Measuring Antimatter over Antarctica
Results of the BESS-Polar Program

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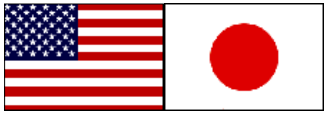
TeV Particle Astrophysics 2013
University of California, Irvine

BESS-Polar Collaboration



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- **Kobe University**
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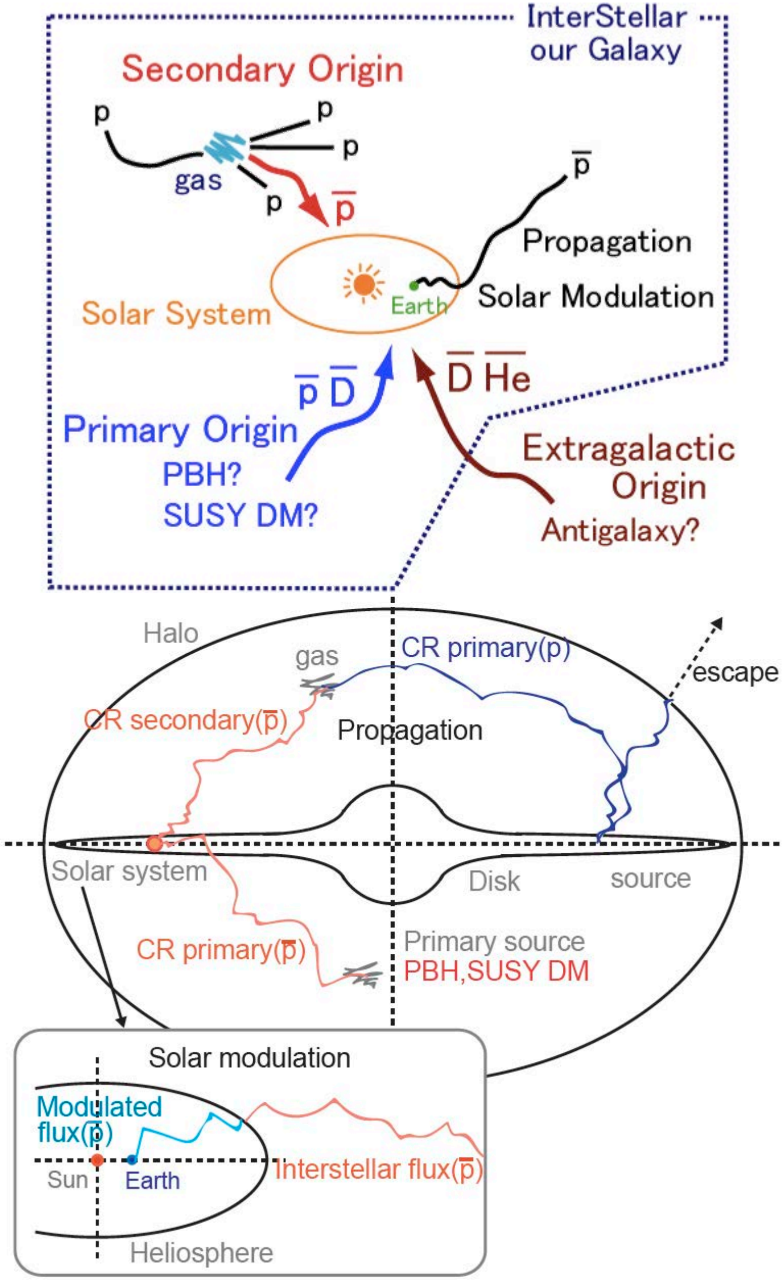
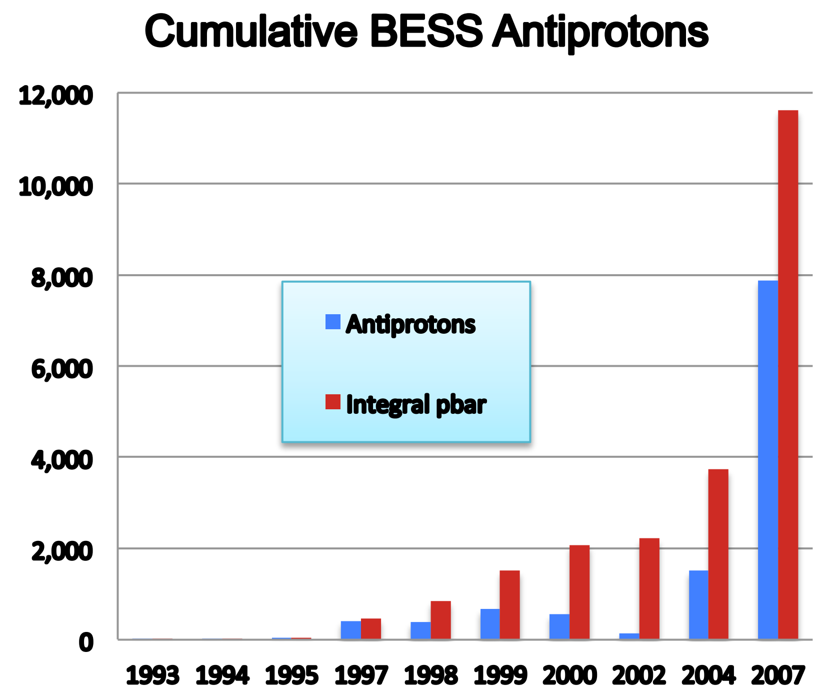
Antimatter in the Cosmic Radiation at Earth



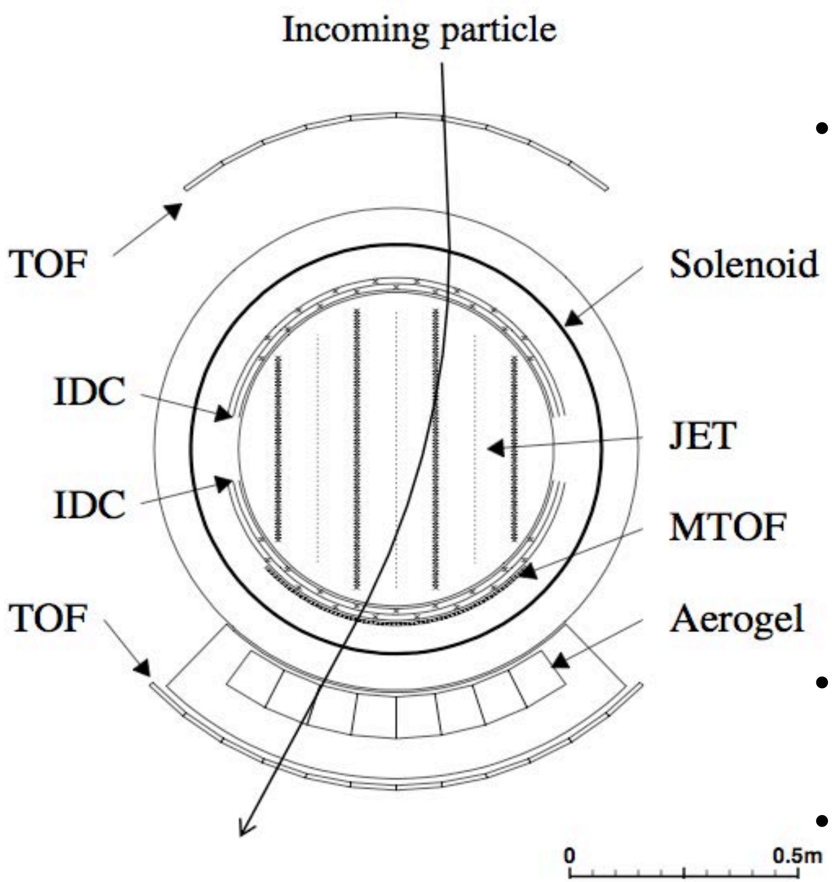
- The Cosmic Radiation is dominated by matter
- Small fraction of antiparticles
- Probe early Universe and particle physics
  - Matter/Antimatter asymmetry
  - Potential primary sources: dark matter annihilation, primordial black holes
- Same galactic and local influences as other cosmic-ray species
  - Production & Propagation
  - Solar modulation
  - Atmospheric production
- GCR antiprotons:
  - Expected as nuclear interaction secondaries (kinematic threshold 6 GeV)
  - pbar/p ≈ 10^{-5} at 1 GeV
  - Spectrum peaked at ~2 GeV
  - Possible "primaries" from e.g. WIMP annihilation or primordial black hole (PBH) evaporation
- Complex antinuclei - none detected to date

BESS Program 1993 - 2007

- Nine northern-latitude flights (1993 – 2002)
- Two Antarctic LDB flights (2004, 2007)
- Broad ranging program: antiproton measurements, light element and isotope spectra, muon spectra, antinuclei search, solar transients and modulation
- "Evolutionary" improvement of instrument
  - 6 antiprotons in 1993 - 43 in 1995
  - From 1997, 400-600 in each flight (~2400 1993 – 2002)
  - BESS-Polar I 1512 - BESS-Polar II >7886



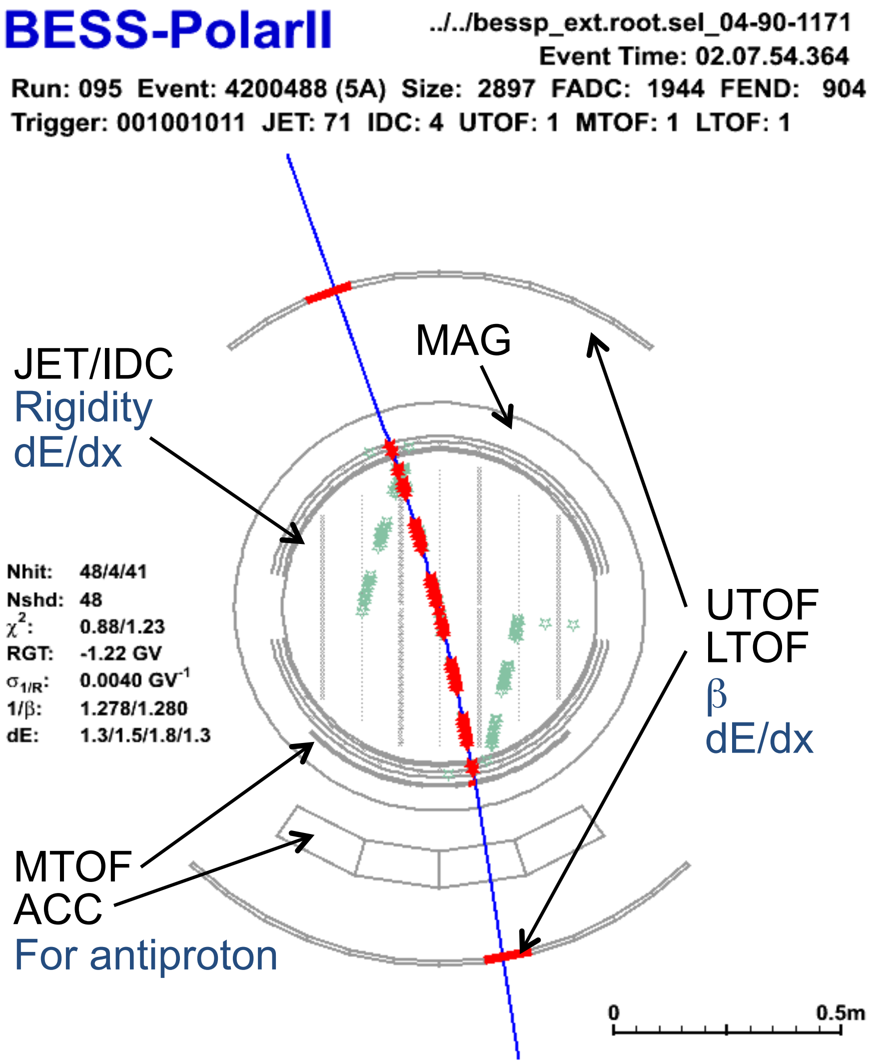
BESS – Balloon Borne Experiment with a Superconducting Spectrometer



- Measures charge, charge-sign, mass, and energy
- Superconducting magnetic spectrometer: momentum from magnetic rigidity
  - Thin solenoidal superconducting magnet
  - Fully active "JET" and "IDC" drift chambers with 52 points on trace, σ <130 μm
  - Geometric acceptance 0.3 m^2 sr
  - MDR: 200 GV BESS; 1400 GV BESS-TeV; 240 GV BESS-Polar
- Time-of-flight system (TOF): velocity and charge - σ = 120 ps for Z=1, β=1
- Silica-aerogel Cherenkov detector (ACC, n=1.02/1.03) - background rejection ~6000

$$m = \frac{RZe}{\gamma\beta c}$$

BESS Instrumentation



Event display with reconstructed Antiproton track is shown.

Rigidity (MDR:240GV)

Solenoid: Uniform field (ϕ=1m, B=0.8T)
Thin material (2.4 g/cm^2)

Drift chamber: Redundant hits
(σ~150μm, 32~48+4hits)

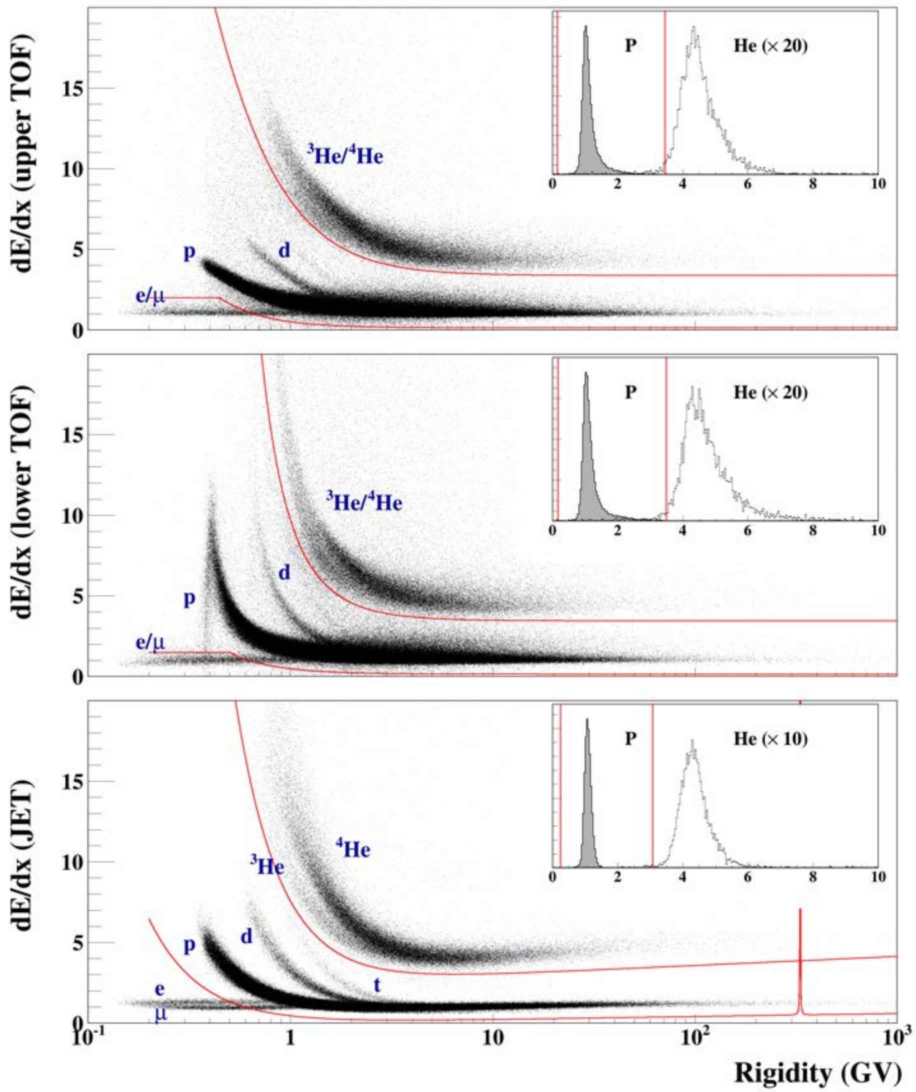
Charge, Velocity

TOF, Chamber: dE/dx measurement
(Z = 1, 2, ...)

TOF: 1/β measurement (σ~1,2%)

$$m = ZeR\sqrt{1/\beta^2 - 1}$$

BESS Particle Identification - Charge

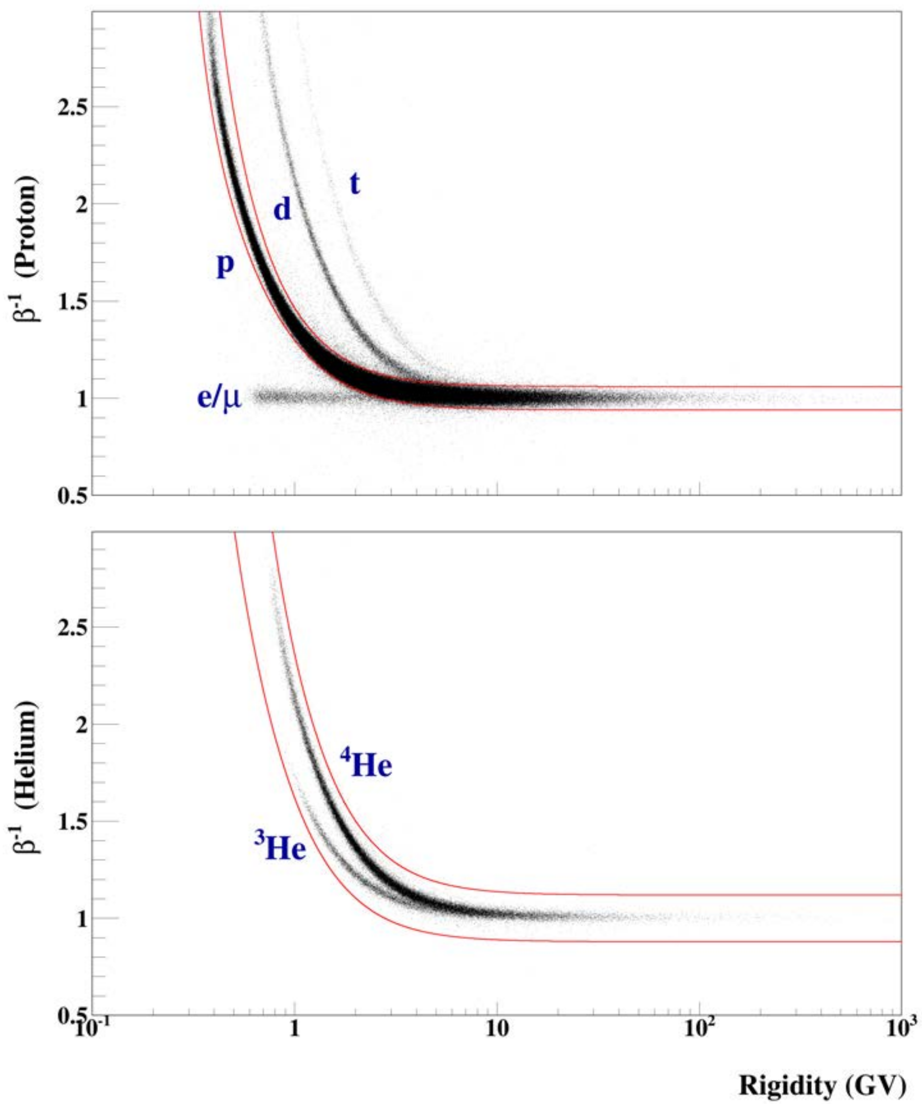


Particle identification uses dE/dx and 1/β as functions of rigidity.

Figures show the proton and helium selection bands in the dE/dx of Upper TOF, Lower TOF and JET.

Superimposed histograms show proton selection criteria above 10 GV.

BESS Particle Identification - Mass



Figures show the proton and helium selection bands in 1/b vs rigidity plane after dE/dx selection.

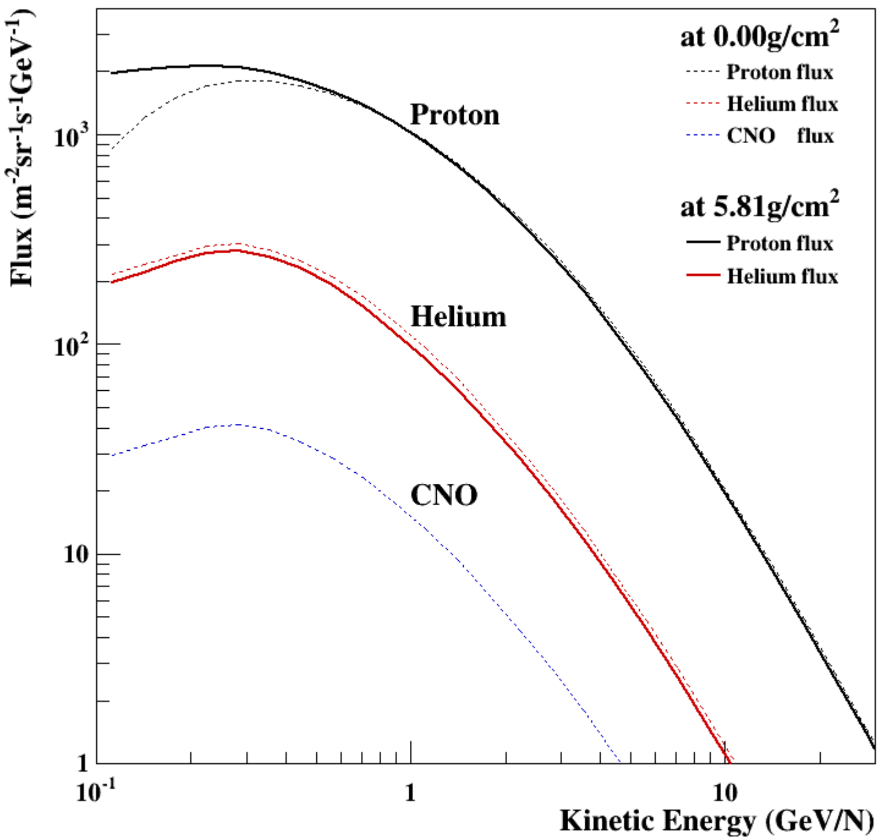
The $1/\beta$ distribution is well described by Gaussian and a half-width of the $1/\beta$ selection band is set at 3σ. The efficiency is very close to unity.

Deuteron contamination is ~ 2% above 3 GV.

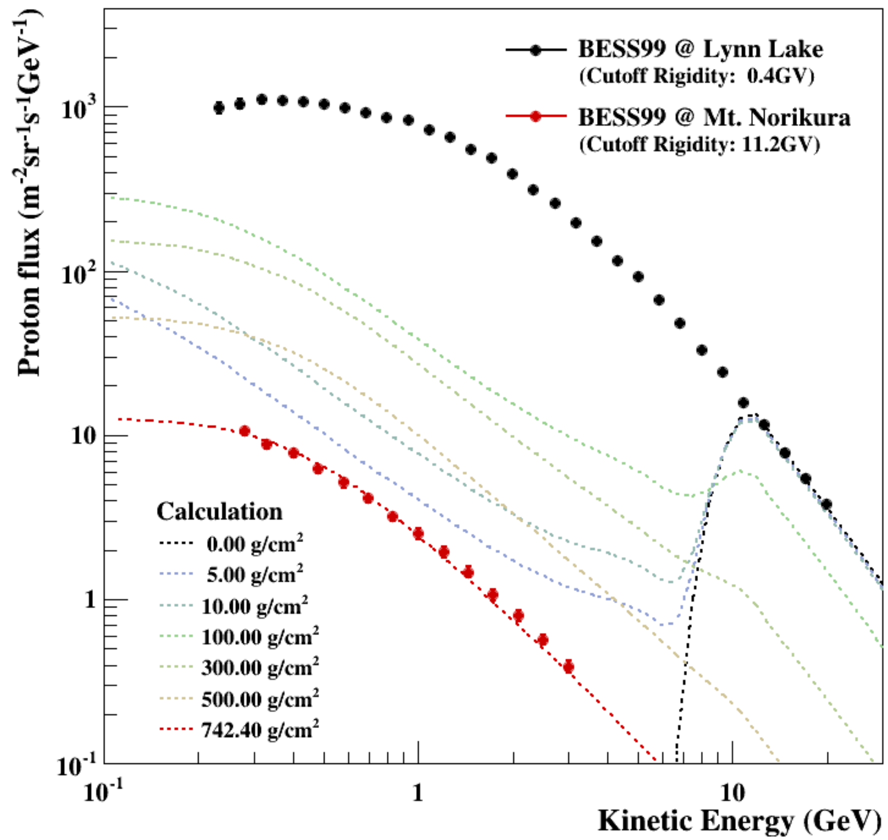
BESS Atmospheric Correction

The secondary particle background from the overlying atmosphere and survival probability are corrected in order to obtain fluxes at the top of atmosphere.

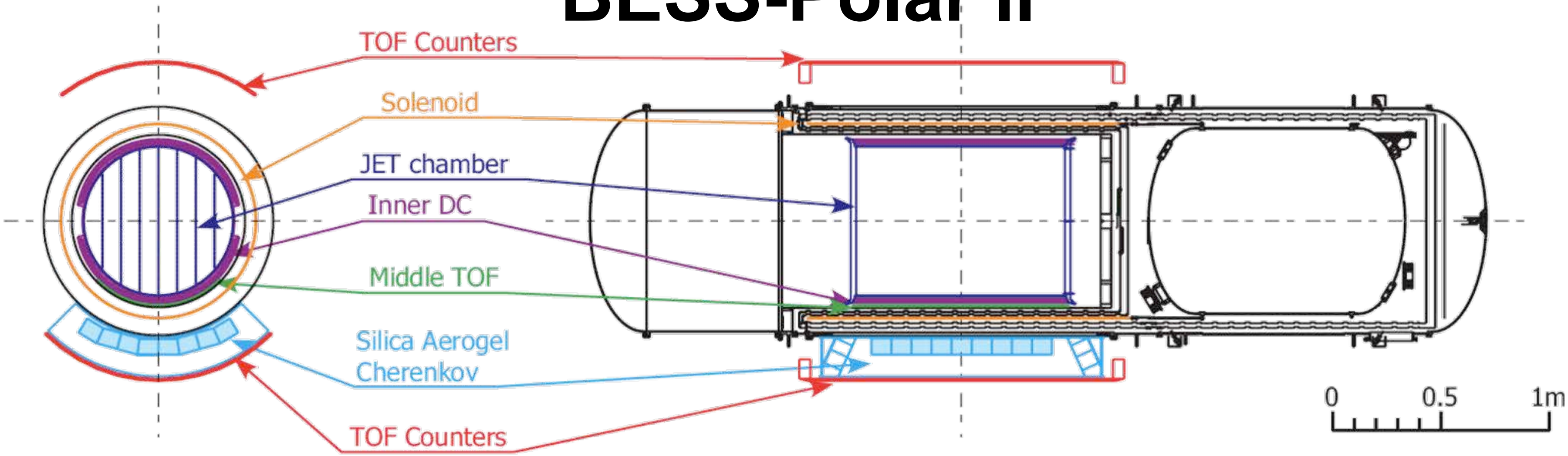
Atmospheric secondary correction for BESS-Polar II



Mountain observations test the calculation

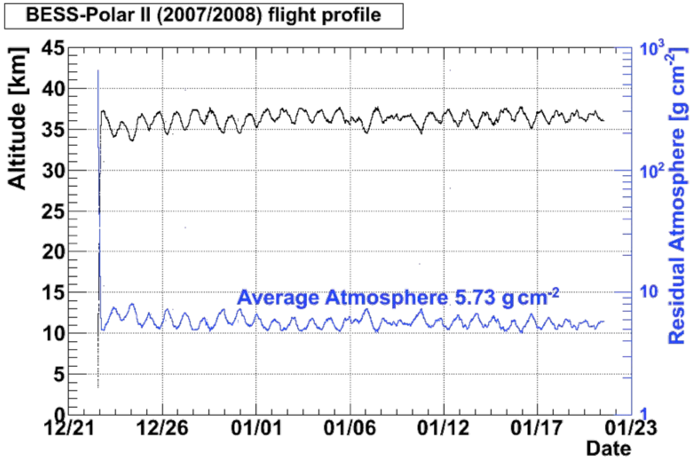


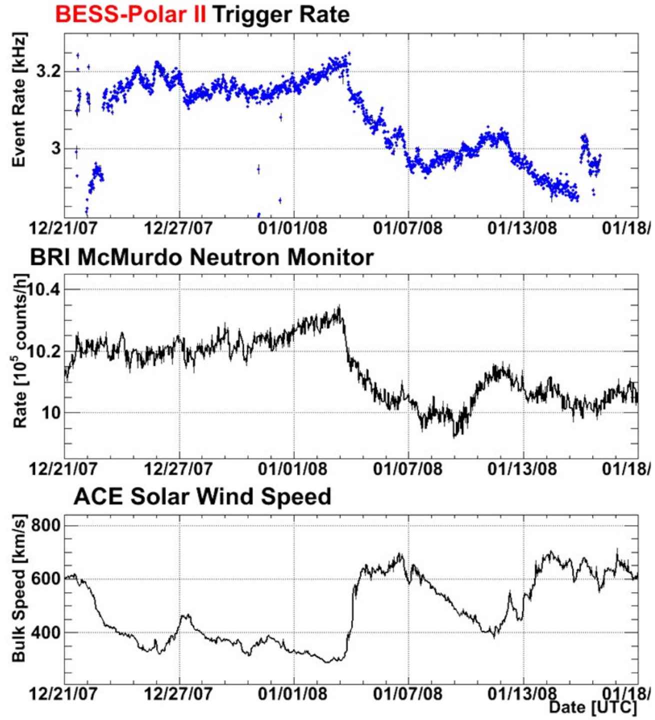
BESS-Polar II

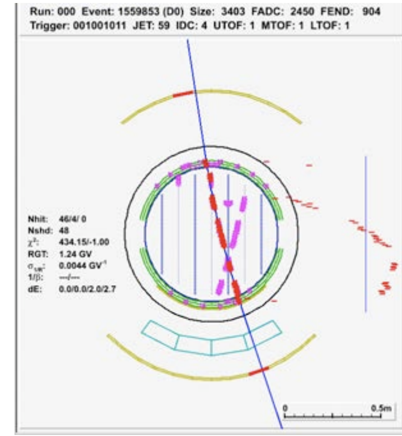


- Minimum material - 4.5 g/cm^2
  - Thin magnet - 2.2 g/cm^2
  - Middle TOF (MTOF) – low E trigger
  - No pressure vessel
- No in-flight data selection
- High speed DAQ - 2.5 kHz event rate
- Long Observing Time
  - Magnet cryogen life: >25 days
    - 520 liters LHe
  - 16 TB data storage

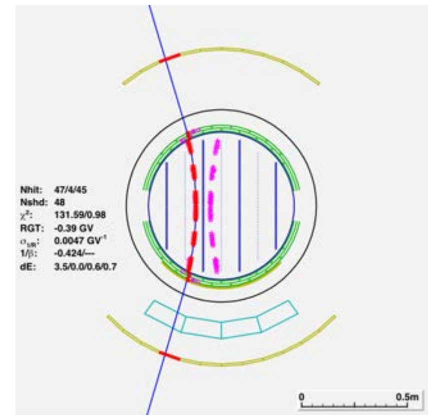
BESS-Polar II Flight



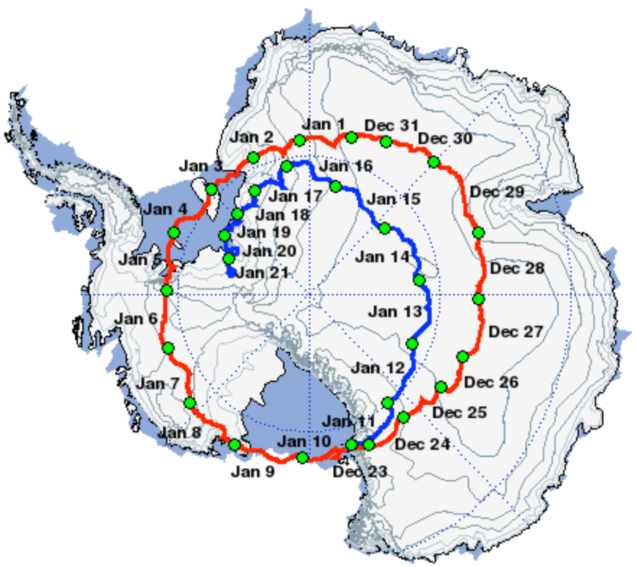




Positive Event



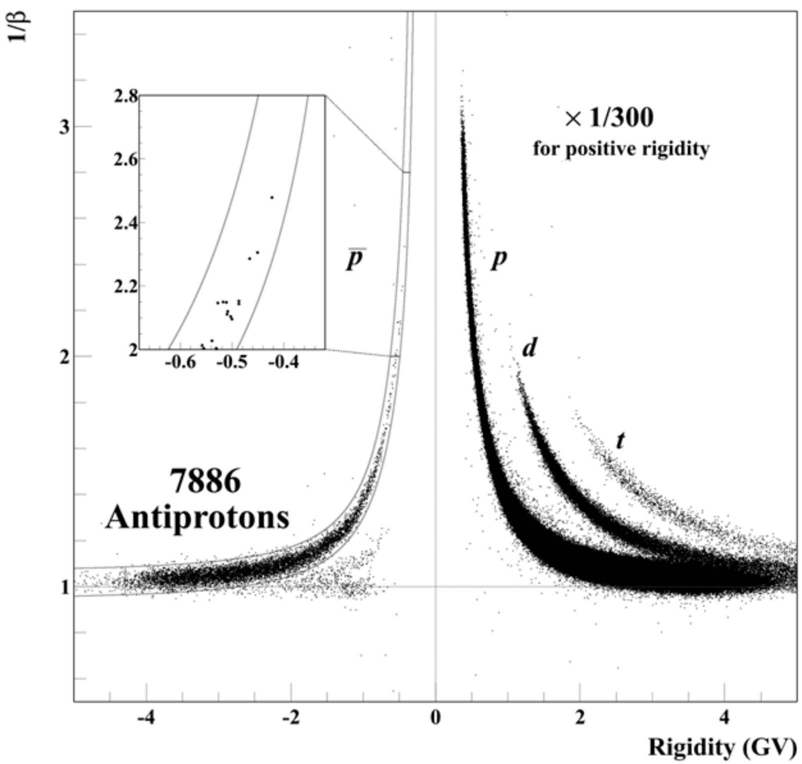
Negative Event



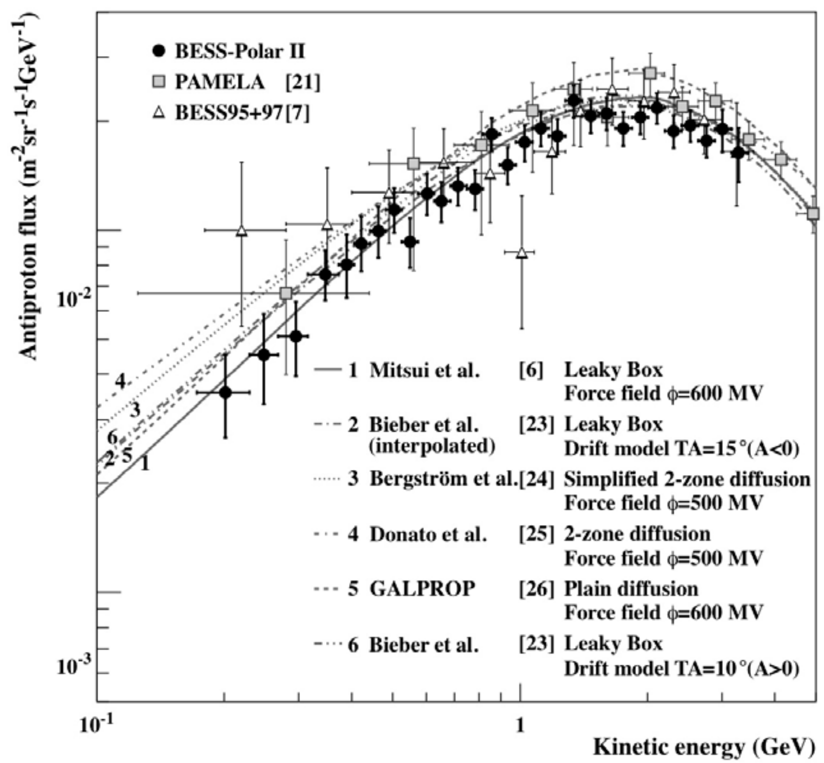
- Float Time: 29.5 days
- Near solar minimum
- Magnet-on 24 days 10 hours (~9.4 PAMELA years)
- Average altitude ~36 km (118,000 ft)
- Latitude 77.9° - 83° South
- Events recorded: > 4.7 x 10^9
- Data volume: ~ 13.5 terabytes

BESS Polar II Antiproton Measurements

BESS-Polar II Z=1 Particle Id



Antiproton Spectrum

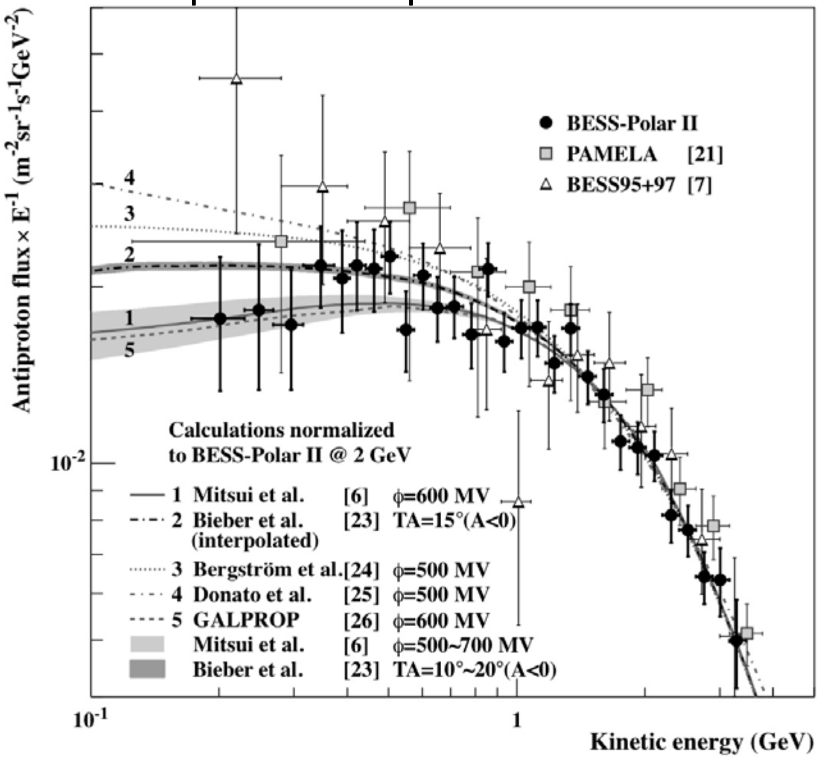


- 7886 Antiprotons ~10-20 times previous BESS solar-minimum dataset (comparison depends on energy)
- Abe *et al*., Phys. Rev. Lett.,108, 051102, 2012.

- BESS-Polar II and PAMELA spectra agree in shape but differ ~14% in absolute flux
- Both agree in shape with secondary calculations

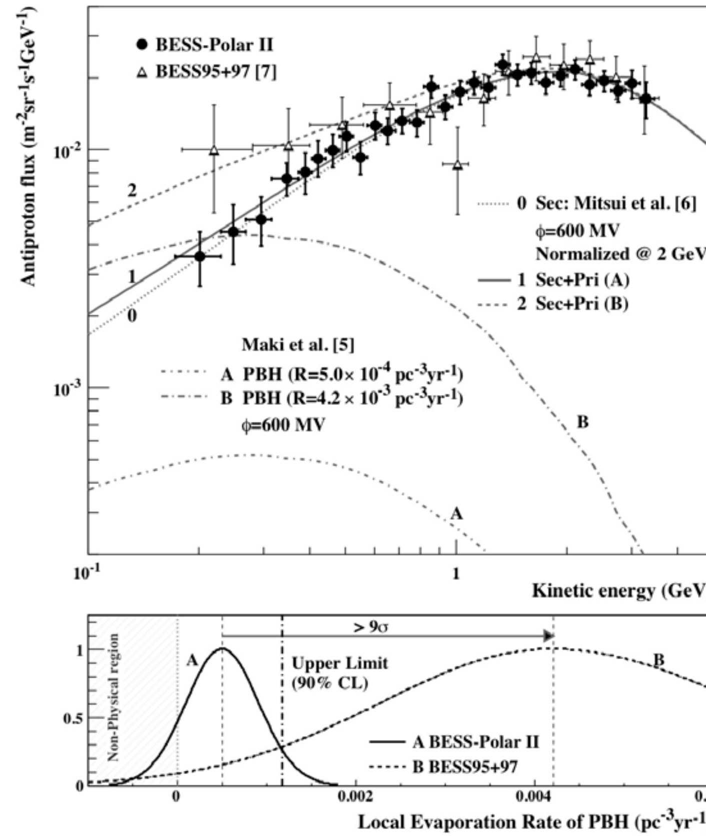
BESS Polar II Antiproton Measurements

Spectral Shape – Flux x E^{-1}



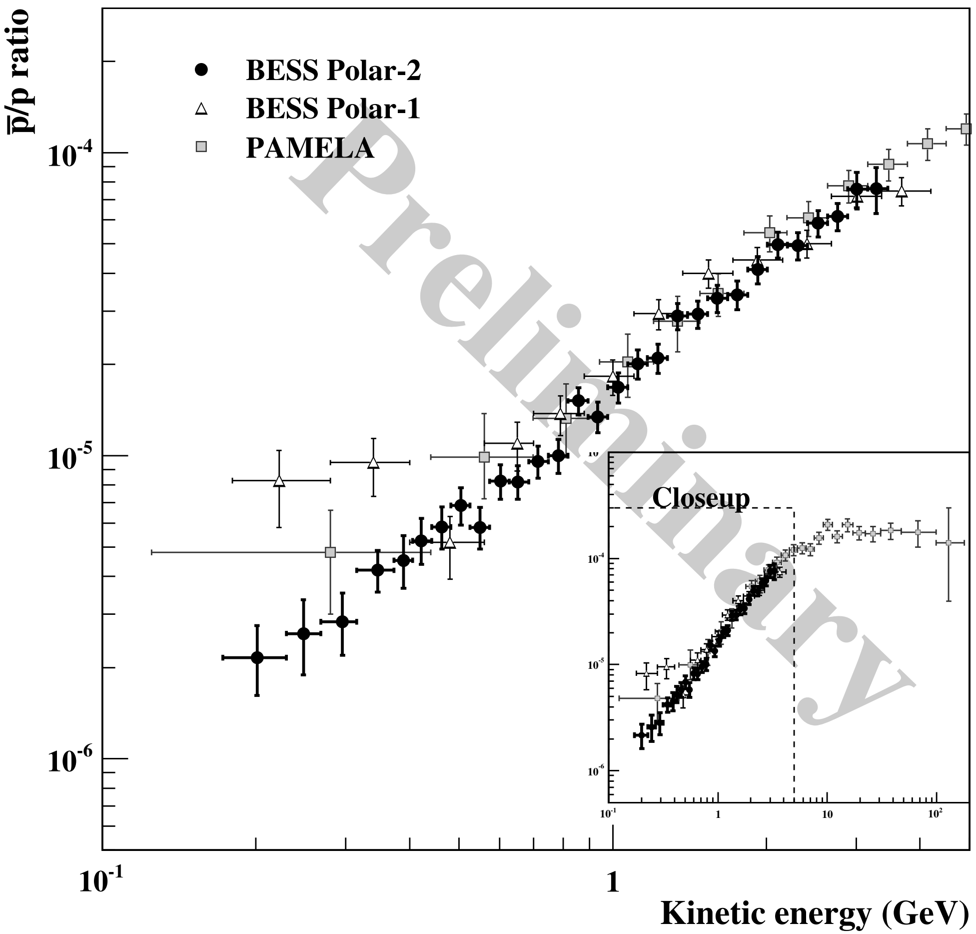
- Comparison of experimental data to calculations normalized to BESS-Polar II at 2 GeV
- Test if low energy antiprotons from PBH evaporation (Hawking radiation) are observed

Level of Possible PBH Primary



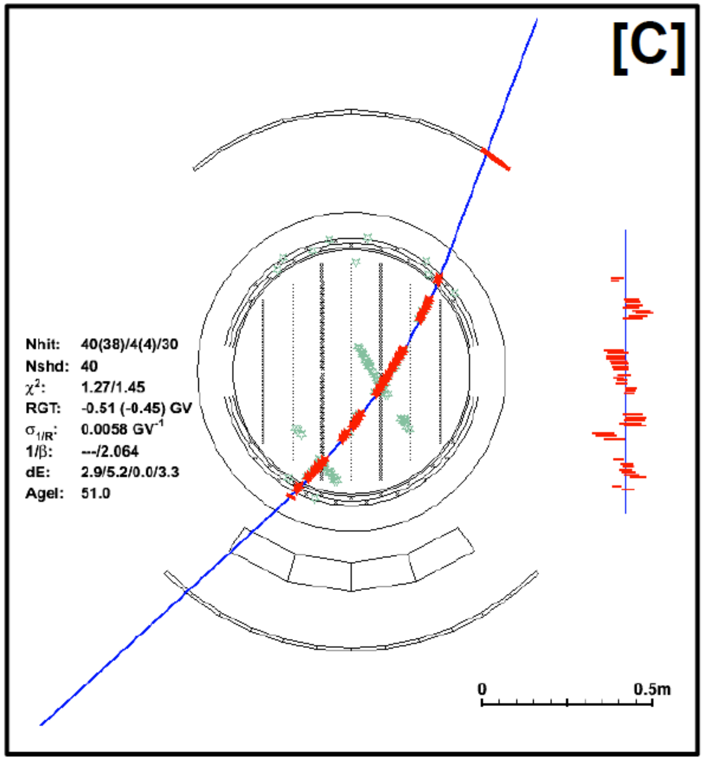
- Best fit evaporation rate: R = ~5x10^{-4} pc^{-3}yr^{-1}
- 9 sigma below BESS-95+97 best fit
- No evidence of antiprotons from PBH evaporation

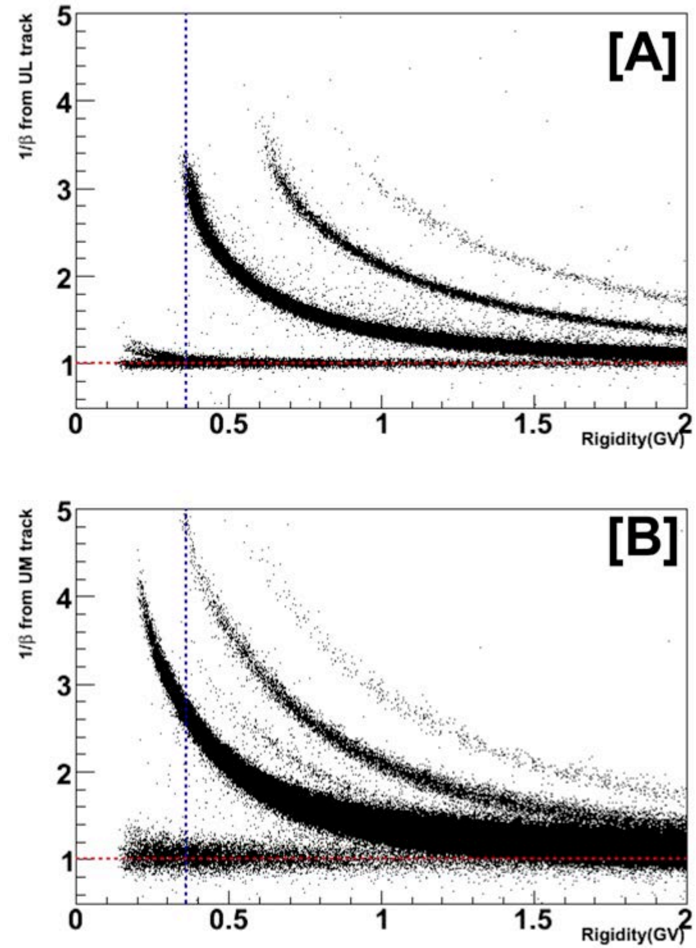
Antiproton/Proton Ratio



- Excellent agreement between BESS-Polar II and PAMELA in common energy range
- BESS-Polar I ratio flatter at low energy than BESS-Polar II or PAMELA due to solar modulation

Low energy Antiprotons with Middle TOF

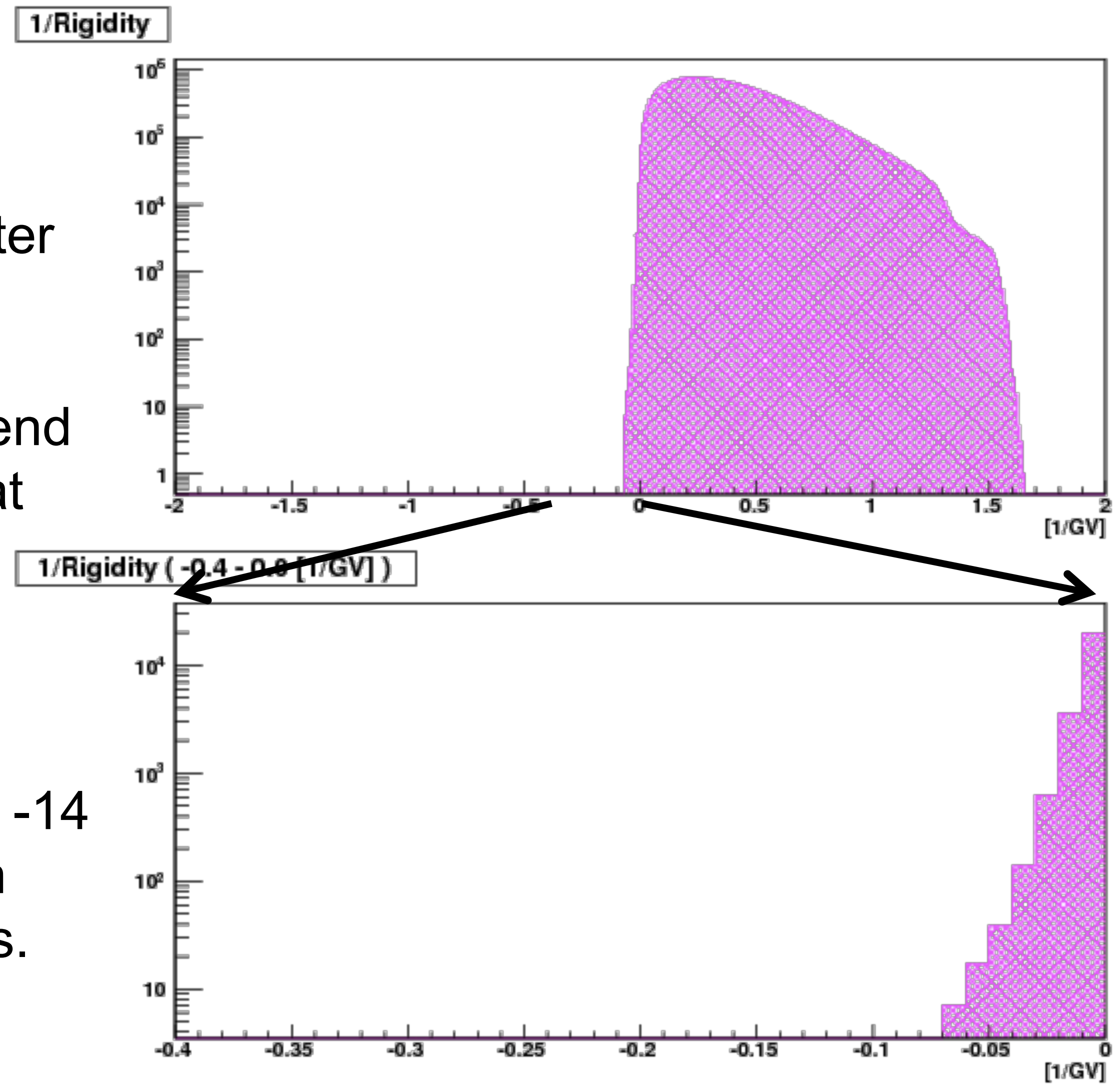




- Measurements extend to low energy with upper-middle TOF combination
- Flight entirely at high latitude gives much higher sensitivity <200 MeV compared to PAMELA or AMS

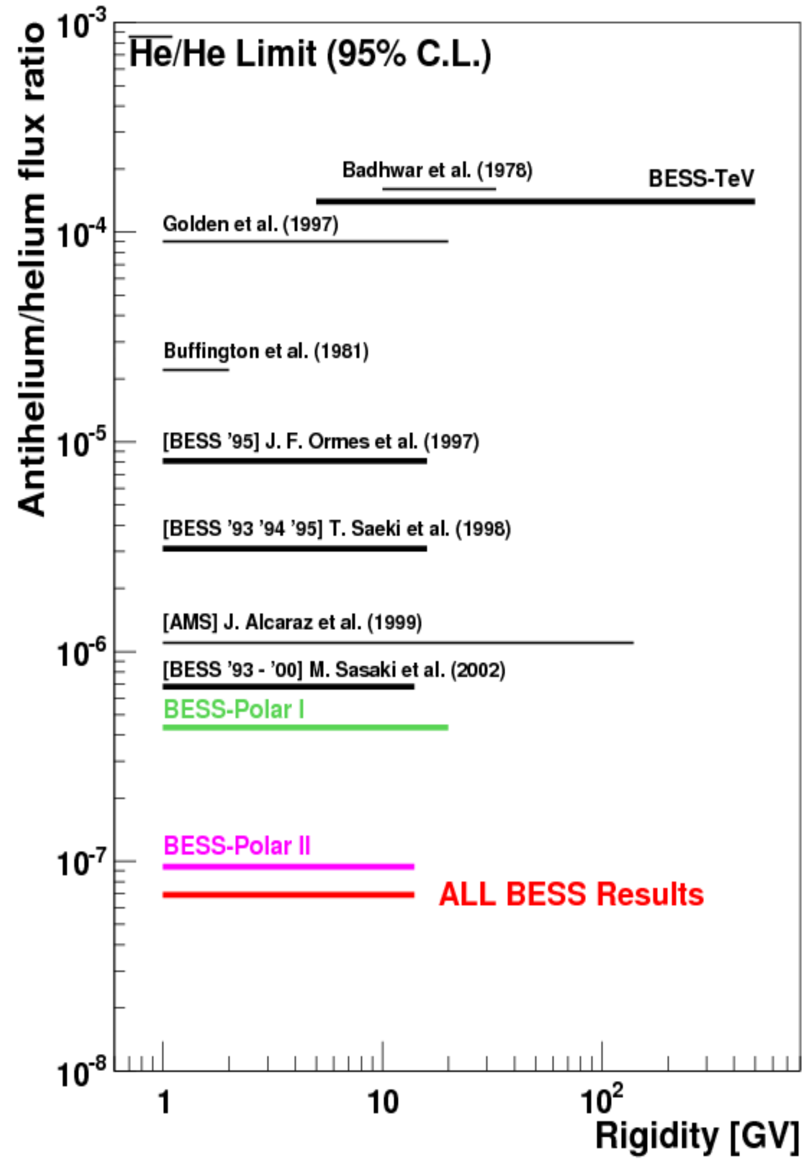
BESS-Polar II Antihelium Search

- Select |Z|=2 events
- Examine remaining events after all selections applied.
- Search range defined at low end by instrument efficiency and at high end by finite rigidity resolution (He spill-over)
- No antihelium candidate was found between energy range -14 to -1 GV after the all selection among 4 x 10^7 Helium events.



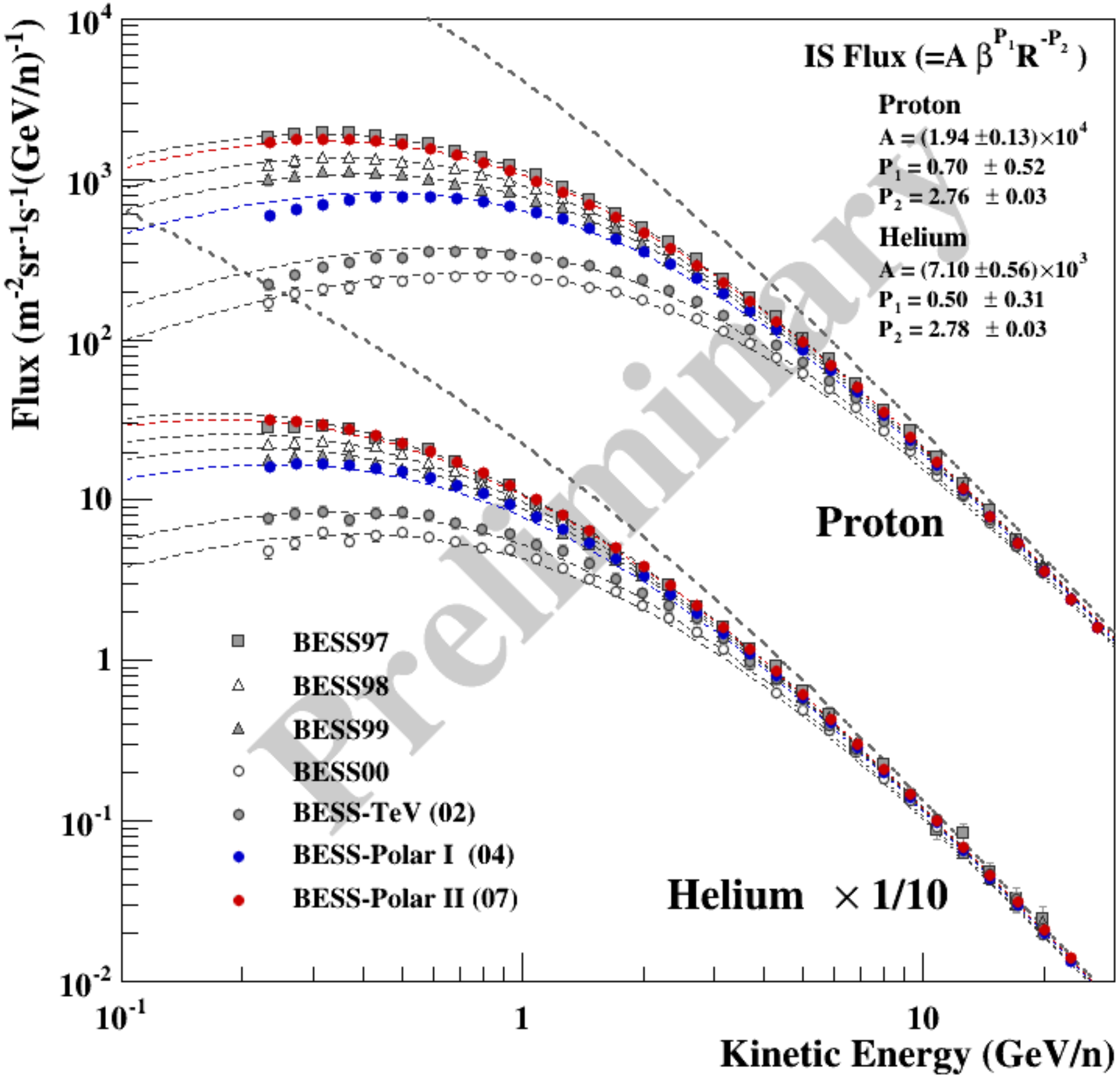
BESS/ BESS Polar Antihelium Search

- No antihelium candidate found in |Z|=2 nuclei
  - BESS-Polar I data 8.4 x 10^6 helium from 1.0 to 20 GV
  - BESS-Polar II data 4.0 x 10^7 helium nuclei from 1.0 to 14 GV.
- If antihelium is assumed to have same spectrum as He all BESS data -> 95% confidence upper limit **6.9 x 10^{-8}** to the possible ratio of antihelium/helium – over
  3 orders of magnitude lower than first limits.
- No spectral assumption - Hebar/He < 10-7



Abe et al., Phys. Rev. Lett. 108, LN12807, 2012

BESS-Polar Proton and Helium Fluxes

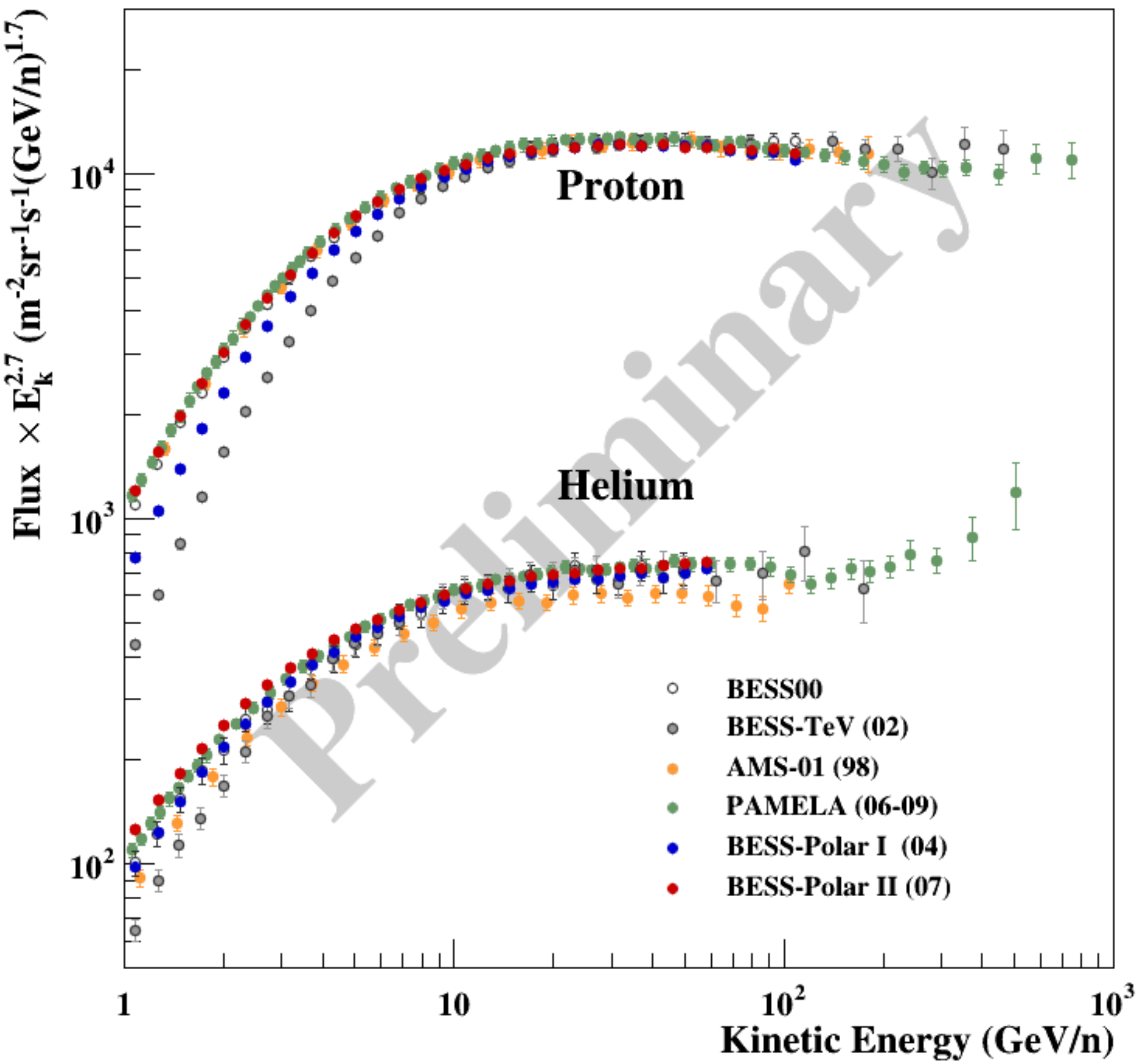


BESS-Polar I and II proton and helium fluxes are shown together with BESS97-00 and BESS-TeV.

Calculations of proton and helium spectra use the BESS interstellar flux and force-field modulation.

The modulation parameters were derived by fitting proton fluxes and applied to both proton and helium fluxes.

BESS-Polar Proton and Helium Fluxes

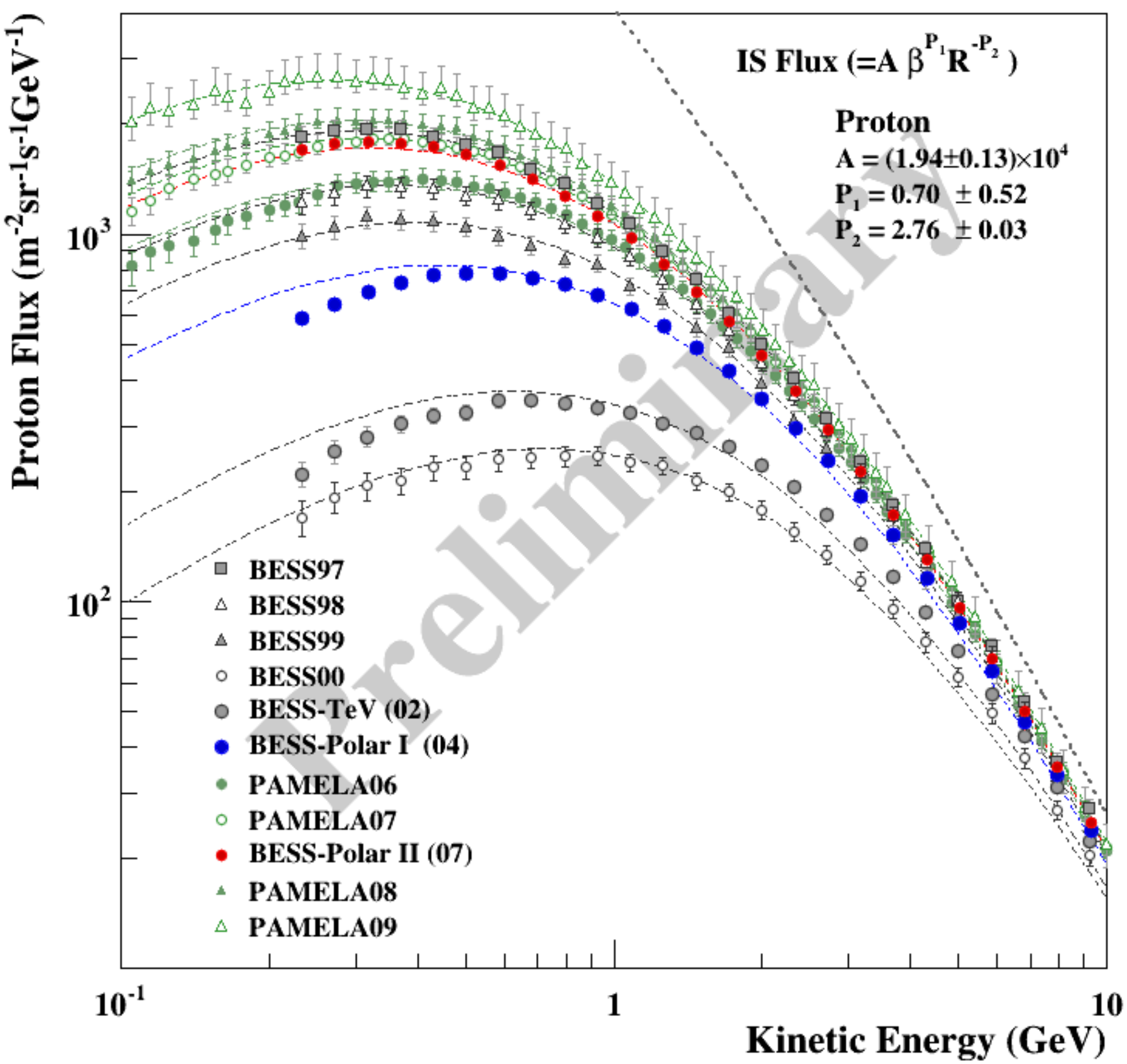


BESS-Polar I and II Proton and Helium fluxes multiplied by $E_k^{2.7}$ are shown together with BESS00, BESS-TeV, AMS-01 and PAMELA.

MDR (maximum detectable rigidity)

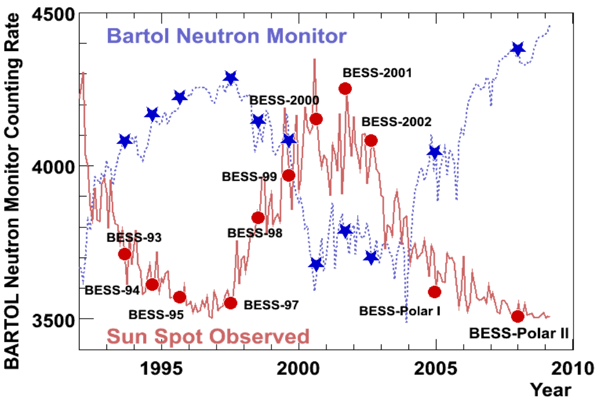
BESS00	200GV
BESS-Polar I	250GV
BESS-Polar II	250GV
PAMELA	1.0TV
BESS-TeV	1.4TeV
AMS II	~2.0TeV

Solar Modulation – Proton Flux



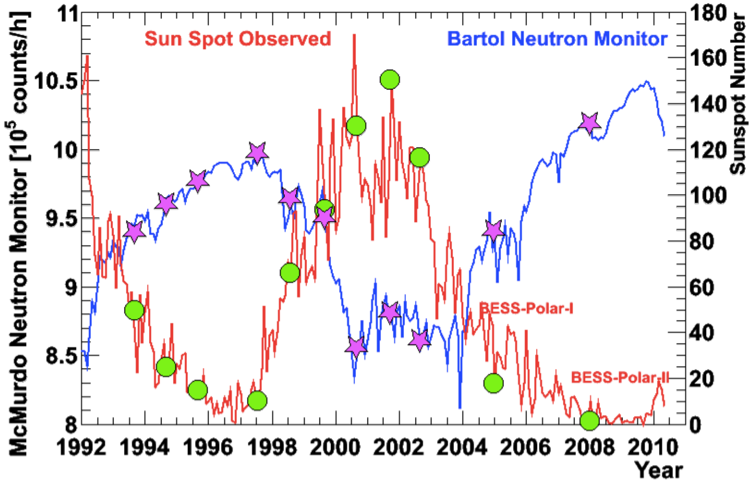
BESS-Polar I and II proton fluxes are shown together with BESS97-00, BESS-TeV and time divided data from PAMELA.

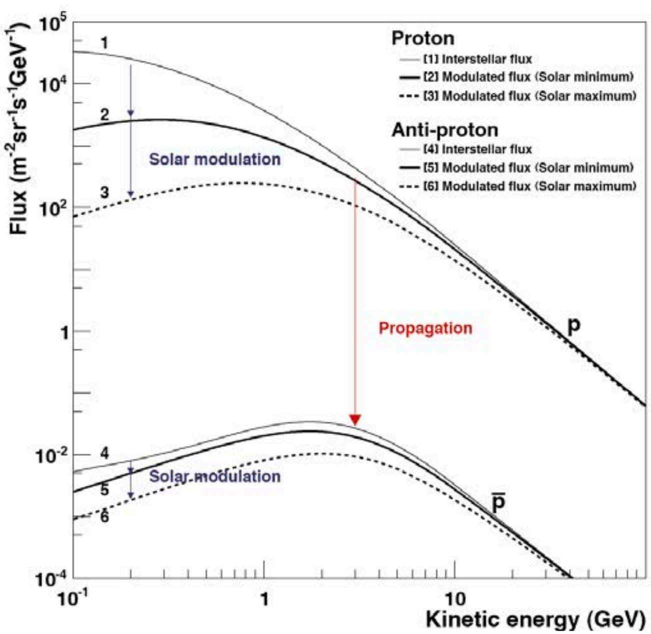
BESS spans two solar minima and a magnetic field reversal 2000-2001.



Solar Modulation – Antiproton/Proton

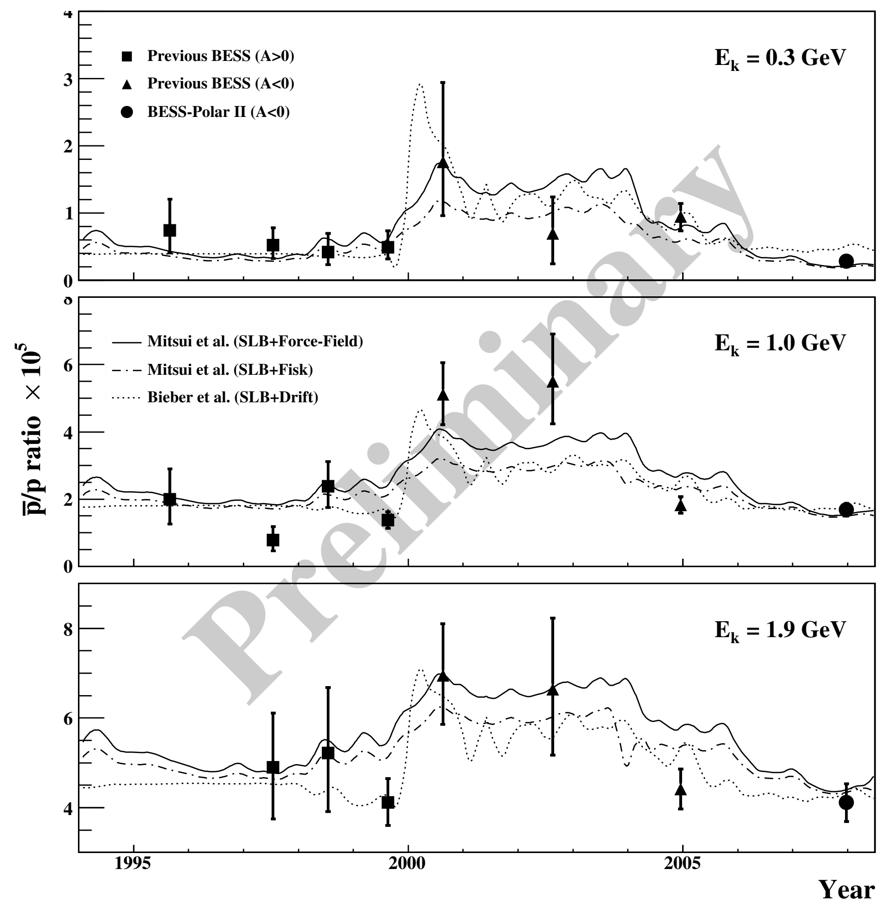
- BESS spans two solar minima and a magnetic field reversal 2000-2001



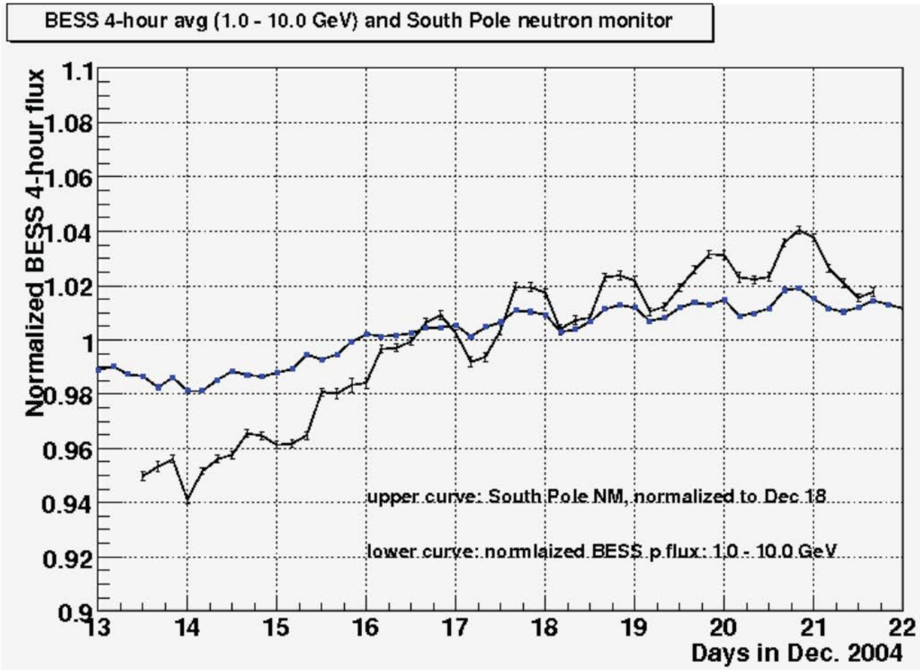


- Antiprotons and protons have same mass and charge
- Differ in charge-sign and spectrum

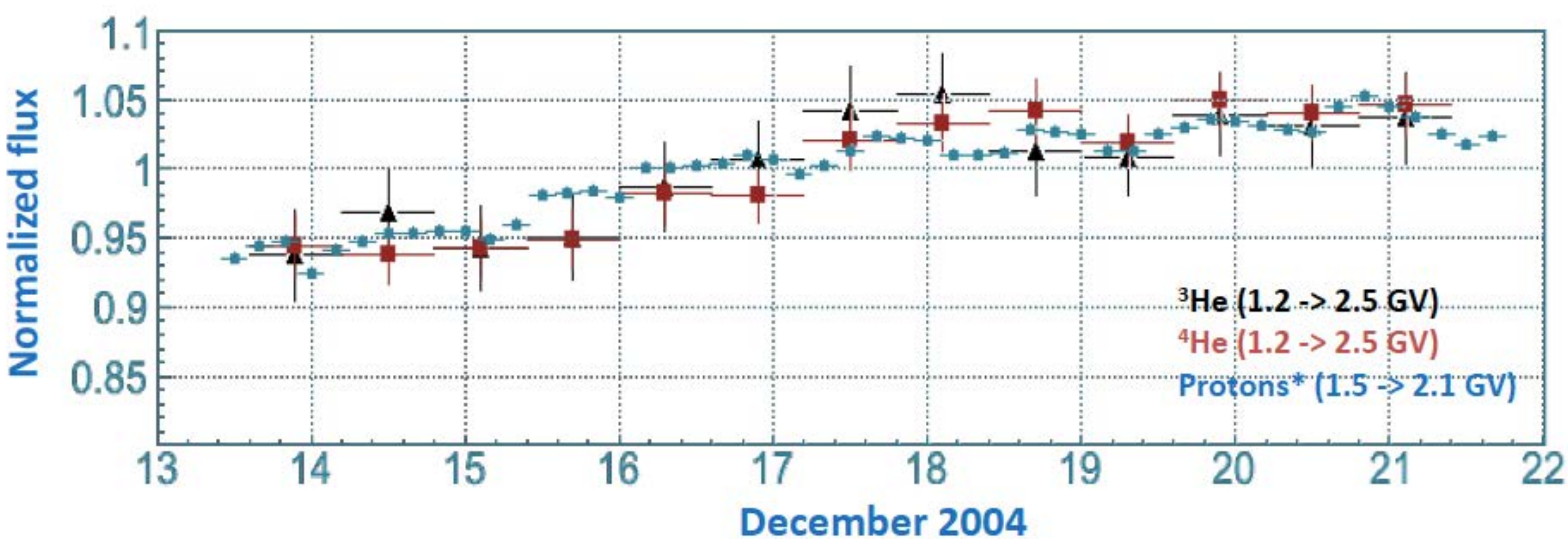
Variation of pbar/p ratio with solar cycle



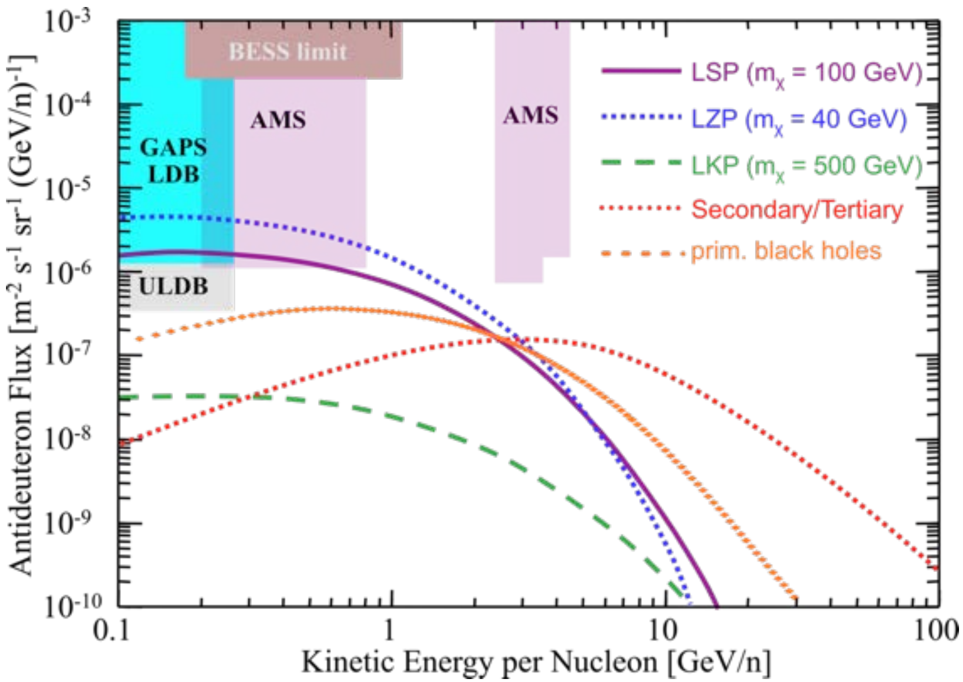
BESS-Polar I – Transient Effects

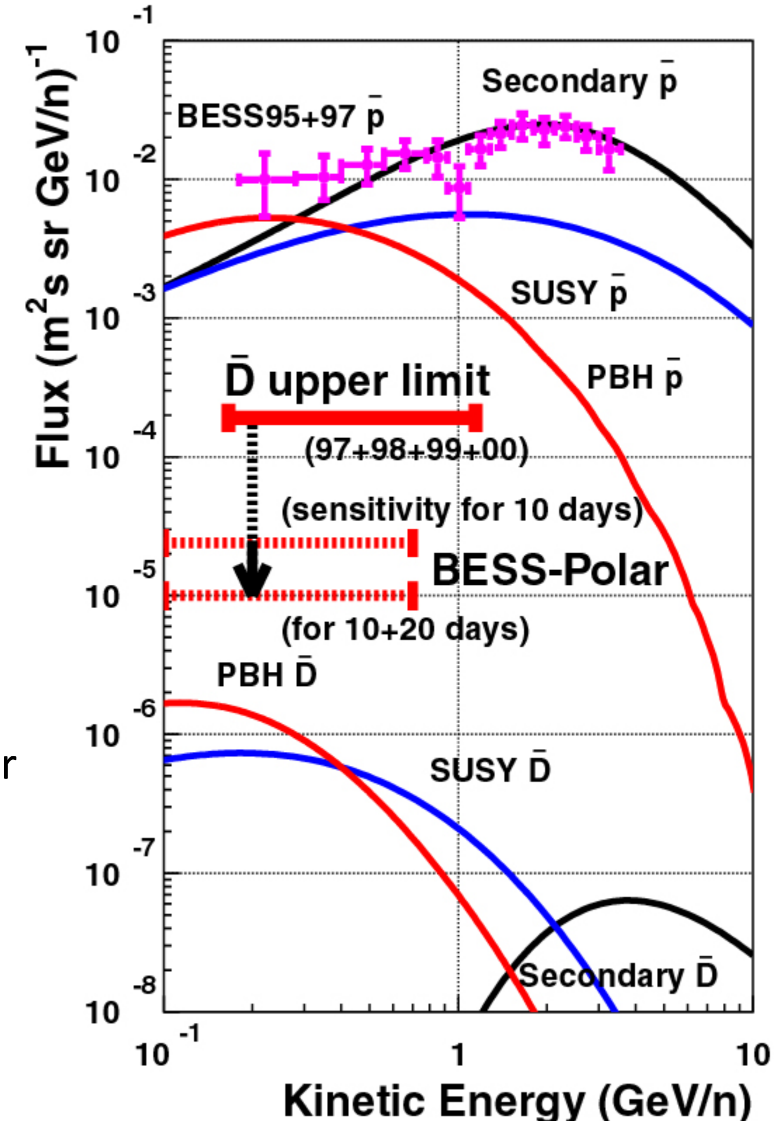


- General trend of BESS-Polar I proton and He isotope fluxes track the neutron monitor
- BESS-Polar I observes diurnal variation in the proton flux
  - First direct measurement of this effect (requires large collecting area)
- Transient and diurnal variation investigation continues with BESS-Polar II



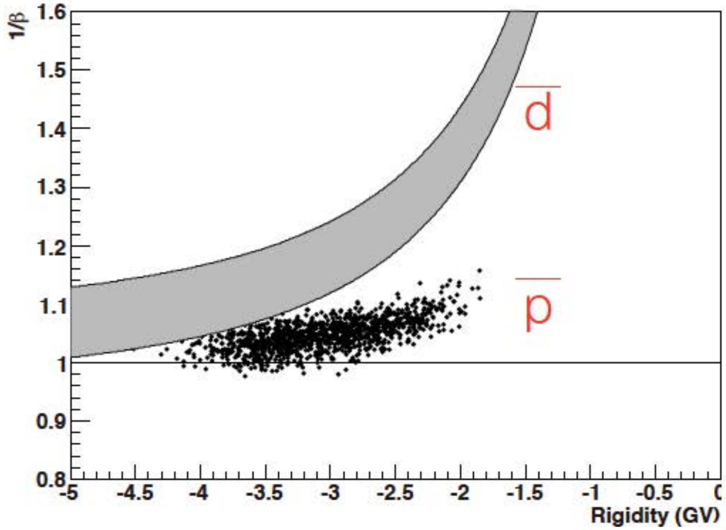
Antideuteron Search

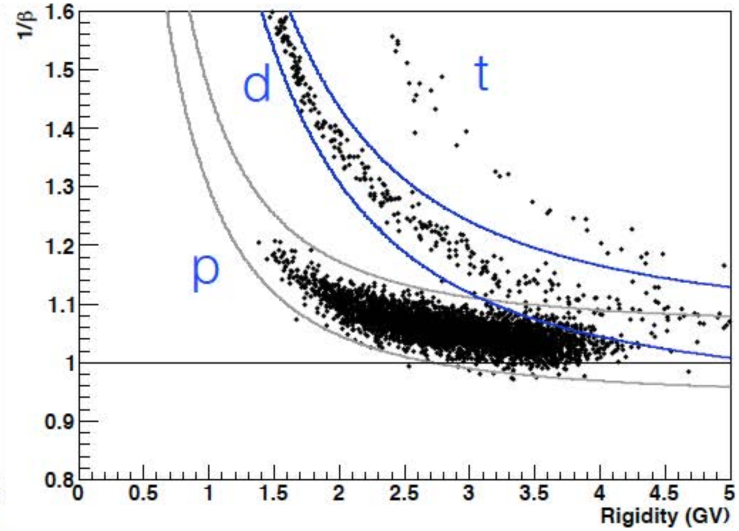


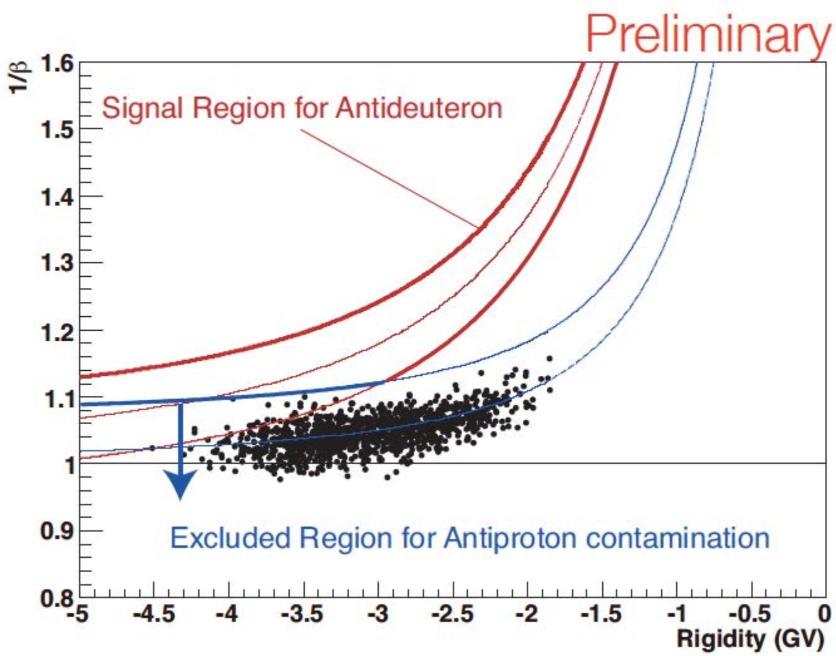


- Secondary antideuterons are produced in nuclear collisions but cross-section is very small.
- Probability is negligible at low energies due to kinematics.
- Any observed antideuteron below 1 GeV almost certainly has a primary origin!
- BESS 97-00 antideuteron 95% upper limit (only limit reported) 1.92 x 10^{-4} (m^2 s sr GeV/n)$^{-1}$

BESS-Polar II Antideuteron Search





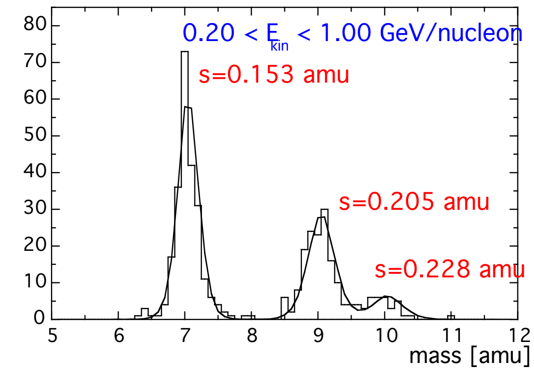


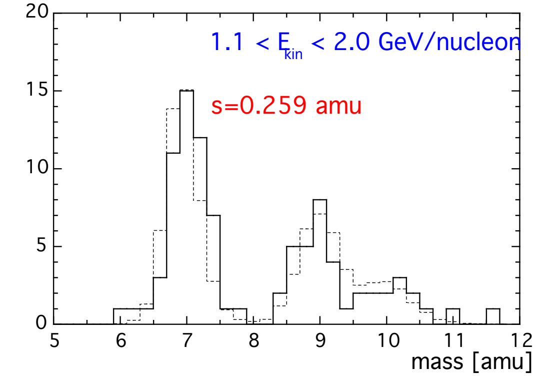
- Preliminary analysis shows no antideuterons in BESS-Polar II data below 5 GeV
- Analysis is underway to insure cuts are not too tight and to produce upper limit if non-detection persists.

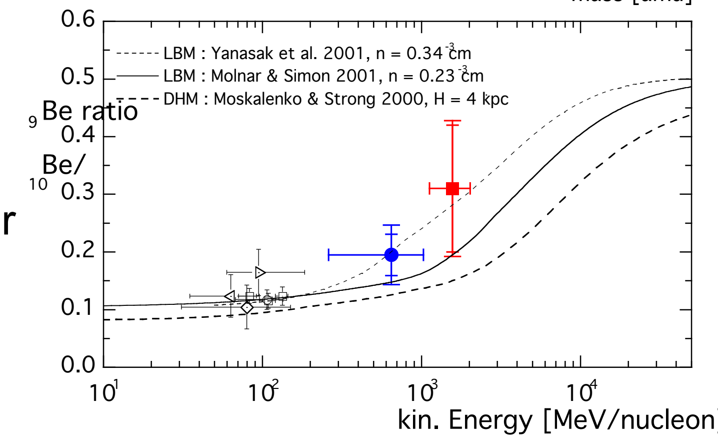
Future Plans – BESS-ISO

- Light isotopes are very important in understanding propagation, but little explored at high energy
  - Clock isotope ^{10}Be probes storage of GCR in Galaxy
  - ^{10}Be/^{9}Be ratio to relativistic energies provides test of diffusive halo model including time GCR spend in the halo
  - Excellent measurements from ACE at low energies but higher energy only ISOMAX 1998 (destroyed 2000)
- BESS-ISO
  - New version of instrument
  - Detector suite optimized for measuring isotopes
    - SSD layers above and below tracker + redistributed JET readout: MDR >> 1TeV
    - Fast TOF (<<50 ps for Be)
    - Aerogel RICH with SiPM focal plane
    - Focusing differential Cherenkov (FDRIC)
  - Be isotopes to energies of tens of GeV/nucleon.
  - Increased magnet cryogen hold time with active cryocooler to exploit LDB flight duration.

ISOMAX 1998 Be Isotopes







Summary

- The BESS Program has addressed a wide range of scientific topics with accurate measurements of antiprotons, light element and isotope spectra, and solar effects as well as searches for heavier antinuclei.

- The rich BESS-Polar datasets continue to be analyzed. Yet to come: lowest energy antiprotons, definitive search for antideuterons, additional light element and isotope specrtra, and detailed solar transient analysis.

- For the future, we are developing a new version of the instrument, BESS-ISO to measure isotope abundances, particularly ^{10}Be and ^{9}Be to 10's of GeV/nucleon.