Consorzio Interuniversitario per la Fisica Spaziale

International School of Space Science

IL MIO VOLER CERCAR OLTRE LA META

L'AQUILA - ITALY

Spectrometers for GCRs: past&future

E.Vannuccini

Outline

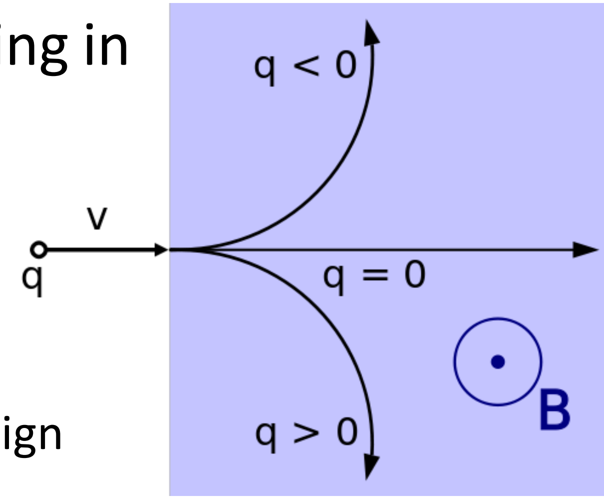
Magnetic spectrometers for GCR physics

- Principle of operation
- Experiments based on magnetic spectrometers
  - The past
  - The present → latest scientific results
  - The (near & far) future
- Conclusions

Lorentz force

- Force exerted on a charged particle moving in an magnetic field

$$\vec{F} = q\,\vec{v} \wedge \vec{B}$$



  - $\vec{F} \parallel \vec{v}$
    - Curved trajectory @ constant velocity
    - Opposite direction depending on the charge sign
  - If uniform $\vec{B}$ and $\vec{v} \perp \vec{B}$
    - Uniform circular motion
    - Radius of curvature (**gyroradius**):

$$r_g = \frac{p}{|q|B} = \frac{R}{Bc} \quad \rightarrow r_g[m] = 3.3 \cdot \frac{|R|[GV]}{B[T]}$$

    - **Magnetic rigidity**

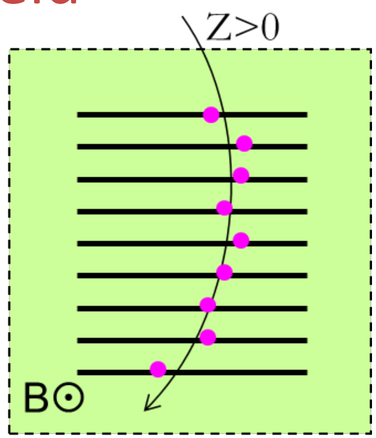
$$R = \frac{pc}{|q|} = \frac{pc}{Ze} \quad \rightarrow R[GV] = \frac{p[GeV/c]}{Z}$$

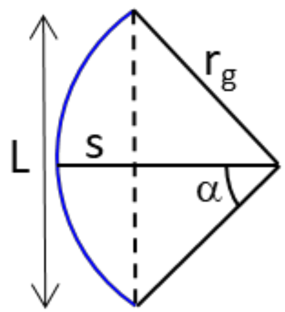
Charged particle motion in a magnetic field described by the **magnetic rigidity**

Magnetic spectrometer

- Tracking system placed inside a magnetic field
  - Trajectory reconstructed by interpolating N position measurements
  - If uniform $\vec{B}$ and $\vec{v} \perp \vec{B}$
    - Curvature $k \equiv {}^{1}/_{r_g}$
    - Sagitta $s \sim k \, {}^{L^2}/_{8}$
    - Large N $\Rightarrow$ **p.d.f. of k ~ gaussian**
    - **Magnetic deflection**

$$|\eta| = \frac{1}{R} \longrightarrow \eta = \frac{k}{Bc}$$





$$\alpha \sim \frac{L}{2r_g}$$

$$s \sim r_g \frac{\alpha^2}{2} = \frac{L^2}{8r_g}$$

$$s[mm] = 38 \cdot L[m]^2 \frac{B[T]}{|R|[GV]}$$

A magnetic spectrometer measures the particle **deflection**

Deflection error

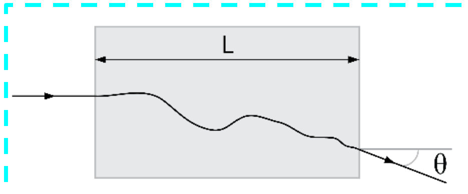
$$(\delta\eta)^2 \approx (\delta\eta_{res})^2 + (\delta\eta_{ms})^2$$

- If uniform $\vec{B}$ and $\vec{v} \perp \vec{B}$
- For a large number N of uniformly spaced measurements along the trajectory in a uniform medium:

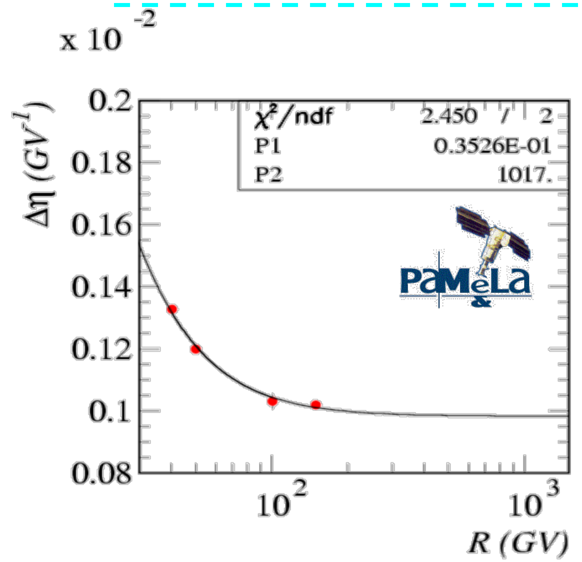
$$\delta\eta_{res} = \frac{\sigma}{L^2}\sqrt{\frac{720}{N+4}} \cdot \frac{1}{Bc}$$

$$\delta\eta_{ms} \approx \frac{0.016\,(GV)}{LR\beta}\sqrt{\frac{L}{X_0}} \cdot \frac{1}{Bc}$$

$\sigma = spatial\ resolution$
$L[m] = track\ length$
$X_0[m] = medium\ radiation\ length$



Multiple Coulomb Scattering from nuclei of the traversed medium



A good spectrometer must be thin and have good tracking resolution

Magnetic spectrometers for GCR study

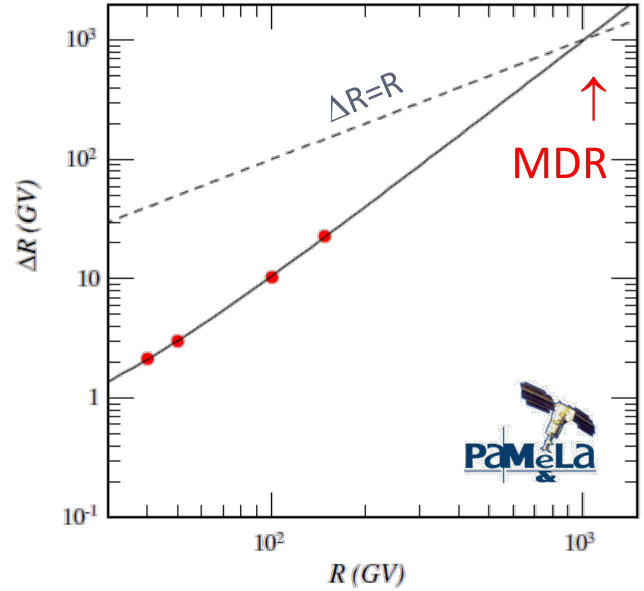
- Rigidity error increasing for increasing rigidity

$$\frac{\delta R}{R} = R\ \delta\eta = \frac{R}{MDR}$$

  - Maximum Detectable Rigidity (MDR)

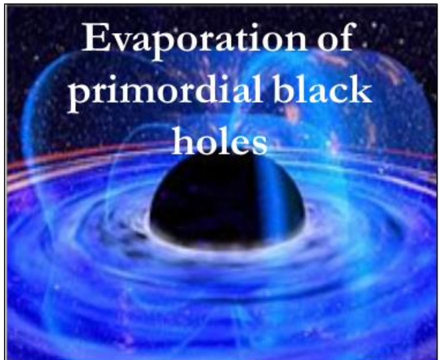
$$\left[\frac{\delta R}{R}\right]_{R=MDR} = 100\% \Rightarrow \mathrm{MDR} = \frac{1}{\delta\eta}$$

Energetic limit of a magnetic spectrometer expressed by the MDR

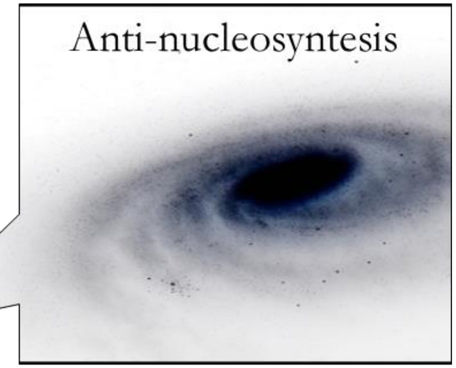


- Magnetic spectrometers provide:
  - Most precise energy measurement over a wide energy range
  - Unique possibility to measure the sign of the electric charge
    - Antimatter !!

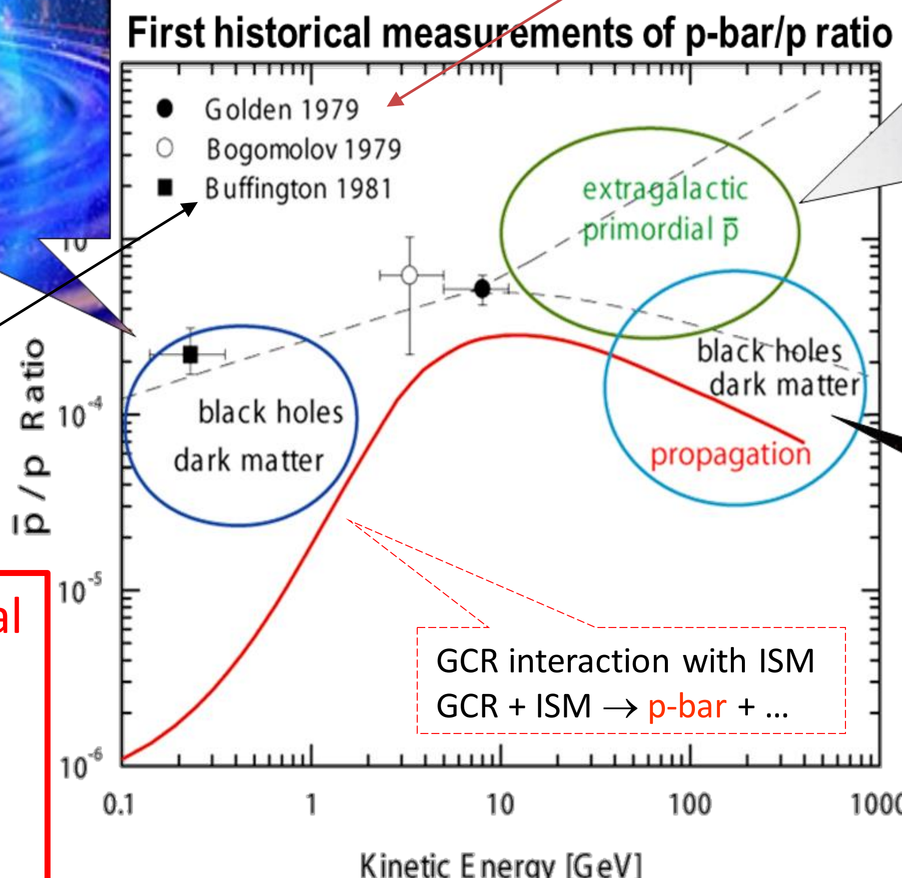
Late 1970s

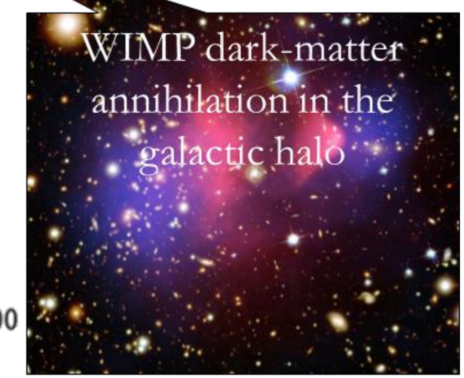


Superconducting magnetic spectrometers



Detection of $\bar{p}$ annihilation star





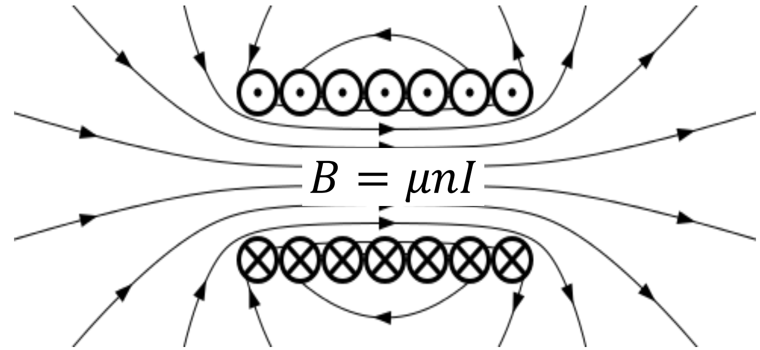
Low astrophysical background

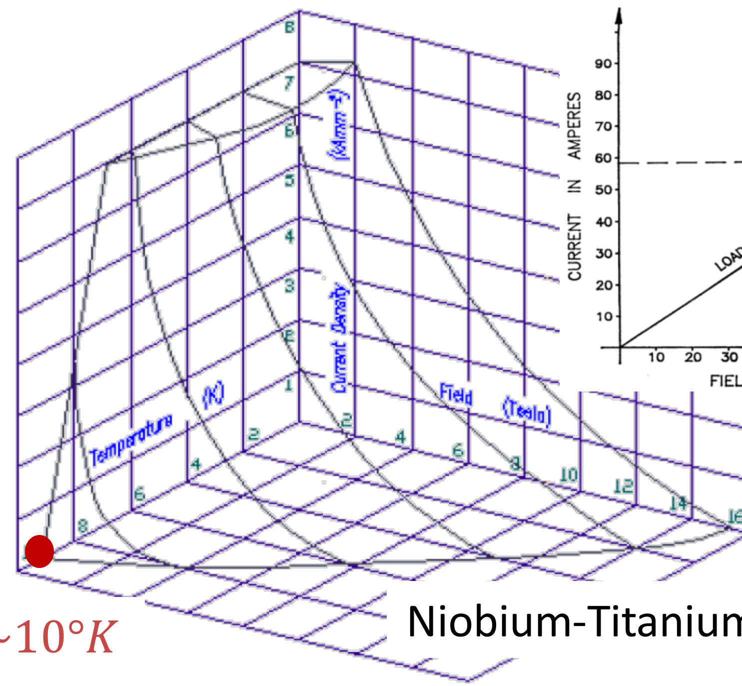
↓

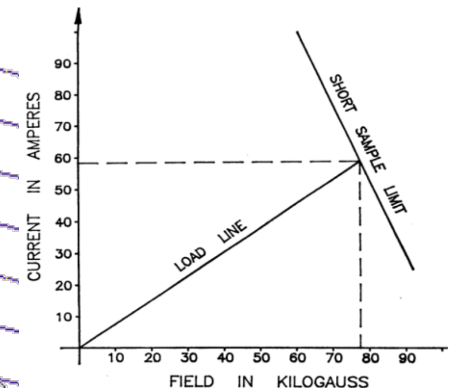
search for new physics !!

Superconducting magnets in space

- Electromagnet made from coils of **superconducting** wire
  - Can carry large currents without dissipating energy
    - Large B field
    - Persistent-mode operation
  - Coil must be cooled below critical temperature T_C
    - It consumes cryogenic fluids



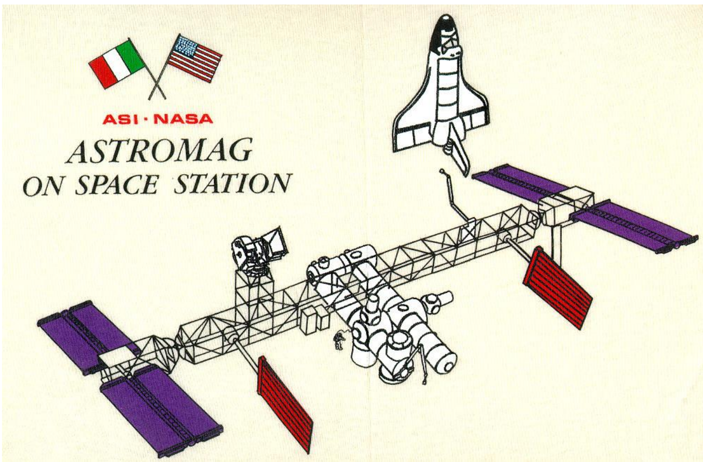


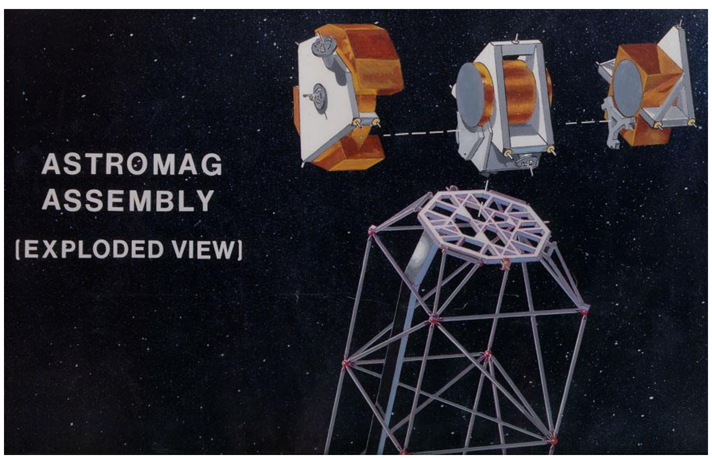


$T_c \sim 10°K$

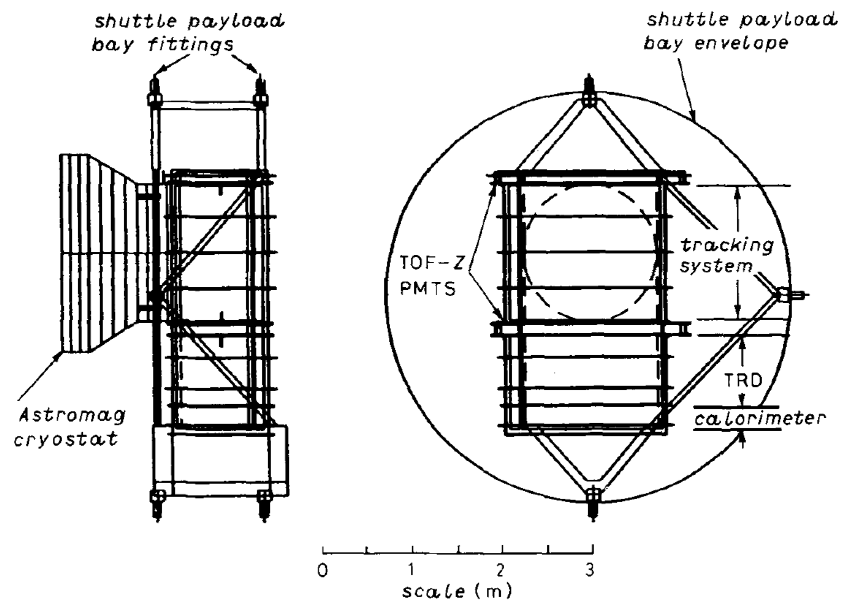
Niobium-Titanium

1980s





- Extensive R&D in the '80s aiming to optimize **superconducting magnet facility** to be flown as a U.S.-Italy project on Space Station Freedom in the late '90s
  - **WiZard** experiment dedicated to search for primoridial antimatter



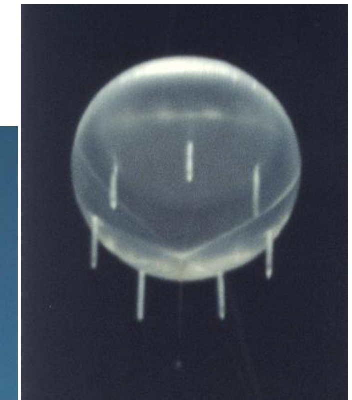
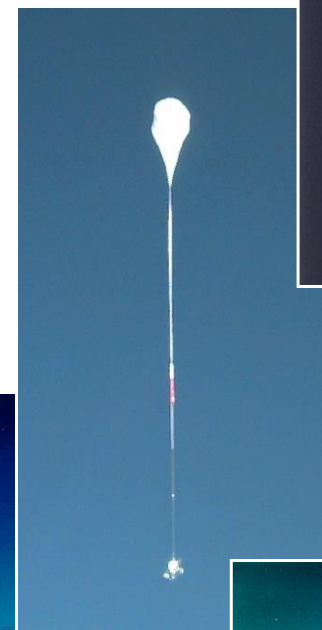
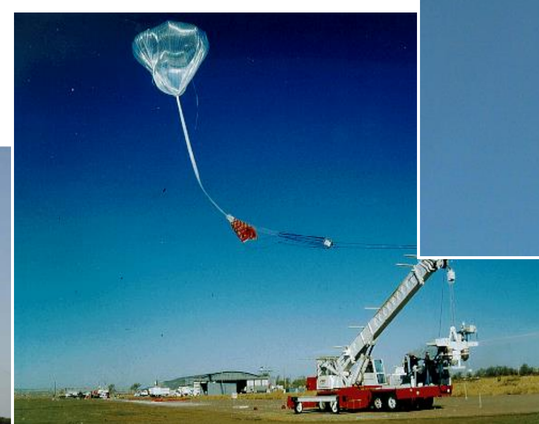
Golden et al N.Cim. 105 (1990) 191

Project canceled!

1990s

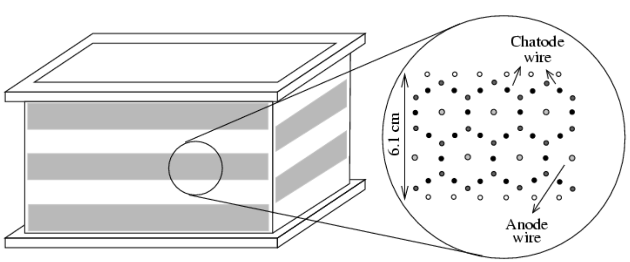
- Extensive campaign of **daily balloon flights** operated by several groups
  - Wizard (MASS, TS, CAPRICE)
  - BESS
  - Others (HEAT, IMAX…)

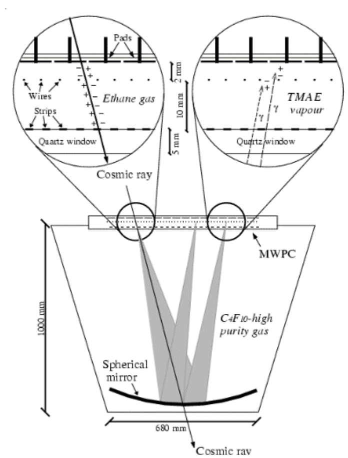
- Main instrument characteristics
  - Superconducting magnets ($\sim 1T$ field)
  - MWPC & drift chamber tracking systems ($O(100\mu m)$ resolution)
  - MDR $\sim 100 \div 300\ GV$

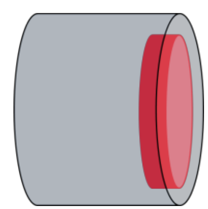




WiZard

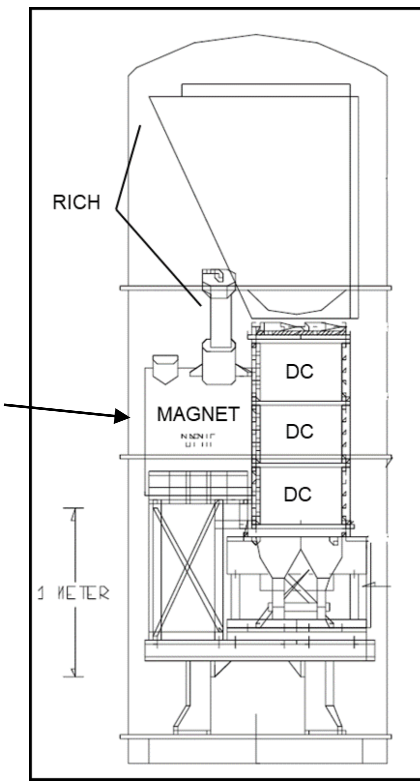
	Matter-Antimatter Superconducting Spectrometer		Tramp-Si	Cosmic AntiParticle Ring-Imaging Experiment	
	MASS89	MASS91	TS93	CAPRICE 94	CAPRICE 97/98
Location Geo. cut-off (GV)	Canada 0.65	NM 4.5	NM 4.5	Canada 0.5	NM 4.3
Magnetic field (T)	0.1÷2				
Tracking system Resolution (μm)	MWPC 160	MWPC+DC 100÷160			DC 100
MDR (GV)	120	200			300
Particle-ID	Time-of-flight ($\sim$200 ps)				
	Cherenkov counter (Freon) $(\beta\gamma)_{th}\sim 25$		TRD $(\beta\gamma)_{th}\sim 1000$	RICH (NaF) $(\beta\gamma)_{th}\sim 1.1$	RICH (C_4F_{10}) $(\beta\gamma)_{th}\sim 19$
Calorimeter	Brass streamer tubes 7.3 X_0 0.8 λ_0		Si-W 4.1 X_0 0.2 λ_0	Si-W 7.2 X_0 0.3 λ_0	



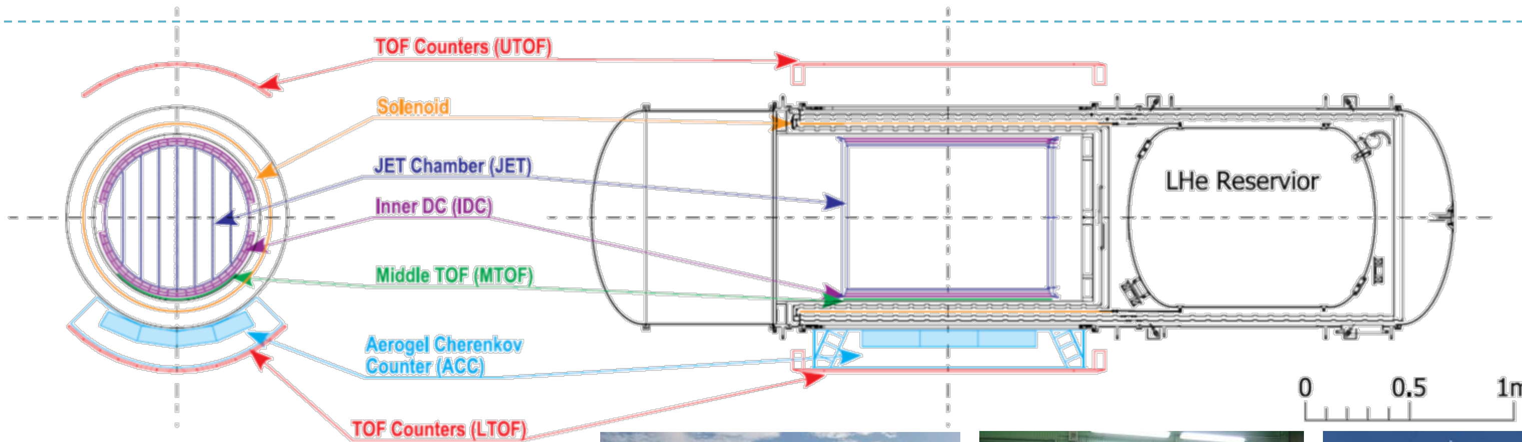




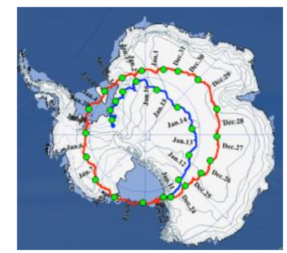
CAPRICE98



BESS



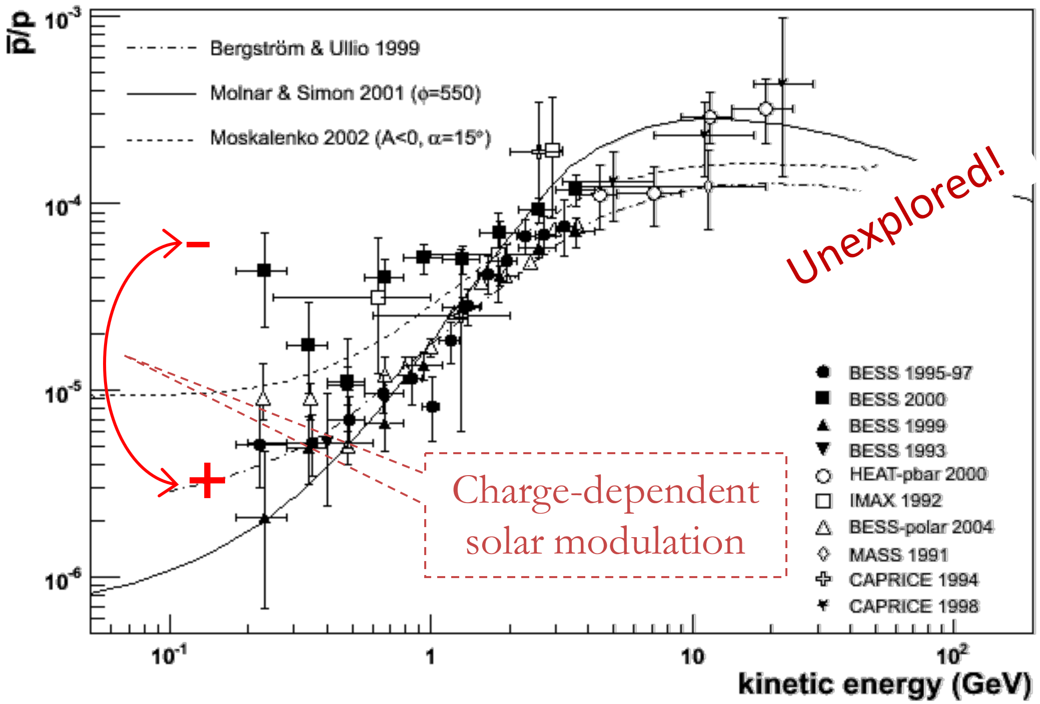
- Balloon-borne Experiment with a Superconducting Spectrometer
- Focus on low-energy antiprotons and antinuclei search (large acceptance!)

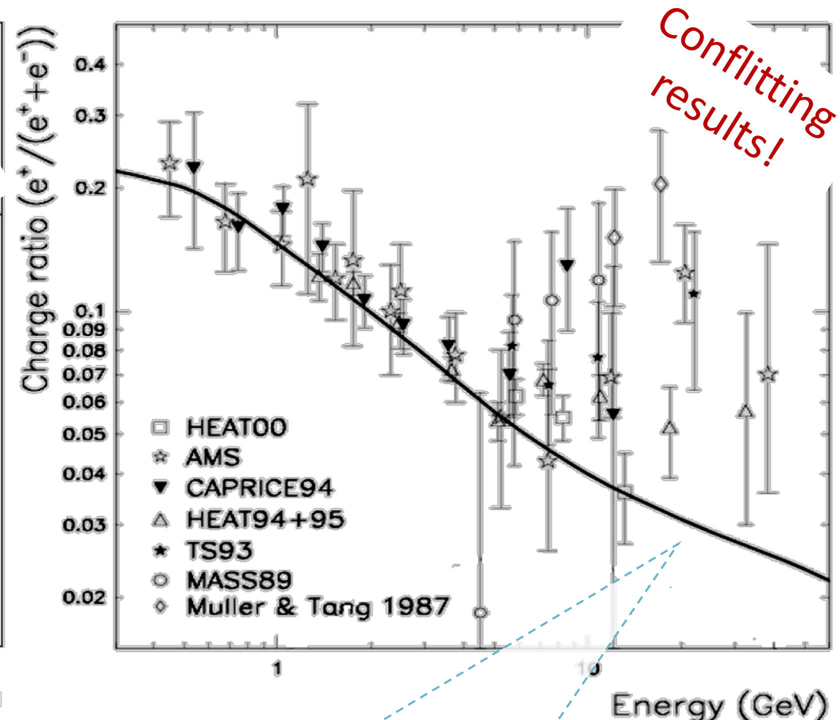


BESS-Polar upgrade

	1993	1994	1995	1997	1998	1999	2000	2001	2002	2004	2007
Location	Canada	≫	≫	≫	≫	≫	≫	US	C.	Ant.	Ant.
Float time (h)	17.5	17	19.5	20.5	22.0	34.5	44.5	1.0	16.5	205	730
Observation time, float (h)	14	15	17.5	18.3	20.0	31.3	32.5	1	11.3	180	588
Observation time, asc./des. (h)						2.8	2.5	12.8	2.3	3.3	3.5
Magnetic field (T)	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.8	0.8
MDR (GV)	200	200	200	200	200	200	200	1,400	1,400	240	270
TOF resolution (ps)	300	300	100	75	75	75	75	75	75	160	120
ACC index	–	–	–	1.03	1.02	1.02	1.02	1.02	1.02	1.02	1.03
Antiproton events observed	6	2	43	415	384	668	558	N/A	147	1520	~8000
Antiproton's energy (GeV)	<0.5	<0.5	<3.6	<3.6	<3.6	<3.6	<4.2	N/A	<4.2	<4.2	<3.5
Anti-He/He upper limit ($\times 10^{-6}$)	22	4.3	2.4	1.4	1.0	0.8	0.68	N/A	0.65	0.27	0.07

Status at the beginning of 2000s





$$\mathrm{GCR + ISM} \rightarrow \pi^{\pm} + \mathrm{x} \rightarrow \mu^{\pm} + \mathrm{x} \rightarrow e^{\pm} + \mathrm{x}$$
$$\mathrm{GCR + ISM} \rightarrow \pi^{0} + \mathrm{x} \rightarrow \gamma\gamma \rightarrow e^{\pm}$$

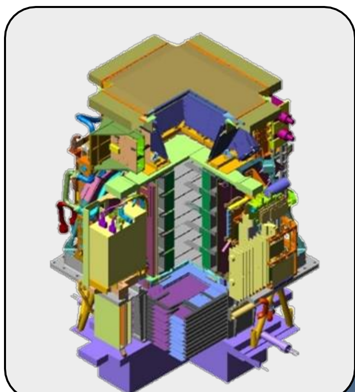
Two directions for the future:

- High-statistics measurement of $\bar{p}$ @low energy$\rightarrow$ BESS-Polar
- $\bar{p}$ and e^+ measurement @ high energy

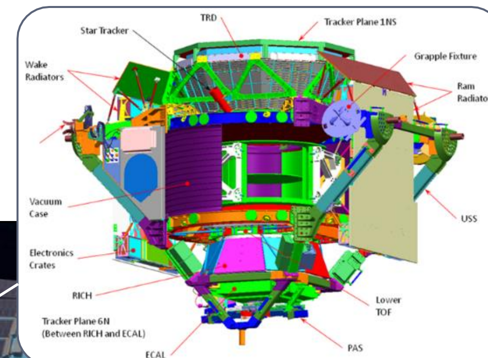
The new generation: PAMELA & AMS

Aiming to extend the antiparticle measurements at high energy

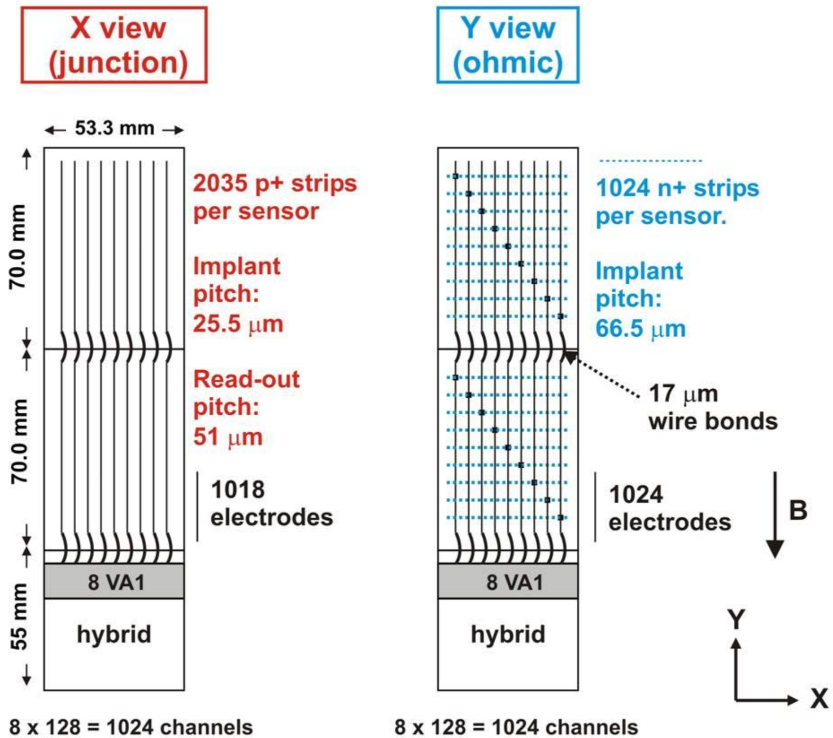
- Instruments placed in **space**
  - GCR path-length @20GeV $\sim$ atmosferic grammage @balloon altitude ($\sim 5\ g/cm^2$)
- Tracking system based on **microstrip Si technology**
  - Improved tracking capabilities

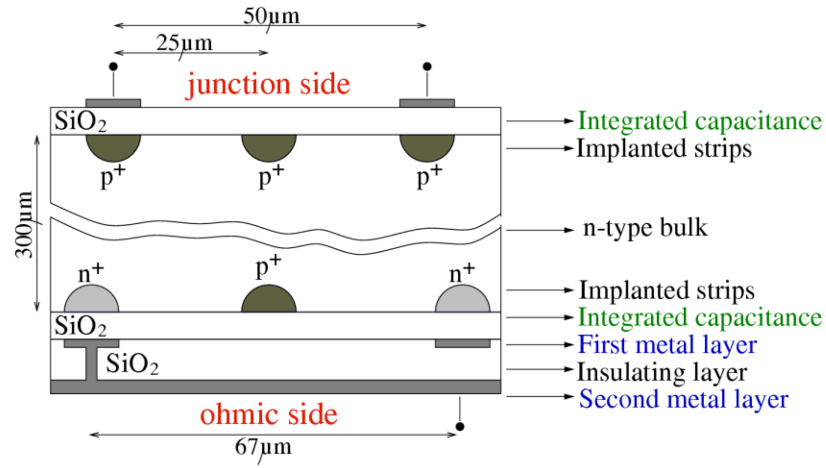


PaMeLa (WiZard heritage)



Micro-strip silicon detectors





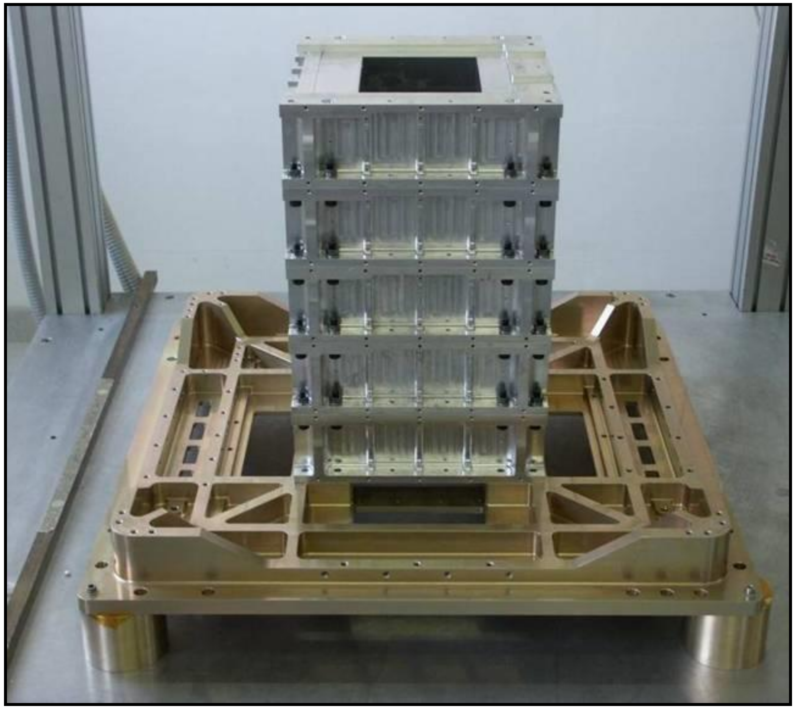
Silicon sensors (Hamamatsu):

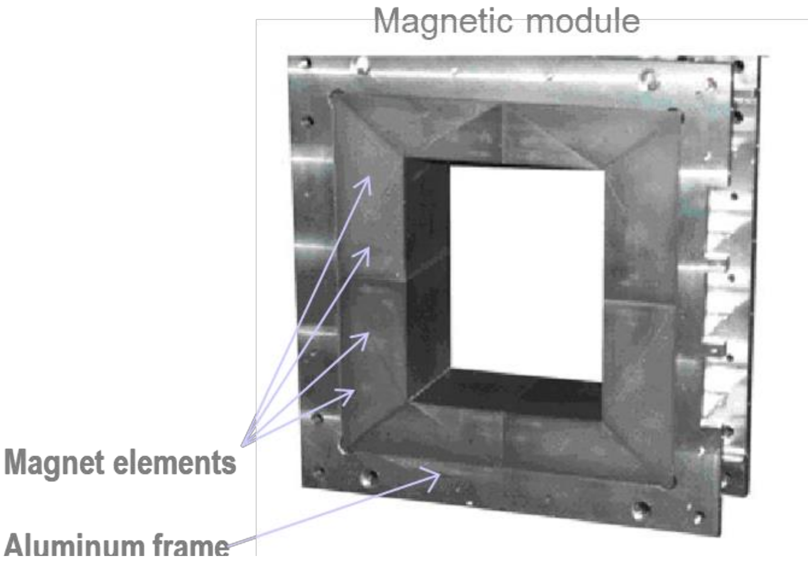
- **300 μm, double sided - x & y view**
- **AC coupled** (no external chips)
- **double metal** (no kapton fanout)
- 1024 read-out channels per view

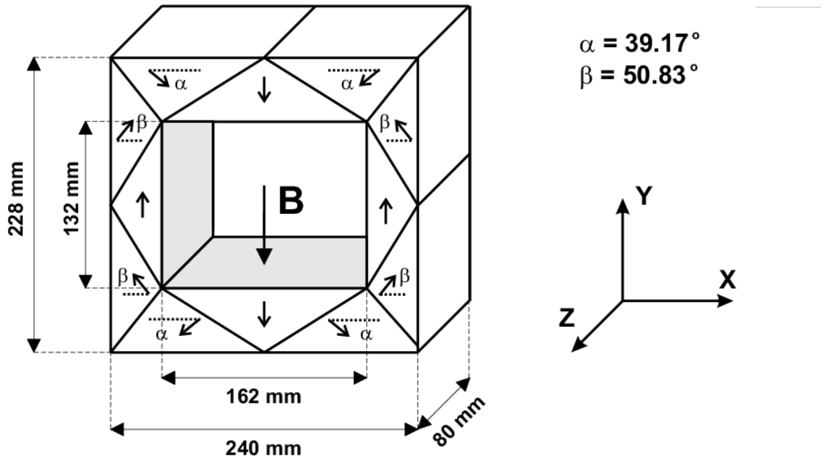
Spatial resolution:

- junction side (X): 3 μm @0°, < 4 μm up to 10°
- ohmic side (Y) 8÷13 μm

The PAMELA magnet





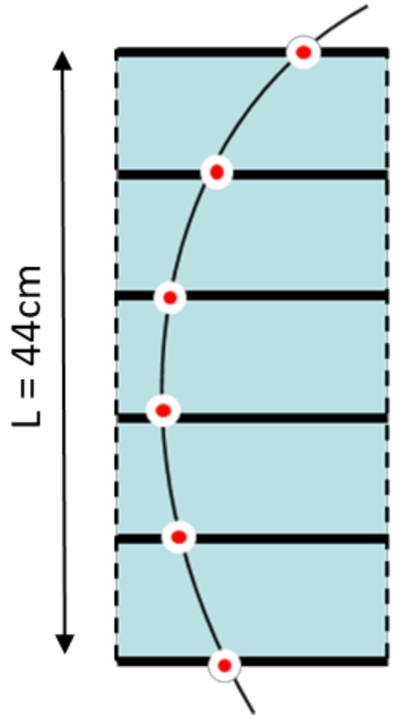


Permanent magnet (Nd-Fe-B alloy):

- 0.48 T @ center
- 0.43 T average along the axis

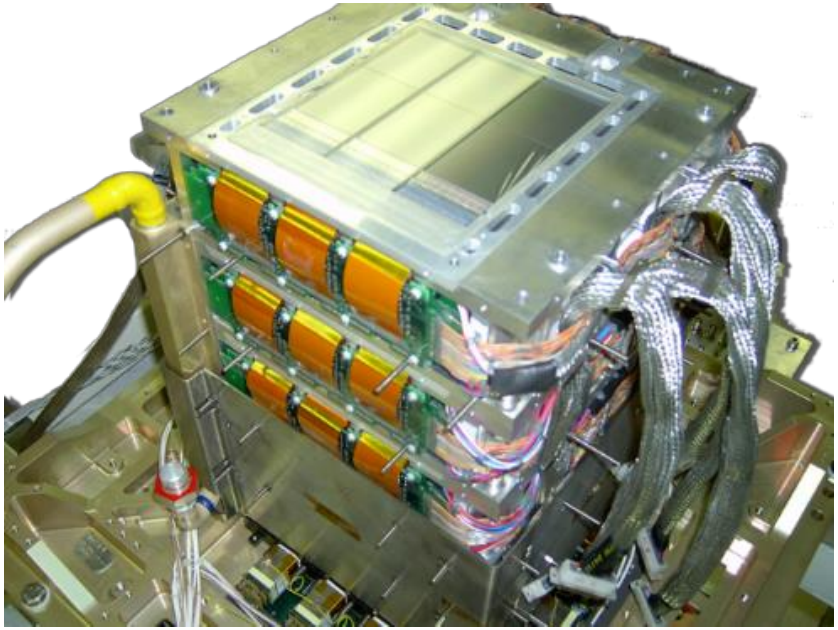
→ Geometric factor 20.5 cm^2sr

The PAMELA tracking system



Mechanical assembly
- aluminum frames
- carbon fibers stiffeners glued laterally to the ladders
- no material above/below the plane

  1 plane = **0.3% X_0** → reduced multiple scattering
- elastic + rigid gluing



- 0.48 T magnetic field @ center
- ~ 4 μm resolution on the bending direction
- ~ 44 cm track-length

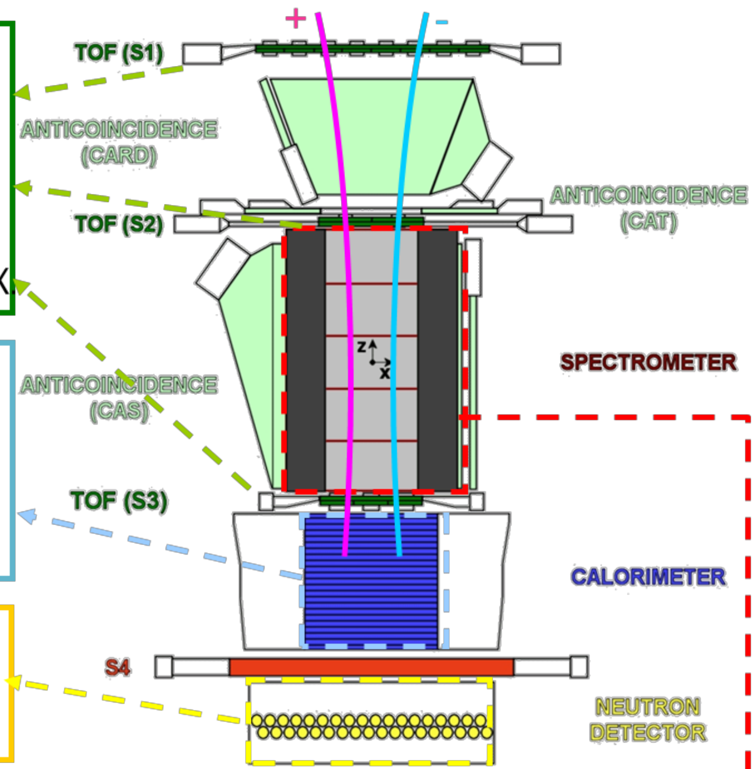
→ **MDR up to ~ 1 TV**

PAMELA detectors

Time-Of-Flight
plastic scintillators + PMT:
- Trigger
- Albedo rejection;
- Mass identification up to 1 GeV;
- Charge identification from dE/dX

Electromagnetic calorimeter
W/Si sampling (16.3 X0, 0.6 λI)
- Discrimination e+ / p, anti-p / e^- (shower topology)
- Direct E measurement for e^-

Neutron detector
plastic scintillators + PMT:
- High-energy e/h discrimination



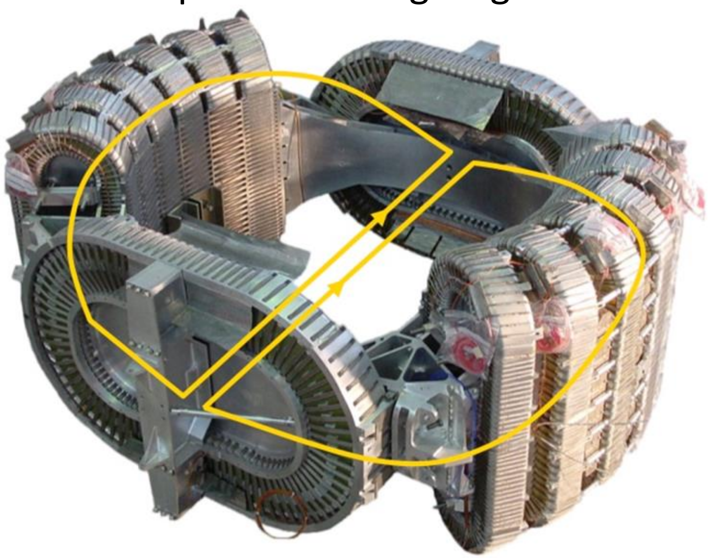
GF: 21.5 cm^2 sr
Mass: 470 kg
Size: 130x70x70 cm^3
Power Budget: 360W

Spectrometer
microstrip silicon tracking system + permanent magnet
It provides:
- *Magnetic rigidity* → R = pc/Ze
- *Charge sign*
- *Charge value from dE/dx*

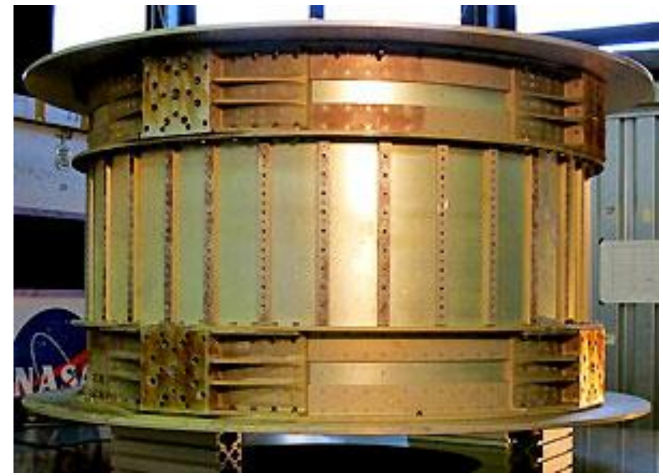
MDR ~1TV

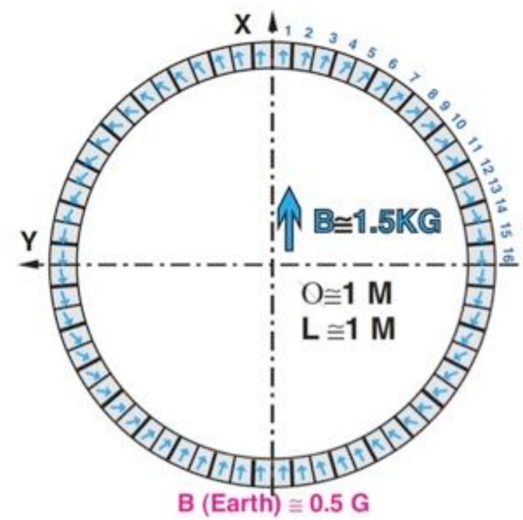
The AMS-02 magnet

Superconducting magnet



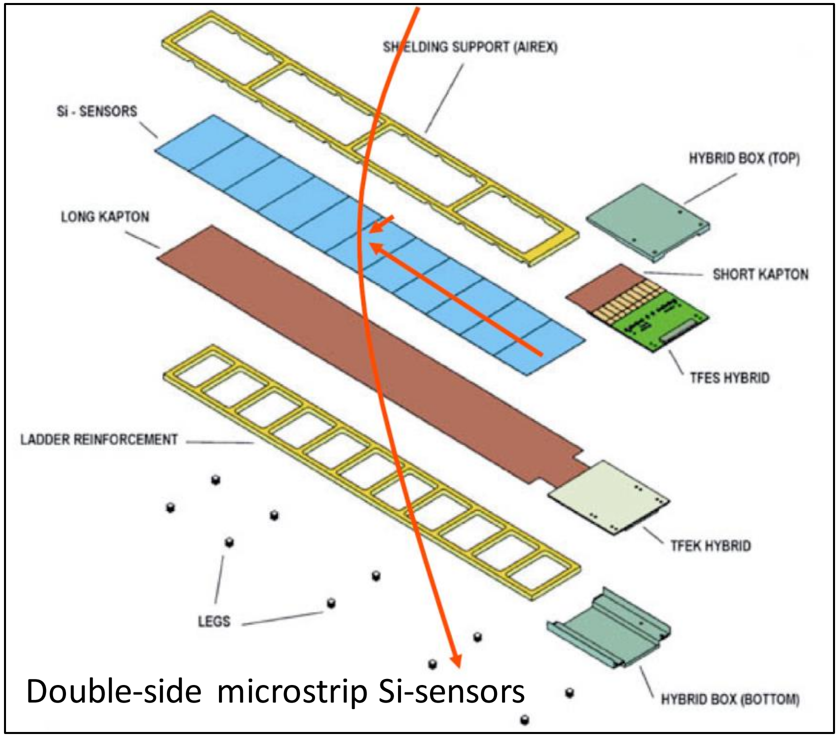
Permanent magnet



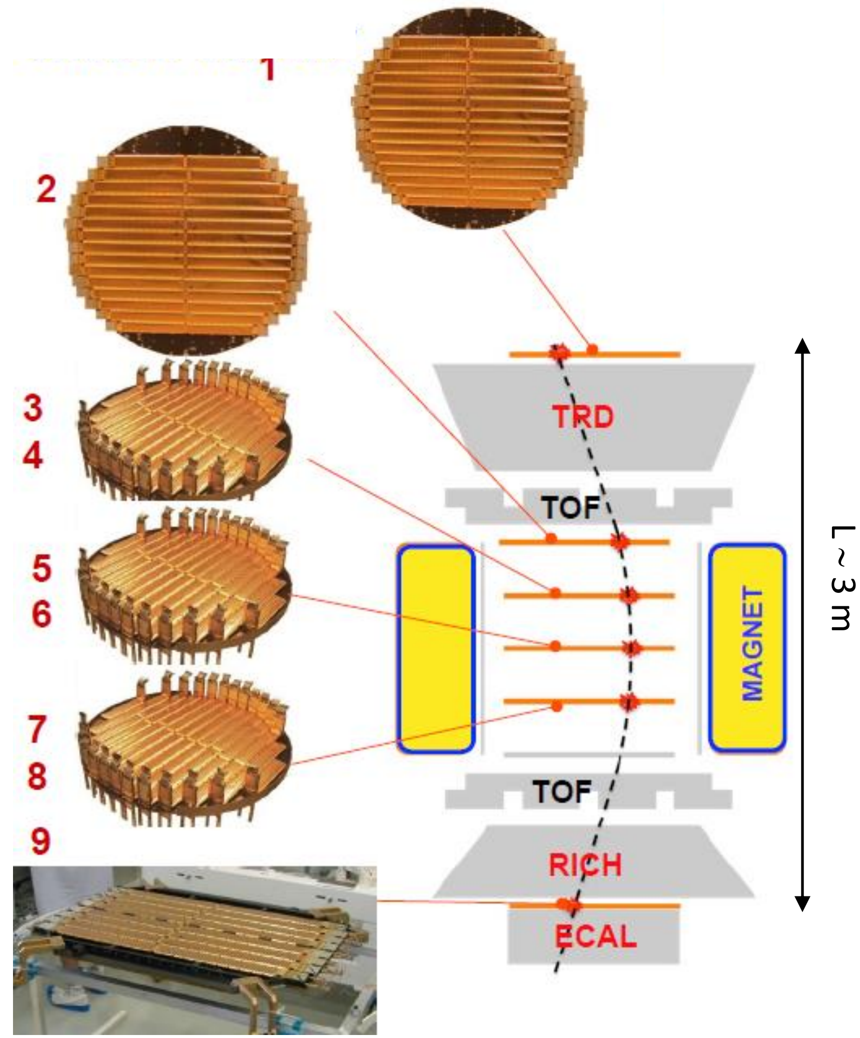


- Both permanent (Nd-Fe-B alloy) and superconducting (Ni-Ti) magnets developed.
- Permanent one chosen, in the perspective of long-duration mission (>3 years)
  - 0.15 T @ center
  - Large cavity 1m $\varnothing \times$ 1m

The AMS-02 tracking system



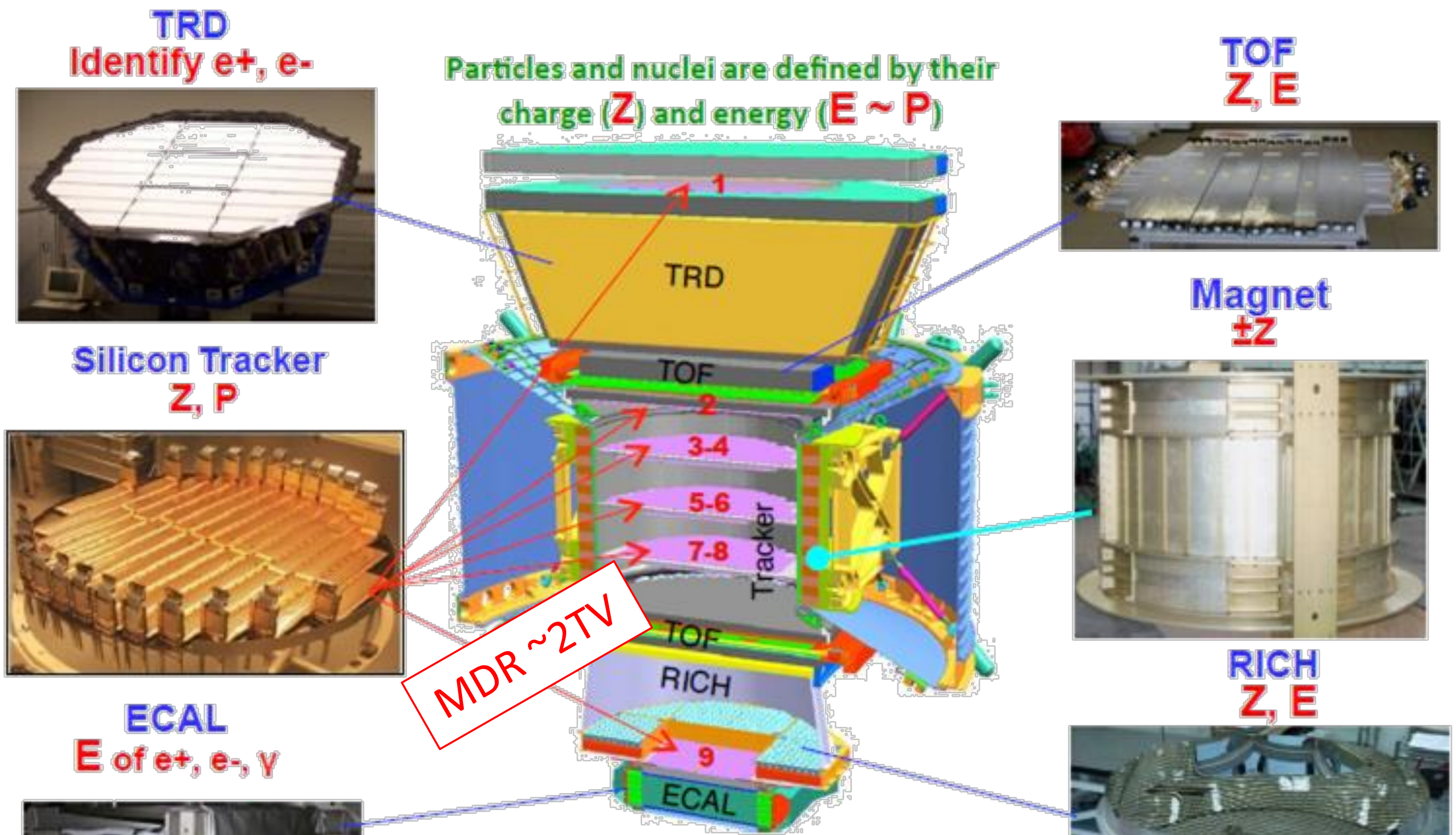
Double-side microstrip Si-sensors



- 0.15 T magnetic field @ center
- **~ 10 µm** resolution on the bending direction
- ~ 3 m track-length

→ **MDR ~ 2 TV**

The AMS-02 detectors



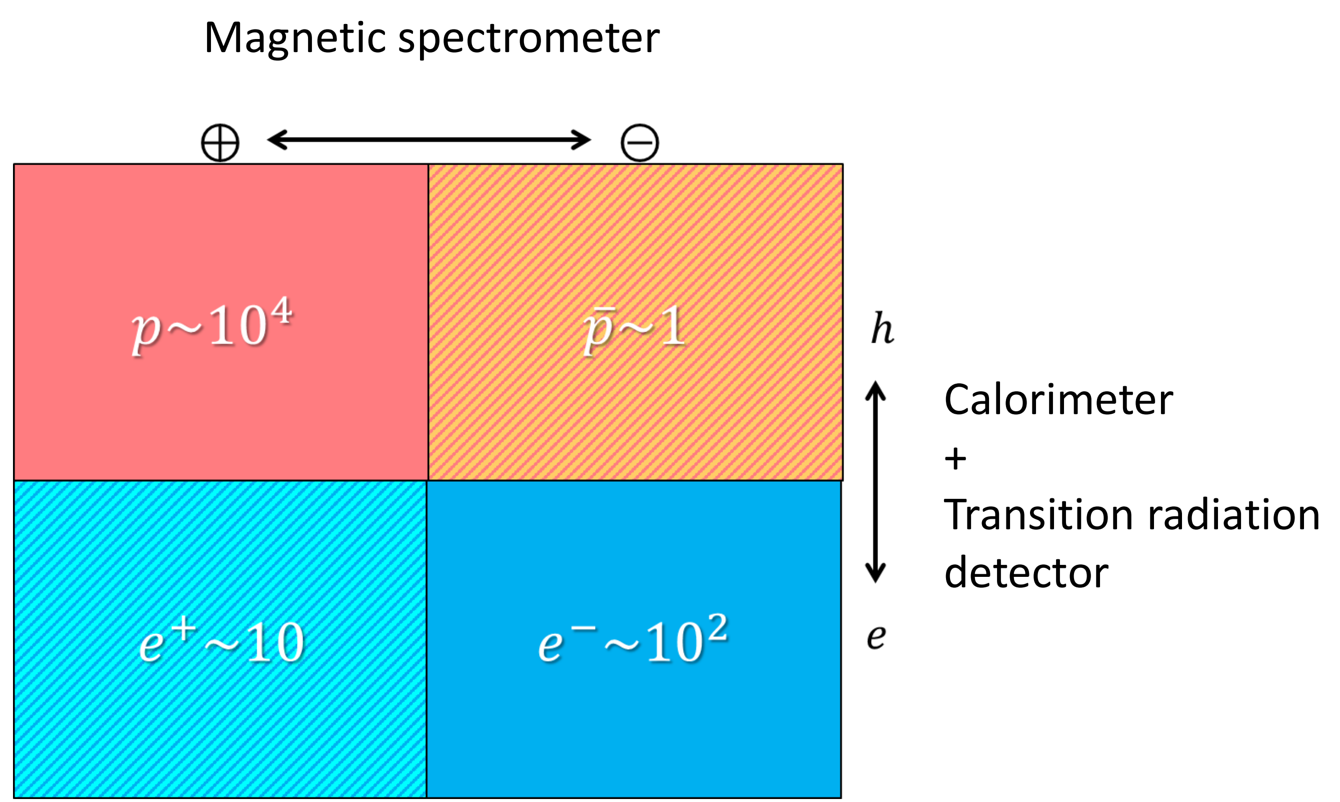
GF ~ 0.5 m² sr (450 cm²sr with ECAL)

Z, P are measured independently by the Tracker, RICH, TOF and ECAL

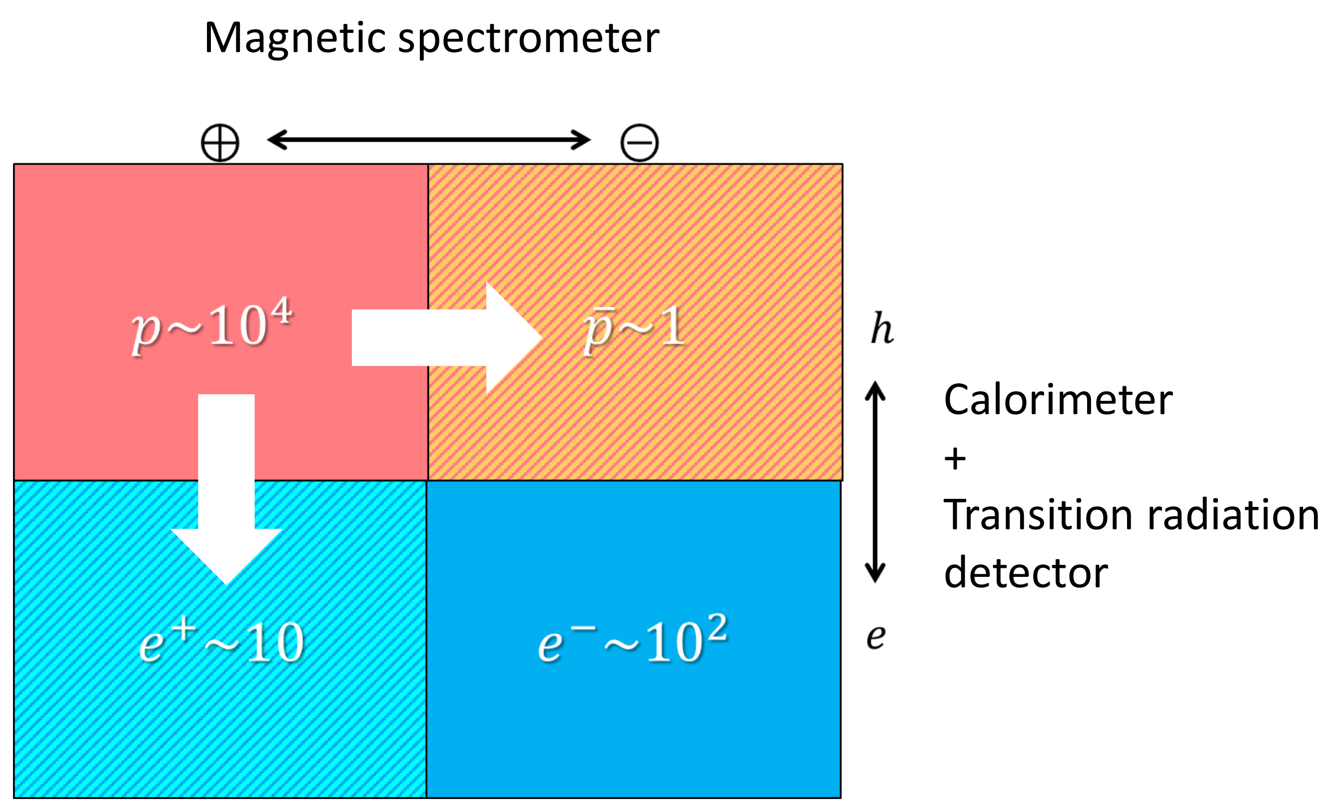
Modern spectrometer-based experiments

	BESS-Polar	**PAMELA**	**AMS-02**
Acceptance m^2str	0.3	0.0022	0.3
Vehicle	Polar LDB	Satellite	Space station
Flight duration	8.5+24.5 days	~ 10 years	> 7 years
Orbit inclination	-	70.4^{o}	51.7^{o}
MDR (GV)	~270	~1000	~2000
Tracking system σ (μm) L (m) N	Drift chamber 140 > 0.8 $\leq$ 52	Si microstrip 3 0.44 $\leq$ 6	Si microstrip 10 3 $\leq$ 6
Magnetic system ⟨B⟩ (T)	Superconducting solenoid 0.8	Permanent 0.43	Permanent 0.15
Particle identification	ToF Cherenkov	ToF	ToF TRD RICH
		Imaging calorimeter	Imaging calorimeter
Main scientific objectives	• Low energy $\bar{p}$ • Antinuclei search	• $\bar{p}$ and e^+ up to high energy	• $\bar{p}$ and e^+ up to high energy • Antinuclei search

Antiparticle identification @ high-energy (Z=1)



Antiparticle identification @ high-energy (Z=1)



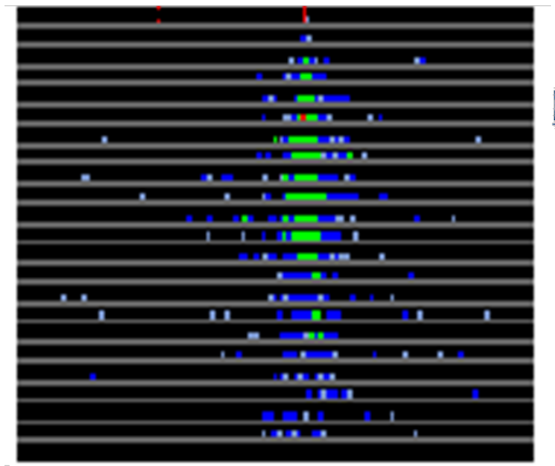
Calorimeter identification

PAMELA and AMS-02 calorimeters designed to have

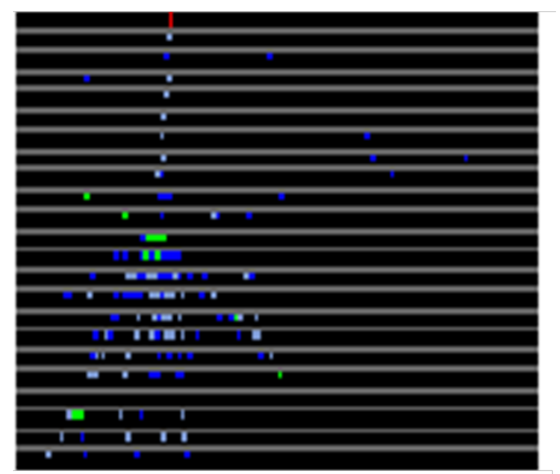
- High granularity
- Maximal ratio between X_0 and λ_I

	PAMELA	AMS-02
Calorimeter	W/Si-strip	Pb/Scintillating-fibers
x/y pitch	2.4 mm	1 mm
Longitudinal samplings	22	18
Depth in X_0	16.3	17
Depth in λ_I	0.6	0.6

electron



hadron



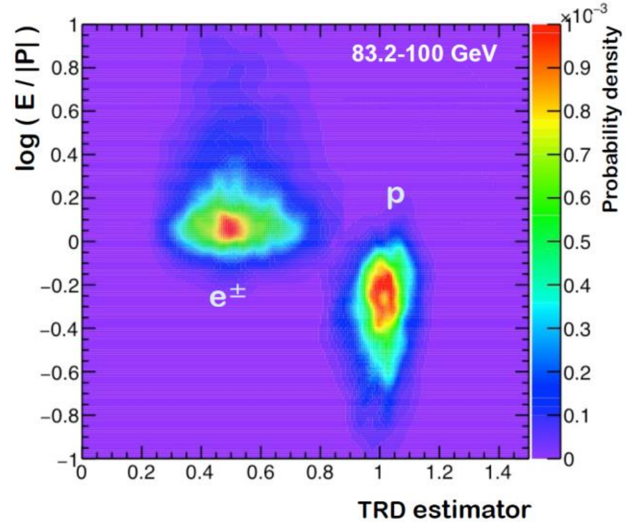
Identification criteria based on:

- Shower topology
  - Starting point
  - Longitudinal containment
  - Lateral spread
- Non-compensation
  - Energy-rigidity match

TRD identification

Transition Radiation → em radiation emitted when a charged particle passes through inhomogeneous media:

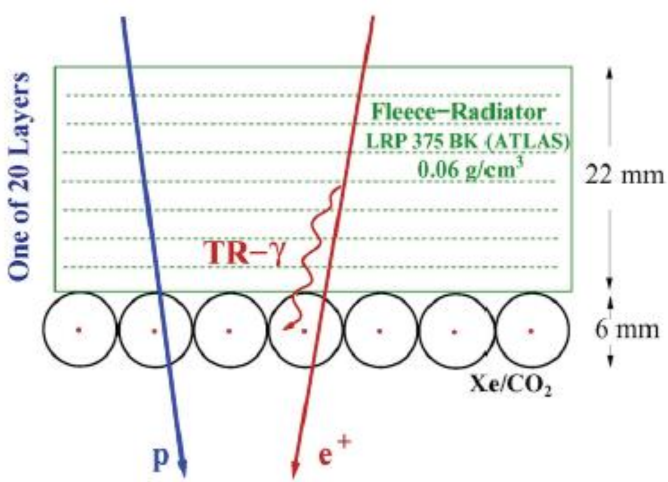
- Radiated energy $\propto \gamma$
- N.photons ~ *const*
- Photon detection in X-ray band → γ_{th}~1000



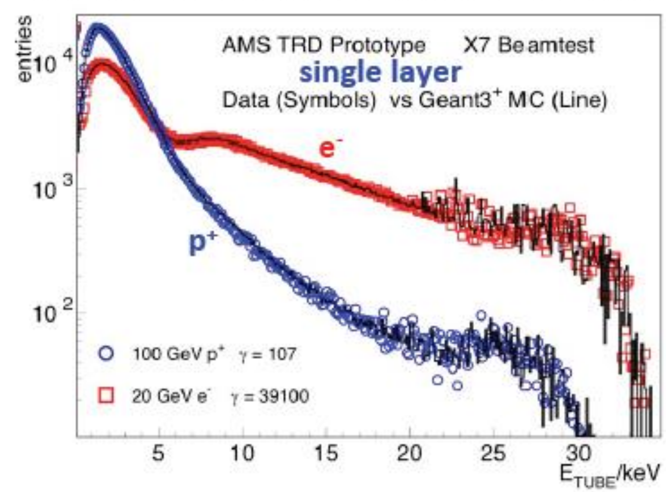
Kounine @ AMS Days at CERN (2015)

20 Layers each existing of:

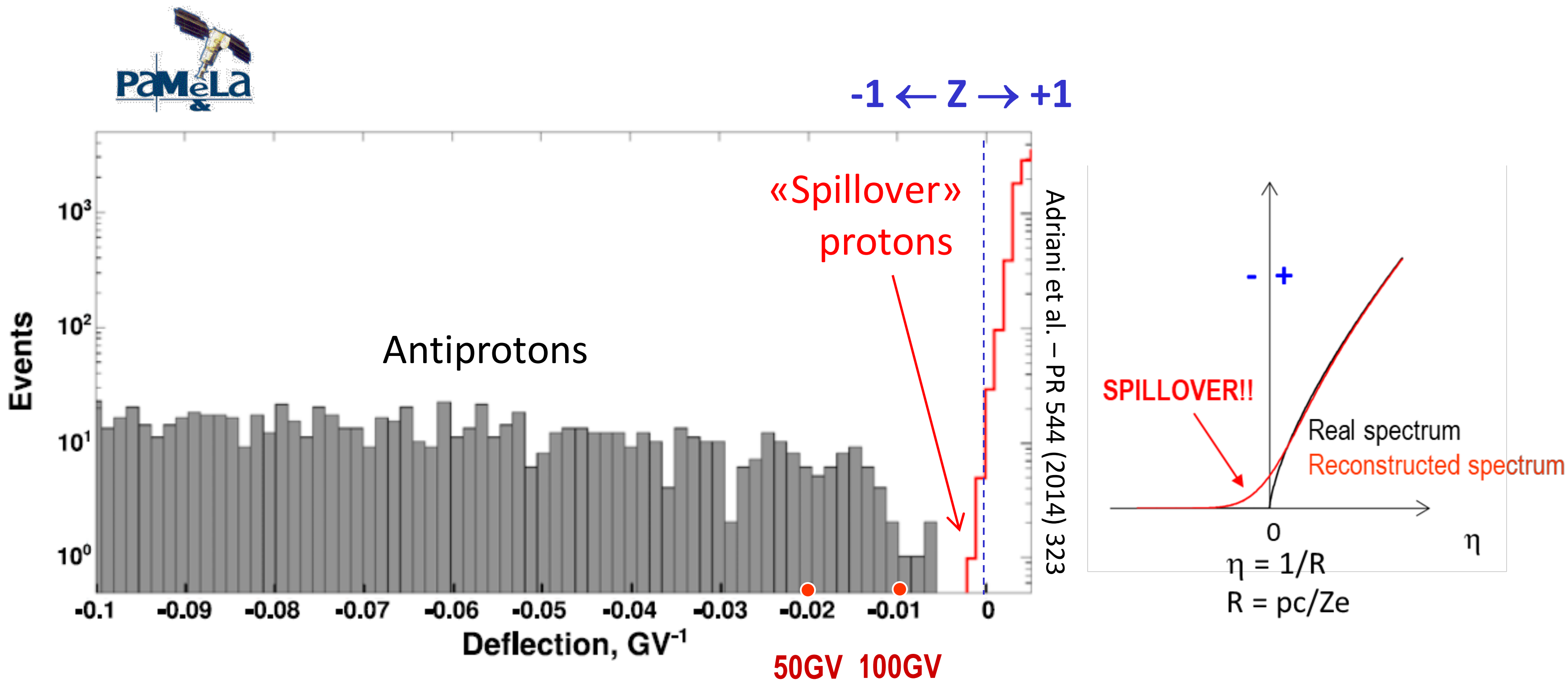
- **22 mm fibre fleece**
- **Ø 6 mm straw tubes filled with Xe/CO_2 80%/20%**



P. Doetinchem et al., Nucl.Instrum.Methods A, 558:608641, 2006.



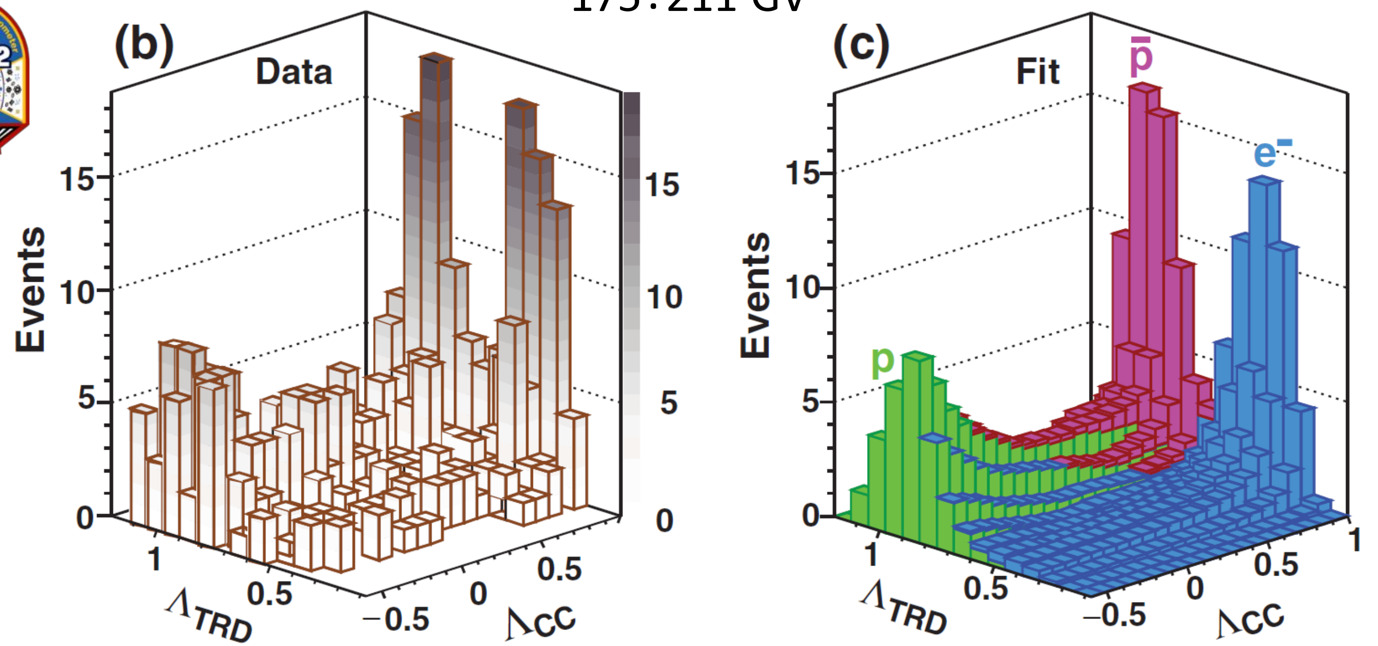
Antiproton identification



Selected particles with h-like pattern in the calorimeter

Antiproton identification

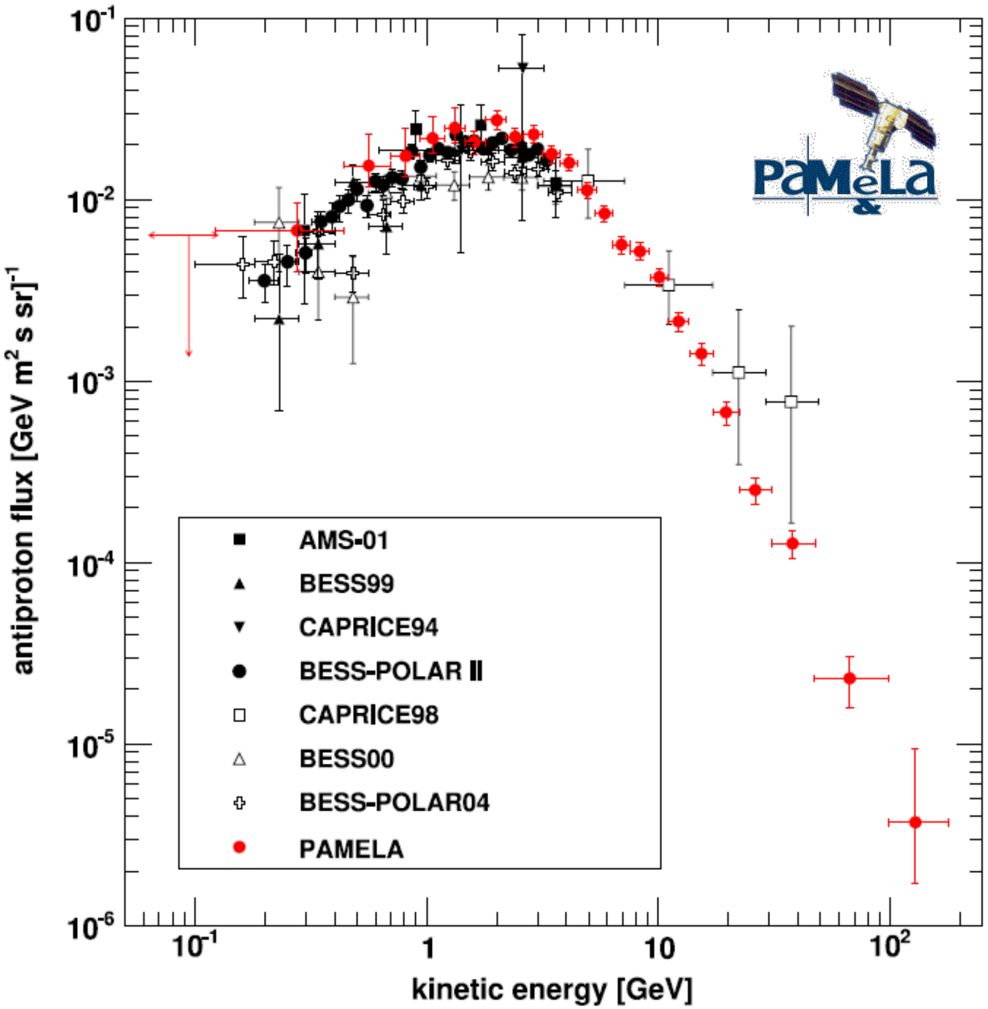
175÷211 GV



Aguilar et al. – PRL - 117 (2016) 09113

Template fitting to subtract “charge confusion” (CC) protons

Antiprotons

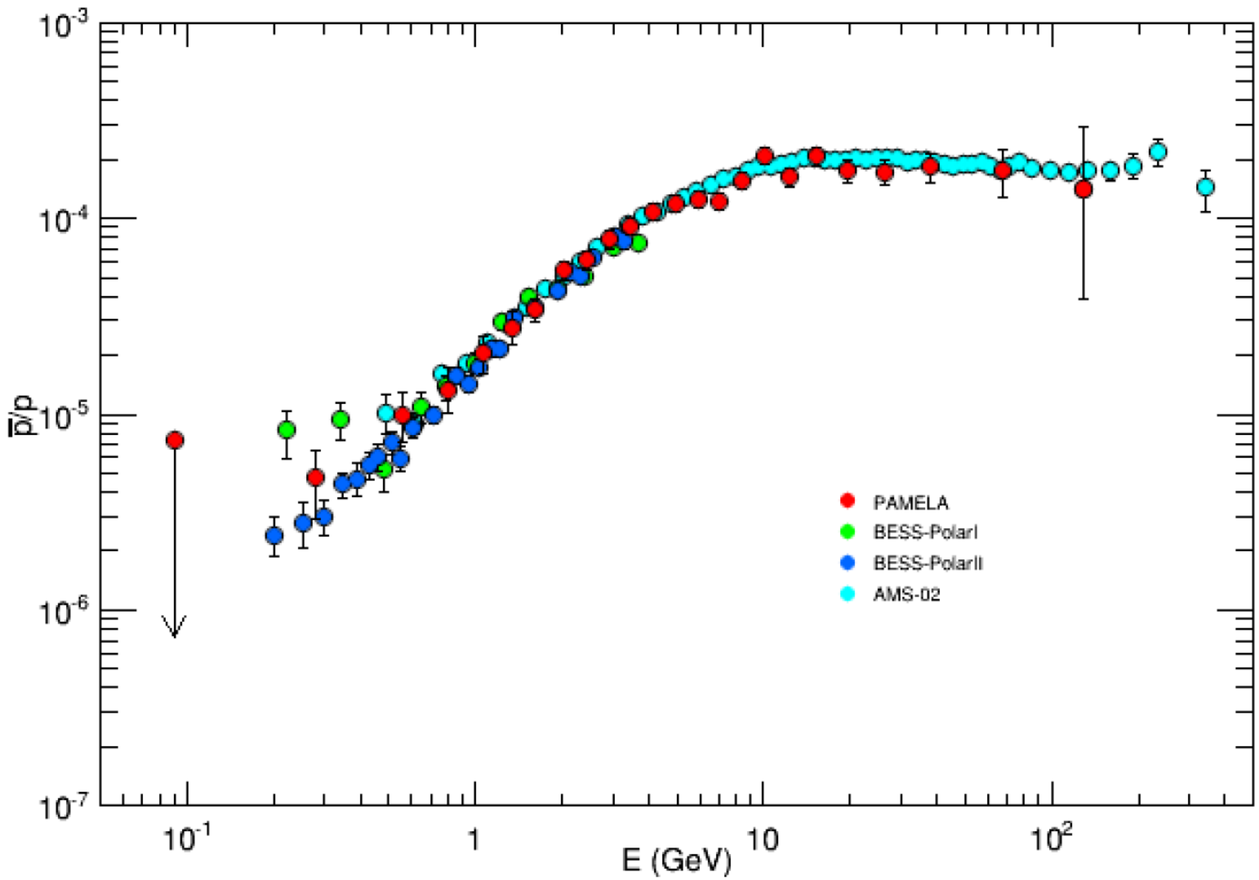


Adriani et al. - PRL 105 (2010) 121101

First measurement extending up to 200 GV

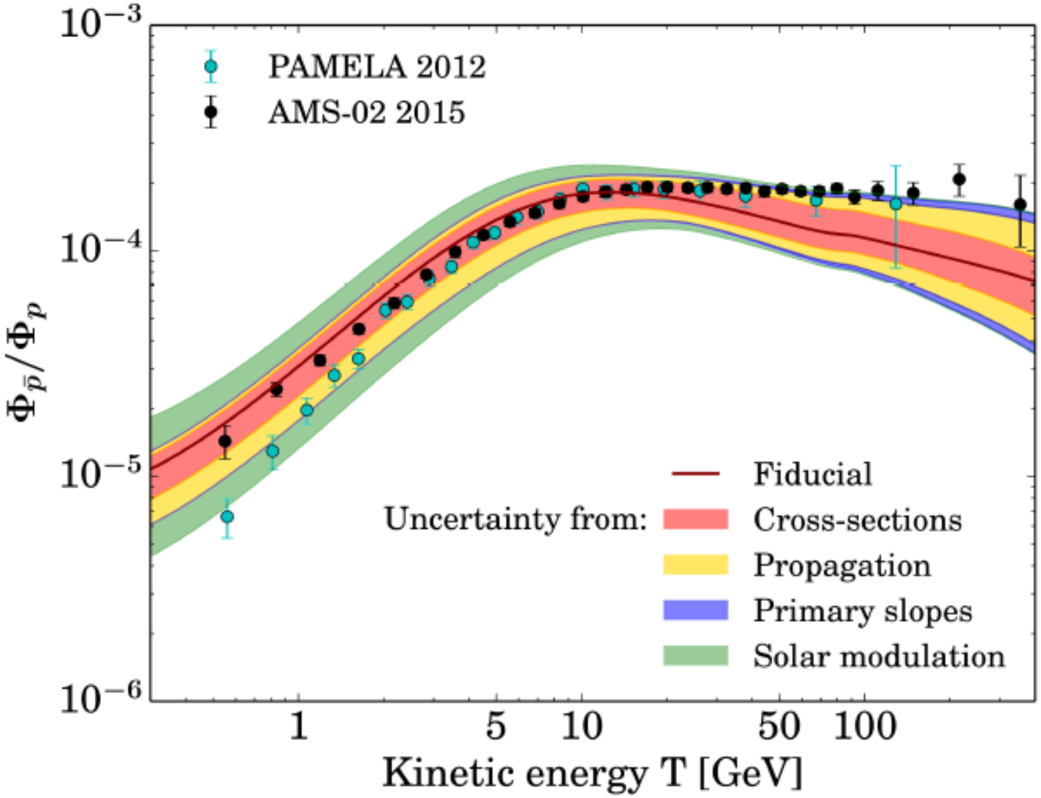
Largest energy range covered up to then

Antiprotons



PAMELA result confirmed by AMS-02 and extended in energy.

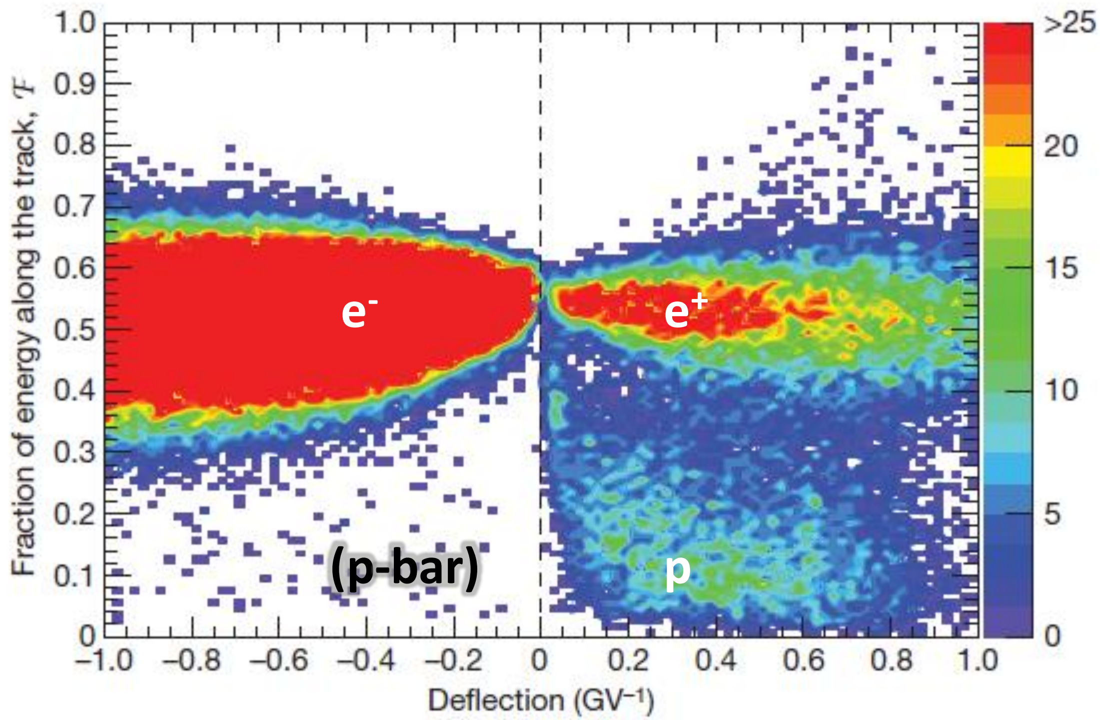
Antiprotons



M. Circelli, Rapporteur talk ICRC 2015

Positron identification

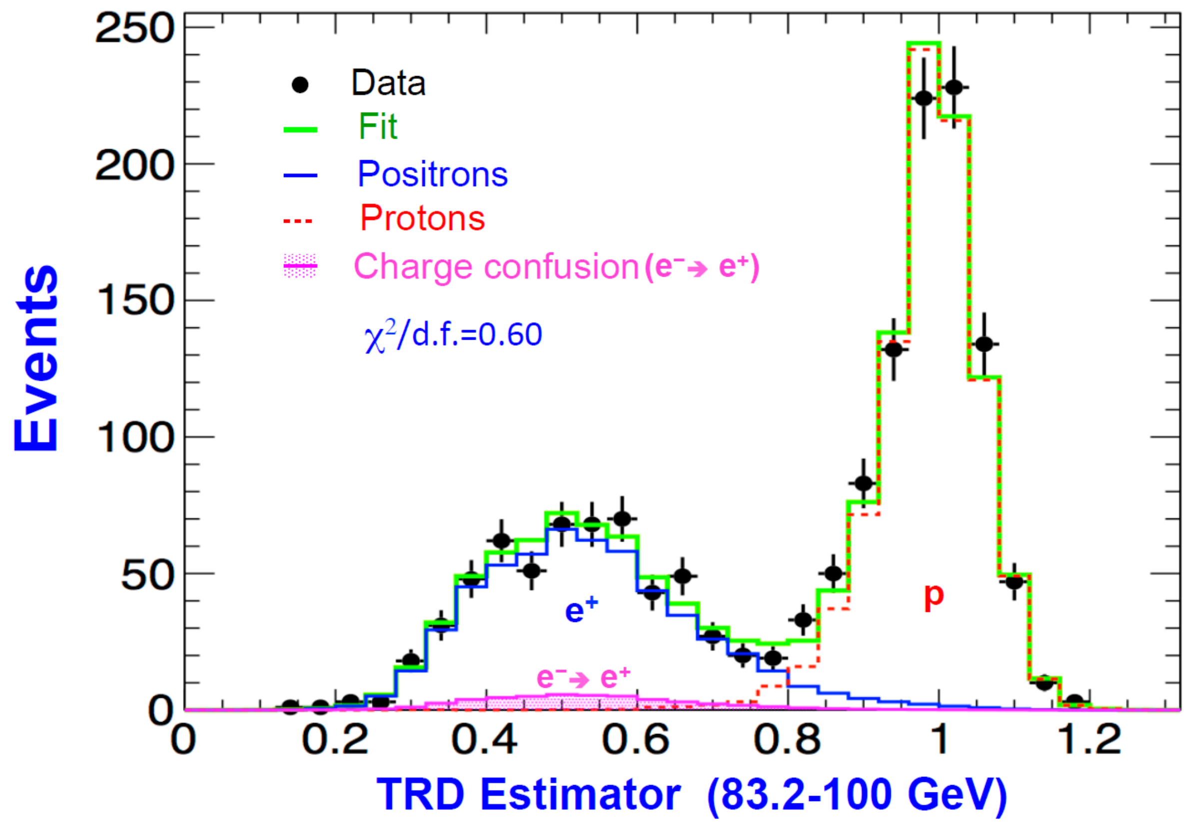
-1 ← Z → +1



Adriani et al. – Nature 458 (2009) 607
Adriani et al. – Astro.Ph. 34 (2010) 1

Fraction of energy along the extrapolated trajectory within 0.3 Moliere radii
(sample of pre-selected em-like events)

Positron identification

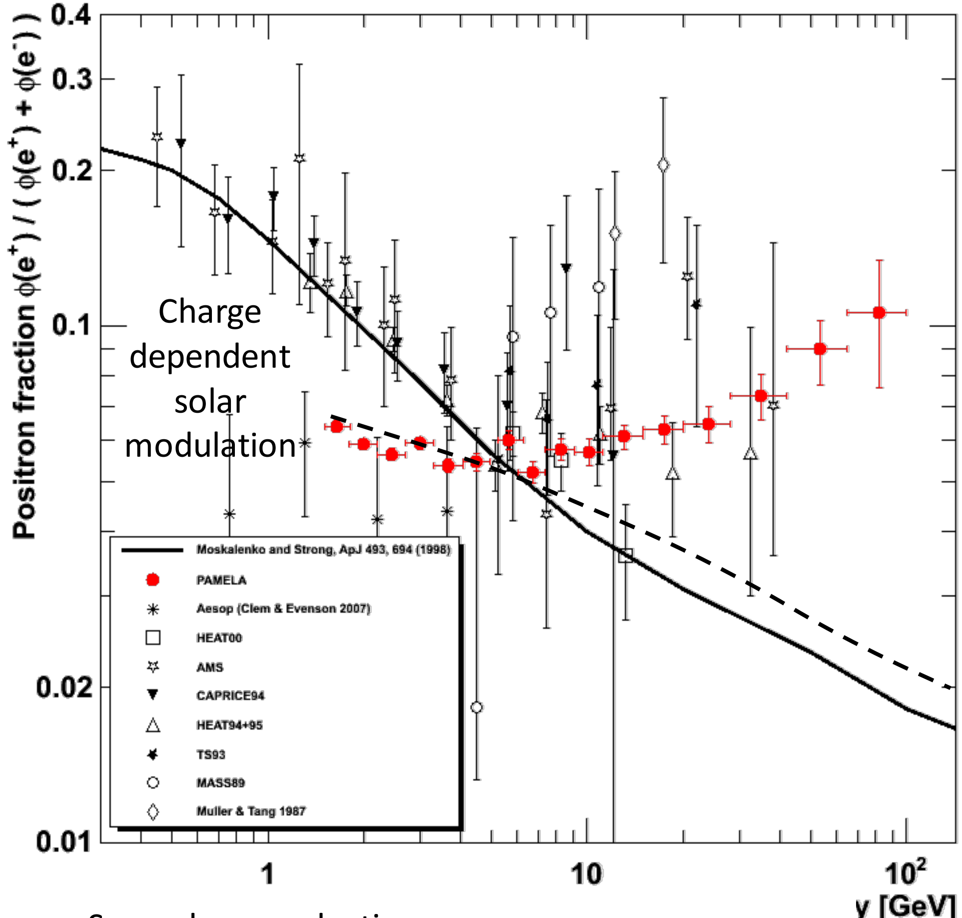


Selected negative particles with em-like pattern in the calorimeter

Positron fraction

First measurement extending up to 200 GV

Clear evidence for a deviation from pure secondary production



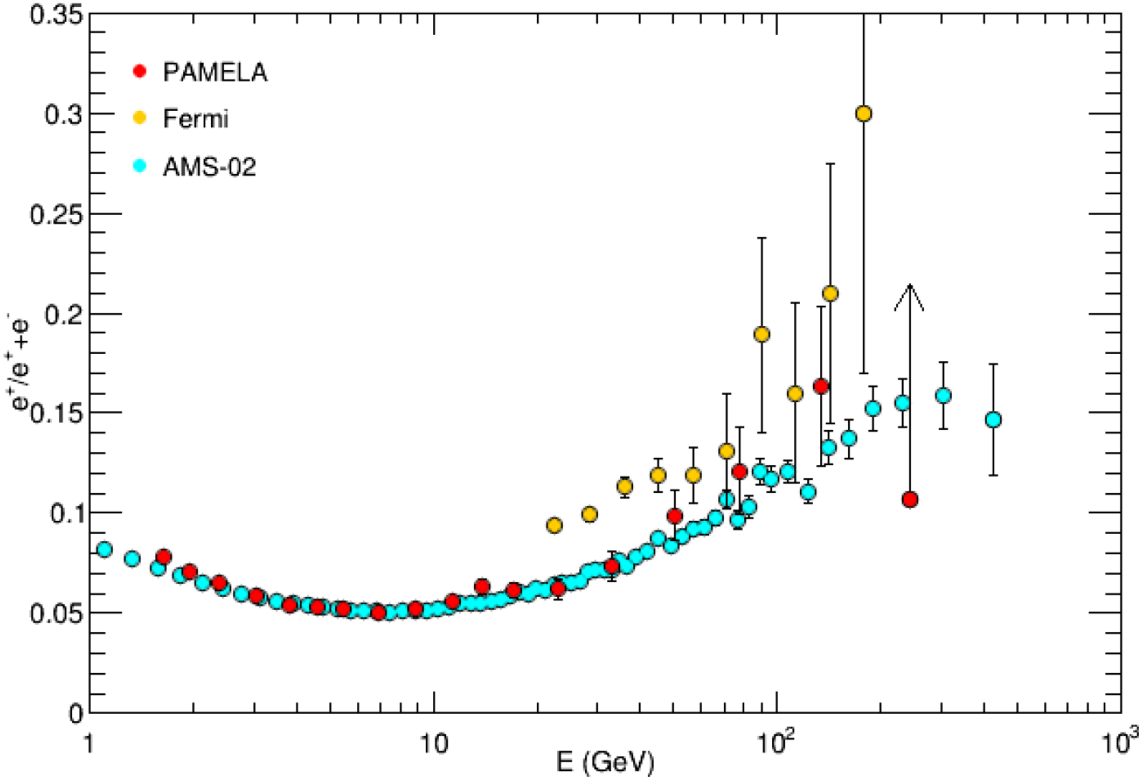
Secondary production:

------ Moskalenko & Strong 1998 (GALPROP code)

- - - - Delahaye et al. 2010

Adriani et al, Nature 458 (2009) 607;
Adriani et al. Astropart. Phys. 34 (2010) 1

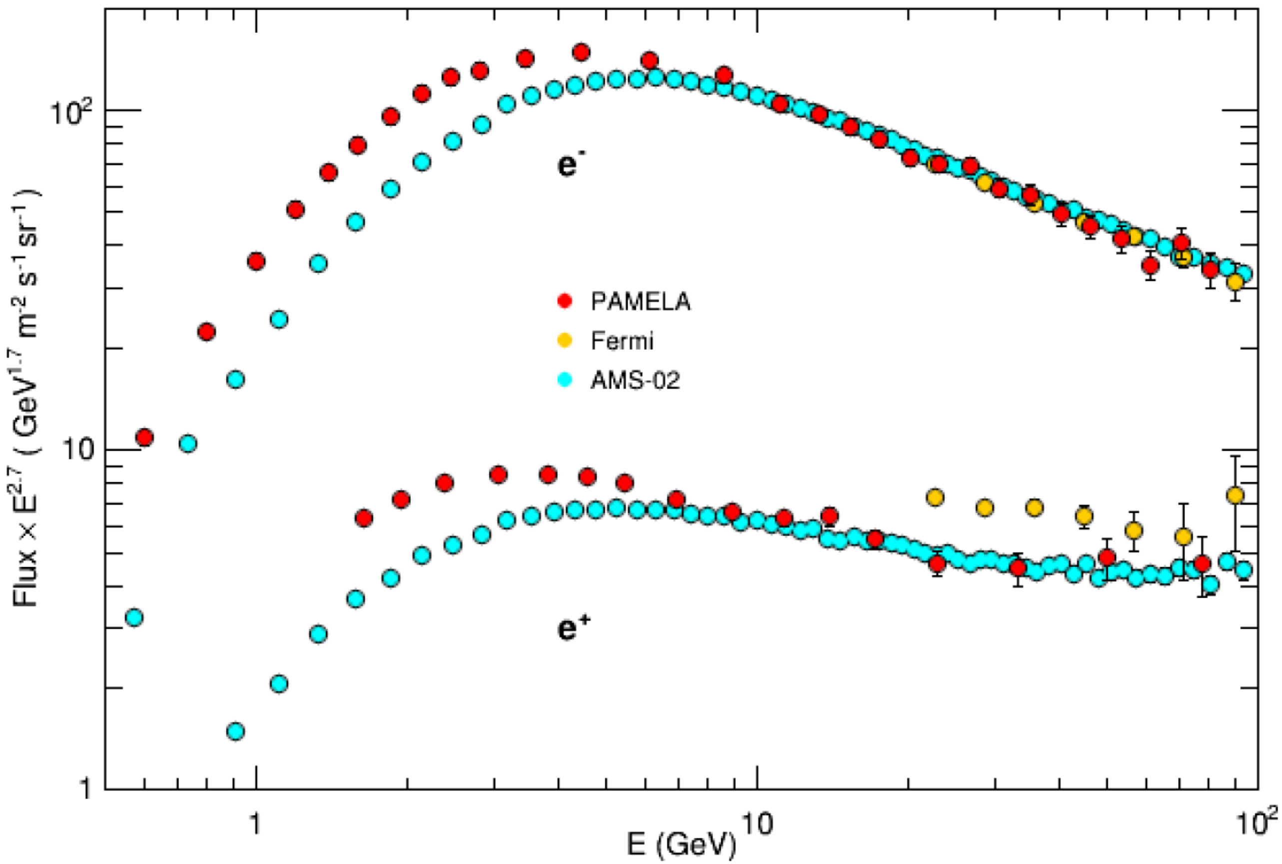
Positron fraction



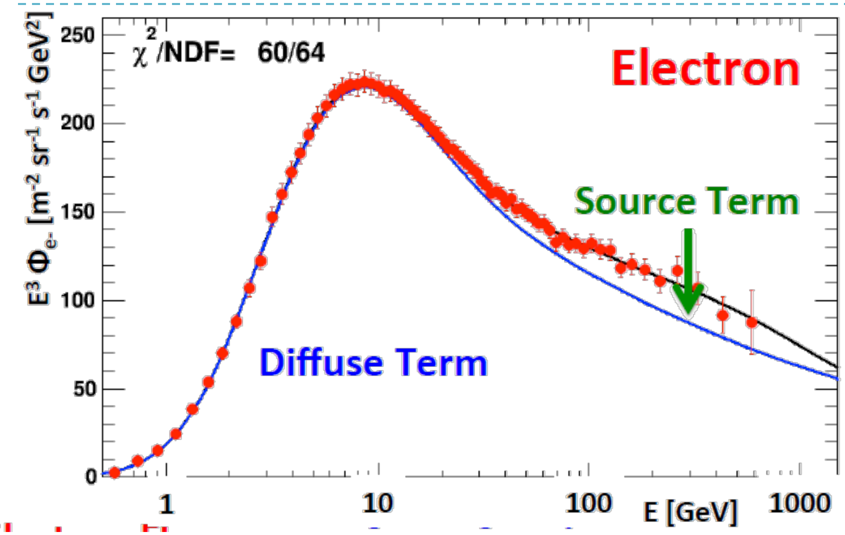
PAMELA result confirmed by AMS-02 and extended in energy.

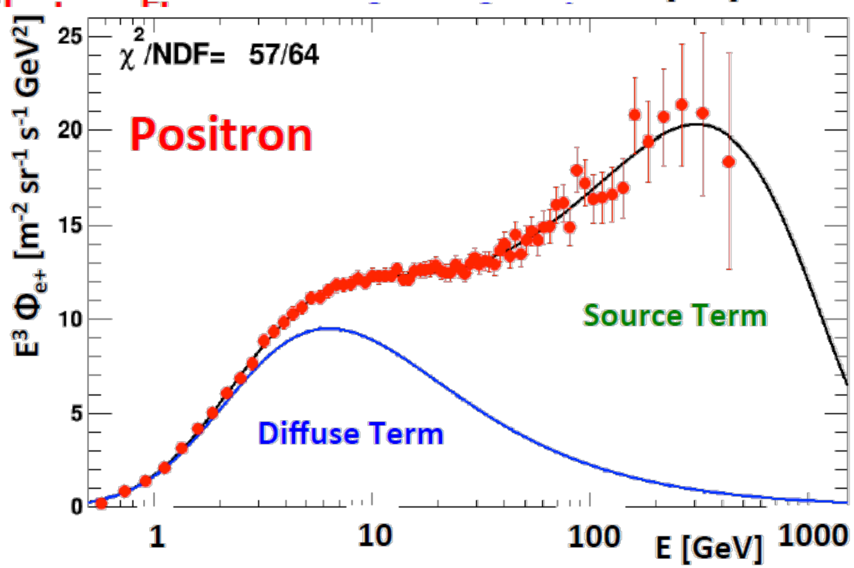
Indication for a decreasing trend above 300 GV.

Electron & positron individual spectra



Electrons & positrons





Measurement of individual spectra confirms the **positron excess**:

Proposed interpretations:

Dark matter

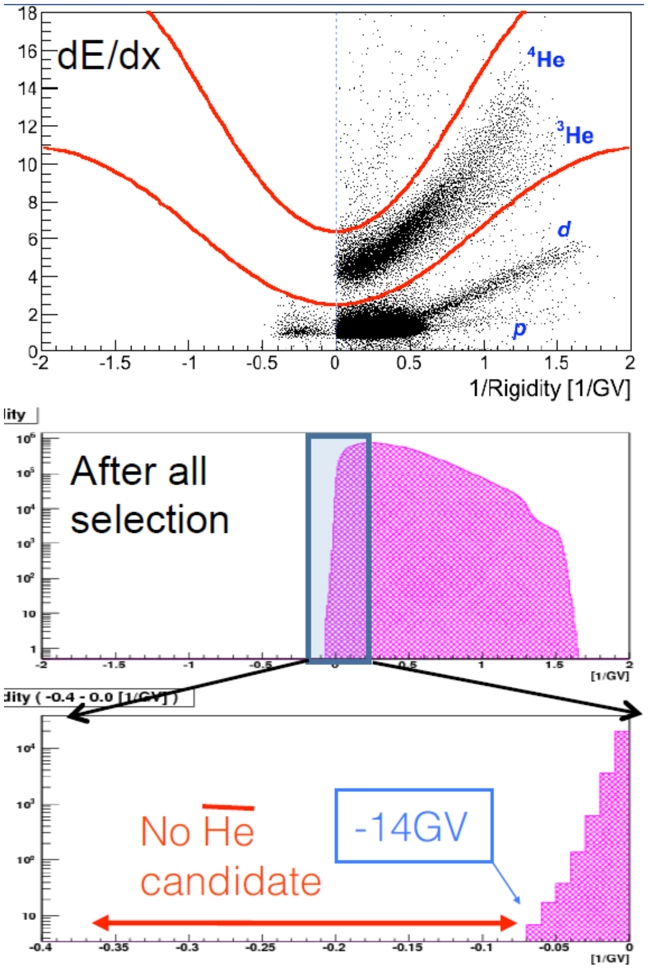
- lepton vs hadron yield must be consistent with $\bar{p}$ observations

Astrophysical processes

- known processes (eg. pulsars)
- large uncertainties on environmental parameters

Antinuclei

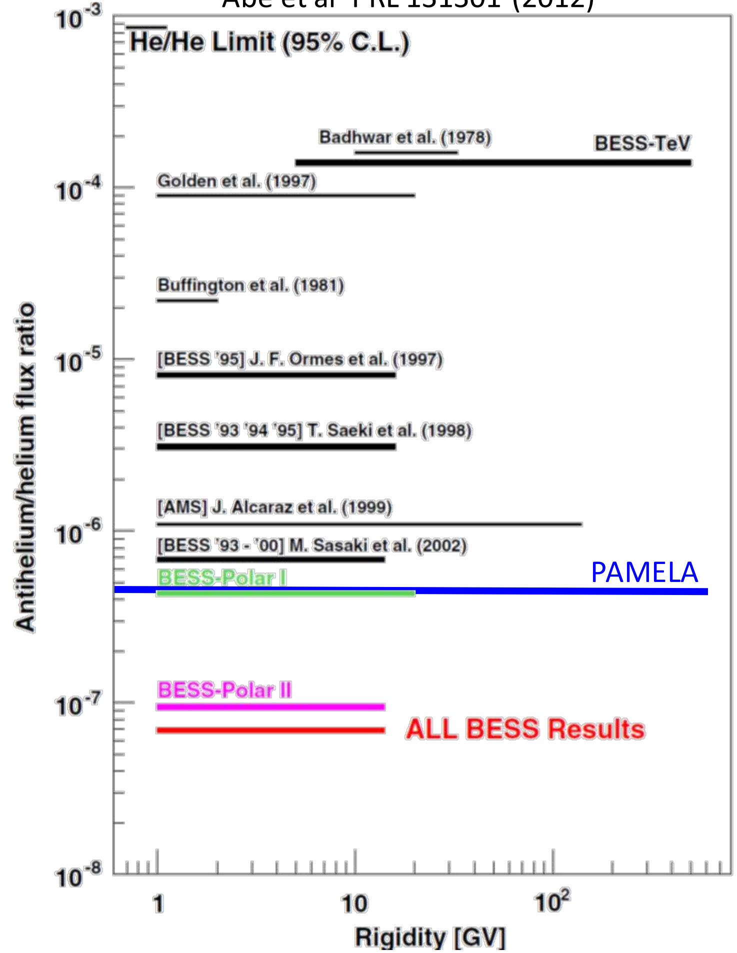
Most stringent limit paced so far from BESS-Polar II on anti-He



Sasaki @ Antideuteron 2014

BESS-Polar II

Abe et al PRL 131301 (2012)



Antinuclei

Giant space magnet may have trapped antihelium, raising idea of lingering pools of antimatter in the cosmos

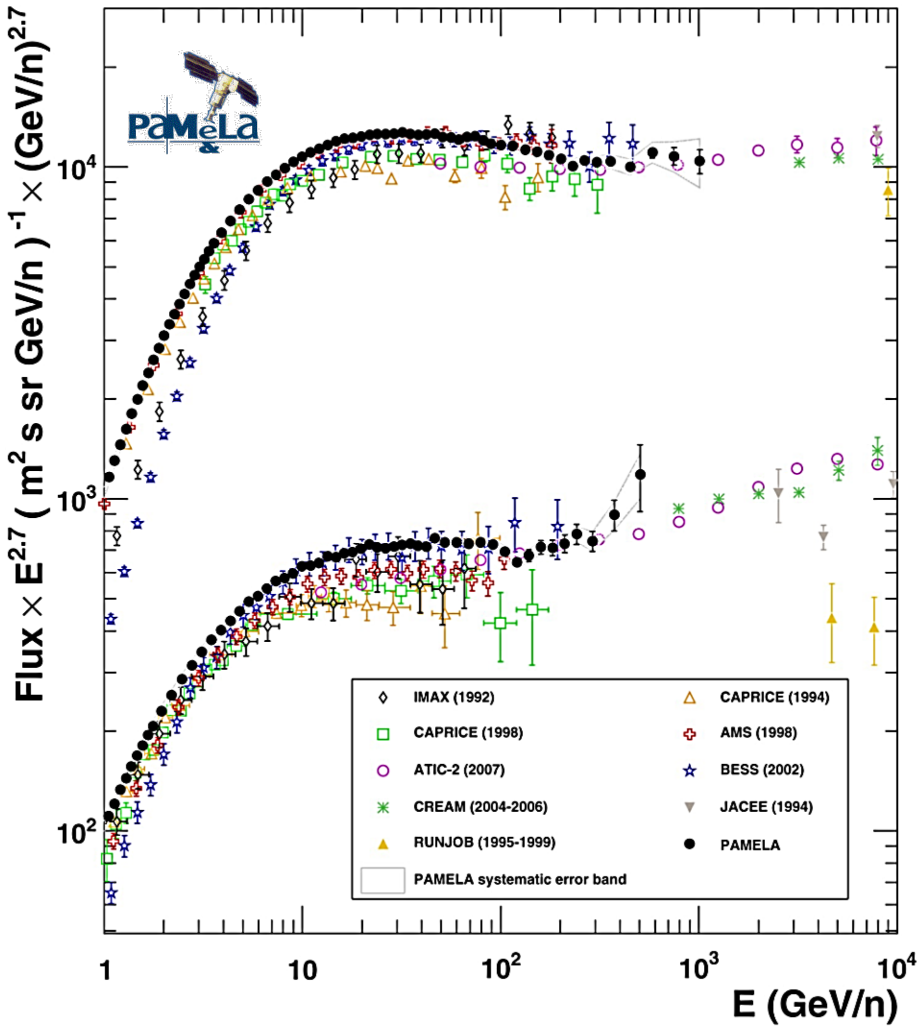
By Joshua Sokol | Apr. 19, 2017 , 3:45 PM

H & He

First high-statistics and high-precision measurement over three decades in energy

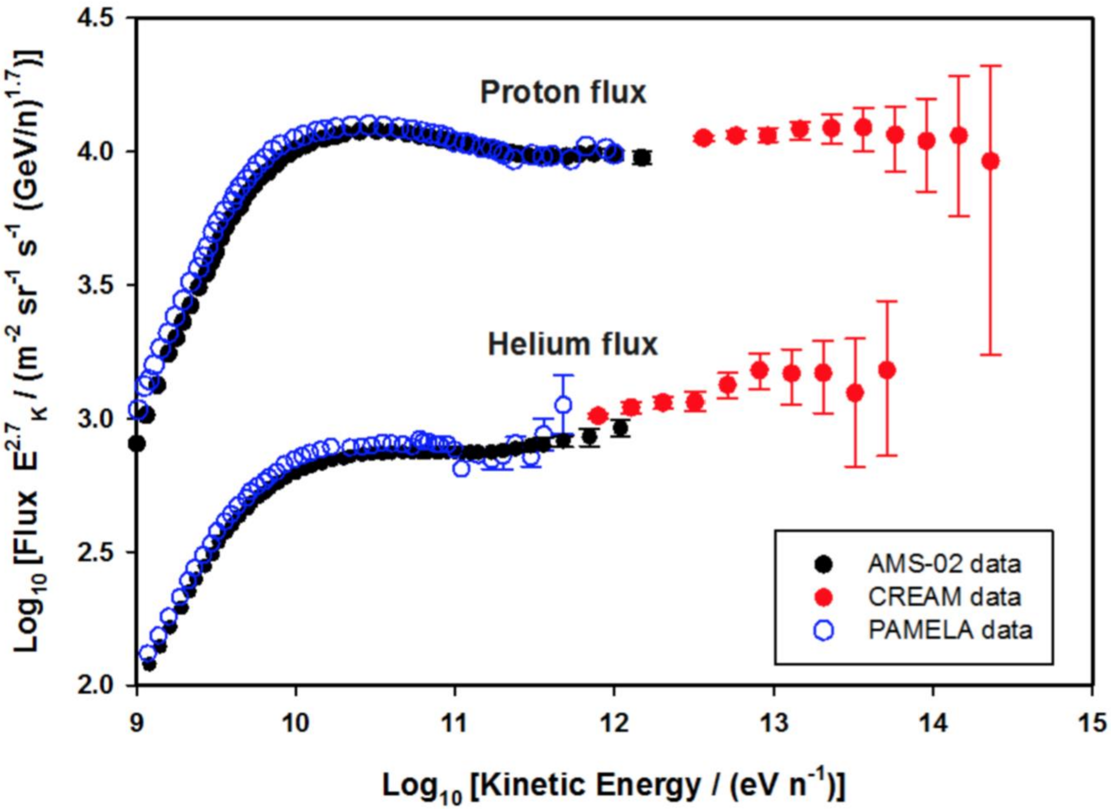
Low energy
→ minimum solar activity
($\phi = 450 \div 550$ GV)

High-energy (>30GV)
→ a complex structure of the spectra emerges…



Adriani et al. - Science - 332 (2011) 6025

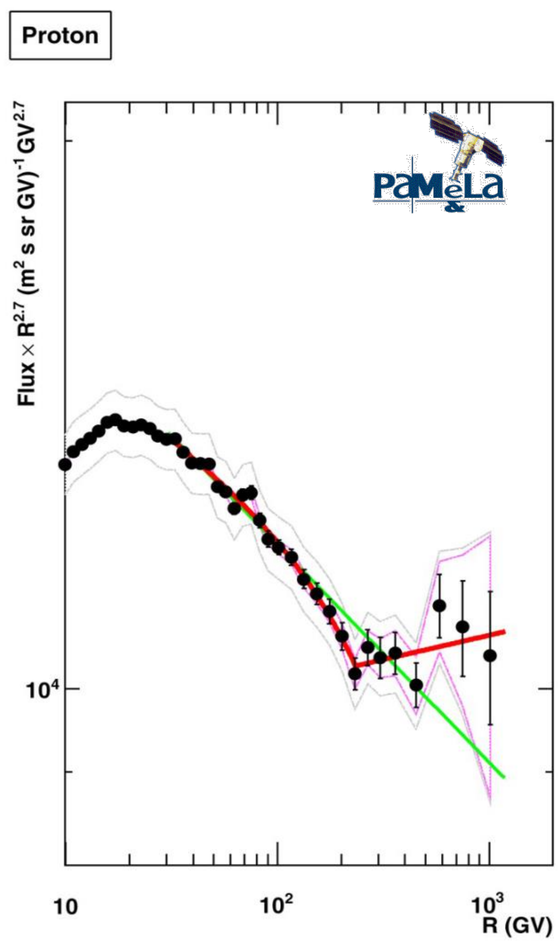
H & He

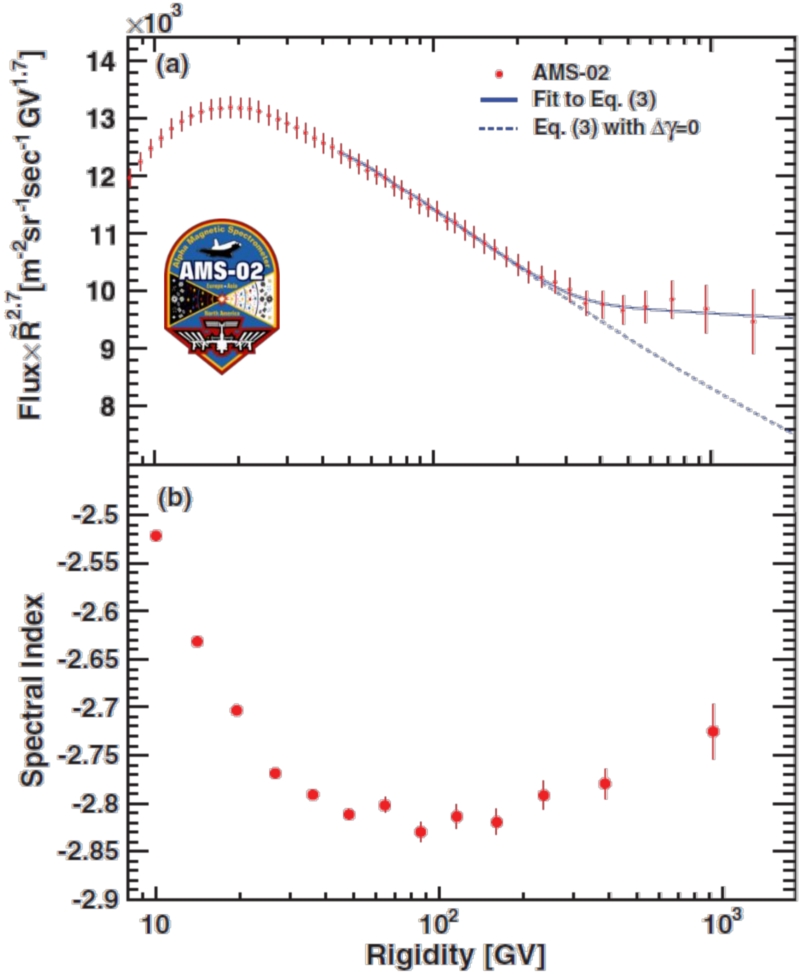


- Excellent agreement between PAMELA and AMS-02 results, within 2%
- Significant hardening above 230 GV for both H and He.
- Consistent with high-energy calorimetric measurements
- Possible explanations:
  - Source effect (multi-population, non-linear DSA)
  - Propagation effect

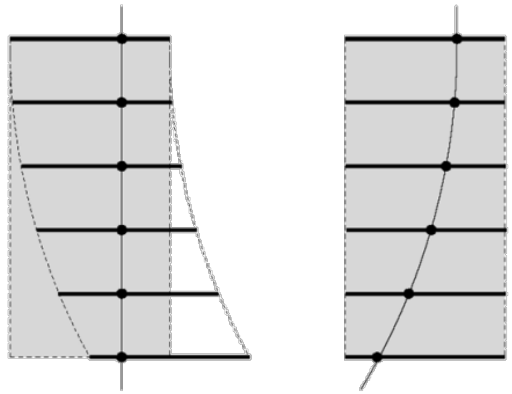
H spectrum

Clear evidence of a spectral hardening above ~200GV





Spectrometer systematic uncertainty



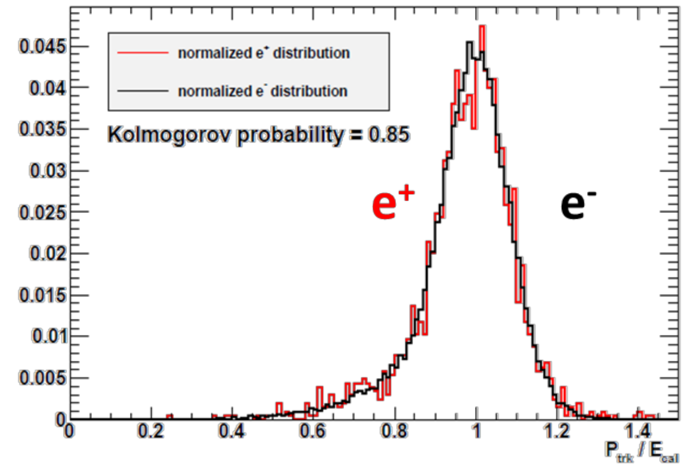
$\Delta\eta_{sys}$

- Due to possible residual distortion of the tracking system

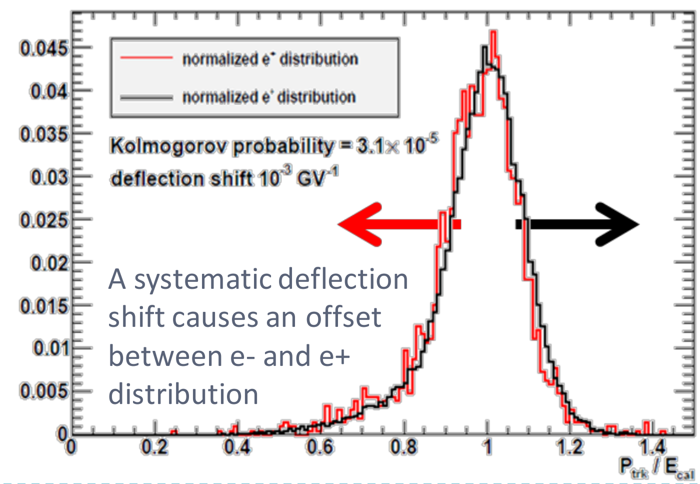
- Evaluated from electron/positron data by comparing the spectrometer momentum with the calorimeter energy

- Upper limit set by positron statistics:
  $$\Delta\eta_{sys} \sim \mathbf{10^{-4}} \boldsymbol{GV^{-1}}$$

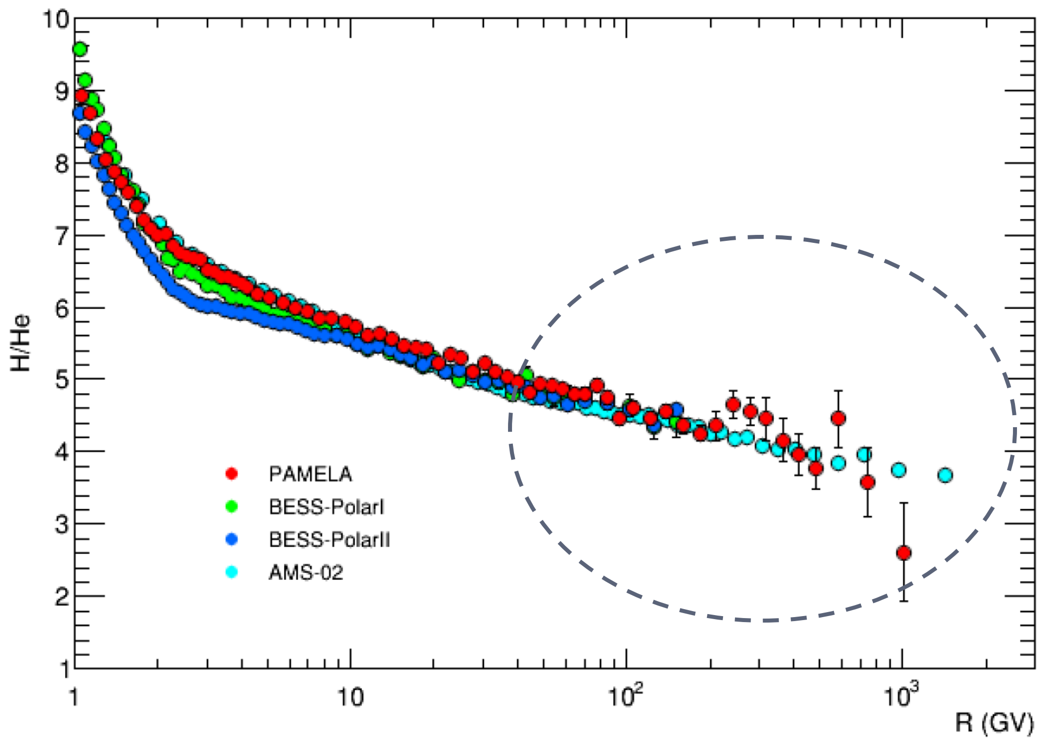
- Dominates the error on H and He fluxes at high energy



$$\frac{P_{trk}}{E_{cal}} \xrightarrow[sys]{} \frac{1}{E_{cal}(1+\varepsilon_{sys})\cdot|\eta_{trk}+\Delta\eta_{sys}|}$$



H/He vs rigidity



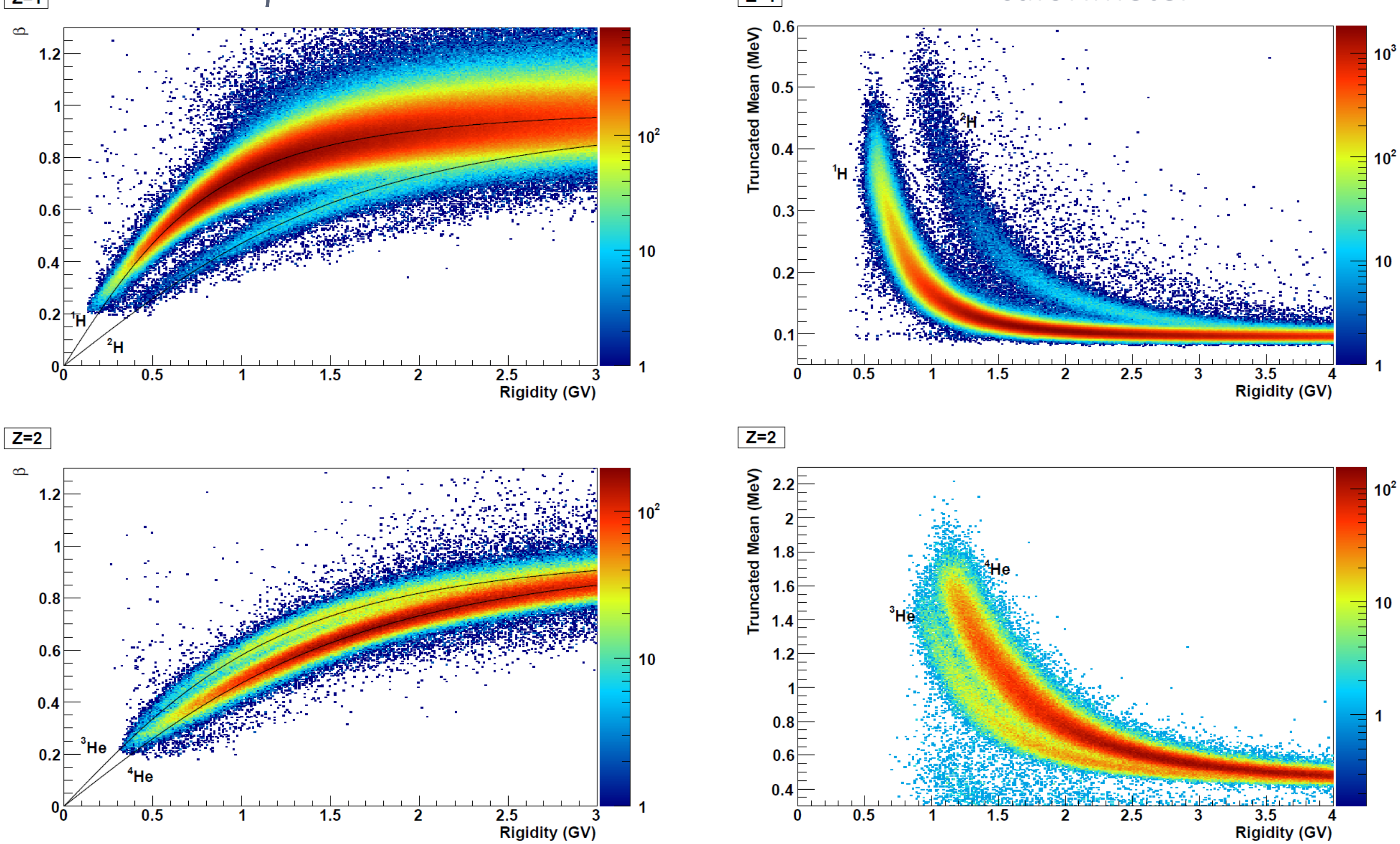
Systematic uncertainties partly cancel out at high energy

- Solar modulation negligible → information about IS spectra down to GV region
- Propagation effects small above ~100GV → information about source spectra
- Different slope for H and He
- No indication of spectral features above 10 GV

H and He isotopes

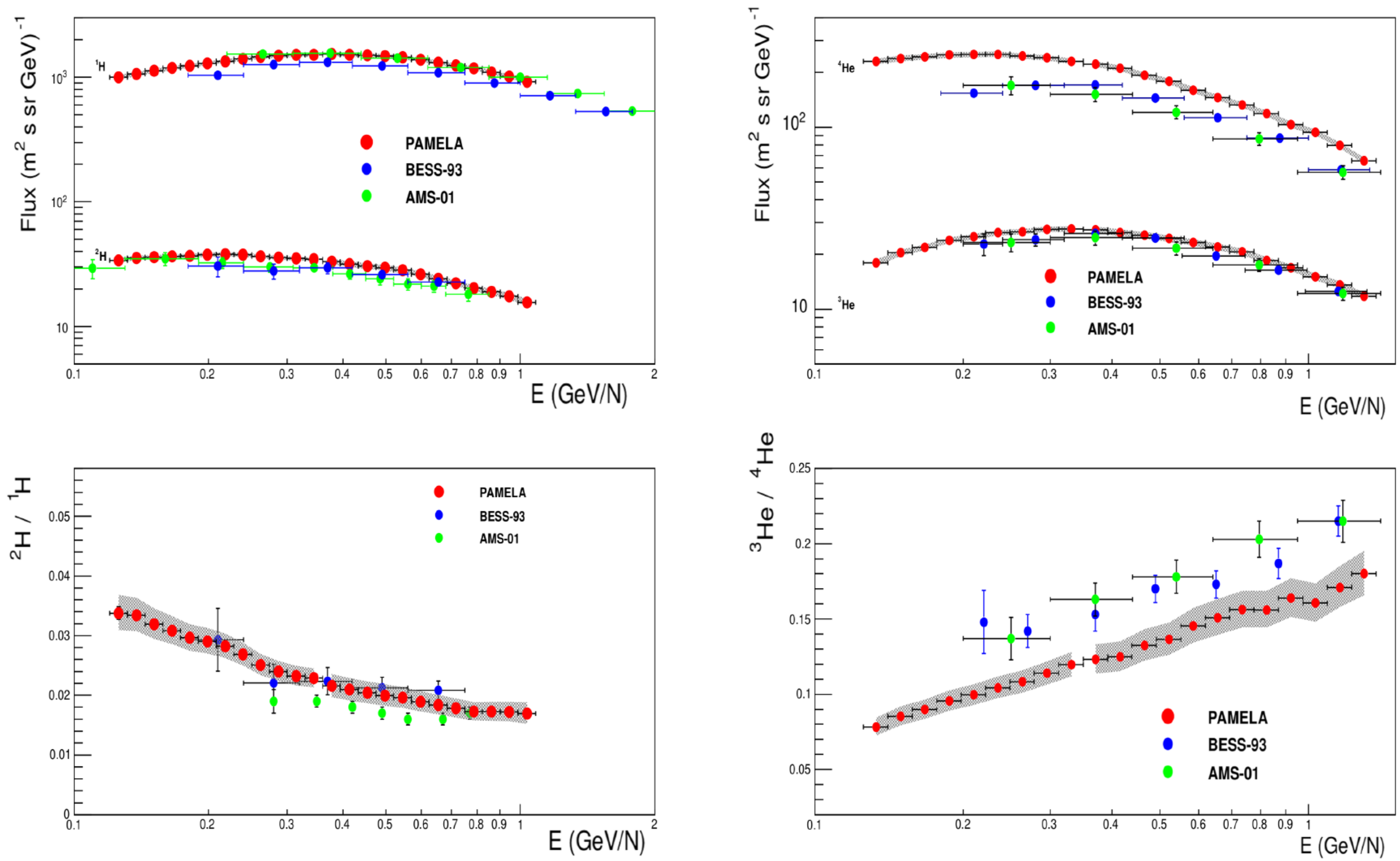
β from ToF

Multiple energy deposits from calorimeter



Reduntant identification cababilities

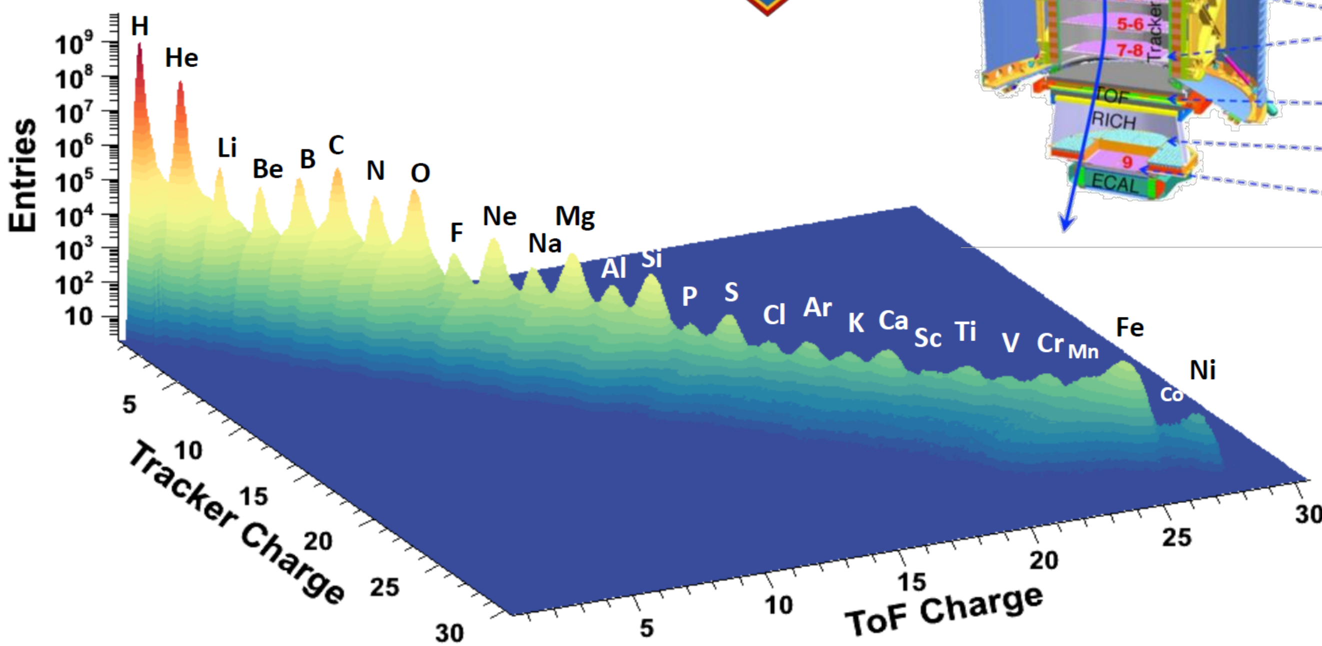
H and He isotopes

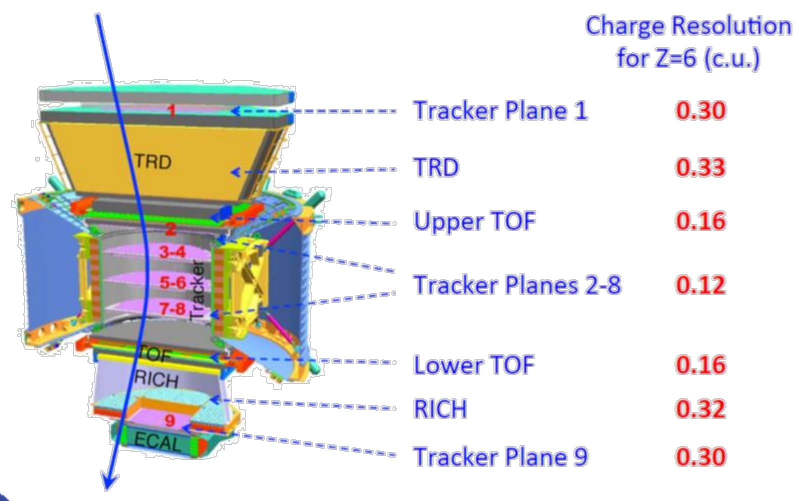


Parameter constraint competitve/complementary to B/C measurement with current instrument precision

Probe different Z/A regime → test «universality» of propagation

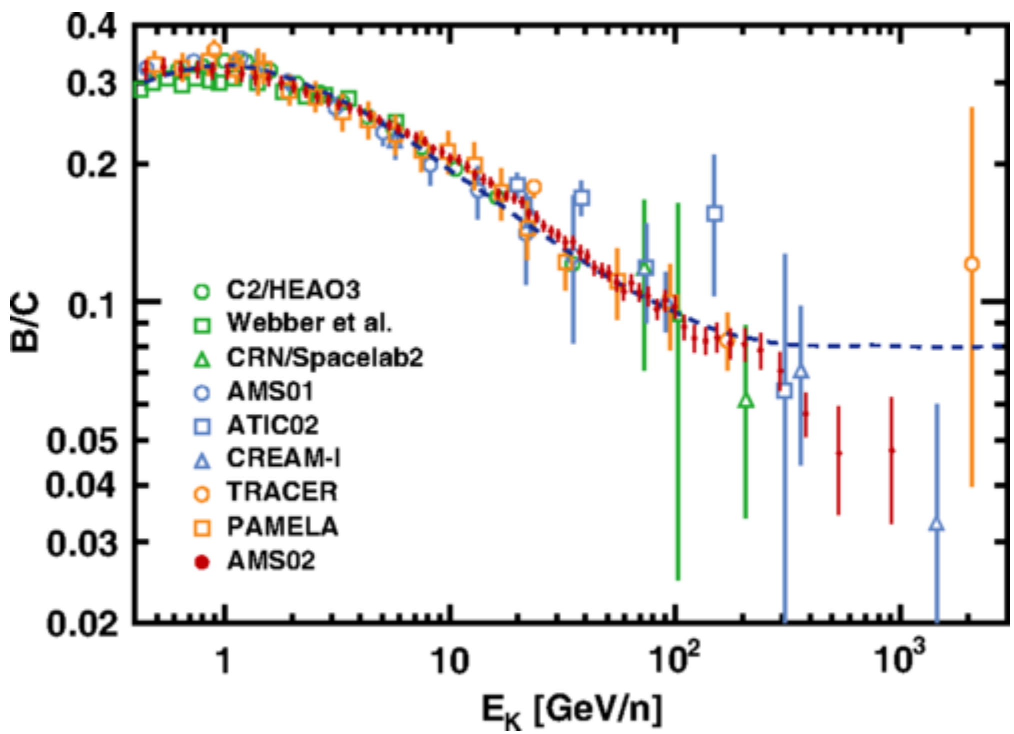
GCR nuclei identification





- Multiple dE/dx measurements ($\propto Z^2$)
- Large dynamic $\rightarrow$ **element identification up to Ni**

Secondary GCRs

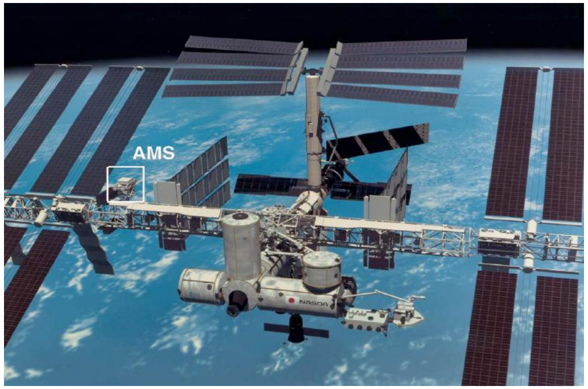


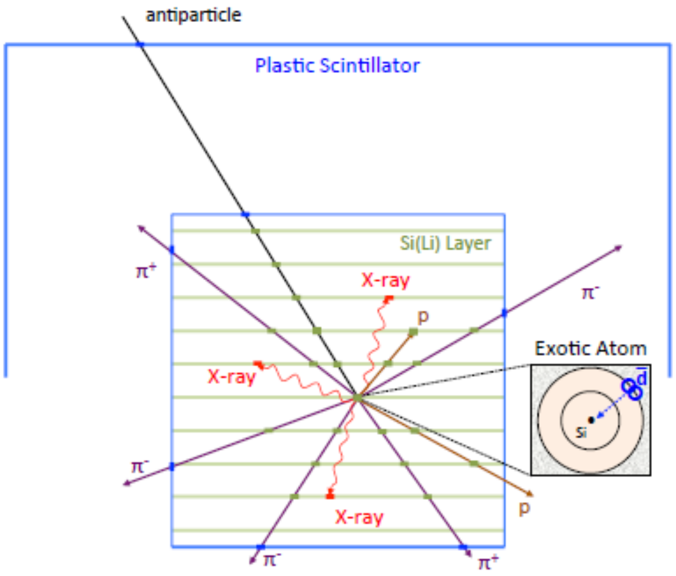
Aguilar et al PRL 117 (2016)

B/C provides the strongest constraint to propagation parameters so far

The near future

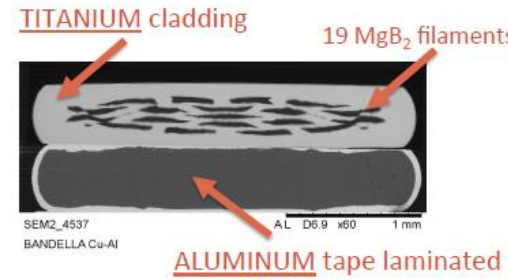
- AMS-02 still in orbit, hopefully until 2024
  - High statistic measurements
    - Antinuclei
    - Anisotropies
    - Flux of nuclei up to Fe
    - …
- Independent approach to anti-nuclei search $\rightarrow$ GAPS
  - General Anti-Particle Spectrometer
    - Low energy $\bar{p}$ measurement and $\bar{D}$ search
    - Detection of the annihilation star

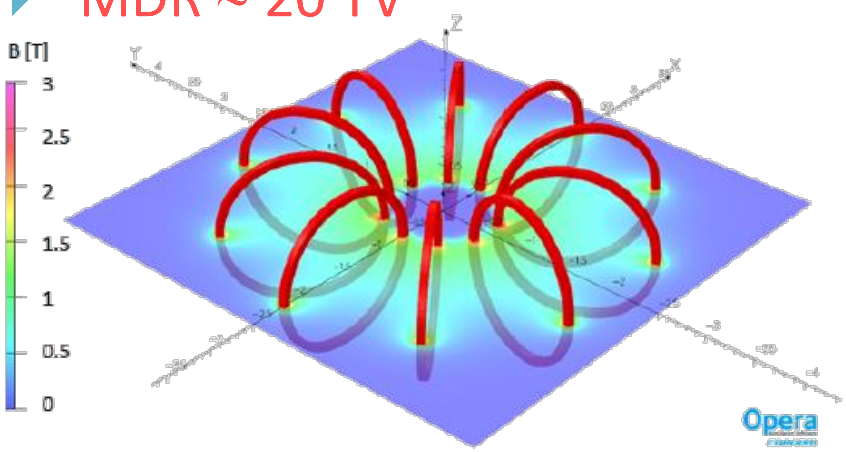


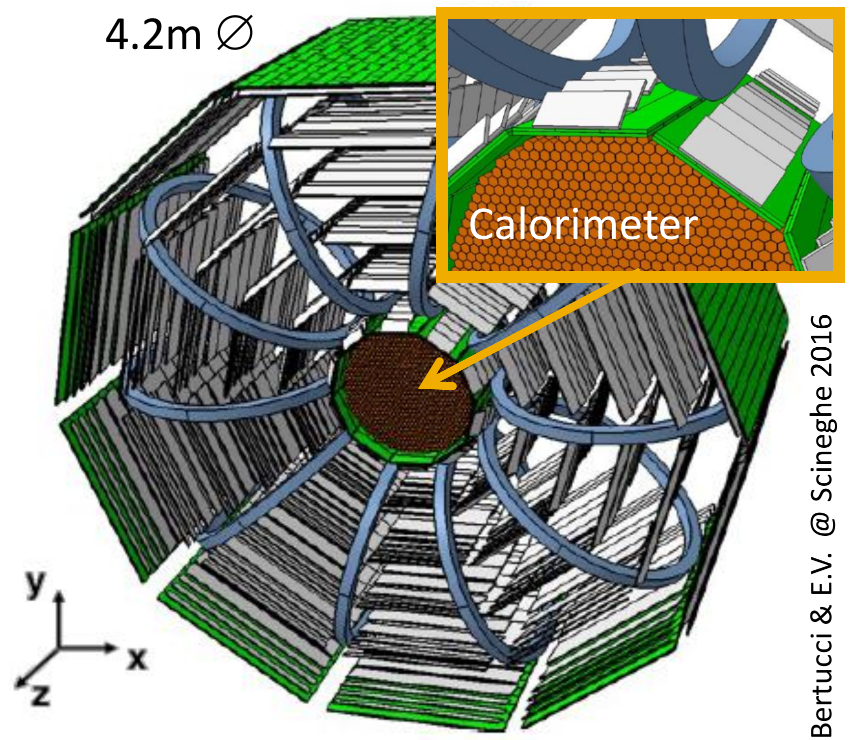


Next generation spectrometers

- Must relay on superconducting magnets
- ALADINO magnetic spectrometer
  - Toroidal superconducting magnet
    - 10 coils wound with high-temperatur (10s°K) superconductor (MgB_2)
    - $\langle B \rangle \sim 0.8$ T average magnetic field
  - Microstrip silicon tracking system
    - 4 layer with O(μm) spatial resolution
  - MDR ~ 20 TV



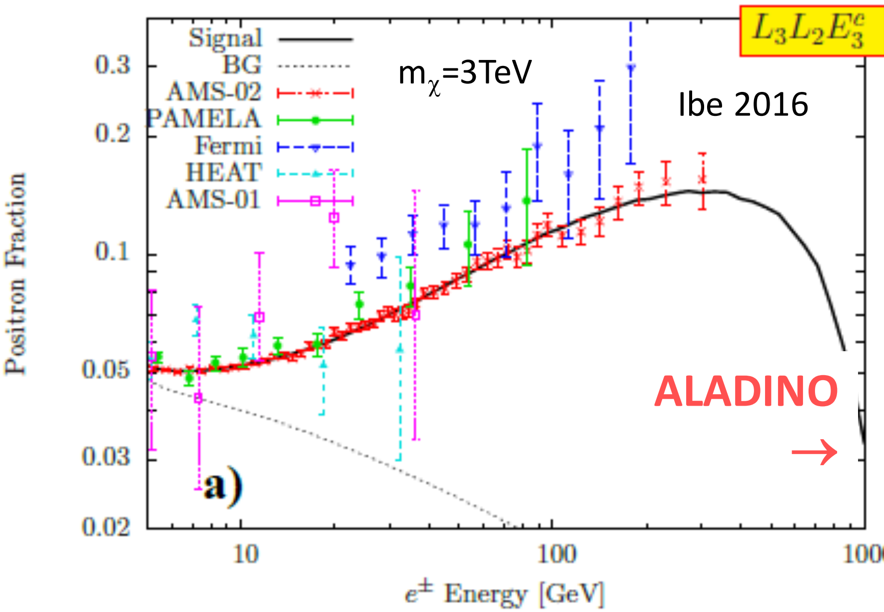


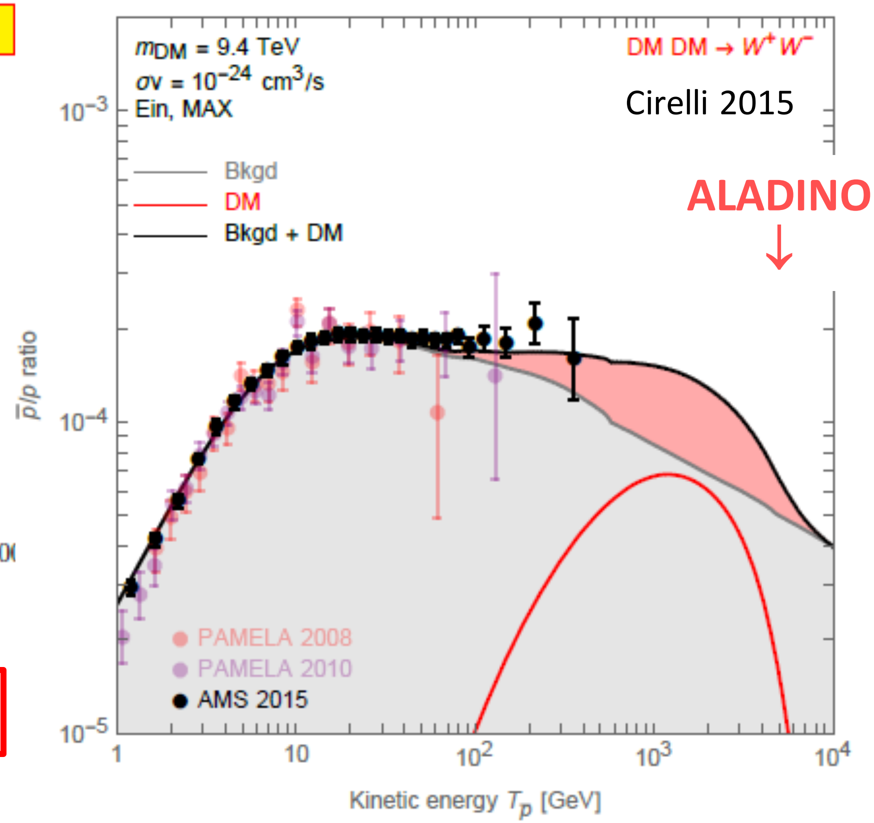


Bertucci & E.V. @ Scineghe 2016

Expected performances

PAMELA/AMS02 → MDR~1TV





MDR~ 20 TV → e^+ and $\bar{p}$ up to 5TeV !!

- Examples of contribution to e^+ and $\bar{p}$ CR abundance from DM annihilation

Conclusions

- Magnetic spectrometers are powerful tools to study GCRs
  - Precise energy measurement over a wide range
  - Possibility to determine the charge sign $\rightarrow$ antimatter!

- Last generation of spaceborne spectrometers (PAMELA & AMS-02) took advantage of microstrip-Si technology
  - Precise measurements of all GCRs performed up to O(TV) MDR
  - Results challenge the standard paradigm of GCR origin
    - Positron excess
    - Unexpected features in the H and He spectra (and maybe heavier nuclei)
    - Hints of $\bar{p}$ excess at high energy
    - Possible first detection of antinuclei
  - Significant progress in understanding galactic phenomena

- Next generation of spectrometers must rely on developments of high-temperature superconductor technology
  - $\rightarrow$ O(10 TV) MDR !!!