The PAMELA experiment: shedding new light on dark matter ?

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Summary

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

The PAMELA experiment: short review

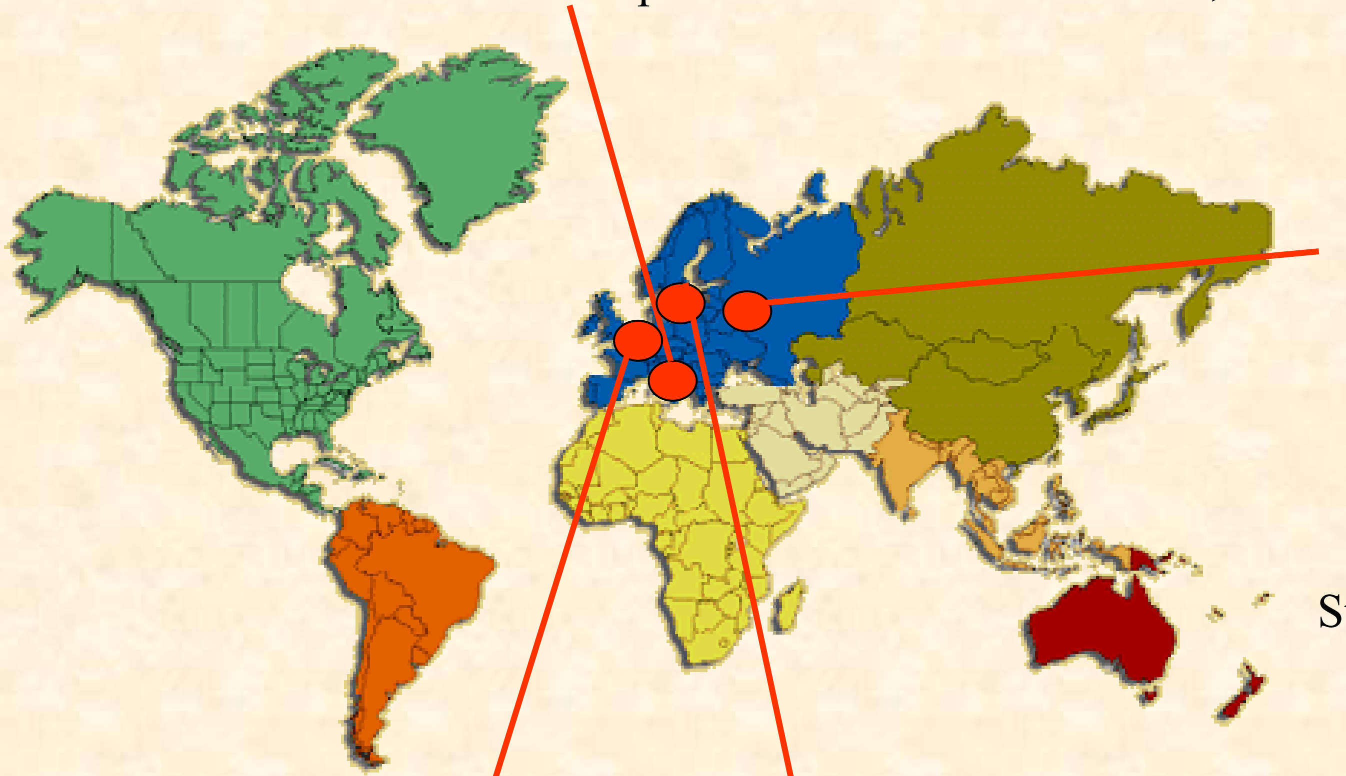
Tha PAMELA collaboration

Italy

Bari Florence Frascati Naples Rome Trieste CNR, Florence

Russia

Moscow
St. Petersburg



Germany

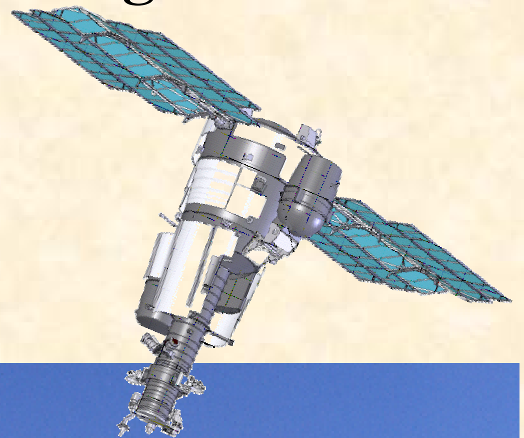
Siegen

Sweden

KTH, Stockholm

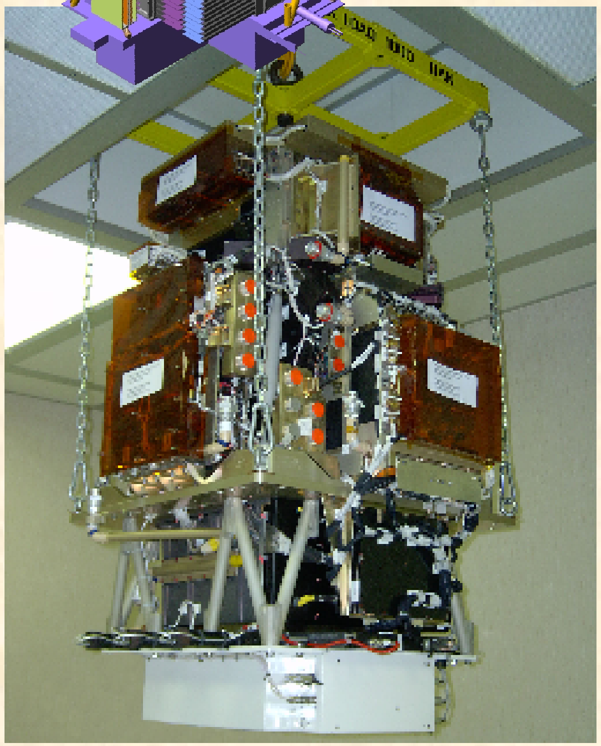
PAMELA

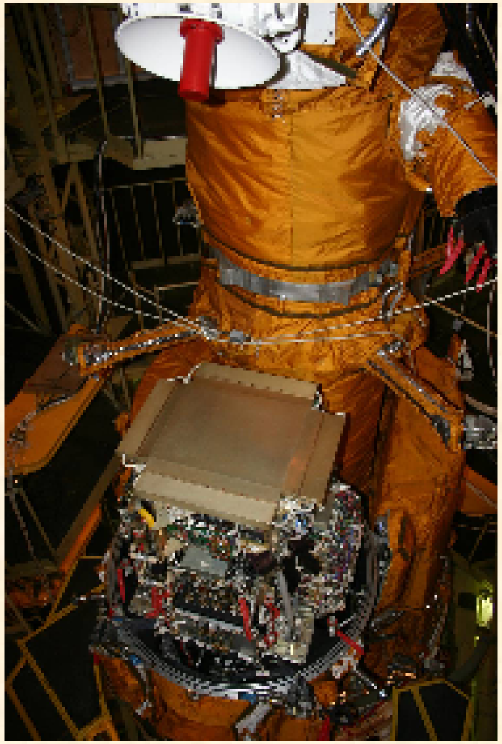
Payload for Antimatter/Matter Exploration and Light-nuclei Astrophysics



→ Direct detection of CRs in **space**

→ Main focus on **antimatter** component



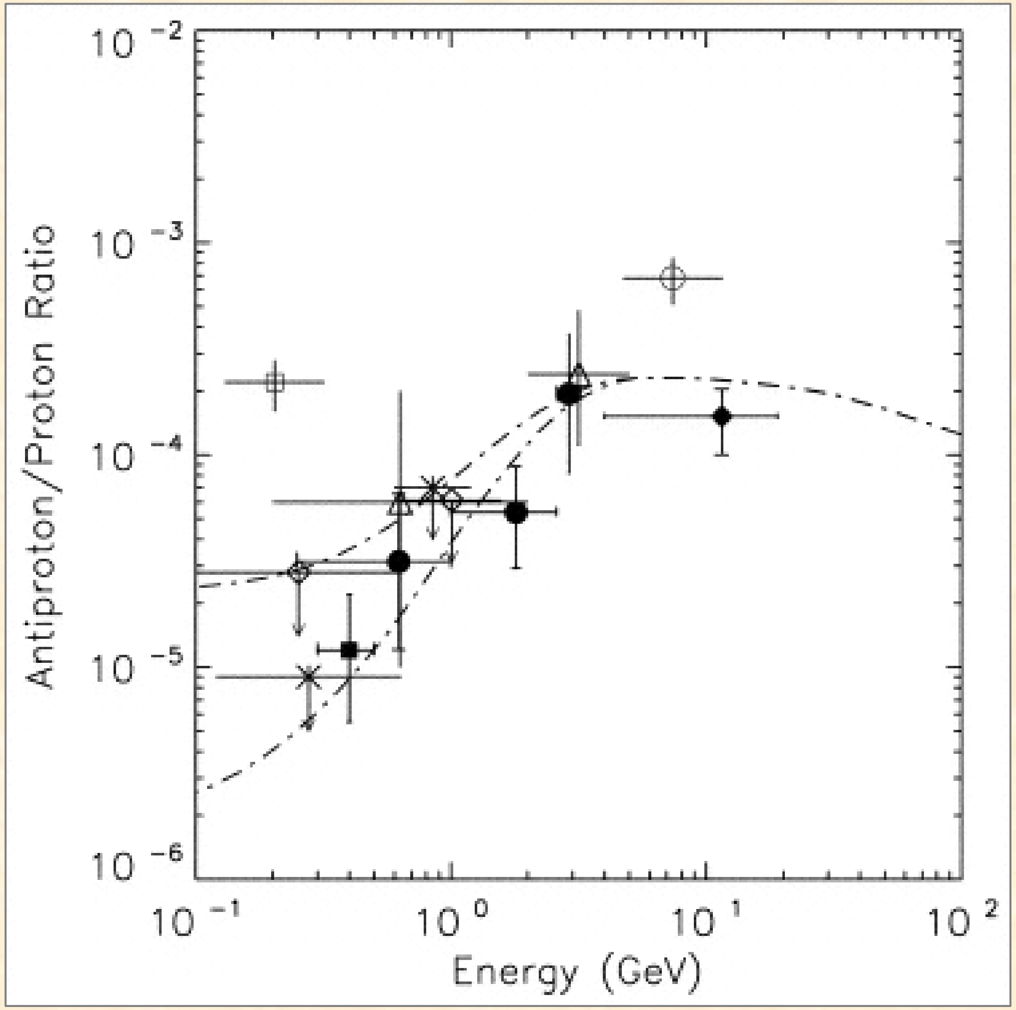


Everything starts with …

- Antiprotons in the cosmic radiation are expected as "**secondary**" products of interactions of the primary cosmic radiation, principally protons, with the ambient interstellar medium (ISM).

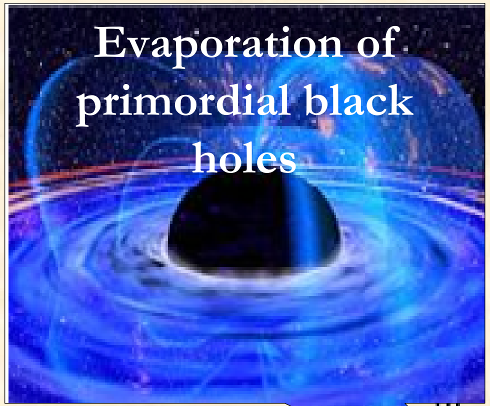
- The first positive measurements [Golden 79,Bogomolov 90, Buffington 82] reported **higher** antiproton fluxes than predicted by contemporary models of cosmic ray transport.

- *Many different theories to justify these data were proposed at that time*

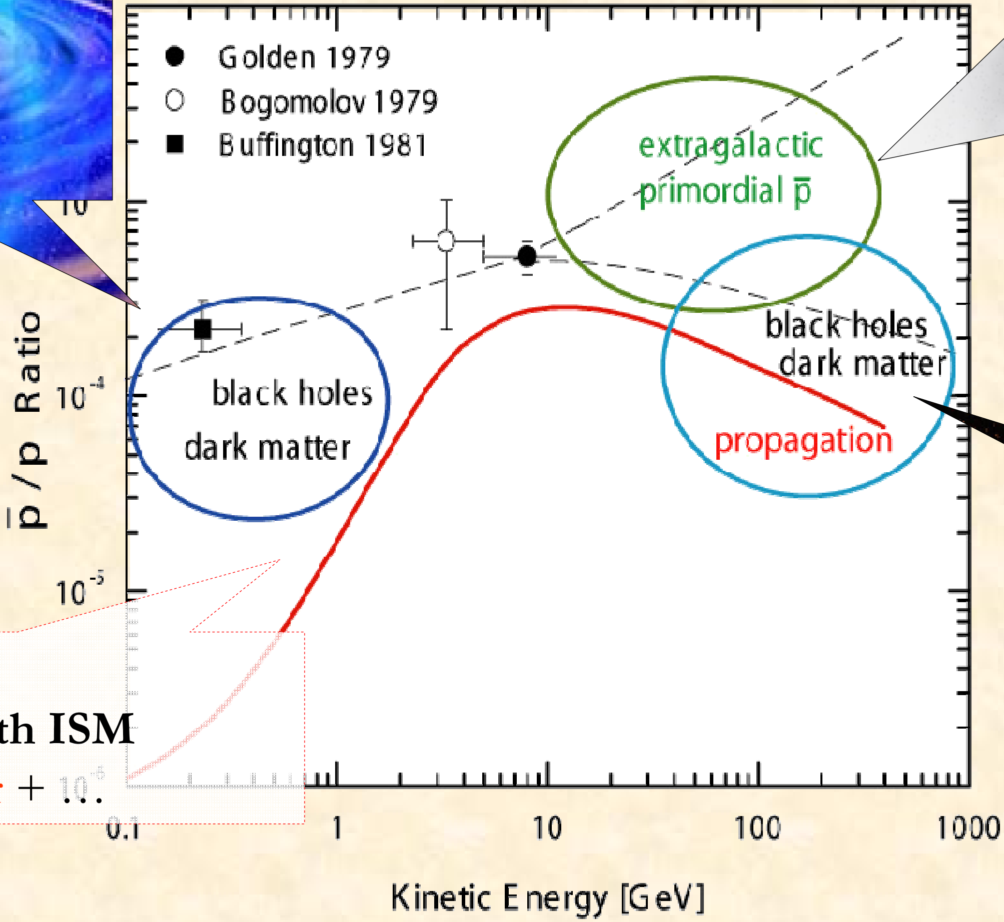


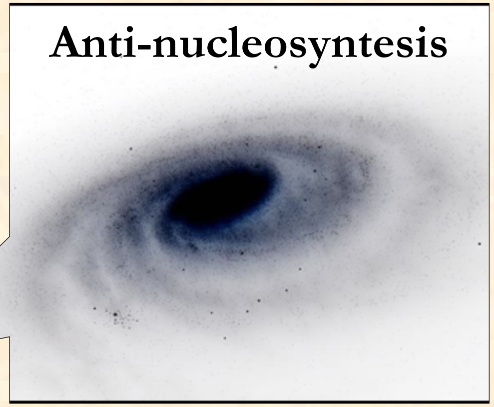
Golden et al. (1984; **open circle**), Bogomolov et al. (1987, 1990; **open triangle**), Buffington et al. (1981; **open square**)

Why CR antimatter?



First historical measurements of p-bar/p ratio





Background:
CR interaction with ISM
CR + ISM → p-bar + …

Cosmic-ray Antimatter from Dark Matter annihilation

Annihilation of relic Weakly Interacting Massive Particles (WIMPs) gravitationally confined in the galactic halo

→ Distortion of antiproton and positron spectra from purely secondary production

- A plausible dark matter candidate is neutralino (χ), the lightest SUSY Particle (LSP).

Most likely processes:

- $\chi\chi \rightarrow qq \rightarrow$ hadrons $\rightarrow$ anti-p, e^+,…
- $\chi\chi \rightarrow W^+W^-, Z^0Z^0$,… $\rightarrow e^+$,…

$\Rightarrow$ positron peak $E_{e+} \sim M_\chi/2$

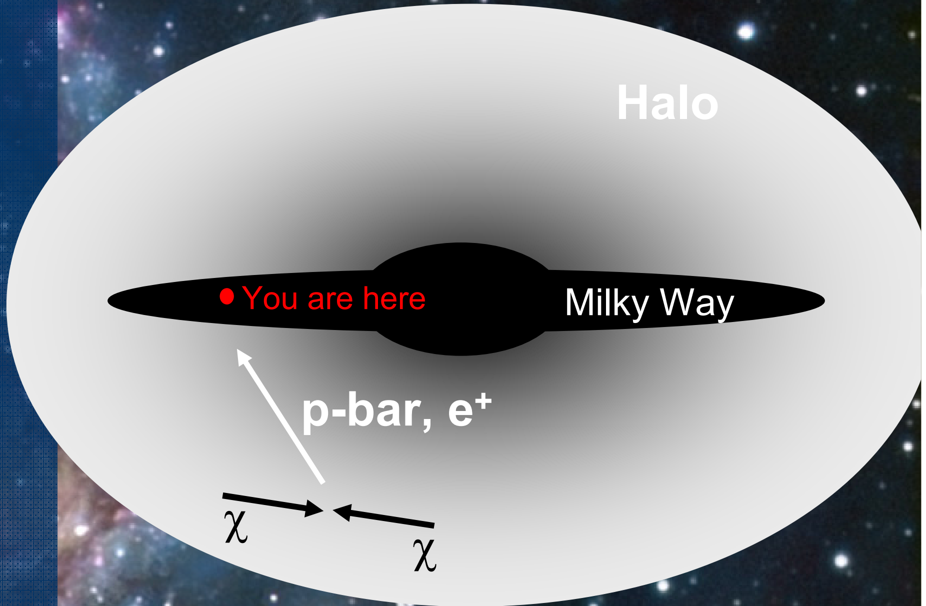
$\Rightarrow$ positron continuum $E_{e+} \sim M_\chi/20$

- Another possible candidate is the lightest Kalusa-Klein Particle (LKP): $B^{(1)}$

Fermionic final states no longer suppressed:

- $B^{(1)}B^{(1)} \rightarrow e^+e^-$

direct decay $\Rightarrow$ positron peak $E_{e+} \sim M_{B(1)}$



$$\chi + \bar{\chi} \rightarrow X + \gamma$$ (GLAST)

$$+\nu$$ (AMANDA / IceCube)

$$+\bar{p}$$

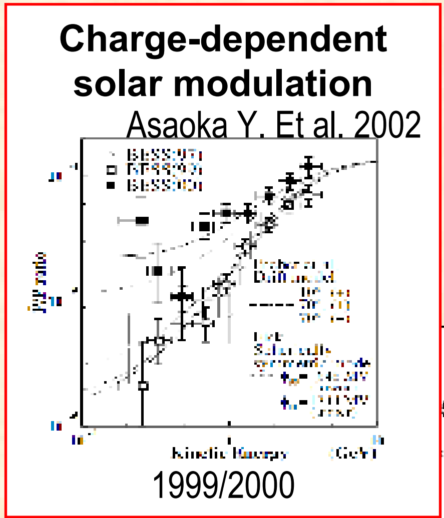
$$+e^+$$

$$+\bar{D}$$

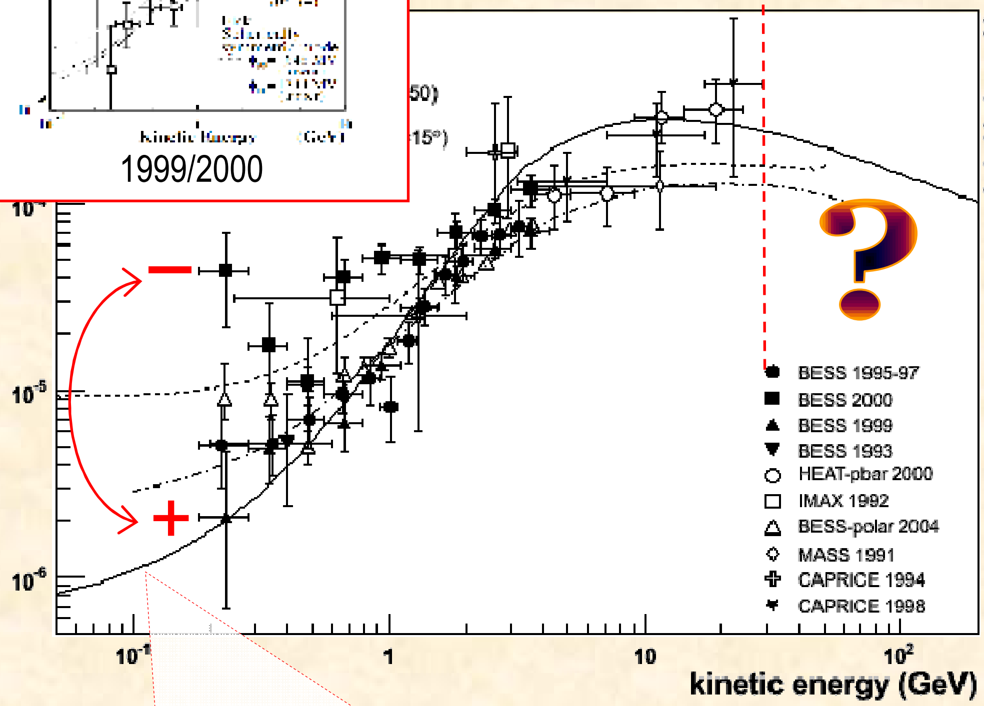
$\bar{p}$, e^+, $\bar{D}$: PAMELA (and Bess, HEAT, AMS etc.)

CR antimatter

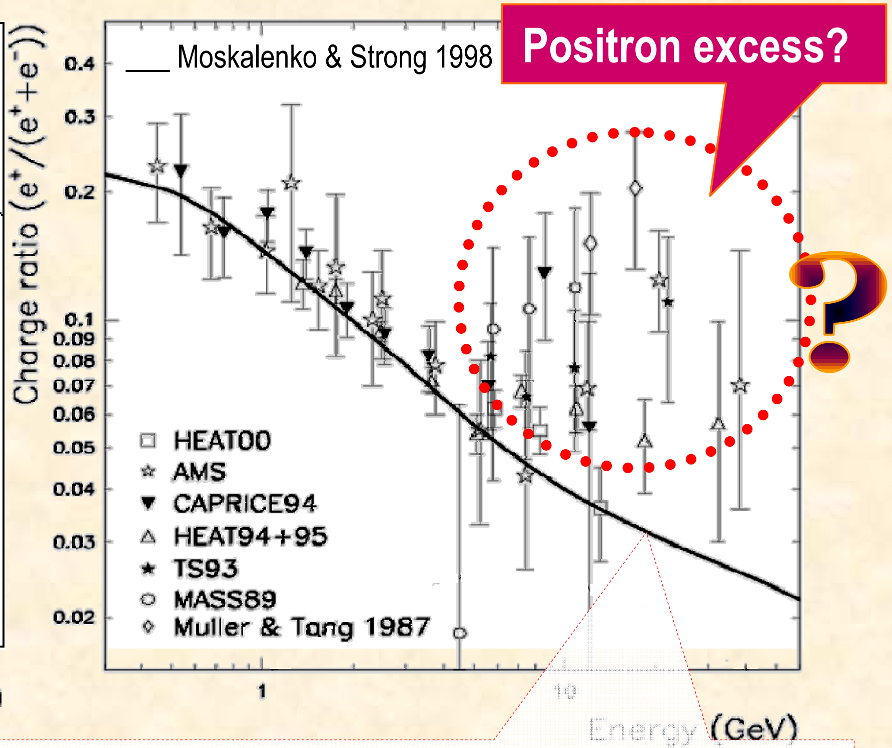
Experimental scenario before PAMELA



Antiprotons



Positrons



CR + ISM → **p-bar** + …

- Propagation dominated by nuclear interactions
- Kinematical threshold: E_{th}~5.6 for the reaction

$$pp \rightarrow \bar{p}ppp$$

CR + ISM → $\pi^{\pm}$ + x → $\mu^{\pm}$ + x → **$e^{\pm}$** + x

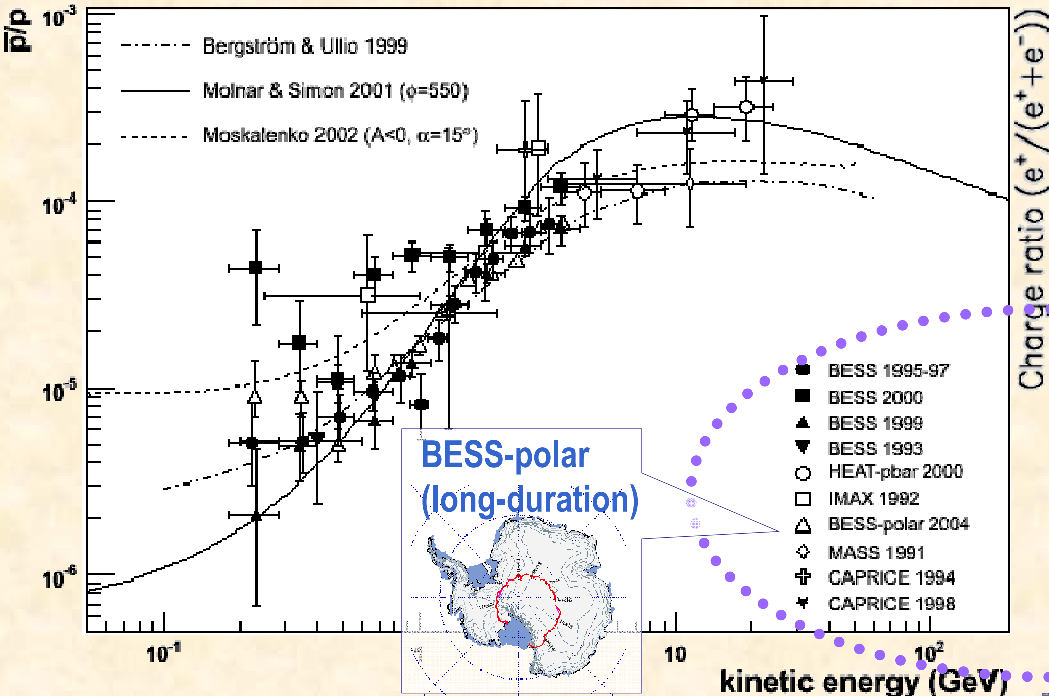
CR + ISM → π^0 + x → $\gamma\gamma$ → **$e^{\pm}$**

- Propagation dominated by energy losses (inverse Compton & synchrotron radiation)
- Local origin (@100GeV 90% from <2kpc)

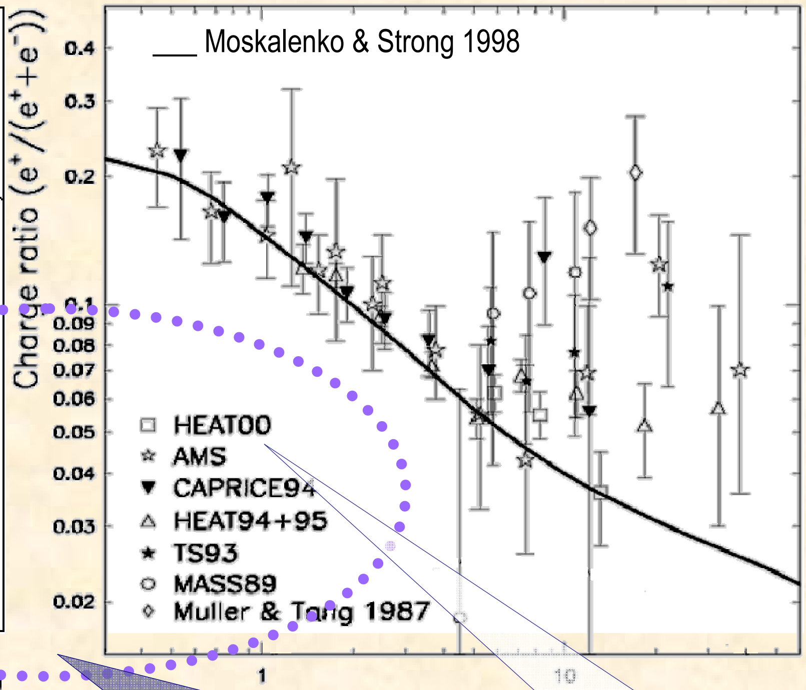
CR antimatter: available data

Why in space?

Antiprotons



Positrons



- low exposure (~20h)

⇒ large statistical errors

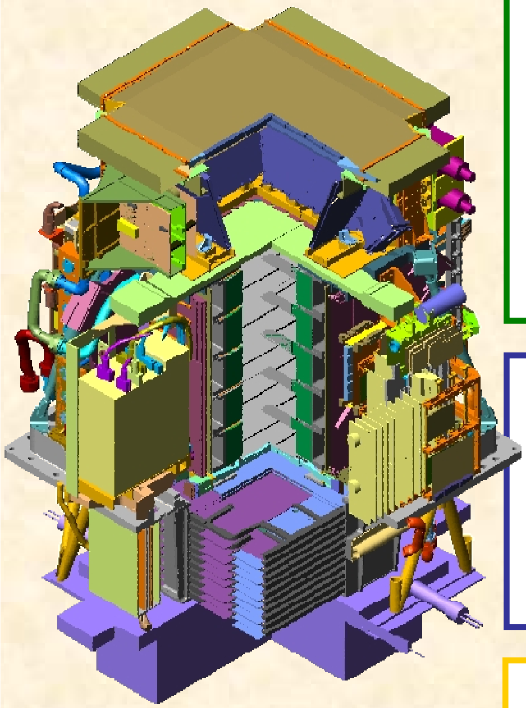
- atmospheric secondaries (~5g/cm2)

⇒ additional systematic uncertainty @low-energy

AMS-01: space shuttle, 1998

PAMELA detectors

Main requirements → high-sensitivity antiparticle identification and precise momentum measure

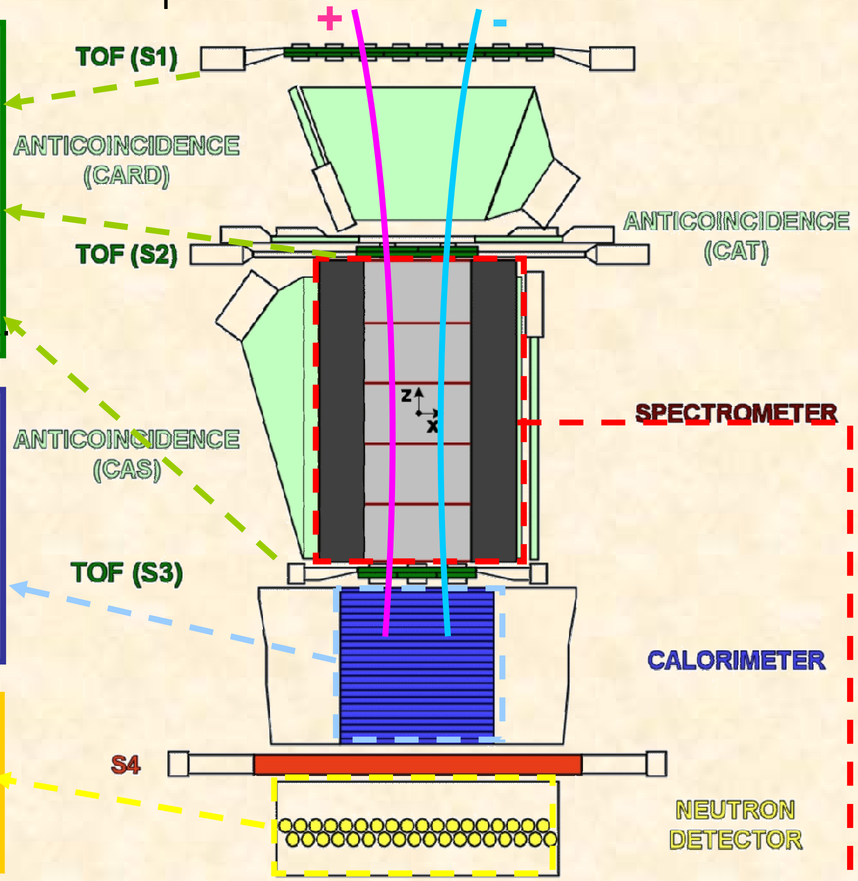


GF: 21.5 cm² sr
Mass: 470 kg
Size: 130x70x70 cm³
Power Budget: 360W

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

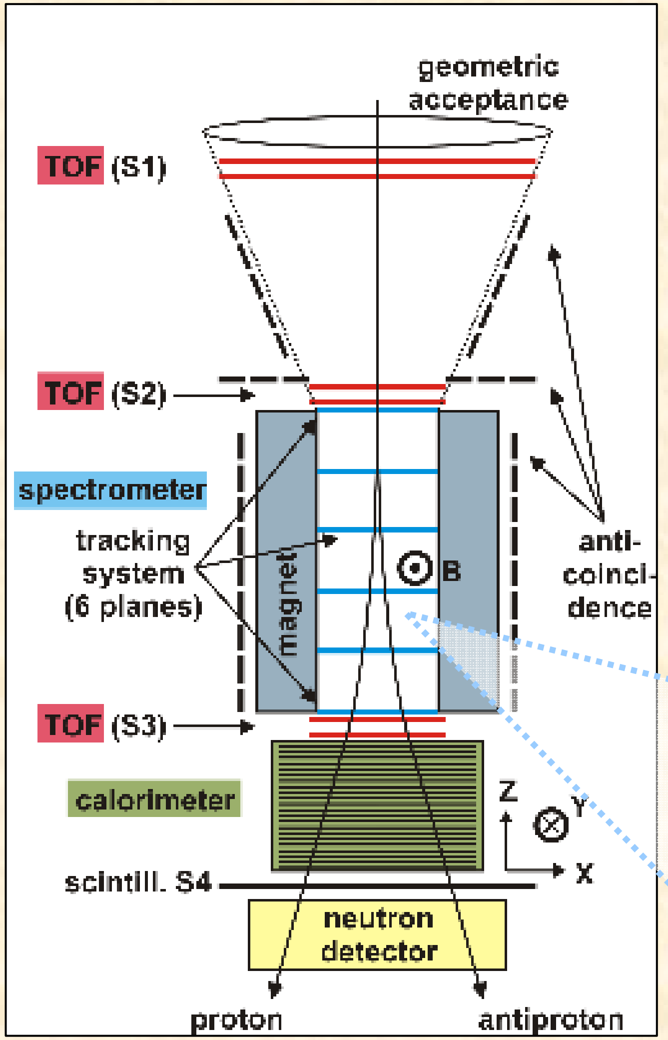
Electromagnetic calorimeter
W/Si sampling (16.3 X0, 0.6 λI)
- Discrimination e+ / p, anti-p / e⁻ (shower topology)
- Direct E measurement for e⁻

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



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

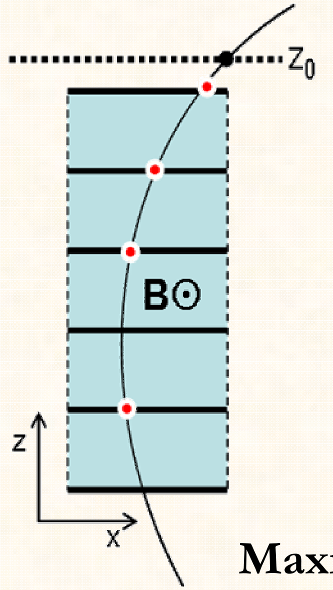
Principle of operation



Track reconstruction

$\alpha = (x_0, y_0, \sin\theta, \phi, \eta)$

Iterative χ^2 minimization as a function of track state-vector components α



Magnetic deflection

$|\eta| = 1/R$

$R = pc/Ze \rightarrow$ **magnetic rigidity**

$\sigma_R/R = \sigma_\eta/\eta$

Maximum Detectable Rigidity (MDR)

def: @ R=MDR $\Rightarrow \sigma_R/R=1$

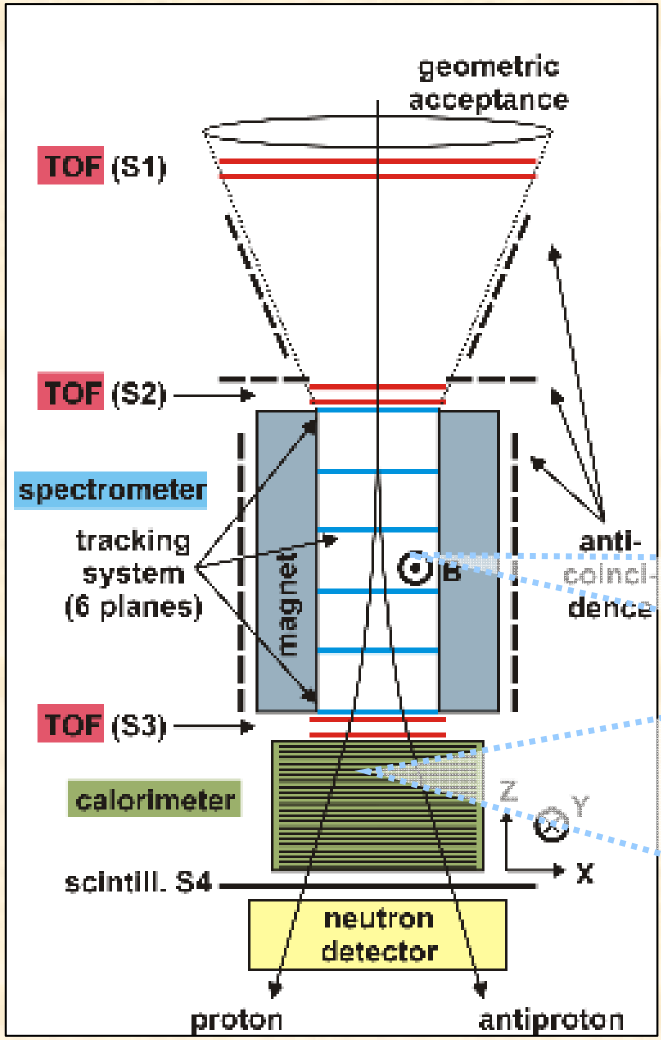
$$\mathbf{MDR = 1/\sigma_\eta}$$

- Measured @ground with protons of known momentum

$\rightarrow$ **MDR~1TV**

- Cross-check in flight with protons (alignment) and electrons (energy from calorimeter)

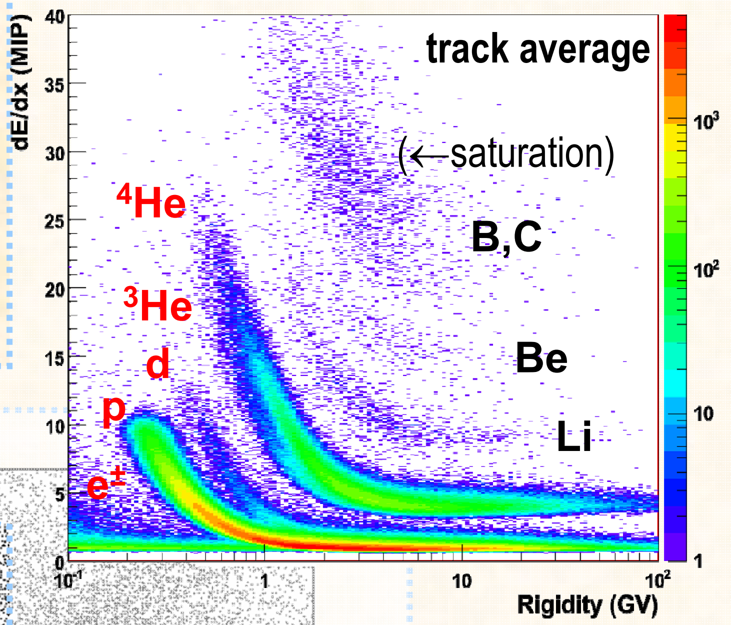
Principle of operation

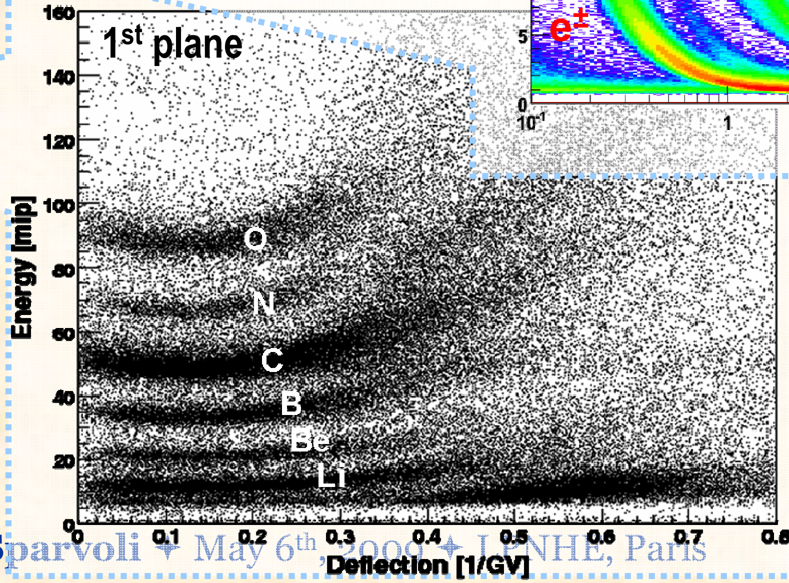


Z measurement

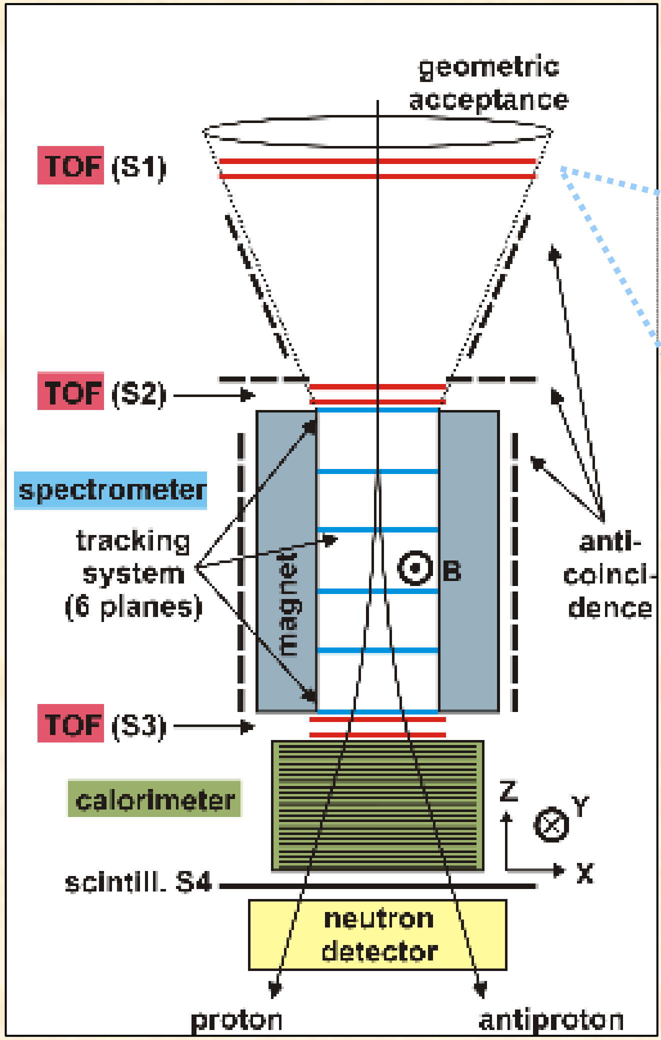
$$-\frac{dE}{dx} = K z^2 \frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_e c^2\beta^2\gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2}\right]$$

Bethe Bloch
ionization energy-loss of heavy (M>>me) charged particles

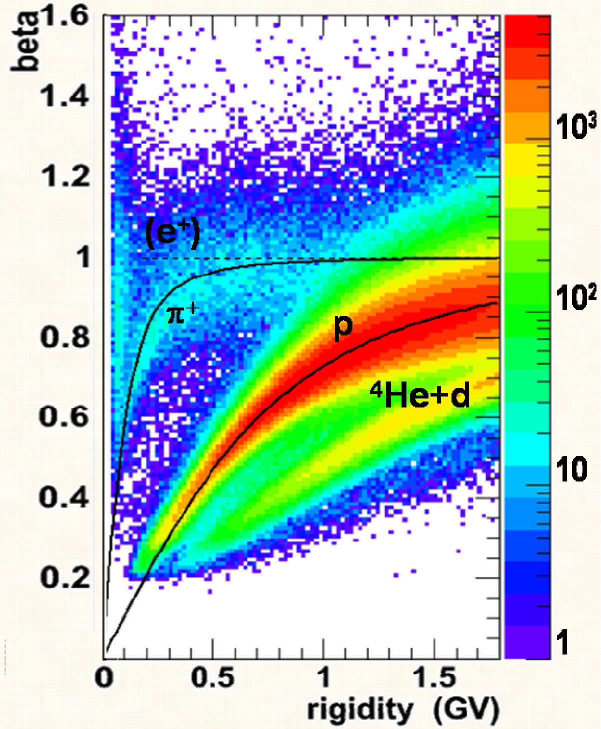




Principle of operation



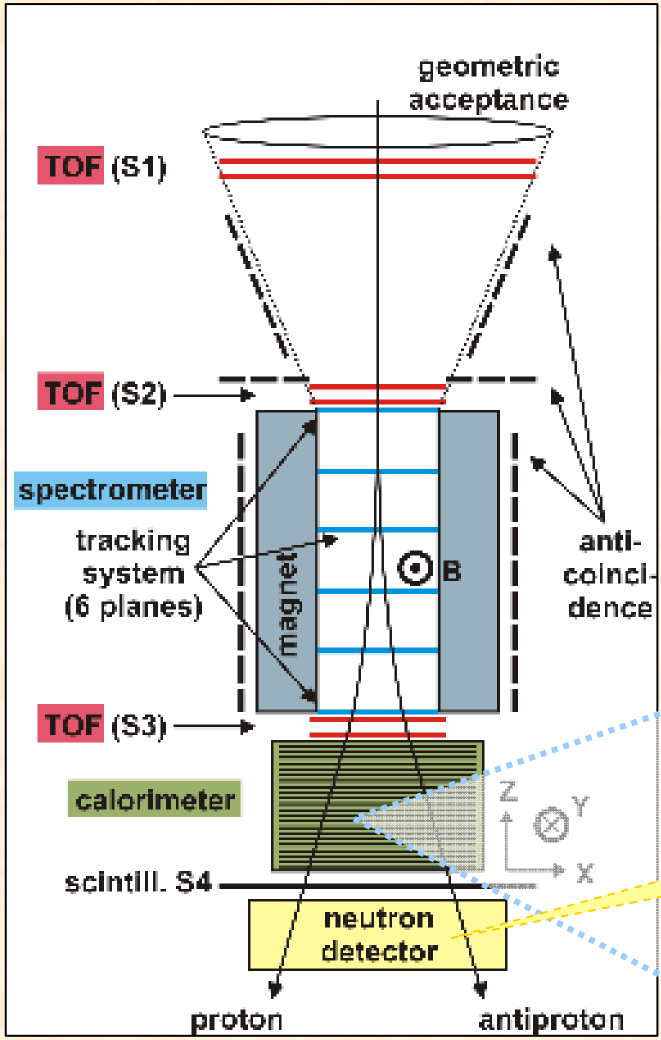
Velocity measurement



- Particle identification @ low energy
- Identify **albedo** (up-ward going particles →β < 0)

→ NB! They mimic antimatter!

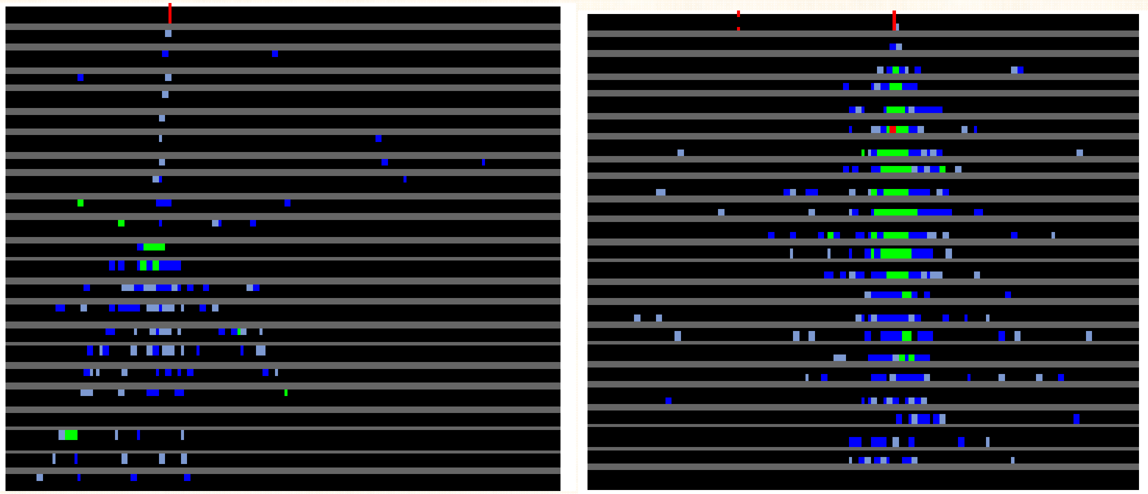
Principle of operation



Electron/hadron separation

- **Interaction topology**

e/h separation



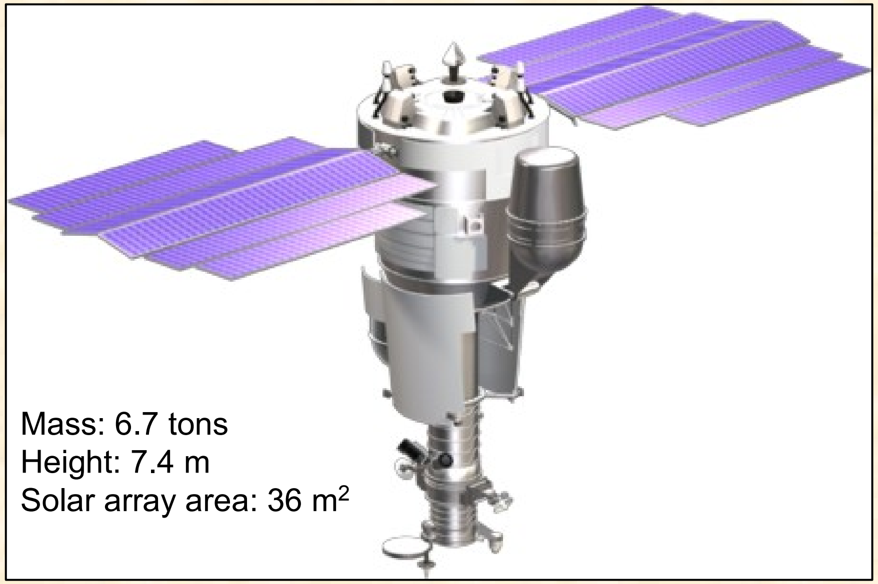
+ NEUTRONS!!

- **Energy measurement of electrons and positrons**

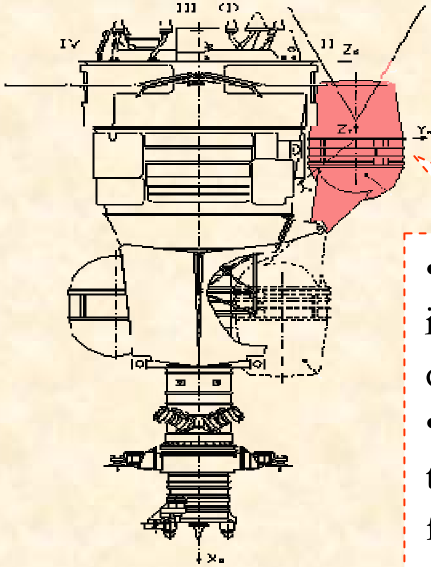
(~full shower containment)

$$\frac{\sigma_E}{E} = a \oplus \frac{b}{\sqrt{E}} \qquad \rightarrow a < 5\%$$

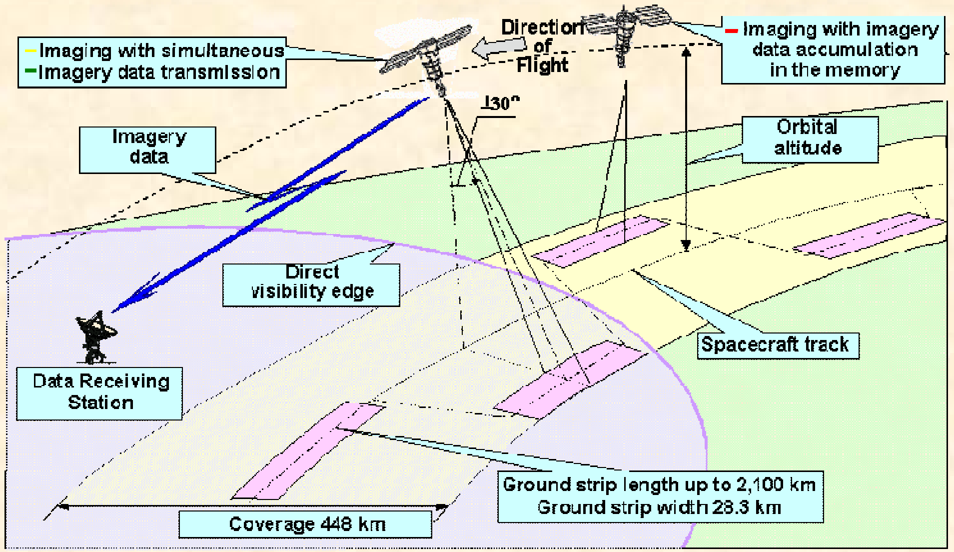
The Resurs DK-1 spacecraft



- Multi-spectral remote sensing of earth's surface
  - *-near-real-time high-quality images*
- Built by the Space factory TsSKB Progress in Samara (Russia)
- **Operational orbit parameters:**
  - **-inclination ~70°**
  - **-altitude ~ 360-600 km (elliptical)**
- **Active life >3 years**
- Data transmitted via Very high-speed Radio Link (VRL)



- PAMELA mounted inside a pressurized container
- moved from parking to data-taking position few times/year



PAMELA design performance

Magnetic curvature & trigger

spillover shower containment Maximum detectable rigidity (MDR)

	energy range		particles in 3 years
Antiprotons	**80 MeV ÷190 GeV**		$O(10^4)$
Positrons	**50 MeV ÷ 270 GeV**		$O(10^5)$
Electrons	up to 400 GeV		$O(10^6)$
Protons	up to 700 GeV		$O(10^8)$
Electrons+positrons	up to 2 TeV	(from calorimeter)	
Light Nuclei	up to 200 GeV/n	He/Be/C:	$O(10^{7/4/5})$
Anti-Nuclei search	sensitivity of 3×10^{-8} in anti-He/He		

→ **Unprecedented statistics and new energy range for cosmic ray physics**
(e.g. contemporary antiproton and positron maximum energy ~ 40 GeV)

→ **Simultaneous measurements of many species**

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

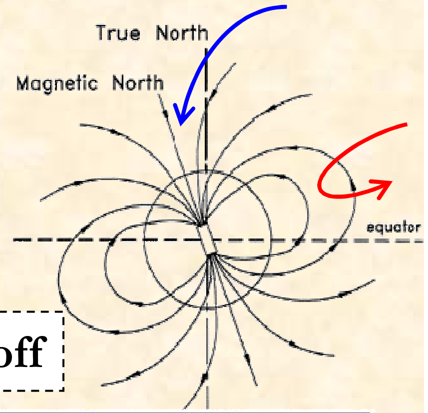
→ **PAMELA in continuous data-taking mode since commissioning phase ended on July 11th 2006**

Main antenna in NTsOMZ

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)

Till May 2008:
~500 days of data taking
~10 TByte of raw data downlinked
~12•10^8 triggers recorded and analysed
(Data from May till now under analysis)

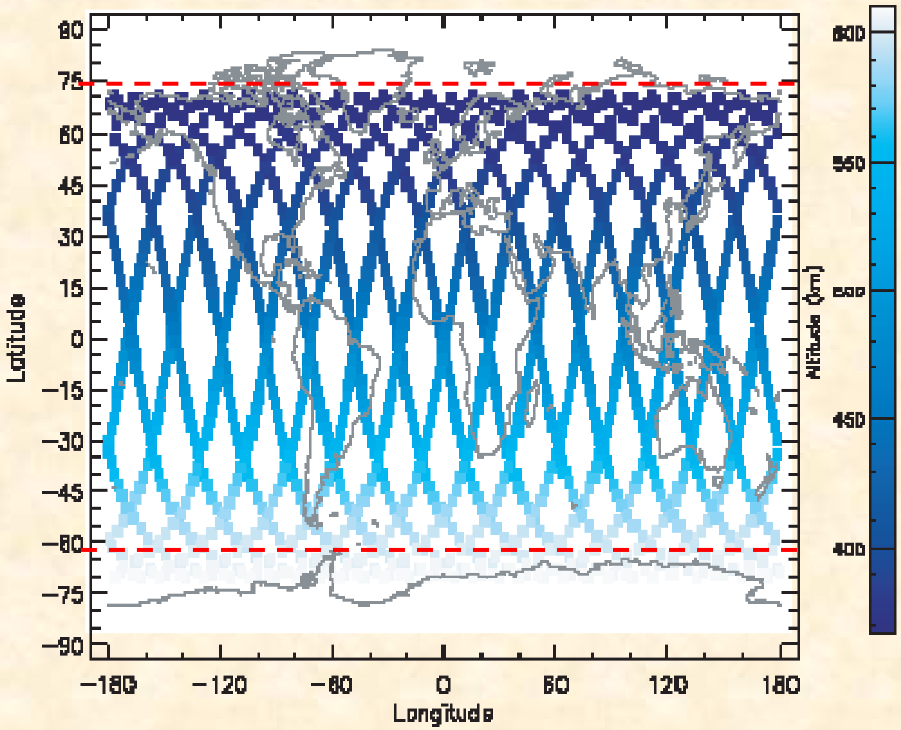
Satellite orbit



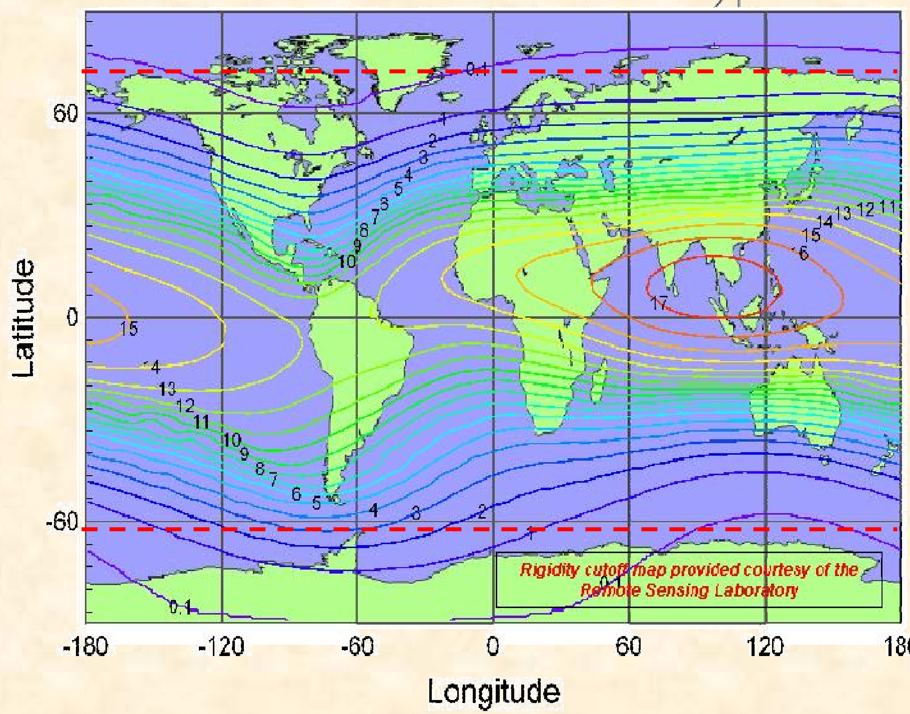
PAMELA orbit

inclination ~70°

altitude ~ 360-600 km

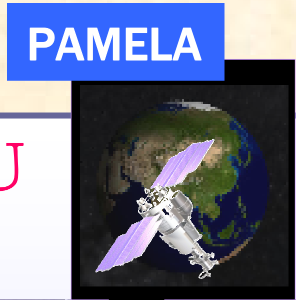


Vertical rigidity cutoff



→ the quasi-polar orbit allows to study low-energy cosmic rays (R>100MV)

PAMELA science

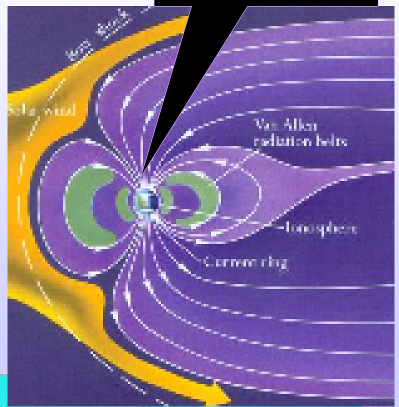


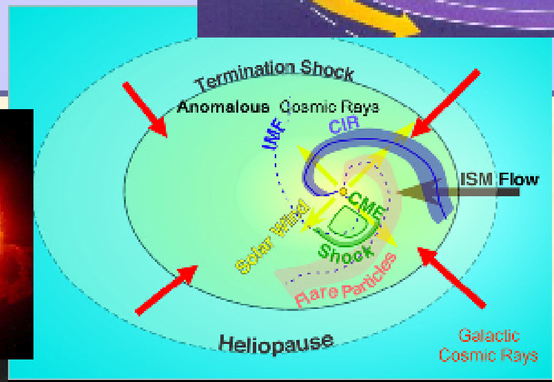
PAMELA is a Space Observatory @ 1AU

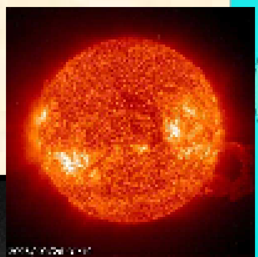
- Search for dark matter
- Search for primordial antimatter

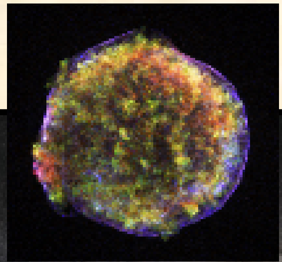
… but also:

- Study of cosmic-ray origin and propagation
- Study of solar physics and solar modulation
- Study of terrestrial magnetosphere









Antiprotons

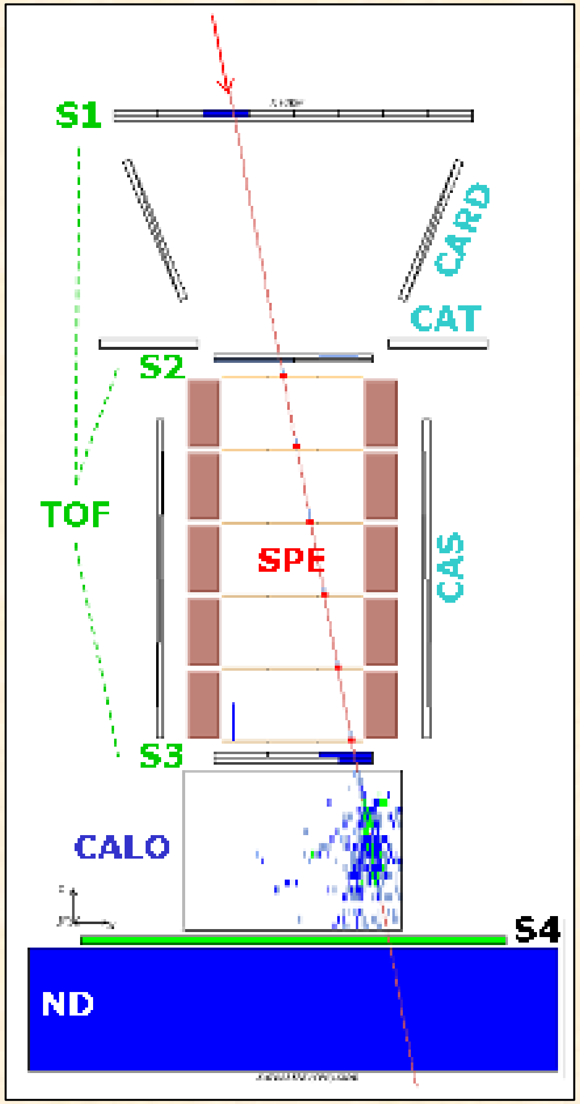
High-energy antiproton analysis

- Analyzed data July 2006 – February 2008 (~500 days)
- Collected triggers ~10^8
- Identified **~ 10 10^6 protons** and **~ 1 10^3 antiprotons** between 1.5 and 100 GeV (**100 p-bar above 20 GeV**)

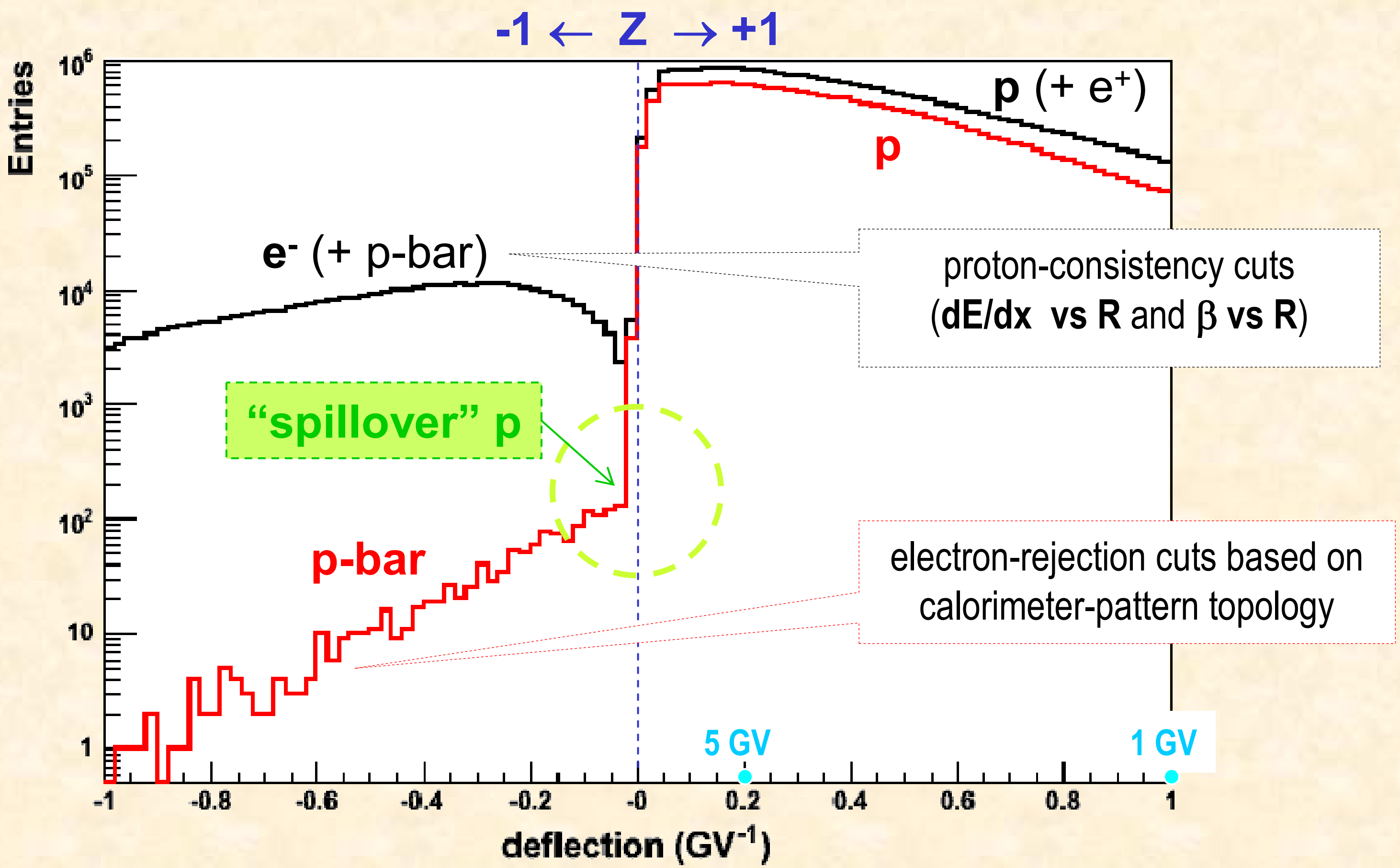
- Antiproton/proton identification:
  - rigidity (R) → SPE
  - |Z|=1 (dE/dx vs R) → SPE&ToF
  - β vs R consistent with M_p → ToF
  - p-bar/p separation (charge sign) → SPE
  - p-bar/e^- (and p/e^+) separation → CALO

- Dominant background → **spillover protons**:
  - finite deflection resolution of the SPE ⇒ wrong assignment of charge-sign @ high energy
  - proton spectrum harder than positron ⇒ p/p-bar increase for increasing energy (10^3 @1GV 10^4 @100GV)

→ Required strong SPE selection

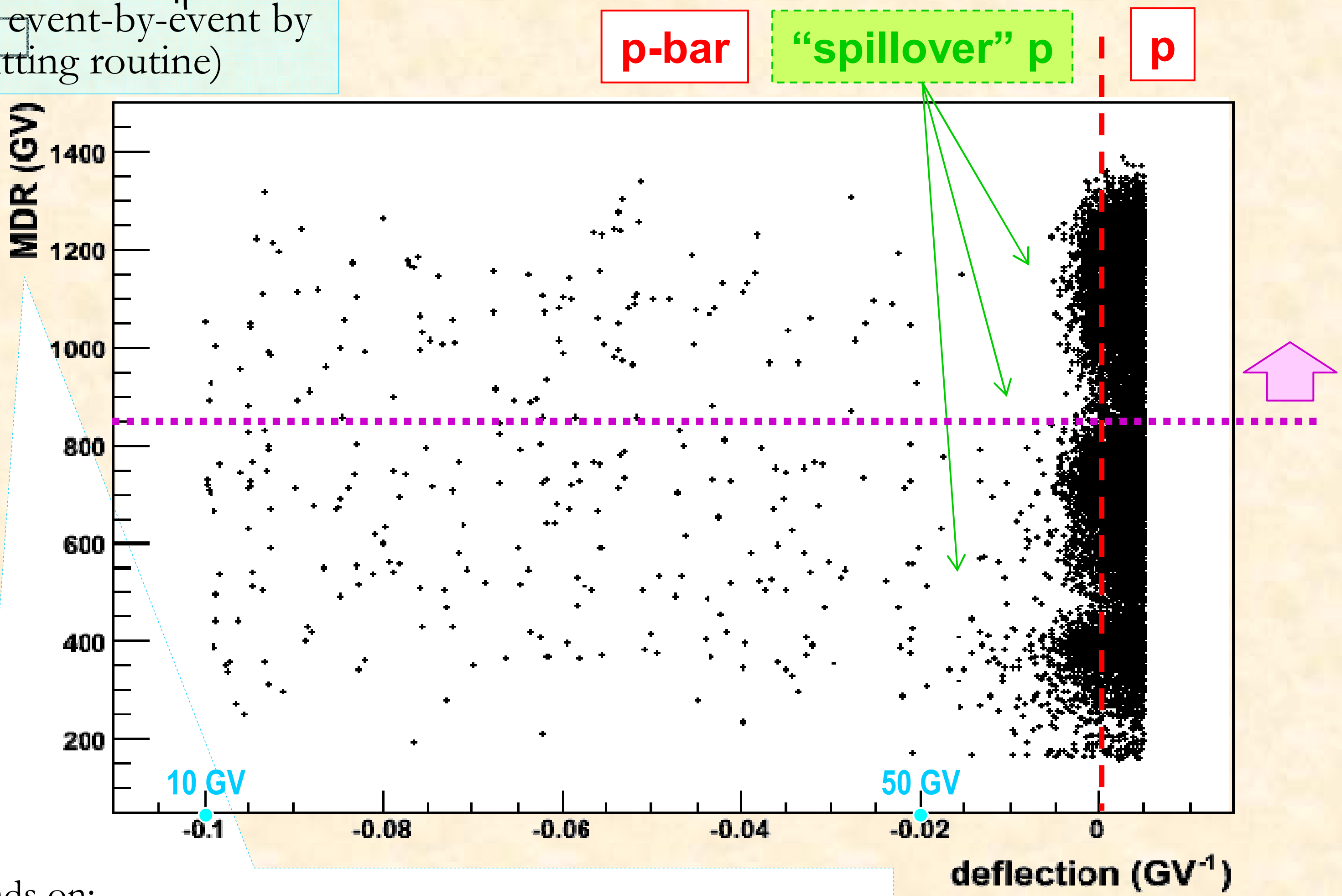


Antiproton identification



Proton-spillover background

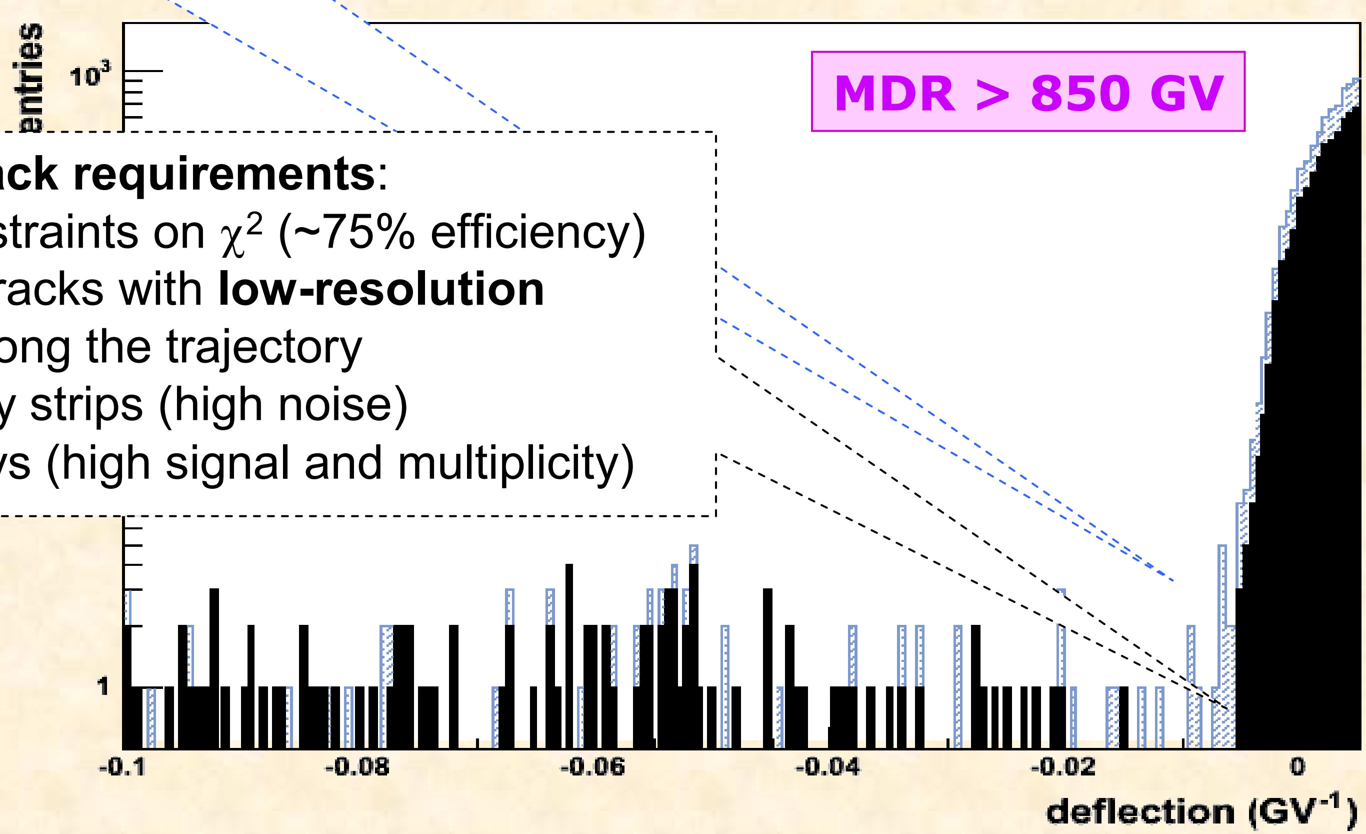
MDR = $1/\sigma_\eta$
(evaluated event-by-event by the fitting routine)



MDR depends on:
- number and distribution of fitted points along the trajectory
- spatial resolution of the single position measurements
- magnetic field intensity along the trajectory

Proton-spillover background

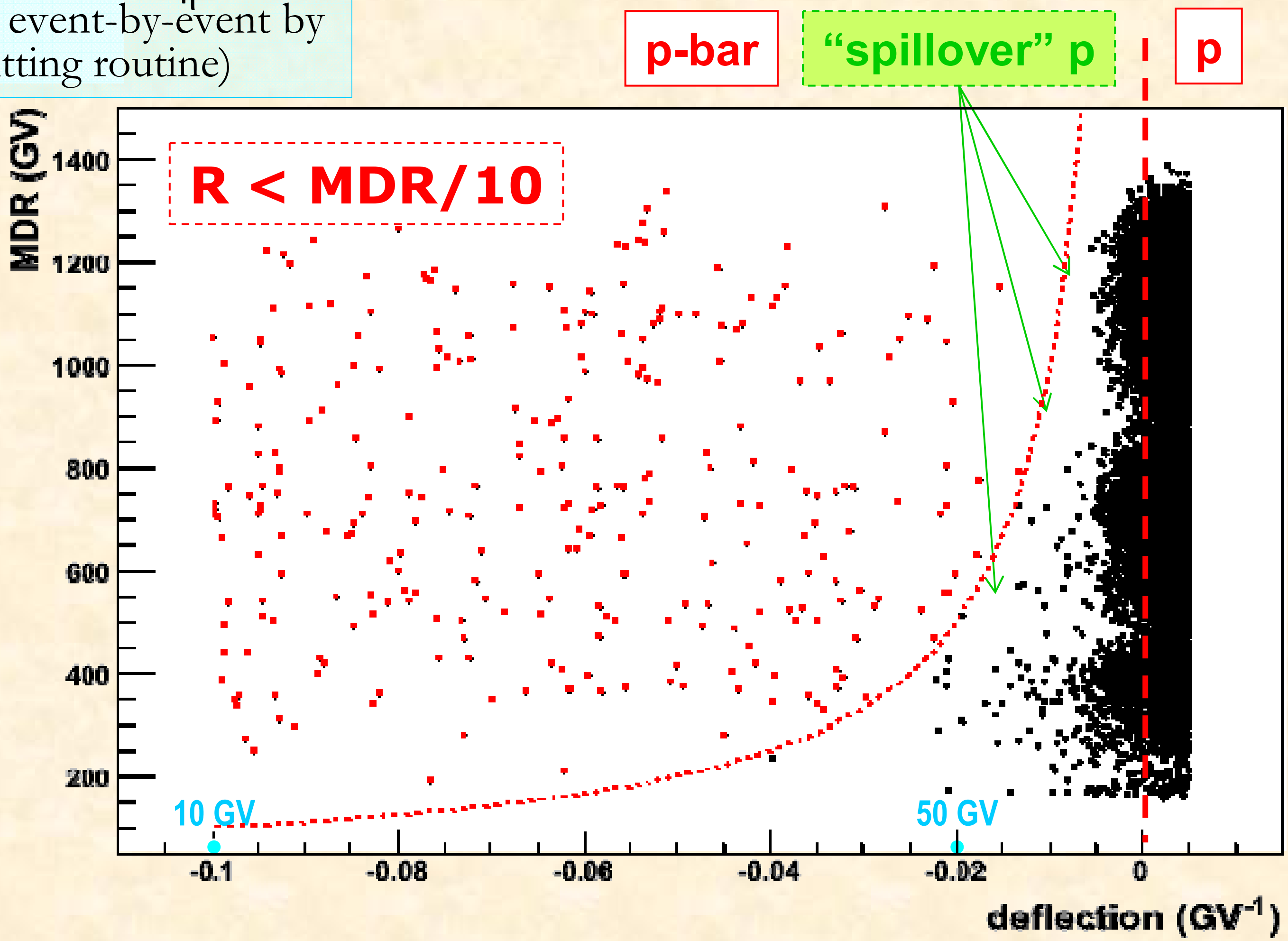
Minimal track requirements



Strong track requirements:
•strict constraints on χ^2 (~75% efficiency)
•rejected tracks with **low-resolution** clusters along the trajectory
- faulty strips (high noise)
- δ-rays (high signal and multiplicity)

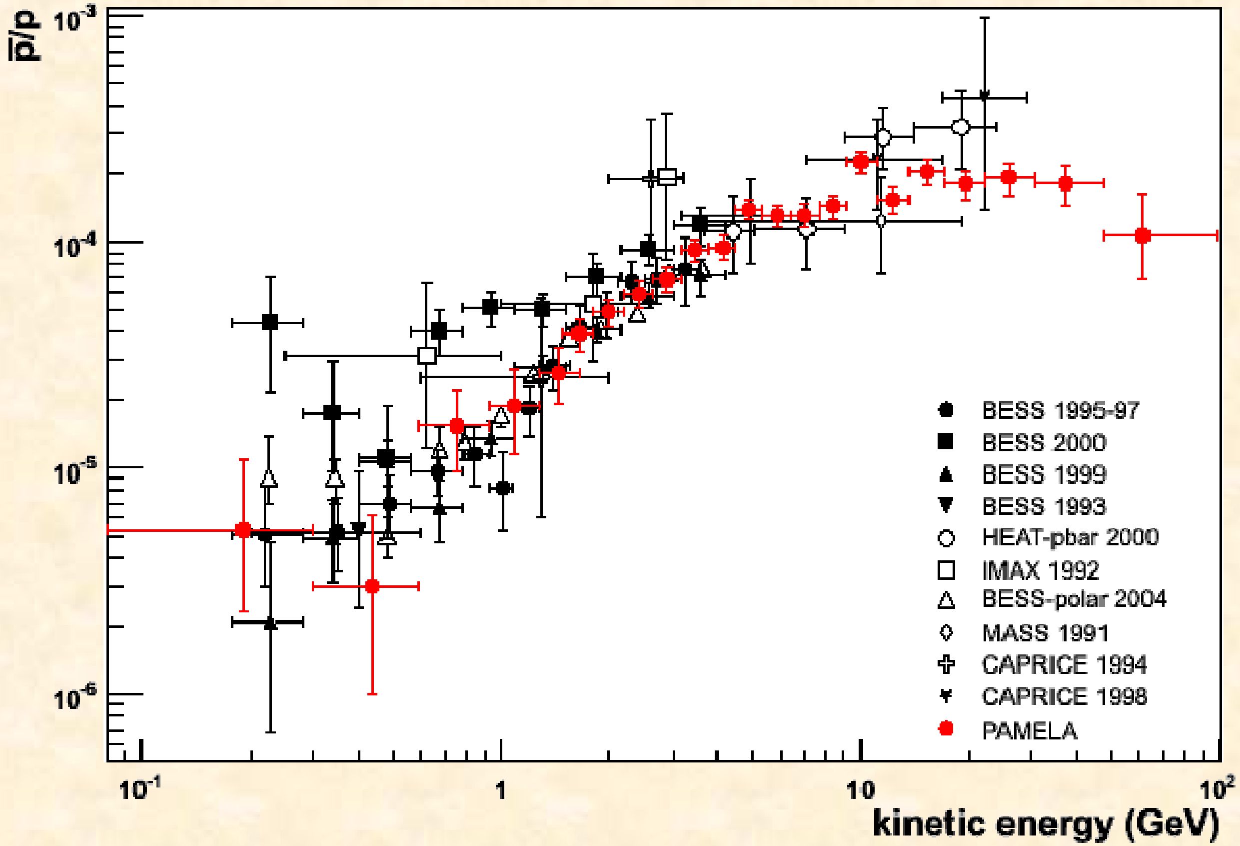
Proton-spillover background

MDR = $1/\sigma_\eta$
(evaluated event-by-event by the fitting routine)



Electrons: efficiently removed by CALO
Pions (from interactions in dome) : about 3% in the pbar sample

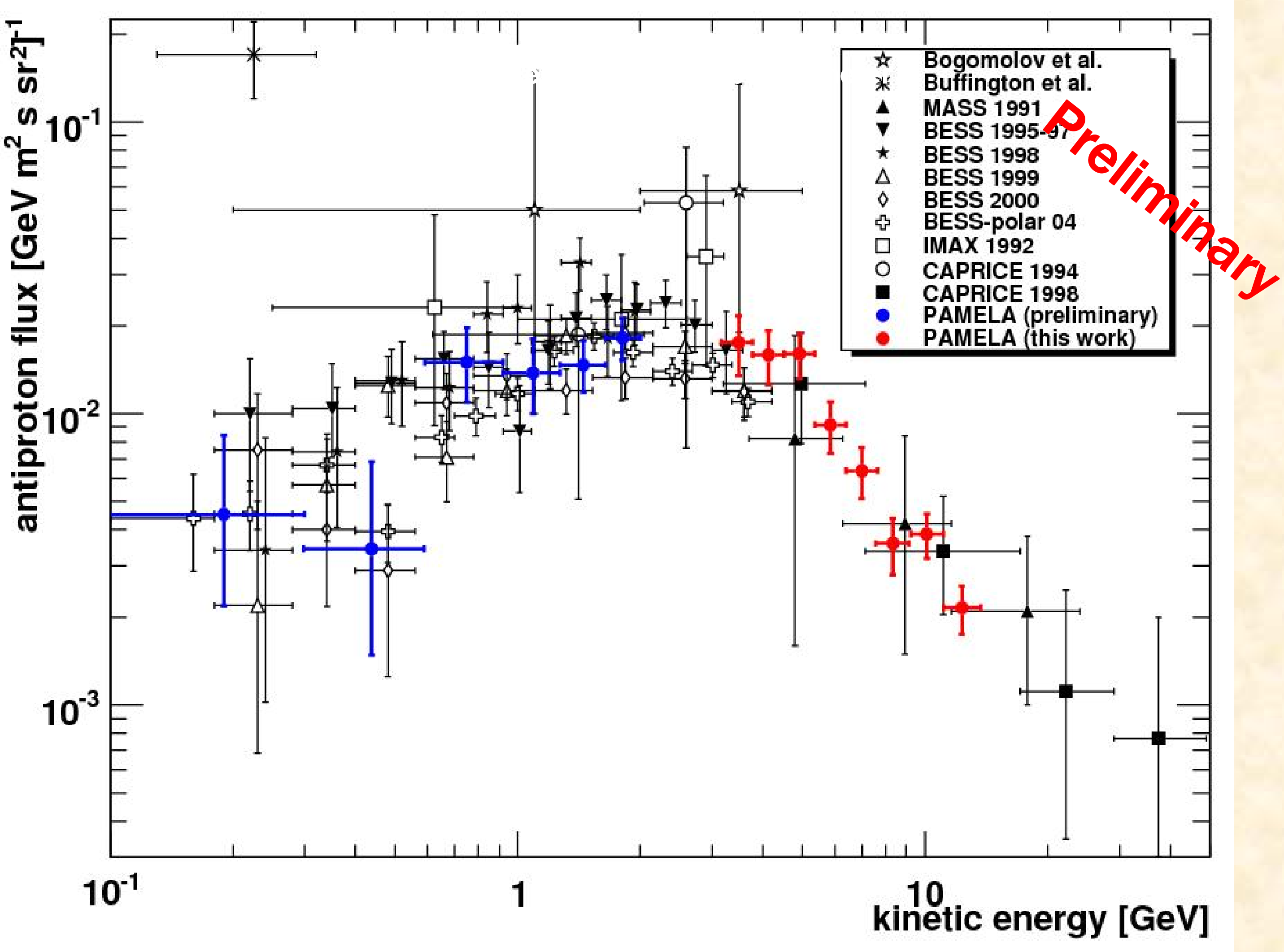
Antiproton-to-proton ratio



preliminary
(Petter Hofverberg's PhD Thesis)

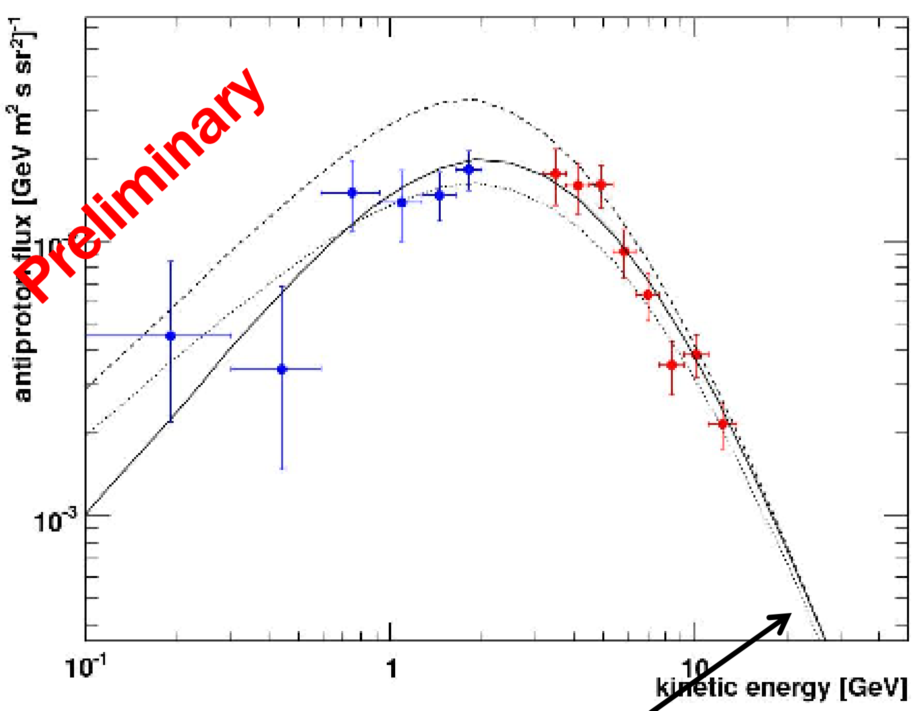
PRL 102, 051101 (2009)

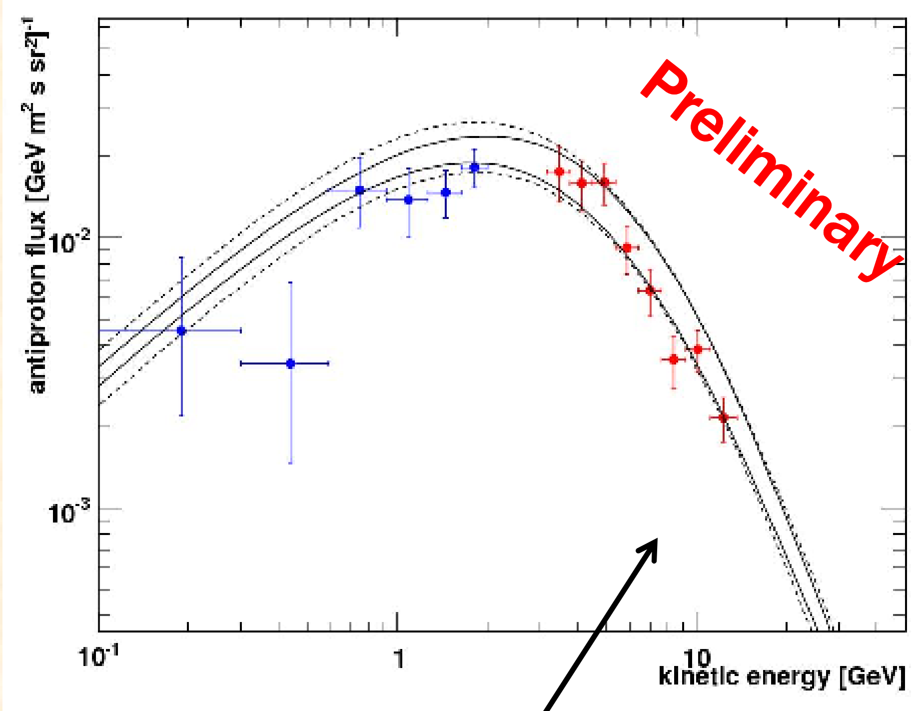
PAMELA: Antiproton Flux



Antiproton Flux

statistical errors only
energy in the spectrometer





<u>Secondary production:</u>
V. S. Ptuskin et al, ApJ 642 (2006) 902

<u>Secondary production:</u>
F. Donato et al., 536 (2001) 172

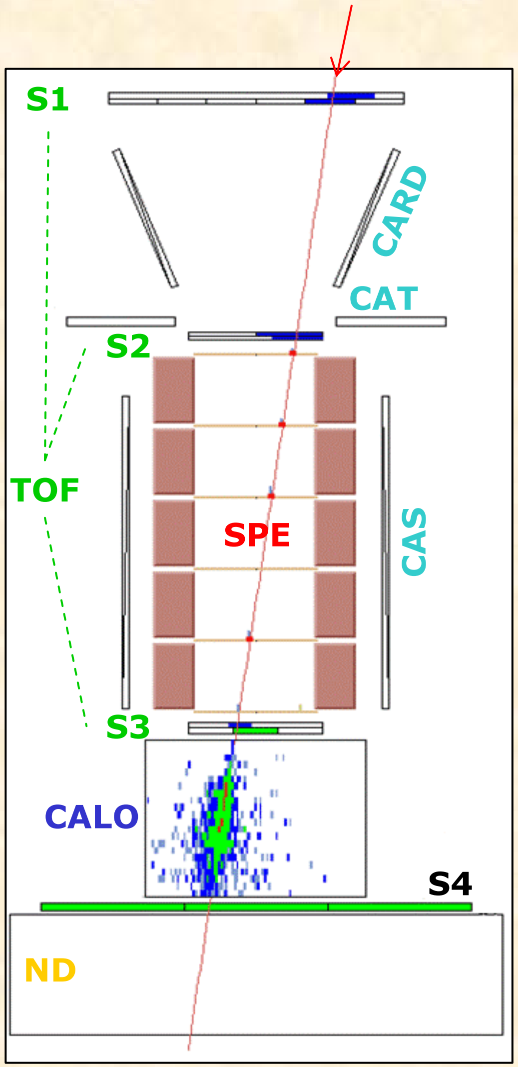
Positrons

High-energy positron analysis

- Analyzed data July 2006 – February 2008 (~500 days)
- Collected triggers ~10^8
- Identified **~ 150 10^3 electrons** and **~ 9 10^3 positrons** between 1.5 and 100 GeV (**180 positrons above 20 GeV**)

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

- Dominant background → **interacting protons**:
    - fluctuations in hadronic shower development ⇒ $\pi_0 \rightarrow \gamma\gamma$ might mimic pure em showers
    - proton spectrum harder than positron ⇒ p/e^+ increase for increasing energy (10^3 @1GV 10^4 @100GV)

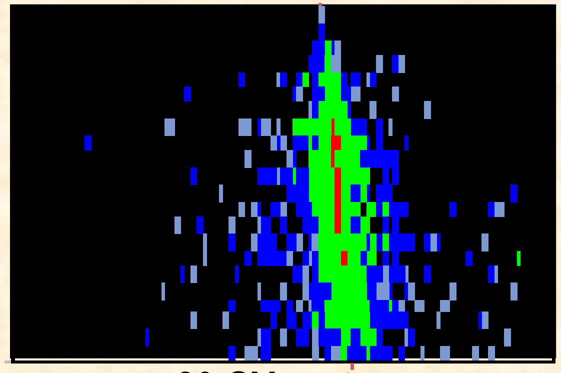


→ Required strong CALO selection

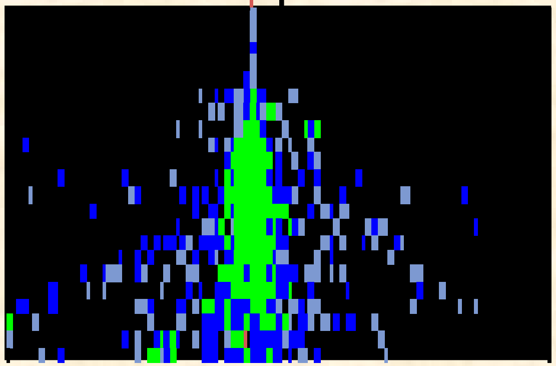
Positron identification with CALO

- Identification based on:
  - **Shower topology** (lateral and longitudinal profile, shower starting point)
  - **Total detected energy** (energy-rigidity match)
- Analysis key points:
  - **Tuning/check of selection criteria with:**
    - test-beam data
    - simulation
    - flight data → dE/dx from SPE & neutron yield from ND
  - **Selection of pure proton sample from flight data** ("pre-sampler" method):
    - *Background-suppression method*
    - *Background-estimation method*

51 GV positron

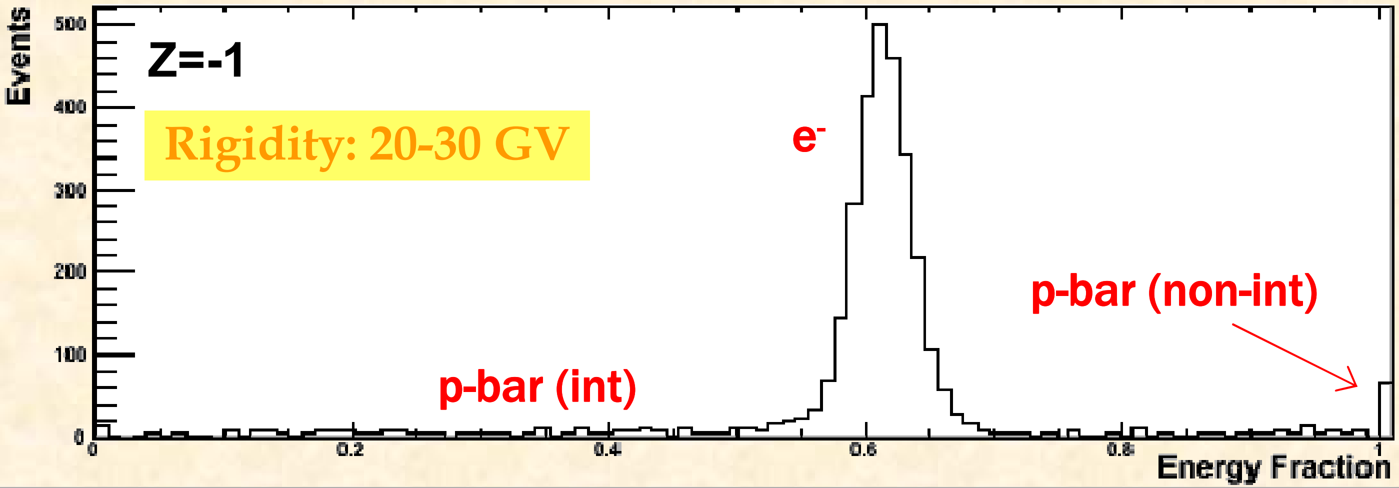


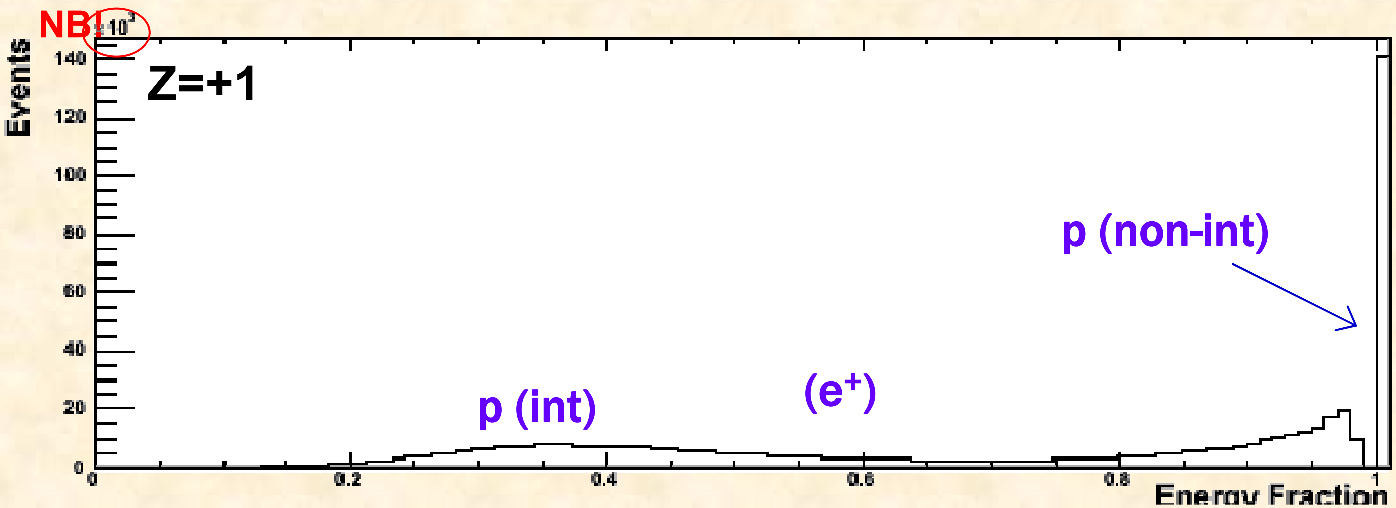
80 GV proton



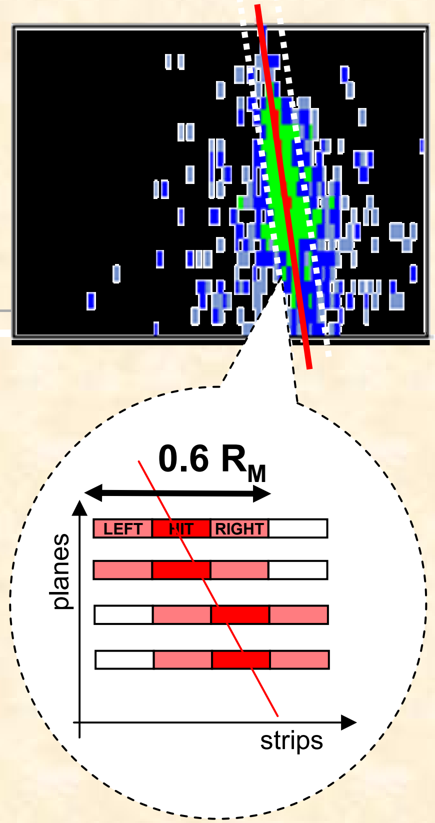
Final results make <u>NO USE</u> of test-beam and/or simulation calibrations.
The measurement is based only on flight data
with the <u>background-estimation</u> method

Positron identification



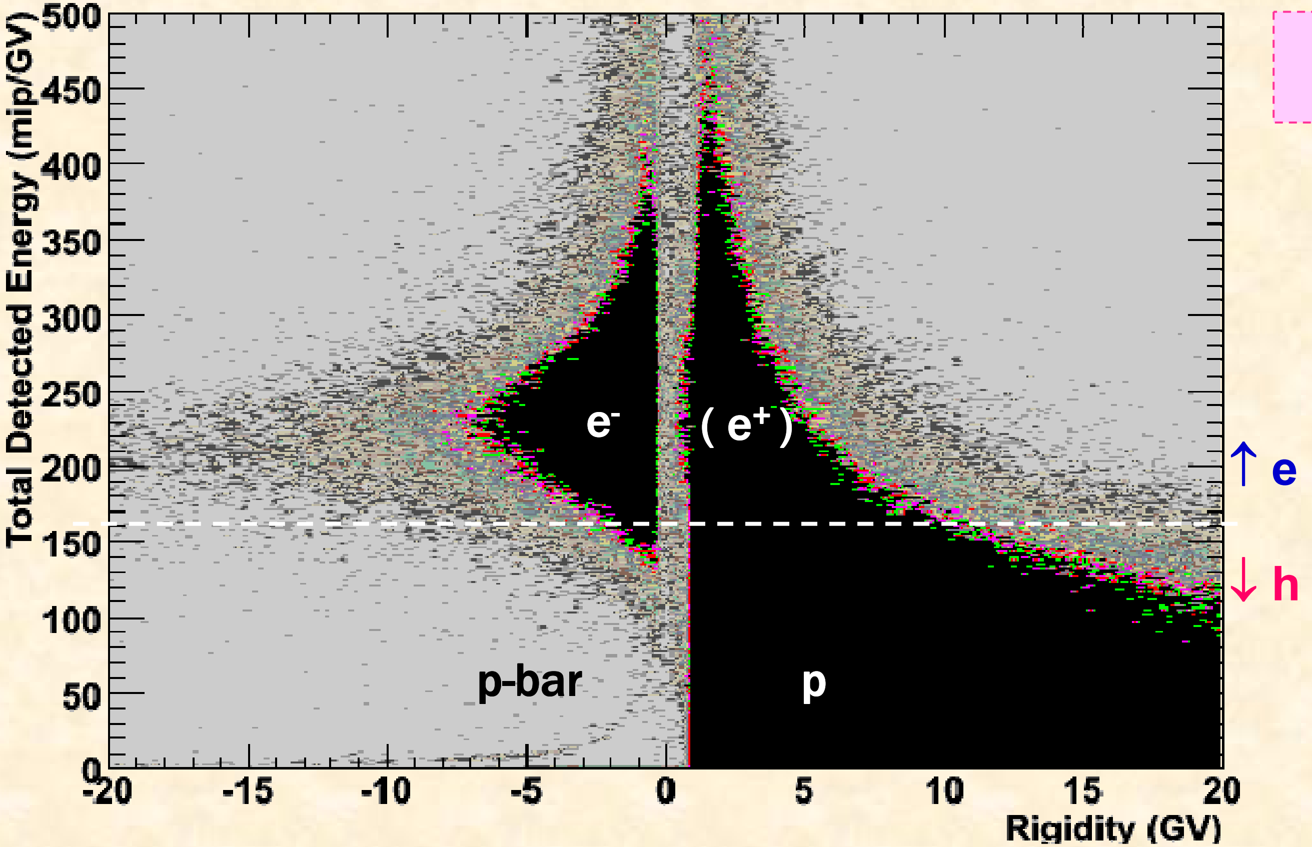


Fraction of charge released along the calorimeter track



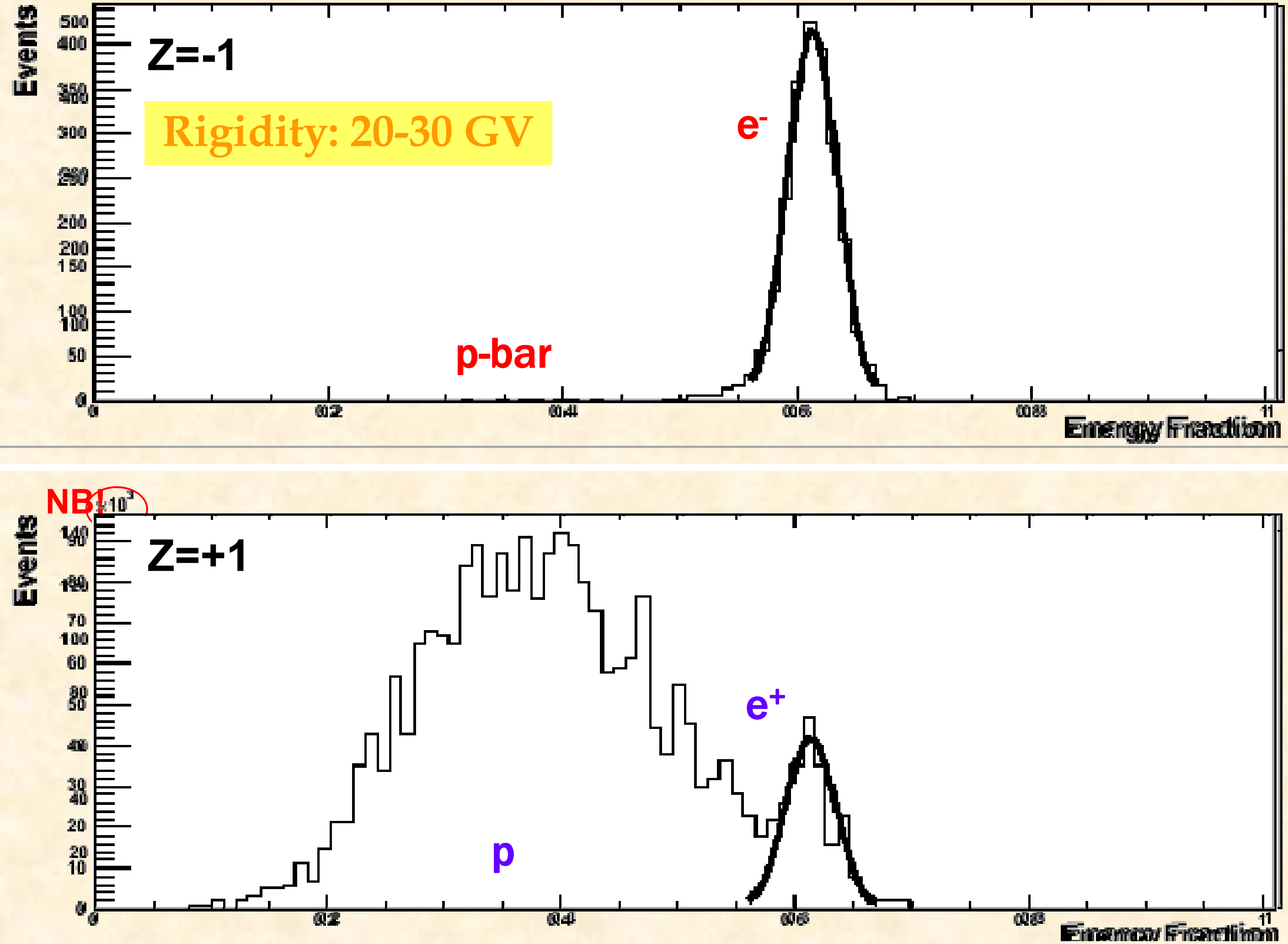
N.B: for em showers 90% of E contained in 1 R_M !

Positron identification



Energy-momentum match

Positron identification



Fraction of charge released along the calorimeter track

+

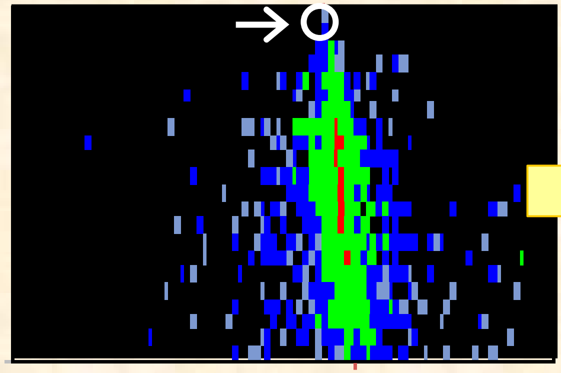
Constraints on:

Energy-momentum match

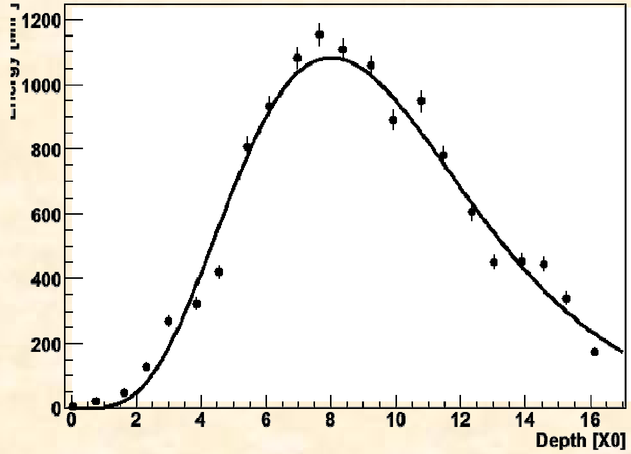
Positron identification

Shower starting-point

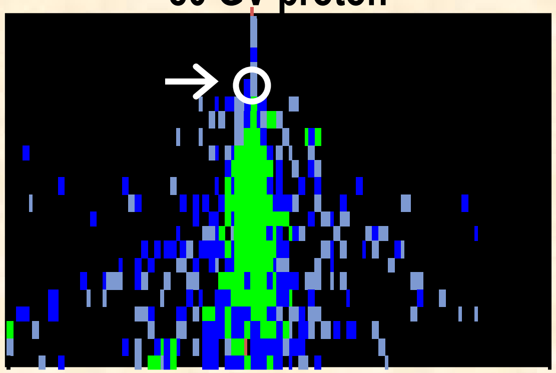
51 GV positron



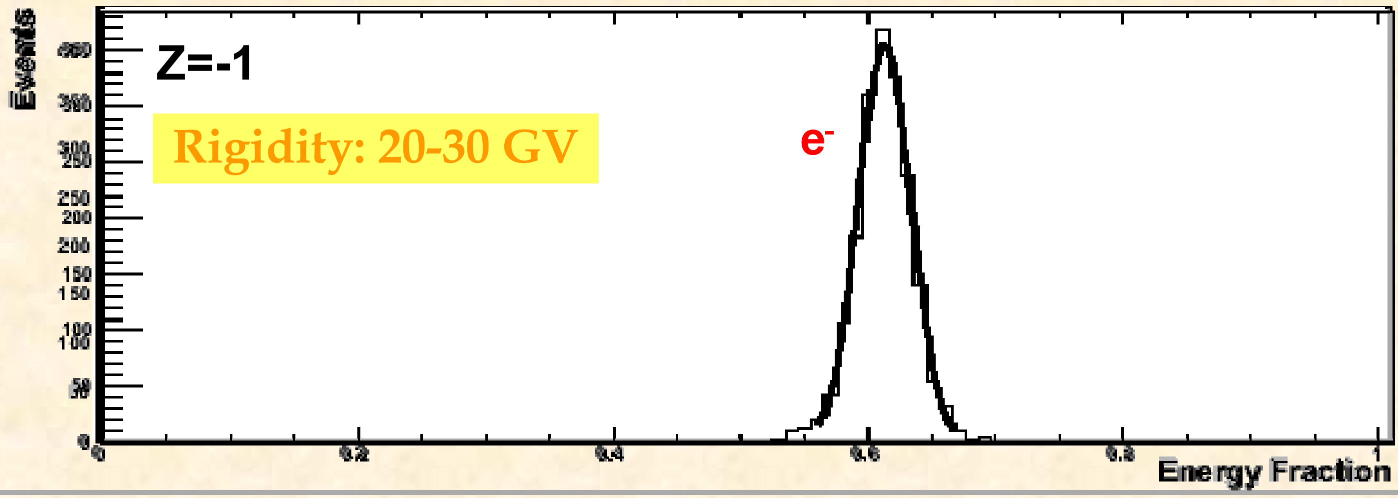
Longitudinal profile

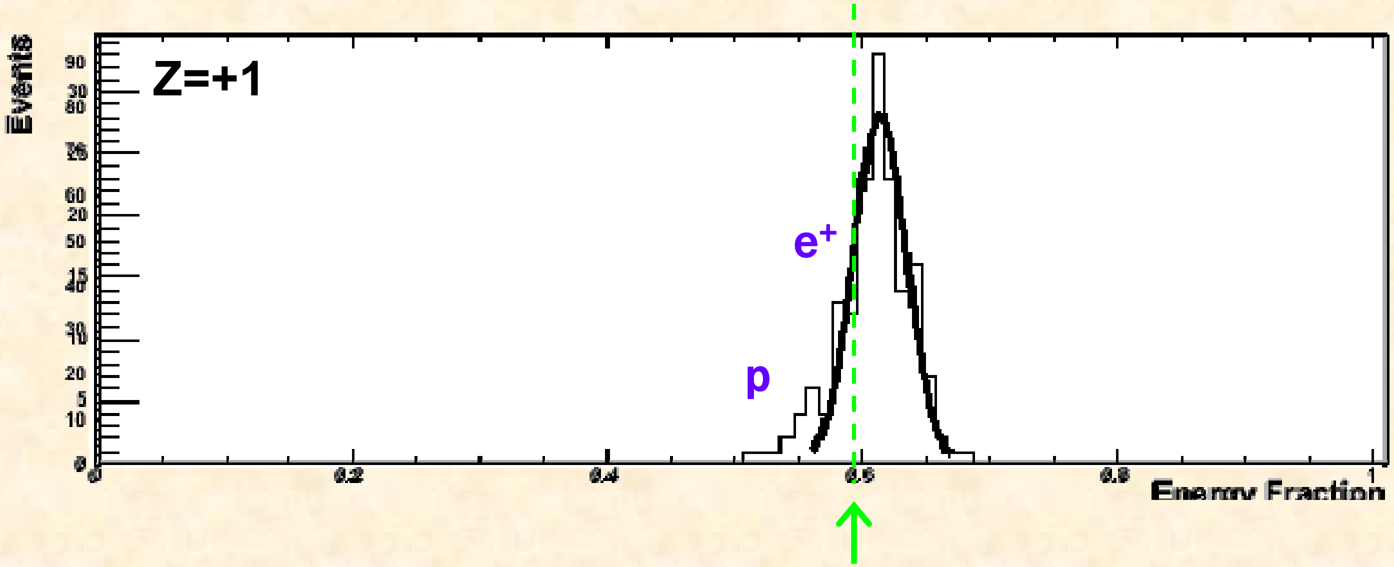


80 GV proton



Positron identification





Fraction of charge released along the calorimeter track

+

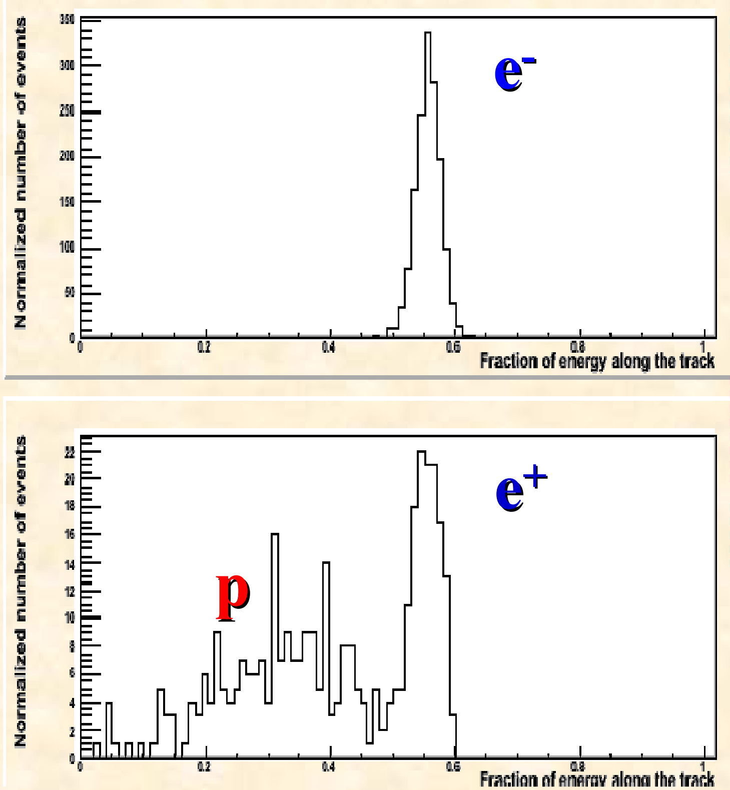
Constraints on:

- Energy-momentum match
- Shower starting-point
- Longitudinal profile
- Lateral profile

BK-suppression method

Check of calorimeter selection

Flight data
Rigidity: 20-30 GV



Fraction of charge released along the calorimeter track

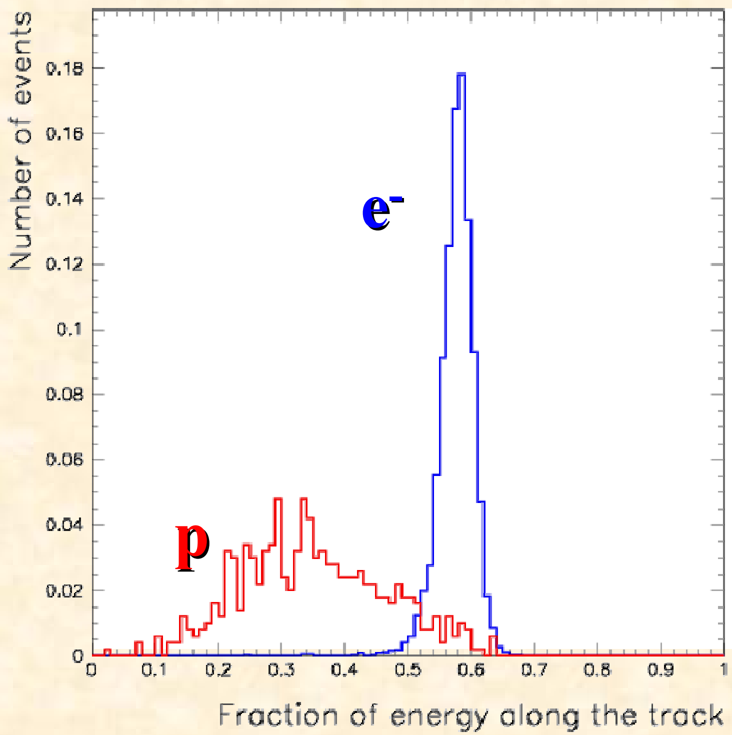
+

Constraints on:

Energy-momentum match

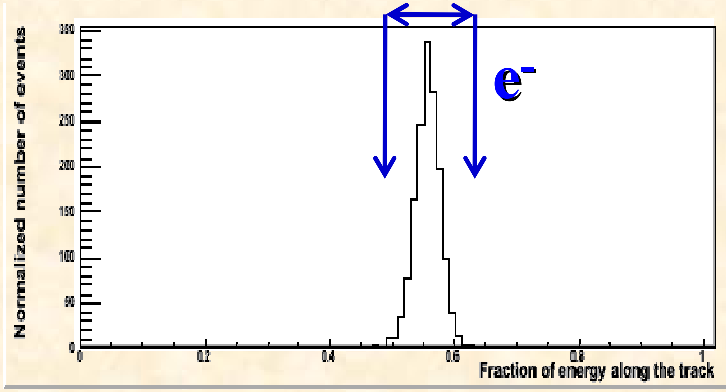
Shower starting-point

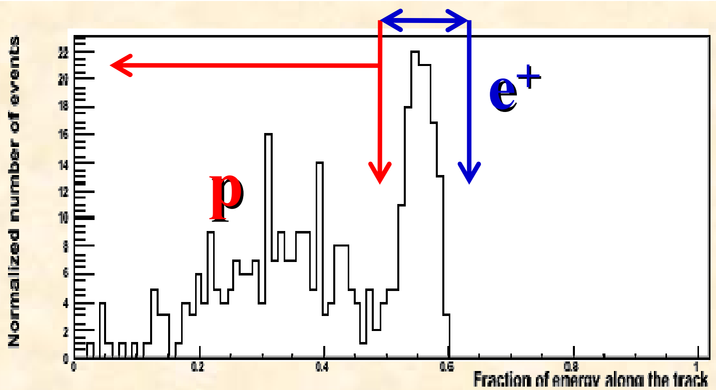
Test beam data
Momentum: 50GeV/c



Check of calorimeter selection

Flight data
Rigidity: 20-30 GV





Fraction of charge released along the calorimeter track

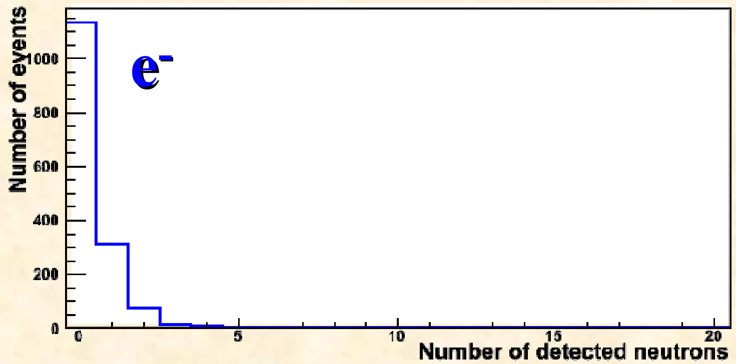
+

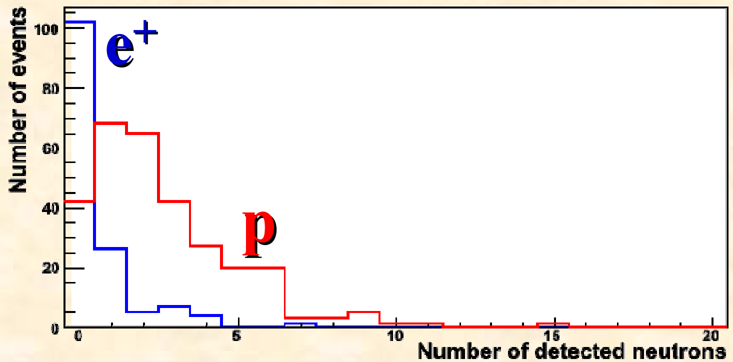
Constraints on:

Energy-momentum match

Shower starting-point

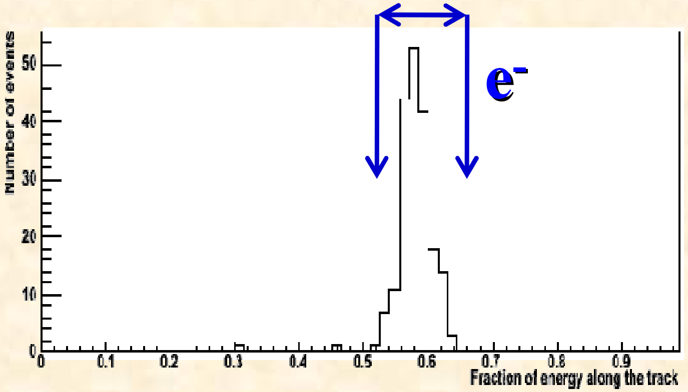
Flight data
Neutron yield in ND

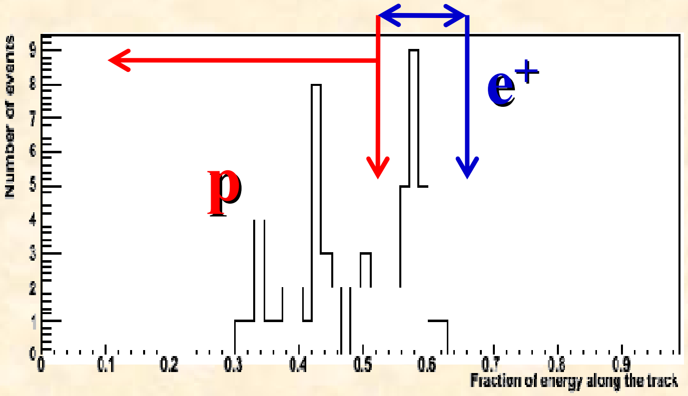




Check of calorimeter selection

Flight data
Rigidity: 42-65 GV





Fraction of charge released along the calorimeter track

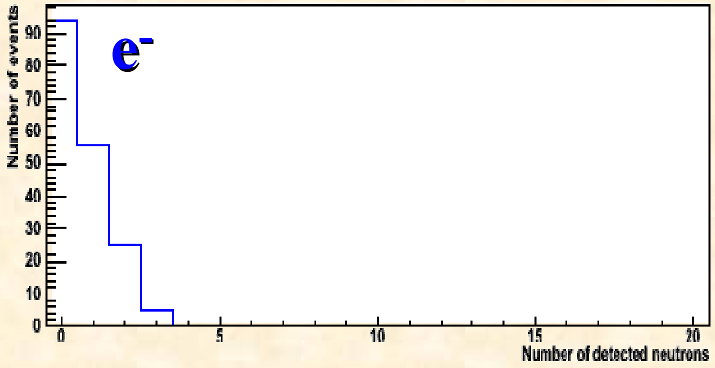
+

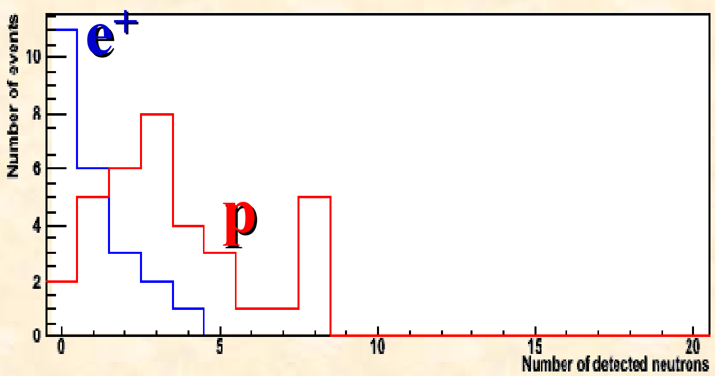
Constraints on:

Energy-momentum match

Shower starting-point

Flight data
Neutron yield in ND





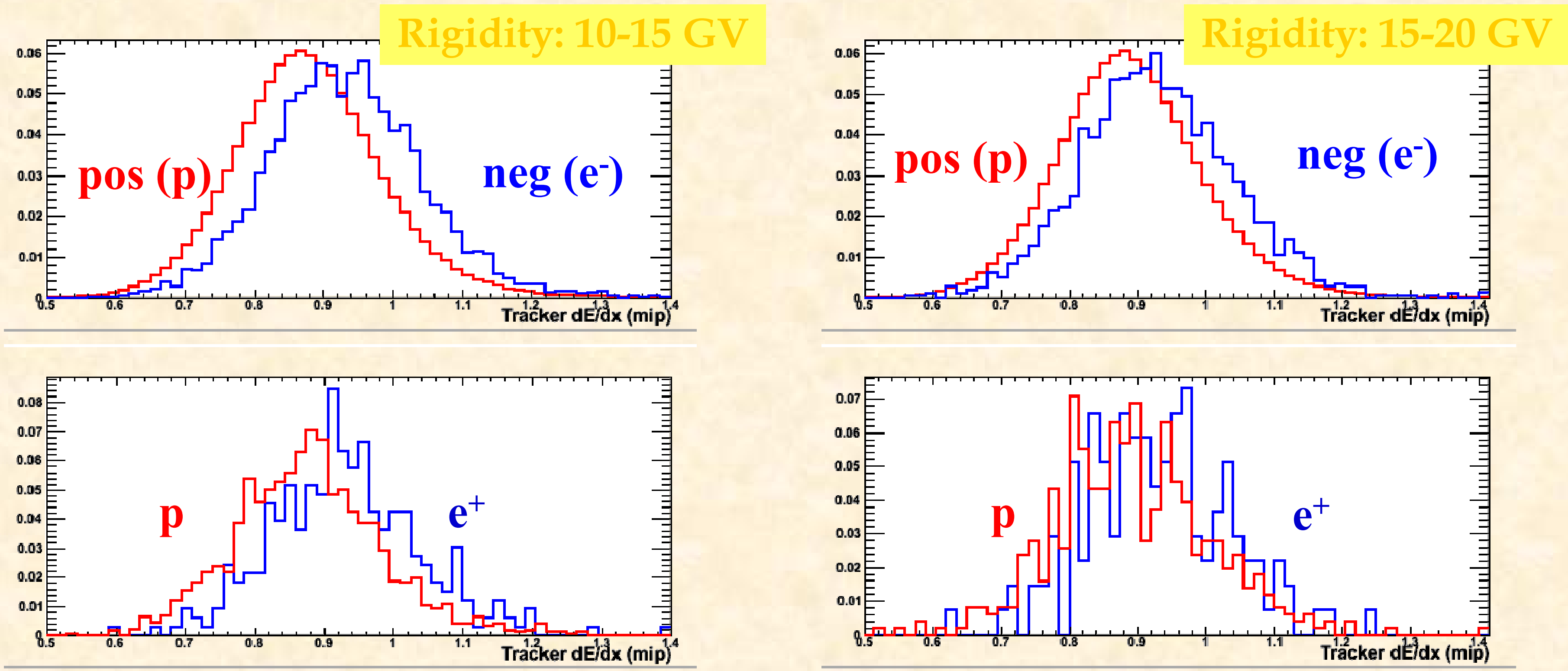
Check of calorimeter selection

Energy loss in silicon tracker detectors:

$$-\frac{dE}{dx} = Kz^2\frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_ec^2\beta^2\gamma^2T_{\mathrm{max}}}{I^2}-\beta^2-\frac{\delta(\beta\gamma)}{2}\right]$$

Relativistic rise

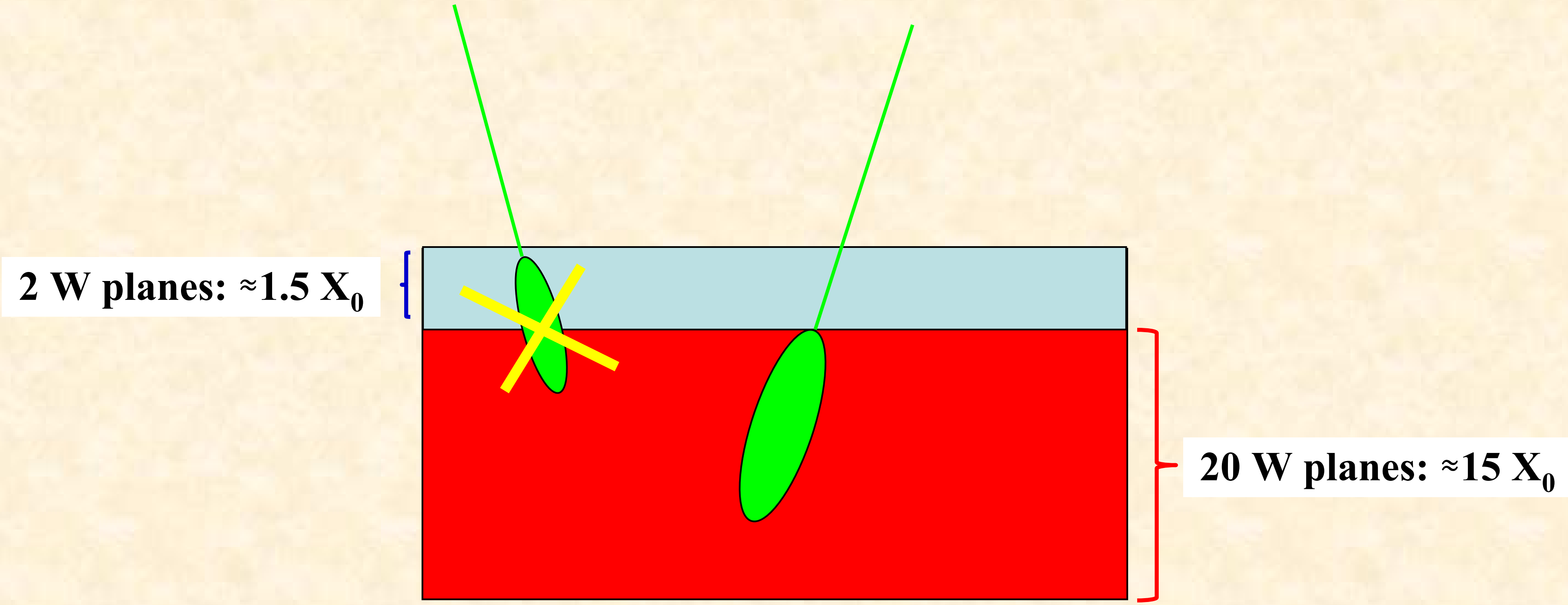
- **Top: positive (mostly p) and negative events (mostly e$^-$)**
- **Bottom: positive events identified as p and e$^+$ by trasversal profile method**



The "pre-sampler" method

Selection of a pure sample of protons from flight data

CALORIMETER: 22 W planes: 16.3 X_0



Only 2% of electrons and positrons do not interact in the first 2 CALO planes

Proton background evaluation

Rigidity: 20-28 GV

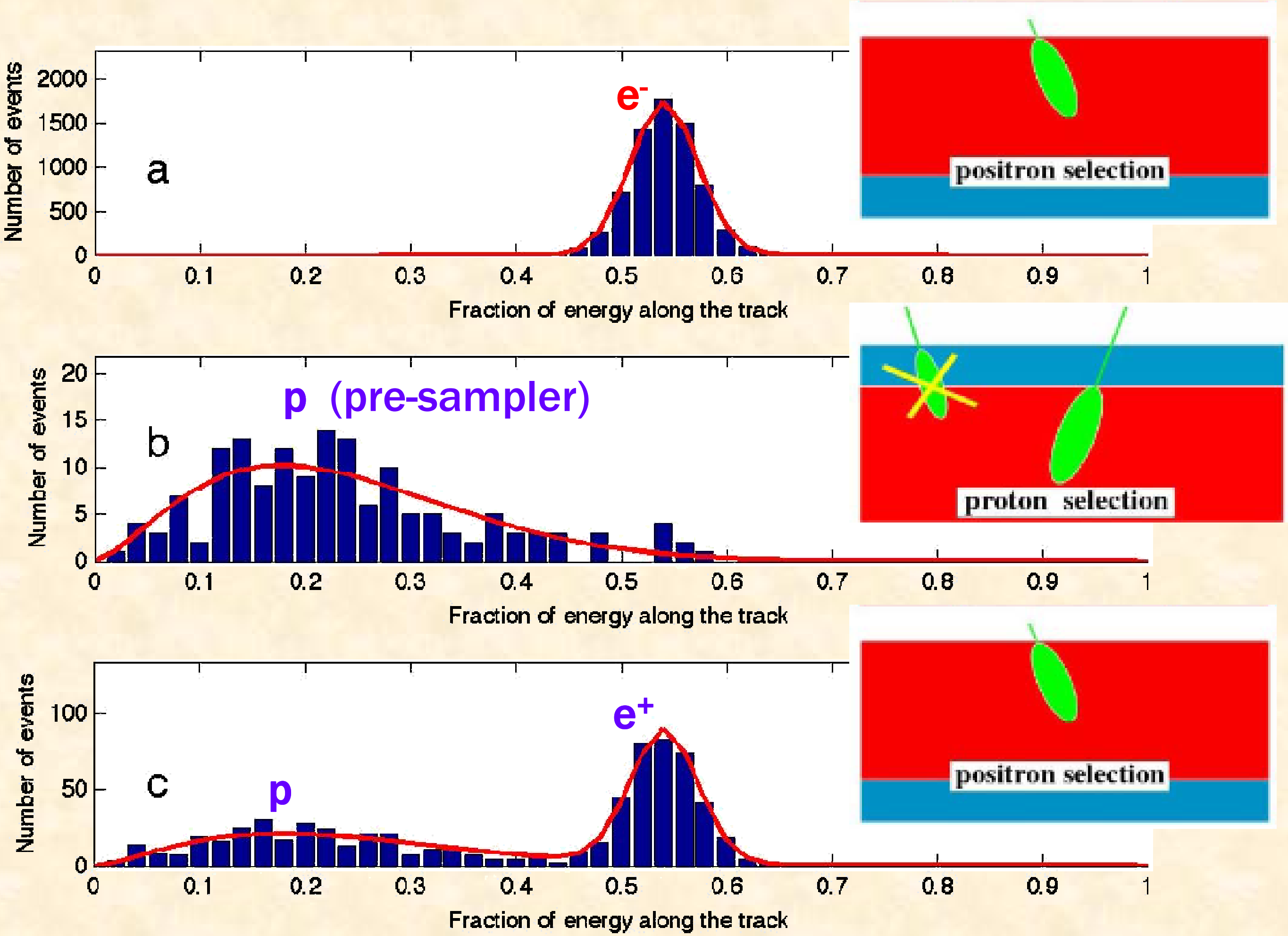
Fraction of charge released along the calorimeter track (left, hit, right)

+

Constraints on:

Energy-momentum match

Shower starting-point



Proton background evaluation

Rigidity: 28-42 GV

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

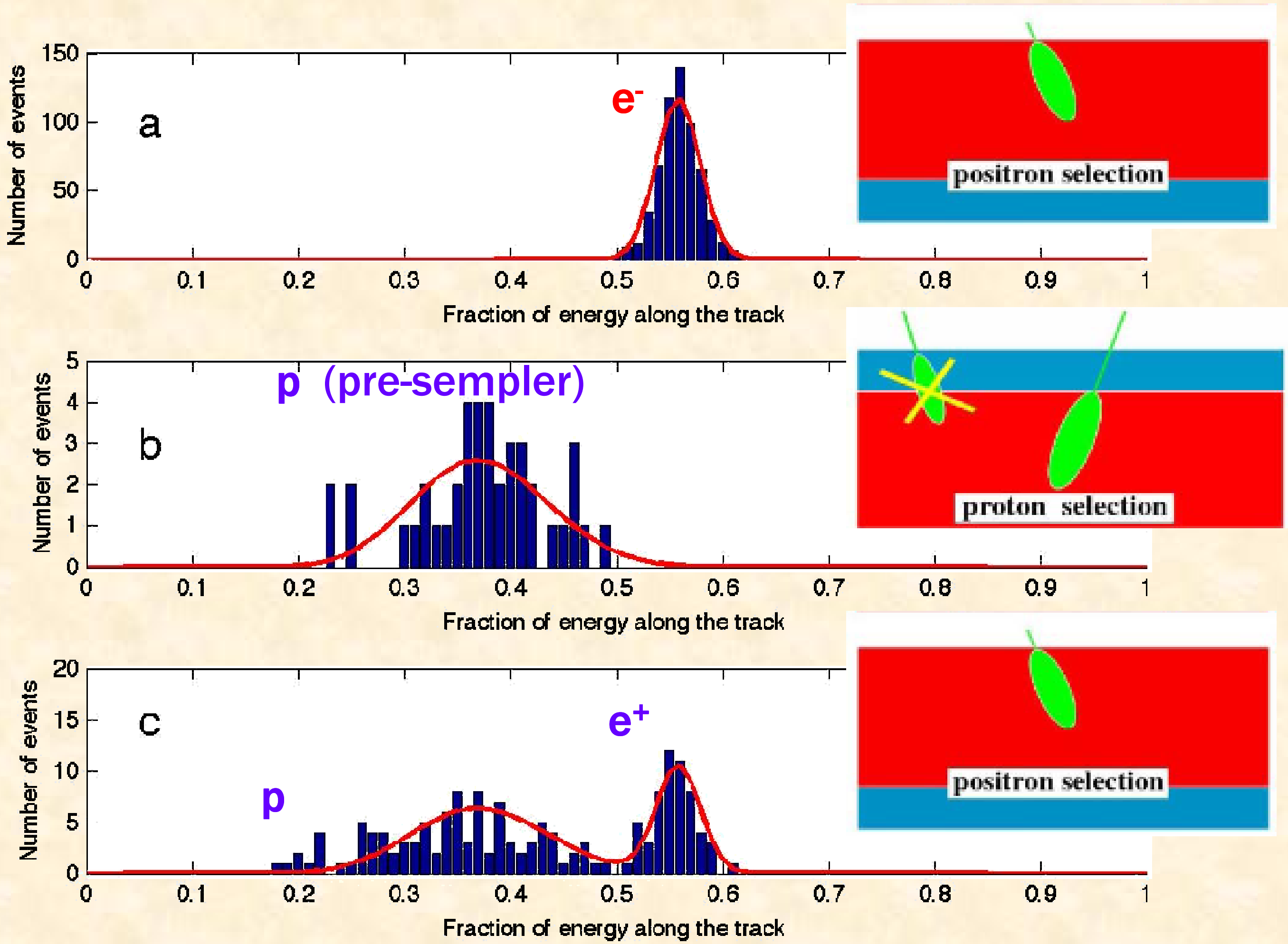
+

Constraints on:

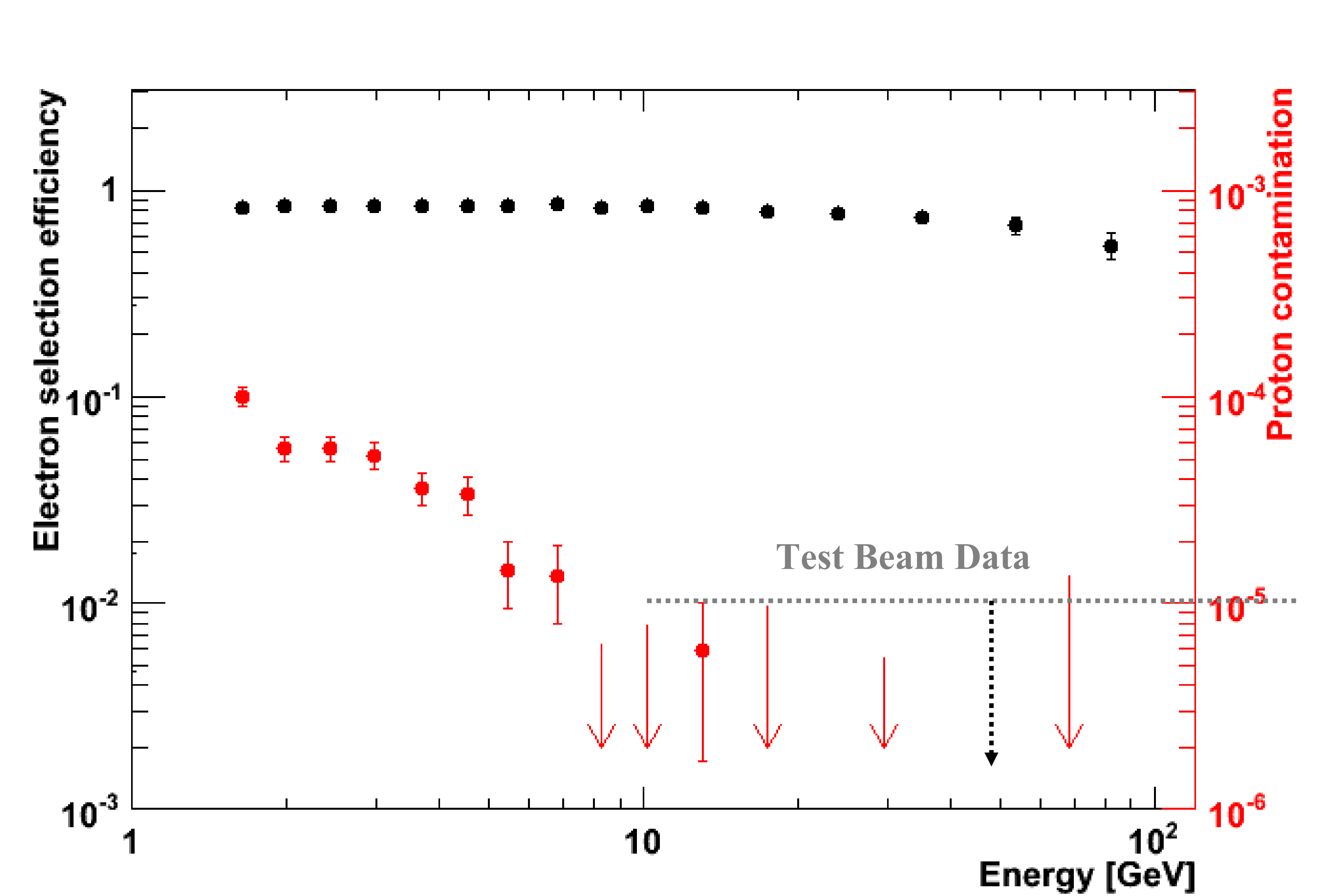
Energy-momentum match

Shower starting-point

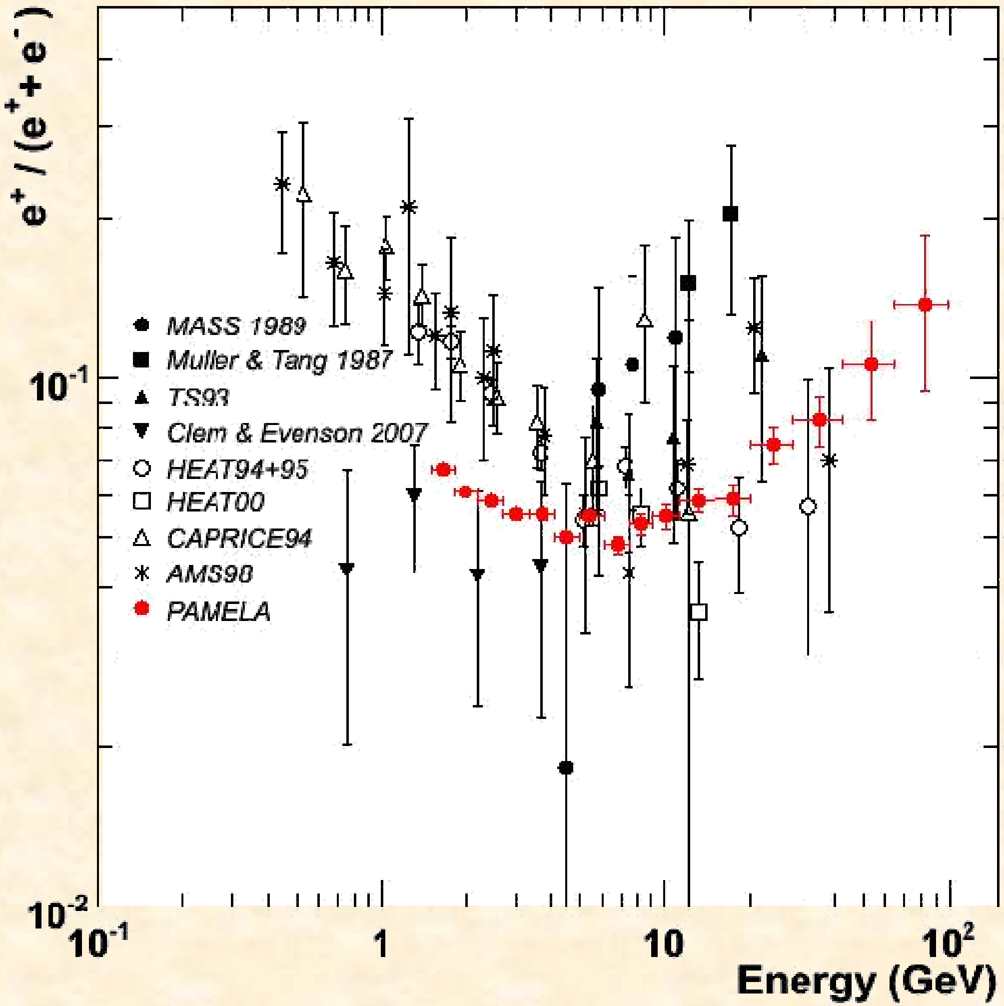
BK-estimation method



Positron selection with calorimeter

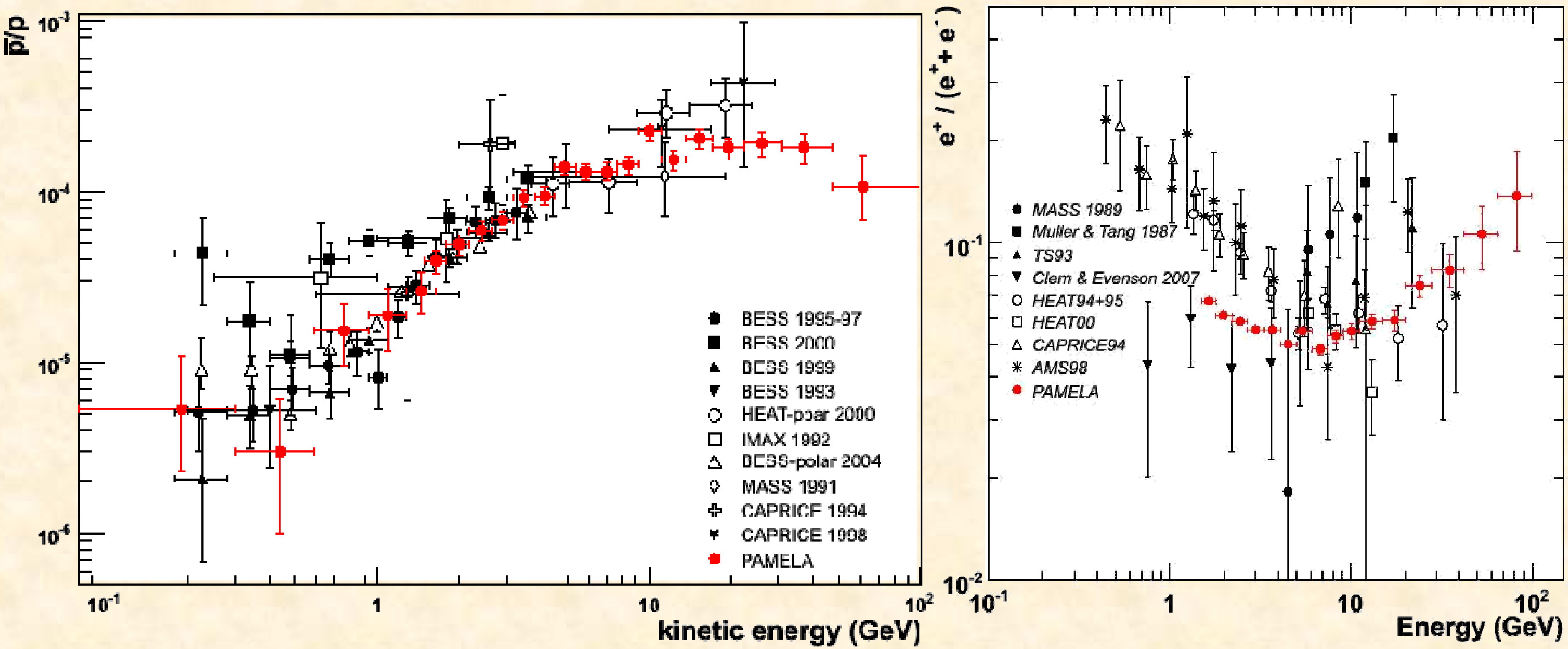


PAMELA: Positron fraction



NATURE 458 (2009)

More than 100 articles published after the release

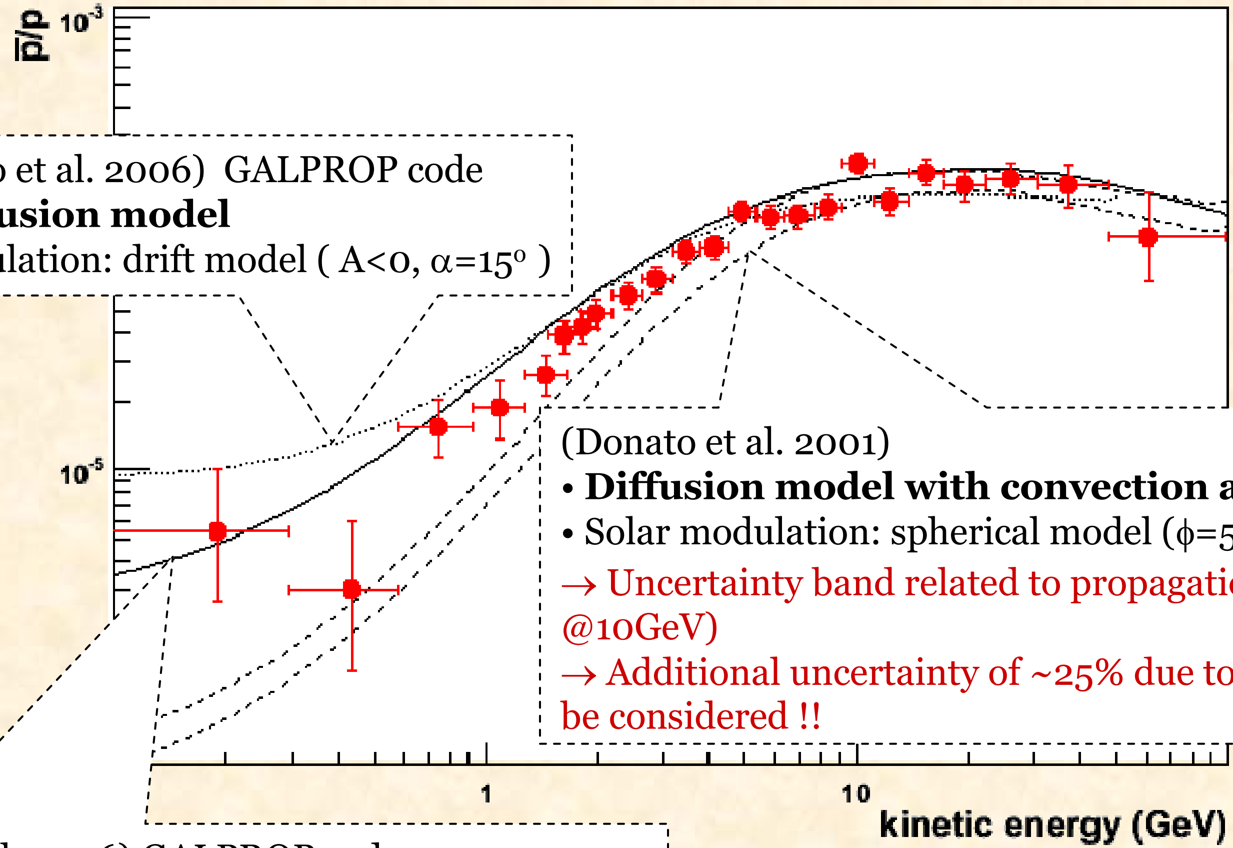


((Do we have any antimatter excess in CRs?))

Antiproton-to-proton ratio

Secondary Production Models

CR + ISM → **p-bar** + …



(Moskalenko et al. 2006) GALPROP code
- **Plain diffusion model**
- Solar modulation: drift model (A<0, α=15°)

(Donato et al. 2001)
- **Diffusion model with convection and reacceleration**
- Solar modulation: spherical model (ϕ=500MV)

→ Uncertainty band related to propagation parameters (~10% @10GeV)

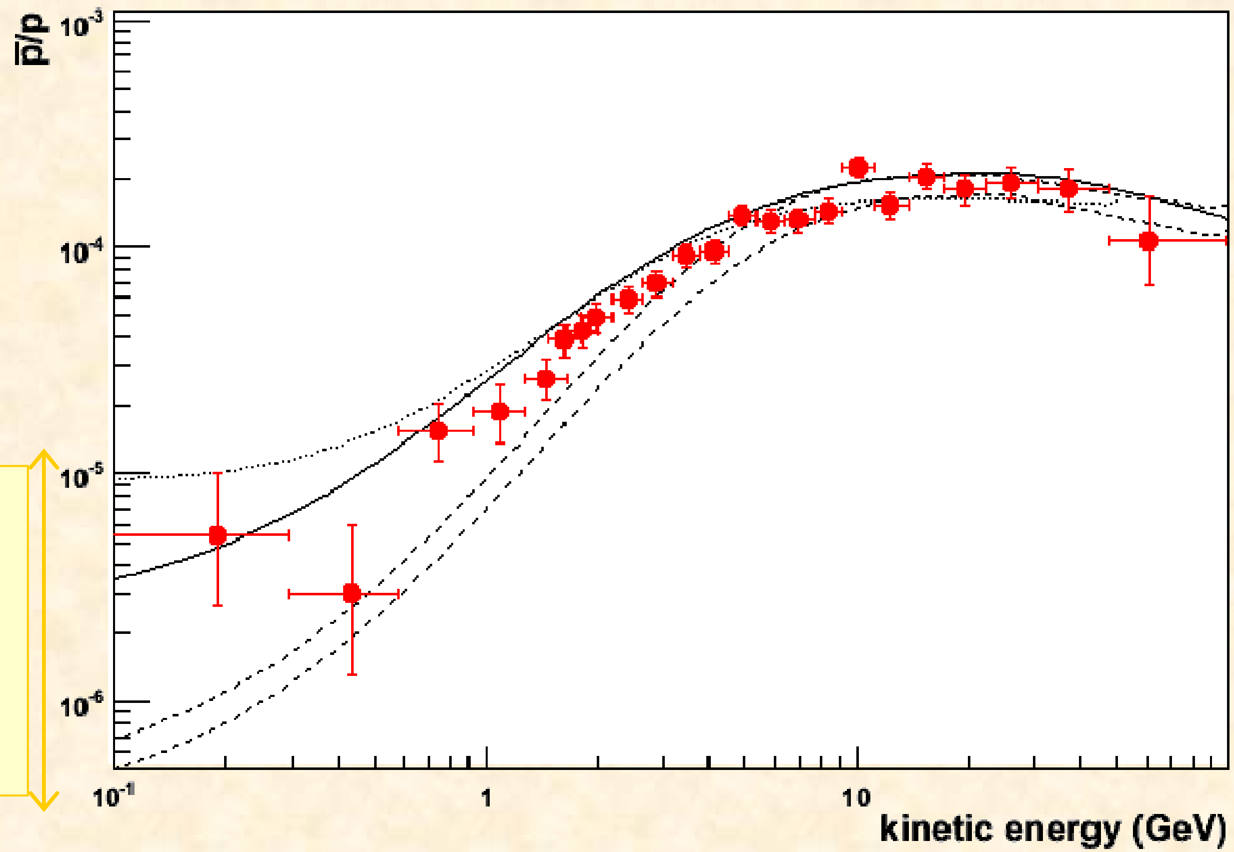
→ Additional uncertainty of ~25% due to production cs should be considered !!

(Ptuskin et al. 2006) GALPROP code
- **Plain diffusion model**
- Solar modulation: spherical model (ϕ=550MV)

Antiproton-to-proton ratio

Secondary Production Models

CR + ISM → **p-bar** + …



~20%

NB!
- **Solar modulation**
- Nuclear cross-section
- …

No evidence for any <u>antiproton</u> excess

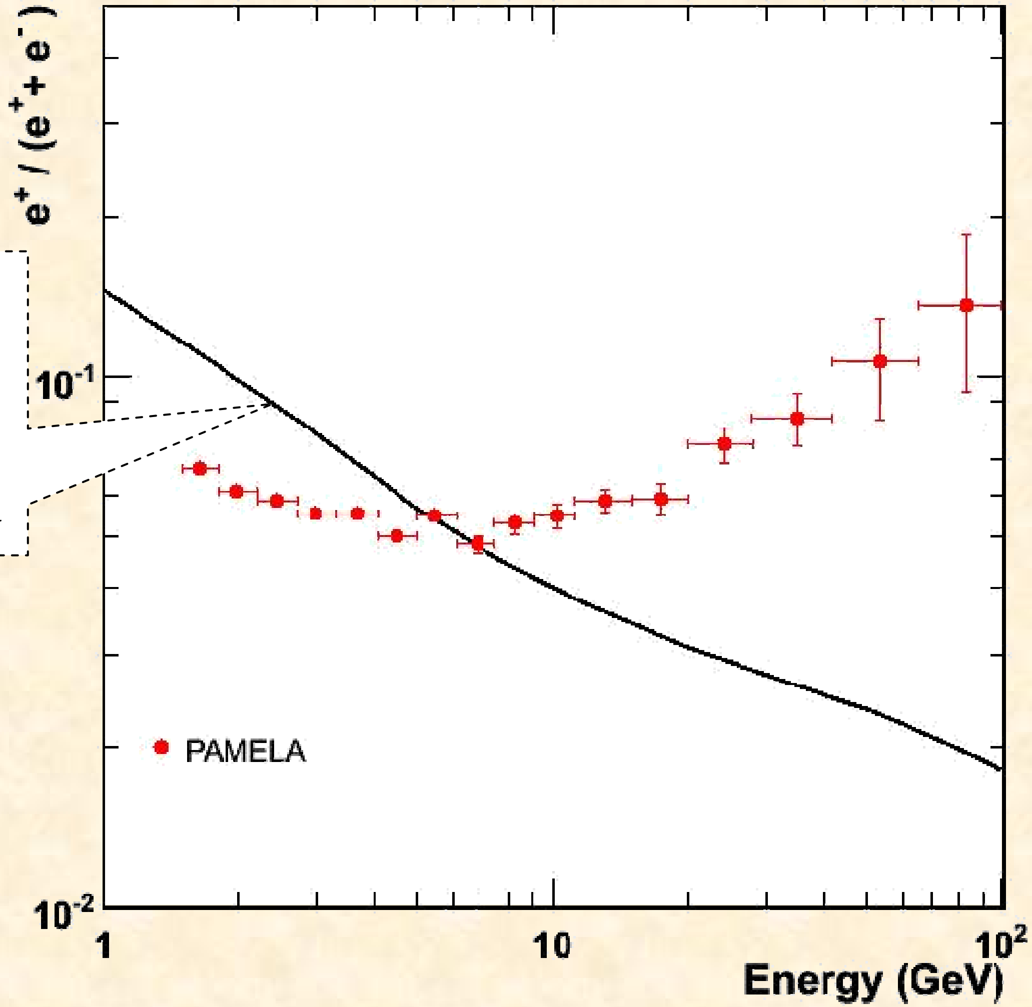
Positron fraction

Secondary Production Models

CR + ISM $\rightarrow \pi^{\pm}$ + … $\rightarrow \mu^{\pm}$ + … $\rightarrow$ **e$^{\pm}$** + …

CR + ISM $\rightarrow \pi^{0}$ + … $\rightarrow \gamma\gamma$ $\rightarrow$ **e$^{\pm}$**

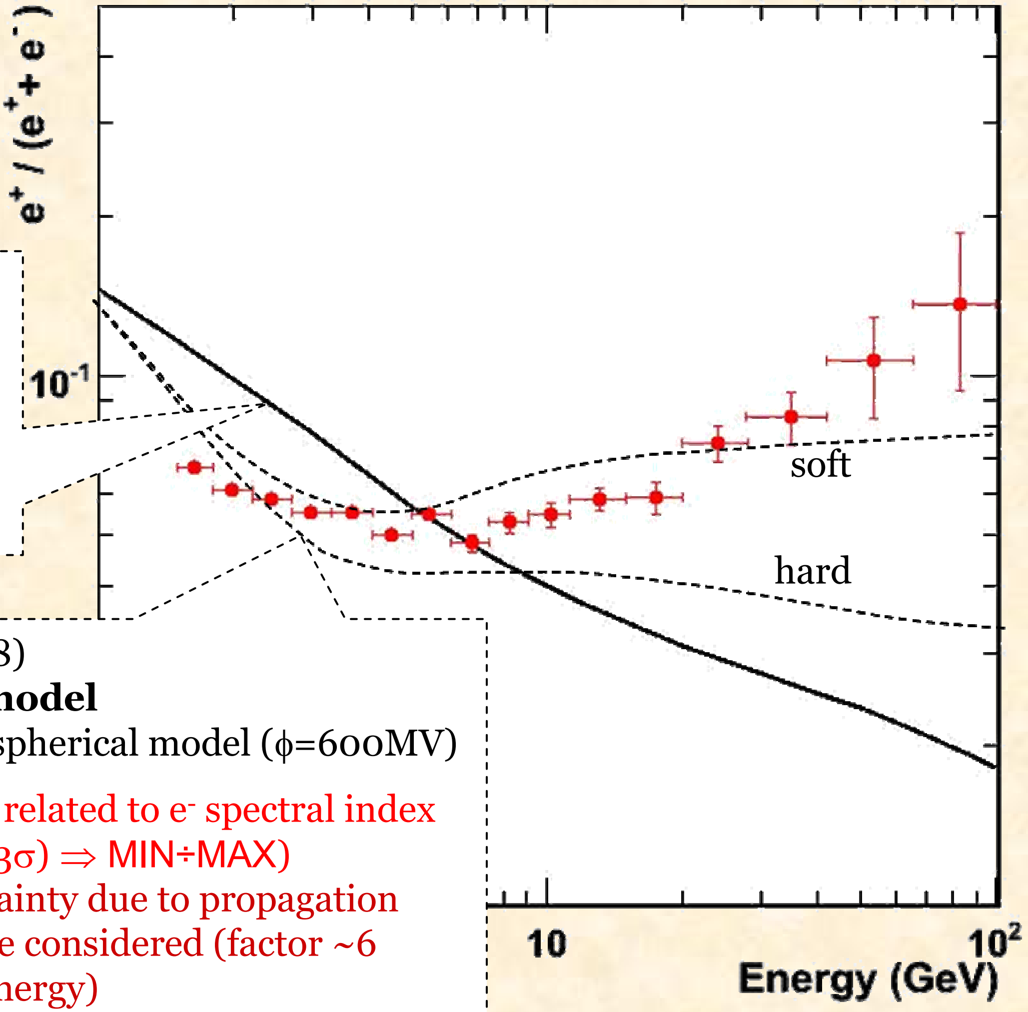
(Moskalenko & Strong 1998)
GALPROP code
- **Plain diffusion model**
- Interstellar spectra



Positron fraction

Secondary Production Models

$$CR + ISM \rightarrow \pi^{\pm} + \ldots \rightarrow \mu^{\pm} + \ldots \rightarrow e^{\pm} + \ldots$$
$$CR + ISM \rightarrow \pi^{0} + \ldots \rightarrow \gamma\gamma \rightarrow e^{\pm}$$



(Moskalenko & Strong 1998) GALPROP code
- **Plain diffusion model**
- Interstellar spectra

(Delahaye et al. 2008)
- **Plain diffusion model**
- Solar modulation: spherical model (ϕ=600MV)

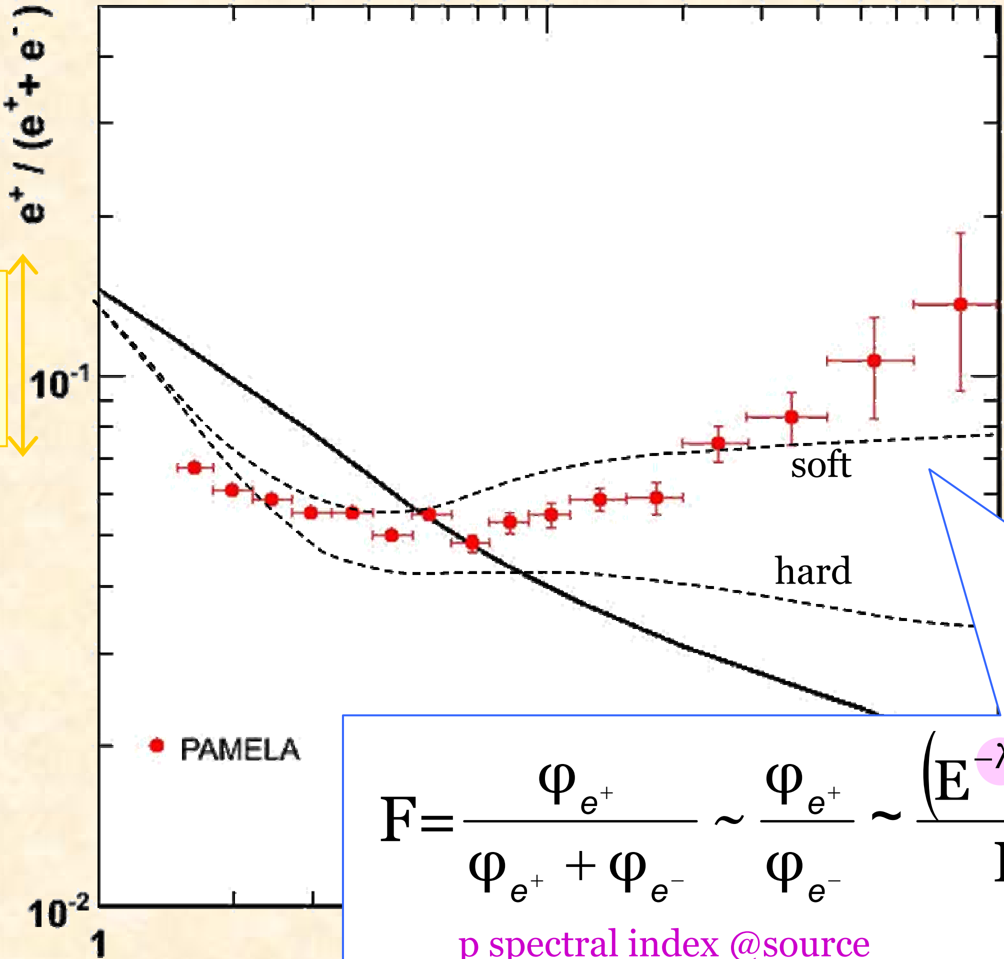
→ Uncertainty band related to e- spectral index (γ_e = **3.44±0.1** (3σ) ⇒ MIN÷MAX)
→ Additional uncertainty due to propagation parameters should be considered (factor ~6 @1GeV ~4 @high-energy)

Positron fraction

Secondary Production Models

$CR + ISM \rightarrow \pi^{\pm} + \ldots \rightarrow \mu^{\pm} + \ldots \rightarrow e^{\pm} + \ldots$

$CR + ISM \rightarrow \pi^{0} + \ldots \rightarrow \gamma\gamma \rightarrow e^{\pm}$



NB!
- **Solar modulation**

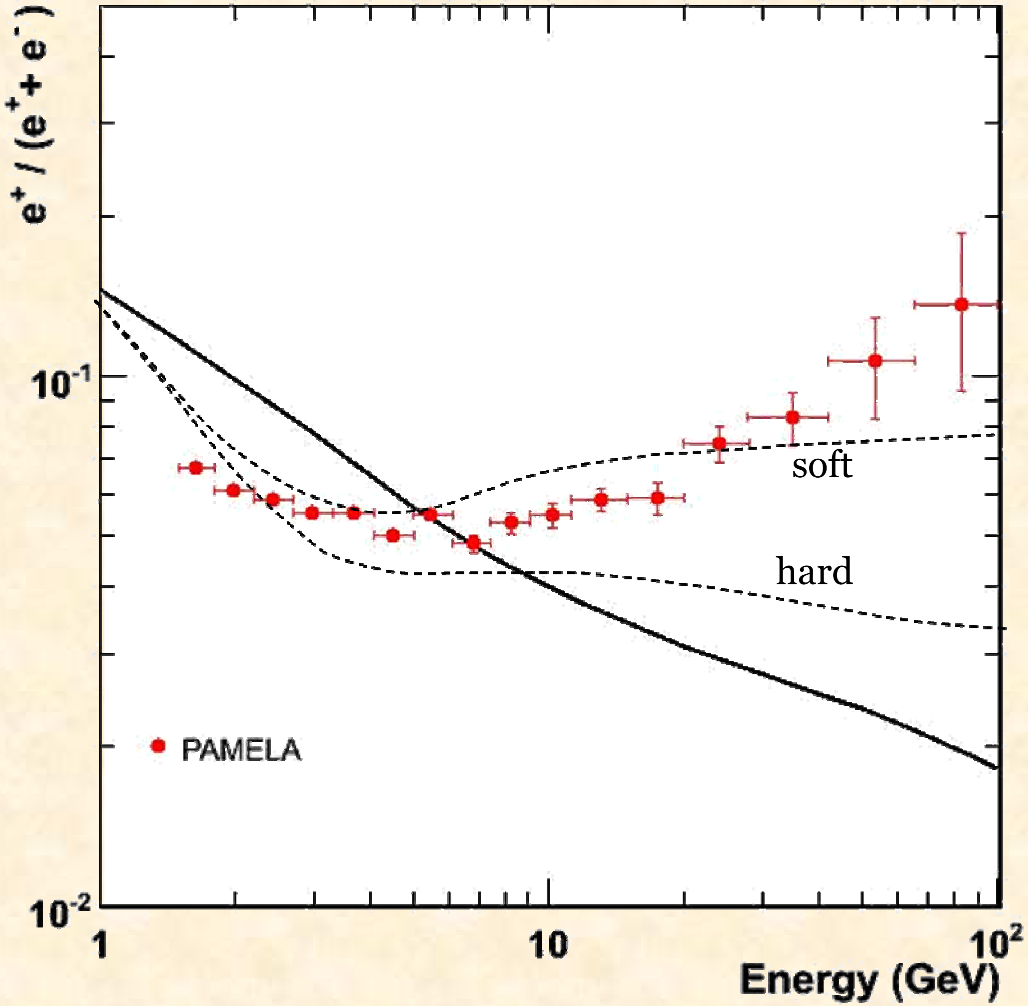
Increasing positron fraction only if $\lambda_e - \lambda_p > 0.6$
$\rightarrow$ **unlikely**
(Serpico 2008)

$$F = \frac{\varphi_{e^+}}{\varphi_{e^+} + \varphi_{e^-}} \sim \frac{\varphi_{e^+}}{\varphi_{e^-}} \sim \frac{\left(E^{-\lambda_p - \delta}\right) \cdot E^{-l}}{E^{-\lambda_e - l}} \sim E^{\lambda_e - \lambda_p - \delta}$$

p spectral index @source
e^- spectral index @source
nuclear diffusion ($\delta \sim 0.6$ from B/C)
lepton diffusion & en.loss (l=1 if en.loss dominate)

Positron fraction

Secondary Production Models

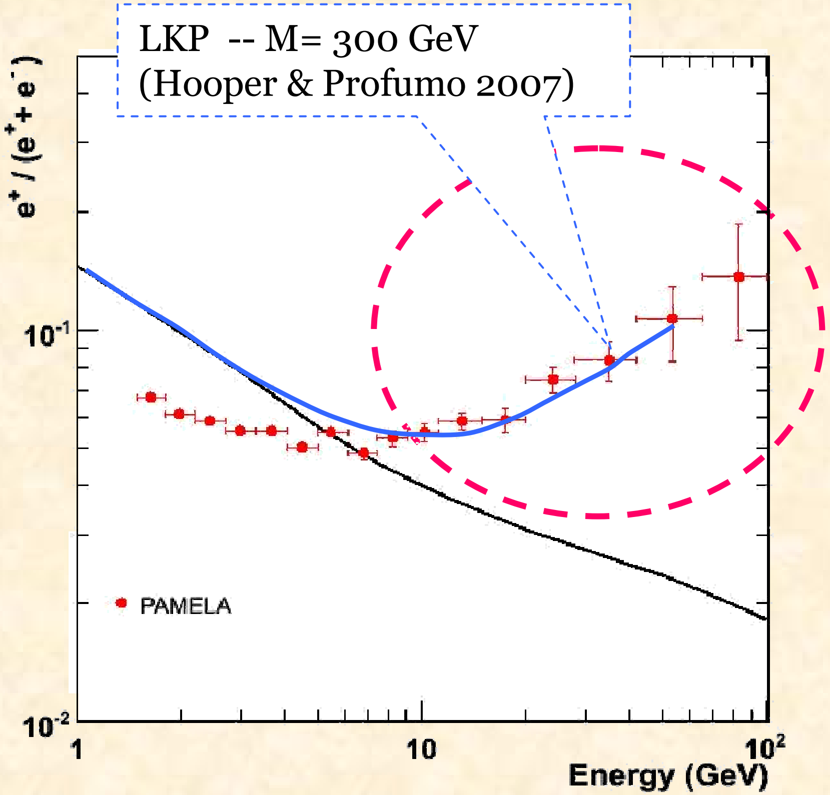


Quite robust evidence for a positron excess

Primary positron sources

Dark Matter

- e^+ yield depend on the dominant decay channel
  - → **LSPs (SUSY)** seem <u>disfavored</u> due to suppression of e^+e^- final states
    - → low yield (relative to p-bar)
    - → soft spectrum from cascade decays
  - →**LKPs** seem <u>favored</u> because can annihilate directly in e^+e^-
    - → high yield (relative to p-bar)
    - → hard spectrum with pronounced cutoff @ M_{LKP} (>300 GeV)
- Boost factor required to have a sizable e^+ signal
  - →NB: constraints from p-bar data!!
- Other hypothesys possible and under study (i.e. decaying DM, a new Dark Force, ….)



Results

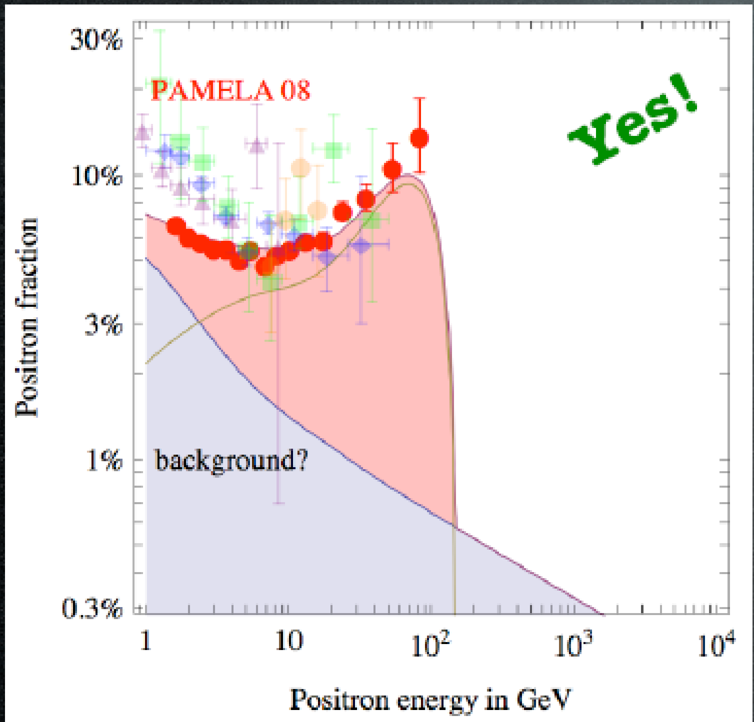
Which DM spectra can fit the data?

E.g. a DM with: -mass $M_{\rm DM} = 150\,\rm GeV$

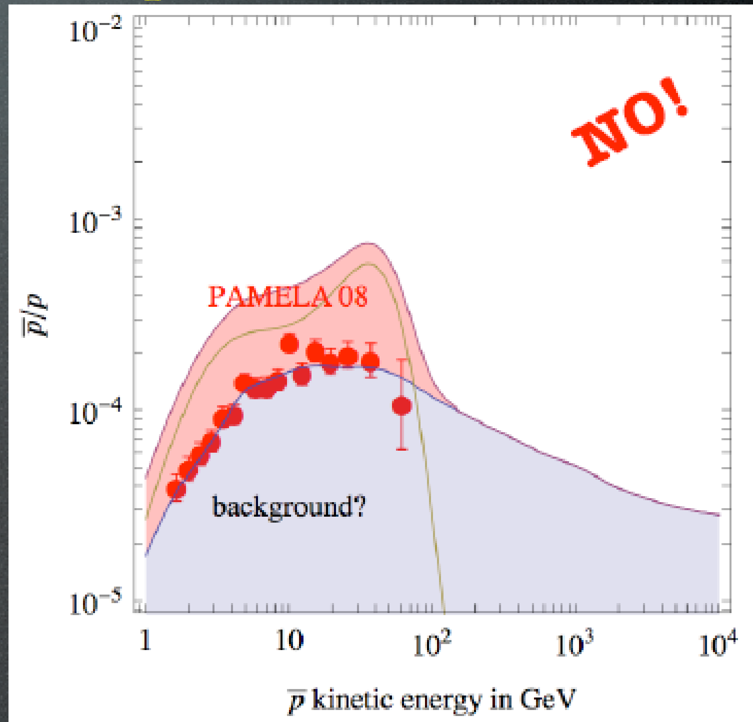
-annihilation $\rm DM\ DM \to W^+W^-$

(a possible SuperSymmetric candidate: wino)

Positrons:



Anti-protons:



[insisting on Winos]

Courtesy of Marco Cirelli

Results

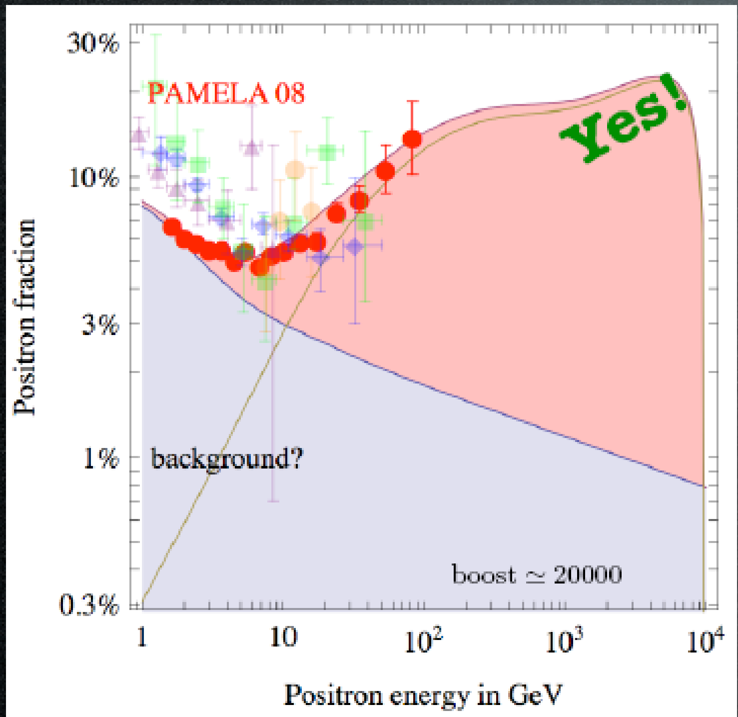
Which DM spectra can fit the data?

E.g. a DM with: -mass $M_{\rm DM} = 10\,\text{TeV}$

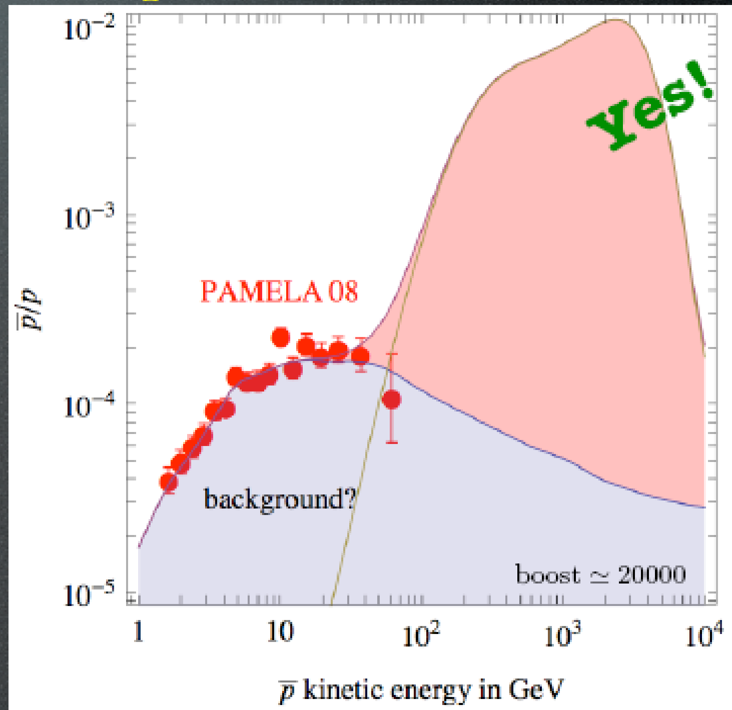
-annihilation $\text{DM DM} \to W^+W^-$

but...: -boost $B = 2 \cdot 10^4$ No...

Positrons:



Anti-protons:



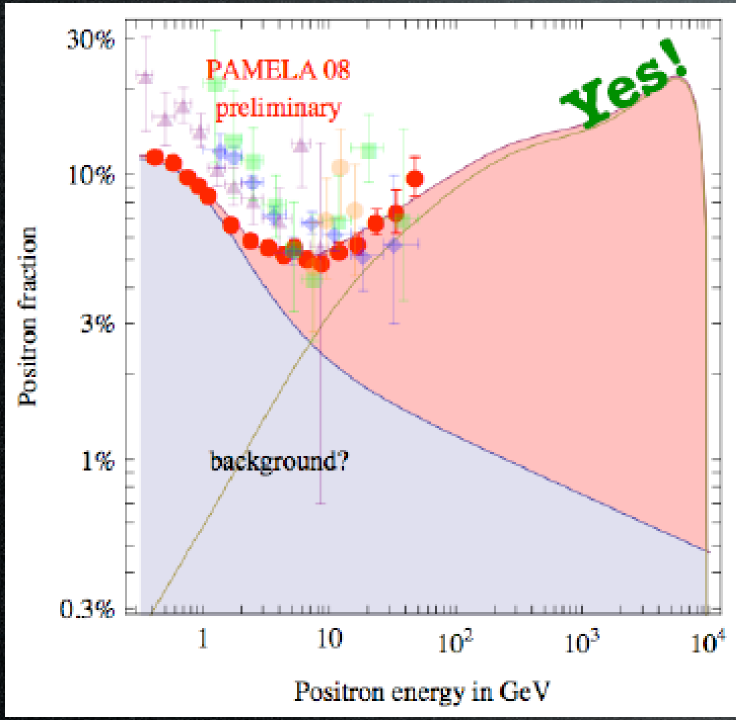
Courtesy of Marco Cirelli

Results

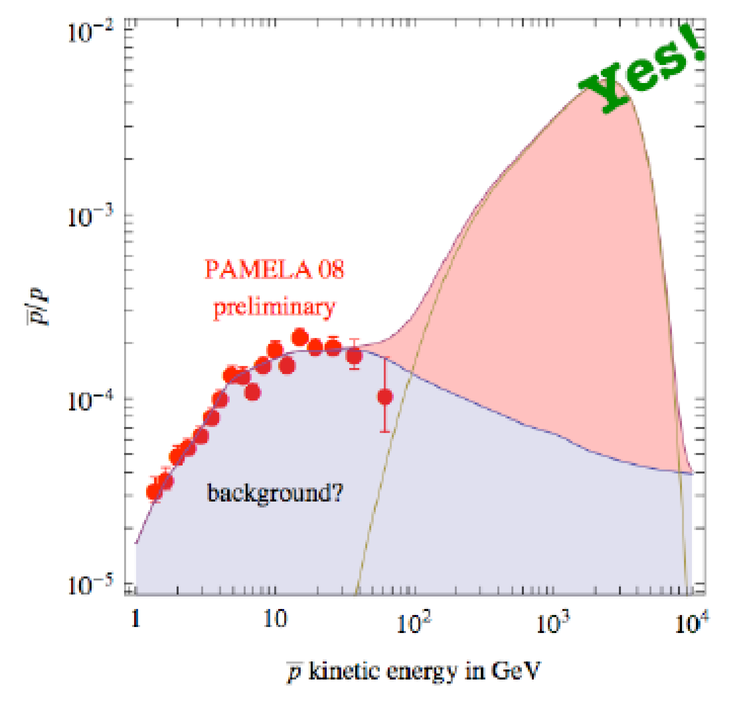
Which DM spectra can fit the data?

E.g. Minimal DM: -mass $M_{\rm DM} = 9.7\,{\rm TeV}$
[Cirelli, Strumia et al. 2006]
-annihilation $\rm DM\ DM \to W^+W^-$
-boost $B \simeq 30$ Yes!

Positrons:



Anti-protons:



Courtesy of Marco Cirelli

Results

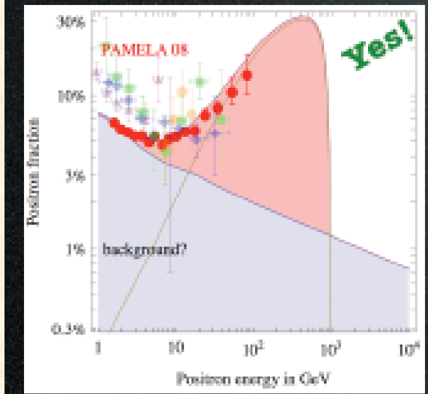
Which DM spectra can fit the data?

A DM with: -mass $M_{\rm DM} = 1\,\text{TeV}$

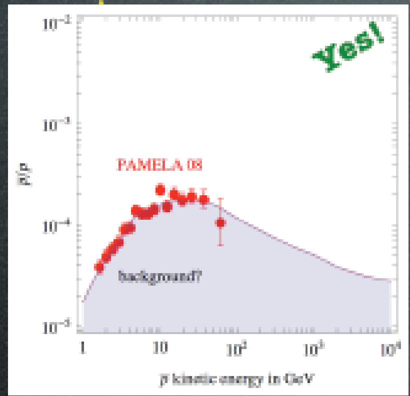
-annihilation $\text{DM DM} \to \mu^+\mu^-$

Positrons **Antiprotons**

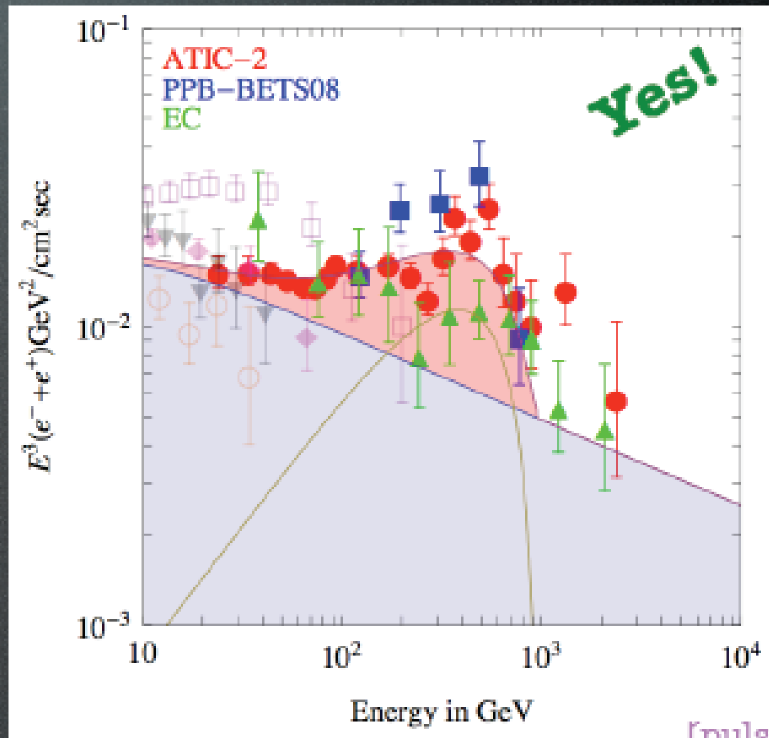
Positrons:



Anti-protons:



Electrons + Positrons:



[pulsar]

Have we identified the DM for the first time???

Arkani-Hamed, Weiner et al. 0810: Yes!
+ a ton of others

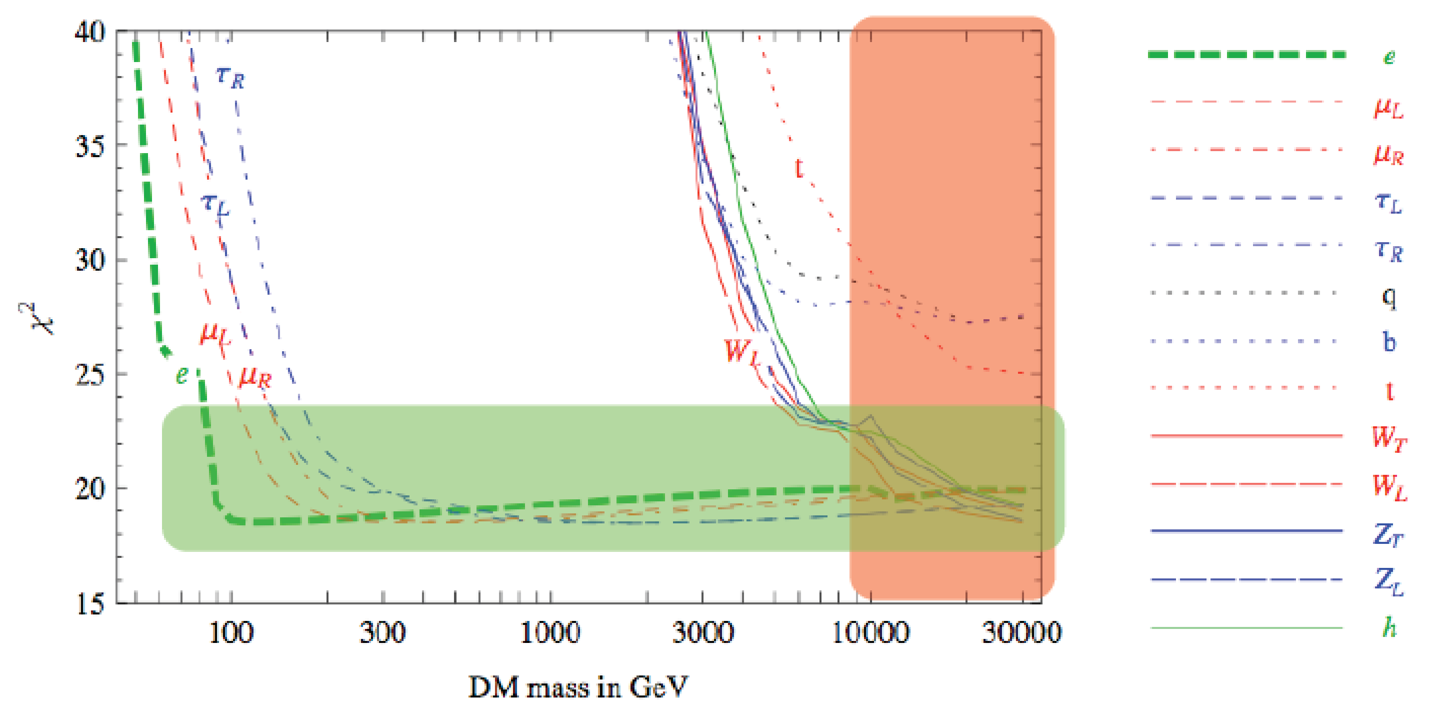
Courtesy of Marco Cirelli

Results

Which DM spectra can fit the data?

Model-independent results:

fit to PAMELA positrons + anti-protons



(1) annihilate into leptons (e.g. $\mu^+\mu^-$) or
(2) annihilate into W^+W^- with mass $\gtrsim$ 10 TeV

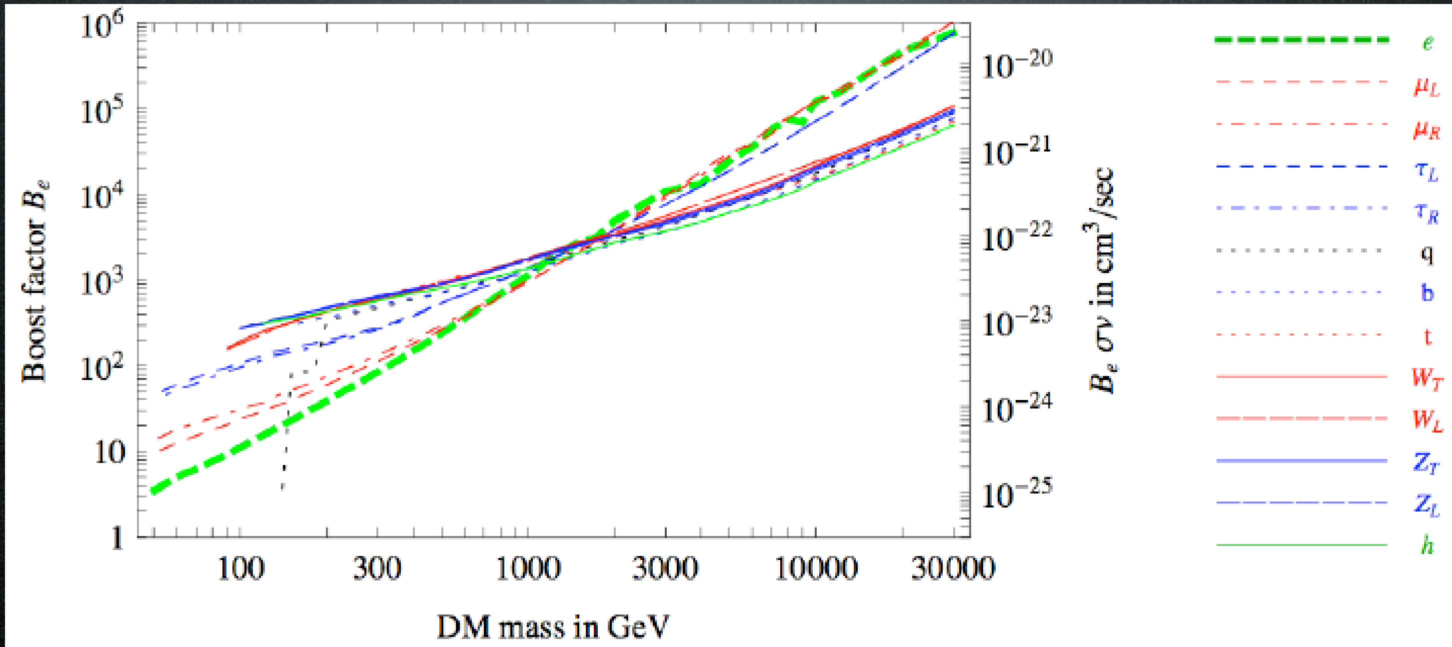
Courtesy of Marco Cirelli

Results

Which DM spectra can fit the data?

Model-independent results:

Boost required by PAMELA



Courtesy of Marco Cirelli

Primary positron sources

Astrophysical processes

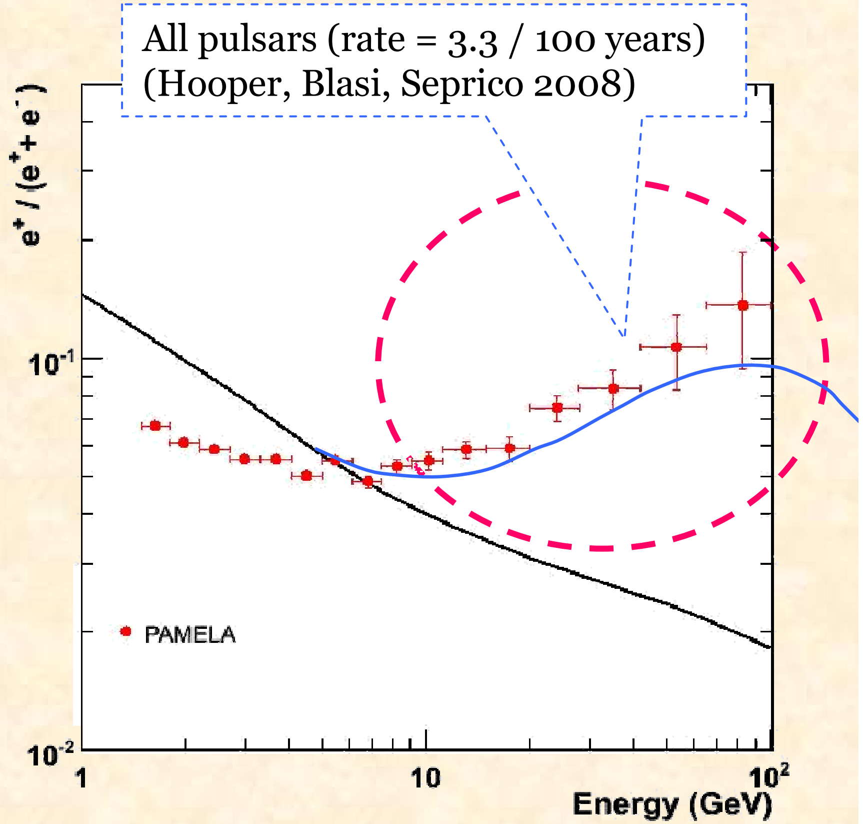
- Local **pulsars** are well-known sites of e^+e^- pair production:

  → they can individually and/or coherently contribute to the e^+e^- galactic flux and explain the PAMELA e^+ excess (both spectral feature and intensity)

  → No fine tuning required

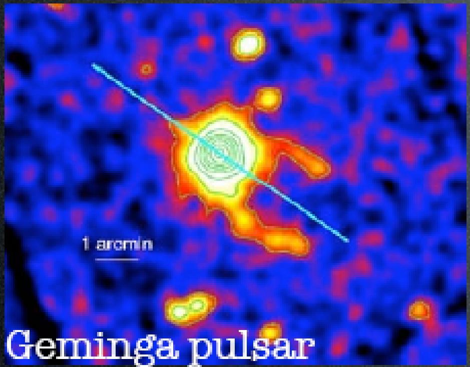
  → if one or few nearby pulsars dominate, anisotropy could be detected in the angular distribution

  → possibility to discriminate between pulsar and DM origin of e^+ excess



Astrophysical explanation?

Or perhaps it's just a young, nearby pulsar...

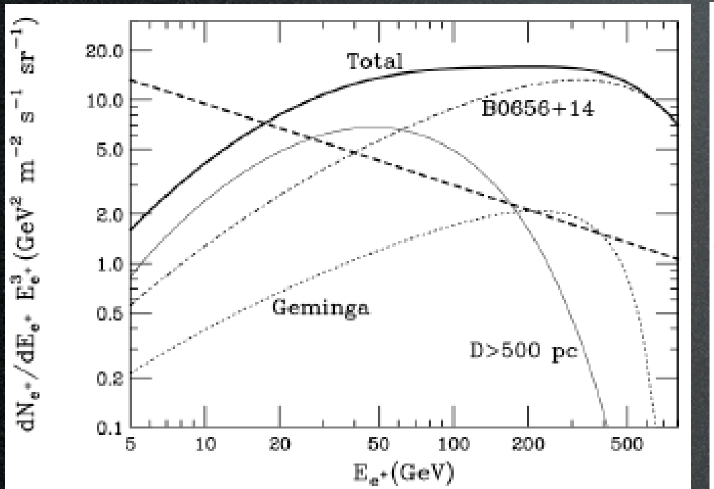


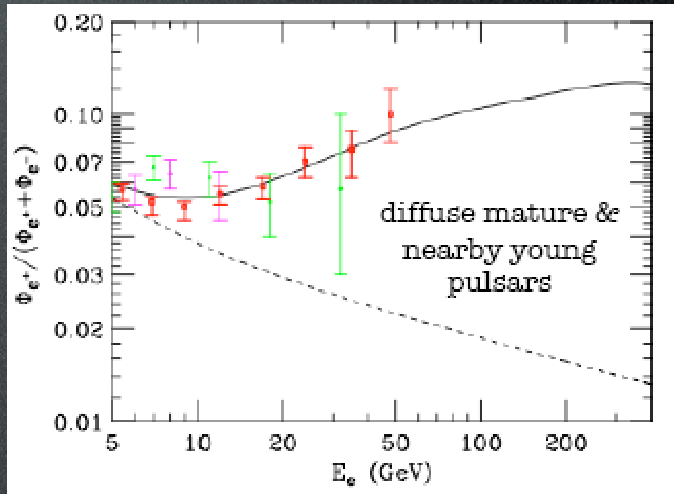
'Mechanism': the spinning $\vec{B}$ of the pulsar strips e^- that emit γ that make production of $e^\pm$ pairs that are trapped in the cloud, further accelerated and later released at $\tau \sim 0 \rightarrow 10^5$ yr.

Must be young (T < 10^5 yr) and nearby (< 1 kpc);
if not: too much diffusion, low energy, too low flux.

Predicted flux: $\Phi_{e^\pm} \approx E^{-p} \exp(E/E_c)$ with $p \approx 2$ and $E_c \sim$ many TeV

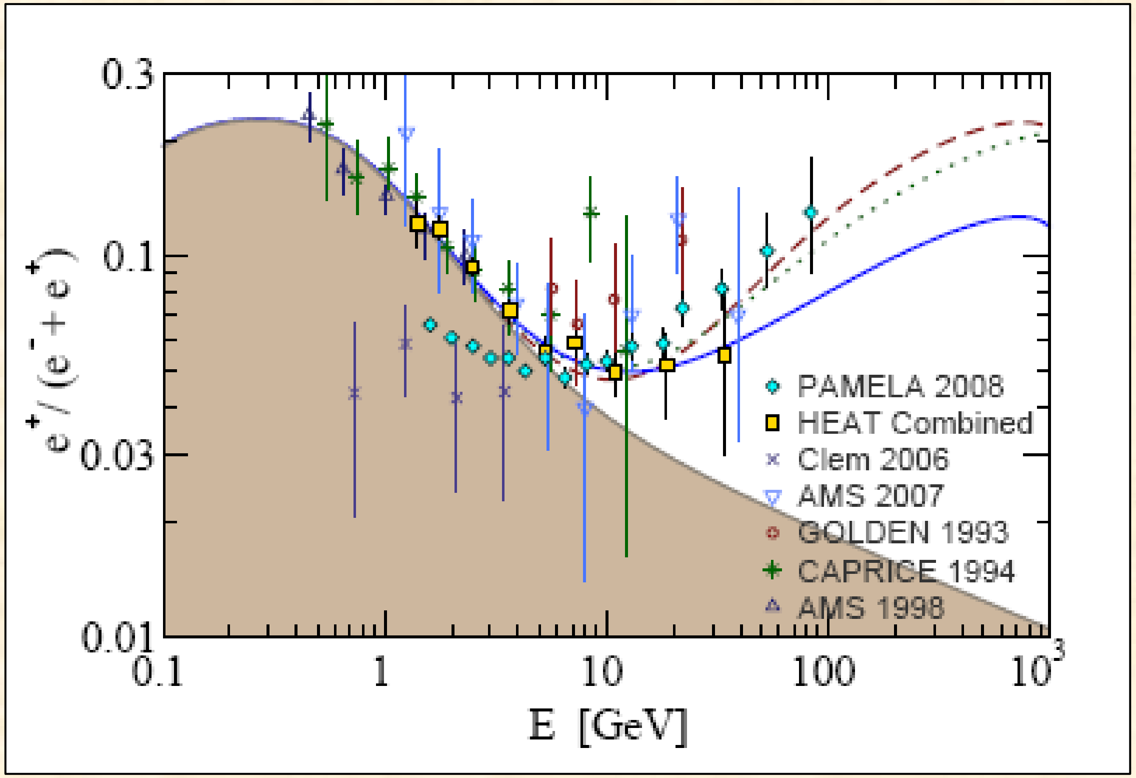
Try the fit with known nearby pulsars and diffuse mature pulsars:



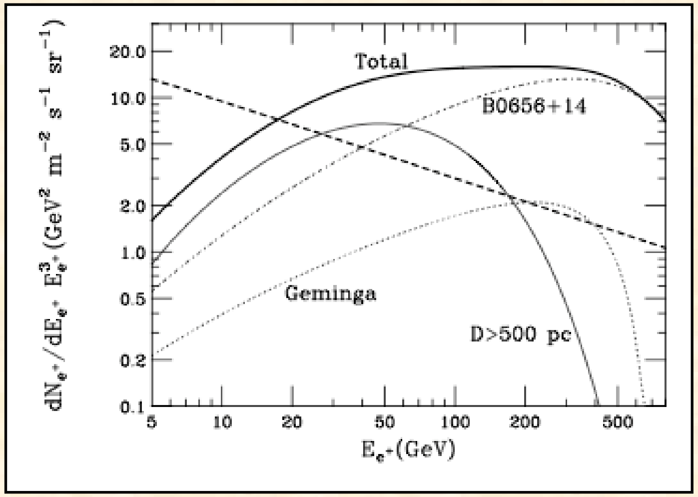


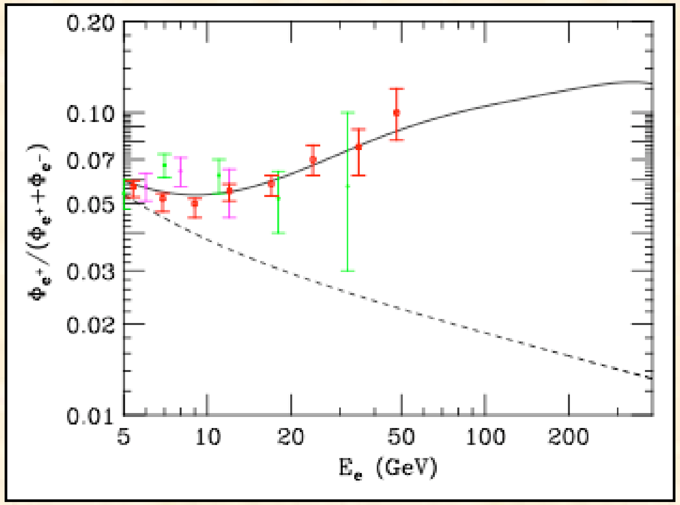
Hooper, Blasi, Serpico 2008

Example: pulsars



H. Yüksak et al., arXiv:0810.2784v2
Contributions of e- & e+ from Geminga assuming different distance, age and energetic of the pulsar





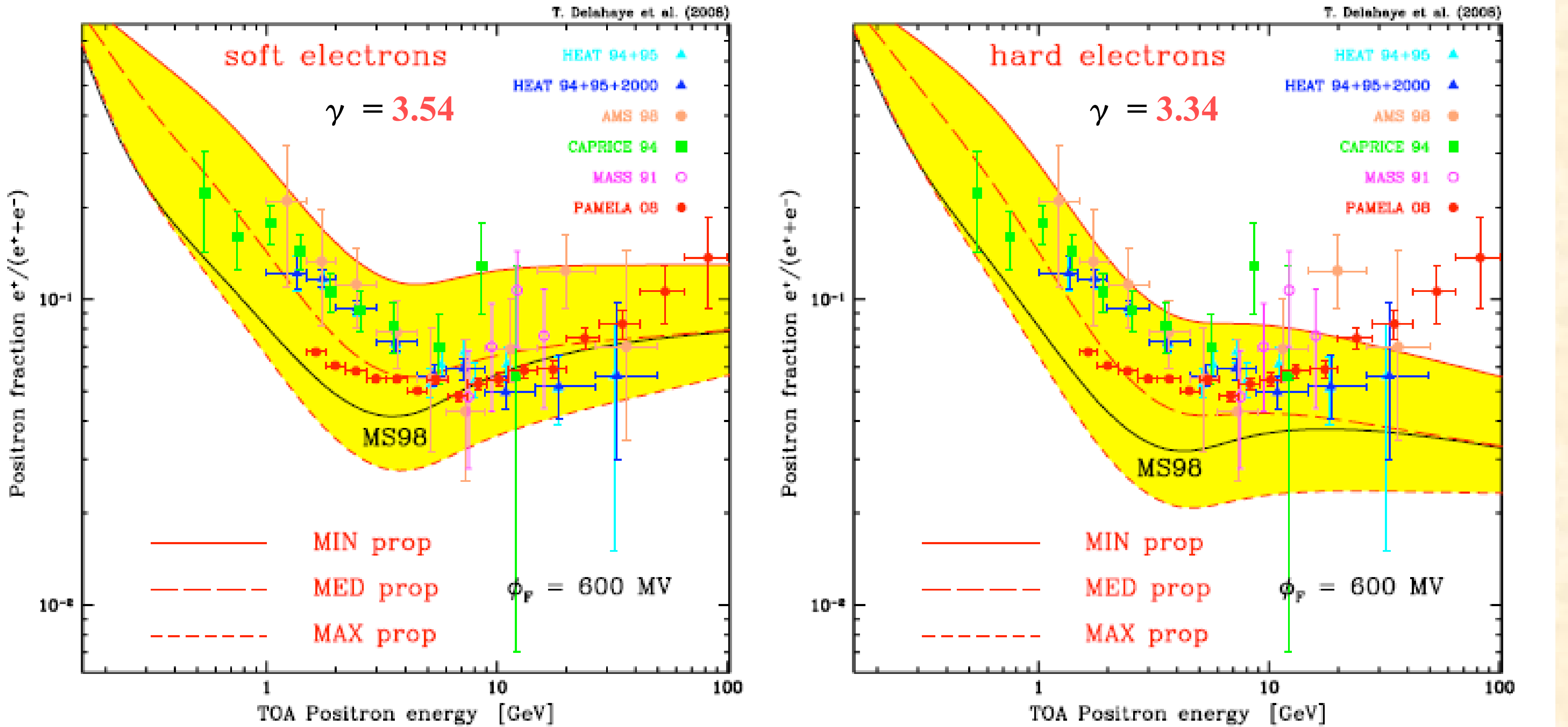
Hooper, Blasi, and Serpico
arXiv:0810.1527

Maybe only secondary production …

- Anomalous primary electron source spectrum
- Spectral feature in the proton flux responsible for secondaries
- Role of Helium nuclei in secondary production
- Difference between local and ISM spectrum of protons
- Anomalous energy-dependent behaviour of the diffusion coefficient
- Rising cross section at high energies
- High energy beaviour of the e+/e-

P. Serpico hep-ph 0810.4846

Standard Positron Fraction
Theoretical Uncertainties



T. Delahaye et al., arXiv: 0809.5268v3

Conclusions on positron excess

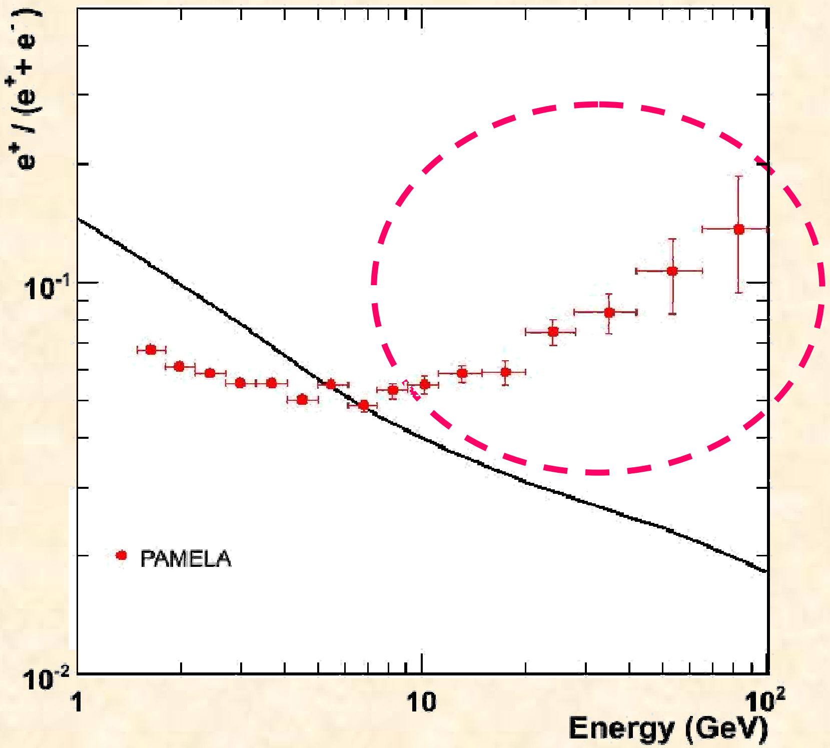
PAMELA positron fraction alone insufficient to understand the origin of positron excess

Additional experimental data will be provided by PAMELA:

- e^+ fraction @ higher energy (up to 300 GeV)
- individual e^- and e^+ spectra
- anisotropy (…maybe)
- high energy $e^+ + e^-$ spectrum (up to 2 TV)

Complementary information from:

- gamma rays
- neutrinos



Electron flux

PAMELA electron flux measurements

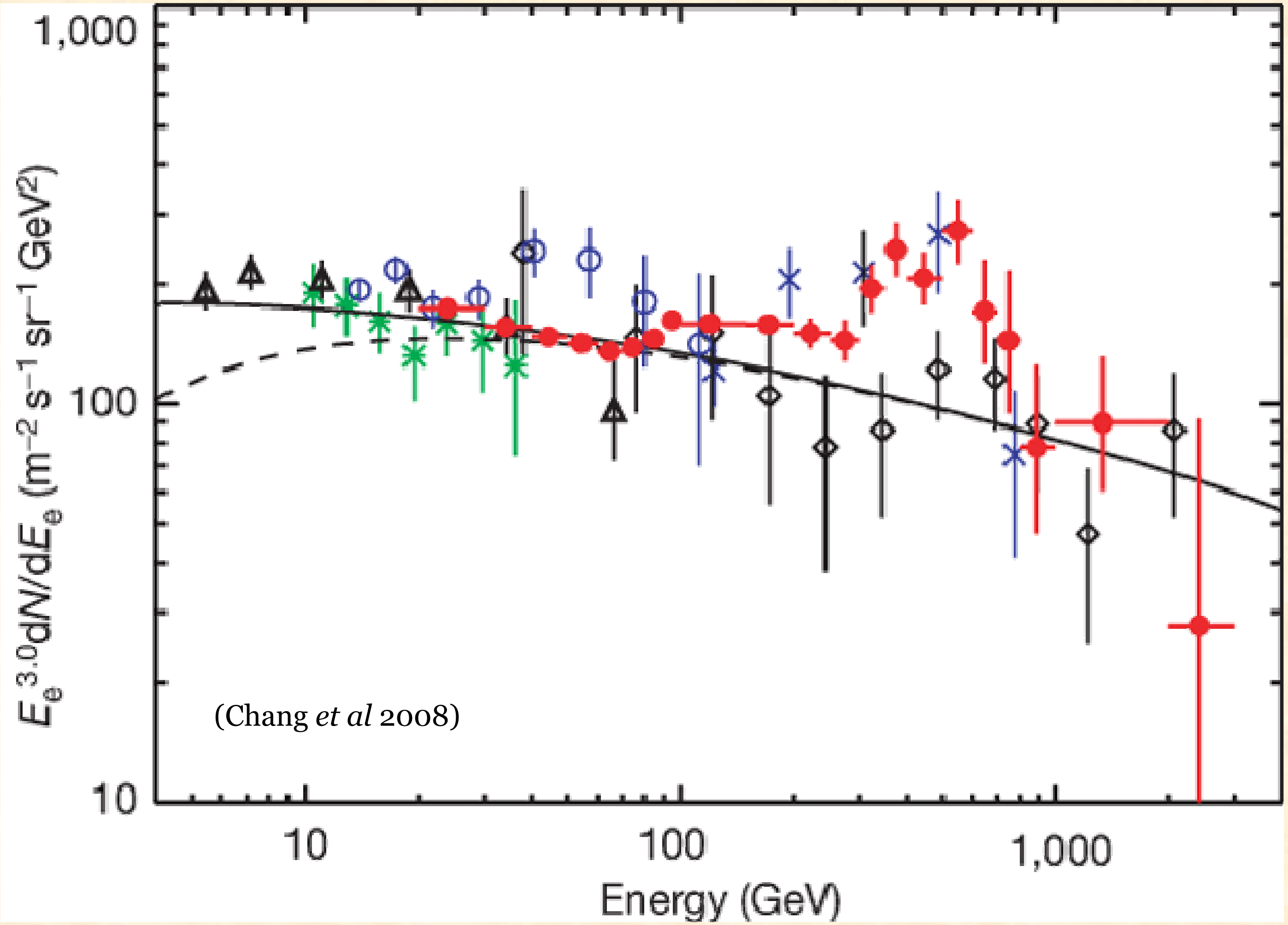
Key points wrt other experiments (ATIC, HESS, FERMI) :

- Combination of CALO and SPECTROMETER allow **energy self-calibration in flight** → no dependence on ground calibrations or MC simulations
- Very deep CALO (16 X_0) → **containment of the shower maximum beyond 1 TeV**
- Neutron detector **help proton rejection**, especially at high energy
- **No atmospheric contamination**

But ..

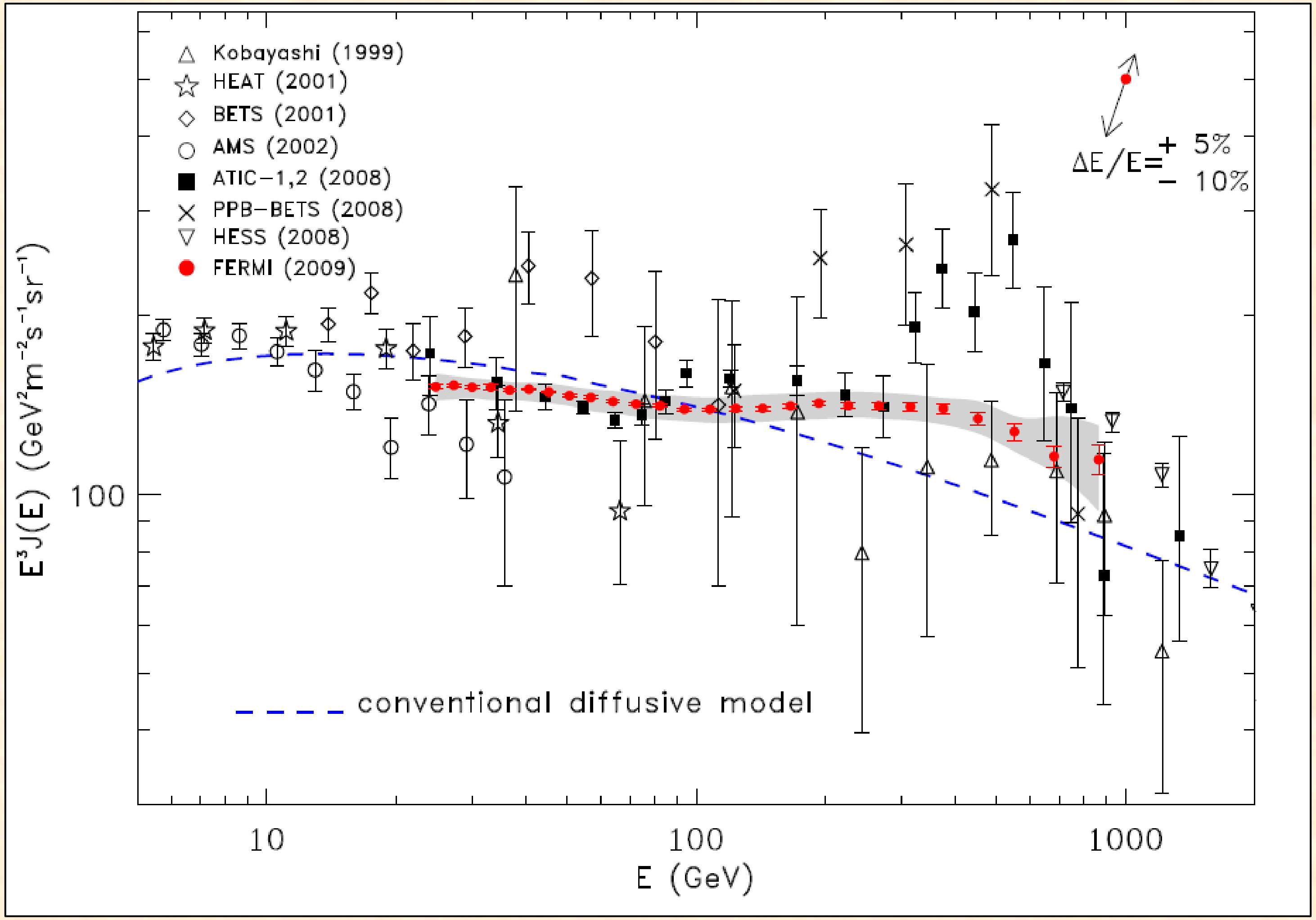
- Smaller acceptance → **lower statistics**

ATIC electron data



PAMELA positron excess might be connected with ATIC electron+positron structures

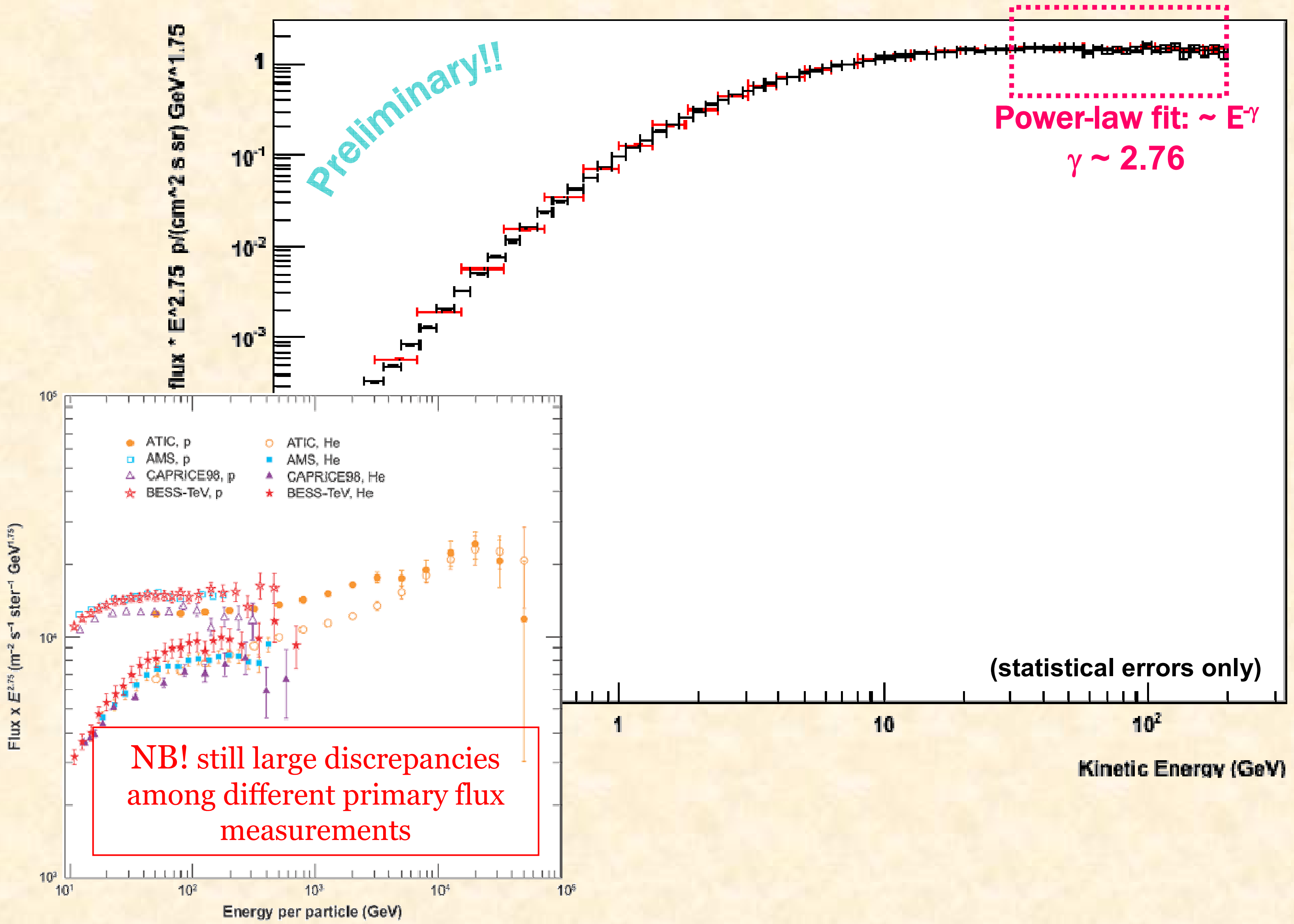
FERMI electron data



FERMI does not confirm the ATIC bump (but attention to systematics !!) but finds an excess wrt conventional diffusive models

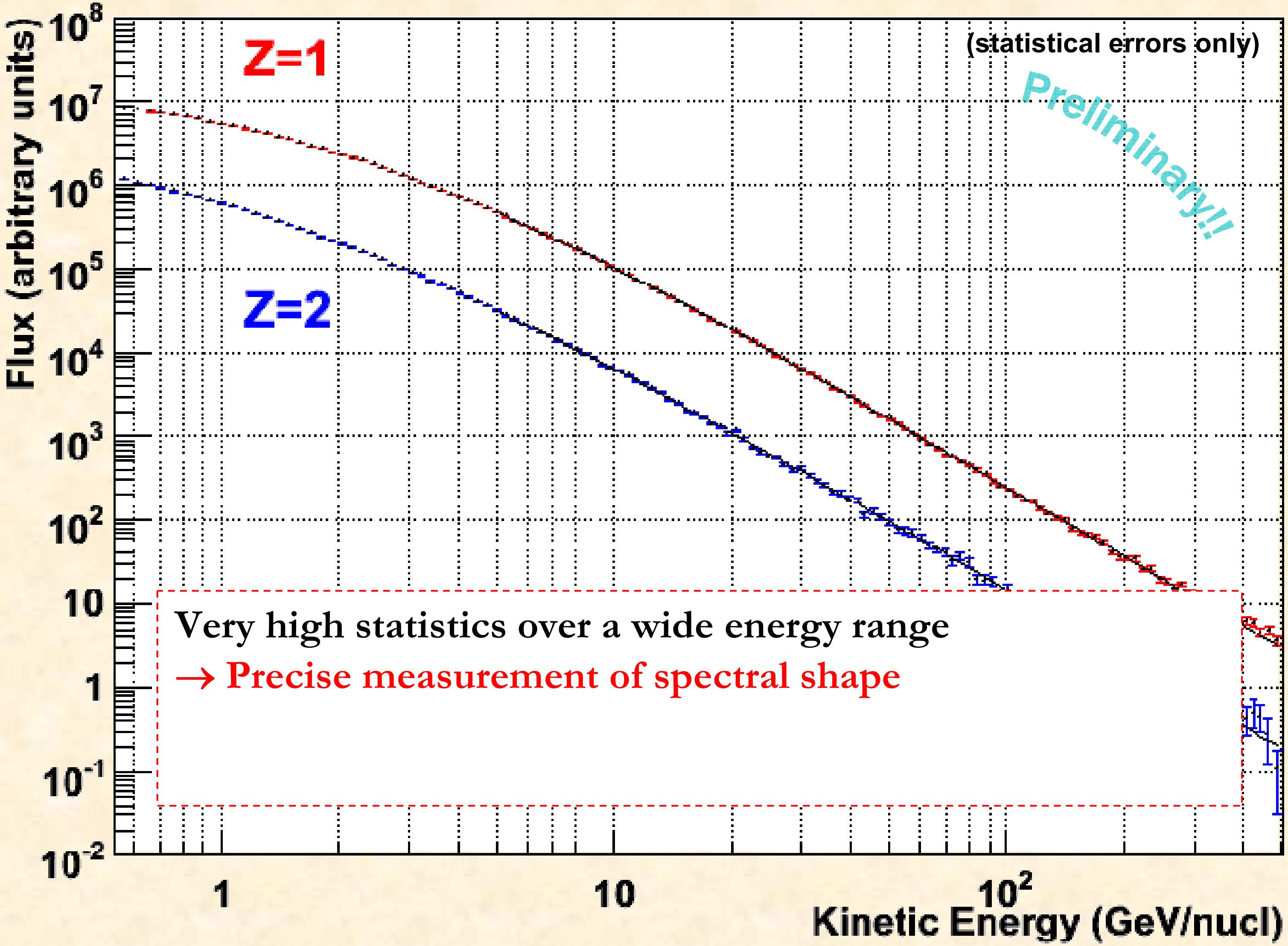
Galactic cosmic-ray origin & propagation

Proton flux



Preliminary!!
Power-law fit: ~ $E^{-\gamma}$
γ ~ 2.76
(statistical errors only)
flux * E^2.75 p/(cm^2 s sr) GeV^1.75
Kinetic Energy (GeV)
ATIC, p
AMS, p
CAPRICE98, p
BESS-TeV, p
ATIC, He
AMS, He
CAPRICE98, He
BESS-TeV, He
Flux x $E^{2.75}$ ($m^{-2} s^{-1} ster^{-1} GeV^{1.75}$)
Energy per particle (GeV)
NB! still large discrepancies among different primary flux measurements

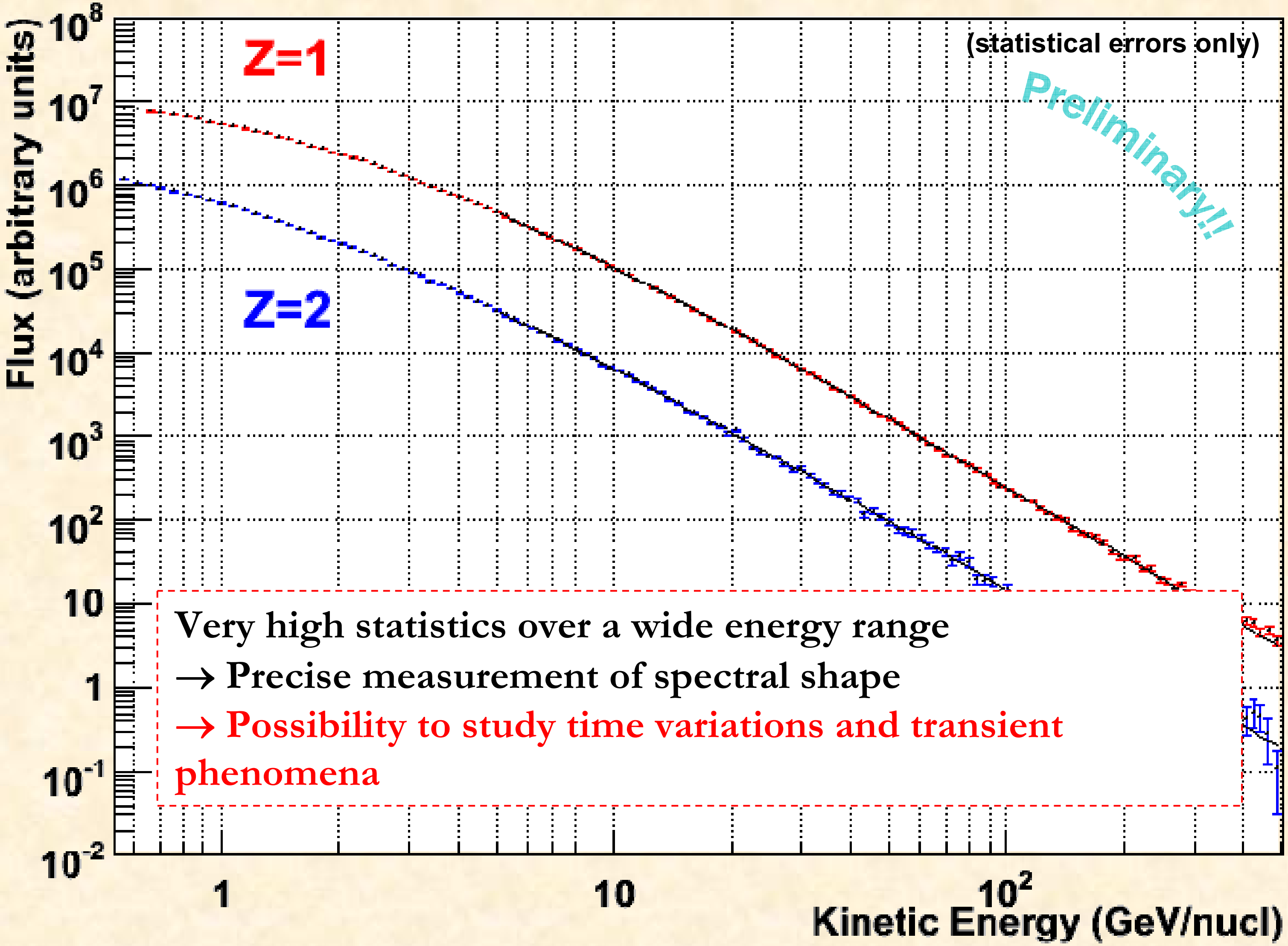
H and He spectra



Very high statistics over a wide energy range

→ Precise measurement of spectral shape

H and He spectra



Very high statistics over a wide energy range

→ Precise measurement of spectral shape

→ Possibility to study time variations and transient phenomena

Light nuclei

Statistics collected until December 2008:

- ❖ **120.000 C nuclei**
- ❖ **45.000 B nuclei**
- ❖ **16.000 Be nuclei**
- ❖ **30.000 Li nuclei**

between 200 MeV/n and 100 GeV/n, with quite stringent selection cuts (30% efficiency and 0.01% contamination among species).

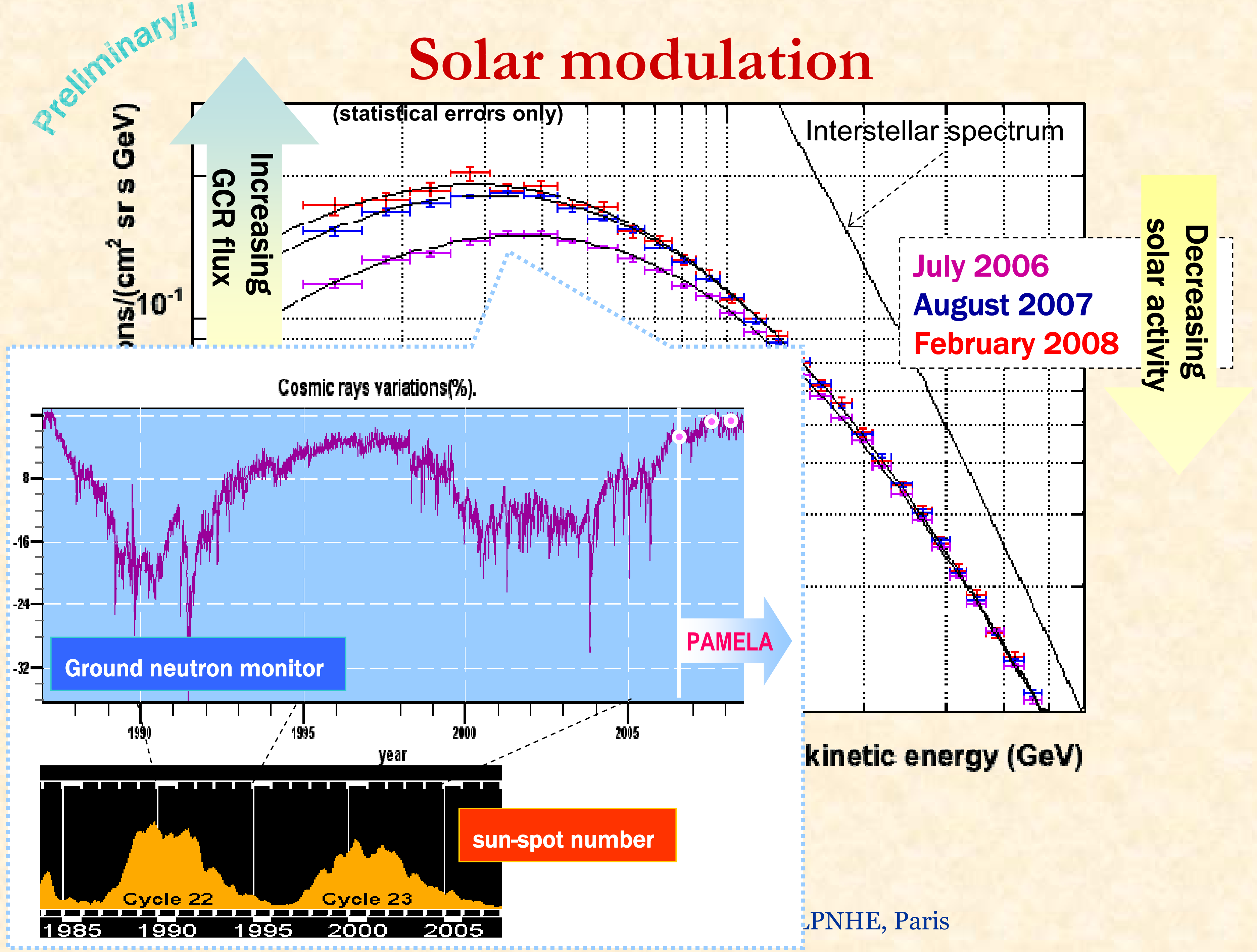
Secondary/Primary ratios in progress !

Solar physics

Solar modulation

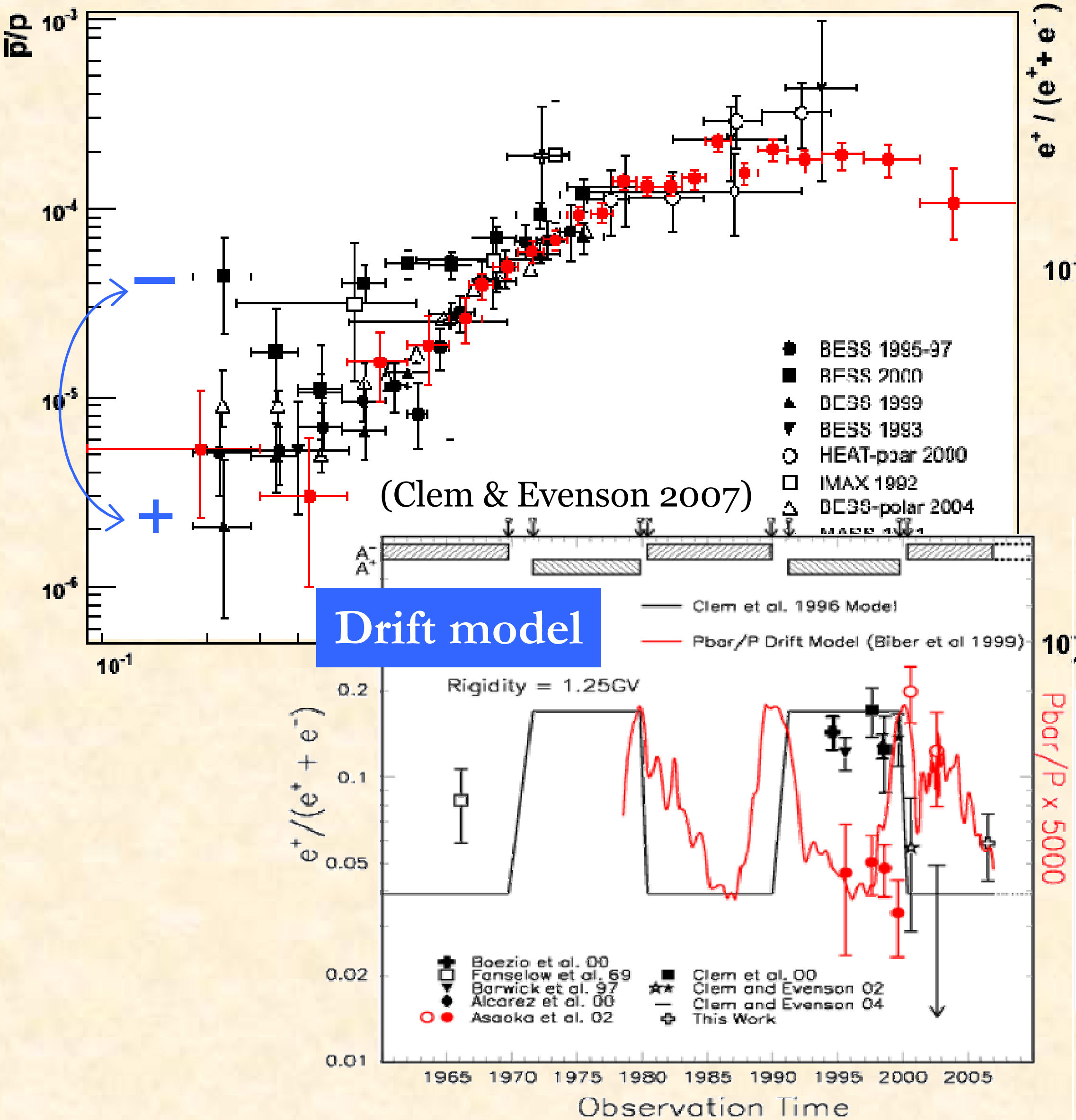
Solar Energetic Particle events (SEPs)

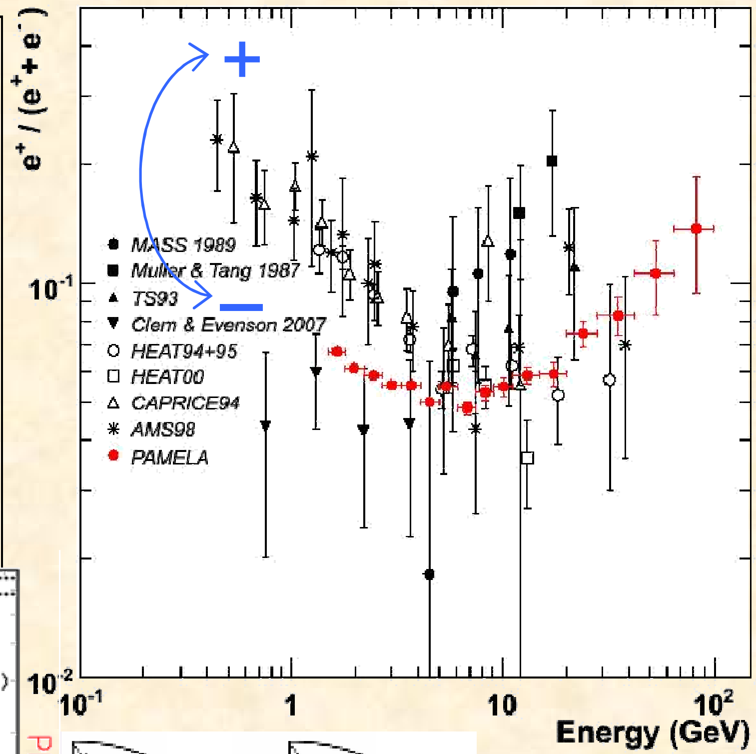
Solar modulation

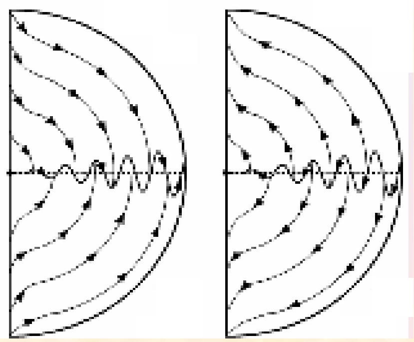


LPNHE, Paris

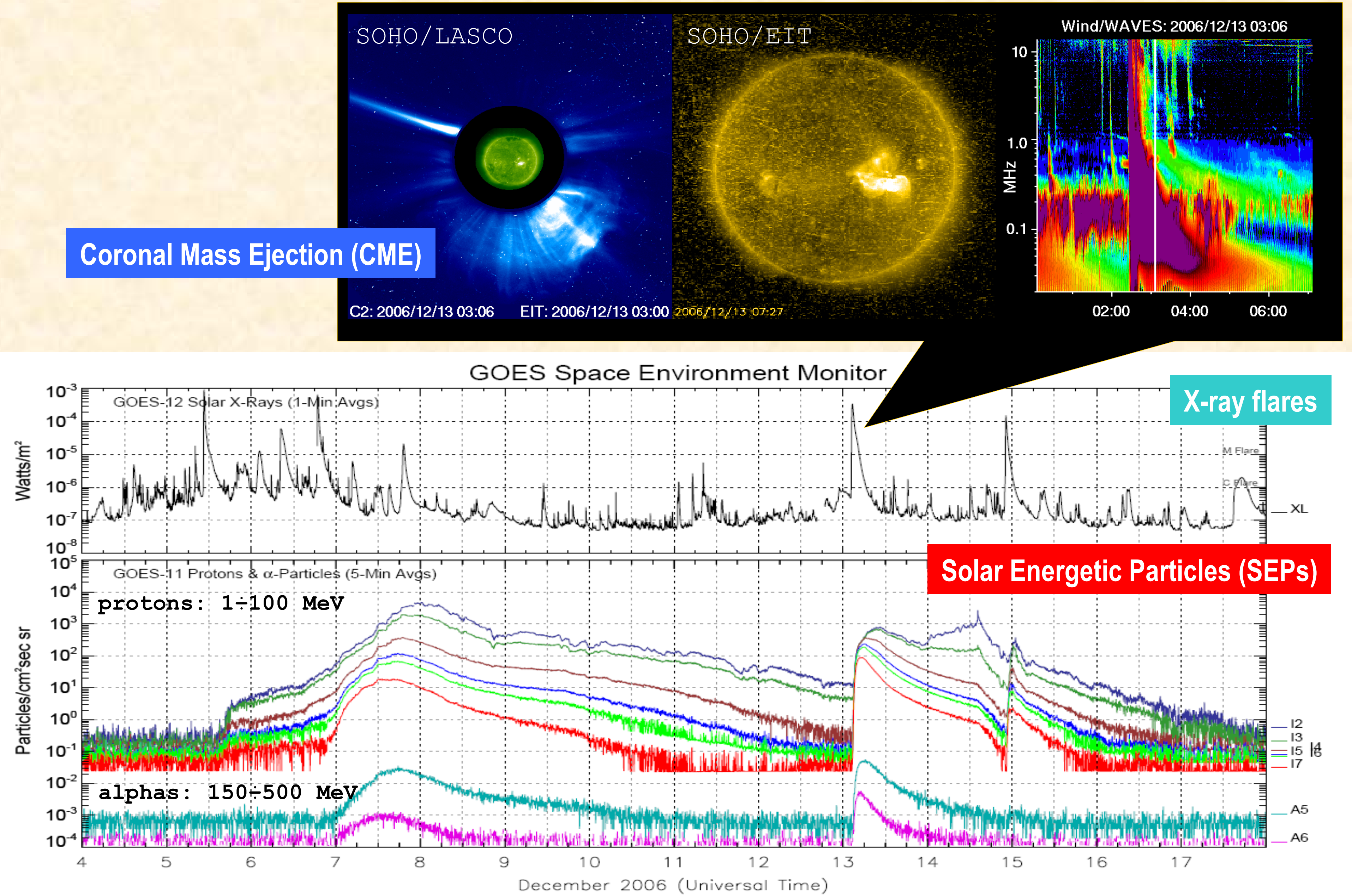
Charge dependent solar modulation



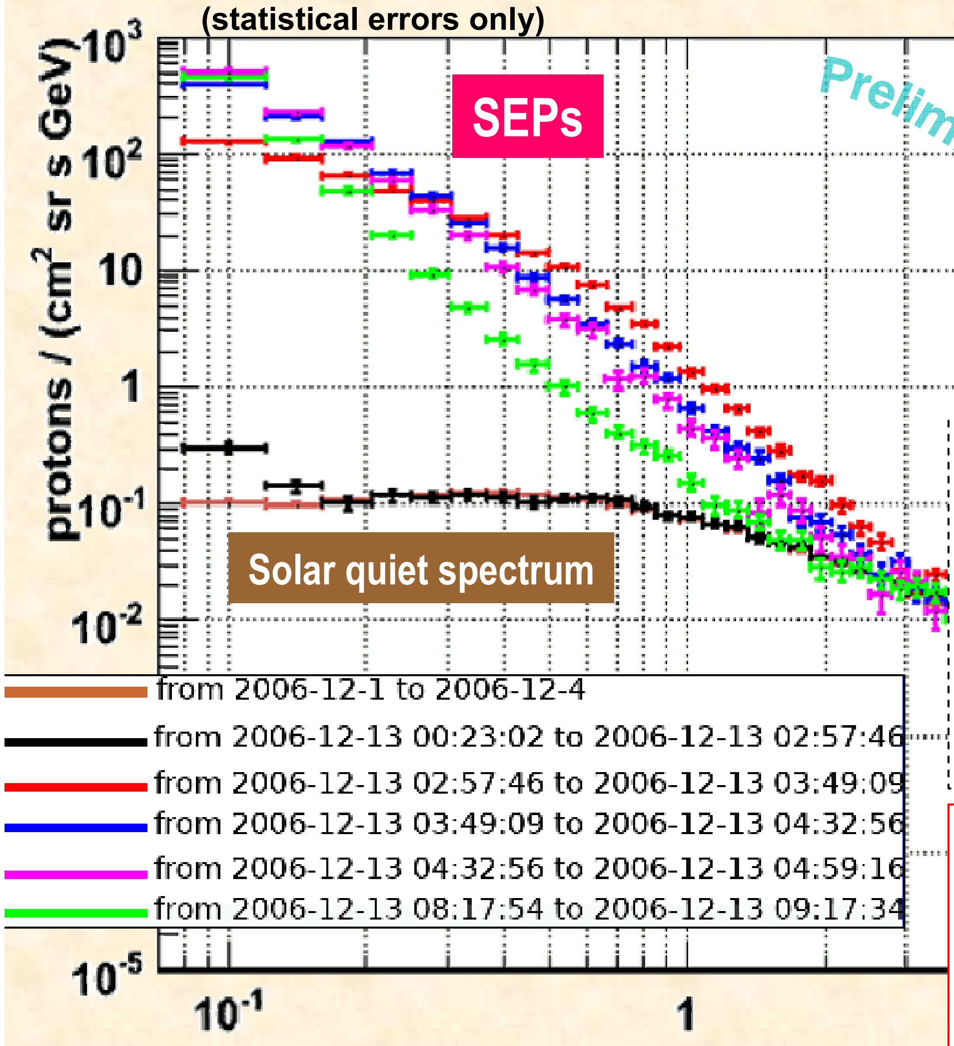


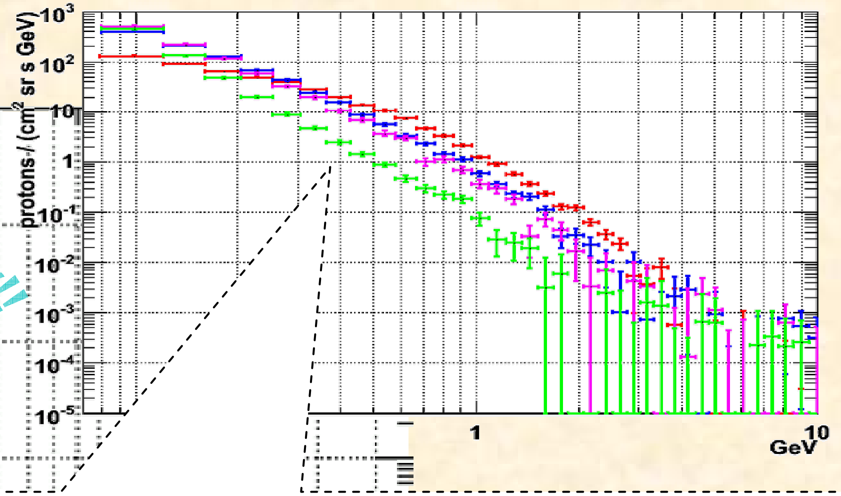


December 2006 CME/SEP events



December 13th 2006 SEP event





SEPs accelerated during CMEs

<u>SEP spectral shape and time evolution</u>
$\Rightarrow$ study of particle acceleration mechanisms in CME

Additional information will be provided by:
- electrons & positrons
- nuclear and isotopic (^{3}He, ^{4}He) composition

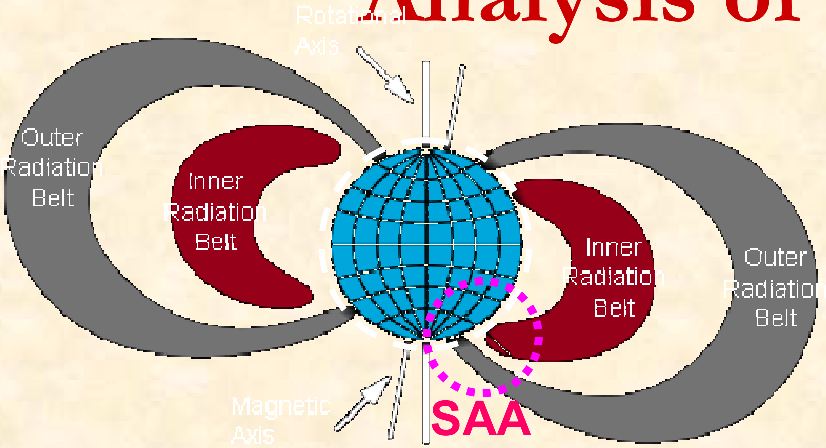
Terrestrial physics

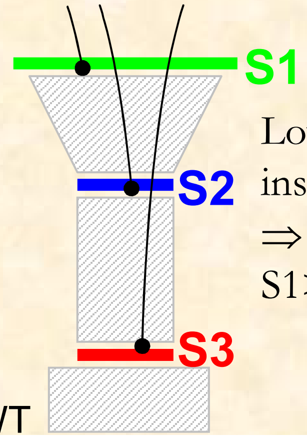
Magnetosphere

Radiation belts & SAA

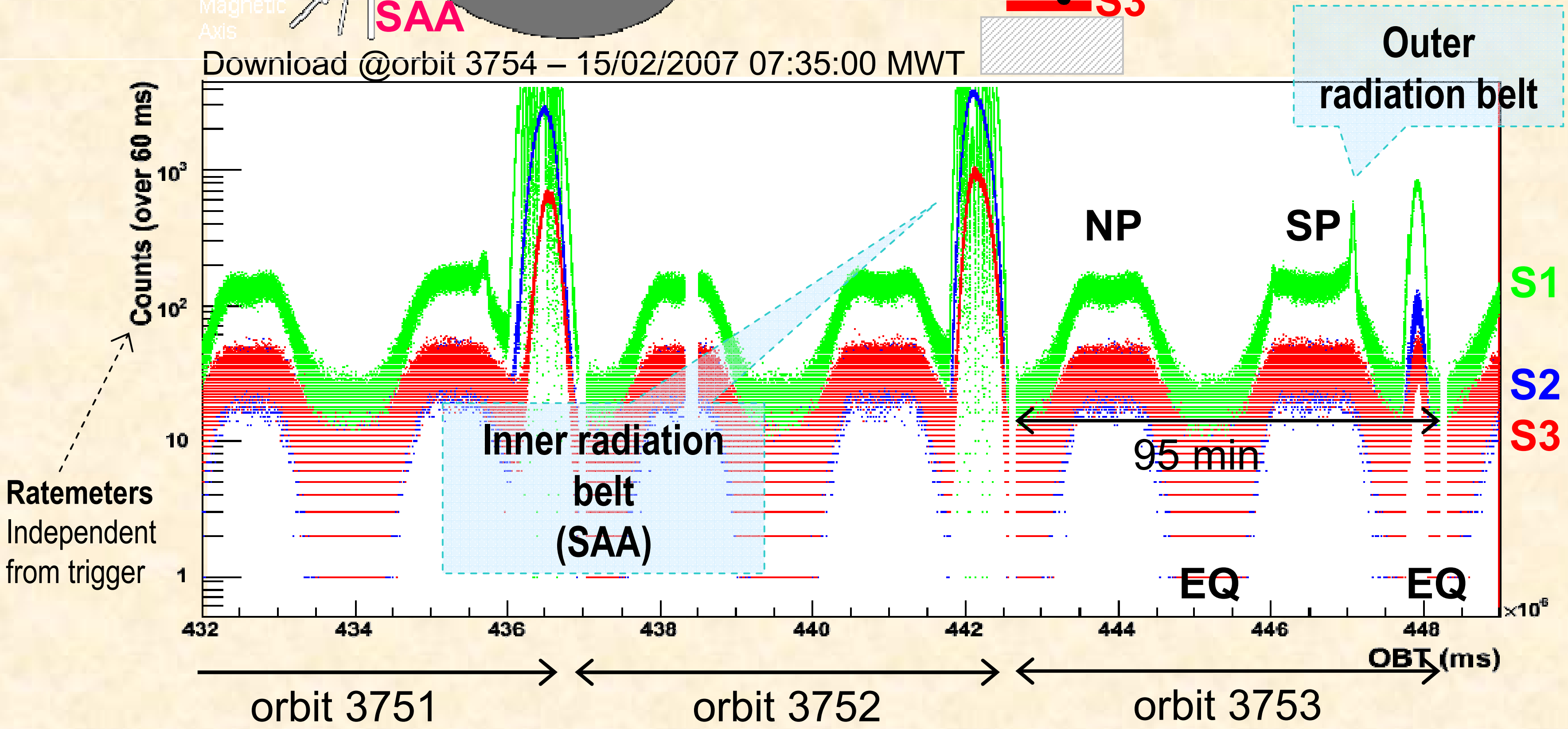
Interactions of CRs with the atmosphere

Analysis of a PAMELA orbit

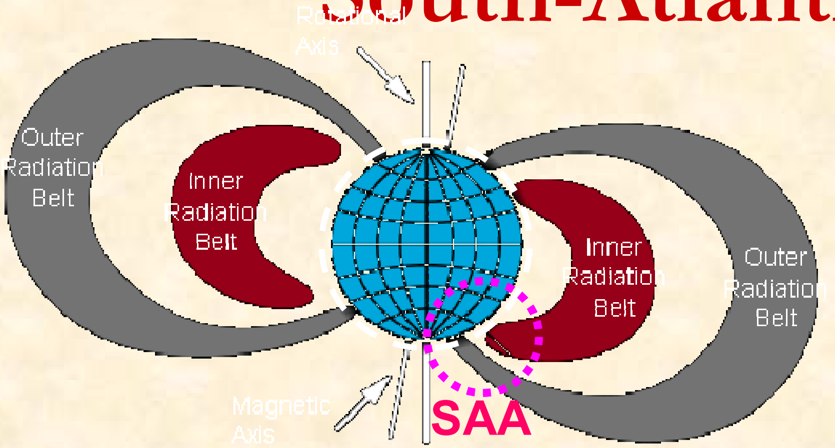


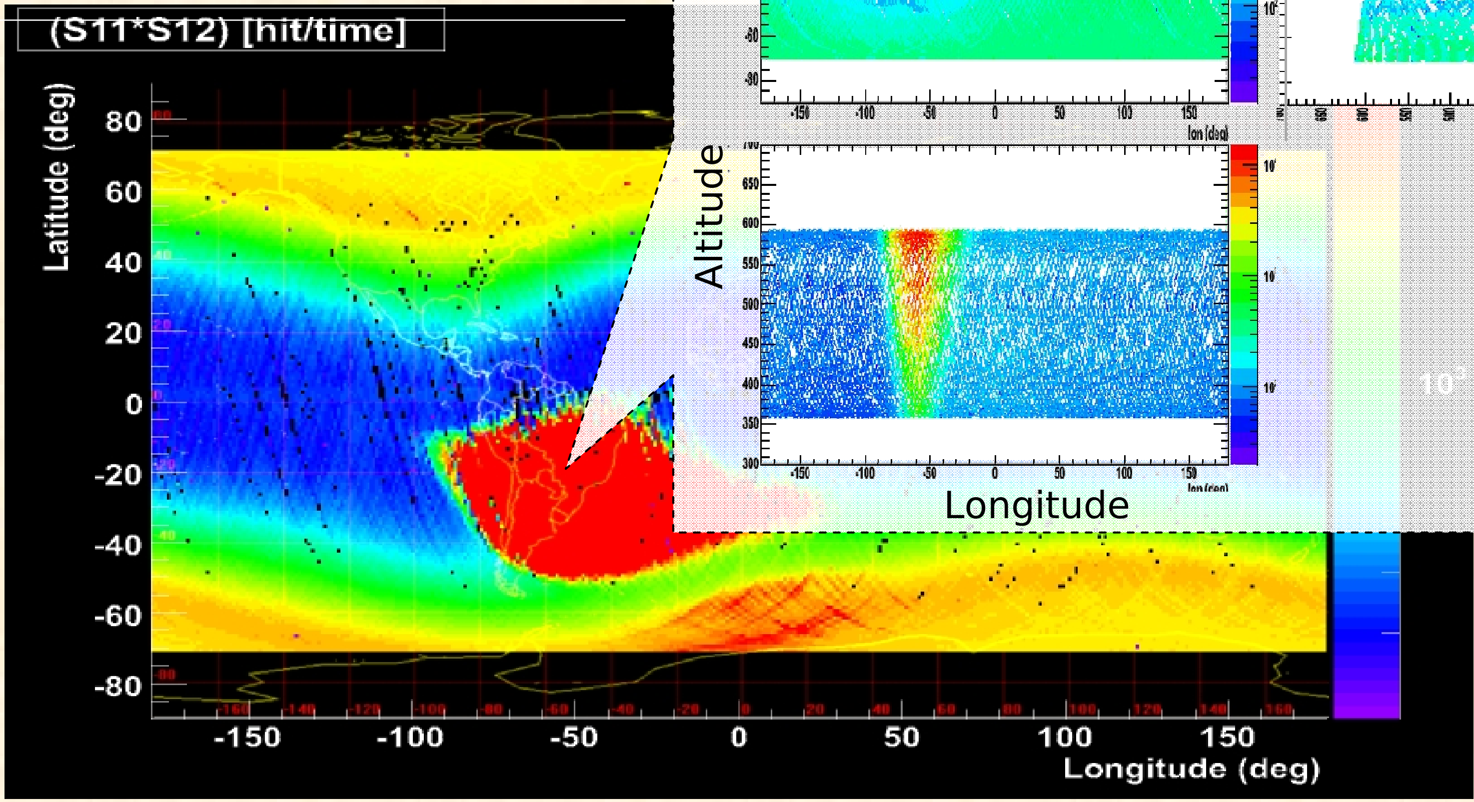


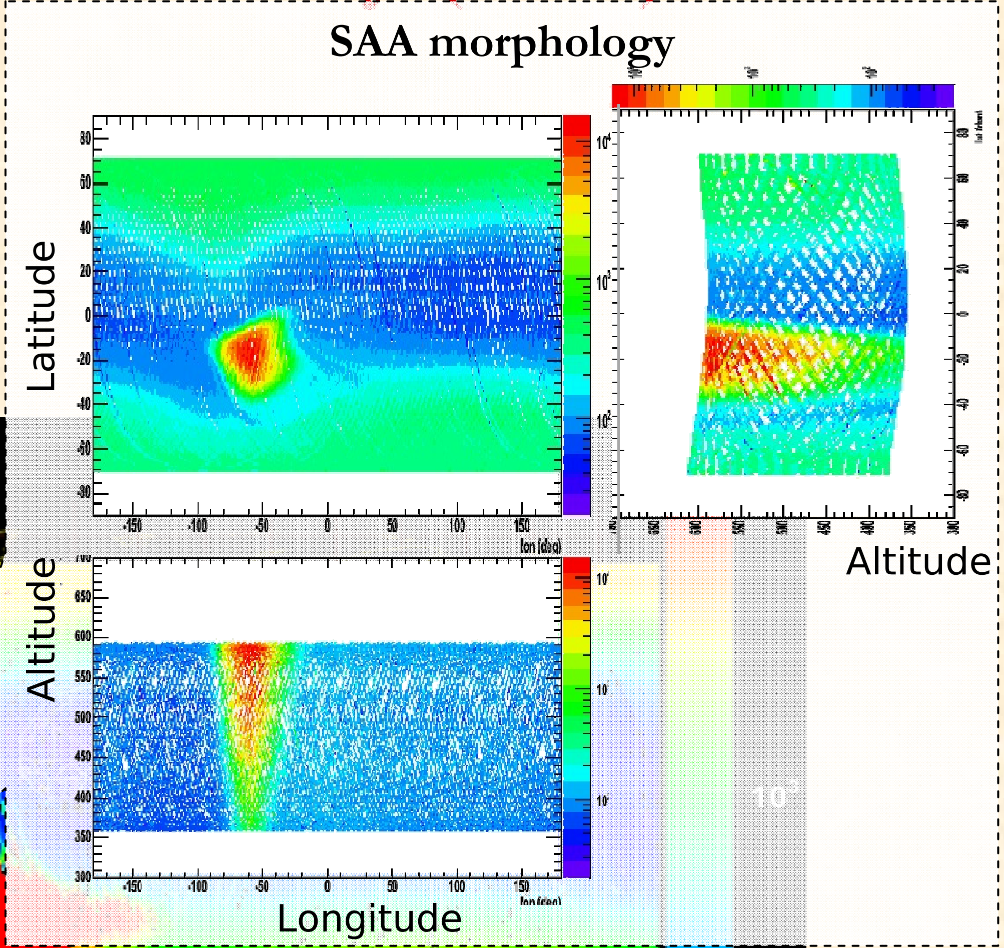
Low energy particles stops inside the apparatus
⇒ Counting rates: S1>S2>S3



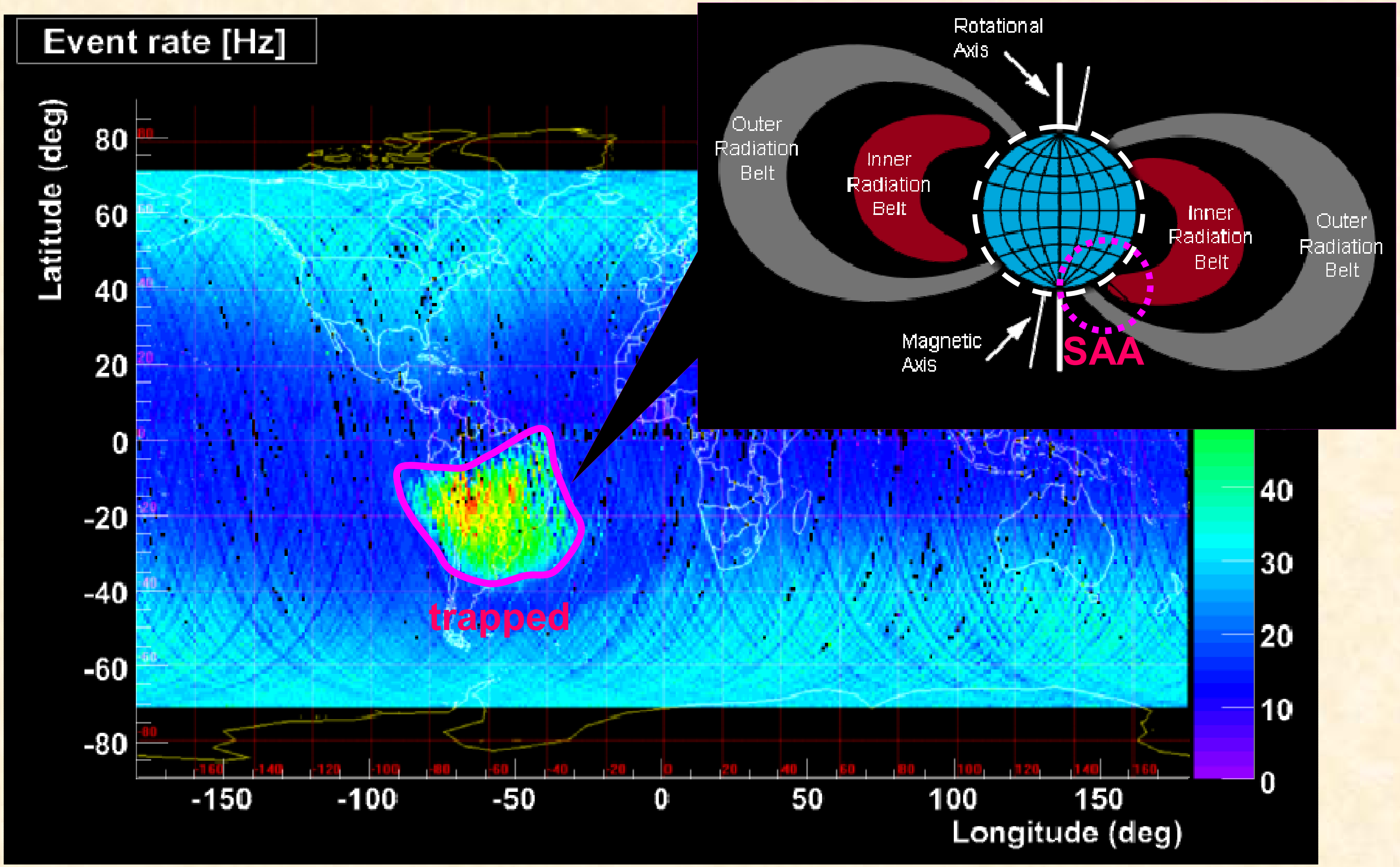
South-Atlantic Anomaly (SAA)

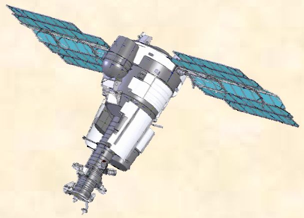






Trigger rate





The future of PAMELA (I)

The PAMELA Collaboration made official request for prolongation of the mission until end 2011.

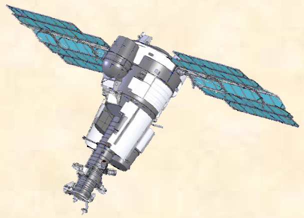
*** High energy antiprotons ***

- Estimated increase of the current statistics by 100%;
- Release of selection cuts (very strict until now):

-> possibility to reach the nominal limit of 200 GeV

6.5 antiproton events between 100-200 GeV expected by end 2011

The future of PAMELA (II)



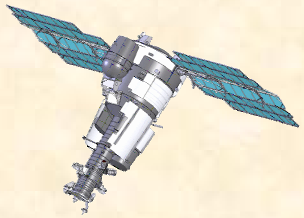
* High energy positrons and electrons *

- Estimated increase of the current statistics by 100%;
- Release of selection cuts (very strict until now):

→ possibility to go beyond 100 GeV

→ possibility to perform *anisotropy studies* **of the incoming direction of e+ and e-, to study astrophysics sources** *(few percent level above 10 GeV)*

Conclusions



- PAMELA is the first space experiment which is measuring the **antiproton** and **positron** cosmic-ray components to the high energies (>100GeV) with an unprecedented statistical precision
  - → search for evidence of DM candidates
  - → "direct" measurement of particle acceleration in astrophysical sources (pulsars?)

- Furthermore:
  - – PAMELA is providing measurements on low-mass elemental (and isotopical) spectra with an unprecedented statistical precision
    - → study of particle origin and propagation in the interstellar medium
  - – PAMELA is able to measure the high energy tail of solar particles.
  - – PAMELA is measuring composition and spectra of trapped and re-entrant albedo particles in the Earth magnetosphere

◈ Thanks!! ◈