AMS: An Experiment in Space for Cosmic Antimatter

AMS logo here

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AMS Collaboration

Outline

- Motivations for Cosmic ray studies
  - Search for antimatter
  - Composition and spectrum
  - Dark matter + exotics
  - High energy γ-ray physics
- Ballon and space experiments for charged cosmics
- AMS-01
  - Apparatus
  - STS-91 Flight on space shuttle, Performances
- AMS-01 astroparticle results
  - Cosmic (primary) spectra for protons, He, $e^{\pm}$, D
  - Anti-matter search
- AMS-01 geo-particle results (magneto-geography)
  - Secondary $e^{\pm}$ spectra (origin)
  - Secondary p spectra (origin + understanding)
  - Secondary ^{3}He spectra
- AMS-02 Apparatus & expected performances
- Conclusion

Motivations for Cosmic ray studies

SEARCH FOR ANTIMATTER

Is the Universe baryon symmetric ?

From the 30's to the 60's the mainstream view was YES

Diracs 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 it seems that we are surrounded by ordinary matter up to a distance of about 10 Mpc

In 1967, Sakharov formulated 3 ingredients necessary for a non symmetric baryogenesis:

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

Motivations for Cosmic ray studies

Indirect evidences: photons

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

$$\bar{N} + N \longrightarrow \pi^0, \pi^\pm \longrightarrow \gamma' s, e^\pm, \nu' s$$

$$e^+ + e^- \longrightarrow \gamma + \gamma$$

BUT this should result in:

- a distortion of the cosmic microwave background *(COBE measures a quite isotropic blackbody radiation for a distance up to about 10 Mpc)*
- a signal in the extragalactic diffuse γ-ray background induced by the *(redshifted)* annihilation photons.

Motivations for Cosmic ray studies

Direct seaches for Antimatter

Antiproton measurements do not provide evidence for extragalactic antimatter.

The $\bar{p}$-flux near the Earth can be explained mainly by secondary interactions of cosmic rays depending on:

- incident spectra
- interstellar gas composition
- solar modulation at lower energies

However the probability to produce antinuclei by high energy interactions falls drastically with the amount of antinucleons. (More than 10^4 per antinucleon)

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

Presently, no antinucleus with $Z \geq 2$ has ever been found in the cosmic radiation

Motivations for Cosmic ray studies

COMPOSITION AND ENERGY SPECTRUM OF COSMIC RAYS

The relative abundance of particles, elements and isotopes is related to:

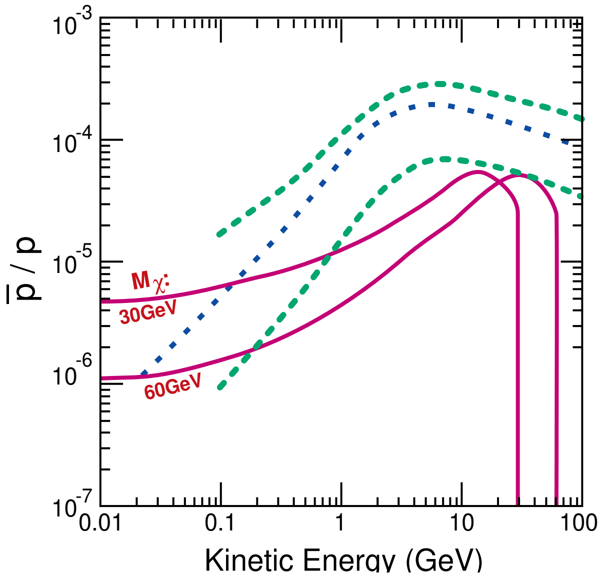
- Primordial nucleosynthesis for the particles created just after the Big-Bang: *(primordials)*
  $\gamma,\ p,\ e,\ D,\ ^4He,\ ^3He,\ ^7Li$
- Astrophysical sources accelerating *primaries*:
  $e,\ p,\ He,\ C,\ O,\ Fe$
- Interactions with interstellar gas create *secondaries*:
  $e^{\pm},\ p,\ \bar{p},\ Li,\ Be,\ B$
- The propagation described by the Leaky Box model

Motivations for Cosmic ray studies

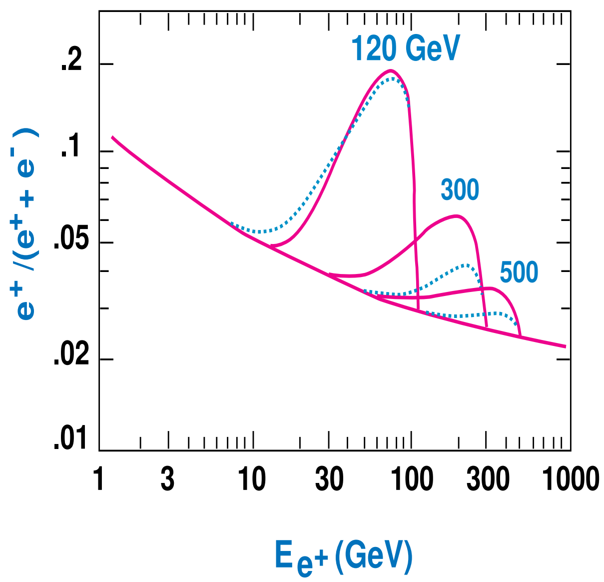
WIMP CONTRIBUTION TO DARK MATTER

A candidate is LSP (neutralino-χ) visible via its annihilations

- $\chi\chi \rightarrow gg$ Fragmentation of gluons gives antiprotons

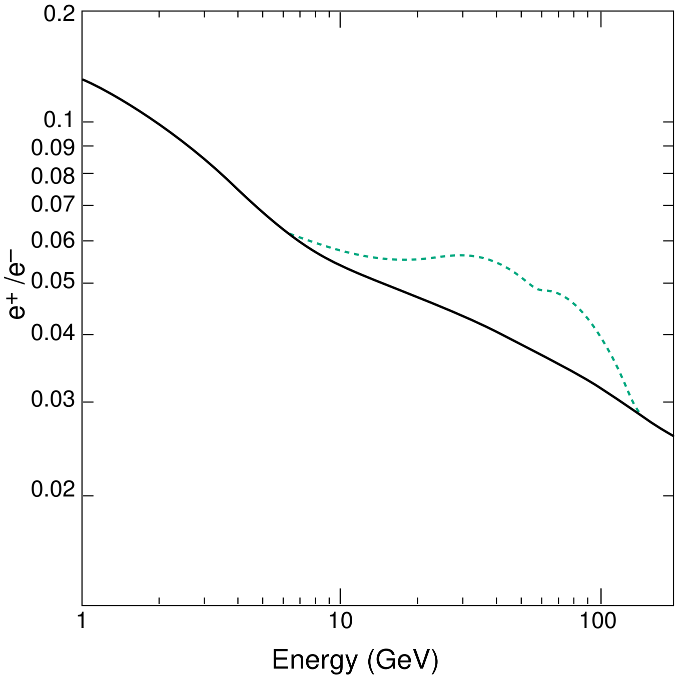


- $\chi\chi \rightarrow W^+W^-, ZZ$ in case χ is a pure higgsino



Motivations for Cosmic ray studies

- $\chi\chi \rightarrow f\bar{f}$ ($\tau^+\tau^-, b\bar{b}, t\bar{t}$) manifests in e^+ enhancement



- $\chi\chi \rightarrow \gamma\gamma, Z\gamma$ Monochromatic lines
- $\chi\chi \rightarrow W^+W^-, ZZ$ Continuum spectra. More abundant than monochromatic lines

Motivations for Cosmic ray studies

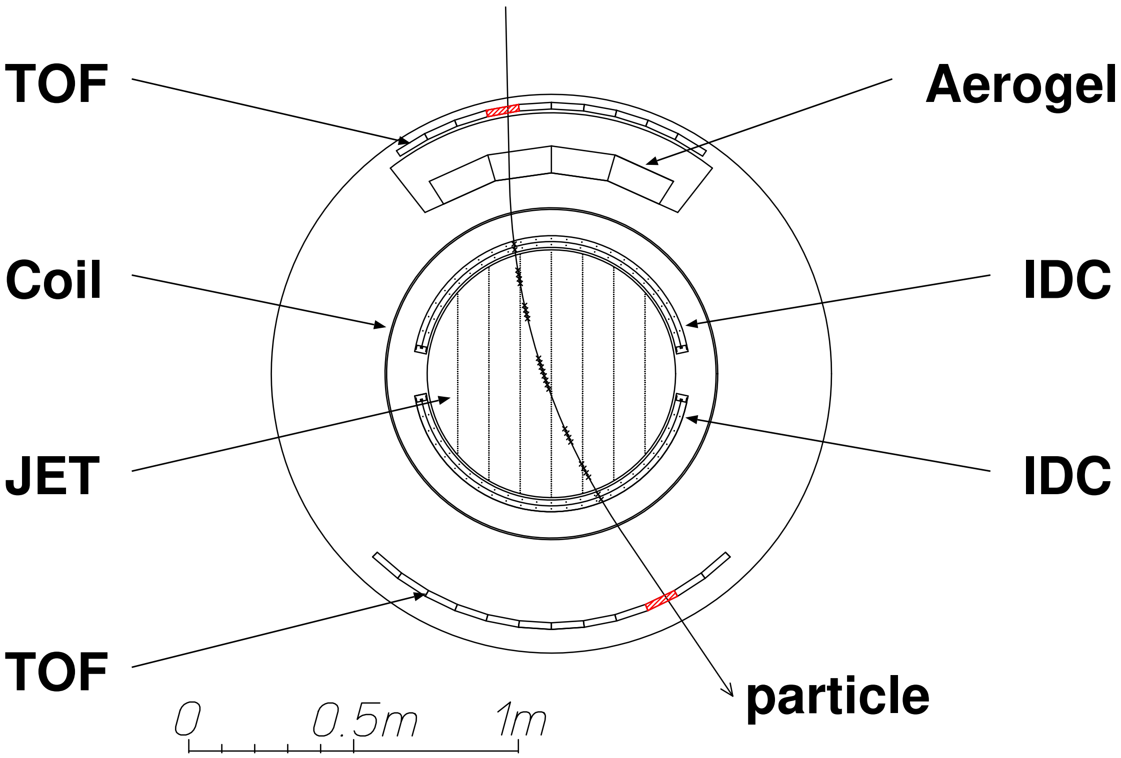
HIGH ENERGY γ -PHYSICS

- Astrophysical sources of γ rays:
  - point sources: blazars and GRB
  - diffuse sources: γ ray background, γ from WIMP annihilation
- Knowledge of γ ray increased last decade due to EGRET
  - EGRET 30 MeV - 30 GeV
  - Ground experiment threshold $\sim$ 200 GeV
  - Next satellite generation
    - AGILE (2002) 30 MeV - 50 GeV
    - GLAST (2005) 20 MeV - 300 GeV

Spectrometers for charged cosmic rays

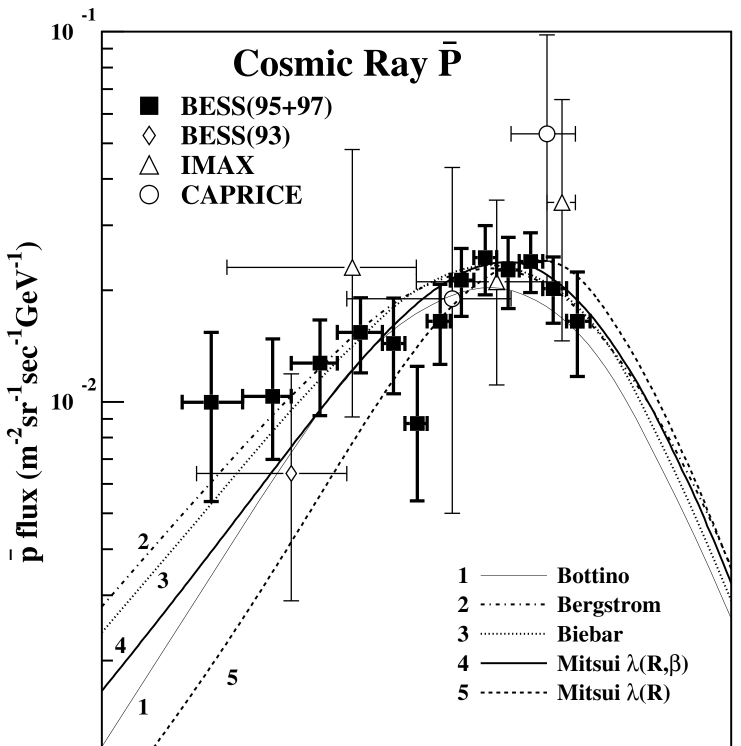
- Balloon-Experiments
  - IMAX
  - HEAT
  - CAPRICE
  - ISOMAX
  - BESS
  - ...
- Space-Experiments
  - NINA 1 (nuclei 10 - 200 MeV/n) 1998
  - AMS-01 (10 days on $Discovery$) 1998
  - NINA 2 $launched$ in 2000
  - PAMELA *to be launched* in 2002
  - AMS-02 *to be installed* late 2003 for 3 years of operation on ISS Station
  - ACCESS *project* after AMS on ISS
  - ...

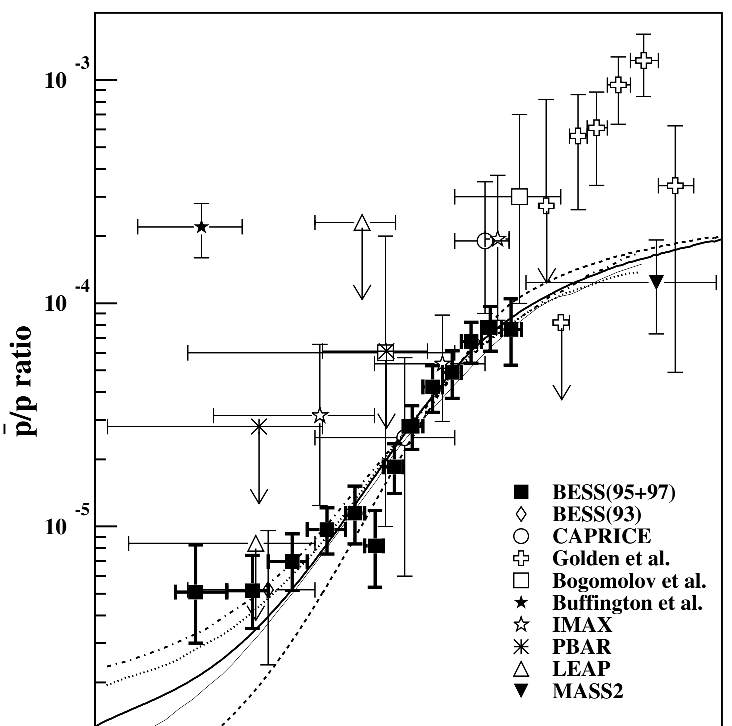
The BESS instrument (baloon)



- *thin* ($5\mathrm{g/cm^2}$) superconducting coil B $=$ 1T. 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

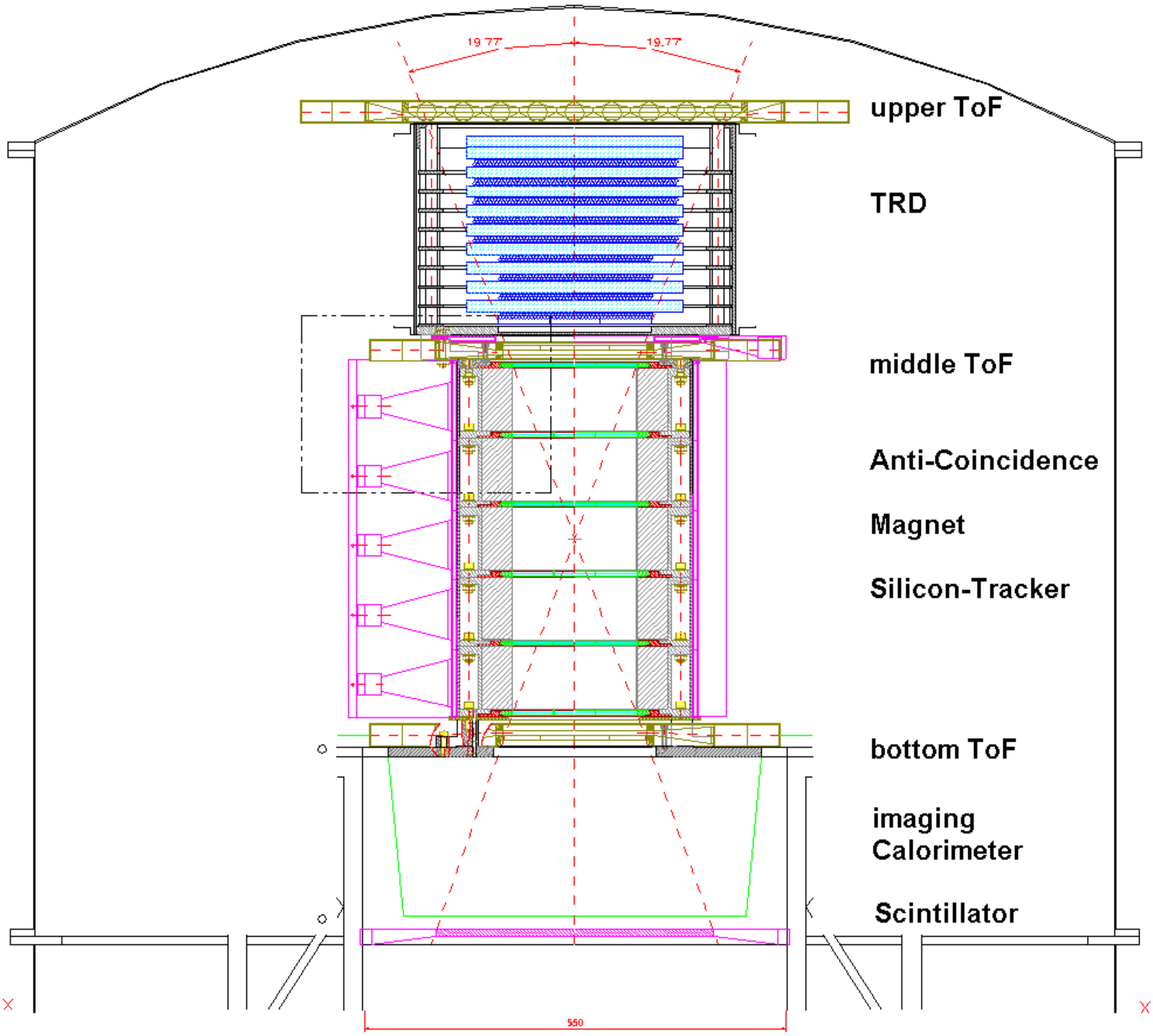
Antiproton spectrum from baloons





The PAMELA instrument (satellite)

Polar orbit 690 km ~2002
Magnetic spectrometer: 100 MeV to 100-300 GeV
6 planes of $\sim 16 \times 16$ cm^2 of Si tracker

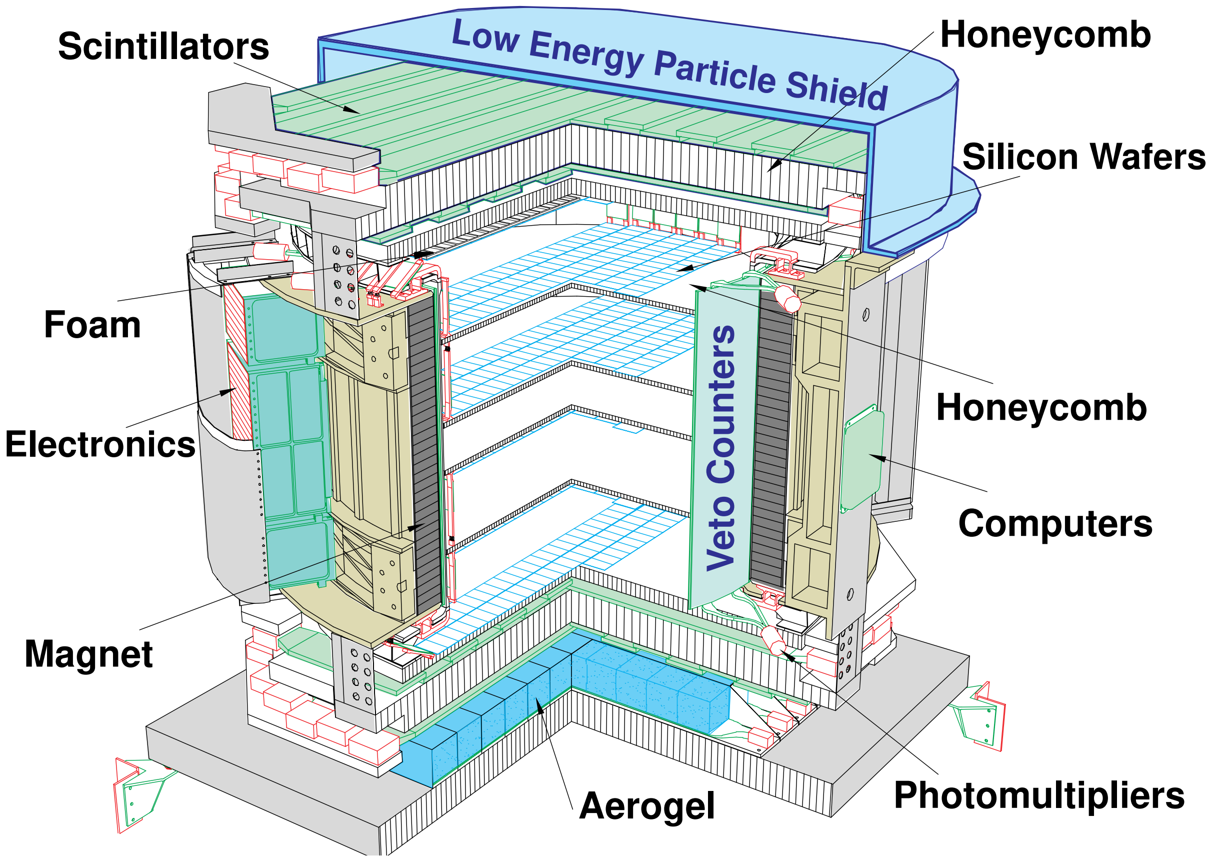


The AMS Experiment

AMS is a particle physics experiment in space

Measurement of Q, p, v and dE/dx of cosmics

- Qualification test flight in 1998 with Space Shuttle
- Installation on ISS scheduled late 2003
- Space operations constraints:
  - Radiation, extreme accelerations and temperature variations
  - Maximum weight $\sim$2 t and power $\sim$2 kW
  - Reliability for 3 years of operation



AMS-01 Characteristics

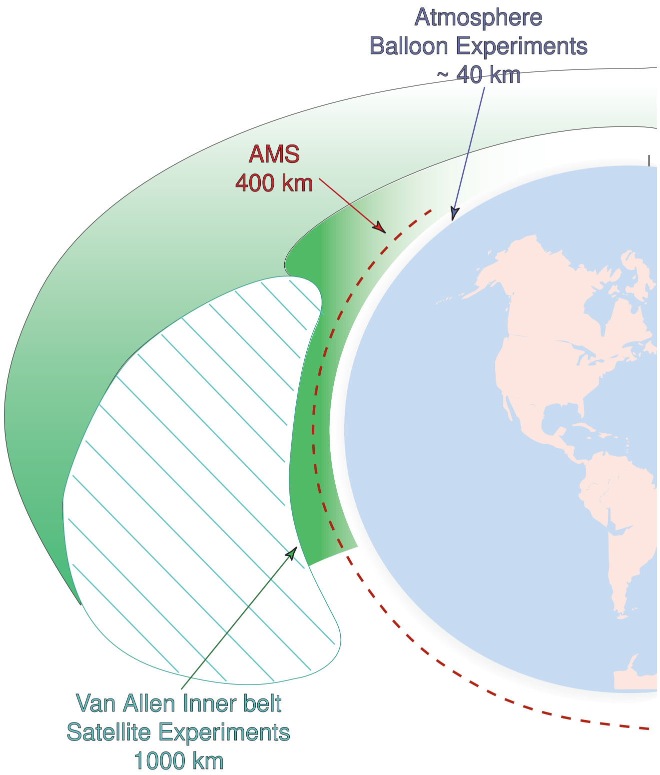
MICROSTRIP SILICON TRACKER

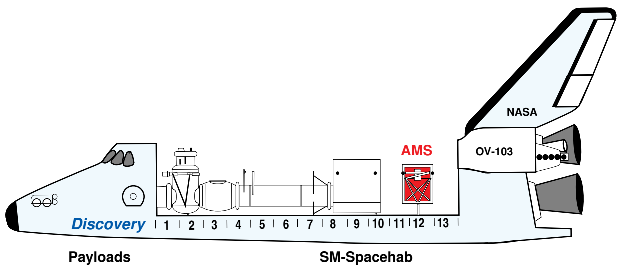
- Resolution: 10μm bending, 30μm non-bending plane
- Large dynamic range for dE/dx: 1 to 100 MIP
- Double sided Silicon sensors: $40 \times 72 \times 0.3$mm^3
- Wafers organised in long *ladders* (7 to 15 per ladder)
- AMS01: 2 m^2, 6 layers, 60k channels (57 *ladders*)
- AMS02: 7 m^2, 8 layers, 200k channels (192 *ladders*)
- Ladders mounted on Al+C honeycomb support plane
  - ladder and support: $X_0 = 0.65$% per plane

PERMANENT MAGNET

- Total magnetic dipole moment must be zero
  - Magic ring type
- Nd-Fe-B with $B_{rem} = 1.4\,T$
- $B_o = 0.14\,T$, $BL^2 = 0.14\,Tm^2$
- Weight = 1900 kg

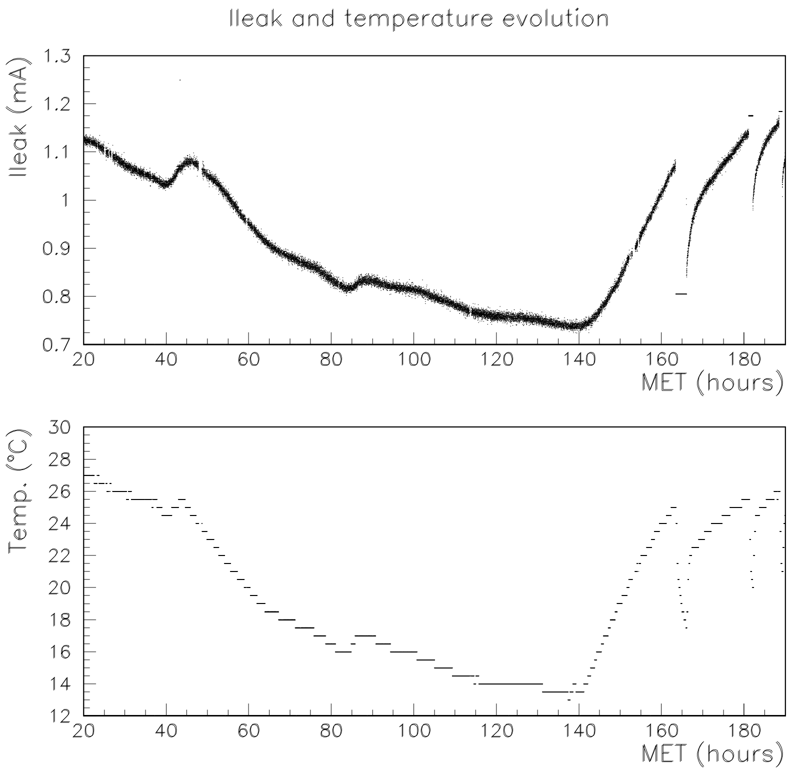
STS91 flight: June 2-12, 1998





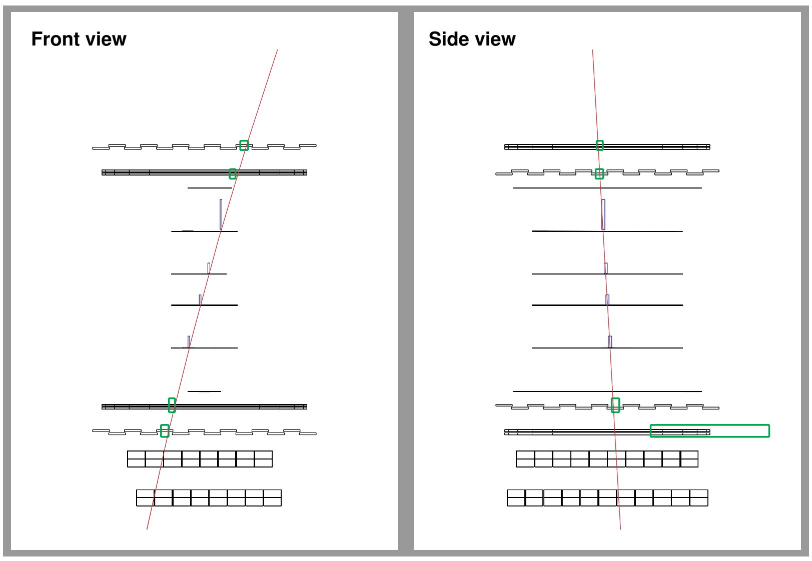
- Primary goal: re-supply and re-man the MIR station
- AMS was secondary payload for test and qualification
- 90 hours of dedicated data taking after MIR undocking
- Various flight attitudes and altitudes (320-390 km)
- Latitudes $\pm 51.7^o$ and all longitudes
- No failure, complete success
- 10^8 triggers recorded on disk
- We learned how to run a particle experiment in space

STS91 flight: On-line controls



Alpha Magnetic Spectrometer Event Display

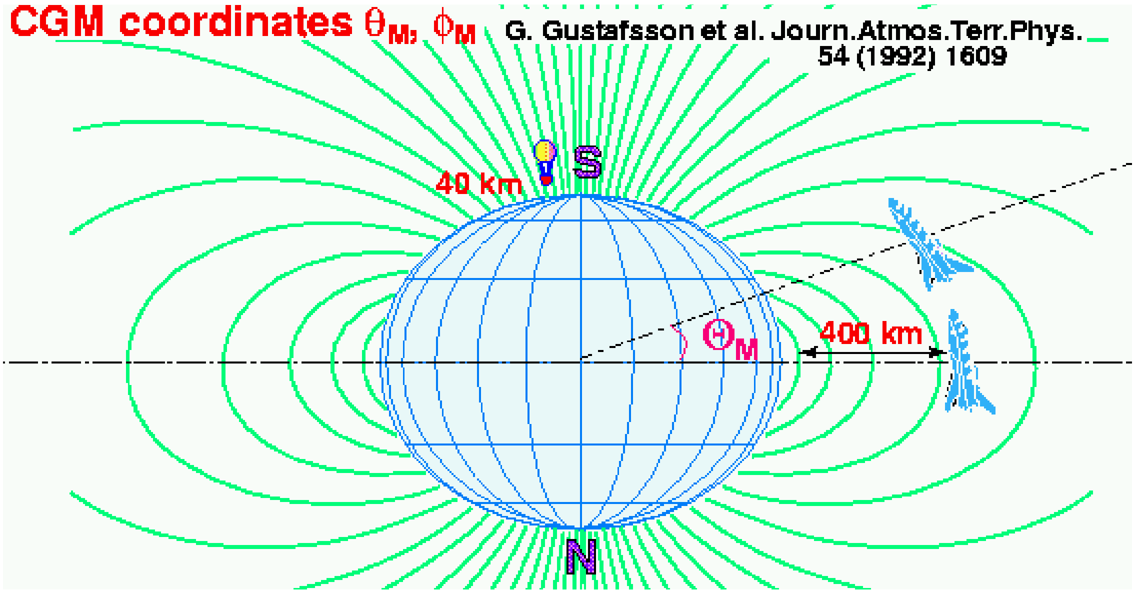
ANTI PROTON CANDIDATES



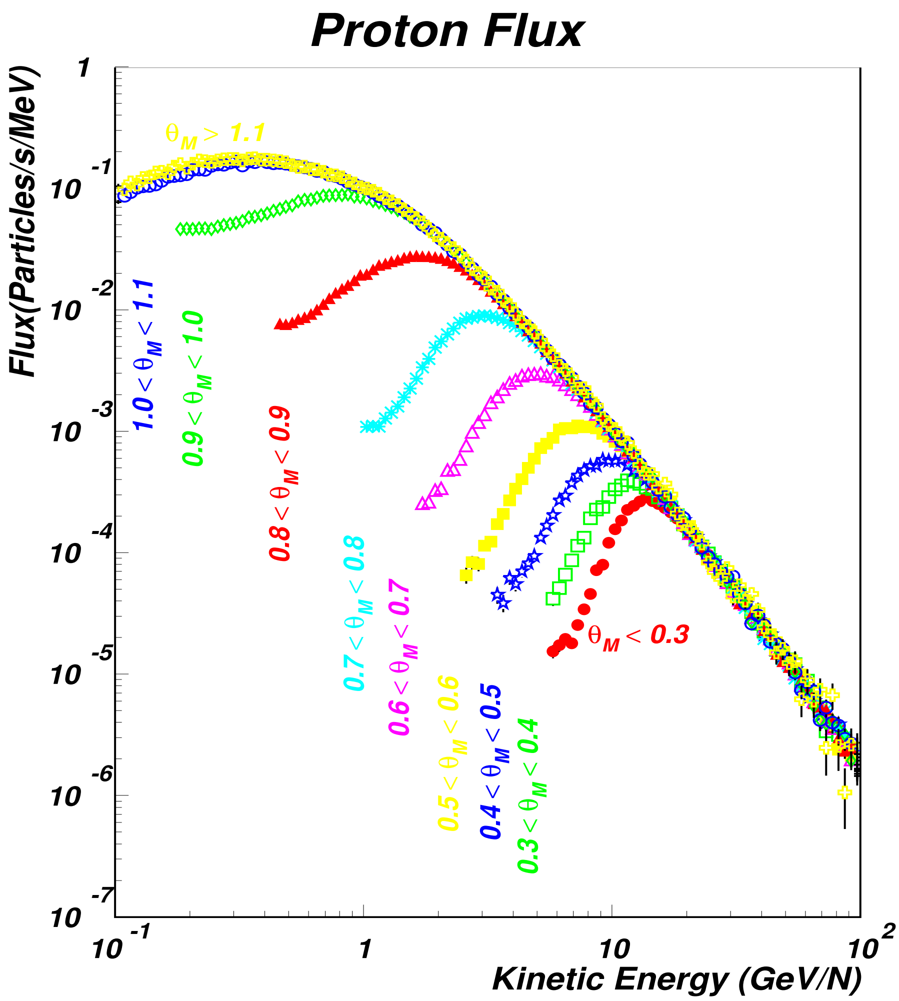
On-line display of antiproton events:

$m = 1.0 \pm 0.15$ GeV/c^2, $p = -0.7 \pm 0.12$ GeV/c, charge = 1.0

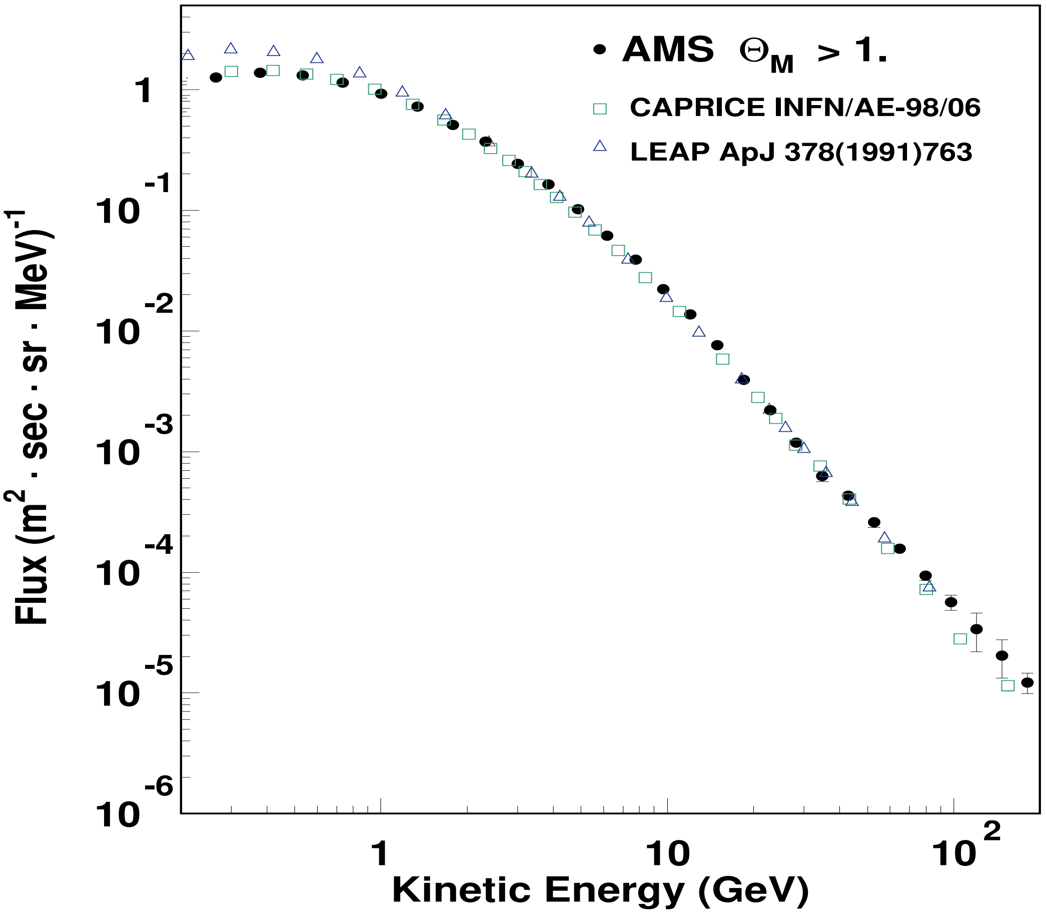
Geomagnetic rigidity cut-off



Maximum *rigidity (p/Z)* depends on *magnetic* latitude



Primary Proton Spectrum



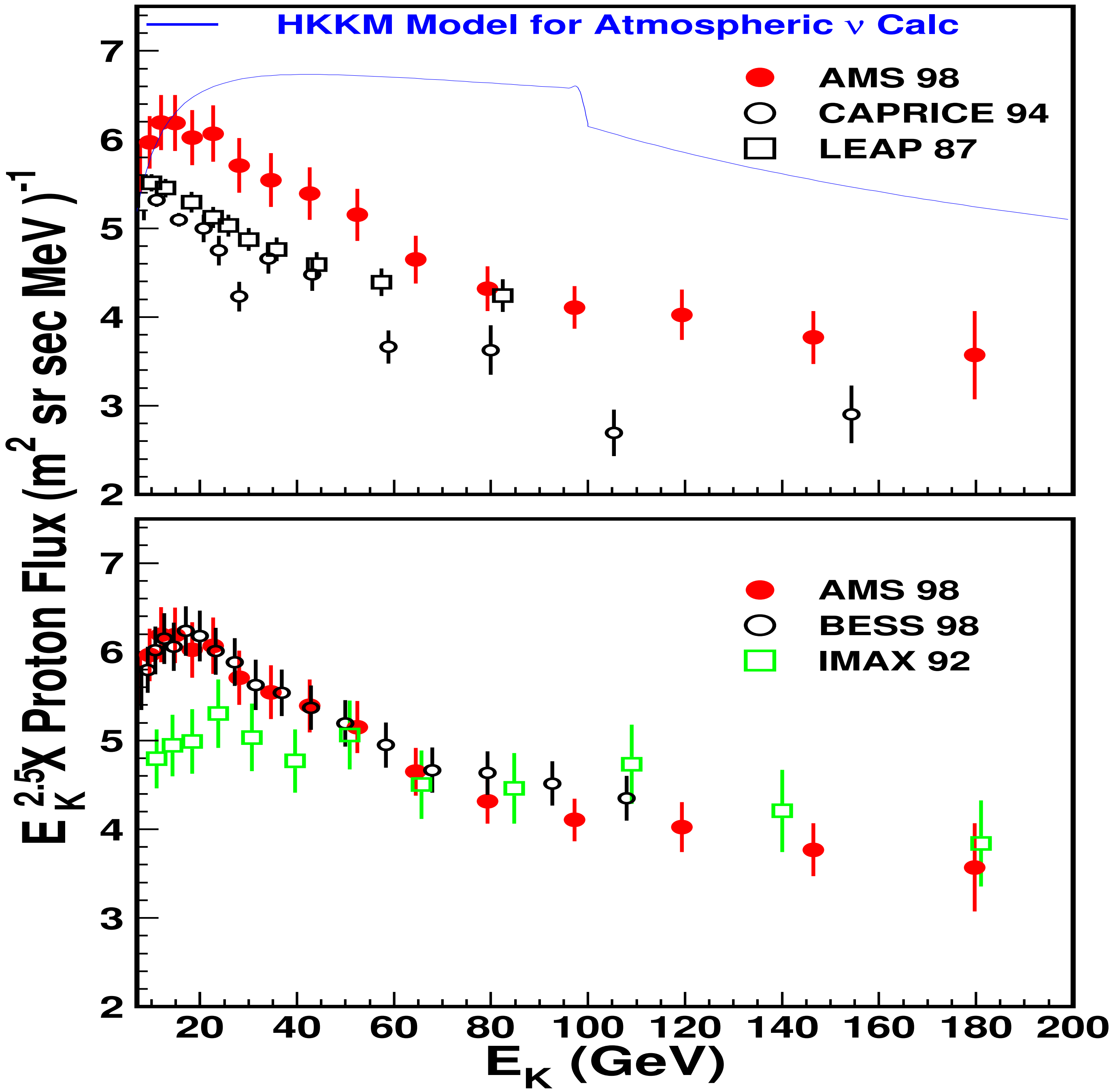
Fitting the spectrum over all latitudes at energies above the geomagnetic cutoff (E>10 GeV):

$$\gamma = 2.79 \pm 0.012\,(\text{fit}) \pm 0.019\,(\text{sys}),$$

$$\Phi_0 = 16.9 \pm 0.2\,(\text{fit}) \pm 1.3\,(\text{sys}) \pm 1.5\,(\gamma)\ \frac{\text{GV}^{2.79}}{\text{m}^2\text{sec sr MV}}$$

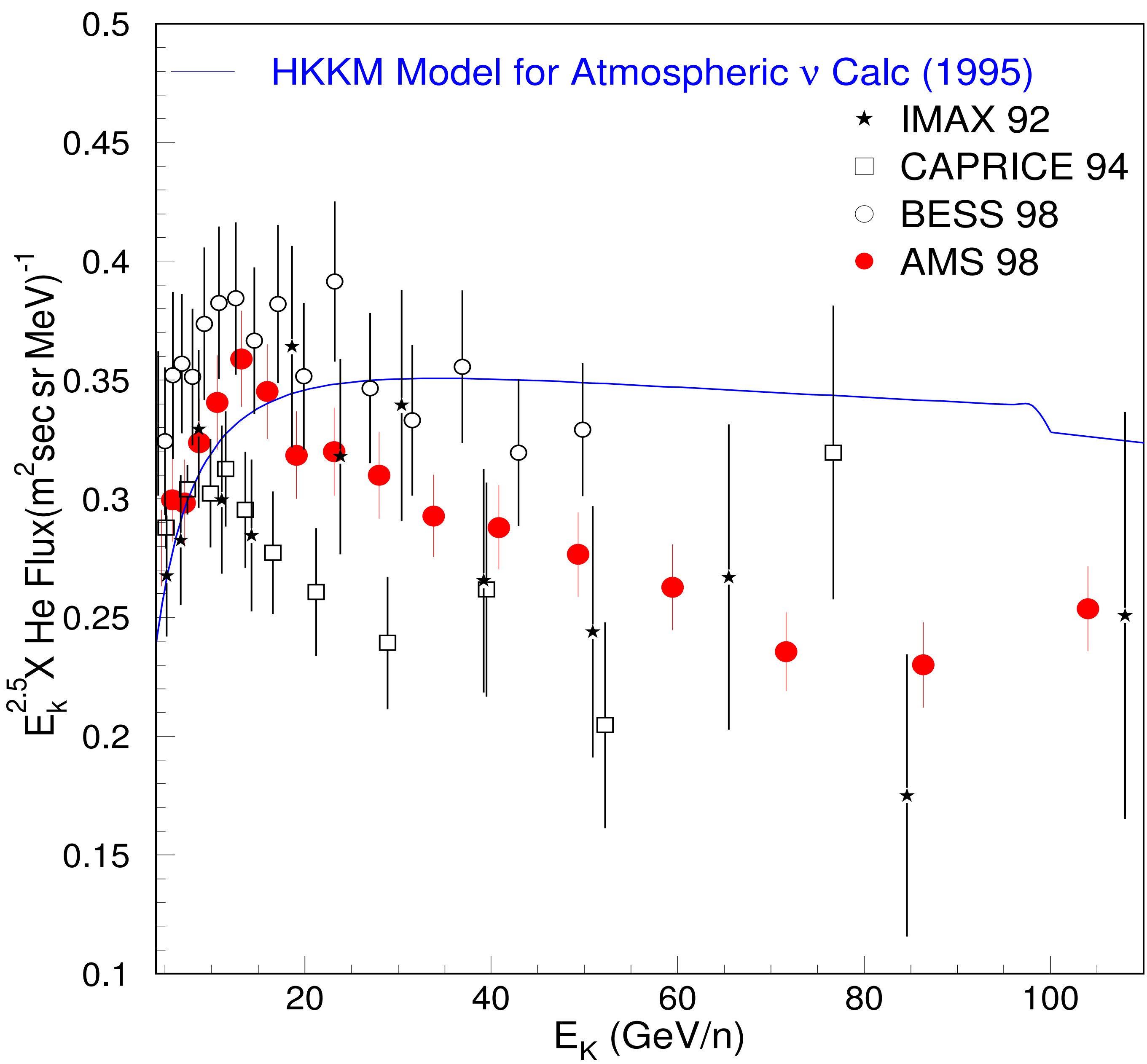
cfr. `Phys.Lett.B.472(2000) 215-226`

Proton Spectrum (High Energy)



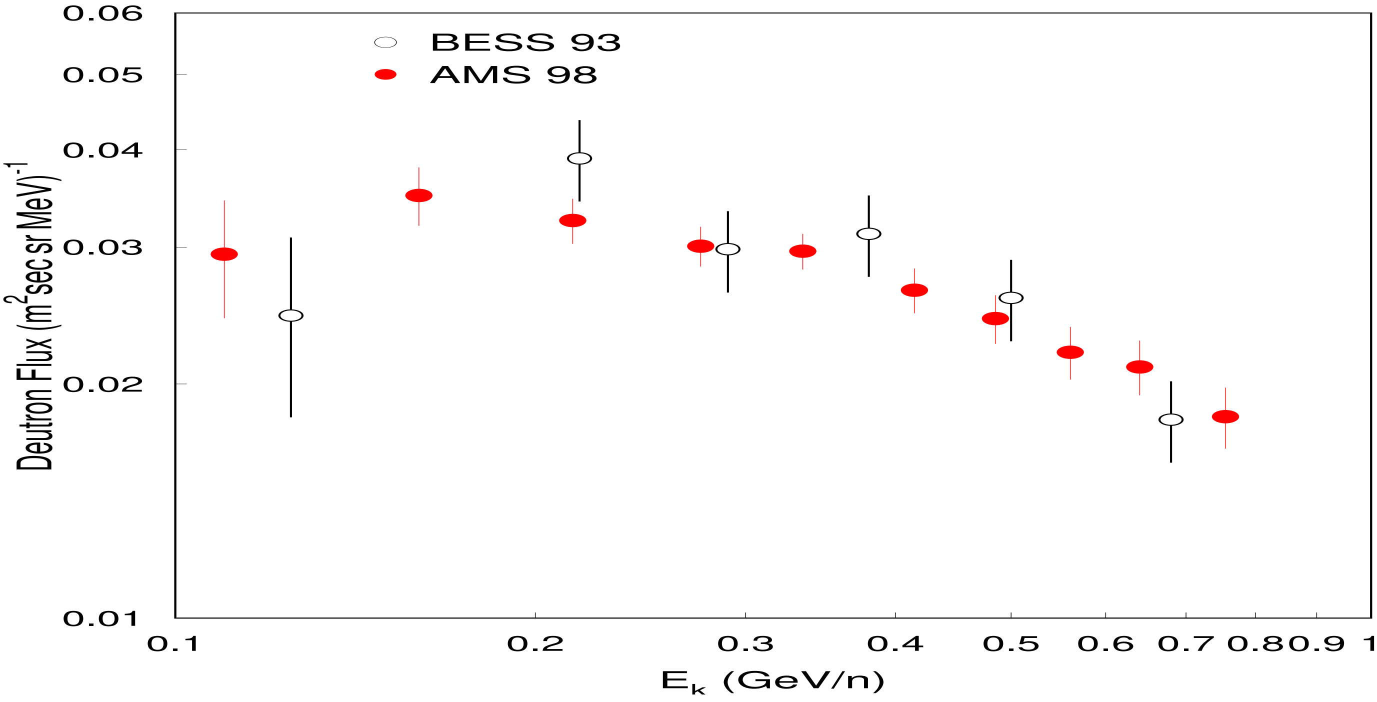
- High Statistics Measurement ($> 6 \cdot 10^6$ Events)

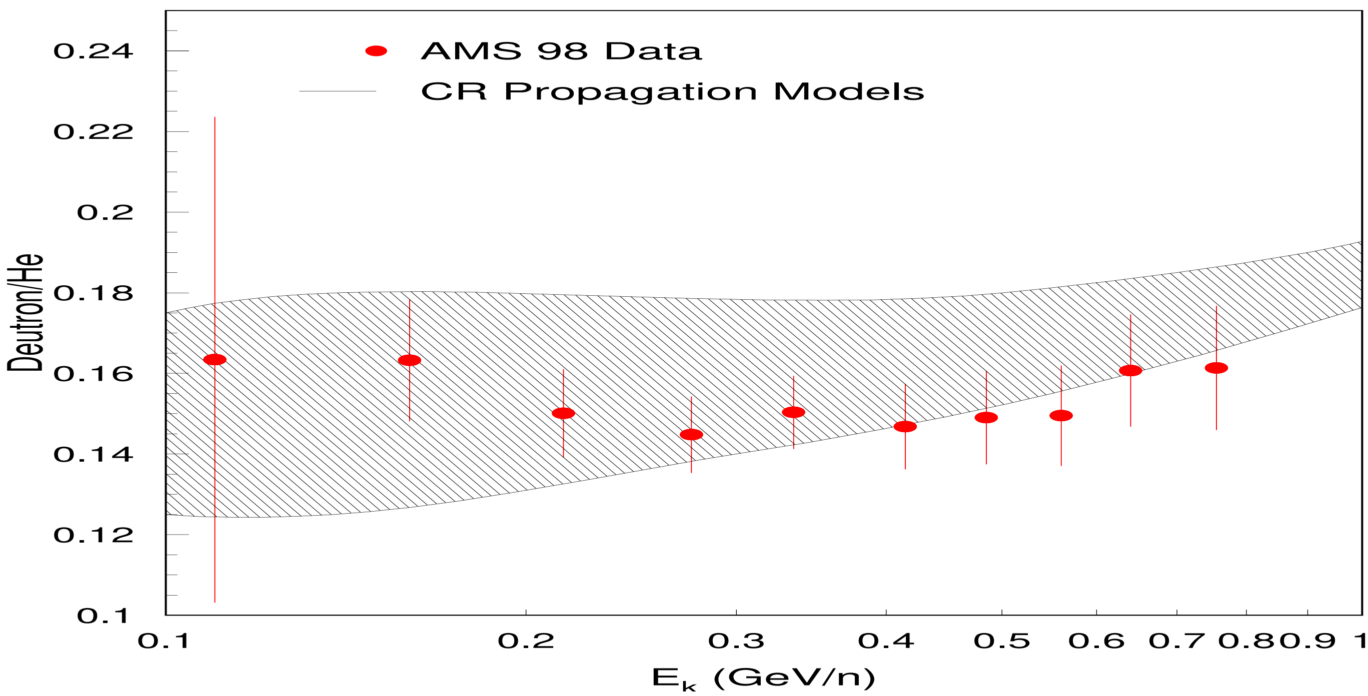
Helium Spectrum (High Energy)



- High Statistics Measurement (about 10^6 Events);
- Power law fit: $\gamma_{He} = 2.74 \pm 0.02$;

Cosmic Deuterons

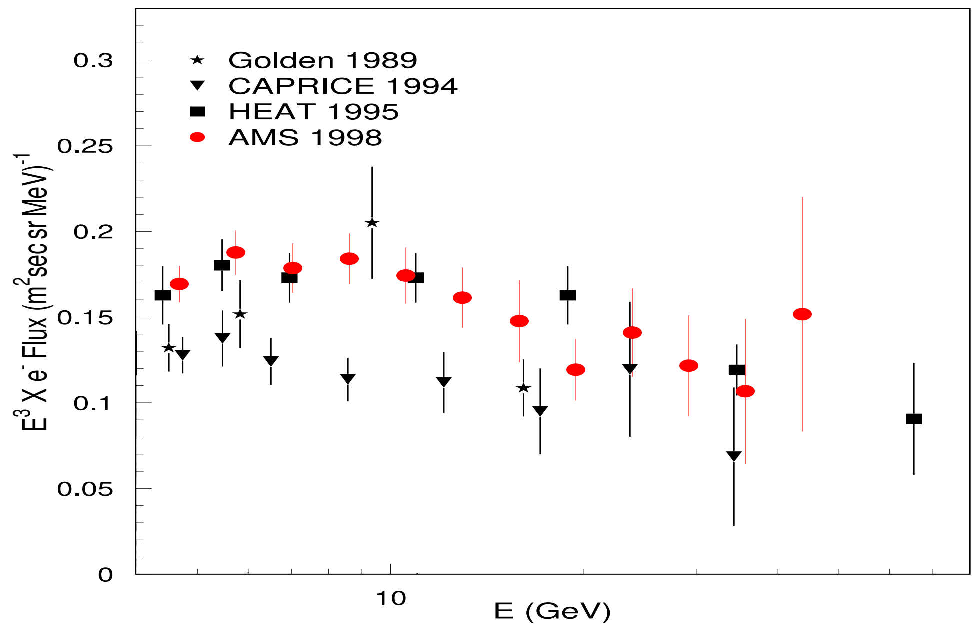




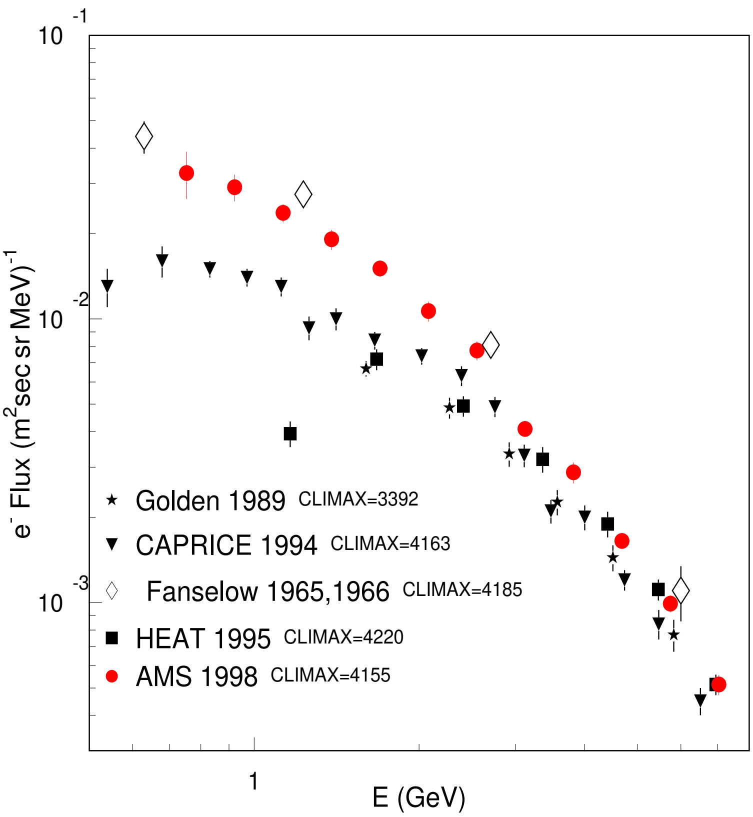
- $\phi_D = 650 \pm 20$ MV, agrees with that of p, He.
- $\frac{\mathrm{D}}{\mathrm{He}}$ is compatible with CR models predictions.

Cosmic electrons

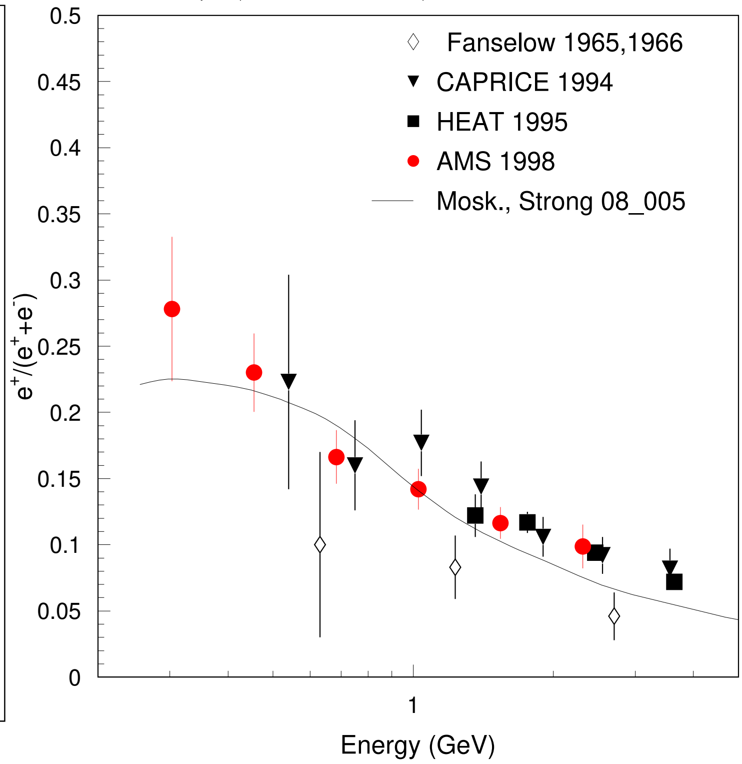
HIGH ENERGY



LOW ENERGY

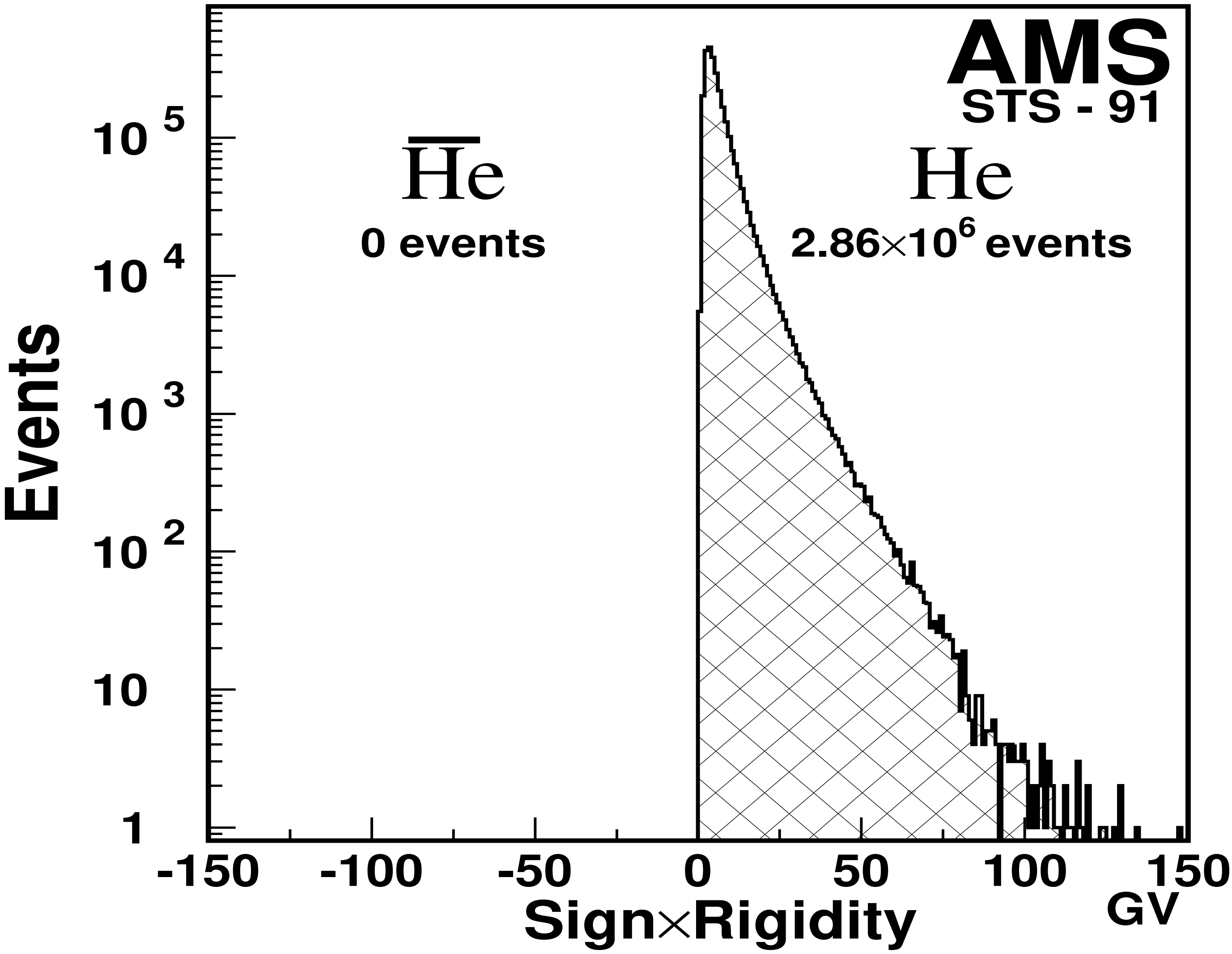


$e^+/(e^+ + e^-)$ RATIO



Search for AntiMatter ($\bar{H}e$)

No $(Z = -2)$ candidate



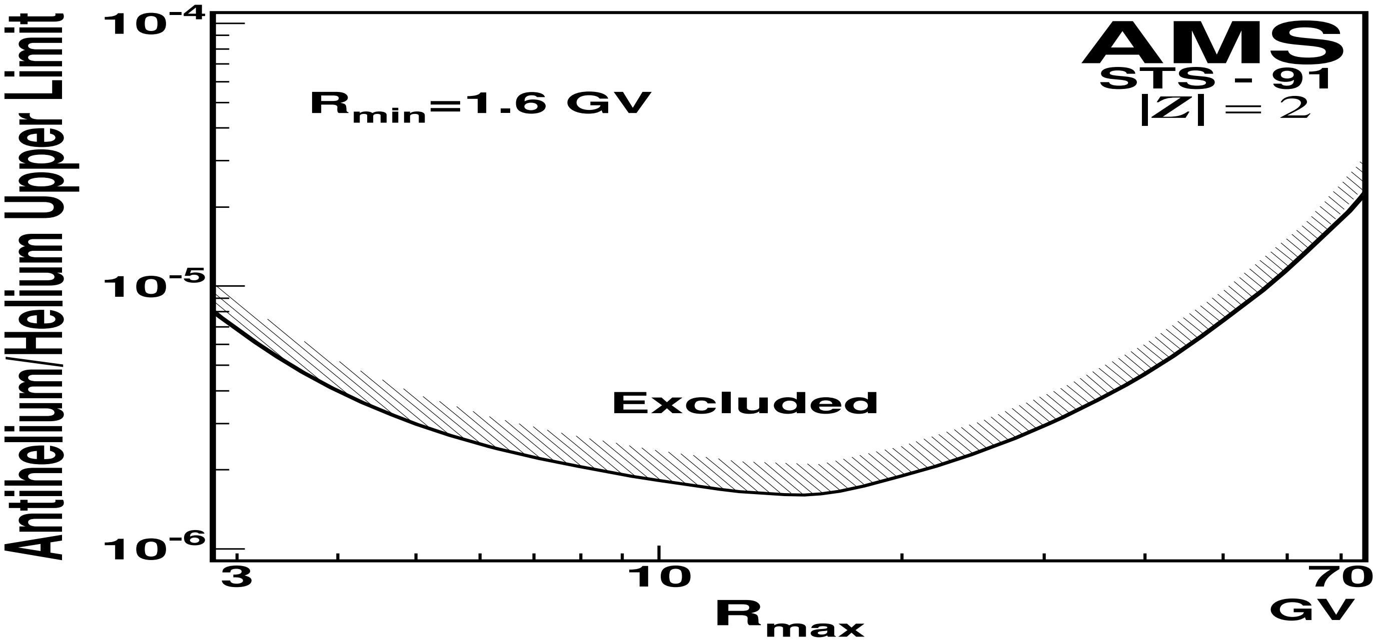
– "Same Spectrum" Limit: $\frac{3}{\int_{\mathrm{R_{min}}}^{\mathrm{R_{max}}} \mathrm{Flux(R)} \cdot \epsilon_{\bar{\mathrm{H}}\mathrm{e}}\mathrm{(R)dR}}$.

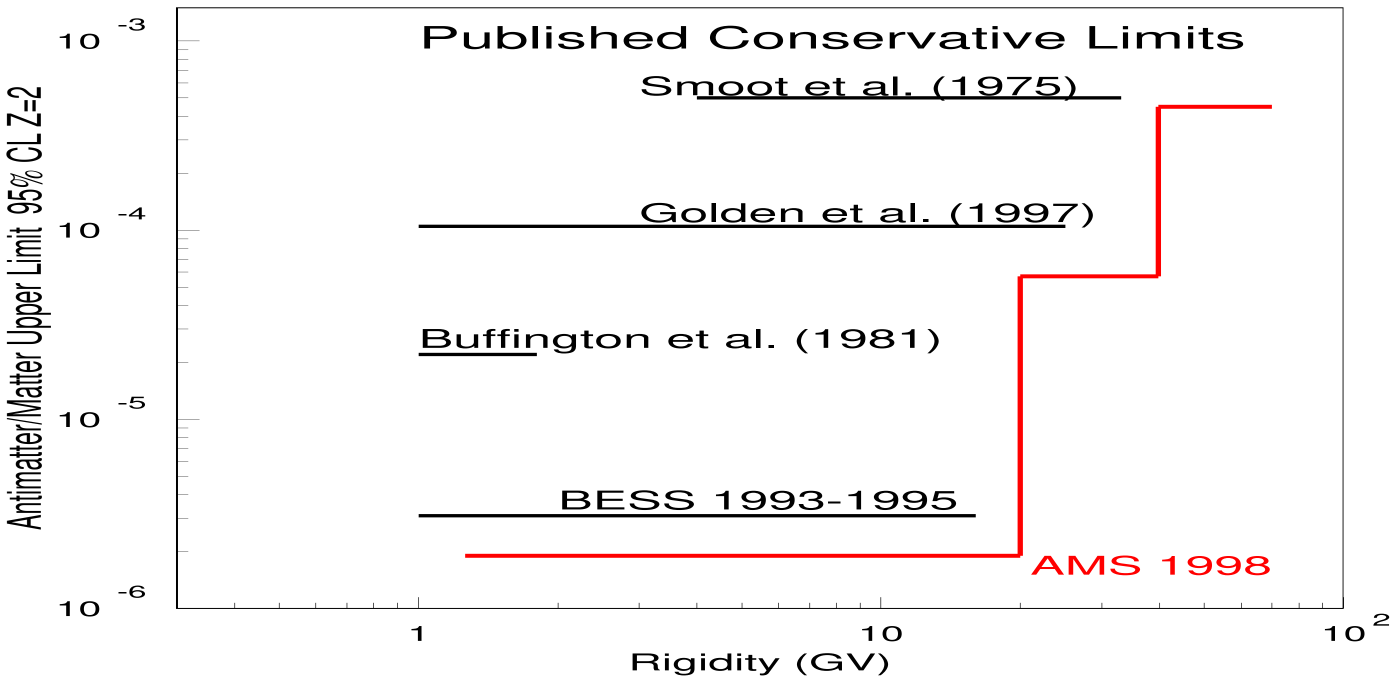
– AMS 98: $\frac{\bar{\mathrm{H}}\mathrm{e}}{\mathrm{He}} < 1.1 \cdot 10^{-6}; \mathrm{R} < 100\ \mathrm{GV}$

– BESS 93-98: $\frac{\bar{\mathrm{H}}\mathrm{e}}{\mathrm{He}} < 1.0 \cdot 10^{-6}; \mathrm{R} < 16\ \mathrm{GV}$

Search for AntiMatter ($\bar{He}$)

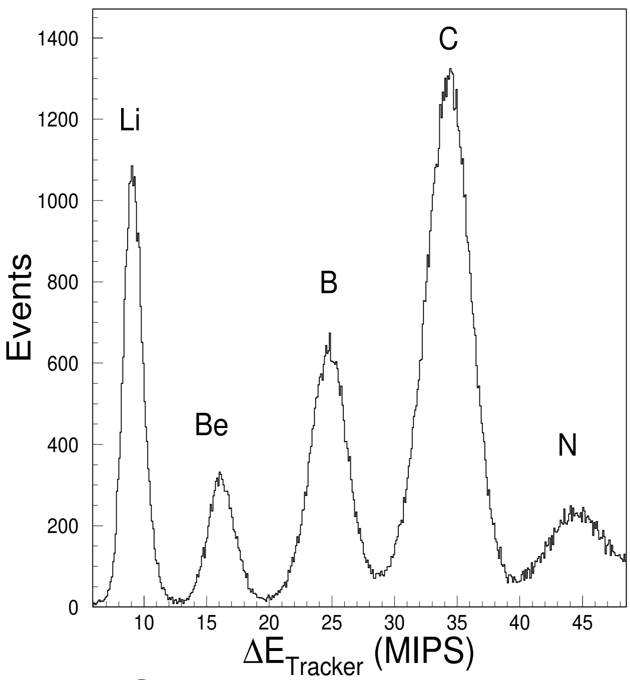
– Conservative Limit: $\dfrac{3}{\mathrm{Acceptance_{min}[R_{min}...R_{max}]} \cdot \int_{\mathrm{R_{min}}}^{\mathrm{R_{max}}} \mathrm{Flux(R)dR}}$.

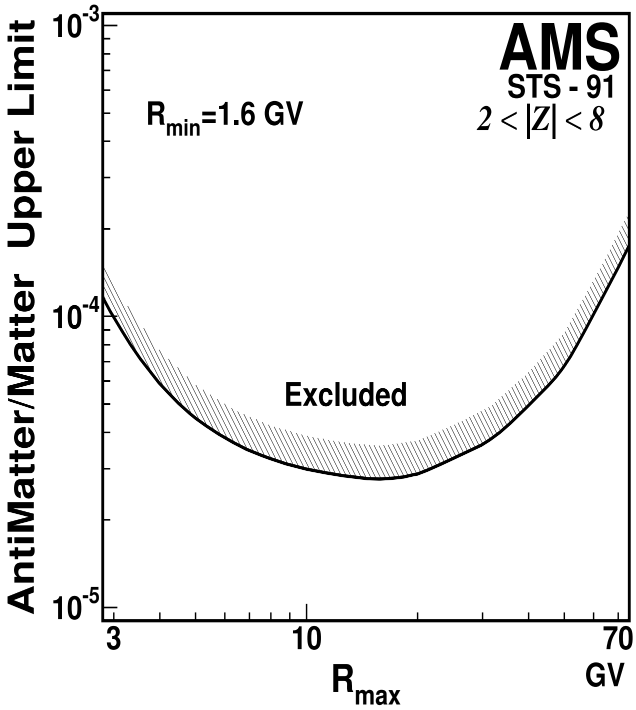


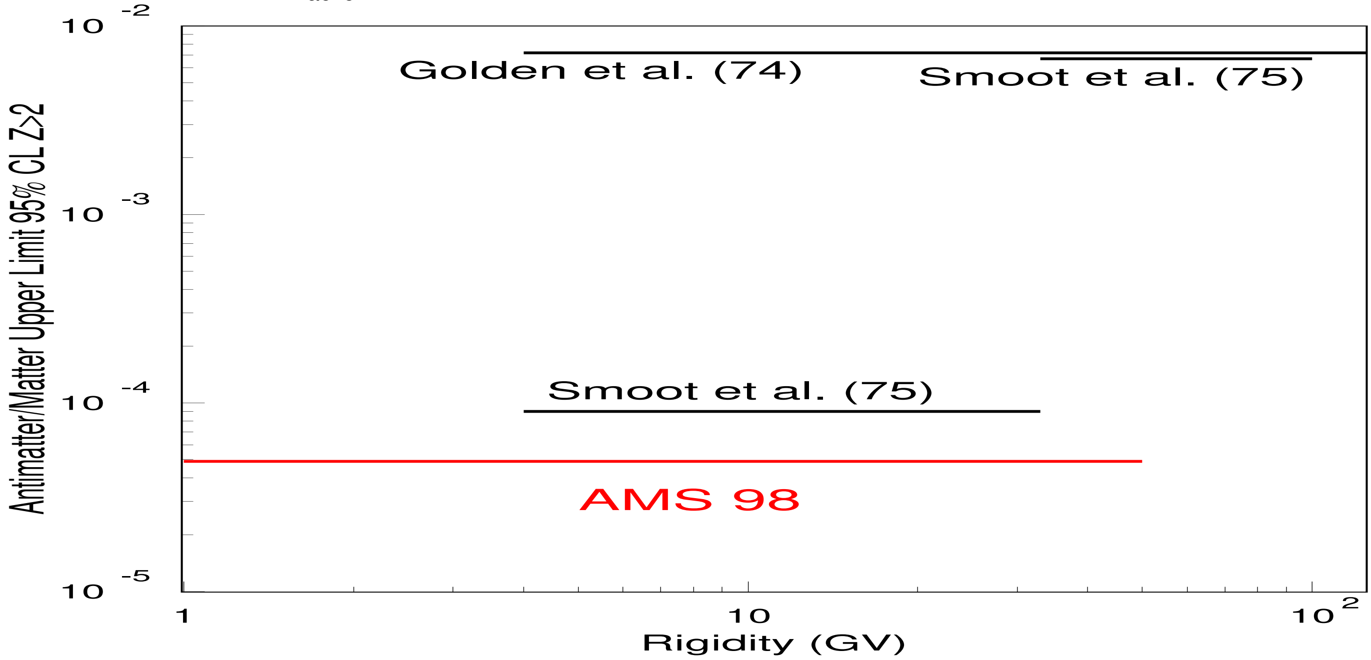


Search for AntiMatter, Havier Nuclei

No $(Z < -2)$ candidate



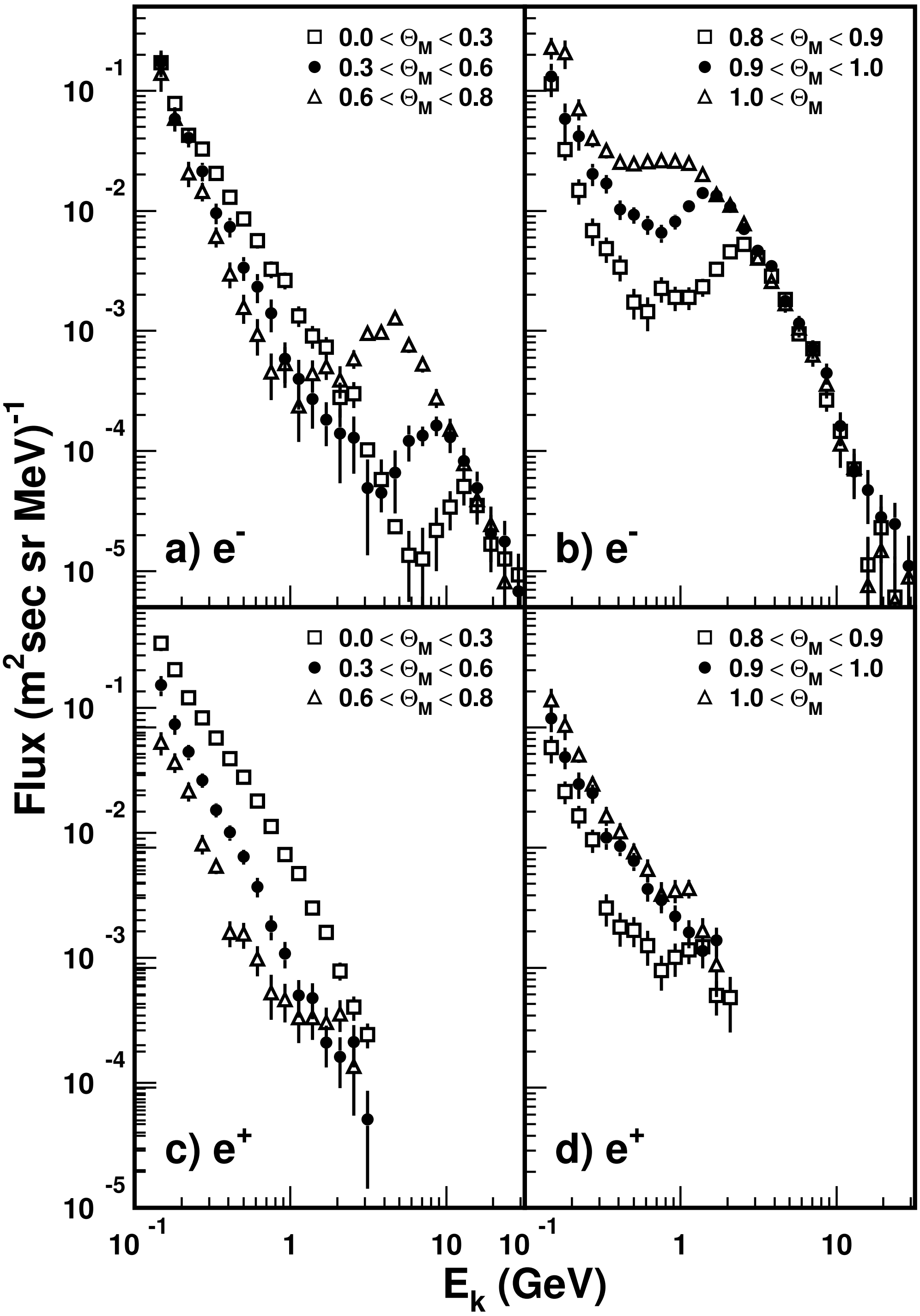




A large flux of particules is detected for rigidities lower than the geomagnetic cutoff

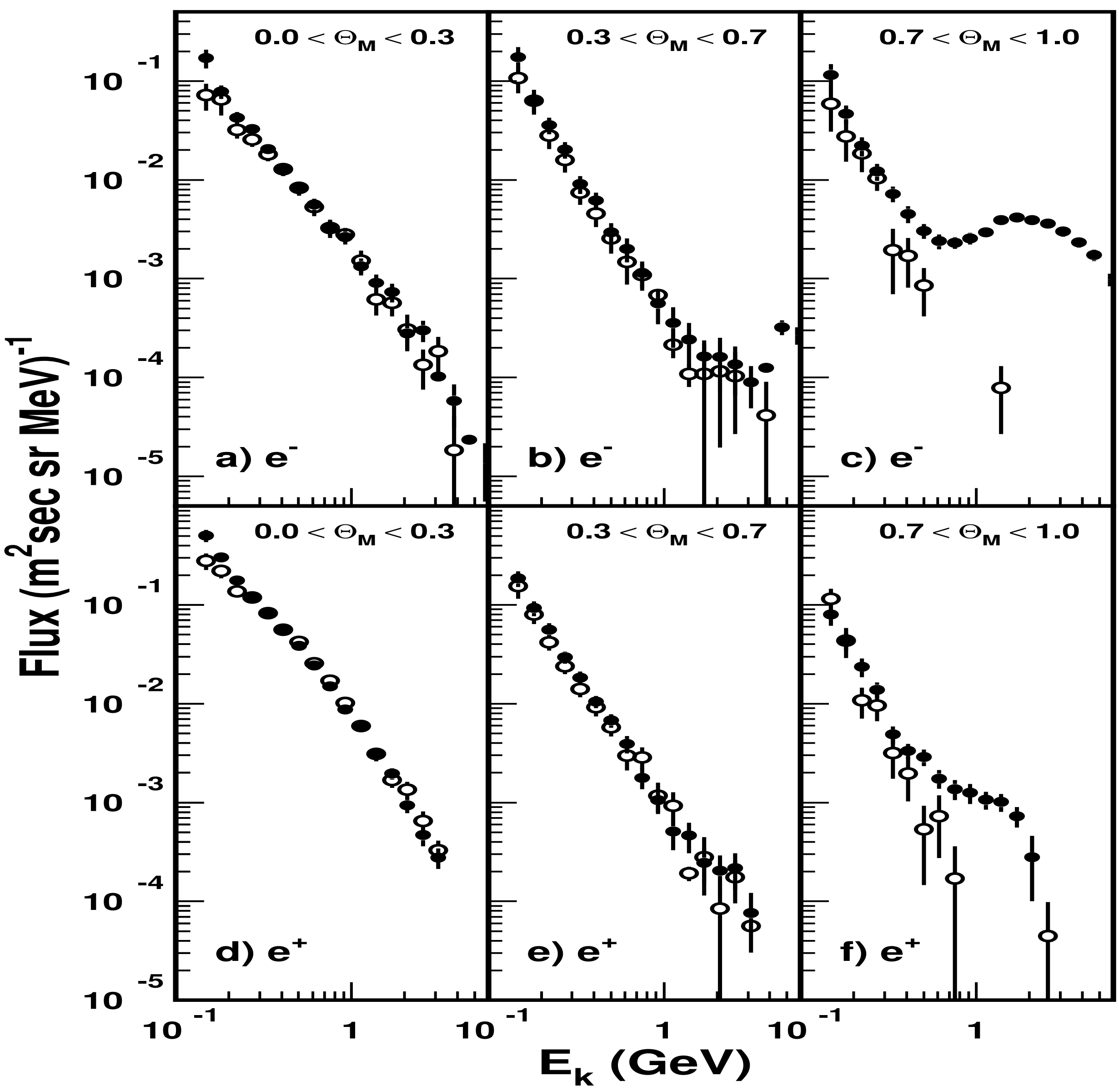
RESULTS ON SECONDARY SPECTRA

Downward going $e^{\pm}$



A substantial secondary spectrum is present under geomagnetic cutoff

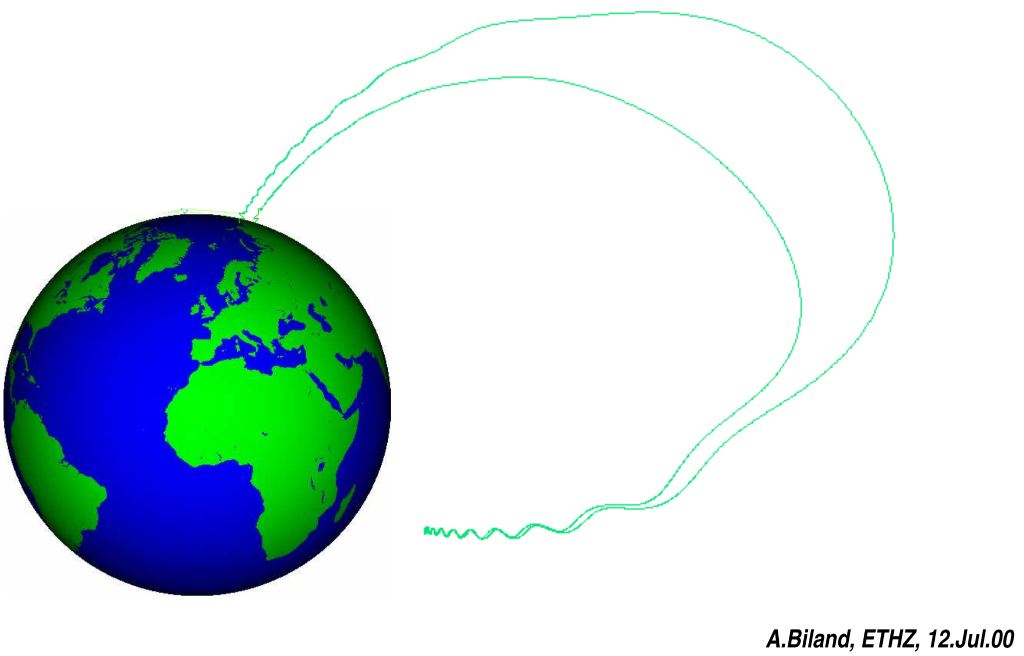
Comparison down/up $e^{\pm}$



- full circles: downward going $e^{\pm}$
- open circles: upward going $e^{\pm}$

Upward and downward fluxes are nearly identical

Tracing in the geomagnetic field

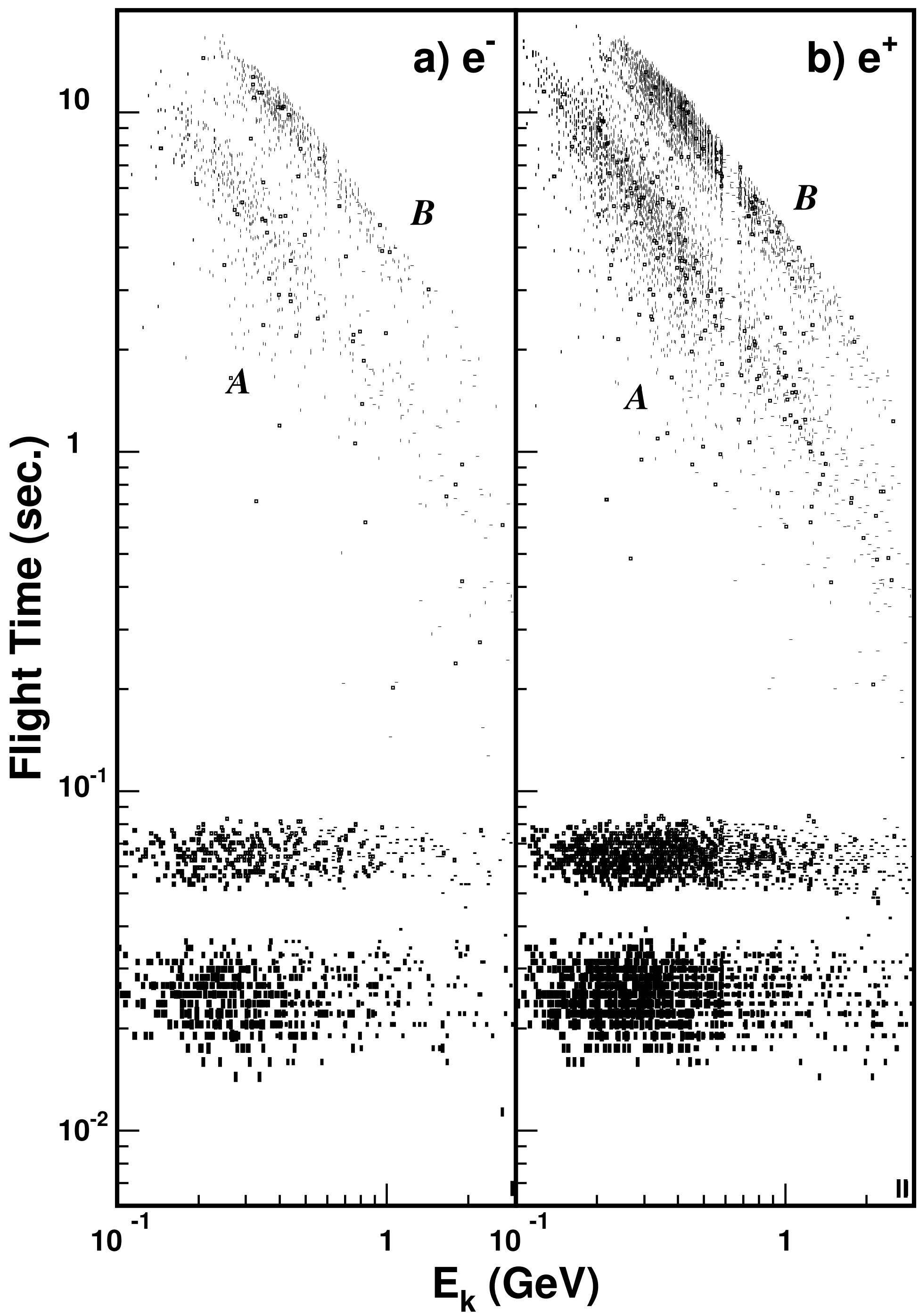


To determine their origin, detected particle trajectories have been backward traced through the Earth magnetic field $\rightarrow$ cfr. Flueckiger et al., Univ. Bern

Starting from the detection location, the trajectories have been backward traced (for max 10 sec) until:

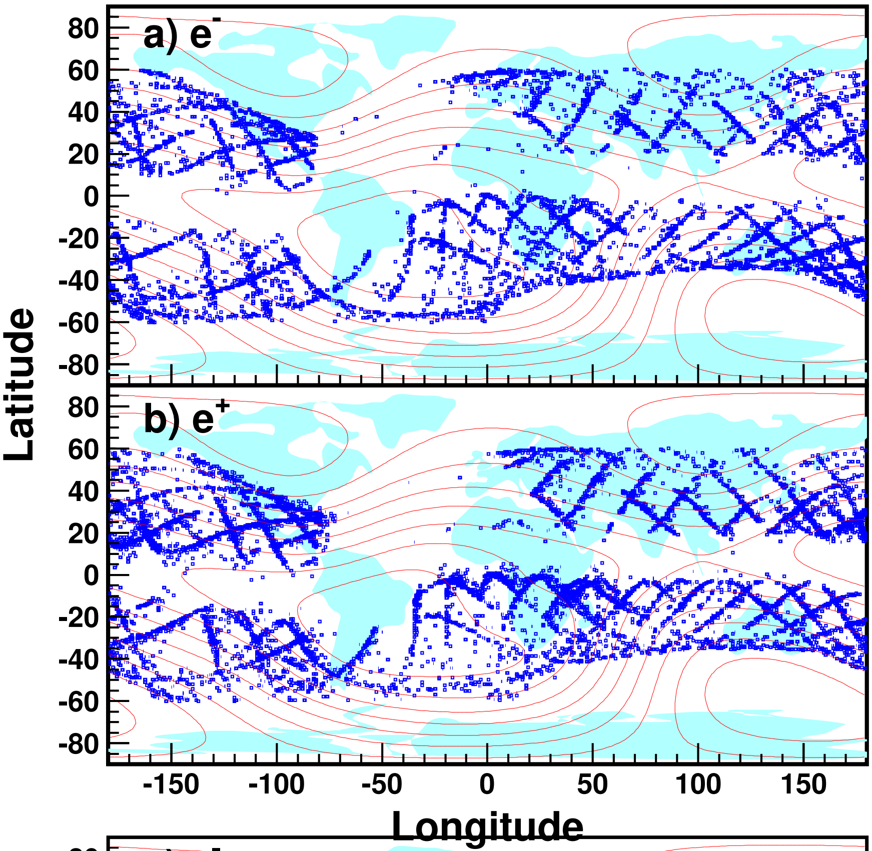
- the trajectory reached outside the magnetosphere
- it reached the atmosphere (altitude 40 km)
  - for these *secondaries* , two components:
    - $t < 200$ msec: short lived
    - $t > 200$ msec: long lived

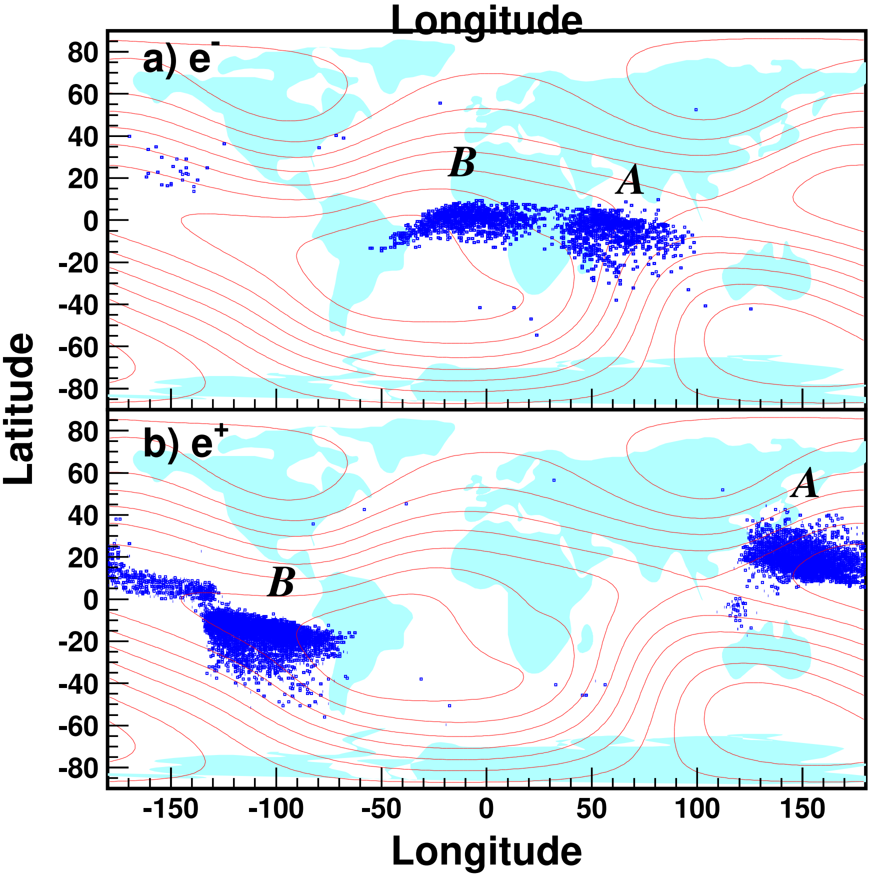
Flight times of secondary e $^{\pm}$



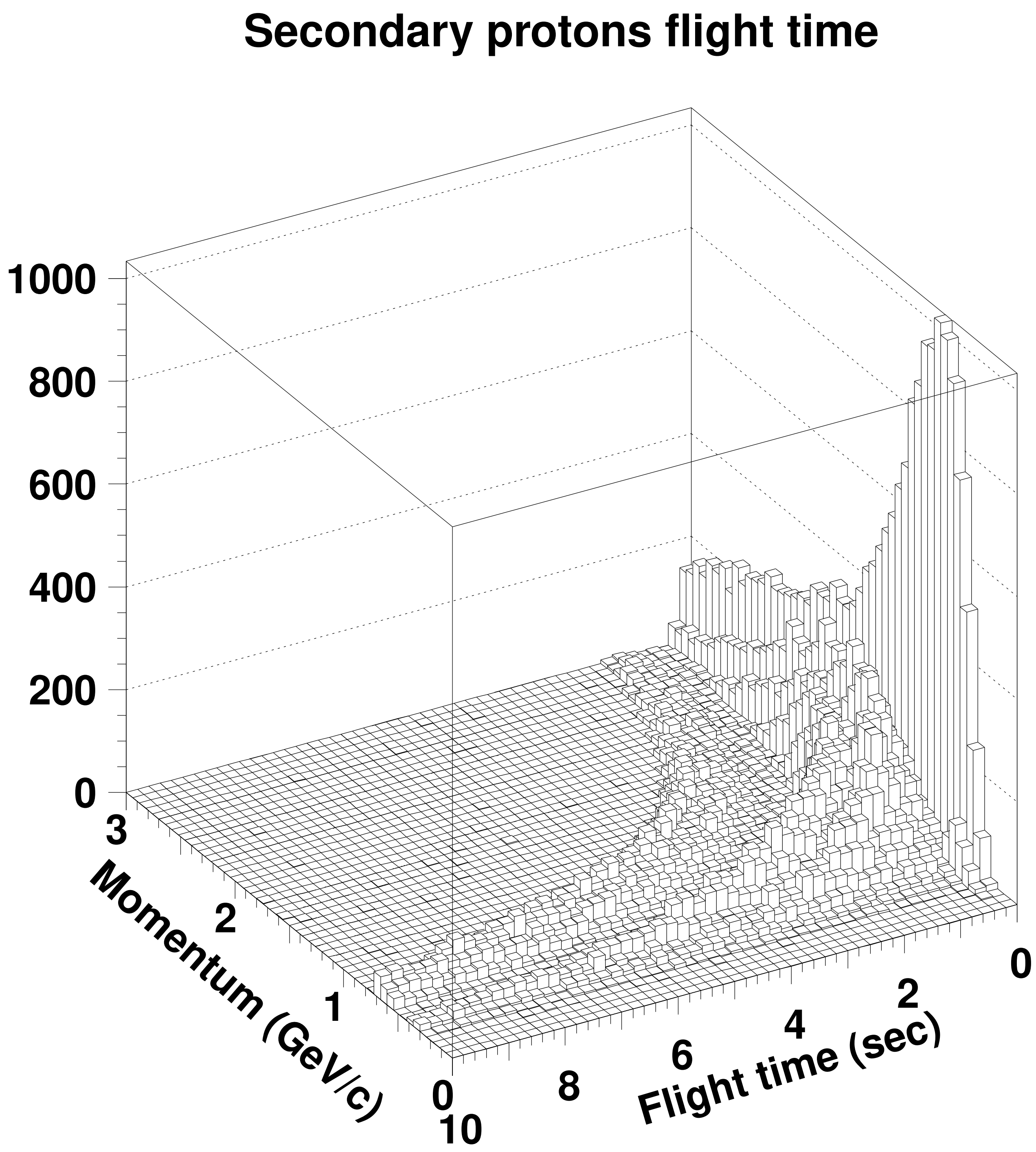
- No energy dependence for short flight times

Origin of secondary e $^{\pm}$

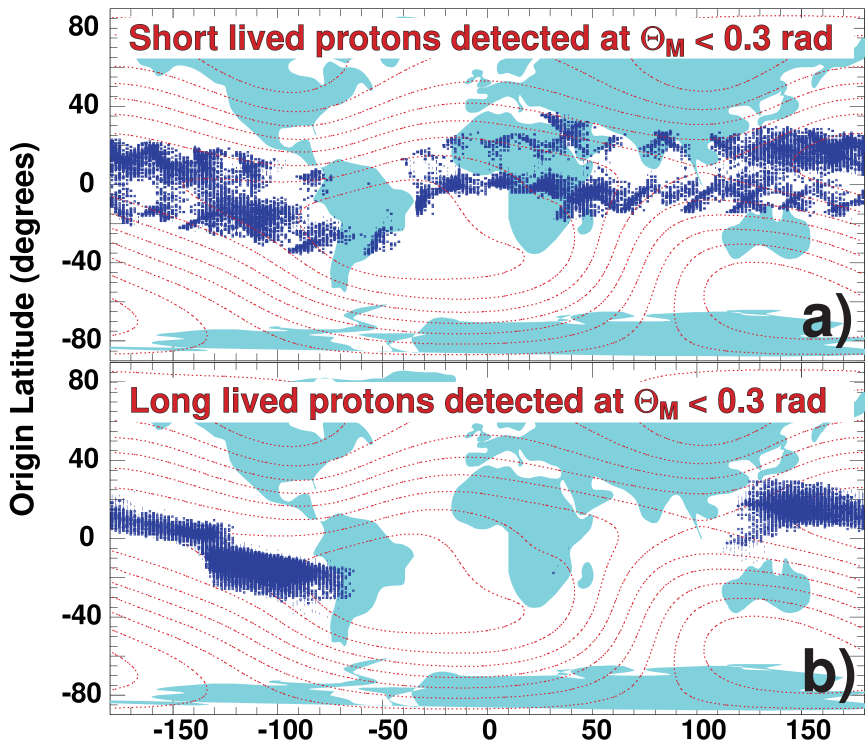




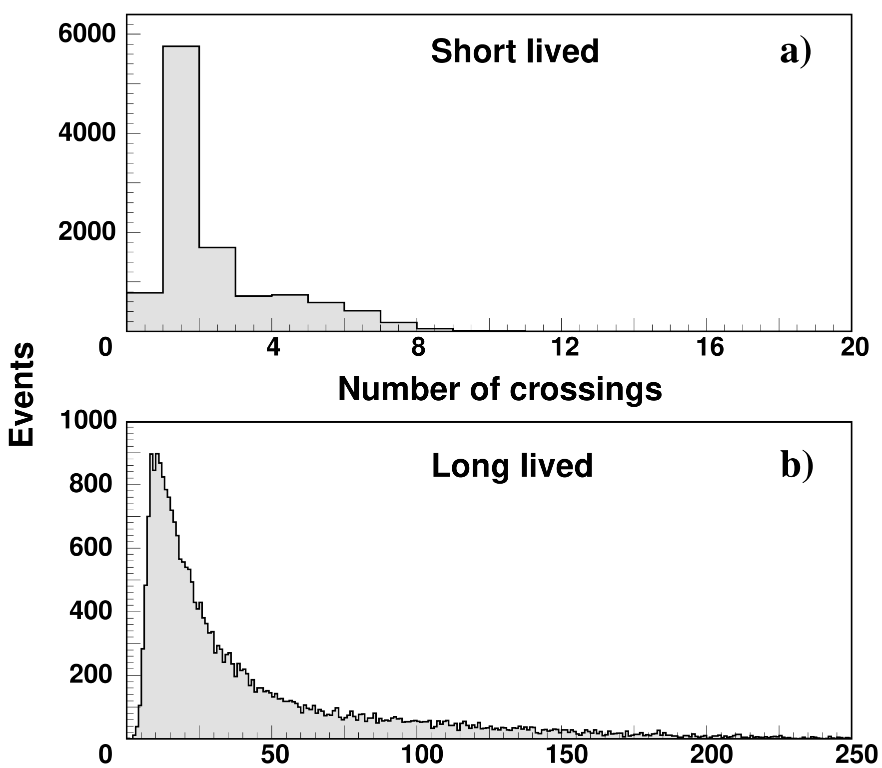
Similar analysis for protons



Origin of secondary protons



Equator crossings



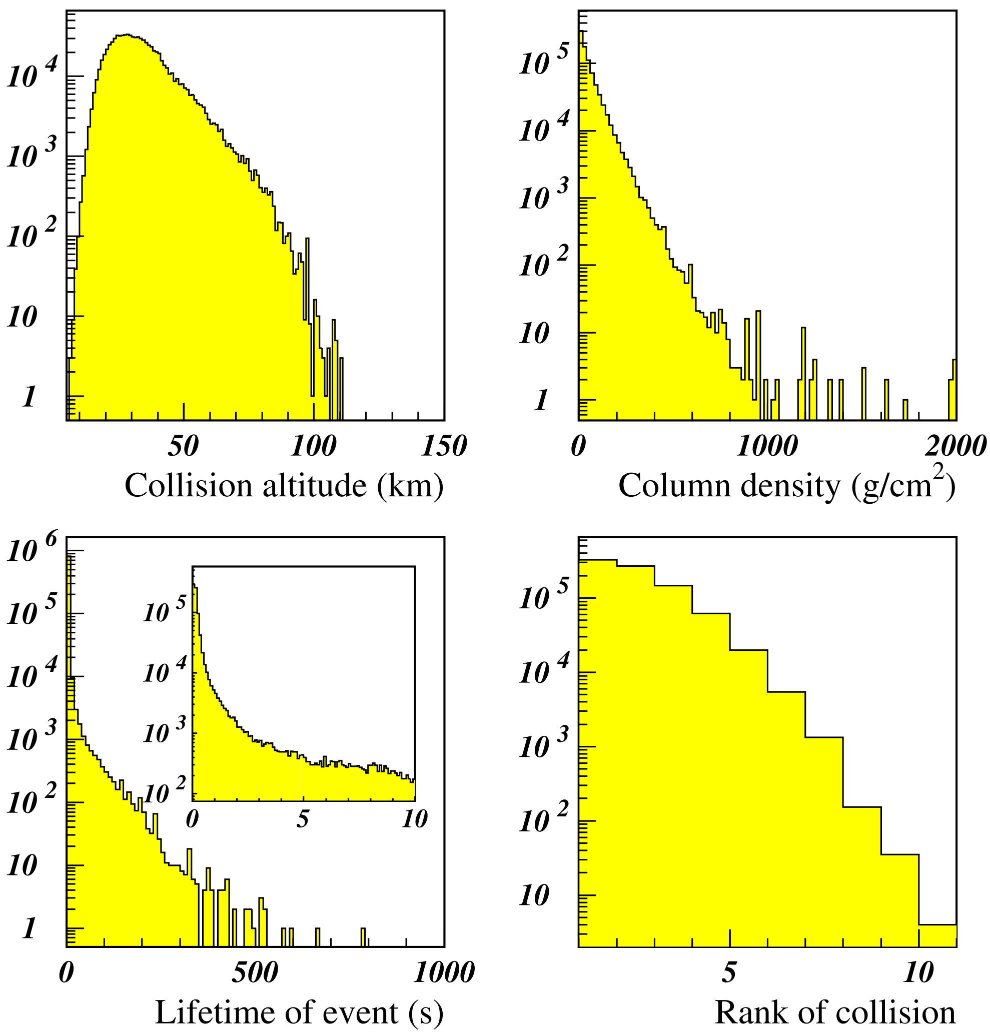
Understanding secondary spectra

Origin of the high energy proton component below the geomagnetic cutoff in near earth orbit

L. Derome et al., ISN Grenoble report 00/48, June 2000

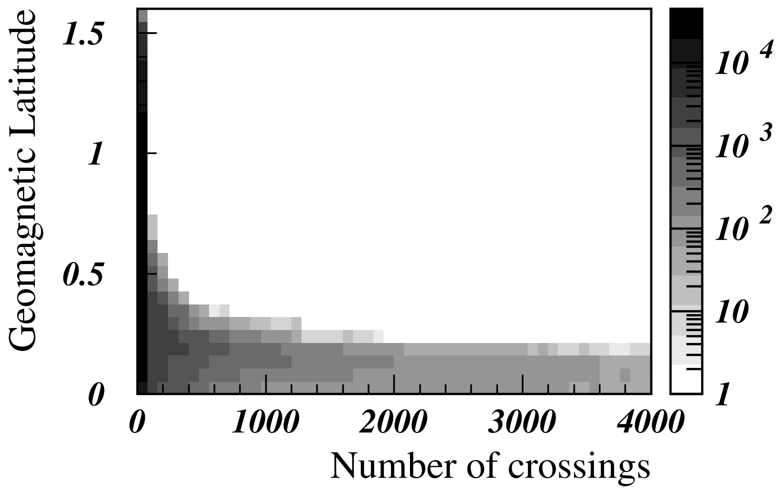
Submitted to Physics Letters B

- Complete simulation of proton-nuclei in atmosphere and propagation in the magnetosphere

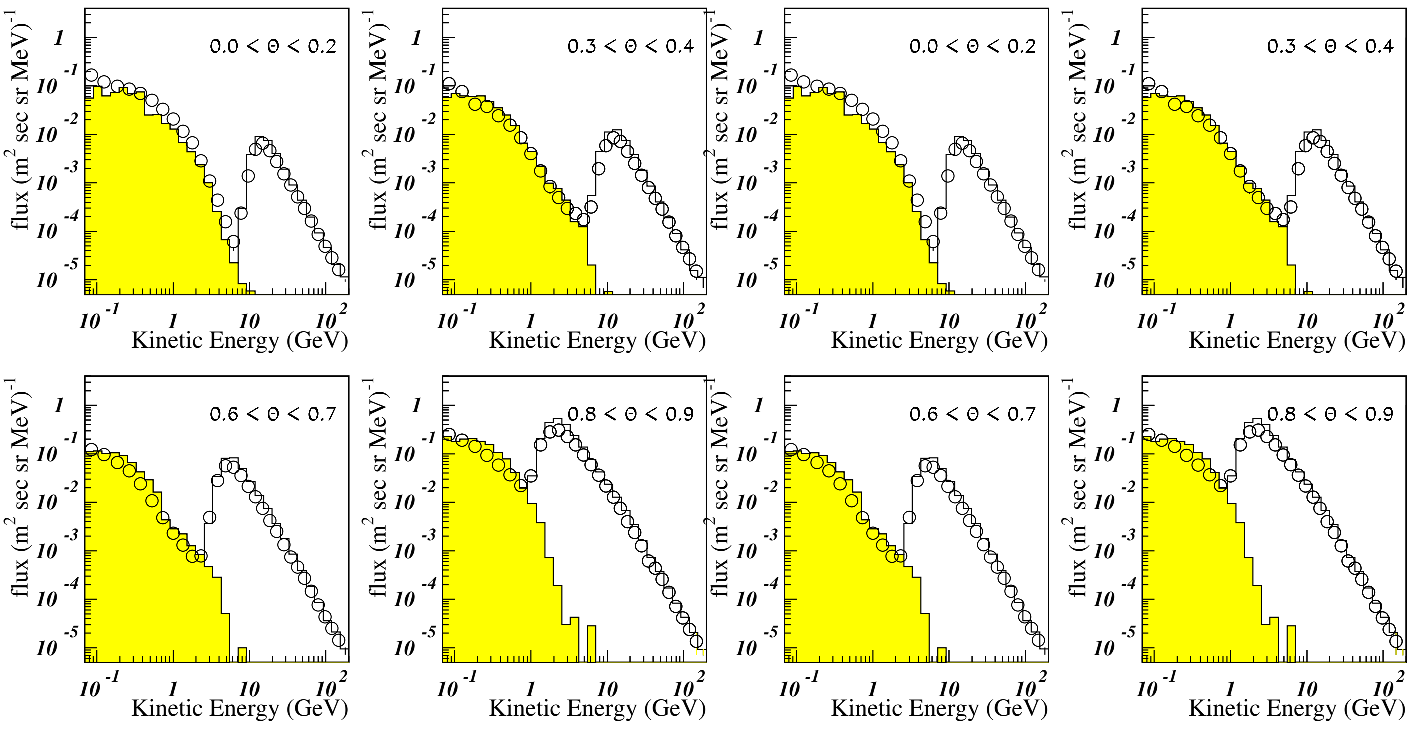


Understanding secondary spectra

- Detector crossings at 400 km altitude

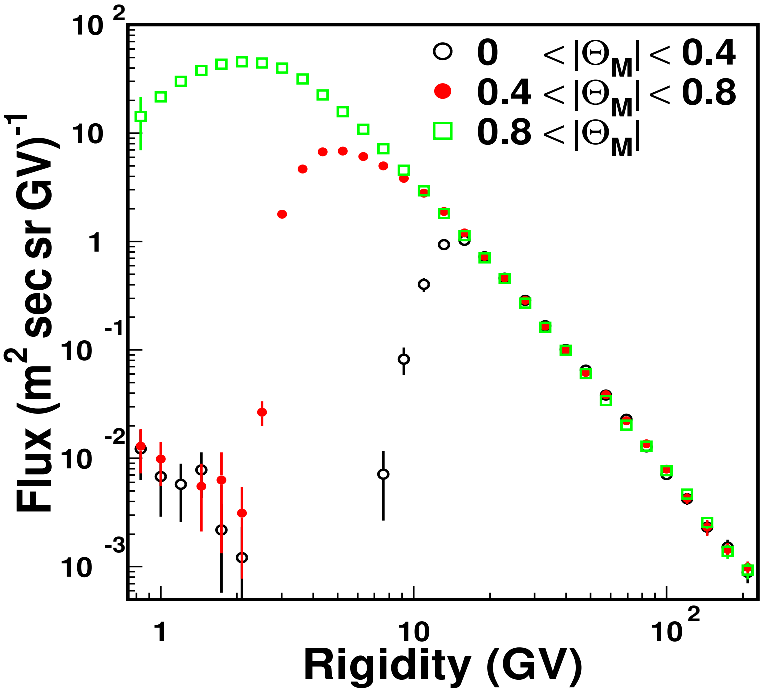


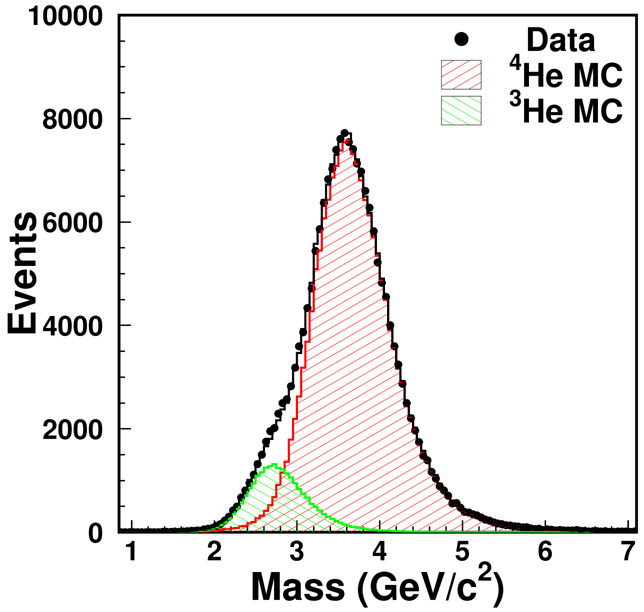
- Spectra (absolute normalisation)

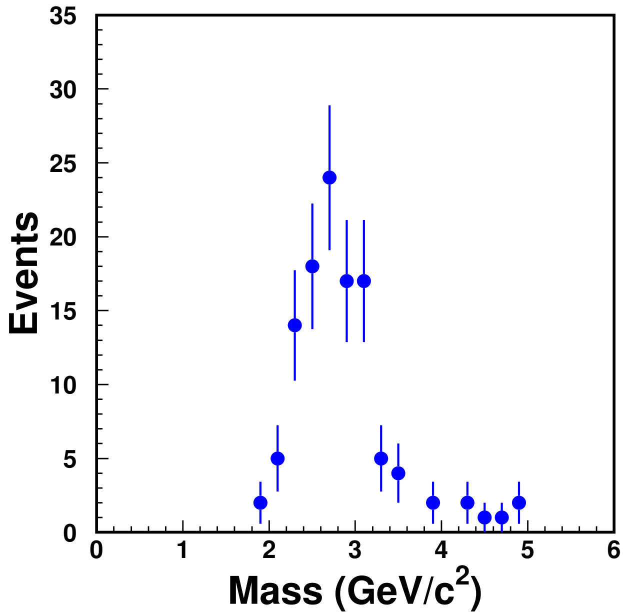


Helium secondary spectra

Secondaries are ^{3}He with *long/short flight* components



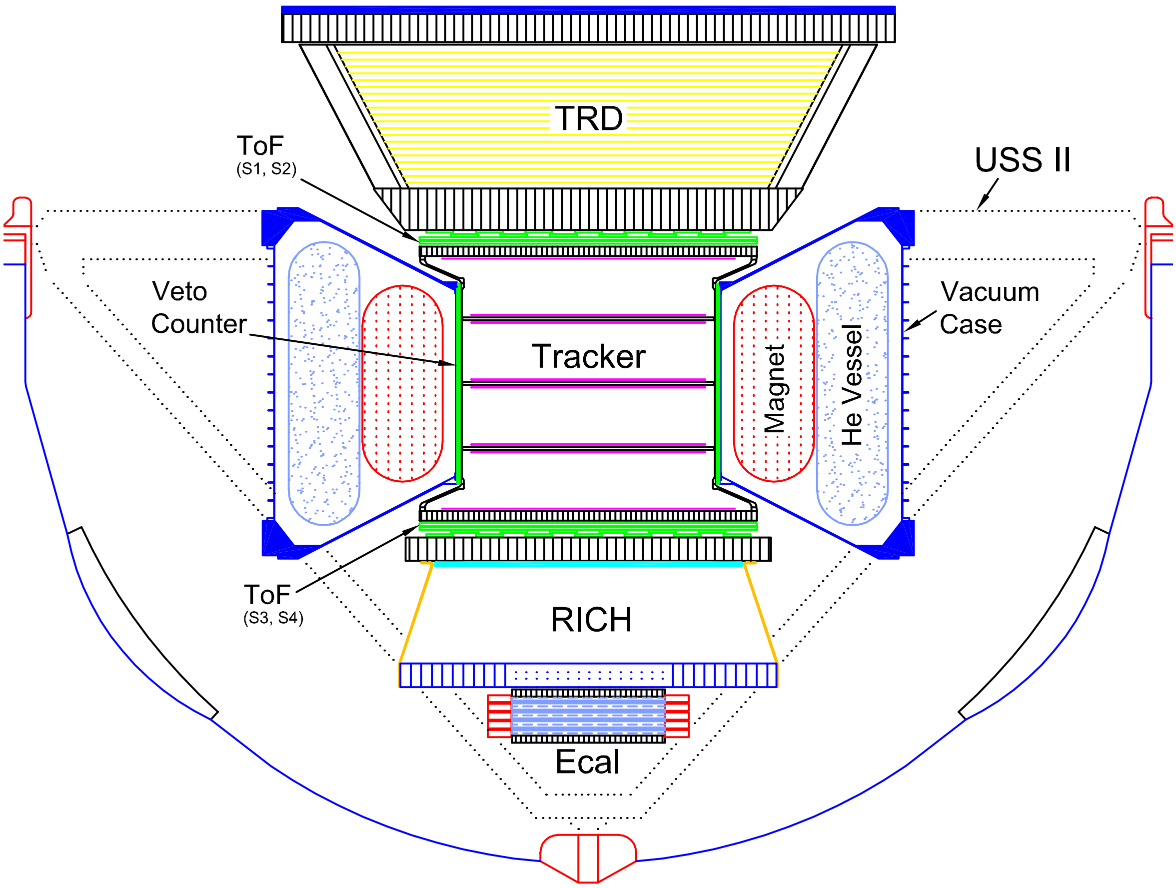




Primaries mass for $\Theta_m > 0.9$
MC simulation with ^{3}He/^{4}He=0.13

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

AMS-02 on ISS for 3 years

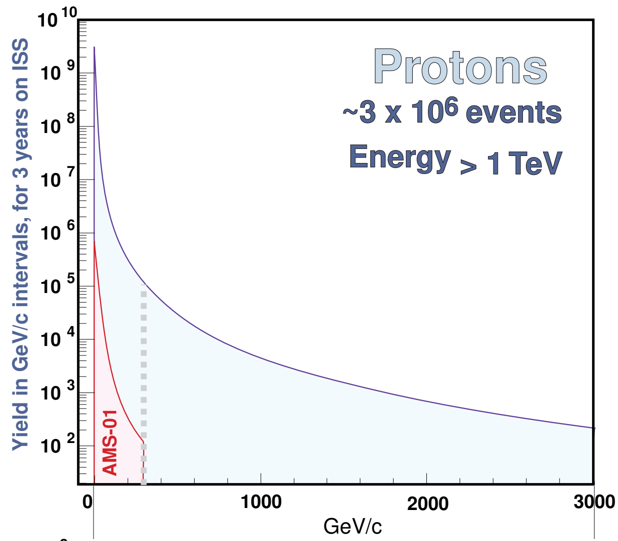


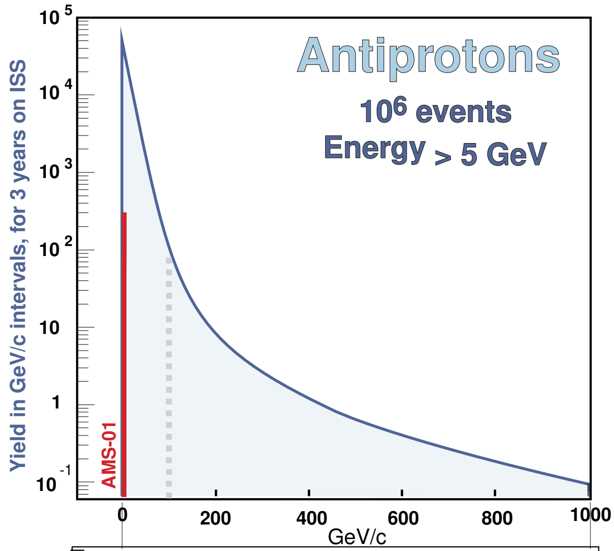
- new *superconducting magnet* : $\sim$1 Tesla (gain 7)
- new *TRD* : separate $e^{\pm}$ from $\bar{p}$,p up to 300 GeV
- new *RICH* : ^{3}He, ^{4}He, B, C, ...
- new *EM calorimeter* : $e^{\pm}$ and photons up to 1 TeV
- improved *Tracker* : entire surface covered with Si
  - 8 layers and 7 m^2 total surface (were 6 and 2.1m^2)
- next flight (for ISS) end of year 2003

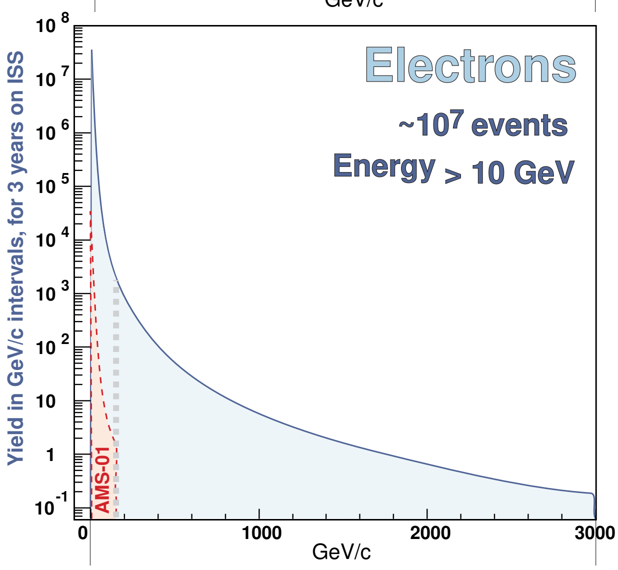
Expected data collection

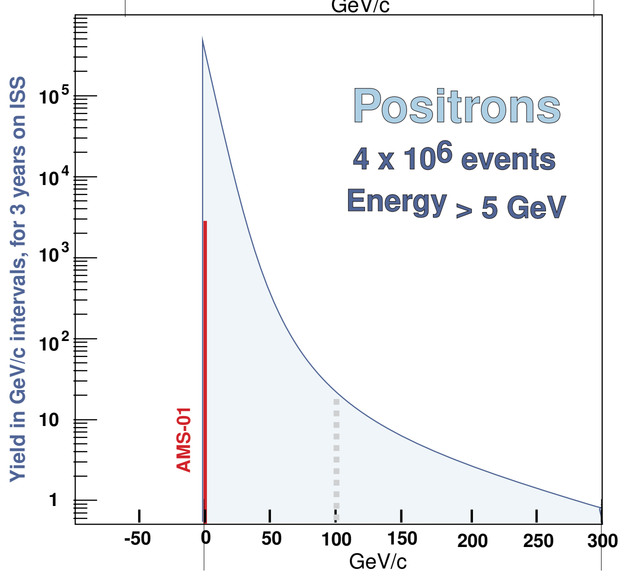
(extreme high energy cosmic rays)

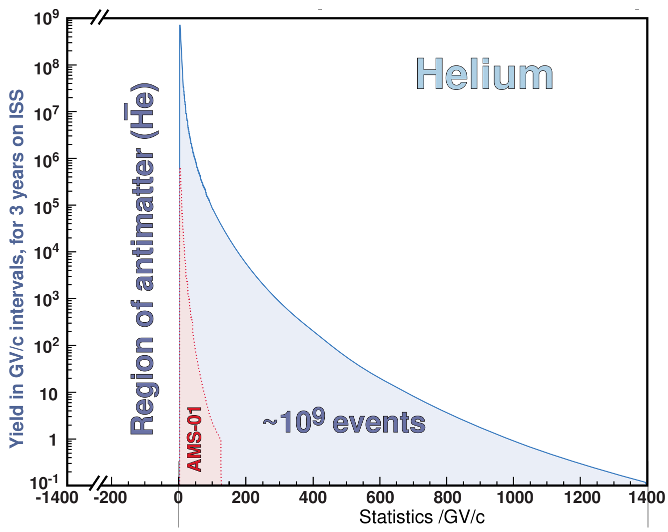
(Search for dark matter)











Conclusion

- AMS-01: a fruiful ”test & qualification” flight
  - Experience gained in space particle physics
  - Search for $\bar{\mathrm{He}}$ and antinuclei
  - Energy spectra for cosmics
    p, $e^{\pm}$, He, D, ($\bar{p}$ and Z$>$2 in progress)
  - Trapped particles. Better understanding of secondary production in high atmosphere
- AMS-02: an exciting challenge
  - Cosmic rays will be measured with orders of magnitude better than before and up to the TeV region
  - Search for antinuclei ($\bar{\mathrm{He}}$ sensitivity: 10^{-9})
  - γ physics
  - Search for exotics