Refractive index of silica aerogel: uniformity and dispersion law

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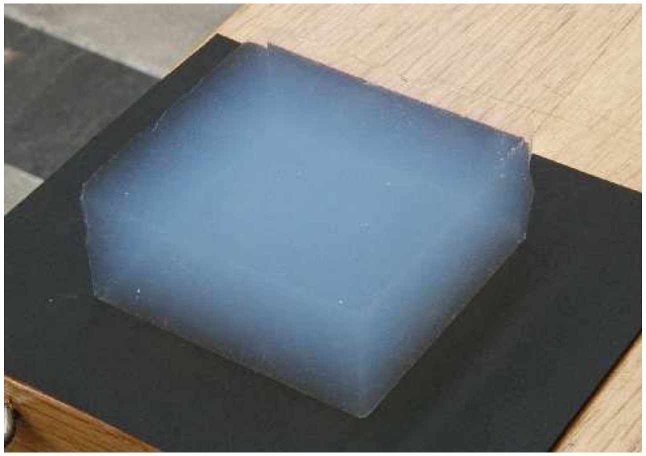
Outline

- Silica aerogel
  - Physical and optical properties
- Refractive index measurement
  - Minimum deflection
- Refractive index uniformity
  - Laser deflection: monochromatic
  - Charged particle beam: Cherenkov spectrum
- Wide spectrum dispersion measurement
  - UV lamp + Monochromator

Silica Aerogel



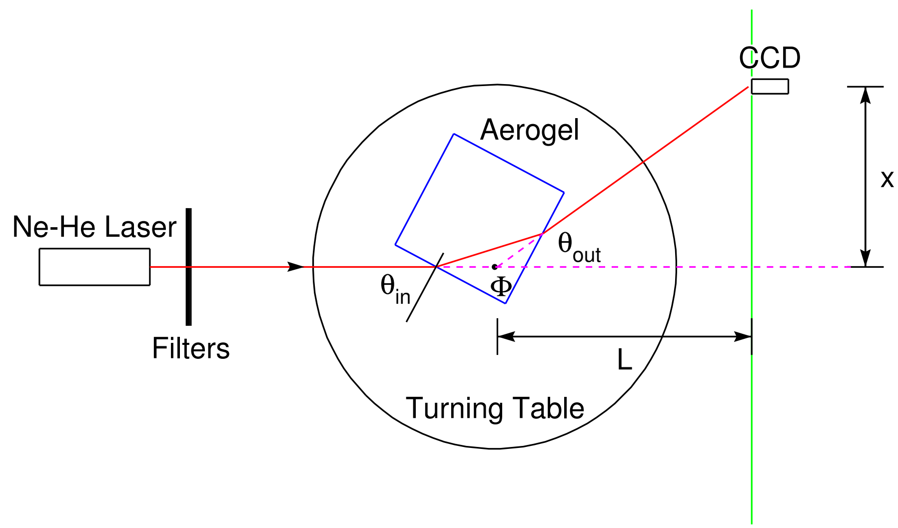
– Silica aerogel is a linked network of SiO_2 nanocrystals, $2-5$ nm in diameter.

– Tunable density ($\rho \sim$ 0.15 g/cm^3) $\rightarrow$ tunable refractive index n

– We tested tiles with dimension 200 $\times$ 200 $\times$ 50 mm^3 and $n \simeq 1.03$ produced by the Boreskov Institute in Novosibirsk.

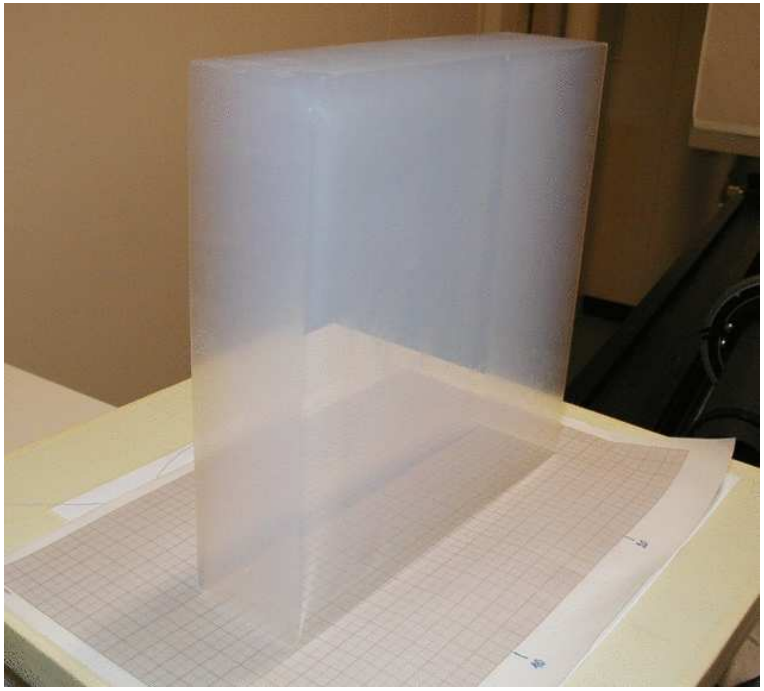
The refractive index is measured with the minimum deviation method.

$$n = \frac{\sin\left(\frac{\Phi + \theta_{out}}{2}\right)}{\sin\left(\frac{\Phi}{2}\right)}$$



Refractive Index Inhomogeneity

- The refractive index of aerogel depends on the density according to $n(\lambda) = 1 + \mathsf{k}(\lambda)\rho$ with $\mathsf{k} \simeq 0.21$ at $\lambda = 400$ nm
- local density fluctuations lead to variations of the refractive index within the tile
- these variations contribute to the θ_C Cherenkov angle accuracy

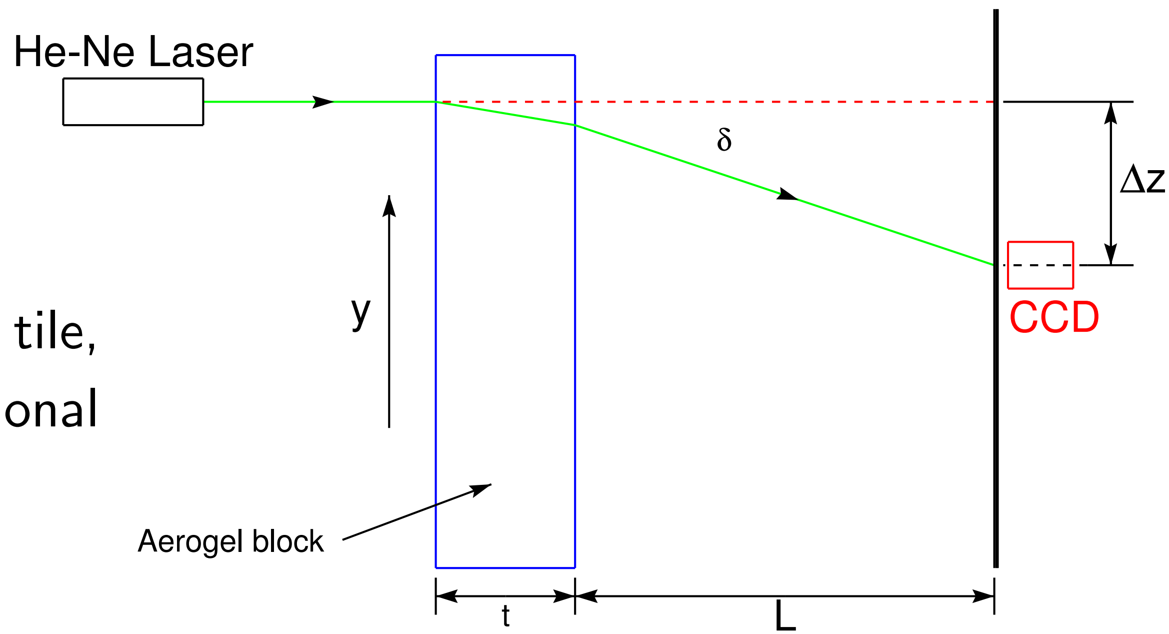


Two methods developed to evaluate the homogeneity

- laser beam deflection
- Cherenkov angle measurement

LHCb requirement:
Max variation $\sigma(n-1)/(n-1) < 1\%$
corresponding to $\sigma_i(\theta_C) \simeq 1.17$ mrad
when $\sigma_{tot}(\theta_C) \simeq 2.6$ mrad

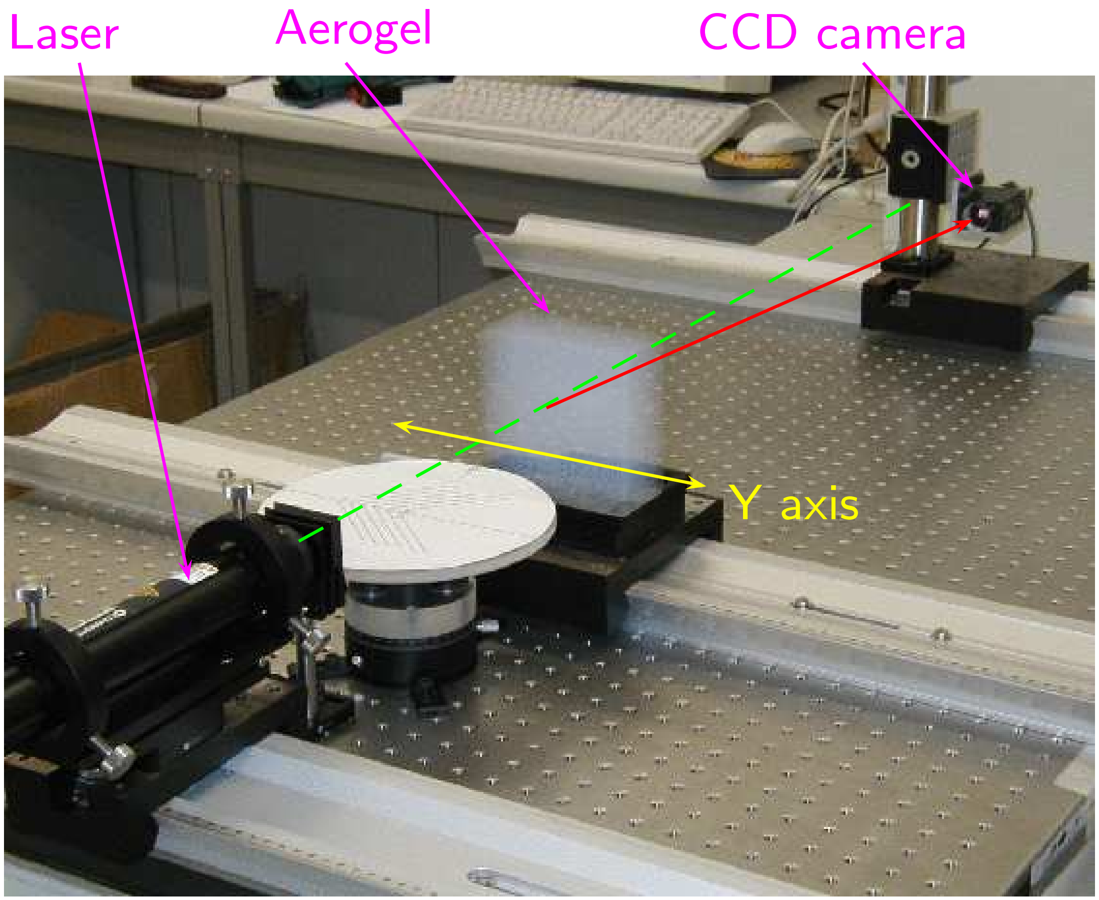
Electromagnetic radiation bends if there is a refractive index gradient transverse to the direction of propagation



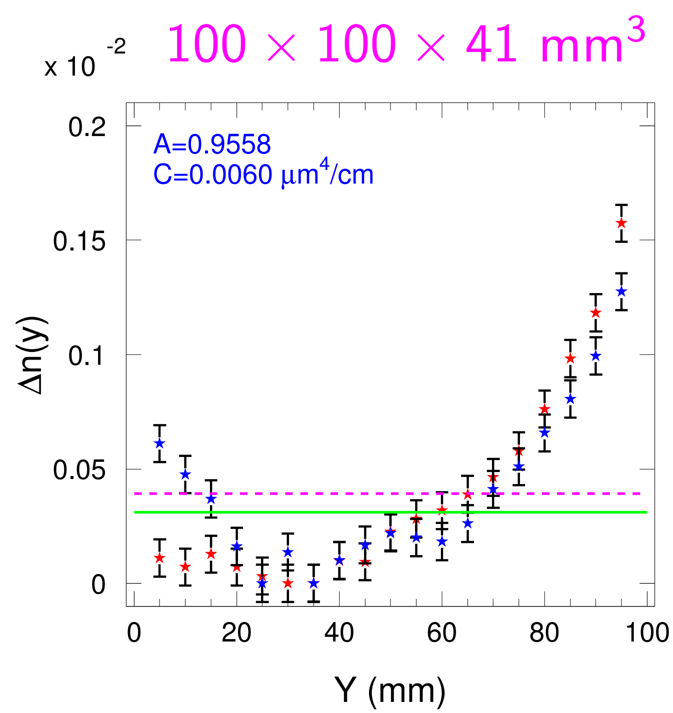
Laser Beam Method

Assuming parallel faces for the tile, the deviation angle δ is proportional to the refractive index gradient

$$\frac{dn}{dy} \simeq n\frac{\delta(y)}{t} \Rightarrow \Delta n(y) = \frac{n}{t}\int_{y_0}^{y} \delta(y)dy$$



Sample measurement with gradient towards the sides:



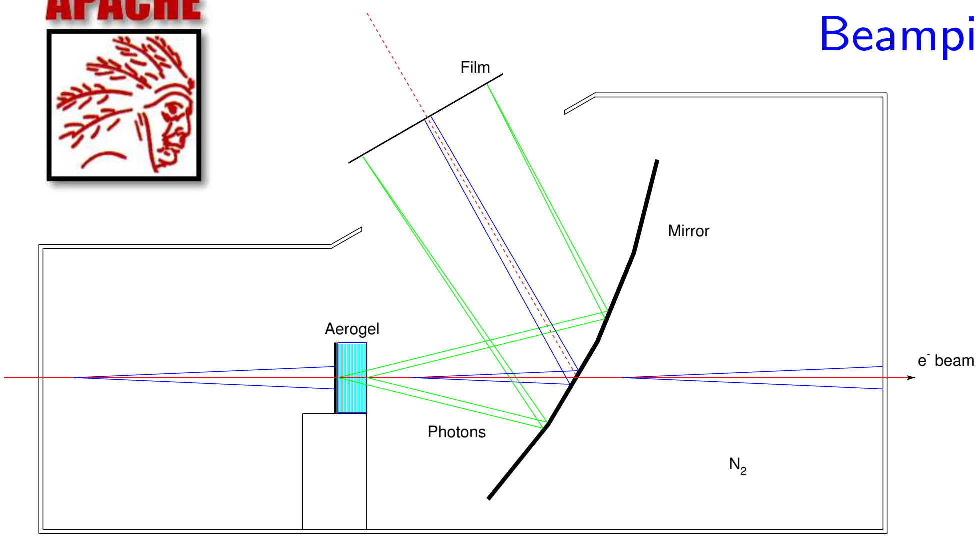
$\sigma(n-1)/(n-1) \sim 1.3\%$

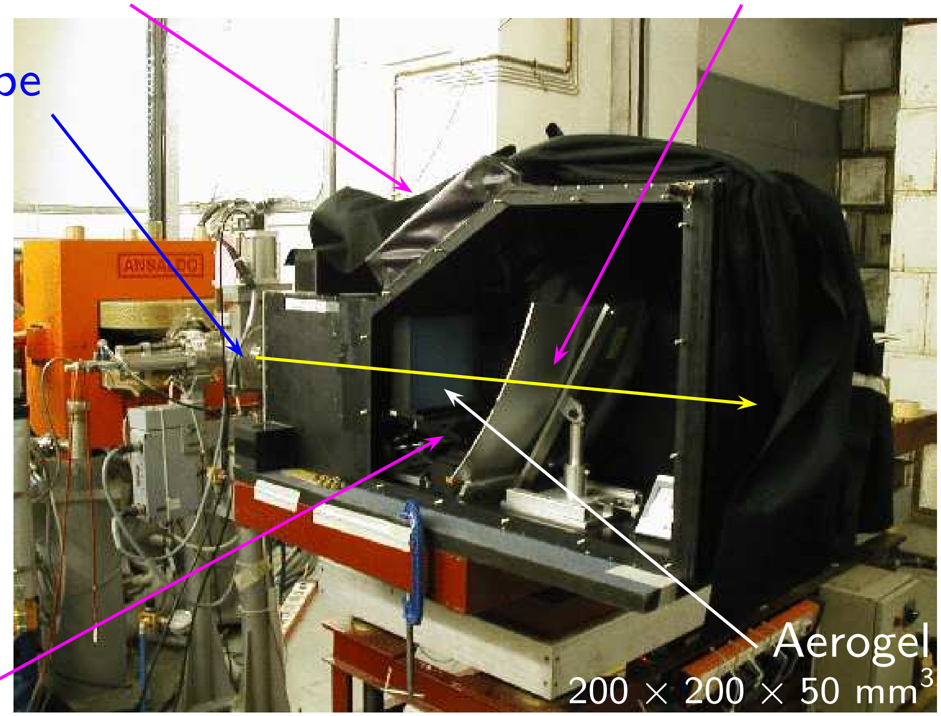
- fast feed–back method
- one wavelength at a time can be monitored
- extrapolation to the full wavelength range

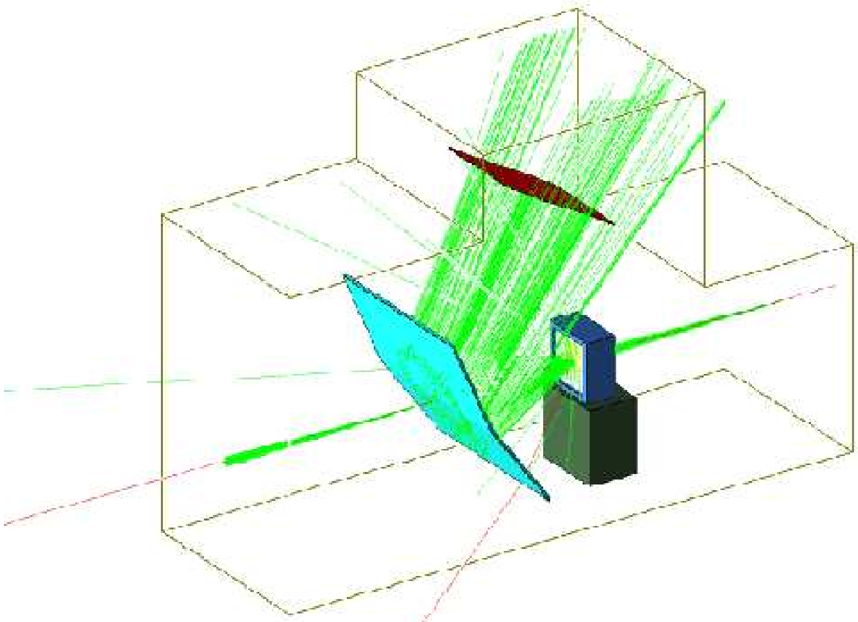
Aerogel Photographic Analysis by CHerenkov Emission

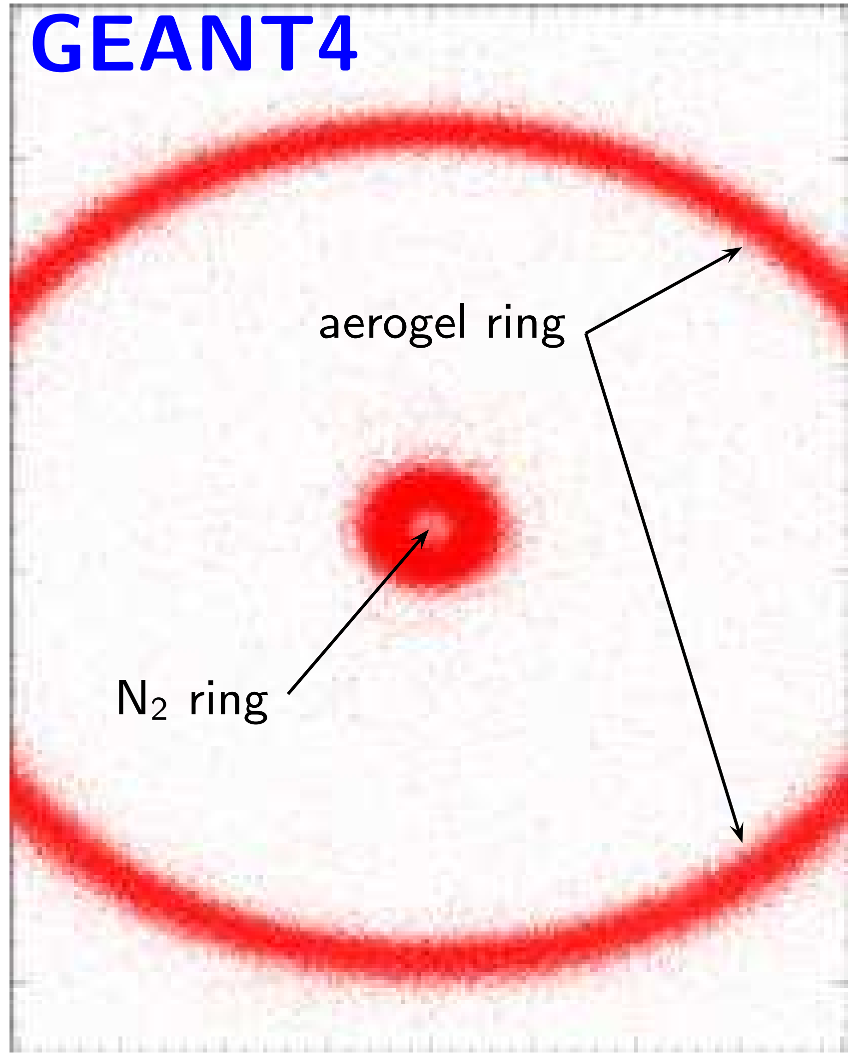
- table–top RICH detector with b/w film as photon detector
- 500 MeV electrons from the DAΦNE Beam Test Facility in Frascati
- scanning the beam entrance point along the aerogel surface

APACHE

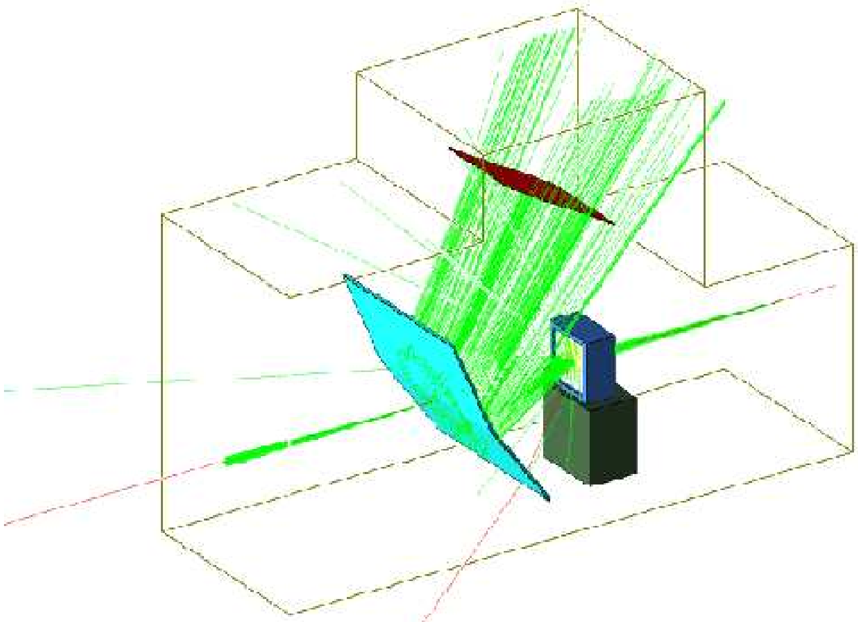


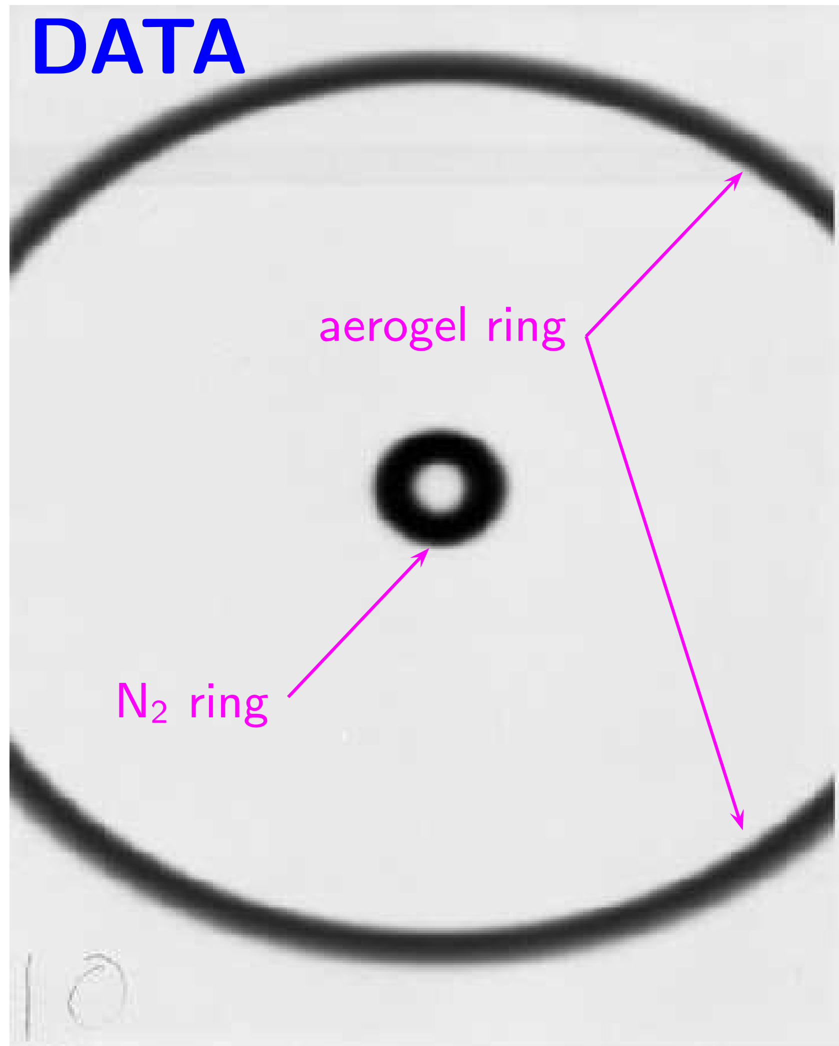






– Cherenkov ring width dominated by chromaticity $n = n(\lambda)$





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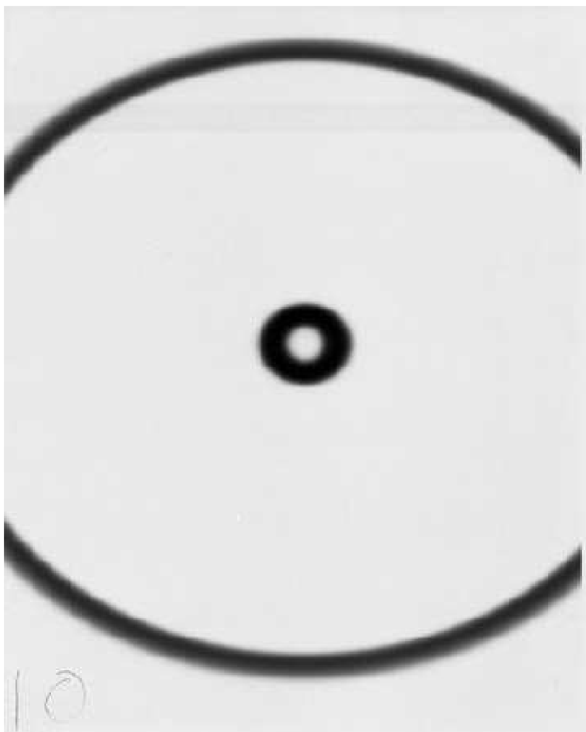
APACHE

- 25 entrance points measured (a $200 \times 200 \times 50$ mm^3 tile tested)
- retracking algorithm to build the distribution of reconstructed θ_C
- resolution: ~ 0.3 mrad, including systematics (GEANT4)



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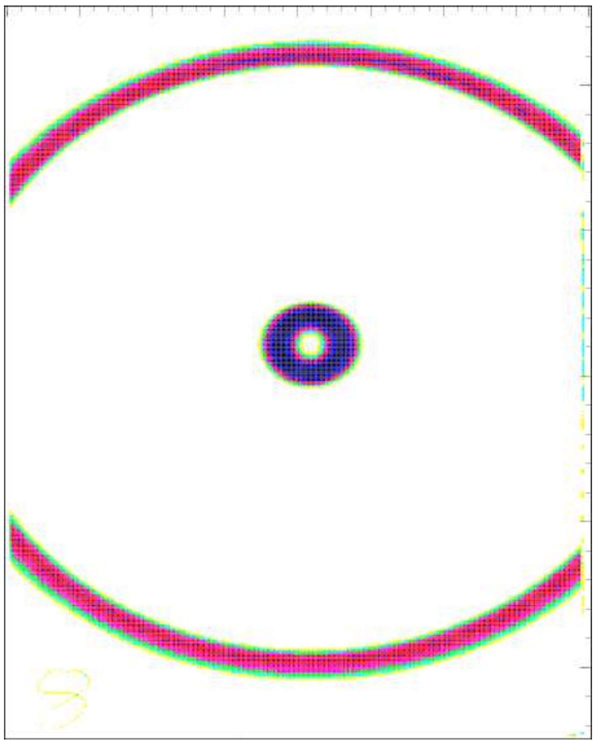

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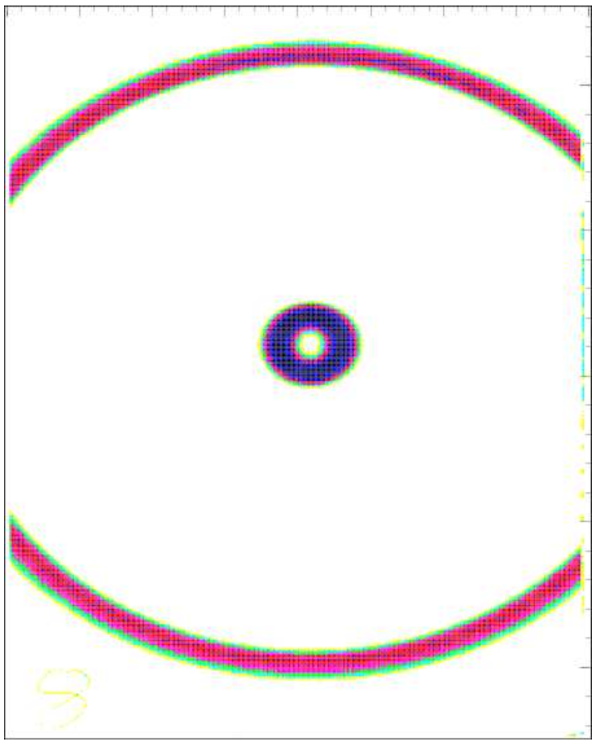

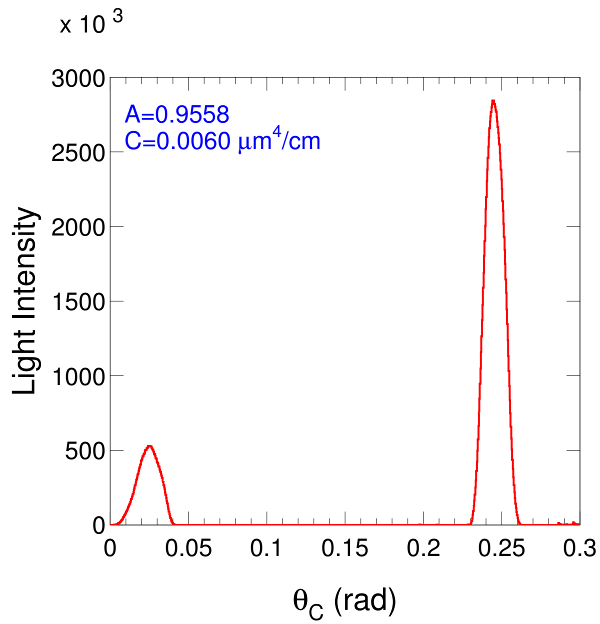

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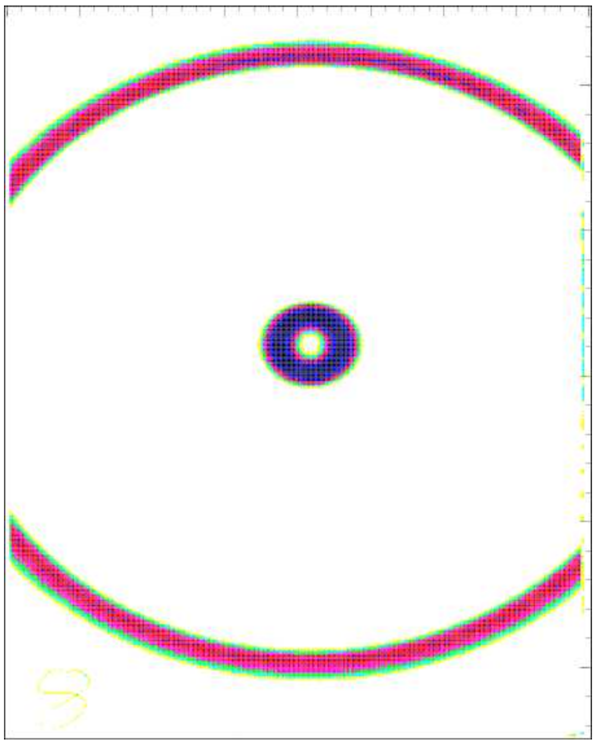
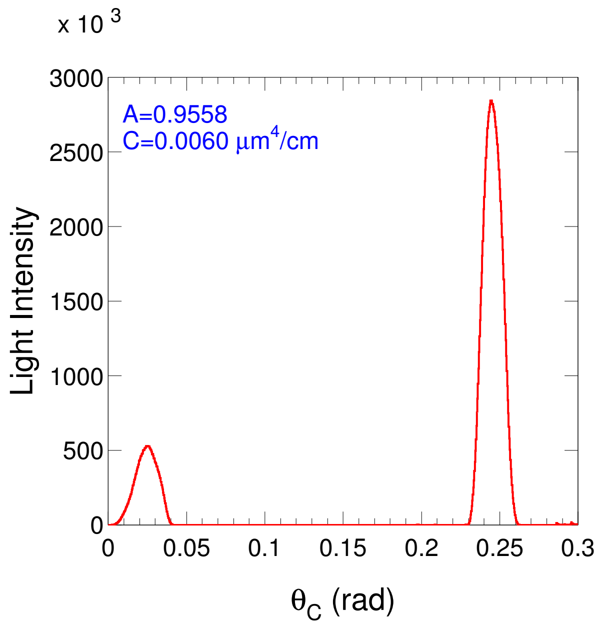
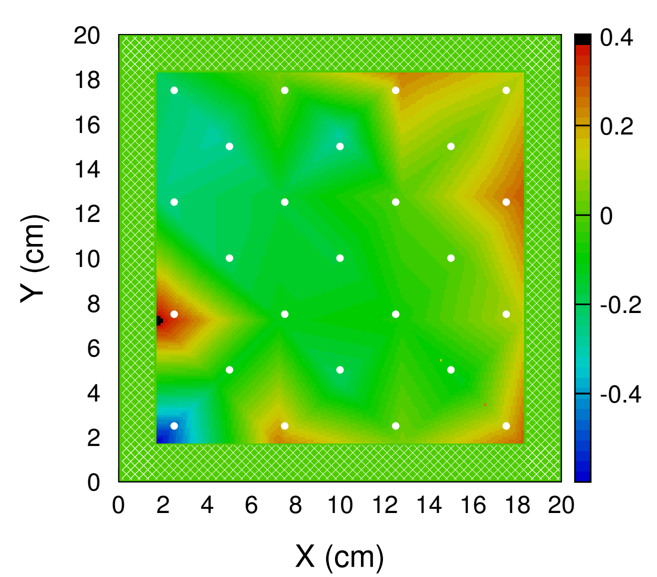




Surface plot of $n - \bar{n}$



$$\sigma(\mathrm{n}-1)/(\mathrm{n}-1) = (0.76 \pm 0.01)\%$$

The very promising results from the APACHE runs show that large transverse size aerogel tiles now available comply with the homogeneity requirements of LHCb

Dispersion law

- Chromatic dispersion is often the source of the dominant contribution to σ_θ in RICH detectors with silica aerogel as radiator
- A correct parameterisation of $n(\lambda)$ is essential for a realistic simulation of the detector and a more performing pattern recognition
- There are several heuristic models, based on the Lorentz-Lorenz law:

$$\frac{n^2-1}{n^2+2} = cf\left(E_\gamma\right) \qquad \text{with} \qquad c = \frac{4\pi a_0^3 \rho N_A}{3M}$$

- $f(E_\gamma)$ can be parameterised in terms of a multi–pole Sellmeier function as:

$$f\left(E\right) = \sum_{j=1}^{N} \frac{F_j}{E_j^2 - E_\gamma^2}$$

Dispersion - Setup

Usual prism method with some important modifications:

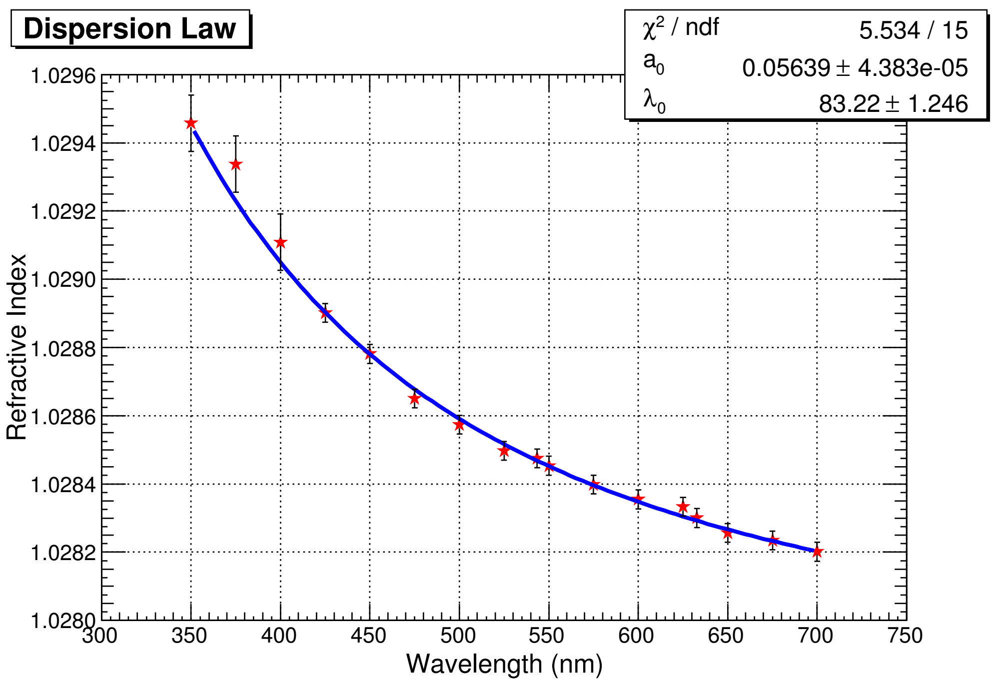
- A UV lamp coupled to a monochromator provides a monochromatic source, an objective allows to have parallel rays at the output
- The refracted beam stops on a fine mesh screen
- Centre of gravity of the spot is calculated taking a picture of the screen with a digital camera
- Measurements taken at fixed angle instead of minimal deviation condition, hard to find at short wavelengths

We were able to take data in the range 350–700 nm, well matched to the spectrum of detected photons from the aerogel in LHCb.
Below 350 nm the transmission of the objective is too poor.

Dispersion

– A one–pole Sellmeier function fits well the data

– Two superimposed poles are found in a two–poles fit



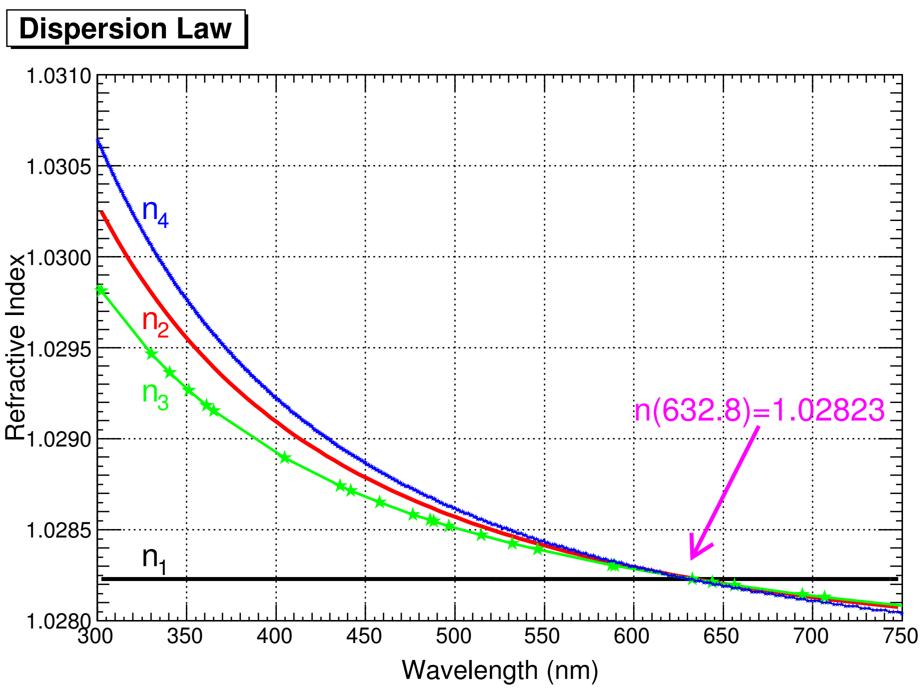
As a function of λ:

$$n^2(\lambda) - 1 = \frac{a_0 \lambda^2}{\lambda^2 - \lambda_0^2}$$

The pole is found at 83.2 nm. The density dependent coefficient is consistent with the one calculated from the measured density of the aerogel sample.

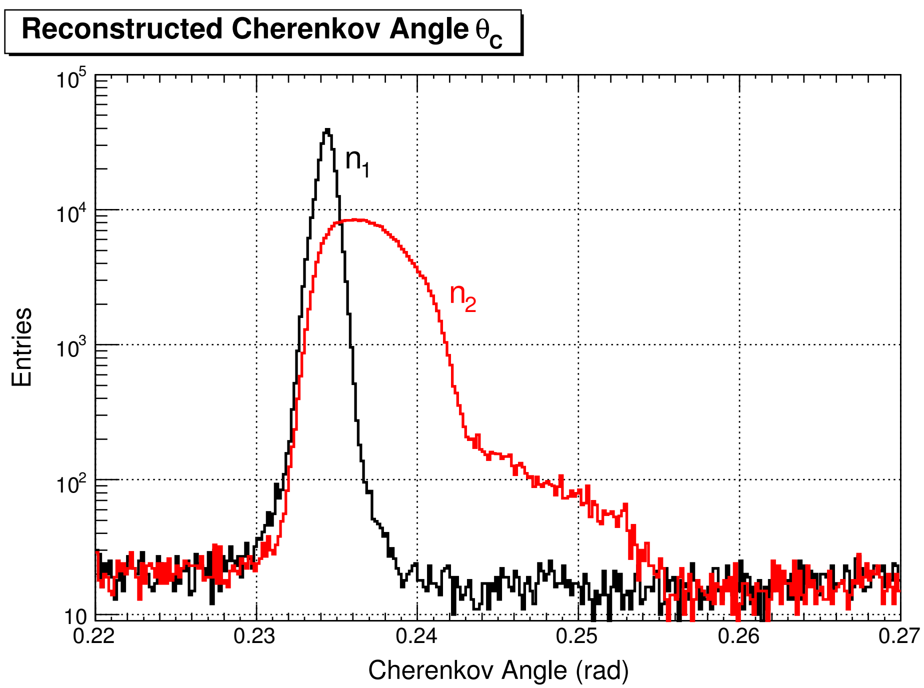
The esperimental points are compared to various parameterisations, all properly scaled to match the laser measurement $n(632.8\ \text{nm}) = 1.0282$.

The same $n(\lambda)$ laws are compared in simulations.



- n_1 is the unphysical approximation n=constant.
- n_2 is the fitted one–pole Sellmeier function
- n_3 is the curve derived from SiO_2 data (the stars) and the Clausius–Mossotti equation for binary mixtures.
- n_4 is a two–pole Sellmeier function for the aerogel used in the LHCb simulation

The APACHE simulation package has been run four times, each time with a different $n_i(\lambda)$, as previously defined. The results are summarized in the table below. The plot shows the log–scale distribution of the reconstructed Cherenkov angle for the constant n and the one–pole Sellmeier.



Mean Cherenkov angle θ_C and single photon resolution σ_θ (mrad) for 10 GeV/c pions.

	θ_C (mrad)	σ_θ (mrad)
n_1	234.3	0.5
n_2	236.3	2.8
n_3	236.1	2.0
n_4	236.4	3.5

Conclusions

– Complete characterization of the aerogel for the LHCb experiment

– It has been verified both with measurement at fixed λ and with a dedicated Cherenkov detector that the material is well inside the specifications for the homogeneity of the refractive index $\sigma(n-1)/(n-1) < 1\%$

– The refractive index has been measured in the range 350 to 700 nm and a one–pole Sellmeier function fits the data very well

– This information is essential for the simulation and the performance of an aerogel–based RICH detector