Technology issues in Čerenkov light images

or

Technologies implications for RICH performance

Clara Matteuzzi
INFN and Universita' di Milano-Bicocca

Istituto Nazionale di Fisica Nucleare

Content of the talk

Relates implications on technologies choices $\sigma(\theta_C)$ to the physics goals

Considering:

- Kind of physics measurements
- Momentum range to be covered
- Machine environments

  Particle density in the final state, operation frequency ,…..

↓

geometry and technologies choices to achieve a given angular resolution

↳ keep all the contributions to the resolution under control during the whole lifetime of the experiment

Many applications of RICH detectors

Hadronic environment
- ALICE
- LHCb
- PANDA
- NA62
- COMPASS

e+e- environment
- BaBar, BELLE
- BELLE upgrade (SUPER-B)

Space experiments (on satellite and baloon)
- AMS (measures flux of charged particles and light nuclei)
- CREAM

Underground
- ANTARES, NESTOR, NEMO , KM3net, AMANDA,ICECUBE

Nuclear physics
- ALICE
- JLAB

Astrophysics
- A long list...

To measure the Čerenkov angle θ_C

Main contributions to angular resolution $\sigma(\theta_C)$ from :

Chromaticity N_γ multiplicity	**Radiator** (n (λ), thickness, transparency…)
$N_{p.e.}$ molteplicity Spatial localization	**Photon detection** (QE, photon collection efficiency,pixel size,…)
Emission point Photon path	**Geometry** (Proximity focus, focussed geometry,…)
Tracking Multiple scattering Decays,interactions,..	**"External" error**

Čerenkov detectors performance

The angular resolution per photon:

$$\sigma(\theta_c) = \sqrt{\sigma(\theta_{rad})^2 + \sigma(\theta_{PD})^2 + \sigma(\theta_{geom})^2 + \sigma(\theta_{tr})^2}$$

$$\sigma_{ring}(\theta_C) = \frac{\sigma(\theta_C)}{\sqrt{N_{pe}}}$$

And the separating power:

$$N_\sigma \approx \frac{(m_1^2 - m_2^2)}{(2 p^2 \sqrt{n^2 - 1}\, \sigma(\theta_c))}$$

The number of photo-electrons N_{pe}:

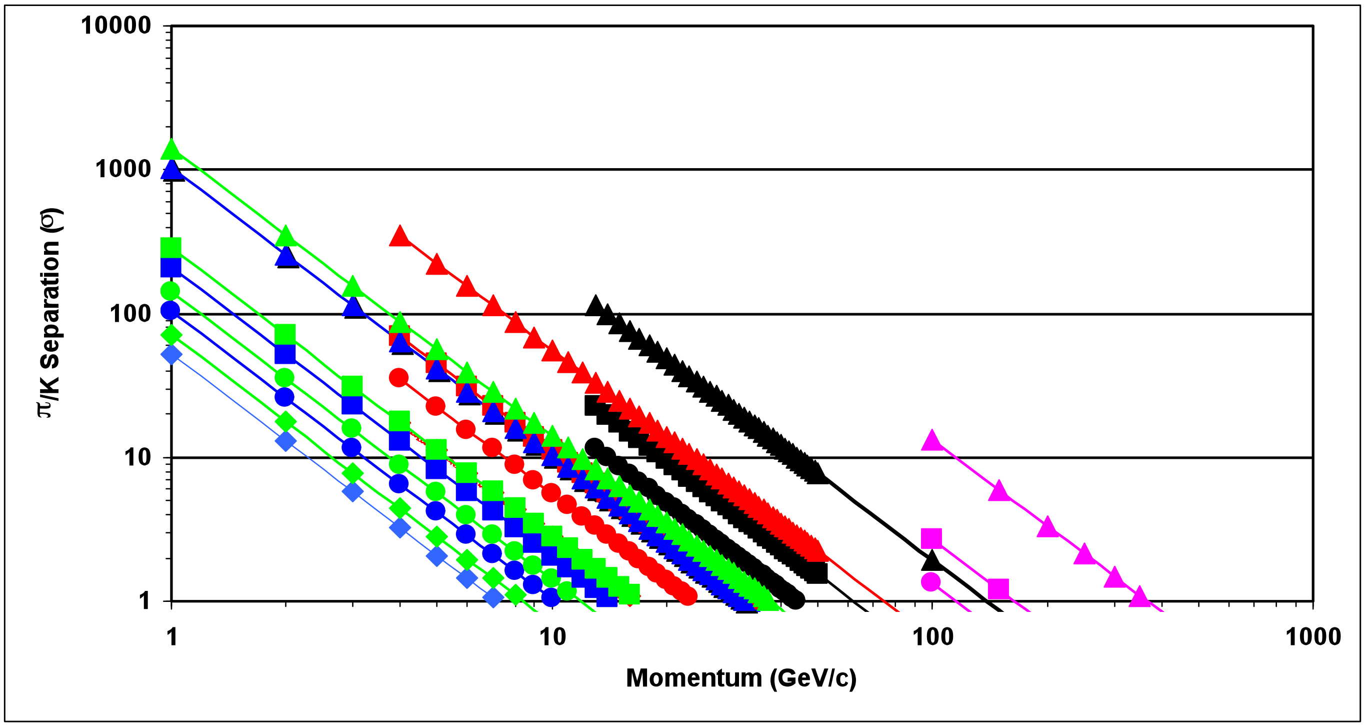
$$N_{pe} = 370 L \int \varepsilon \sin^2\theta_c dE = L N_0 \sin^2\theta_c$$

Usually N_o between ~ 20 and 100

General rule: **minimize** $\sigma(\theta_c)$
maximize N_{pe}

Čerenkov angle resolution and separating power

π/K separation



(Plot from B.Ratcliff)

Refractive Indices

N=1.474 (Fused Silica)

N=1.27 (C_6F_{14} CRID)

N=1.02 (Typical Silica Aerogel)

N=1.001665 (C_5F_{12}/N_2 CRID Mix)

N=1.0000349 (He)

$\sigma(\theta_c)$

◆ 2 mrad

● 1 mrad

■ 0.5 mrad

▲ 0.1 mrad

RICH detectors by angular resolution

$\sigma(\theta_C) \approx$ O(10 mrad)

Ex: ALICE, BELLE, BELLE upgrade,JLAB, CLEO-C,
BaBar and HERMES (closed)

differ by machine environment machine, particle density,
BUT momentum range similar

(….in between the AMS experiment)

$\sigma(\theta_C) \approx$ O(1 mrad)

Ex.: COMPASS, LHCb, NA62

RICHes in experiments at hadron accelerators

Example of RICH detectors with $\sigma(\theta_c) \approx O(10\ \mathrm{mrad})$

ALICE started to operate **at LHC**

The RICHes detectors of HERMES, BaBar DIRC, BELLE, CLEO-c have operated succesfully with this range of resolution.

Examples of RICH detectors with $\sigma(\theta_c) \approx O(1\ \mathrm{mrad})$

LHCb started to operate **at LHC**

NA62 starting to operate in 2012 **at SPS**

The RICH of ALICE

See detailed talks by P. Martinengo at this conference

Physics aims:

mainly proton ID in the range O(few GeV), d and α also interesting
physics measurement: inclusive hadron spectra from Pb-Pb collisions
measurement of particle ratios vs pT
For particle ID over the momentum range also dE/dx, TOF, TRD are used
The RICH must cover the range 1-5 GeV/c (1-3 GeV/c for π/k and 2-5 Gev/c for p)

Environment:

Pb-Pb collisions

Density of charged particles about 2000/ rapidity unit

Low rate (< 10KHz)

Geometry:

limited 'radial' space → compact detector → proximity focus

The RICH of ALICE : the HMPID choice

Proximity focused

Radiator: 15 mm C_6F_{14} (liquid) with n=1.2989 @ 175 nm
θ_C = 694 mrad

Photon converter: Reflective layer of CsI (QE= 25% @ 175 nm)

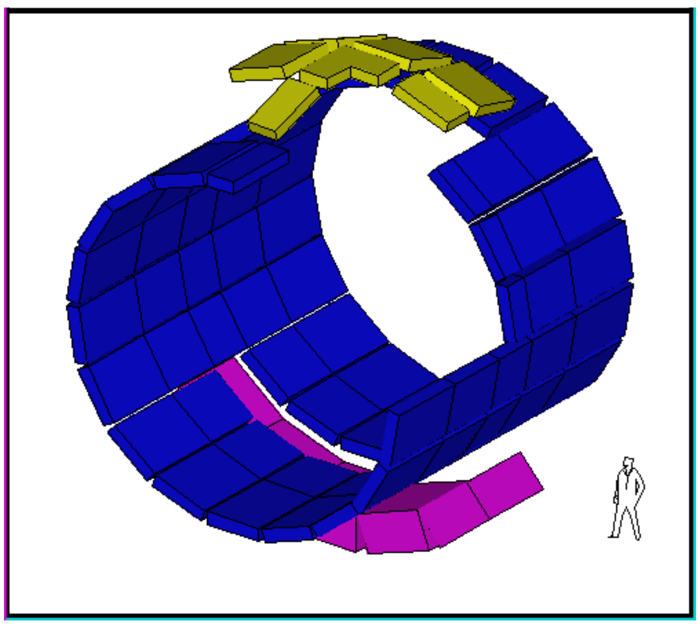
Photodetectors:
MWPC with CH4 at atmospheric pressure (4 mm sensitive gap)
analogue pad readout

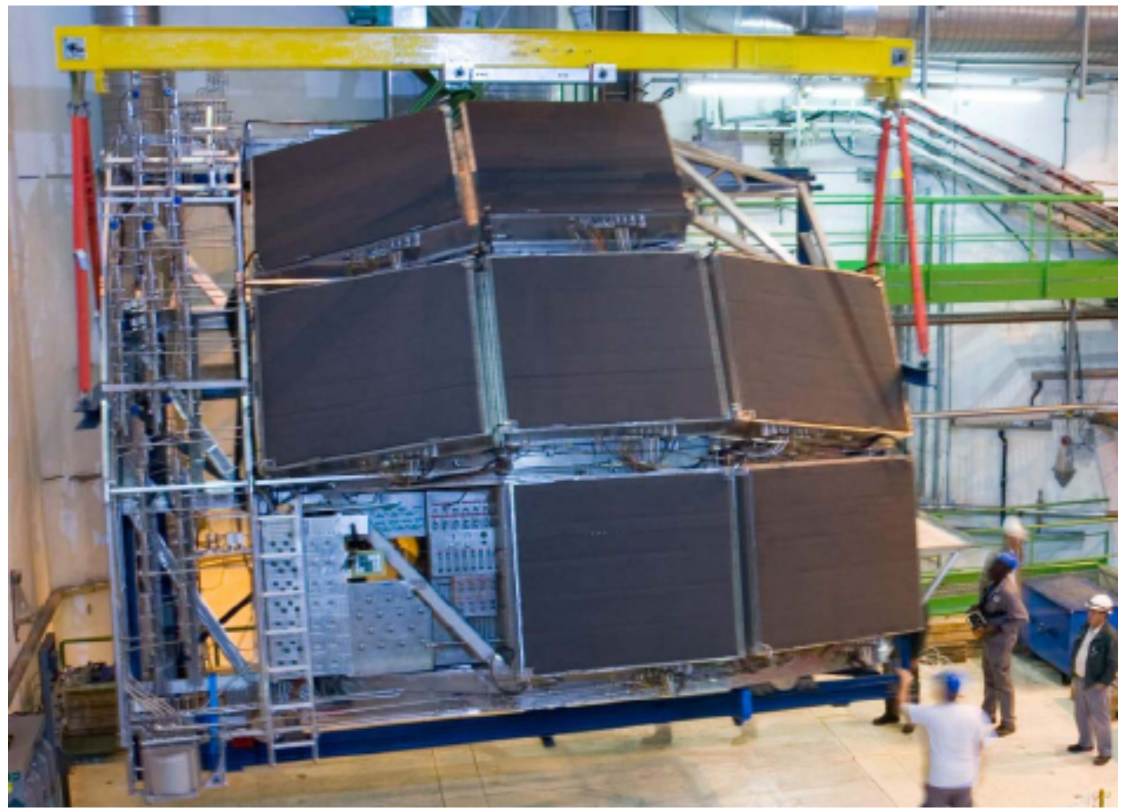
VHMPID: upgrade planned to extend PID to 30 GeV/c.
C_5F_{12} gas radiator (1m) mirror-focused RICH
CsI photocathode + GEM photon detector
(talks by A. DiMauro at this conference)

The RICH of ALICE

The HMPID RICH identifies hadrons π/K/p in the range 1/3/5 GeV/c

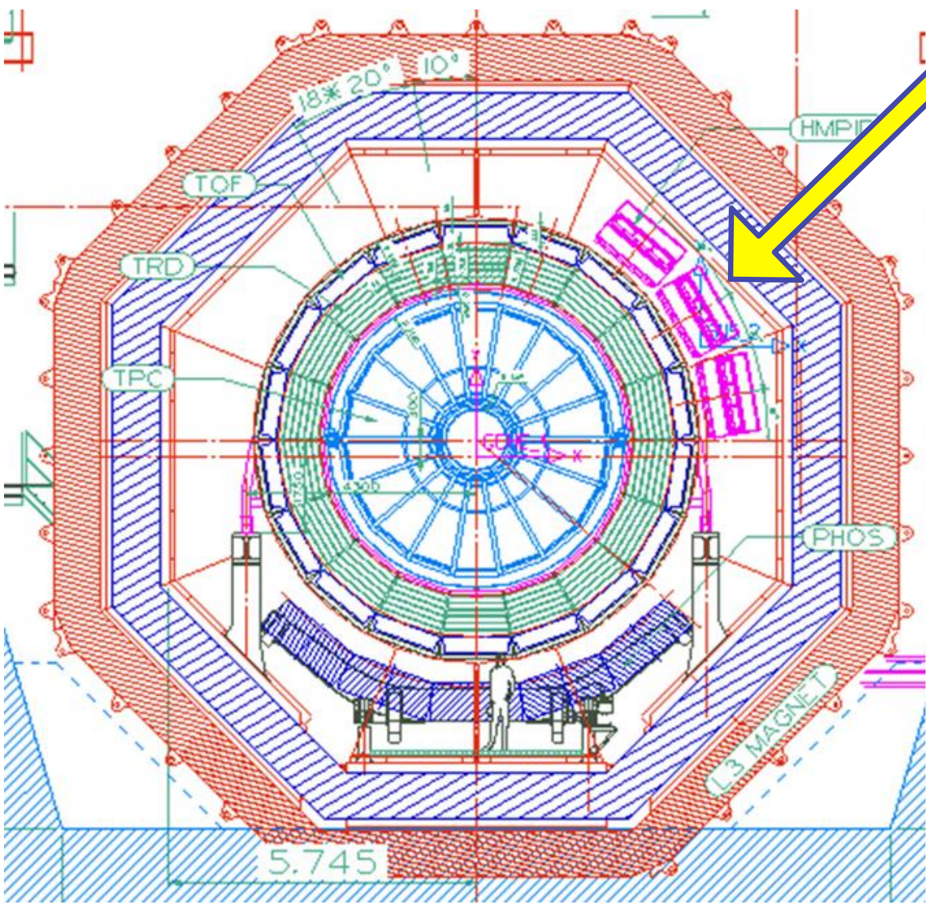
7 modules of 1.5m x 1.5m (5% of barrel)

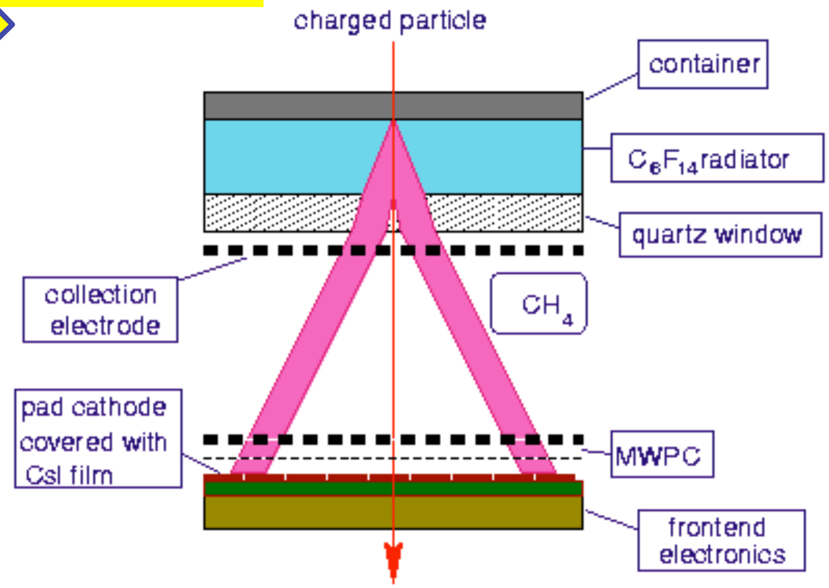


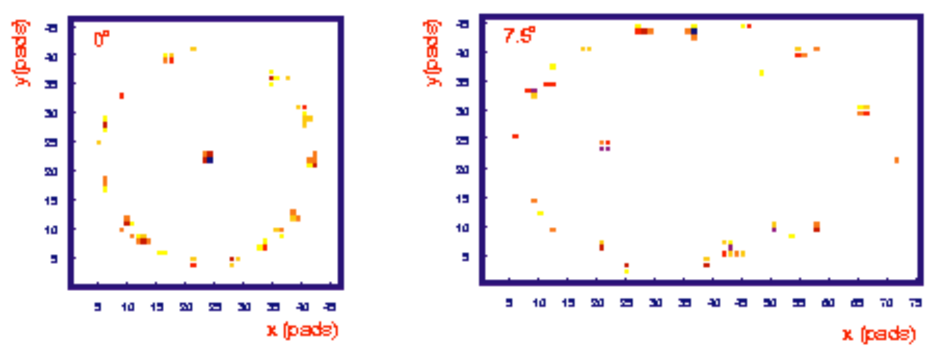


The RICH of ALICE

7 RICH modules
5 m from the collision







The RICH of ALICE : the resolution

Contributions to the angular resolution (per single photon and $\beta=1$, θ_C = 694 mrad):

1. **Chromaticity** determined by the basic property of dispersion of radiator, convoluted with the media on the UV path and the QE of CsI

   → ~ 10 mrad

2. **Spatial error** : determined by the granularity of the photodetector

   → ~ 5 mrad

3. **Geometry:** determined by the legth of the radiator and the proximity gap thickness

   → ~ 4 mrad

4. **Track error:** negligible but requires investigation

Dominant contribution to sigma: chromaticity of the radiator.

$\mathbf{N_{p.e.} \approx 18}$ for $\beta=1$

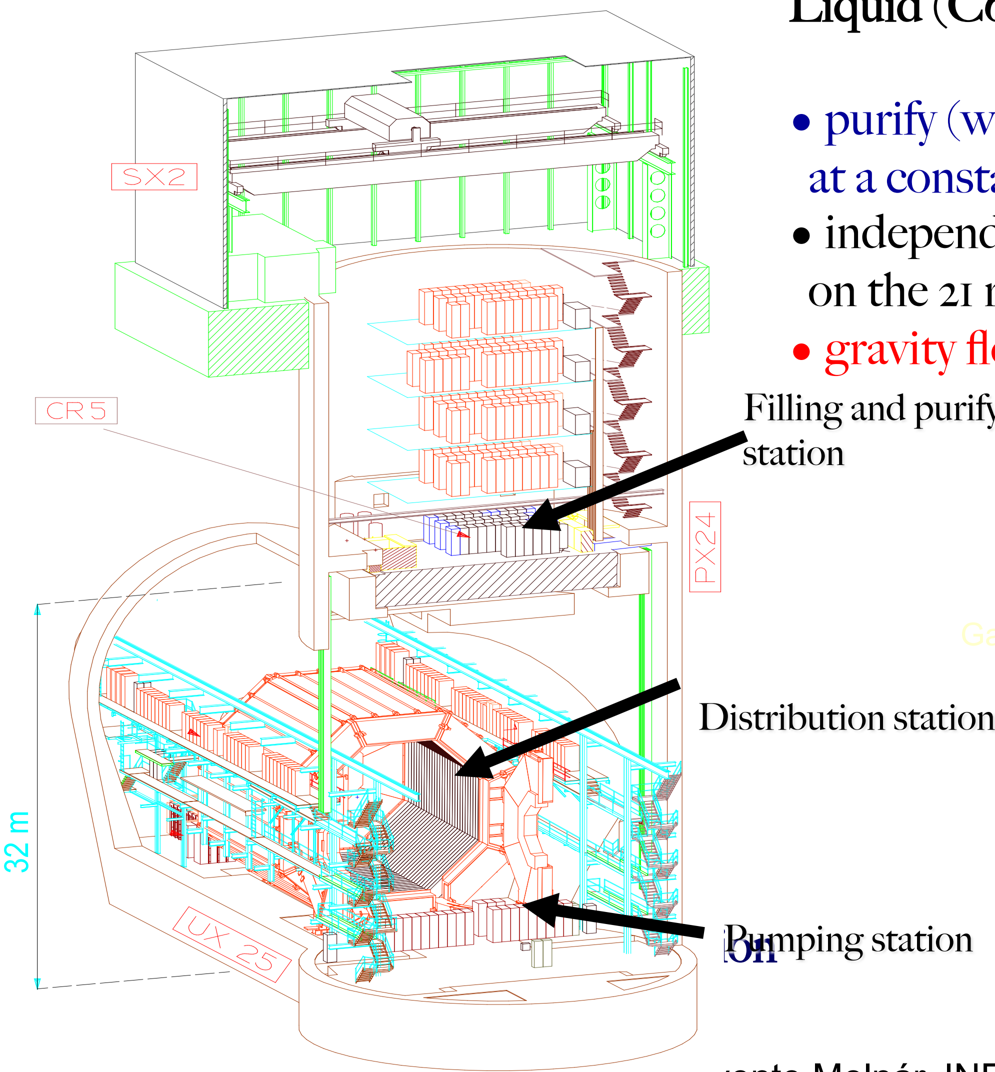
The RICH of ALICE

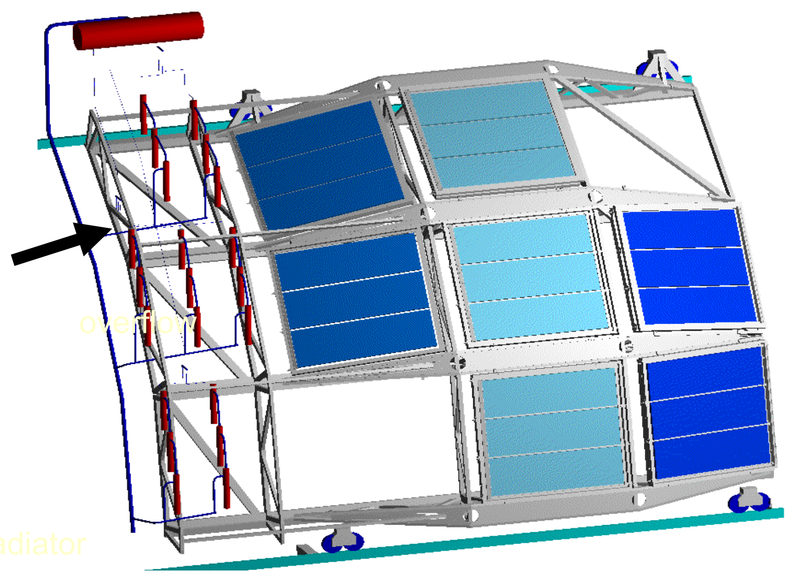
(taken from L. Molnar)

The C_6F_{14} circulation system

Liquid (C_6F_{14}) circulation system has to:

- purify (water, oxygen), fill and empty at a constant flow (4 *l*/h)
- independently, remotely and safely on the 21 radiator planes
- gravity flow to avoid forced liquid circulation





The RICH of LHCb

See detailed talks by C.Blanks, F.Muheim, R.Young, A.Powell at this conference

Physics aims:

separate K /π/p in the range 2-100 GeV/c to reconstruct rare (and less rare) B decays
(ex. $B \rightarrow KK$ and $K\pi$, $B \rightarrow D_s K$ and $D_s \pi$, …)

Environment:

Works at hadronic machine (LHC) , high particle density
Works at 1 MHz
Must reject pion better than at the percent level

Geometry:

focussed, 2 RICHes with 3 different radiators

The RICH of LHCb : the choices

Focussed geometry

Radiators: 5 cm aerogel n = 1.03 @ 400 nm
95 cm C_4F_{10} n=1.0014 @ 400 nm
180 cm CF_4 n=1.0005 @ 400 nm

Mirrors : 4 spherical (f= 135 cm)+ 16 plane *(R>600m)* in RICH1
52 spherical (f= 430 cm)+ 40 plane *(R=80 m)* in RICH2

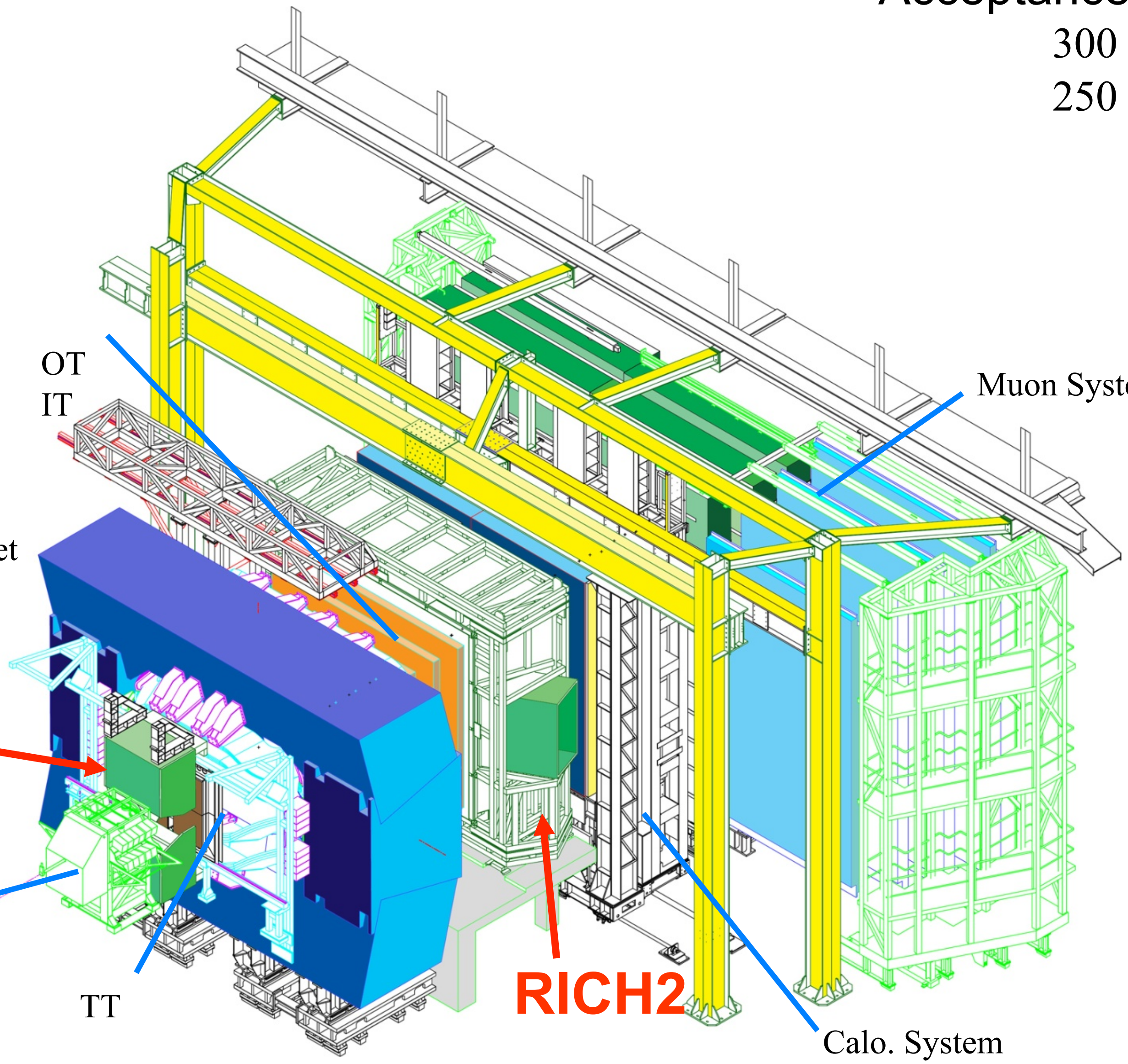
Photodetectors:
484 Hybrid Photon detectors (HPD) granularity 2.5 mm at the photocathode level

The RICH of LHCb

Acceptance:

300 mrad horizontal

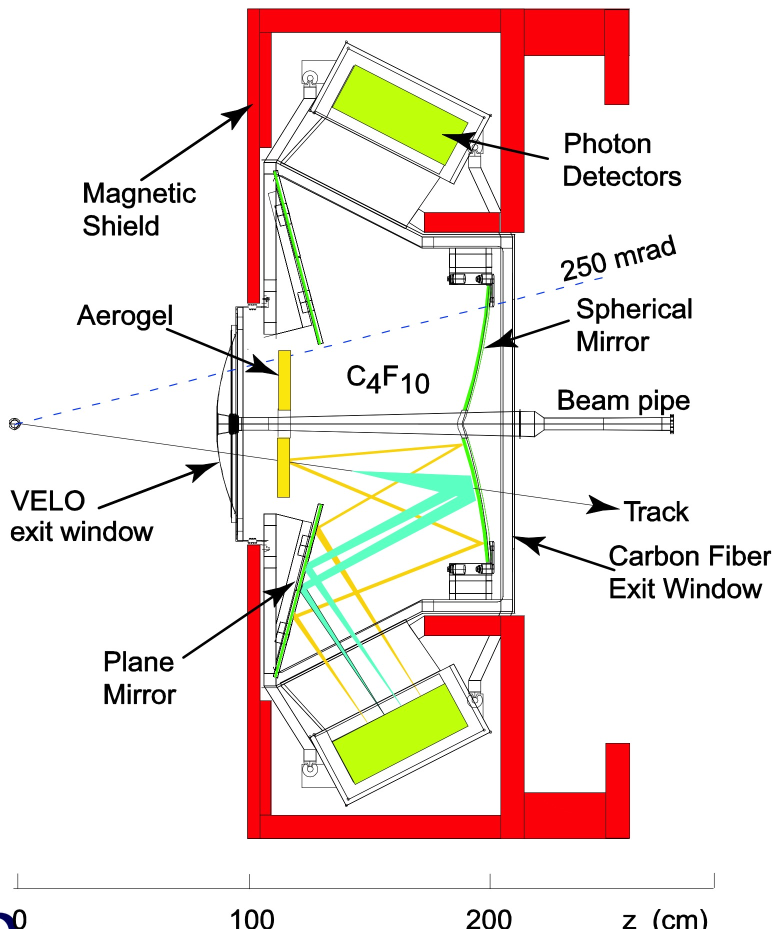
250 mrad vertical

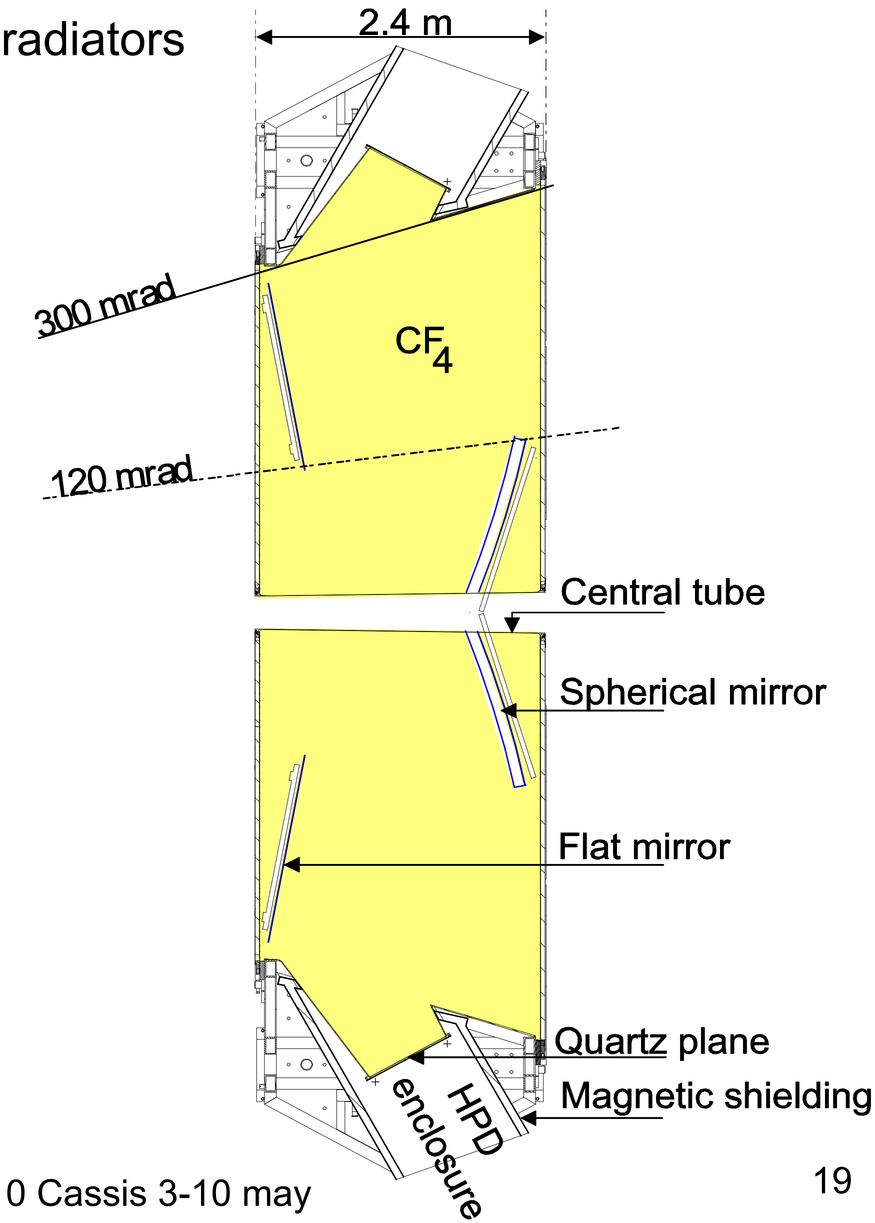


INFN Istituto Nazionale di Fisica Nucleare

The RICH of LHCb

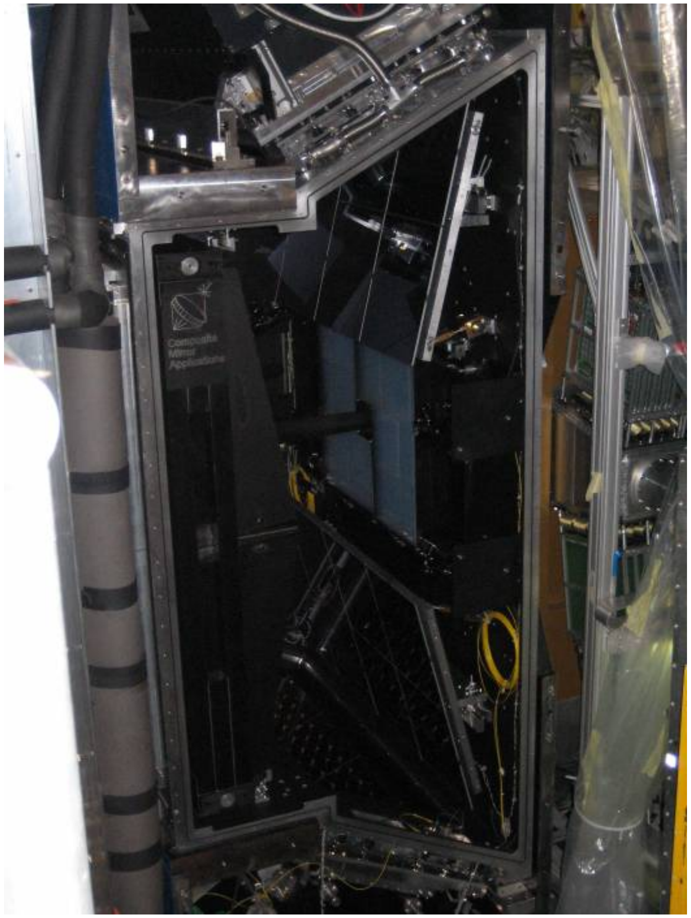
The solution of LHCb: 2 RICHes with 3 radiators





The RICH of LHCb

RICH-1 vessel



RICH-2 vessel

The RICH of LHCb : the resolution

Needs a resolution In the range of O(1 mrad) , sub mrad in RICH2

Units : mrad

	RICH-1		RICH-2
	Aerogel	C_4F_{10}	CF_4
Emission	0.4	0.8	0.2
Chromatic	2.1	0.9	0.5
HPD	0.5	0.6	0.2
Track	0.4	0.4	0.4
Total	2.6	1.5	0.7
Expected N_{pe} ≈	6.5	30	22

The RICH of LHCb: the resolution

Needs to control:

Radiators:

Composition of gas radiators (some air, $N2$, $CO2$ contamination)
gas composition measured by chromotography to calibrate n-1
Control P and T continuously for correcting automatically the density ρ_{gas}

Geometry:

Mirror alignment with data. Down to 0.1 mrad

Spatial precision:

Monitor ageing of PD (HPD) ➔ *see talk by R. Young on tuesday*
Corrections for magnetic distorsion ➔ *see poster by F. Xing*
Alignment of HPDs

Tracking:

must be well described by the Montecarlo. $\sigma(\theta_C)$ relies on track information also for alignment.

The RICH of LHCb : the resolution

The alignment of the mirrors is crucial ➔ see talk by C. Blanks and MDMS corrections (poster by P. Xing)

Monitor on-line: from the behaviour of the hardware to the PID performance

After several millions of pp collision events :

	C4F10	aerogel	CF4
Achieved resolution	2.2	8.0	0.9
Expected resolution (from simulation)	1.5	2.6	0.7

Mirrors and HPD hit not yet aligned
(and C4F10 absorption has degraded $\sigma(\theta)$*)*

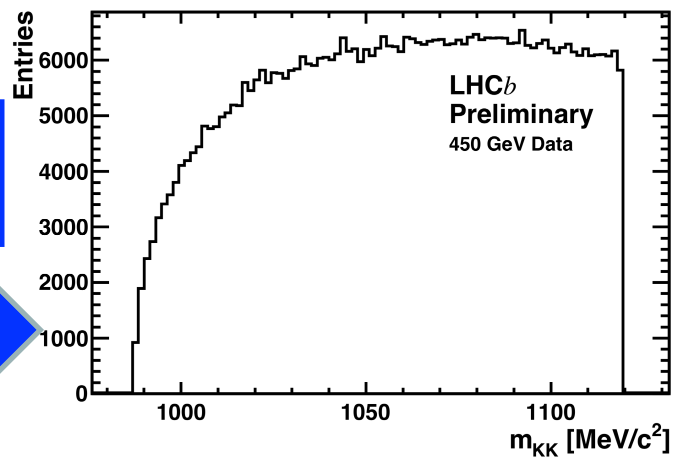
What does the RICH of LHCb sees in the very first data?

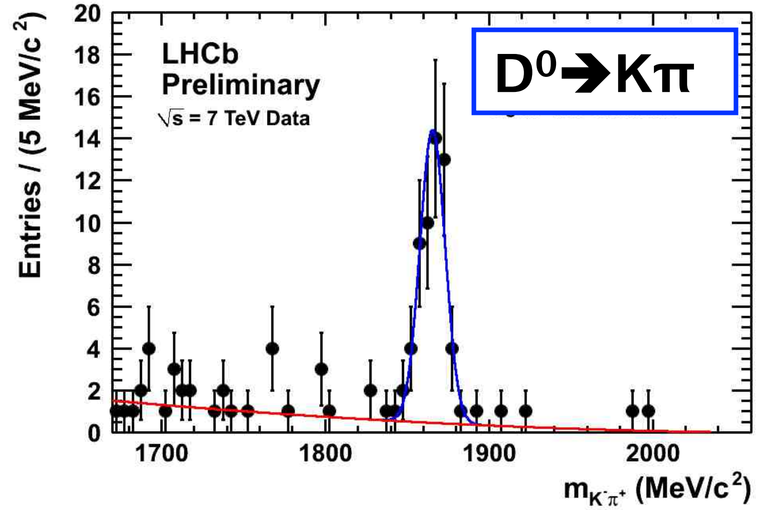
Observation of $\phi \rightarrow K^+K^-$

Observation of D^0 and D^+

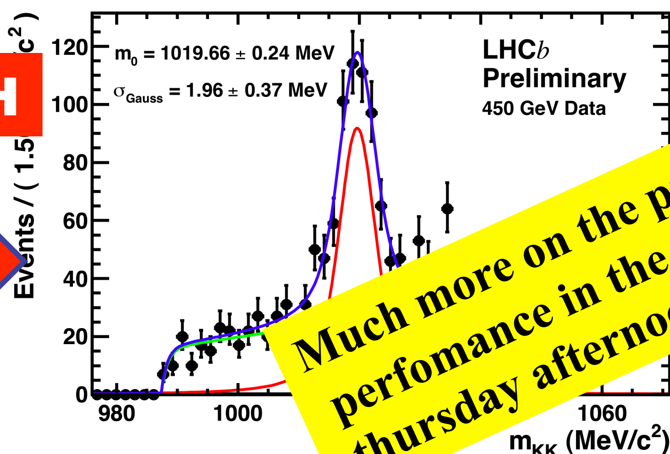
See talk by F. Muheim at this conference

Only tracking



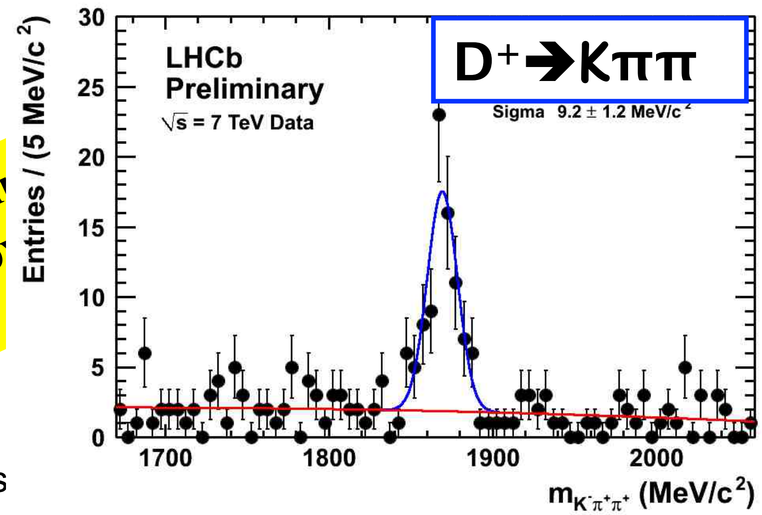


With RICH



Much more on the prelimi
perfomance in the talk b
thursday afternoon

assis



INFN Istituto Nazionale di Fisica Nucleare

The RICH of NA62

See detailed talks by M. Lenti at this conference

Physics aims:

measure BR($K^+ \rightarrow \pi^+ \nu\nu$) expected in the Standard Model to be O(10^{-11}) at 10% precision

Present result: **1.73 (+1.15 -1.05) $\times 10^{-10}$(BNL E787/E949)**

Dominant Background : $K^+ \rightarrow \mu^+ \nu$ ($K_{\mu 2}$ largest BR: 63.4%)

→ 3σ $\pi - \mu$ separation (15-35 GeV/c)

Need ~10^{-12} rejection factor of which from Particle ID: 10^{-2}
(Kinematics: 10^{-5} and Muon Veto: 10^{-5})

The RICH of NA62

See detailed talks by M. Lenti at this conference

Environment:

Kaon beam at 800 MHz

Needs to match a pion (10 MHz rate) with a kaon seen by the beam spectrometer (800 MHz rate)

→ measure the pion crossing time at 100 ps level

Geometry:

focussed

The RICH of NA62 : the choice

Based on SELEX RICH idea

Focussed geometry

Radiator:

17 m Neon (n-1=62 ×10^{-6} @ 300 nm) at 1 atm

θ_C =11.3 mrad (π thresh.:12 GeV/c)

Mirrors:

spherical (20 exagonal elements with 17 m focal length)

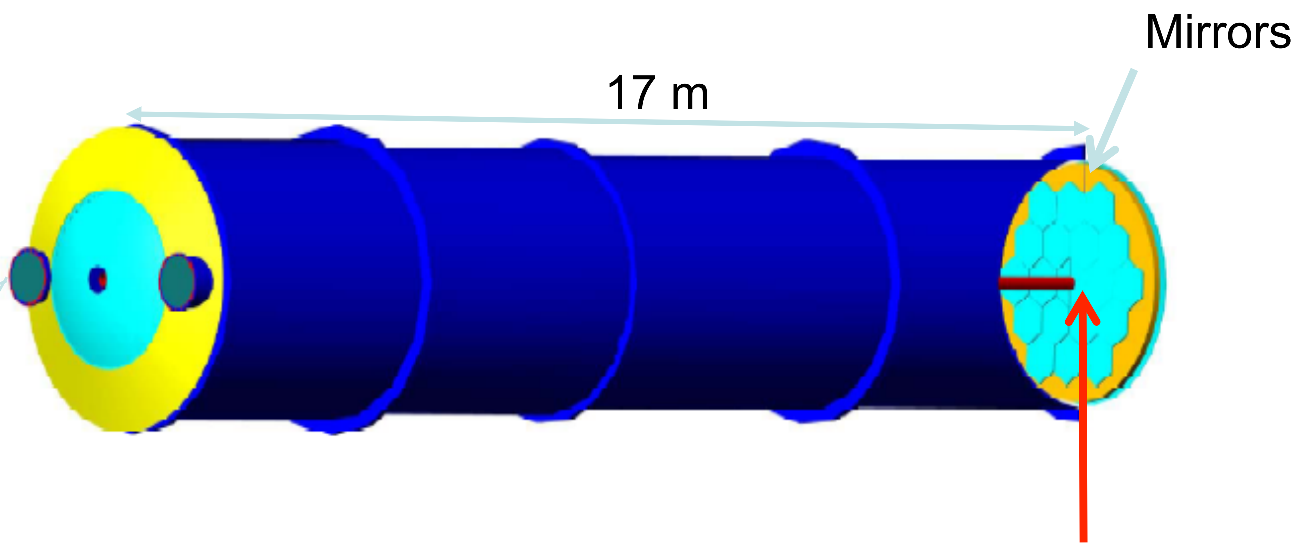
Photon detector:

2000 PMT Hamamatsu R7400-U03 with granularity 18 mm and time resolution better than 100 ps.

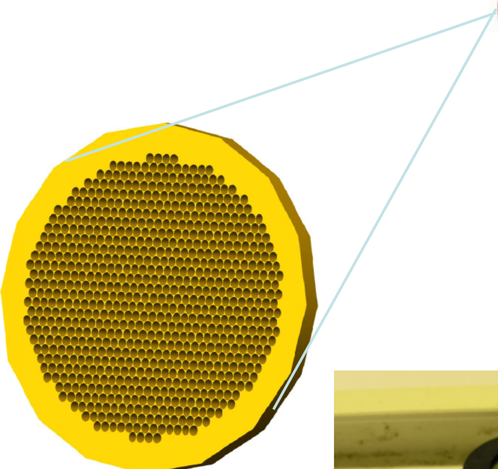
The RICH of NA62

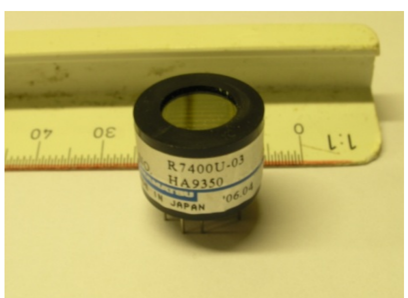
Vessel volume: 200 m^3 , 17 m long

(between straw tubes and liquid Kr calorimeter)



Beam pipe (Ø 157 mm) going through





Hamamatsu R7400 U03

The RICH of NA62

- vessel under construction (steel)
- max overpressure: 150 mbar
- 4 m wide (upstream), 3.4 m wide (downstream)
- thin aluminum entrance and exit windows

Contaminants < 1%

CO_2 used to purge the vessel

- The gas is then circulated in closed loop, and the Neon is introduced while absorbing the CO_2 in a molecular sieve filter.
- At the end the vessel is valve closed

The RICH of NA62 : the resolution

Contributions to the angular resolution (per single photon and $\beta=1$, θ_C =11.3 mrad):

1. **Chromaticity** determined by the basic property of dispersion of radiator,

   → ~ 125 μrad

2. **Spatial error** : determined by the granularity of the photodetector

   → ~ 265 μrad

3. **Geometry:** emission point, mirrors

   → ~ 15 μrad

4. **Track error:** ≈ 55 μrad (35 GeV/p)

The RICH of NA62

Needs to control :

The gas radiator

- monitor n through $n=1+(n_0-1)\ \rho/\rho_0$
  with ρ is the gas density at operating conditions of T and P
  Neon density stability < 1%
- leak rate < 1×10^{-2} Std.cc/s
  (if not achieved needs a purifier module)

- Contaminants < 1%

Mirror alignment is important : with data and with laser to a level of O(50 μrad)

Photocathode QE

RICHes IN SPACE EXPERIMENTS

In space: stability is mandatory (essentially no maintenance).
Solid radiators are more suitable.

Proximity focus (no optical element to align etc.,)
What could change: optical quality of the radiator,
QE of photocathode to count photons.

The RICH of AMS

See detailed talks by R.Pereira at this conference

Physics aims:

Cosmic ray spectrum, search for antimatter and dark matter.
Must measure particle velocity β and charge

Environment:

Operates in space (on satellite) for a period of at least 3 years

Geometry:

proximity focus

The RICH of AMS : the choice

Proximity focussed

Solid radiators :
2.5 cm aerogel n=1.05
0.5 cm NaF (sodium fluoride)crystal n=1.334
Conical reflector around

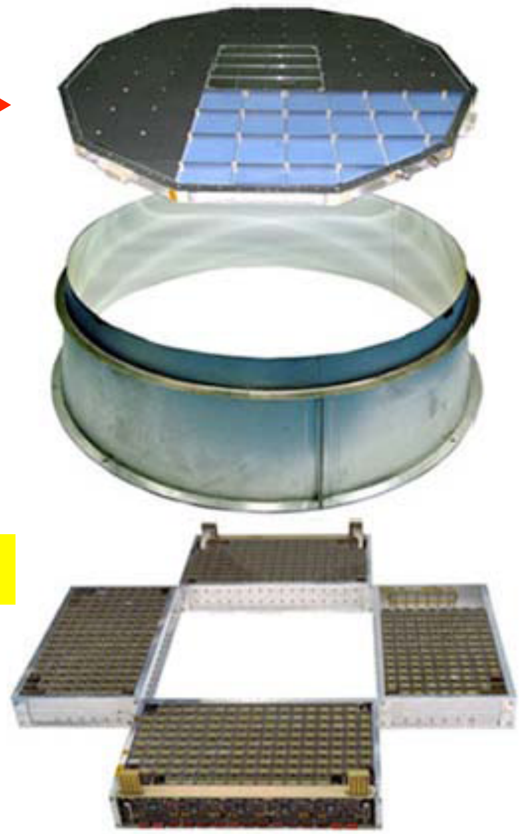
Photodetectors:
680 PMT Hamamatsu R7600-M16 with plastic light guide
Pixel size : 8.5 mm
Each PMT individually shielded from the stray field
(up to 300 Gauss)

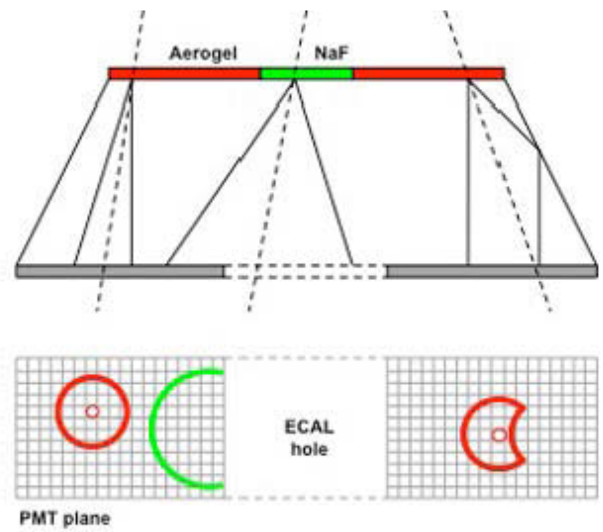
The RICH of AMS

radiators

reflector

PMTs matrix





Scheme of the radiators and ring images

The RICH of AMS: the velocity resolution

Aim: must measure β with $\sigma(\beta)/\beta \sim 0.1\%$ for charge 1

Velocity measured from $\beta = 1/n \cos\theta_C$

$$\text{with} \quad \sigma(\beta)/\beta = \tan\theta_C \frac{\sigma(\theta_C)}{\sqrt{N_{pe}}}$$

Contributions to the resolution:

Radiator chromaticity
Radiator thickness
Pixel size (8.5 mm)

The RICH of AMS: the velocity resolution

Contributions to the resolution (Units: mrad)

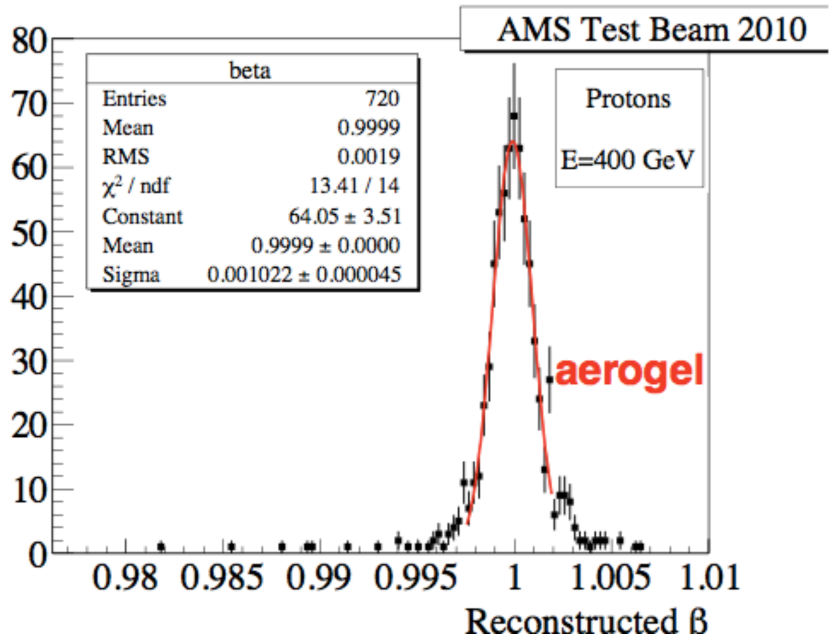
	Aerogel	NaF
Radiator chromaticity	3.2	4.8
Radiator thickness	3.3	0.3
Pixel size (8.5 mm)	4.6	0.6
$\sigma(\theta_C)$	6.5	4.8
$\sigma(\beta)/\beta \approx$	2×10^{-3}	4×10^{-3}

Possible degradation from natural ageing of aerogel ?

Istituto Nazionale di Fisica Nucleare

The RICH of AMS: the velocity resolution

Test beam measurement in 2010 with 400 GeV protons protons



The RICH of AMS: the charge resolution

Aim: must measure Z (also measured with TOF, dE/dx in Si tracker) with $\Delta Z = 0.2$ for electric charge

Charge measured by $Z^2 \alpha (N_{pe}/\varepsilon)\, 1/\sin^2 \theta_C$

ε= acceptance and photon detection efficiency

Contributions to the resolution ΔZ:

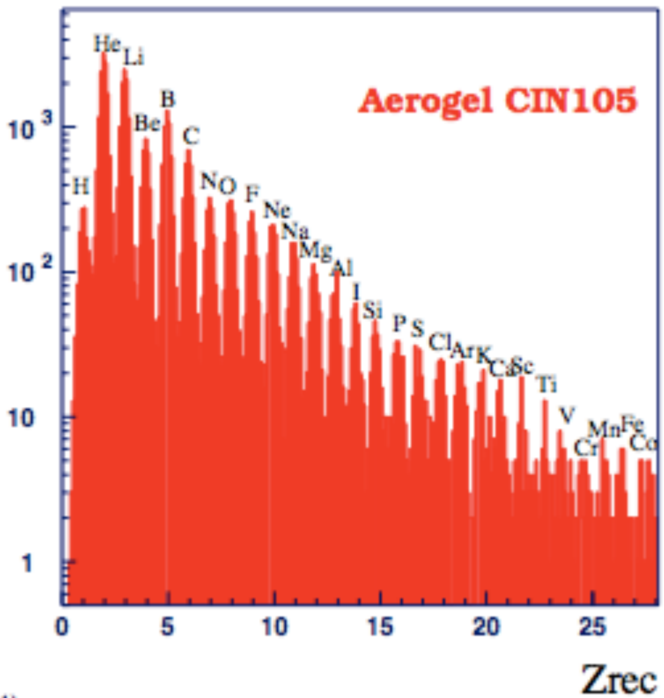
Statistical error on N_{pe}

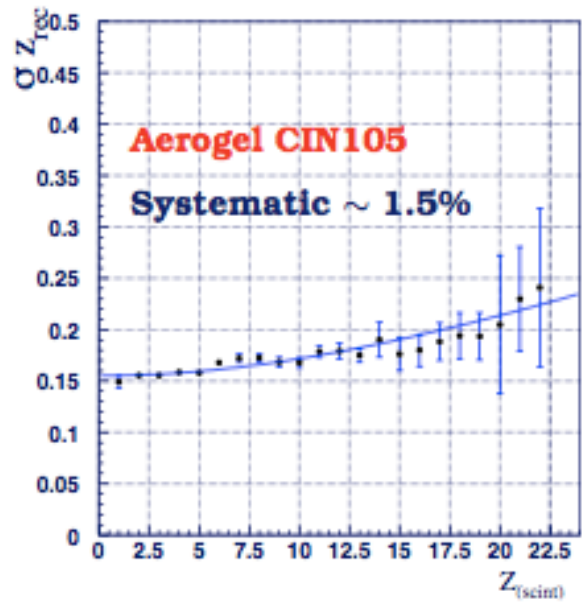
Systematics from non-uniformity of
- radiator (n, thickness, clarity,…)
- photon detection (PMT, temperature effects,…)

The RICH of AMS: the charge resolution

$$\Delta Z = \frac{1}{2}\sqrt{\frac{1+\sigma_{p.e}^2}{N_0} + Z^2\left(\frac{\Delta\varepsilon}{\varepsilon}\right)^2}$$

Results from test beam 2003 with fragmented ions :





A good precedent : **the RICH of CREAM**

A collaboration of

US, Korea, Italy, Mexico, France, NASA

4 succesfull flights. Launched from US McMurdo base in Antarctica

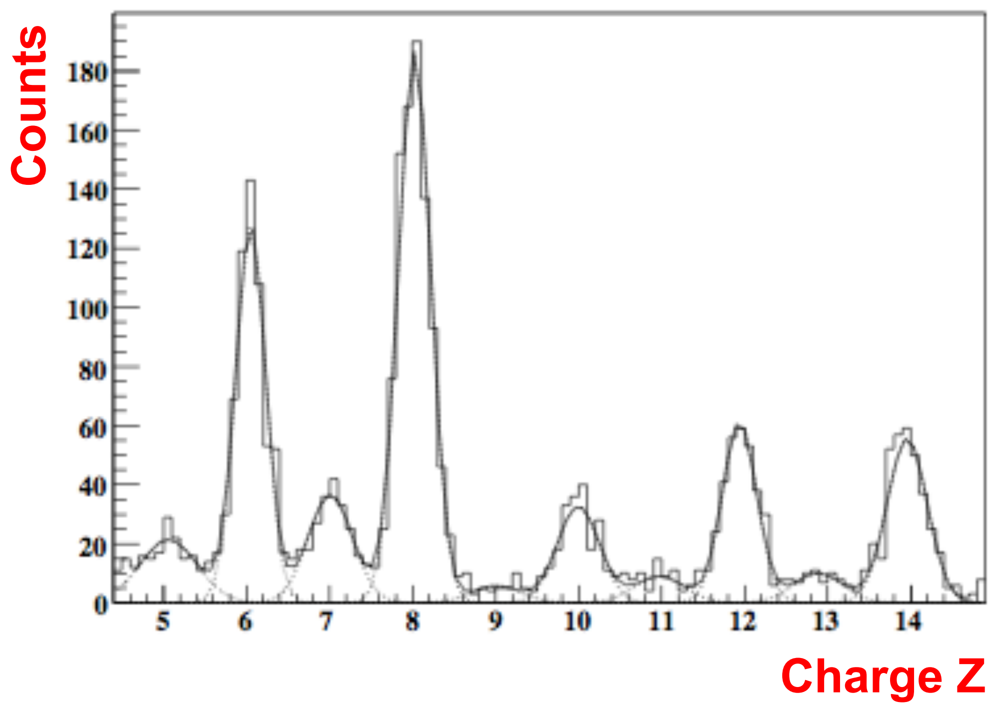
The RICH was proposed, designed, built
in less than 2 years
by a Mexican-French collaboration.

200 Aerogel tiles + 1600 PMT Photonis XP1232

Measure charge from N_{ph} α $\sin^2\theta_C Z^2$ with similar systematics requirements as in AMS (uniformity of thickness, optical index dispersion of aerogel tiles and in each tile,….)

A good precedent : **the RICH of CREAM**

Measurement of charge by CREAM during the second balloon flght



Concluding comments

- RICH technique is extremely powerful and widely used for PID in different environments
- Choices of technologies make flexible RICH designs for different applications. Stability is often to be favoured.
- Technological developments in Photodetectors sector will even improve performance (ex. high time resolution,high QE)
- BUT: RICH detectors are in general sophisticated tools and need important effort to keep under control the different components of the Čerenkov angle resolution
- And, not least, powerful software tools are mandatory to translate the detector response into physics measurements.

W. Kandinski