Status and results of the AMS-02 experiment

L. Arruda on behalf of LIP-AMS group

Jornadas LIP 2014

The AMS experiment

- Broad international collaboration for the detection of primary CRs in space: around 500 scientists, >50 institutes from 17 countries
- LIP group:
  - Team leader: Fernando Barão
  - 1 Post-Doc: Luísa Arruda (R.Pereira left Nov 2013)
  - 2 Master Students: Pedro Nunes & Miguel Orcinha
  - 2 former master students:
    - L. Batalha - Solar Modulation effects on Cosmic Rays: Modelization with force field approximation, 1D and 2D numerical approaches and characterization with AMS-02 proton fluxes , IST, July 2012
    - B. Santos - Effect of Cerenkov polarization in the cosmic rays charge reconstruction: charge reconstruction with RICH/AMS-02 data, IST, Nov 2013

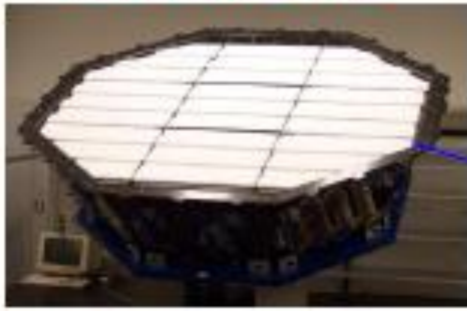
The AMS-02 detector on the International Space Station

The AMS experiment

- AMS-02 installed on ISS on 19th May 2011 for direct detection of Galactic CRs
- Data taking: ~until 2020 or more on the ISS
- Main goals:
  - *Detailed study of CR spectra* (~100 MeV and ~1 TeV)
    - Charge identification up to iron (Z=26)
  - *Search for dark matter*
  - *Search for antinuclei*
- LIP group works mainly on RICH detector & data analysis
  - Beta and electric charge measurement
  - e/p separation at low energy
  - Solar modulation effects on AMS data
  - Deuteron fluxes measurement, d/p separation

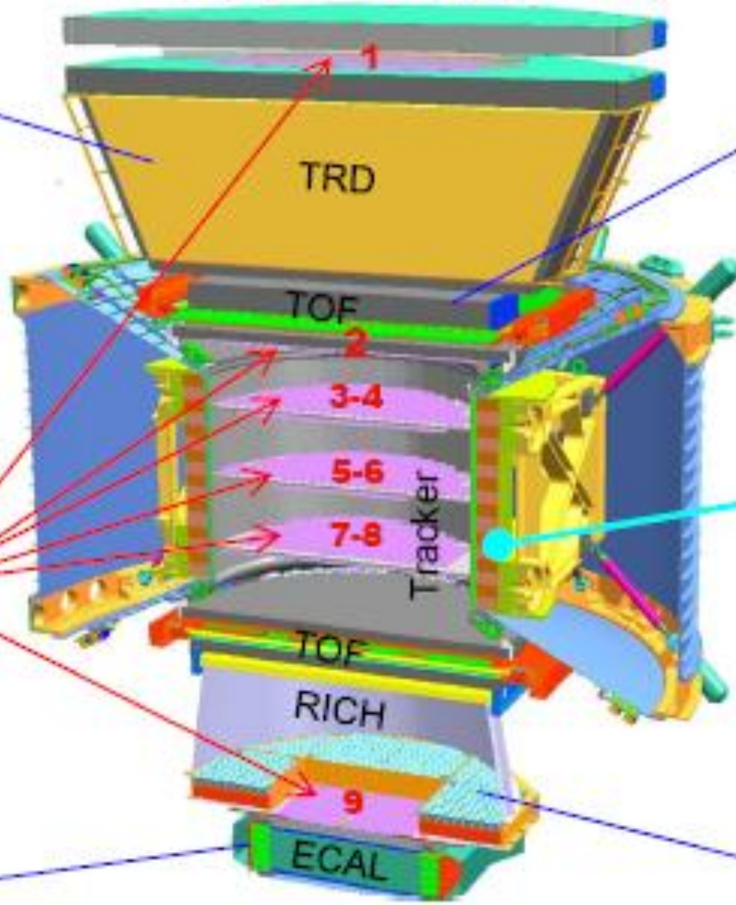
AMS: A TeV precision, multipurpose particle physics spectrometer in space.

TRD
Identify e+, e-

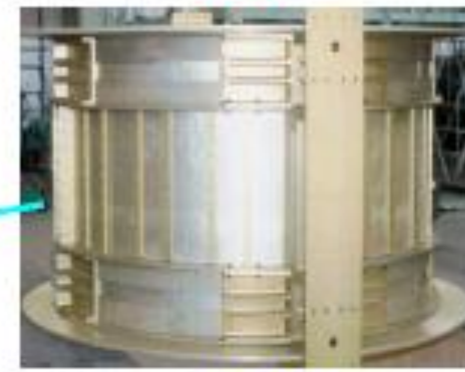


Particles and nuclei are identified by their charge (**Z**) and energy (**E ~ P**)

TOF
Z, E



Magnet
±Z



Silicon Tracker
Z, P

RICH
Z, E

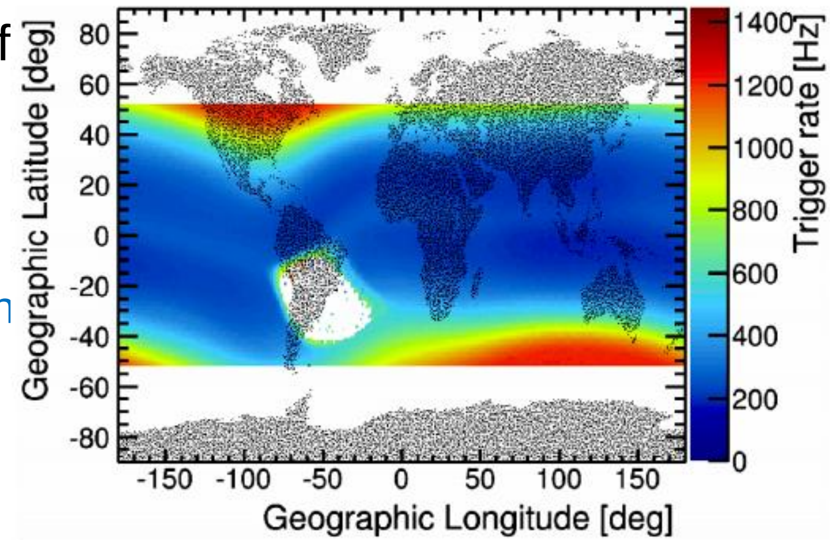
ECAL
E of e+, e-, γ

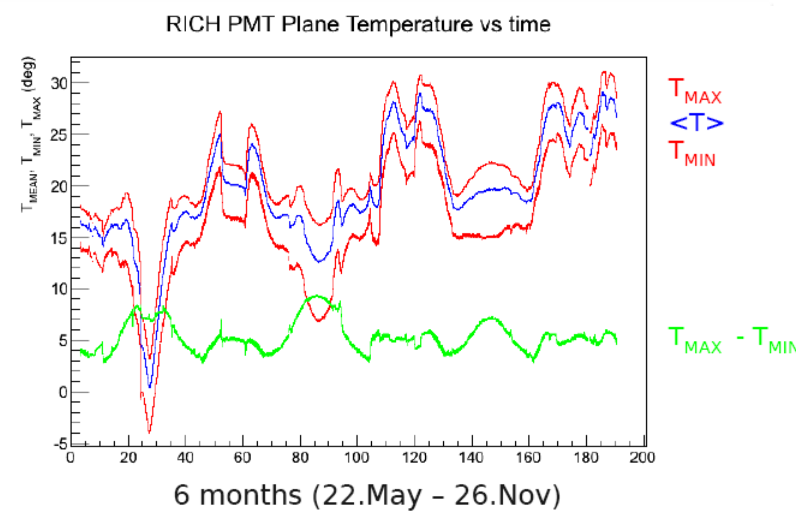
5m x 4m x 3m   7.5 tons

***Z, P** are measured independently from Tracker, RICH, TOF and ECAL*

AMS-02 on the ISS

- ✔ orbiting around Earth at around 400 Km of altitude
  orbit ~ 90 min long
- ✔ around 40 million events gathered/day
  ~ 100 GBytes to transfer/day at 10 Mb/s through relay satellites (TDRS)
- ✔ 16 x10^9 triggers/year
  35 TBytes of raw data
- ✔ 46 billions of events collected till now (Mar 2014)
- ✔ Detector monitored 24h/24h from a Payload Control Center installed at CERN (Geneva) and in Taiwan
  (LIP has one week assigned each 2 months)
- ✔ Extreme thermal environment in Space
- ✔ Data Analysis performed at CERN computers
  More computer power/storage needed @LIP

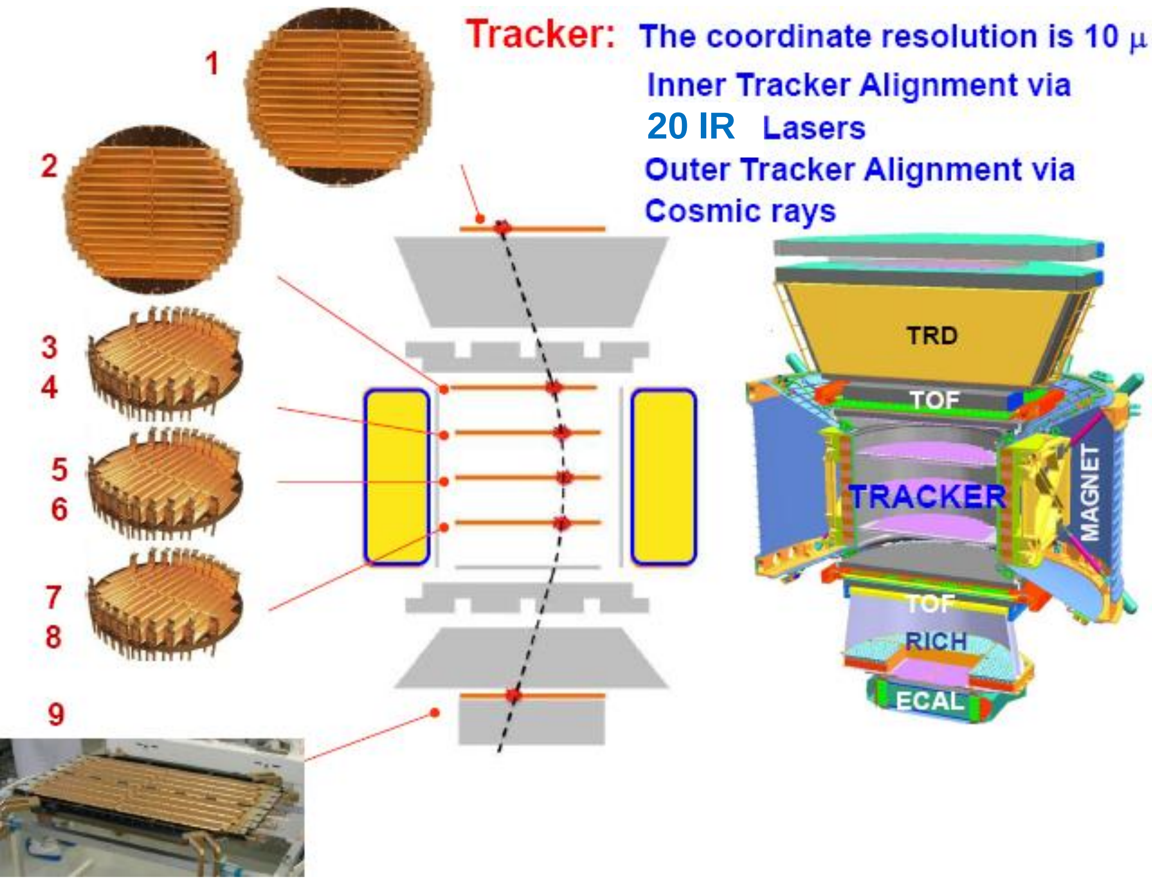




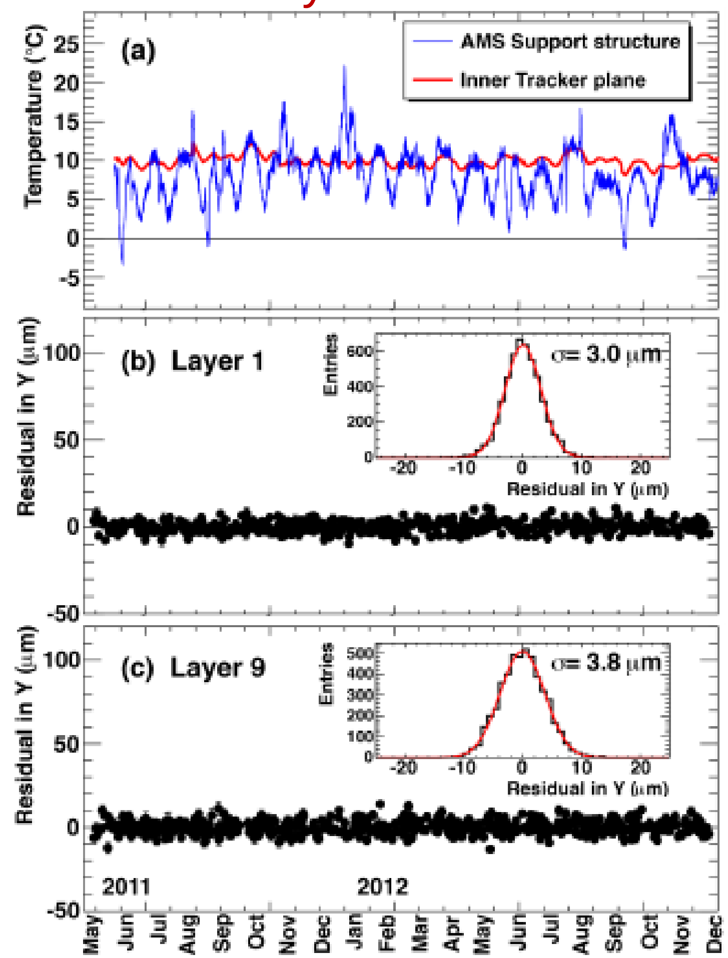
RICH: PMTs [-25,+45]
HV [-15,+60]
ERPD [-15,+45]

Detector Systematic studies

- During the first 2 years of AMS on the ISS the colaboration was concentrated on controlling systematics.
  - ***Tracker alignment***



1 year & half



TRD operation

- ***TRD refill*** twice per month: leakrate 5µg/s by CO_2 diffusion.

  Onboard gas supplies ensures ~30ys operation in Space

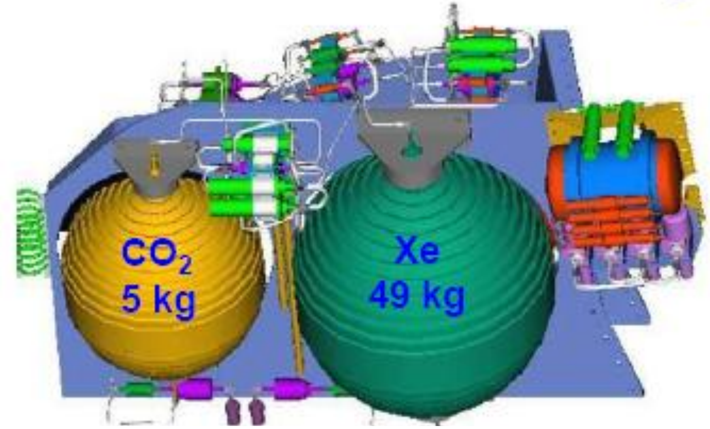
- ***TRD particle separation (estimator)***

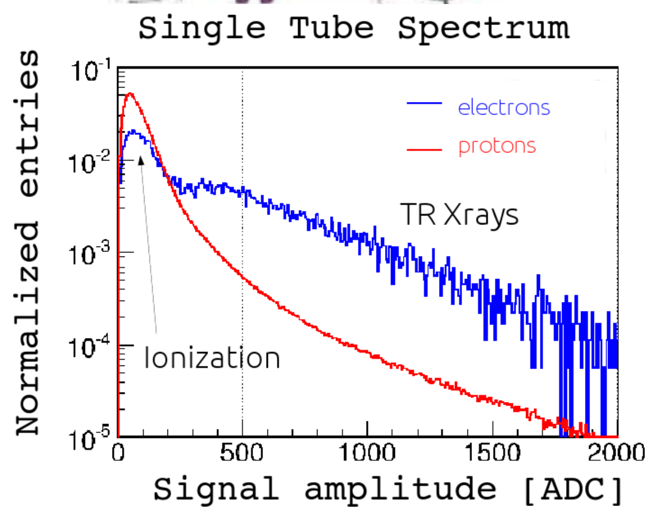
e & p track signal is sampled up to 20 times

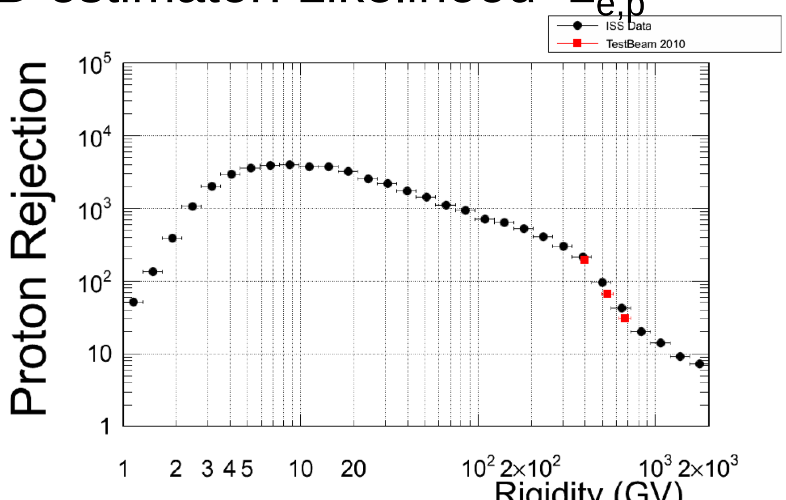
$$P_{e,p} = \sqrt[n]{\prod_{i=1}^{n} p_i^{e,p}} \qquad L_e = -\ln\left(\frac{P_e}{P_e + P_p}\right)$$

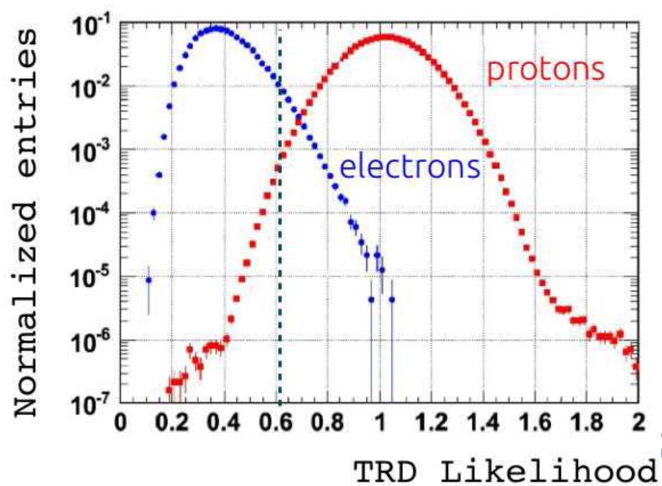
$p_i^{e,p}$: layer probability of an electron or proton signal deposition

TRD estimator: Likelihood $L_{e,p}$









Ring Imaging Čerenkov Detector (RICH)

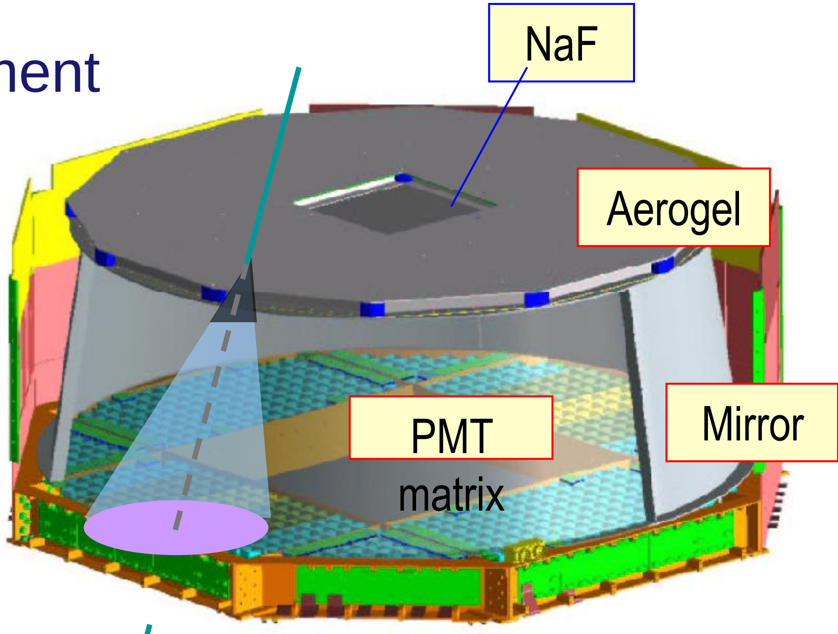
- ✔ accurate particle velocity measurement

$\Delta\beta/\beta \sim 0.1\%$ for protons

- ✔ electric charge determination

$\Delta Z \sim 0.29$

- ✔ mass separation at low energy



Velocity obtained from θ_c measurement

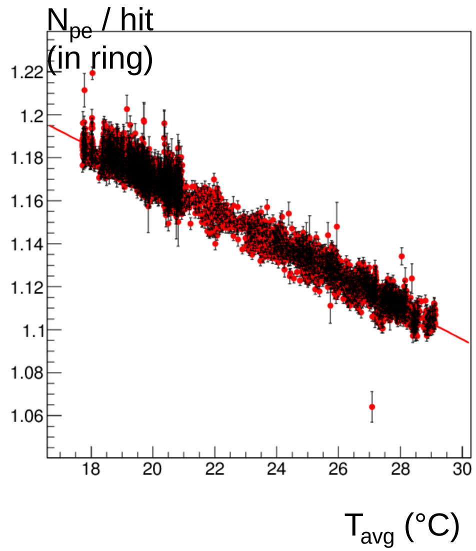
$\beta = 1/n \cos\theta c$

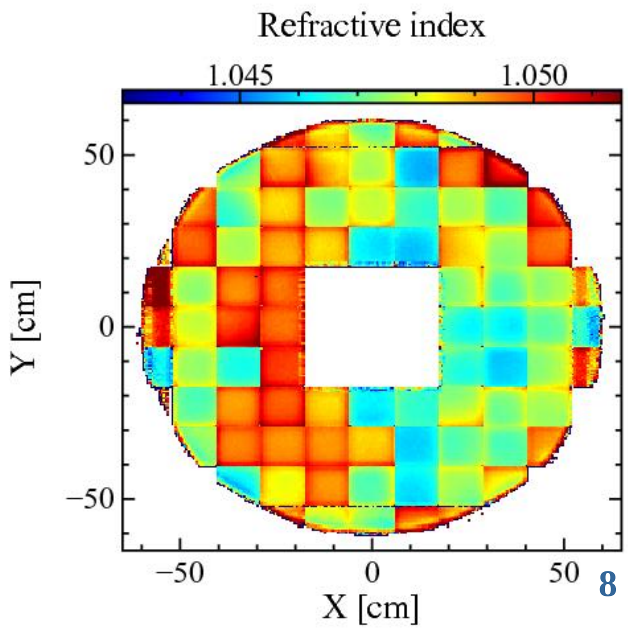
Charge obtained from $Z^2 \propto \frac{N_{pe}}{\varepsilon}$

ε = total ring efficiency calculated by a sampling method (LIP algorithm)

Sources of systematics for β and Z measurement:

- ✓ radiator: n, thickness, clarity, ... (in DB)
- ✓ detection: LG, PMT, temperature effects

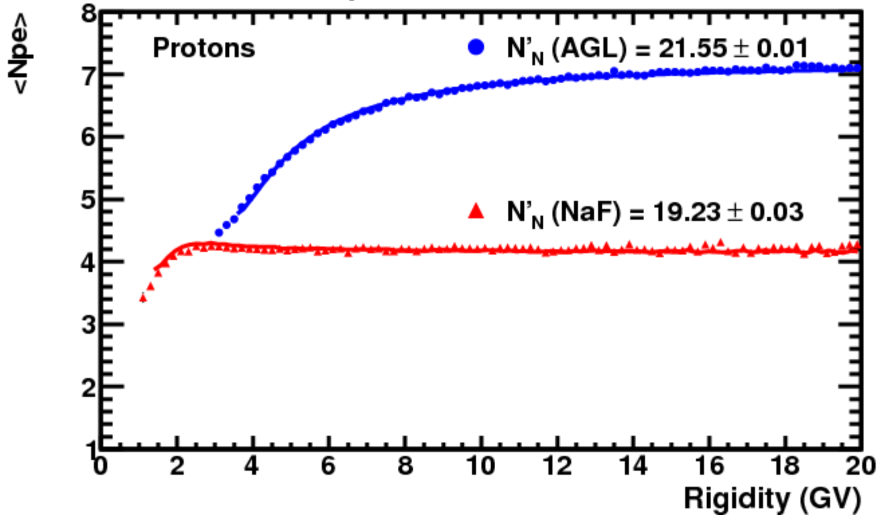




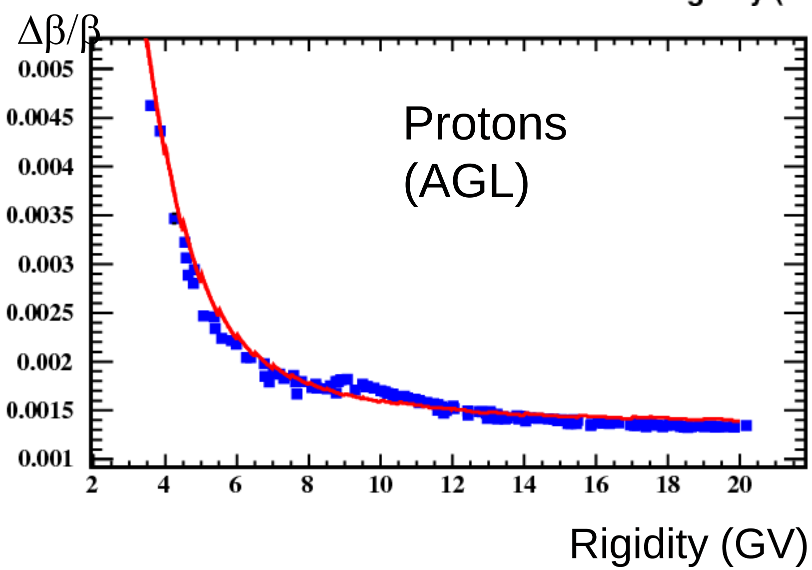
RICH LY and velocity measured in data

(L. Arruda & F. Barão & P. Nunes work)

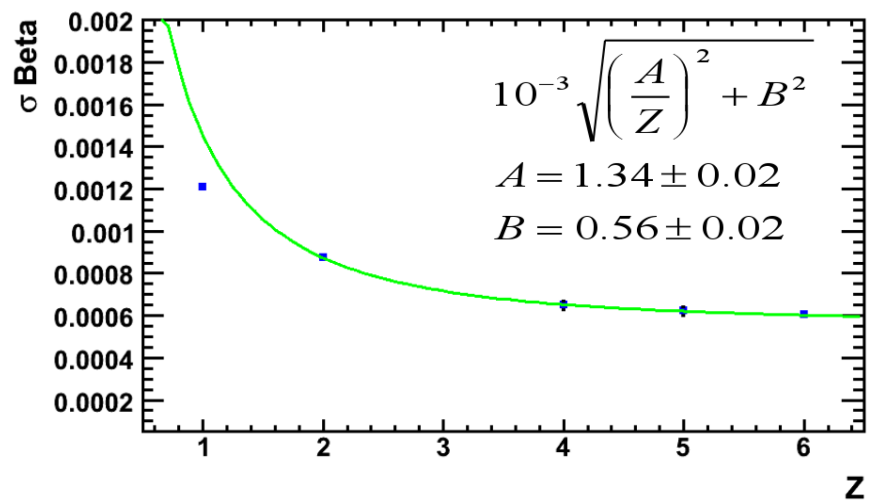
- The different radiator indexes (AGL, NaF) imply different light yields and velocity resolutions



N´$_N$, number of photoelectrons for fully contained rings and particle inciding vertically in the detector



p>20GeV/c

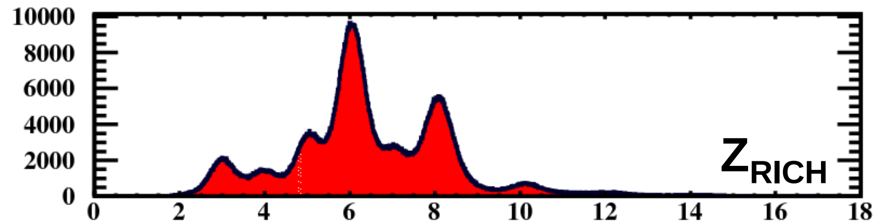


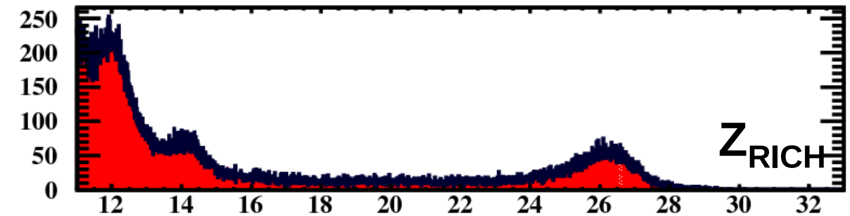
RICH Z measurement *(F. Barão & R. Pereira work)*

Z uncertainties:

- ✓ statistical
- ✓ systematics from non-uniformities:
  - ✓ radiator: n, thickness, clarity, ... (data base with values)
  - ✓ detection: LG, PMT, temperature effects

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

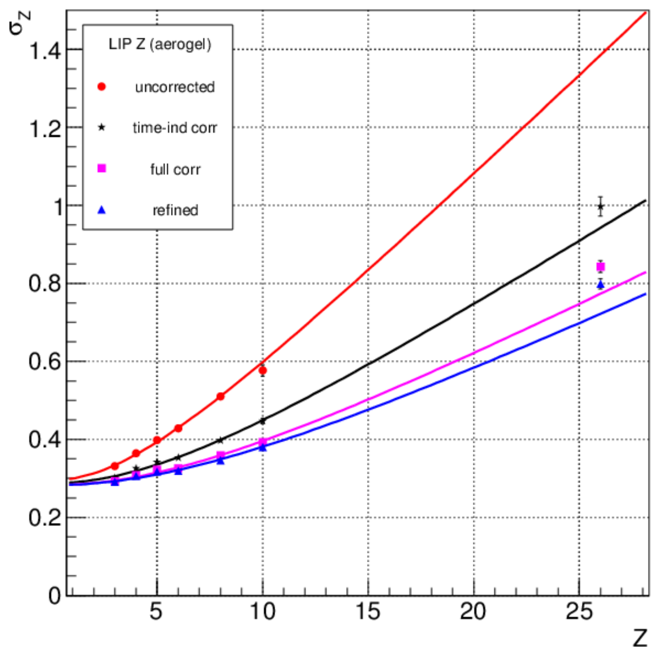




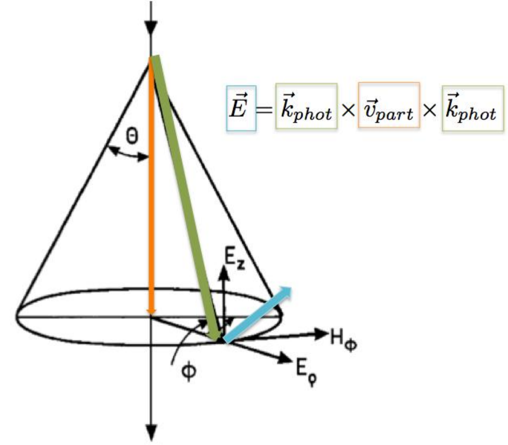
Charge corrections apllied:

- ✓ PMT gain
- ✓ Cell efficiency (light transmission in LG, PMT/pixel quantum eff) **Time independent**
- ✓ Temperature effects (gains and eff) **Time dependent**

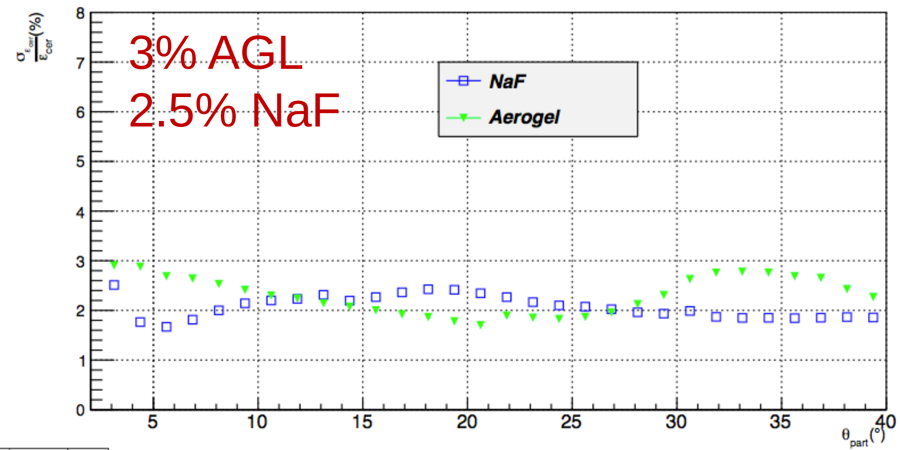
	uncorr	time-ind corr	+time-dep corr	final
σ stat	0.295	0.288	0.283	**0.283**
σ syst	5.20%	3.45%	2.77%	**2.56%**

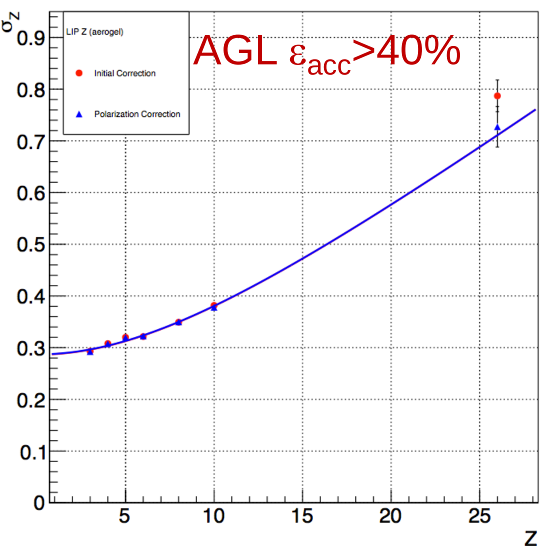


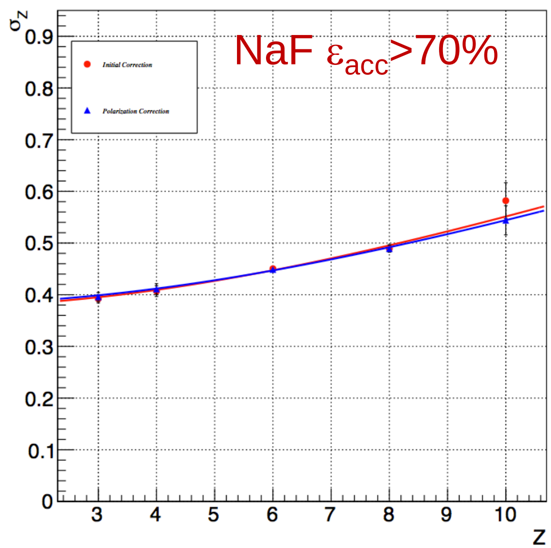
Polarization effect on Z measurement *(F. Barão & B. Santos)*



- Cherenkov γ are polarized. Initial eff without this effect
- The effect of the polarization on the ring efficiency was evaluated with a toy MC.
- Interfaces considered:
  - Radiator interface (dielectric/air);
  - Mirror surface (metal/air);
- According to Fresnel relations, transmittance and reflectance vary with polarization







AGL ε_{acc}>40%

	Initial correction	Polarization correction	Final
σ_Z^{stat}	0.2864 ± 0.0013	0.2869 ± 0.0013	0.2869 ± 0.0013
$\sigma_Z^{sys}(\%)$	2.503 ± 0.038	2.502 ± 0.040	2.502 ± 0.040

NaF ε_{acc}>70%

	Initial correction	Polarization correction	Final
σ_Z^{stat}	0.3762 ± 0.0078	0.3738 ± 0.0079	0.3807 ± 0.0079
$\sigma_Z^{sys}(\%)$	4.029 ± 0.1948	3.881 ± 0.199	3.881 ± 0.199

RICH e/p estimator (L. Arruda & F. Barão work)

Particle with mass m and measured rigidity Rig, probability density functions (PDFs) for the expected velocity *β(m,Rig)* and expected signal $N_{pe}(m,Rig)$

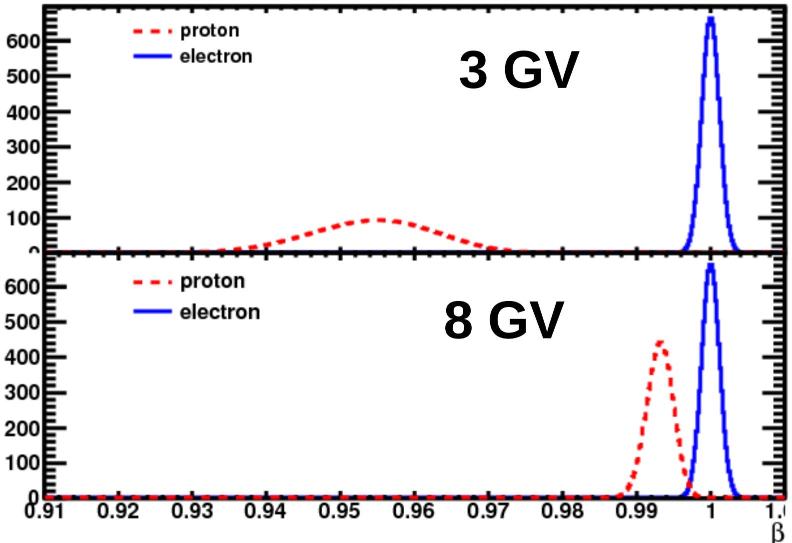
$$dP(x,\beta') = G(x; X_m, \triangle X_m)dx\, G\left(\beta'; \beta(m,x), \triangle\beta\right) d\beta'$$

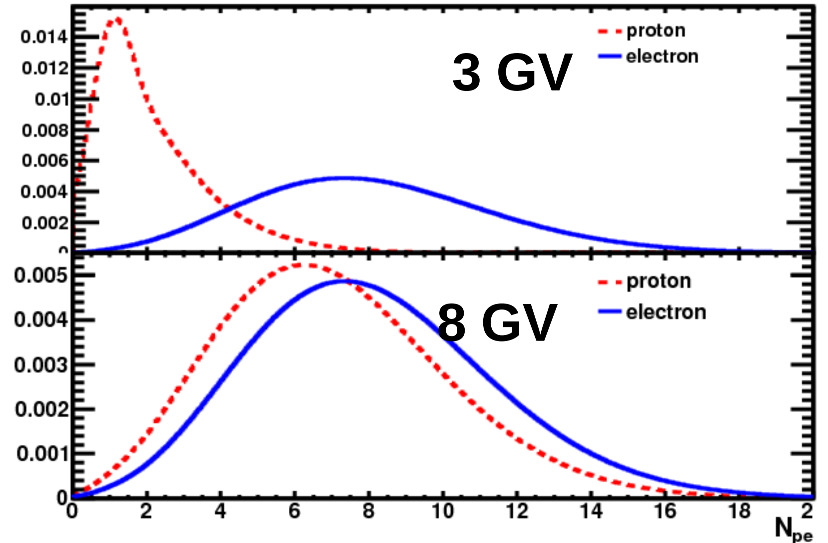
$$dP(x,N_{pe}) = G(x; X_m, \triangle X_m)dx\, P\left(N_{pe}; \mu\right)$$

where

variables *X*= inverse rigidity; *β'* = measured velocity

parameters *m*= Mass; *Z*= charge; X_m= inverse of measured rigidity; ΔX_m= error on X_m.



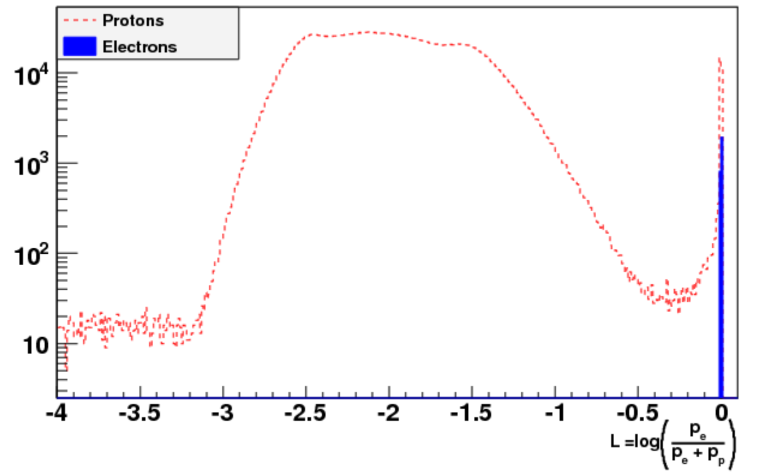


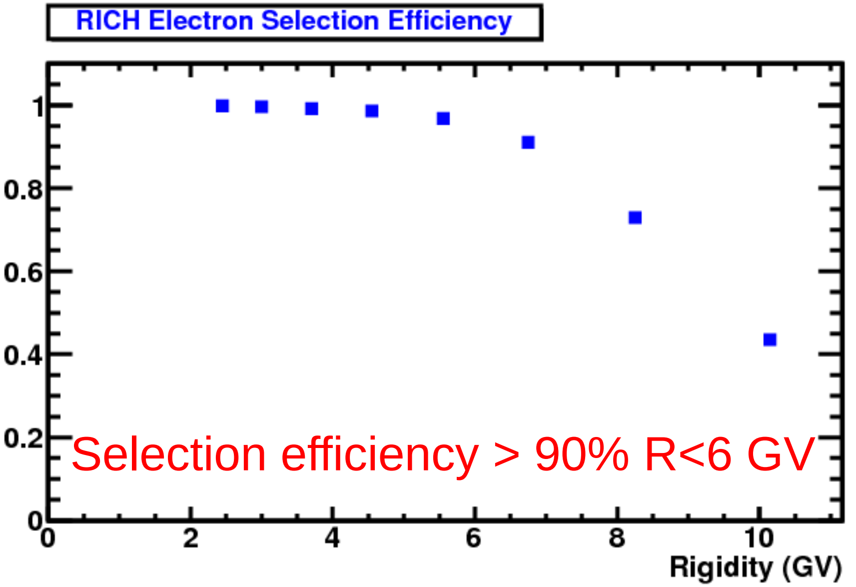
RICH e/p estimator

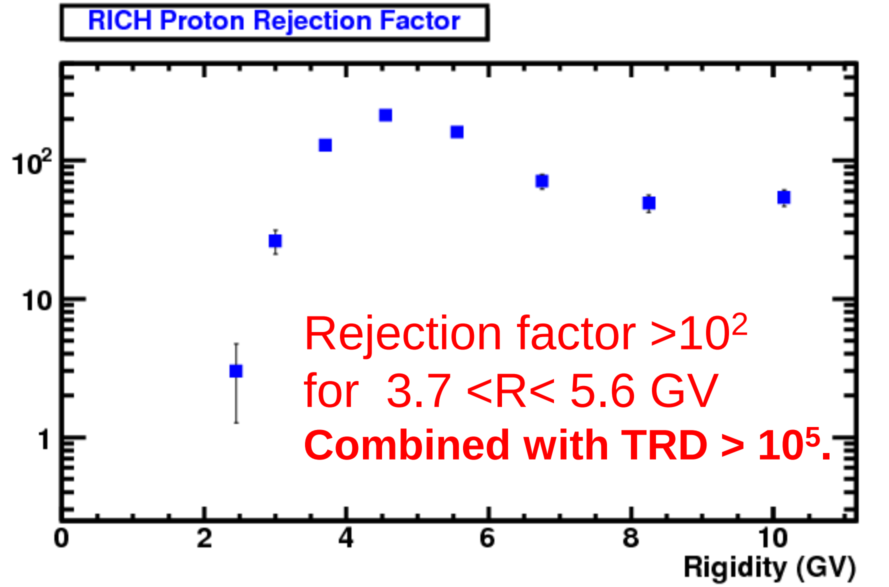
Estimator based on the RICH independent measurements of β and N_{pe} and is built as

$$\mathcal{L} = log\left(\frac{p_e}{p_e + p_p}\right)$$

$$p_e = \sqrt{p_e^{\beta} \cdot p_e^{s}} \qquad p_p = \sqrt{p_p^{\beta} \cdot p_p^{s}}$$

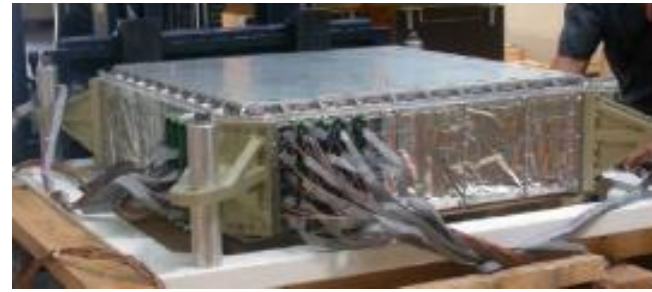




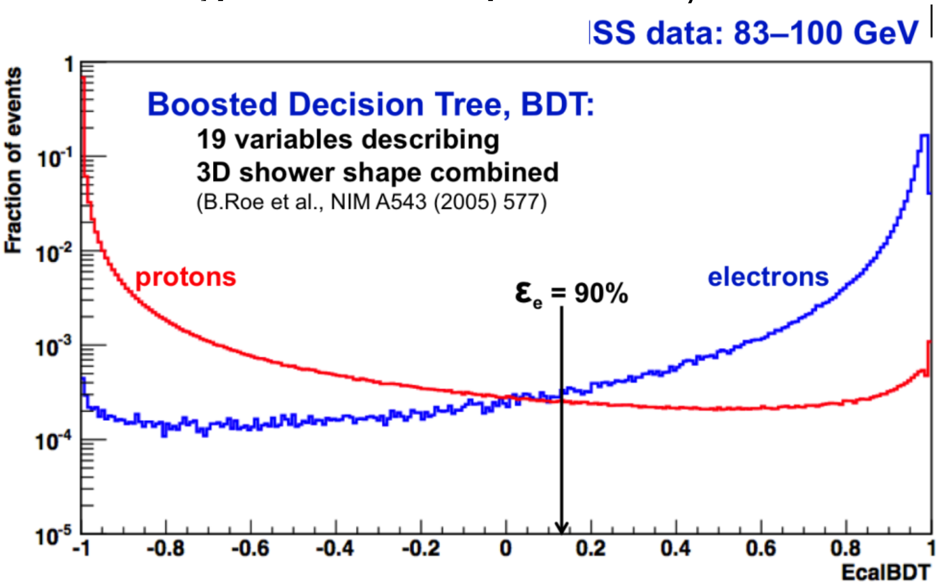


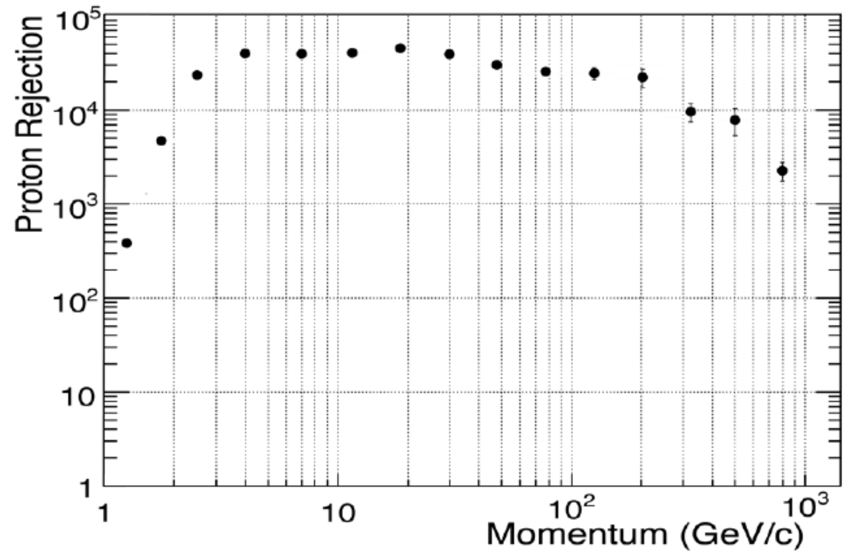
ECAL estimator

- electron and proton create different "tracks" in ECAL
- Boost Decision Tree (BDT) folds the different observables that can distinguish both particles, into one



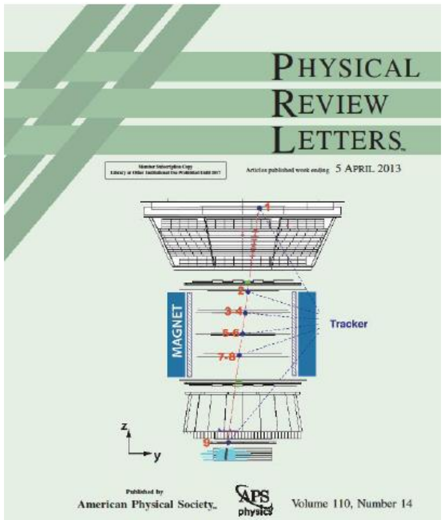
rejection > 10^4 at 90% efficiency





AMS analysis results

Analysis with 2 years of data taking (only 10% of the total statistics foreseen for AMS-02 lifetime).



33RD INTERNATIONAL COSMIC RAY CONFERENCE, RIO DE JANEIRO 2013
THE ASTROPARTICLE PHYSICS CONFERENCE

ICRC 2013

Precision measurement of the proton flux with AMS

S. HAINO[1] ON BEHALF OF THE AMS-02 COLLABORATION.

Precision Measurement of the Cosmic Ray Helium Flux with AMS Experiment

V. CHOUTKO[1], ON BEHALF OF THE AMS COLLABORATION.

Precision measurements of the electron spectrum and the positron spectrum with AMS

S. SCHAEL[1] FOR THE AMS COLLABORATION.

Precision measurement of the positron fraction in primary cosmic rays of 0.5–350 GeV

A. KOUNINE[1], ON BEHALF OF THE AMS COLLABORATION[2].

Precision measurement of the $e^+ + e^-$ spectrum with AMS

B.BERTUCCI[1], FOR THE AMS COLLABORATION.

Precision Measurement of the Cosmic Ray Boron-to-Carbon Ratio with AMS

A. OLIVA[1] ON BEHALF OF THE AMS COLLABORATION.

Determination of the positron anisotropy with AMS

J. CASAUS[1], ON BEHALF OF THE AMS COLLABORATION[2].

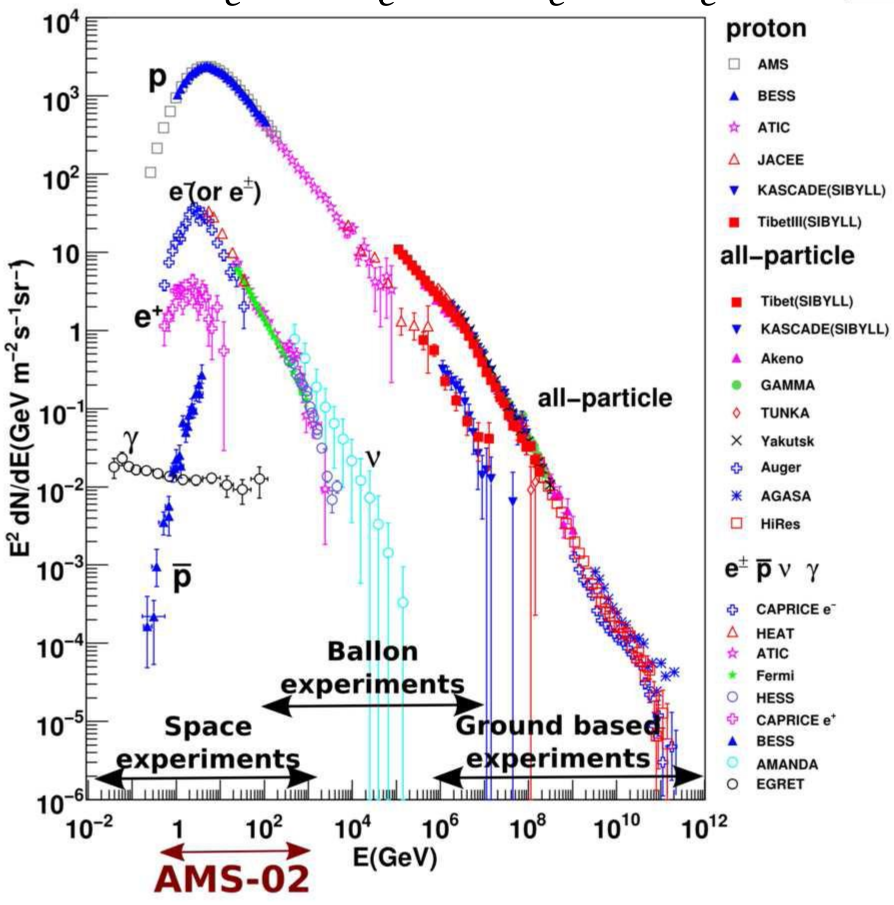
Positron ratio

$$f = \frac{\Phi_{e^+}}{\Phi_{e^+} + \Phi_{e^-}} = \frac{N_{e^+}}{N_{e^+} + N_{e^-}}$$

- e^+ low signal and high p background: p~(10^3-10^4) e^+
- p rejection factor: 10^5-10^6 to identify e^+ with an error at % level
- AMS detector requirements: good e^+ identification and strong capability of rejecting p

ECAL, TRD, TRACKER

at low energy TOF and RICH also contribute



Positron and electron counting

The number of positrons in every energy bin is obtained :

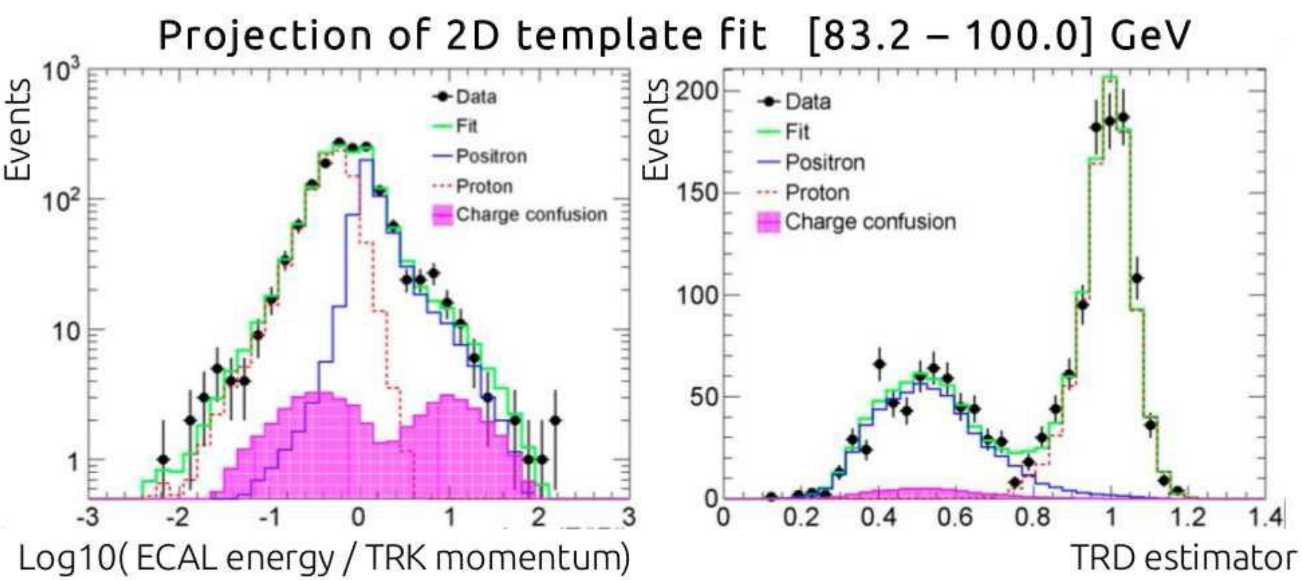
❒ apply the ECAL shower topology cut (BDT), energy dependent

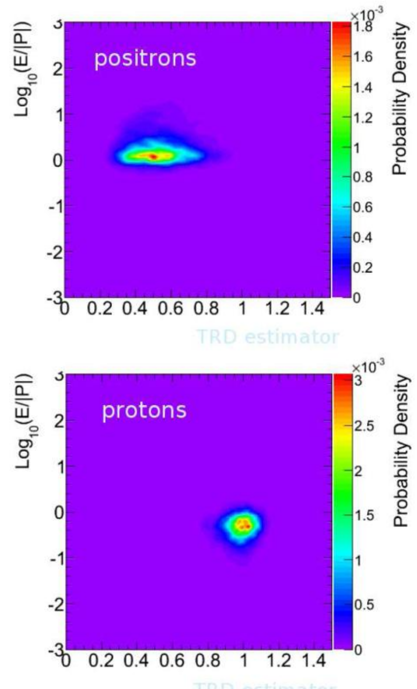
❒ split sample in negative ($Q < 0$) and positive $Q > 0$ particles

❒ number of positrons and electrons obtained from a fit on the two remaining discrimination observables : **TRD estimator and E/p**

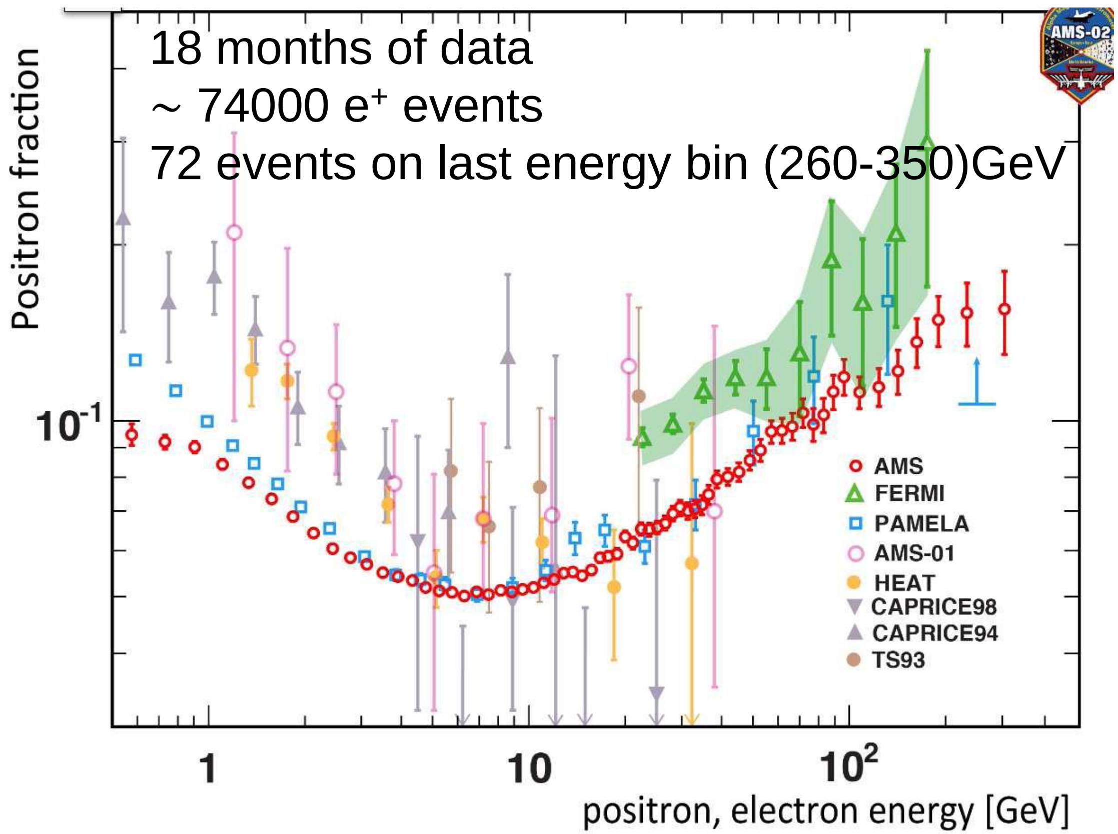
✔ reference spectra from electron and proton samples selected with ECAL

✔ wrong-sign events (charge confusion) spectrum taken into account





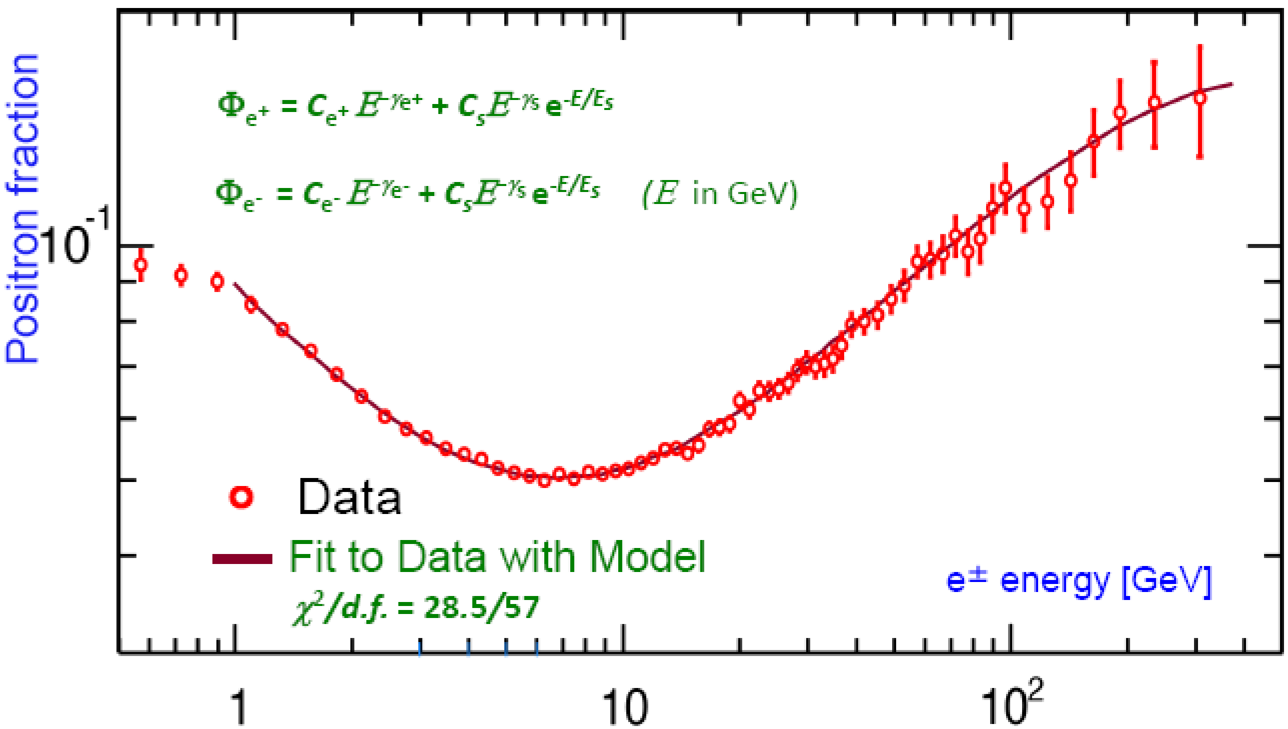
Positron ratio ($N_{e^+}/N_{e^+}+N_{e^-}$)



- ✓ E<10GeV positron fraction decreases with increasing energy.
- ✓ The positron fraction is steadly increasing from 10 to ~250GeV.
- ✓ No structure in the spectrum.
- ✓ From 20 to 250 GeV the slope decreases by an order of magnitude.
- ✓ The determination of the behaviour of the fraction from 250 to 350 GeV and beyond requires more statistics.

On the origin of the excess of positrons

- Limits on the amplitude of a dipole anisotropy in any axis in galactic coordinates on the positron to electron ratio **$\delta \leq 0.036$ at the 95% confidence level**, compatible with isotropy
- These observations show the existence of new physical phenomena, whether from a particle physics or an astrophysical origin.

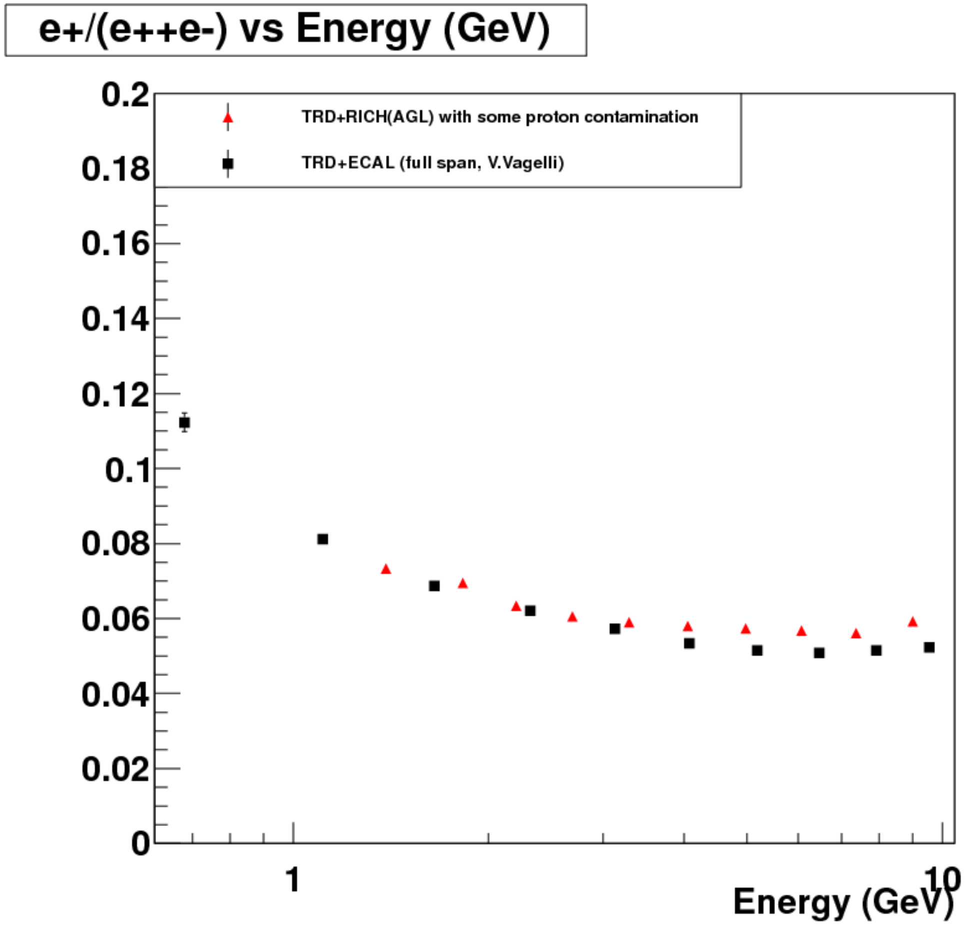


✓ The agreement between data and the model shows that the positron fraction spectrum is consistent with e^{+-} fluxes each of which is the sum of its diffuse spectrum and a single common power law source.

AMS02 positron ratio at low energies (<10GeV)

(L. Arruda & F. Barão work)

- ✓ RICH e-like estimator used to perform e/p separation at low energy.
- ✓ Combined with TRD rejection factor > 10^5.
- ✓ Larger acceptance : 4-5 more events collected compared to TRD + ECAL selection.



Electron and Positron fluxes

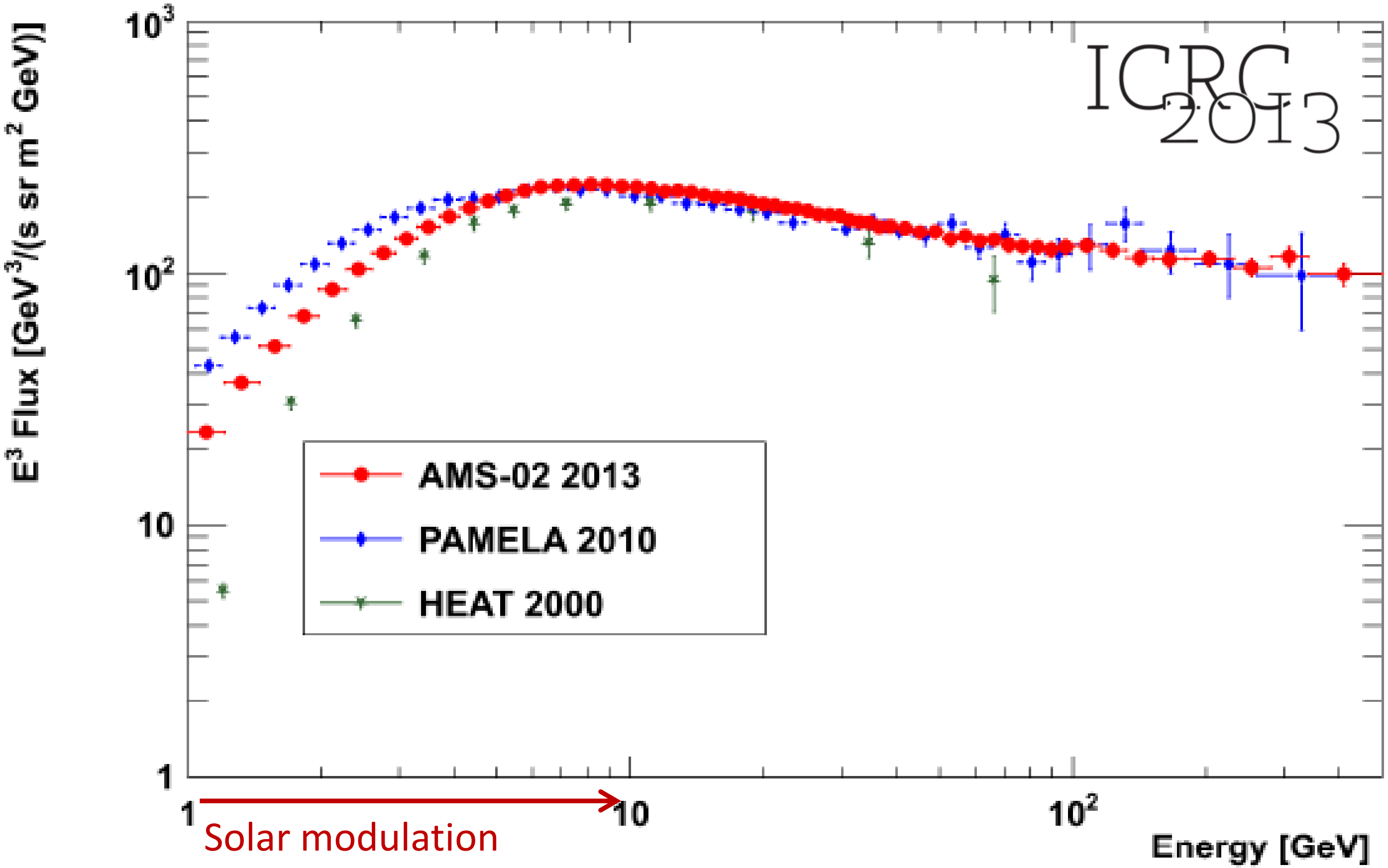
Individual fluxes carry more information to the models than the fraction

$$\Phi(E) = \frac{N_{obs}}{A(E) \times \varepsilon_{Trig}(E) \times \varepsilon_{Sel}(E) \times L(E) \times dE}$$

where
$\Phi(E)$ = Absolute differential flux ($m^{-2}sr^{-1}s^{-1}GeV^{-1}$)
E = Measured energy (GeV)
A = effective acceptance (m^2sr)
ε_{trig} = trigger efficiency
ε_{sel} = selection efficiency
L = detector livetime (s)
dE = energy bin width (GeV)

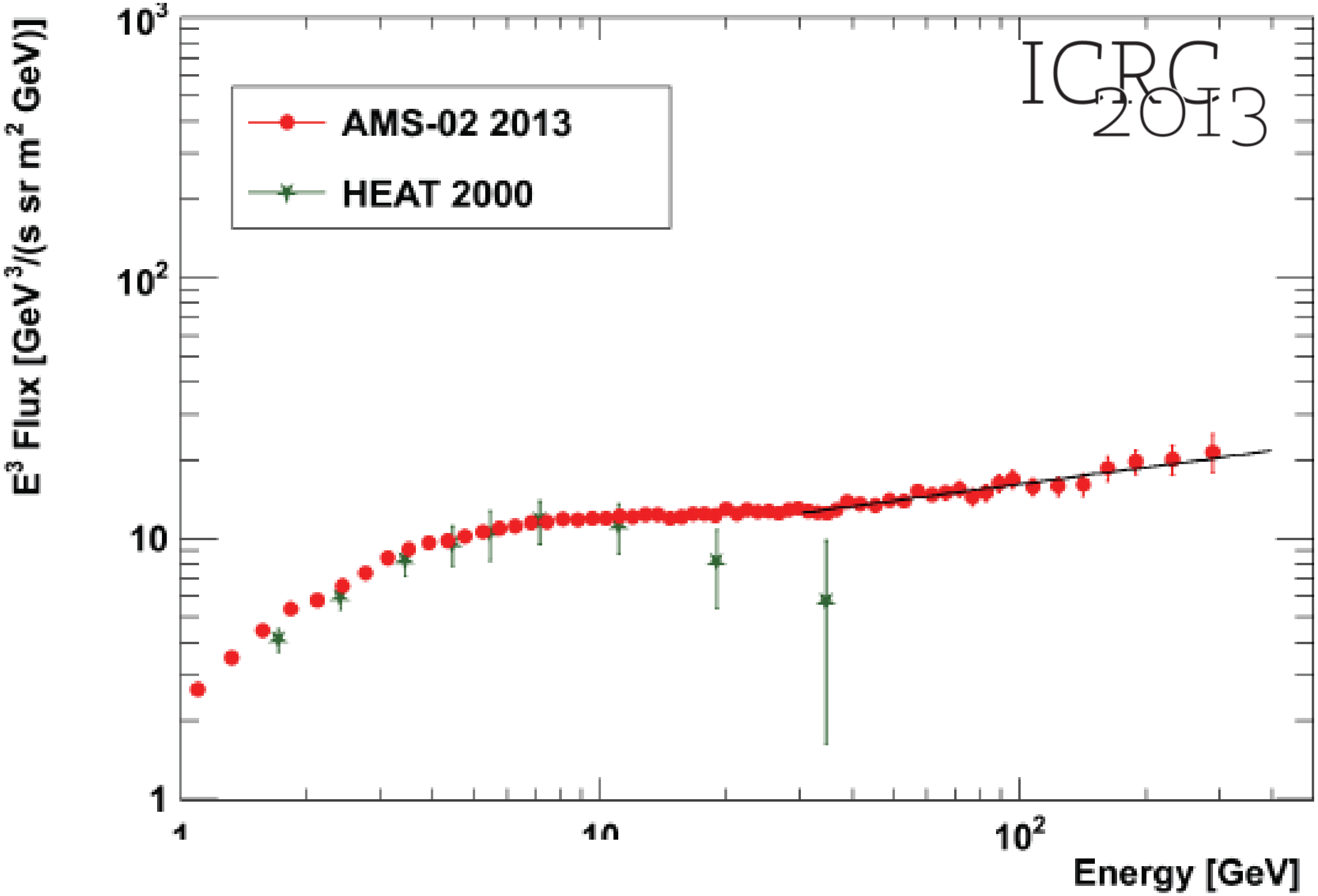
Electron Flux

- Flux (x E^3) up to 500GeV
- Raises up to 10 GeV and is a smooth, slowly falling curve above
- Good agreement with previous data



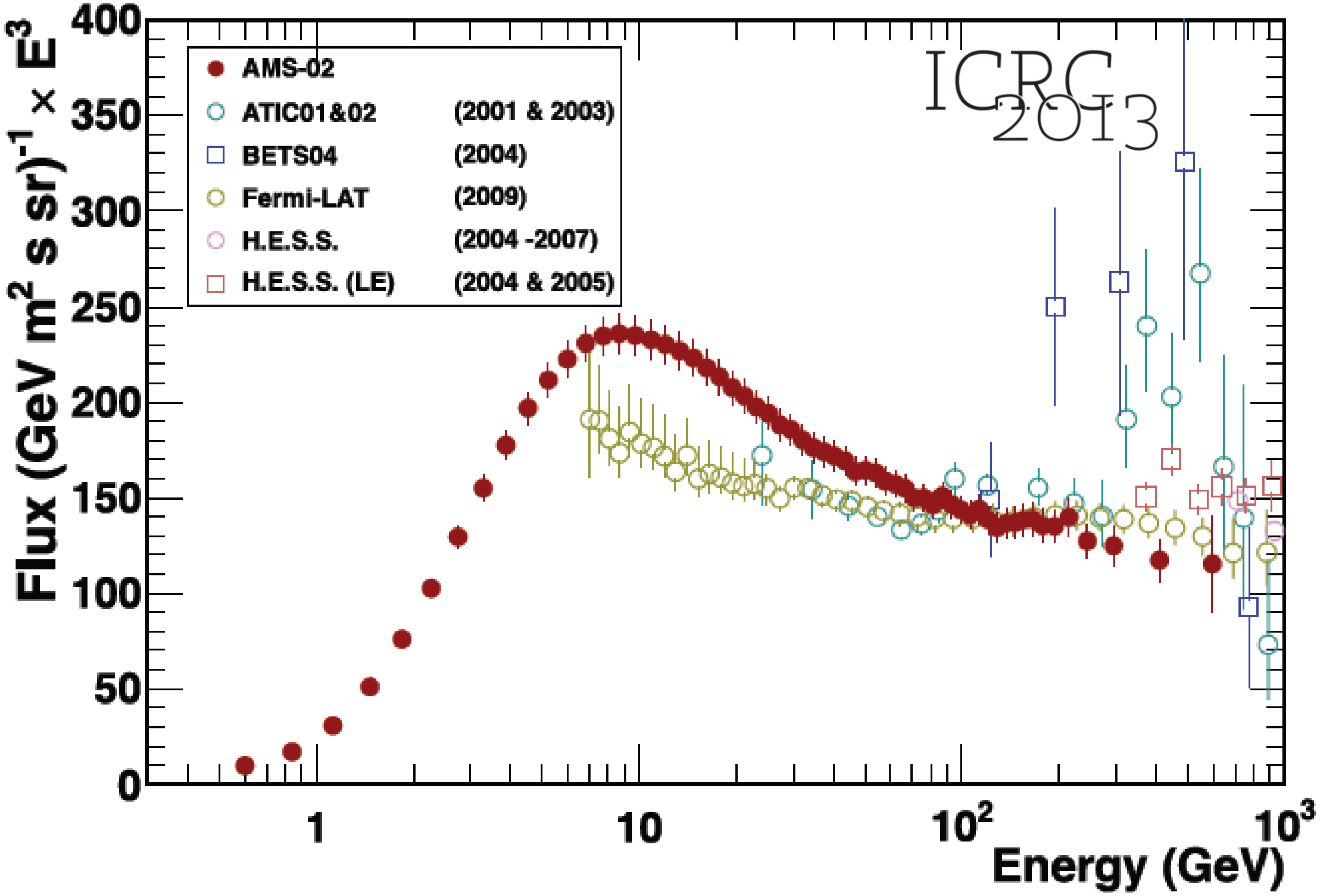
Positron Flux

- Flux (x E^3) up to 350GeV
- Raises up to 10 GeV, from 10-30 GeV is flat and above raises
- Different spectrum index and dependence on E from electrons
- Good agreement with HEAT data at low energy



Electron+Positron Flux

- up to 700 GeV (xE^3) shows no evidence of structures.
- Change in spectral distribution with increasing energy compatible with fraction.
- AMS disagrees with FERMI measurements 6-100 GeV.



Proton Flux

Dominant component of CR:

- Not limited by statistics
- Negligible contamination
- High precision measurement
- Absolute flux and spectral shape fundamental to understand:
    - Origin & propagation history of CR in the Galaxy
    - Solar modulation efefcts
- No fine structures nor break found

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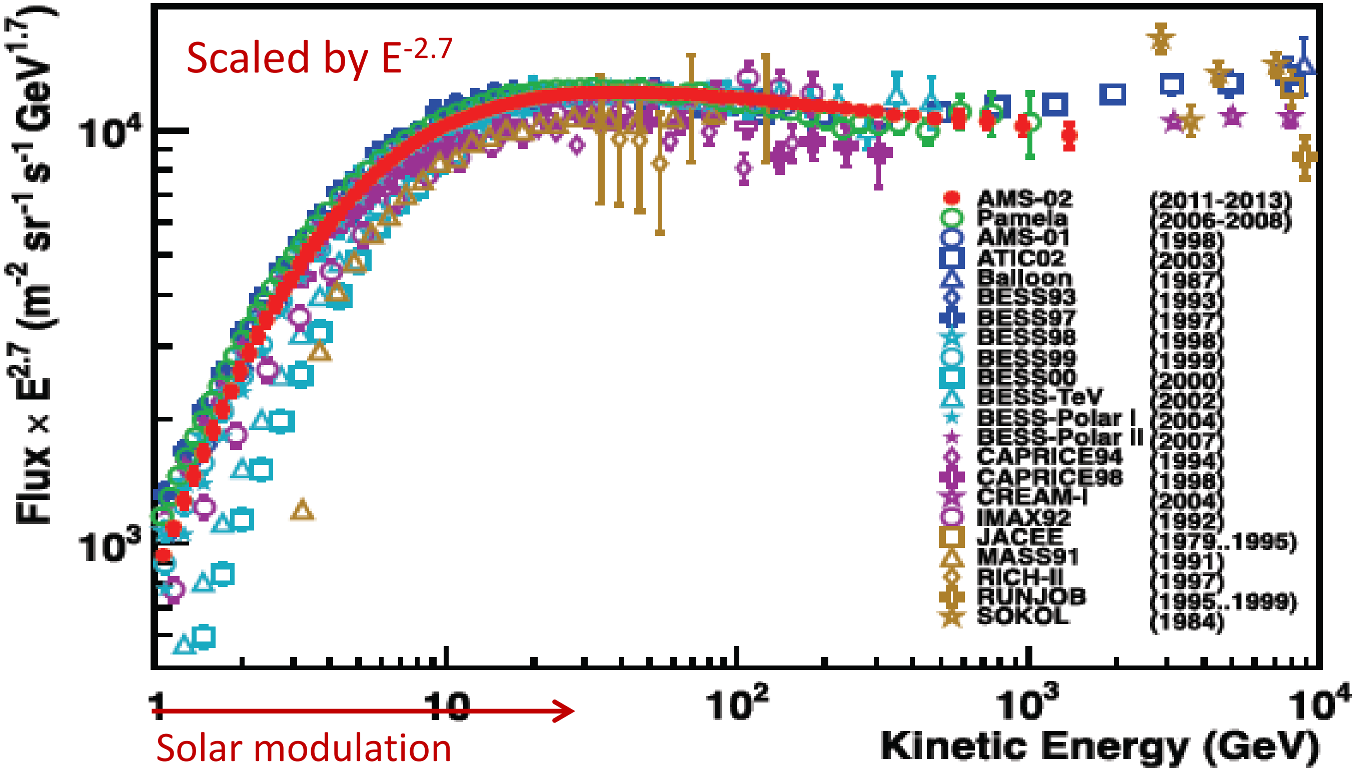
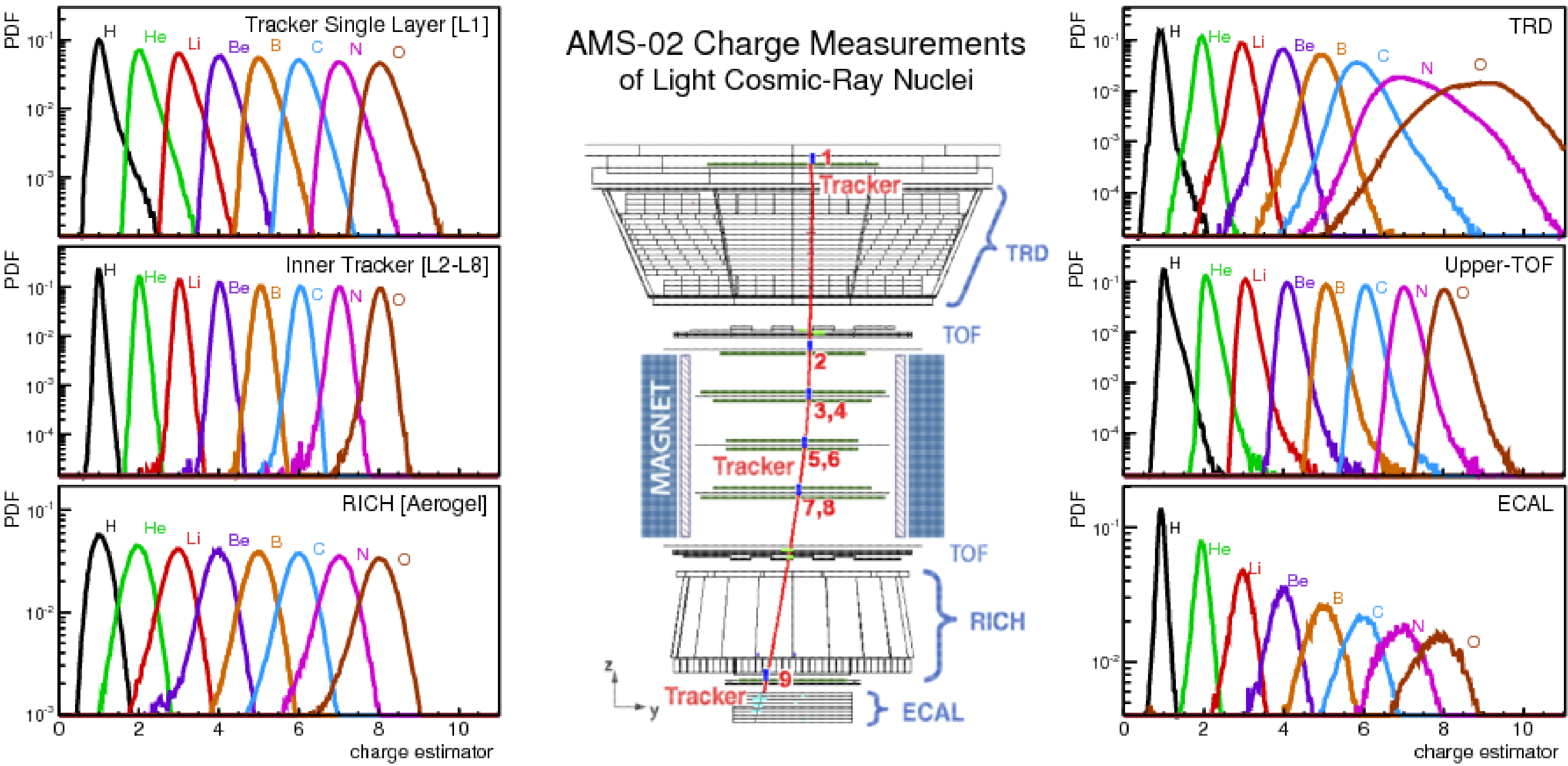
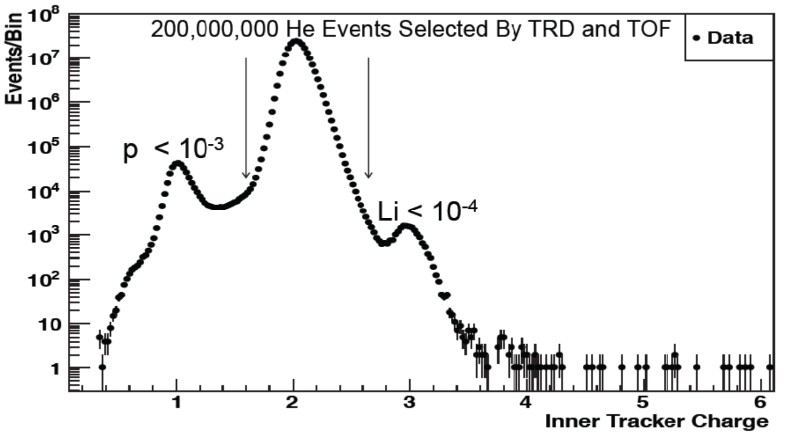


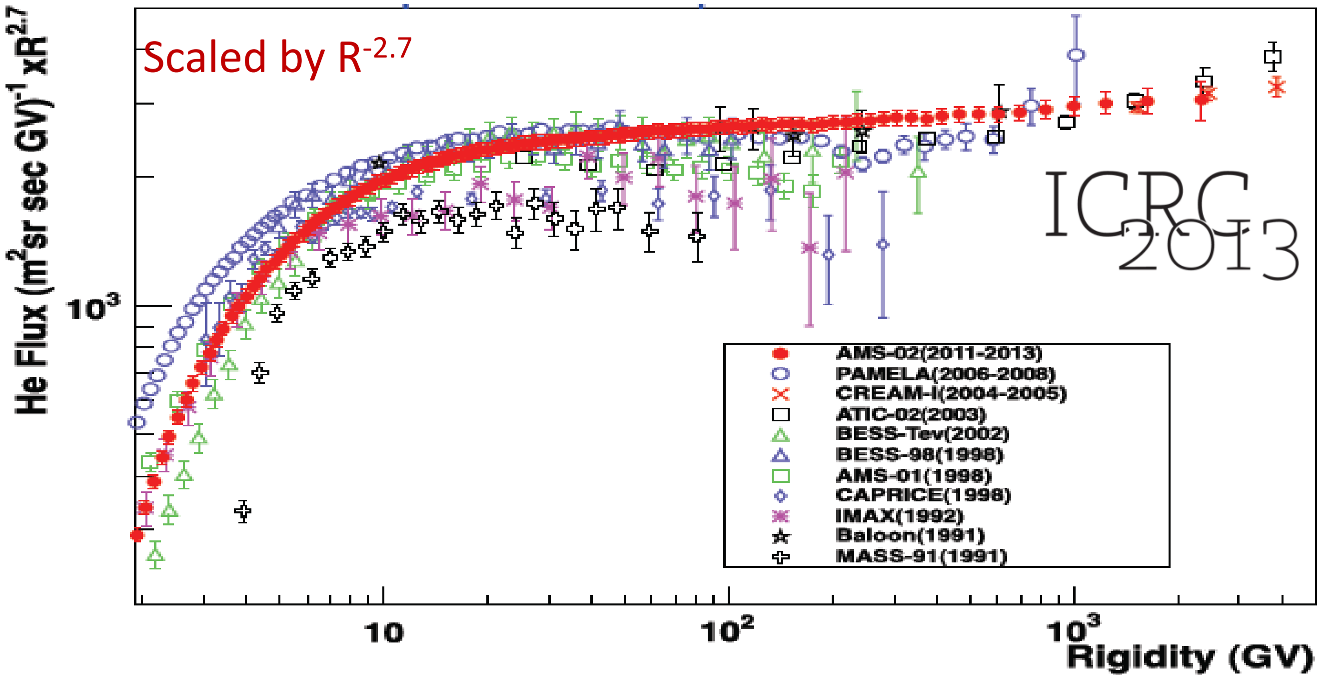
Charge measurement on AMS subdetectors



Helium Flux

- Helium flux interesting for understanding the acceleration mechanism of charged CR in our Galaxy
- Proton background: 10^{-5}
- Main remaining background: ions interacted on top of AMS

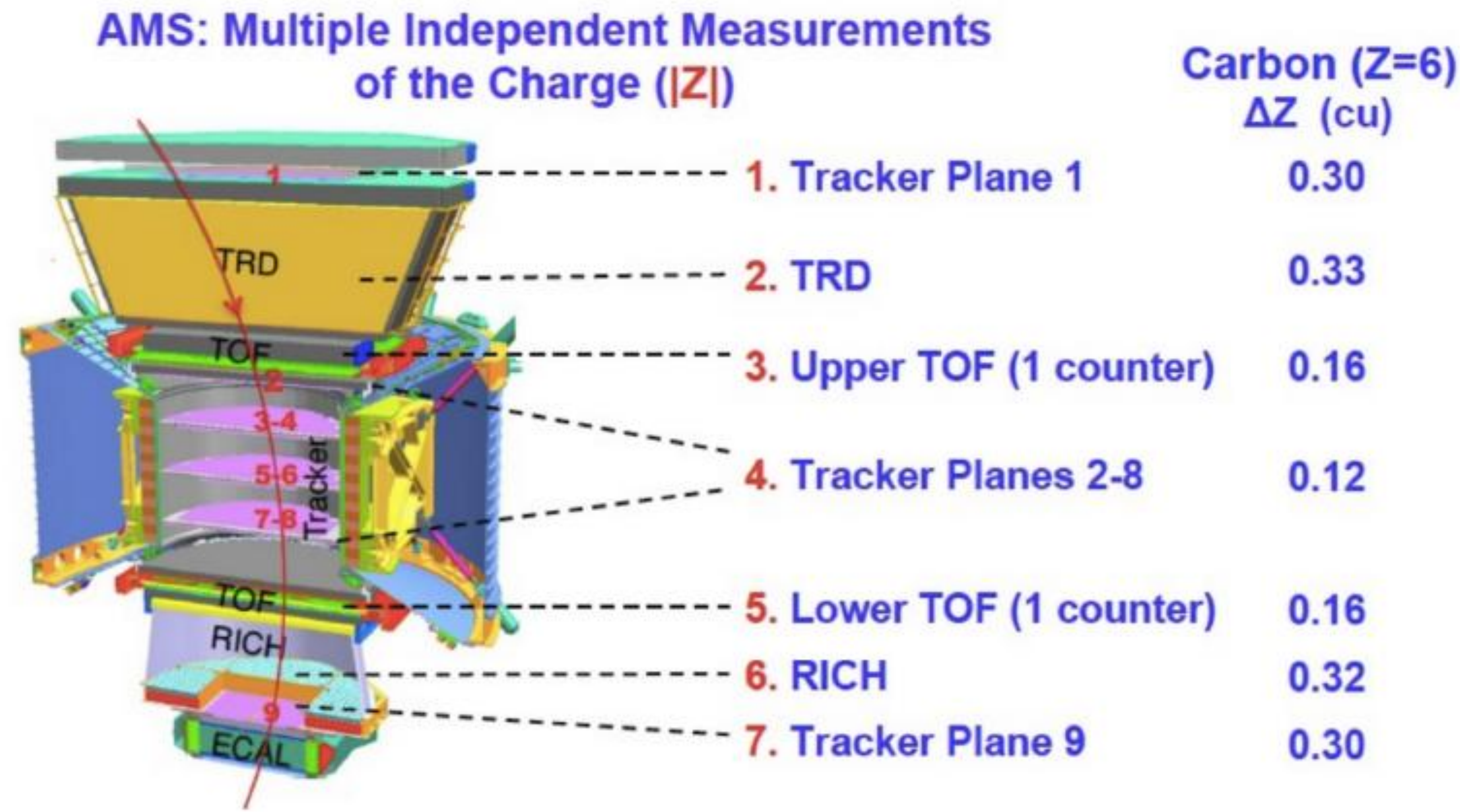




- The helium flux (multiplied by $R^{2.7}$) measured from 2 GV to 3.2 TV
- Above 10 GV the spectrum can be paramtrized by a single power law
- No fine structures were found on the spectrum

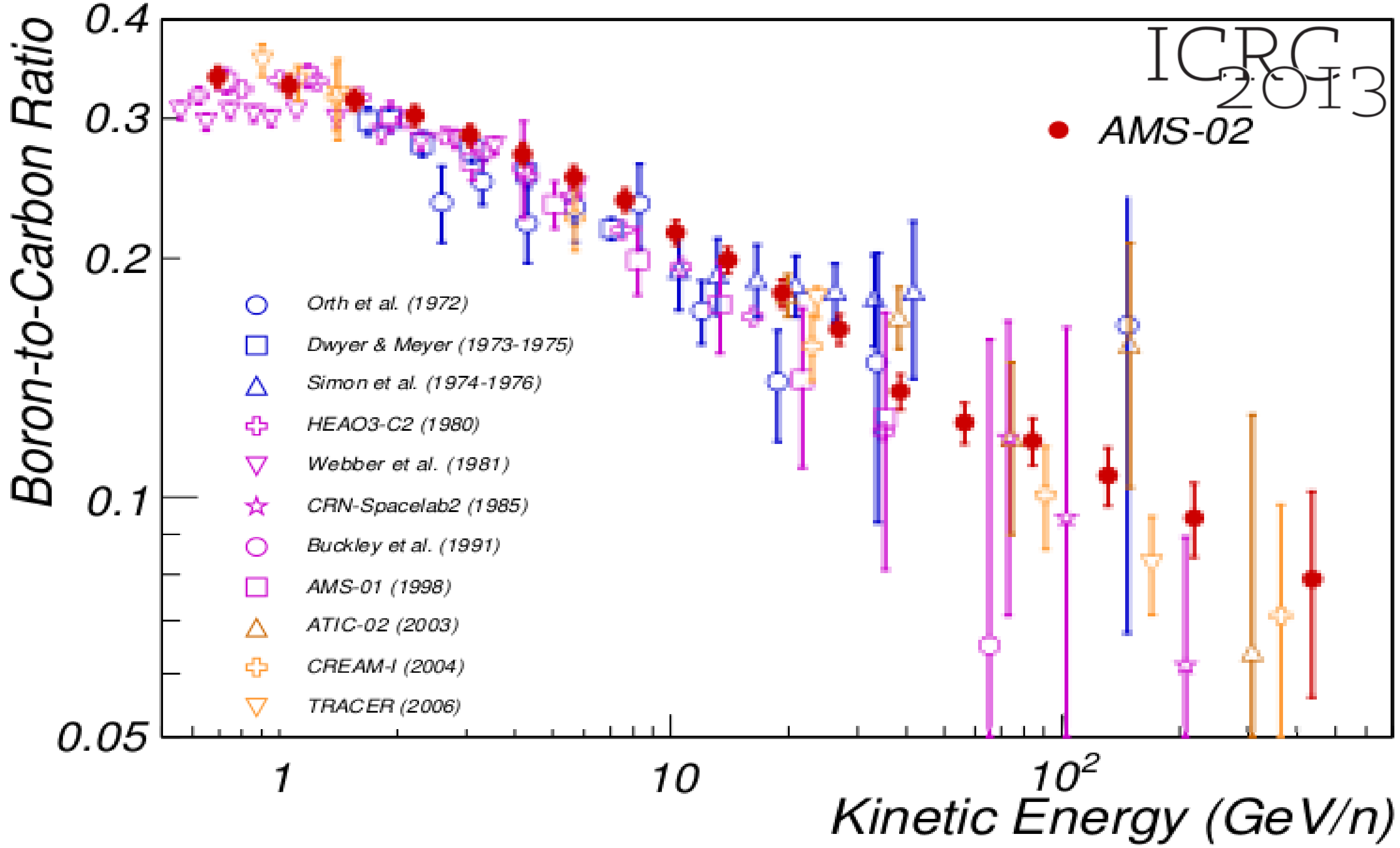
B/C measurement

- B is a secondary spallation product of heavier primary elements (C, O).
- Allow to study CR propagation in the Galaxy
  - Strongly constrain propagation models specially in the high energy regime
- Identify nuclei with Z= 5 and Z=6



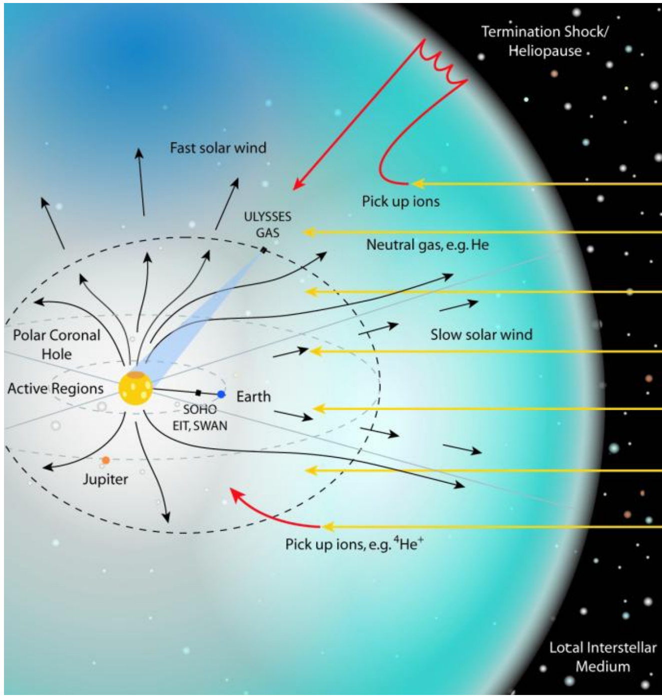
B/C measurement

- B and C samples separated using Inner tracker and TOF Z measurements.
- Measurement of B/C between 0.5 to 670 GeV/n measured by AMS
- Statistics is the main limitation for the ratio measurement and systematic error measurent (only 10% analyzed)
- B/C behaviour at high energy more clear with more data

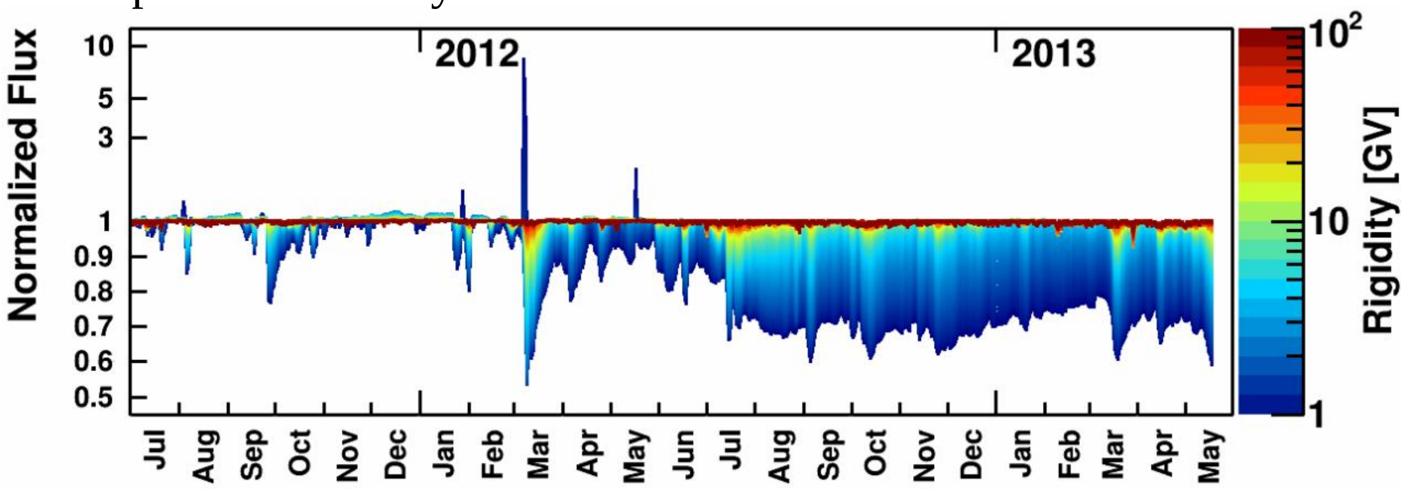


Solar Modulation *master thesis M. Orcinha*

- A continuous flow of charged particles from SUN with velocities around 400Km/s
  - mainly composed of e^- and p
- Carries the sun magnetic field to the interplanetary space
- Predictions from CR propagation in the heliosphere can be extracted from solving Parker equation.
  - Numerical solution of Parker Equation (1D, 2D) done

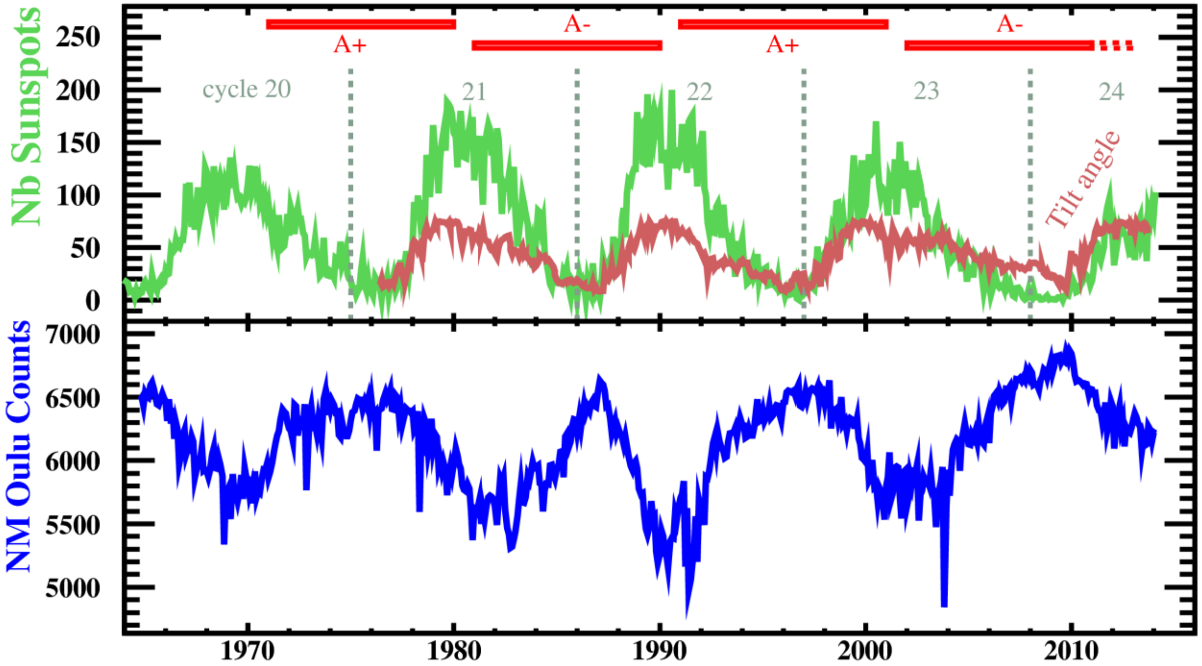


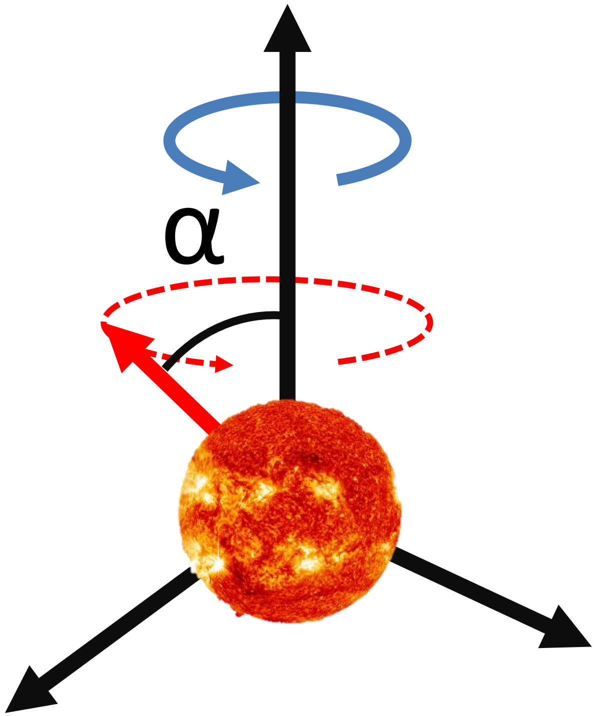
AMS proton flux daily variations

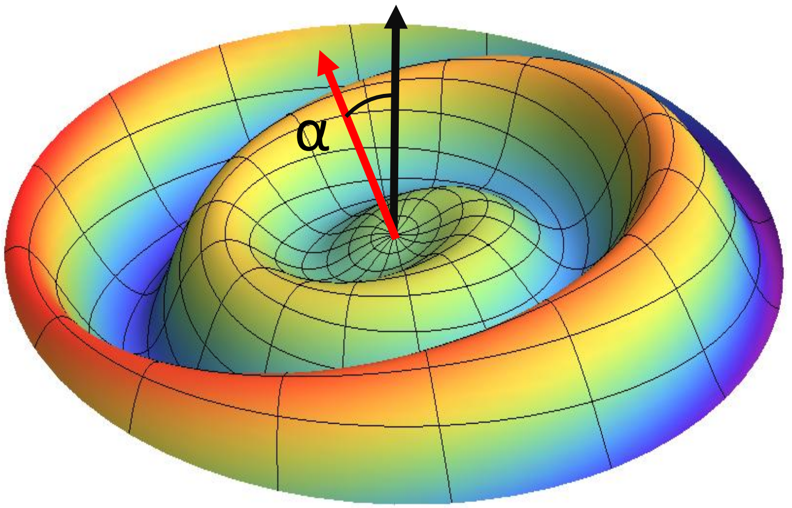


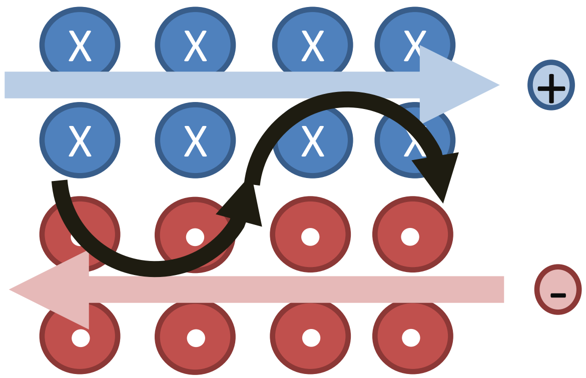
Spikes at R ~1 GV =) solar events on 9.8.11, 27.1.12, 7.3.12, 17.5.12

Solar Modulation *master thesis M. Orcinha*

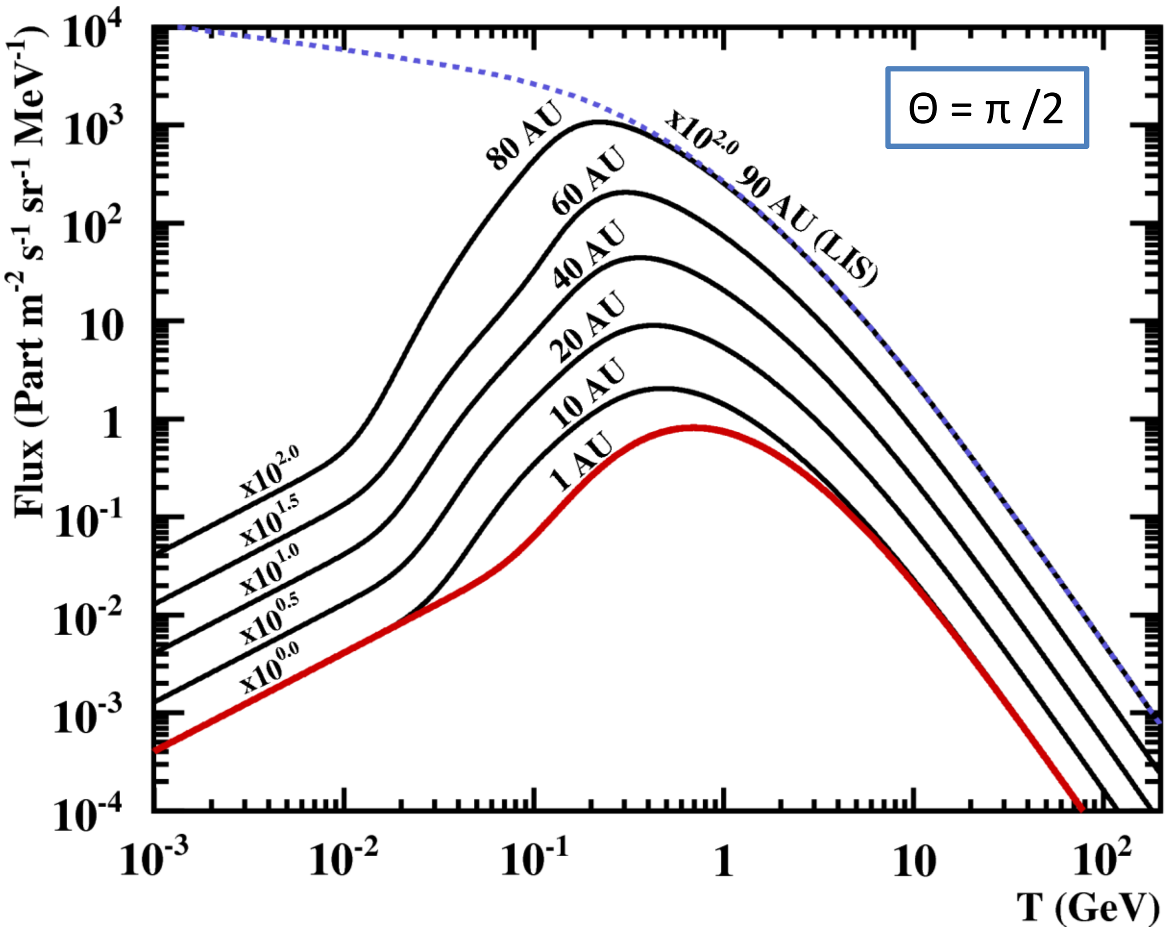








Solar Modulation *master thesis M. Orcinha*



Numerically solved (2D)
Variables: p, r, θ

$$k_{ij} \propto \beta P \frac{B_0}{B}$$

$$\mathbf{V}_d = \frac{pv}{3q} \nabla \times \left(\frac{\mathbf{B}}{B^2} \right)$$

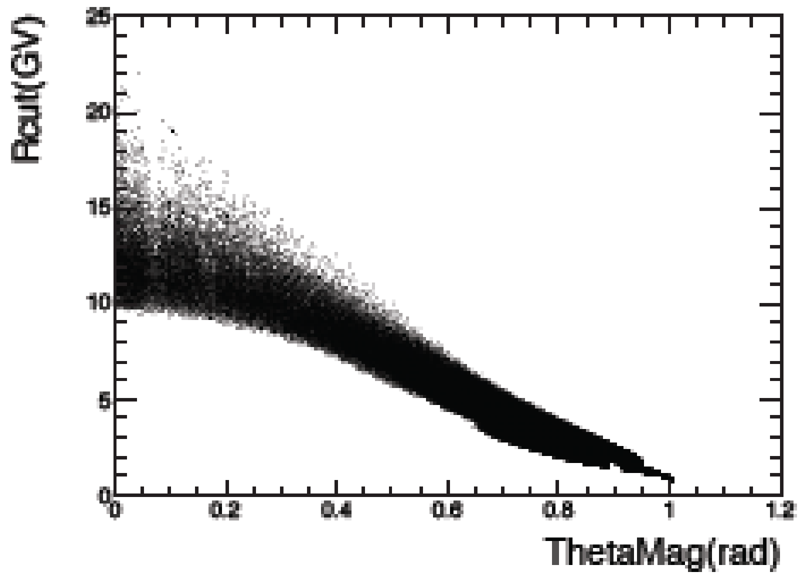
$$\frac{\partial f}{\partial t} = \overbrace{k_{rr}\frac{\partial^2 f}{\partial r^2} + k_{\theta\theta}\frac{\partial^2 f}{\partial \theta^2} + \left(\frac{2k_{rr}}{r} + \frac{\partial k_{rr}}{\partial r}\right)\frac{\partial f}{\partial r} + \frac{\cot\theta k_{\theta\theta}}{r^2}\frac{\partial f}{\partial \theta}}^{\text{diffusion}} - \overbrace{V_{wr}\frac{\partial f}{\partial r}}^{\text{convection}} + \overbrace{V_{wr}\frac{\partial f}{\partial r} + \frac{V_{d\theta}}{r}\frac{\partial f}{\partial \theta}}^{\text{drift}} + \overbrace{\frac{2V_{wr}}{3r}\frac{\partial f}{\partial \ln p}}^{\text{adiabatic cooling}}$$

d/p separation *master thesis P. Nunes*

- Deuterons result mainly from the nuclear interactions of primary CR p and He nuclei with ISM.
  - Should provide important info for CR propagation in the space.
- The selection of deuterons is very complex due to the large p background (d/p≈ 2%)
- Geomagnetic rigidity cut-off can be used to separate deuterons

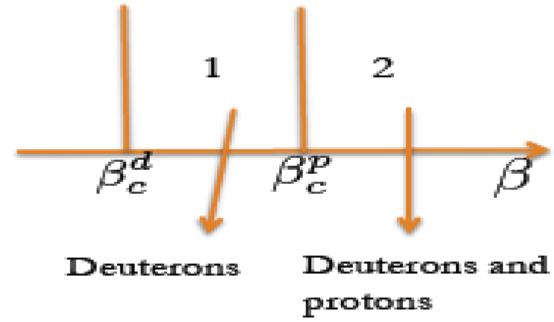
- **Geomagnetic Rigidity Cutoff:** Minimal rigidity (R=pc/Ze) that a particle coming from the Galaxy must have in order to reach a point near the Earth surface

$$R_c(h,\lambda,\alpha) = \frac{60}{\left(1+\frac{h}{R_E}\right)^2}\frac{\cos\lambda^4}{\left[\sqrt{1+\cos\alpha\cos\lambda^3}+1\right]^2}$$



Rcut versus Latitude
Computed with particles entering AMS

d/p separation



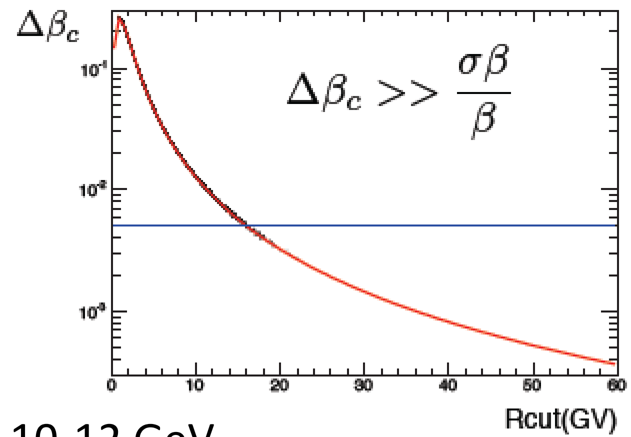
IDEA: (orig. Balasubramanyan and Hubert)

- Accept particles R>Rcut (Selects only primaries)
- Each CR particle has a cutoff that depends on its mass for every orbit position

$$\beta_c^{-2} = 1 + \left(\frac{A}{Z} \frac{m}{R_c(h,\lambda,\alpha)} \right)^2$$

Velocity region where **d** are naturally separated from **p**

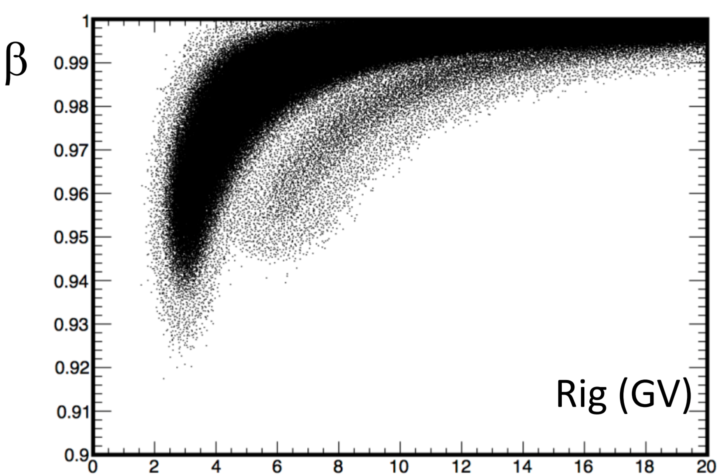
- This region decreases with energy: Higher cut-off energies correspond to lower geomagnetic latitudes



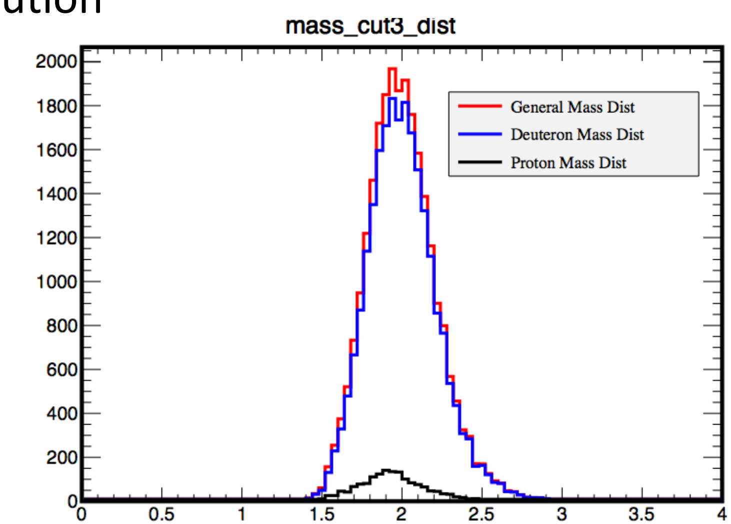
✓ Direct use of precise β measurement by RICH

✓ Expect to measure a deuteron flux and a d/p ratio up to 10-12 GeV

MC: d & p simulated according to β^{RICH} and Rig resolution



Deuterons selected ($\beta_d^c < \beta m < \beta_p^c$)



Near future

- AMS-02 remains for the next years a singular experiment in space
- AMS-02 physics analysis
    - More statistics -> more precision
    - Extend studies to higher energies
- More physics channels to be covered
    - Antiprotons
    - Antiheliums
    - Antideuterons
    - more light isotope measurements $^{3}He/^{4}He$, $^{10}Be/^{9}Be$
    - Sub-Fe elements, Sub-Fe/Fe
    - γ-rays

BACKUP Slides

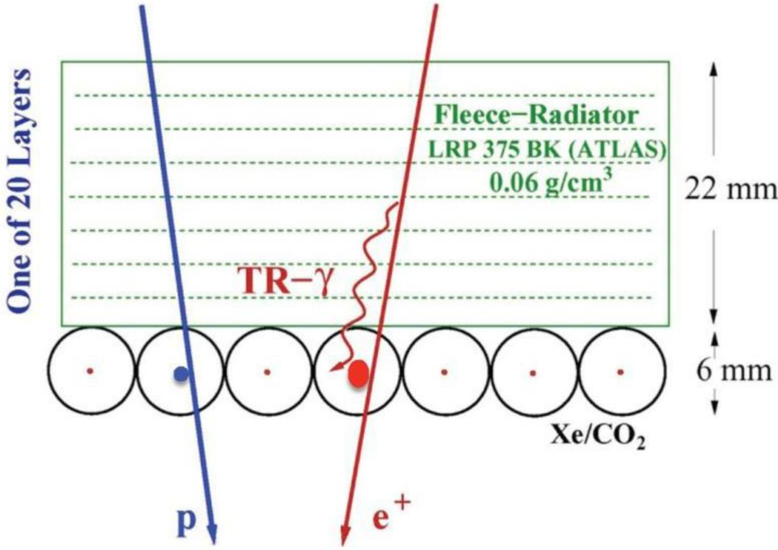
Transition Radiation Detector (TRD)

✔ Electromagnetic radiation is emitted (X-rays) when a charged particle traverses a medium with a varying dielectric permittivity (ε)

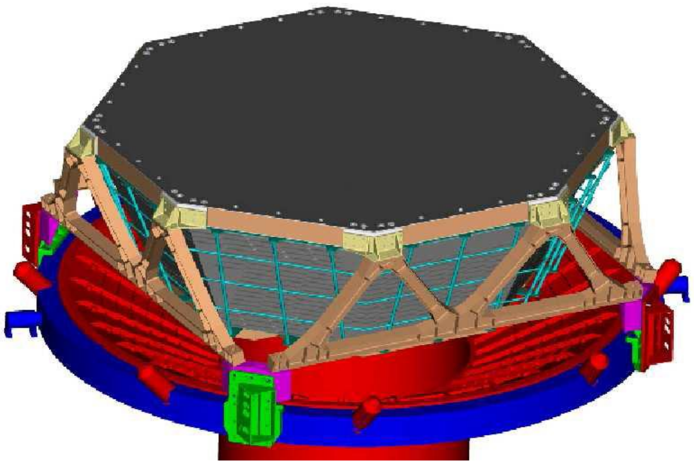
✔ AMS-02 transition radiator consists on a series of foils and air gaps

- 328 modules of fleece

✔ The X-rays are detected by proportional tubes (straw tubes) filled with a mixture of Xe/CO_2 (80%/20%)



✔ evaluation of the particle γ = E/m (boost)
✔ separation of particles with extreme mass differences



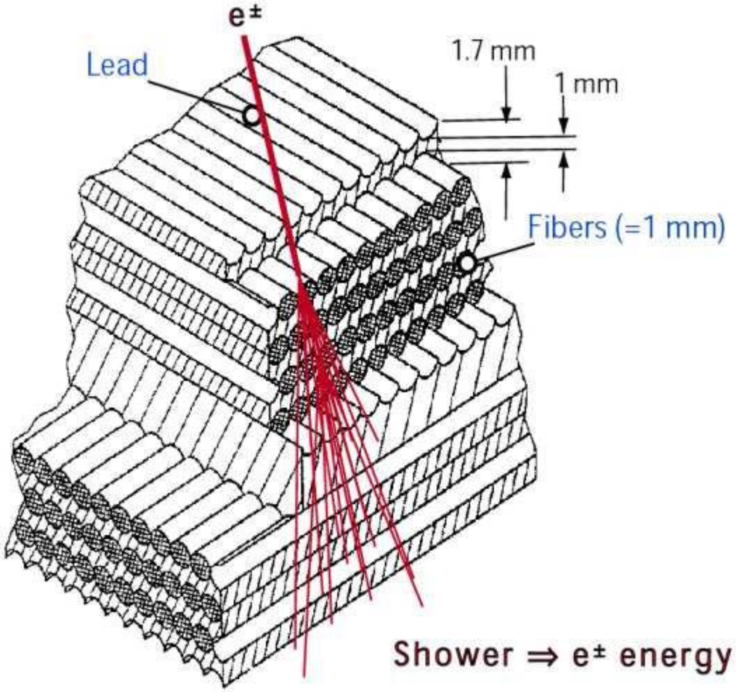
Electromagnetic calorimeter (ECAL)

✓sampling e.m. calorimeter with lead+scintillating fibers structure

648 × 648 × 167 mm^3

lead (58%), fibers (33%), optical glue (9%)

ρ ~ 6.8 g/cm^3



✓ 9 superlayers disposed along X and Y alternately

4(5) disposed along the X (Y)

✓~ $17X_0$ (~1cm) radiation lengths

✓ multi-pixel (2 × 2) photomultiplier's

large dynamic range

✓18 samplings of e.m shower

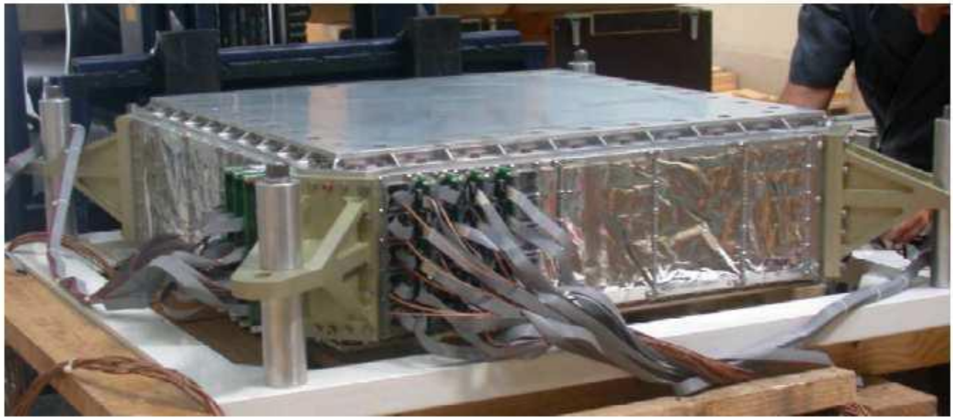
cell granularity ~ 0.5 R_M (35 fibers per PM pixel)

✓detector acceptance : 0.06 m^2.sr

❒ e±, γ energy measurement

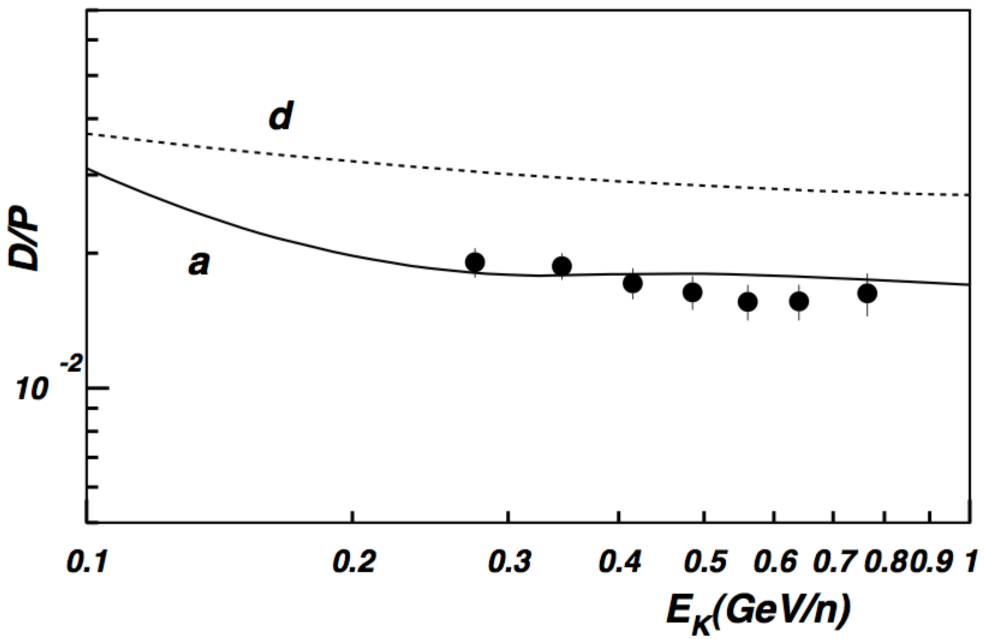
❒ particle direction

❒ fast trigger signal



d/p separation *on going master thesis P. Nunes*

- Deuterons = Rare hydrogen isotopes in CR that are believed to be of secondary origin.
  - d results mainly from the nuclear interactions of primary CR p and He nuclei with ISM.
- Should provide important info for CR propagation in the space.
- Achieving a flux of deuterons to higher energies is fundamental.
- The selection of deuterons is very complex due to the large p background (d/p≈ 2%)
- Standard method: mass separation



$$M = \frac{p}{\gamma\beta} \qquad \left(\frac{\sigma_M}{M}\right)^2 = \left(\frac{\sigma_p}{p}\right)^2 + \left(\frac{\gamma^2\sigma_\beta}{\beta}\right)^2$$

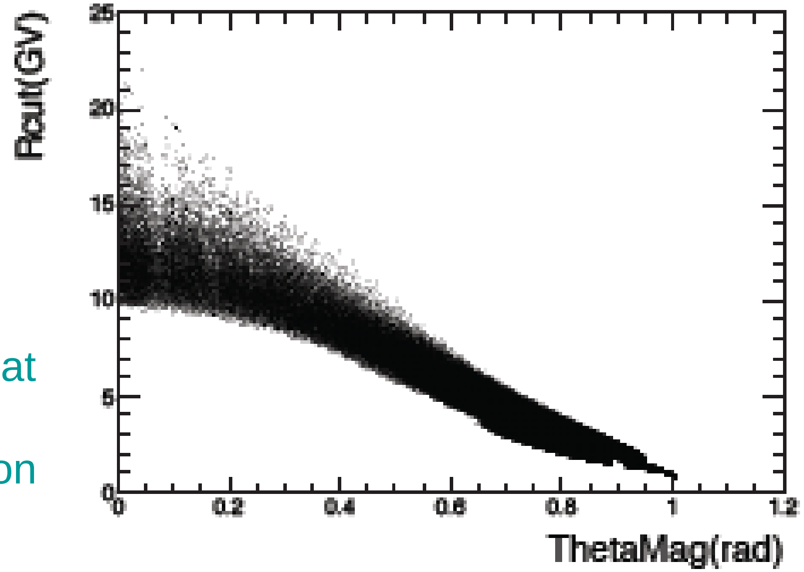
For 10GeV proton
$\gamma^2 \sim 113.65$
$\sigma_M/M \sim 0.15$

Momentum measured by the tracker $\sigma_p/p \sim 10\%$
Velocity measured by the RICH $\sigma_\beta/\beta \sim 10^{-3}$

d/p separation

- Geomagnetic rigidity cut-off can be used to separate deuterons
- **Geomagnetic Rigidity Cutoff:** Minimal rigidity (R=pc/Ze) that a particle coming from the Galaxy must have in order to reach a point near the Earth surface

$$R_c(h,\lambda,\alpha) = \frac{60}{\left(1+\frac{h}{R_E}\right)^2} \frac{\cos\lambda^4}{\left[\sqrt{1+\cos\alpha\cos\lambda^3}+1\right]^2}$$



IDEA: (orig. Balasubramanyan and Hubert)

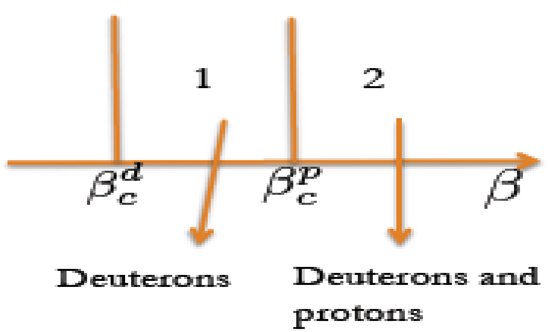
• Accept only particles with a rigidity higher that the cutoff. Select only primary particles

• Each CR particle has a cutoff that depends on its mass for every orbit position

$$\beta_c^{-2} = 1 + \left(\frac{A}{Z}\frac{m}{R_c(h,\lambda,\alpha)}\right)^2$$

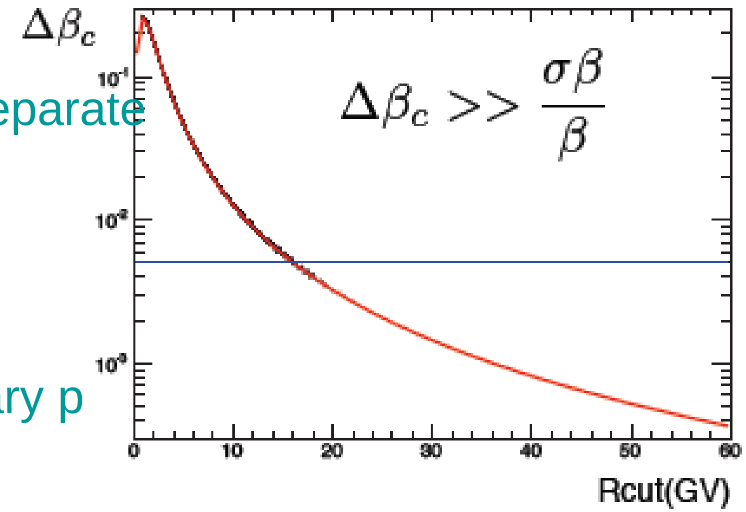
•There is a velocity region where deuterons are naturally separated from protons

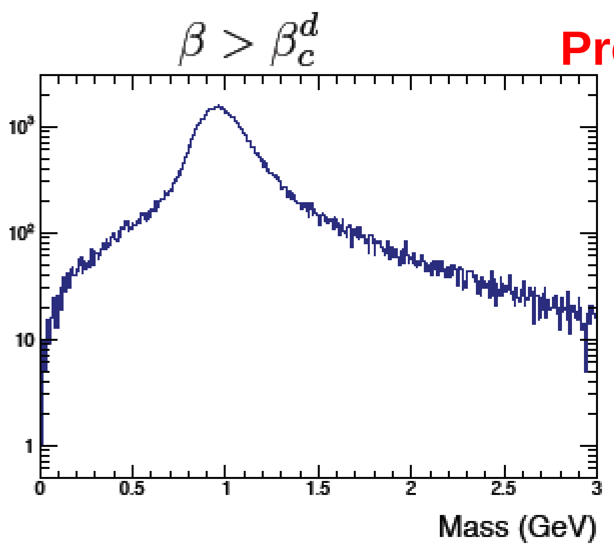
• This region decreases with energy: Higher cut-off energies correspond to lower geomagnetic latitudes



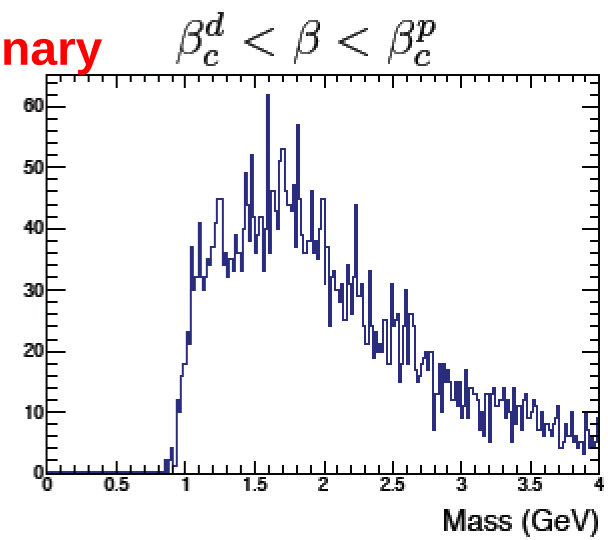
d/p separation

- ✓ Advantages of this method:
  - ✓ Direct use of precise β measurement to separate
- ✓ Steps to perform d/p separation:
  - ✓ Accept only Z=1 particles
  - ✓ Quality cuts in R & β measurements
  - ✓ Accept particles with R>Rcut
  - ✓ Use β_{RICH} to separate primary d from primary p
  - ✓ Obtain a mass distribution





Preliminary



- ✓ Expect to measure a deuteron flux and a d/p ratio up to 10-12