



The PAMELA Space Experiment

Emiliano Mocchiutti
(INFN - Trieste)

on behalf of the *PAMELA collaboration*

- Rencontres de Moriond, Electroweak Session - La Thuile - March 11th 2009 -

2430
07:57:29

Presentation outline

- The PAMELA experiment: short review
- Results on cosmic-ray antiparticles abundance:
 - Antiprotons
 - Positrons
- Other results:
 - Cosmic-ray galactic light nuclei (primaries & secondaries)
 - Solar physics
 - Terrestrial physics
- Summary

PAMELA

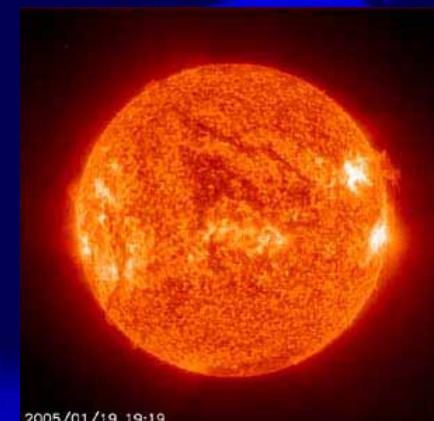
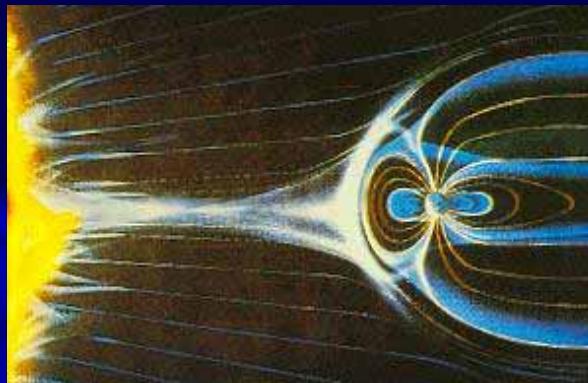
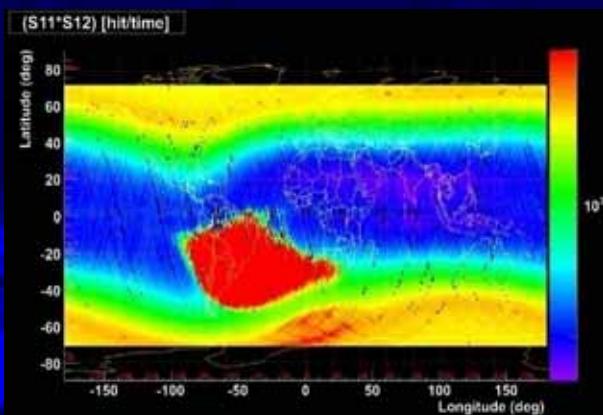


Emiliano Mocchiutti, INFN Trieste - Rencontres de Moriond EW Session, La Thuile, March 11th 2009



PAMELA: a Space Observatory at 1 AU

- **Search for dark matter annihilation**
- **Search for antihelium (primordial antimatter)**
- **Search for new Matter in the Universe (Strangelets?)**
- **Study of cosmic-ray propagation**
- **Study of solar physics and solar modulation**
- **Study of terrestrial magnetosphere**
- **Study of high energy electron spectrum (local sources?)**



PAMELA apparatus



GF: 21.5 cm² sr
Mass: 470 kg
Size: 130x70x70 cm³
Power Budget: 360W

Today:
1001th flight day!

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 λl)

- Discrimination e+ / p, anti-p / e- (shower topology)
- Direct E measurement for e-

Neutron detector

plastic scintillators + PMT:

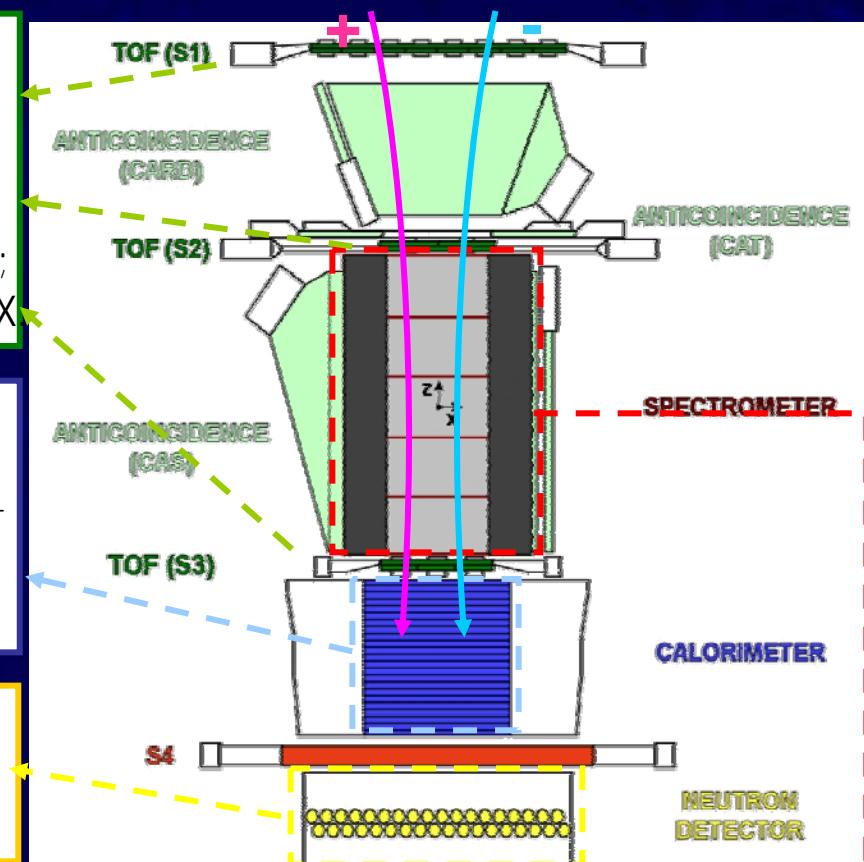
- High-energy e/h discrimination

Spectrometer

microstrip silicon tracking system + permanent magnet

It provides:

- Magnetic rigidity $\rightarrow R = pc/Ze$
- Charge sign
- Charge value from dE/dx



PAMELA design performance

<u>Particle</u>	<u>Energy range</u>	
Antiprotons	80 MeV ÷ 150 GeV	
Positrons	50 MeV ÷ 300 GeV	
Electrons	up to 500 GeV	
Protons	up to 700 GeV	
Electrons+positrons	up to 2 TeV	(calorimeter)
Light Nuclei	up to 200 GeV/n	

- Unprecedented statistics
- New energy range for cosmic ray physics
- Simultaneous measurements of many species

Antiprotons

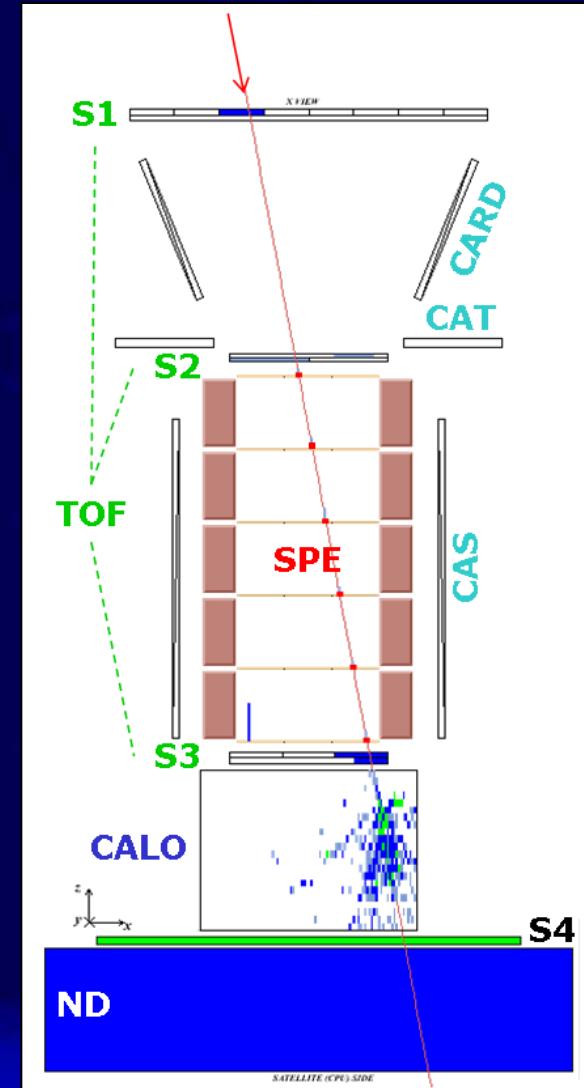
Antiproton identification

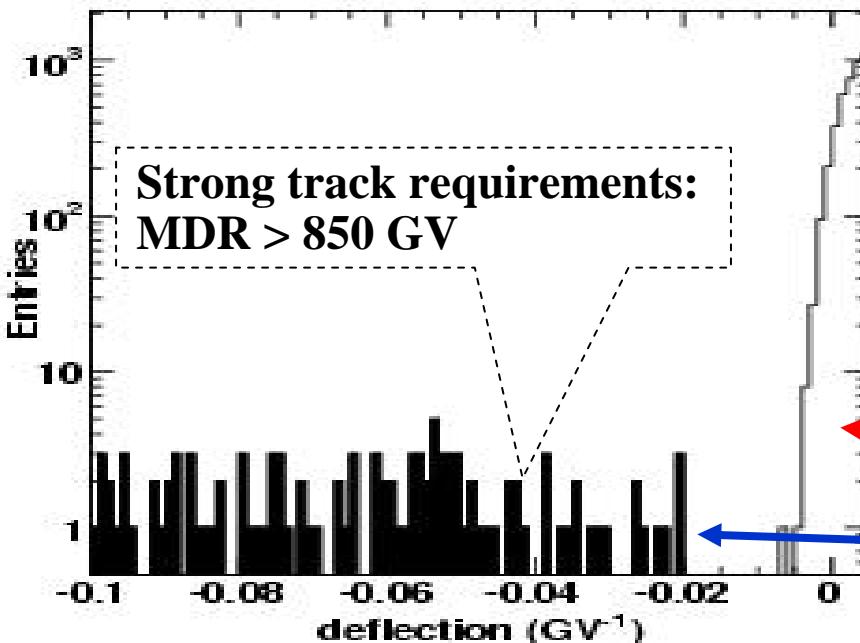
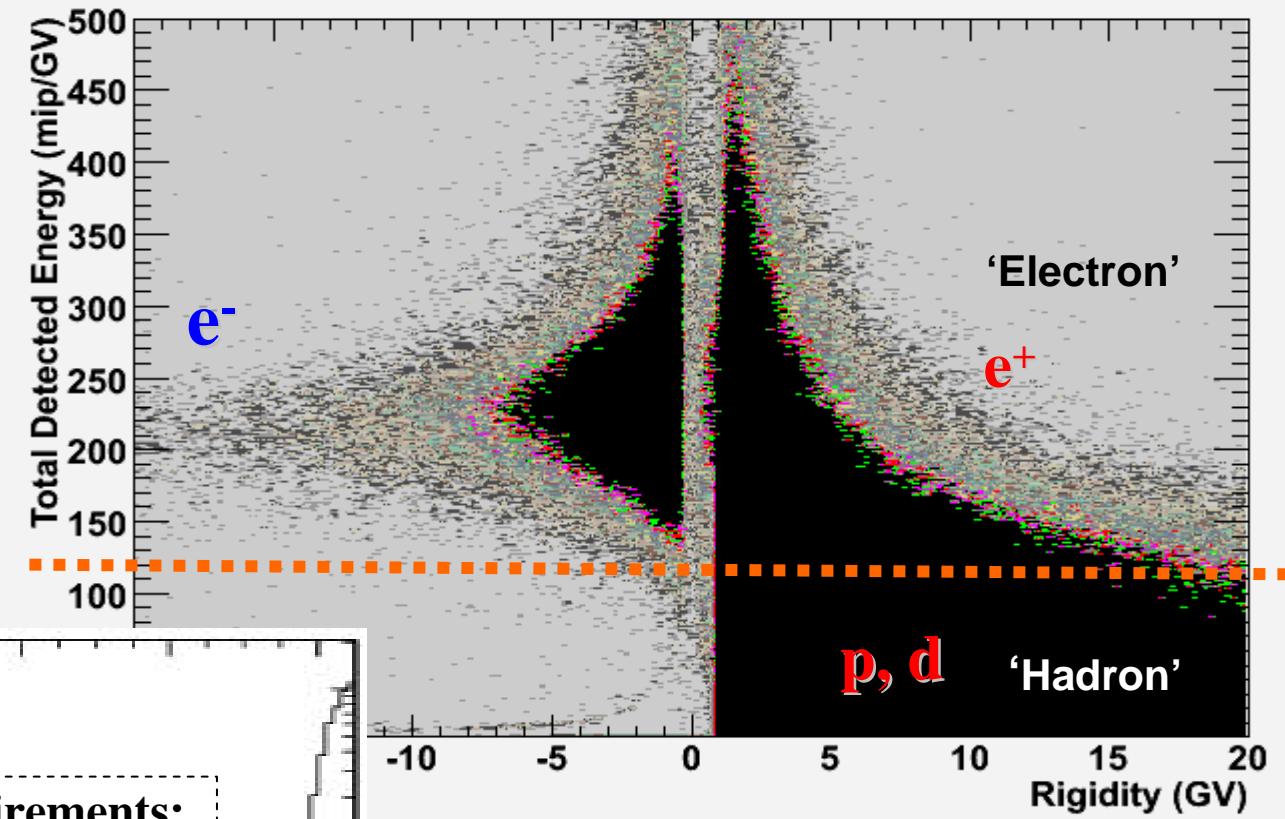
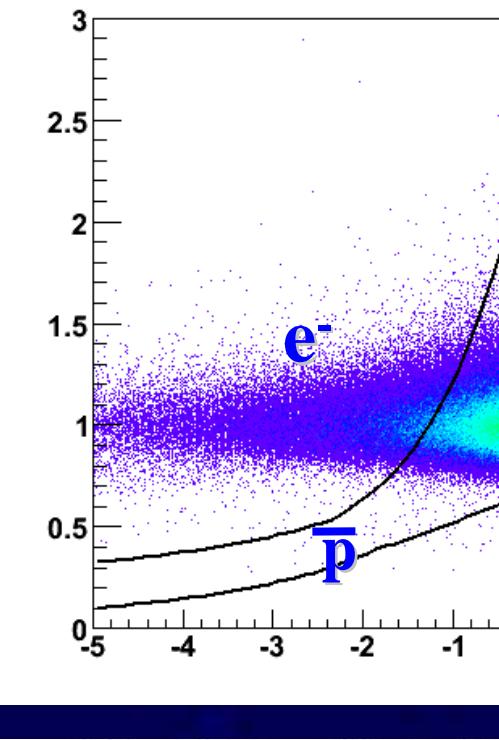
- Analyzed data July 2006 – February 2008 (~500 days)
- Collected triggers $\sim 10^8$
- Identified $\sim 10^7$ protons and $\sim 10^3$ antiprotons between 1.5 and 100 GeV - 100 p-bar above 20GeV

- Antiproton/proton identification:
 - rigidity (R) \rightarrow SPE
 - $|Z|=1$ (dE/dx vs R) \rightarrow SPE&ToF
 - β vs R consistent with M_p \rightarrow ToF
 - $p\text{-bar}/p$ separation (charge sign) \rightarrow SPE
 - $p\text{-bar}/e^-$ (and p/e^+) separation \rightarrow CALO

- Dominant background \rightarrow spillover protons:
 - finite deflection resolution of the SPE
 \Rightarrow wrong assignment of charge-sign @ high energy

→ Strong SPE selection required



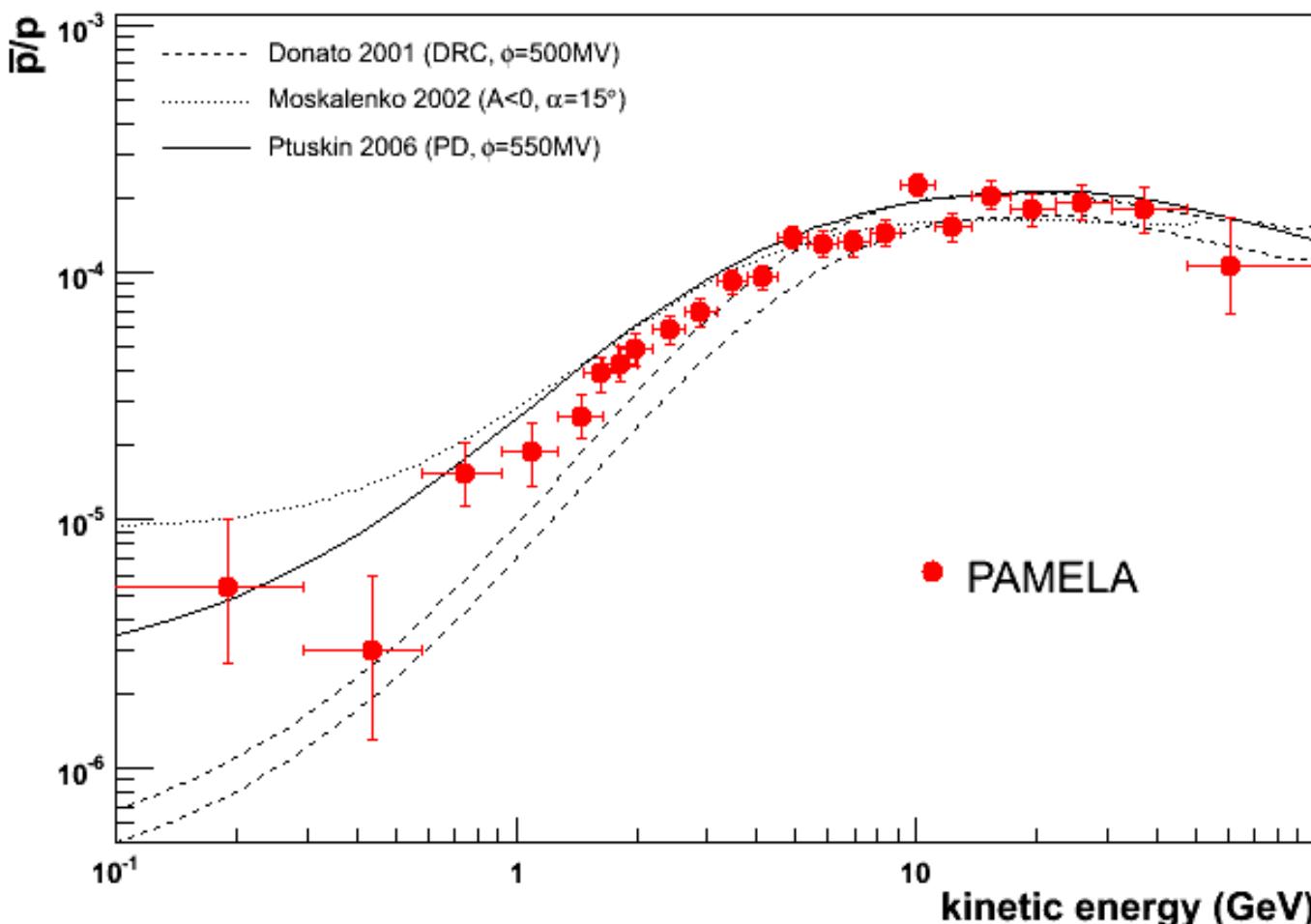


Tracker Identification
Protons (& spillover)
Antiprotons

PAMELA antiproton to proton ratio

Seconday Production Models

PRL 102:051101 (2009)



PAMELA Antiproton Flux

Preliminary

P. Hofverberg's and A. Bruno's PhD theses



Positrons

Positron identification

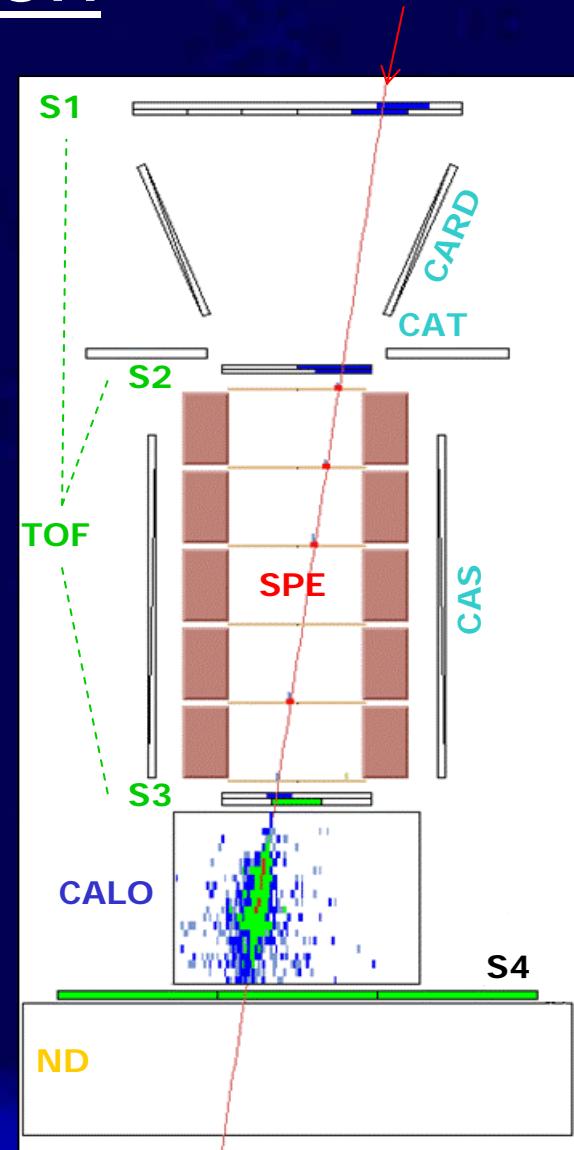
- Analyzed data July 2006 – February 2008 (~500 days)
- Collected triggers $\sim 10^8$
- Identified $\sim 1.5 \cdot 10^4$ electrons and $\sim 9 \cdot 10^3$ positrons between 1.5 and 100 GeV - 180 positrons above 20GeV

Electron/positron identification:

- rigidity (R) \rightarrow SPE
- $|Z|=1$ ($dE/dx = MIP$) \rightarrow SPE&ToF
- $\beta=1$ \rightarrow ToF
- e-/e+ separation (charge sign) \rightarrow SPE
- e+/p (and e-/p-bar) separation \rightarrow CALO

- Dominant background \rightarrow interacting protons:

proton spectrum harder than positron
 $\Rightarrow p/e+$ increase for increasing energy (10^3 @1GV 10^4 @100GV)



\rightarrow Strong CALO selection required

Positron selection with calorimeter

Methods:

**Presented results:
“background estimation”
method**

Data from test-beams and simulations were *NOT USED* in any step of flight data calibration, selection and analysis

This measurement is based purely on flight data

Background estimation:
• “weak” selection criteria
• p rejection factor $\sim O(10^4)$
• estimate p contamination
• statistical analysis
(parametric bootstrap analysis with maximum likelihood fitting)



RESULTS

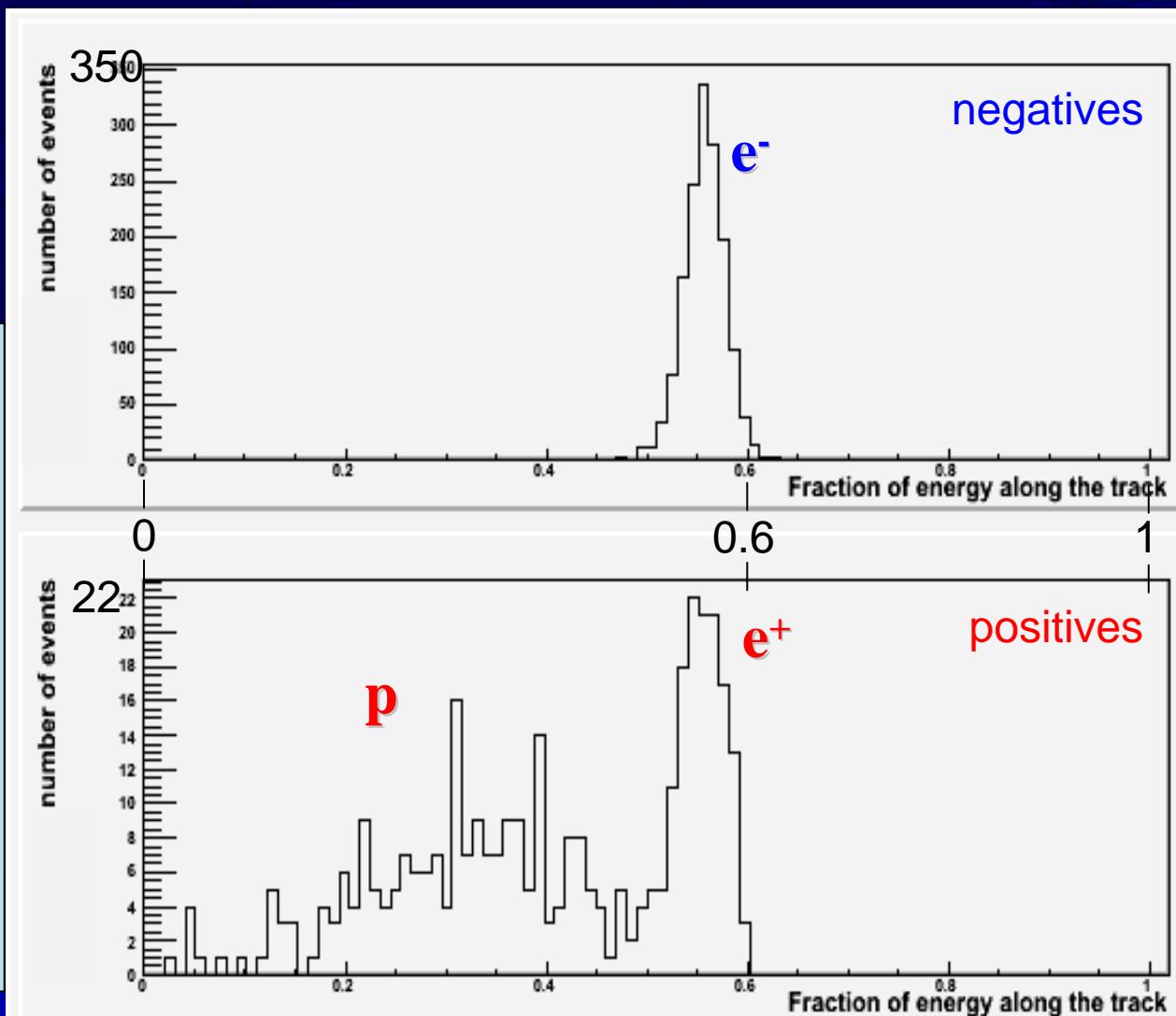
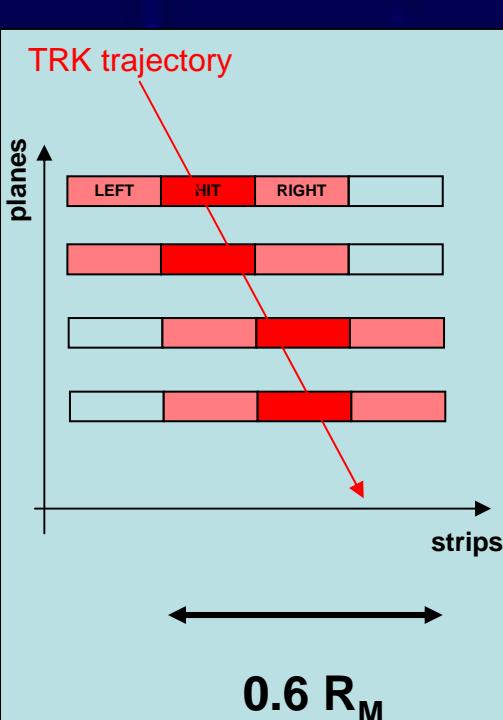
Positron selection

Fraction of energy released along the track (left, hit, right) in the calorimeter

Pre-selections:

- Energy-momentum match
- Starting point of shower

Rigidity: 20-30 GV



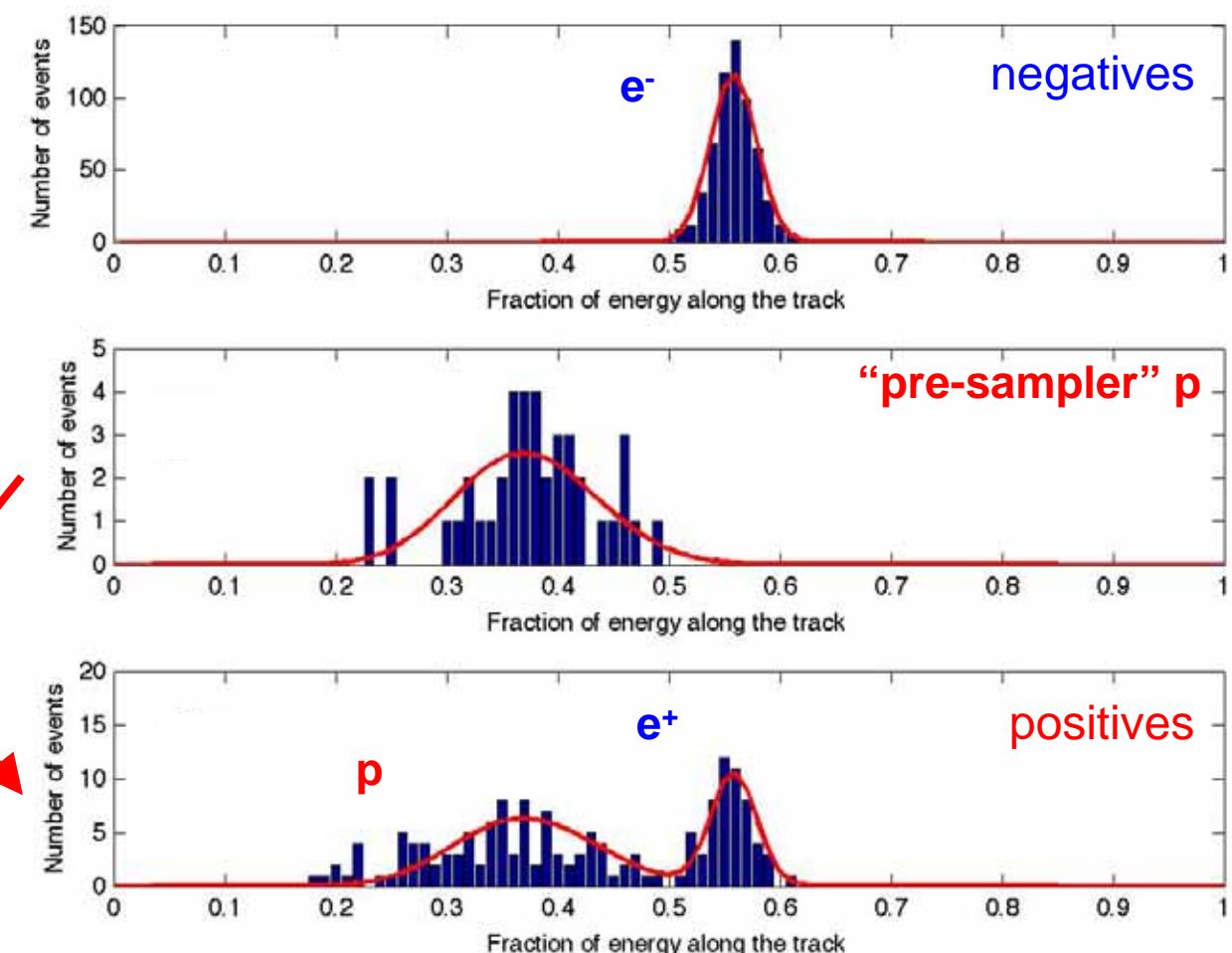
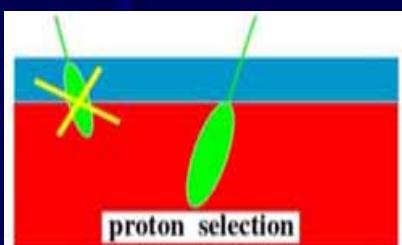
Background estimation from data

Fraction of energy released along the track (left, hit, right) in the calorimeter

Pre-selections:

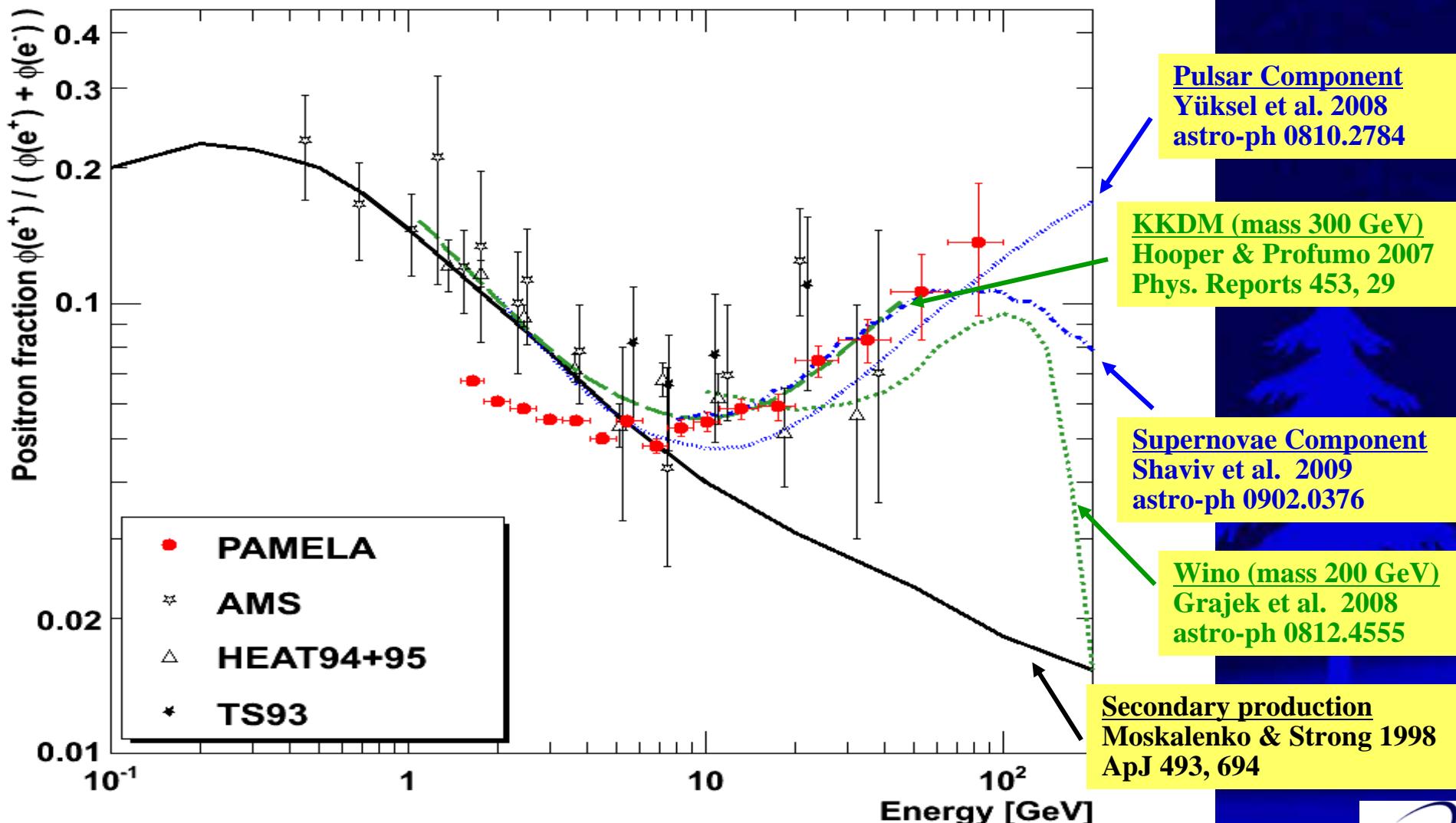
- Energy-momentum match
- Starting point of shower

Rigidity: 28-42 GV



PAMELA Positron Fraction

[astro-ph 0810.4995](#) - accepted by Nature, to appear soon



Electron (e^- , e^+ & e^-+e^+) fluxes with PAMELA

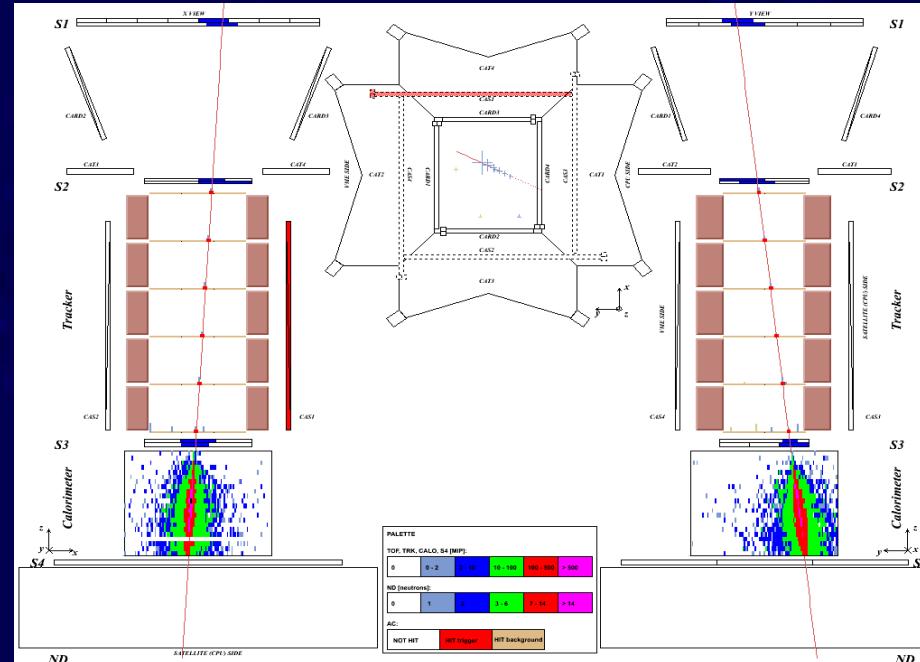
- Two independent energy measurements:

Rigidity from Tracker

Energy from Calorimeter

- Charge sign

Very Preliminary!!!



PAMELA Electron (e^-) Flux

$$\gamma \approx -3.28 \pm 0.05$$

$$\approx E^{-3.28 \pm 0.05}$$

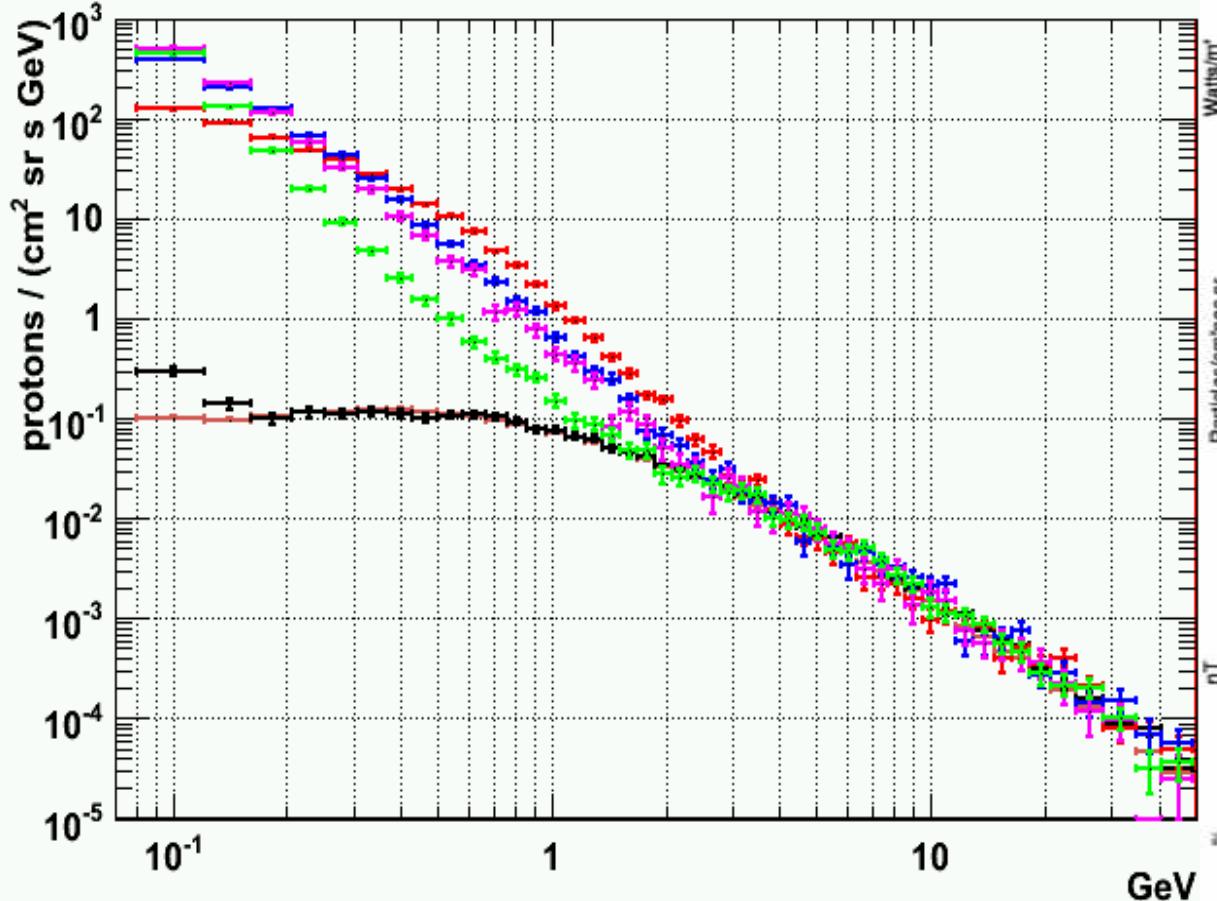
Very Preliminary!!!



Other results

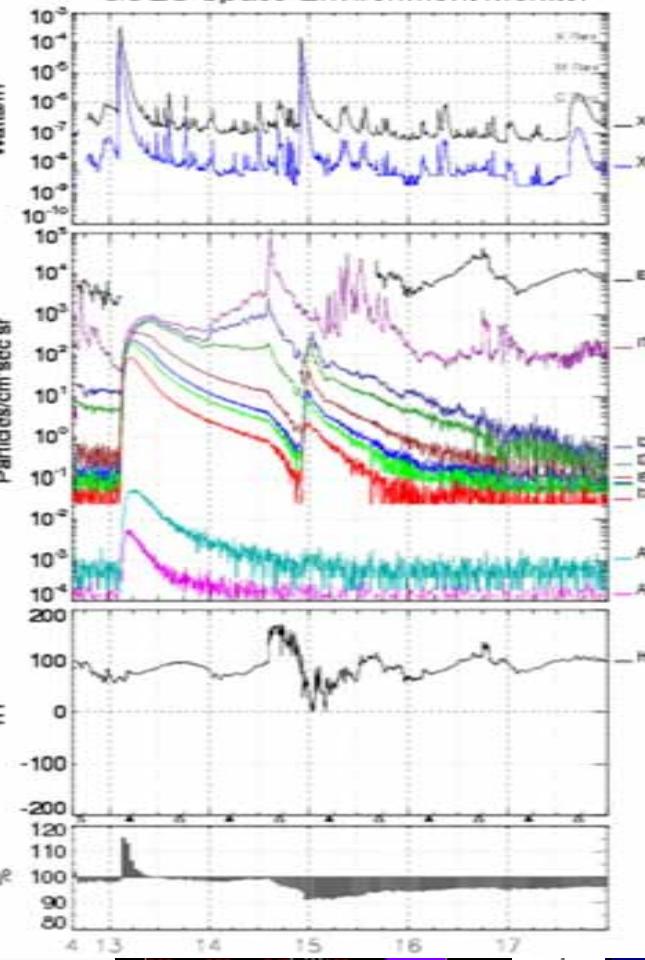
Furthermore:

Rotational



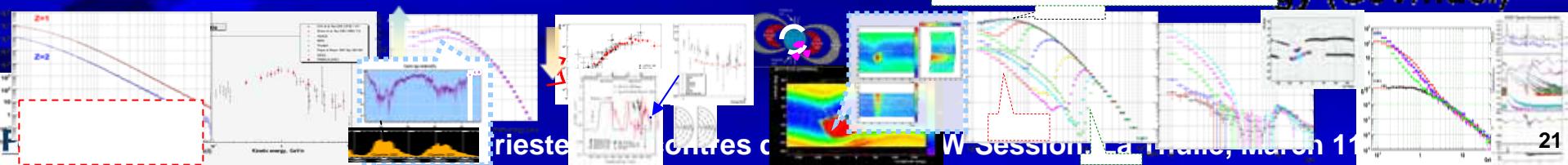
Always: $10 \text{ GeV} < \text{cuto}$

GOES Space Environment Monitor



Magnetic equator

(eg) $\text{GeV}^{-1} \text{sr}^{-1} \text{eV}^{-1} \text{nuc}^{-1}$



Summary

- PAMELA has been in orbit and studying cosmic rays for ~32 months. $>10^9$ triggers registered, and >13 TB of data has been down-linked.
- Antiproton-to-proton flux ratio (~ 100 MeV - ~ 100 GeV) shows no significant deviations from secondary production expectations. Additional high energy data in preparation (up to ~ 150 GeV).
- High energy positron fraction (>10 GeV) increases significantly (and unexpectedly!) with energy. Primary source? Data at higher energies will help to resolve origin of rise (spillover limit ~ 300 GeV).
- Analysis ongoing to measure the e^- spectrum up to ~ 500 GeV, e^+ spectrum up to ~ 300 GeV and all electrum ($e^- + e^+$) spectrum up to ~ 1 TeV.
- Furthermore:
 - PAMELA is going to provide measurements on elemental spectra and low mass isotopes with an unprecedented statistical precision and is helping to improve the understanding of particle propagation in the interstellar medium
 - PAMELA is able to measure the high energy tail of solar particles.
 - PAMELA is able to measure composition and spectra of trapped particles.



Thanks!

PAMELA Physics Workshop
Auditorium Via Rieti - Rome (Italy)
11-12 May 2009

<http://pamela.roma2.infn.it/workshop09>

Backup slides



The PAMELA Collaboration

Italy:



Bari



Florence



Frascati



Naples



Rome



Trieste



CNR, Florence

Russia:



Moscow
St. Petersburg



Germany:



Siegen

Sweden:



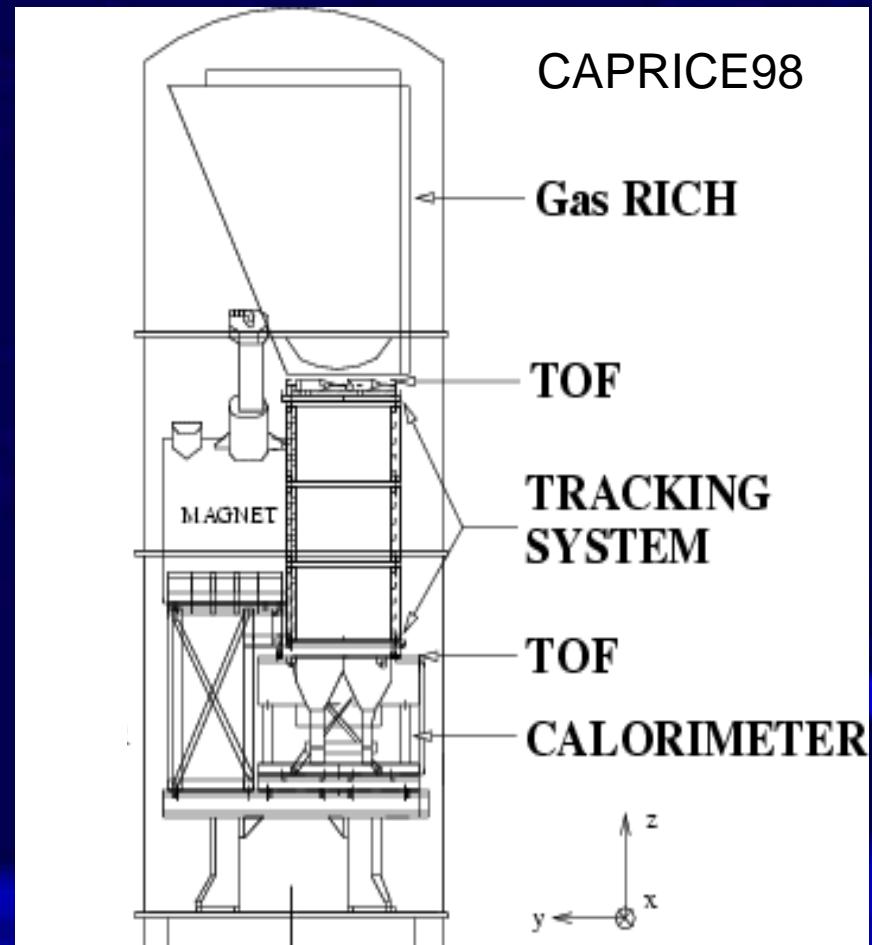
KTH, Stockholm



Proton rejection power: C98 vs PAMELA

	CAPRICE98	PAMELA
TRACKER MDR	~ 350 GV	~ 1000 GV
CALO DEPTH	$7.2 X_0$	$16.3 X_0$
LONGITUDINAL SAMPLING	$0.9 X_0$	$0.7 X_0$
TRANSVERSAL SAMPLING (strip width)	$0.3 R_M$ (3.6 mm)	$0.2 R_M$ (2.44 mm)
PROTON REJECTION	$\sim 10^5$	$>10^5$

tested with
RICH up to 50 GV



Gamma-rays?

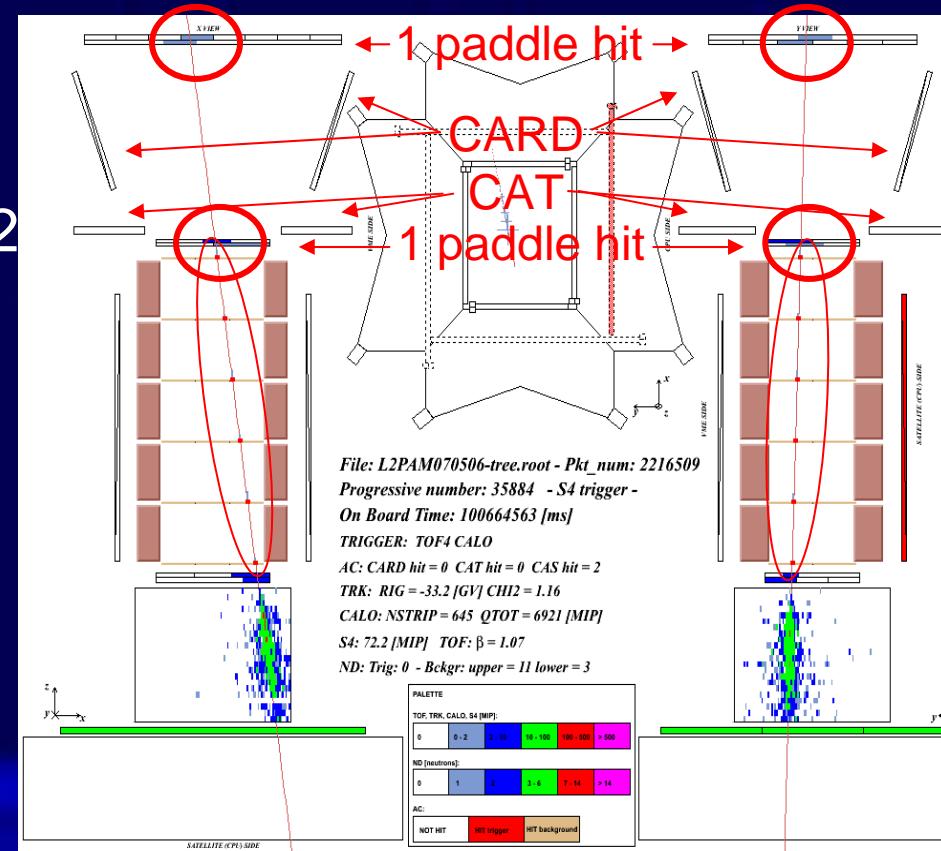
$\gamma/e^+ : \sim 0.1 @ 10\text{GeV}$
 $\sim 0.2 @ 100\text{GeV}$

Positron selection requires:

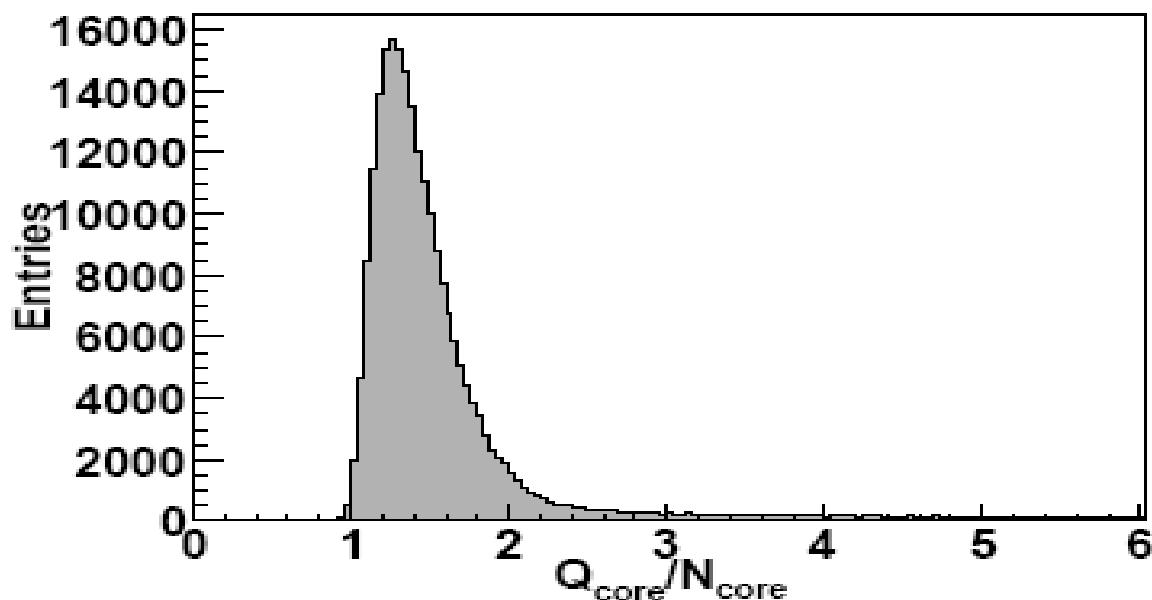
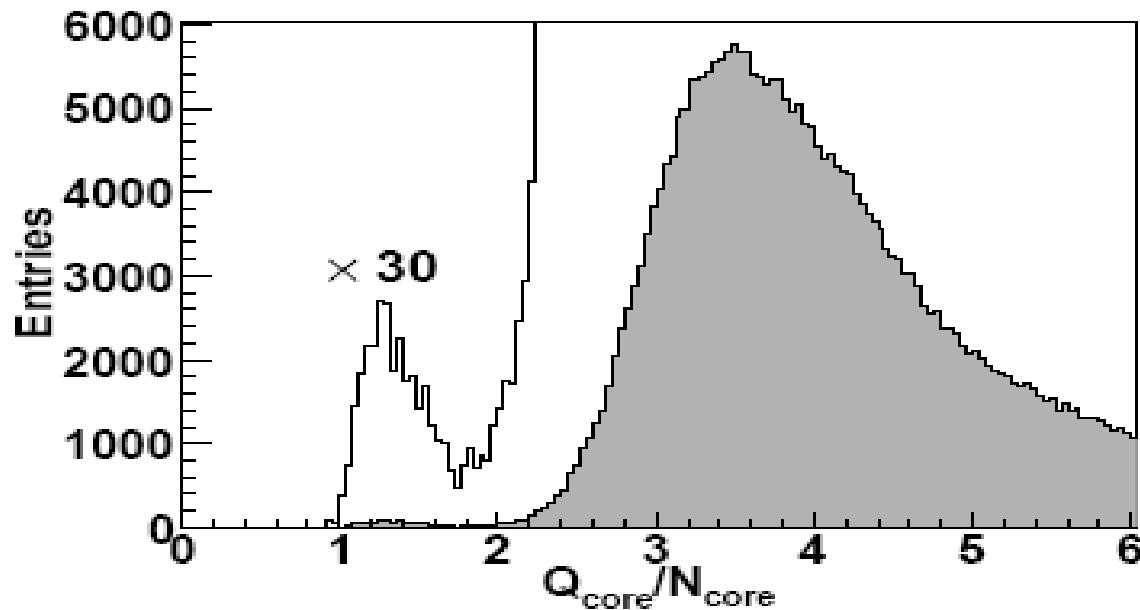
- A. 1 MIP (>0.2MIP) signal on S1/S2
- B. no multiple paddle hit on S1/S2
- C. no hit on CARD and CAT
- D. clean track in TRK
(no spurious hits, no clusters not used in track fitting)

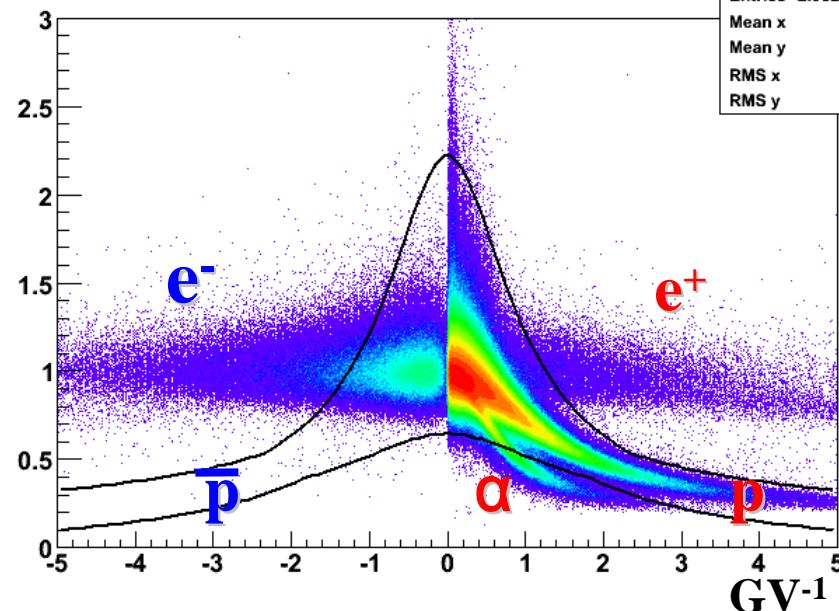
From simulations:

γ/e^+ after cuts A-B-C:
 $< 4 \times 10^{-3} @ 10\text{GeV}$
 $< 2 \times 10^{-3} @ 100\text{GeV}$

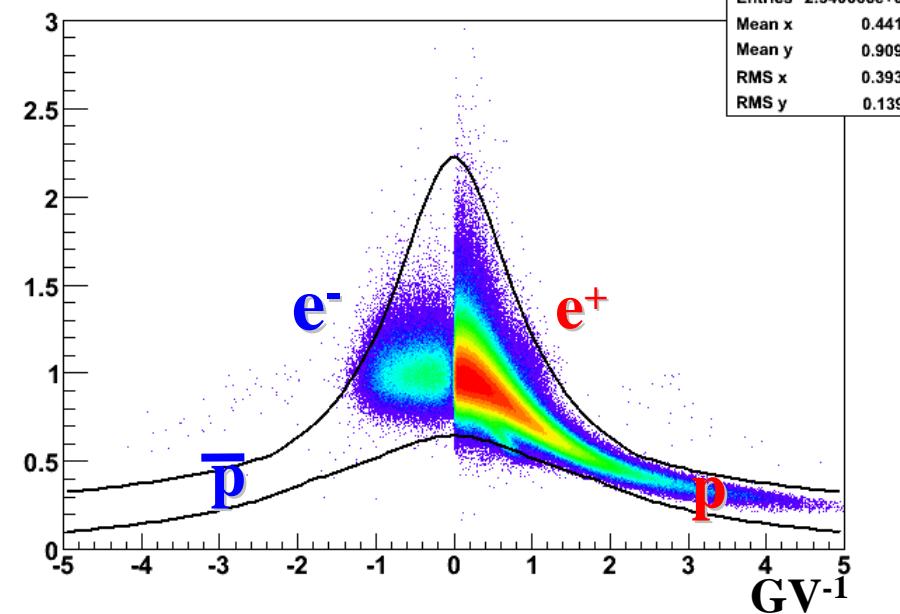
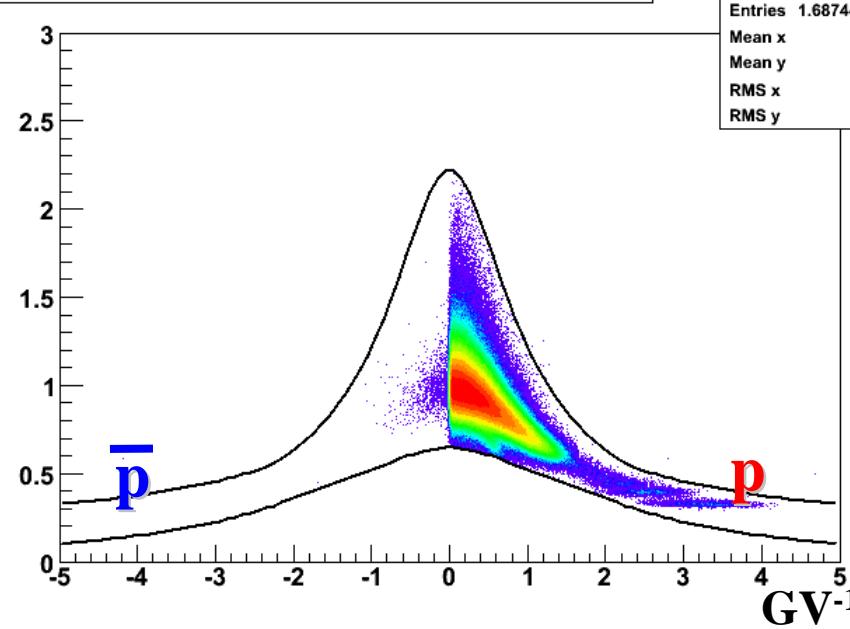


Calorimeter selection

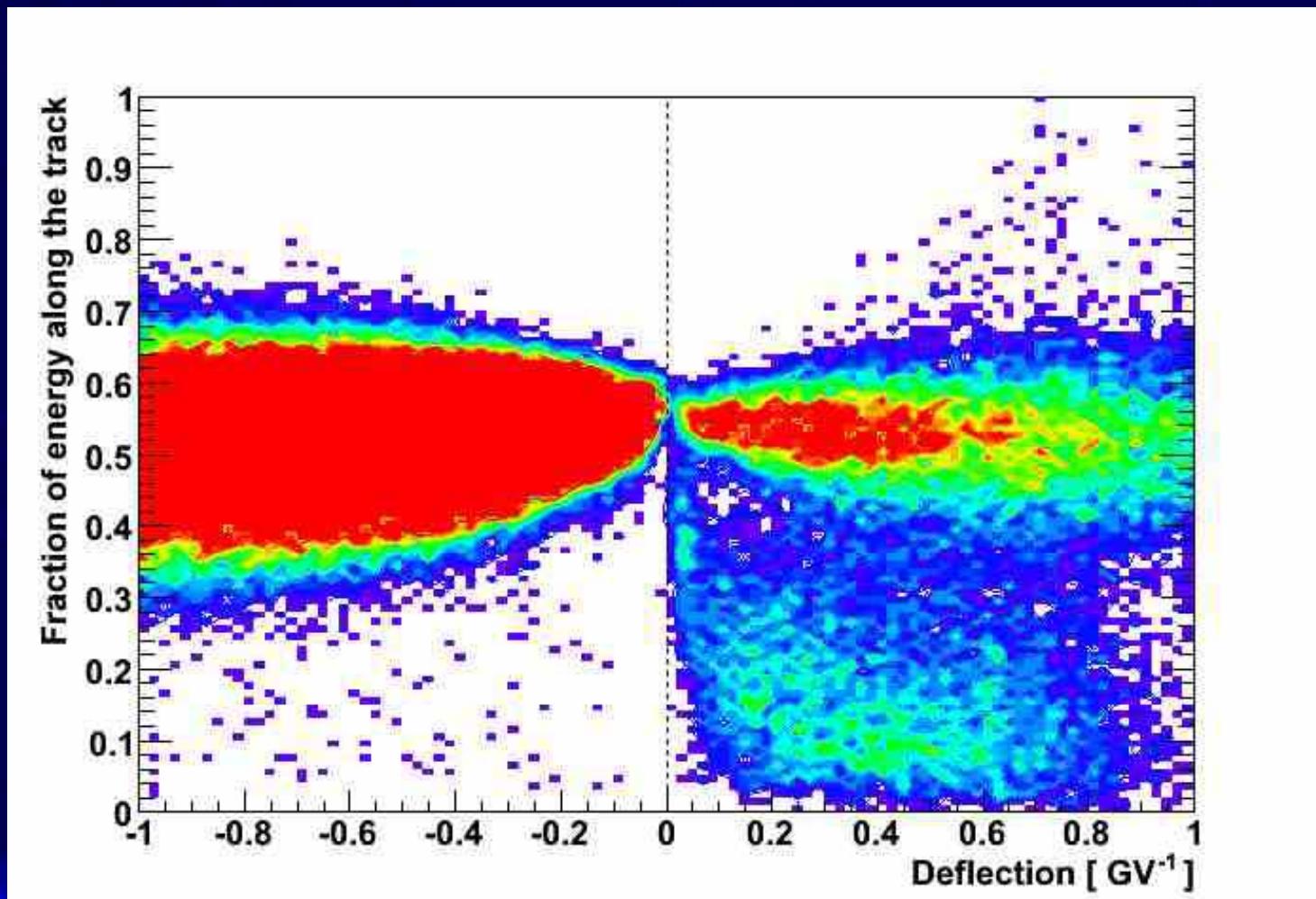


beta vs deflection

Antiproton identification

beta vs deflection -- after Z1 sel (Trk+ToF)**beta vs deflection -- after Z1&&BETA sel -- no electrons**

Positron selection with calorimeter



Fraction of charge released along the
calorimeter track (left, hit, right)



Energy-momentum match
Starting point of shower

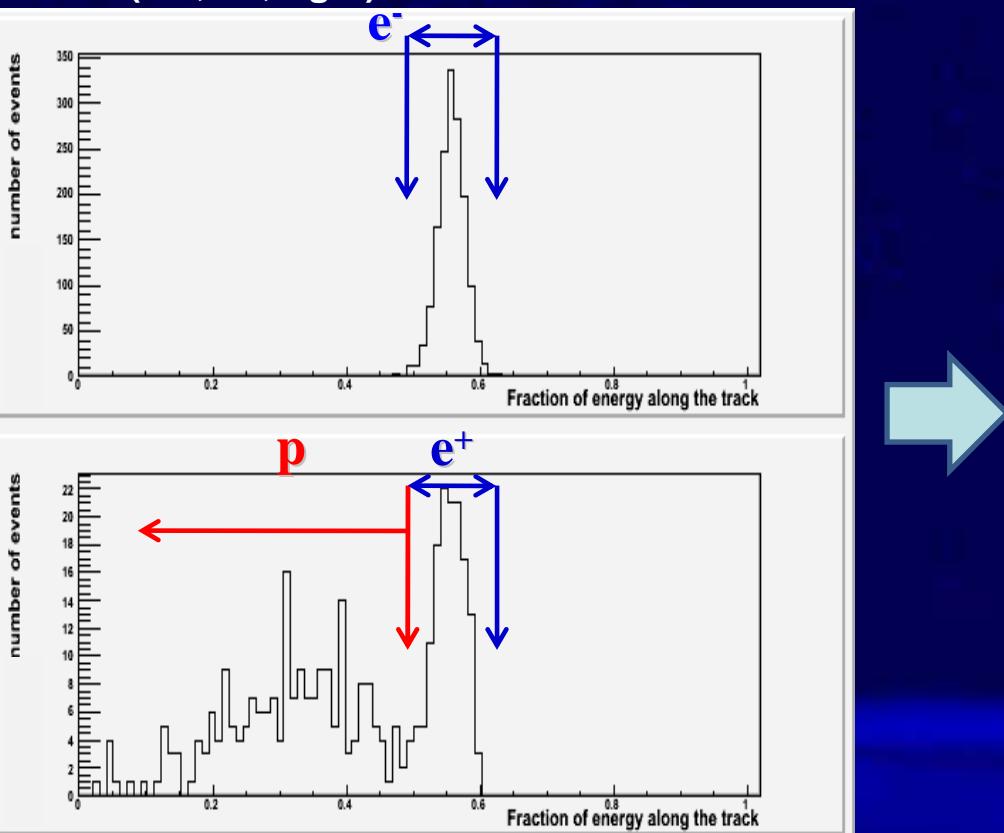
Positron selection

Pre-selections:

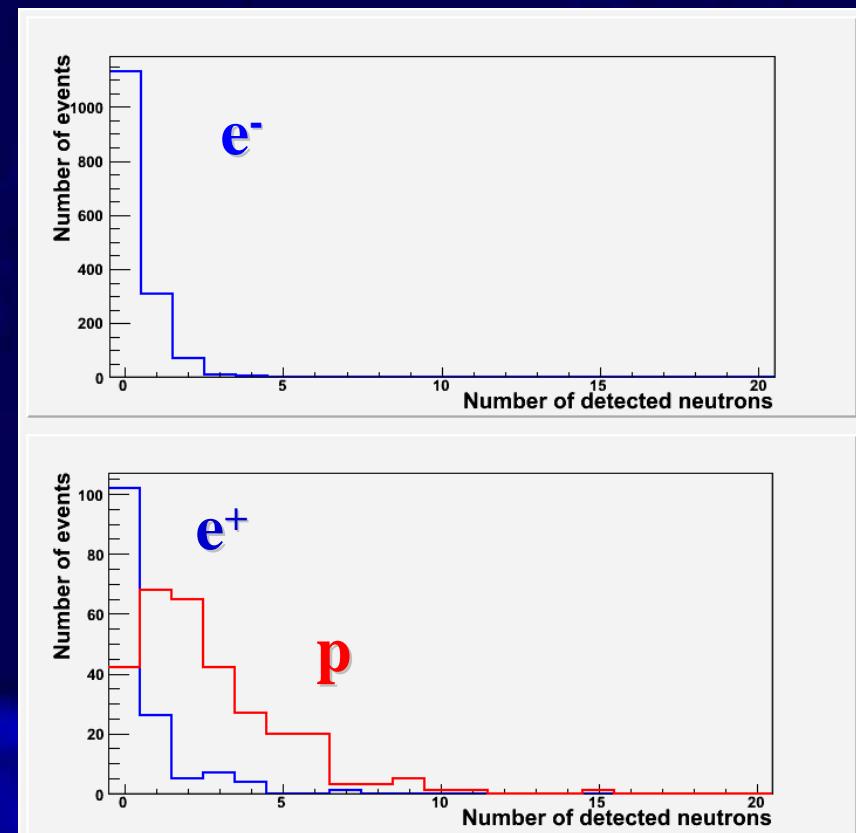
- Energy-momentum match
- Starting point of shower

Rigidity: 20-30 GV

Fraction of charge released along the track
(left, hit, right) in the calorimeter



Neutrons detected by ND



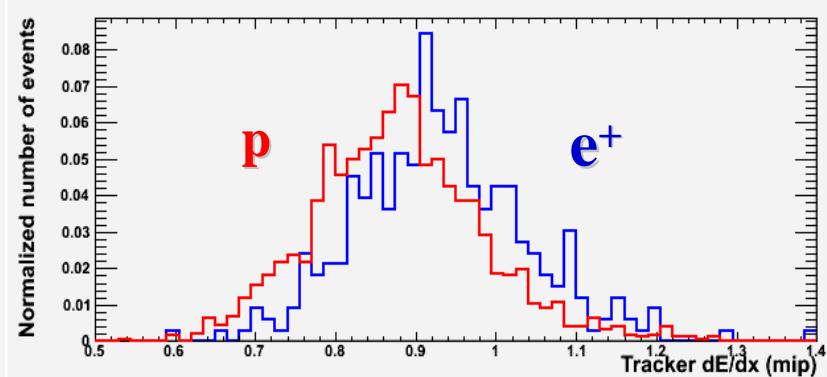
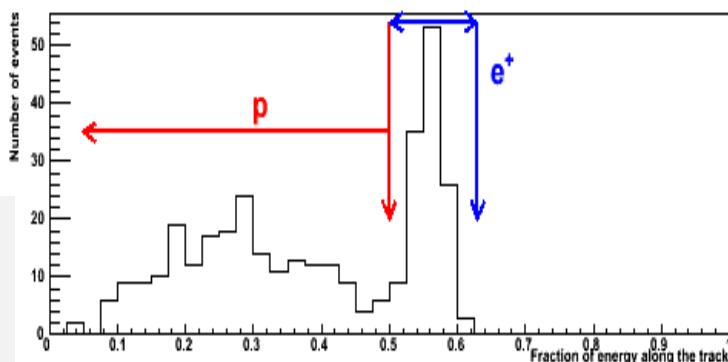
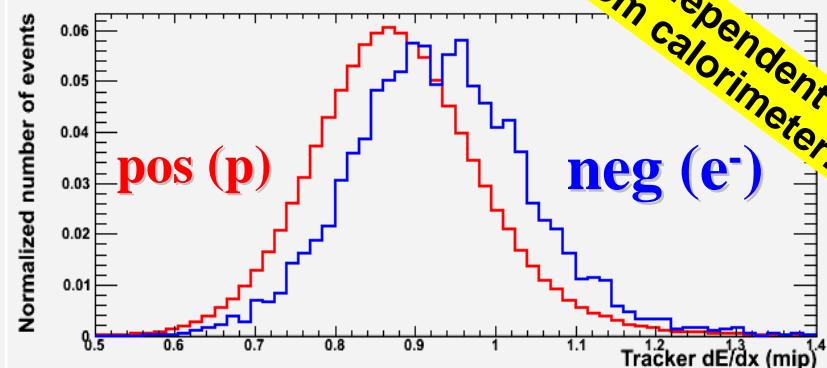
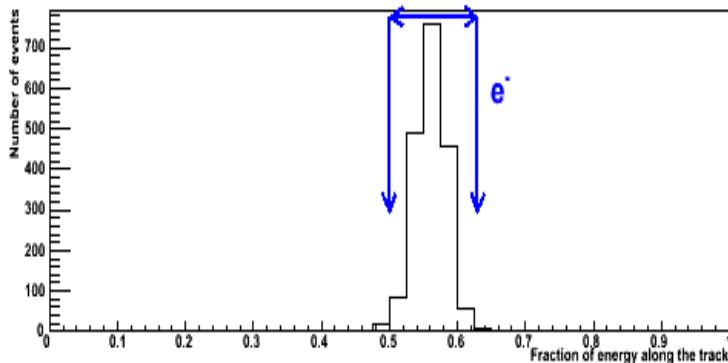
Positron selection

$$-\frac{dE}{dx} = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$

Energy loss in silicon tracker detectors:

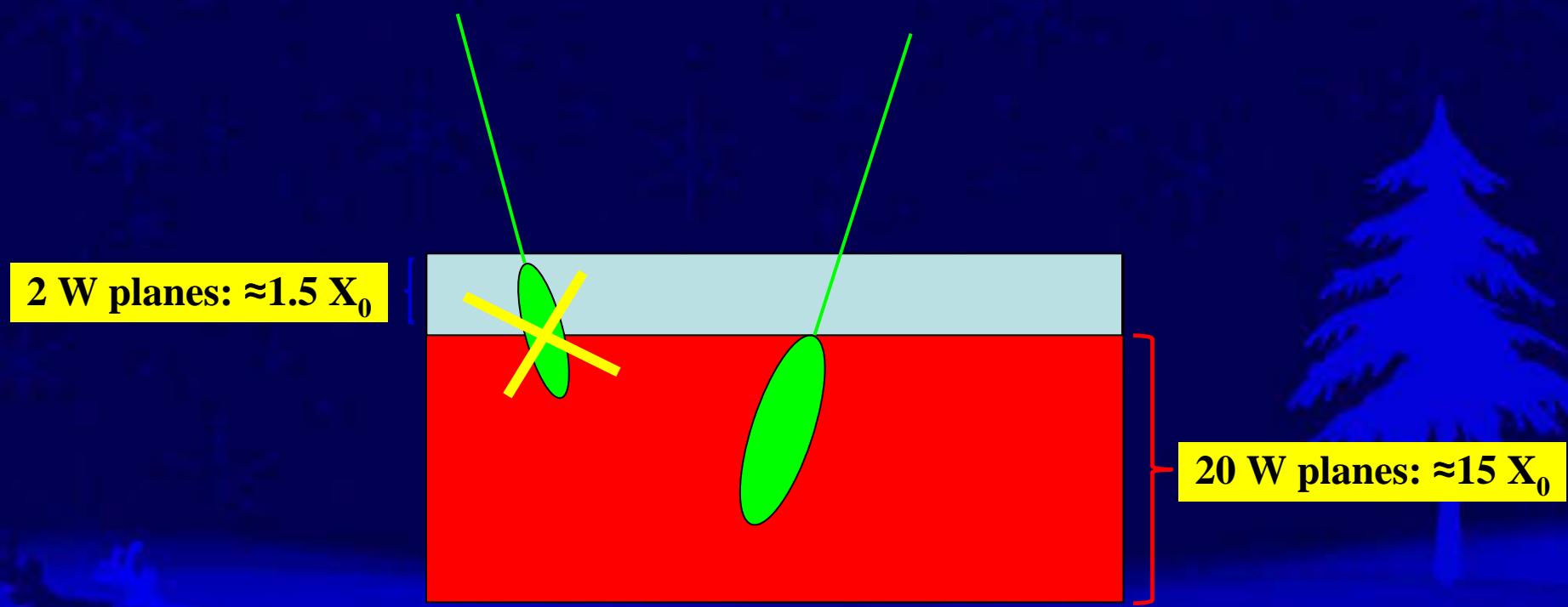
- Top: positive (mostly p) and negative events (mostly e⁻)
- Bottom: positive events identified as p and e⁺ by trasversal profile method

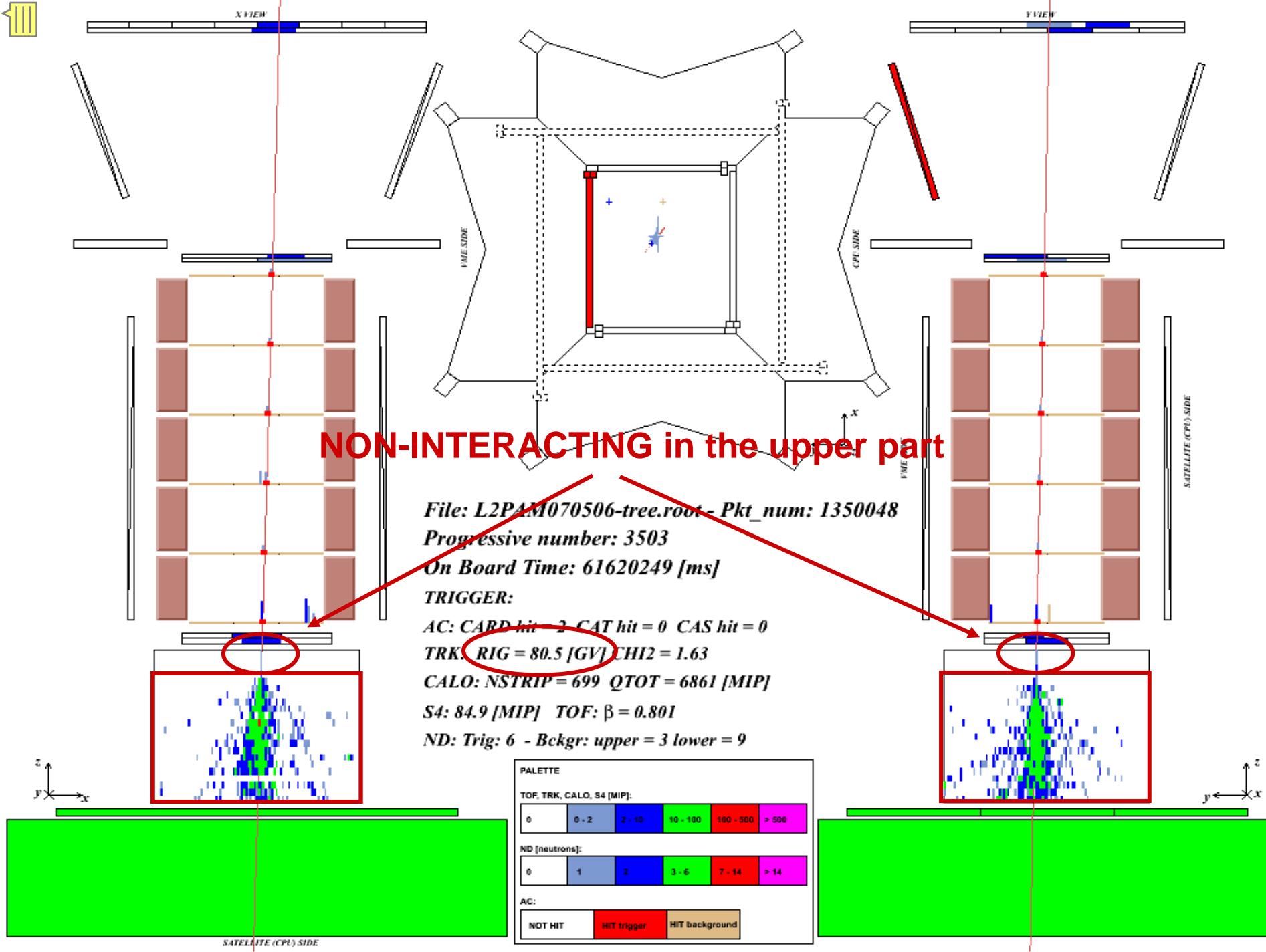
Rigidity: 10-15 GV

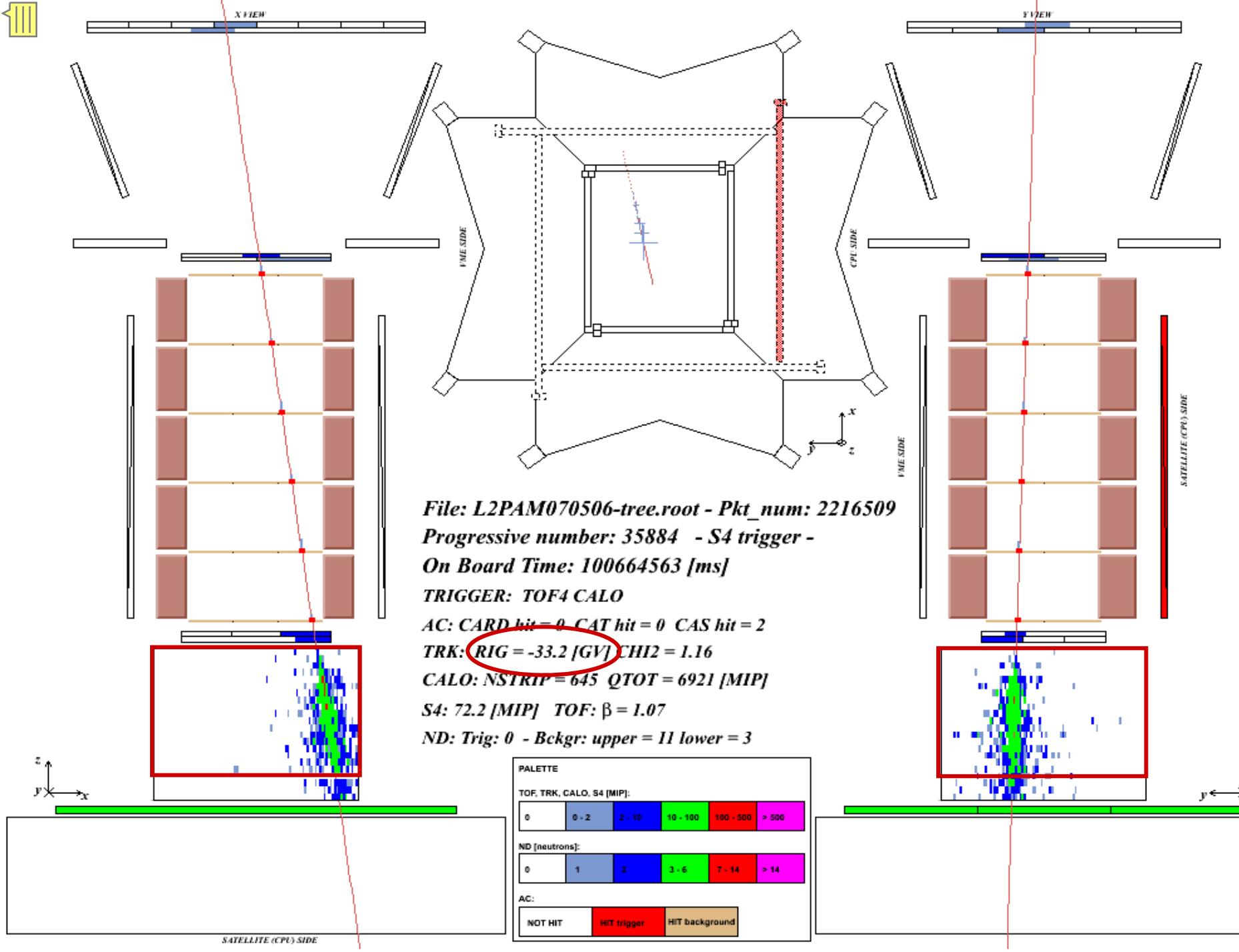


The “pre-sampler” method

CALORIMETER: 22 W planes: $16.3 X_0$







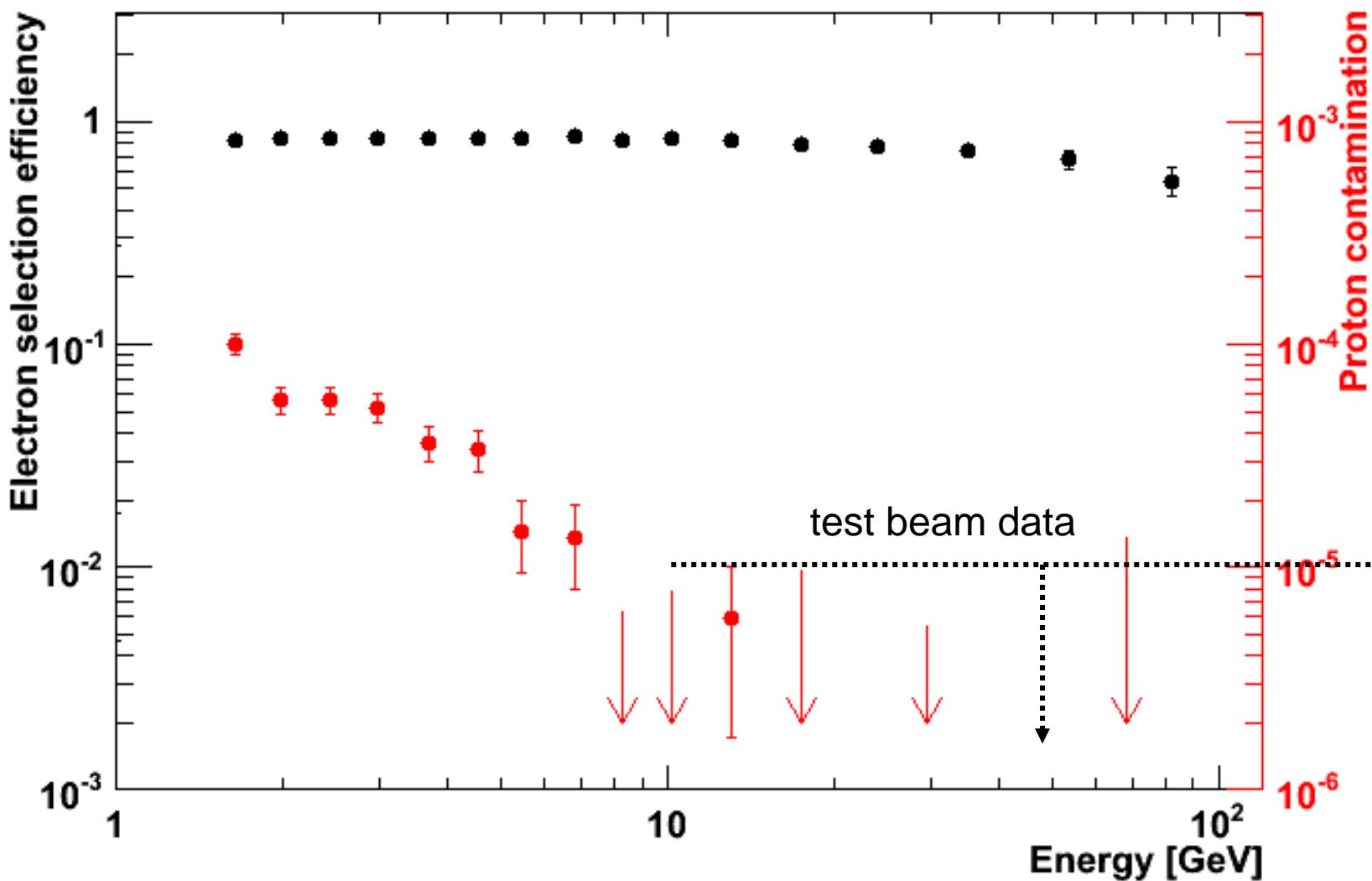
Positron selection with calorimeter

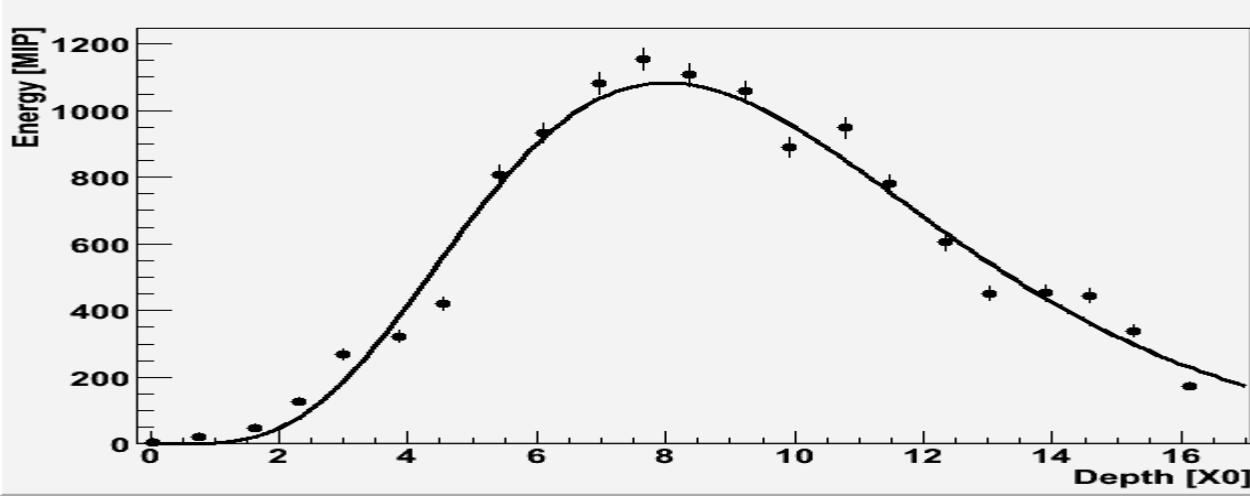
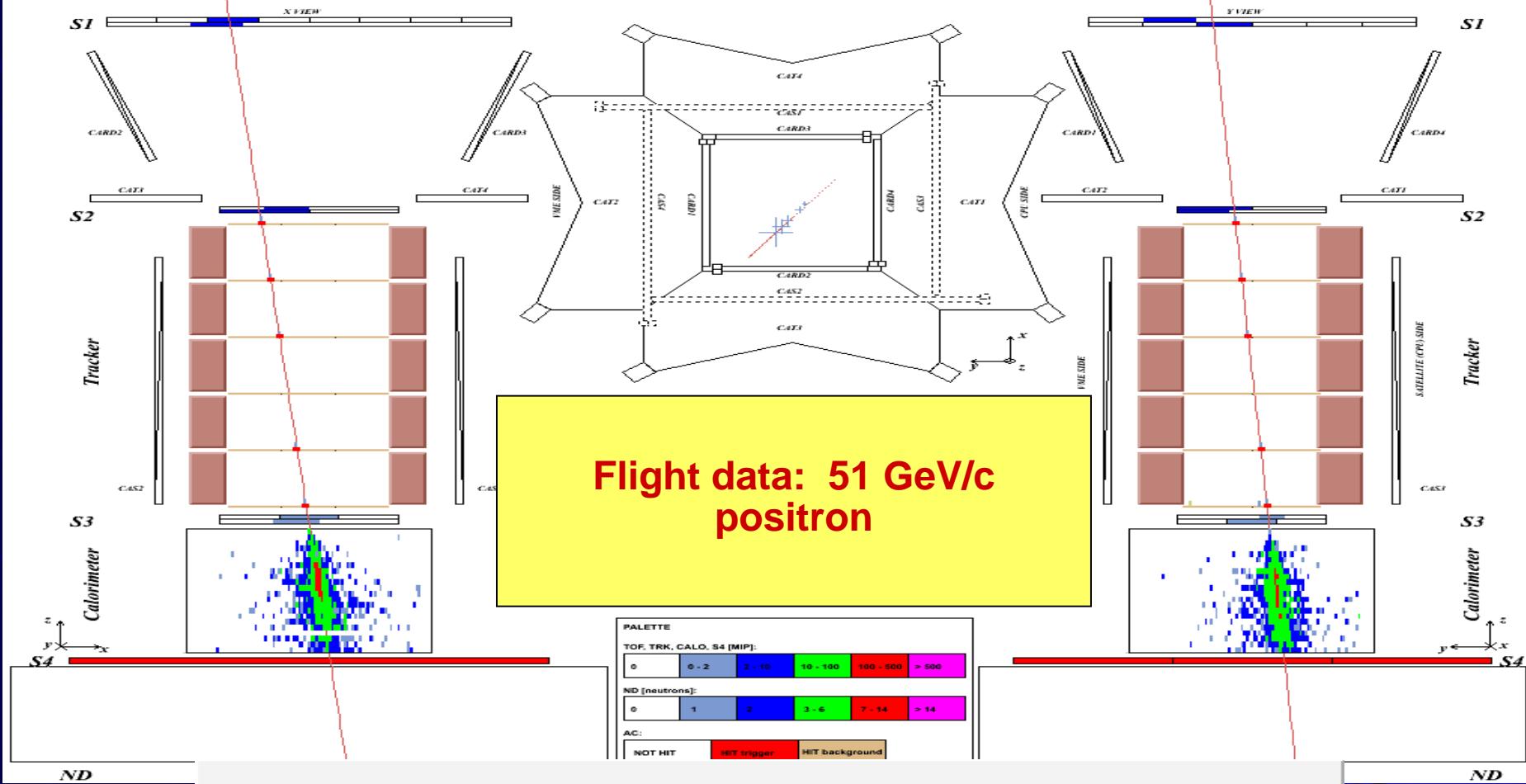
TMVA: Toolkit for MultiVariate data Analysis
<http://tmva.sourceforge.net/>

TMVA host large variety of multivariate classification algorithms (cut optimization with genetic algorithm, linear and non-linear discriminant and neural networks, support vector machine, boosted decisional trees, ...)



Positron selection with calorimeter



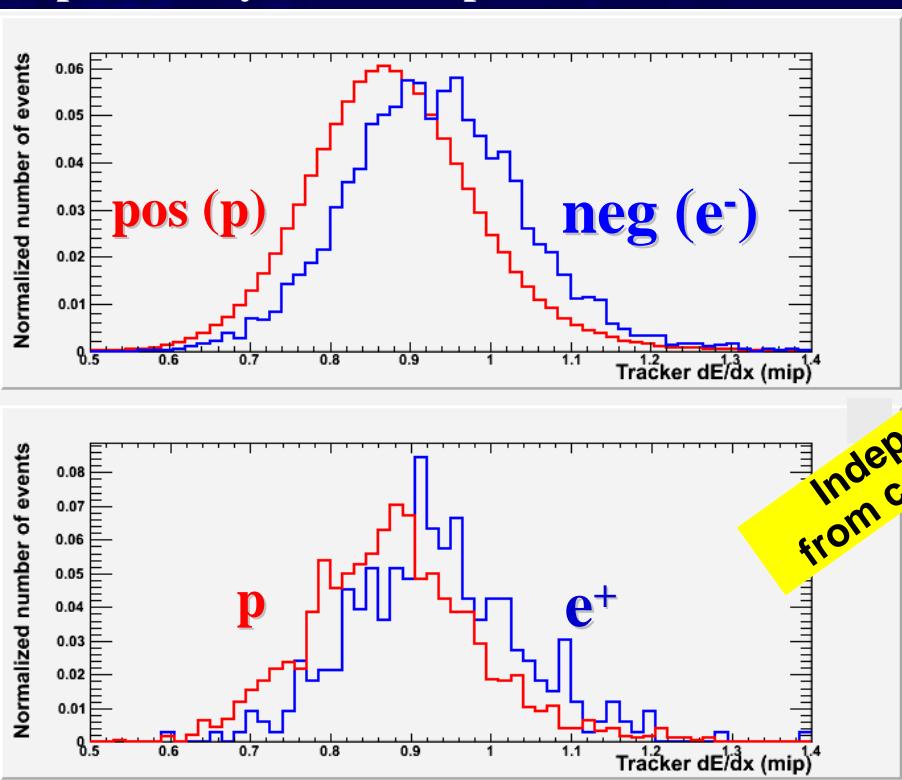


Positron selection

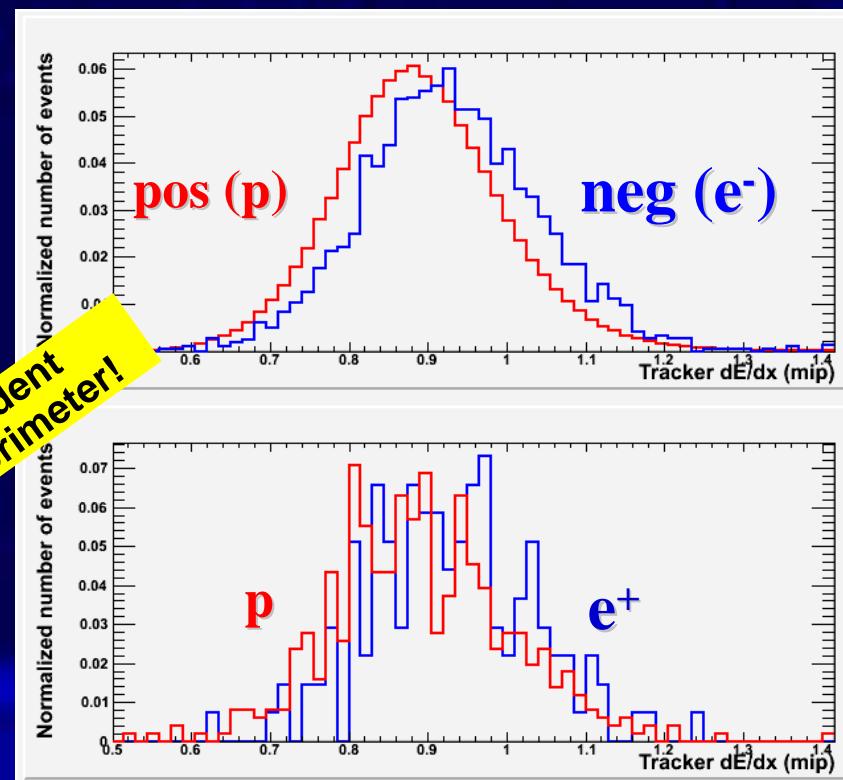
Energy loss in silicon tracker detectors:

- Top: positive (mostly p) and negative events (mostly e⁻)
- Bottom: positive events identified as p and e⁺ by transversal profile method

$$-\frac{dE}{dx} = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 T_{max}}{I^2} - \frac{\delta(\beta\gamma)}{2} \right]$$



Rigidity: 10-15 GV



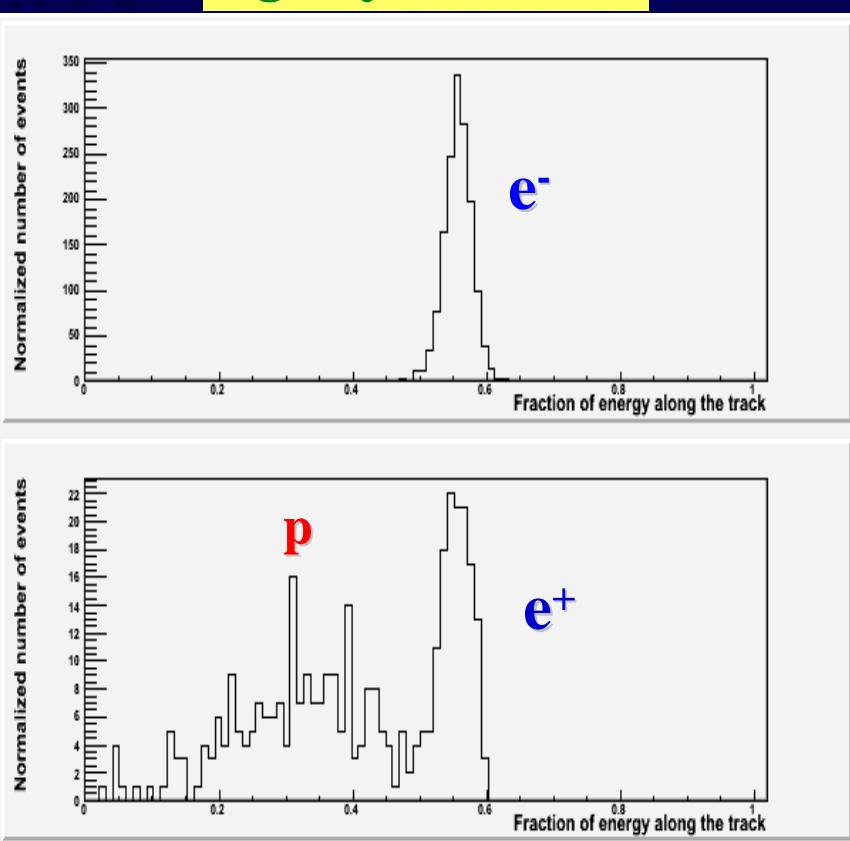
Rigidity: 15-20 GV



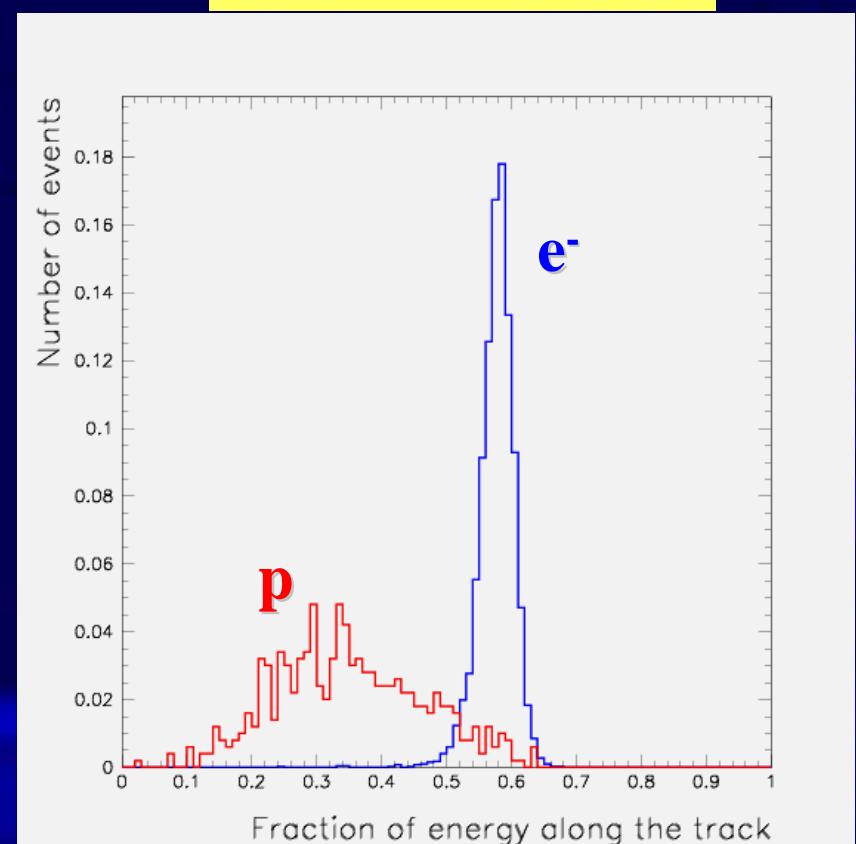
Positron selection with calorimeter

Fraction of energy released along the calorimeter track
(left, hit, right)

Flight data:
rigidity: 20-30 GV



Test beam data
Momentum: 50GeV/c



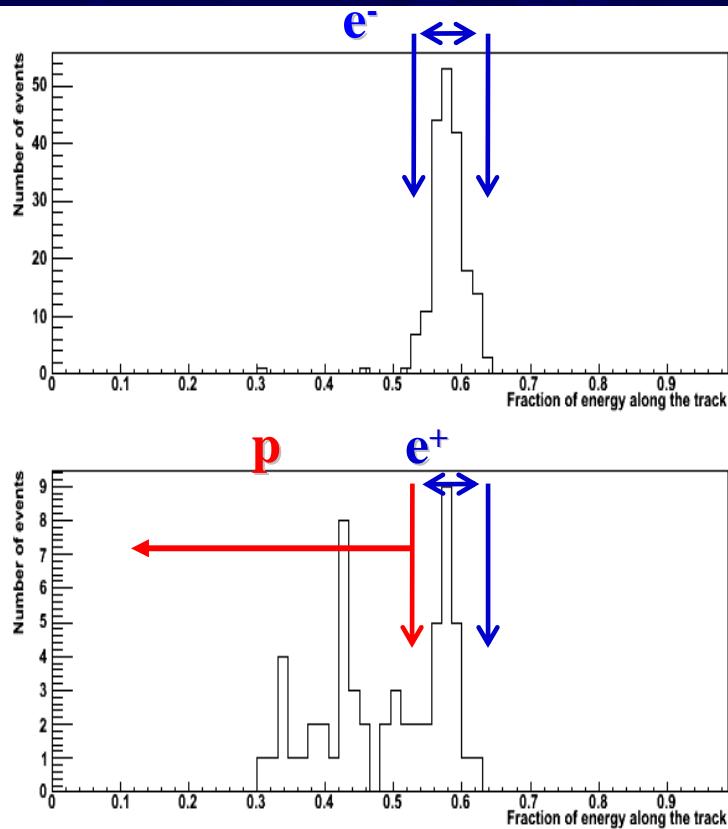
Energy-momentum match
Starting point of shower



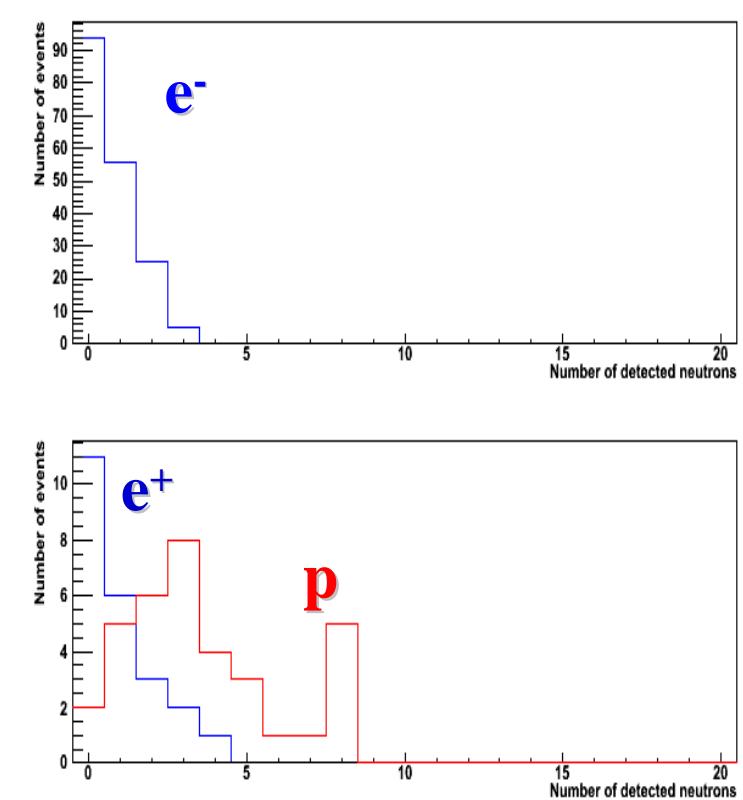
Positron selection with calorimeter

Rigidity: 42-65 GV

Fraction of charge released along the calorimeter track (left, hit, right)



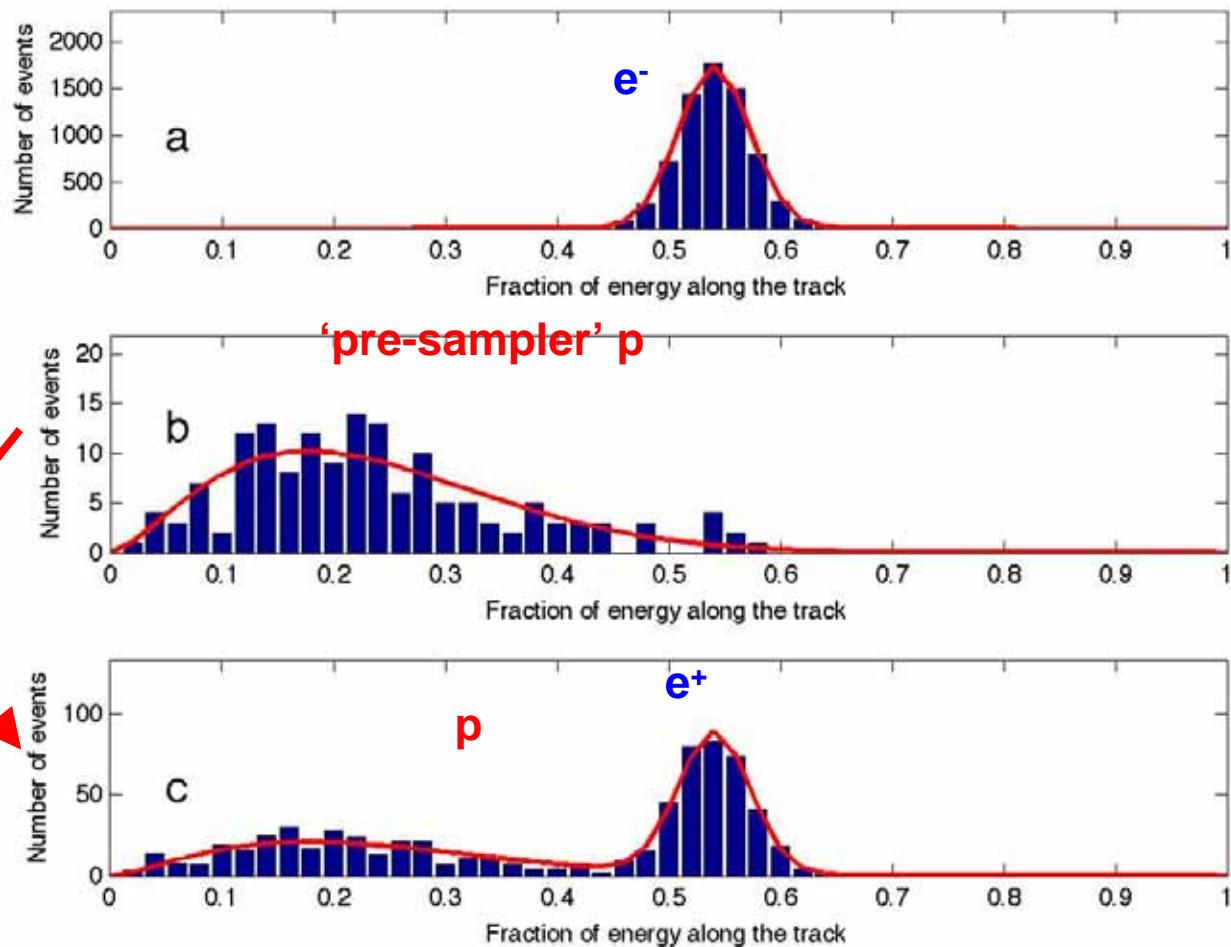
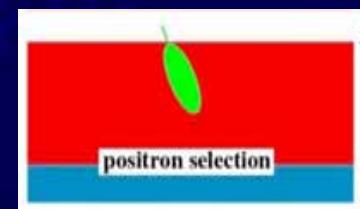
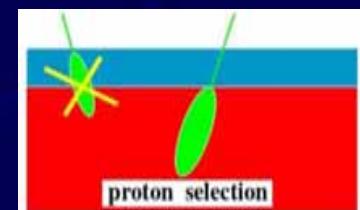
Neutrons detected by ND



Energy-momentum match
Starting point of shower

Background estimation from data

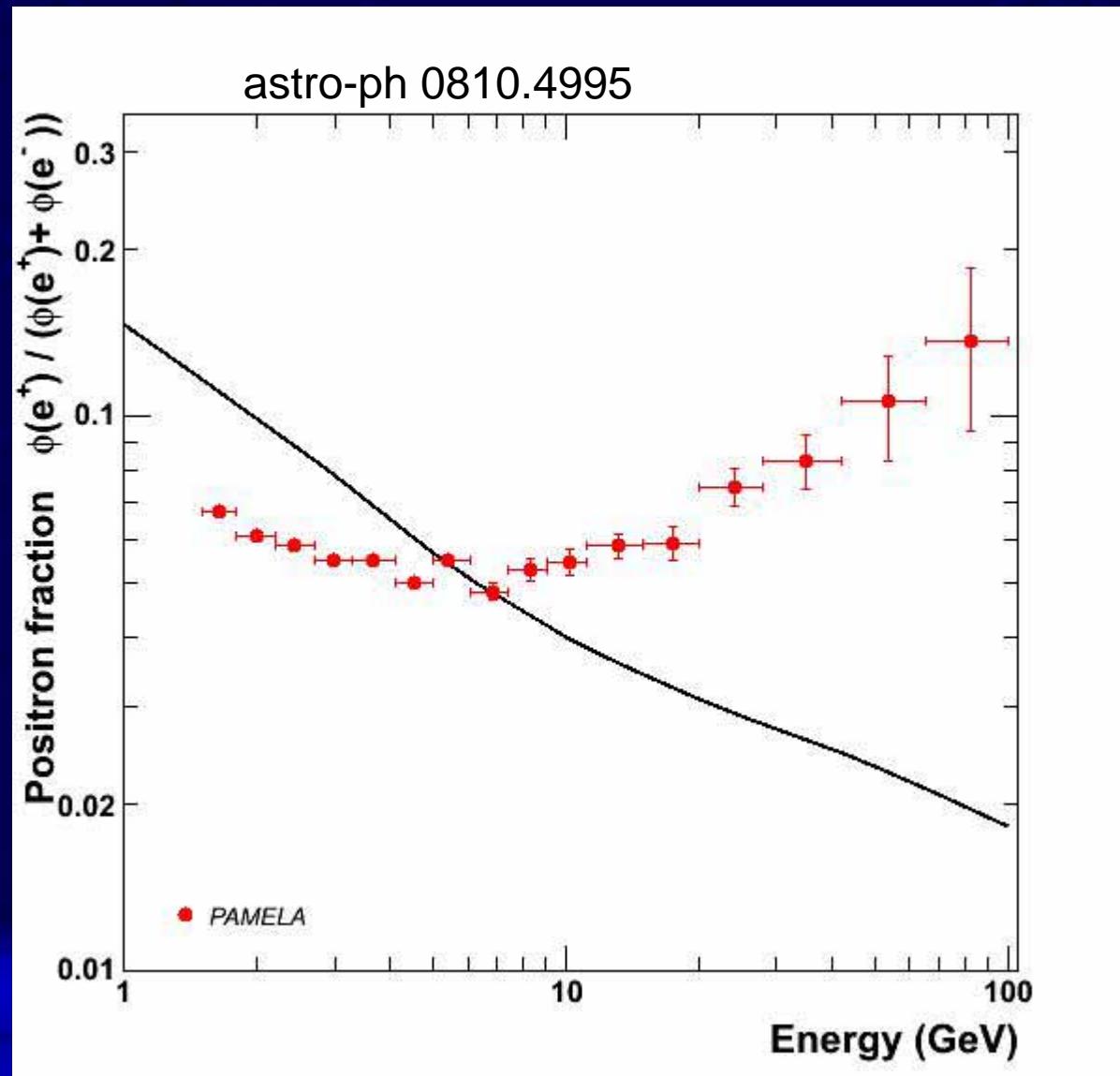
Rigidity: 20-28 GV



- Energy-momentum match
- Starting point of shower

PAMELA Positron Fraction

End 2007:
~10 000 e⁺ > 1.5 GeV
~2000 > 5 GeV

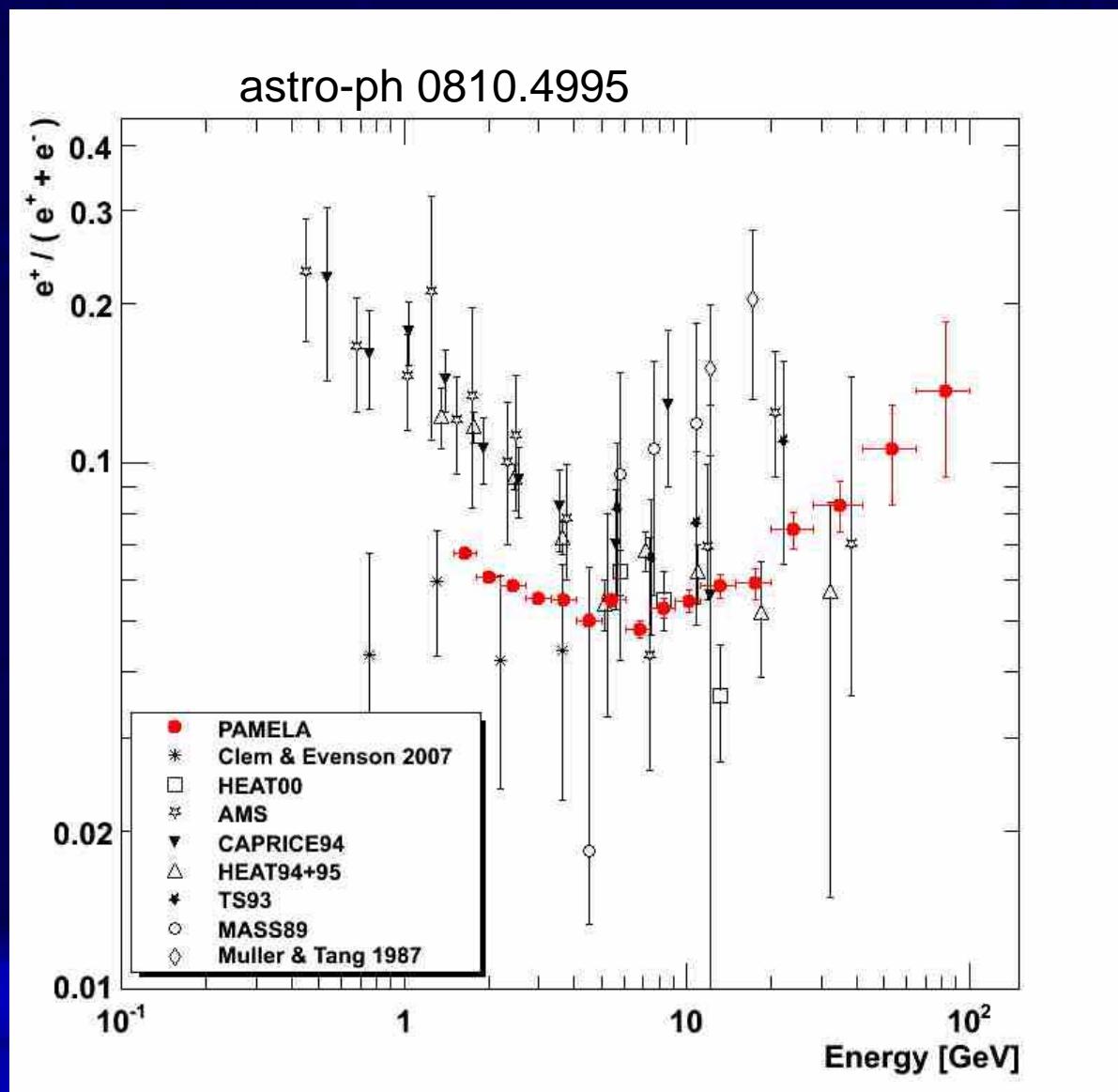


PAMELA Positron Fraction

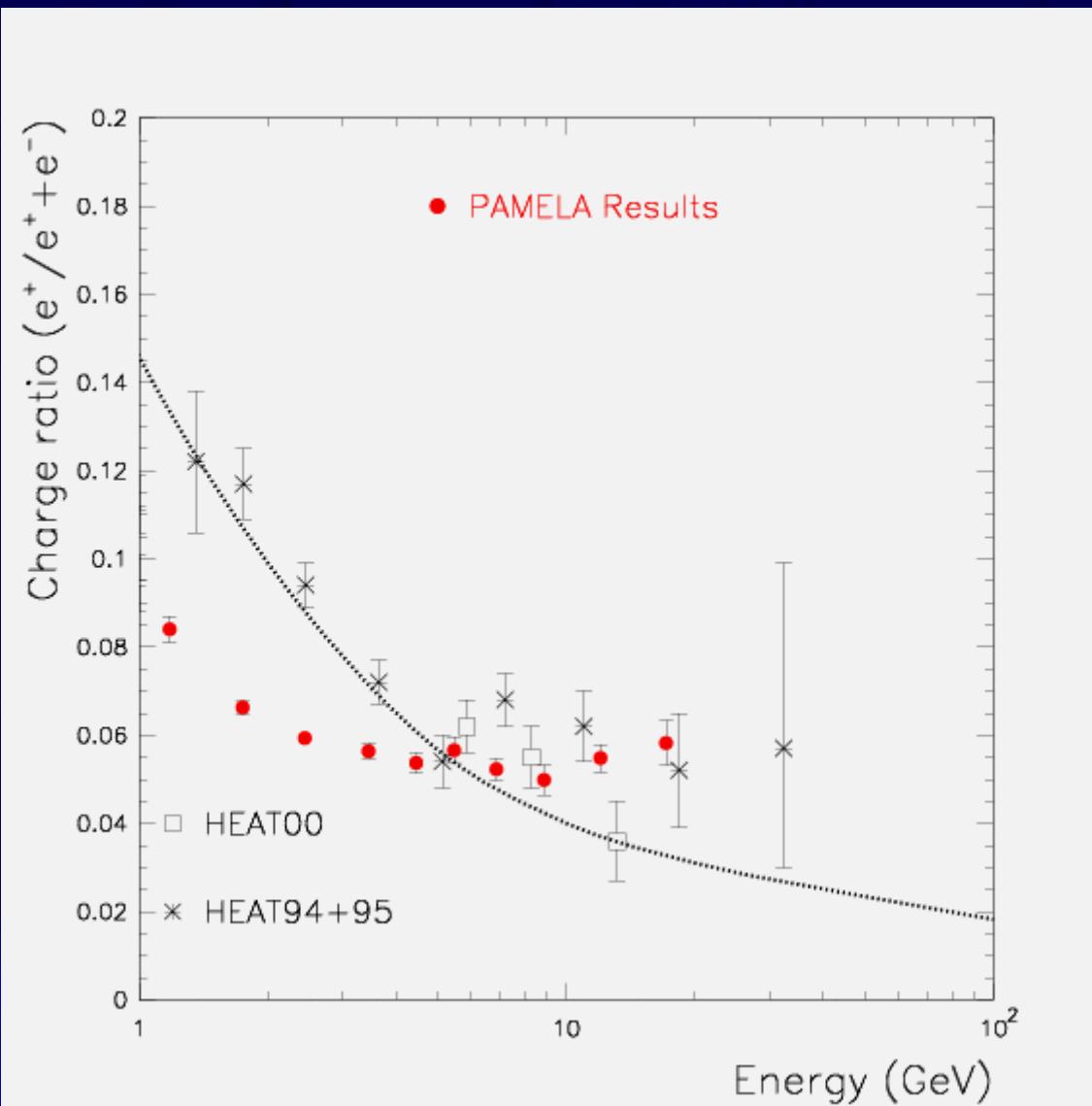
End 2007:

~10 000 e⁺ > 1.5 GeV

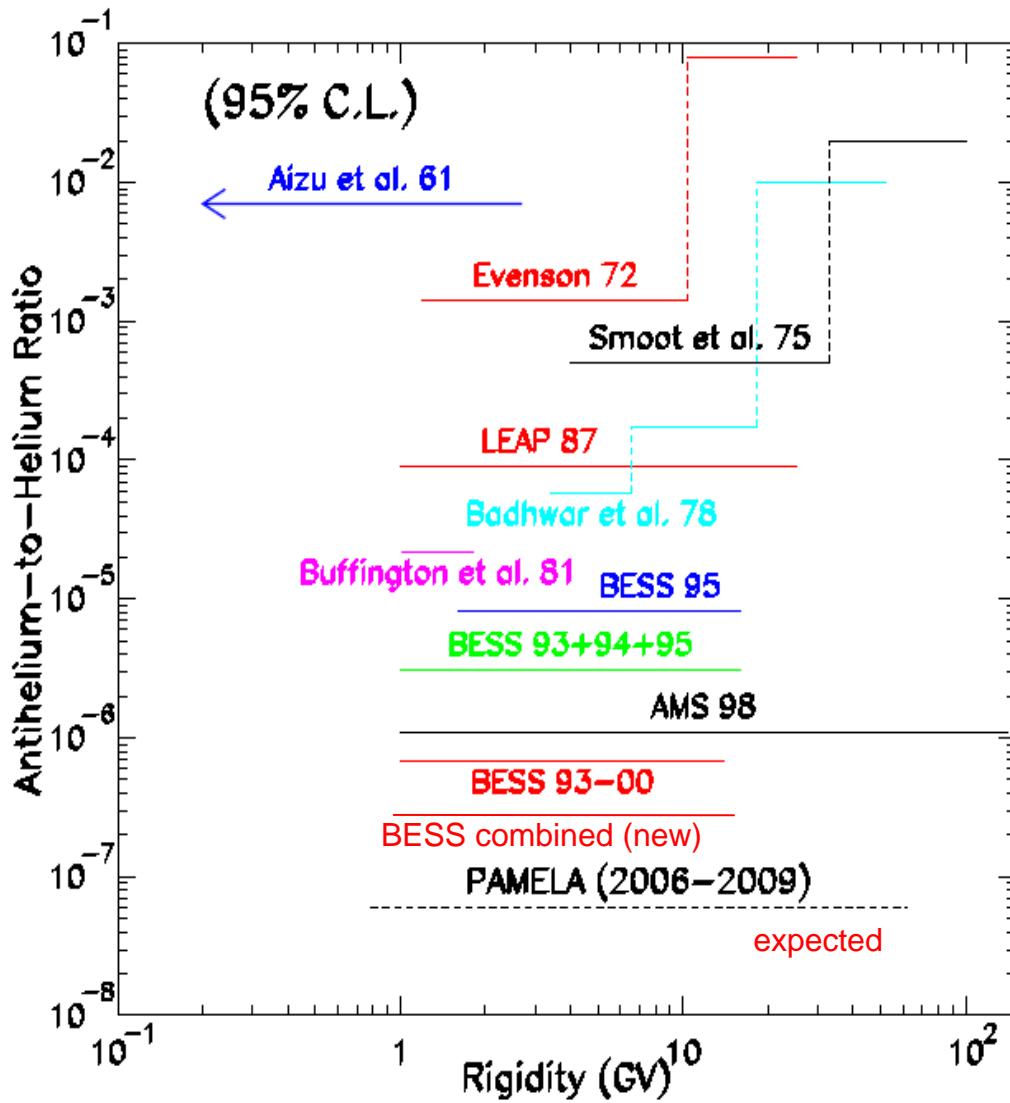
~2000 > 5 GeV



Positrons with HEAT & PAMELA



Cosmic-ray antimatter search



"We must regard it rather an accident that the Earth and presumably the whole Solar System contains a preponderance of negative electrons and positive protons. It is quite possible that for some of the stars it is the other way about"

P. Dirac, Nobel lecture (1933)

**Flight data: 0.763 GeV/c
antiproton annihilation**

PALETTE					
TOF, TRK, CALO, S4 [MP]:					
0	0 - 2	2 - 10	10 - 100	100 - 1000	> 1000
ND [neutrons]:					
0	1	2	3 - 5	7 - 14	> 14
AC:					
NOT HIT	HIT trigger	HIT background			

PAMELA Antiproton Flux

Preliminary

Ptuskin *et al.* 2006

[Ap. J. 642 902]

PD model

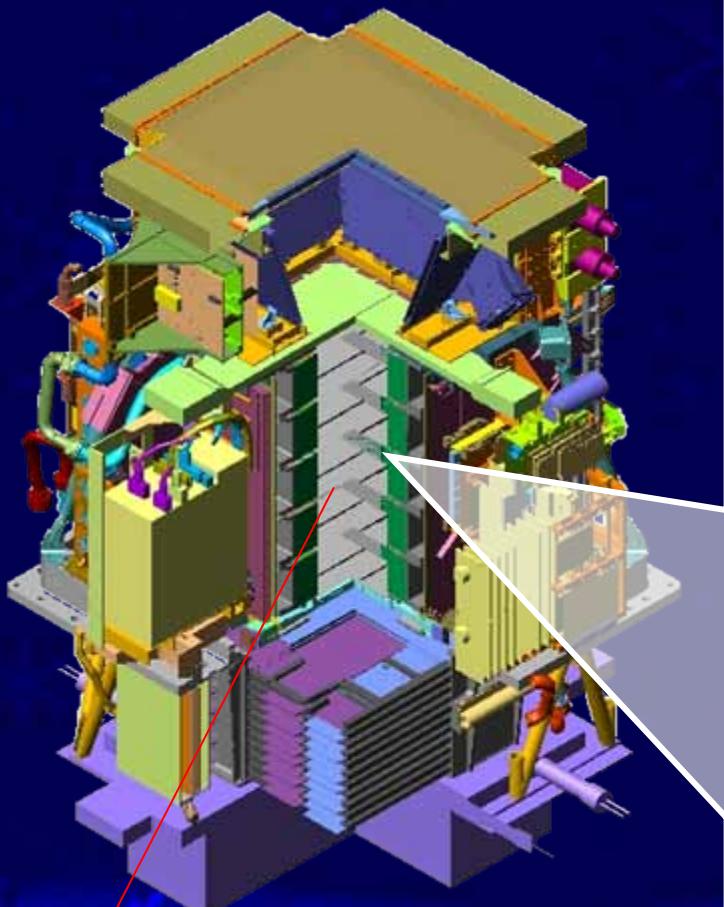
DR model

DRD model

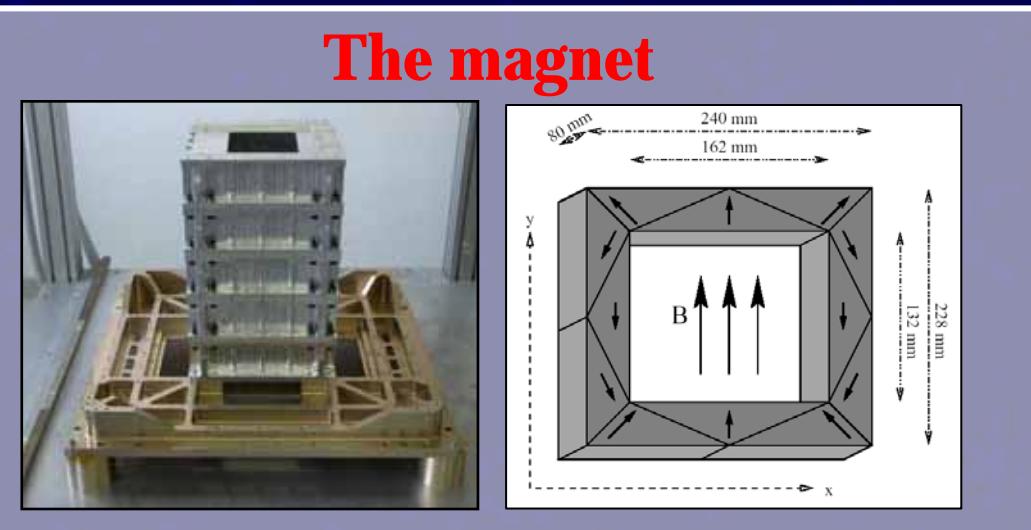
A. Bruno's and P. Hofverberg's PhD theses



PAMELA

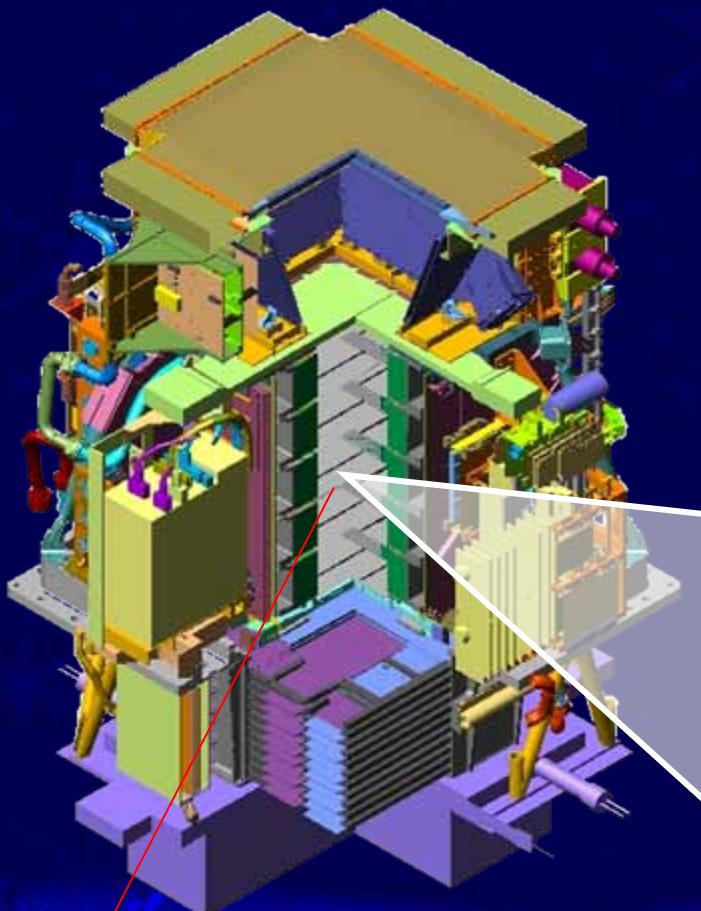


SPECTROMETER



Characteristics:

- 5 modules of permanent magnet (Nd-B-Fe alloy) in aluminum mechanics
- Cavity dimensions $162 \times 132 \times 445 \text{ cm}^3$
→ GF **21.5 cm²sr**
- Magnetic shields
- 5mm-step field-map
- **B=0.43 T** (average along axis), B=0.48 T (@center)



SPECTROMETER

The tracking system



Main tasks:

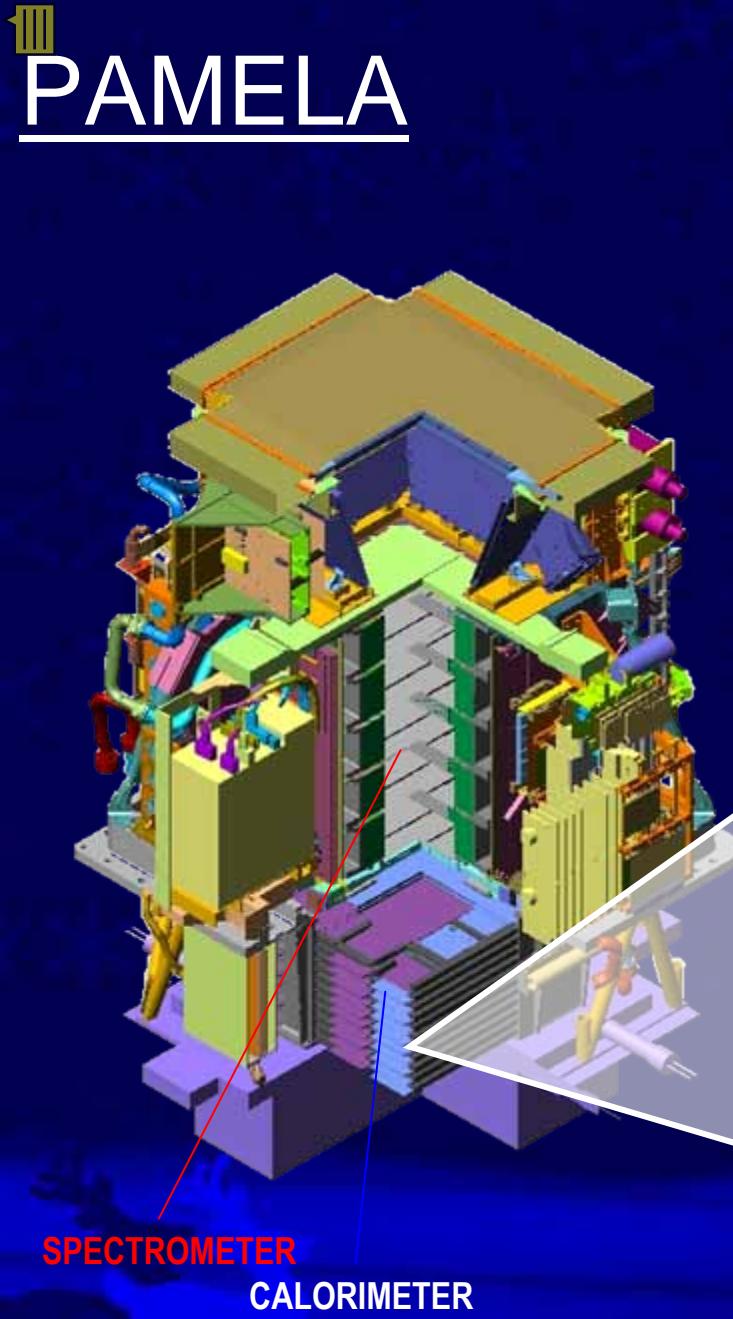
- Rigidity measurement
- Sign of electric charge
- dE/dx

Characteristics:

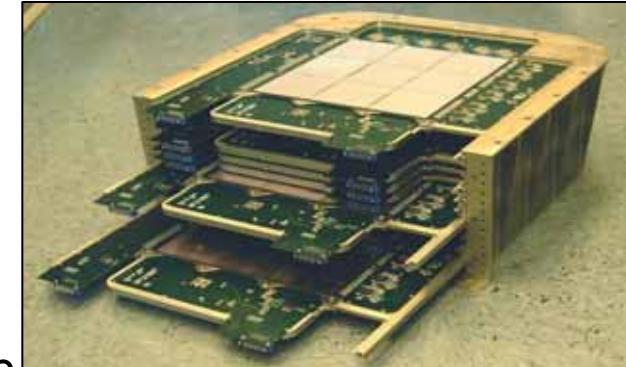
- **6 planes double-side (x&y view)
microstrip Si sensors**
- 36864 channels
- Dynamic range 10 MIP

Performances:

- Spatial resolution: **3÷4 μ m**
- **MDR ~1TV** (from test beam data)



The electromagnetic calorimeter



Main tasks:

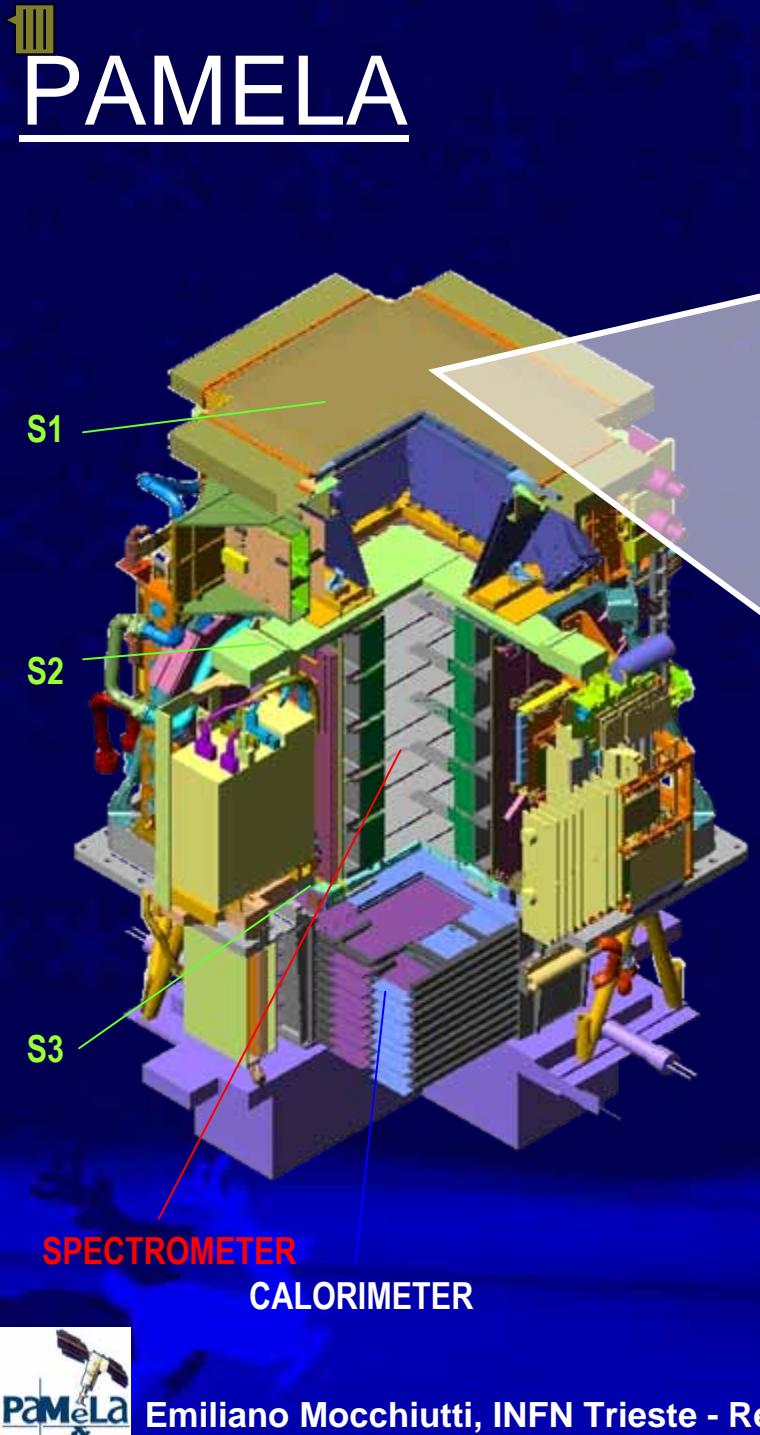
- e/h discrimination
- $e^{+/-}$ energy measurement

Characteristics:

- 44 Si layers (X/Y) +22 W planes
- $16.3 X_0 / 0.6 I_0$
- 4224 channels
- Dynamic range ~ 1100 mip
- Self-trigger mode (> 300 GeV GF ~ 600 cm 2 sr)

Performances:

- p/e $^+$ selection efficiency $\sim 90\%$
- p rejection factor 10^5
- e rejection factor $> 10^4$
- Energy resolution $\sim 5\% @ 200\text{GeV}$

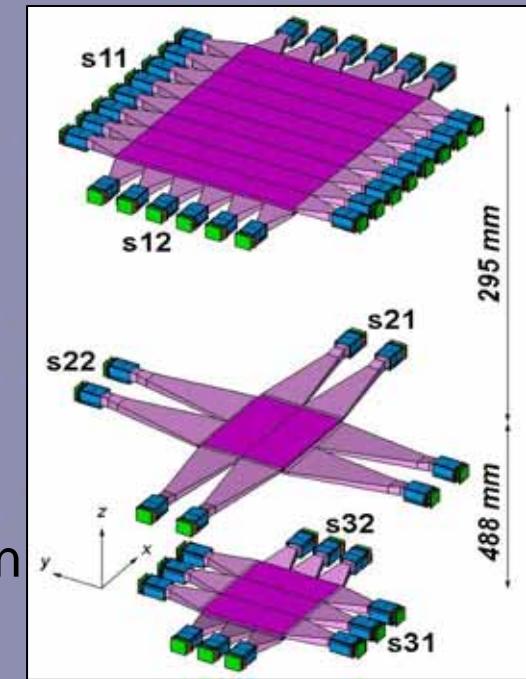


The time-of-flight system



Main tasks:

- First-level trigger
- Albedo rejection
- dE/dx
- Particle identification ($<1\text{GeV}/c$)

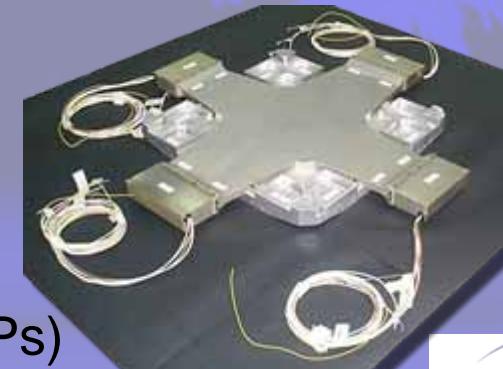


Characteristics:

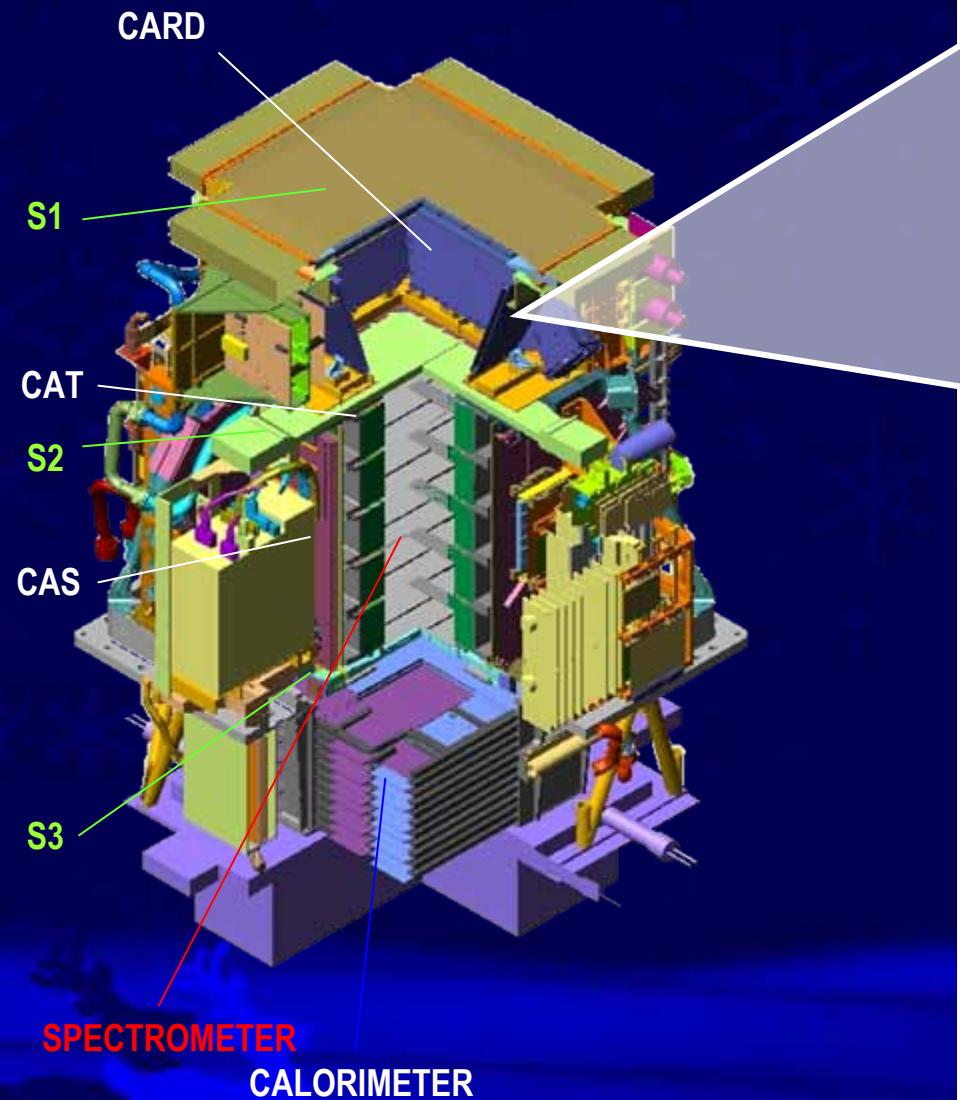
- **3 double-layer scintillator paddles**
- X/Y segmentation
- Total: 48 Channels

Performances:

- $\sigma_{\text{paddle}} \sim 110\text{ps}$
- $\sigma_{\text{TOF}} \sim 330\text{ps}$ (for MIPs)



PAMELA



The anticounter shields

Main tasks:

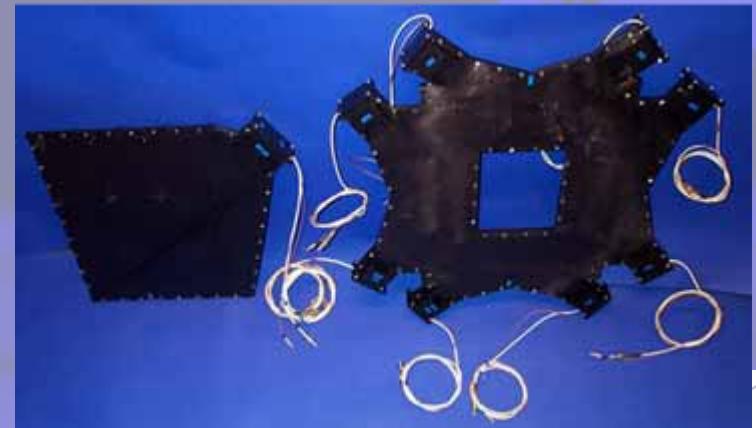
- Rejection of events with particles interacting with the apparatus (off-line and second-level trigger)

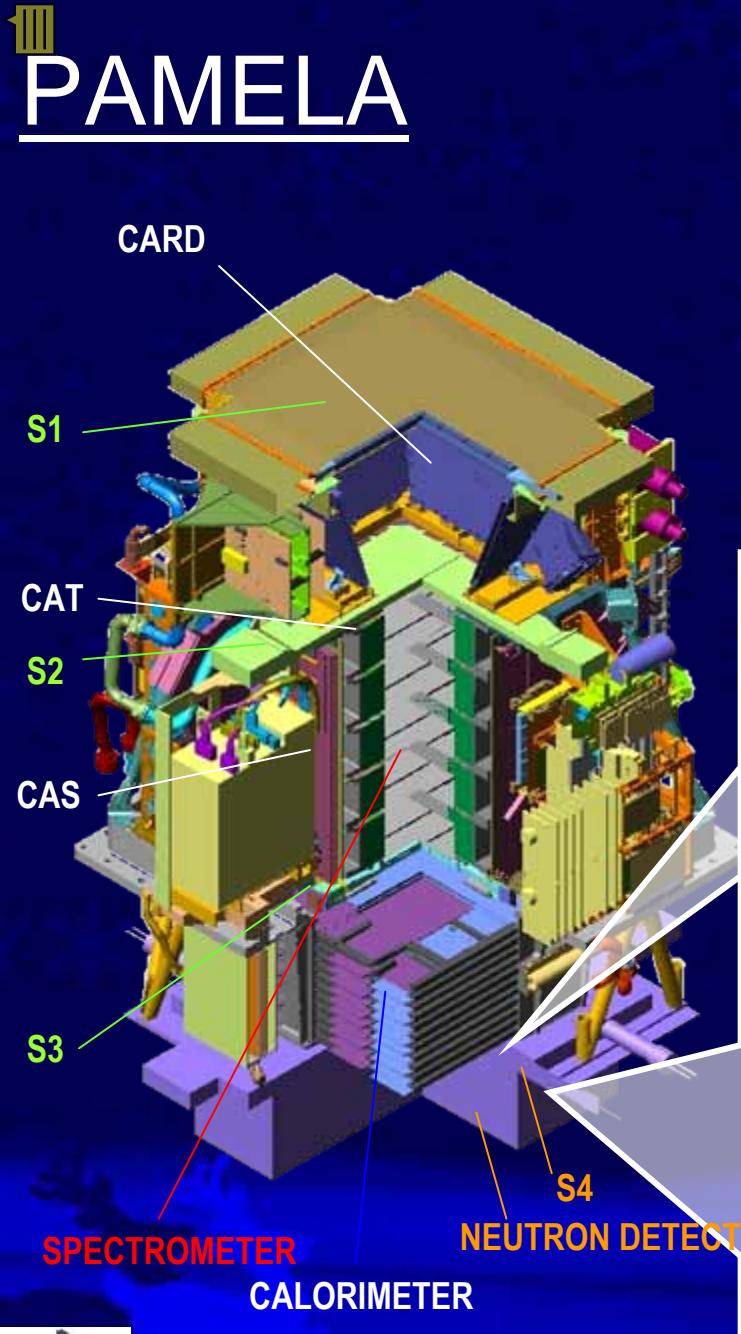
Characteristics:

- scintillator paddles 10mm thick
- 4 up (**CARD**), 1 top (**CAT**), 4 side (**CAS**)

Performances:

- Efficiency > 99.9%





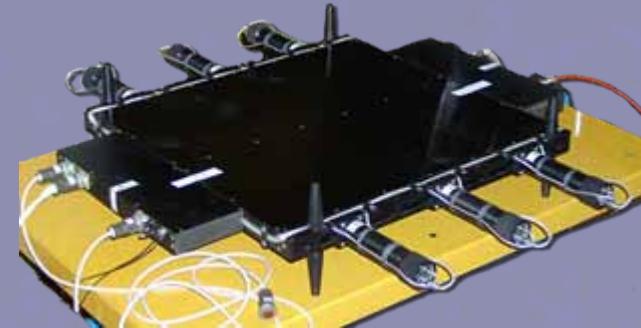
Shower-tail catcher (S4)

Main tasks:

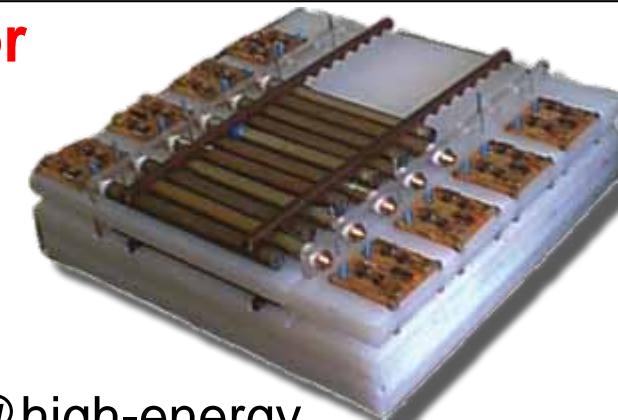
- ND trigger

Characteristics:

- 1 scintillator paddle
10mm thick



Neutron detector



Main tasks:

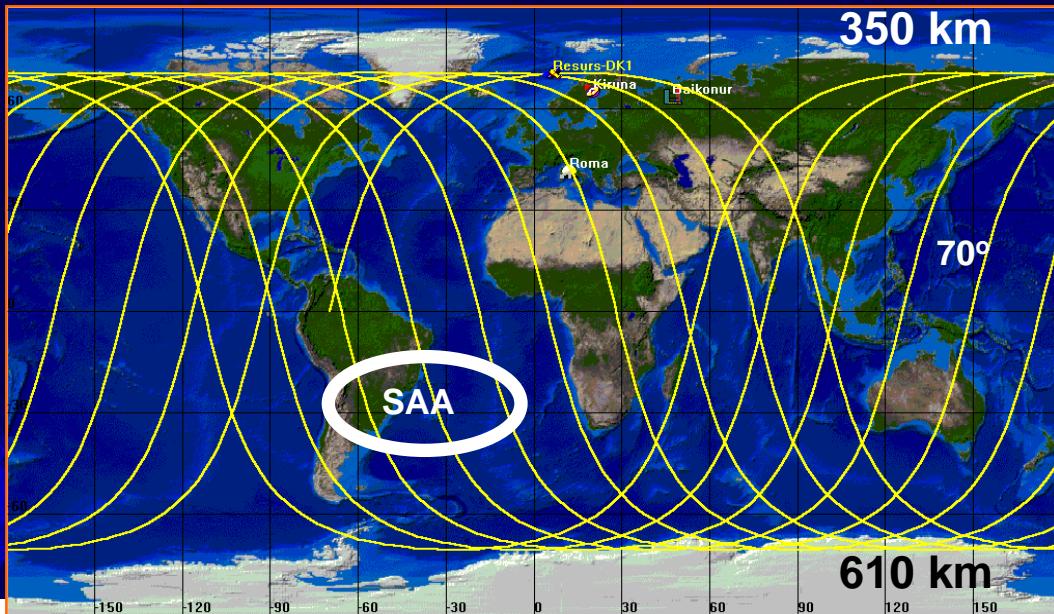
- e/h discrimination @high-energy

Characteristics:

- **36 ^3He counters:** $^3\text{He}(n,p)\text{T} \rightarrow E_p = 780 \text{ keV}$
- 1cm thick polyethylene moderators
- n collected within 200 μs time-window



Resurs-DK1 Satellite and Orbit



- Resurs-DK1: multi-spectral imaging of earth's surface
- PAMELA mounted inside a pressurized container
- Lifetime >3 years (assisted)
- Data transmitted to NTsOMZ, Moscow via high-speed radio downlink.
- Quasi-polar and elliptical orbit (70.0°, 350 km - 610 km)
- Traverses the South Atlantic Anomaly
- Crosses the outer (electron) Van Allen belt at south pole

PAMELA milestones

Launch from Baikonur → June 15th 2006, 0800 UTC.

'First light' → June 21st 2006, 0300 UTC.

- Detectors operated as expected after launch
- Different trigger and hardware configurations evaluated

→ **PAMELA in continuous data-taking mode since commissioning phase ended on July 11th 2006**

Trigger rate* ~**25Hz**

Fraction of live time* ~ **75%**

Event size (compressed mode) ~ **5kB**

25 Hz x 5 kB/ev → ~ **10 GB/day**

(*outside radiation belts)



Main antenna in NTsOMZ

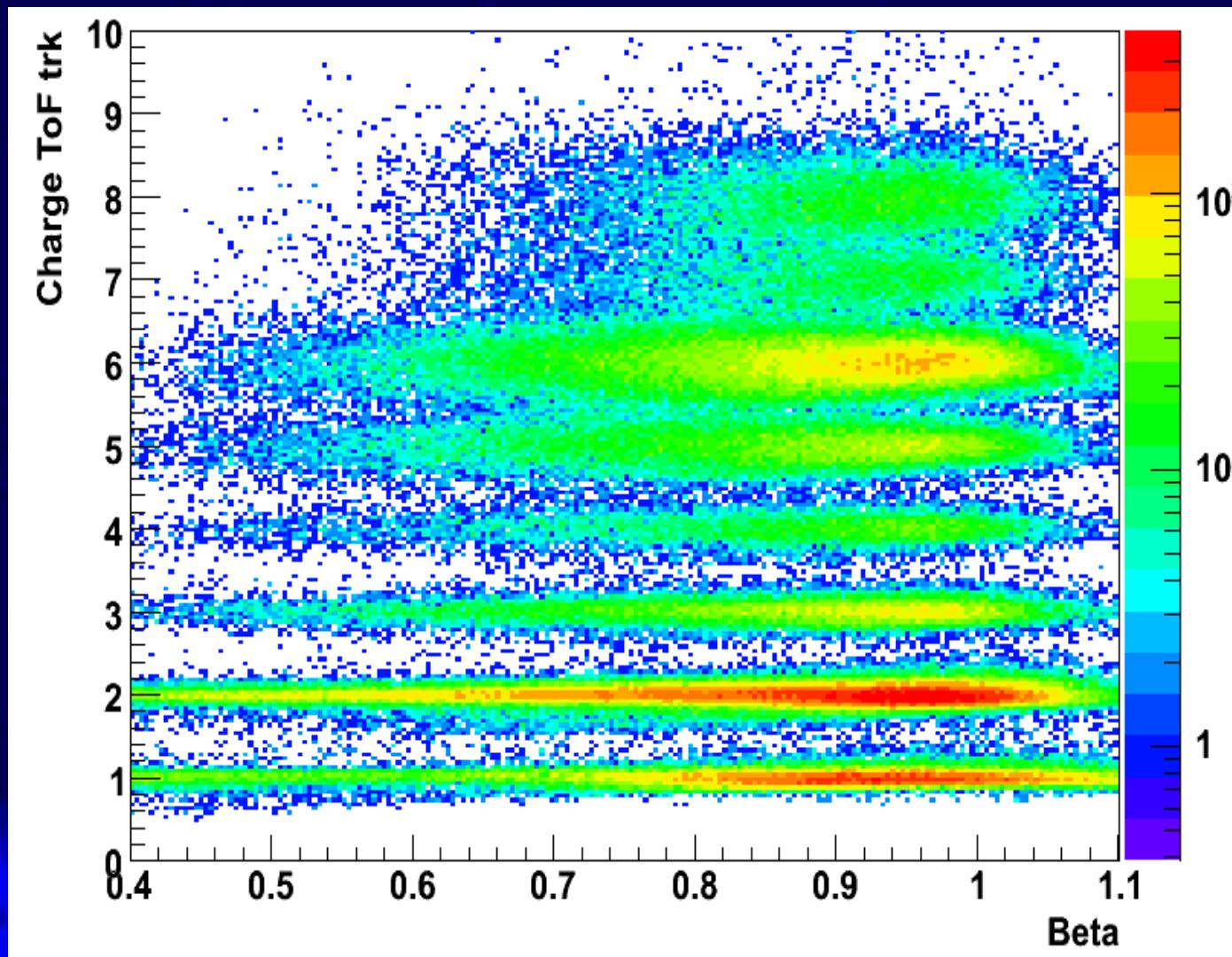
Till ~now:

~650 days of data taking

~12 TByte of raw data downlinked

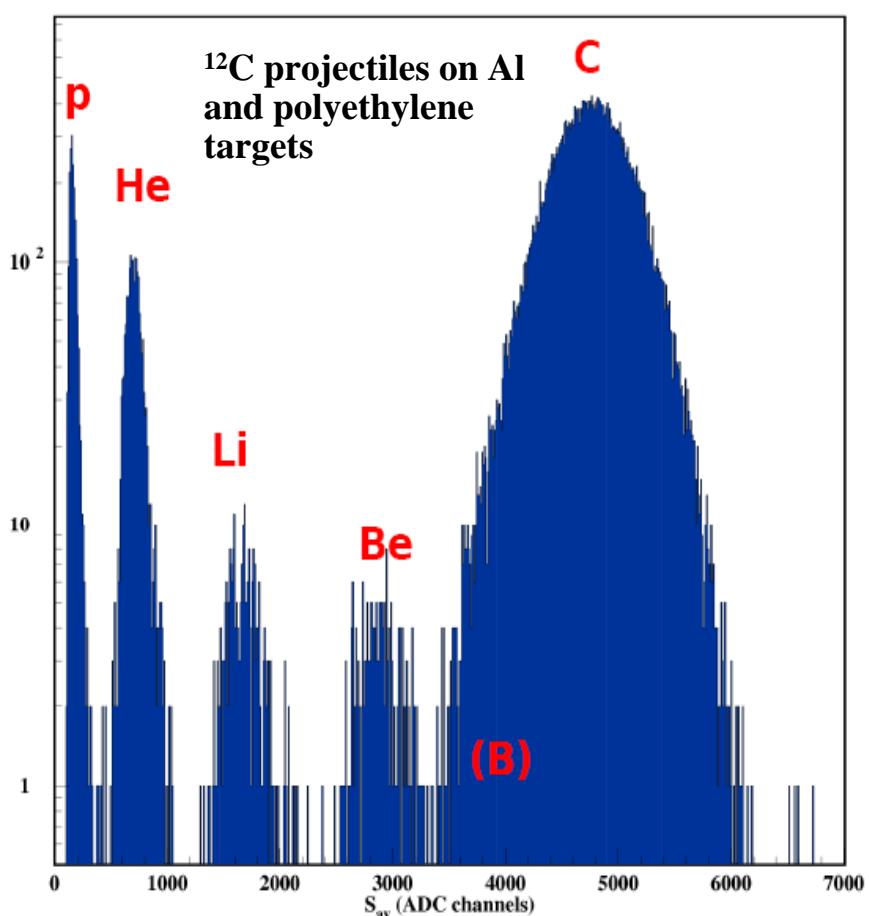
~ $12 \cdot 10^8$ triggers recorded and analyzed
(Data from April till now under analysis)

Charge identification capabilities (ToF)



Charge identification capabilities (tracker)

Beam-test data (@GSI 2006)



flight data (preliminary)

