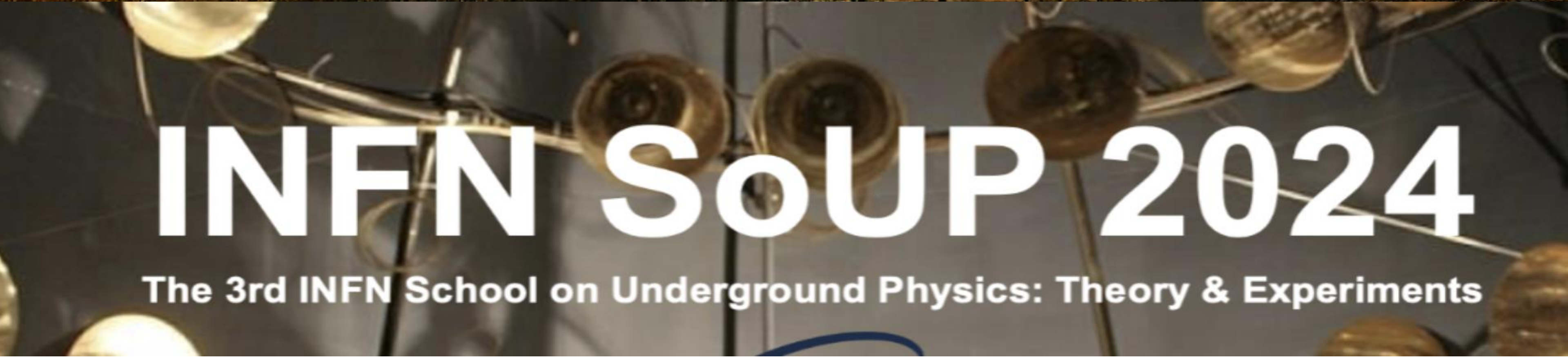
Cherenkov Detectors



Outline

- History and Theory
- Cherenkov technique(s)
- Cherenkov detectors in HEP: Delphi, LHCb, Babar
- Cherenov detectors in APP:

Vetos:	Xenon neutron veto
RICH:	AMS, Super Hyper –Kamiokande HAWC, LHAASO, SWGO, PAO
(S)IACT:	Hegra, Veritas, Cangaroo, Magic, Hess, CTA
Neutrino Telescopes:	Bakal GVD, Antares, IceCube, KM3NeT
Radio Cherenkov	

- Medical physics

History

Predicted by Heaviside in 1888
Blue light seen in fluids containing radium (Marie Skłodowska & Pierre Curie)

The Nobel Prize in Physics 1958

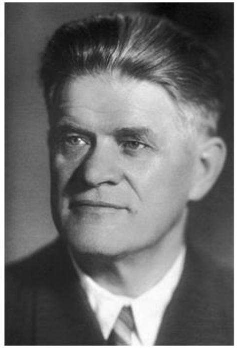


Photo from the Nobel Foundation archive.
Pavel Alekseyevich Cherenkov
Prize share: 1/3


Photo from the Nobel Foundation archive.
Il´ja Mikhailovich Frank
Prize share: 1/3


Photo from the Nobel Foundation archive.
Igor Yevgenyevich Tamm
Prize share: 1/3

Cherenkov - Discovery: 1936
Tamm and Frank- Theoretical explanation 1937

IGOR' E. TAMM

General characteristics of radiations emitted by systems moving with super-light velocities with some applications to plasma physics

Nobel Lecture, December 11, 1958

PAVEL A. ČERENKOV

Radiation of particles moving at a velocity exceeding that of light, and some of the possibilities for their use in experimental physics

Nobel Lecture, December 11, 1958

IL'JA M. FRANK

Optics of light sources moving in refractive media

Nobel Lecture, December 11, 1958

Peculiarities of radiation in a medium

Emission of UV-visible light by HE particles in transparent radiators:
large (cheap) particle detectors widely used in experiments and applications

History

Consider a system which in principle is able to emit the radiation in question - e.g. an electrically charged particle in the case of light, a projectile or an airplane in the case of sound, etc. As long as the velocity of this system as a whole is smaller than the velocity of propagation of waves in the surrounding medium, the radiation can be produced only by some oscillatory motion of the system or of some of its parts - e.g. by the oscillation of an electron in an atom or by the revolutions of the propellers of a plane. The frequency of the radiation emitted is evidently determined by the frequency of the oscillations in question. To be more exact, for the radiation to be possible the motion has not necessarily to be a periodic one, but it has to be non-uniform* (i.e. its velocity should not be constant in time).

But when a velocity of the system becomes greater than that of the waves in question, quite a new mechanism of radiation is introduced, by means of which even systems possessing a constant velocity radiate.

All these general properties of the radiation in question were for a very long time well known in aerodynamics. The air waves emitted at supersonic velocities are called Mach waves. The emission of these waves sets in when the velocity of a projectile or of a plane begins to exceed the velocity of sound in the air. Emitting waves means losing energy and these losses are so large that they constitute the main source of resistance to the flight of a supersonic plane.

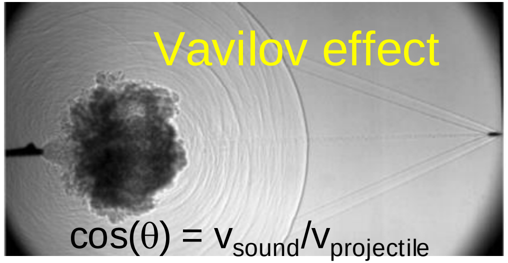
That is why in order to cross the sound barrier, i.e. to achieve supersonic velocities in aviation, it was necessary to increase very substantially the power of the engines of a plane.

We perceive the Mach waves radiated by a projectile as its familiar hissing or roaring. That is why, having understood the quite similar mechanism of the Vavilov-Čerenkov radiation of light by fast electrons, we have nicknamed it « the singing electrons ».

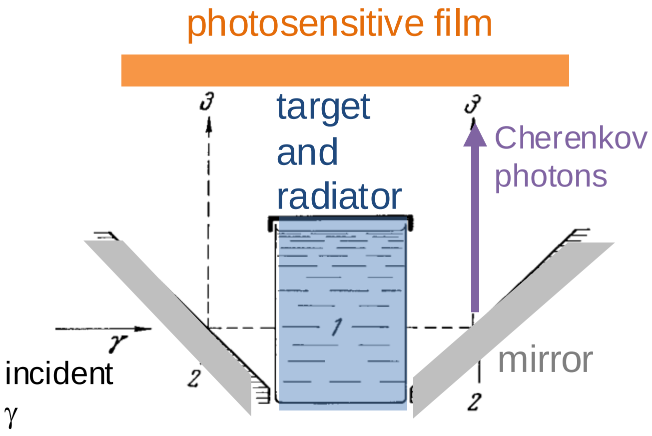
I should perhaps explain that we in the USSR use the name « Vavilov-Čerenkov radiation » instead of just « Čerenkov radiation » in order to emphasize the decisive role of the late Prof. S. Vavilov in the discovery of this radiation.

(Vavilov)-Cherenkov light is produced by:

- charged particles
- moving through a radiatior medium at a speed larger than the speed of light in the medium



History

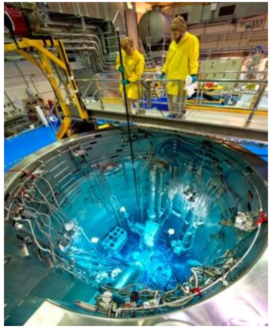


Compton scattering of γ
fast electrons

Light produced only by electrons above a velocity threshold
N of photons protortional to the electron path length
Light emission is prompt
Light spectum is continuous
Light angular distribution depends on the radiator n(λ)
(Light is polarized)

History

G.B. Collins and V.G. Reiling (1938)



Experiment:
Monochromatic electron beam (2 MeV) strongly focused
Several liquids and solids

Result:
Direction of the emission of radiation is precisely described by the ratio $\cos\theta = 1/(\beta n)$
Continuous spectrum with increasing intensity from IR to UV in all media
Each electron emits about 40 photons in the range of 4000 Å up to 6700 Å

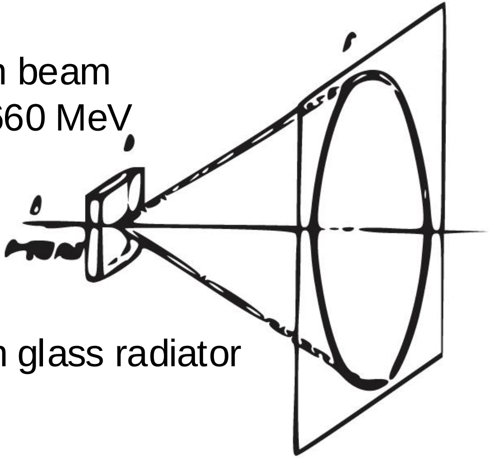
R.L. Mather (1951)

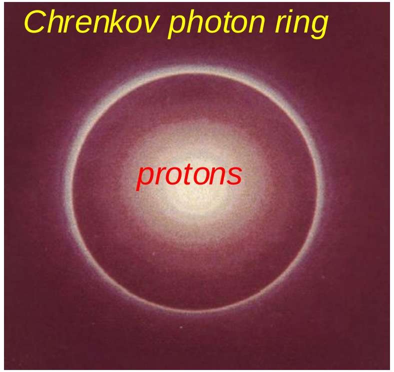
First observation using a proton beam

History

V.P. Zrelov et al. JINR Dubna, 1970

Birth of RICH (Ring Imaging CHerenkov)





Theory

Passage of a charged particle (not accelerated) induces polarisation of the dielectric medium
Oscillation of dipole field causes radiation emission (coherent with Maxwell e.m. theory)

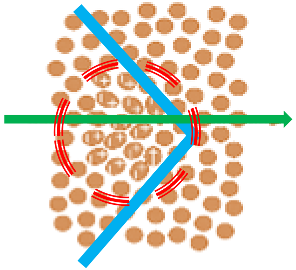
Cherenkov threshold

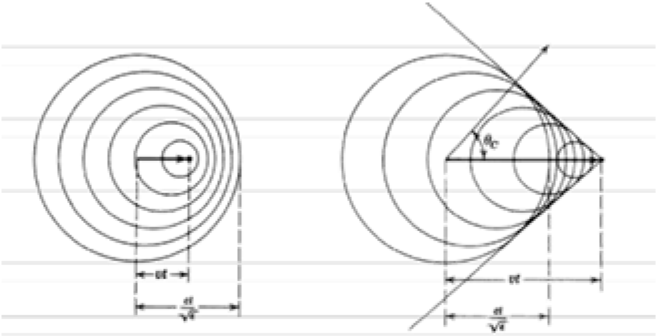
$v_{particle} < c / n(\lambda)$

- dipoles are symmetrically produced along the particle track
- destructive interference
- no escaping radiation

$v_{particle} > c / n(\lambda)$

- shock wave
- dipoles are not symmetrical
- coherent light emission angle (Huygens)





Cherenkov threshold detectors use $n(\lambda)$ as particle velocity selector

$\cos\theta_c = 1/\beta_{thershold}$ $n(\lambda) = 1 \rightarrow \theta_c = 0$

The Cherenkov angle increseas with β
$\theta = \theta_c$ at $\beta = 1$

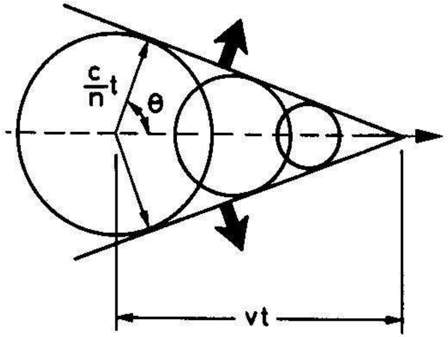
$n(\lambda)$ = medium/radiator refractive index (note λ dependence!)

Theory

Cherenkov angle

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

- θ_c (β,n(λ)) measures the particle momentum
- for $\beta \approx 1$ the Cherenkov angle is constant (saturated) for a given particle species



v t = β c t

Ring Image CHerenkov detectors

Caveat: ‘Chromatic Error’: photons from the same charged track can have different cos (θ)= 1 /n(λ) β

- Filter photons (wavelength selector)
- Use radiators with constant n(λ)
- Measure Time-Of-Propagation (TOP) of photons

Theory

Cherenkov energy loss

about 10^{-3} (weaker) wr to Bethe-Block energy loss

Frank-Tamm

$$\frac{d^2N_\gamma}{dE_\gamma dx} = z^2 \frac{\alpha}{\hbar c} \sin^2 \vartheta_C$$

$$\frac{dN_\gamma}{dE} = \left(\frac{\alpha}{\hbar c}\right) Z^2 L \sin^2 \theta_C$$

L = track length

Number of photons/Energy loss per track length

$$\frac{dN_\gamma}{dx} = \int_{E_1}^{E_2} \frac{d^2N_\gamma}{dE_\gamma dx} dE_\gamma = \int_{E_1}^{E_2} z^2 \frac{\alpha}{\hbar c}\left(1 - \frac{1}{\beta^2 n^2}\right) dE_\gamma$$

$$\frac{\Delta E_{Cher}}{dx} = \int_{E_1}^{E_2} E_\gamma \frac{d^2N_\gamma}{dE_\gamma dx} dE_\gamma = \int_{E_1}^{E_2} E_\gamma z^2 \frac{\alpha}{\hbar c}\left(1 - \frac{1}{\beta^2 n^2}\right) dE_\gamma .$$

Theory

Cherenkov energy loss

Frank-Tamm

$$\frac{d^2 N_\gamma}{dE_\gamma dx} = z^2 \frac{\alpha}{\hbar c} \sin^2 \vartheta_C$$

about 10^{-3} (weaker) wr to Bethe-Block energy loss

$$\frac{dN_\gamma}{dE} = \left(\frac{\alpha}{\hbar c}\right) Z^2 L \sin^2 \theta_C$$

L = track length

Only few hundreds photons /(eV cm) require:

- optimal radiator
- very sensitive photon detectors

Number of photons/Energy loss per track length

$$\frac{dN_\gamma}{dx} = \int_{E_1}^{E_2} \frac{d^2 N_\gamma}{dE_\gamma dx} dE_\gamma = \int_{E_1}^{E_2} z^2 \frac{\alpha}{\hbar c}\left(1 - \frac{1}{\beta^2 n^2}\right) dE_\gamma$$

$$\frac{\Delta E_{Cher}}{dx} = \int_{E_1}^{E_2} E_\gamma \frac{d^2 N_\gamma}{dE_\gamma dx} dE_\gamma = \int_{E_1}^{E_2} E_\gamma z^2 \frac{\alpha}{\hbar c}\left(1 - \frac{1}{\beta^2 n^2}\right) dE_\gamma .$$

Cherenkov ligth is mainly produced at small λ, with a cutoff at UV

Cherenkov Detectors

properties of Cherenkov light production can be used to
- tag particle ID
- measure particle momentum

medium	n	θ_{max} (deg.)	N_{ph} (eV^{-1} cm^{-1})
air	1.000283	1.36	0.208
isobutane	1.00127	2.89	0.941
water	1.33	41.2	160.8
quartz	1.46	46.7	196.4
aerogel	1.03	13.86	0.12

$$\beta_{thershold} = [n(\lambda)]^{-1}$$

$$\gamma^2_{thershold} = [\,1 - 1/n^2(\lambda)\,]^{-1}$$

$$p_{thershold} = m_0 \cdot [n(\lambda)-1]^{-1/2}$$

$$\beta = \frac{p}{E} = \frac{\sqrt{E^2 - m^2}}{E} = \sqrt{1 - m^2/E^2}$$

Cherenkov Detectors

properties of Cherenkov light production can be used to

- tag particle ID
- measure particle momentum

$\beta_{thershold} = [n(\lambda)]^{-1}$

$\gamma^2_{thershold} = [\, 1 - 1/n^2(\lambda)\,]^{-1}$

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$$\beta = \frac{p}{E} = \frac{\sqrt{E^2 - m^2}}{E} = \sqrt{1 - m^2/E^2}$$

Example of radiators

Medium	n-1	γ_{th}	Photons/m
He (STP)	$3.5\ 10^{-5}$	120	3
CO_2 (STP)	$4.1\ 10^{-4}$	35	40
Silica aerogel	0.025-0.075	4.6-2.7	2400-6600
water	0.33	1.52	21300
Glass	0.46-0.75	1.37-1.22	26100-33100

Cherenkov Detectors

Allow efficient detection and fast counting of single charged particles at energies in excess of the Cherenkov threshold

Have prompt response and do not suffer paralysis effects

Cherenkov vs Scintillation:

- $N^{\phi}_{scintillation} = 10^2 \, N^{\phi}_{Cherenkov}$
- $\Delta t^{\phi}_{scintillation} >> \Delta t^{\phi}_{Cherenkov} \sim 0$
- Cherenkov ligth allows measurement of particle direction information

Cherenkov Detectors

Used in many fields of High energy physics and astrophysics

Ingredients:

- radiator(s): n(λ), thickness
- light collection devices / mirrors
- light detectors

mirrors used to:

→ guide Cherenkov light to detectors

→ focus the light

Particle ID: θ (p,m) ; If we measure p and θ, we can calculate m and identify different particles

Used in accelerator based experiments:
momentum (p) measured by magnetic spectrometer (Tracking system + magnet)

Cherenkov detectors:

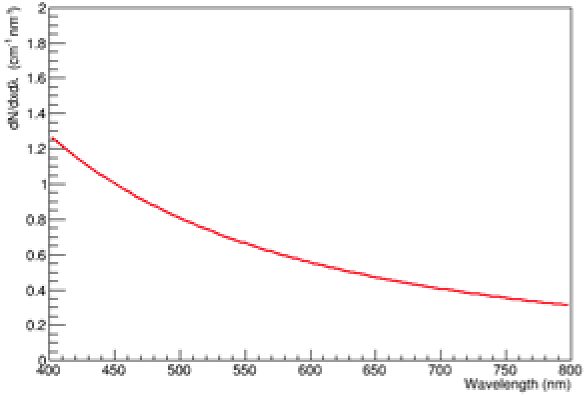
- Measure θ
- Resolution can be expressed in terms of (Δ β /□ β)

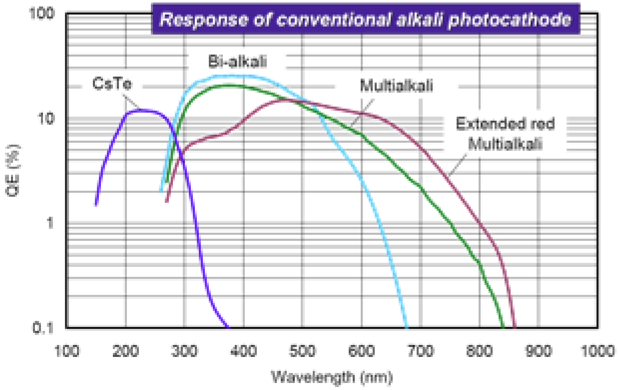
$$\frac{\sigma_\beta}{\beta} = \tan\theta_c\,\sigma_{\theta_c} = \tan\theta_c\sqrt{\frac{\sigma_{\theta_i}^2}{N_{p.e.}} + \sigma_{det}^2}$$

Cherenkov Detectors

$$\frac{dN_\gamma^{detetced}}{dx} = \int_{E_1}^{E_2} z^2 \frac{\alpha}{\hbar c}\left(1 - \frac{1}{\beta^2 n^2(E_\gamma)}\right) P(E_\gamma)\, dE_\gamma$$

- radiator n(λ)
- photon detector efficiency vs. photon energy





Cherenkov Detectors

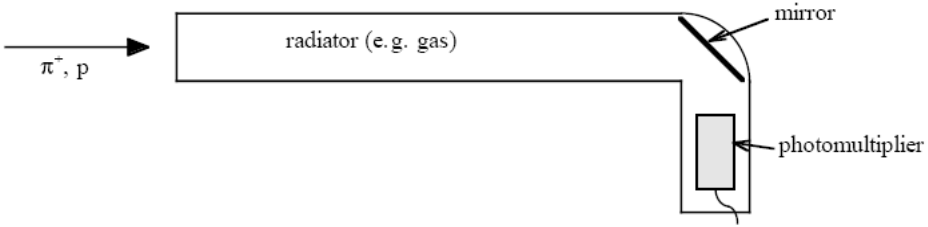
- Simplest: Threshold Cherenkov counters → Select particles with $\beta > 1/n$
- Simple: Differential Cherenkov counters → Select particles in a range of b ($1/n < \beta < \beta_{max}$)

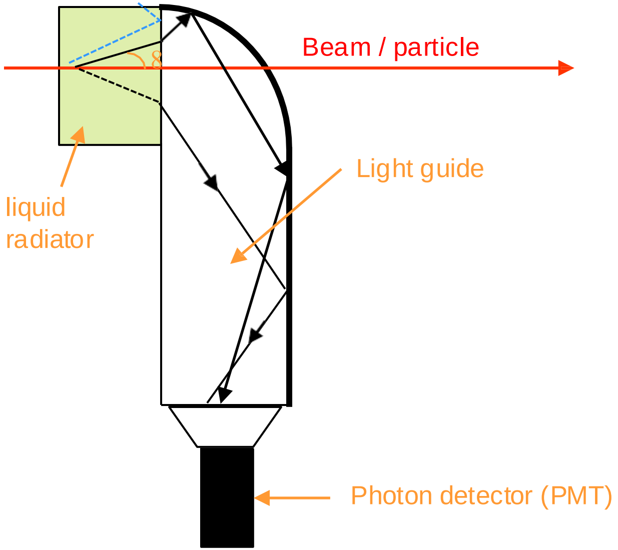
  e.g.: jointly used with momentum measurement (magnetic) → identification of $m_{particle}$
- Smart(er): Imaging → Measure particle velocity (θ_c) and/or direction and/or energy

Cherenkov Threshold Detectors

- Simplest: Threshold Cherenkov counters → Select particles with $\beta > 1/n$

Often used in beamlines for particle ID → identify different particles with same momentum





count the number of photons

$N_{photon} / L = N_0 * (m_1^2 - m_2^2)/(p^2 + m_1^2)$

$\Delta \beta / \beta = \tan^2\theta / [2 * \mathrm{sqrt}(N_{ph})]$

At p= 1 GeV/c

$N_{ph}^{pion} / L = 16$ /cm

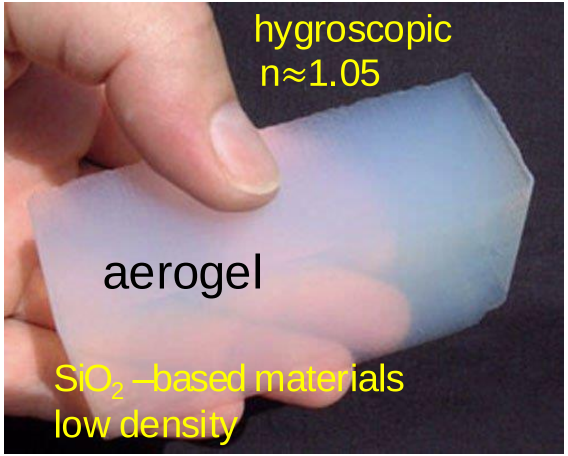
$N_{ph}^{kaon} / L = 0$

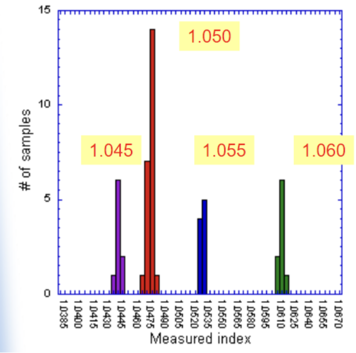
$n(\lambda) = 1.05$ → only pions emit Cherenkov light

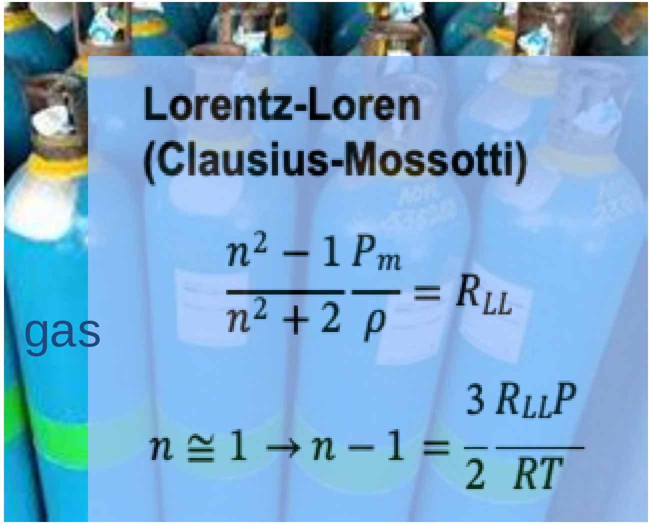
Cherenkov Detectors

how to obtain a well-defined n(λ) ?

- use aerogels
- gas mixtures; change pressure and/or temperature







Cherenkov Threshold Detectors

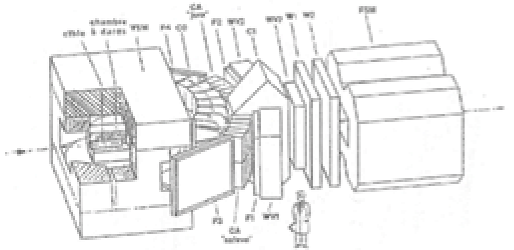
- Simplest: Threshold Cherenkov counters → Select particles with β>1/n

Can use radiators with different reractive index for β discrimination

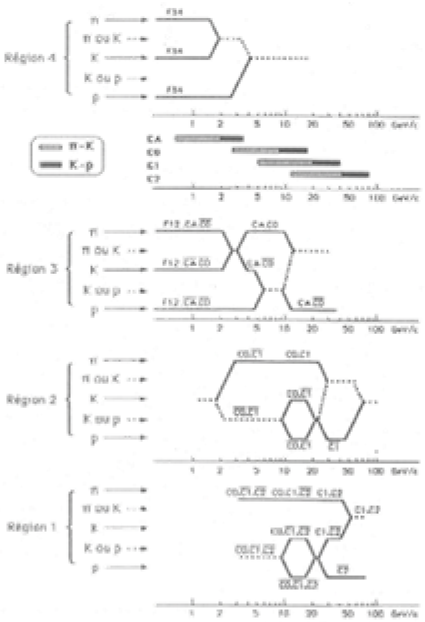
$$\beta_i = \frac{1}{n_i} \rightarrow n_i = \sqrt{\frac{\gamma^2{}_i}{\gamma^2{}_i - 1}}$$

Change gas type or pressure to change n
→ change threshold

NA 49



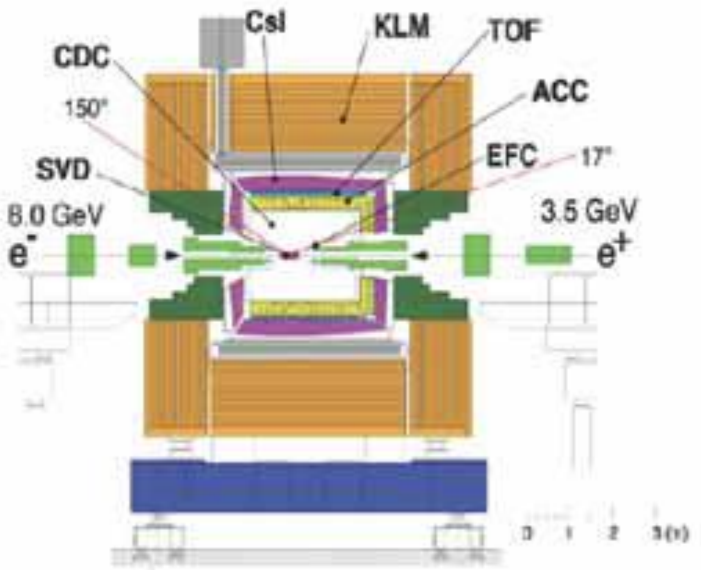
Détecteur	Couverture angulaire horizontale	Zone sensible (cm²)	Taille des cellules	Radiateur $n-1=$ (valeurs approximatives)	Valeurs des seuils π/K/p (GeV/c)
F1,F2 F3,F4	$\pm(10-34)^\circ$ $\pm(32-60)^\circ$	160×106 160×252	160×10 160×15	NE 110 NE 110	π/K < 1,5 K/P < 2,5
CA	$\pm(10-32)^\circ$	2×150×130	65×30	aérogel 0,030	0,6/2/3,8
C0	$\pm 32^\circ$	2×300×100	12×14 25×28	néopentane 0,0015	2,6/9,1/17
C1	$\pm 9^\circ$	109×143	14×18	azote 3×10^{-4}	5,6/20/38
C2	$\pm 7^\circ$	150×300	23×25	néon 6×10^{-5}	12/42/79

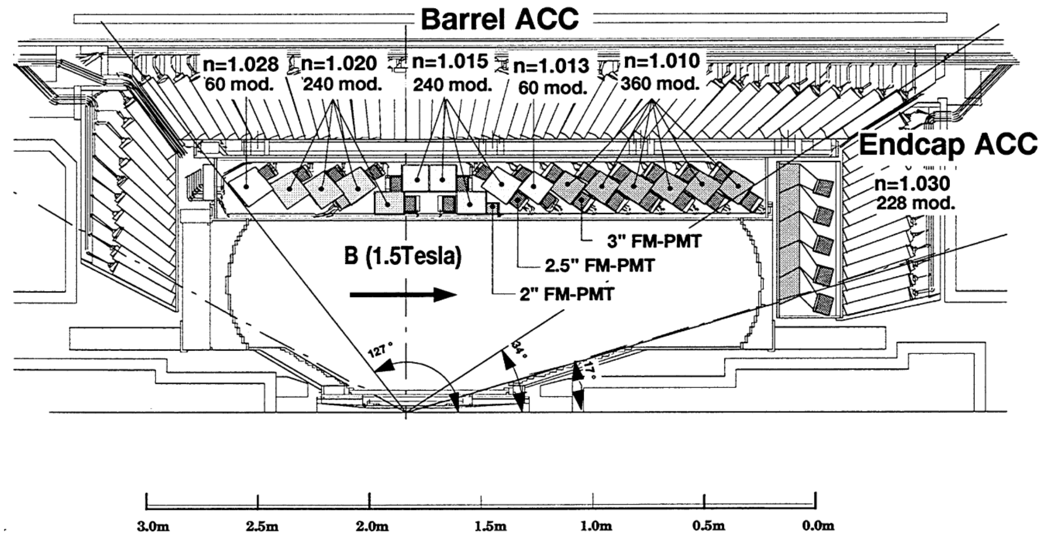


Cherenkov Threshold Detectors

BELLE (KEKB, e+e- collider): CP violation in B mesons
threshold aerogel

1200 independent detector modules
6 different aerogels





Cherenkov Threshold Detectors

BELLE (KEKB, e+e- collider): CP violation in B mesons
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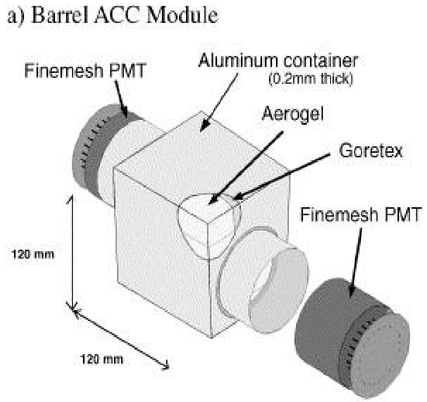
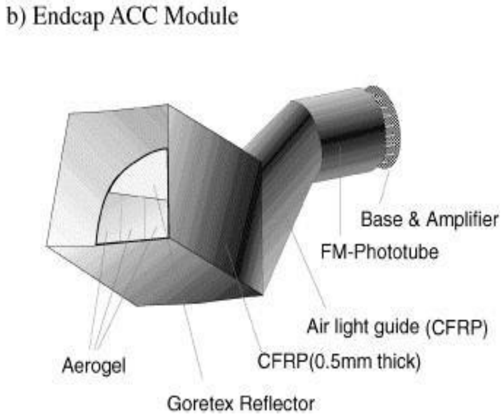
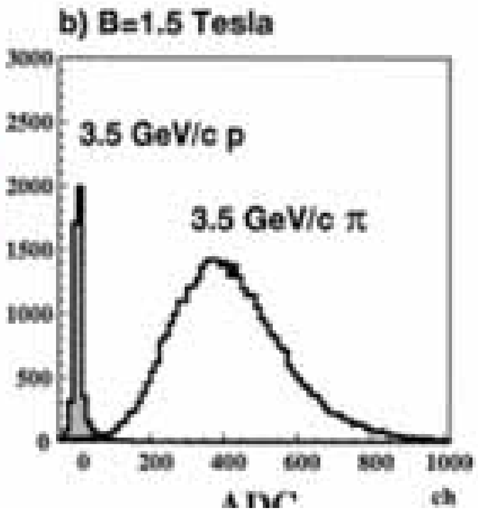




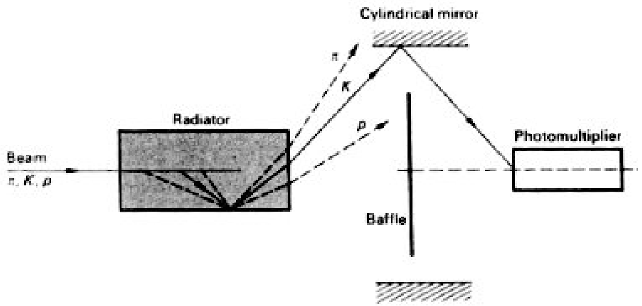


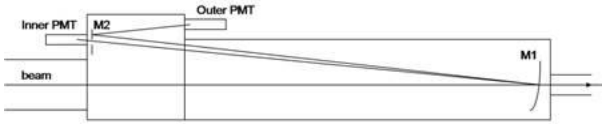
pion → 20 photons / track
π/p separation up to 3.5 GeV/c

Differential Cherenkov Detectors

- Simple: Differential Cherenkov counters → Select particles in a range of b ($1/n < \beta < \beta_{max}$)

Identify particles in the beam lines e.g. Mesons beams ($\pi^{\pm}$, $K^{\pm}$)
Very small acceptance in band direction of the charged particle
(Narrow range in velocity and direction intervals)





Chamberlain and Segre at BNL (1955)
Discovery of anti-proton (Nobel Prize in 1959)

Resolution:

- $\Delta\beta/\beta = (m_1^2 - m_2^2)/2p^2 = \tan\theta \quad \Delta\theta$

m_1, m_2 (particle masses)<< p (momentum)

- $\Delta\beta/\beta$ from 0.011 to $4 * 10^{-6}$ achieved.

RICH (Ring Imaging Cherenkov Detectors)

Widely used in HEP and APP experiment:

First time in DELPHI at LEP (Ypsilantis and Seguinot, 1977)

$$\theta_C = \arccos\left(\frac{1}{n\beta}\right) = \arccos\left(\frac{1}{n}\cdot\frac{E}{p}\right)$$

$$= \arccos\left(\frac{1}{n}\cdot\frac{\sqrt{p^2+m^2}}{p}\right)$$

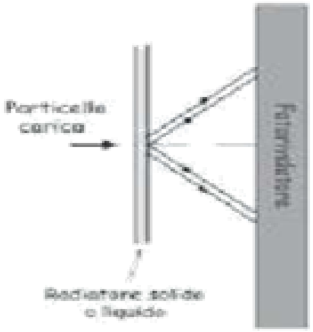
Light emitted in cones around the particle

Cherenkov cones appear as rings in the RICH photodetector surface

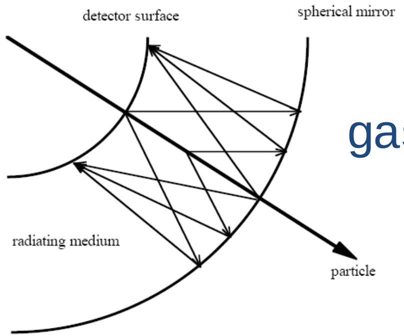
Cherenkov ring radius → θ_c → β

- gas radiator: solid or liquid radiator
- Cherenkov light focalisation systems
- large photodetector wall

separation between 2 species $S \approx \dfrac{|m_1^2 - m_2^2|}{2p^2\sigma_{\theta_c}\sqrt{n^2-1}}$



liquid or solid



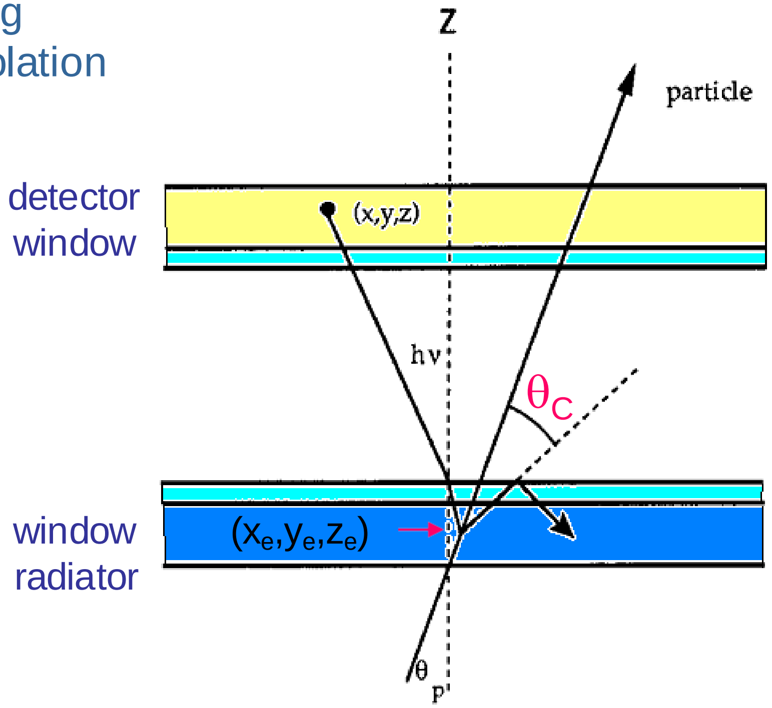
gas

RICH (Ring Imaging Cherenkov Detectors)

The RICH detectors are sandwiched between tracking detectors which provide precise particle track extrapolation

Determination of θ_C requires:

- space point of the detected photon (x,y,z)
  photodetector granularity (σ_x, σ_y), depth of interaction (σ_z)
- emission point (x_e,y_e,z_e)
  keep radiator thin
  or use focusing mirror
- particle direction
  RICH require good tracker



RICH (Ring Imaging Cherenkov Detectors)

Caveat:
Refractive index n varies with photon wavelength

$n = n(\lambda)$

→ change of θ_c

Solution:
limit detectable photon wavelegths
…But this reduces the total photon number (resolution)

RICH (Ring Imaging Cherenkov Detectors)

Radiator Choice

The most crucial parameter is the refractive index

low p: large n to lower threshold and increase separation

high p: $n \approx 1$ preferable (tunable n with aerogels)

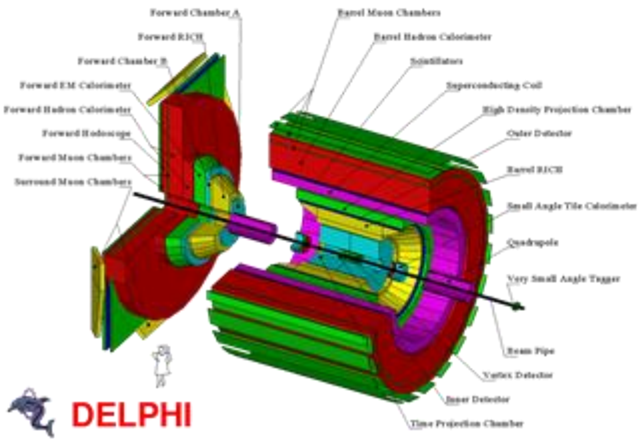
Other optical properties: dispersion and absorption

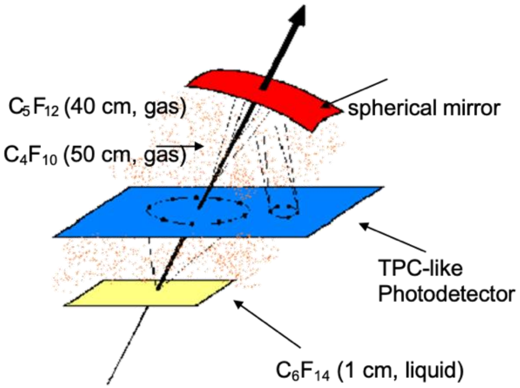
Radiation length

Radiation hardness

RICH (Ring Imaging Cherenkov Detectors)

DELPHI two radiators and a common photodetector plane



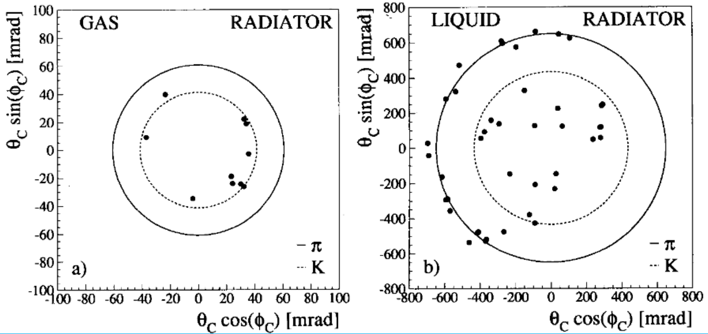


$$\frac{\Delta\beta}{\beta} = \tan(\theta)\Delta\theta_C$$

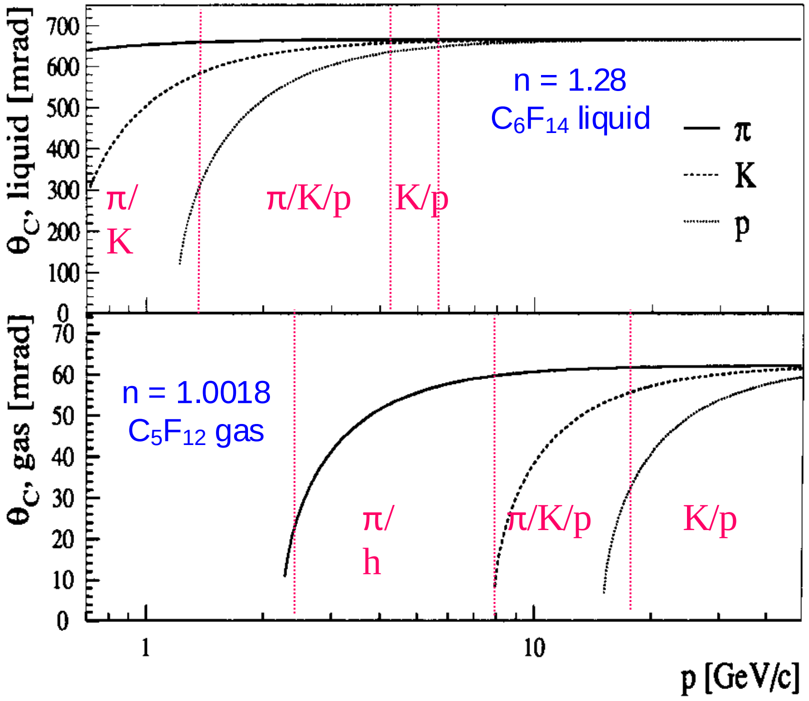
where $\Delta\theta_C = \langle\Delta\theta_C\rangle/\sqrt{N_{ph}} + C$

For 1.4m long CF_4 gas radiator at stp and $N_0 = 75\text{cm}^{-1}$, $\frac{\Delta\beta}{\beta} = 1.6 \cdot 10^{-6}$

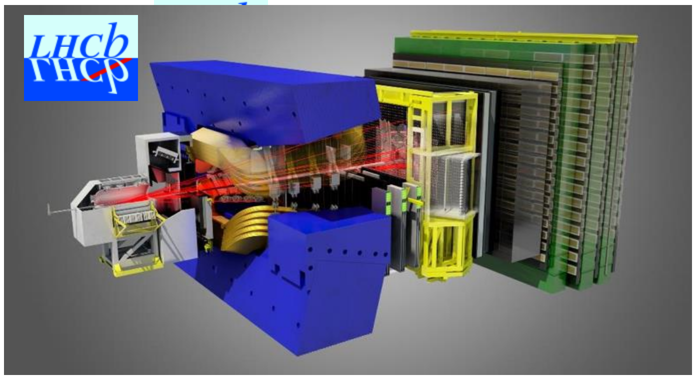
Two particles from a hadronic jet (Z-decay) in the gas and liquid radiator

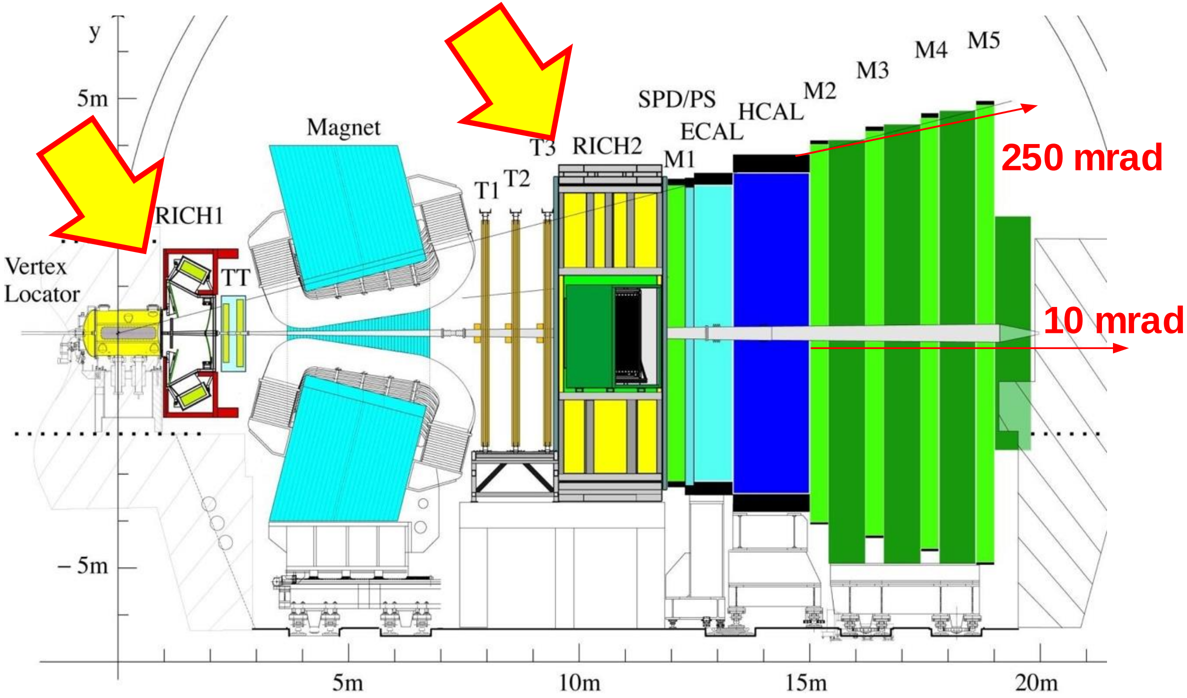


RICH (Ring Imaging Cherenkov Detectors)



RICH (Ring Imaging Cherenkov Detectors)





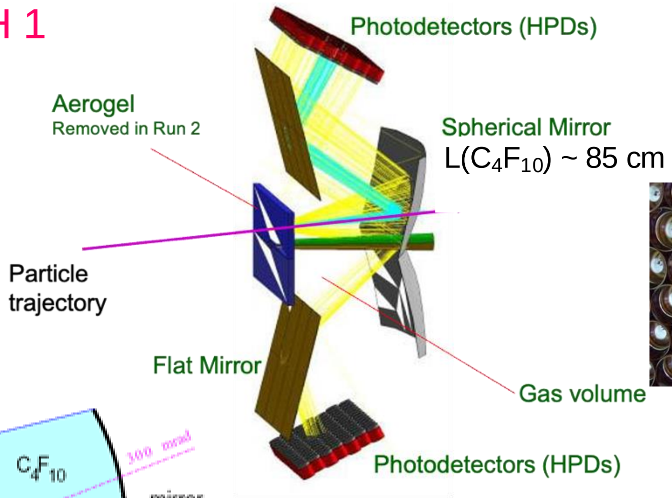
Precision measurement of B-Decays

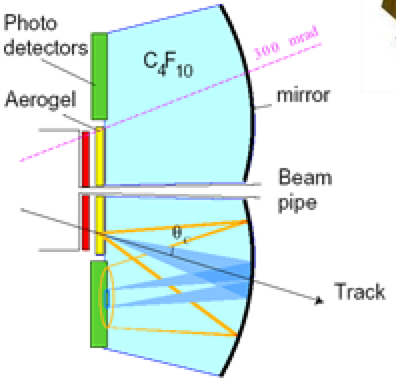
2 < η< 5 Forward spectrometer
Overall acceptance 10:250mrad
Momentum range : 2-100 GeV/c

Two RICH detectors
Rich 1: Aerogel (Till 2014) and C_4F_{10}
Rich 2: CF_4

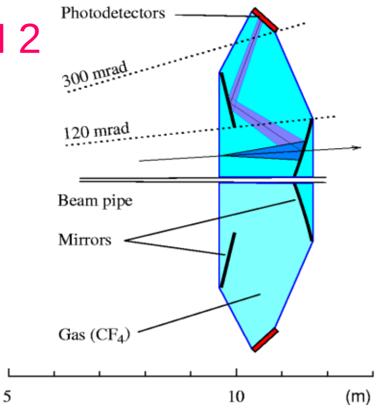
RICH (Ring Imaging Cherenkov Detectors)

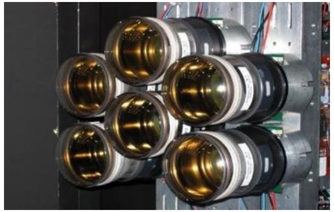
RICH 1

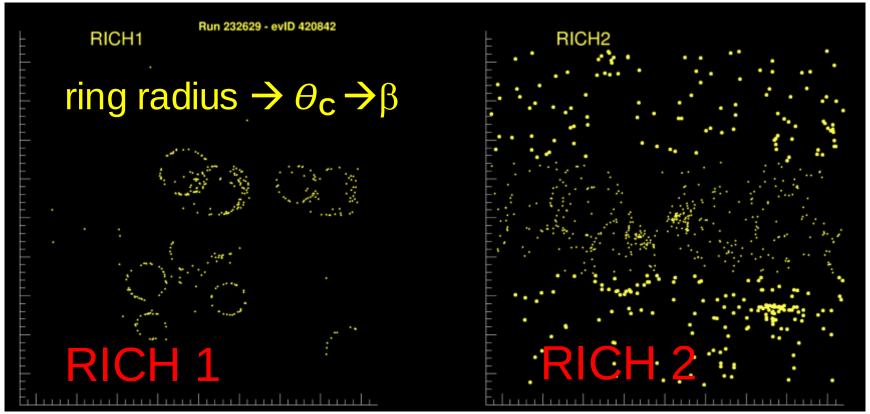




RICH 2

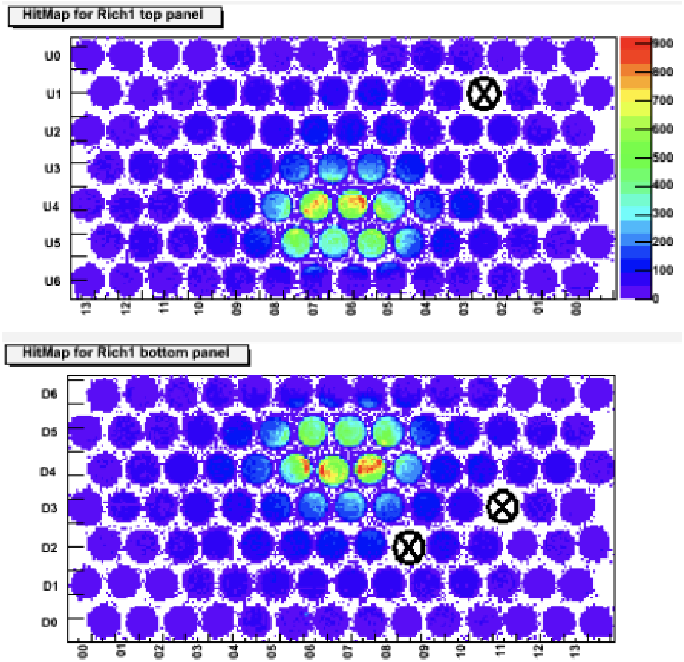






single photon efficiency
large area (>>1 m^2)
granularity! (2 mm^2 pixels)
high rate (1 MHz)

RICH (Ring Imaging Cherenkov Detectors)



n(λ) is dependent on the pressure(P) and temperature (T) of the gas radiator

→ monitor T,P

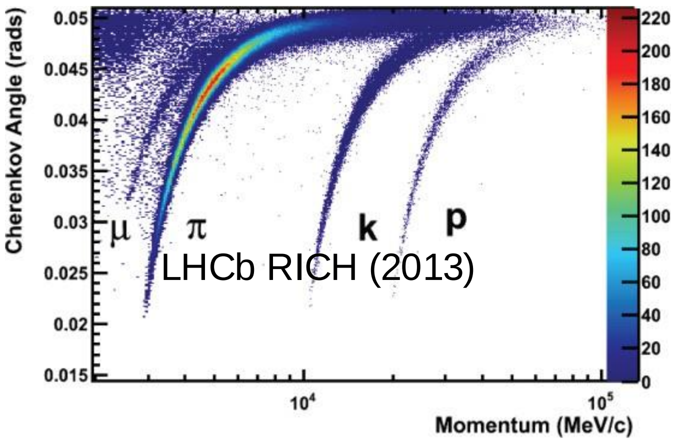
CF_4 scintillates

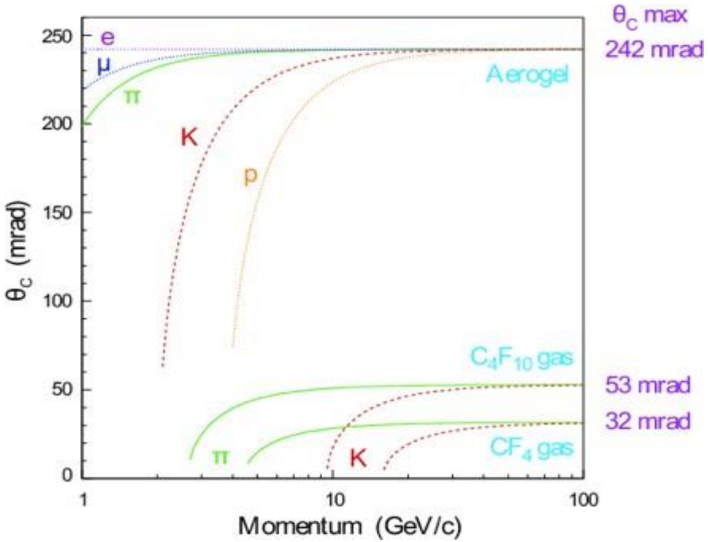
→ mixing gas with CO2 (quenches most of the scintillation photons)

RICH (Ring Imaging Cherenkov Detectors)

independent measurement of momentum (tracker) allows PID

separation between curves→ particle ID





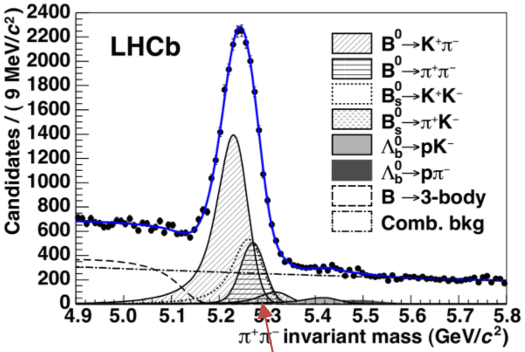
$$\sigma(\theta_C^{\mathrm{ring}}) = \sigma(\theta_C)/\sqrt{N_{pe}}$$

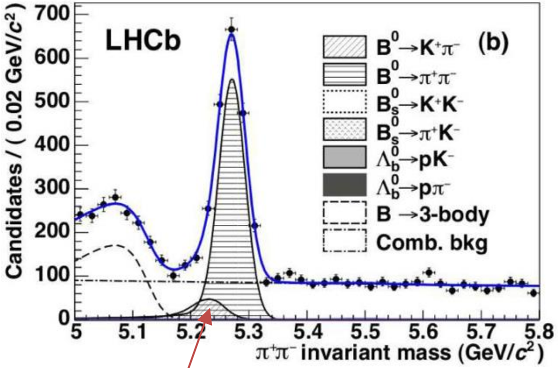
N_{pe}:

- radiator n, length
- mirrors and photodetector wall performances

RICH (Ring Imaging Cherenkov Detectors)

independent measurement of momentum (tracker) allows PID





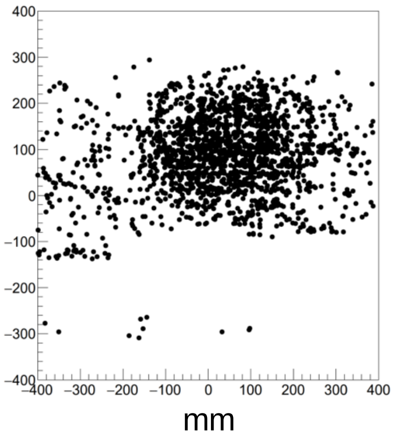
Before RICH PID

After RICH PID

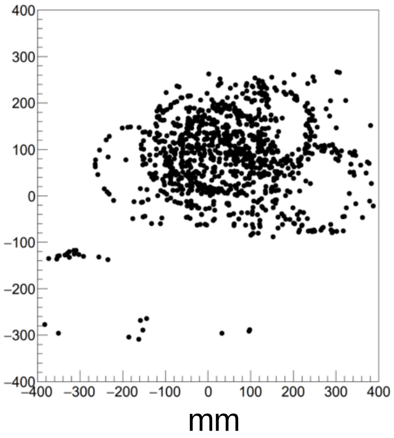
Without RICH PID:
$B_0 \to \pi^+\pi^-$ dominated by $B_0 \to K^+\pi^-$

RICH (Ring Imaging Cherenkov Detectors)

Fast timing (new readout chips and new types of photons detectors)

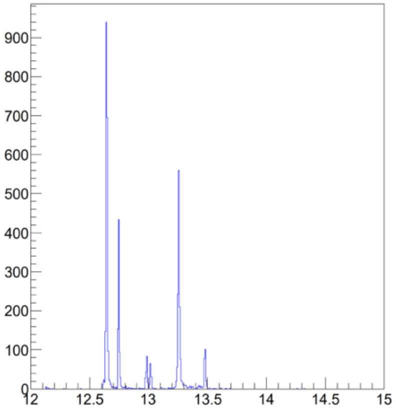


no hit time selection 12-15 ns



hit time12.6 : 12.7 ns

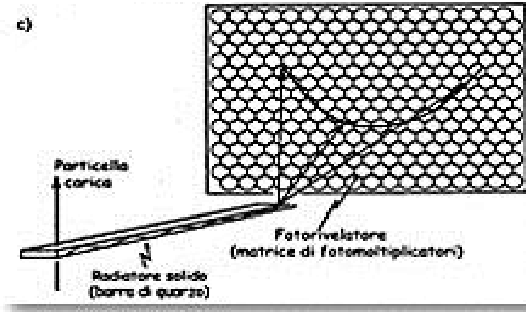
RICH1 hit time

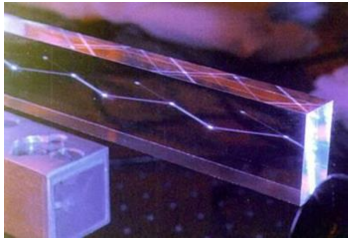


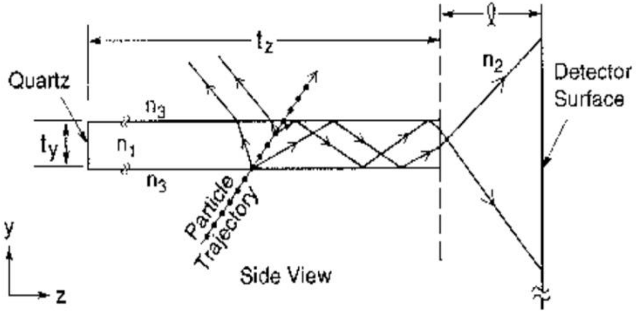
DIRC (Detector of Internally Reflected Cherenkov)

A special RICH: x, y, t of Cherenkov hit →θ_c, φ_c, t_c
Cherenkov ligth produced and trapped (by total reflection) within Cherenkov the radiator (or light guide)

ring radius → θ_c →β







Radiator light guide:

Long, rectangular bars (e.g. Fused Silica n= 1.47, low chromatic dispersion)

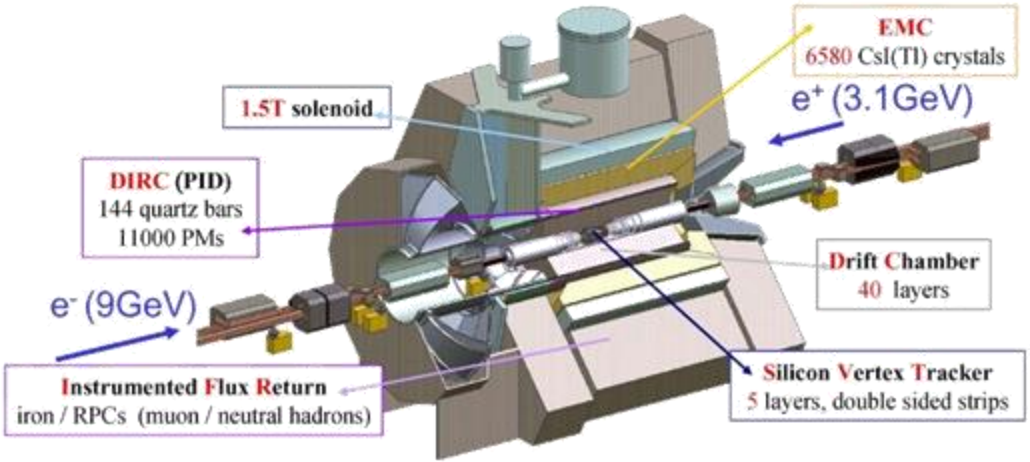
Expansion region:

water (n = 1.33)

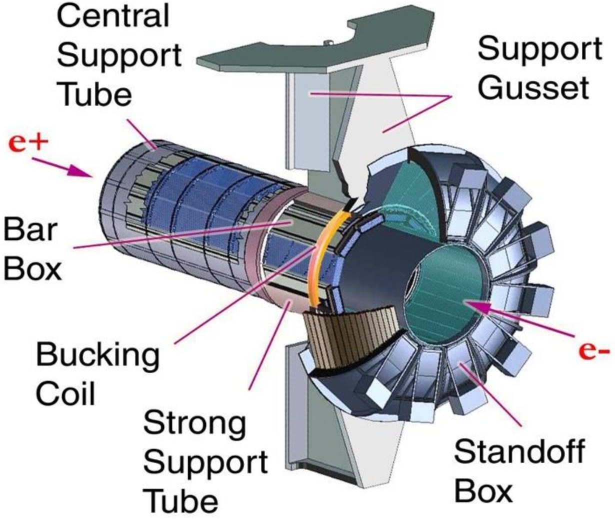
Photosensor wall:

imaging on photosensor wall (e.g. PMT array, D>>PMT diameter)

DIRC of BABAR



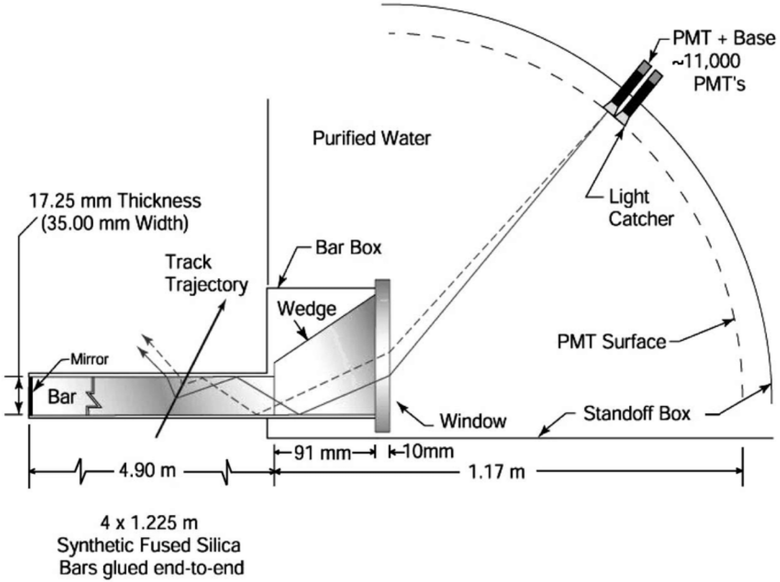
The Cherenkov radiator is a cylinder around the beam collision axis



DIRC of BABAR

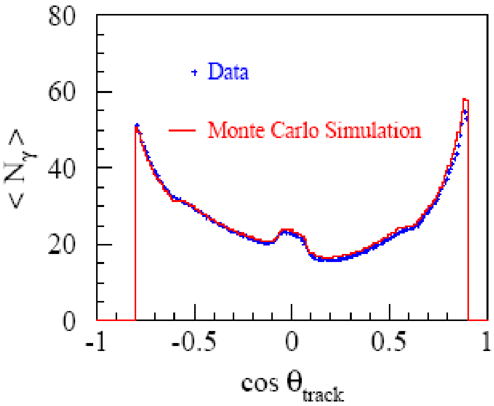
- Bar dimensions (glued out of 4 segments): 488 cm x 3.5 cm x 1.7 cm
- ~11,000 1 inch dia. ETL PMTs, sitting in water to minimize the photon loss.

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

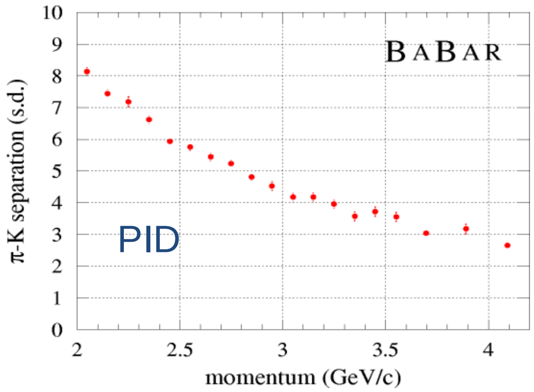


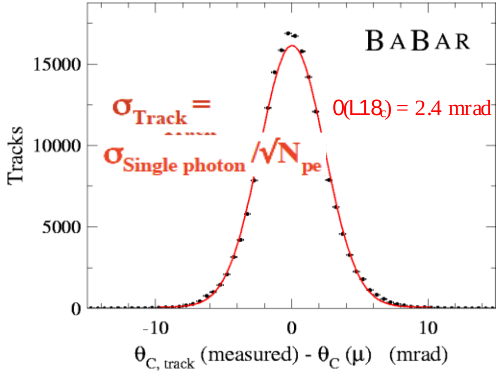
During photon propagation the angle of Cherenkov light is conserved,
except: left/right and up/down ambiguities

DIRC (Detector of Internally Reflected Cherenkov)



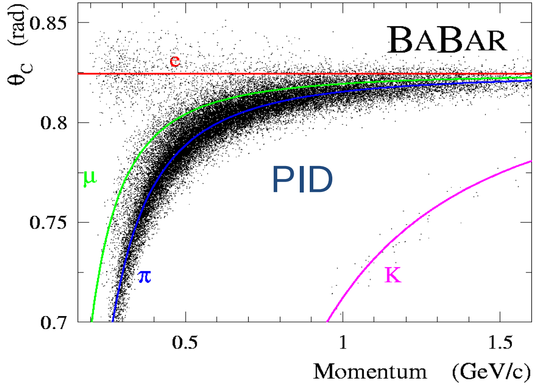
Number of Cherenkov photons
per track (di-muons) *vs*. polar angle:





Resolution of Cherenkov angle fit
per track (di-muons)

Kaon selection efficiency
typically above 95% with mis-ID of 2-10%
between 0.8-3GeV/c



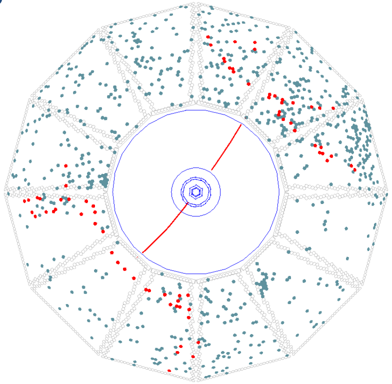
DIRC (Detector of Internally Reflected Cherenkov)

DIRC “ring” images

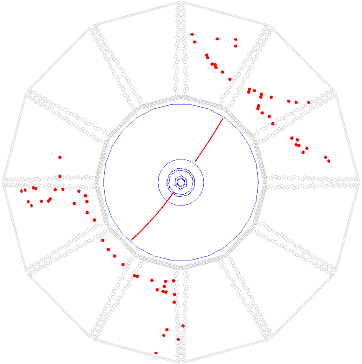
- Ambiguities per PMT hit
- Cherenkov ring images are distorted
- Complex, disjoint images

→ use timing

All PMTs ±300 ns wrt trigger



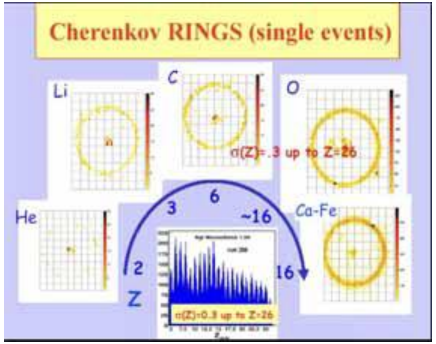
All PMTs ±8 ns wrt trigger



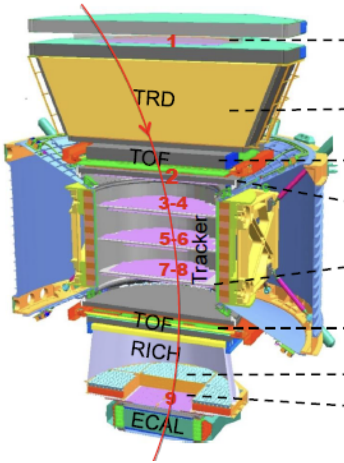
Cherenkov detectors for Astroparticle physics

Particle identification: Charge measurement of primary cosmic rays

Cherenkov imaging (RICH) and charge measurement



AMS: Multiple Independent Measurements of the Charge (|Z|)



	Carbon (Z=6) ΔZ (cu)
1. Tracker Plane 1	0.30
2. TRD	0.33
3. Upper TOF (1 counter)	0.16
4. Tracker Planes 2-8	0.12
5. Lower TOF (1 counter)	0.16
6. RICH	0.32
7. Tracker Plane 9	0.30

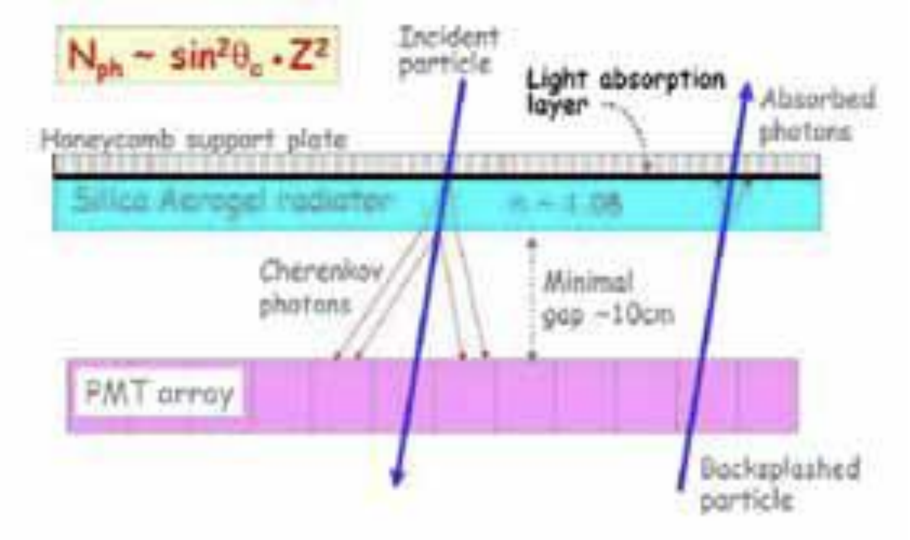
AMS-1 Aerogel (threshold)

AMS-2 Ring Imaging Cherenkov

Cherenkov detectors for Astroparticle physics

Particle identification: Charge measurement of primary cosmic rays

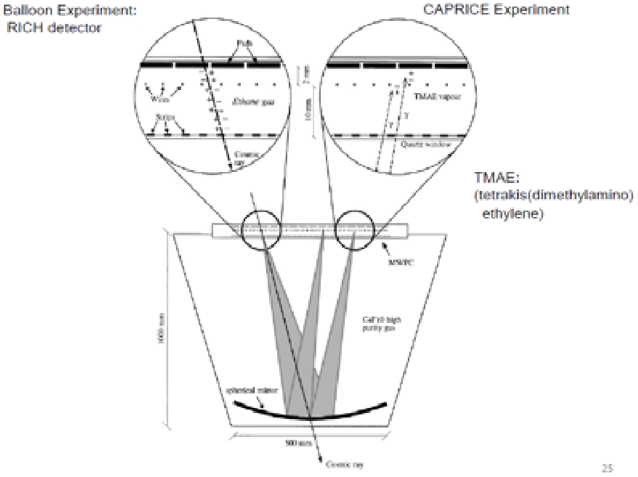
Cherenkov imaging (RICH) and charge measurement



Cherenkov detectors in High Atmosphere

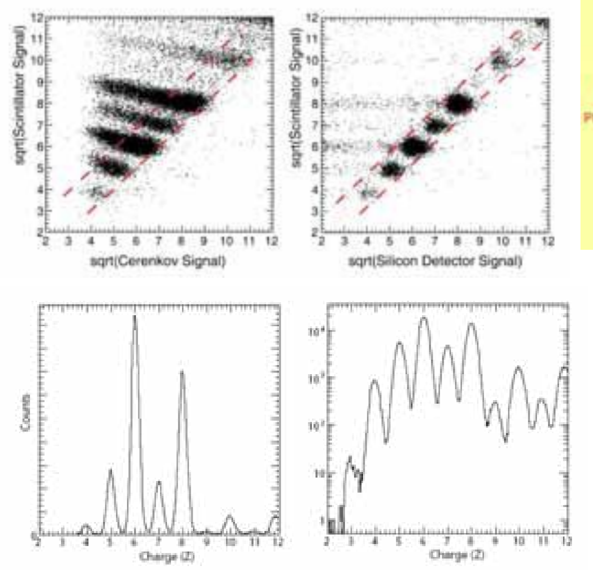
Long Duration Balloons

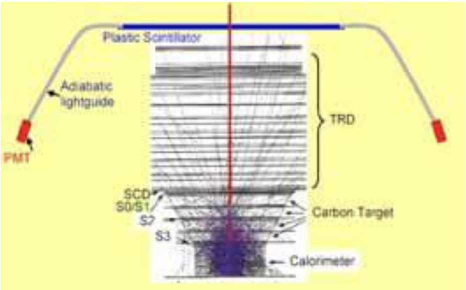
CAPRICE



CREAM Cosmic Ray Energetics and Mass
CR composition and spectrum (TeV: ~500 TeV)

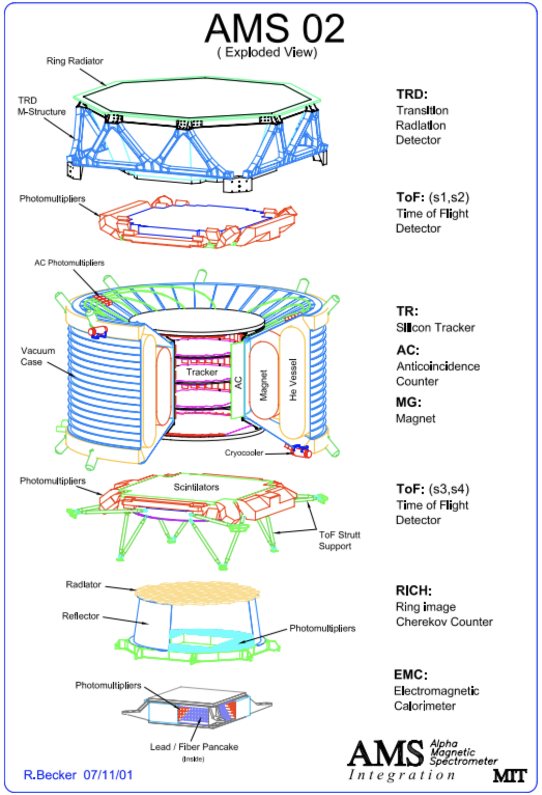
- Acceptance : 2,2 m^2 sr
- Energy measurement: Calorimeter, TRD
- PID: TRD, Cherenkov CAM





CHERCAM measured time of through going particles (Calorimeter VETO)
achieved precise charge measurement (± 0,3 e)

RICH in space



The AMS RICH uses two radiators

Silica aerogel (n=1.050)

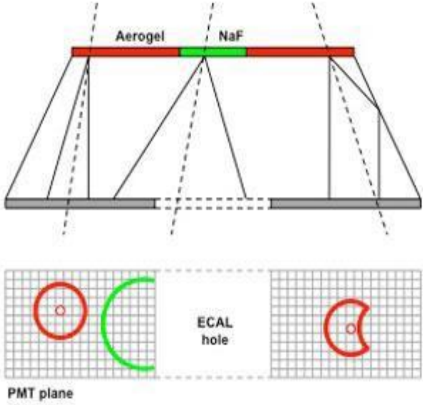
NaF(n=1.334)

A large conical mirror directs the light onto a plane of 680 PMT’s

The RICH achieves

$\Delta\beta/\beta \sim 10^{-3}/Z$

charge ID for Z up to 26 (Fe) [The number of photons goes as Z^2]

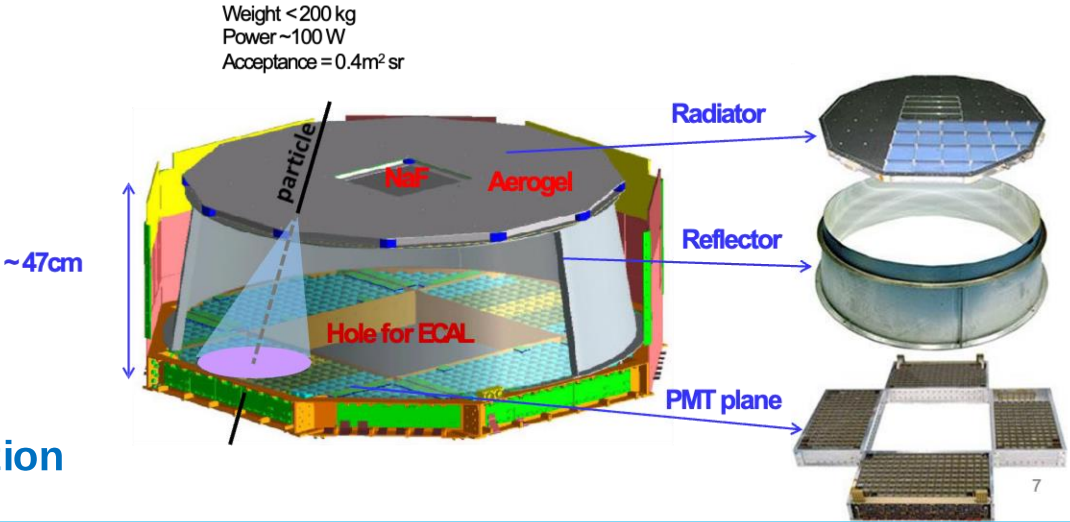


RICH in space

NaF:
16 tiles of sodium fluoride, each 85 x 85 x 5 mm^3 ring ≈85cm for β=1
refractive index n = 1.33, p>4.2GeV/c (^4He), Kn > 0.5 GeV/n

Aerogel:
92 tiles of silica aerogel, each 113 x 113 x 25 mm^3 ring ≈31cm for β=1
refractive index n = 1.05, p>11.7GeV/c (^4He), Kn >2.1 GeV/n

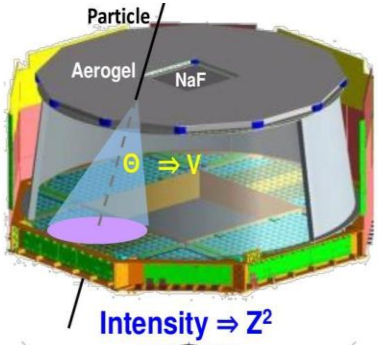
Detection plane:
The RICH detection Plane is made of 680 multianode pmts (10880 pixels)
Detection granularity: 8.5 x 8.5 mm^2

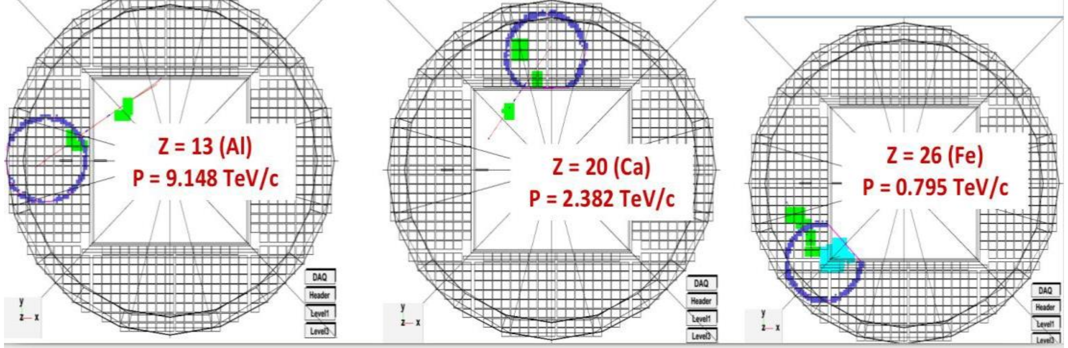


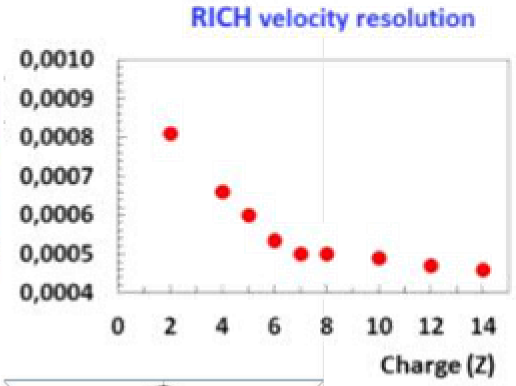
One ring per event reconstructed
tracker provide the entry point and direction

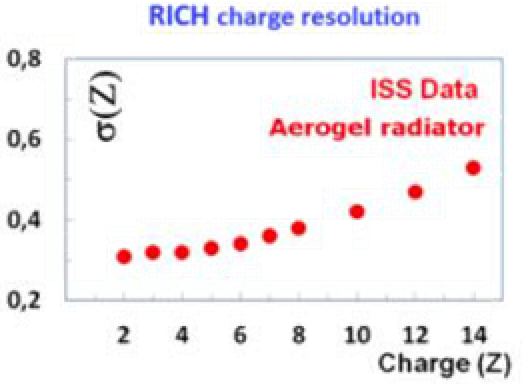
RICH in space

Measurement of Charge (Z^2) and Velocity









Backup

Theory

Cherenkov energy loss

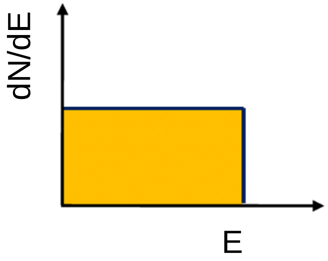
Frank-Tamm

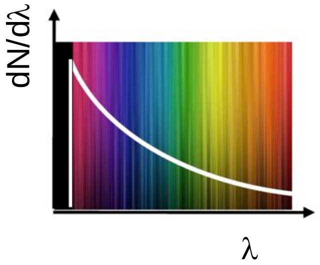
about 10^{-3} (weaker) wrt Bethe-Block energy loss

$$\frac{d^2 N_\gamma}{dE_\gamma dx} = z^2 \frac{\alpha}{\hbar c} \sin^2 \vartheta_C = const.$$

$$\frac{d^2 N}{d\lambda dx} = \frac{2\pi z^2 \alpha}{\lambda^2}\left(1 - \frac{1}{\beta^2 n^2(\lambda)}\right)$$

$$\frac{dN}{dx} = 2\pi z^2 \alpha \left(1 - \frac{1}{\beta^2 n^2(\lambda)}\right)\int_{\lambda_1}^{\lambda_2} \frac{d\lambda}{\lambda^2} = 2\pi z^2 \alpha \sin^2 \theta_C \left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2}\right)$$

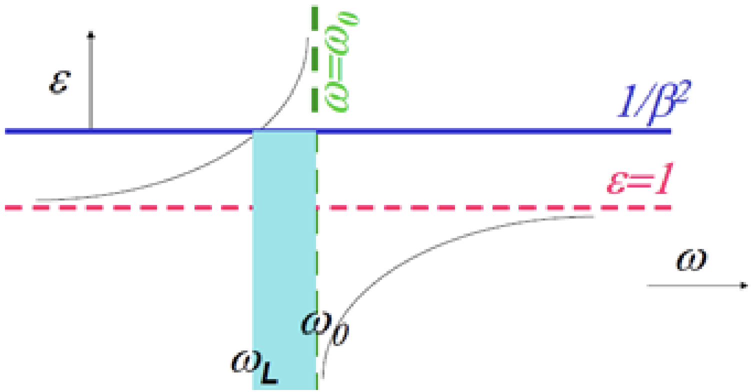


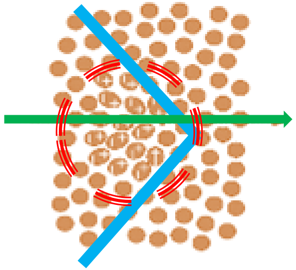


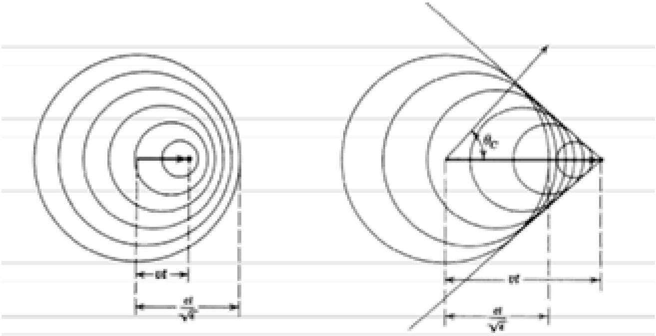
Theory

Passage of a charged particle (not accelerated) induces polarisation of the dielectric medium
Oscillation of dipole field causes radiation emission (coherent with Maxwell e.m. theory)

$$\epsilon(\omega) = 1 + \frac{\omega_p^2}{\omega_0^2 - \omega^2 - i\omega\Gamma}$$







Cherenkov Detectors

Example: pion-kaon separation
particle momentum selector p < 2GeV/c

$$\beta = \frac{p}{E} = \frac{\sqrt{E^2 - m^2}}{E} = \sqrt{1 - m^2/E^2}$$

β_π<0.997 (m_π = 139.5 MeV)
β_K<0.971 (m_k = 439.7 MeV)

$n(\lambda)$=1.05 → only pions emit Cherenkov light

Detection thresholds in water (n=1.33)

$e^\pm$ →0.768 MeV
$\mu^\pm$ →158.7 MeV
$p^\pm$ →209.7 MeV

RICH (Ring Imaging Cherenkov Detectors)

RICH detectors

Resolution:

- $\Delta\beta/\beta$ = tan(θ) * $\Delta\theta_c$ = K where $\Delta\theta_c = \langle\Delta\theta\rangle / \sqrt{N_{ph}} + C$

  where $\langle\Delta\theta\rangle$ is the mean resolution per single photon in a ring and C is the error contribution from the tracking , alignment etc.

- For example , for 1.4 m long CF_4 gas radiator at STP and a detector with N_0 = 75 cm^{-1} K = 1.6 * 10^{-6} .

- This is better than similar threshold counters by a factor 125.
  This is also better than similar differential counters by a factor 2.
  Reason: RICH measures both θ and N_{ph} directly.
- RICH detectors have better resolution than equivalent differential and threshold counters.

- Let u= $\sin^2(\theta)$ = 1- $(1/n^2)$ - $(m/p*n)^2$ for a particle with mass m and momentum p

  Number of standard deviations to discriminate between particles with masses, m_1 an m_2 = N_σ = $(u_2-u_1) / (\sigma_u * \sqrt{N_{ph}})$ where σ_u : $\Delta\theta$ converted into the parameter u.
  ($\Delta\theta$ = error in single photon θ measurement)

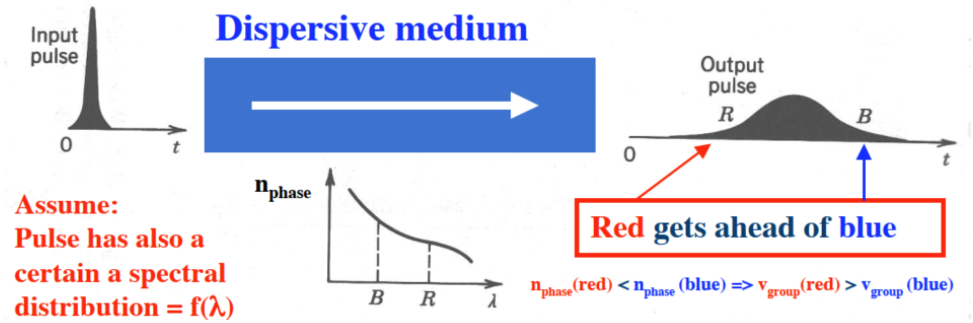
- At momentum p (=β E), N_σ= sqrt((m_2^2-m_1^2)/(2 * K * p)) , for β ~1

  This equation gives a general idea regarding number of σ separation achievable, during in the design of the RICH detectors. However it has limitations in giving a good prediction, in multi particle events with high occupancy.
  In practice, detailed simulations are carried out for detector design.
- One of the first large size RICH detector: in DELPHI at LEP.

26

Cherenkov Detectors

- Photon production depends on the phase velocity (v_{phase}) of photons
- Photon propagation depends on the group velocity (v_{group}) of photons



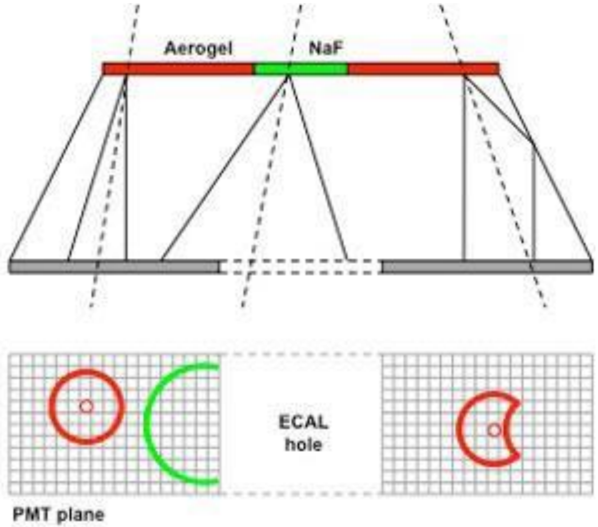
$$v_{group} = c / n_{group} = c / [n_{phase} - \lambda * dn_{phase}/d\lambda]$$

$$t \equiv TOP = L_{path} / v_{group} = L_{path} [n_{phase} - \lambda * dn_{phase}/d\lambda] / c \quad = \text{time-of-propagation}$$

$$dt = L \lambda \, d\lambda / c * (- d^2 n_{phase}/d\lambda^2)$$

Calibrate dt (variation TOP) with dθ (variation in Cherenkov angle) for the photons.
Measure the time of arrival at the photon detectors and correct for dθ
This assumes association between tracks and photons. (*Covered later in the lecture*) 17

RICH in space



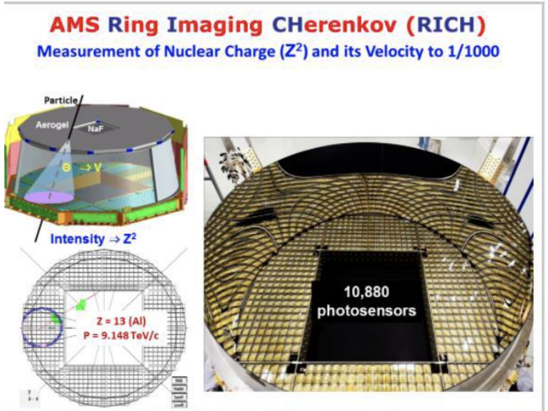


Figure 1. The RICH detector and an event display with $Z = 13$ and $P = 9.148$ TeV/c.

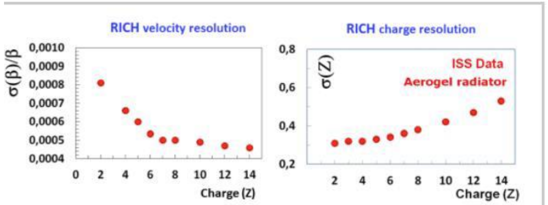
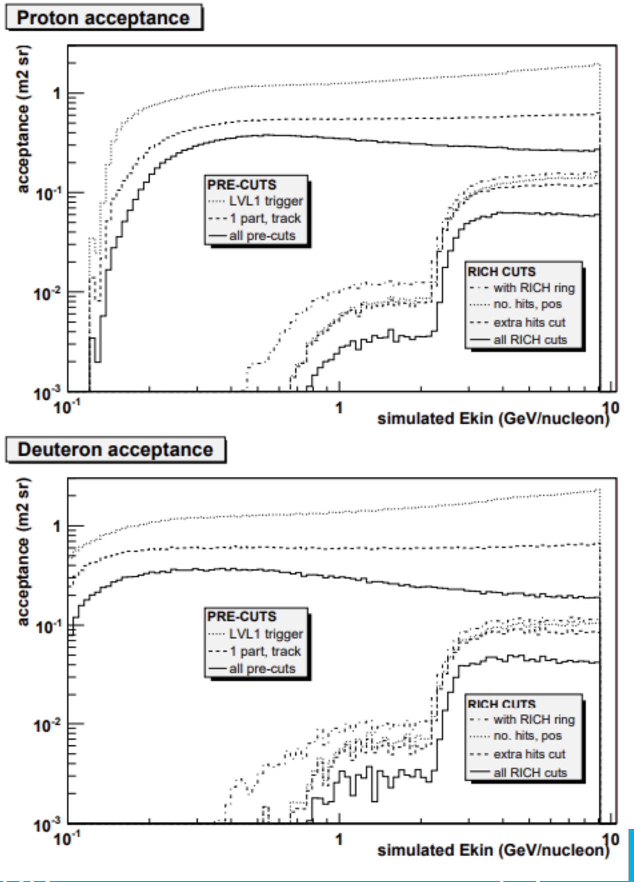


Figure 2. The RICH velocity and charge resolution vs charge Z.



RICH in space

AMS RICH detector measures beta with high precision, combined with AMS Tracker rigidity measurement, AMS can identify particles depend on mass.

isotopic composition of CRs antiproton/proton ratio of

CRs

By the combined use of ToF, RICH, and Silicon Tracker, AMS is able to measure isotopic composition of cosmic rays in the kinetic energy range from few GeV/n to ~10 GeV/n for elements with charge |Z| up to 4 with unprecedented statistics.

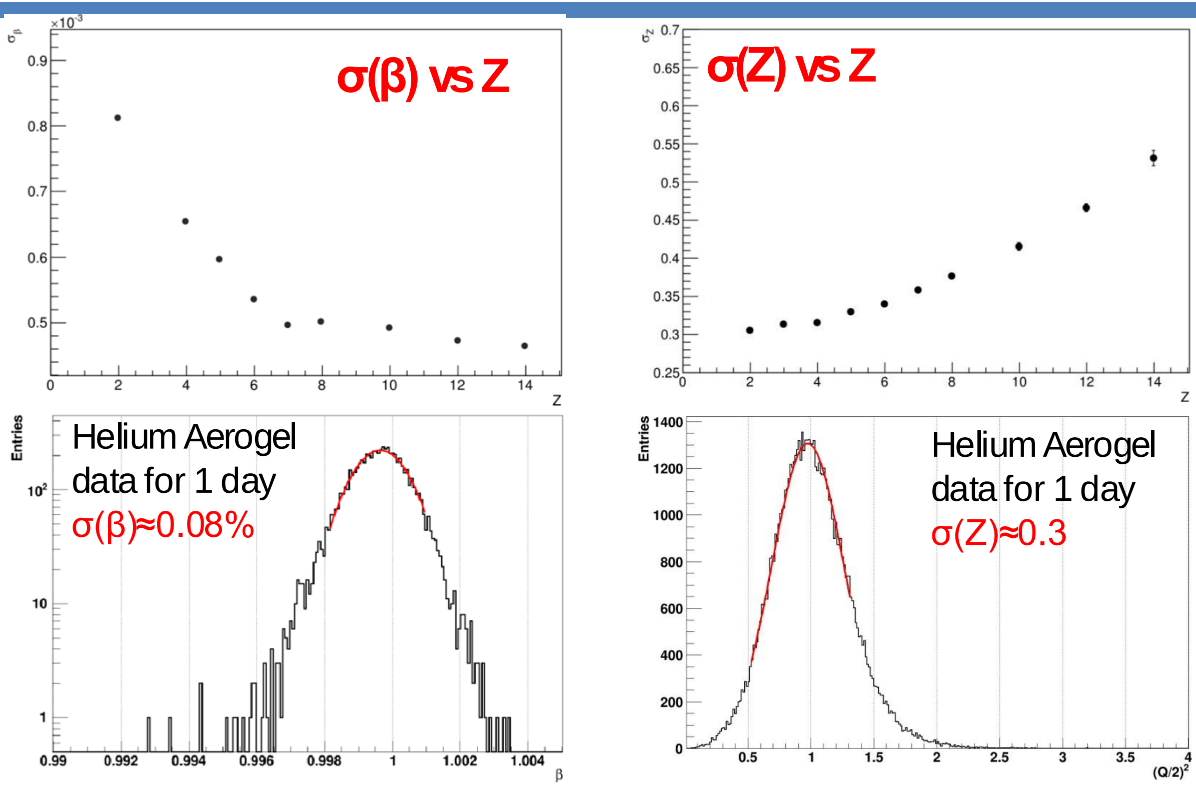
$$\frac{A}{Z} = \frac{R}{\gamma\beta}$$

$$\left(\frac{\Delta R}{R} \geq 10\%\right)$$

$$\left(\frac{\Delta A}{A}\right)^2 = \left(\frac{\Delta R}{R}\right)^2 + \gamma^4 \left(\frac{\Delta\beta}{\beta}\right)^2$$

$$\left(\frac{\Delta\beta}{\beta} \sim 0.1\% \ for\ aerogel\right)$$

RICH Performance on ISS (Aerogel)



After 5 years of data taking > 95% of the channels are working properly