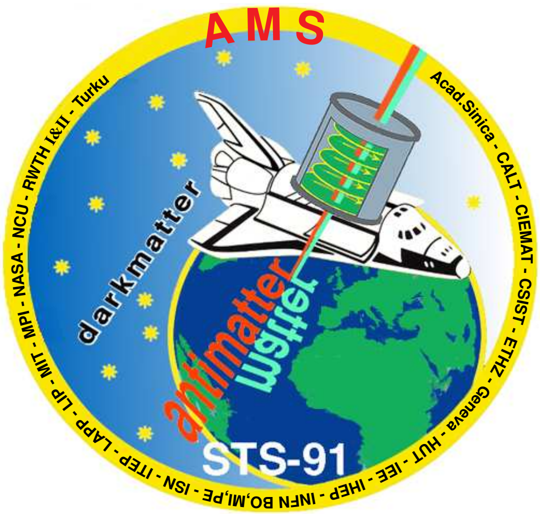
First Results of AMS

Markus Cristinziani
Université de Genève

June 13, 2000
Seminarvortrag ETH Zürich



Outline

- AMS on the STS-91 mission
- Search for antimatter
- Flux measurements (p, $e^{\pm}$ and He)
- Geomagnetic effects
- Outlook to AMS-02

The Alpha Magnetic Spectrometer

- Designed to operate 3 to 5 years on the International Space Station
- Goal: Measure cosmic matter and antimatter with great sensitivity
- Constraints:

$\longrightarrow$ maximum weight 3t

$\longrightarrow$ maximum power consumption 2kW

$\longrightarrow$ survival temperature range -60°,+40° C

$\longrightarrow$ vacuum environment

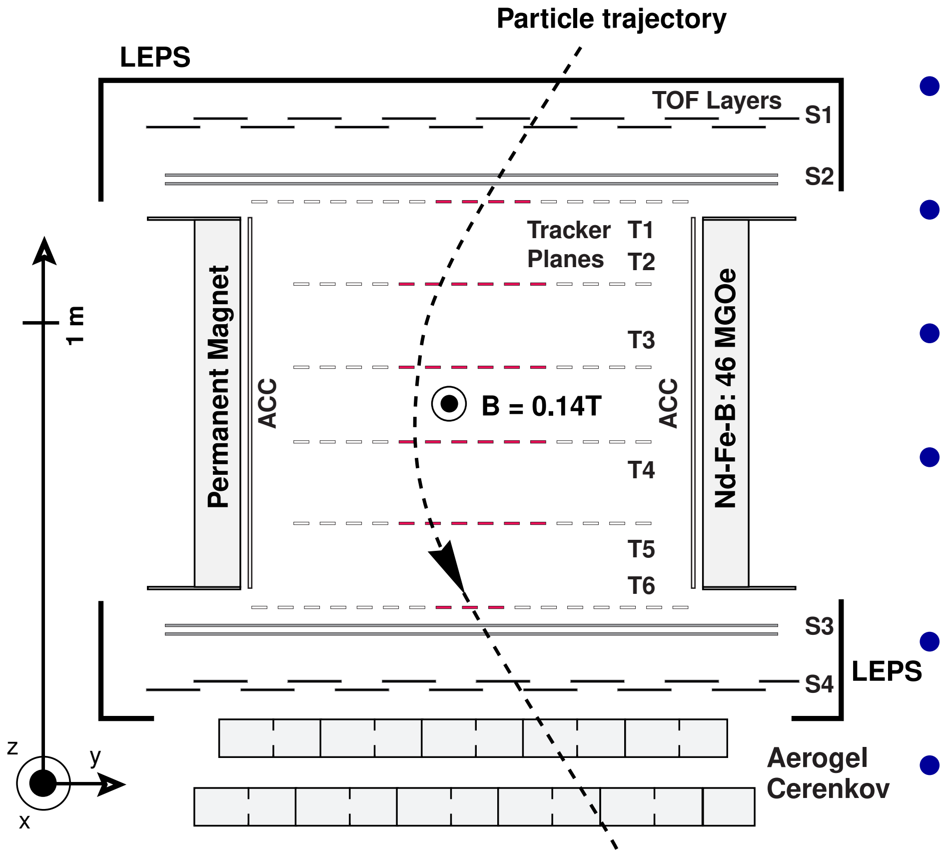
$\longrightarrow$ acceleration at launch 10g

$\longrightarrow$ zero gravity

- 10 days precursor flight on Space Shuttle in June 1998 :

AMS-01

The AMS-01 spectrometer



- Nd-Fe-B alloy permanent magnet BL^2=0.14 Tm^2
- LEPS: Screen against low energy particles
- TOF: Four planes, velocity (β) ($\Delta\beta/\beta \approx 2.4\%$) & Z
- Tracker: 2.1m^2, 6 planes of double sided silicon microstrip detectors: sgn(Z), Z and R
- Aerogel Threshold Cerenkov: additional β measurement
- ACC: Anticoincidence counters reject multiparticle events
- Electronic boxes: power supply, monitoring, DAQ

The STS-91 mission

STS-91 flight: 2-12 June 1998

- Total data taking period: 184 hours
- Flight attitudes: 1°, 20°, 40°, 180° with respect to zenith
- Flight altitude: 320 - 390 km
- Orbit: 51.7°, all longitudes (SAA excluded)

NASA-DOE Memorandum of Understanding, 20 Sept. 1995

"Primarily a test flight that would enable the AMS team to gather data on background sources, adjust operating parameters and verify the detector's performance under actual space flight condition"

The STS-91 mission

A complete success !!

- detector was performing in space as during tests on ground
- 100 million events were recorded on disk
- trigger rates between 0.1 and 1 kHz
- DAQ livetime 90-40 %

AMS-01 gives already accurate results on:

- search for antimatter
- charged cosmic ray spectra
- geomagnetic effects on cosmic rays

Antimatter on Earth

- 1928 *P.A.M. Dirac*
  Relativistic quantum theory requires that particles come in pairs
- 1933 *C.D. Anderson*
  Discovery of the positron by means of a cloud chamber
- 1955 *O. Chamberlain et al.*
  Detection of the antiproton in pp-collisions at Bevatron/LBL
- 1965 *PS/CERN*
  Detection of antideuteron in pBe-collisions
- 1995 *LEAR/CERN*
  Synthetic Antimatter. Antihydrogen built through positron-capture of an antiproton

Is the Universe baryon symmetric ?

From the 30's into the 60's the mainstream view of the Universe is that of a baryon symmetric one

Dirac's Nobel speech: *We must regard it rather as an accident that the Earth [...] contains a preponderance of negative electrons and positive protons. It is quite possible that for some stars it is the other way about.*

But: There is only matter in our environment ?!

In 1967 **Sakharov** formulated three ingredients necessary for baryogenesis

1. Direct violation of baryon number conservation
2. C and CP-violation
3. Period out of thermal equilibrium

Baryon symmetric scenarios

Brown, Stecker (79) and Sato (81):
Provided the Sakharov conditions are fullfilled, a symmetric universe can exist if the sign of CP violation is not universal
(spontaneous symmetry breaking).
Matter and antimatter domains in the Early Universe + Inflation

$\Longrightarrow$ Domains of astronomical dimensions

Recent theories by e.g. Cohen et al.(98) and Adams et al.(97):

- the domain size could be greater than the cosmological horizon
- the intergalactic magnetic field could introduce an important cutoff for low energy particles

Indirect measurements: Photons

If the Universe contains regions of antimatter and matter, annihilation radiation at the boundaries should occur via the process:

$$
\begin{array}{rcl}
N + \overline{N} & \longrightarrow & \left\{ \begin{array}{l} \pi^0 \rightarrow \gamma + \gamma \\ \pi^\pm \rightarrow \mu^\pm + \nu(\overline{\nu}) \end{array} \right. \\
\mu^\pm & \longrightarrow & e^\pm + \nu_e(\overline{\nu_e}) + \nu_\mu(\overline{\nu_\mu})
\end{array}
$$

BUT this should result in:

- a distortion of the cosmic microwave background (COBE measures a quite isotropic blackbody radiation)
- a signal in the extragalactic diffuse γ-ray background induce by the (redshifted) annihilation photons (MeV bump? CGRO)

Direct Searches for Antimatter: $\overline{p}$

It is not easy to interprete the $\overline{p}$-flux near Earth:

- An $\overline{p}$ background is produced by interactions of cosmic rays with the ISM which can be subtracted provided the knowledge (assumptions) of:

$\longrightarrow$ incident spectra

$\longrightarrow$ interstellar gas composition

$\longrightarrow$ relevant cross-sections

$\longrightarrow$ solar modulation at lower energies

- Since 1979 (Golden et al.) measurements show hints of excess in different energy regions which later on could be explained by adjusting parameters

Antiproton measurements do not provide evidence for extragalactic antimatter

Direct Searches: Antimatter $Z \geq 2$

The probability to produce antinuclei through high energy interactions falls drastically with the amount of antinucleons

Hagedorn 1973

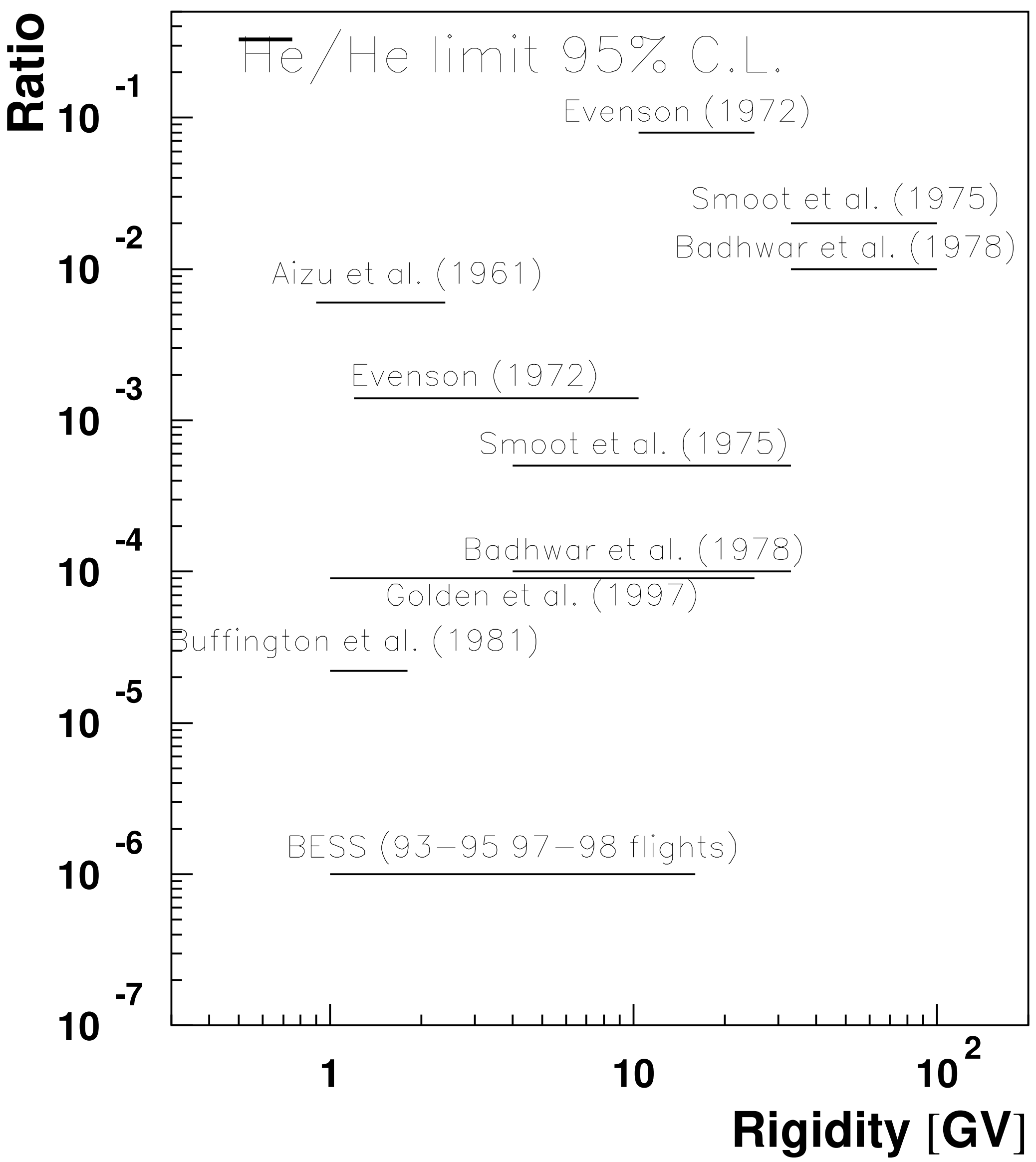
$$\overline{N}/\overline{p} \approx exp[-2(M - M_p)c^2/kT_0]$$

Expected secondary production $\bar{\mathrm{C}}/\overline{p} = 10^{-56}$

- Discovery of antinucleus (e.g. antihelium) $\Longrightarrow$ evidence for cosmologically significant amounts of antimatter
- Discovery of just one anticarbon nucleus $\Longrightarrow$ antistars

No antinucleus with $Z \geq 2$ has ever been found in the cosmic radiation

Summary of balloon experiments

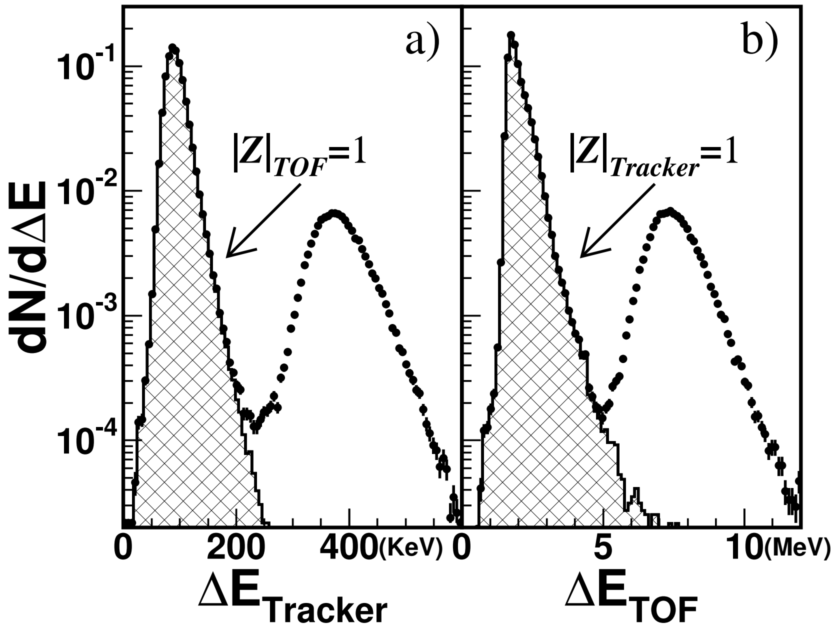


Search for Antimatter: Data Analysis

The event parameters are reconstructed:

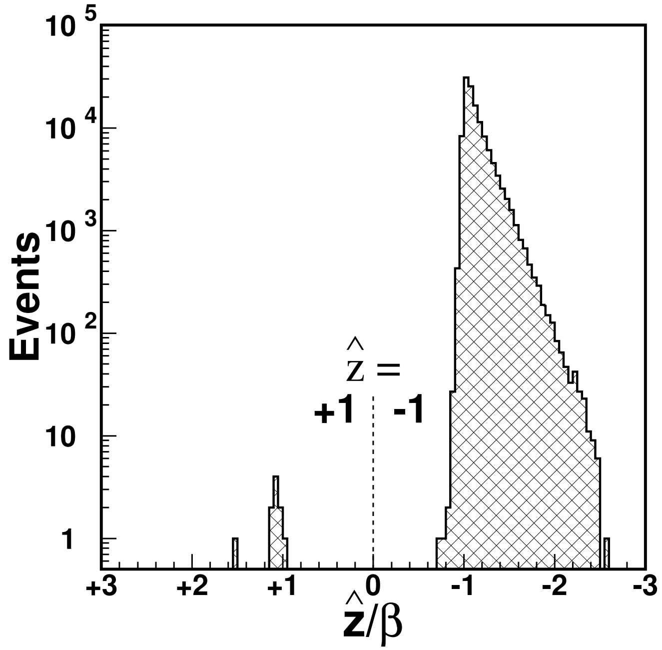
- Rigidity: from the deflection of the trajectory measured by the Tracker; at least 4 hits and agreement of the two fitting algorithms required
- Particle's velocity and direction from TOF
- The charge magnitude is determined by the multiple energy loss measurements in the scintillators and in the silicon
- the sign of the charge and the particles' mass are derived
- Major background for antimatter search: p, e^- and He

Z=2 events selection



Two independent measurements of the energy loss allow to keep background as low as 10^{-7}

The accuracy of the redundant TOF system (105 ps) ensures an always correctly assigned direction

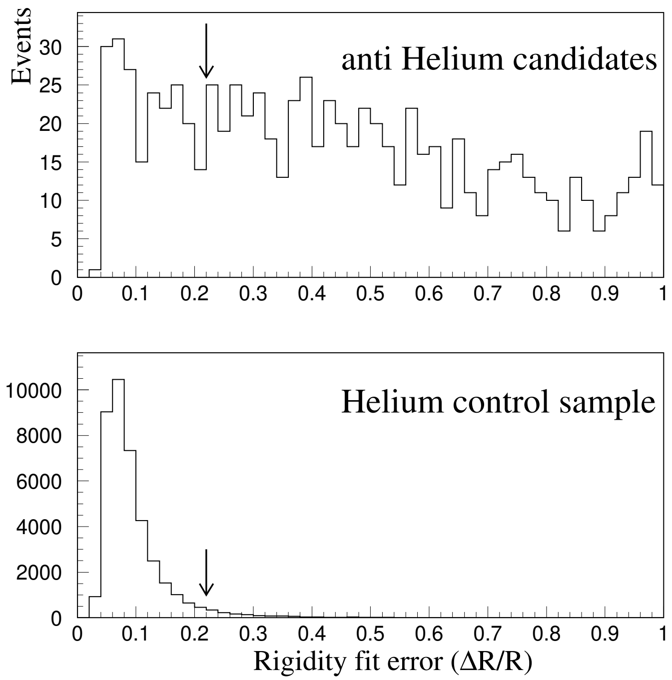


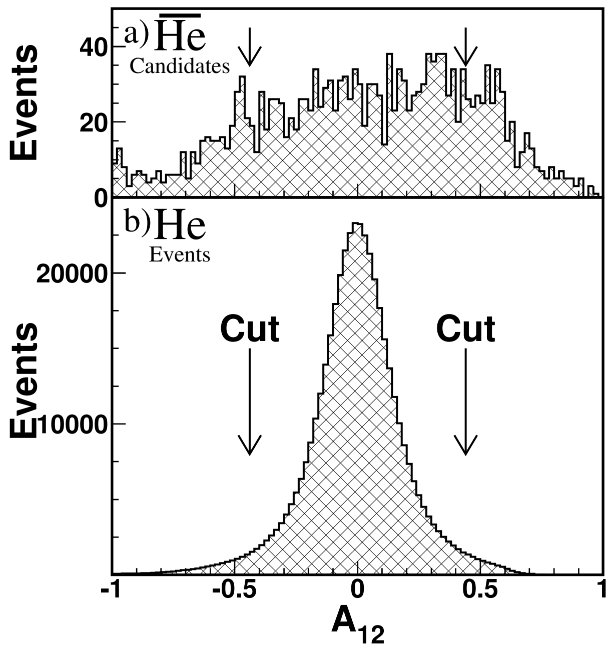
Large angle nuclear scattering

A single nuclear scattering can introduce a large kink in the trajectory
this can result in a wrongly determined charge sign

cut on estimated rigidity error

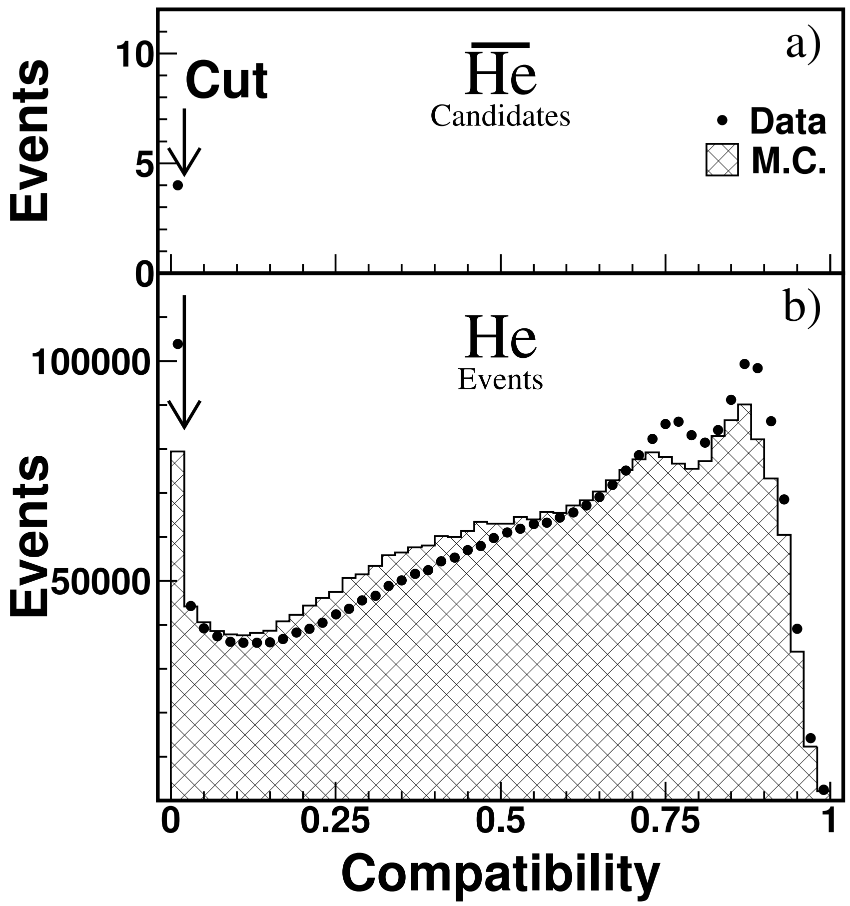
$$A_{12} = (R_1 - R_2)/(R_1 + R_2)$$





Compatibility check

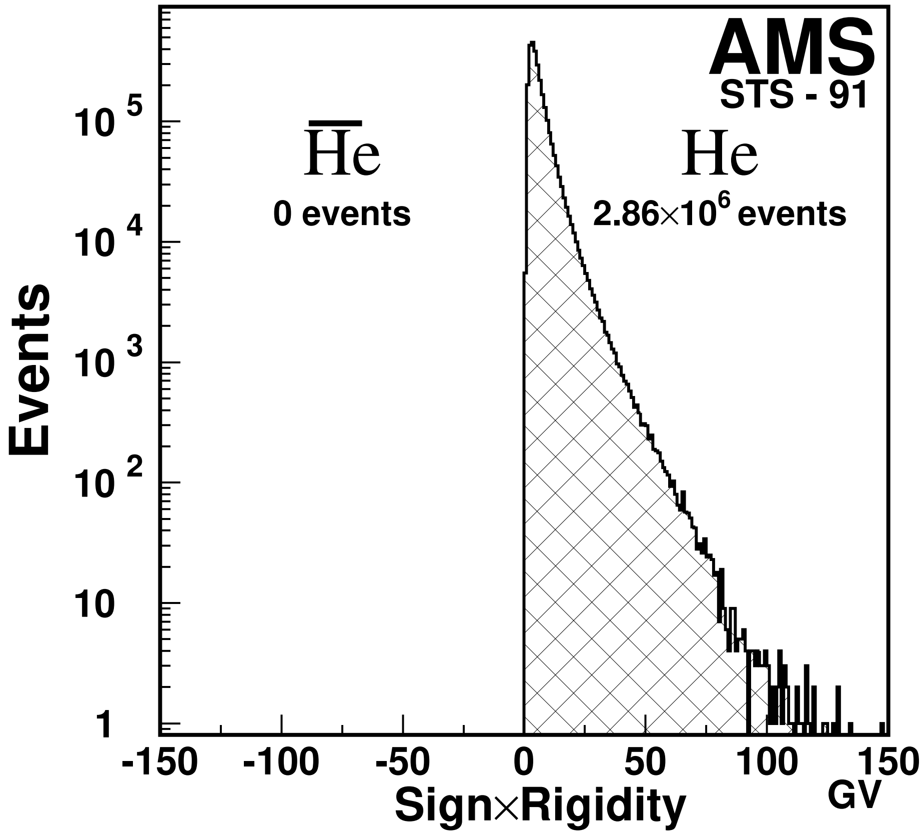
Last step of event selection: check whether the measured event parameters β, R and $|Z|$ are compatible to be an $\overline{\mathrm{He}}$-nucleus



Markus Cristinziani
Université de Genève

Result for $|Z|=2$

(cfr. Phys.Lett.B461(1999) 387–396)

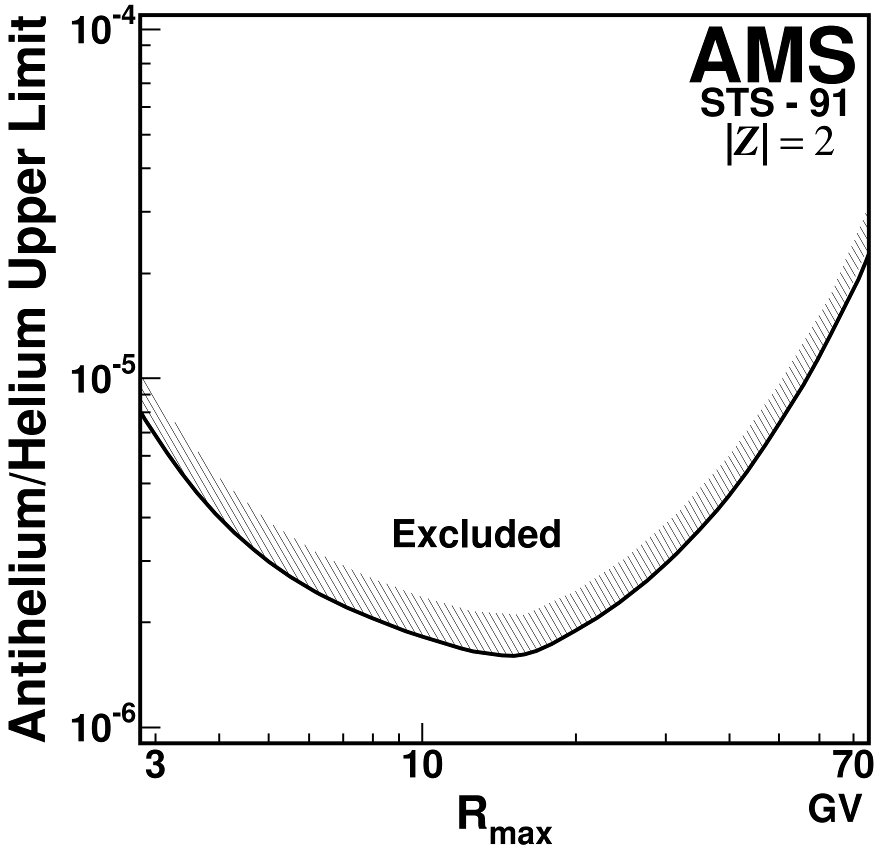


No antihelium events were found at any rigidity. Assuming the (unknown) incident $\overline{\mathrm{He}}$–spectrum to be the same as He:

$$\frac{N_{\overline{\mathrm{He}}}}{N_{\mathrm{He}}} < 1.1 \times 10^{-6} \text{ at } 95\% \text{ C.L.}$$

Model independent result

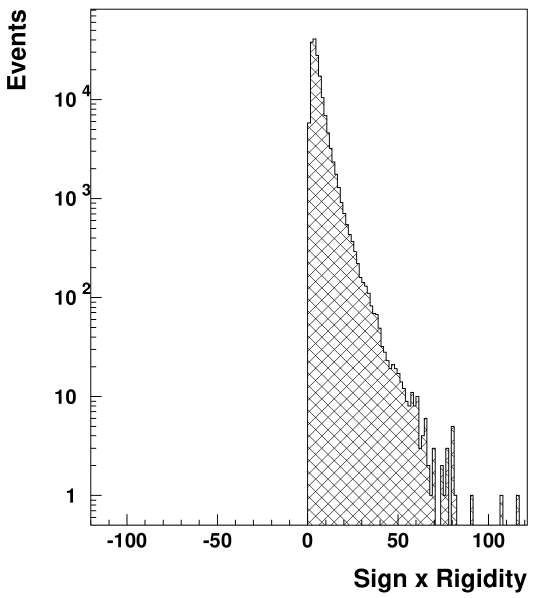
After corrections of the raw spectrum for Livetime(Θ_m), rigidity resolution and different inelastic cross sections

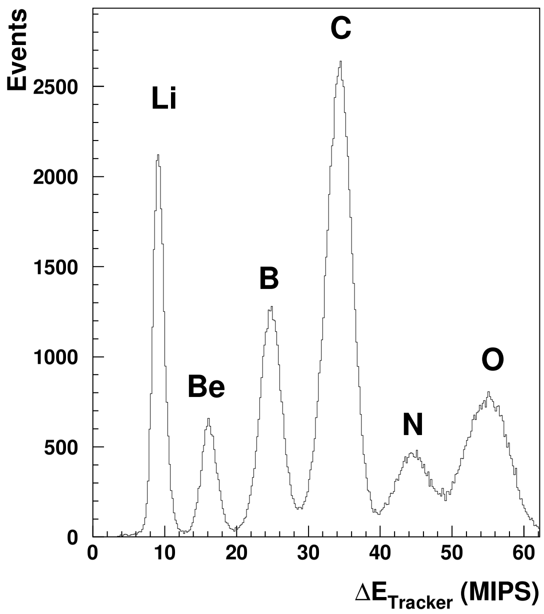


Upper limit on the flux ratio as a function of the rigidity interval $[\mathrm{R}_{min} = 1.6\mathrm{GV} \ldots \mathrm{R}_{max}]$

Result is independent of the incident $\overline{\mathrm{He}}$-spectrum

Search for heavier antinuclei





- A total of 1.65×10^5 heavy ions have been identified.
- These nuclei range from lithium to oxygen, in the rigidity interval [1 GV; 100 GV]
- No antinucleus was found
- Understanding of trigger efficiency is in progress

Charge particles spectra: protons

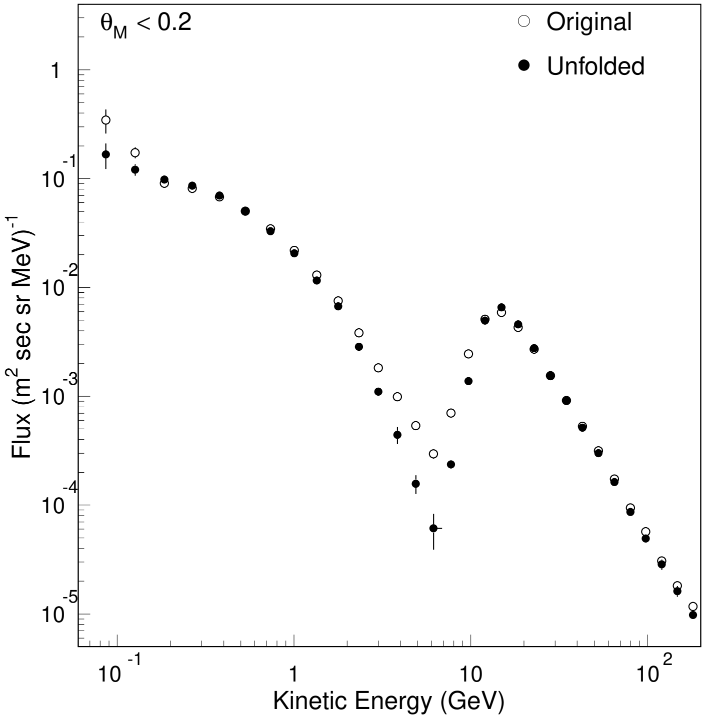
Protons are the most abundant charged particles in space
Their study improves the understanding of the interstellar propagation and acceleration of cosmic rays

They have been studied in three distinct regions in space:

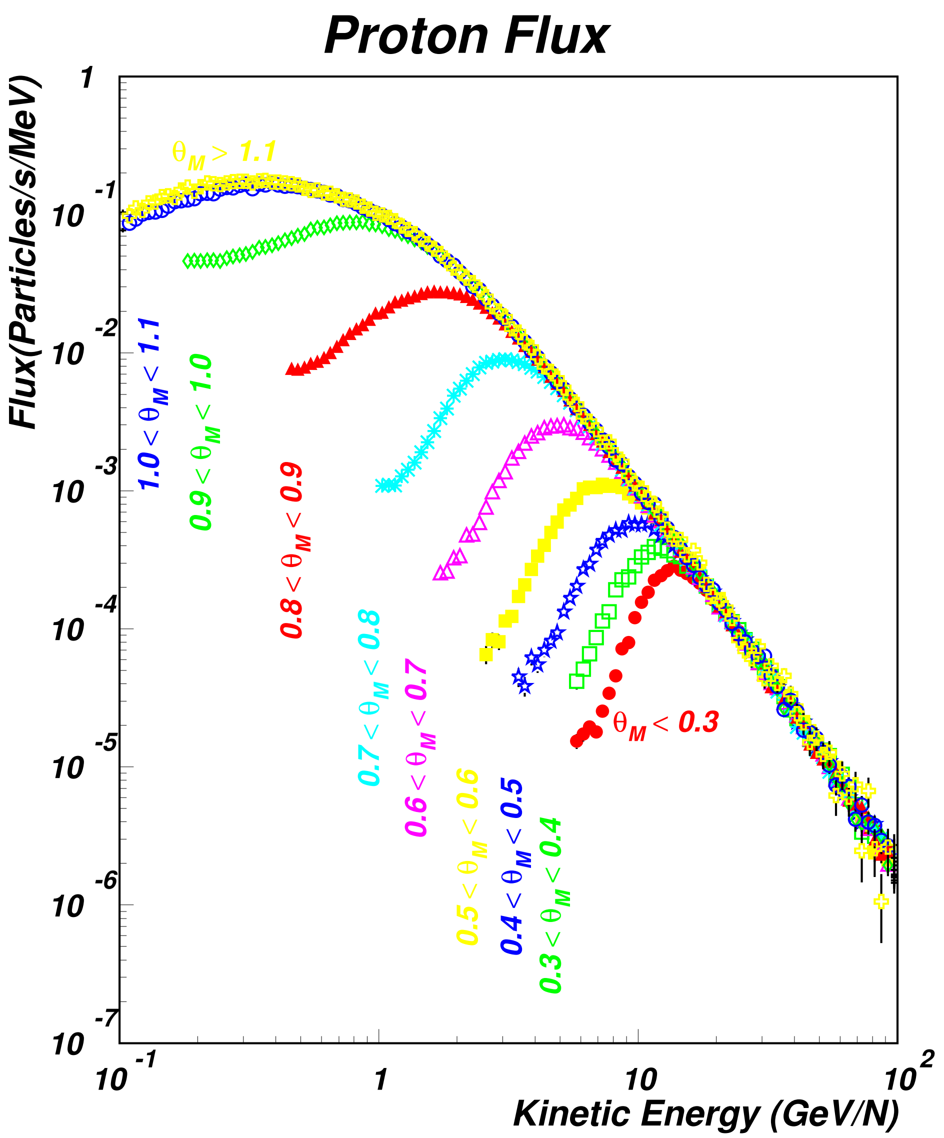
- Altitudes 30-40 km: balloon measurements; atmospheric secondaries
- Inner and outer radiation belts from 1000 km: small size satellite detectors; high intensity
- The intermediate region $\Rightarrow$ AMS

Determination of the differential flux

- Proton selection is easy since dominant contribution in CR
- background: $\pi^{\pm}$ at low energy produced in the shield, $d \longrightarrow$ Mass-cut
- acceptance is estimated via Monte Carlo simulation: 0.15 $\mathrm{m}^2\mathrm{sr}$ on average
- detector resolution is simulated and checked with test beam
- data are unfolded using a method based on Bayes' theorem

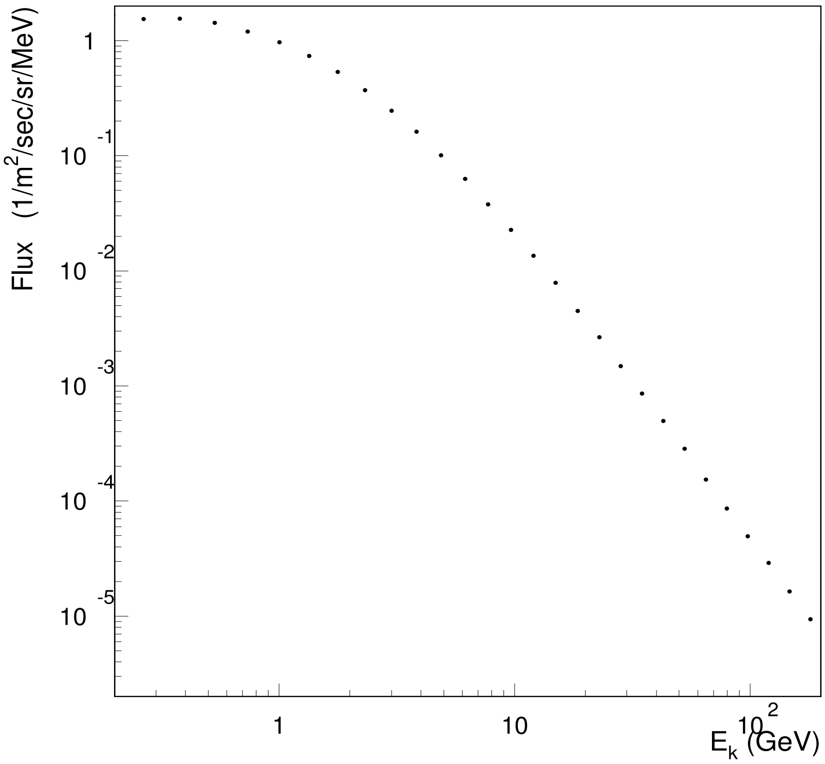


Comparison of a spectrum before and after unfolding



Cutoff: depending on the magnetic latitude, a charged particle must have a minimal rigidity in order to overcome the Earth's magnetic field

Primary Proton spectrum



Fitting the spectrum over all latitudes at energies above the geomagnetic cutoff (E>10 GeV) to

$$\Phi_0 \times \mathrm{R}^{-\gamma}$$

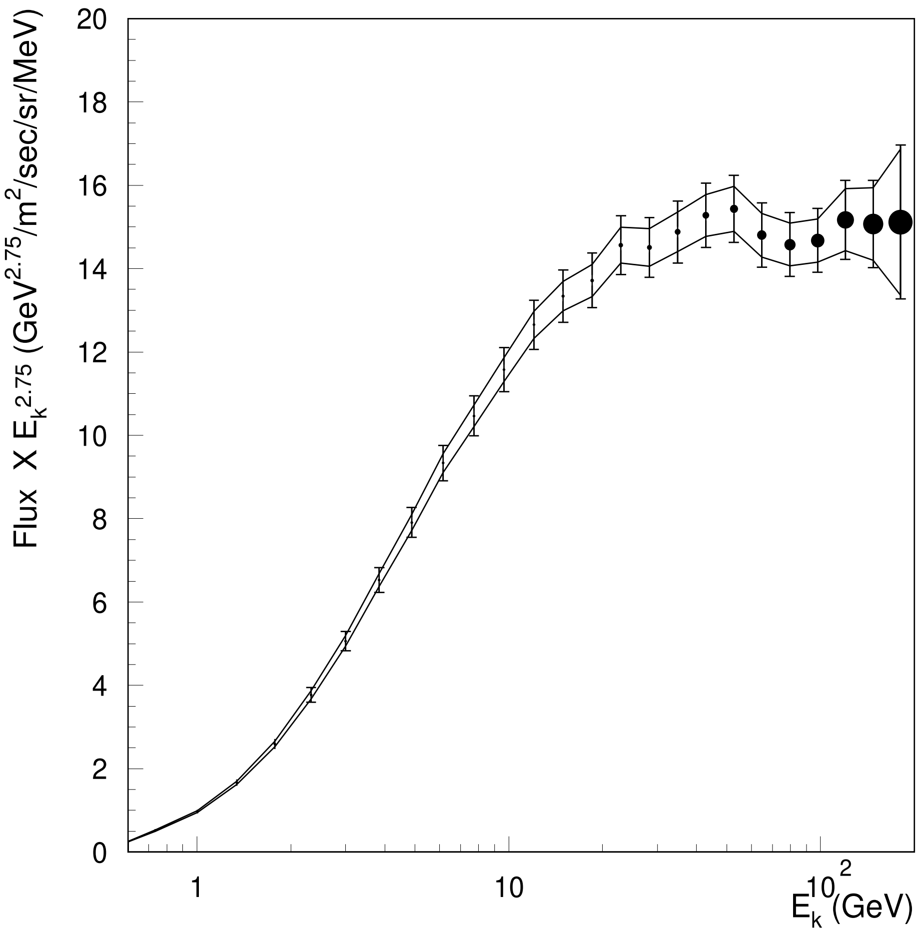
γ=2.79 $\pm$ 0.012 (stat) $\pm$ 0.019 (sys),

Φ_0=16.9$\pm$0.2(stat)$\pm$1.3(sys)$\pm$1.5(γ)$\frac{\mathrm{GV}^{2.79}}{\mathrm{m}^2\mathrm{secsrMV}}$

$\longrightarrow$ `Phys.Lett.B 472 (2000) 215-226`

Primary proton spectrum: errors

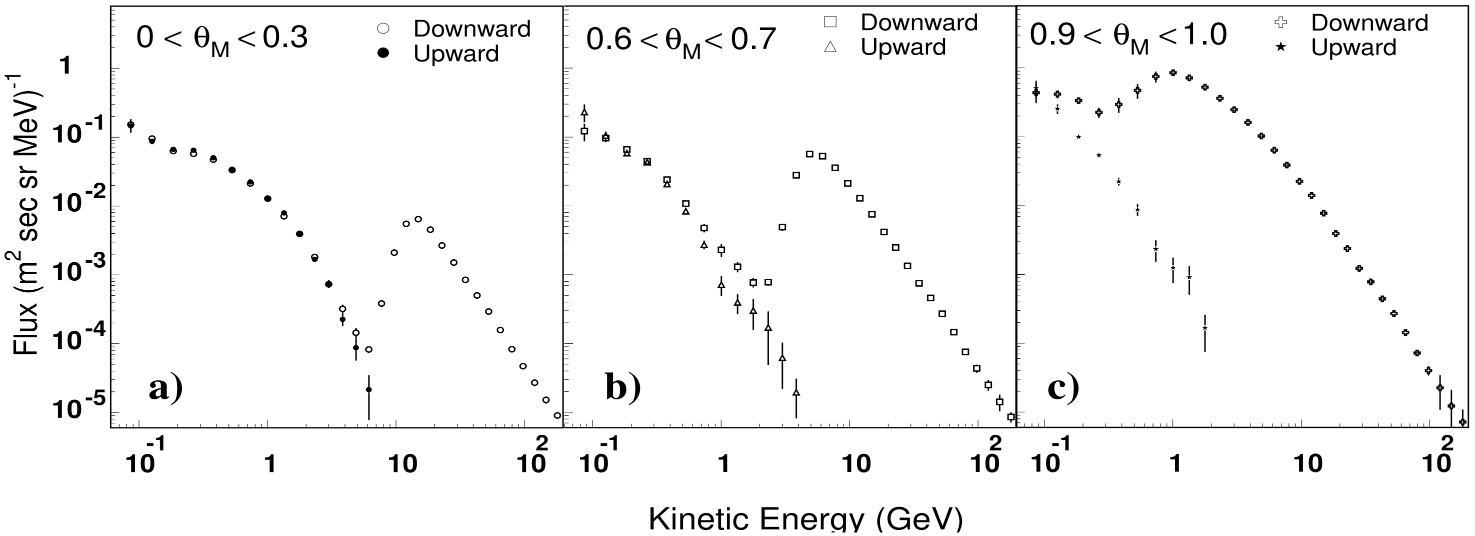
Spectrum multiplied by $\mathrm{E}^{2.75}$



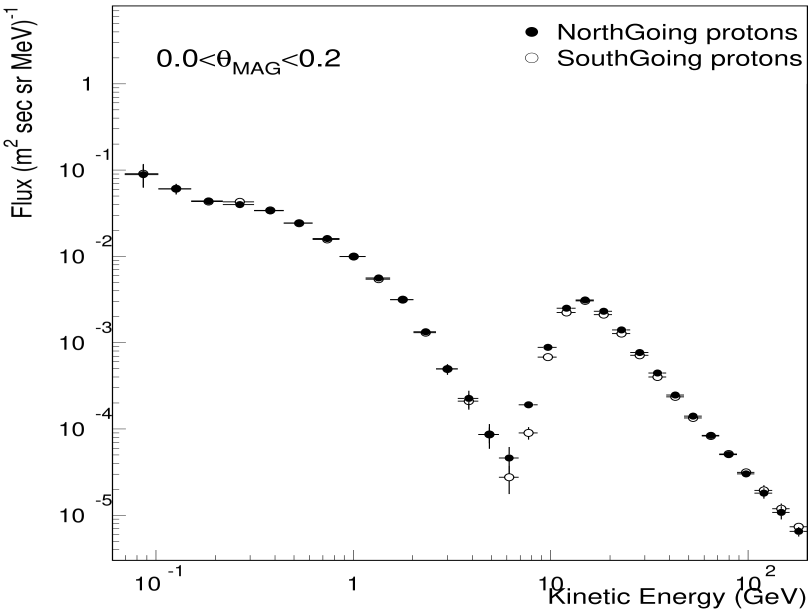
- Marker size: statistical error
- Lines: systematical error
- Error bars: Full error

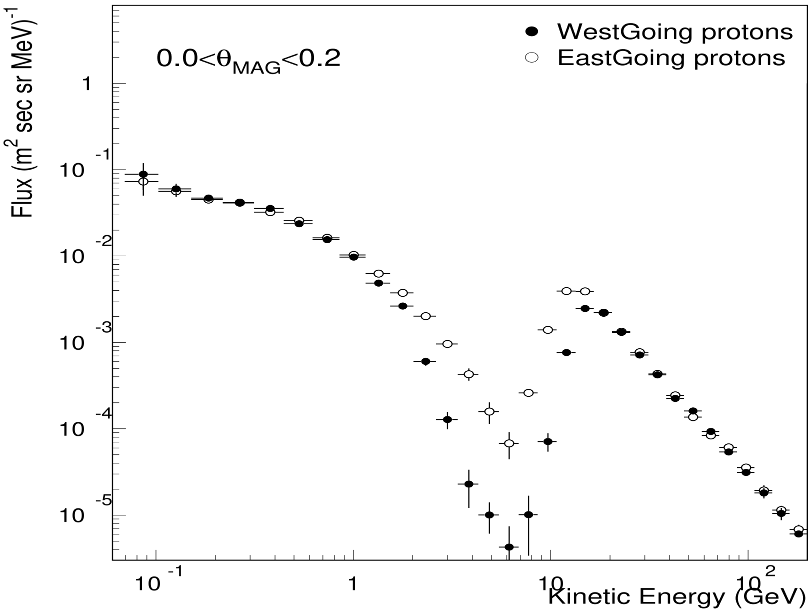
Full Proton spectra: behaviour at different Θ_m

A substantial second spectrum under cutoff is observed



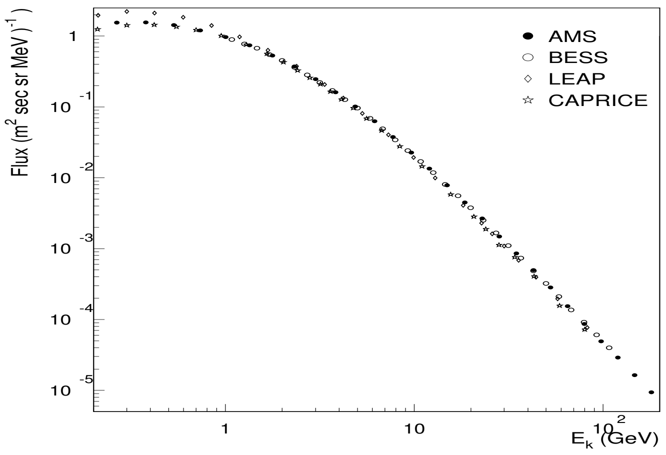
- at geomagnetic equator, it extends from 0.1 GeV to 6 GeV
- over the wide range $0.3 < \Theta_m < 0.8$ the flux is nearly constant
- the up- and downward fluxes are identical for $0 < \Theta_m < 0.8$
- at polar latitudes downward is affected by primary spectrum

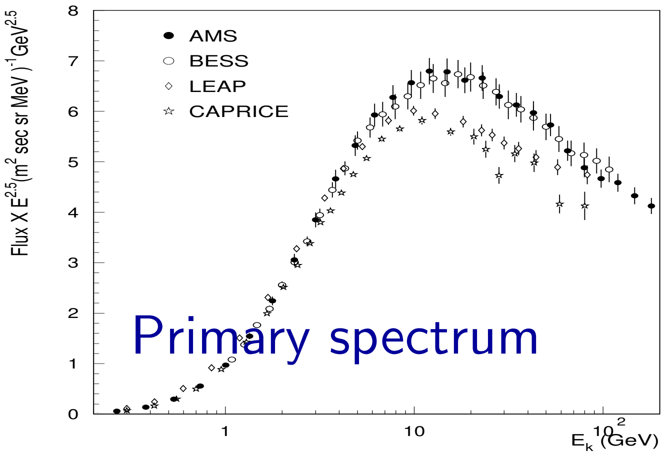




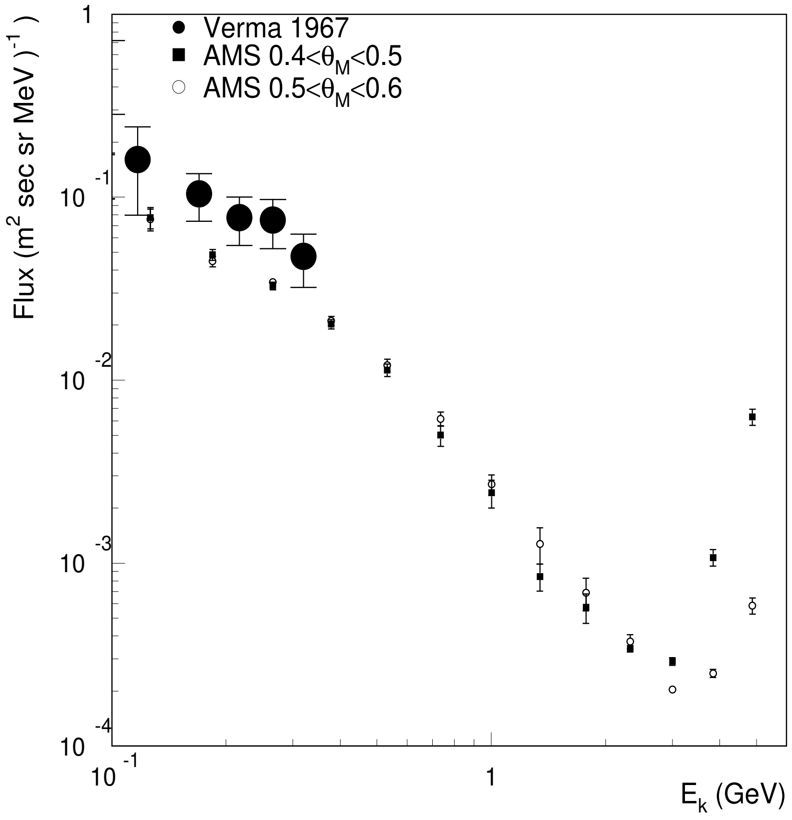
- Second spectra of p going to South and to North coincide
- Starting from 1 GeV, an East-West anisotropy is seen

Comparison with other experiments





Second spectrum



Data analysis on e$^{\pm}$

AMS measured the spectrum of electrons in the range 0.2 - 30 GeV

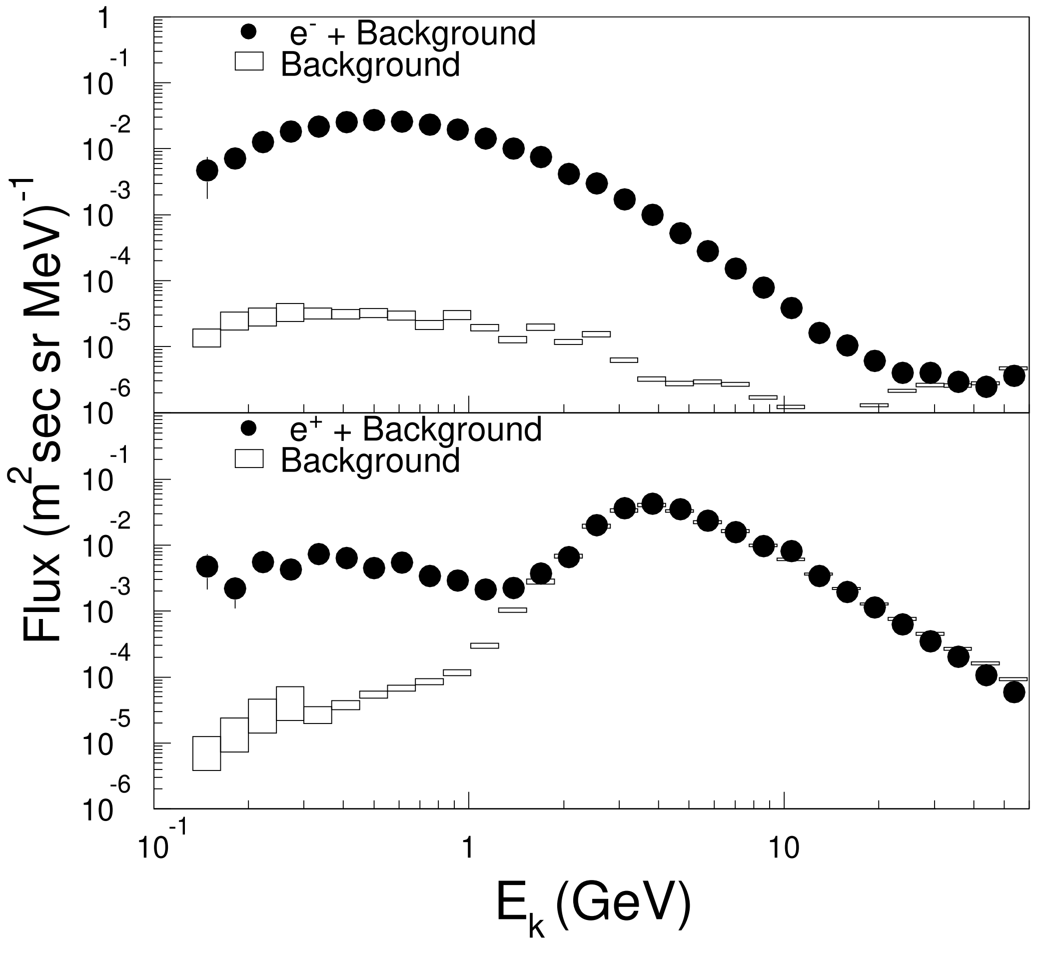
- background : protons with bad p, secondary pions: $\mathcal{O}(10^{-4})$
- signal from Cerenkov required (independent β measurement)
- total selection efficiency (MC + test beam): 39%

AMS measured the spectrum of positrons in the range 0.2 - 3 GeV

- background : protons with bad β
- at low energy: tenfold dE/dx of scintillator and tracker
- at higher energy: additional cuts on Cerenkov (only up to 3 GeV)
- total selection efficiency (MC + test beam): 28%

Background subtraction

Electron and positron spectra together with the estimated background for the geomagnetic polar regions, where the background conditions are more severe

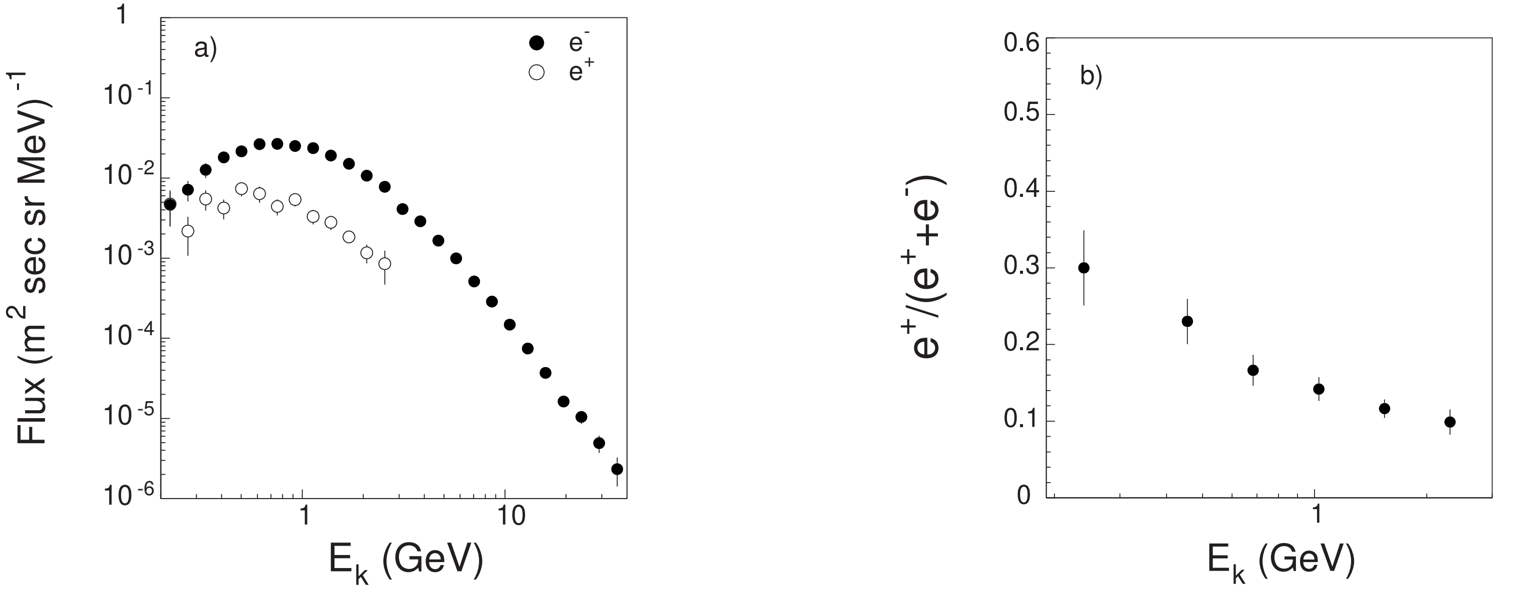


The overall systematic error is 5%

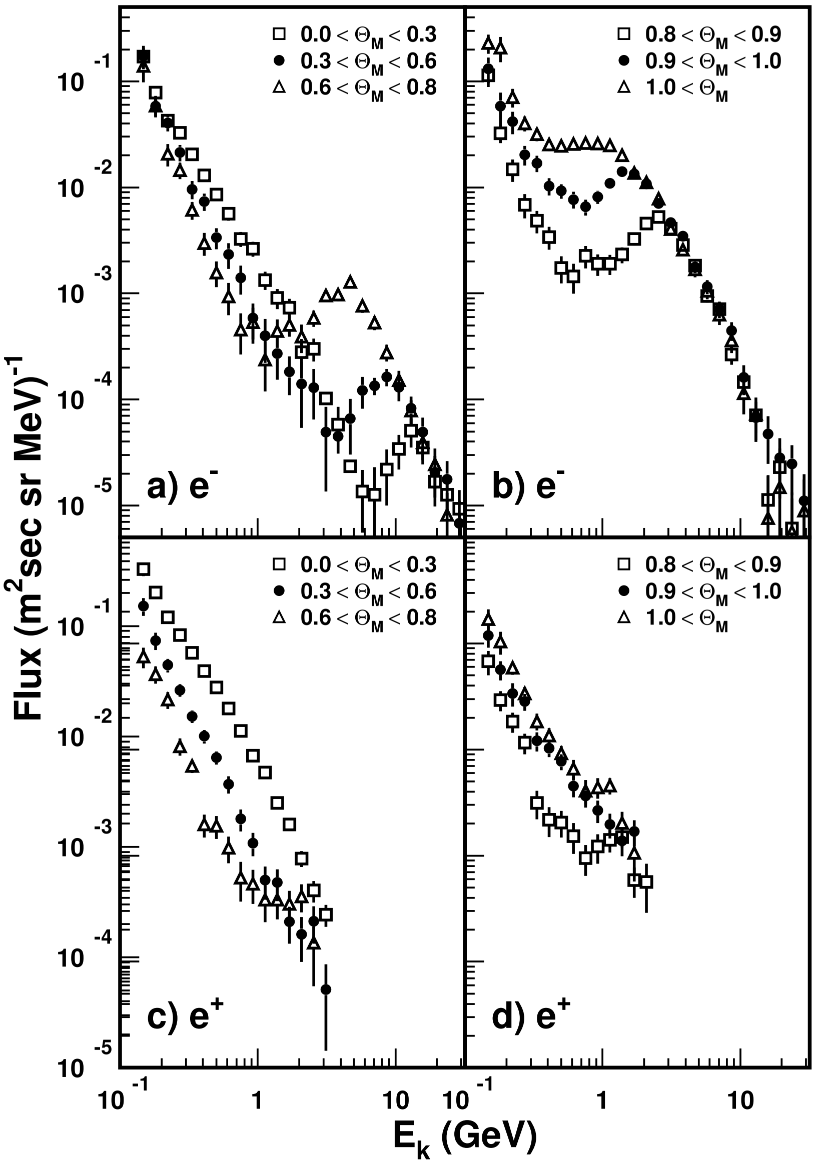
Primary electrons

- high energy electrons originate from primary acceleration sites (supernova explosions)
- high energy electron-positron pairs are produced from collisions of hadrons and gamma rays with interstellar gas

$$\Rightarrow \text{more } \mathrm{e}^- \text{ than } \mathrm{e}^+ \text{ expected}$$

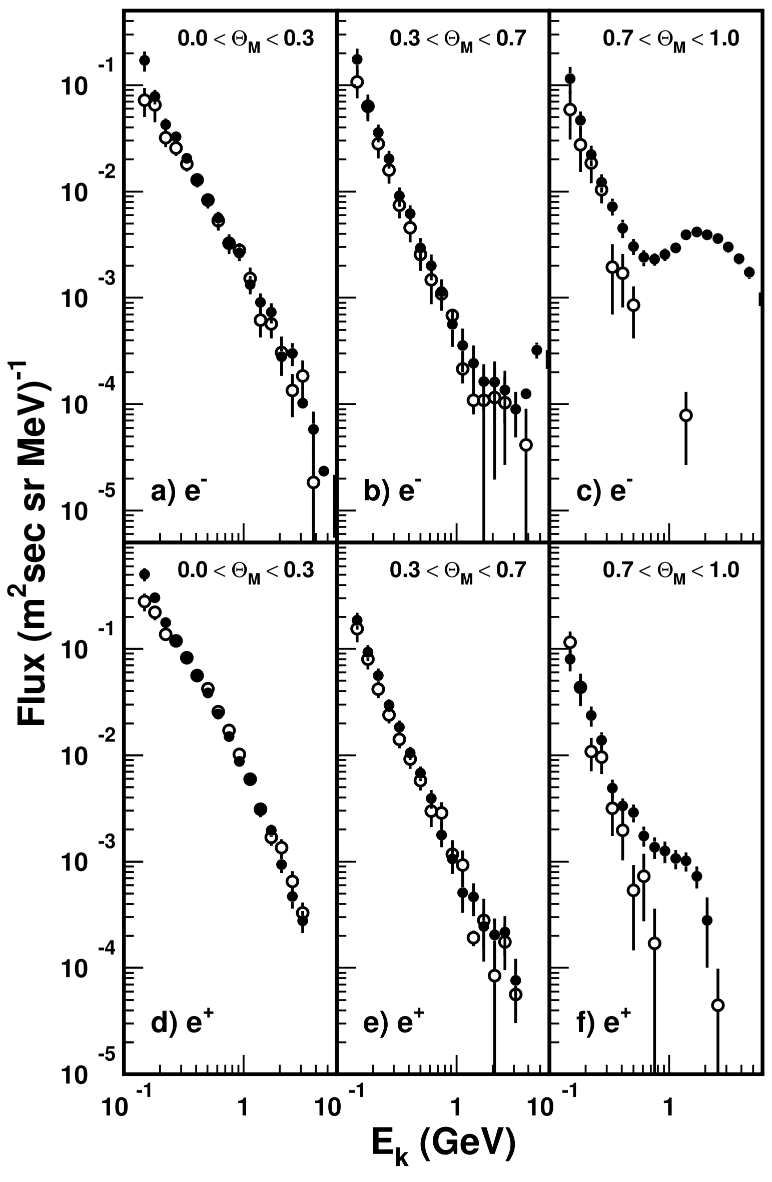


Downward going $e^{\pm}$



A substantial second spectrum under cutoff is observed for electrons and positrons

Comparison down/up



- full circles: downward going particles
- open circles: upward going particles

Upward and downward fluxes are nearly identical

Tracing

In order to better understand the second spectra, trajectories have been traced through the Earth magnetic field $\longrightarrow$ cfr. Flückiger et al.,Bern

Starting from the measured incident angle, location and rigidity, particles were traced back- and forward until

- the trajectory reached outside the magnetosphere
- it reached the atmosphere at an altitude of 40 km

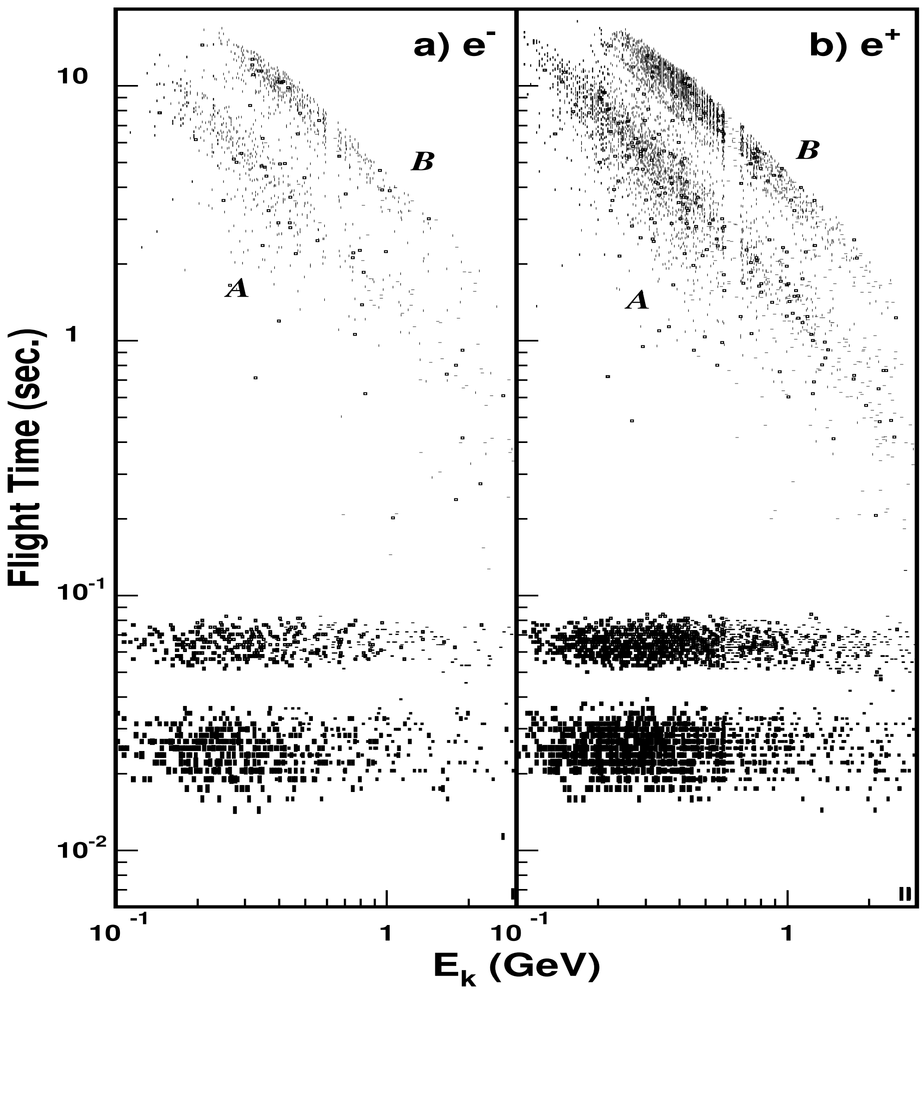
This allows a better separation of primary and second spectrum and gives interesting new results...

Livetime of particles

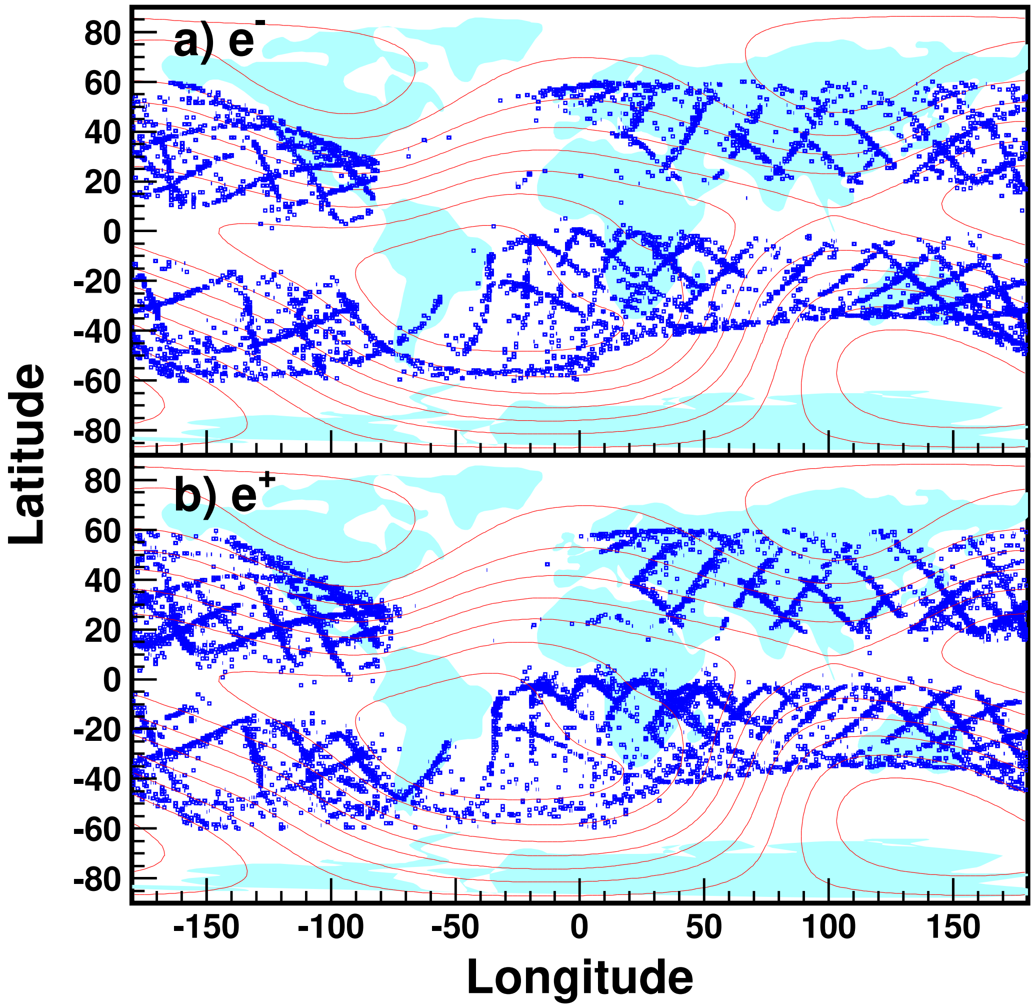
Two distinct components are observed:

- horizontal bands: $t < 0.2$ sec short-lived
- diagonal bands: $t > 0.2$ sec long-lived

Most of the particles (70%) are long-lived

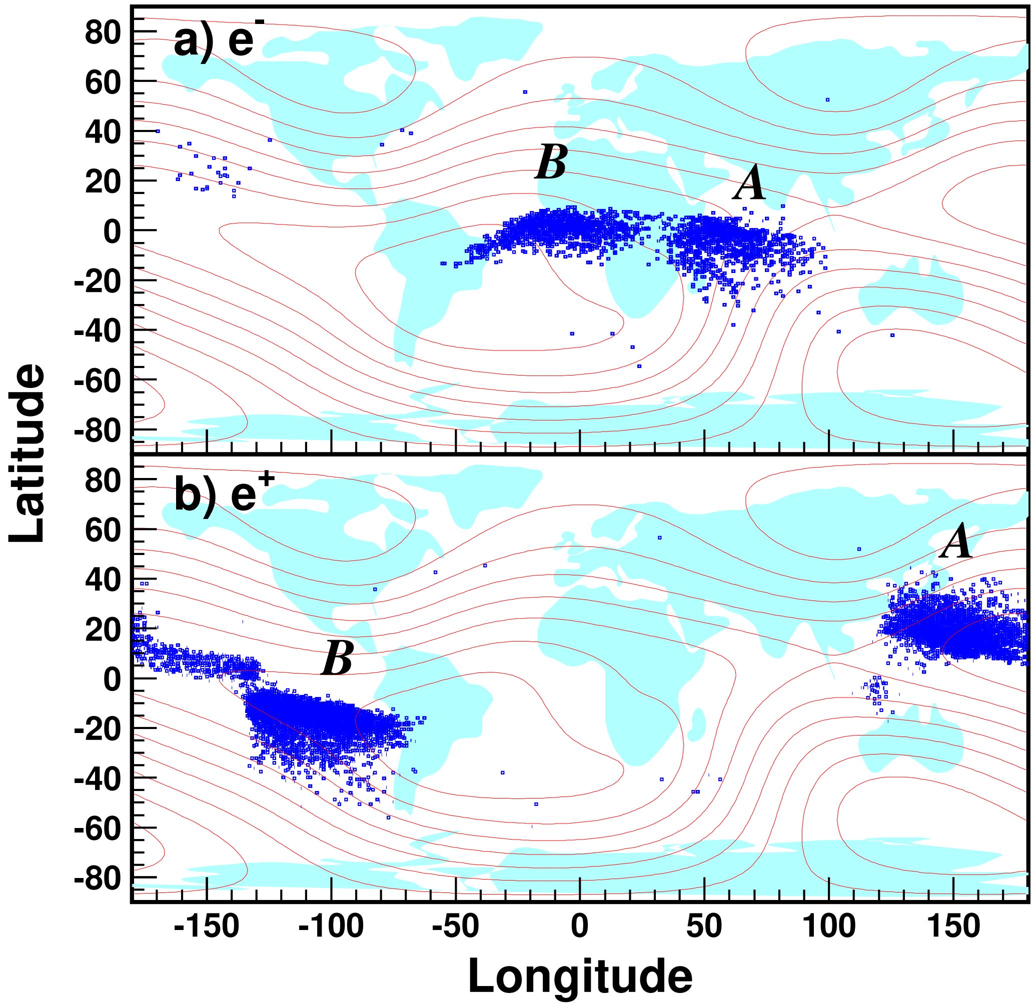


Short lived production points



- origin show no longitude dependence
- they do not originate from $\Theta_m < 0.4$
- flight-time is energy independent
- flux independent on attitude and isotropic

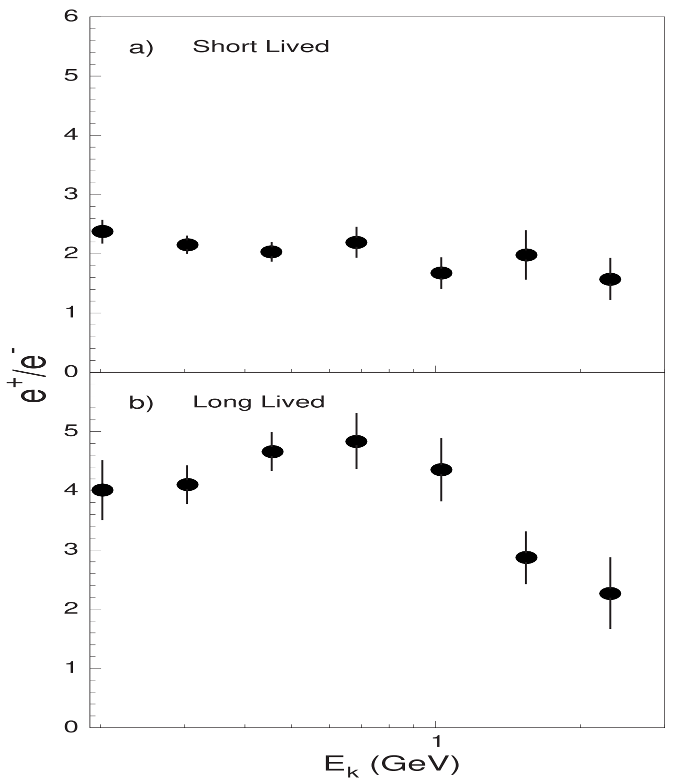
Long lived production points



- e^- and e^+ originate from well defined, complementary geographic regions
- origin for e^+ coincide with sink for e^-
- they are reflected hundreds of times (decreasing with energy)
- flux depends on attitude

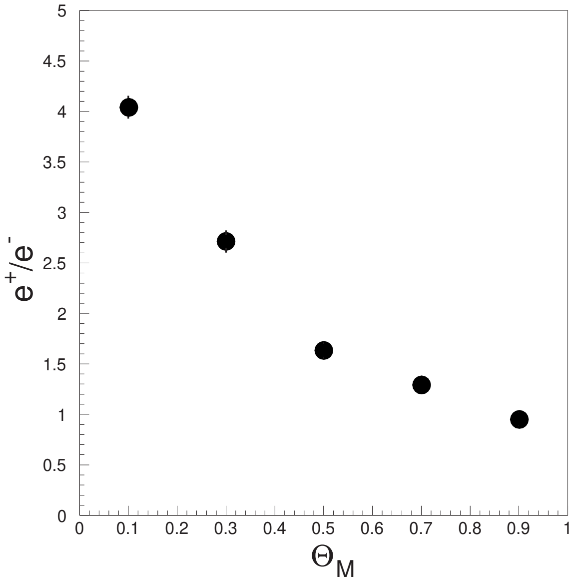
Second spectrum e^+/e^-

Short- and long-lived
behave differently



Combined second spectra ratio
integrated over 0.2 to 2.5 GeV

We observe an excess of positrons
increasing at magnetic equator



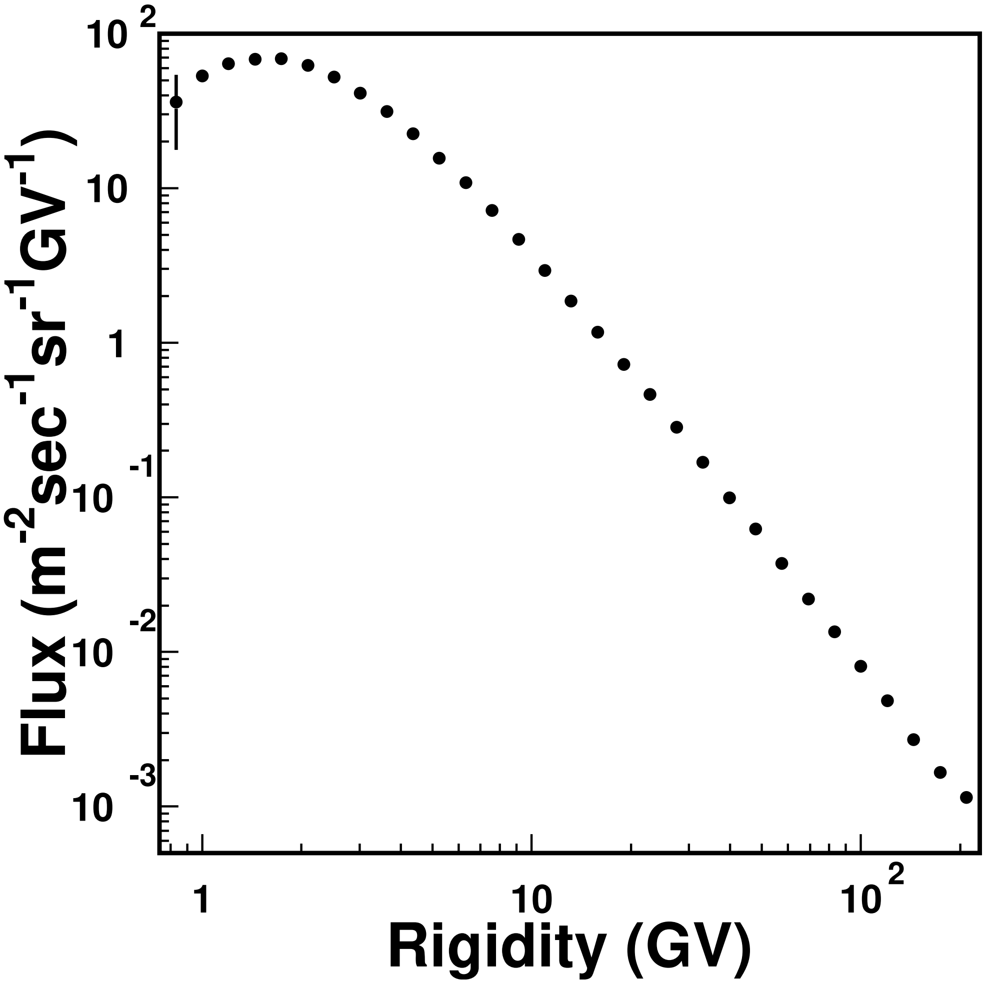
Helium

- Helium nuclei are the second most abundant element in cosmic rays
- balloon measurements : no difference in spectrum between helium and protons $\Rightarrow$ same source
- however there might be a difference at 10-100 GeV or higher

preliminary results ...

- AMS measured 10^6 nuclei in the range 0.1 to 100 GeV/n
- Detection of a second spectrum under cutoff

Helium primary spectrum

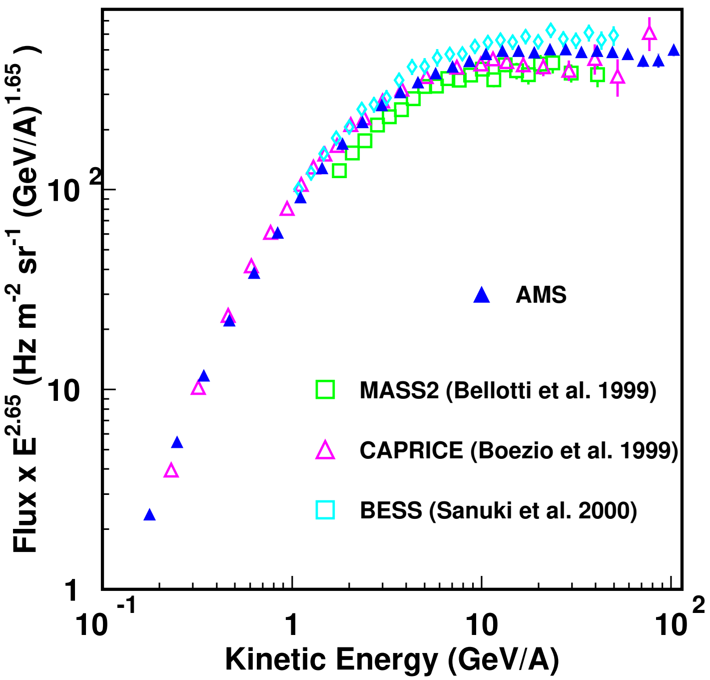


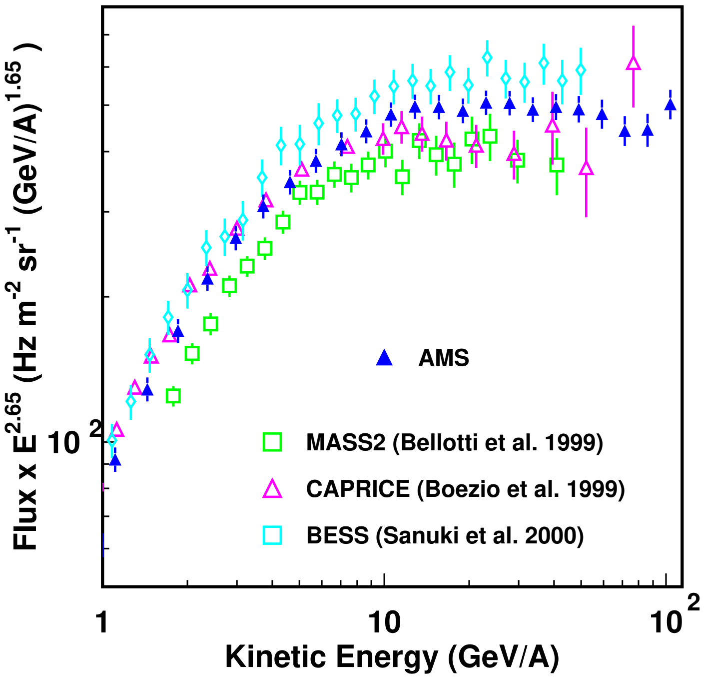
The fit above 20 GV gives

γ=2.74 $\pm$ 0.010 (stat) $\pm$ 0.016 (sys),

Φ_0=2.49$\pm$0.09 (stat)$\pm$0.14 (sys)$\pm$0.14 $(\gamma)\frac{\mathrm{GV}^{2.74}}{\mathrm{m^2 sec sr MV}}$

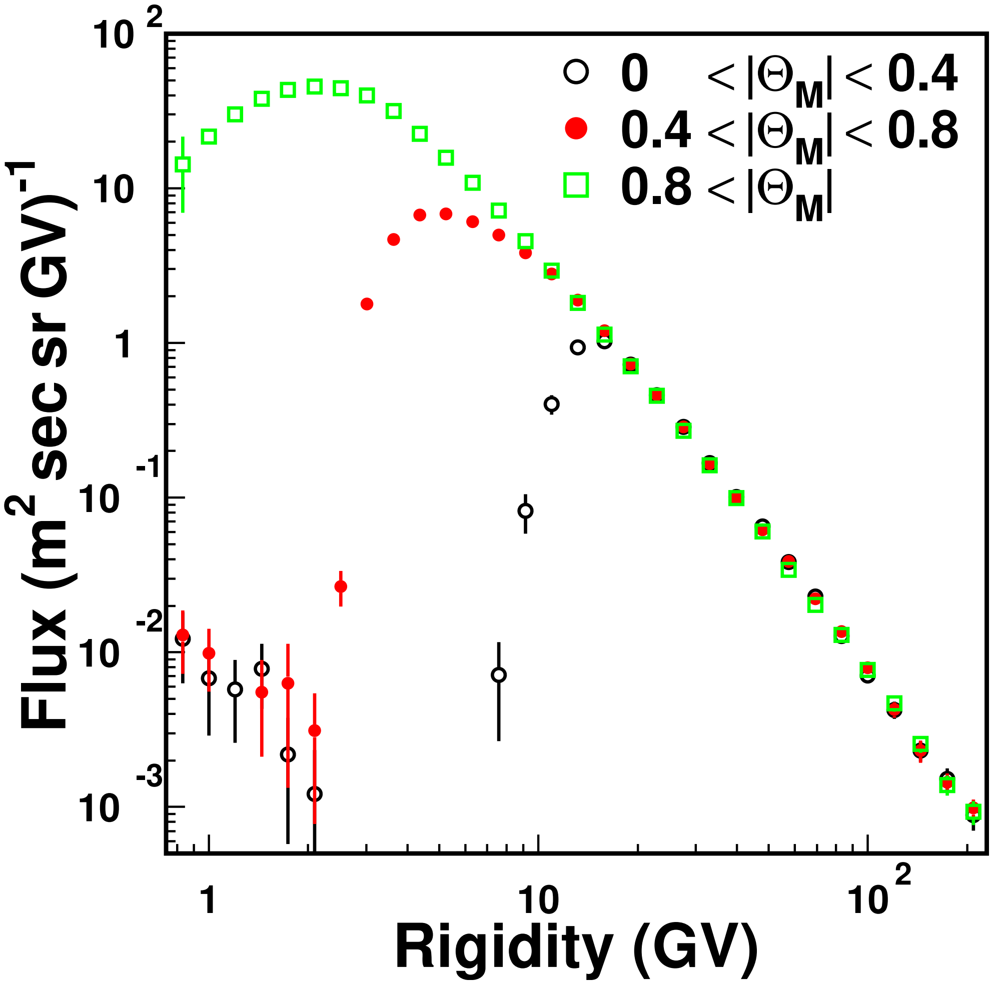
Comparison with others





Most precise measurement up to date

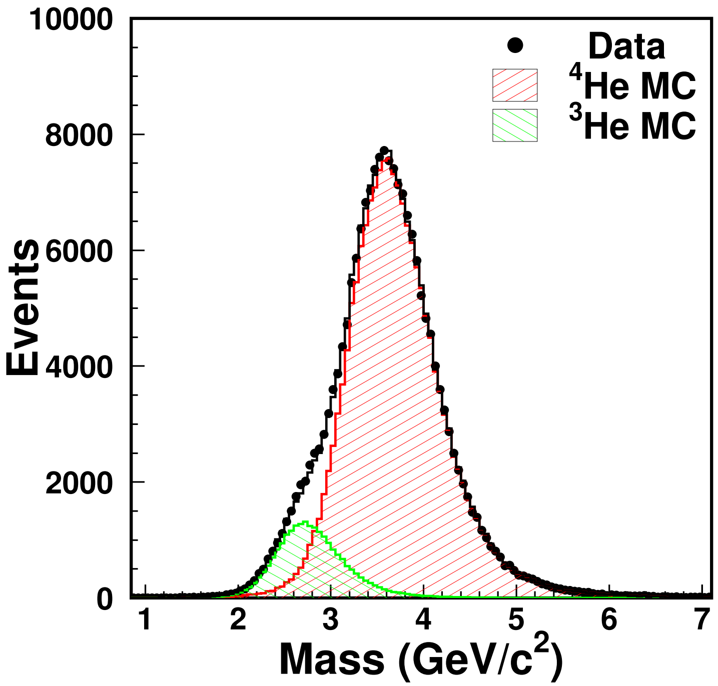
Helium second spectra

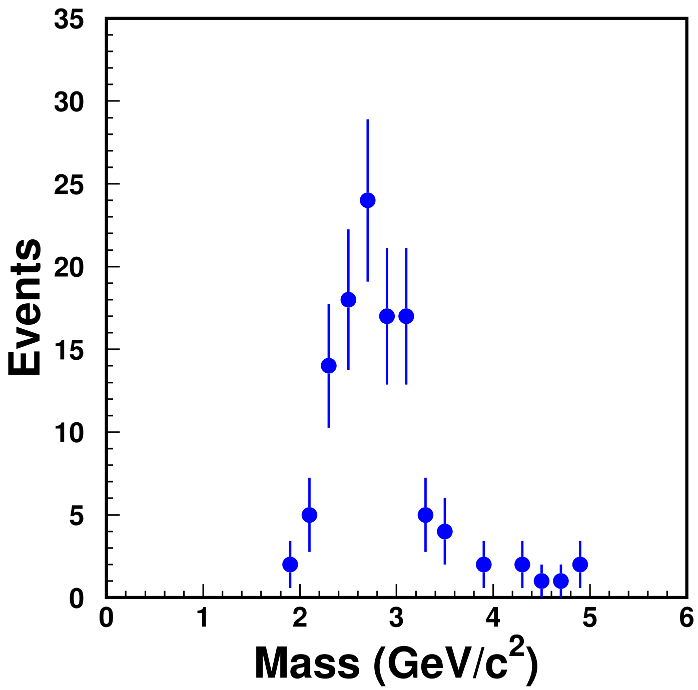


- second spectra are observed for $\Theta_m < 0.8$
- short- and long-lived behaviour

more stringent cuts are applied

Helium isotopes





Primaries mass for $\Theta_m > 0.9$
MC simulation with ^{3}He/^{4}He=0.13

Under cutoff mass distribution:
^{3}He/(^{3}He+^{4}He)>0.9 (90 % CL)

AMS-01 Results

- best limit on antimatter flux extending to 140 GV
- primary spectra of protons, helium and leptons measured with never obtained accuracy
- second spectra show interesting interplay of CR with the geomagnetic field

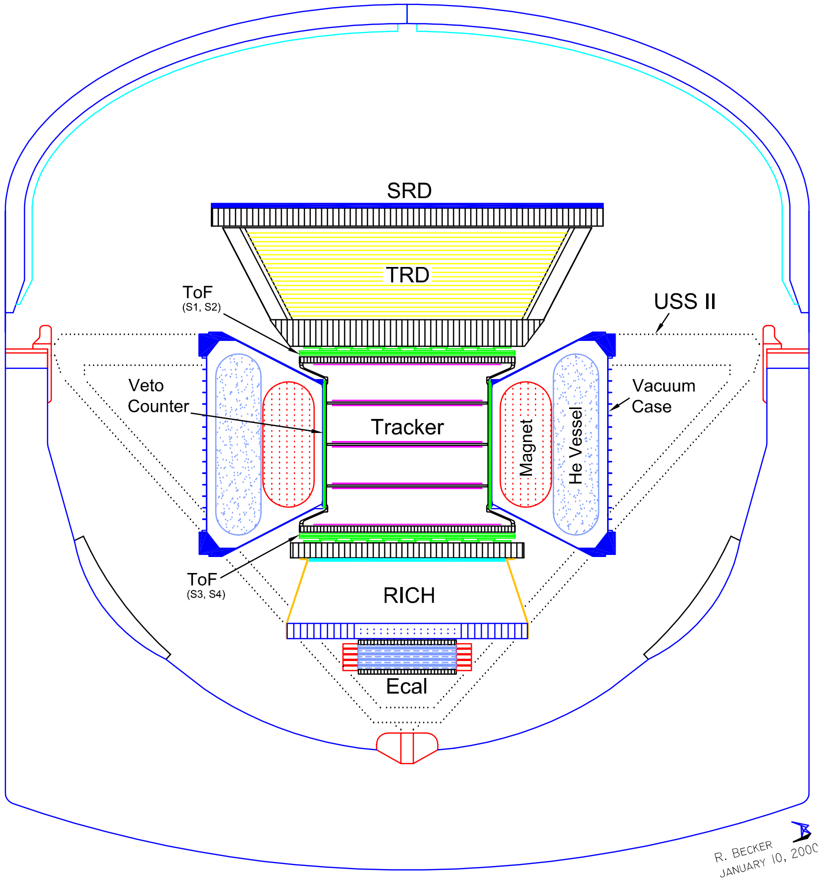
$\longrightarrow$ downgoing = upgoing (in average)

$\longrightarrow$ two categories of particles: long- and shortlived

$\longrightarrow$ the positron flux is enhanced (esp. at equator)

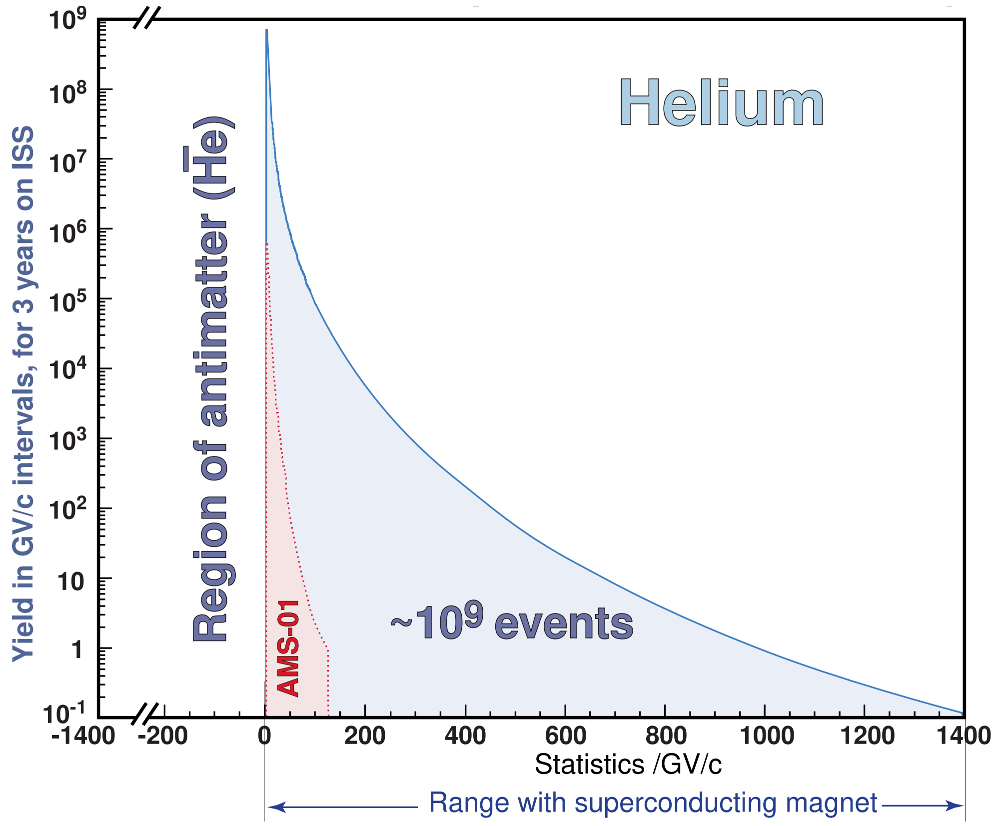
$\longrightarrow$ undercutoff ^{3}He

The AMS-02 detector



- Scheduled to take data during 3 years on ISS
- Superconducting magnet in space: B field $\times 6$
- SRD high energy $e^{\pm}$ through synchrotron X-rays
- TRD e/h rejection up to 300 GeV
- Tracker completion and geometry optimization
- RICH additional β measurement for isotopes
- ECAL energy measurement of $e^{\pm}, \gamma$ to 1 TeV

Expected Range with AMS-02



With three years of exposure on ISS we will collect:

- $\approx 10^7$ electron events with E $>$ 10 GeV
- $\approx 4 \times 10^6$ positron events with E $>$ 5 GeV
- $\approx 10^6$ proton events with E $>$ 1 TeV
- $\approx 10^6$ antiproton events with E $>$ 5 GeV

AMS/γ

Astrophysical sources of γ-rays:

- point sources: blazars and GRB
- diffuse sources: γ-ray background, γ from WIMP annihilation

AMS-02 will be able to detect γ-rays via:

- conversion in the TRD
- the high quality tracking
- the increased bending power
- the electromagnetic calorimeter
- a Star Tracker for positioning

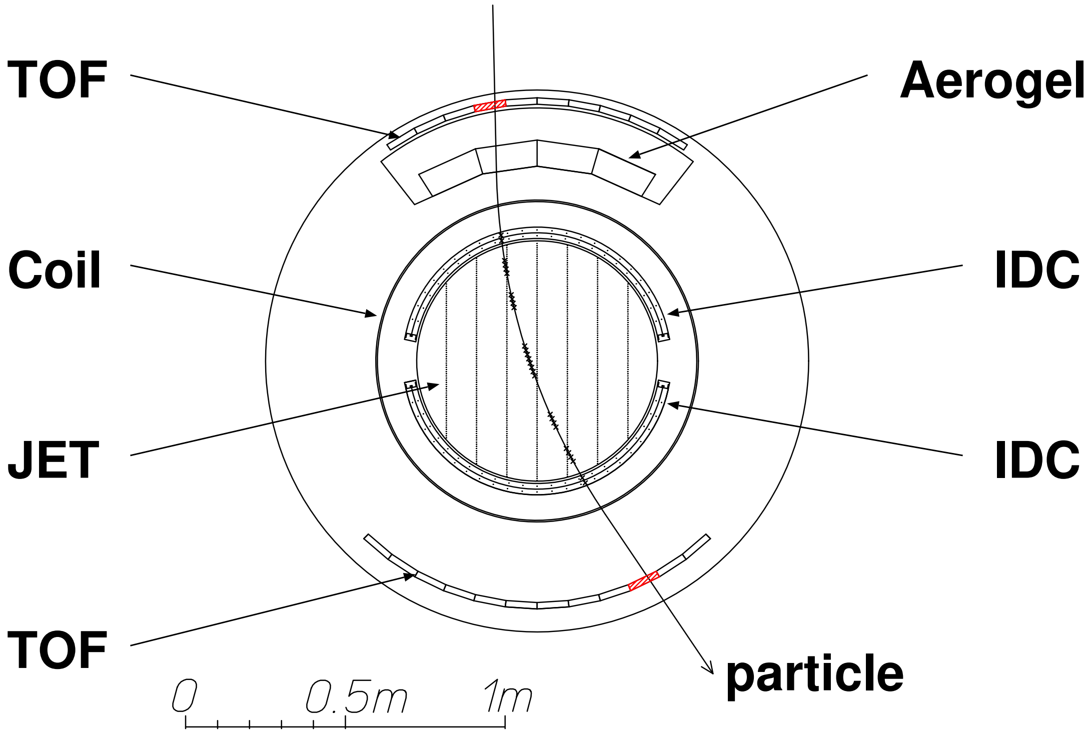
AMS will close the gap between EGRET(-30GeV)
and ground based experiments (200GeV-)

Antimatter Searches before AMS

- Aizu 1961
  Stack of photographic emulsions to search for annihilation topologies. Disadvantage : particles have to be stopped in the stack $\rightarrow$ limited energy range $<$ 700 MeV$/n$
- Greenhill 1971
  Gas Cerenkov detector and scintillators. Flown at equator at different orientations. Identification using east-west effect. Energy up to 9 GeV$/n$
- Verma 1972, Evenson 1972
  Magnet spectrograph $B = 0.2T$, two spark chambers and emulsion plates/scintillators. 2200 events
- Buffington 1972, Golden 1974
  Superconducting magnet spectrometer $BL = 0.43Tm$
  acceptance $0.066m^2\mathrm{sr}$; $R < 100$ GV
  $\rightarrow$ Smoot 1975 improved version for a total of $\sim 10^4$ events

- Badhwar 1978, see also Golden 1997
  Additional position measuring MWPCs resulting in greater momentum resolution. Limit improved by a factor 5 (CR $\overline{p}$ are discovered)
- Buffington 1981
  Pb-Al spark chamber calorimeter with selective trigger to enhance negative data sample. Up to 320 MeV$/n$.
- Lund 1986
  Danish-French Cosmic Ray Spectrometer on the HEAO-3 satellite. Stack of 5 Cerenkov counters. Problems with direction determination $\Rightarrow$ only $|Z| > 9$ data. Antimatter candidates are excluded by backtracing.
- BESS since 1993
  Balloon-borne experiment with superconducting magnet: lately reported a limit of 10^{-6} up to 16 GV

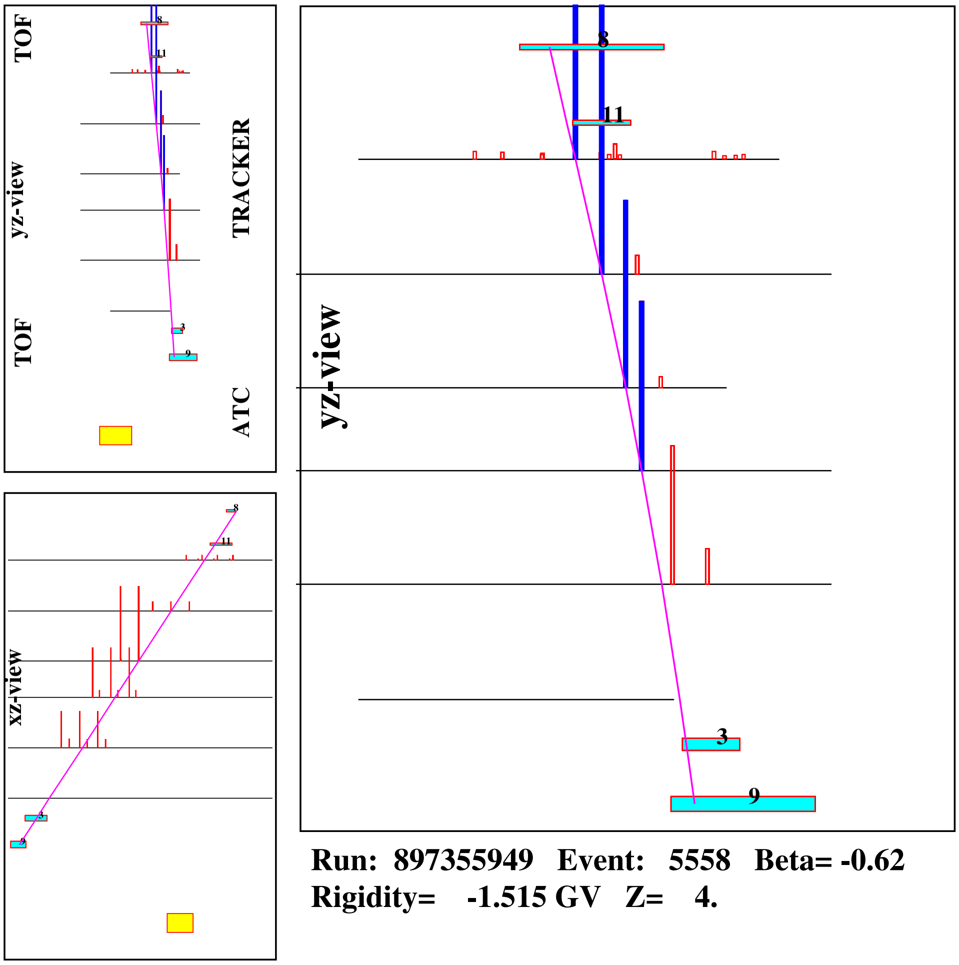
The BESS instrument



- *thin* ($5\mathrm{g/cm^2}$) superconducting coil B $= 1$T. Acceptance $0.3\mathrm{m^2sr}$
- jet type + inner drift chambers: 24 points tracking for p measurement ($\sigma_p/p = 0.5\%$ at 1GeV)
- TOF scintillators $\sigma_t = 75ps$ provide dE/dx measurement
- aerogel Cerenkov
- residual air thickness $5\mathrm{g/cm^2}$
- floating time $\sim$ 17 hours

Example of a "bad" event

Tracks with a kink (interaction in the tracker) or with a big energy deposit in the tracks' vicinity (problems with reconstruction) are eliminated



Run: 897355949 Event: 5558 Beta= -0.62
Rigidity= -1.515 GV Z= 4.