\tan^2\theta\,(\Delta\theta)^2 + \left(\frac{\Delta n}{n}\right)^2\right]^{\frac{1}{2}}, \tag{2}$$

with $\Delta\beta$, $\Delta\theta$ and Δn the r.m.s. error in the measurement of β, θ and n respectively. Litt and Meunier[2]) show that with a "differential isochronous self collimating" type Cherenkov counter (DISC) a resolution of $\Delta\beta/\beta \approx 10^{-7}$ is possible. This corresponds to a γ resolution of $\Delta\gamma/\gamma = [illegible]\,\Delta\beta/\beta = 0.4\%$ at $\gamma = 200$. In such counters the Cherenkov photons emitted at different points along the particle's straight line trajectory are focused by a reflective mirror (radius R, focal length $f = \frac{1}{2}R$) to give a circular ring image of radius r at the mirror focal plane. In the small angle approximation the focal surface is a plane and the radius of the ring image is

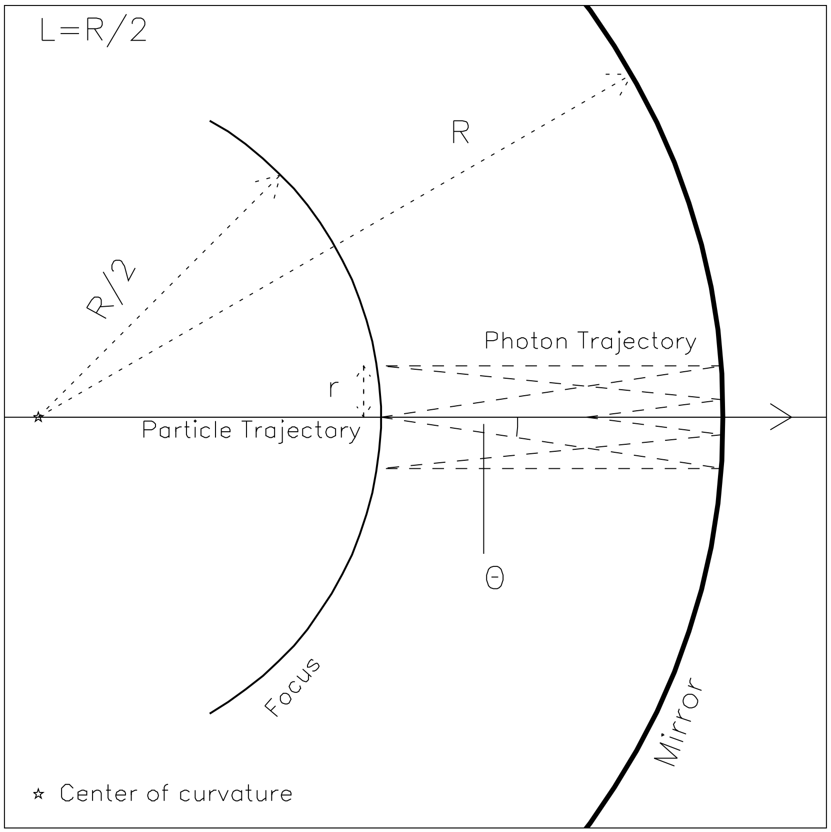
$$r = f\tan\theta, \tag{3}$$

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 (see fig. 1) as consisting of a spherical mirror of radius R whose centre is the source of secondary particles (target) and a spherical detector surface at radius $\frac{1}{2}R$ with the Cherenkov radiating medium



Ring Imaging Cherenkov – The Basics



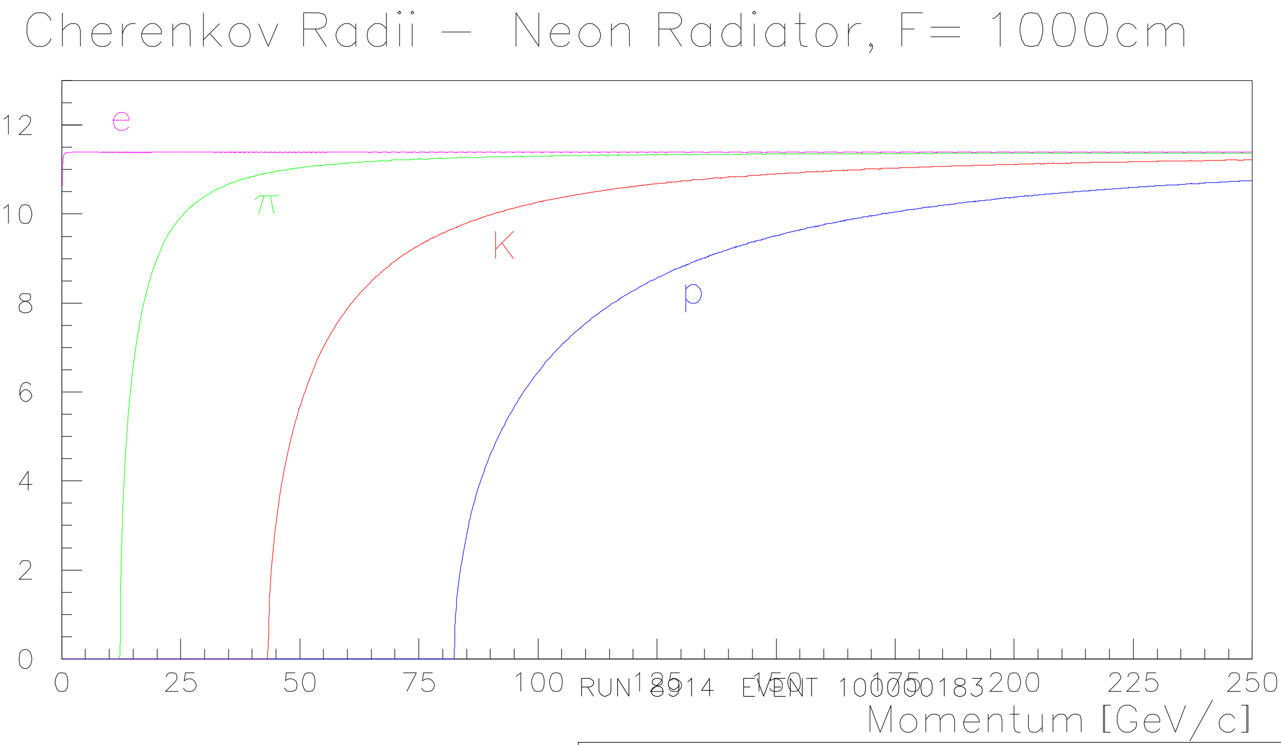
$$\cos\theta_c = \frac{1}{\beta \cdot n}$$

$$r = F \cdot \theta_c = \frac{R}{2} \cdot \theta_c$$

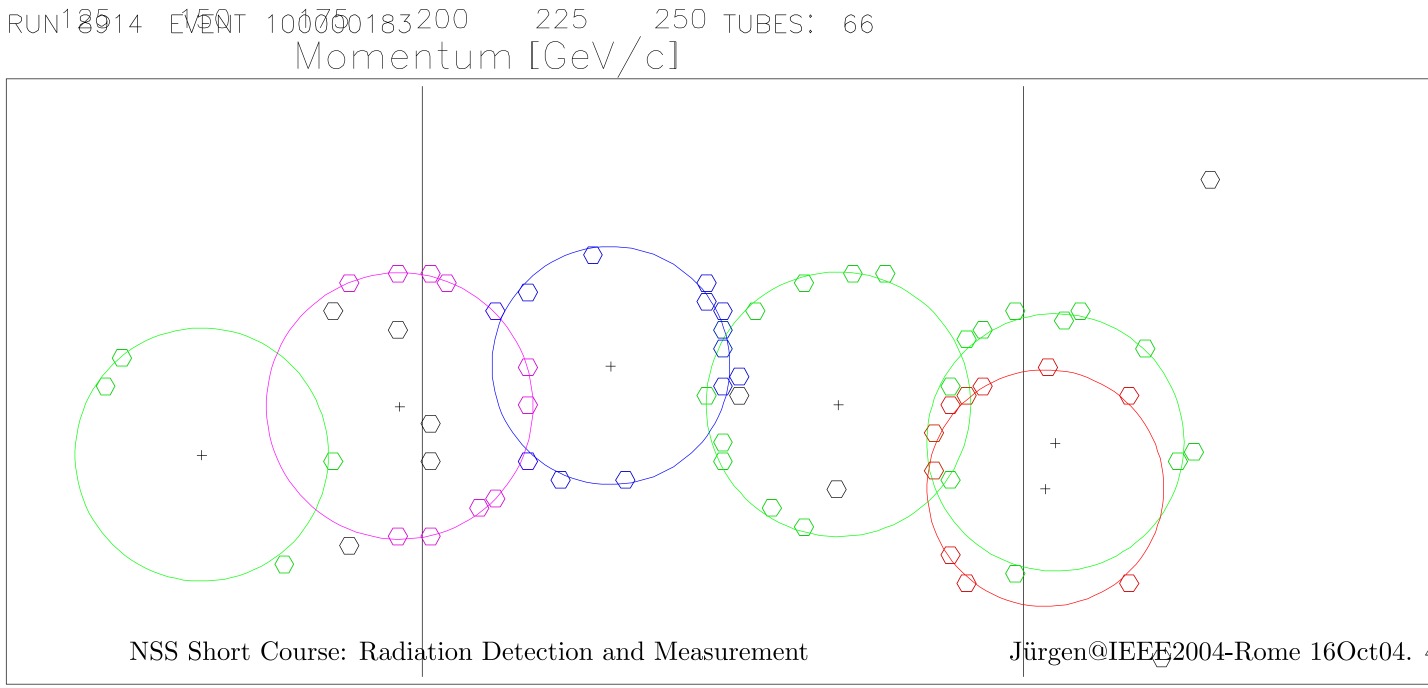
$$N_{ph} = N_0 \cdot L \cdot \sin^2\theta_c$$

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 $L = F$)

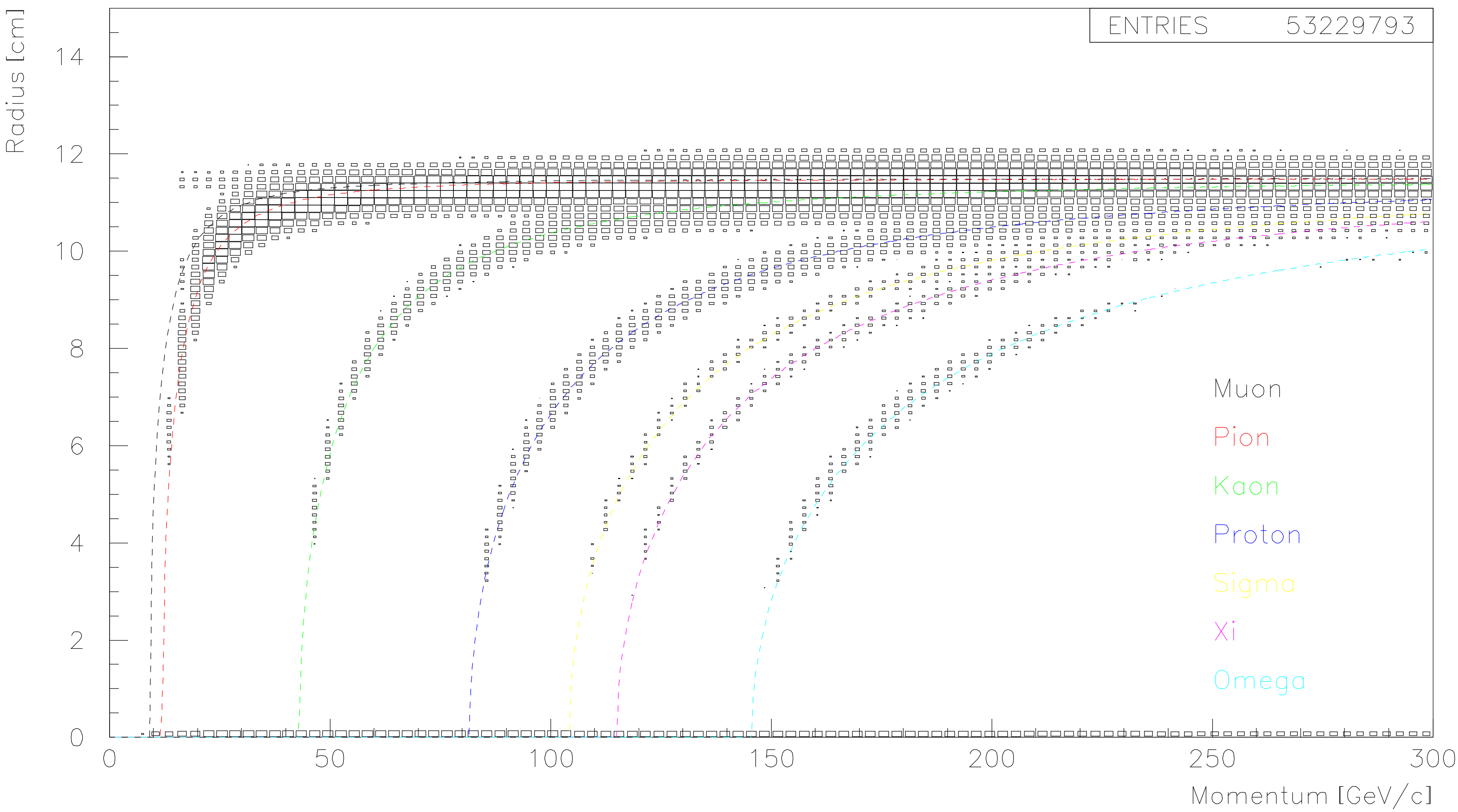
Parallel particles have the same ring image



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



SELEX RICH: Particle Id negative tracks



Short History of RICHes

First Generation: Beginning of 1980's.
Examples: Omega RICH (WA69, WA82), E653 RICH.

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

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

New Generation: BaBar–DIRC, PHENIX, CLEO–III, COMPASS

Future: ALICE, LHC–B, BTeV, CKM, . . .

RICH – The Reality

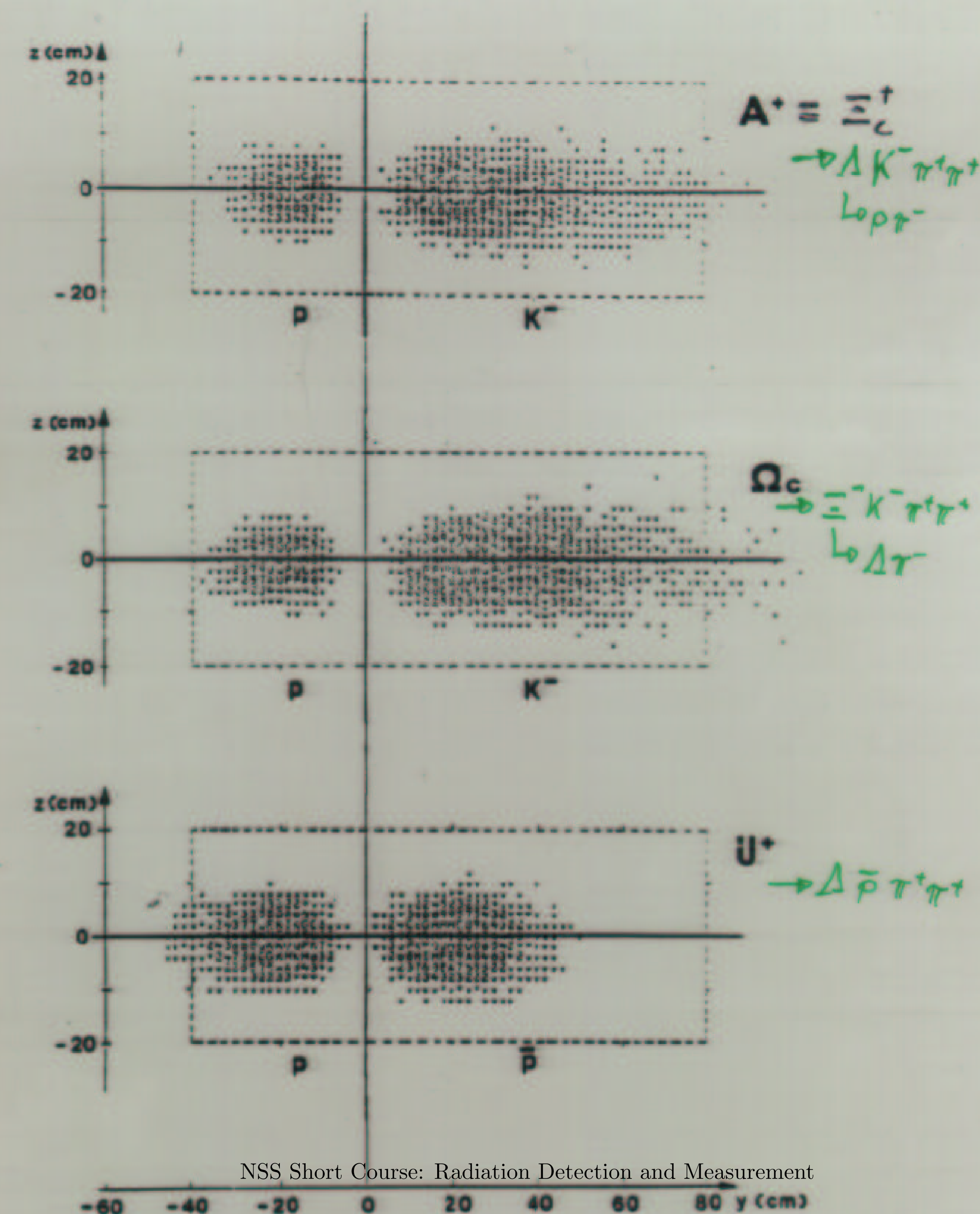
- **Center of ring depends on track angle $\Longrightarrow$ large detector surface (up to square meters)**
- **good resolution of photon position $\Longrightarrow$ large number of "pixels" (up to 100000 or more)**
- **Spectrum of Cherenkov photons**

$$\frac{dN}{d\lambda} = \frac{2\pi\alpha}{\lambda^2} L \sin^2\theta_c$$

$\Longrightarrow$ Ultraviolet

- **refractive index $n = n(\lambda) \Longrightarrow$ Chromatic dispersion**
- **Detection of UV-photons: convert photon in electron (photoeffect)**
  1. **small (up to a few thousand) number of pixels: Photomultipliers**
  2. **large number of pixels or area: Time Expansion Chambers with TEA or TMAE**
- **When using TEC: particle pass through the chambers: dE/dx**
- **When using TEC: response (memory) time limit rate**

Distribution of Ring Centers



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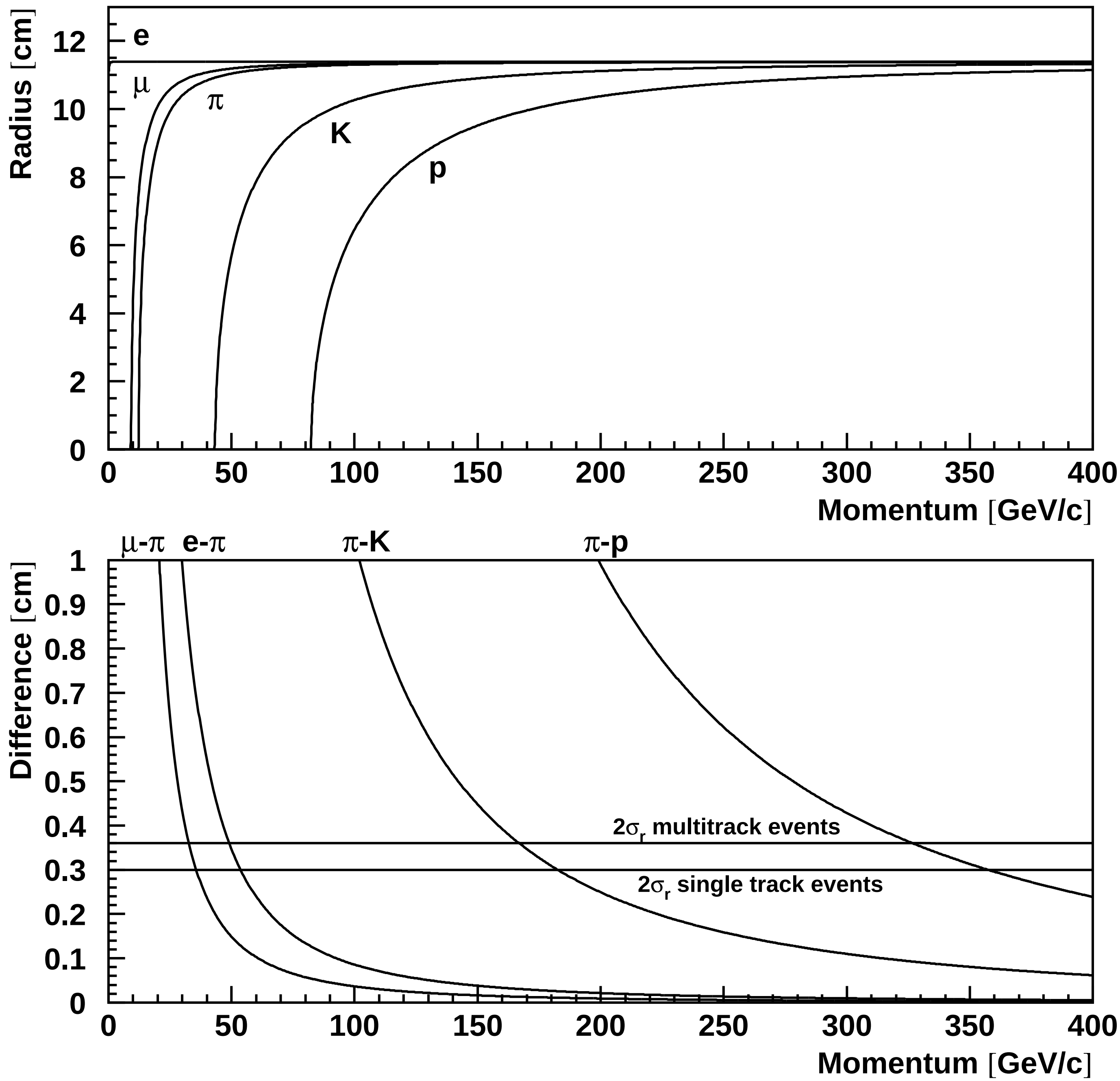
- **When using TEC: particle pass through the chambers: dE/dx**
- **When using TEC: response (memory) time limit rate**



Radius [cm]
e
μ
π
K
p
Momentum [GeV/c]
μ-π
e-π
π-K
π-p
Difference [cm]
2σr multitrack events
2σr single track events
Momentum [GeV/c]

RICH – The Reality

- **Center of ring depends on track angle $\Longrightarrow$ large detector surface (square meters)**
- **good resolution of photon position $\Longrightarrow$ large number of "pixels" (100000)**
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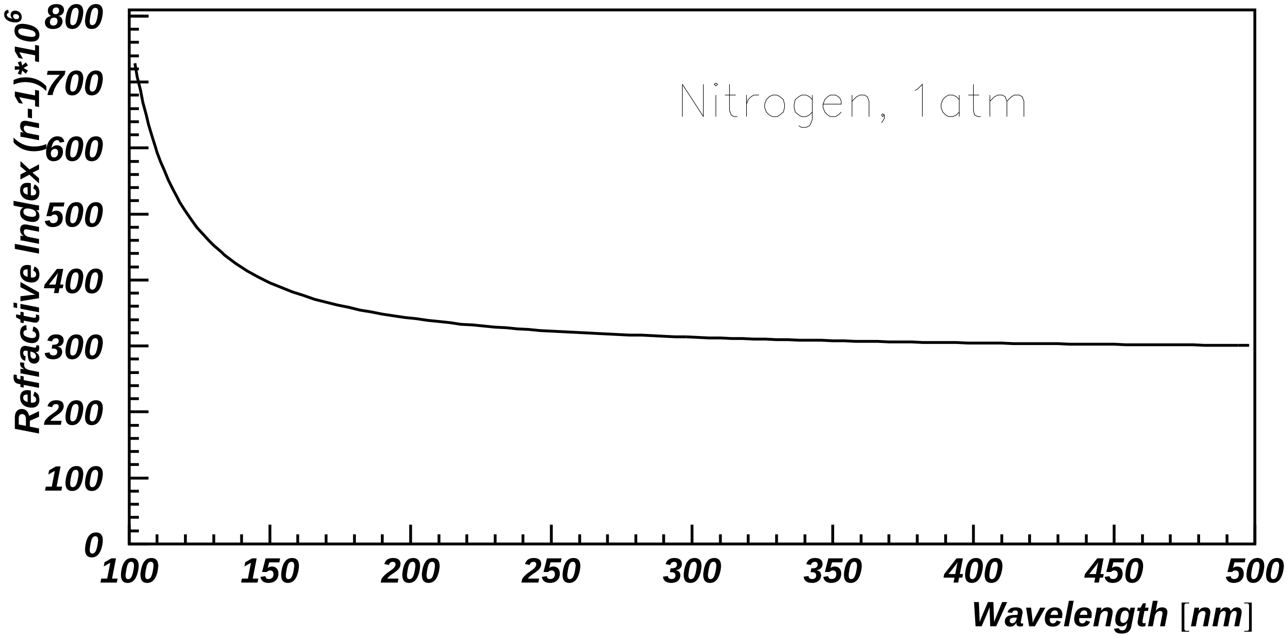
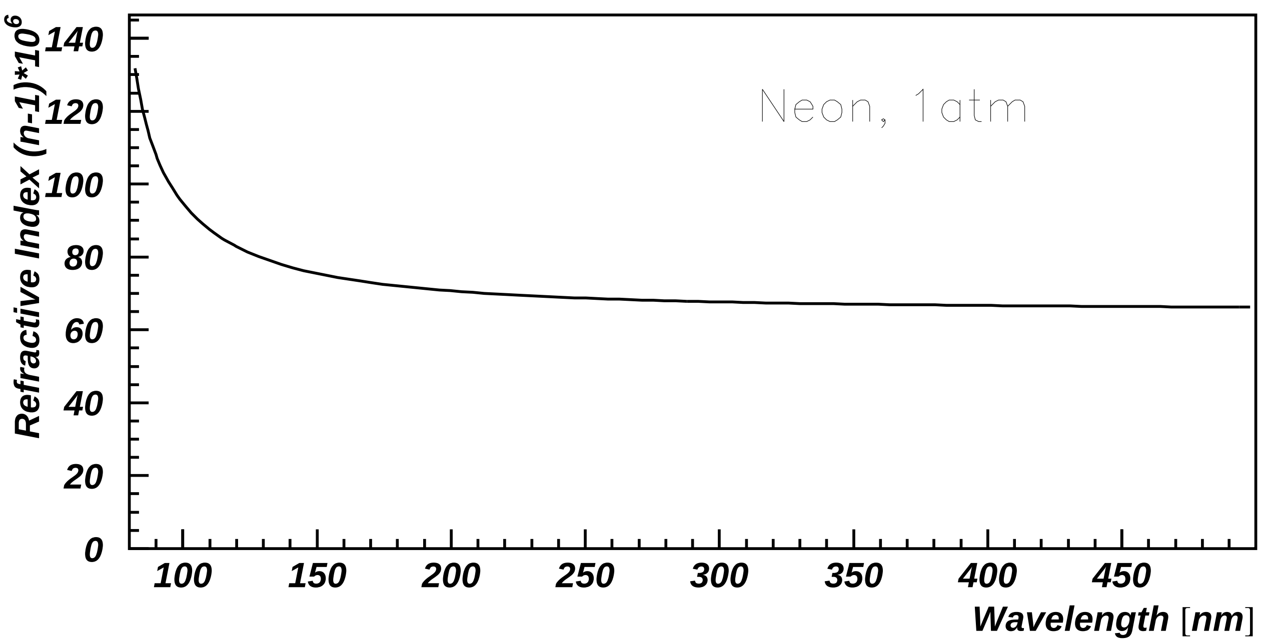

Nitrogen, 1atm
Refractive Index (n-1)*10^6
0
100
200
300
400
500
600
700
800
100
150
200
250
300
350
400
450
500
Wavelength [nm]


Neon, 1atm
Refractive Index (n-1)*10^6
0
20
40
60
80
100
120
140
100
150
200
250
300
350
400
450
Wavelength [nm]

RICH – The Reality

- Center of ring depends on track angle $\Longrightarrow$ large detector surface
- good resolution of photon position $\Longrightarrow$ large number of "pixels" (100000)
- Spectrum of Cherenkov photons

$$\frac{dN}{d\lambda} = \frac{2\pi\alpha}{\lambda^2} L \sin^2 \theta_c$$

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  2. large number of pixels or area: Time Expansion Chambers with TEA or TMAE
- When using TEC: particle pass through the chambers: dE/dx
- When using TEC: response (memory) time limit rate

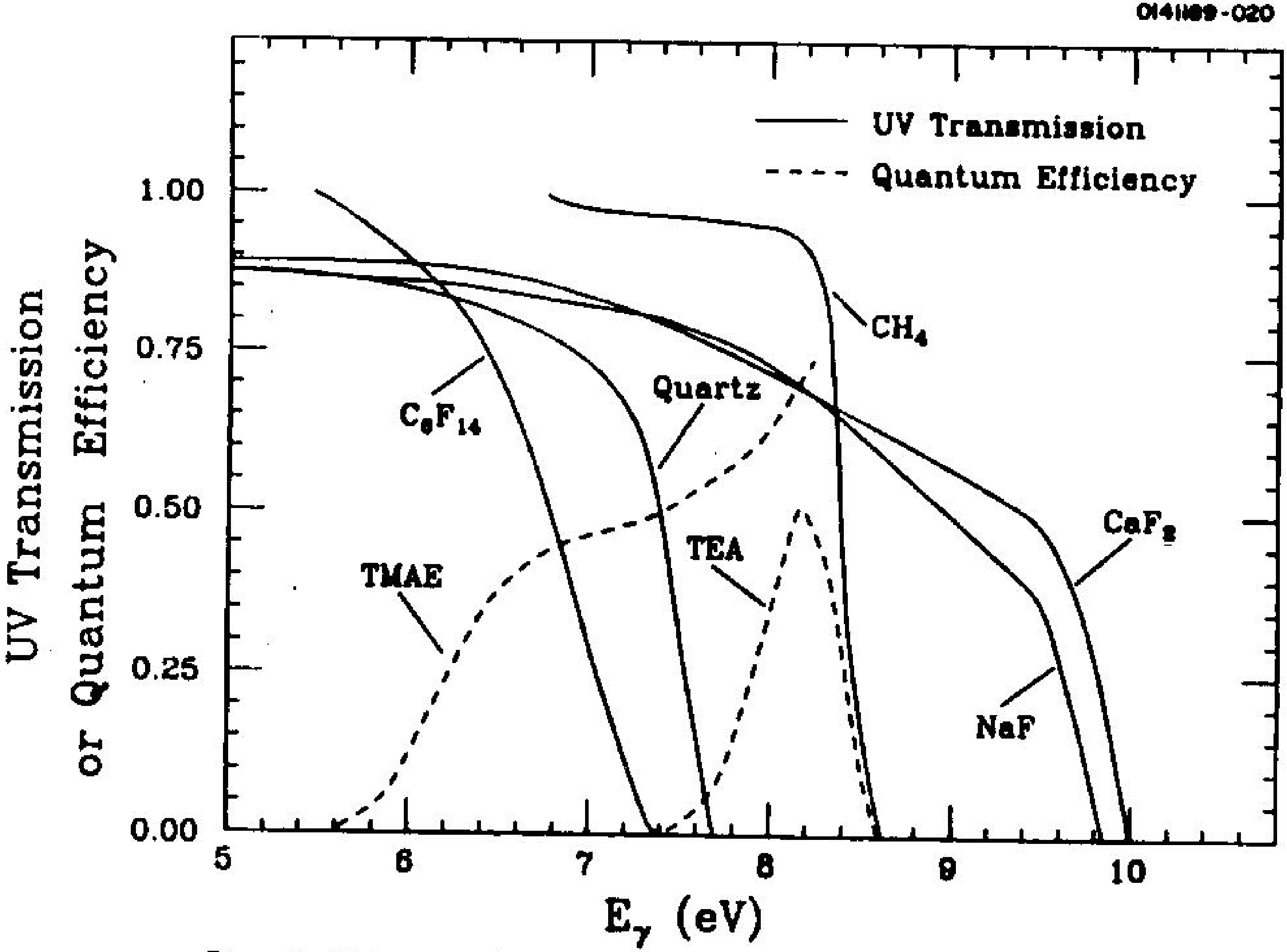
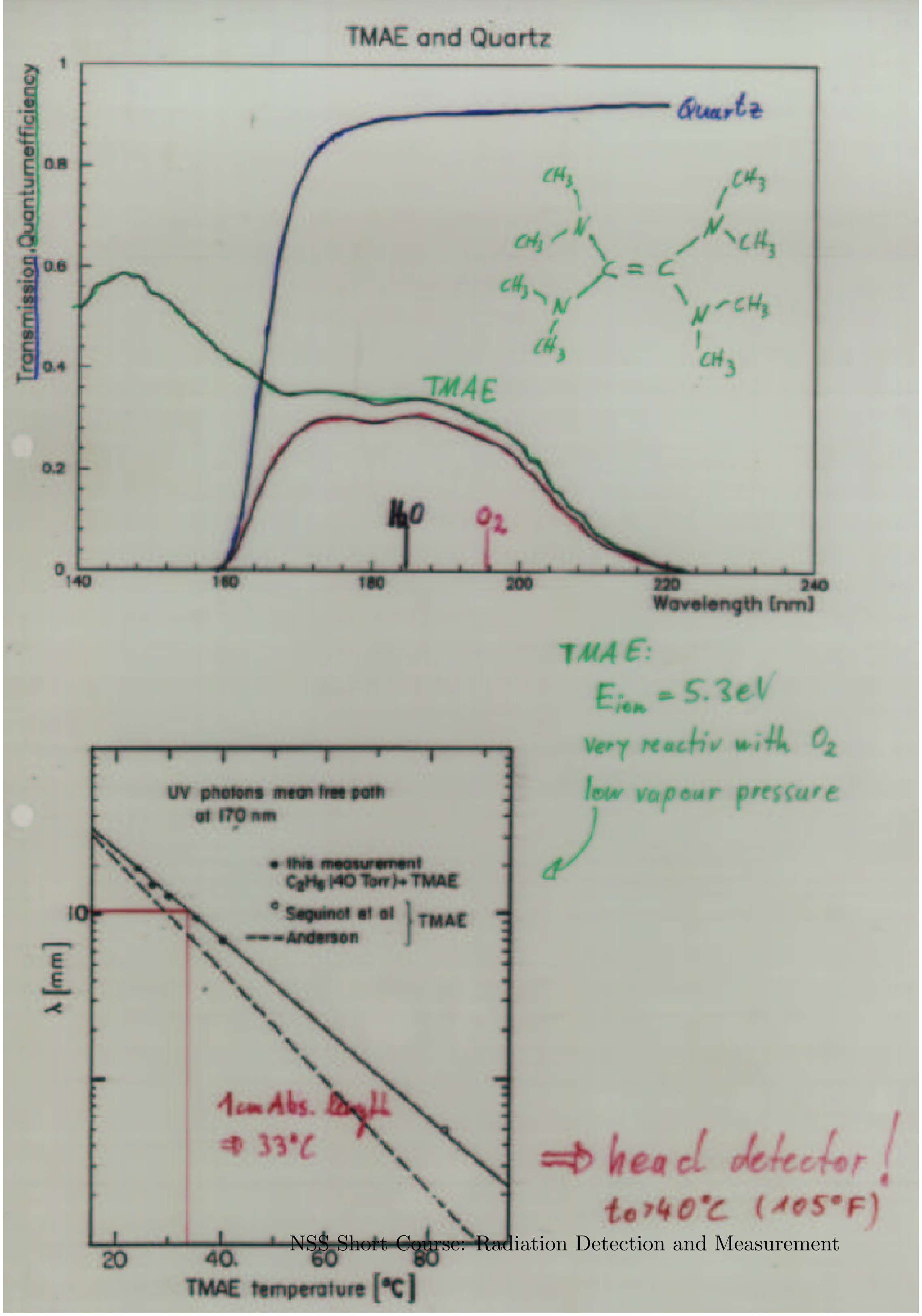


Figure 13: Photon transmission and photoionization quantum efficiency for various CRID materials as function of photon energy in the UV range. (Reproduced from


TMAE and Quartz
Transmission, Quantumefficiency
Quartz
TMAE
H_2O
O_2
Wavelength [nm]
TMAE:
E_{ion} = 5.3eV
very reactiv with O_2
low vapour pressure
UV photons mean free path at 170 nm
this measurement C_2H_6 (40 Torr) + TMAE
Seguinot et al
Anderson
TMAE
λ [mm]
1cm Abs. length
⇒ 33°C
TMAE temperature [°C]
⇒ heat detector!
to>40°C (105°F)

RICH – The Reality

- **Center of ring depends on track angle $\Longrightarrow$ large detector surface**
- **good resolution of photon position $\Longrightarrow$ large number of "pixels" (100000)**
- **Spectrum of Cherenkov photons**

$$\frac{dN}{d\lambda} = \frac{2\pi\alpha}{\lambda^2} L \sin^2 \theta_c$$

  $\Longrightarrow$ Ultraviolet

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  1. **small (up to a few thousand) number of pixels: Photomultipliers**
  2. **large number of pixels or area: Time Expansion Chambers with TEA or TMAE**
- **When using TEC: particle pass through the chambers: dE/dx**
- **When using TEC: response (memory) time limit rate**

First RICH Example: The Omega RICH

WA89: A Hyperon Beam Experiment at the CERN-SPS Using the Omega Facility

Bologna Univ./INFN, CERN, Genoa Univ./INFN Grenoble Univ./IN2P3, Heidelberg MPI, Heidelberg Univ., Mainz Univ., Moscow Lebedev Phys. Inst.

Bologna
A. Forino, R. Gessaroli, P Mazzanti, A. Quareni-Vignudelli, F. Viaggi

CERN
F. Antinori, W. Beusch, J.P. Dufey, B.R. French, P. Grafström

Genoa Univ./INFN
M. Dameri, R.B. Hurst, B. Osculati, L. Rossi, G. Tomasini

Grenoble Univ./IN2P3
D. Barberis, C. Bérat, M. Buénerd, F. Charignon, J. Chauvin, J.T. Hostachy, Ph. Martin, M. Rey–Campagnolle, R. Touillon

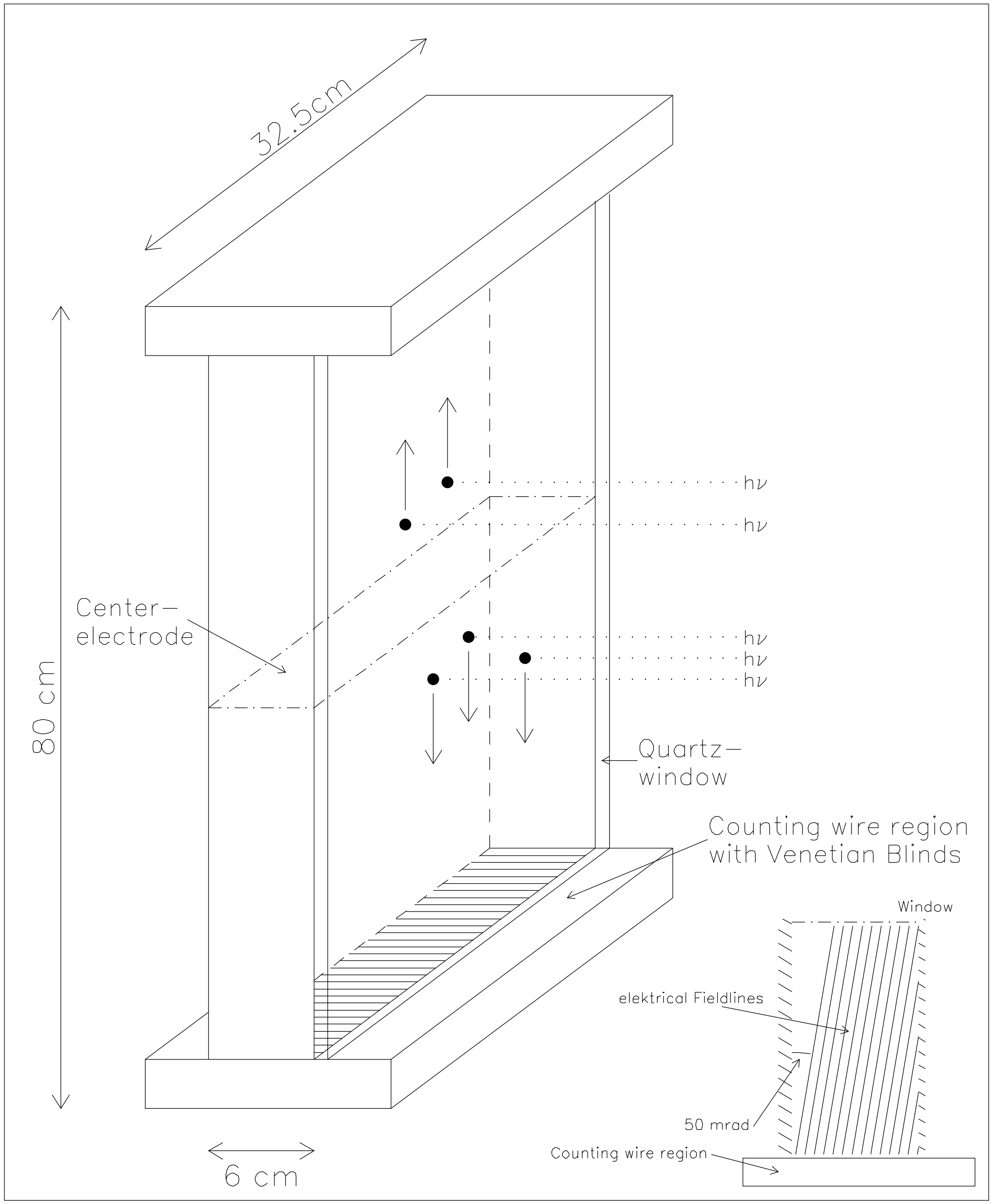
Heidelberg MPIfK
E. Albertson, K.-H. Brenzinger, W. Brückner, F. Dropmann, S.G. Gerassimov, M. Godbersen, T. Kallakowsy, R. Michaels, S. Paul, B. Povh, K. Röhrich, A. Trombini, A. Wenzel, R. Werding

Heidelberg Univ.
J. Engelfried, F. Faller, J. Heintze, S. Kluth, S. Ljungfelt, P. Lennert, K. Martens, H. Rieseberg, H.-W. Siebert, A. Simon, G. Wälder

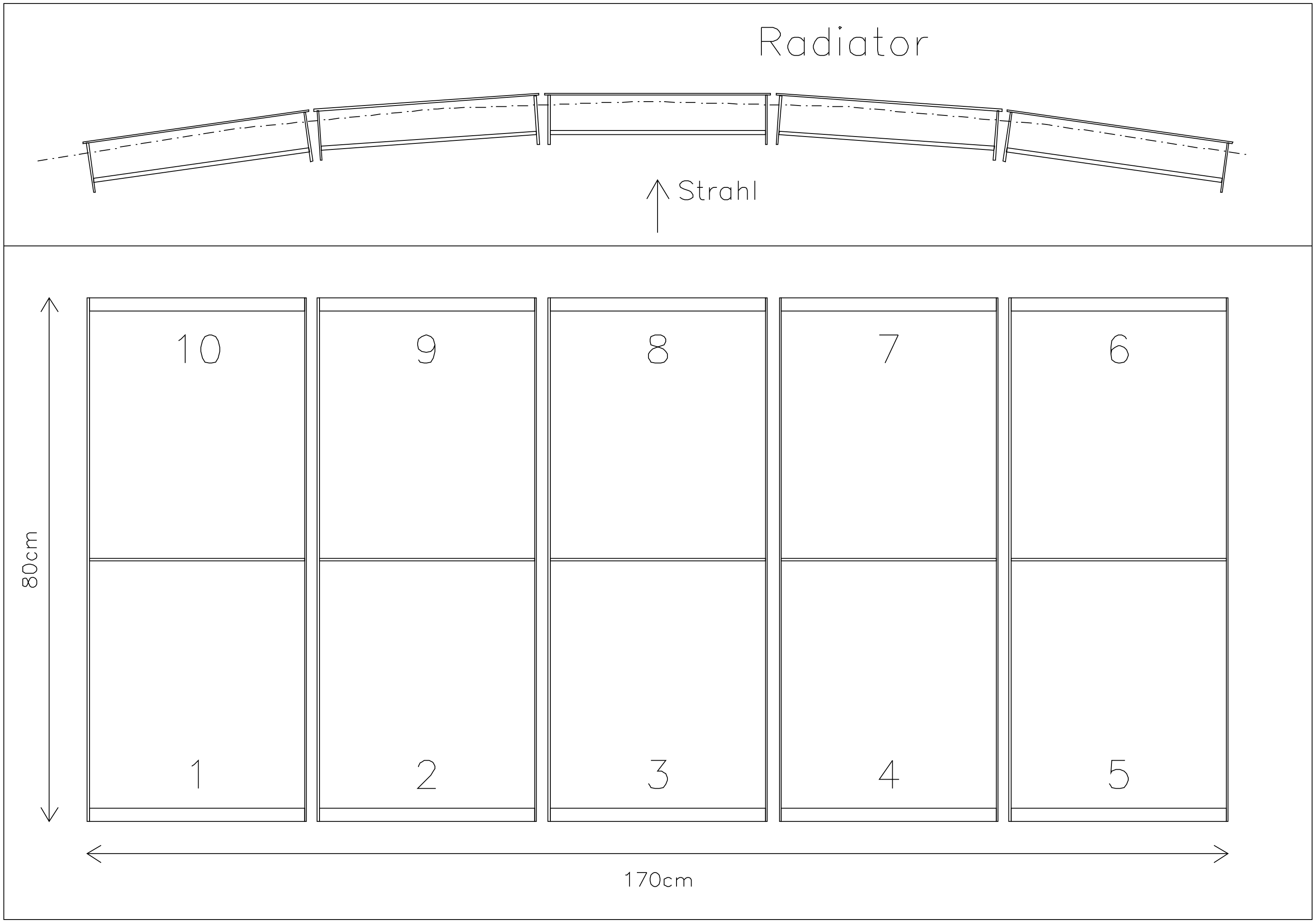
Mainz Univ., Inst. of Nucl. Physics
E. Chudakov, U. Müller, G. Rosner, H. Rudolf, B. Volkemer, Th. Walcher

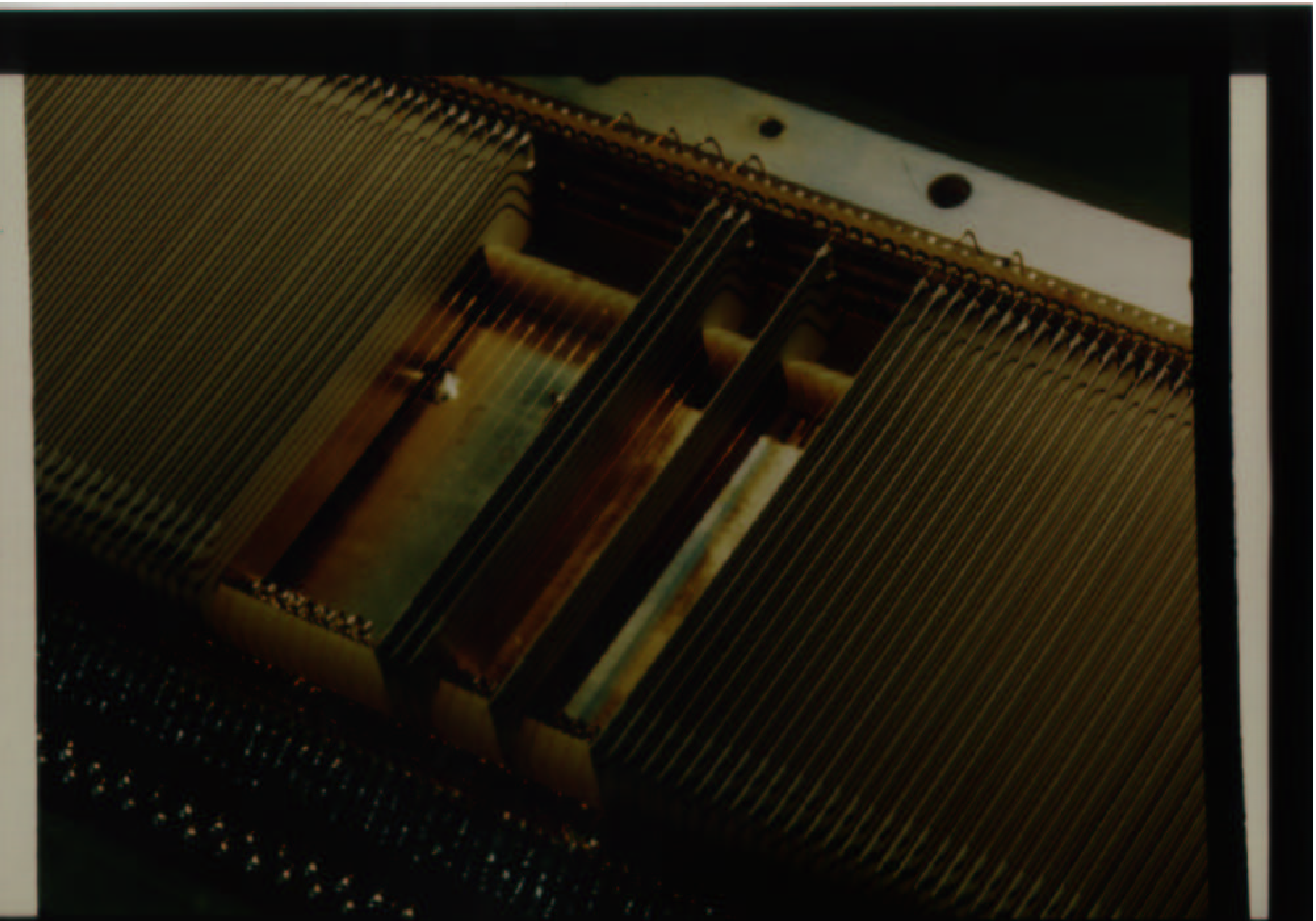
Moscow Lebedev Phys. Inst.
M.I. Adamovich, Yu.A. Alexandrov, S.P. Kharlamov, L.N. Malinina, N.G. Peresadko, M.V. Zavertyaev

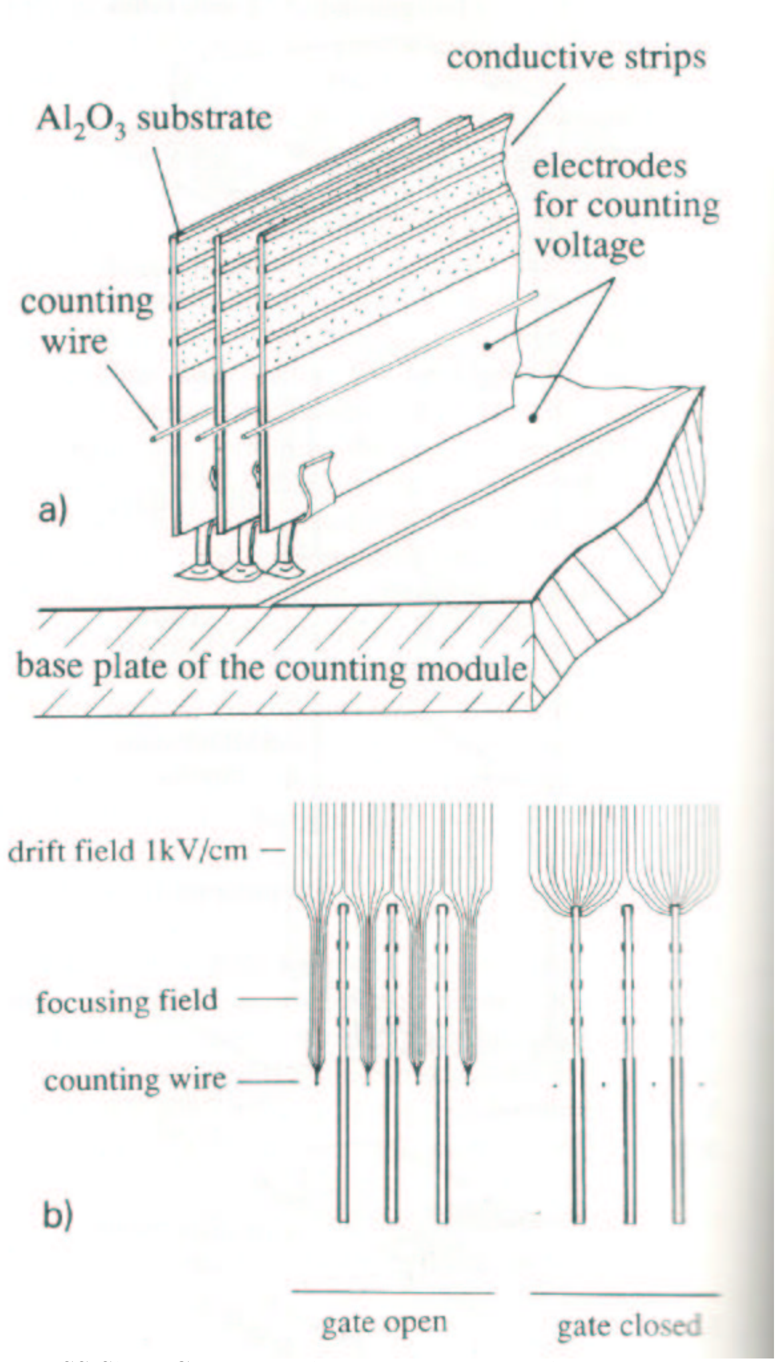
RICH Group



Counting gas: Ethan + TMAE,
1 KV/cm, 5 cm/μsec


Radiator
Strahl
10
9
8
7
6
1
2
3
4
5
80cm
170cm




conductive strips
Al_2O_3 substrate
electrodes for counting voltage
counting wire
a)
base plate of the counting module
drift field 1kV/cm
focusing field
counting wire
b)
gate open
gate closed

Particle Identification Algorithm

- **only discrete particle masses: e, μ, π, K, p, Σ, etc.**
- **Track parameter and momentum known**
  $\Longrightarrow$ Calculate ring radius for each hypothesis
- **"Compare" measured and expected rings for each hypothesis with a maximum likelihood method**
- **for identification, make cuts on likelihood ratios**

published in:
U.Müller, J.Engelfried et al.:
Particle identification with the RICH detector in experiment WA89 at CERN.
Nucl. Instr. Meth. A 343 (1994) 279-283.

Second RICH Example: The SELEX RICH

The SELEX Collaboration

G.P. Thomas
Ball State University, Muncie, IN 47306, U.S.A.

E. Gülmez
Bogazici University, Bebek 80815 Istanbul, Turkey

R. Edelstein, S.Y. Jun, A.I. Kulyavtsev[1], A. Kushnirenko, D. Mao[1], P. Mathew[2], M. Mattson, M. Procario[3], J. Russ, J. You[4]
Carnegie-Mellon University, Pittsburgh, PA 15213, U.S.A.

A.M.F. Endler
Centro Brasiliero de Pesquisas Físicas, Rio de Janeiro, Brazil

P.S. Cooper, J. Kilmer, S. Kwan, J. Lach, E. Ramberg, D. Skow, L. Stutte
Fermilab, Batavia, IL 60510, U.S.A.

V.P. Kubarovsky, V.F. Kurshetsov, A.P. Kozhevnikov, L.G. Landsberg, V.V. Molchanov, S.B. Nurushev, S.I. Petrenko, A.N. Vasiliev, D.V. Vavilov, V.A. Victorov
Institute for High Energy Physics, Protvino, Russia

Li Yunshan, Mao Chensheng, Zhao Wenheng, He Kangling, Zheng Shuchen, Mao Zhenlin
Institute of High Energy Physics, Beijing, P.R. China

M.Y. Balatz[5], G.V. Davidenko, A.G. Dolgolenko, G.B. Dzyubenko, A.V. Evdokimov, M.A. Kubantsev, I. Larin, V. Matveev, A.P. Nilov, V.A. Prutskoi, A.I. Sitnikov, V.S. Verebryusov, V.E. Vishnyakov
Institute of Theoretical and Experimental Physics, Moscow, Russia

U. Dersch[6], I. Eschrich[7], I. Konorov[8], H. Krüger[9], J. Simon[10], K. Vorwalter[11]
Max-Planck-Institut für Kernphysik, 69117 Heidelberg, Germany

I.S. Filimonov[5], E.M. Leikin, A.V. Nemitkin, V.I. Rud
Moscow State University, Moscow, Russia

A.G. Atamantchouk, G. Alkhazov, N.F. Bondar, V.L. Golovtsov, V.T. Kim, L.M. Kochenda, A.G. Krivshich, N.P. Kuropatkin, V.P. Maleev, P.V. Neoustroev, B.V. Razmyslovich, V. Stepanov, M. Svoiski, N.K. Terentyev[12], L.N. Uvarov, A.A. Vorobyov
Petersburg Nuclear Physics Institute, St. Petersburg, Russia

I. Giller, M.A. Moinester, A. Ocherashvili, V. Steiner
Tel Aviv University, 69978 Ramat Aviv, Israel

J. Amaro-Reyes, A. Blanco C., J. Engelfried[4], A. Morelos I. Torres, E. Vázquez-Jáuregui
Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico

M. Luksys
Universidade Federal da Paraíba, Paraíba, Brazil

V.J. Smith
University of Bristol, Bristol BS8 1TL, United Kingdom

M. Kaya, E. McCliment, K.D. Nelson[13], C. Newsom, Y. Onel, E. Ozel, S. Ozkorucuklu, P. Pogodin
University of Iowa, Iowa City, IA 52242, U.S.A.

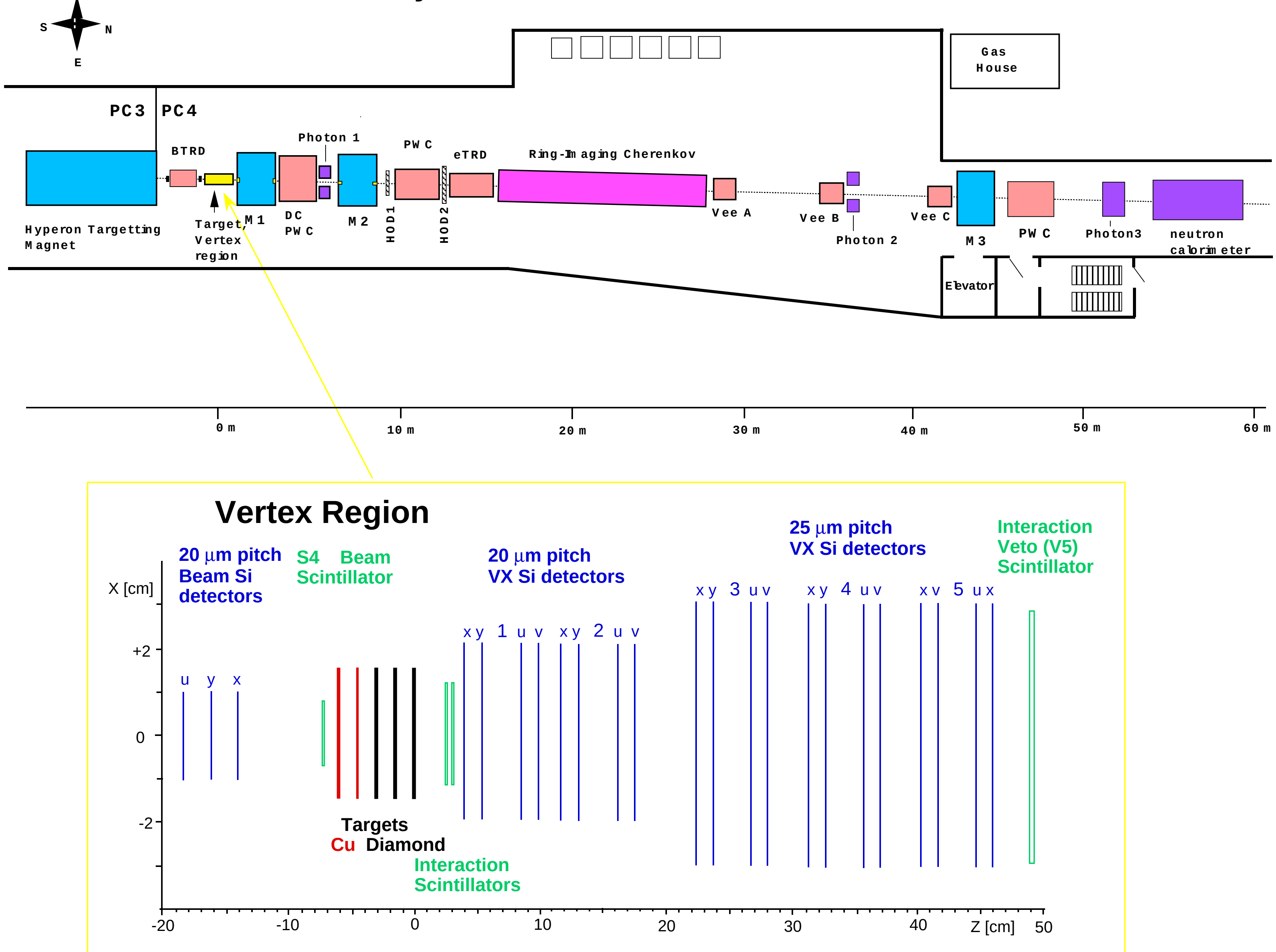
L.J. Dauwe
University of Michigan-Flint, Flint, MI 48502, U.S.A.

M. Gaspero, M. Iori
University of Rome "La Sapienza" and INFN, Rome, Italy

L. Emediato, C.O. Escobar[14], F.G. Garcia[4], P. Gouffon, T. Lungov[15], M. Srivastava, R. Zukanovich-Funchal
University of São Paulo, São Paulo, Brazil

A. Lamberto, A. Penzo, G.F. Rappazzo, P. Schiavon
University of Trieste and INFN, Trieste, Italy

Selex (E781)
Proton Center Layout



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Nuclear Instruments and Methods in Physics Research A 431 (1999) 53–69

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

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The SELEX phototube RICH detector

J. Engelfried[a,*,1], I. Filimonov[b,2,3], J. Kilmer[a,1], A. Kozhevnikov[c,3], V. Kubarovsky[c,3], V. Molchanov[c,3], A. Nemitkin[b,3], E. Ramberg[a,1], V. Rud[b,3], L. Stutte[a,1]

[a]*Fermi National Accelerator Laboratory, Batavia, IL, USA*
[b]*Moscow State University, Moscow, Russia*
[c]*Institute for High Energy Physics, Serpukhov, Russia*

Received 6 November 1998

Abstract

In this article, construction, operation, and performance of the RICH detector of Fermilab experiment 781 (SELEX) are described. The detector utilizes a matrix of 2848 phototubes for the photocathode to detect Cherenkov photons generated in a 10 m neon radiator. For the central region an N_0 of 104 cm^{-1}, corresponding to 13.6 hits on a $\beta = 1$ ring, was obtained. The ring radius resolution measured is 1.6%.

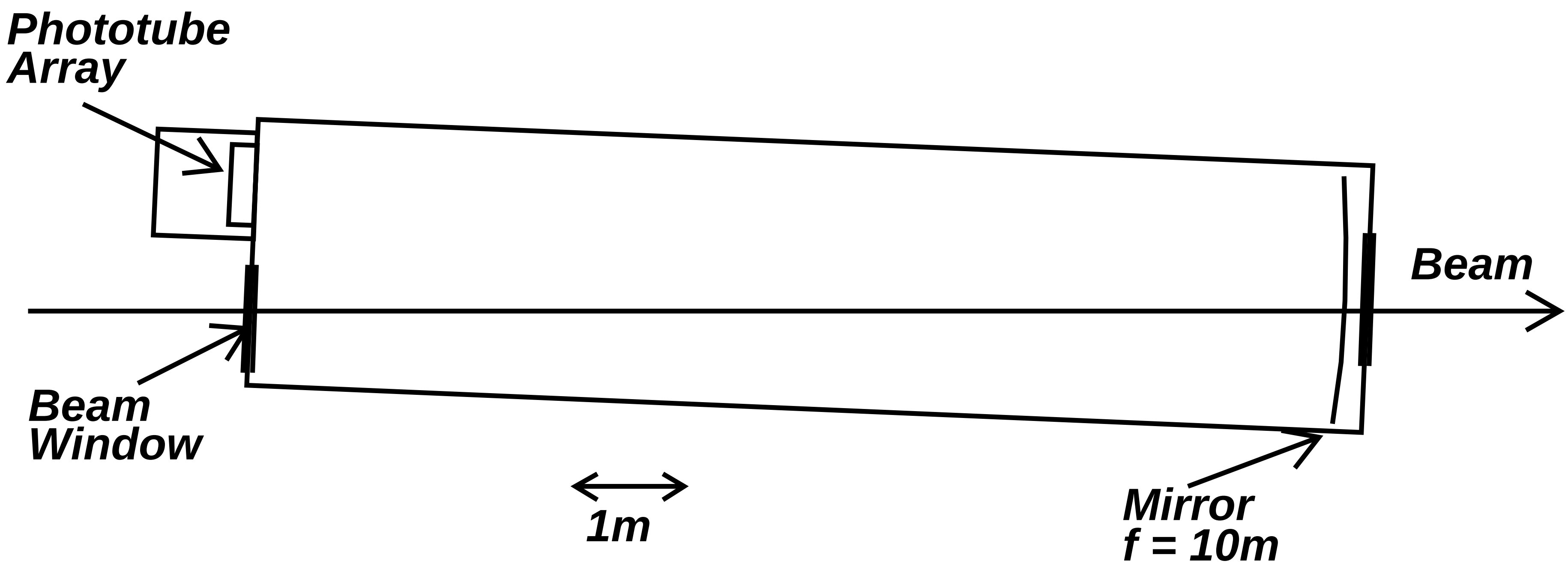
1. Introduction

The Fermilab experiment E781 (SELEX): a segmented large x_F Baryon spectrometer [1,2], which took data in the 1996/1997 fixed target run at Fermilab, is designed to perform high statistics studies of production mechanisms and decay physics of charmed baryons such as Σ_c, Ξ_c, Ω_c and Λ_c. The physics goals of the experiment require good charged particle identification to look for the different baryon decay modes. One must be able to separate π, K and p over a wide momentum range when looking for charmed baryon decays like $\Lambda_c^+ \rightarrow pK^-\pi^+$.

A RICH [3] detector with a 2848 phototube photocathode array has been constructed [4,5] to do this. The detector begins about 16 m downstream of the charm production target, with two

* Corresponding author. Now at Instituto de Física, Universidad Autonoma de San Luis Potosí, Manuel Nava # 6, Zona

SELEX RICH Vessel and Gas System



Vessel: 10.3 m long

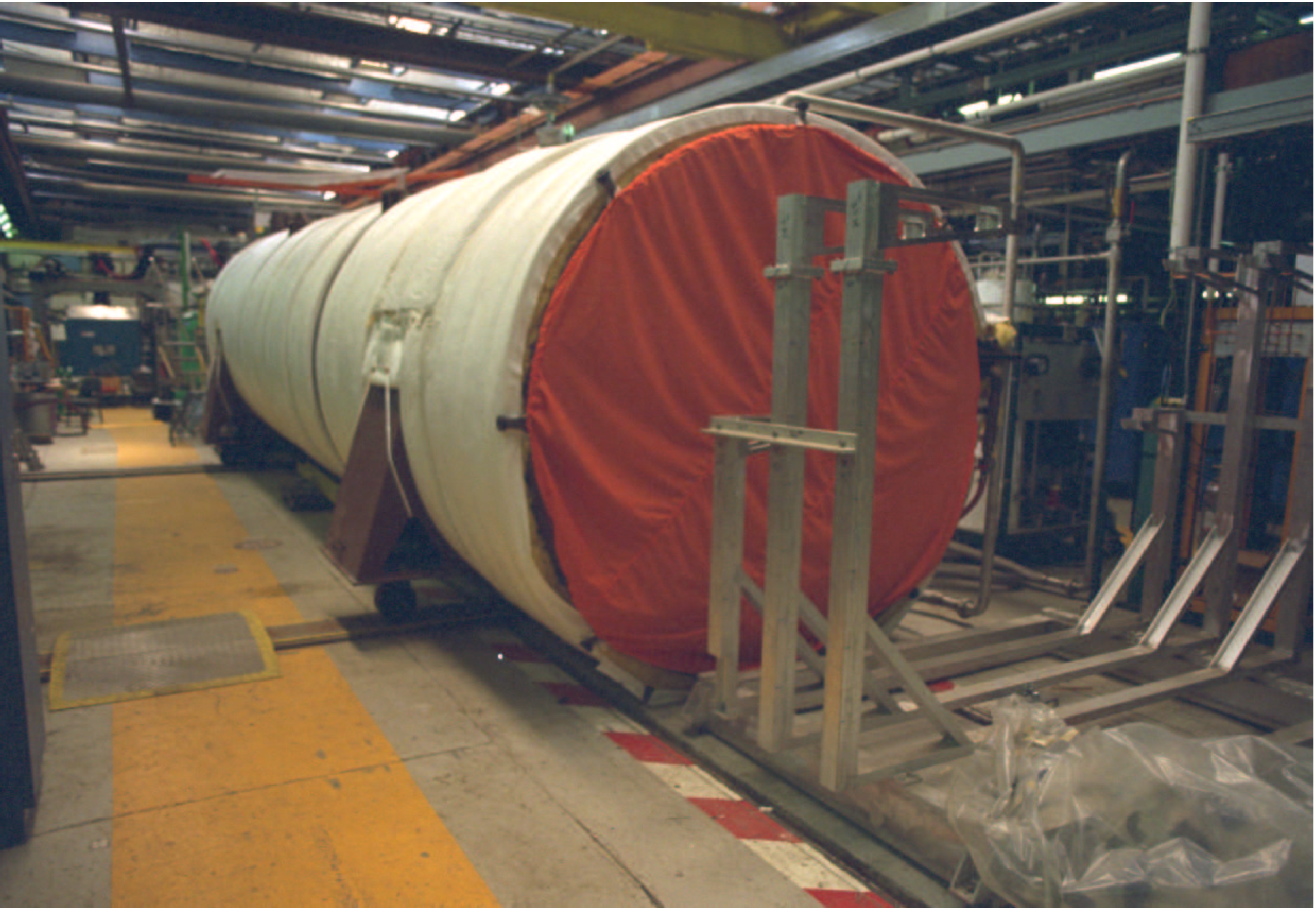
2.4 m diameter ($50\,m^3$)

Gas: Neon @ 1 atm

closed volume ($\Rightarrow$ constant refractive index)

Filling:

- purge with CO_2 (≈ 1 day)
- freeze out CO_2, replace with Ne
- remove remaining O_2 and water
- started with 3 ppm O_2
- after 15 months: (20 ± 12) ppm



SELEX RICH Mirrors

Spherical, nominal 20 m Radius
16 hexagonal mirrors, 46 cm tip to tip

- **Glass**
  - **low expansion glass (Schott Tempax), 10 mm thick.**
  - **Polished to 19.82 m $\pm$ 5 cm**
  - **Measured with Ronchi Method (NIMA 369 (1996) 69-78)**
- **Coating**
  - **Aluminum, with MgF_2 overcoating (Acton)**
  - **Reflectivity $> 85\,\%$ at 160 nm**
- **Mounting**
  - **3 point mount**
  - **Ball bearing, double differential screw**
  - **Honeycomb panel with carbon fiber matrix**
- **Alignment**
  - **Theodolite with Laser in Center of Curvature**
  - **Vessel movable on wheels lateral to beam**

Reprinted from

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH

Section A

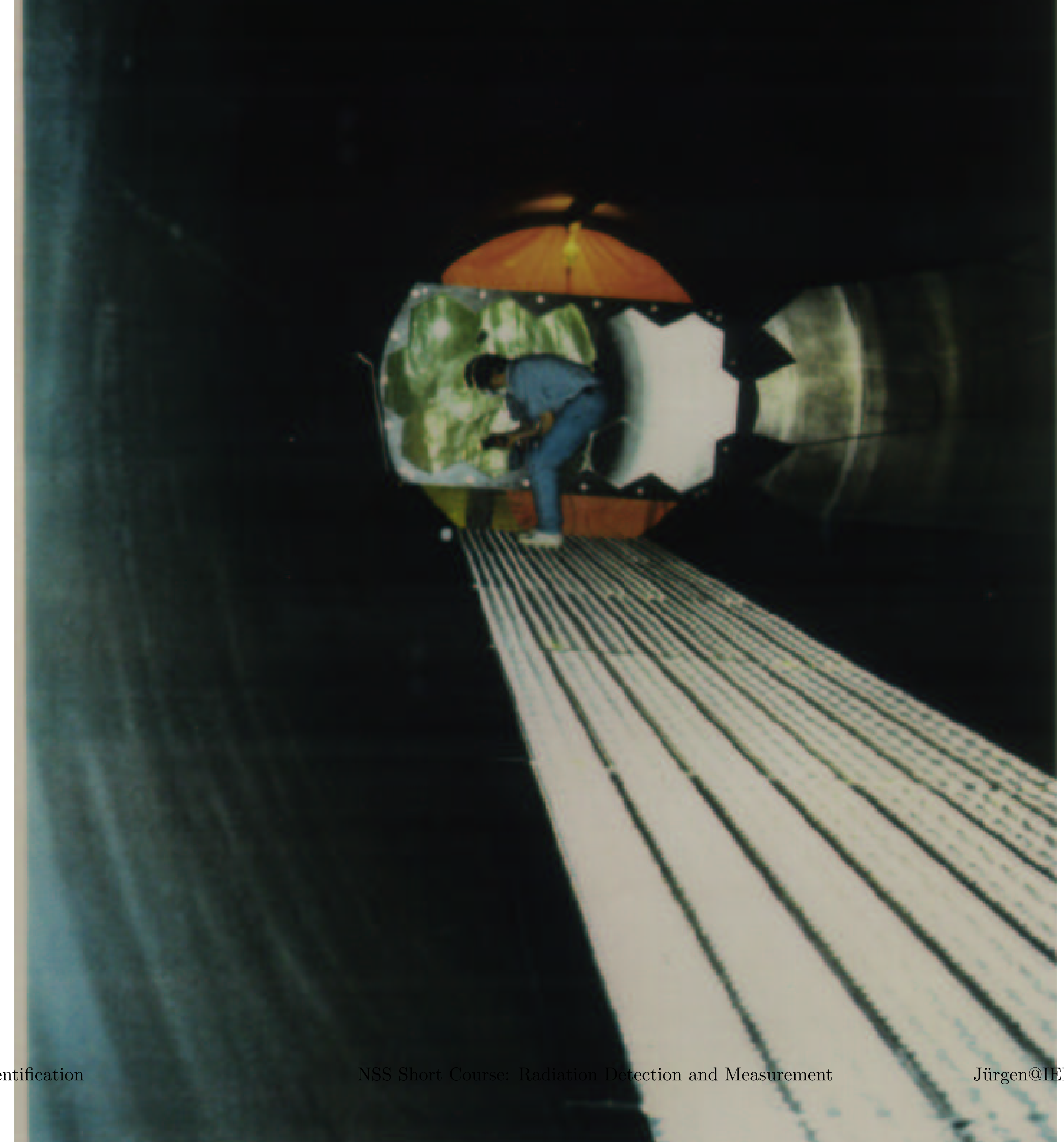
Nuclear Instruments and Methods in Physics Research A 369 (1996) 69–78

A method to evaluate mirrors for Cherenkov counters

Linda Stutte*, Jürgen Engelfried, James Kilmer

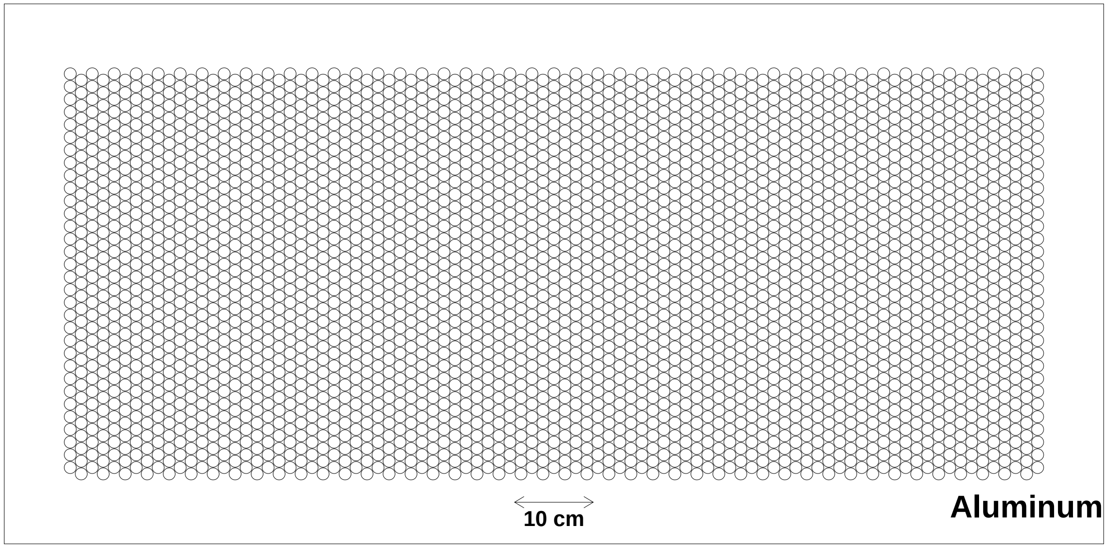
Fermi National Accelerator Laboratory[1], P.O. Box 500, Batavia, IL 60510, USA

Received 19 June 1995

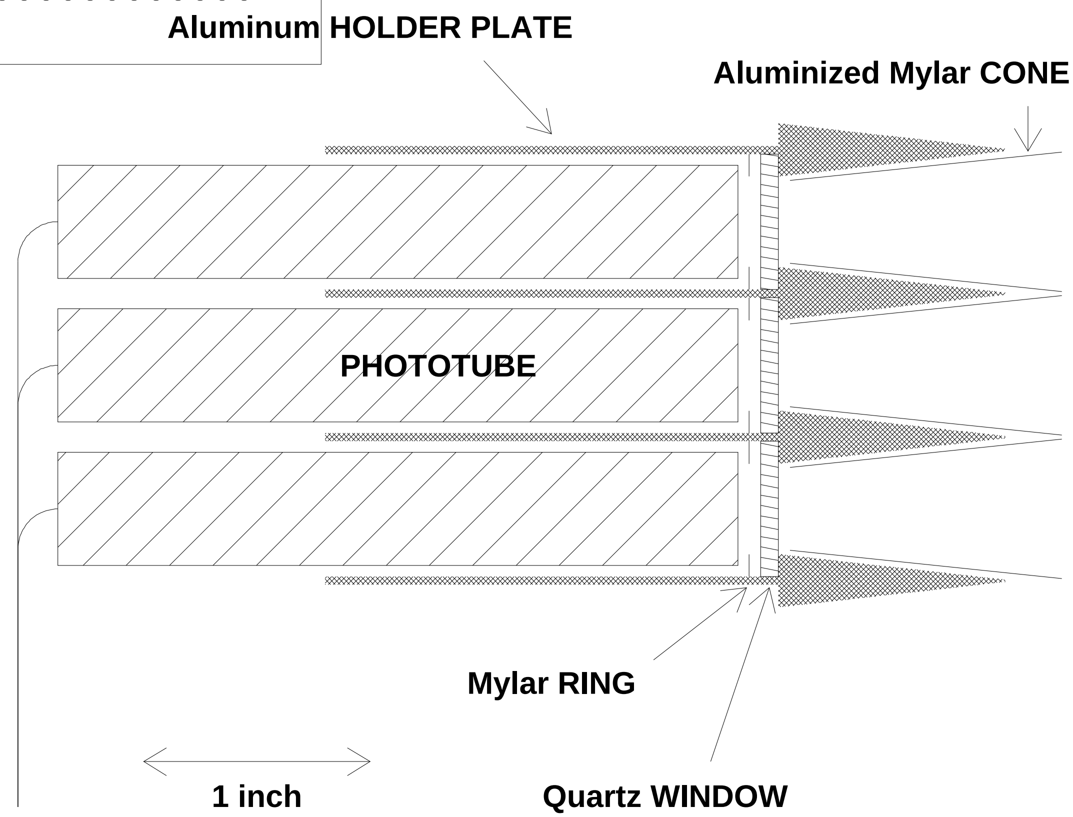


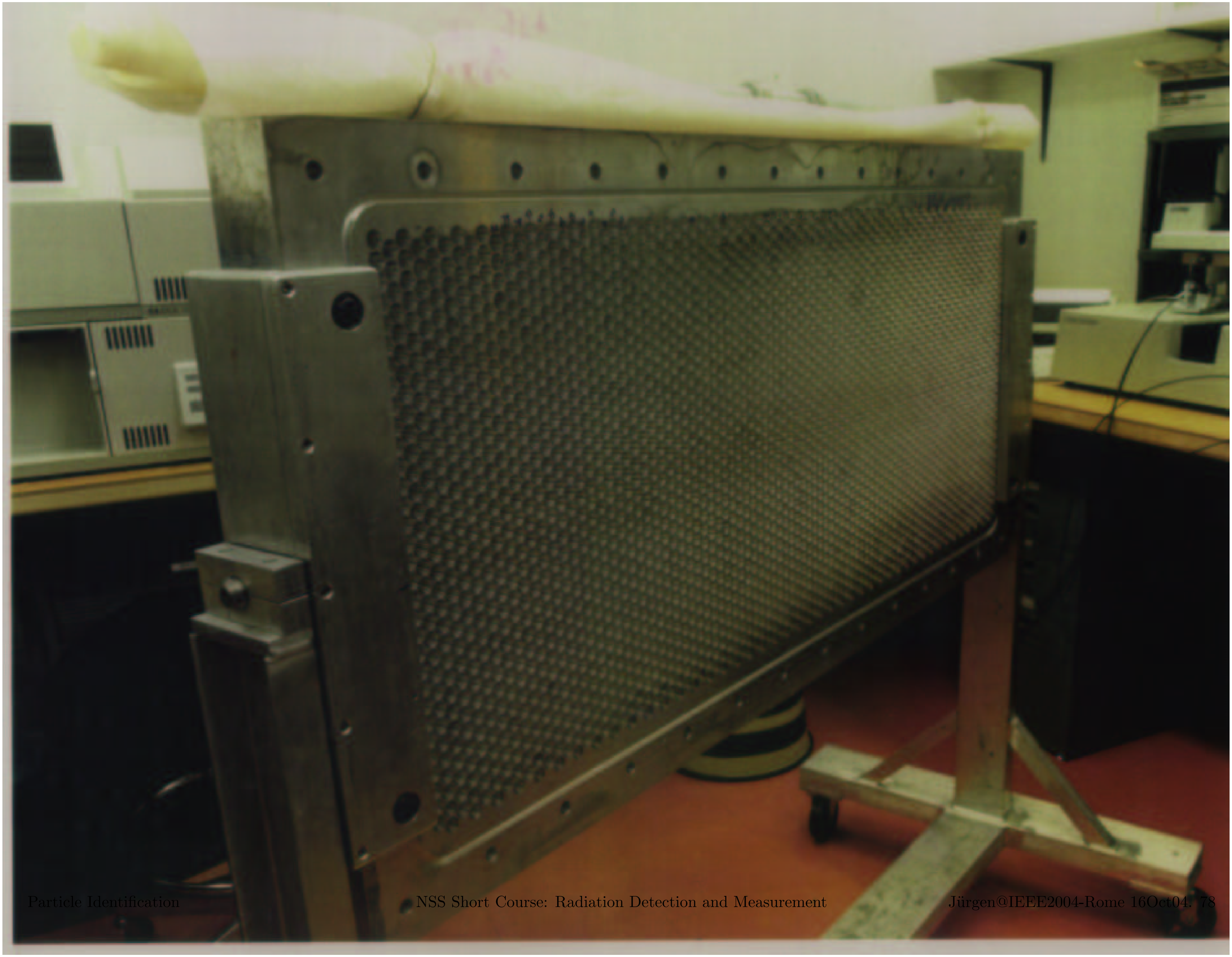
SELEX RICH Photon Detection

- **Photomultiplier Holder**
  - **Aluminum plate, 2848 (89 × 32) holes**
  - **individual quartz windows as gas seal**
  - **aluminized mylar Winston cones**
- **Photomultipliers**
  - **$\frac{1}{2}$" diameter, Photocathode 10 mm**
  - **608 Hamamatsu R760**
  - **2240 FEU60 (with wavelength shifter)**
  - **all PM measured to find operating voltage**
  - **groups of 32 run on same HV**
- **High Voltage**
  - **Operating Voltage 900 V...1900 V**
  - **6 HV Supplies**
  - **Zener Box (á la "Berkeley Cow"), 96 outputs**
- **Crates with Hybrid Chips**
  - **Hybrids contain Amplifier, Discriminator, diff. ECL Driver**
- **Readout: CROS PWC System**
  - **Integration time 170 nsec**

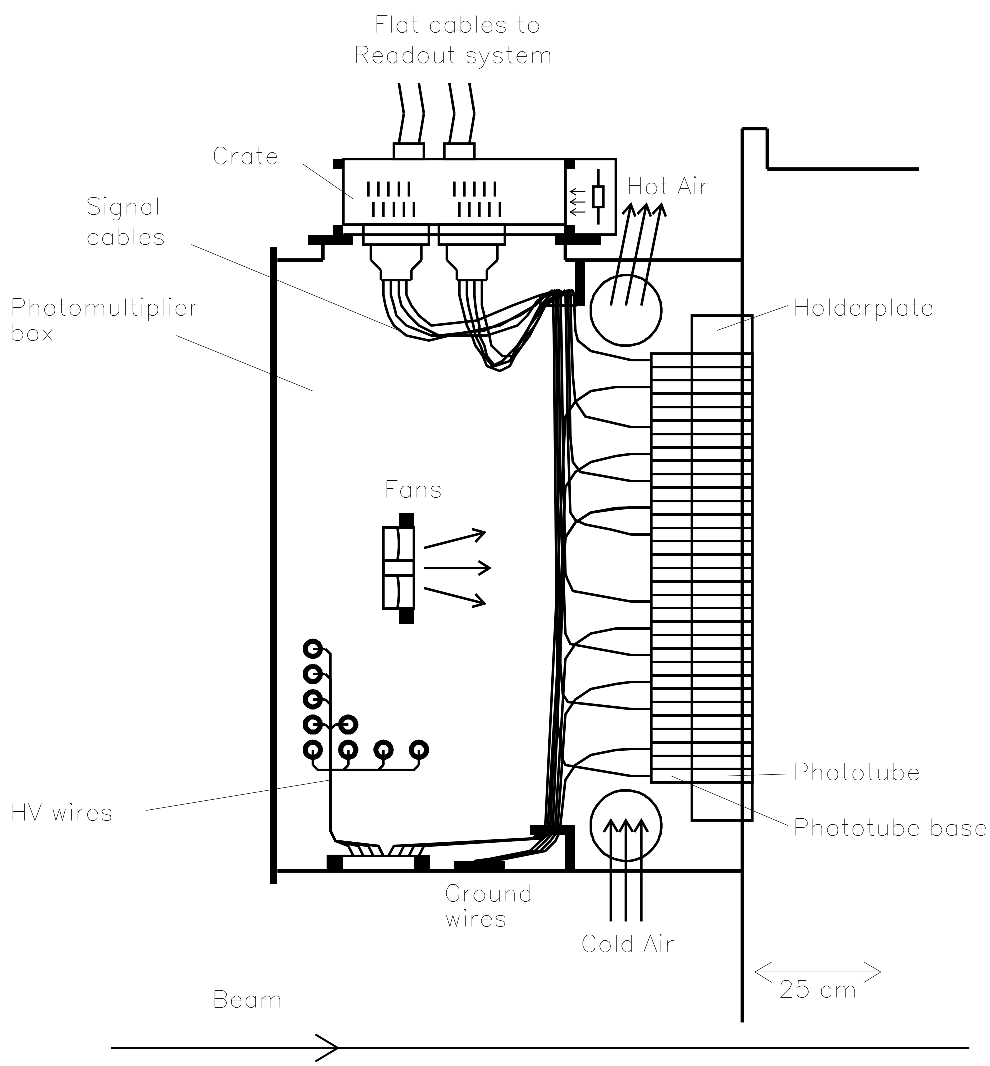

10 cm

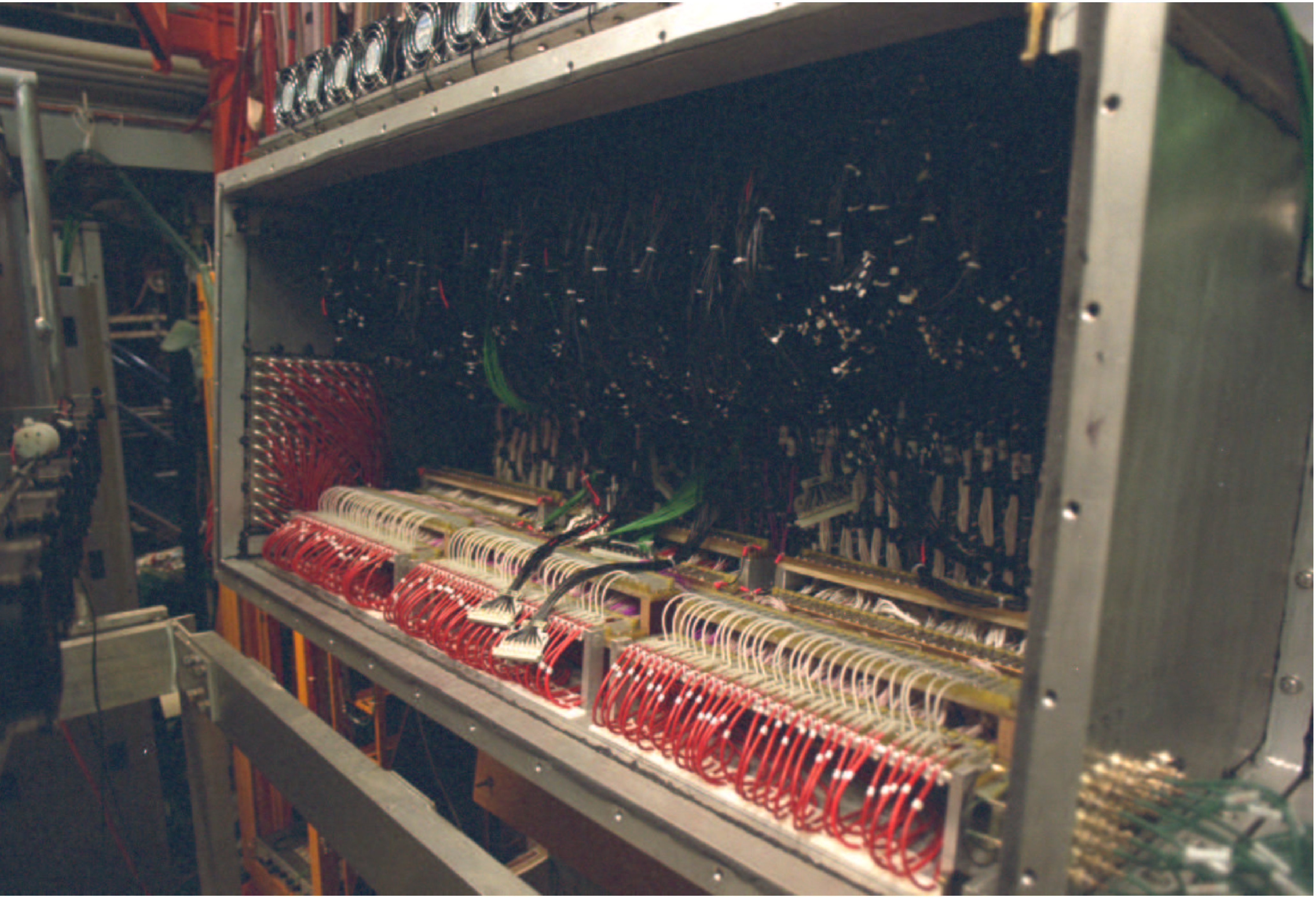

HAMAMATSU
Photomultiplier
Tube
TYPE R760
No. EA111


Aluminum HOLDER PLATE
Aluminized Mylar CONE
PHOTOTUBE
Mylar RING
1 inch
Quartz WINDOW



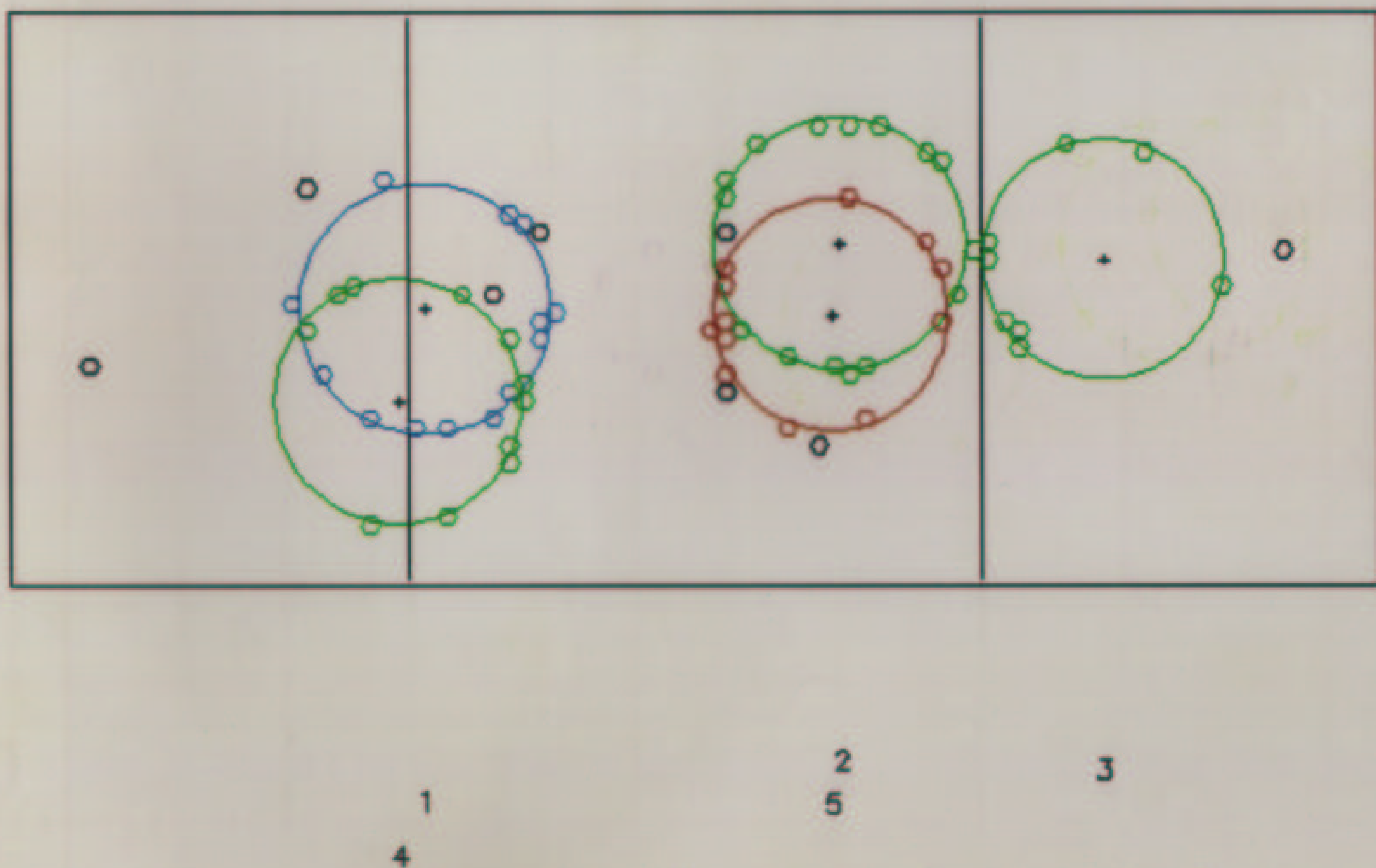
SELEX RICH PM Box



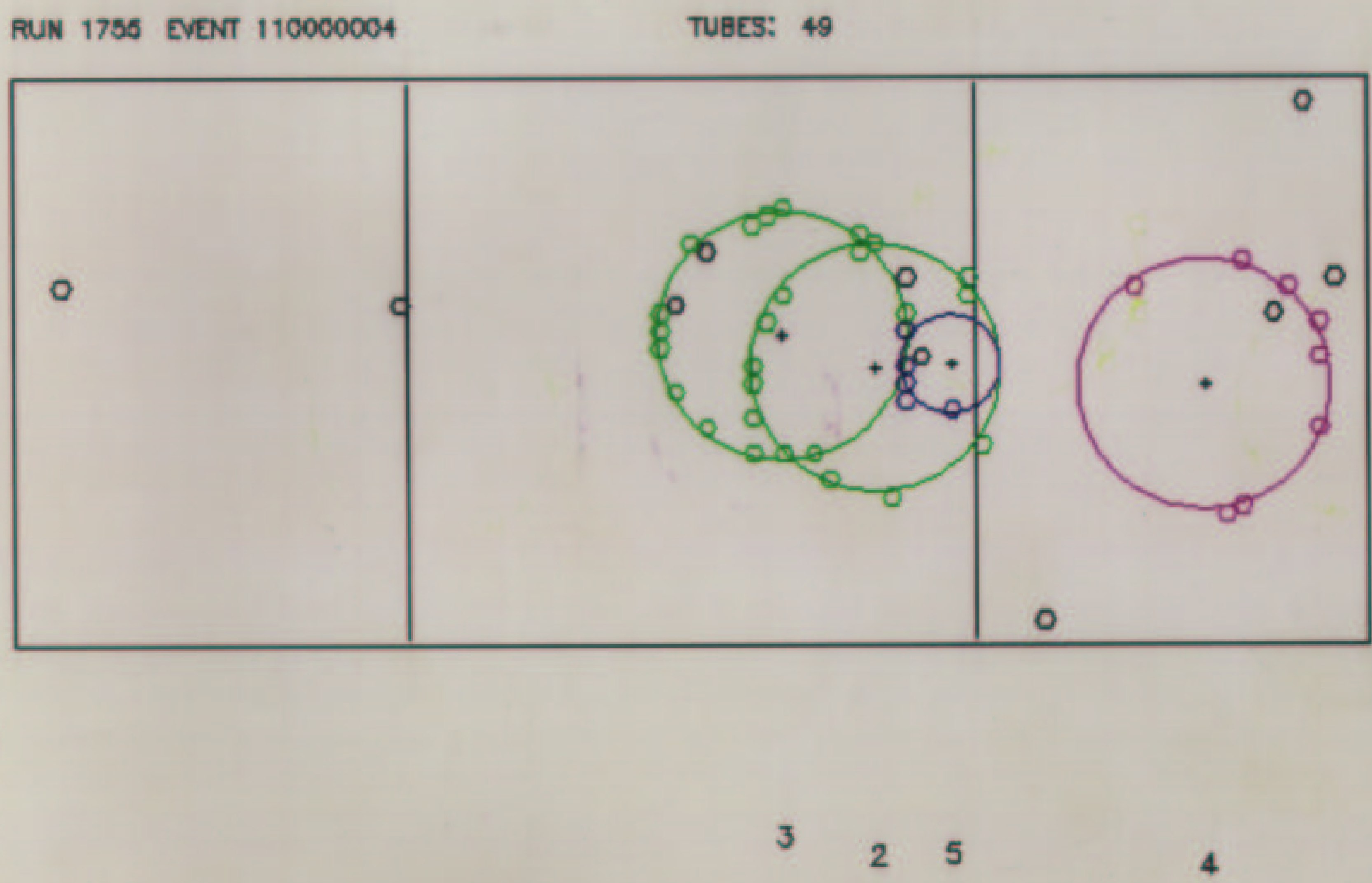


trk	momnt	pid	pckge	stat	gam	bckg	e	muon	pion	kaon	p	sigma
1	71.4	5	rich	8	-1.00	0.00	0.79	1.00	0.88	0.00	0.00	0.00
2	-136.8	9	rich	8	-1.00	0.00	0.88	0.96	1.00	0.00	0.00	0.00
3	-38.1	9	rich	8	-1.00	0.00	0.00	0.06	1.00	0.00	0.00	0.00
4	50.0	8	rich	8	-1.00	0.00	0.24	0.81	1.00	0.00	0.00	0.00
5	-107.7	12	rich	8	-1.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00

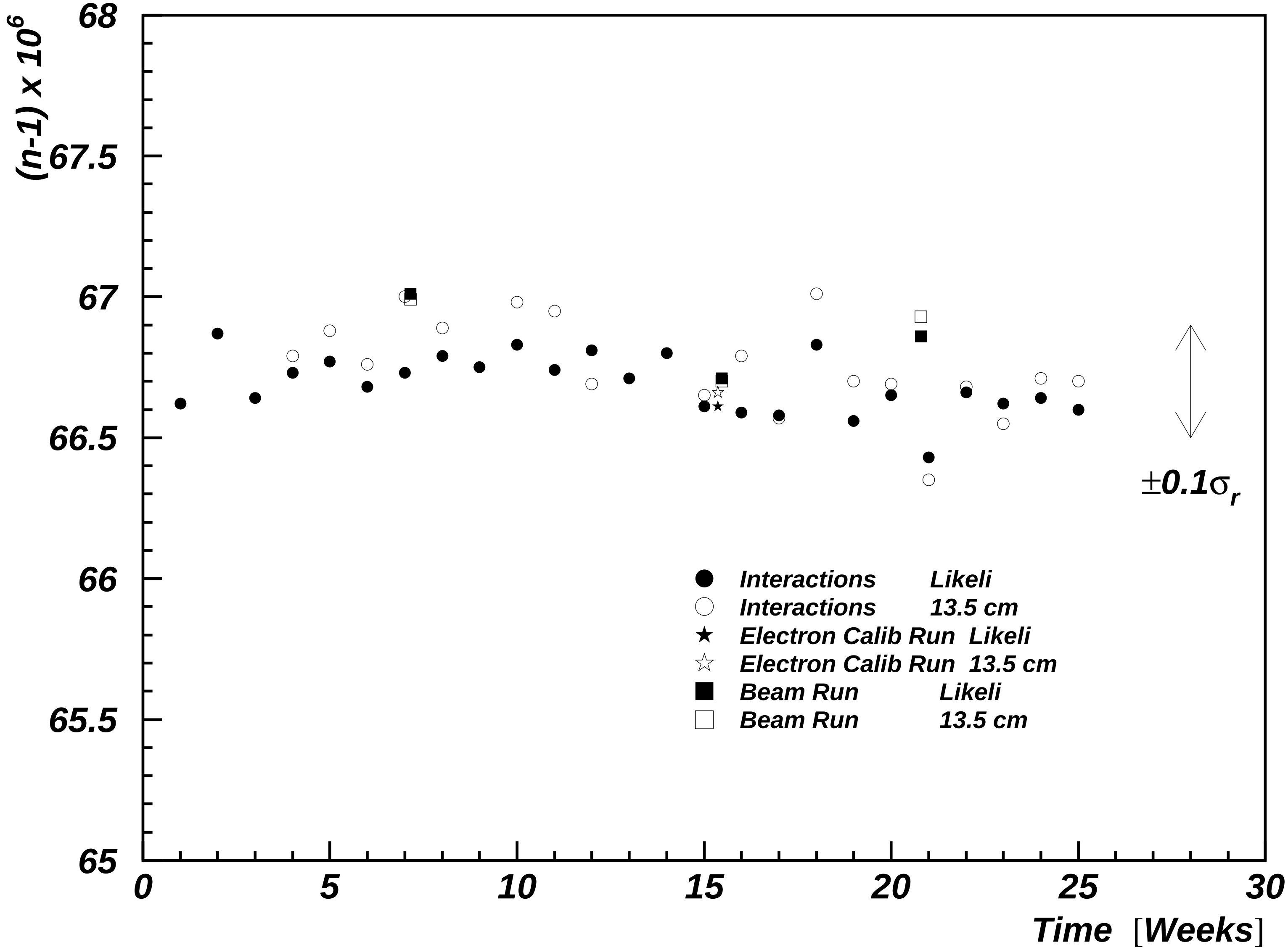
RUN 1755 EVENT 10000030 TUBES: 67



trk	momnt	pid	pckge	stat	gam	bckg	e	muon	pion	kaon	p	sigma
2	-81.9	9	rich	8	-1.00	0.00	0.75	0.96	1.00	0.00	0.00	0.00
3	-120.2	9	rich	8	-1.00	0.00	0.61	0.82	1.00	0.00	0.00	0.00
4	-22.5	3	rich	8	-1.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00
5	-88.1	15	rich	8	-1.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00

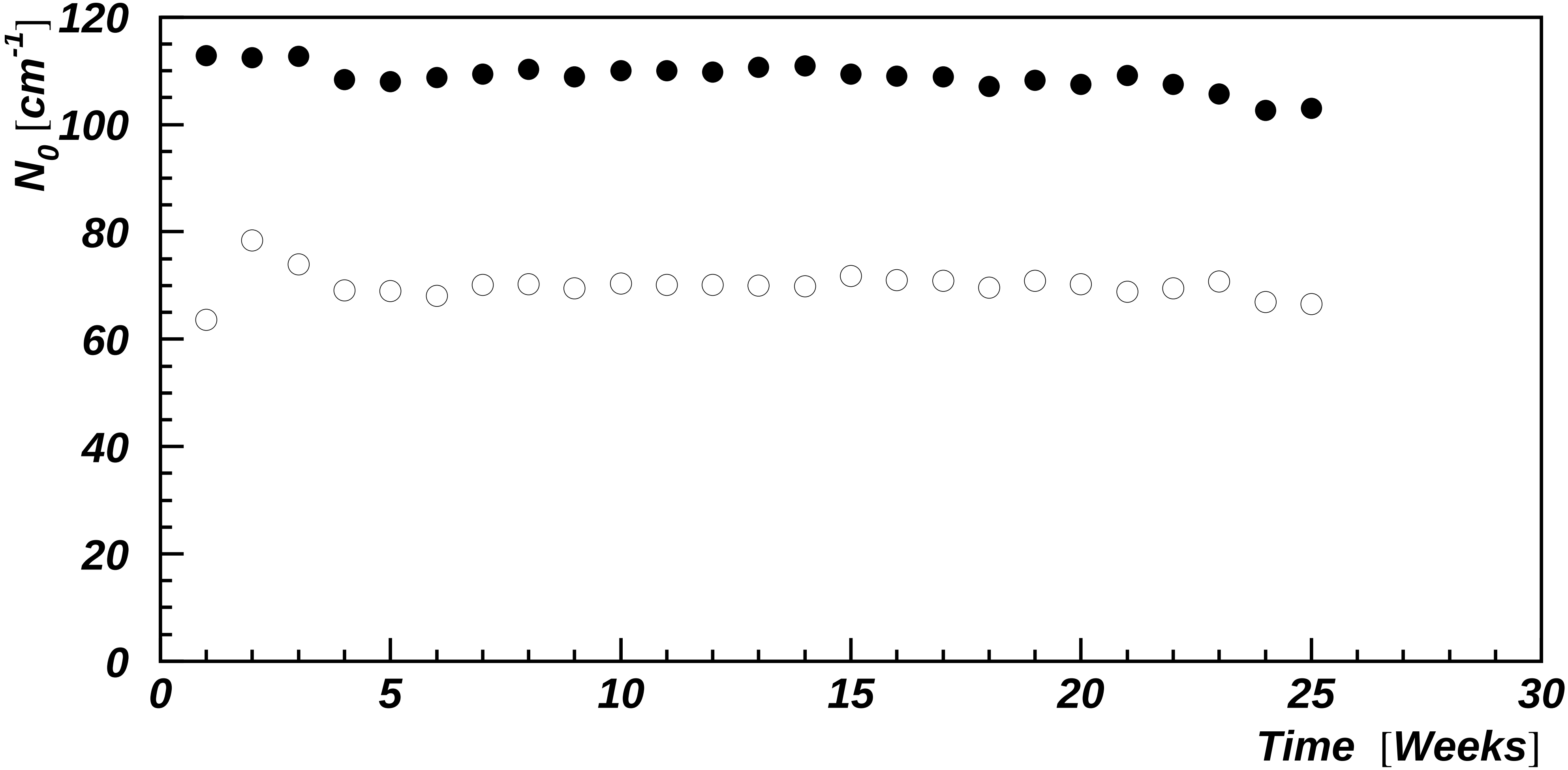


SELEX RICH Stability – Refractive Index



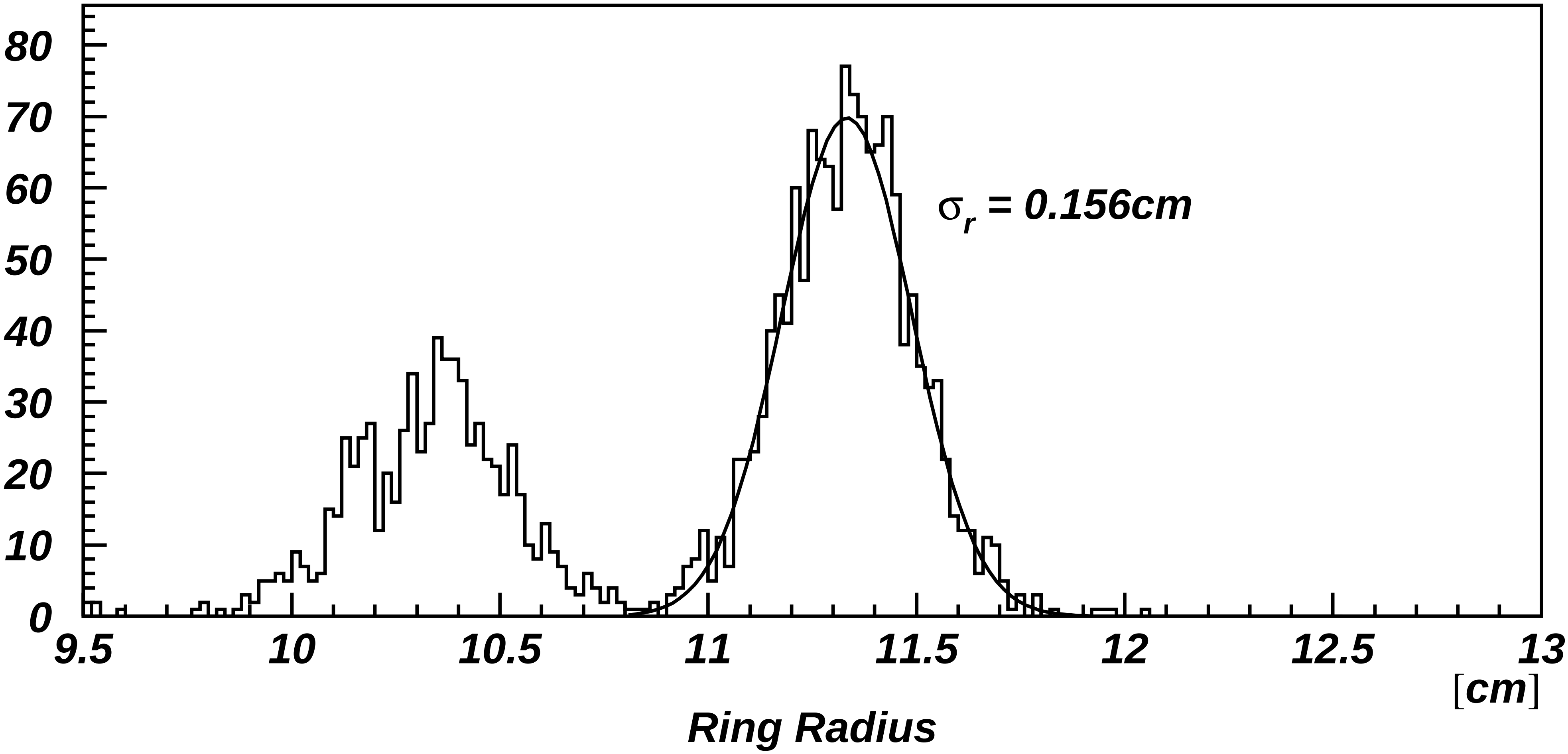
SELEX RICH Stability – N_0

$$N_{\mathrm{ph}} = N_0 \cdot L \cdot \sin^2 \theta_c$$

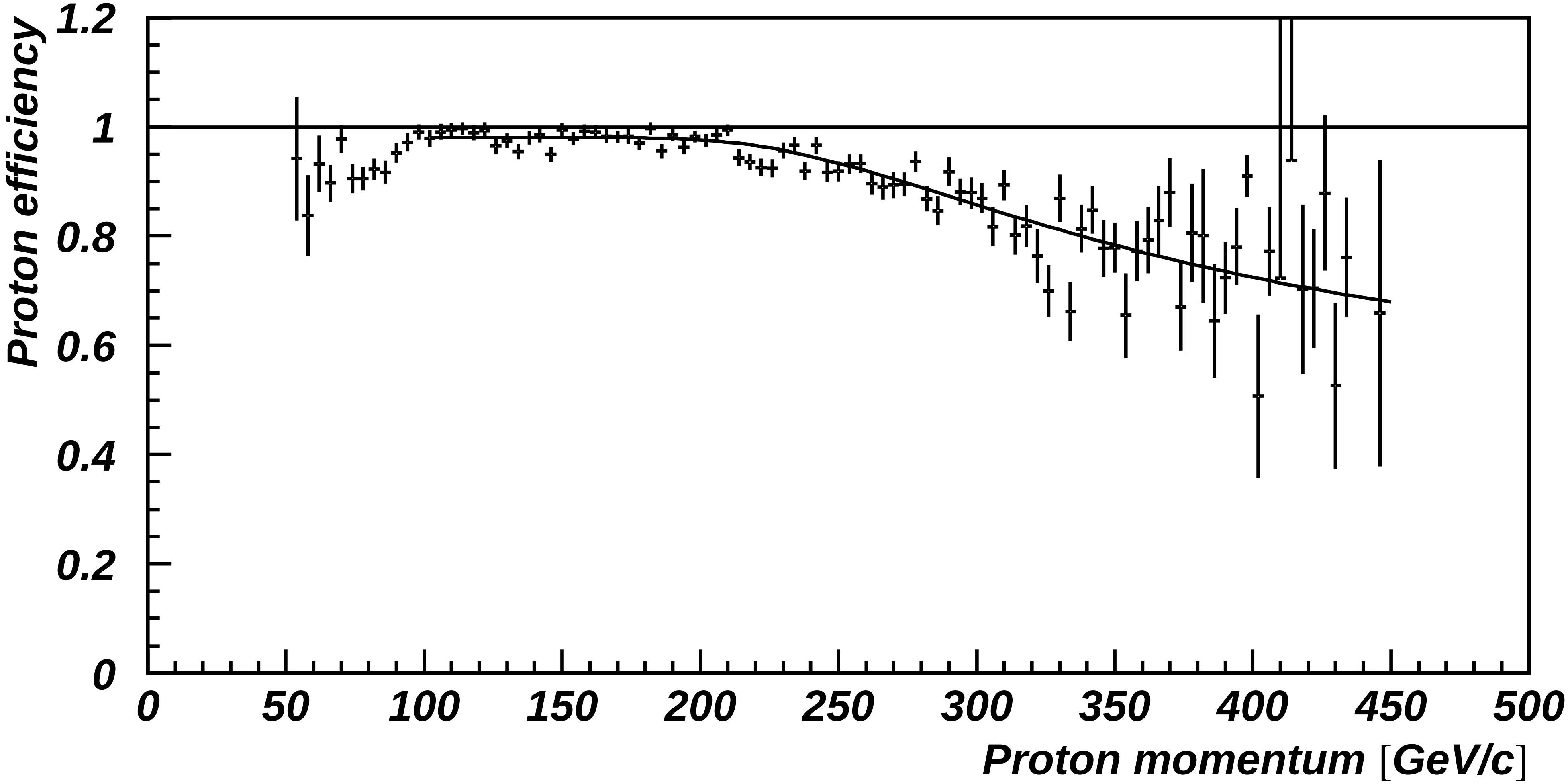


SELEX RICH Separation

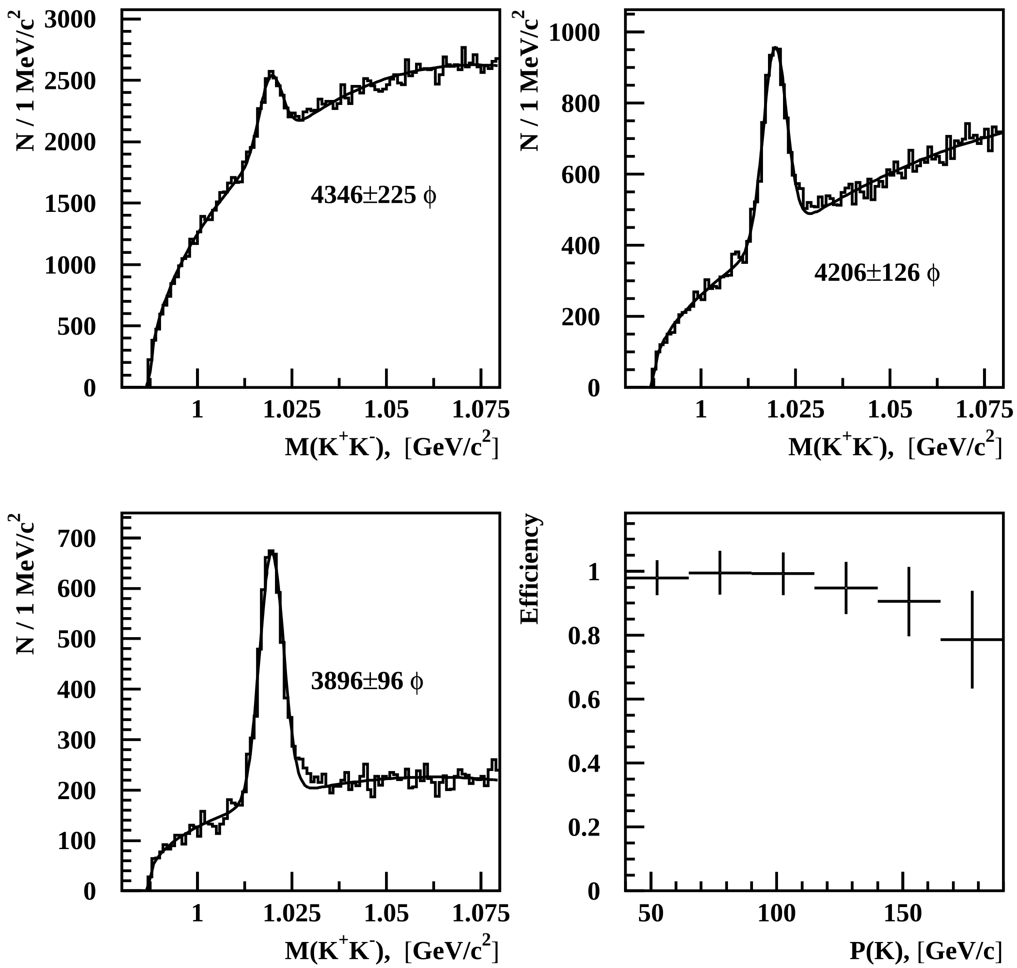
Momentum of particles: $95\,\mathrm{GeV}/c - 105\,\mathrm{GeV}/c$



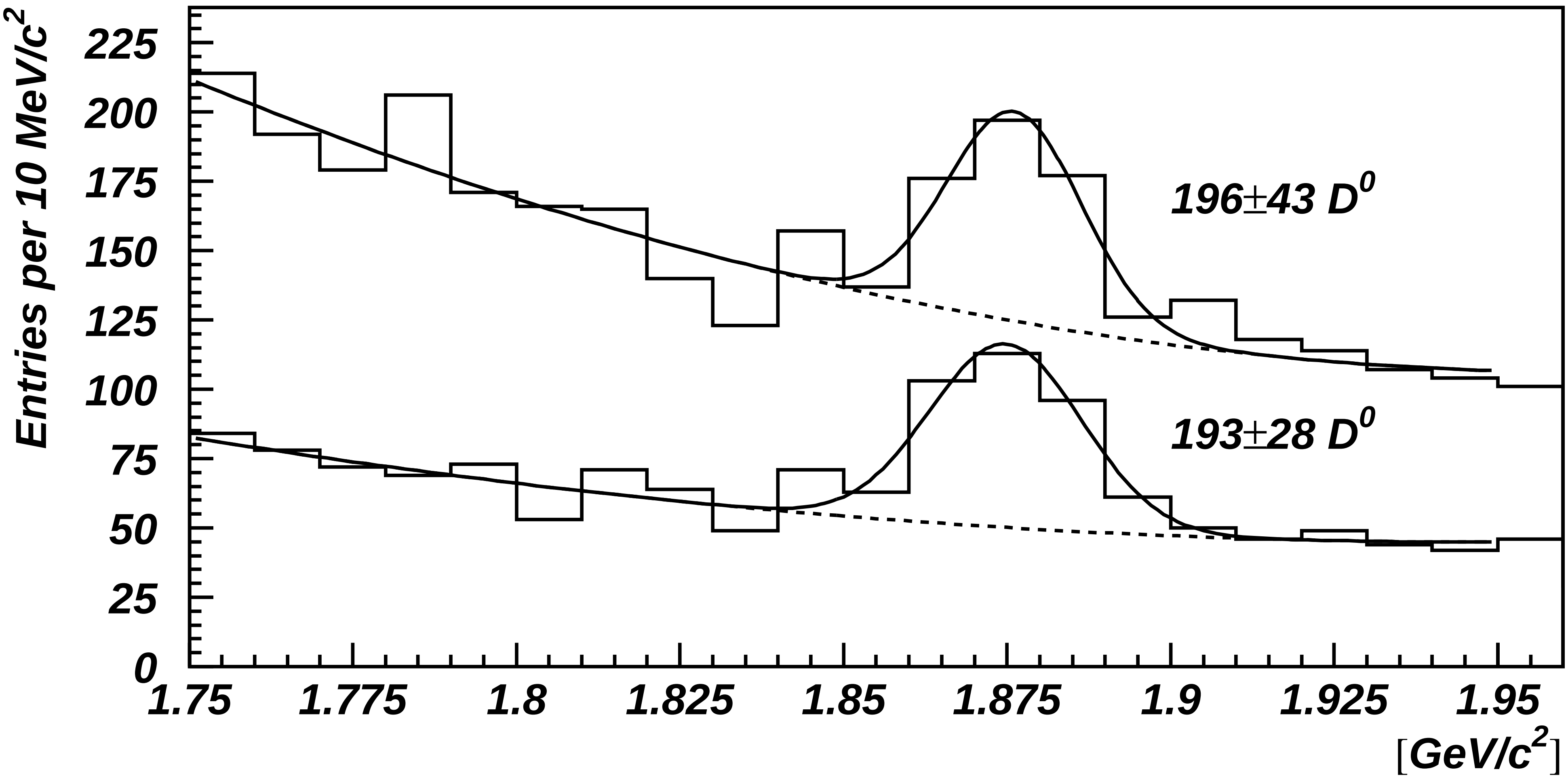
SELEX RICH Efficiency – Protons



SELEX RICH Efficiency – Kaons



SELEX RICH Efficiency – $D^0 \to K^{\mp}\pi^{\pm}$

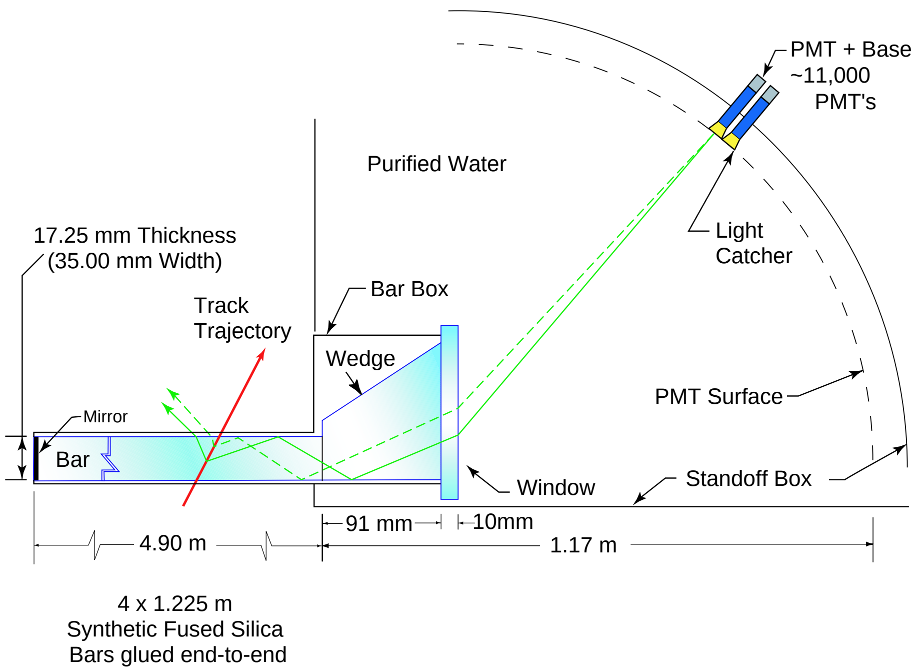


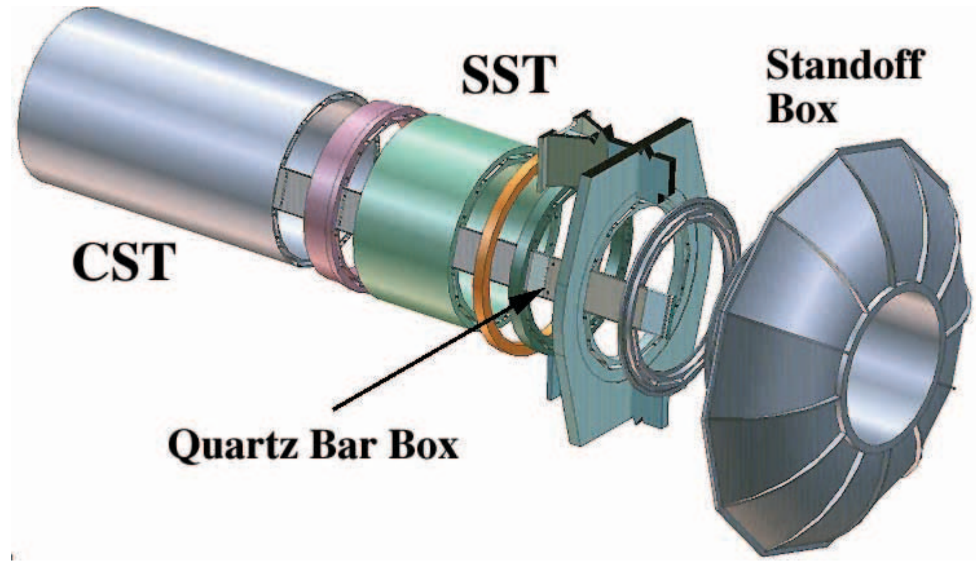
Small statistic: The RICH is too good!!

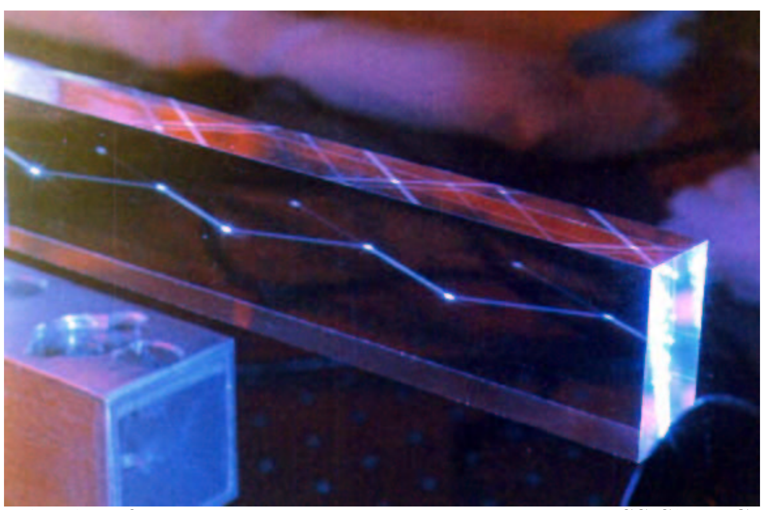
A Current RICH: DIRC at BaBar

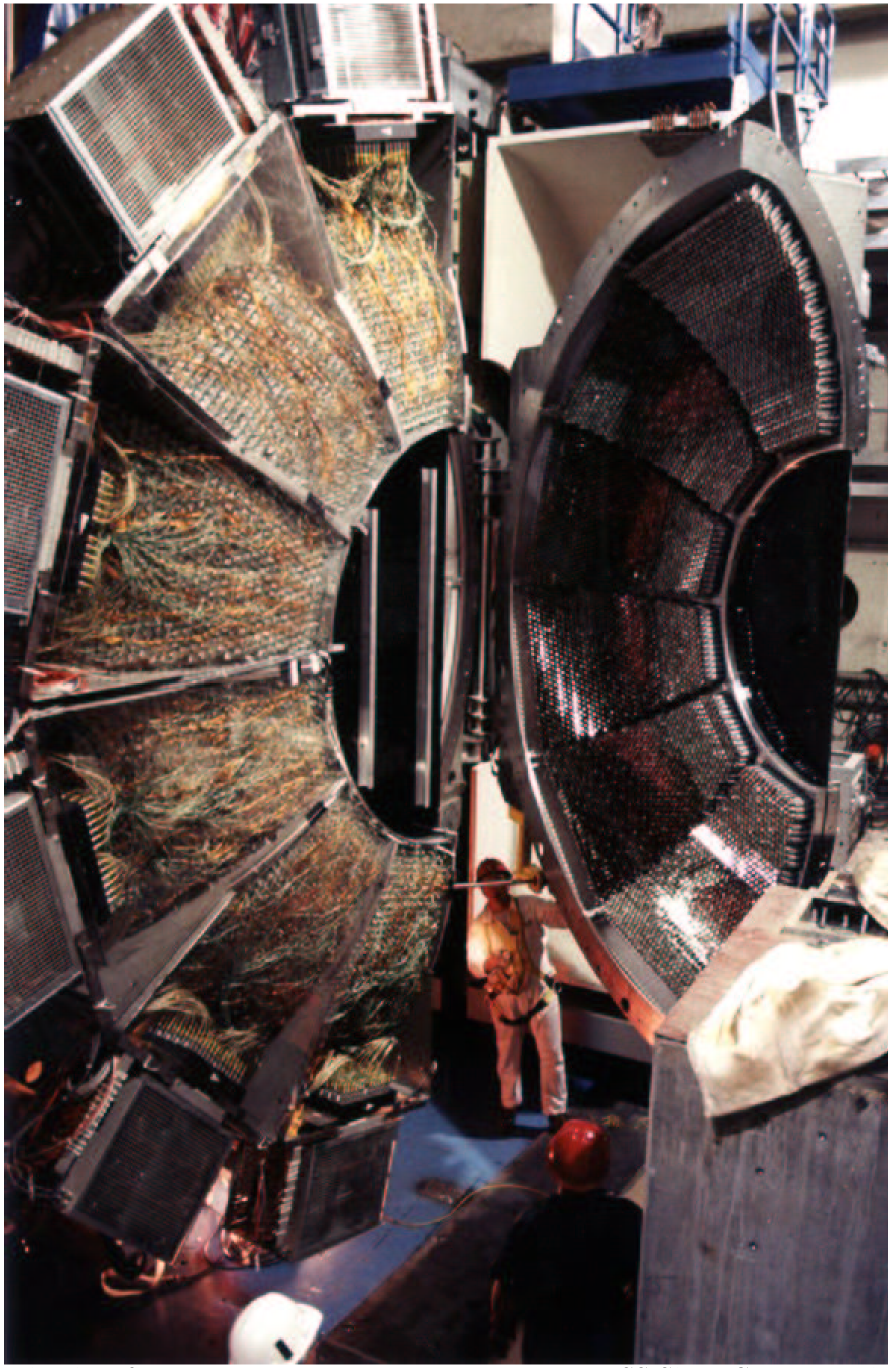
DIRC at BaBar

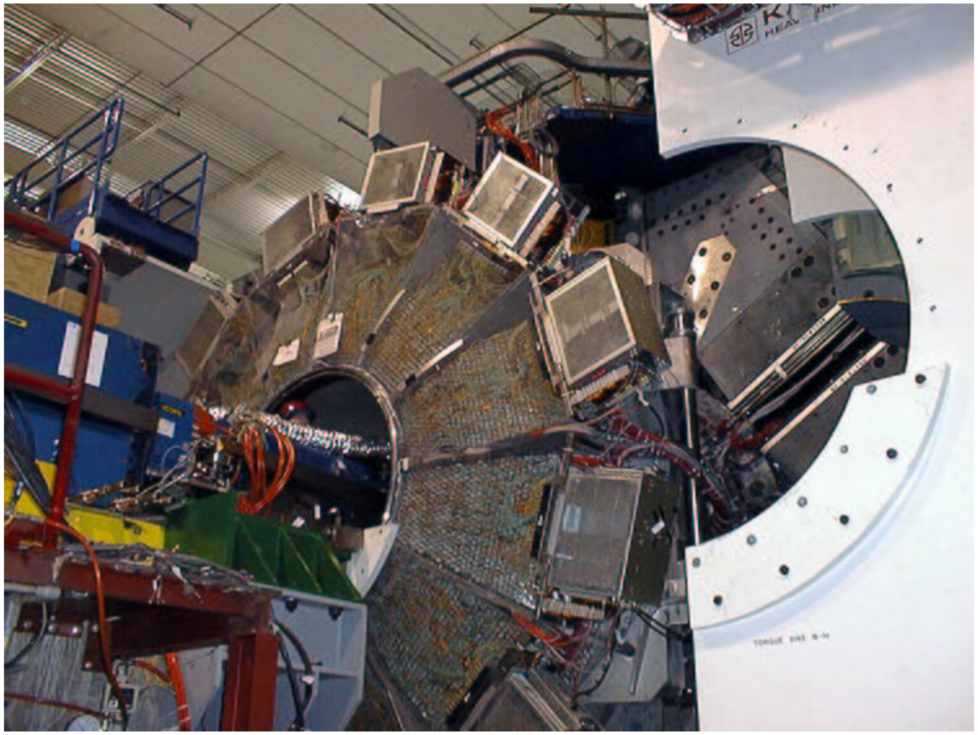
Detection of internally reflected Cherenkov light



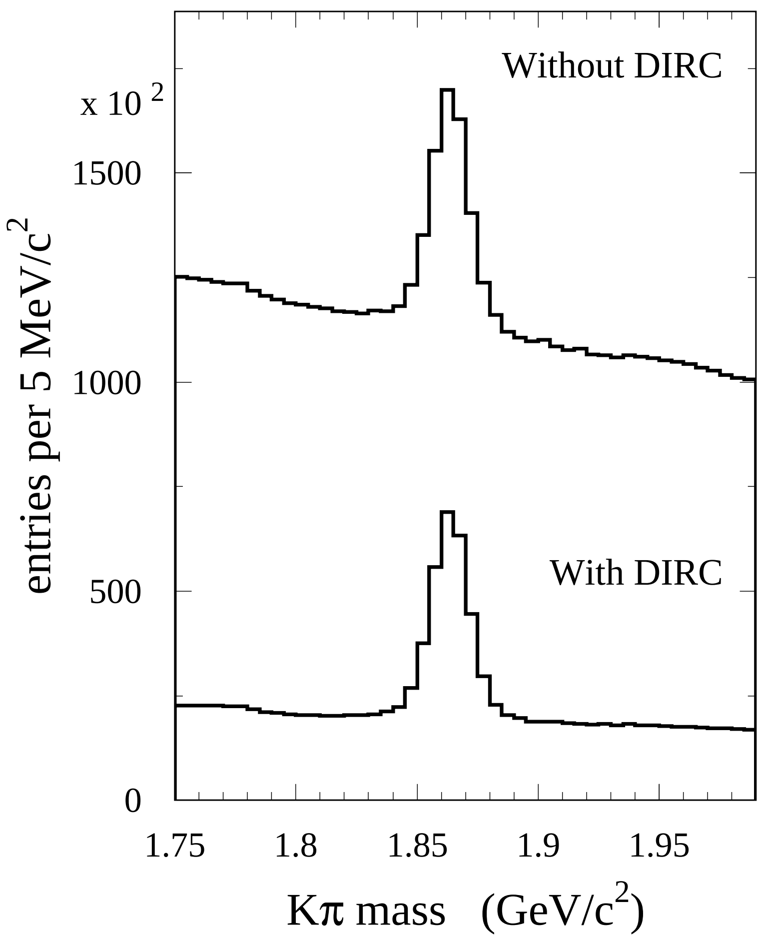


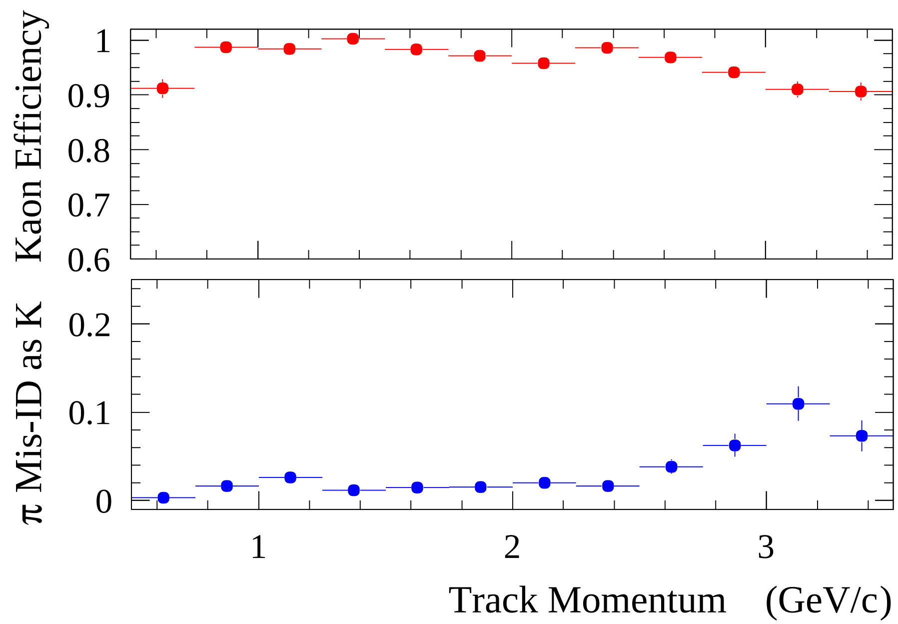






DIRC at BaBar – Performance





Future in RICH: CKM RICHes

Future Use: CKM

Will use 2 RICHes to really measure velocity. Particle ID comes for free.

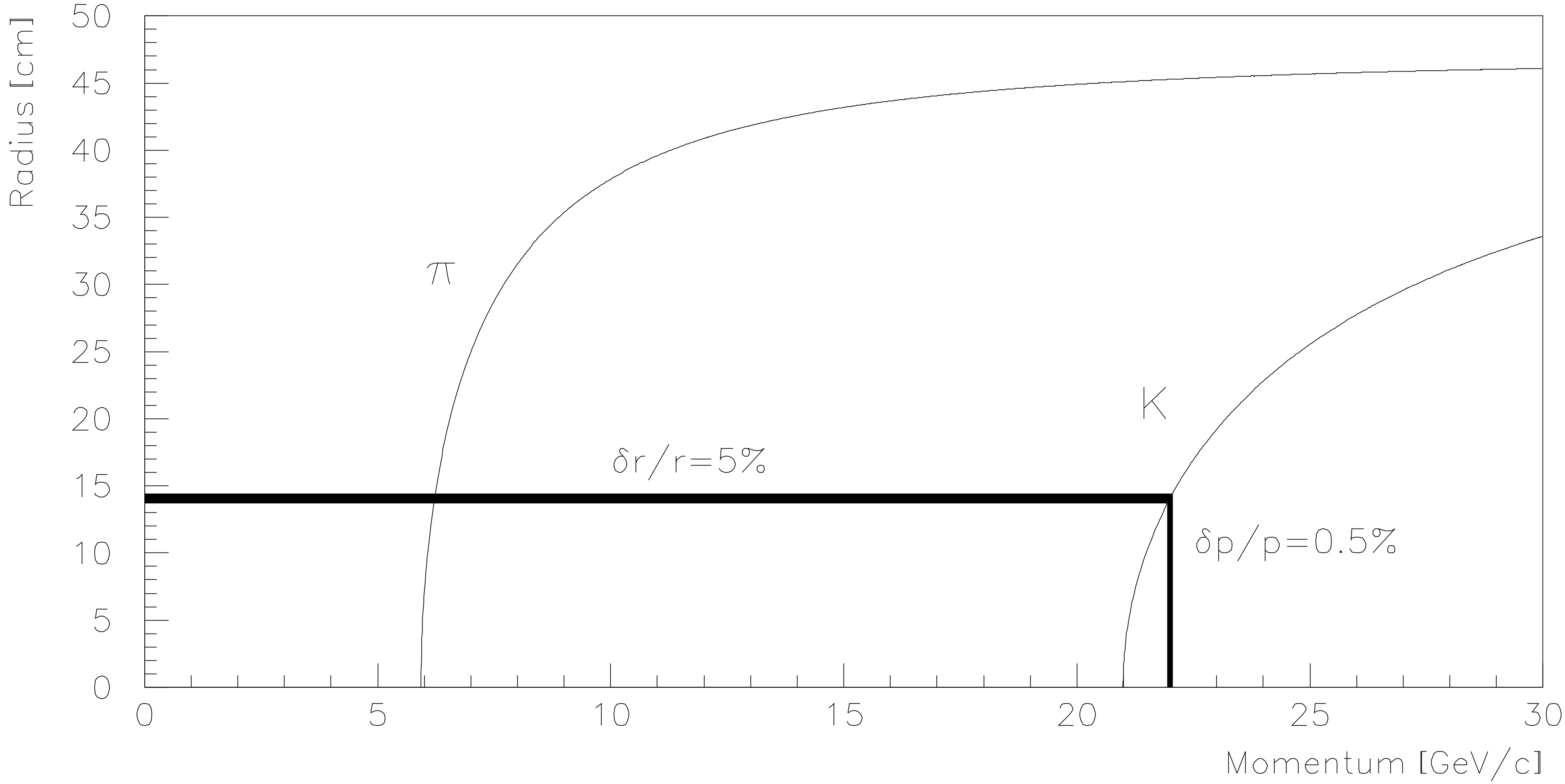
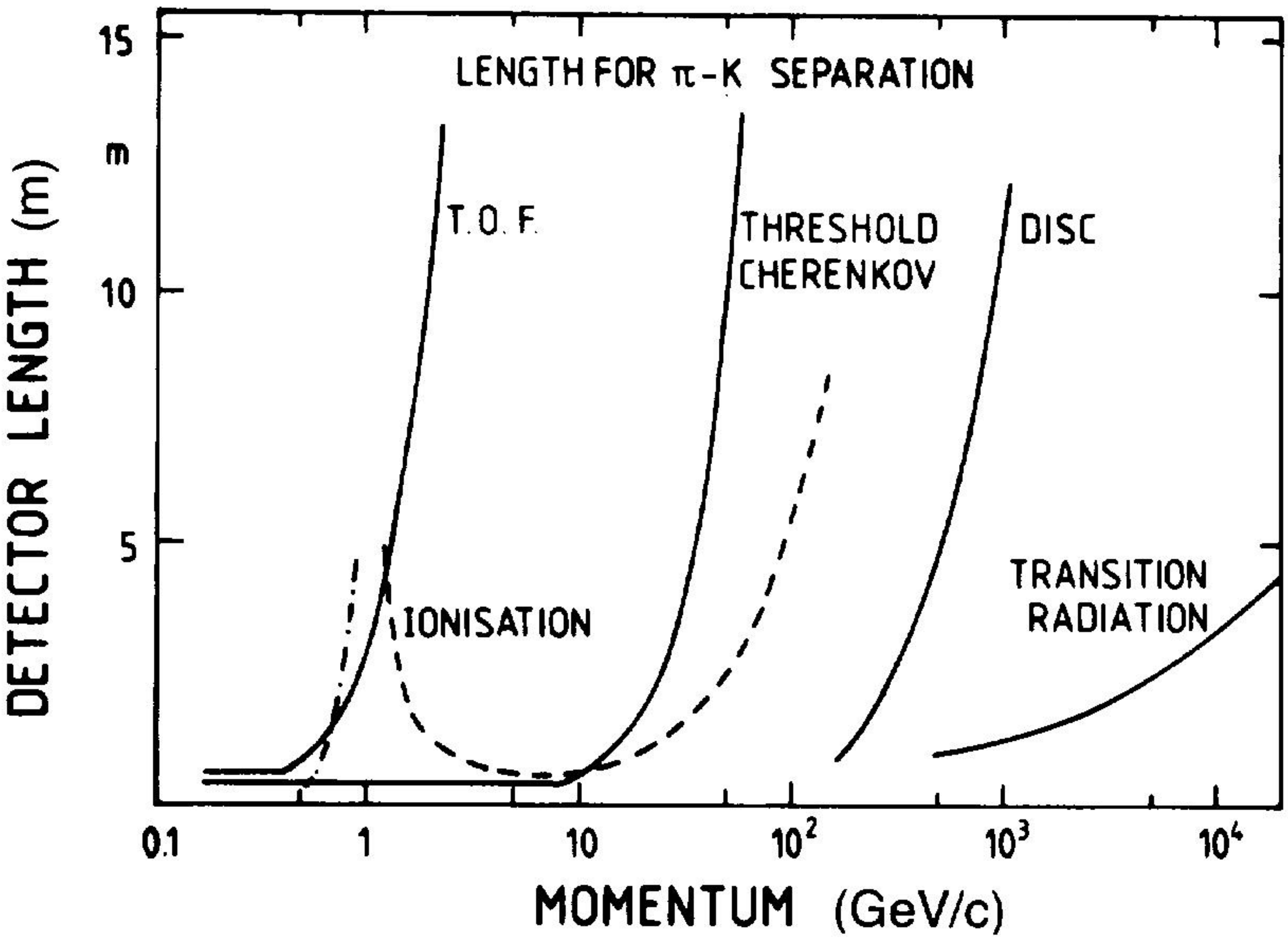


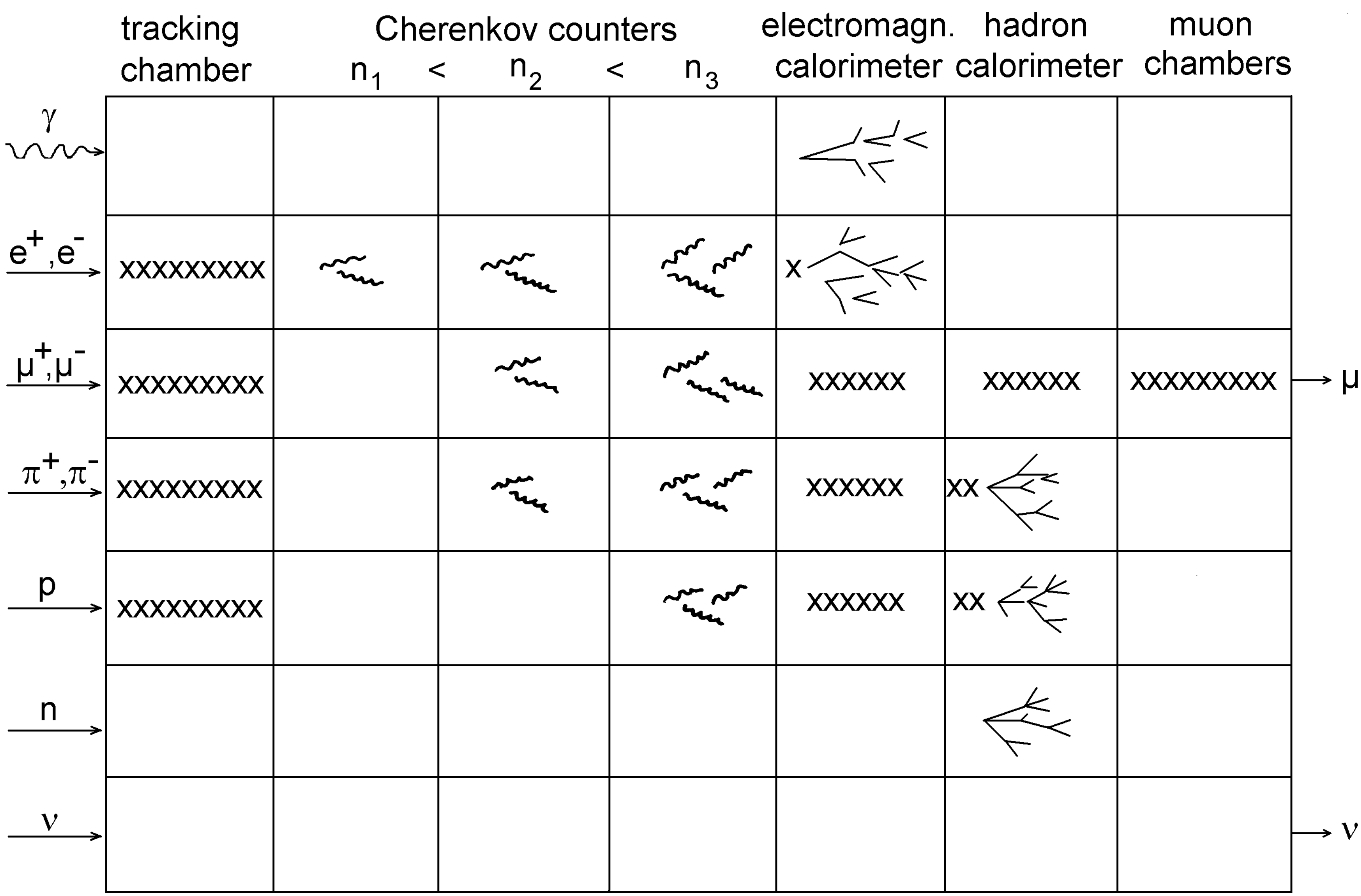
Fig. 5.30. Length of detectors needed for separation of π and K mesons.



Summary Particle Identification

- **Particle Identification (for charged particles) usually measures the velocity of the particle, identification is achieved combined with the already known momentum.**
- **Transition Radiation Detectors mostly used in beamlines, but also to measure decay products (mostly electron–pion separation)**
- **Cherenkov effect is used in Threshold Cherenkov Counters**
- **Cherenkov effect is used in RICH detectors**
- **RICHes are an established standard detector now, and have a bright future.**

Summary Particle Identification (cont.)



Recommended Literature

- **Claus Grupen: Particle Detectors. Cambridge University Press, 2000.**
- **Konrad Kleinknecht: Detectors for particle radiation. Cambridge University Press, 2nd edition 1998.**
- **Richard C. Fernow: Introduction to experimental Particle Physics. Cambridge University Press, 1986.**
- **Richard Wigmans: Calorimetry. Oxford Science Publishing, 2000.**
- **Lecture notes and Proceedings of ICFA Instrumentation Schools (since 1987 every two years).**
- **Particle Data Book. short summaries of important things.**

That's it.....