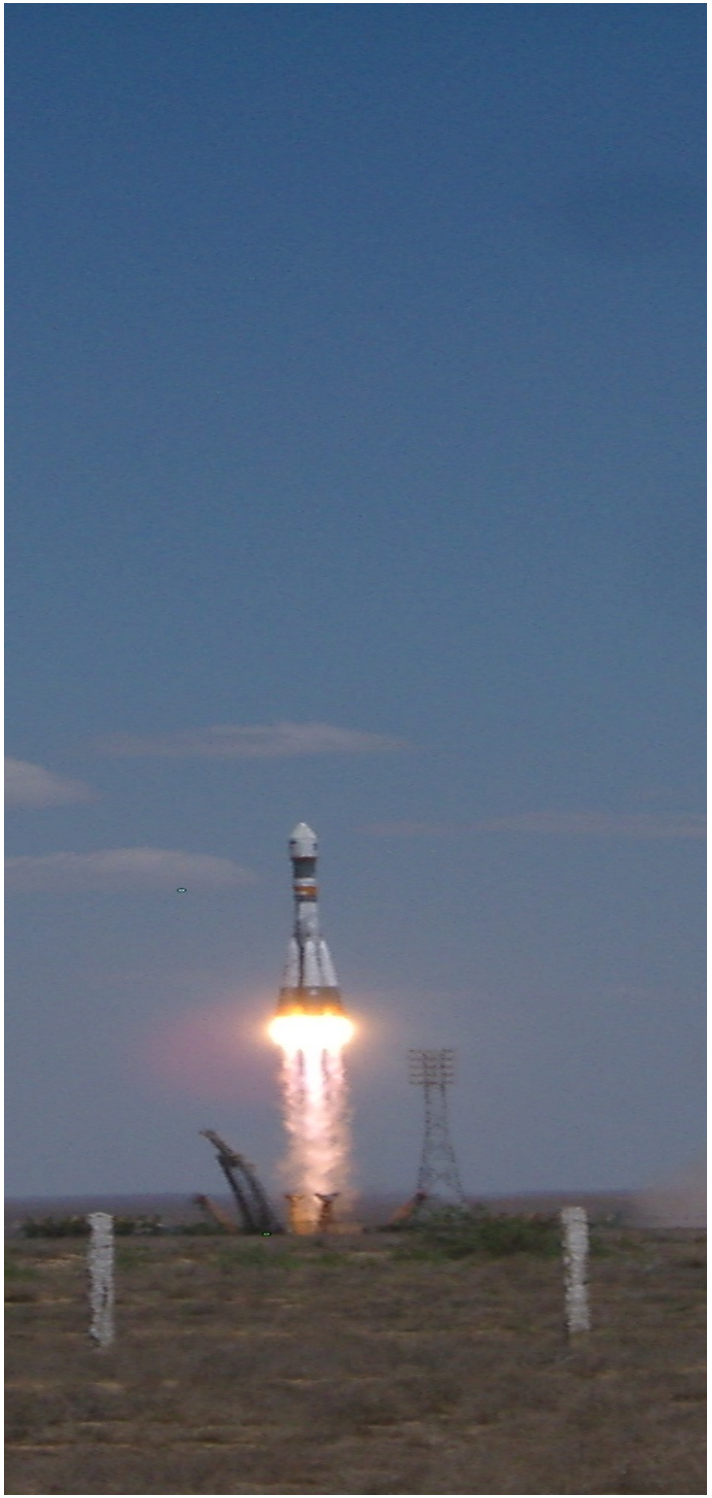


WIN09

22nd International Workshop on
Weak Interactions and Neutrinos
Perugia, September 14-19 2009

Cosmic ray antiparticles: results from PAMELA

Paolo Papini
INFN - Florence

INFN

PaMeLa

The PAMELA collaboration

Italy

Bari · Florence · Frascati · Naples · Rome · Trieste · CNR, Florence

Russia

Ioffe Physico-Technical Institute

Moscow

St. Petersburg

Germany

Universität Gesamthochschule Siegen

Siegen

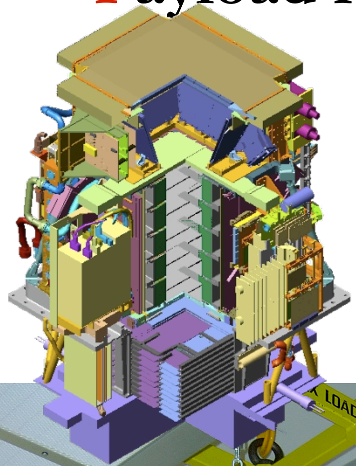
Sweden

Kungl Tekniska Högskolan

KTH, Stockholm

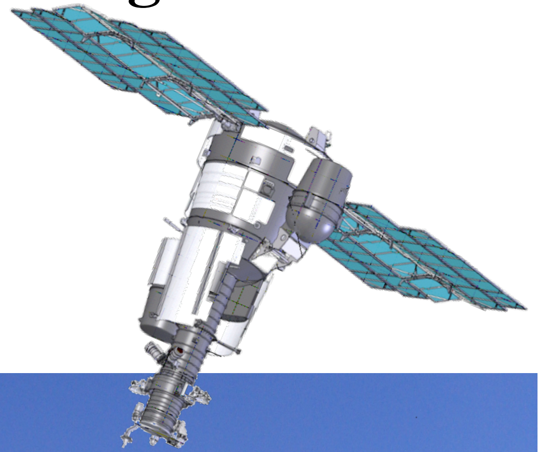
PAMELA

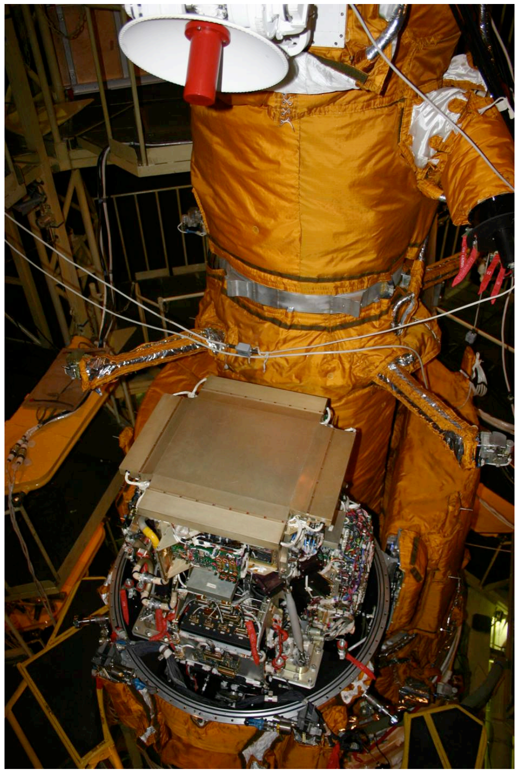
Payload for Antimatter/Matter Exploration and Light-nuclei Astrophysics



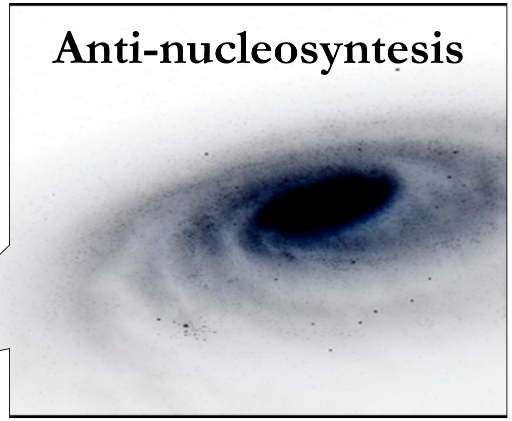
→ Direct detection of CRs in **space**

→ Main focus on **antiparticles** component

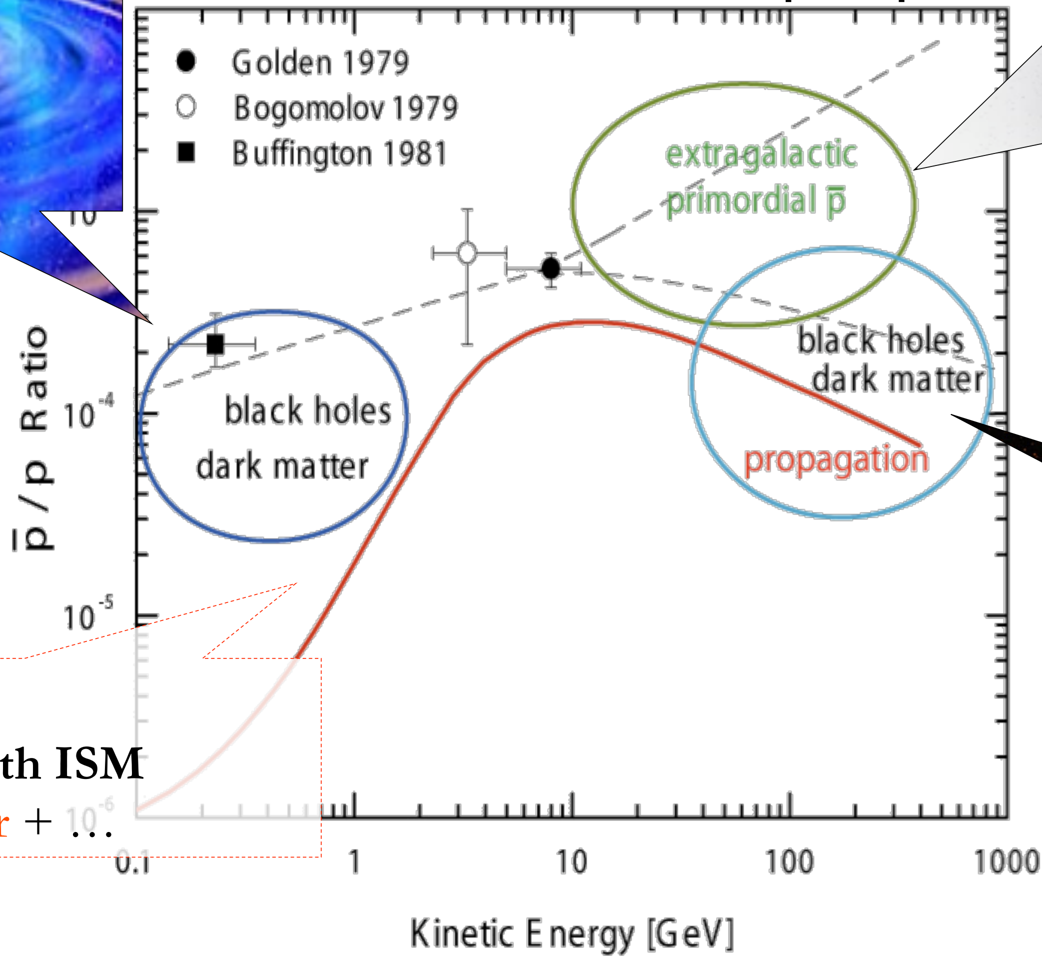




Why CR antimatter?



First historical measurements of p-bar/p ratio



<u>**Background**</u>**:**

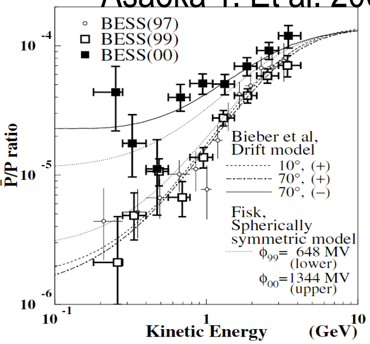
CR interaction with ISM

CR + ISM → p-bar + …

CR antimatter

Charge-dependent solar modulation

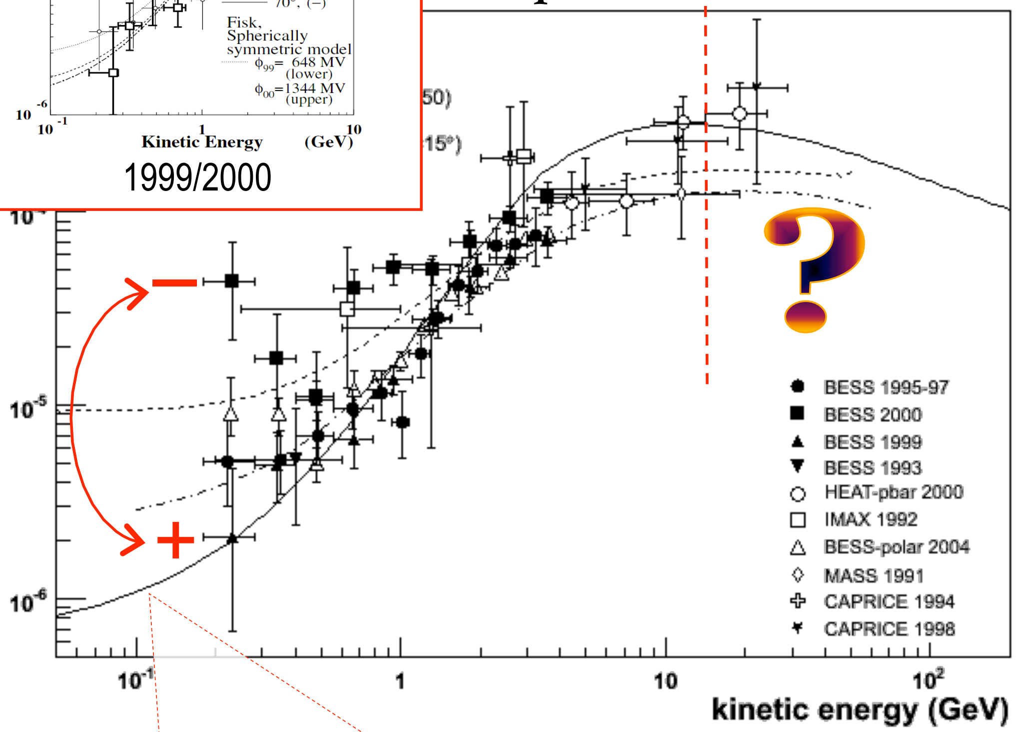
Asaoka Y. Et al. 2002



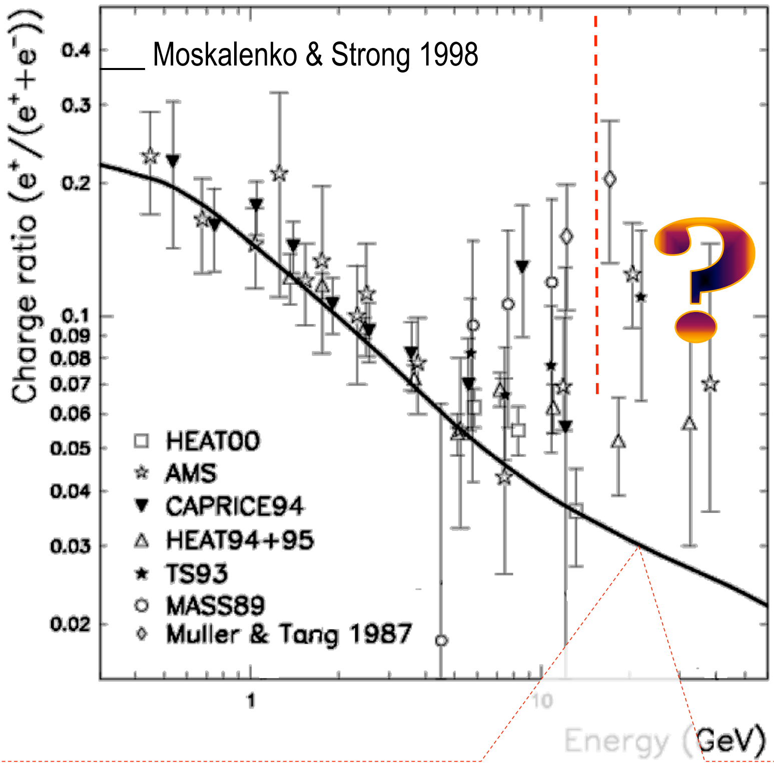
1999/2000

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 → $\mathbf{e^\pm}$ + x

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

- Propagation dominated by energy losses (inverse Compton & synchrotron radiation)
- Local origin (@1ooGeV 90% from <2kpc)

PAMELA nominal capabilities

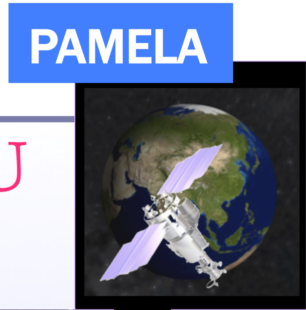
	Energy range
• Antiprotons	80 MeV - 190 GeV
• Positrons	50 MeV – 300 GeV
• Electrons	up to 500 GeV
• Protons	up to 1000 GeV
• Electrons+positrons	up to 2 TeV (from calorimeter)
• Light Nuclei	up to 200 GeV/n He/Be/C
• AntiNuclei search	

→ **Simultaneous measurement of many cosmic-ray species**

→ **New energy range**

→ **Unprecedented statistics**

PAMELA science

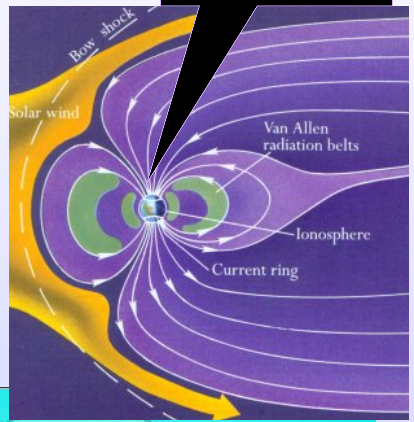


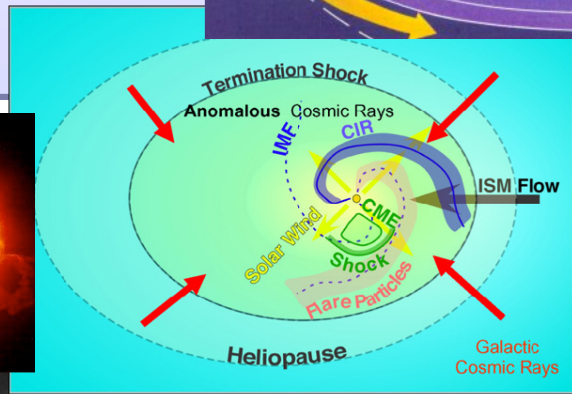
PAMELA is a Space Observatory @ 1AU

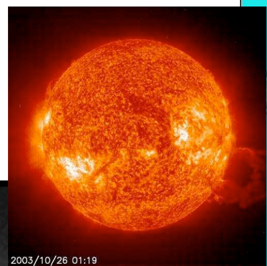
- Search for dark matter
- Search for primordial antimatter
- Search for primary sources of antiparticles

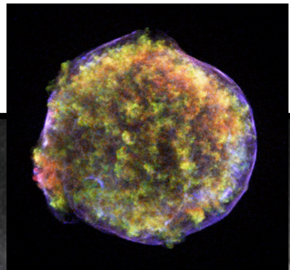
… but also:

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



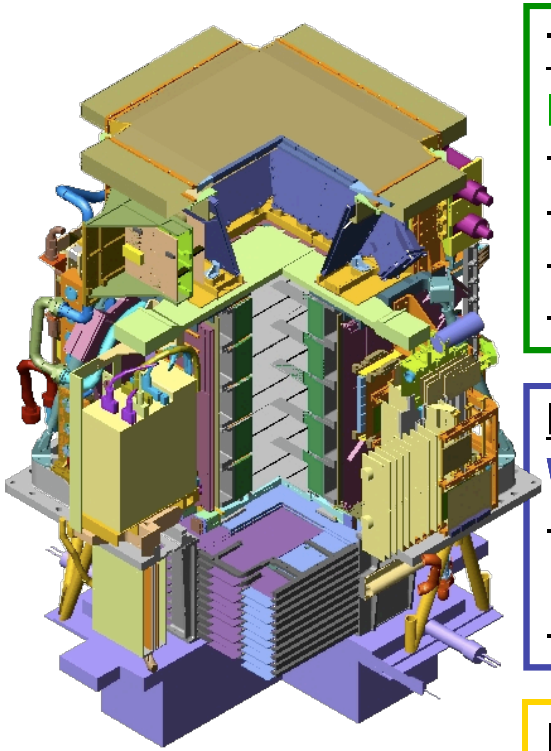






PAMELA detectors

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



Time-Of-Flight

plastic scintillators + PMT:

- Trigger
- Albedo rejection;
- Mass identification up to 1 GeV;
- Charge identification from dE/dX.

Electromagnetic calorimeter

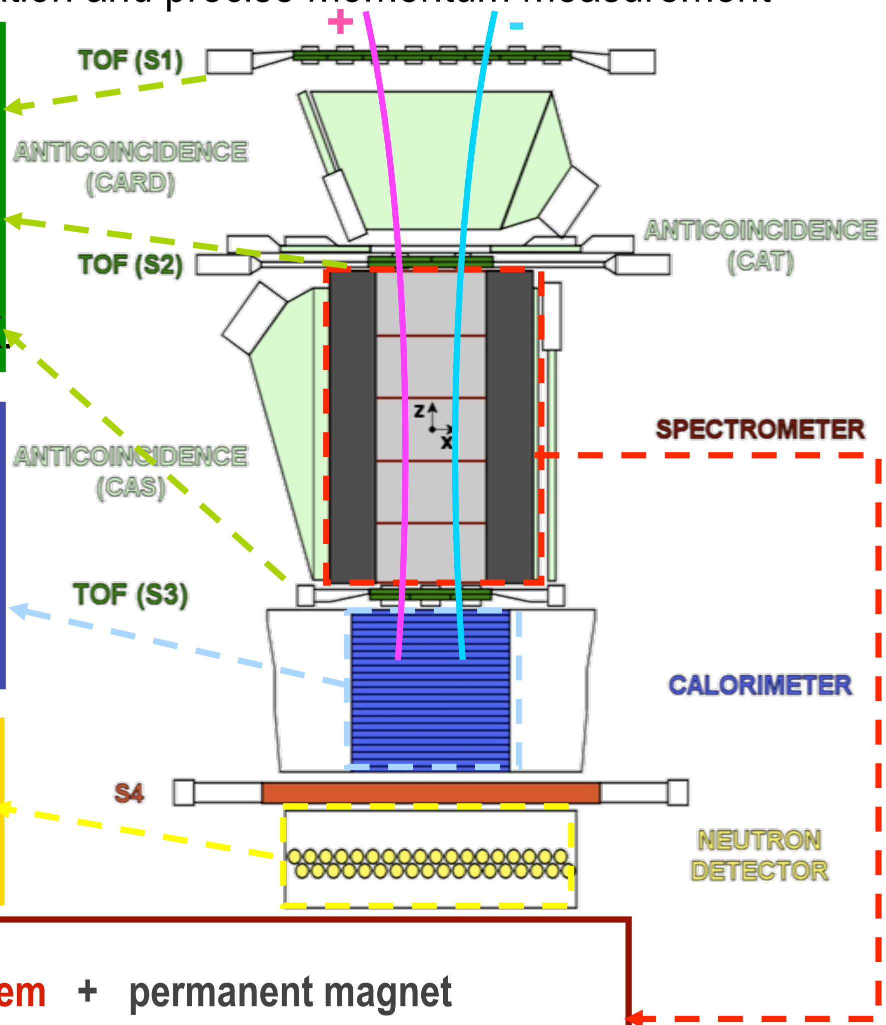
W/Si sampling (16.3 X0, 0.6 λI)

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

Neutron detector

^{3}He Tubes:

- High-energy e/h discrimination



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

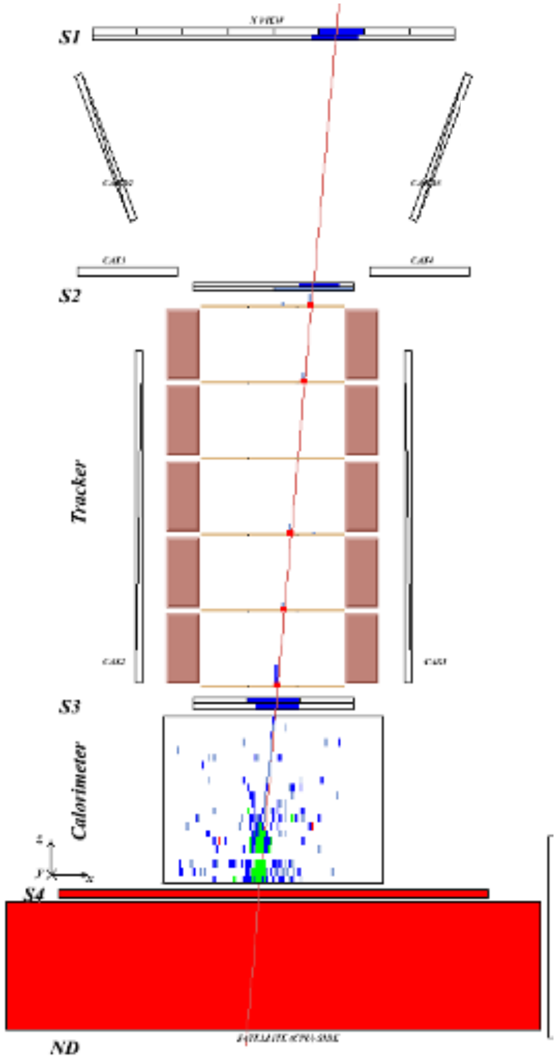
Spectrometer

microstrip silicon tracking system + permanent magnet

It provides:

- ***Magnetic rigidity*** → R = pc/Ze
- ***Charge sign***
- ***Charge value from dE/dx***

Particle identification with PAMELA



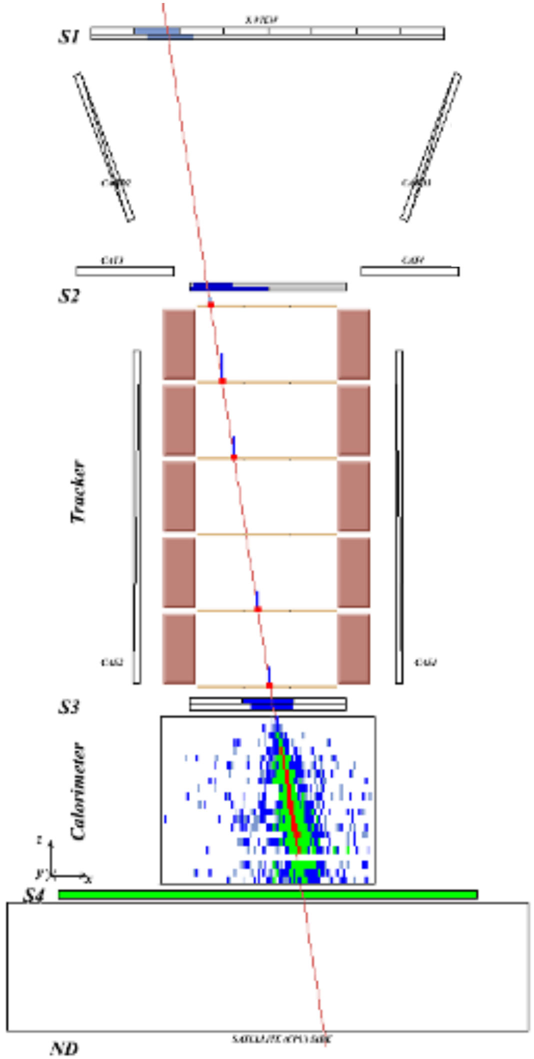
Antiproton
(NB: $e^-/\bar{p} \sim 10^2$)

Time-of-flight: trigger, albedo rejection, mass determination (up to 1 GeV)

Bending in spectrometer: sign of charge

Ionisation energy loss (dE/dx): magnitude of charge

Interaction pattern in calorimeter: electron-like or proton-like, electron energy



Positron
(NB: $p/e^+ \sim 10^{3-4}$)

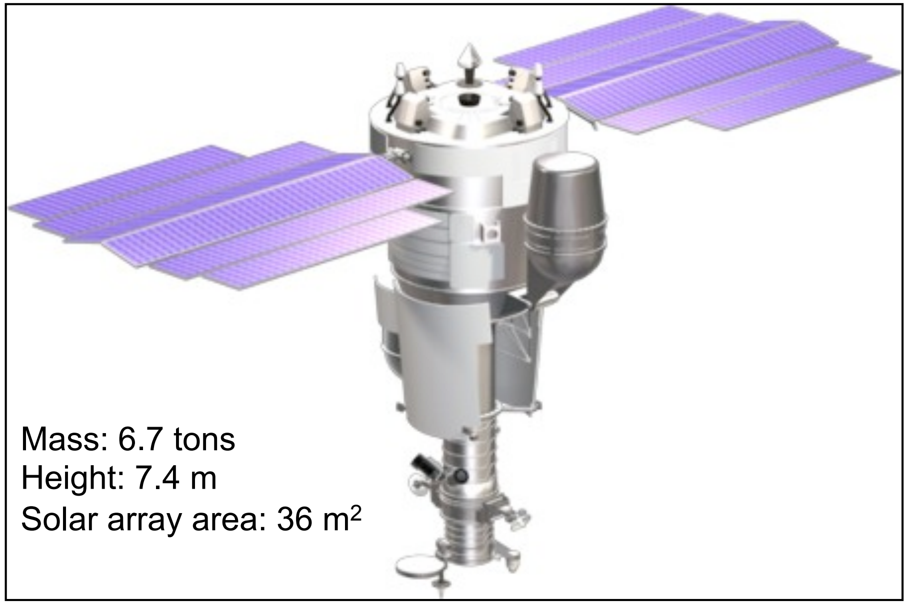
PAMELA milestones

- Launch from Baikonur: June 15th 2006, 0800 UTC.
- Power On: June 21st 2006, 0300 UTC.
- Detectors operated as expected after launch

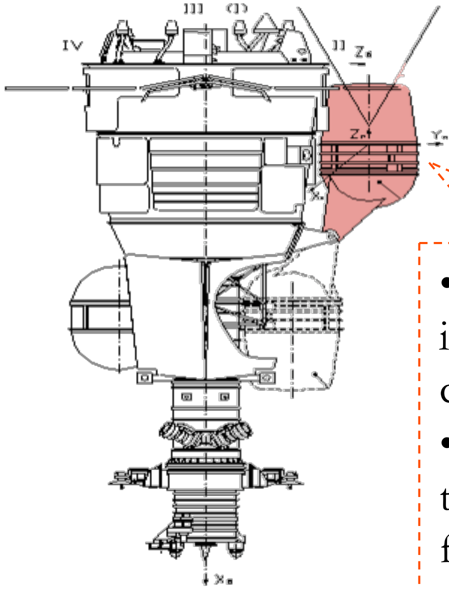
- PAMELA in continuous data-taking mode since commissioning phase ended on July 11th 2006

- As of now:
  - ~1150 days in orbit
  - Trigger rate ~ 25 Hz
  - Data taking ~73% live-time
  - >13 TByte of raw data downlinked
  - >10^9 triggers recorded and under analysis

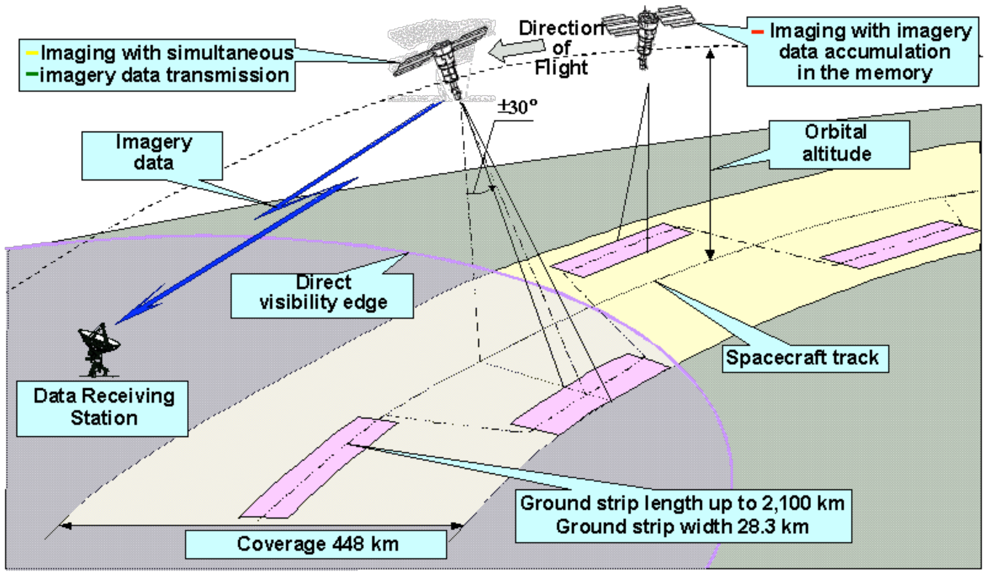
The Resurs DK-1 spacecraft



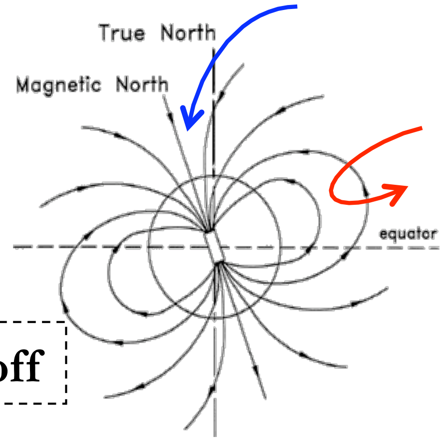
- Multi-spectral remote sensing of earth's surface
  - *-near-real-time high-quality images*
- Built by the Space factory TsSKB Progress in Samara (Russia)
- **Operational orbit parameters:**
  - **-inclination ~70°**
  - **-altitude ~ 360-600 km (elliptical)**
- **Active life >5 years**
- Data transmitted via Very high-speed Radio Link (VRL)



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



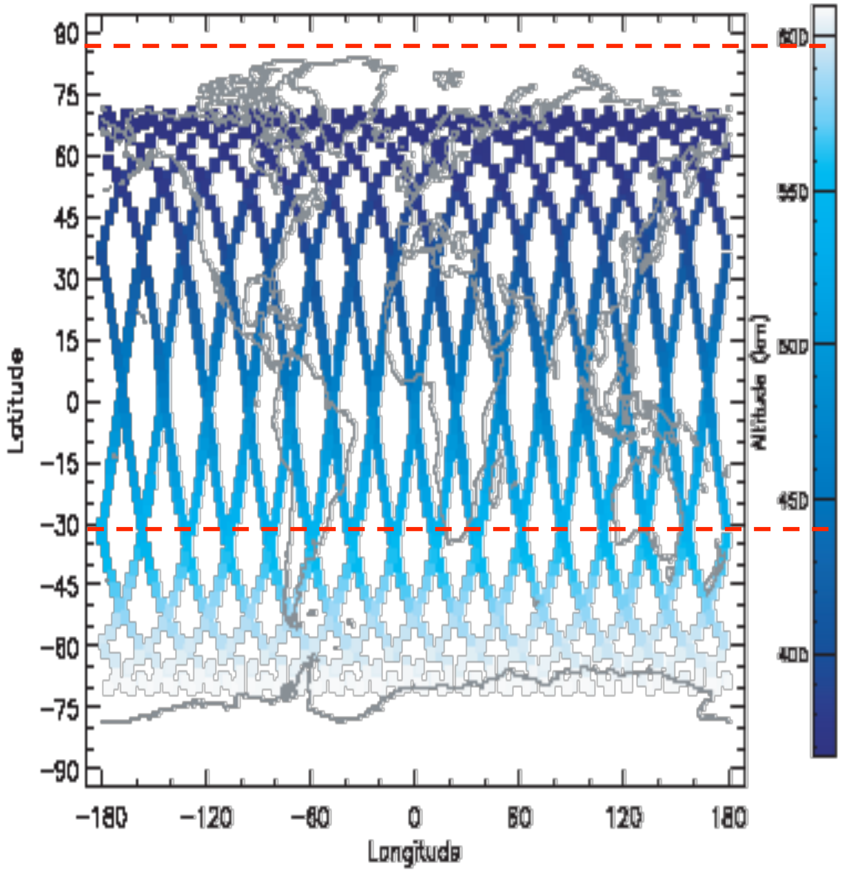
Satellite orbit



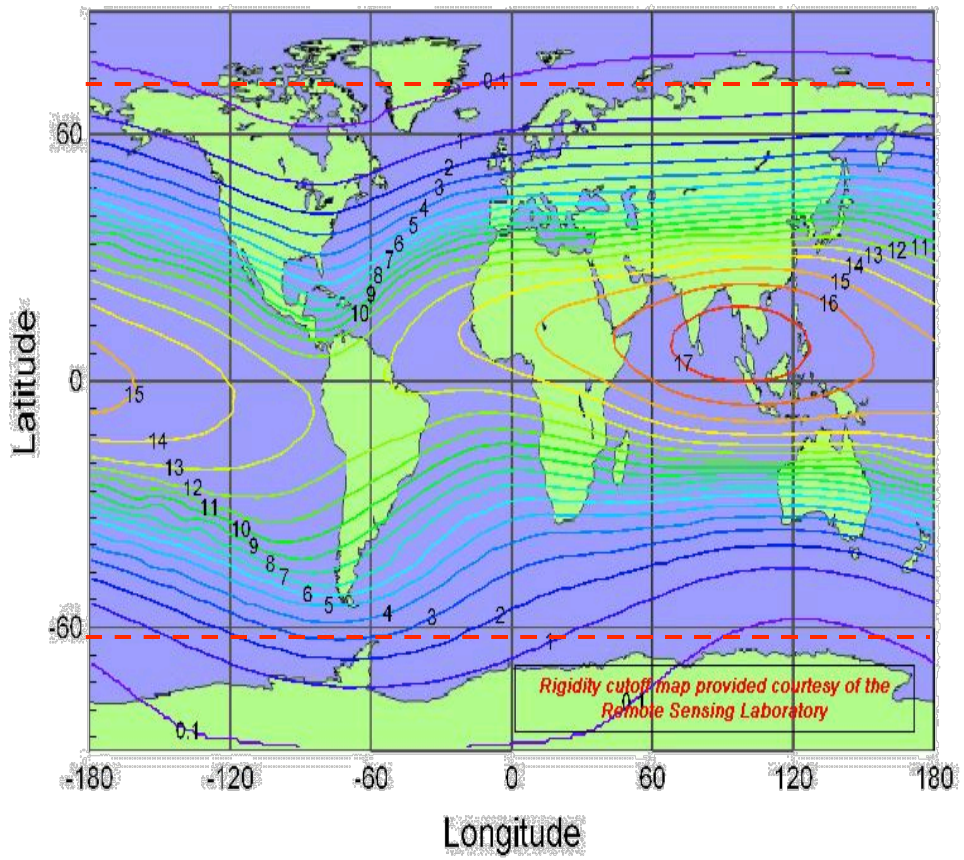
PAMELA orbit

inclination ~70°

altitude ~ 360-600 km



Vertical rigidity cutoff

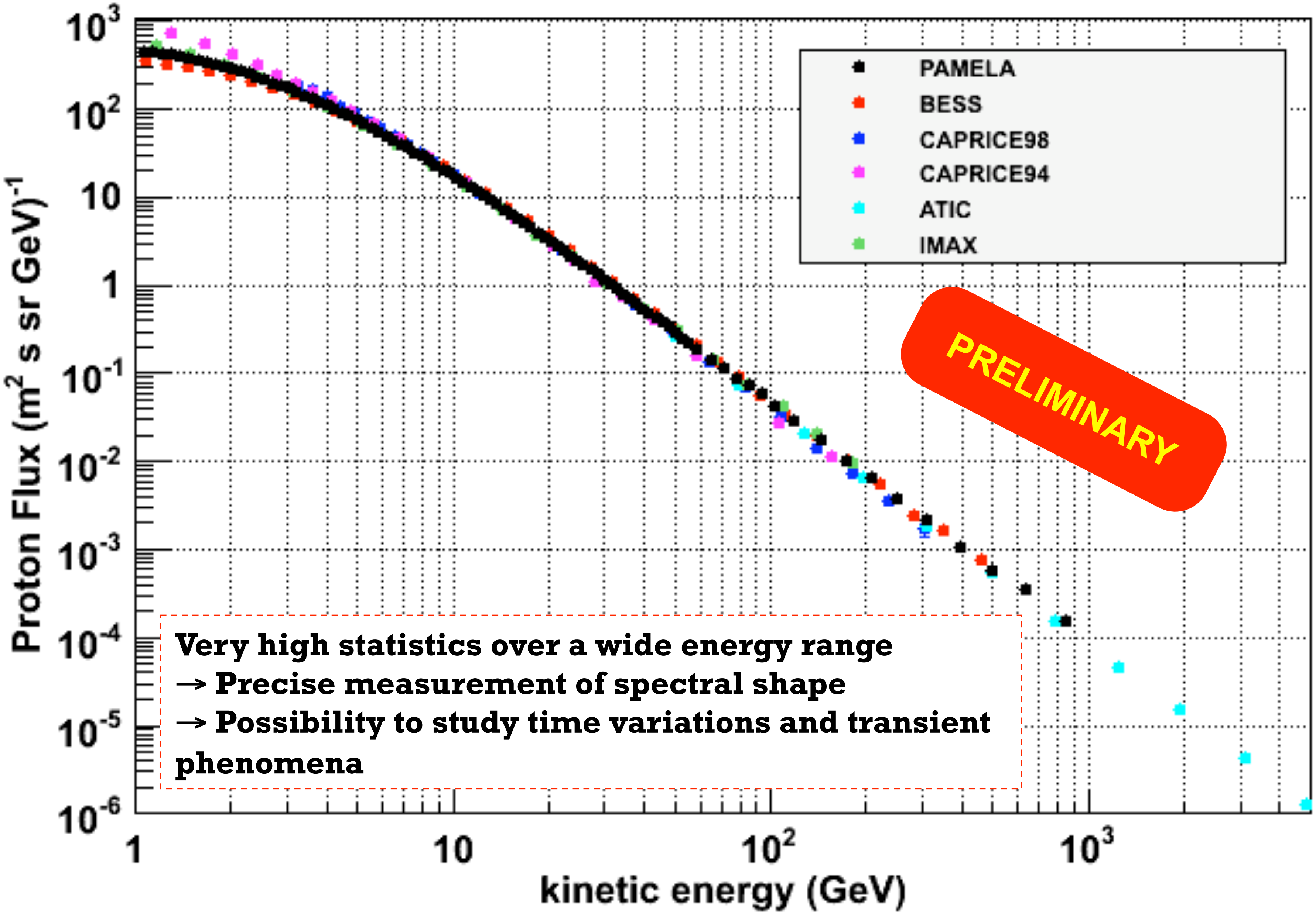


→ the quasi-polar orbit allows to study low-energy cosmic rays (R>100MV)

Some short hints on 'additional' physics items ($\neq$ pbar, e^+, e^-)

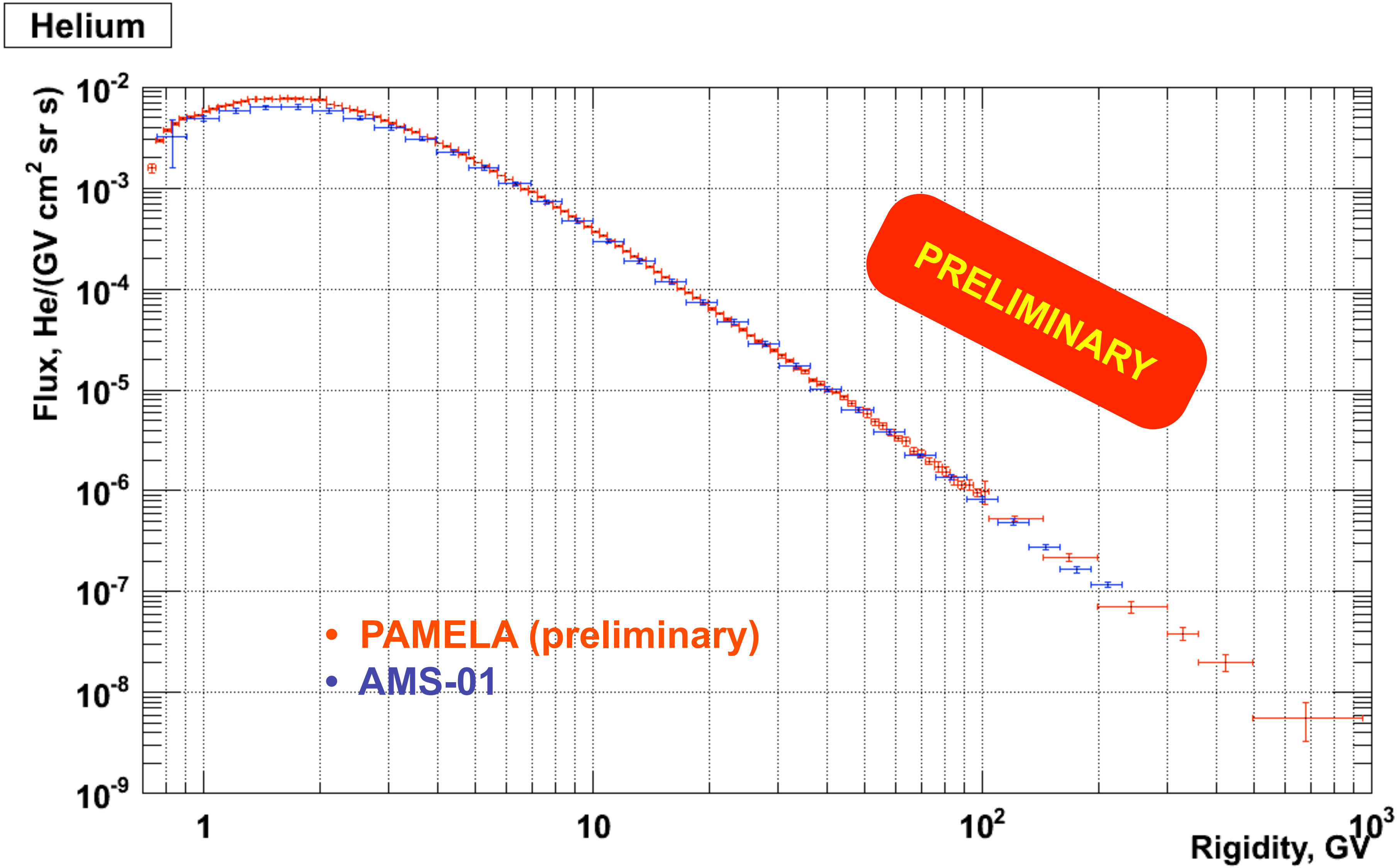
A long dedicated talk will be necessary, sorry!

Preliminary proton spectrum

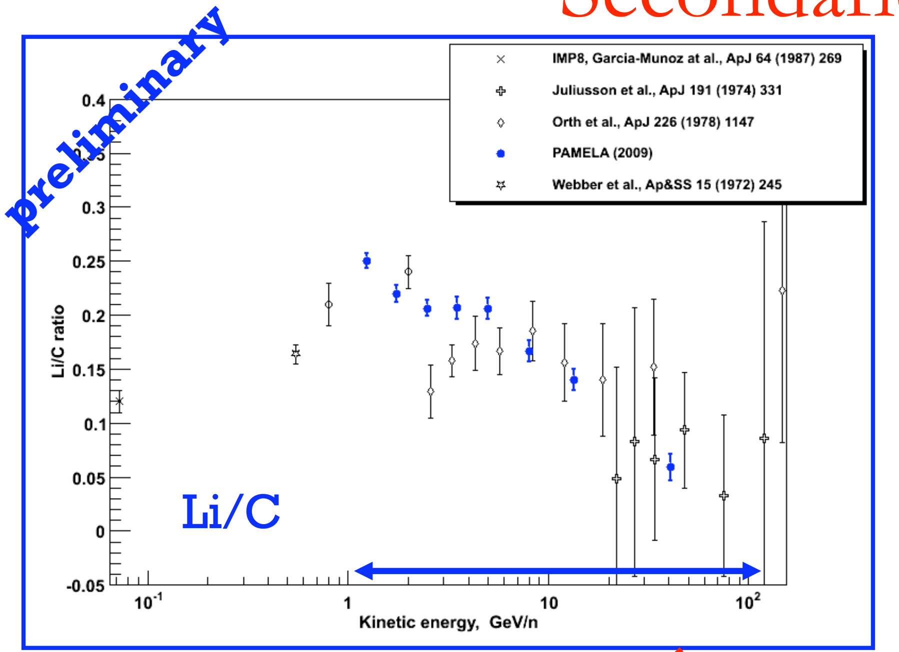


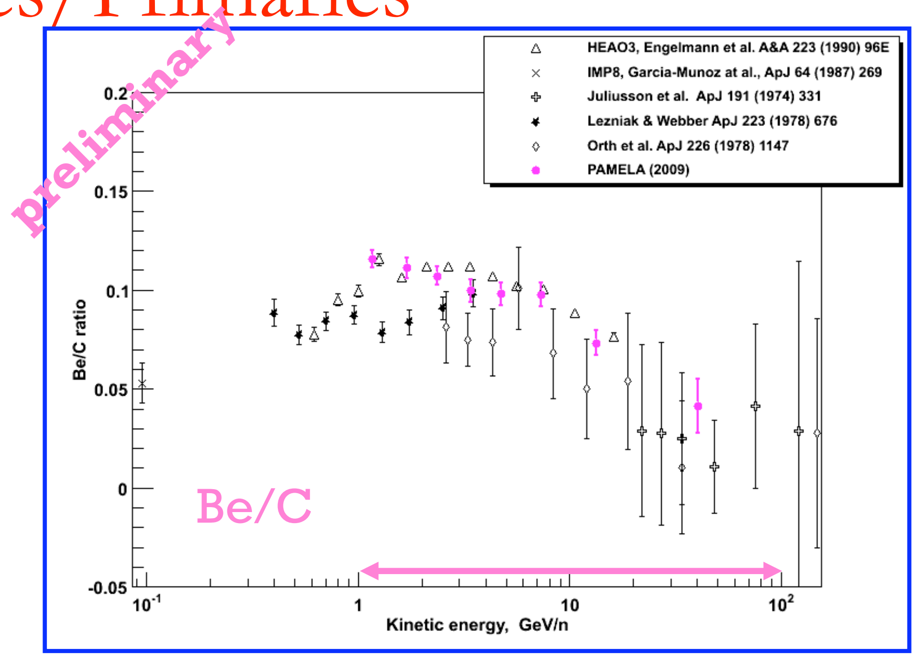
Very high statistics over a wide energy range
→ Precise measurement of spectral shape
→ Possibility to study time variations and transient phenomena

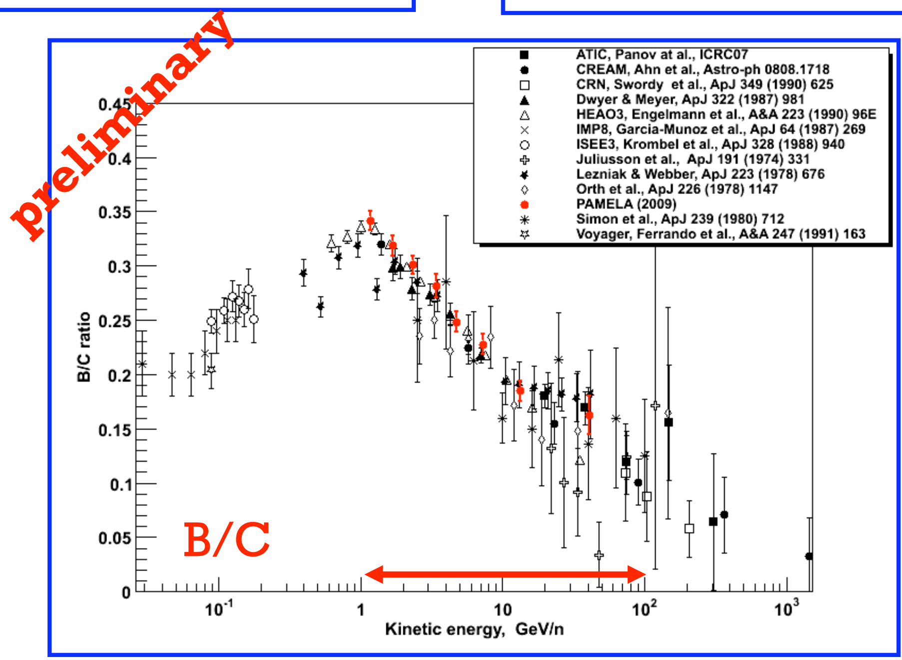
Preliminary He spectrum



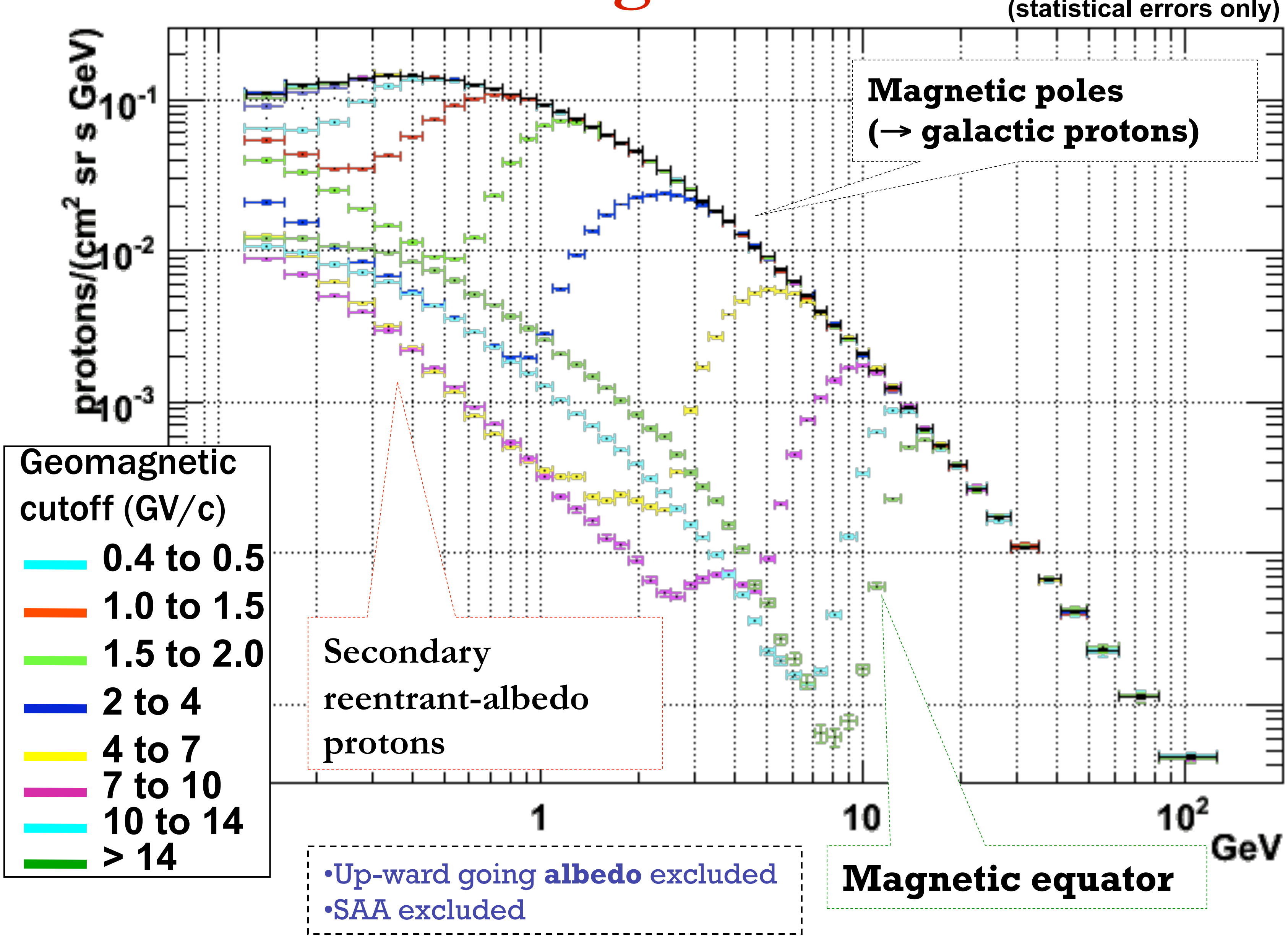
PAMELA preliminary results
Secondaries/Primaries



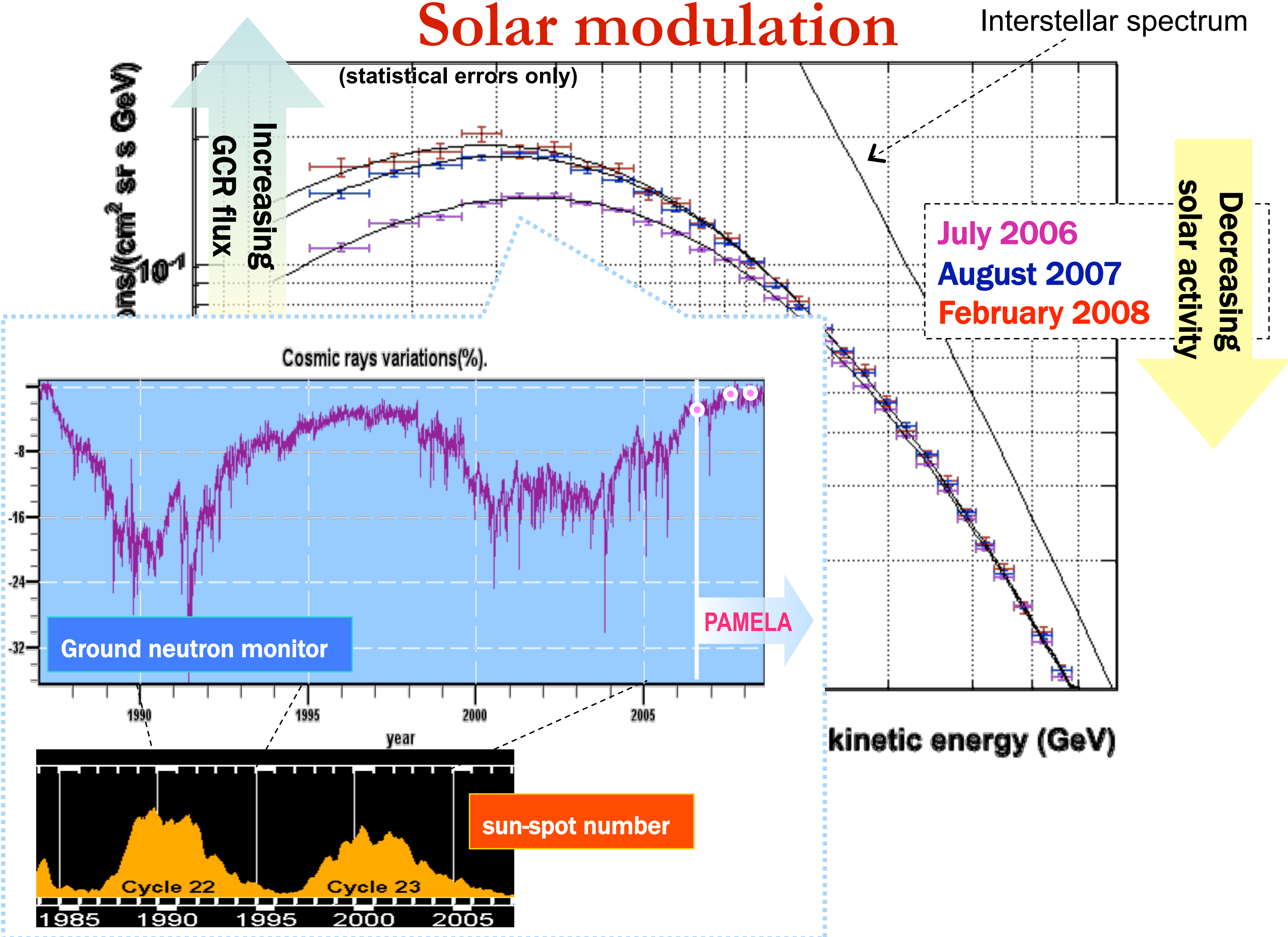




Geomagnetic cutoff



Solar modulation



Antiprotons

High-energy antiproton analysis

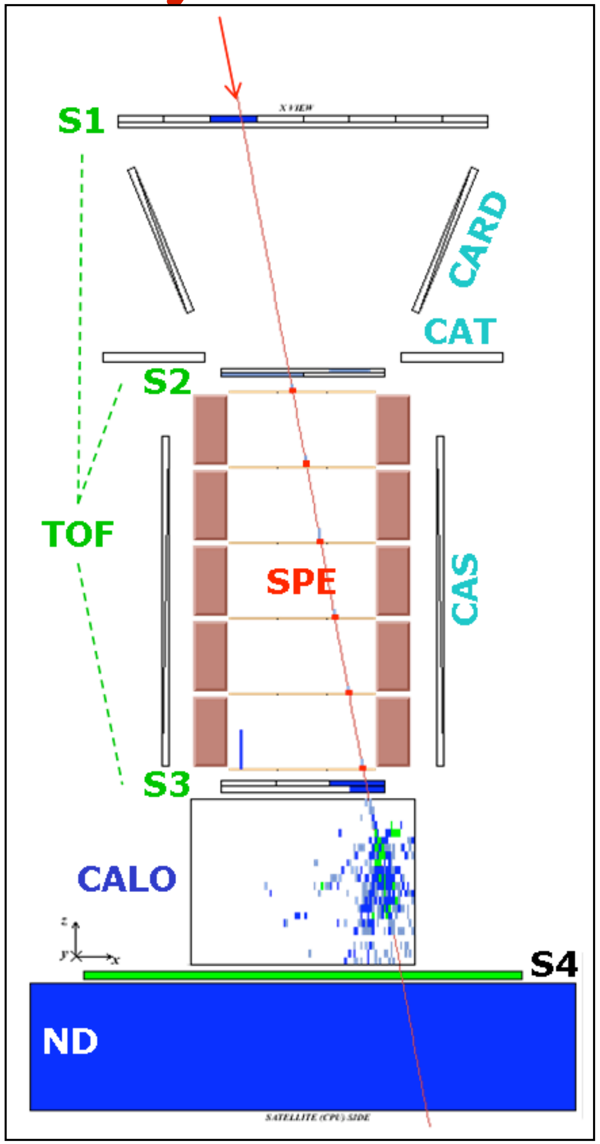
- Analyzed data ~950 days
- Collected triggers ~10^9

- **Basic selection criteria**
  - rigidity (R) → SPE
  - |Z|=1 (dE/dx vs R) → SPE&ToF
  - β vs R consistent with M_p → ToF

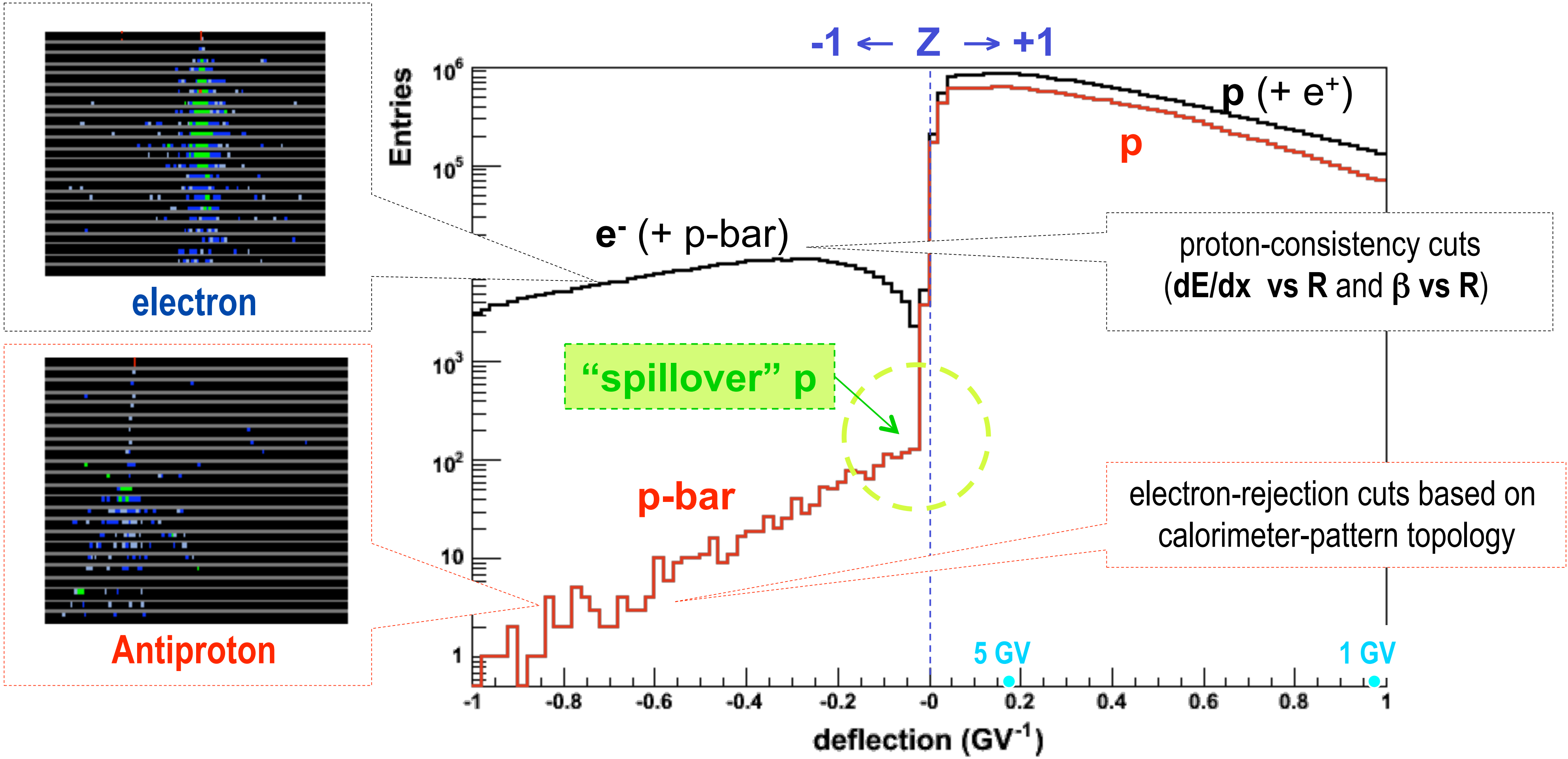
- **Galactic particle**

  measured rigidity above geomagnetic cutoff
  Down-ward going particle (no albedo)

- **Antiprotons identification**
  - p-bar/p separation (charge sign) → SPE
  - p-bar/e^- (and p/e^+) separation → CALO



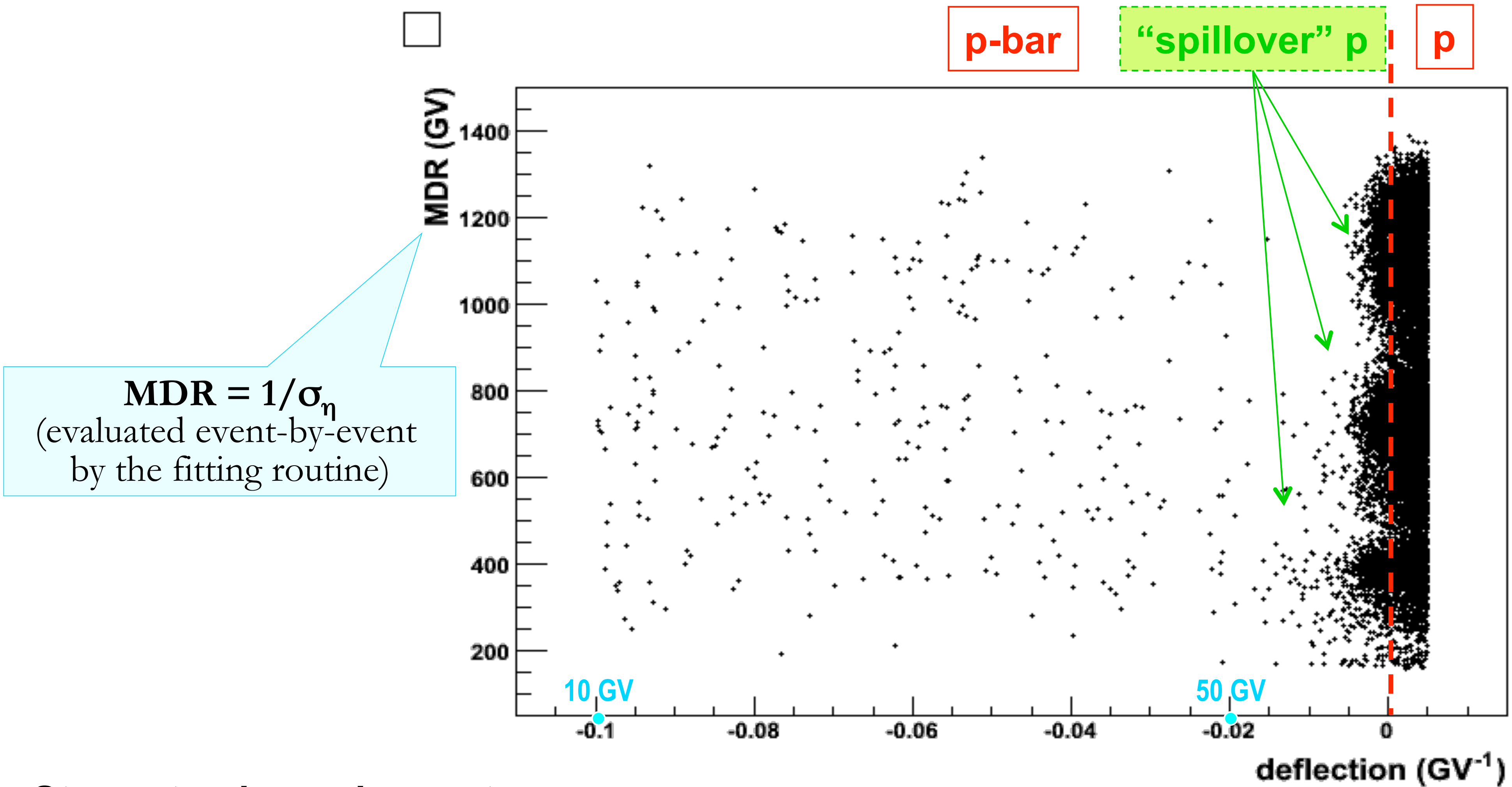
Antiproton identification



Dominant background → **spillover protons**:
finite deflection resolution of the SPE ⇒ wrong assignment of charge-sign@high energy

Required strong SPE selection

Proton-spillover background



Strong track requirements:

strict constraints on c2 (~75% efficiency)

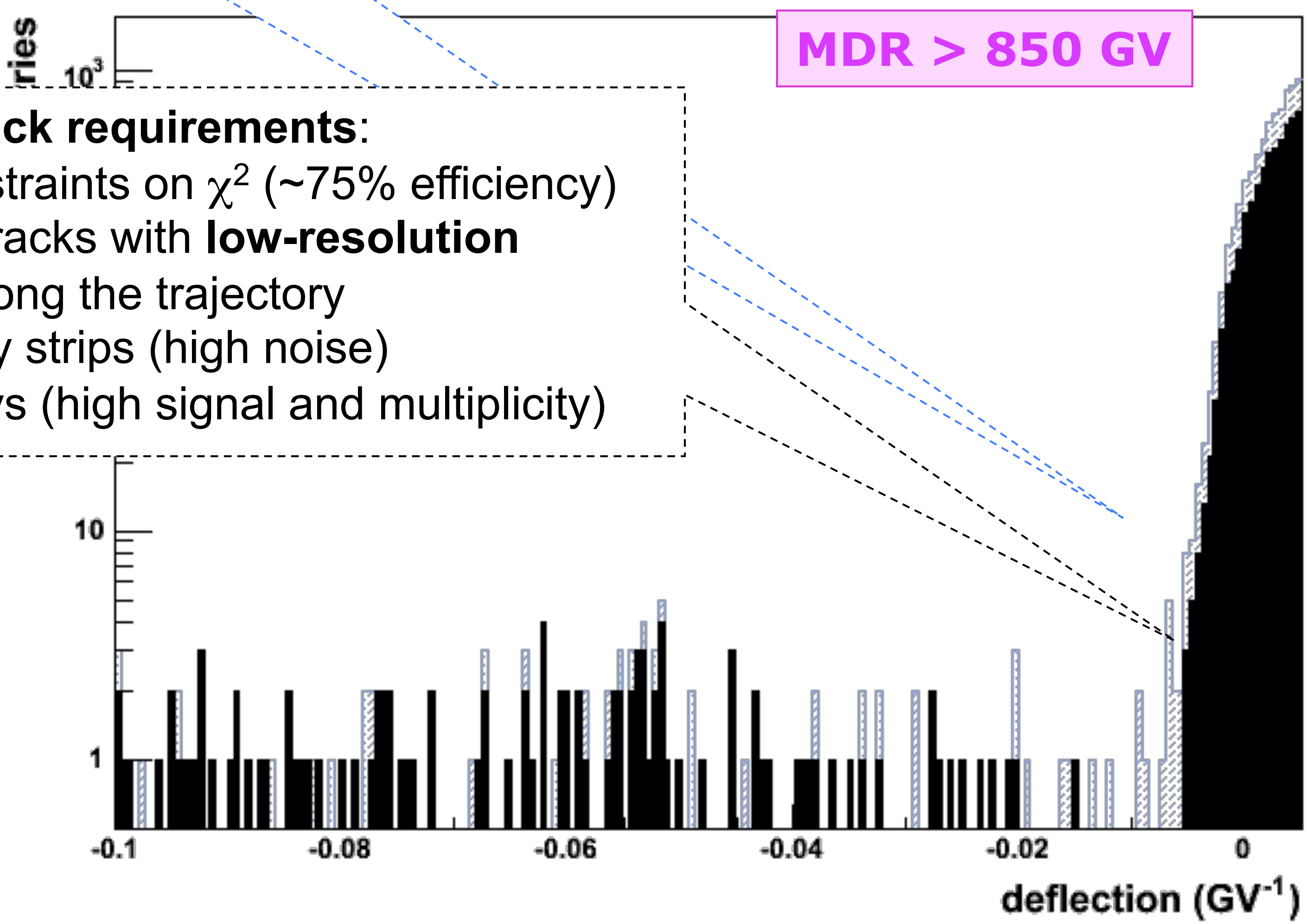
rejected tracks with **low-resolution** clusters along the trajectory

- faulty strips (high noise)
- d-rays (high signal and multiplicity)

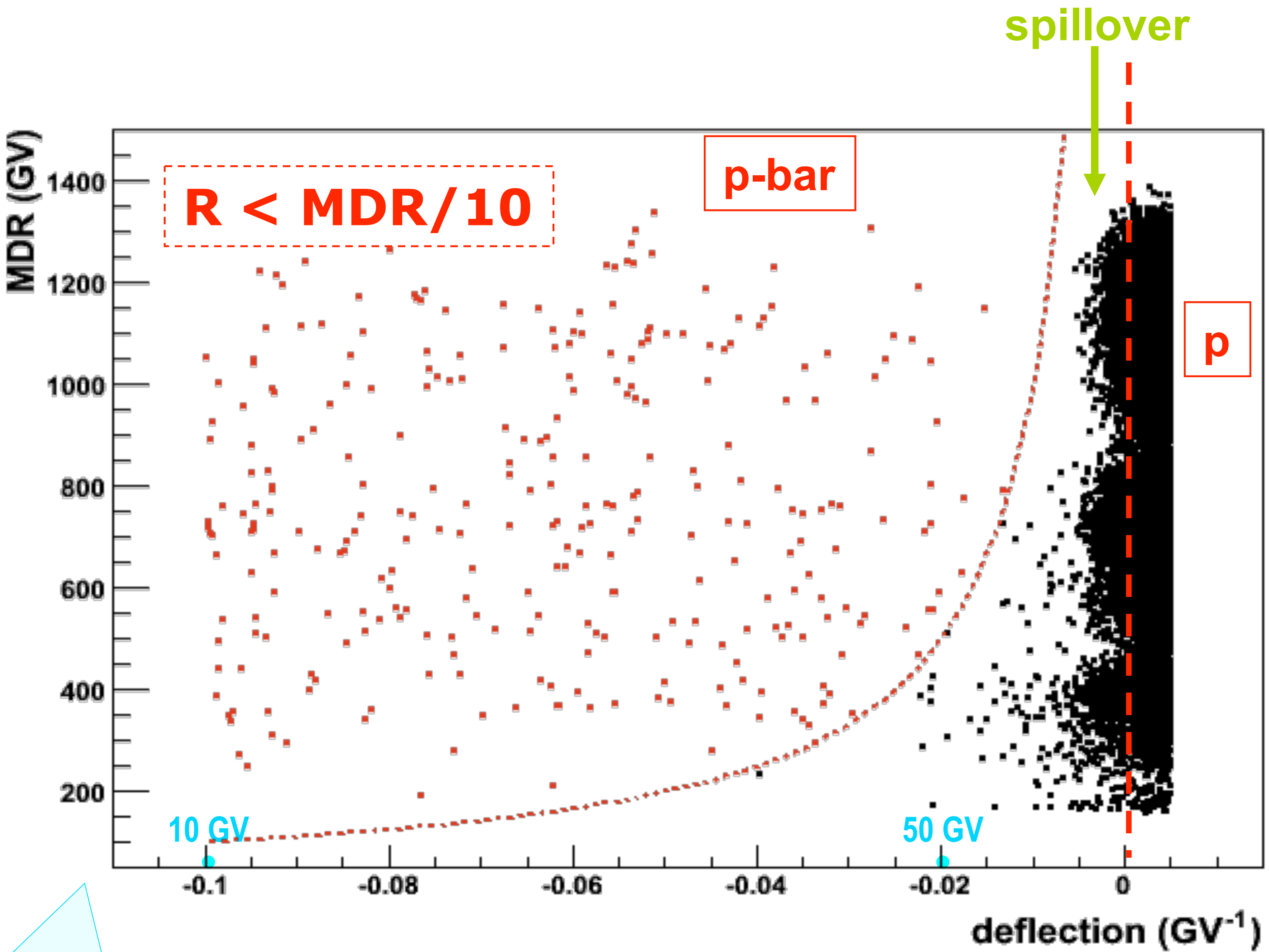
Proton-spillover background

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

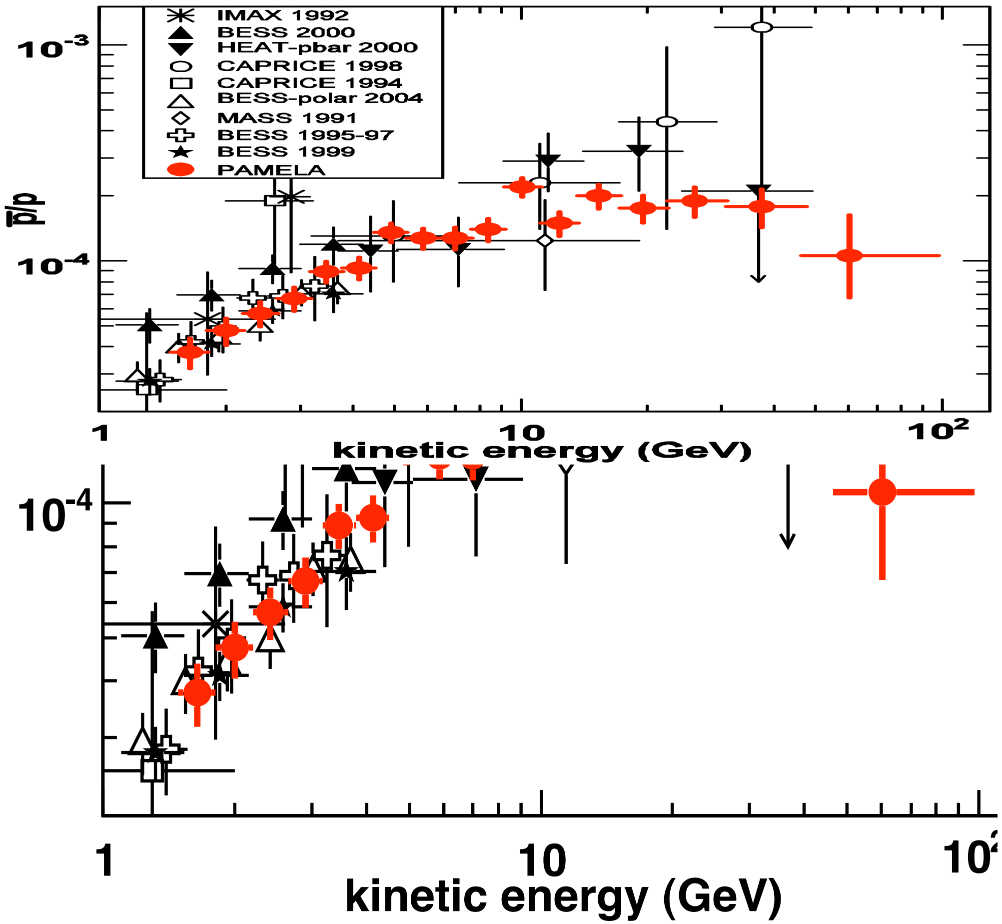


MDR = $1/\sigma_\eta$
(evaluated event-by-event by the fitting routine)

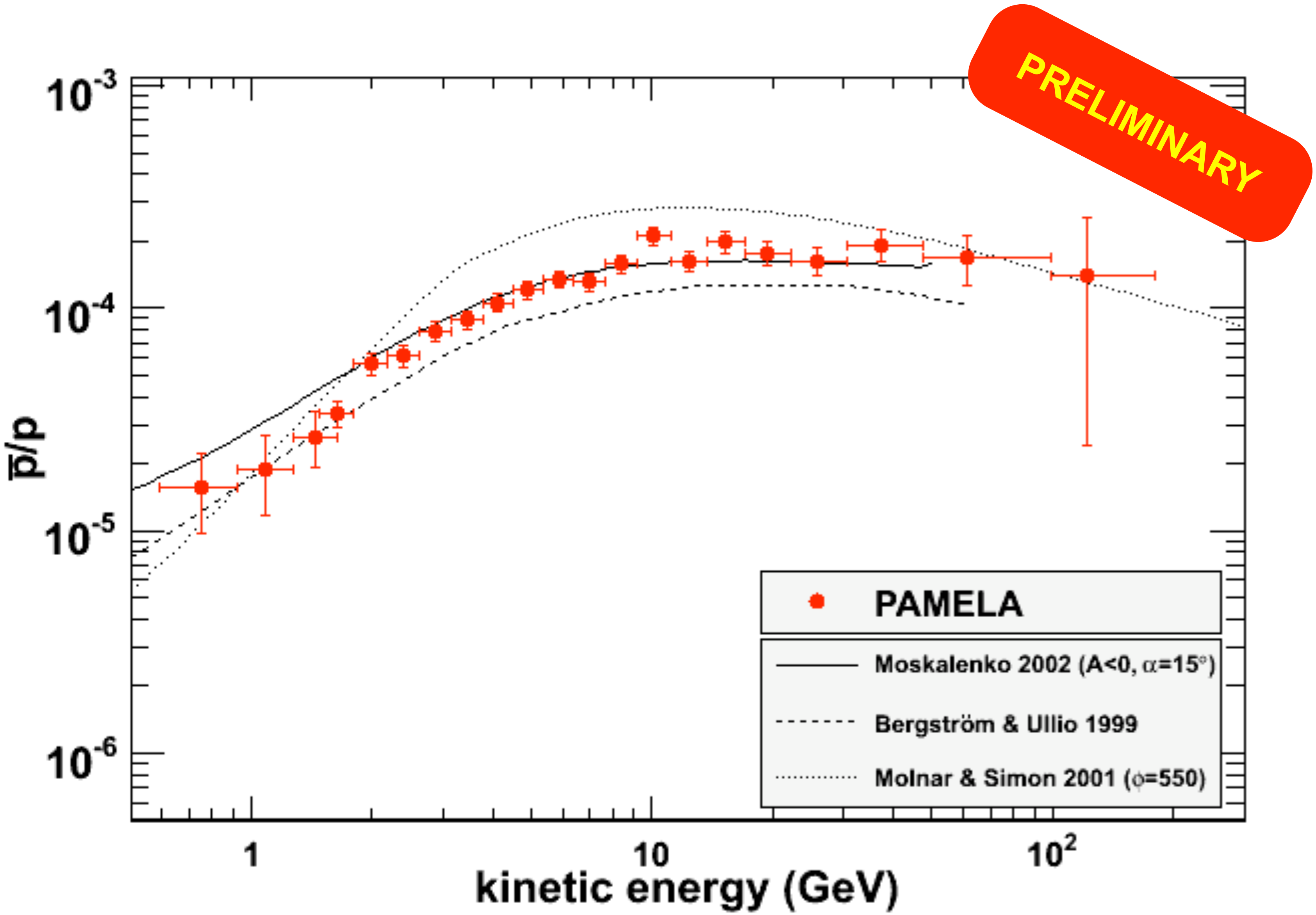
Antiproton/proton ratio (PRL 102, 2009)

- **Excellent agreement with recent data from other experiments.**
  - **One order of magnitude improvement in statistics.**
  - **Most extended energy range ever achieved.**

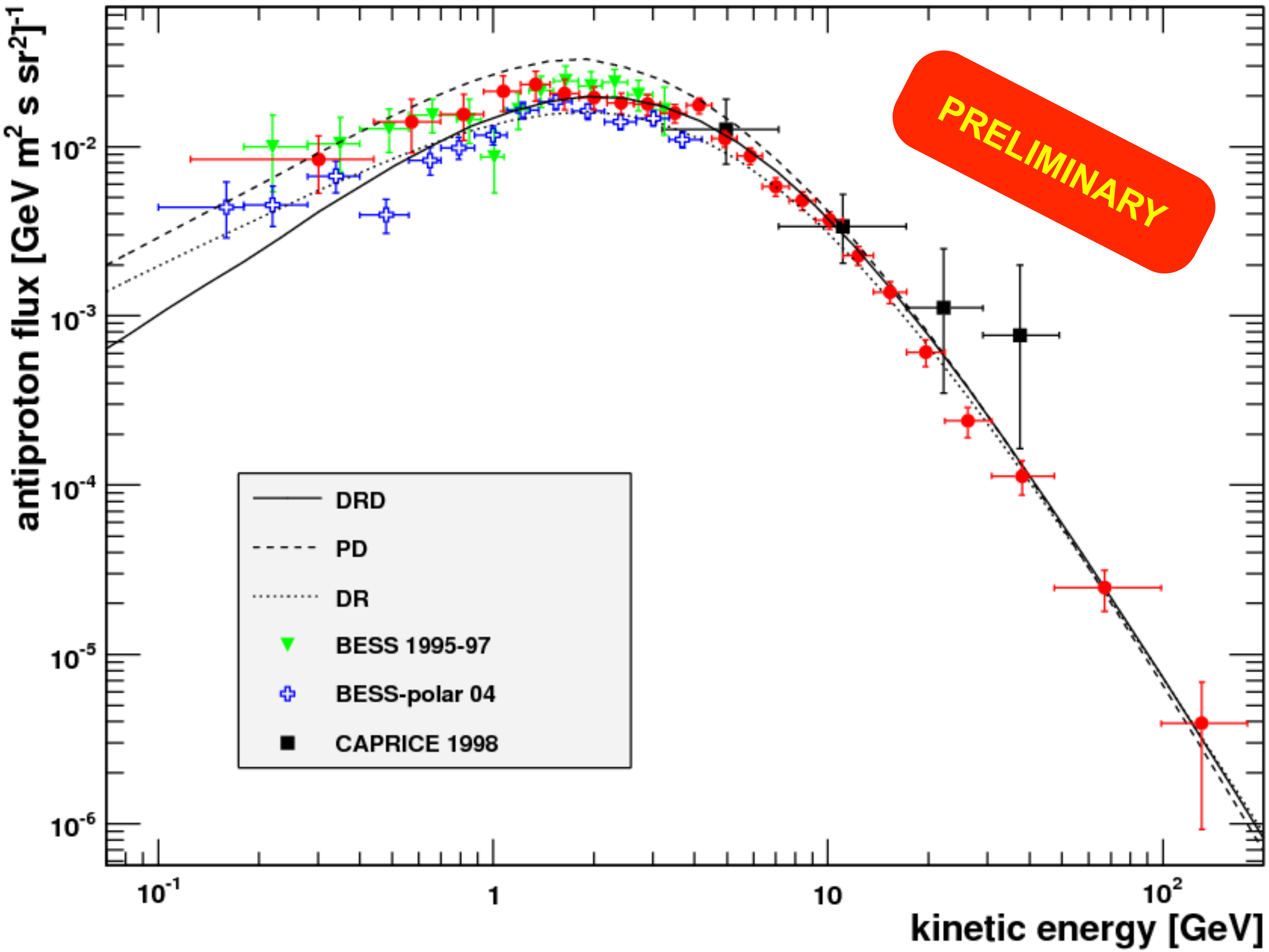
- **Correction factors are included and ~ one order of magnitude less than statistical error.**
  - **CALO efficiency (different for p-bar and p);**
  - **loss of particles for interactions.**



Antiproton to proton ratio



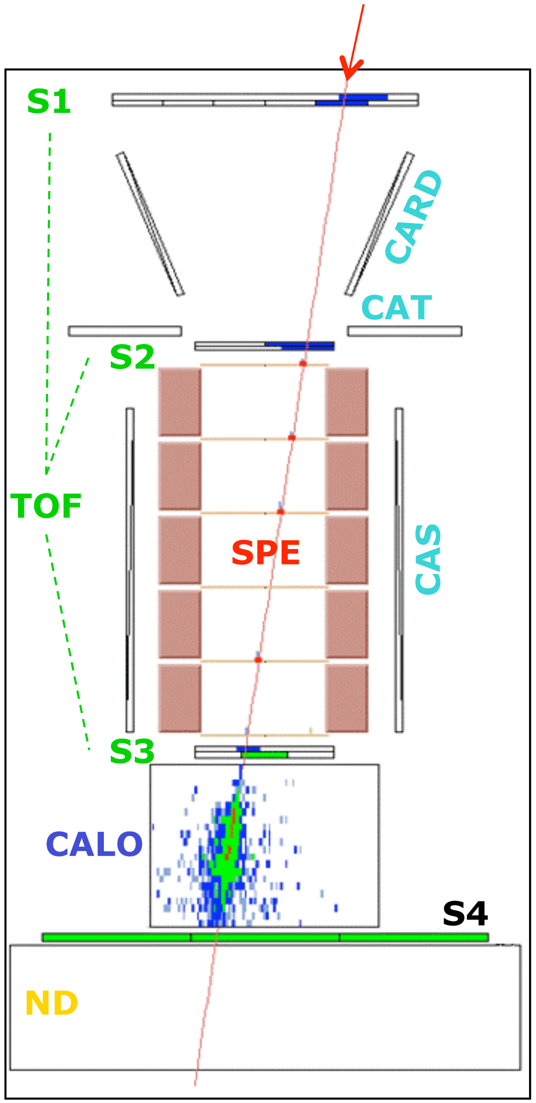
Antiproton Flux



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 20GeV**)



- **Basic selection criteria**
  - rigidity (R) → SPE
  - |Z|=1 (dE/dx vs R) → SPE&ToF
  - b=1 → ToF

- **Electron/positron identification:**
  - e^-/e^+ separation (charge sign) → SPE
  - e^+/p (and e^-/p-bar) separation → CALO

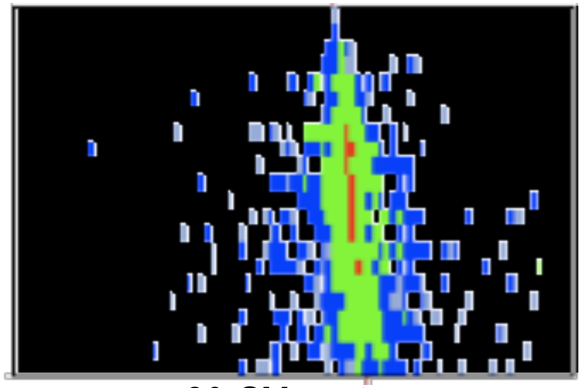
- Dominant background → **interacting protons:**
  - fluctuations in hadronic shower development ⇒ $\pi_0 \rightarrow \gamma\gamma$ might mimic pure em showers
  - proton spectrum harder than positron ⇒ p/e^+ increase for increasing energy (10^3 @1GV 10^4 @100GV)

→ Required strong CALO selection

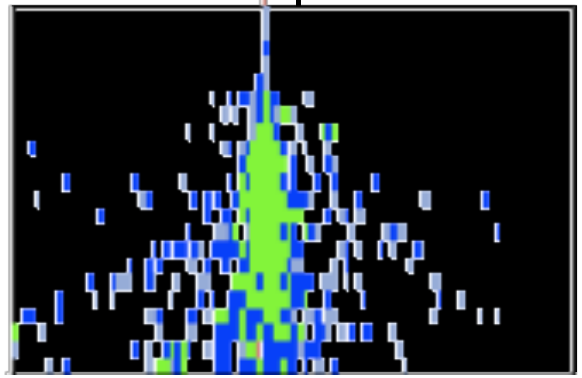
Positron identification with CALO

- Identification based on:
  - **Shower topology** (lateral and longitudinal profile, shower starting point)
  - **Total detected energy** (energy-rigidity match)
- Analysis key point:
  - **Tuning/check of selection criteria with:**
    - test-beam data
    - simulation

51 GV positron

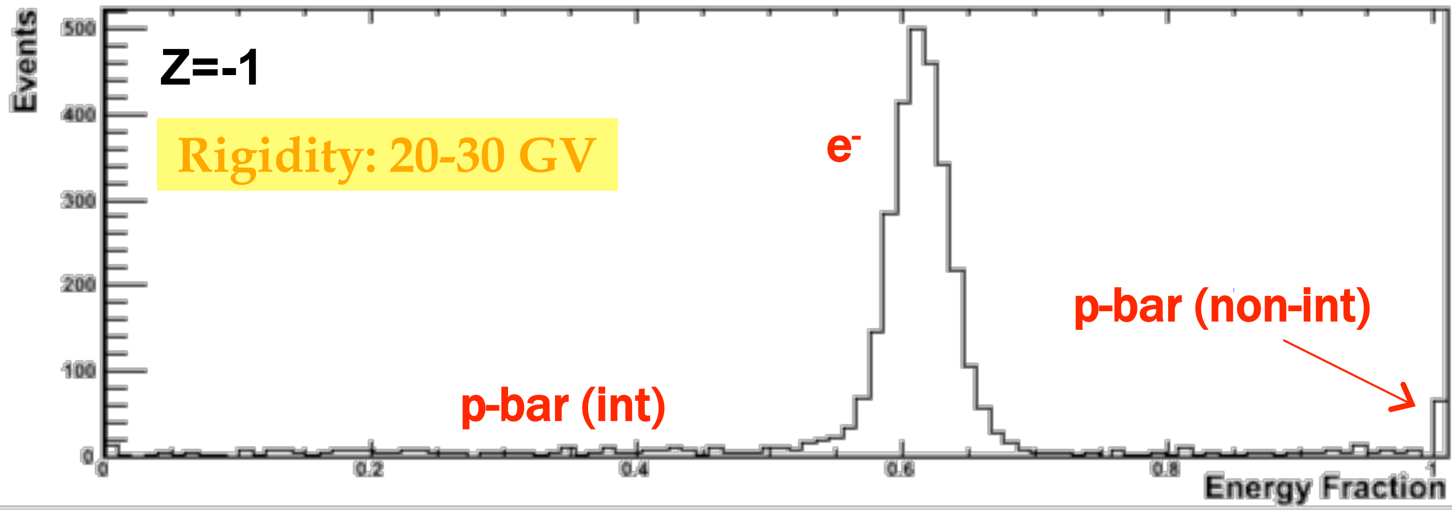


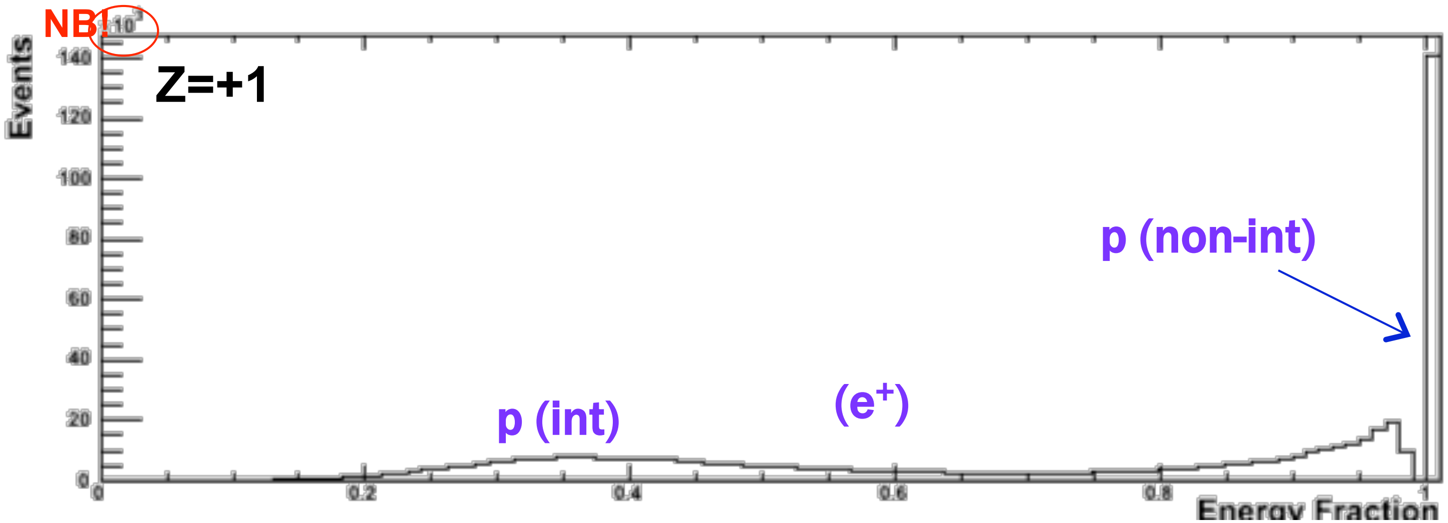
80 GV proton



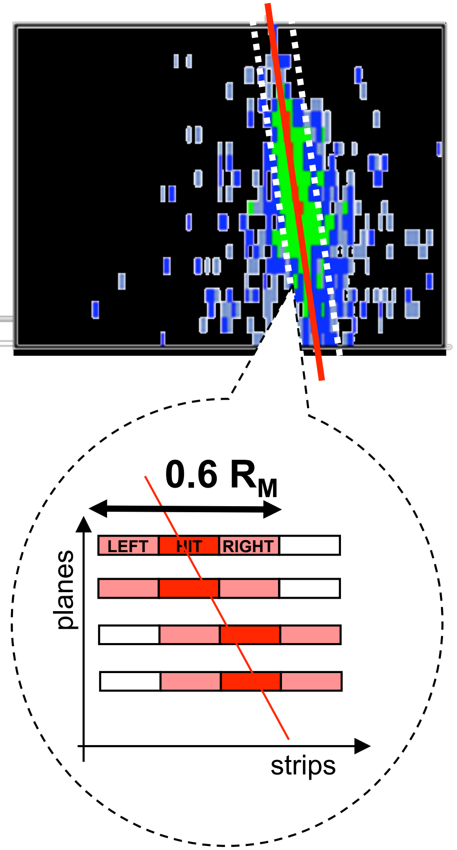
Final results make <u>NON USE</u> of test-beam and/or simulation calibrations.
The measurement is based only on flight data
with the <u>background-estimation</u> method

Positron identification

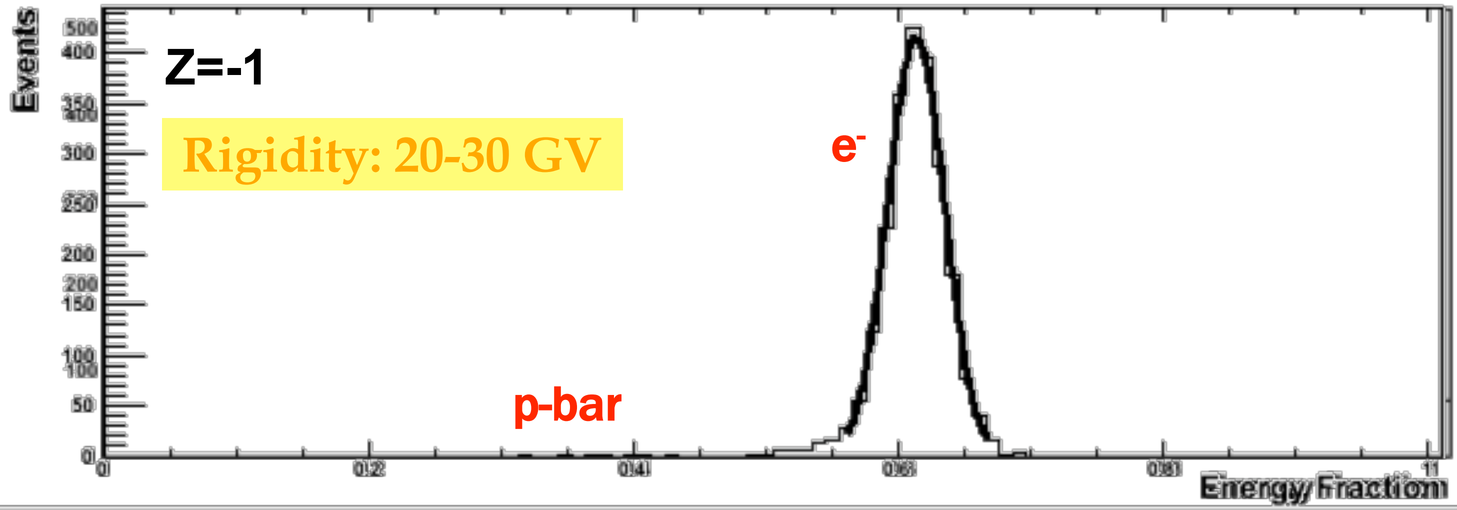




Fraction of charge released along the calorimeter track



Positron identification

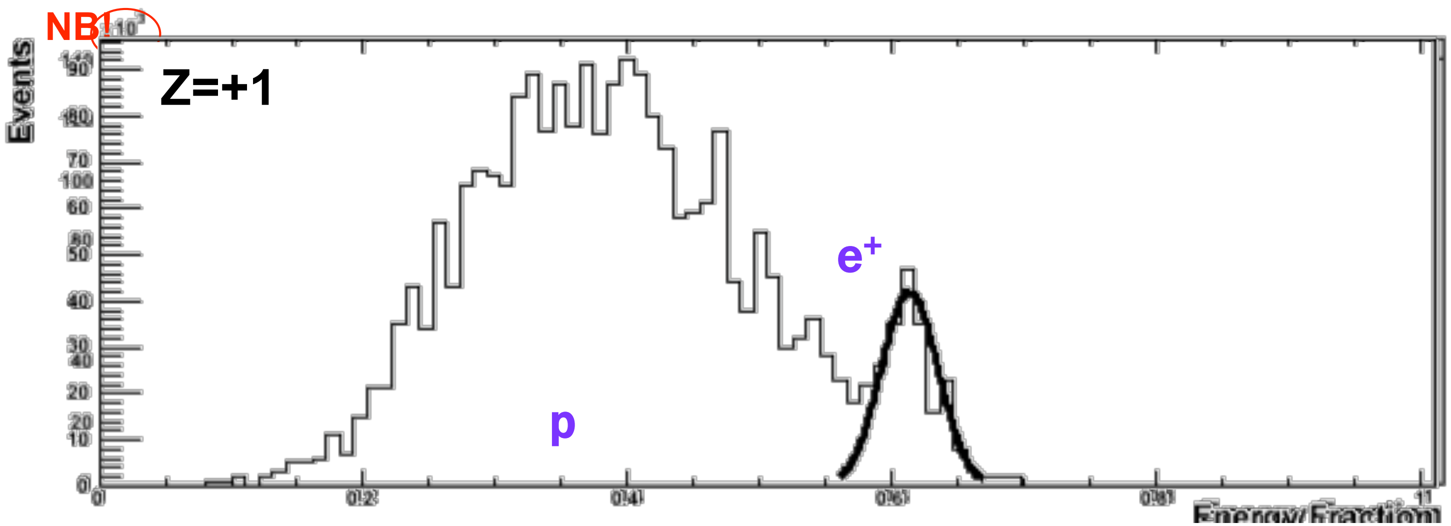


Fraction of charge released along the calorimeter track

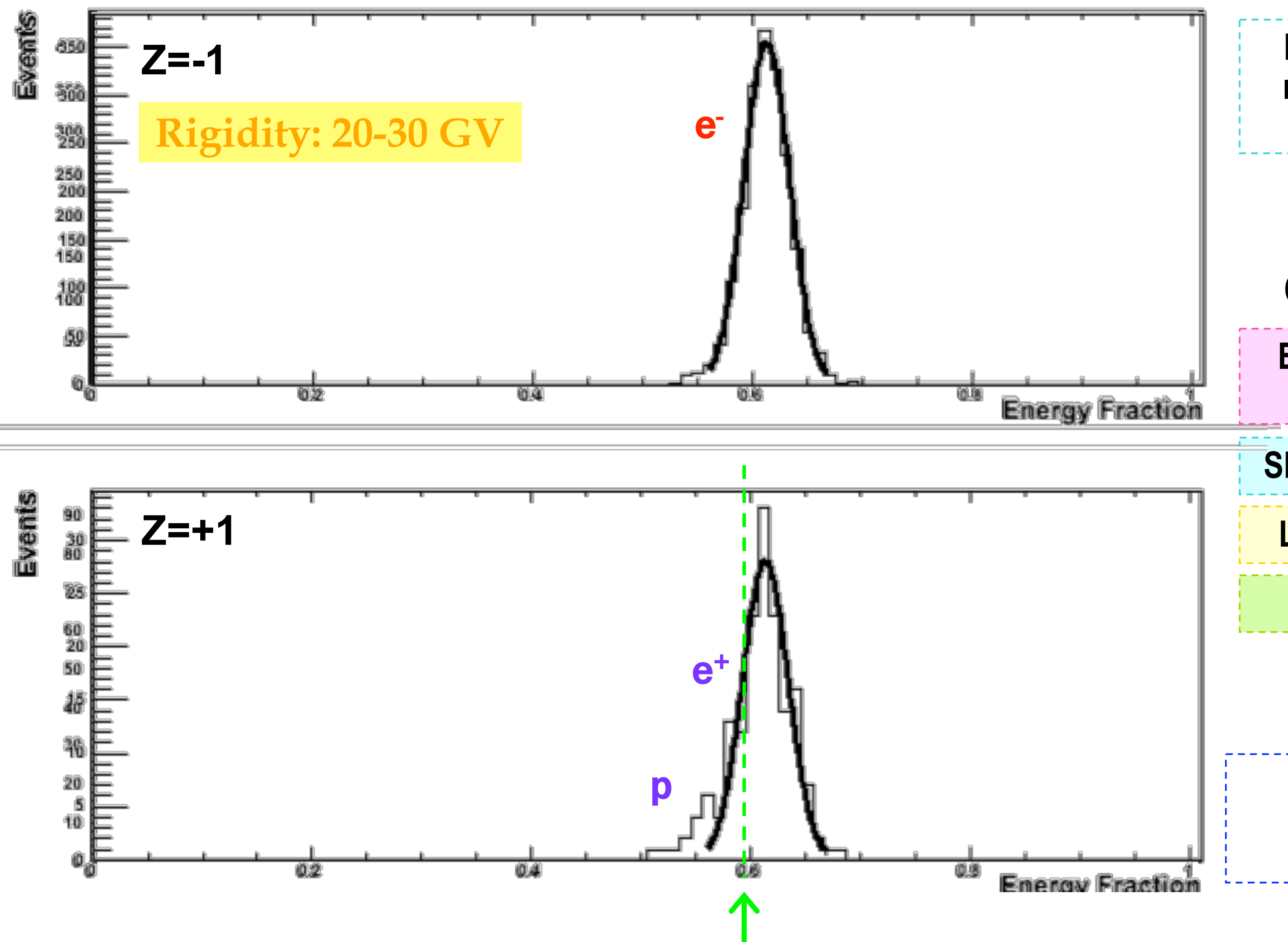
+

Constraints on:

Energy-momentum match



Positron identification



Fraction of charge released along the calorimeter track

+

Constraints on:

Energy-momentum match

Shower starting-point

Longitudinal profile

Lateral profile

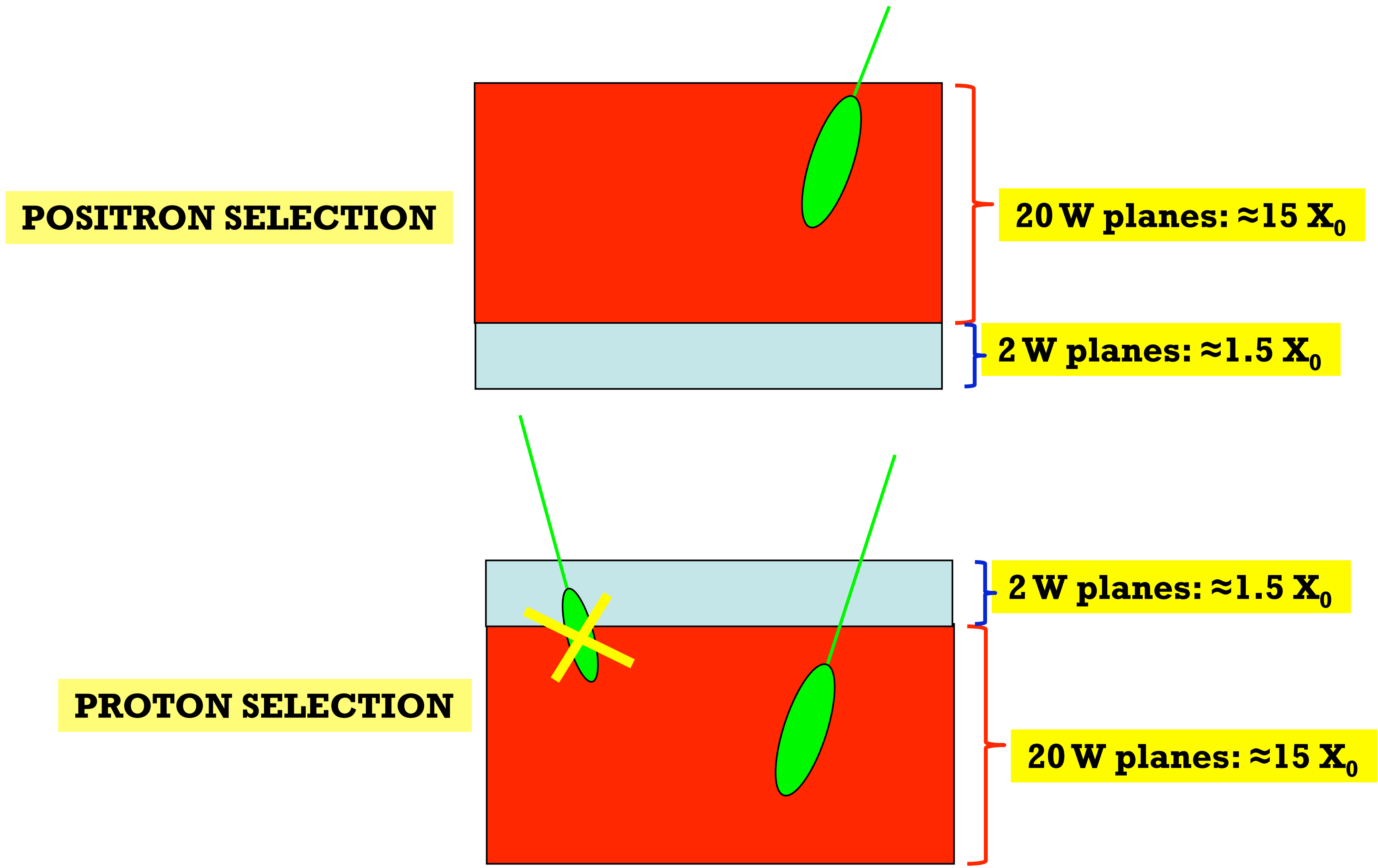
BK-suppression method

REJECTION FACTOR < **10^{-5}**, VALIDATE BY **TEST BEAM** AND **MC**

The “pre-sampler” method

Selection of a pure sample of protons from flight data

CALORIMETER: 22 W planes: 16.3 X_0



Proton background evaluation

Rigidity: 20-28 GV

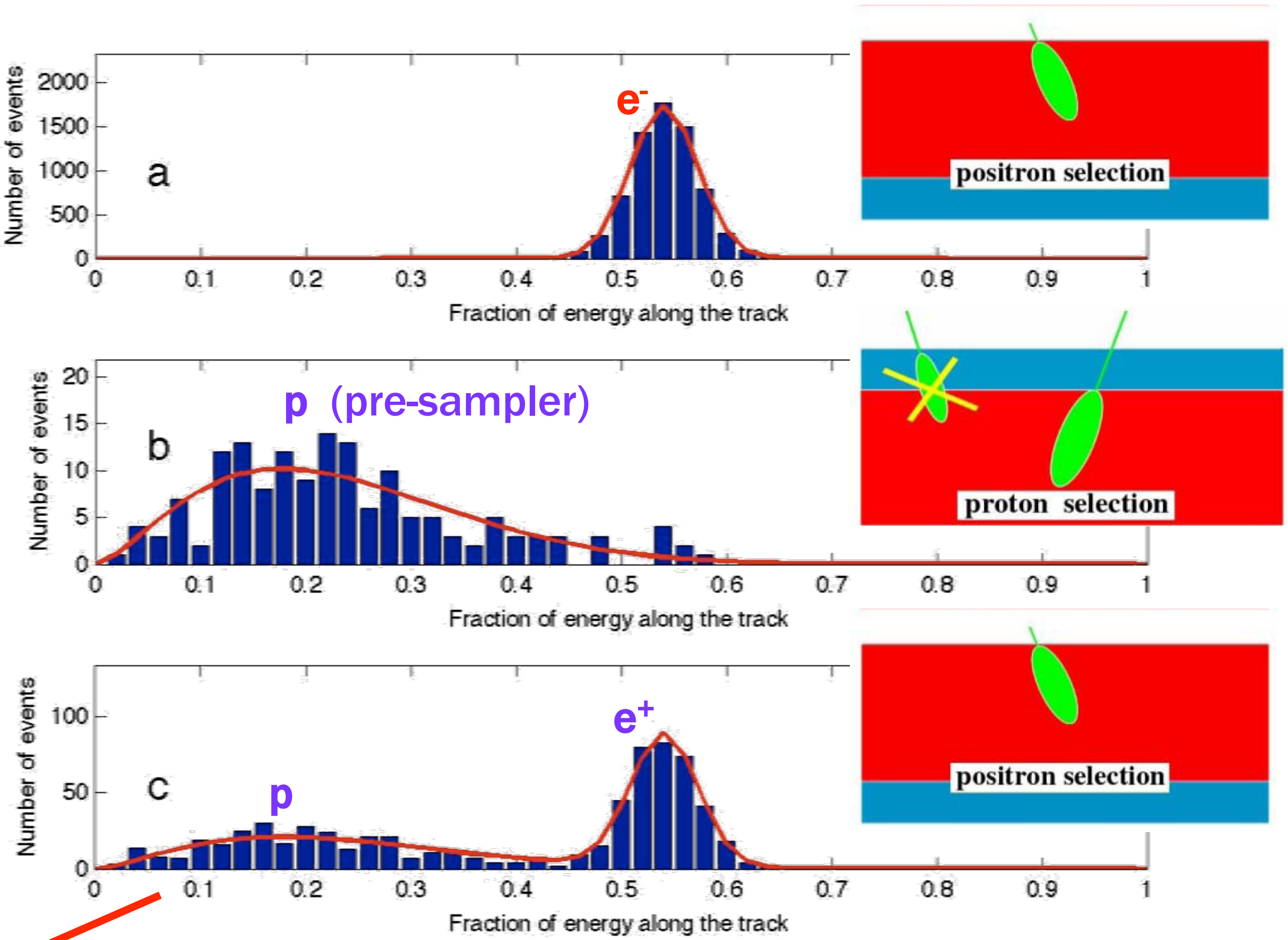
Fraction of charge released along the calorimeter track (left, hit, right)

+

Constraints on:

Energy-momentum match

Shower starting-point



Topological variable

Estimation of contamination directly from the data!!!!

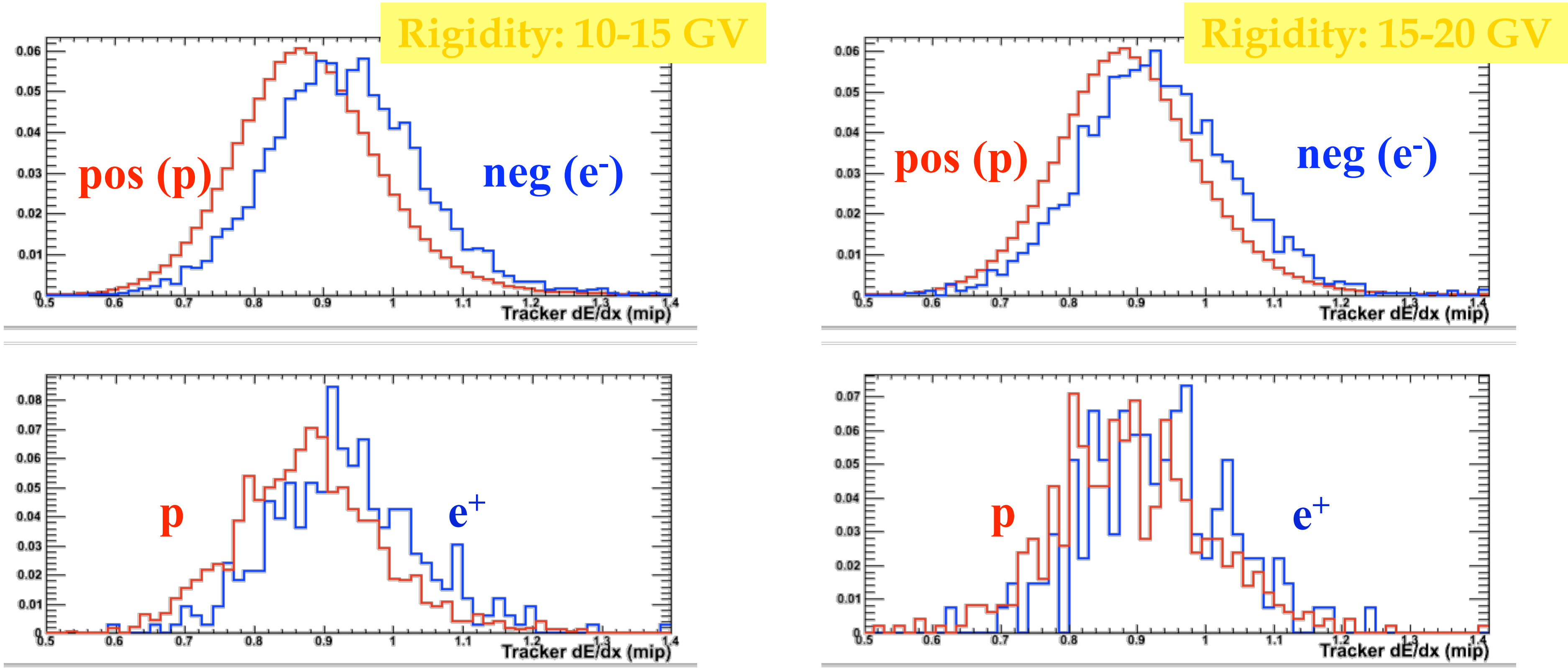
Check of calorimeter selection

Energy loss in silicon tracker detectors:

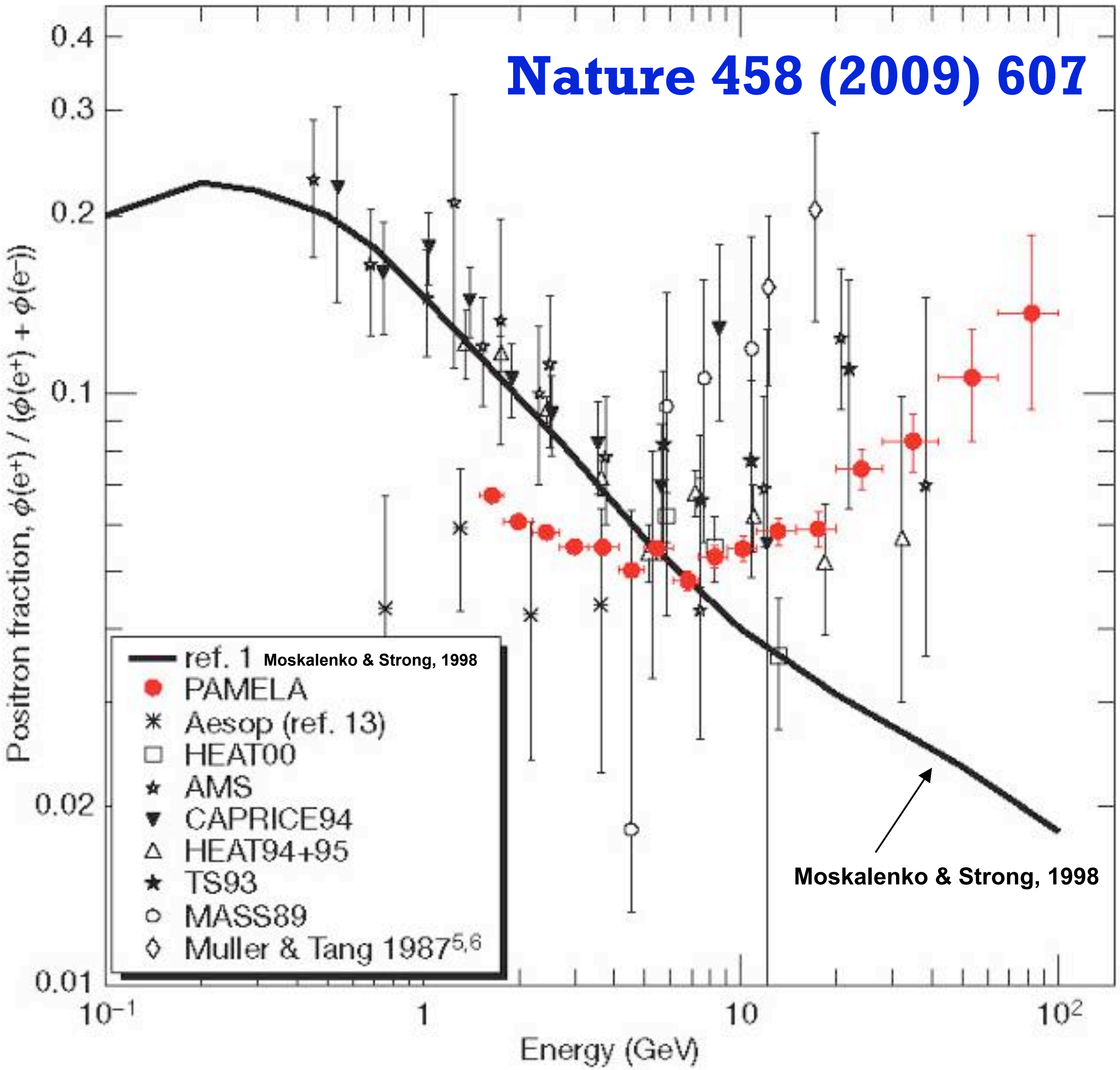
$$-\frac{dE}{dx} = Kz^2\frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_ec^2\beta^2\gamma^2T_{\max}}{I^2}-\beta^2-\frac{\delta(\beta\gamma)}{2}\right]$$

Relativistic rise

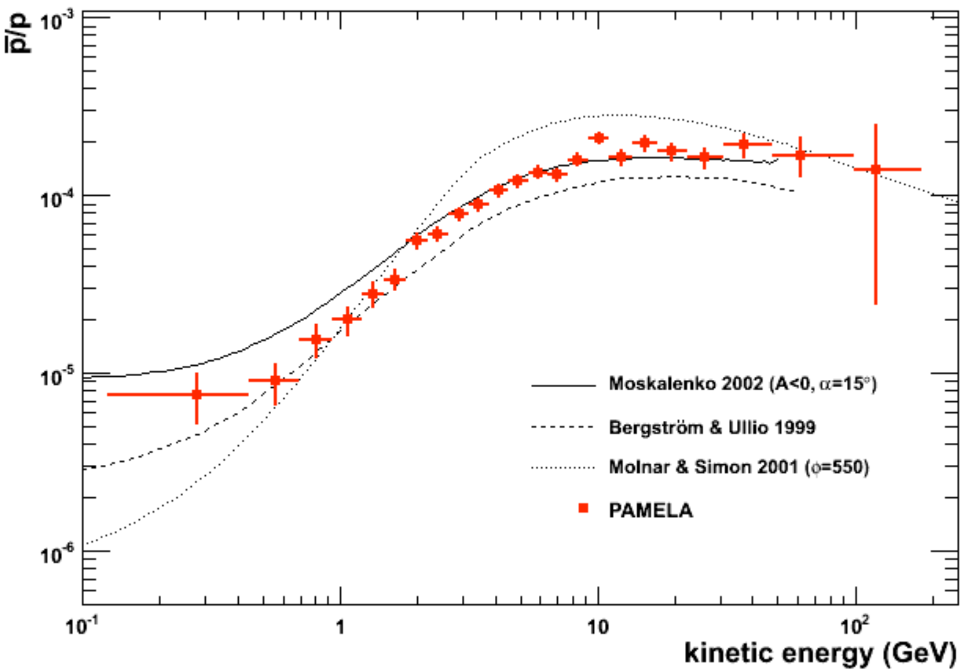
- **Top: positive (mostly p) and negative events (mostly e^-)**
- **Bottom: positive events identified as p and e^+ by trasversal profile method**

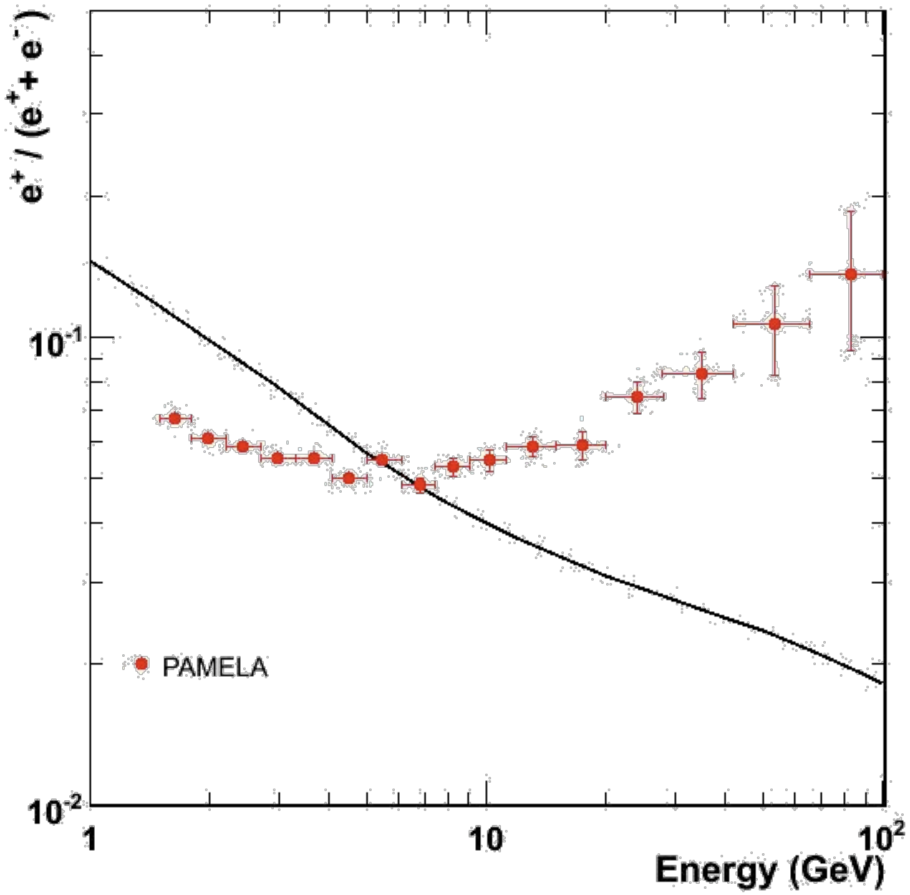


Positron to all electron ratio



Antiprotons / Positrons



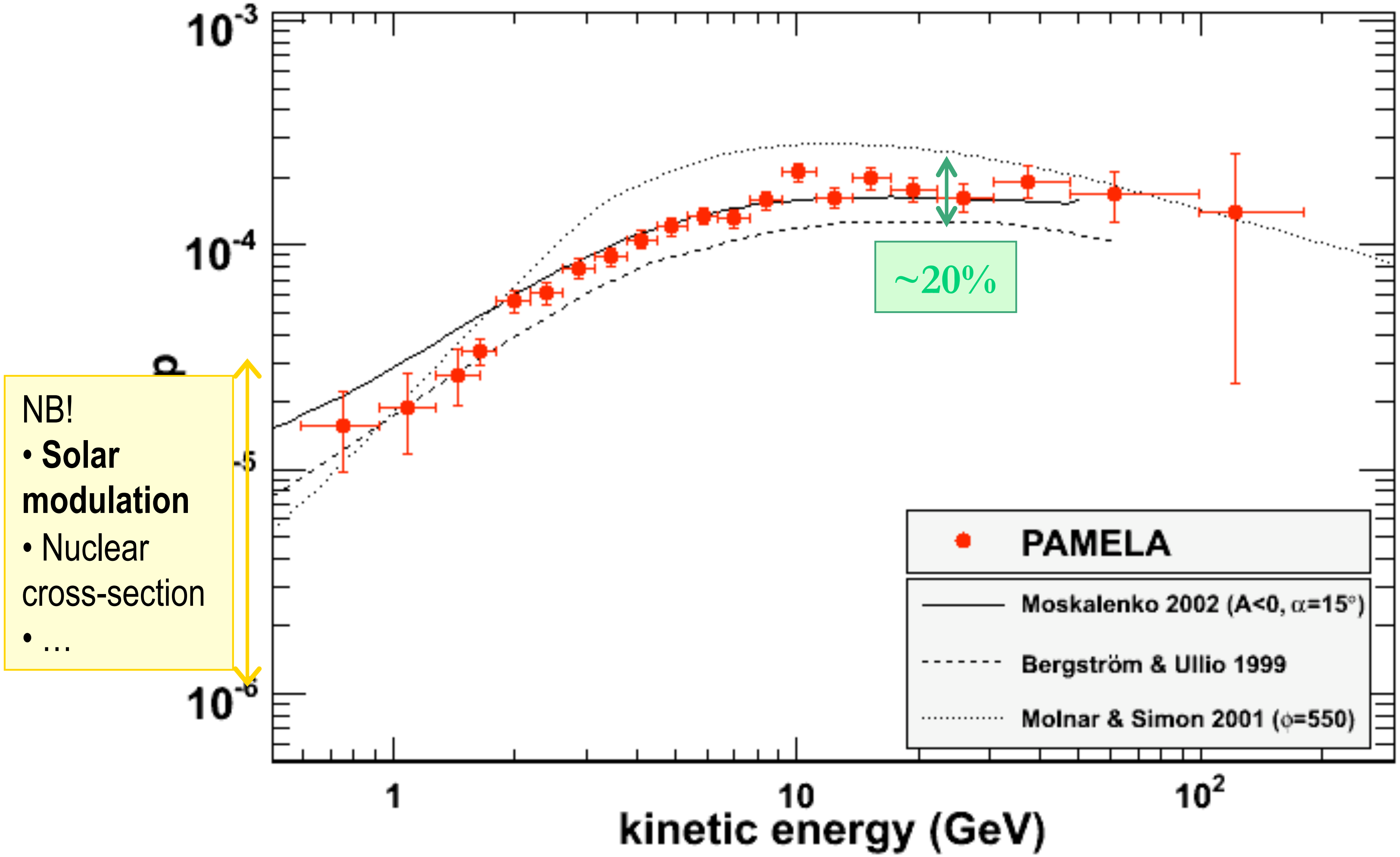


((Do we have any antimatter excess in CRs?))

Antiproton-to-proton ratio

Secondary Production Models

CR + ISM → **p-bar** + …



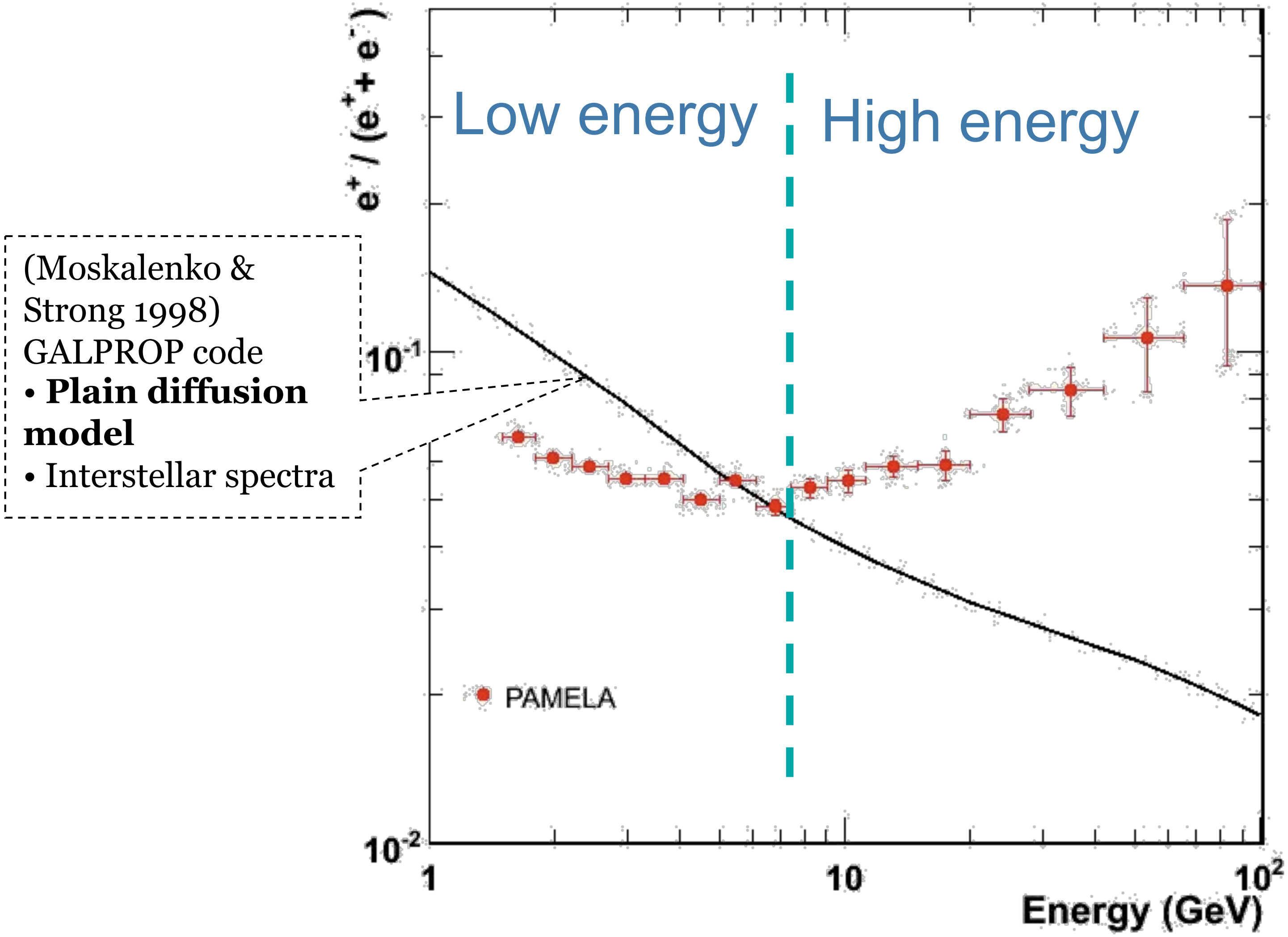
No evidence for any antiproton excess

Positron fraction

Secondary Production Models

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

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



Quite robust evidence for a positron excess above 10 GeV

Primary positron sources

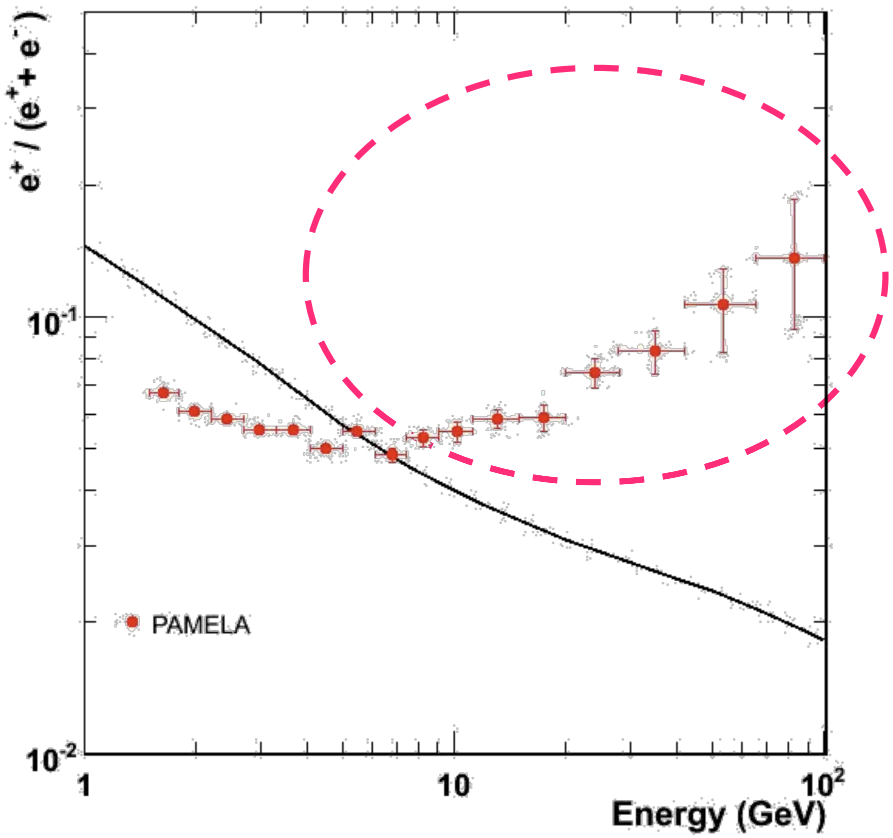
- constraints from p-bar data -

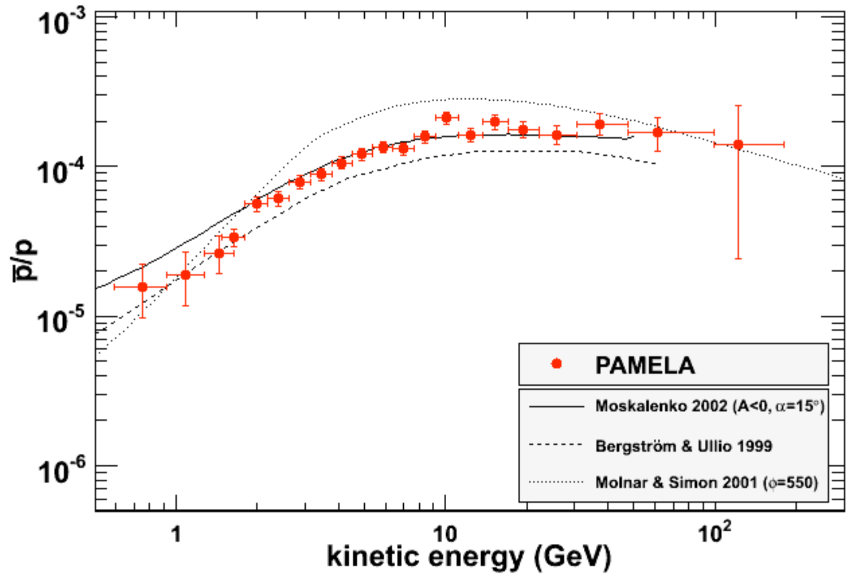
Dark Matter

- e^+ yield depend on the dominant decay channel
  - → **Super Symmetric Model**
  - → **Kaluza Klein Model**
  - → **other…**
- Boost factor required to have a sizable e^+ signal

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



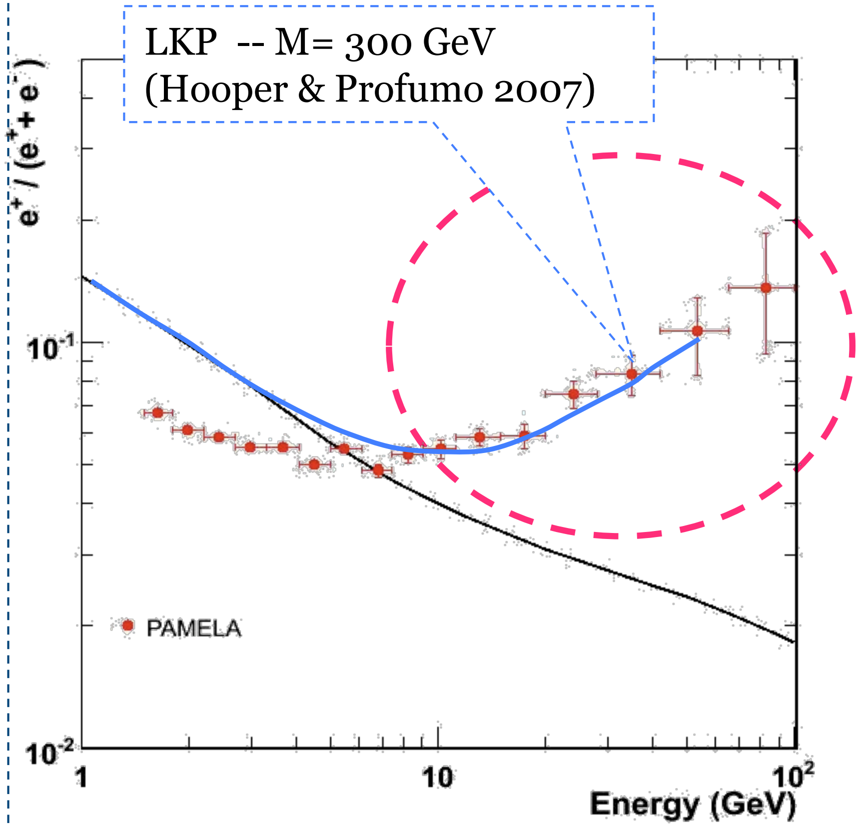


Primary positron sources ?

Dark Matter annihilation

- constraints from p-bar data -

- e^+ yield depend on the dominant decay channel
  - → Super Symmetric Model
  - → **Kaluza Klein Model**
  - → other…
- Boost factor required to have a sizable e^+ signal

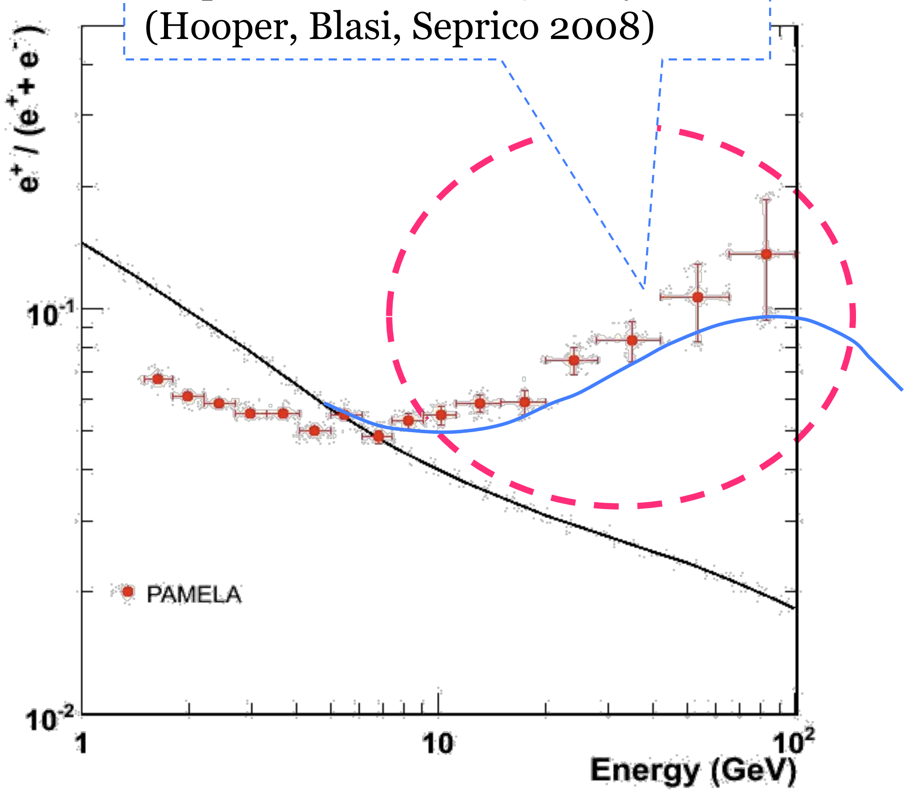


Primary positron sources ?

Astrophysical processes

- Local **pulsars** are possible 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)
    - → Ad hoc pulsar scenario required
  - → if one or few nearby pulsars dominate, anisotropy could be detected in the angular distribution

All pulsars (rate = 3.3 / 100 years)
(Hooper, Blasi, Seprico 2008)



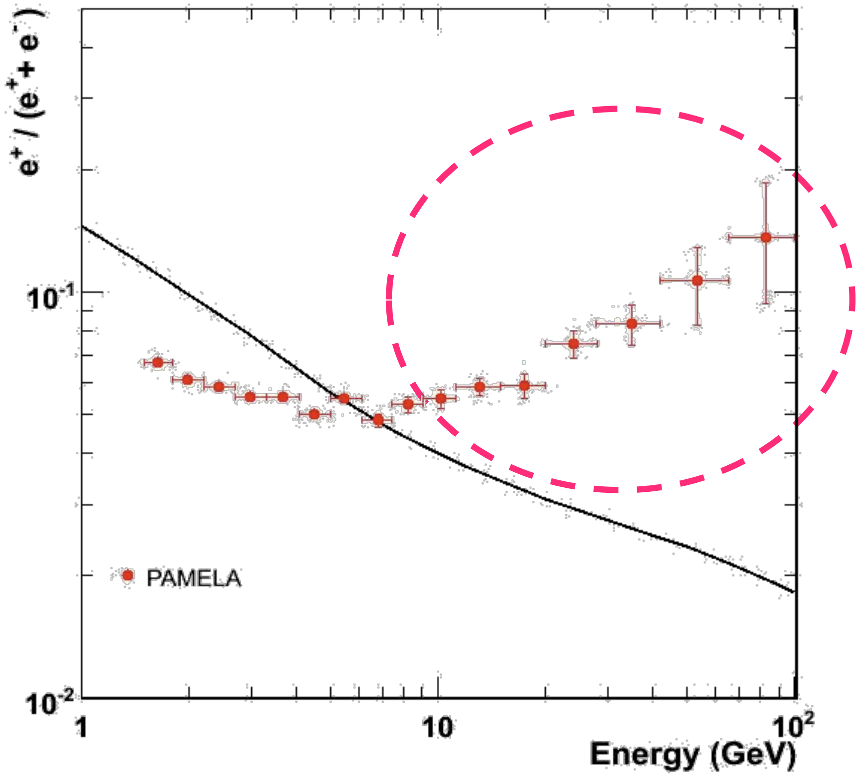
Primary positron sources

Additional experimental data will be provided by PAMELA:

- e^+ fraction @ higher energy (up to 270 GeV)
- individual e^- e^+ spectra
- anisotropy (…maybe)
- high energy e^++e^- spectrum (up to 1-2 TV)

We need complementary information from:

- gamma rays
- neutrinos



Electrons

Basic electron selection criteria

Relativistic Z=-1 galactic
particles with clean pattern
inside the apparatus

Electrons
+
Background:
Antiprotons
Spillover protons

Tracker selection:

Spillover cuts

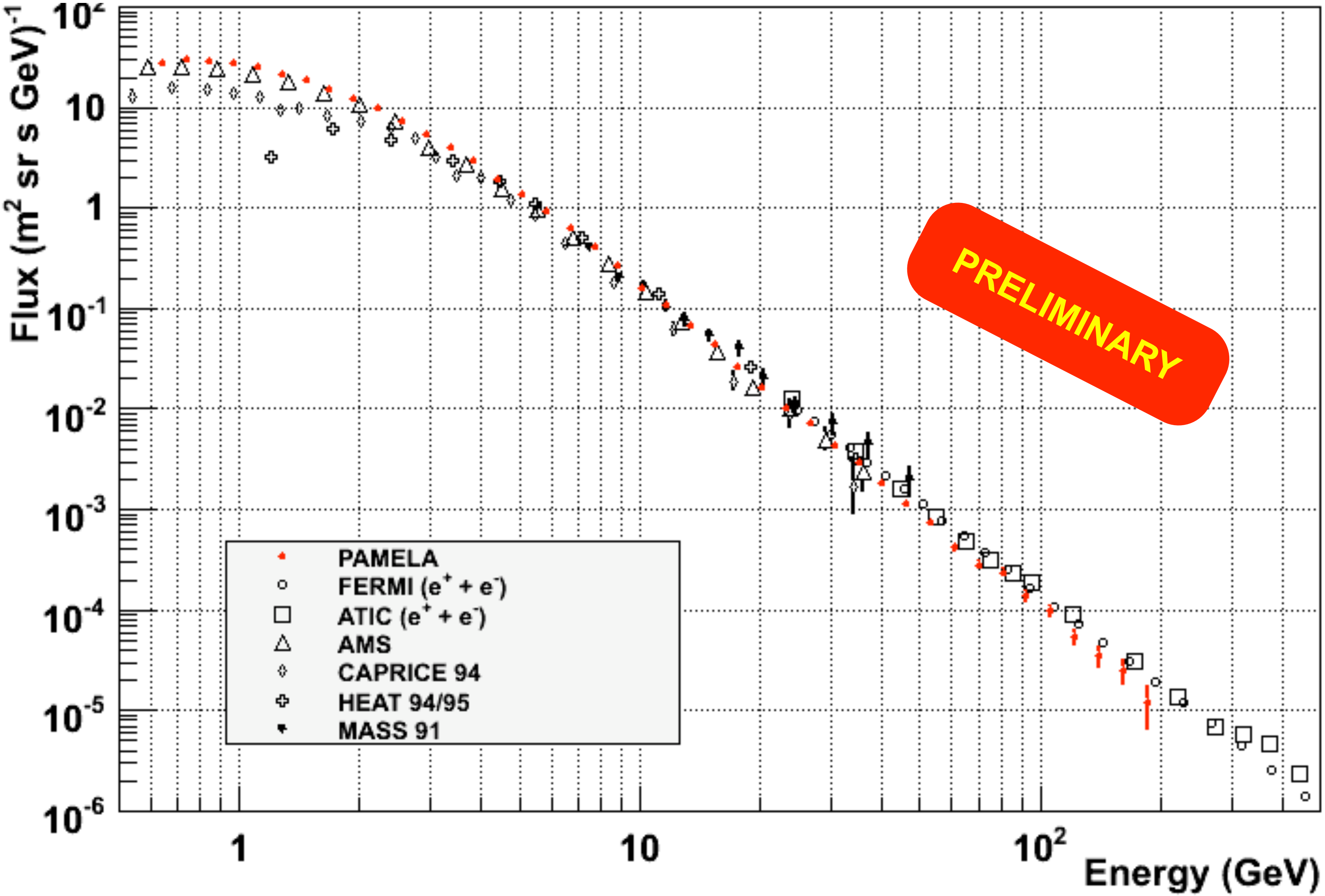
R < MDR/c

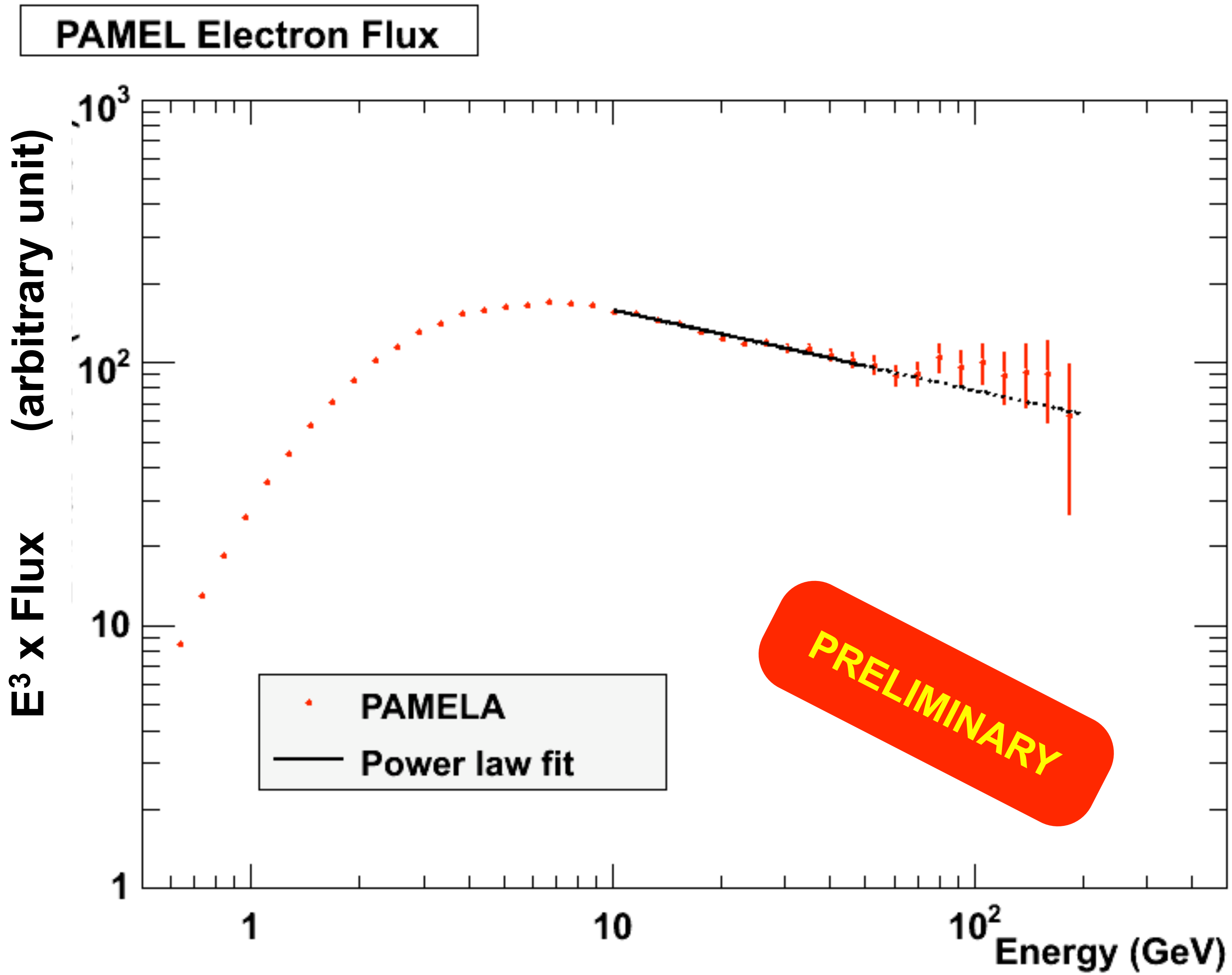
Calorimeter selection:

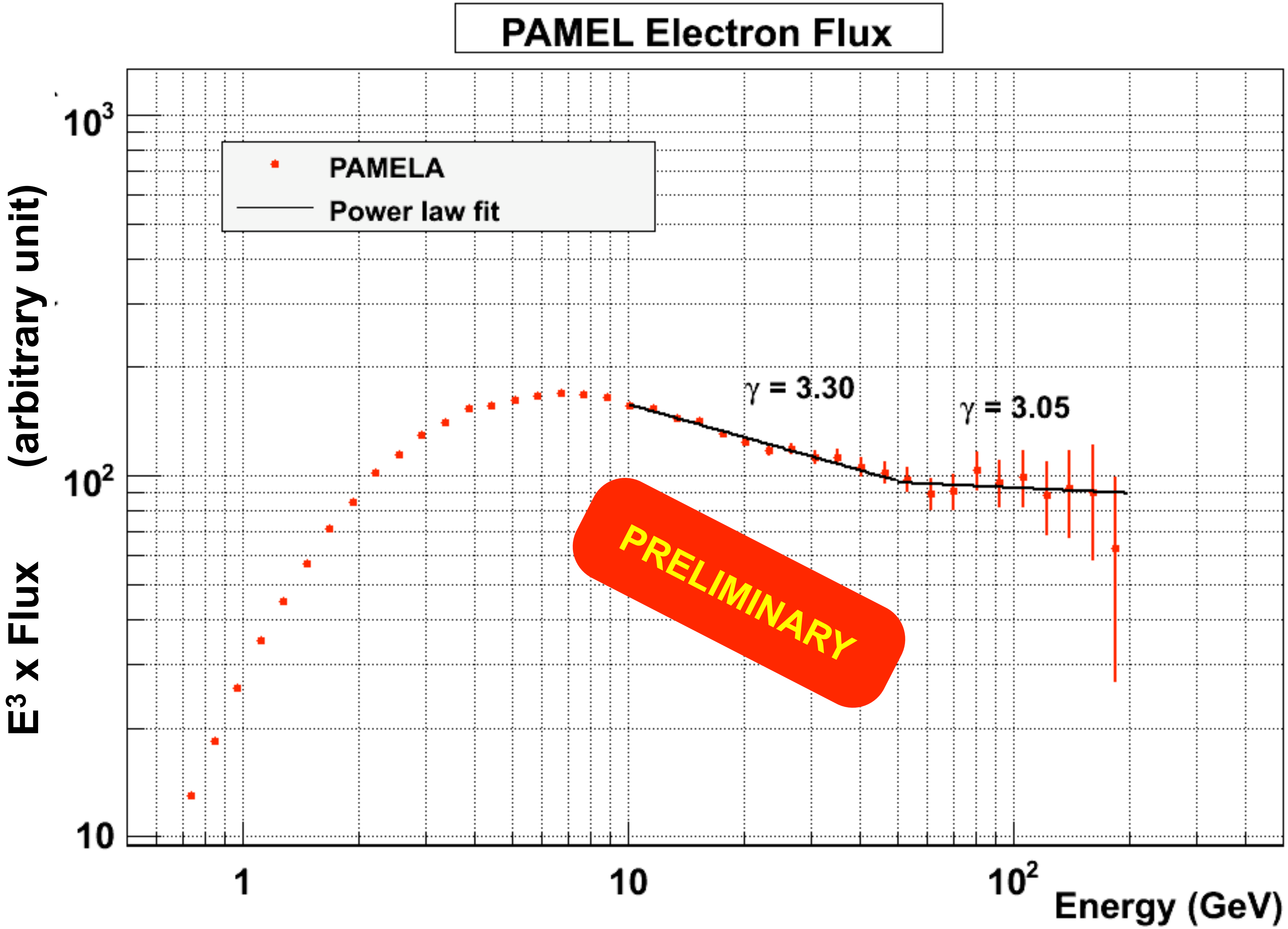
(Loose) calorimeter cuts
high and ~constant selection efficiency

Energy/Rigidity match

Pamela electron Flux




PAMEL Electron Flux
E3 x Flux (arbitrary unit)
10³
10²
10
1
1
10
10²
Energy (GeV)
PAMELA
Power law fit
PRELIMINARY



PAMEL Electron Flux
PAMELA
Power law fit
E3 x Flux (arbitrary unit)
10
10^2
10^3
1
10
10^2
Energy (GeV)
γ = 3.30
γ = 3.05
PRELIMINARY

Conclusions

- PAMELA is continously taking data since July 2006

- We presented results from ~500/950 days of data:
  - → Antiproton charge ratio and antiproton flux (~0.1 GeV ÷180 GeV)
    - → no evident deviations from secondary expectations
  - → Positron charge ratio (~1 GeV ÷100 GeV)
    - → Clear excess with respect to secondary production models
    - → Charge dependent modulation effects
    - → More data to come at lower and higher energies (up to 300 GeV)
  - → Preliminary Electron spectrum up to 200 GeV
  - → Galactic primary proton and He spectra
  - → Preliminary galactic secondary-to-primary ratio (Li/C, B/C, Be/C)

- Analysis ongoing to measure the e^- spectrum up to ~500 GeV, e^+ spectrum up to ~300 GeV and all electron (e^- + e^+) spectrum up to ~1 TeV.

→ PAMELA is really providing significant experimental results, which help and will help in understanding CR origin and propagation

→ **Pamela mission has been officially extended up to 2011**

→ More new and exciting results will certainly come in the next few years!