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SEARCHES FOR DARK MATTER, ANTIMATTER AND COSMIC RAY COMPOSITION WITH THE ALPHA MAGNETIC SPECTROMETER

24-01-2001

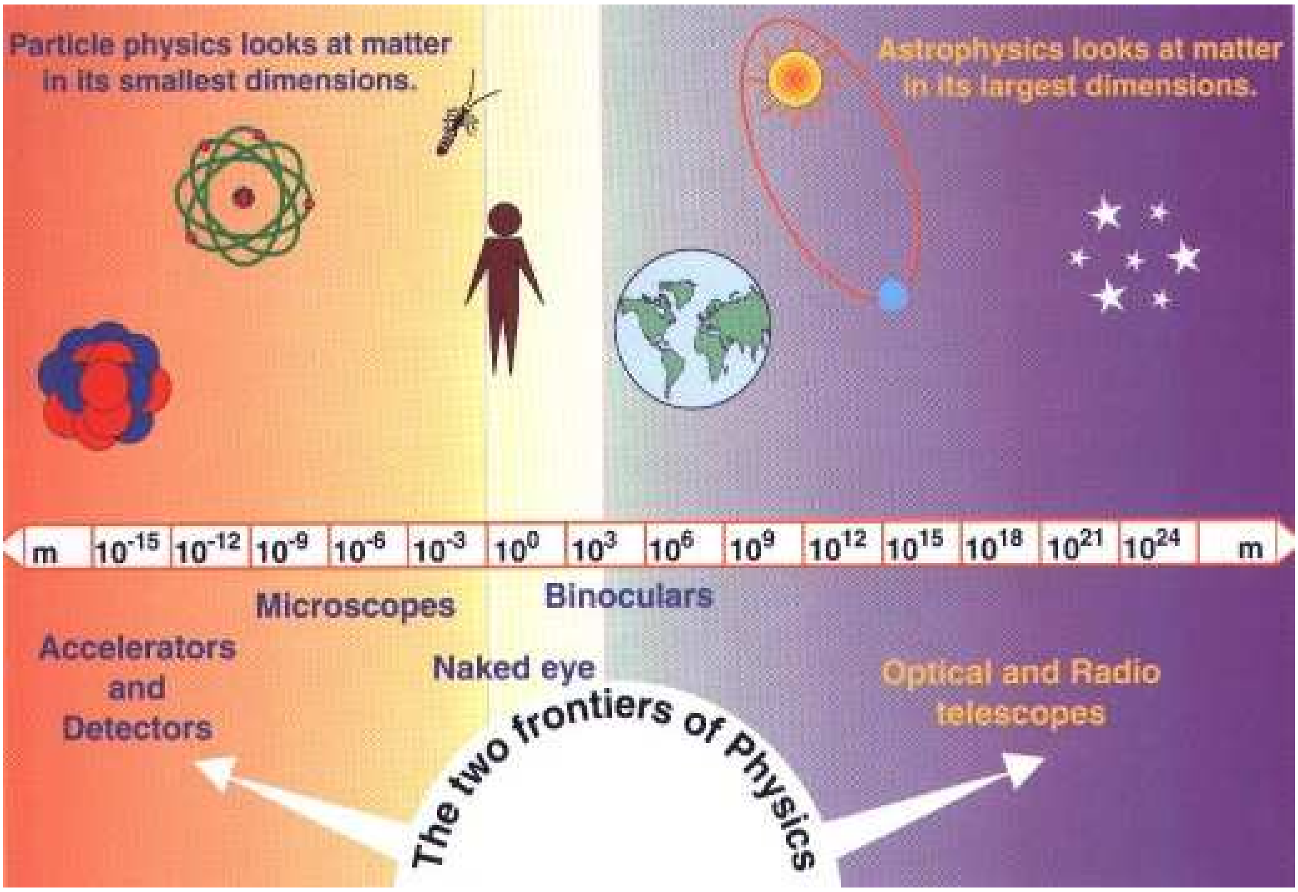
PhD students seminar

GSI Darmstadt

Outline:

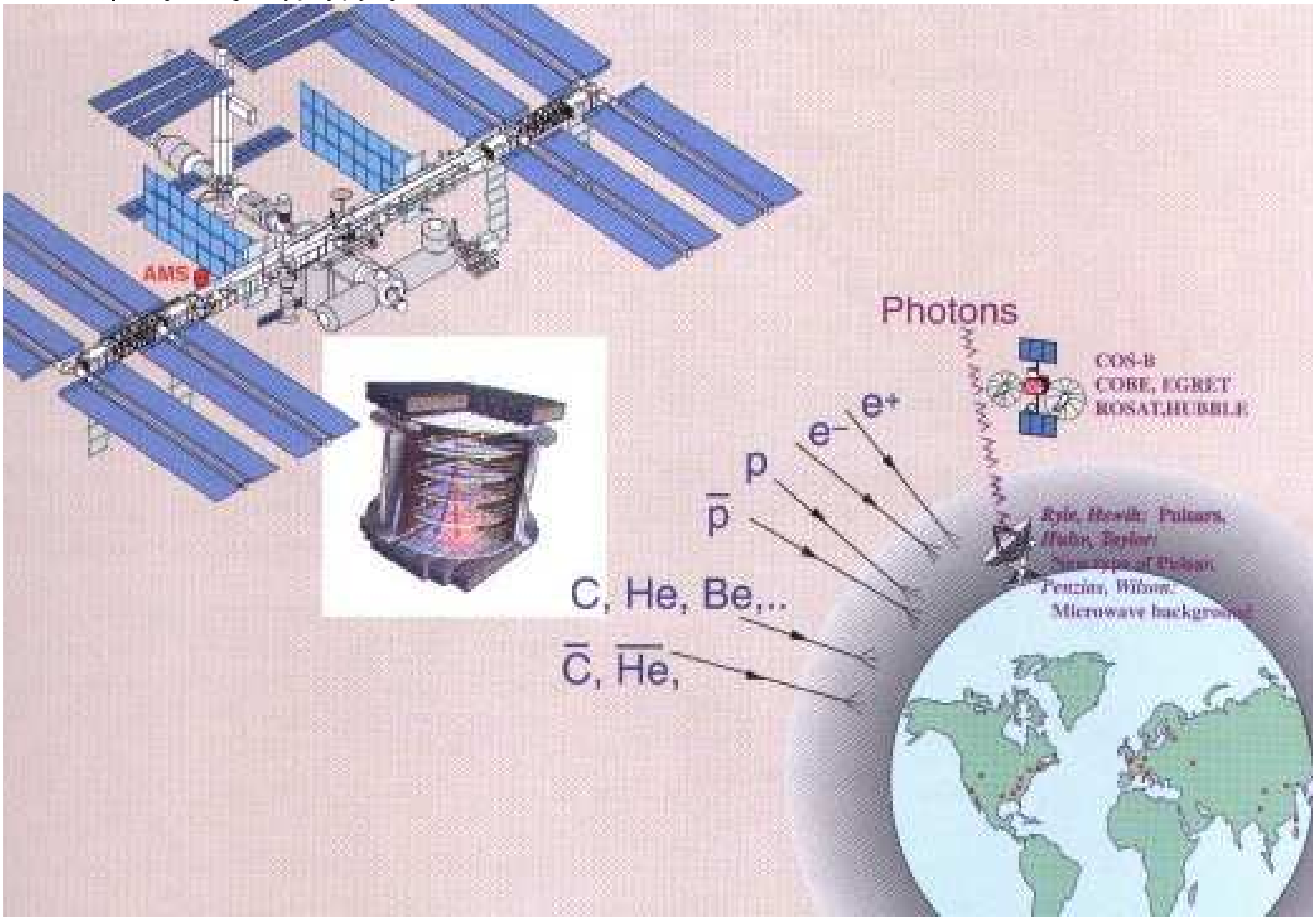
1. The Alpha Magnetic Spectrometer and its motivations:
   - 1.1 Search for Dark Matter
   - 1.2 Search for Antimatter
   - 1.3 Measurement of Charged Cosmic Rays
   - 1.4 The AMS Detector
2. Results from the Discovery flight in 1998
3. A RICH detector on AMS
   - 3.1 Čerenkov radiation principles
   - 3.2 RICH motivations
   - 3.3 Simulation results & analysis

The AMS experiment seeks to understand fundamental issues shared by physics, astrophysics and cosmology
on the origin and structure of the Universe.



Open questions that relate the two frontiers of Physics:

	Large Scale	Small Scale
Dark Matter	• Photon Gravitational Lensing (no matter observed) • Rotation of Spiral Galaxies • Slowing down of universe expansion (?)	• neutrino mass? • SUSY (WIMPs' neutralino?)
Antimatter	• Isotropy of the Cosmic Microwave Background Radiation @ T ~ 3K • No γ-ray excess from matter-antimatter annihilation	• Standard Model • CP-violation • GUT



History:

- the discovery of pulsars by Ryle and Hewish (Nobel Prize 1974);
- the discovery of cosmic microwave background radiation by Penzias and Wilson (Nobel Prize 1978);
- the discovery of new types of pulsars (binaries), a discovery that has opened up new possibilities for the study of gravitation, by Hulse and Taylor (Nobel Prize 1993);
- the discovery that cosmic radiation background is uniform by the Cosmic Background Explorer (COBE) satellite;
- the many dramatic discoveries by EGREI COS-B and the ROSAT satellites as well as the images transmitted by the Hubble telescope. An important example is the discovery of gamma rays and x-rays from neutron stars, by G.Bignami.

Measurements in astronomy imply that up to 90% or more of the Universe is in the form of dark matter.

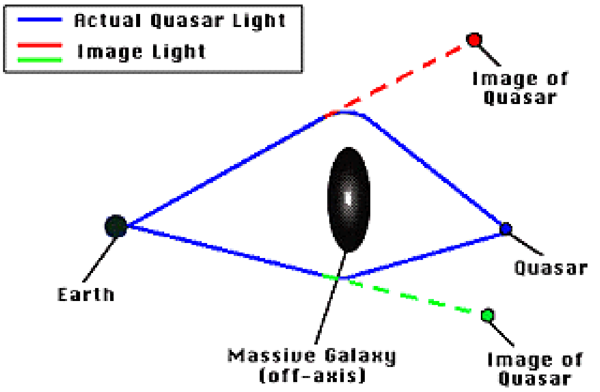
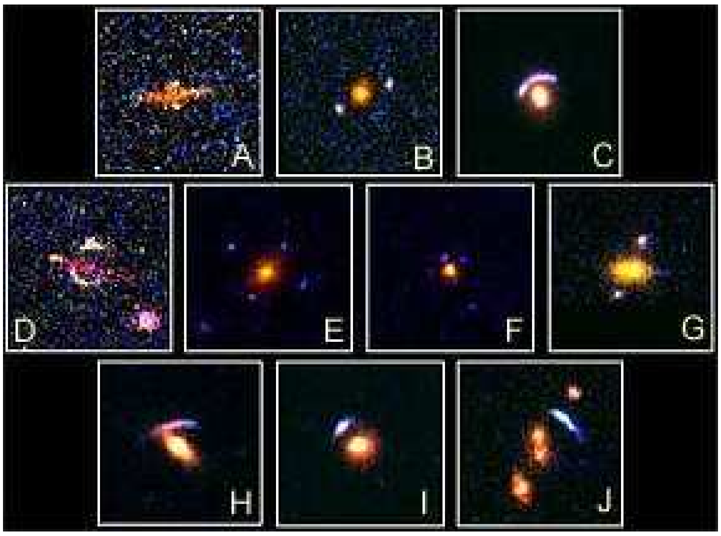
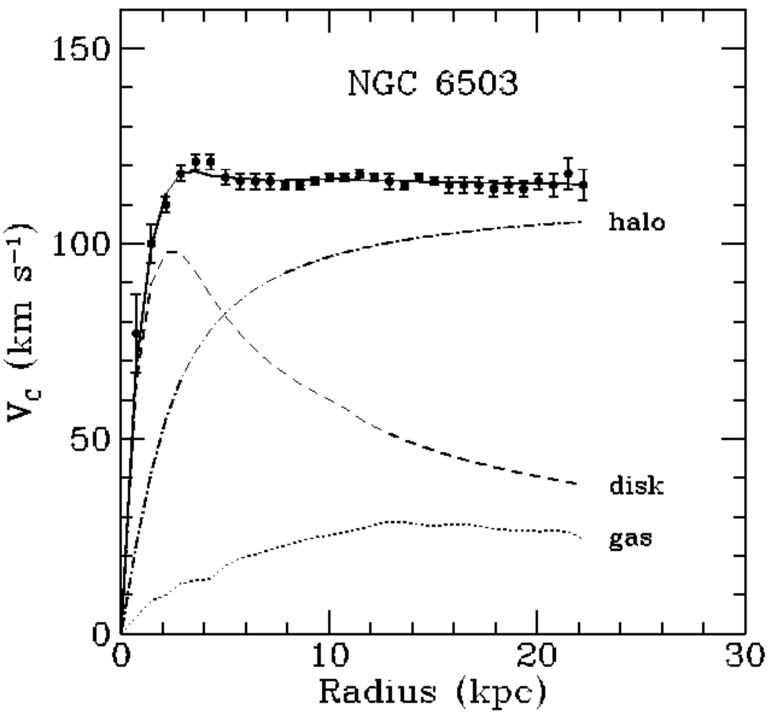


Fig: Depiction of the gravitational lensing effect induced by a massive galaxy (or cluster of galaxies) to the light of a quasar.



Pic: Huble Space Telescope images of optical mirages produced by gravitational lens.
CREDIT: Cavan Ratnatunga (Carnegie Mellon Univ., and NASA,



Pic: Measured rotation curve for the spiral galaxy NGC6503. Contributions from observed disk and gas are shown together with the one from the dark halo.

Dark Matter candidates:

- MACHOs (**M**assive **A**strophysi**C**al **H**alo **O**bjects):

  - primordial black holes ($M < 100\ M_{\odot}$)
  - brown dwarfs ($M < 0.08\ M_{\odot}$)
  - white dwarfs ($M < 0.4 \div 2\ M_{\odot}$)
  - neutron stars ($M < 0.4 \div 2\ M_{\odot}$)
  - planetary type objects ($M < 10^{-3}\ M_{\odot}$); [$M_{\odot}$ = solar mass]

  But MACHO collaboration results (after 8.5×10^6 stars observed in the LMC galaxy) $\Rightarrow$ not enough matter for the DM in the halo of our Milky Way.

- **Neutrinos** ν_e , ν_μ, and ν_τ ("hot" dark matter):

  - There are recent observed hints [S-KAMIOKANDE (Japan) and LSND (USA)] of ν oscillation ($\Rightarrow$ ν has mass)

    · neutrino solar flux

    only 40÷50% of ν_e detected (ν_e oscillation?)

    · behavior of atmospheric ν

    $\pi \rightarrow \mu\nu_\mu$, $\mu \rightarrow e\nu_e\nu_\mu$; ie, $R_{expect} \equiv \nu_\mu:\nu_e \approx 2:1$

    downward going ν's : R_{data} consistent with R_{expect}

    upward going ν's : R_{data} to small (ν_μ oscillation?)

    · LSND experiment:

(target) $\pi^+ \rightarrow \mu^+\nu_\mu$ data: excess of $\overline{\nu_e}$ (from $\overline{\nu_\mu}$?)

$e^+\nu_e\overline{\nu_\mu}$

(in flight) $\pi^+ \rightarrow \mu^+\nu_\mu$ data: excess of ν_e (from ν_μ?)

But data leads to $\Delta M^2_{12} + \Delta M^2_{23} + \Delta M^2_{31} \neq 0$ (CAN'T BE)

- Sterile neutrino (ν_s) ? (Ruled out by SuperK)
- Combination of vacuum and matter-enhanced oscillations?

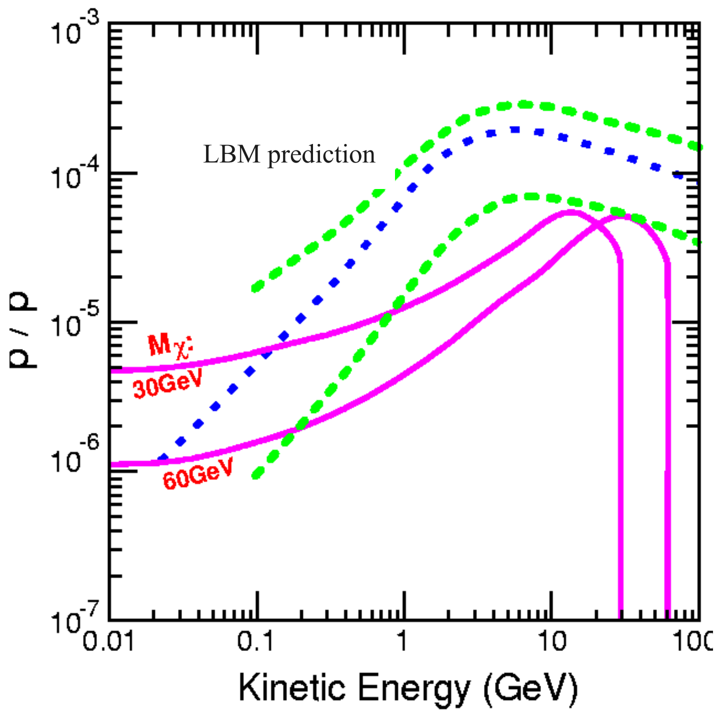
$\Rightarrow$ experiments in progress

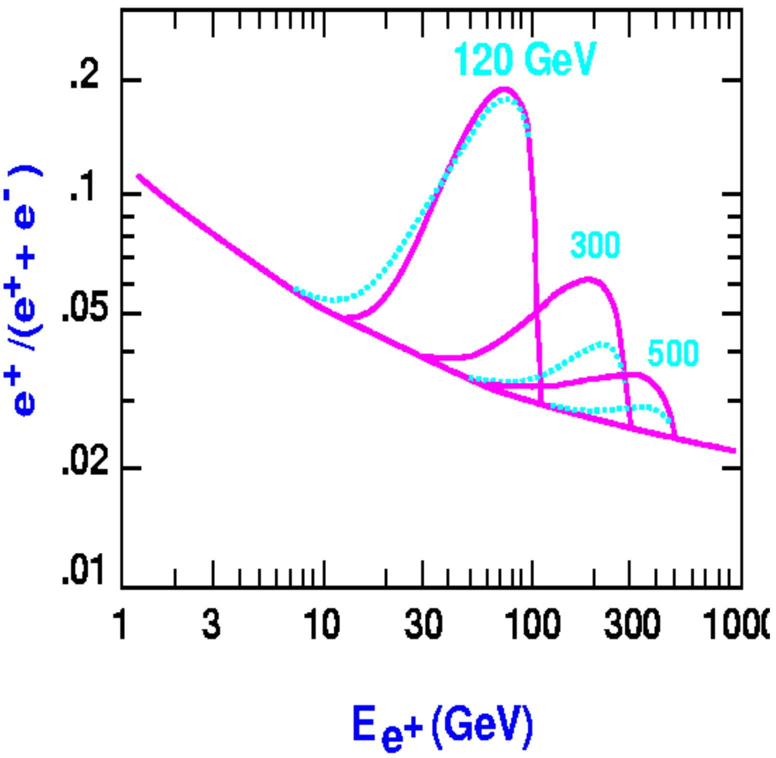
- **SU**per **SY**mmetry "cold" DM (WIMPs)

- Neutralino (χ) is believed to be the Lightest SUSY Particle (LSP) and is expected to be stable $\Rightarrow$ present in todays' universe as a cosmological relic.

- IF the galactic halo consists of χ's (χ is a Majorana part.) THEN

$$\chi\chi \rightarrow \bar{p} + \ldots, e^+ + \ldots, \gamma + \ldots$$





The Big Bang model is validated by three key experimental observations:

- Hubble expantion

  - observed redshift (Doppler effect) of galaxies confirmes the expantion of our universe.

- Relative abundances of light isotopes

  - primordial abundances of D, ^{3}He, ^{4}He and ^{7}Li inferred from observed data are in good agreement with BBN (Big-Bang Nucleosynthesis).

- Uniformity of **C**osmic **M**icrowave **B**ackground [COBE satellite]

  - CMB highly uniform, with T = 2.7 K $\Rightarrow$ radiation from the decoupling (~300 000 yrs after BB) that cooled down.

BUT the Standard Model (confirmed by HEP experiments) implies that matter and antimatter are always created in equal quantities. A fourth basic observation is missing: Antimatter

- COBE results:

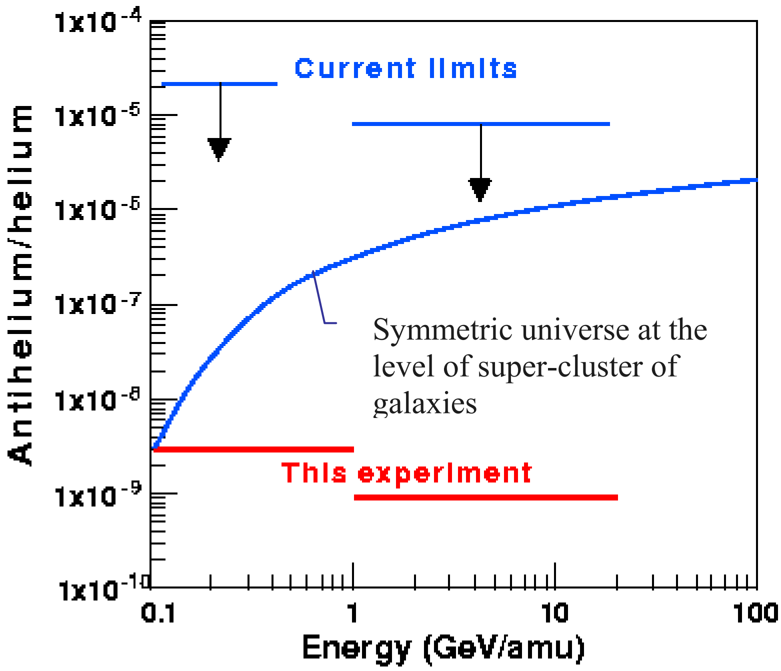
  - No annihilation sources (uniform CMB) $\Rightarrow$ no antimatter (observations relevant to R ~ 10 Mpc)

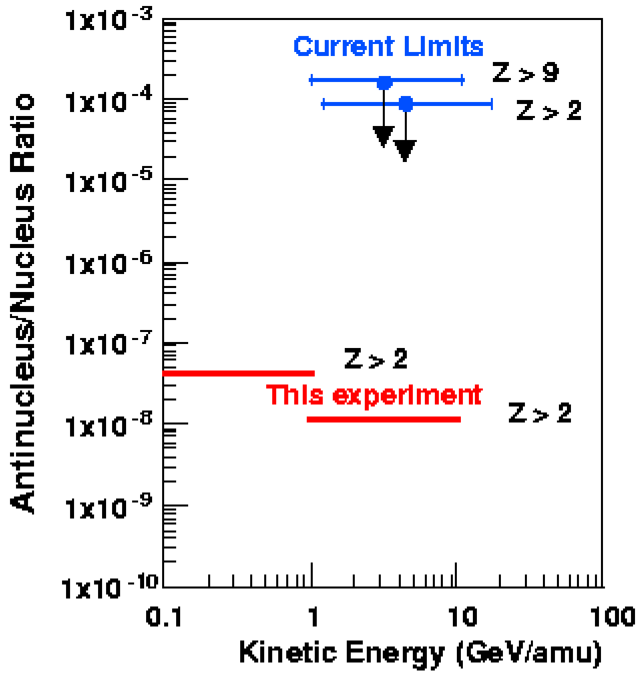
  - Present universe horizon radius ~ 10 Gpc

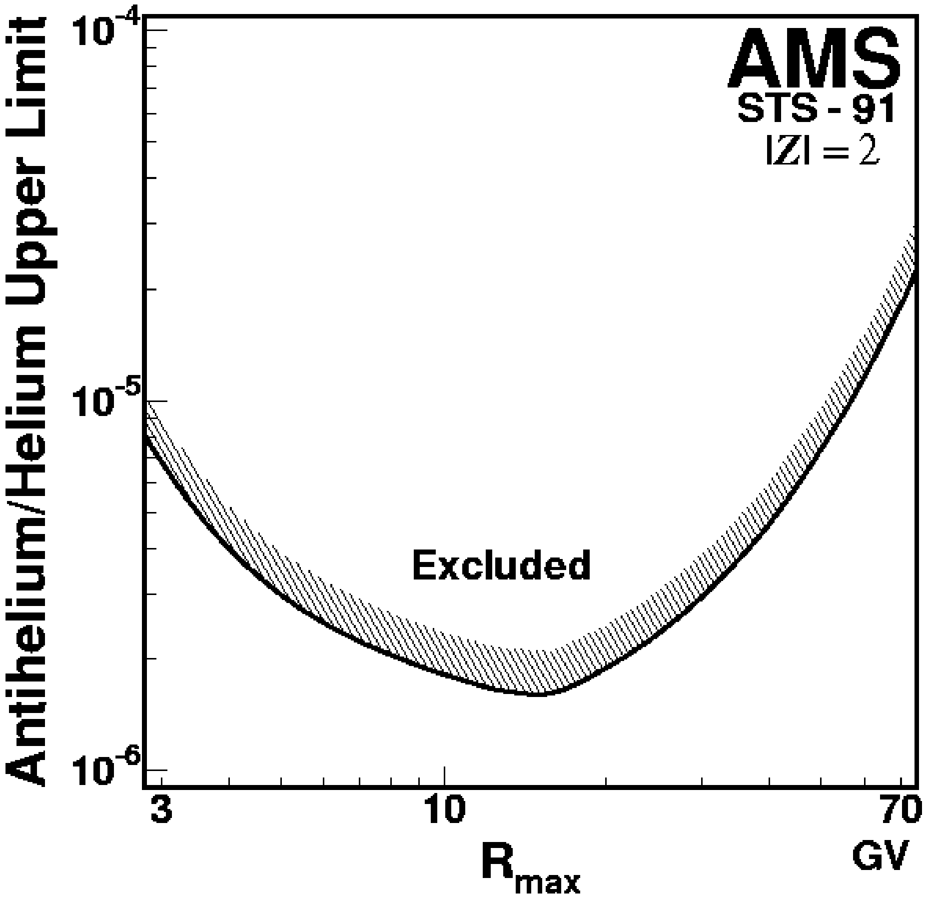
  $\Rightarrow$ we have seen only 1/10^9 by searching for excess annihilation radiation, but there is another method:

- Search for Antinuclei in Cosmic Rays ($\overline{He}$ and $\overline{C}$)

Phys Lett. B461 (Sep 99) 387-398.







- AMS has flown and will fly with a magnet at an altitud of ~370 km.

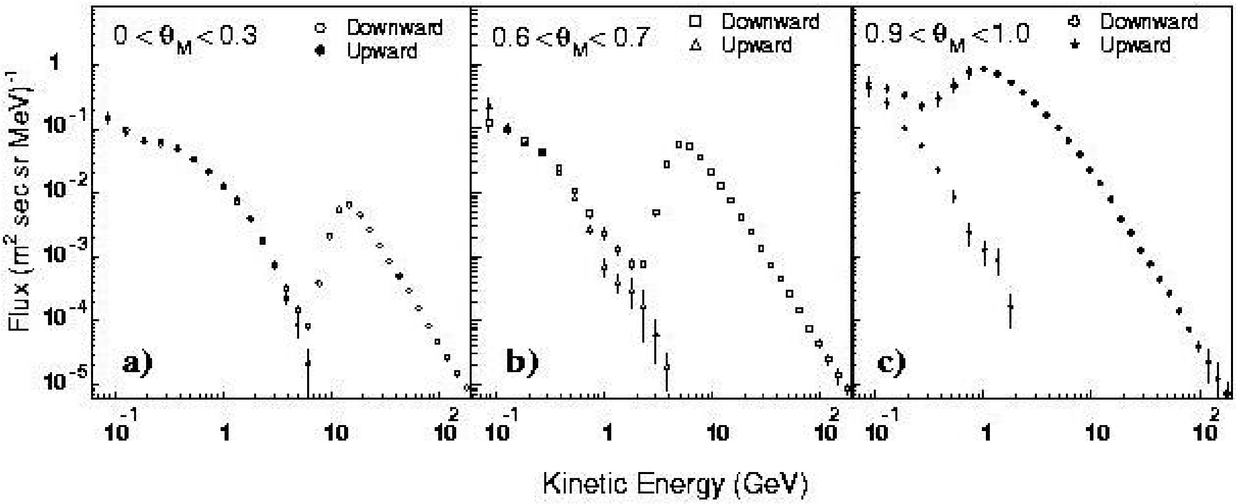
- Precision measurements of isotopes and elemental abundances in Cosmic Rays give very important informations regarding:

- Origin of CR's
  - primary
    - produced in stars, supernovas…
    - spread out by supernova explosions
  - secondary
    - result of interaction of primaries with interstelar gas (mostly p and He)
- CR propagation inside and between galaxies
  - Leaky Box Model
    - no accelerion during diffusion of CR's inside the gallaxy
  - Difusive Reacceleration model
    - CR's accelerated to large energy (by shock waves produced in the aftermath of supernova explosions)
- CR galactic confinement time
  - the $^{10}Be/^{9}Be$ clock

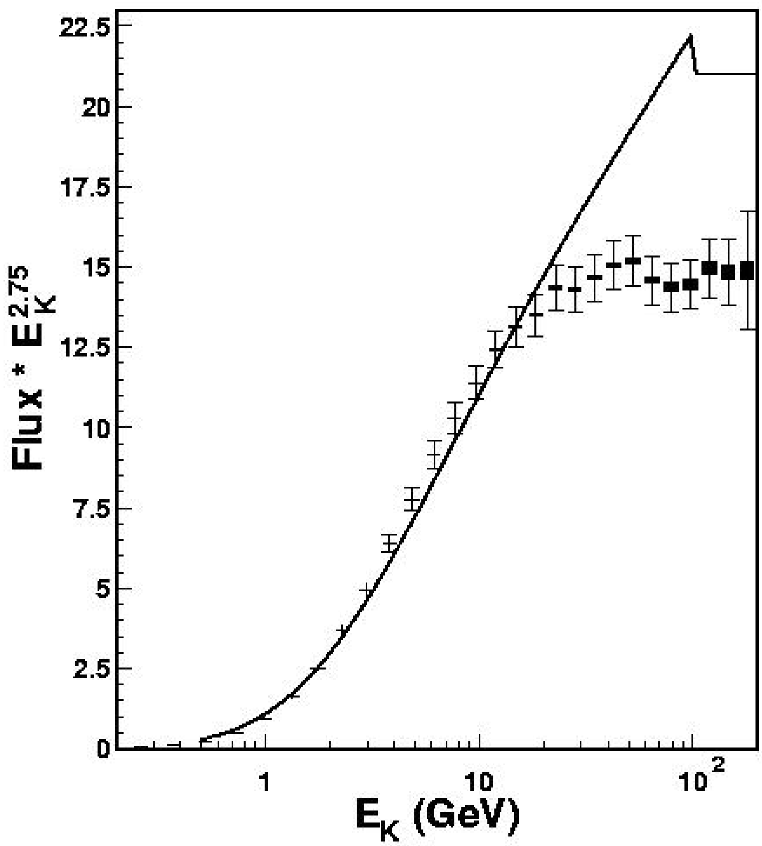
- These three points are deeply related to the search for antinuclei.

Improvement of the BBN ratios (eg. D/p)

Proton flux results:

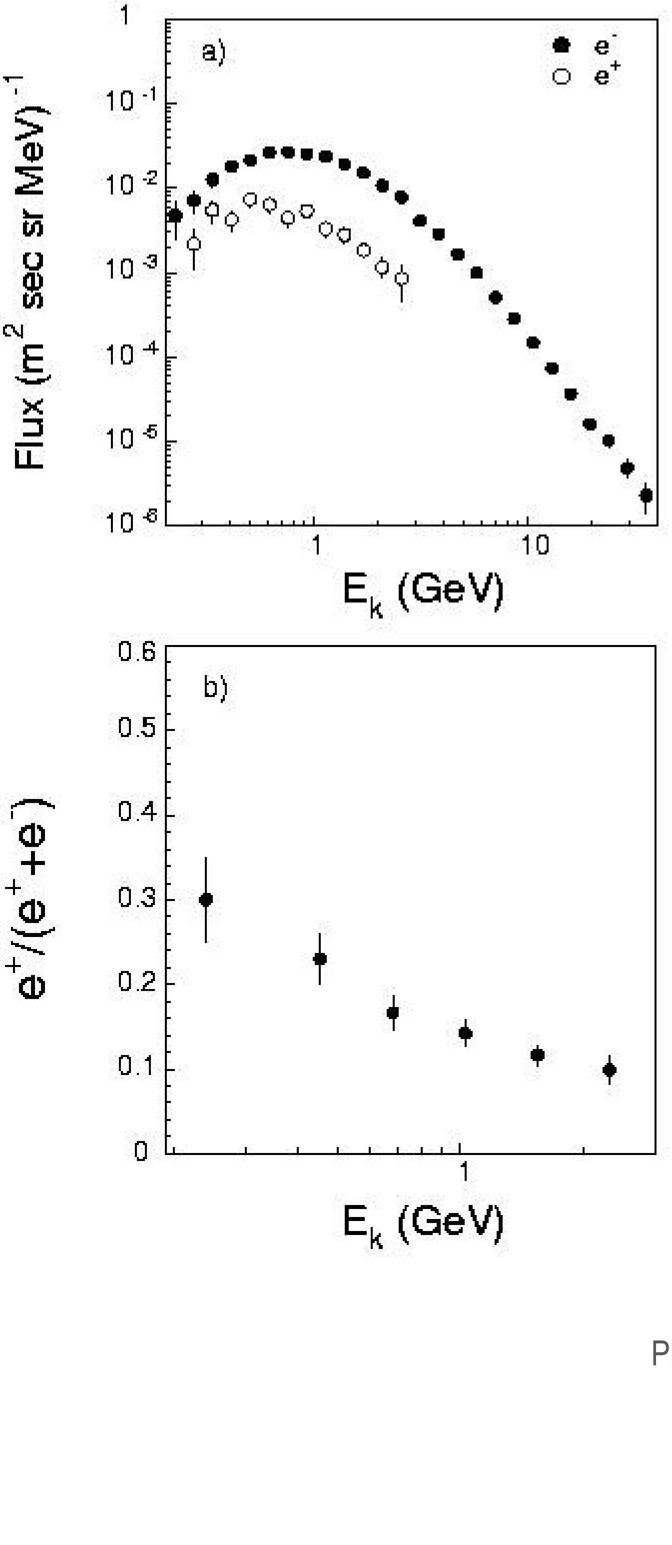


Phys Lett. B472 (Jan 00) 215-226.

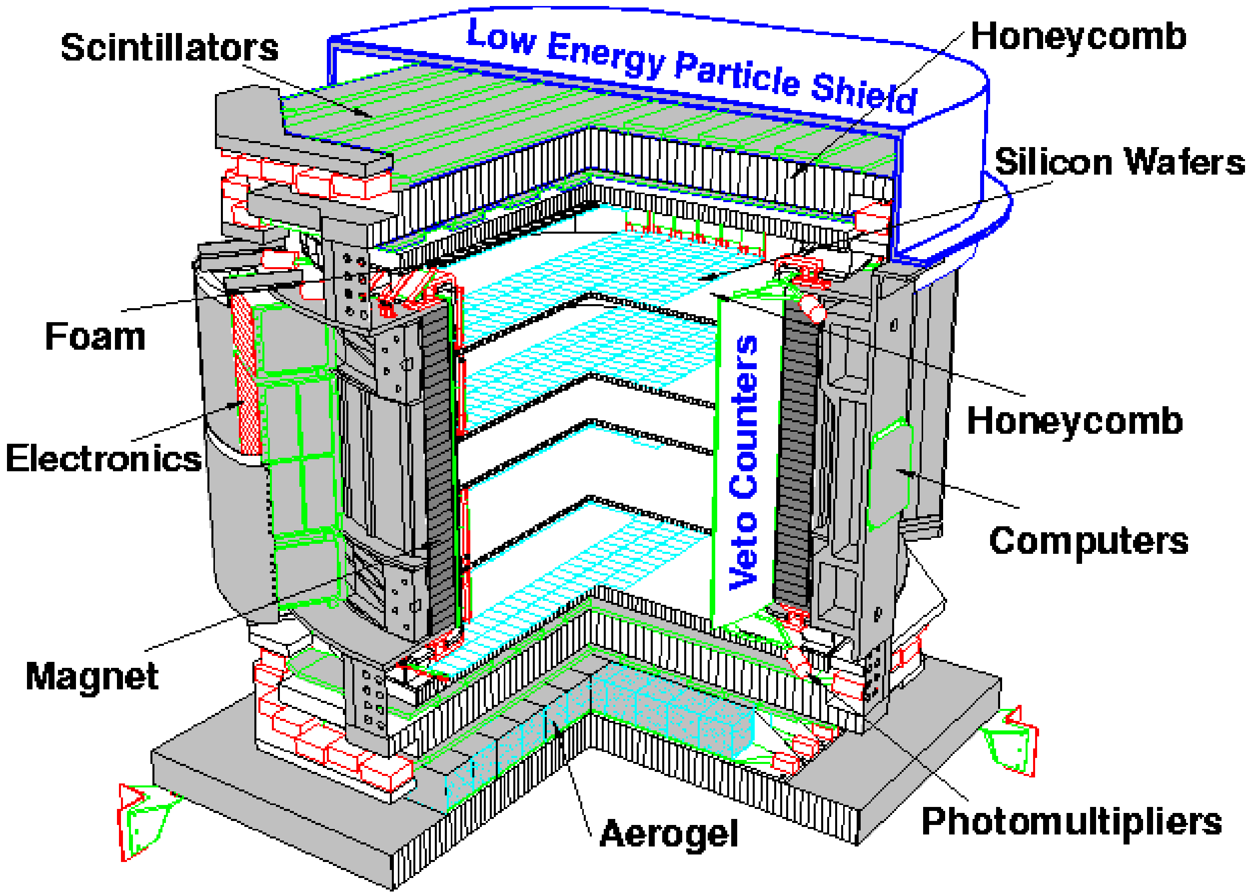


Phys Lett. B490 (Sep 00) 27-35.

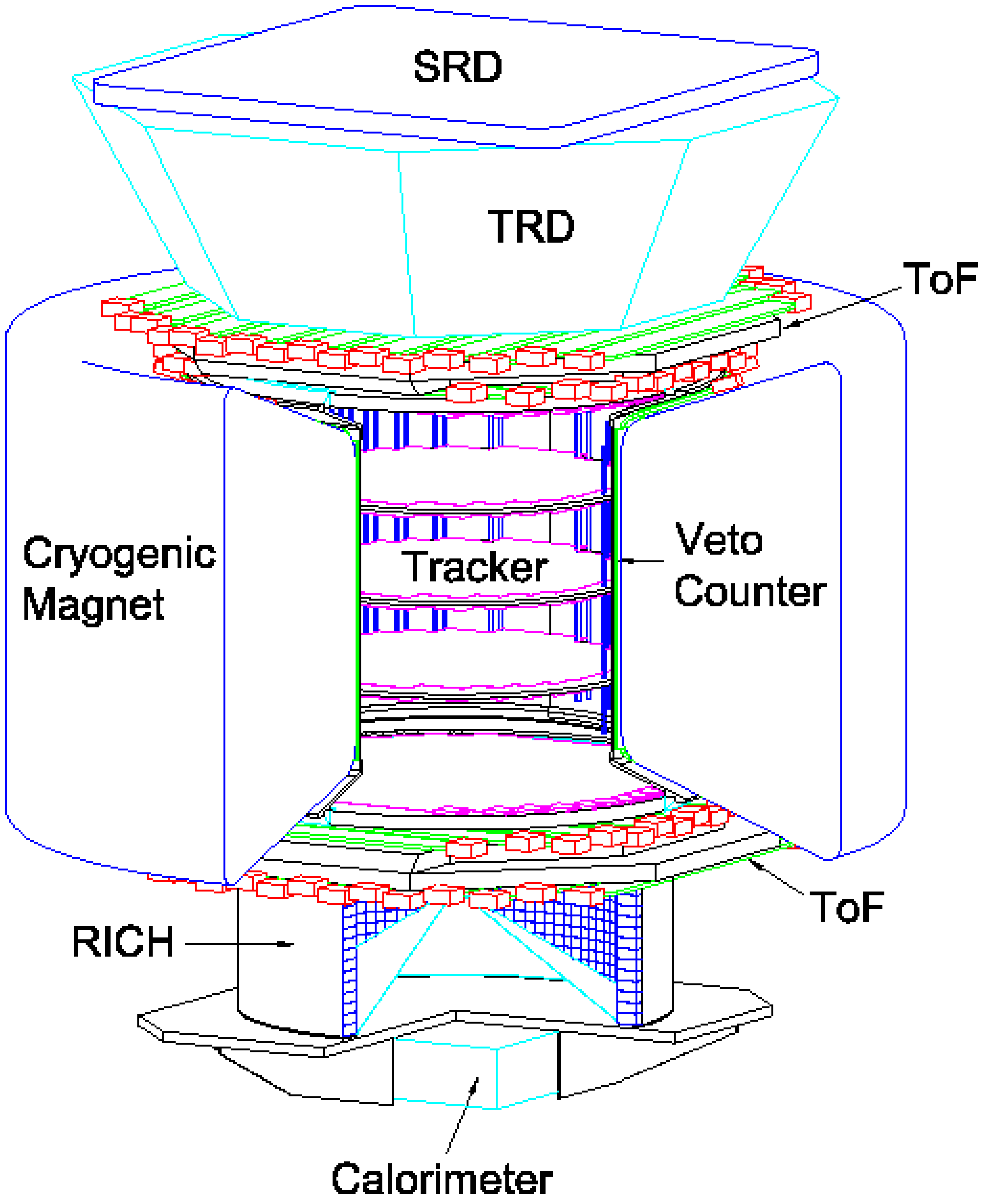
Lepton results:



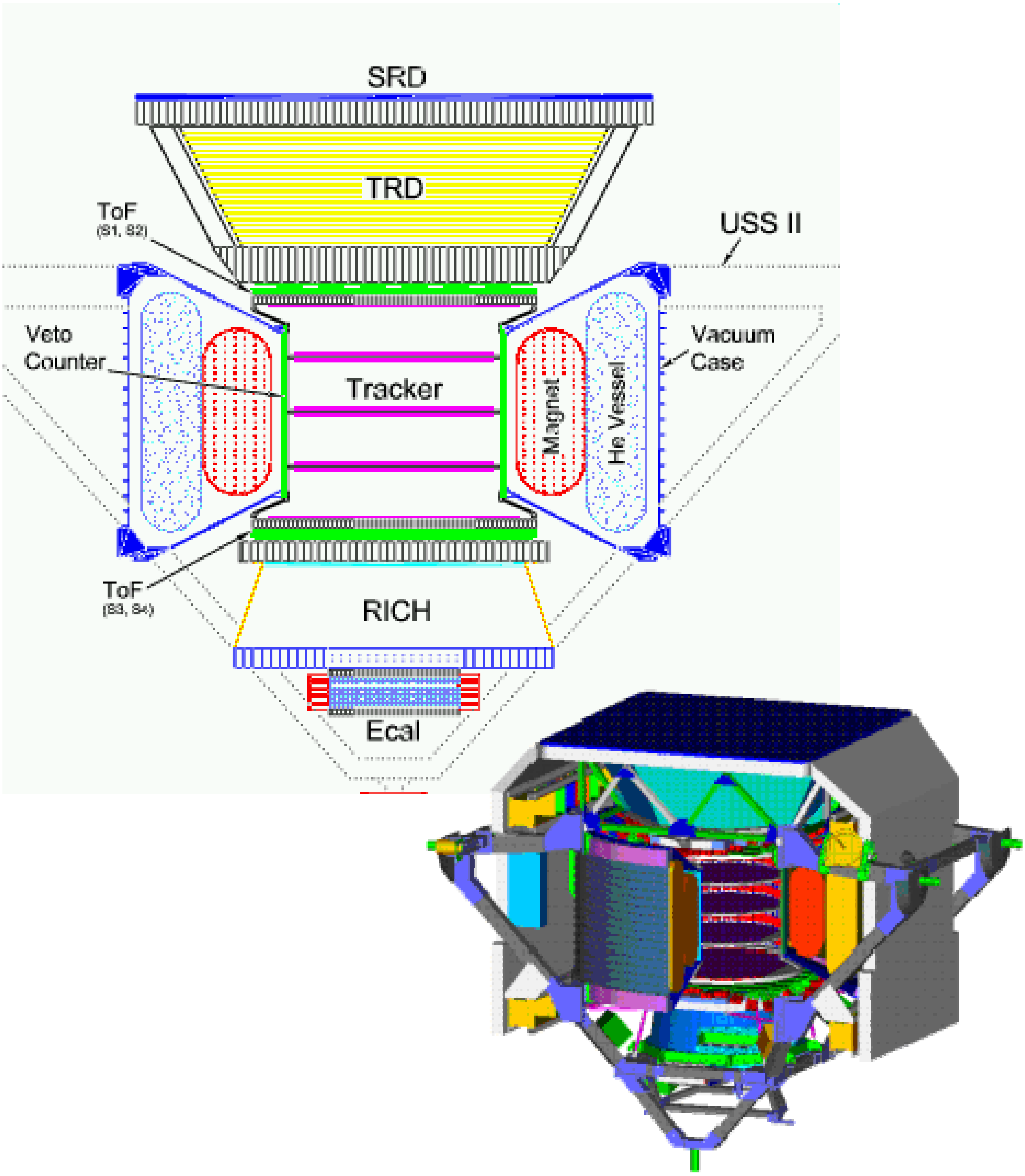
Phys Lett. B484 (Jun 00) 10-22.



Pic: The AMS (phase I) that flew on board the Discovery Space-Shuttle (STS-91 mission) on June-98.
(CREDIT: Robert Becker, CERN)



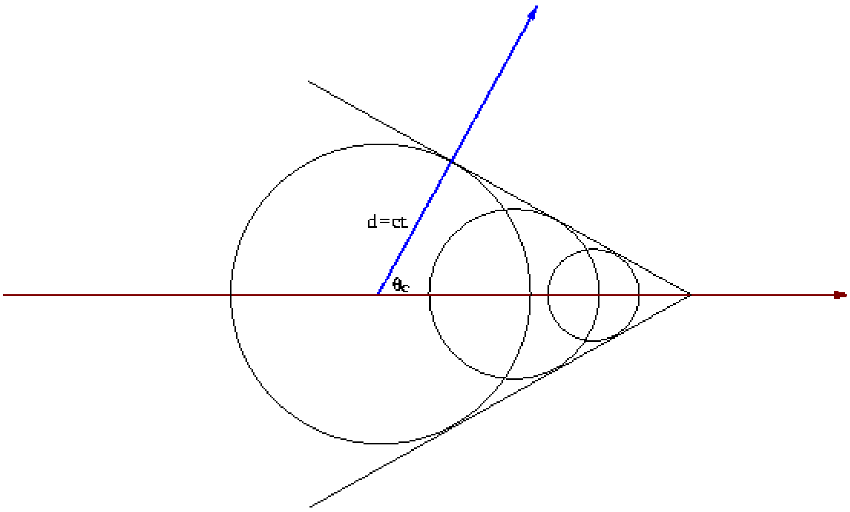
Pic: Intermediate stage of the study of the AMS detector (phase II).
(CREDIT: Robert Becker, CERN)



Pic: The AMS detector (phase II) that is planned to integrate the ISS for a total period of 3 years. SRD still under evaluation.
(CREDIT: Robert Becker, CERN)

A particle will emit an electromagnetic shock-wave in a dielectric medium if

$$V_{part} > C_{diel} \Leftrightarrow \beta_{part} > \frac{1}{n(\lambda)}$$

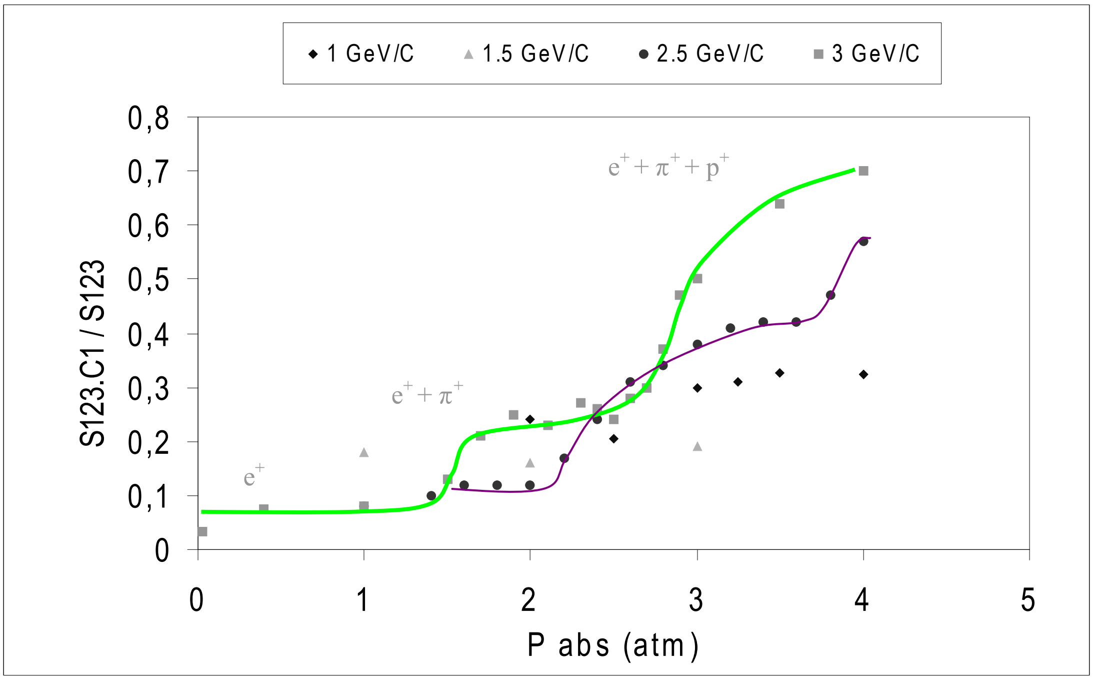


or

$$p_{th} > \frac{m}{\sqrt{n^2 - 1}}$$

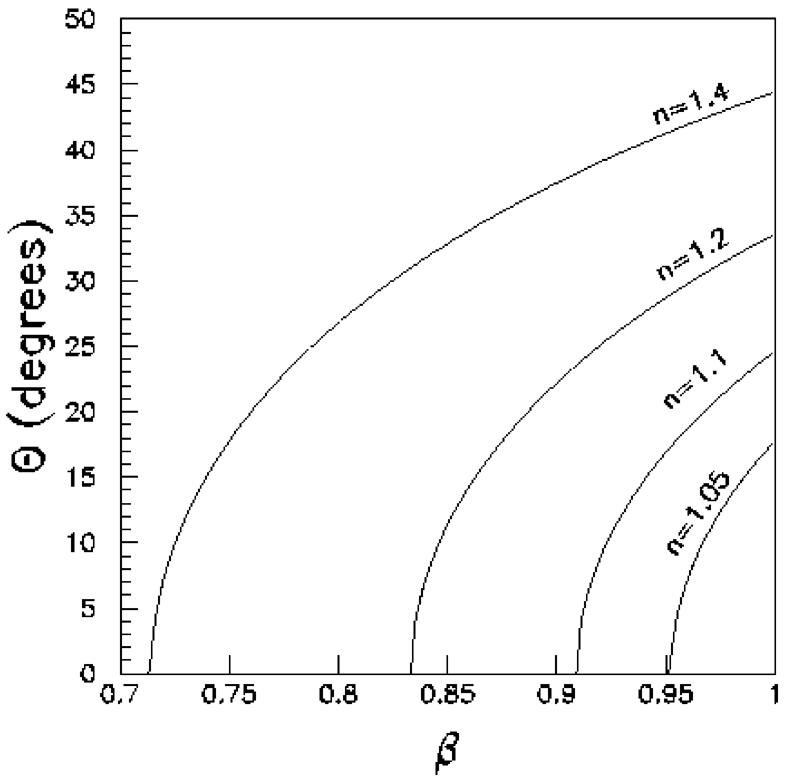
- AMS-I calibration at CERN used an external Čerenkov counter:

$$n - 1 = (n_0 - 1)\frac{P}{P_0}$$



⌊ the emission angle θ_{cer} depends on the the particle speed β and on the index of refraction of the medium $n(\lambda)$:

$$\cos(\theta_{cer}) = \frac{1}{\beta . n(\lambda)}$$



⌊ The light yield is given by

$$\frac{d^2N}{dx dE} = \left(\frac{2\pi\alpha}{hc}\right) Z^2 \underbrace{\left(1 - \frac{1}{\beta^2 n^2}\right)}_{sin^2\theta_c}$$

that is, it increases with

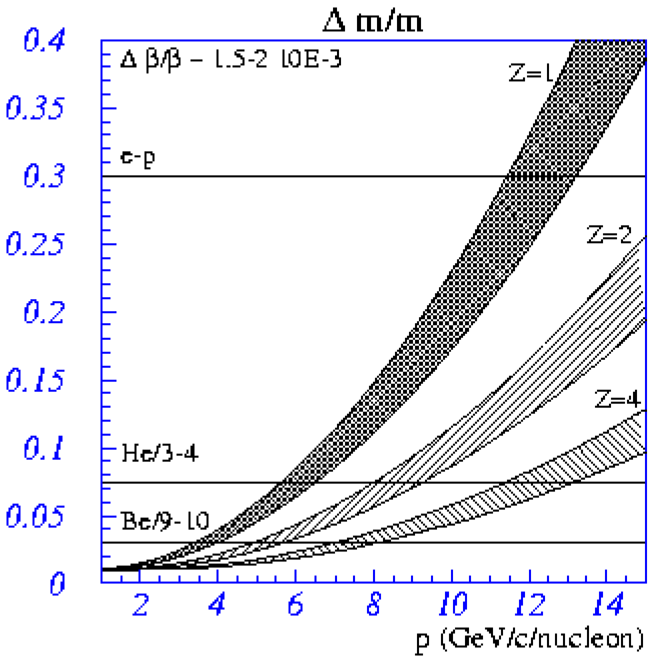
- Radiator thickness (L)
- Charge (Z^2)
- Velocity (β)
- Refractive index (n)

⌊ The detected light depends also on the photon detection efficiency (geometrical reasons and PMTs Q.E.)

Advantages of a RICH detector:

- Albedo rejection & multiple scattering rejection:
  - eliminated by requiring a pure ring pattern
- Particle identification (with p from the tracker) by providing $\Delta\beta/\beta \sim 10^{-3}$

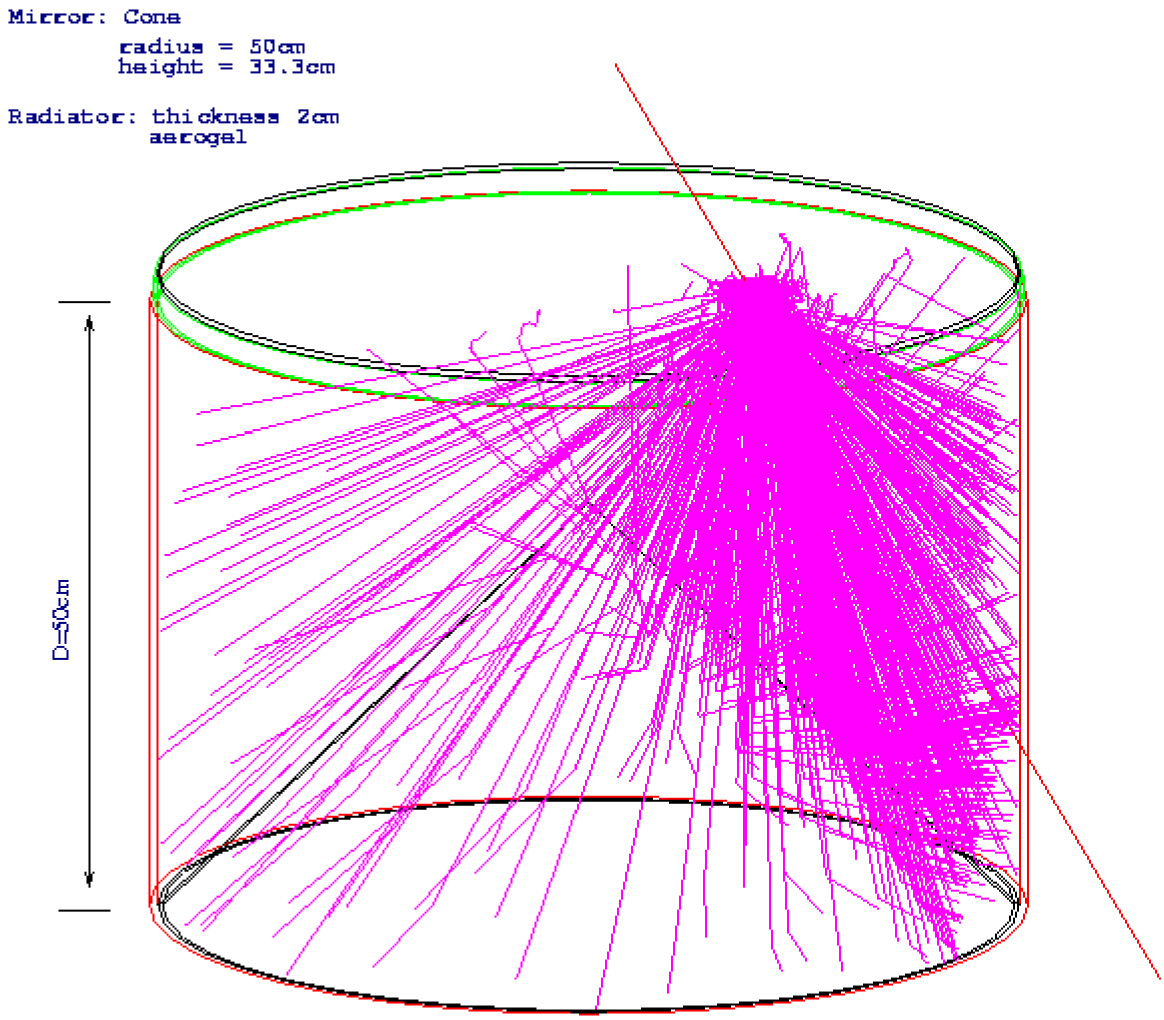
$$\frac{\Delta m}{m} = \frac{\Delta p}{p} + \gamma^2 \frac{\Delta\beta}{\beta}$$



Pic: Mass resolution versus momentum per nucleon for e, p, ^{3}He, ^{4}He, ^{9}Be and ^{10}Be. The horizontal lines mark the 3σ separation assuming $\Delta p/p \sim 1\%$ and $\Delta\beta/\beta \sim 0.15\%$ and 0.2%.

- Identification of $e^{\pm}$ from the geomagnetic cutoff to proton threshold in radiator (5 to 10 GeV/c)
- Improve the anti-nucleus capabilities of AMS by providing an independent measure of $|Z^2|$

The RICH with a conical mirror was simulated through GEANT for different cylinder and mirror heights.



Reconstruction studies: Method

- knowledge of the particle impact point and its direction at the radiator (tracker extrapolation)
- The vertex of the Cerenkov photons is assumed in a single point
- The photon is propagated to the detector plane taking into account:
  - photon refraction in the radiator boundary
  - possible mirror reflection
- The following quantity is minimized for every event, giving the best Cerenkov emission angle.

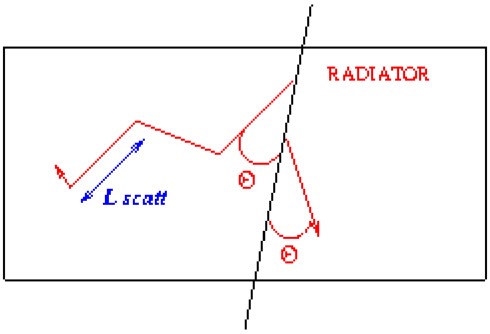
$$\chi^2 = \sum_{i=1}^{N_\gamma} \left(\vec{R}_i^{det} - \vec{R}_i^{hyp}(\theta_c, \phi_i) \right)^2$$

Reconstructed Cerenkov angle

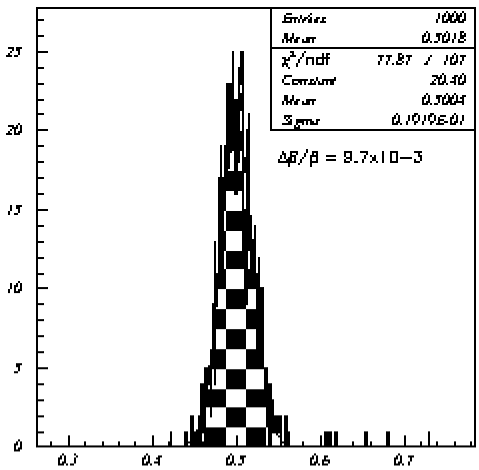
Radiator effects: Rayleigh scattering

The rayleigh scattering is a major effect in the aerogel ($L_{scatt} \sim \lambda^4$).

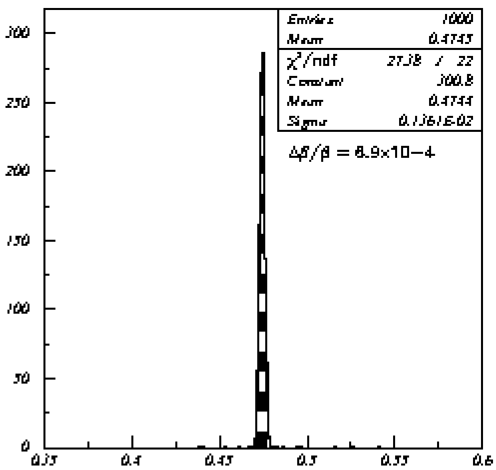
It affects resolution and it shifts systematically the reconstructed Cerenkov angle.



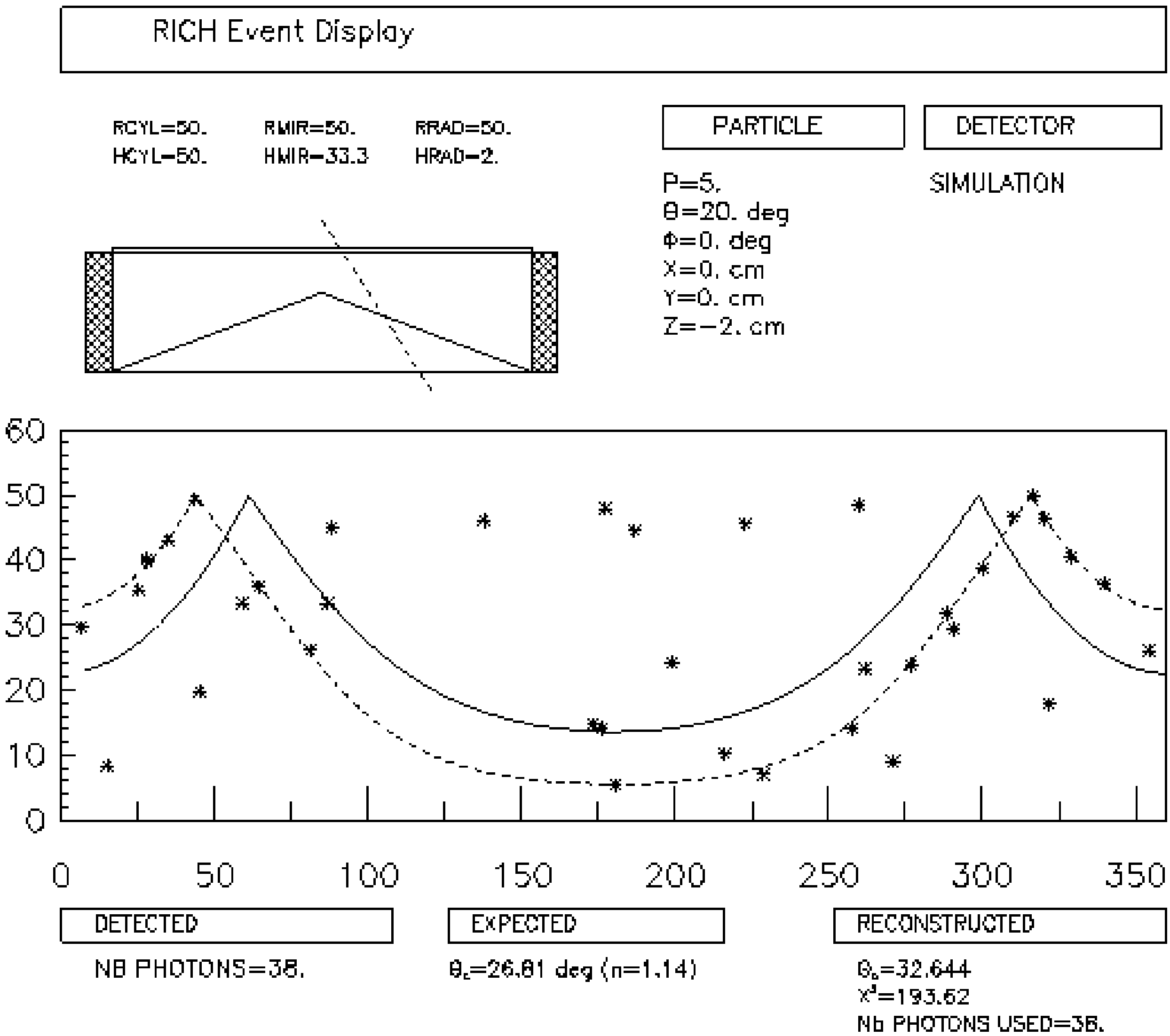
RAYLEIGH ON



RAYLEIGH OFF



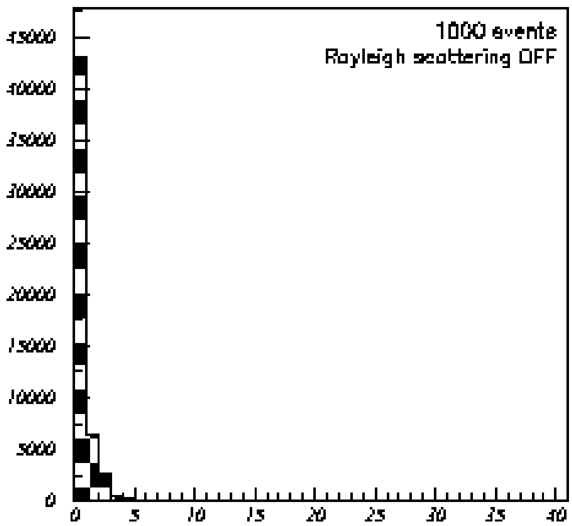
Event display



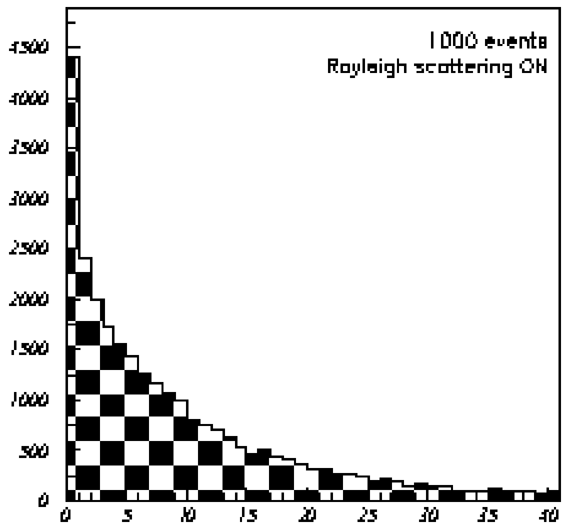
Radiator effects: Rayleigh scattering

The reconstruction method has to deal with the scattered photons.

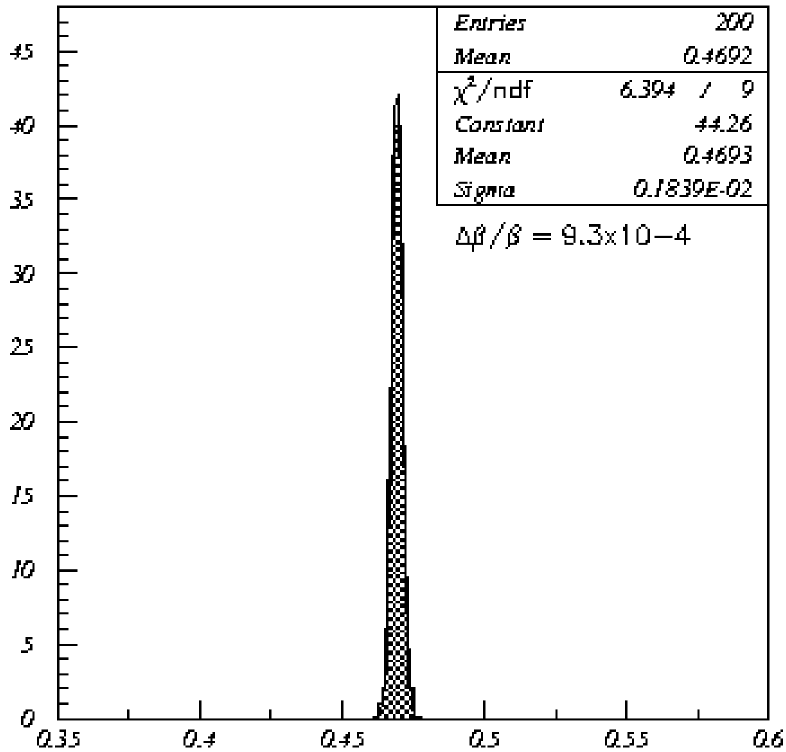
A cut on the χ^2 contribution of every photon can be imposed, keeping a high rate ($\geq$ 95%) of successfull reconstructed events.



Photon χ^2



Photon χ^2

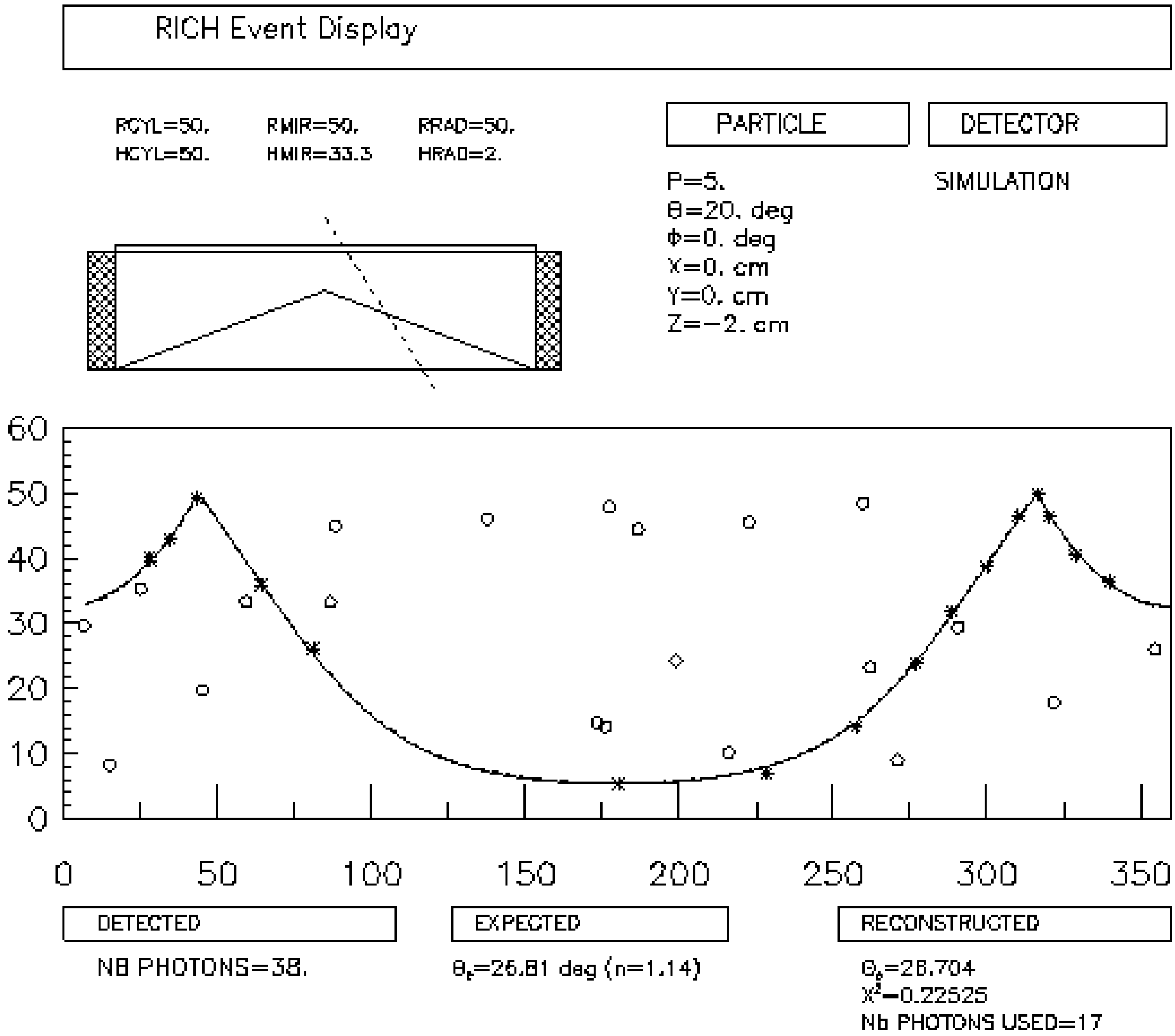


Reconstructed $\theta_{cerenkov}$

Event display

CUTS:

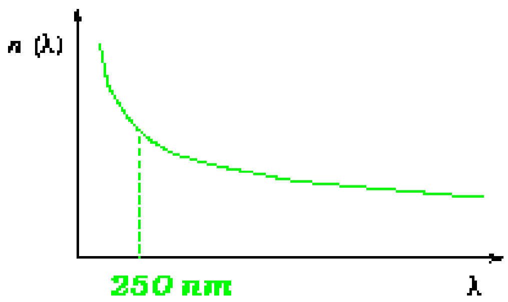
- χ^2/photon < 5 $\quad (N_\gamma^{rec}/N_\gamma^{det} > 20\%)$

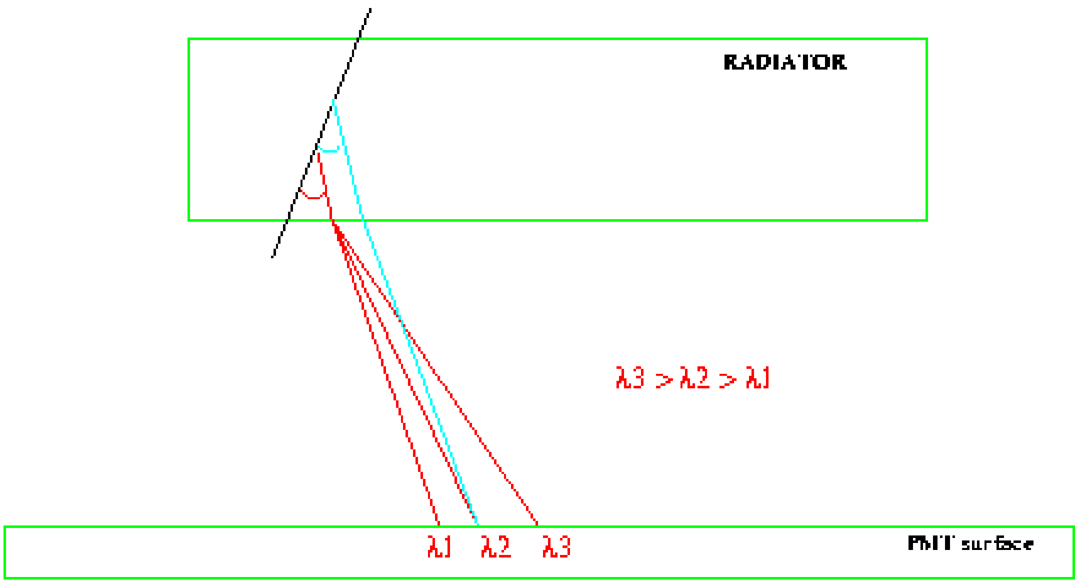


Radiator effects: chromatic dispersion

Chromatic dispersion, altough not as crucial as Rayleigh scattering, will also worsen $\Delta\beta/\beta$ and introduce a bias in the value of θ_c.

$$n(\lambda) \sim a + b/\lambda^2$$





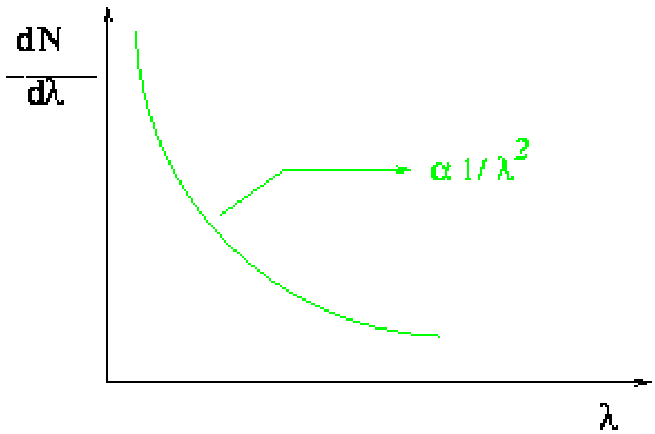
Radiator effects: chromatic dispersion (cont'd)

Let's assume the existence of a Mylar foil cutting wavelengths lower than $\lambda_{cut} = 320$ nm.

The chromatic dispersion will be reduced, but ...

it also reduces the total Nb of detected γs

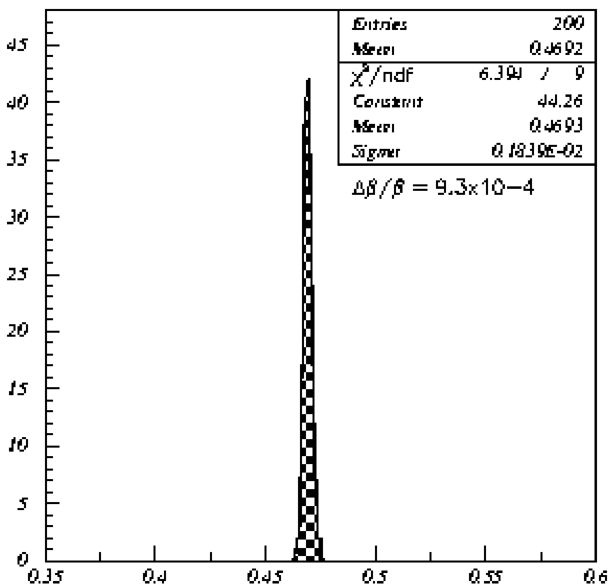
QUESTION: Does it improve β resolution?



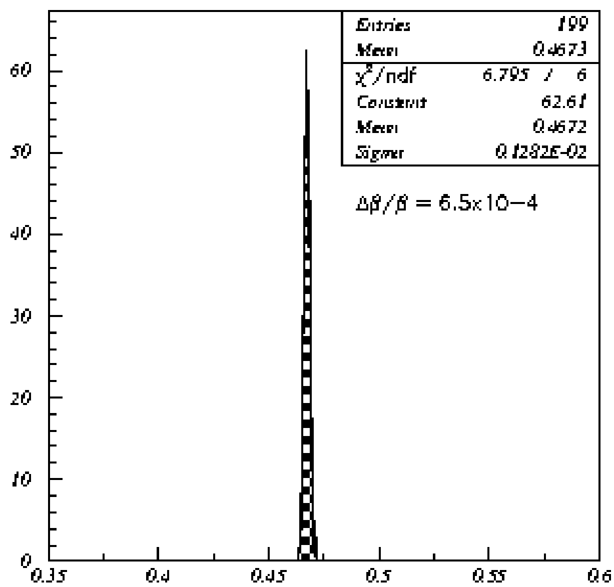
Radiator effects: chromatic dispersion (cont'd)

ANSWER: The cut on λ DOES reduce $\Delta\beta/\beta$

NO CUT IN λ



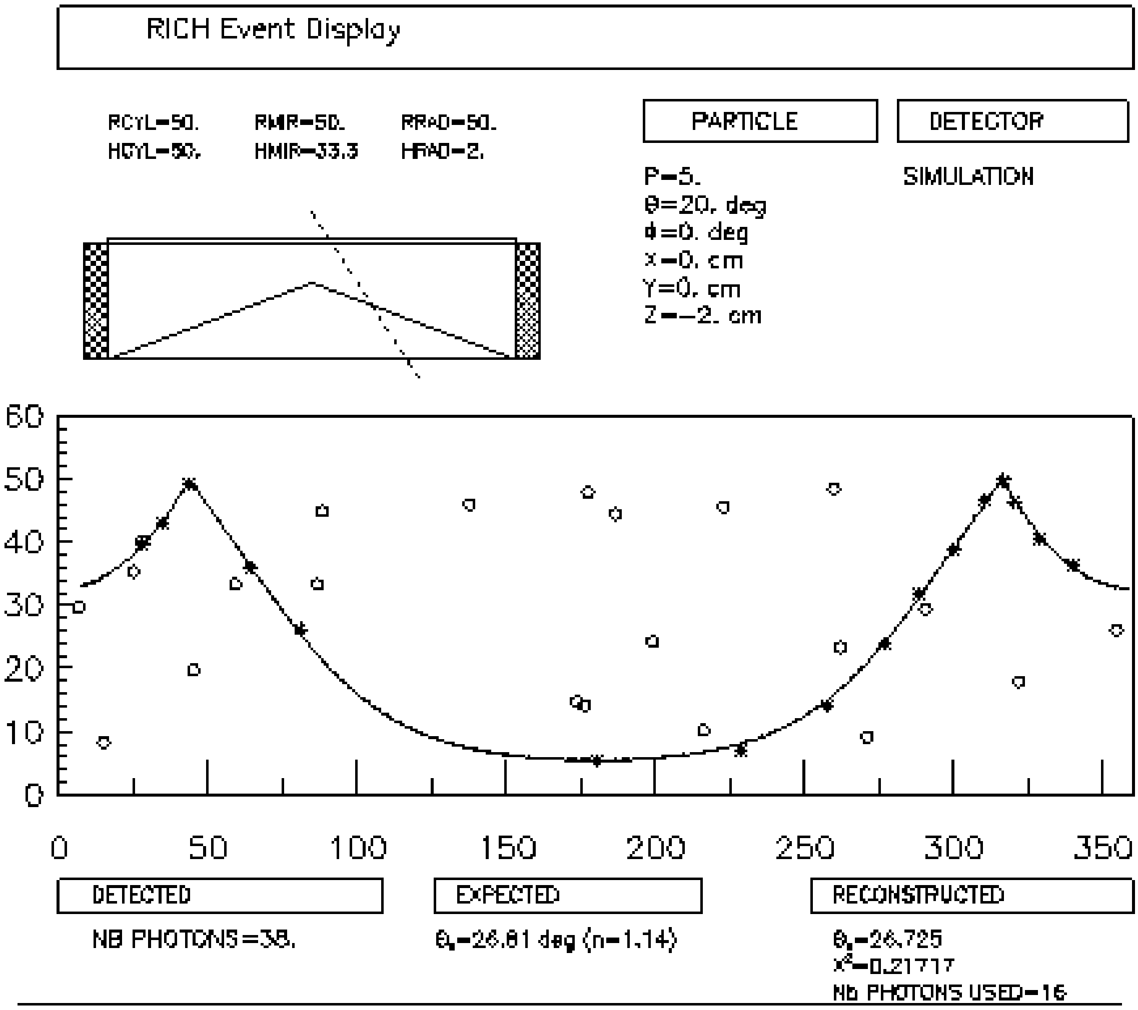
λ_{cut} = 320 nm



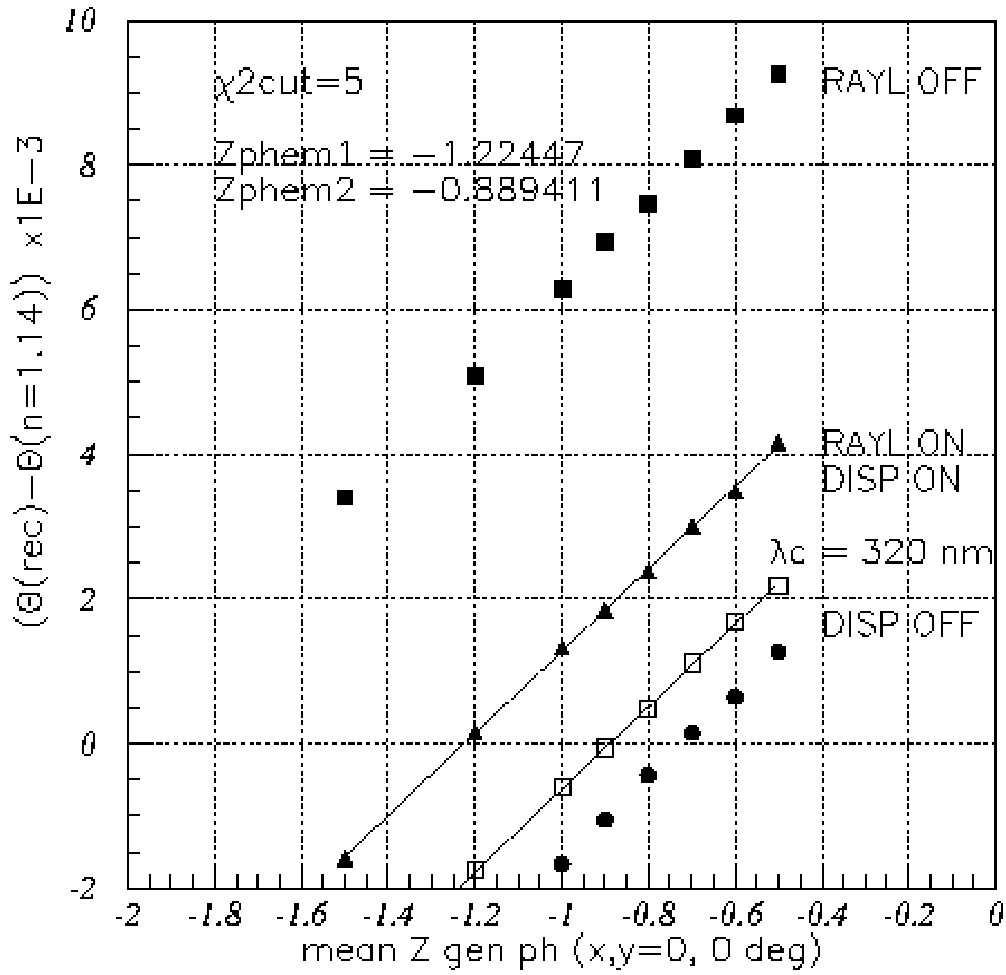
Event display

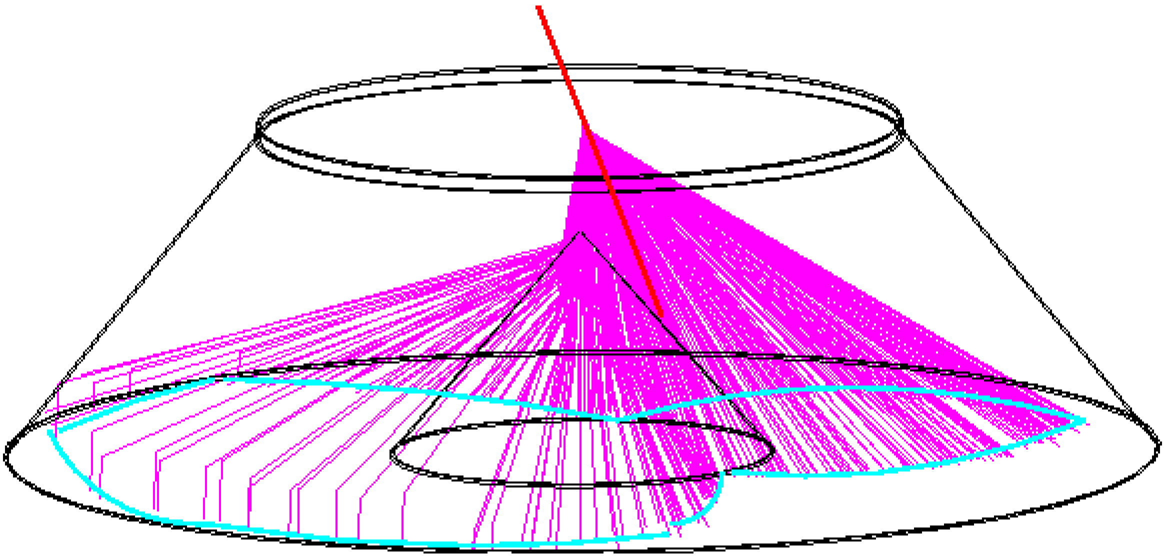
CUTS:

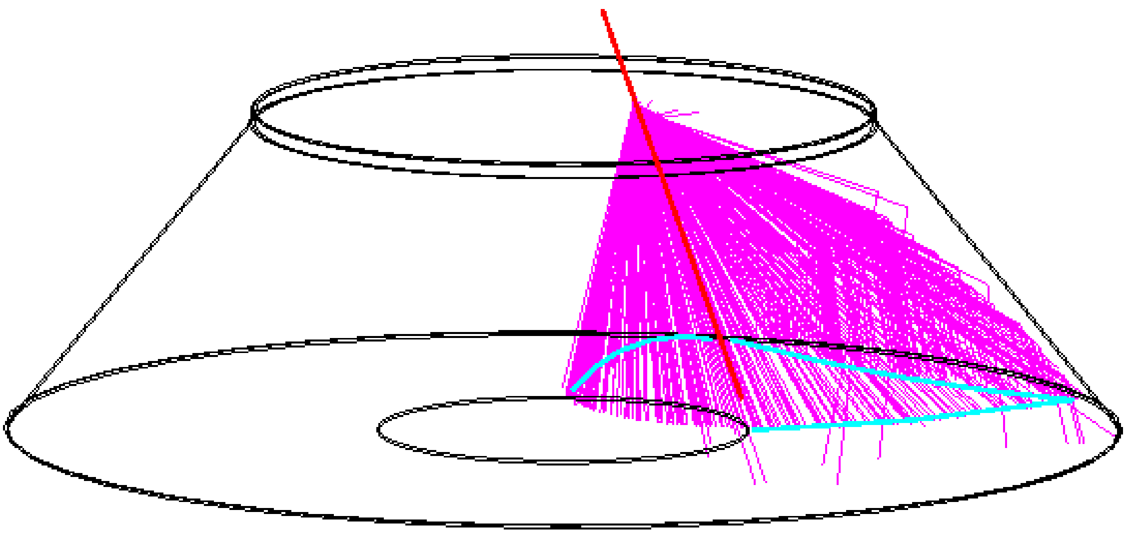
- χ^2/photon < 5
- $\lambda > 320$ nm

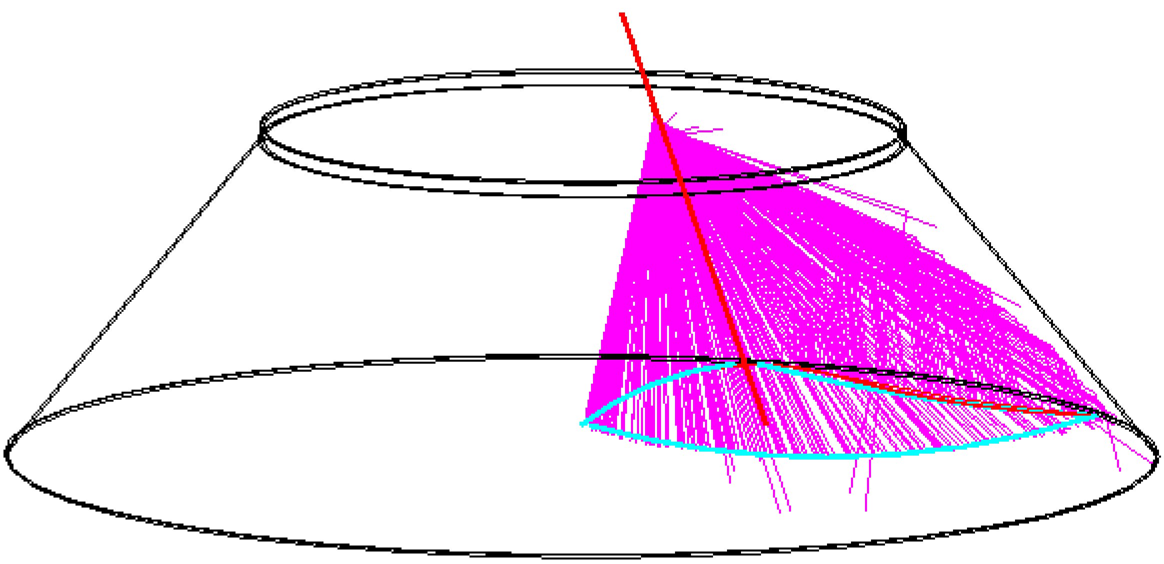


Systematic bias on θ_c









- The final version of the RICH, due to the magnetic field problem, is now a proximity focusing one, with a hole on the surface overlapping he ECAL.

- Some results from AMS-I:
    - Radiation belt at 400 km altitud:
      Excess of protons below geomagnetic cutoff (explained).
    - Excess of under cut-off ^{3}He found (to be published).
    - Ratio $e^+ / (e^+ + e^-)$ is as expected for primary leptons.