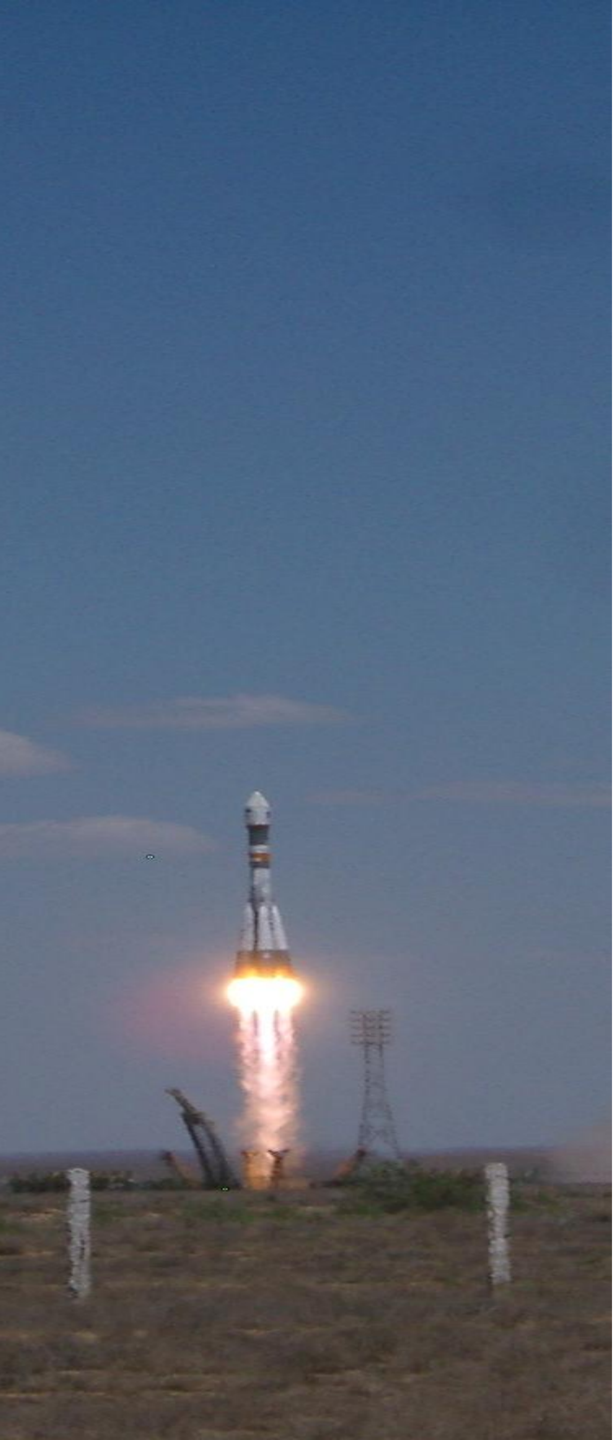


Cosmic-Ray Measurements with the PAMELA Space-Borne Experiment

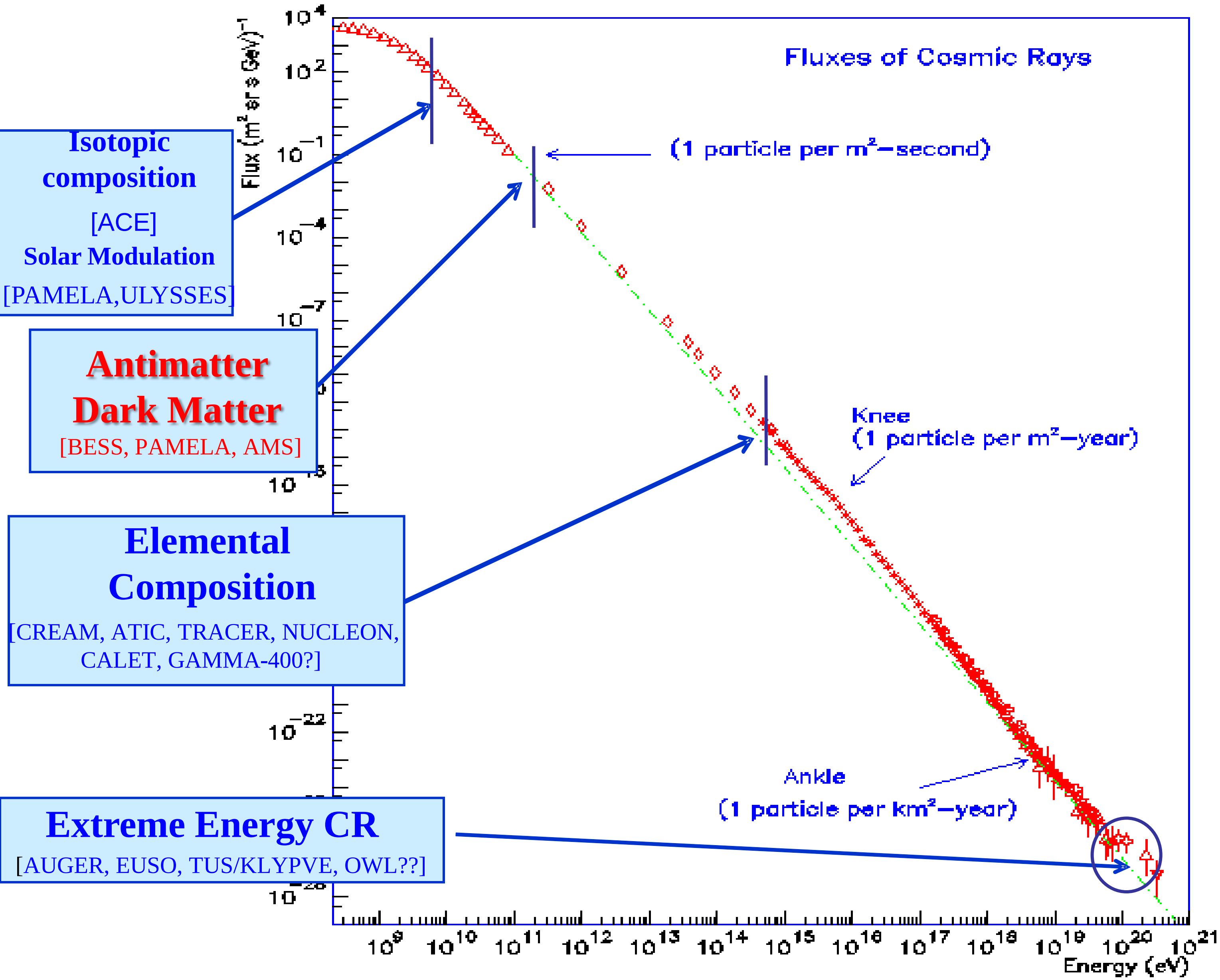
Mirko Boezio

INFN Trieste, Italy

On behalf of the PAMELA collaboration

Cosmic Rays and the Heliospheric Plasma Environment - Bochum

September 13th 2011


Fluxes of Cosmic Rays
Flux (m² sr s GeV)⁻¹
Energy (eV)
(1 particle per m²-second)
Knee
(1 particle per m²-year)
Ankle
(1 particle per km²-year)
Isotopic composition
[ACE]
Solar Modulation
[PAMELA,ULYSSES]
Antimatter
Dark Matter
[BESS, PAMELA, AMS]
Elemental Composition
[CREAM, ATIC, TRACER, NUCLEON, CALET, GAMMA-400?]
Extreme Energy CR
[AUGER, EUSO, TUS/KLYPVE, OWL??]

PAMELA Apparatus

PAMELA detectors

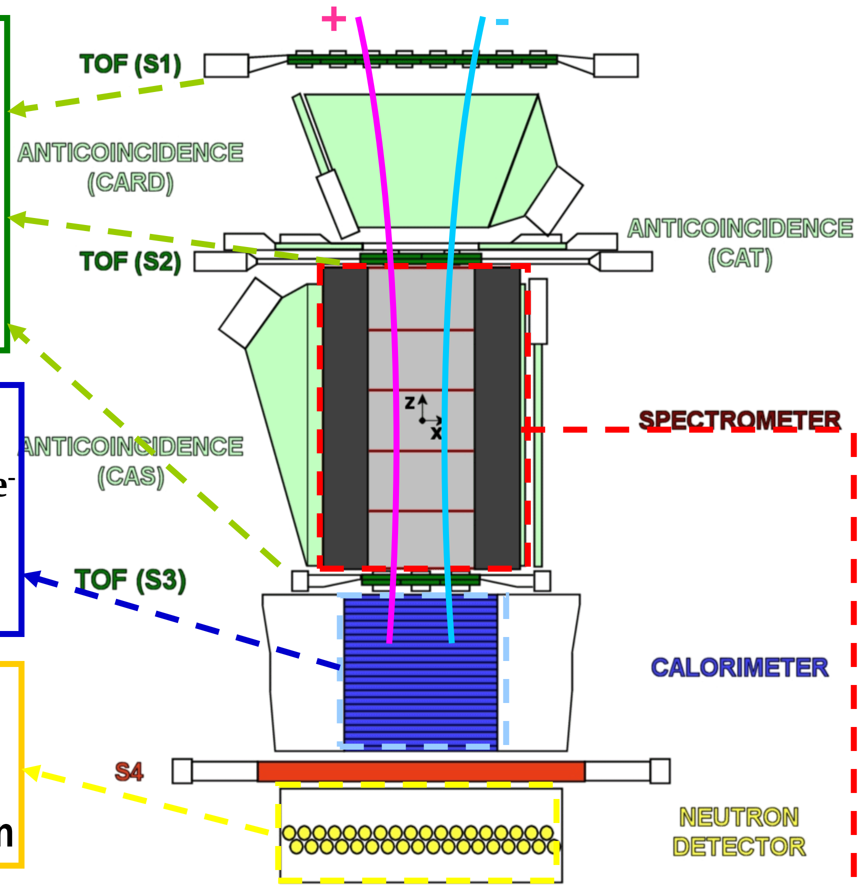
Main requirements → high-sensitivity antiparticle identification and precise momentum measure

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 X_0, 0.6 λI)
- Discrimination e+ / p, anti-p / e^- (shower topology)
- Direct E measurement for e^-

Neutron detector
^{3}He tubes + polyethylene moderator:
- High-energy e/h discrimination



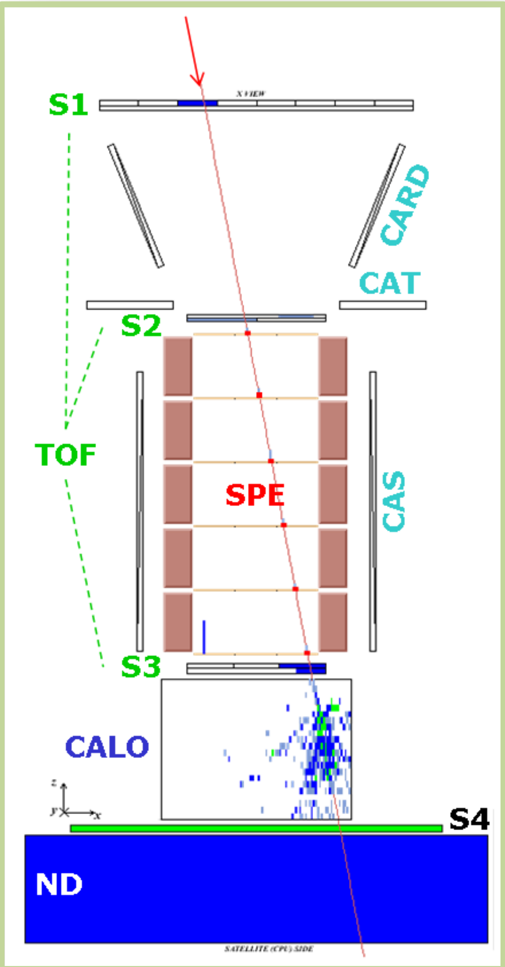
Spectrometer
microstrip silicon tracking system + permanent magnet
It provides:
- *Magnetic rigidity* → R = pc/Ze
- *Charge sign*
- *Charge value from dE/dx*

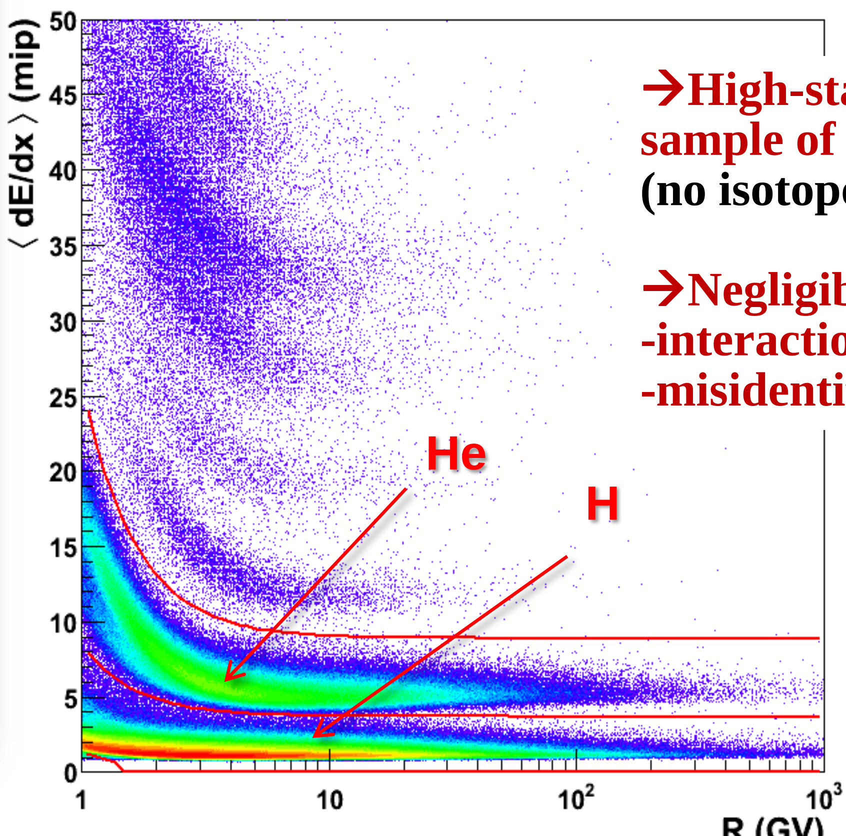
Cosmic Ray Spectra

Cosmic-Ray Acceleration and Propagation in the Galaxy

H/He Selection

- Single good-quality track in the spectrometer
  → Particle rigidity (R = pc/Ze)
- Downward-going (β>0) & positive-curvature (R>0) trajectory
  → Positive-charge particle from above
- Clean pattern through the apparatus
  → Not an interaction product
- Energy deposits in the tracking system consistent with H and He nuclei





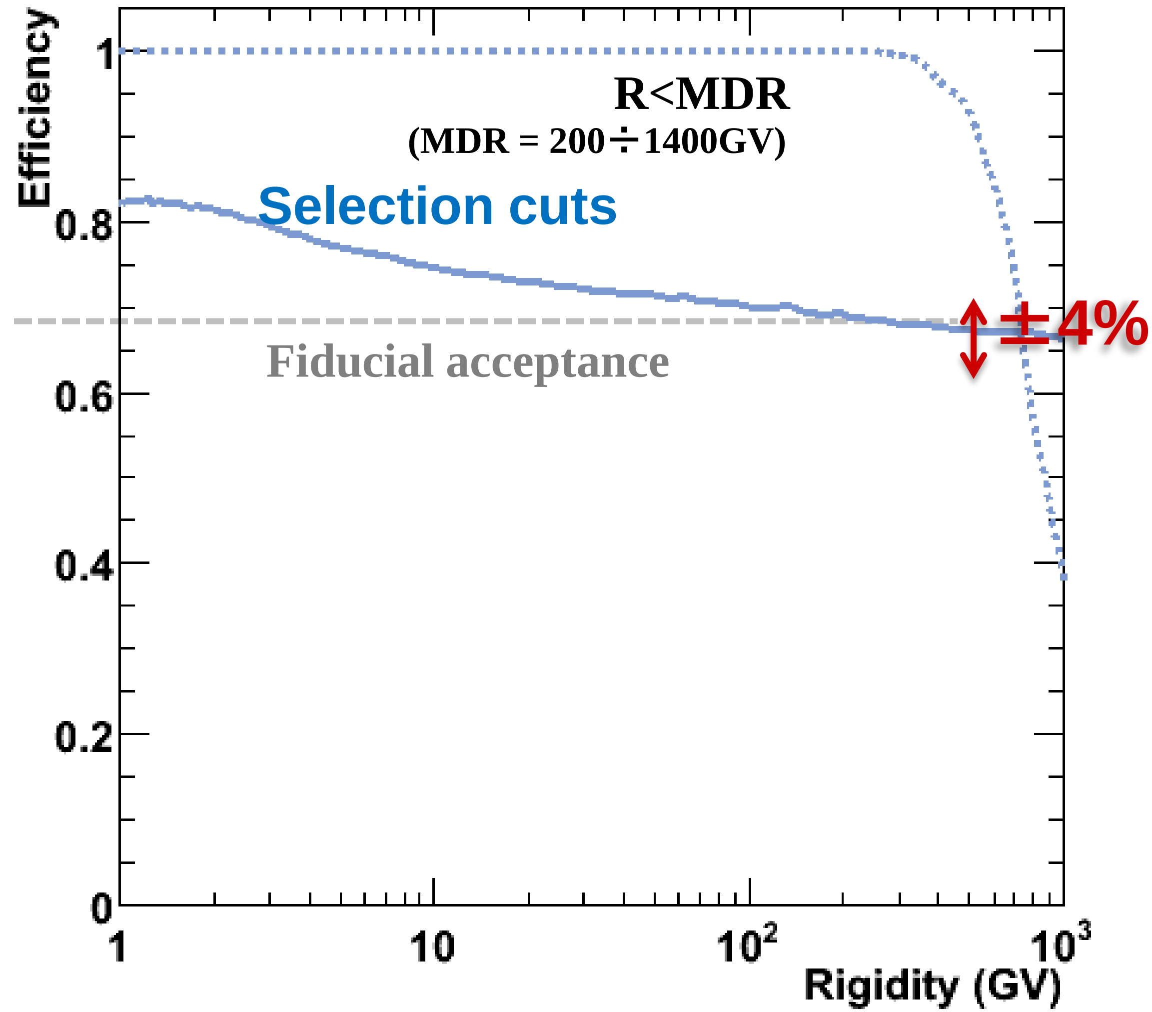
→High-statistic (~10^8) sample of H and He (no isotope separation)

→Negligible bk of
-interaction products
-misidentified particles

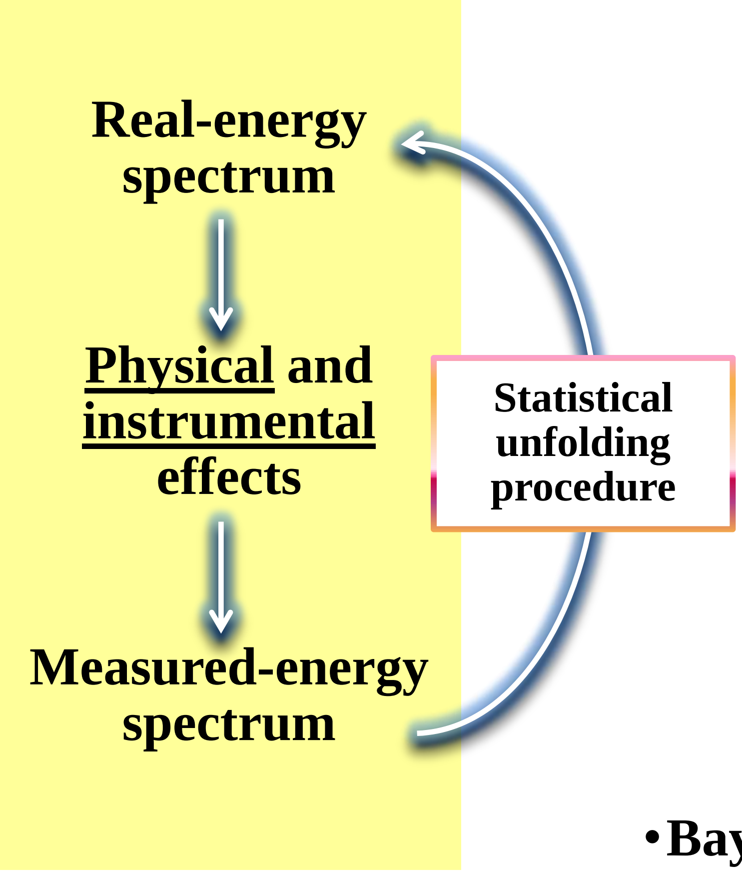
Selection efficiencies

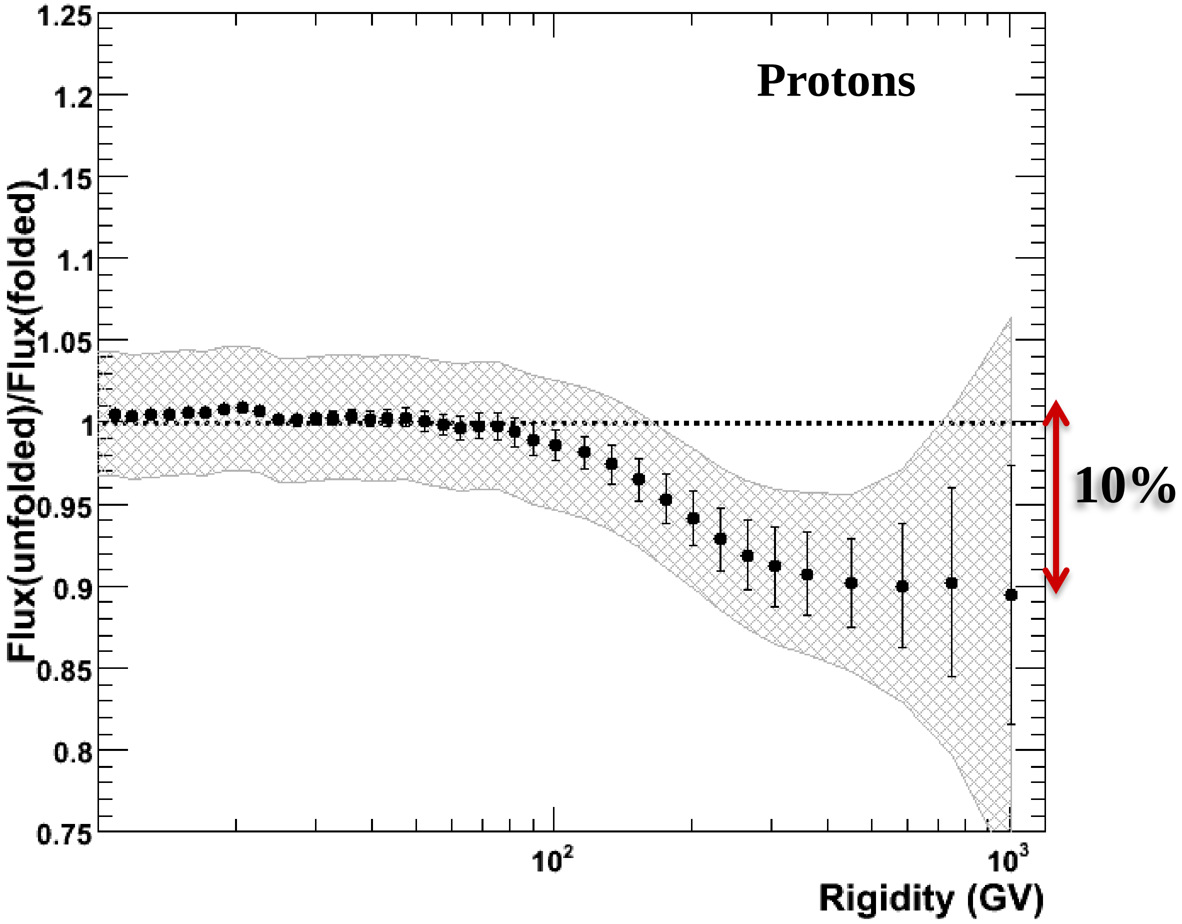
General approach:

- Efficiency evaluated from flight data
  - → Real performances
- Cross-checks and corrections from MC simulation
  - → Complete information
  - → Test of measurement procedure
- Evaluated every 2 months



Spectrum unfolding





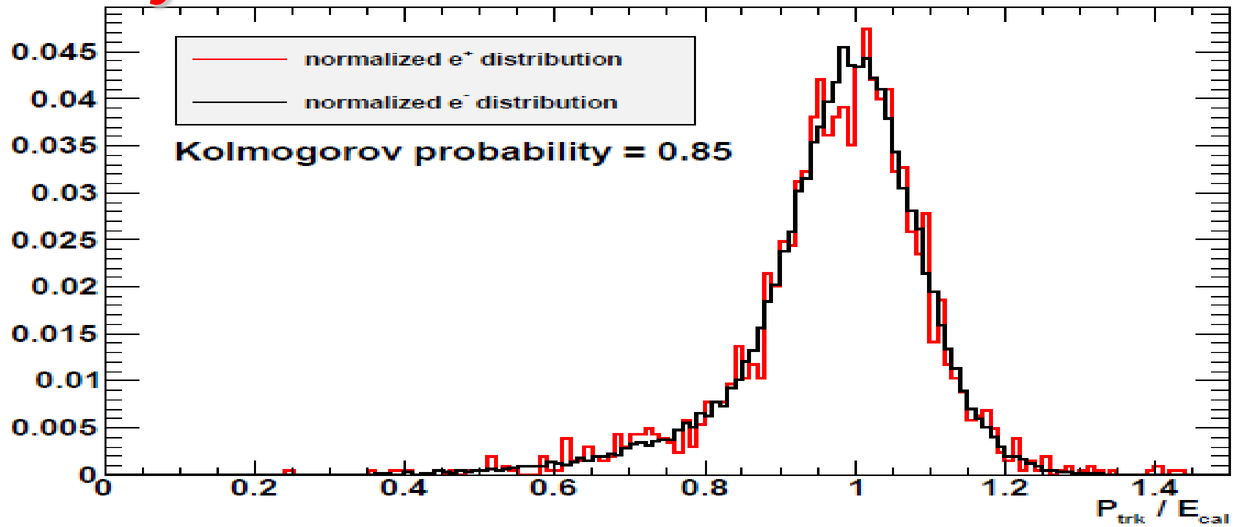
- Bayesian unfolding
- Spectrometer response matrix from MC

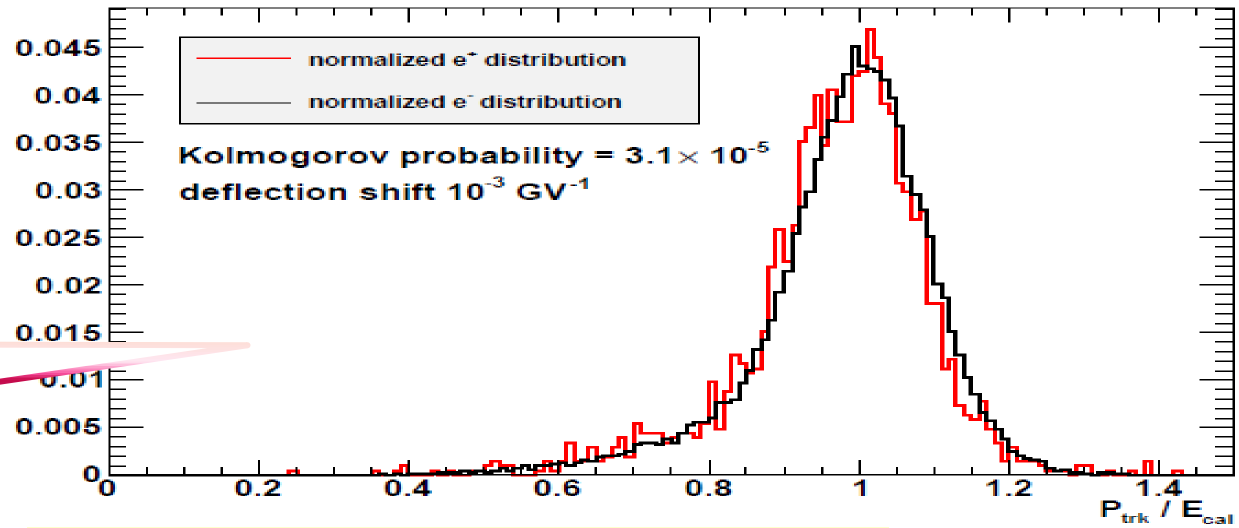
Spectrometer Systematic Uncertainties

With real data:

$$z = \frac{1}{E_C|\eta_S|} \longrightarrow \frac{1}{E_C(1+\varepsilon)(|\eta_S| \pm \Delta\eta)}$$

- **The spectrometer may have a <u>charge-sign</u> dependent systematic**
- **A calorimeter systematic has <u>no such dependence</u>**





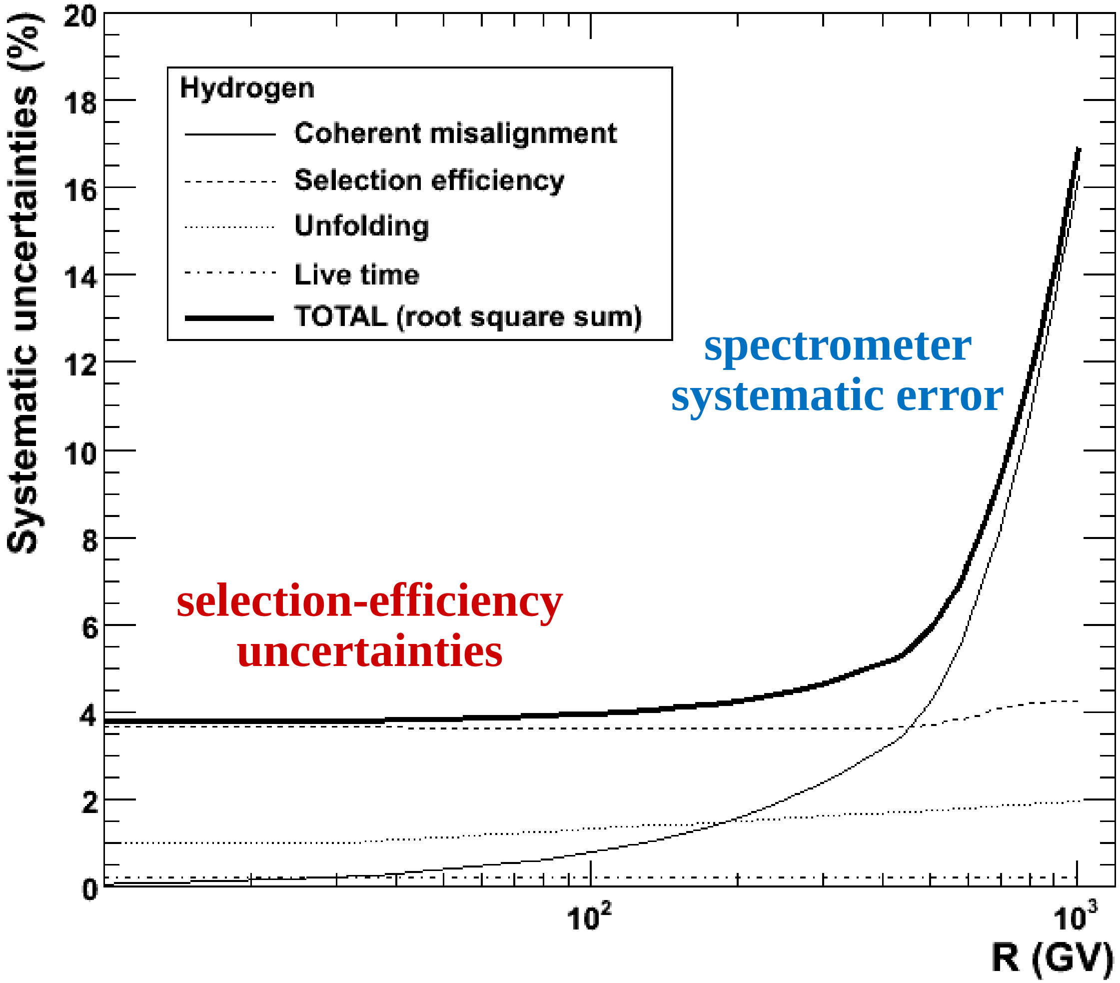
A systematic deflection shift causes an offset between e^- and e^+ distribution

Upper limit set by positron statistics:

- **$\Delta\eta_{sys} \sim 1\cdot10^{-4}$ GV^{-1}**

Overall systematic uncertainties

- At low R selection-efficiency uncertainties dominate
- Above 500GV tracking-system (coherent) misalignment dominates



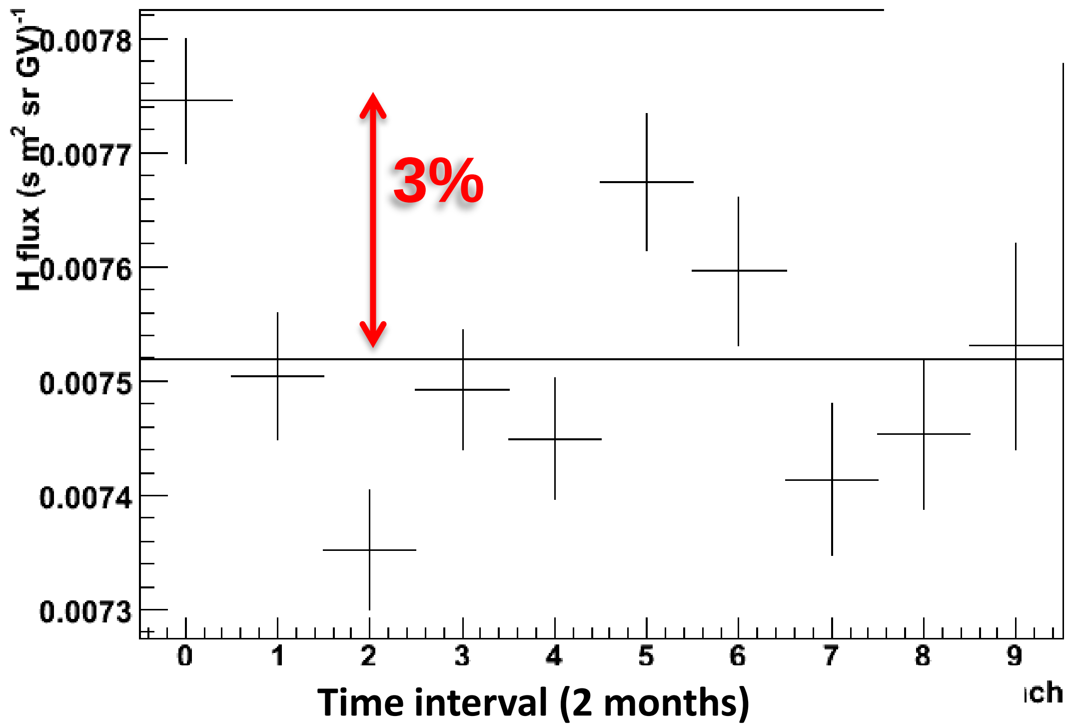
Check of systematics

Fluxes evaluated by varying the selection conditions:

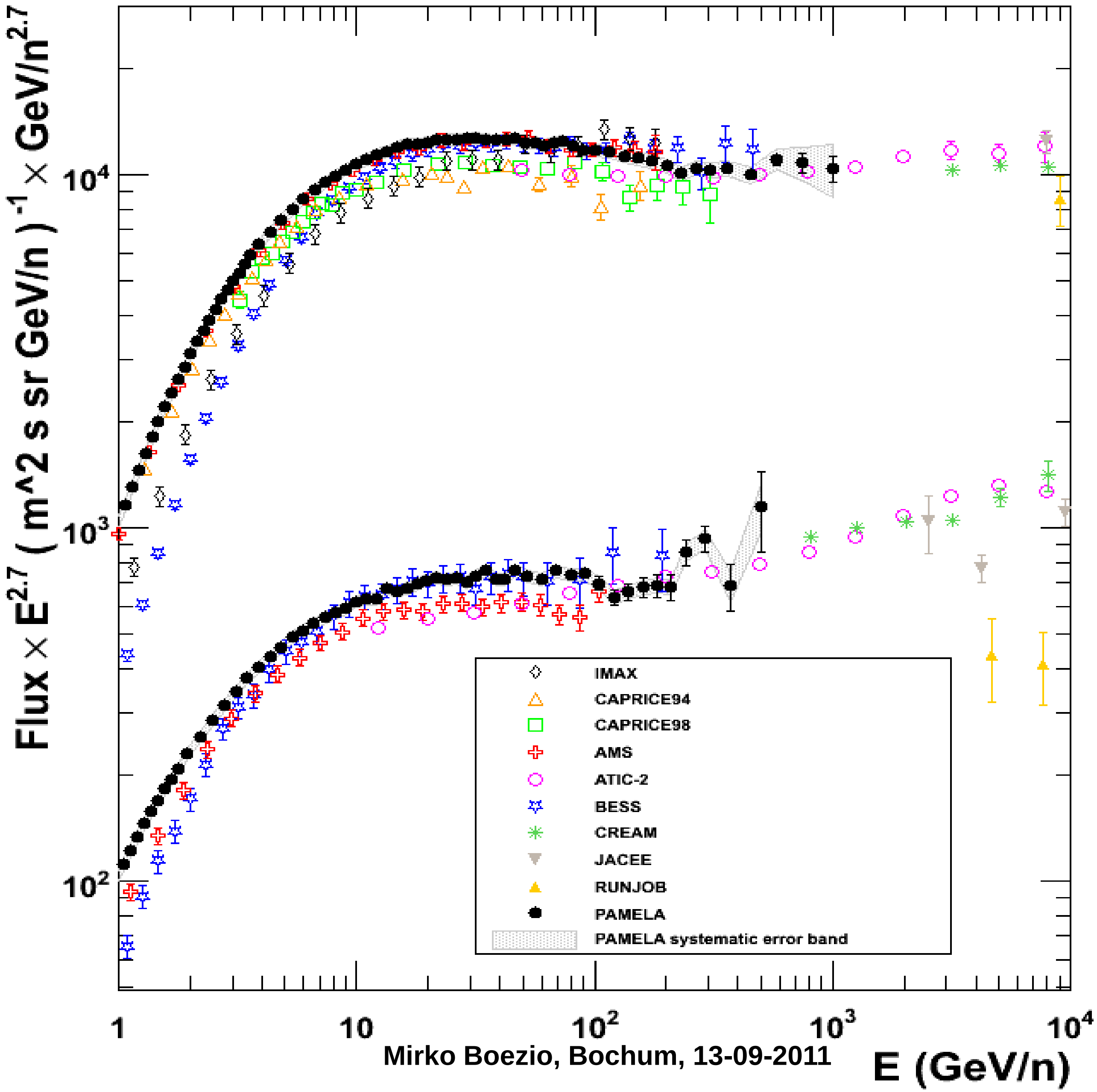
- Flux vs time
- Flux vs polar/equatorial
- Flux vs reduced acceptance
- Flux vs different tracking conditions (⇒ different response matrix)

…

Integral proton flux (>50GV)



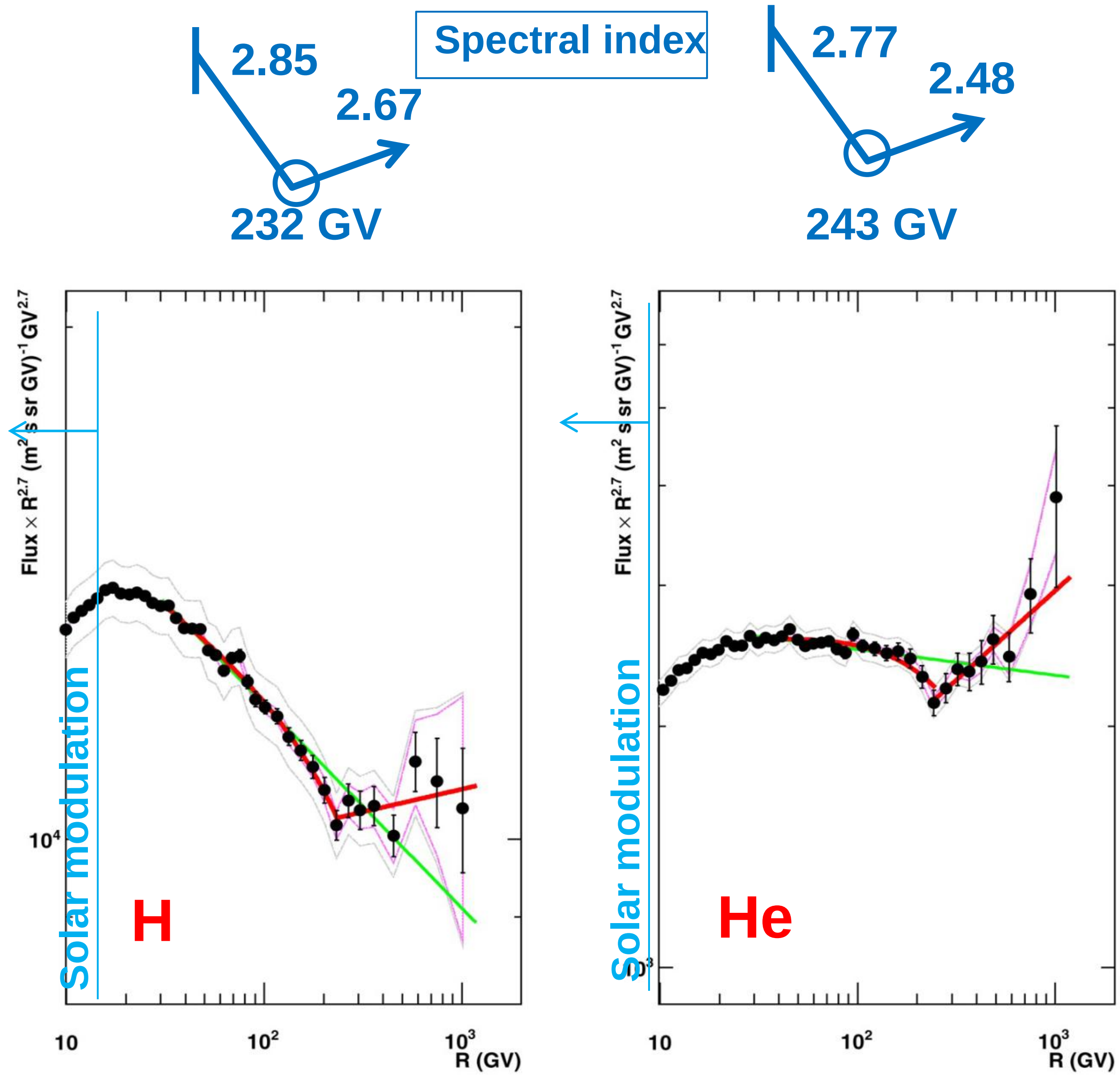
Proton and Helium Nuclei Spectra



O. Adriani et al., Science 332 (2011) 69

Mirko Boezio, Bochum, 13-09-2011

H & He absolute fluxes @ high energy



Deviations from single power law (SPL):

- Spectra gradually soften in the range 30÷230GV
- Spectral hardening @ R~235GV Δγ~0.2÷0.3

SPL is rejected at 98% CL

Origin of the structures?

- At the sources: multi-populations, non-linear DSA

- Propagation effects

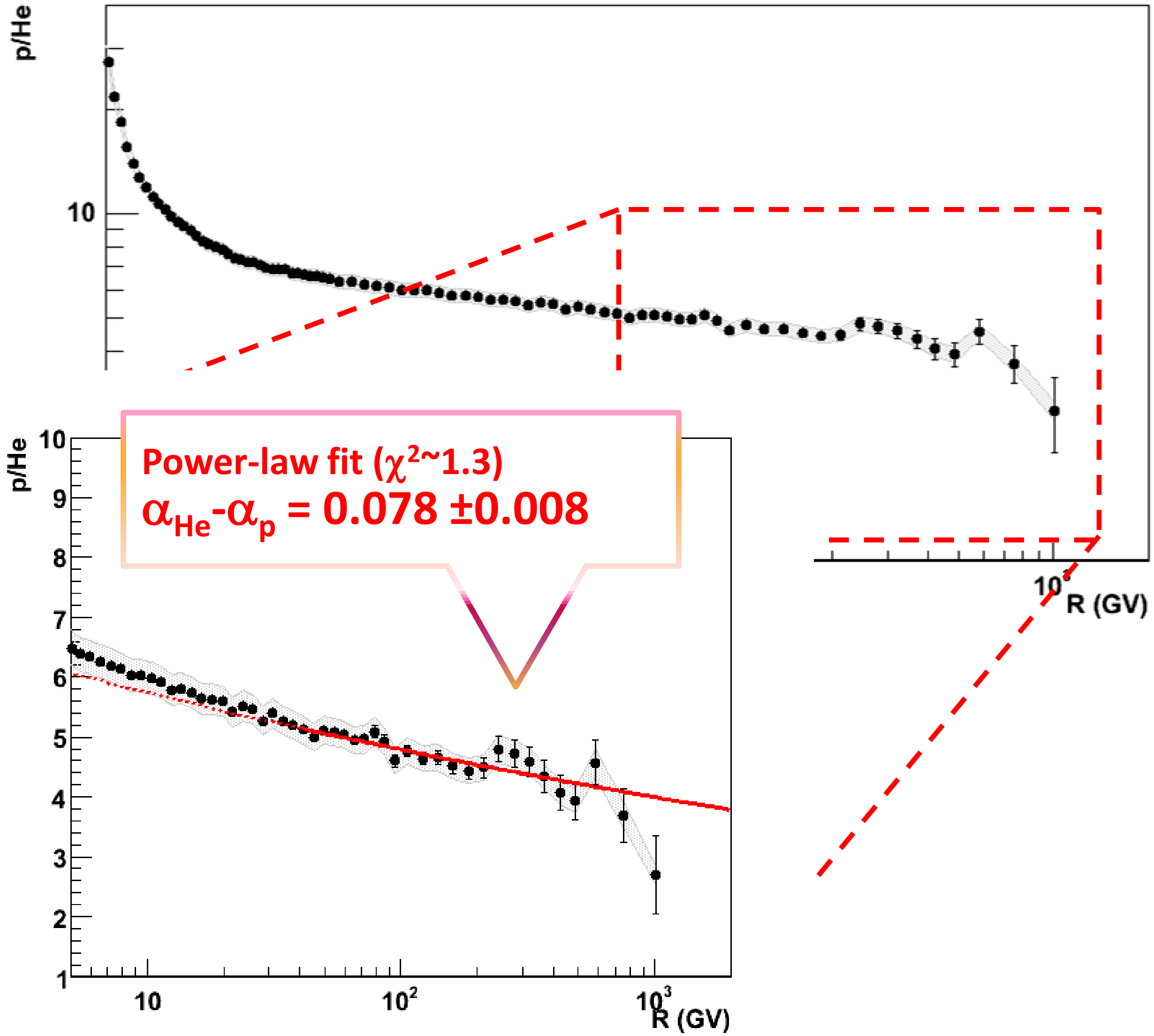
H/He ratio vs R

Instrumental p.o.v.

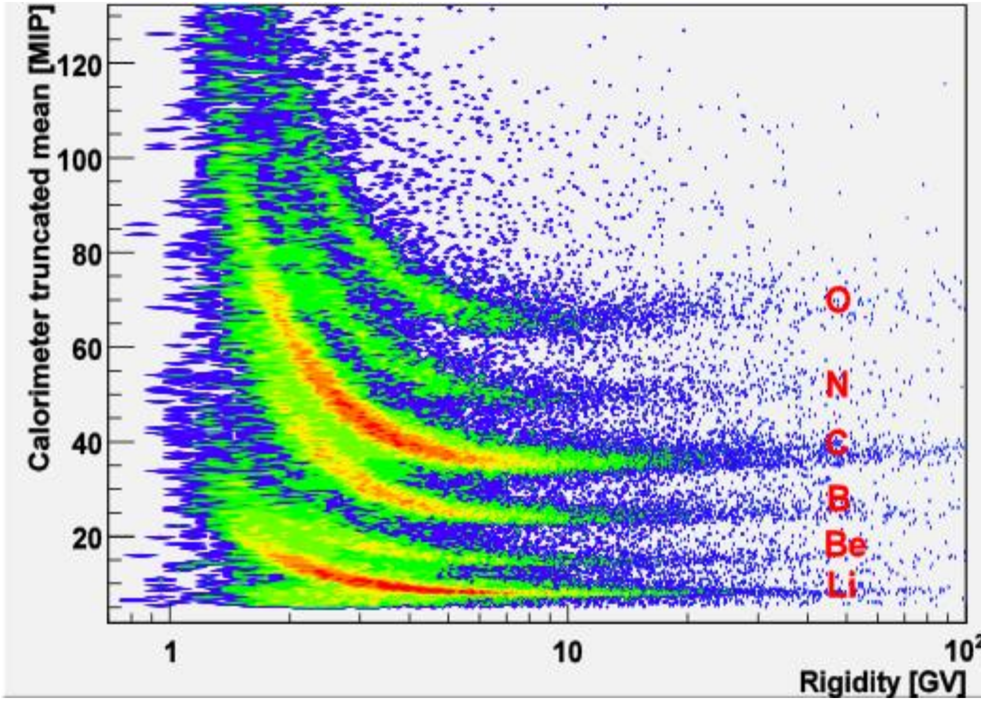
- Systematic uncertainties partly cancel out

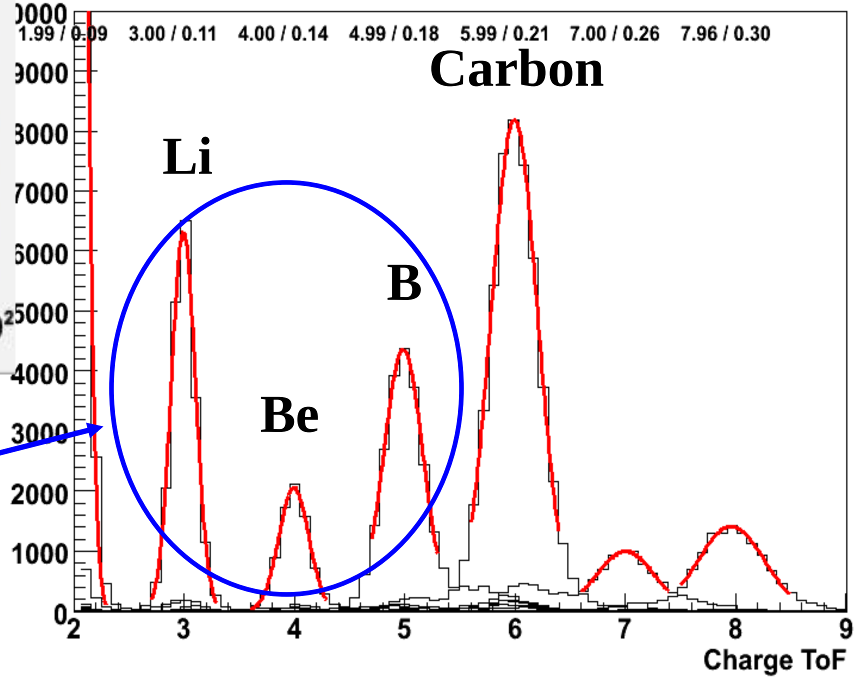
Theoretical p.o.v.

- Solar modulation negligible
  → information about IS spectra down to GV region
- Propagation effects small above ~100GV
  → information about source spectra



Light Nuclei Selection

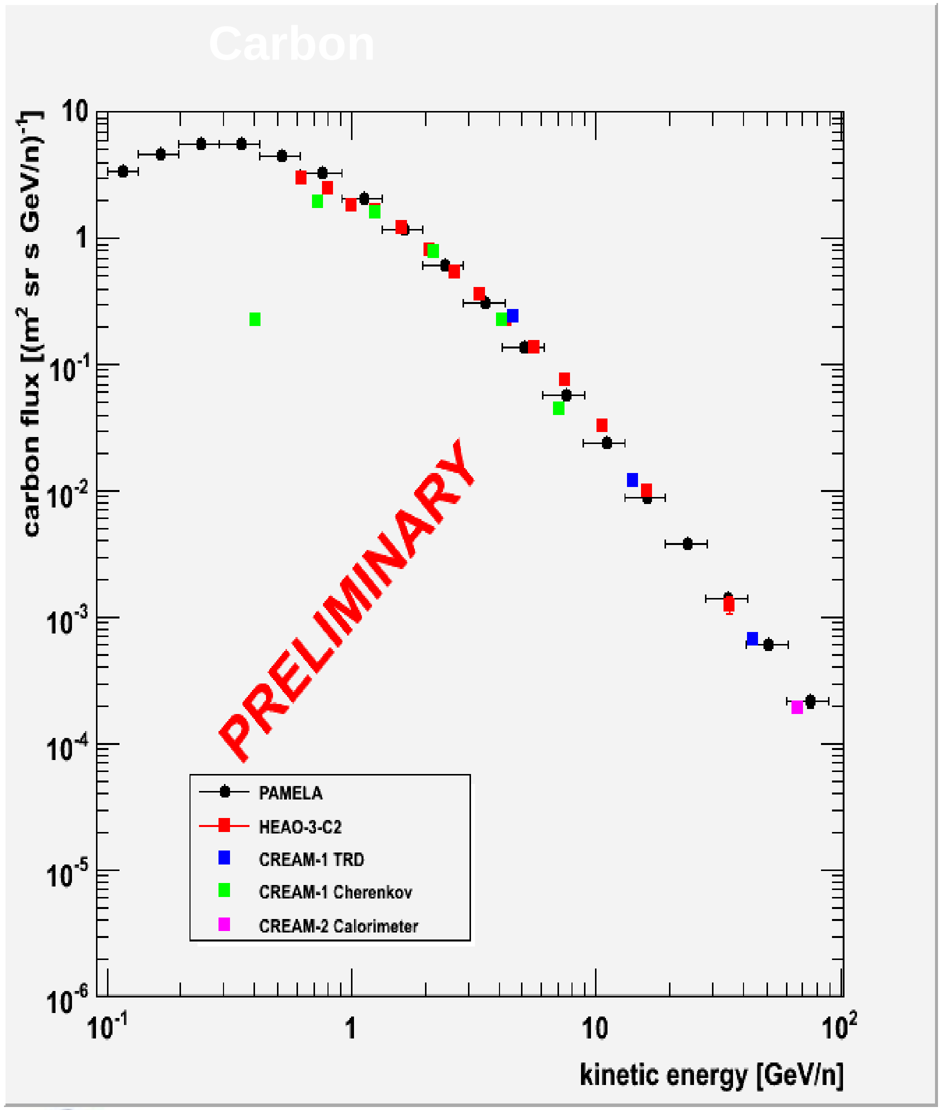


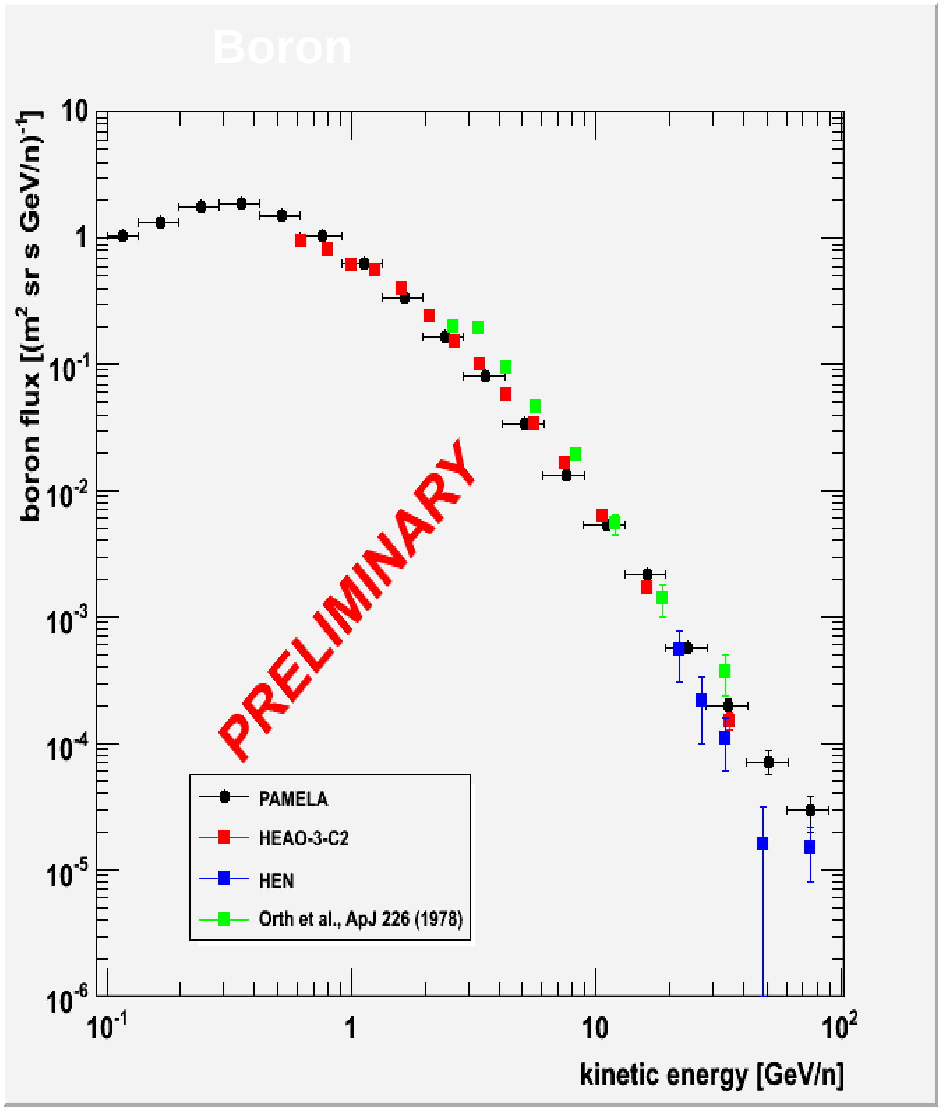


Produced as Secondaries

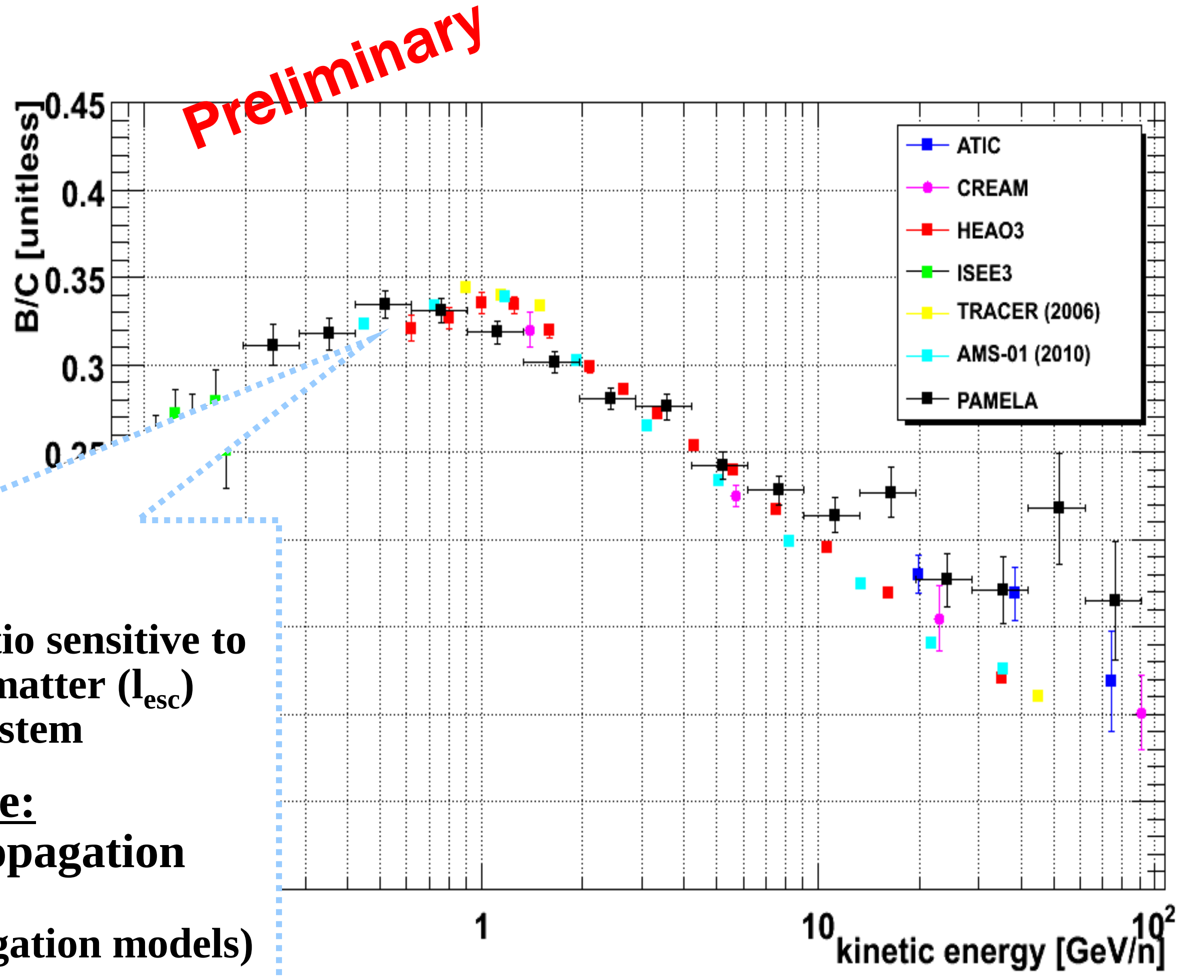
Information on Cosmic Ray Transport

Boron and Carbon nuclei Spectra





Secondary nuclei



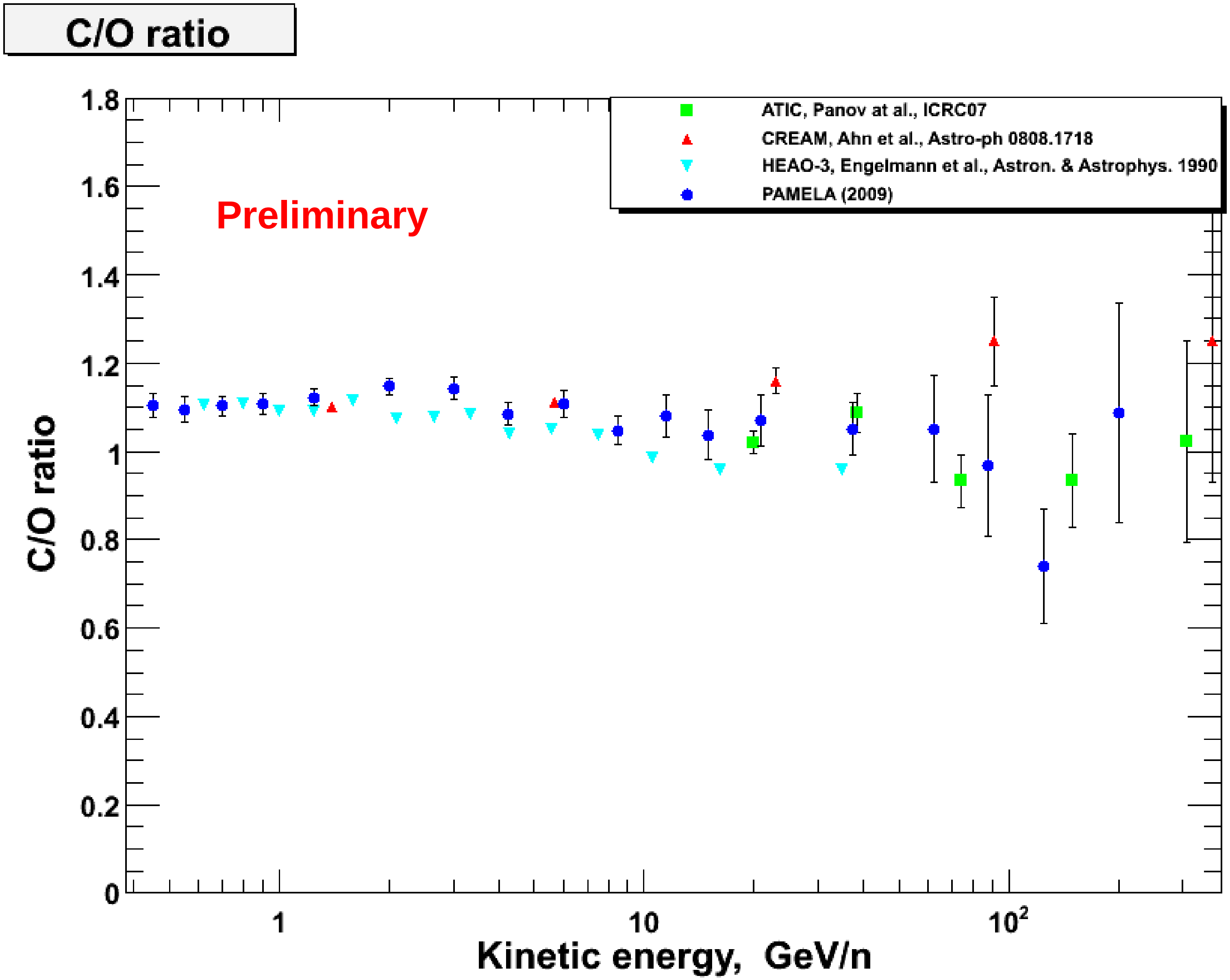
$$\frac{N_S}{N_P} \propto \lambda_{esc} \cdot \sigma_{P \to S}$$

- **B nuclei of secondary origin:**
  CNO + ISM → B + …
- **Local secondary/primary ratio sensitive to average amount of traversed matter (l_{esc}) from the source to the solar system**

Local secondary abundance:
⇒ study of galactic CR propagation

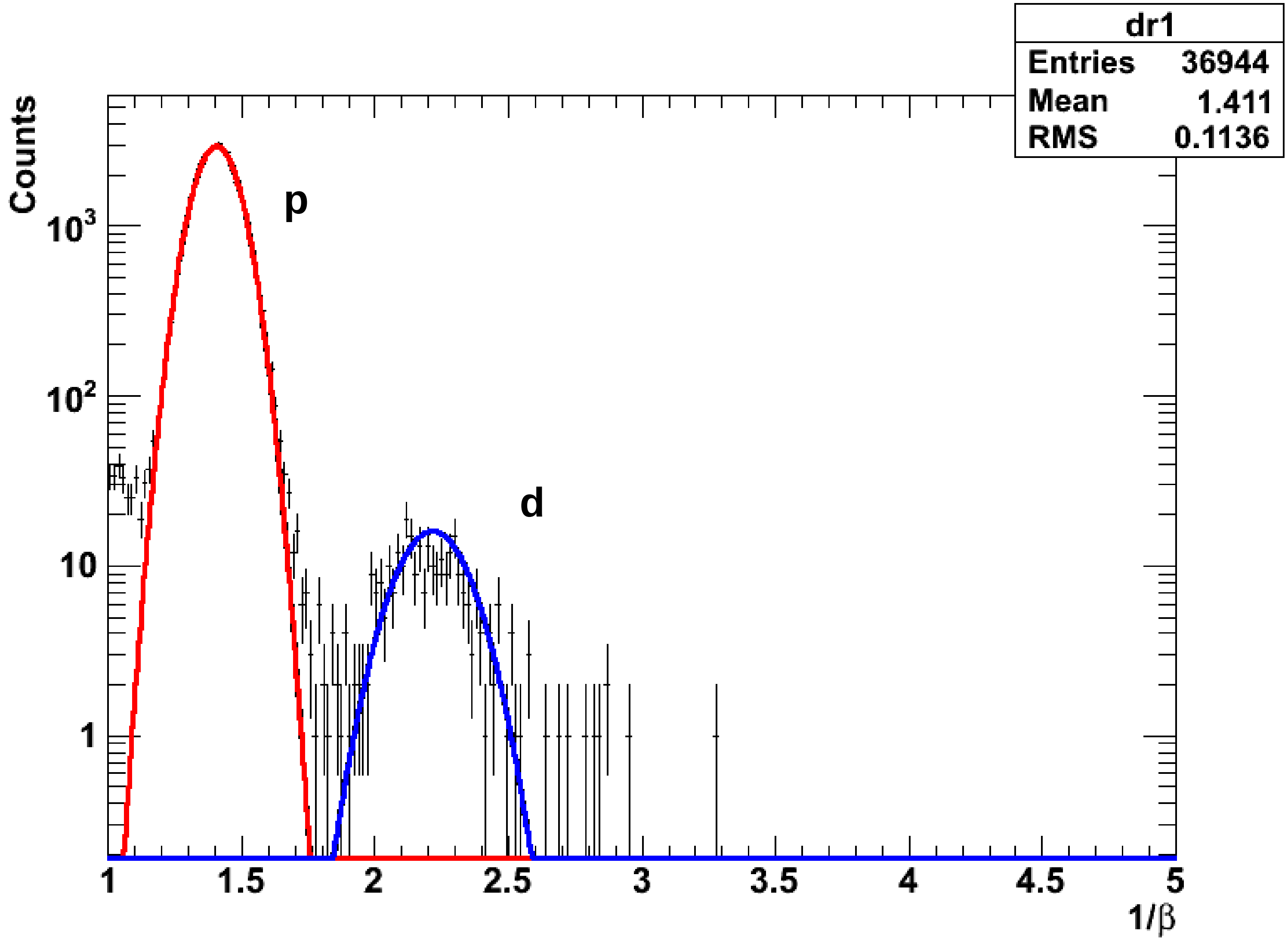
(B/C used for tuning of propagation models)

C/O ratio

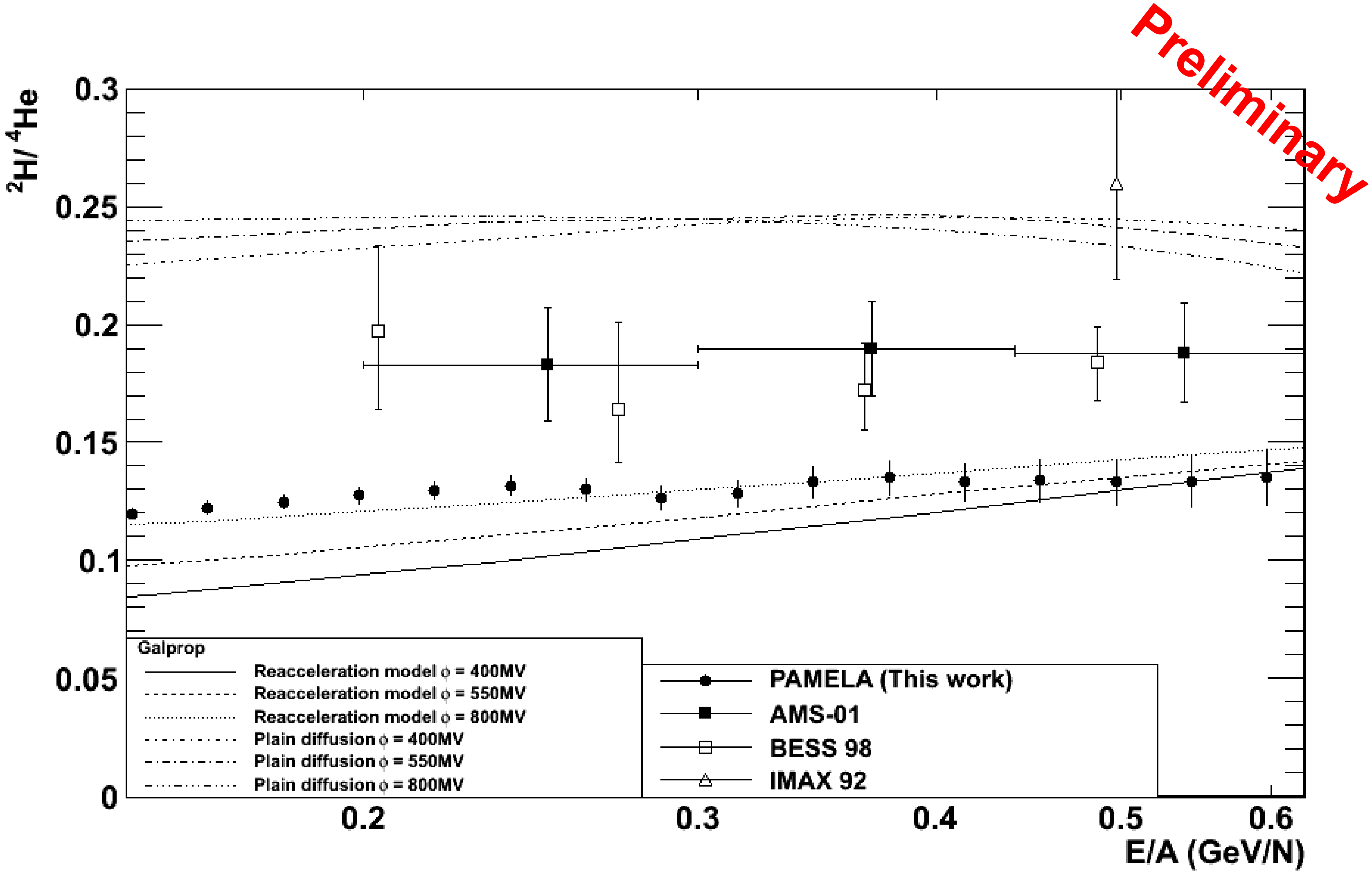


C/O ratio
Preliminary
ATIC, Panov at al., ICRC07
CREAM, Ahn et al., Astro-ph 0808.1718
HEAO-3, Engelmann et al., Astron. & Astrophys. 1990
PAMELA (2009)
C/O ratio
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
1
10
10^2
Kinetic energy, GeV/n

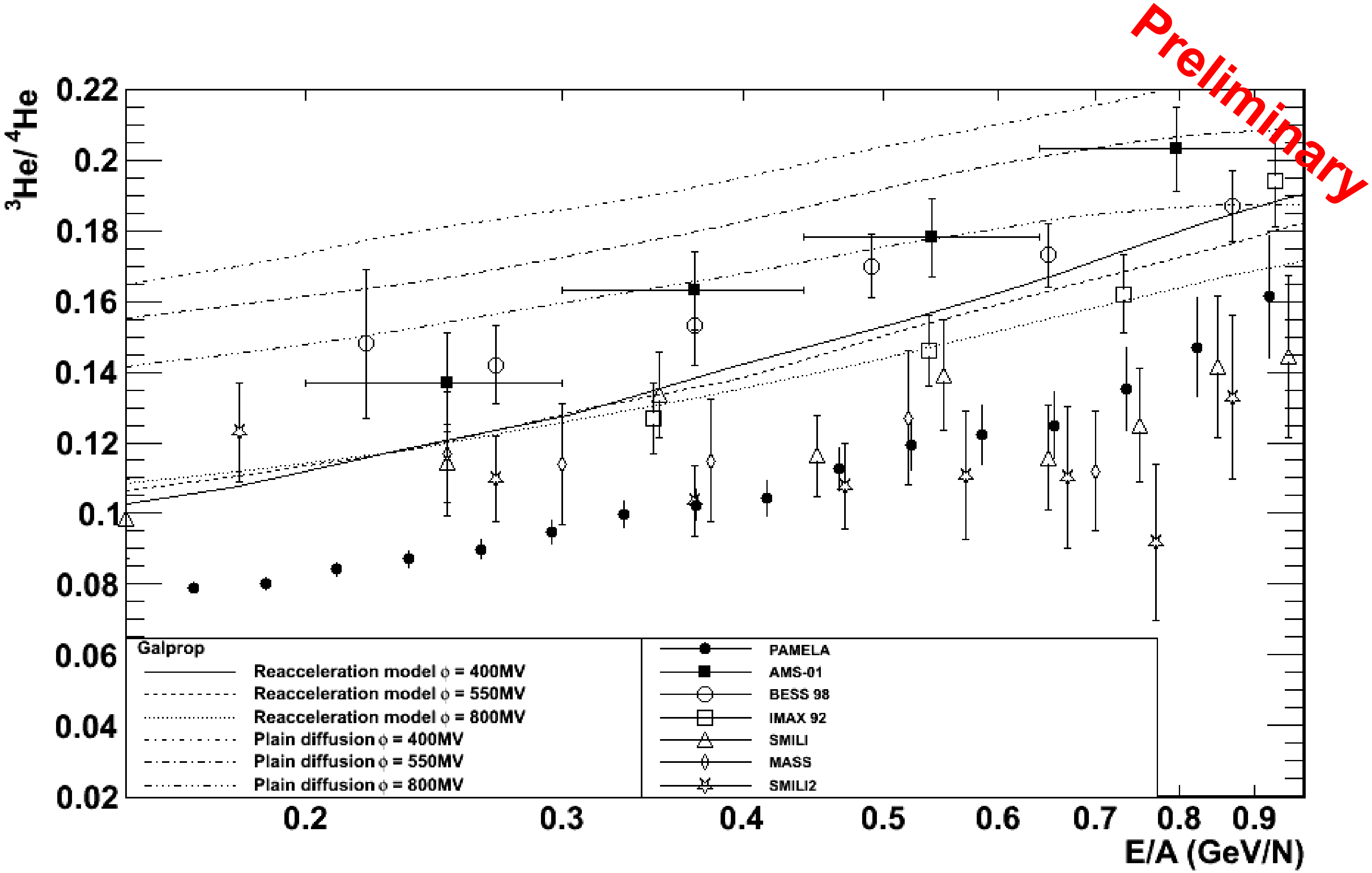
H isotopes separation



PAMELA $^2H/^4He$

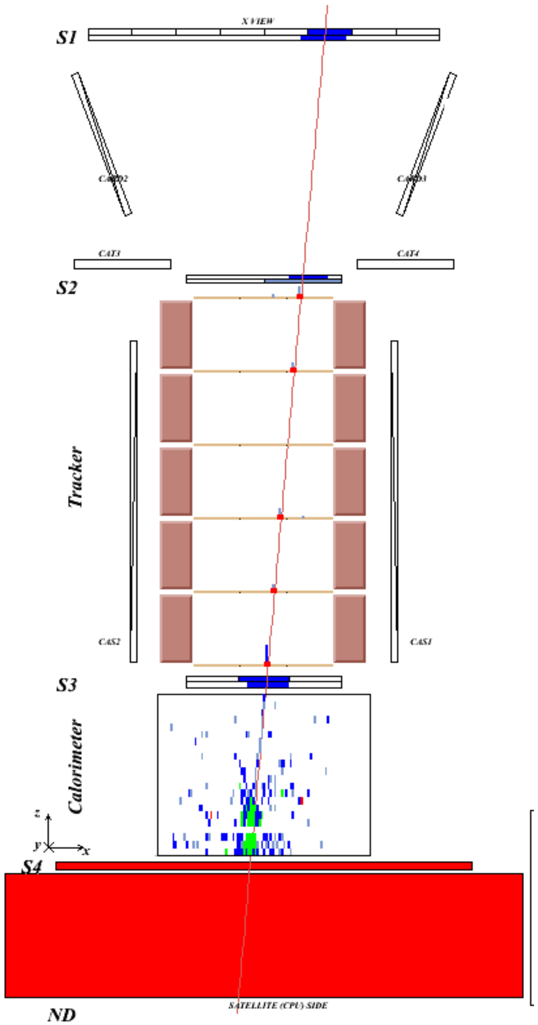


PAMELA $^3He/^4He$



Antiparticles with PAMELA

Antiproton / positron identification



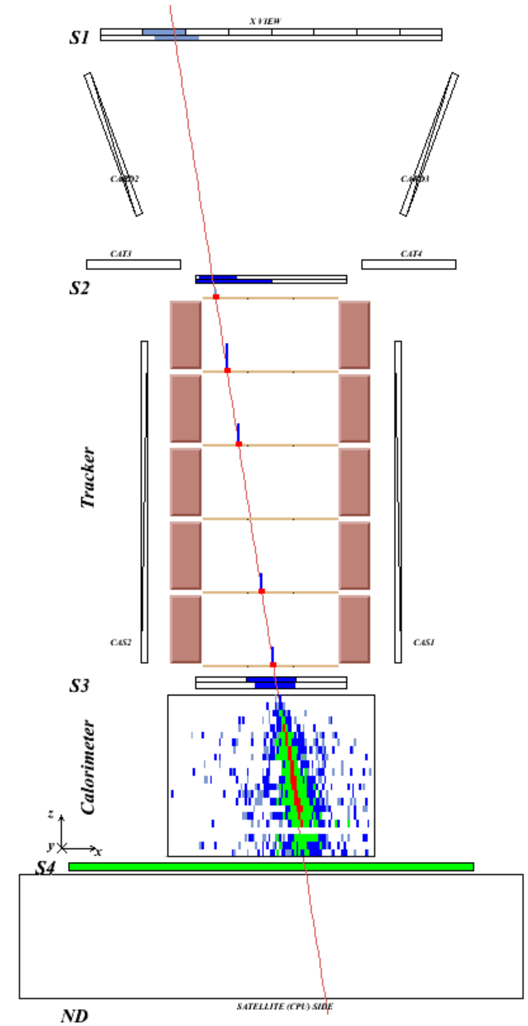
Antiproton
(NB: $e^-/\bar{p} \sim 10^2$)

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

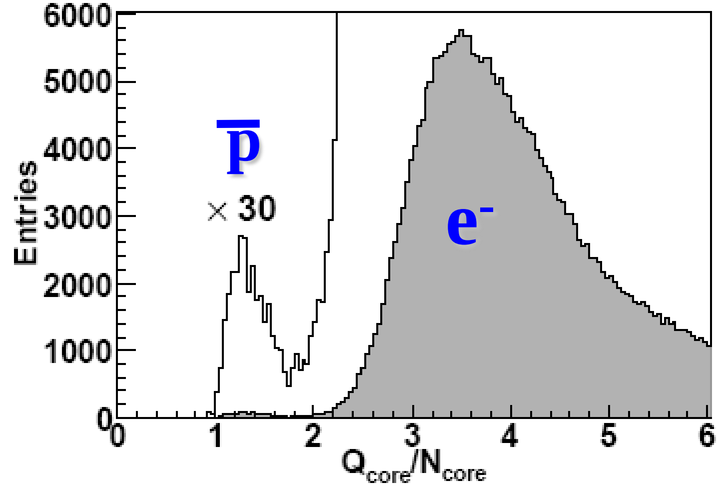


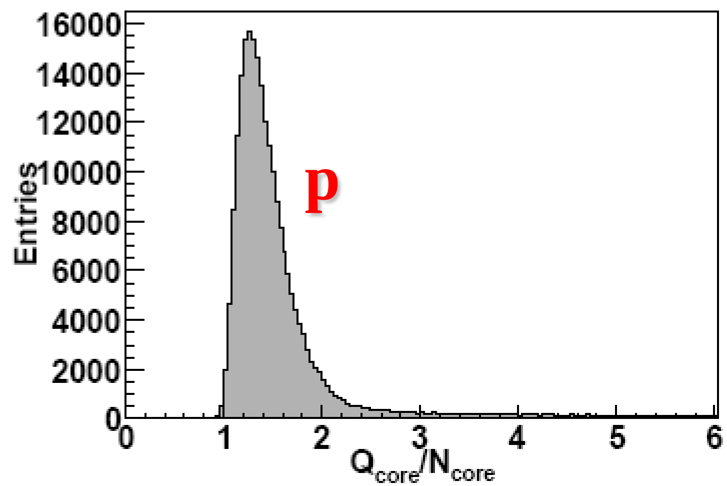
Positron
(NB: $p/e^+ \sim 10^{3-4}$)

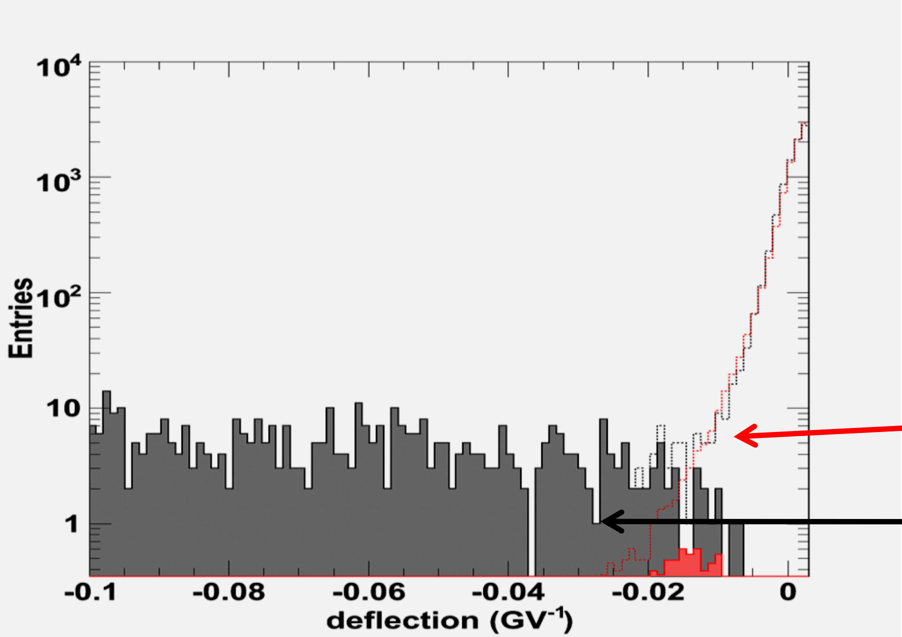
ANTIPROTONS

Antiproton Identification

Calorimeter selection





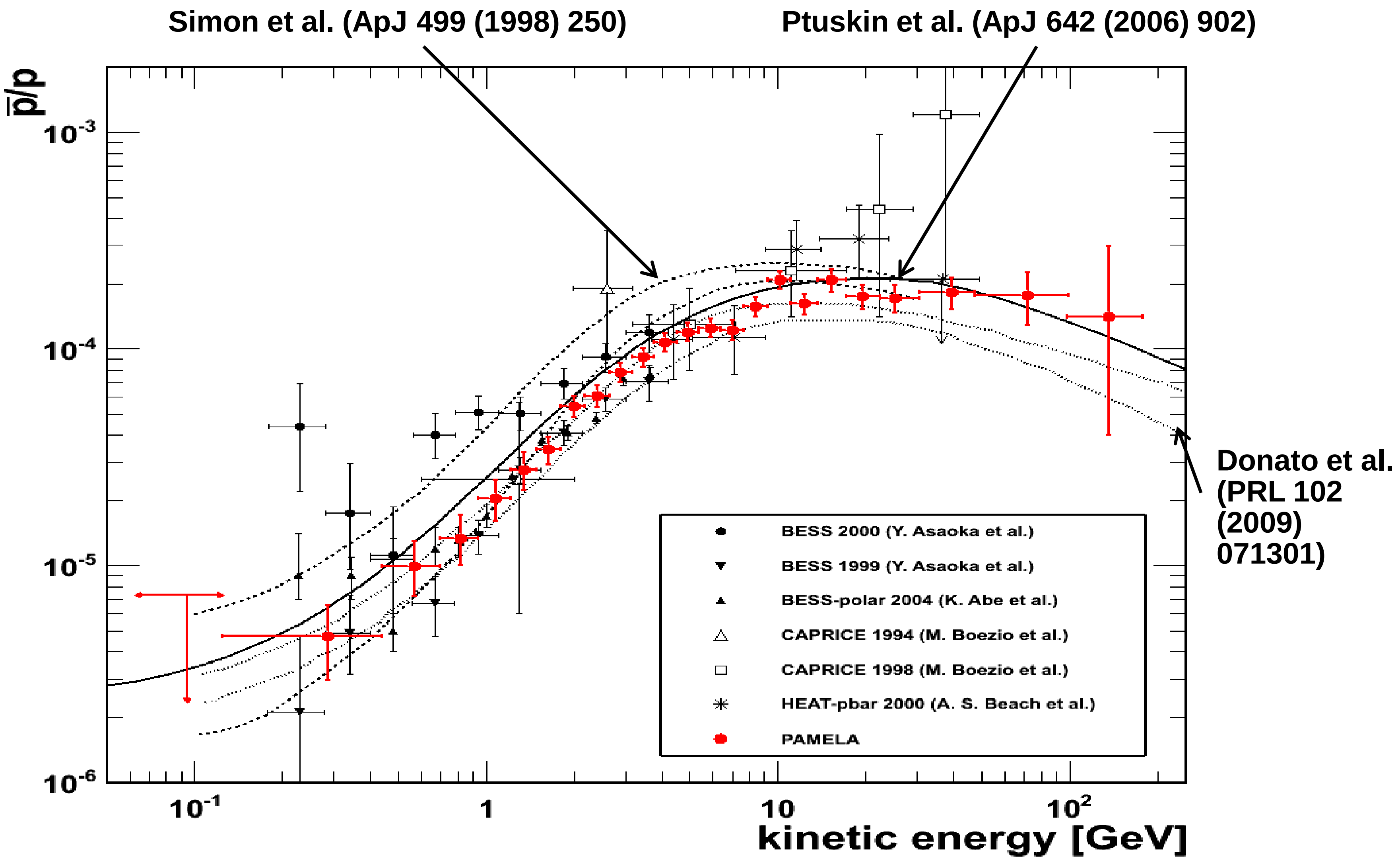


Tracker Identification

Protons (& spillover)

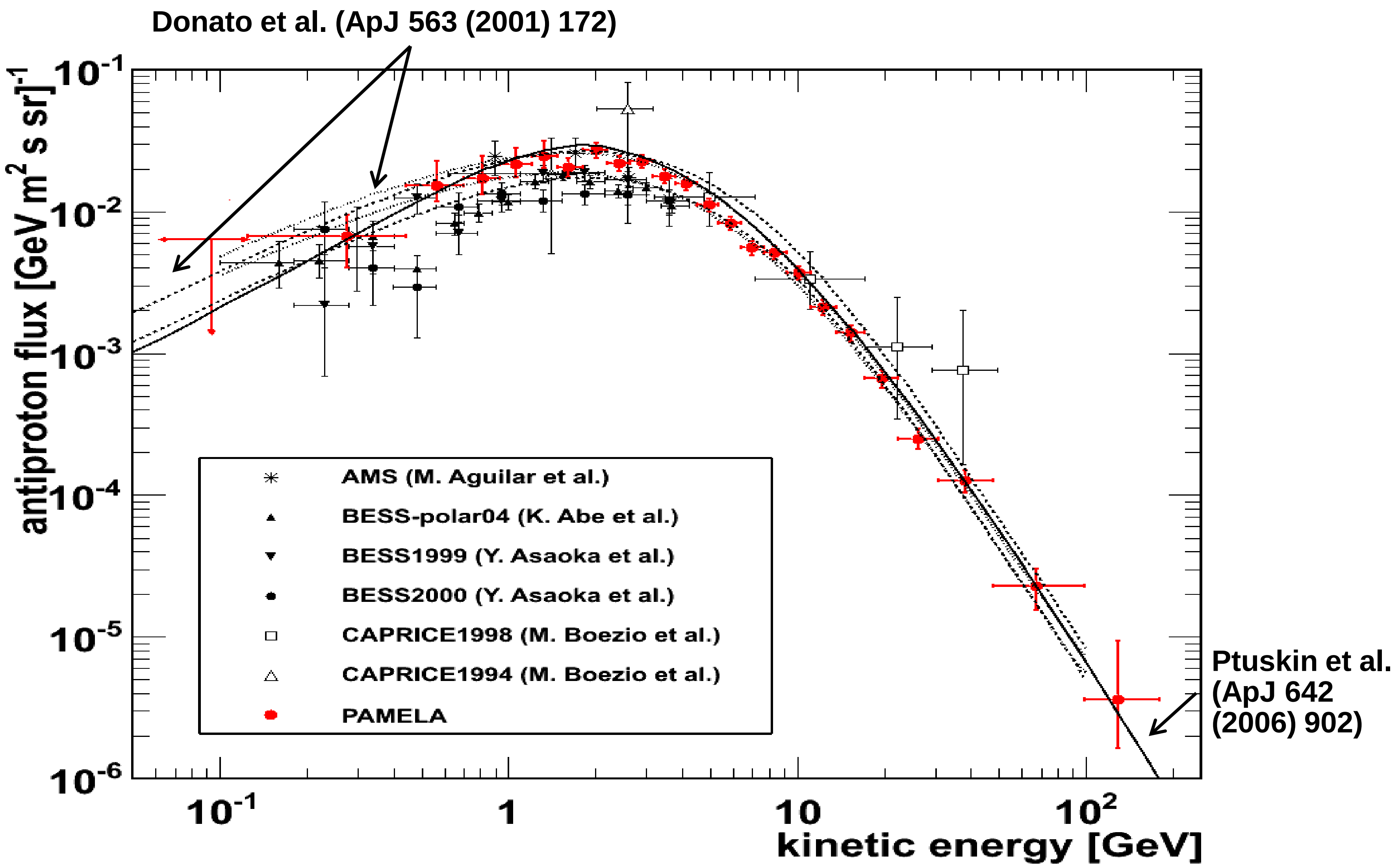
Antiprotons

Antiproton to proton ratio
(0.06 GeV - 180 GeV)



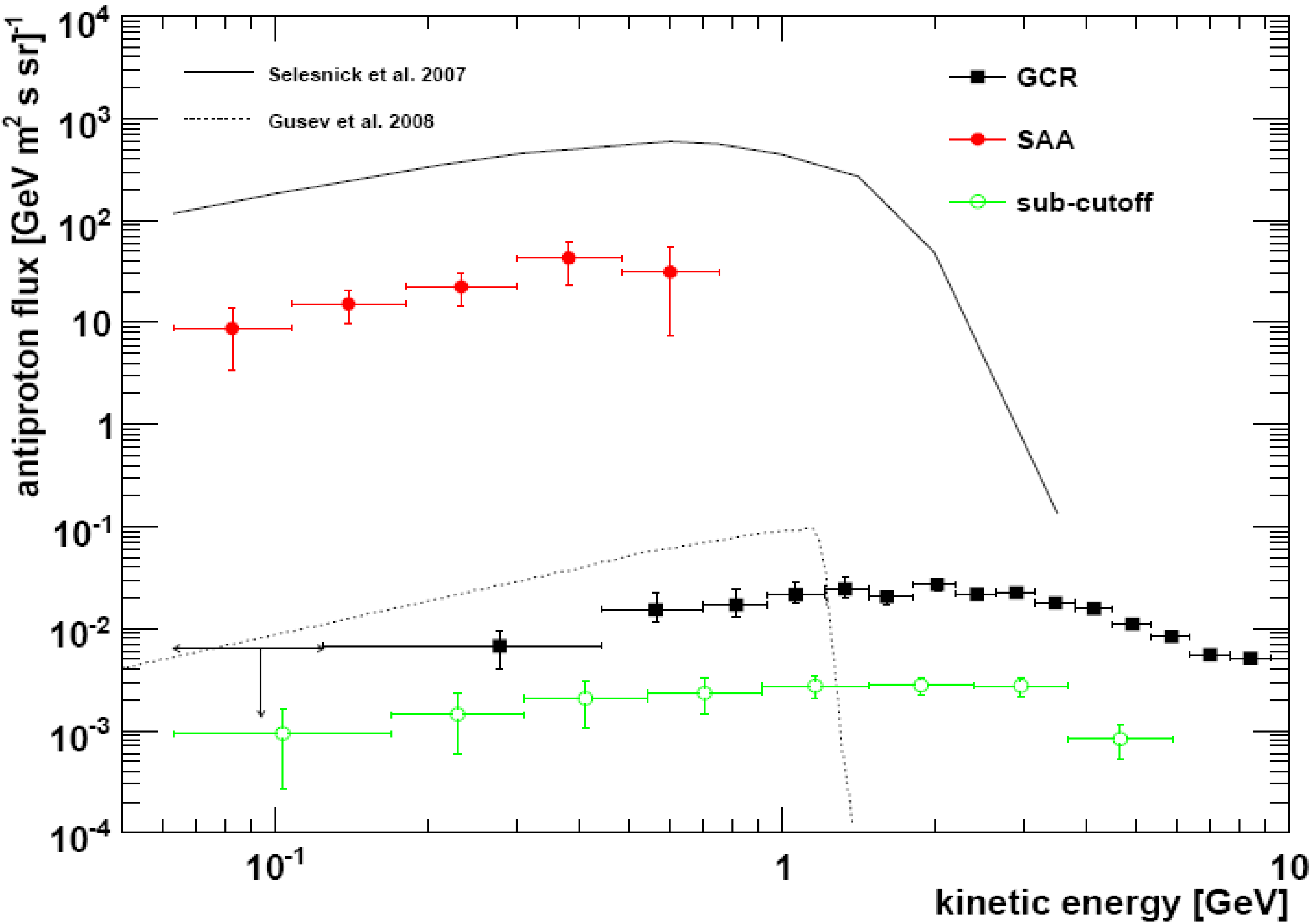
O. Adriani et al., PRL 102, 051101 (2009); PRL 105, 121101 (2010)

Antiproton Flux
(0.06 GeV - 180 GeV)



O. Adriani et al., PRL. 105, 121101 (2010)

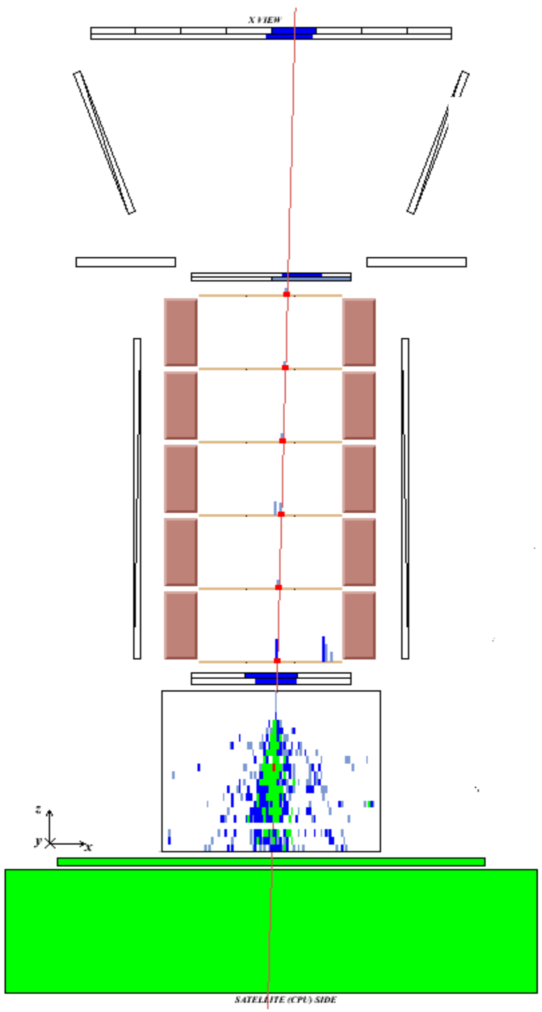
PAMELA trapped antiprotons



O. Adriani et al., APJL 737 L29 (2011); arXiv:1107.4882

POSITRONS

Proton / positron discrimination



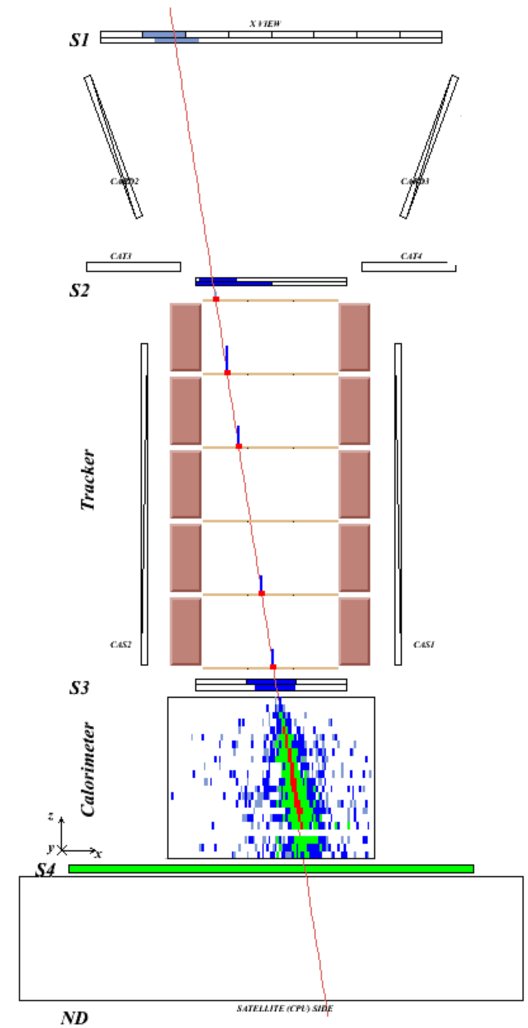
Proton

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

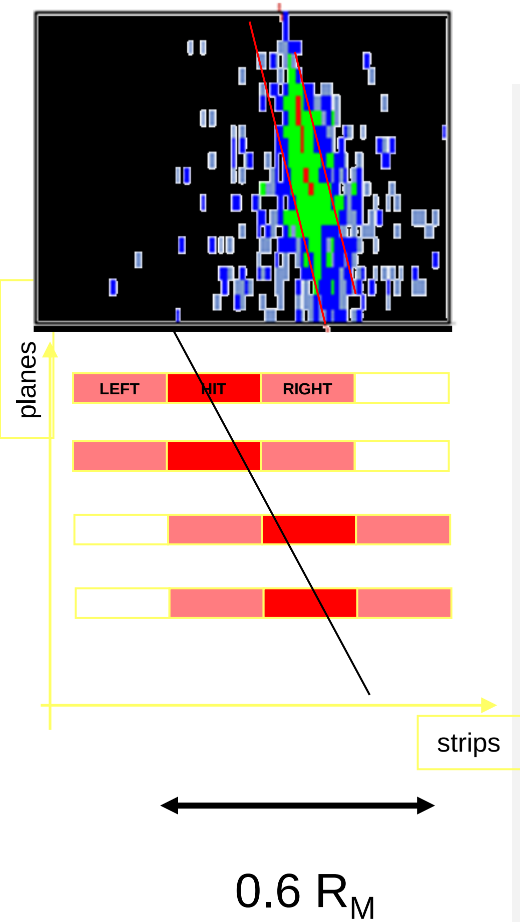
Interaction pattern in calorimeter:
electron-like or proton-like, electron energy

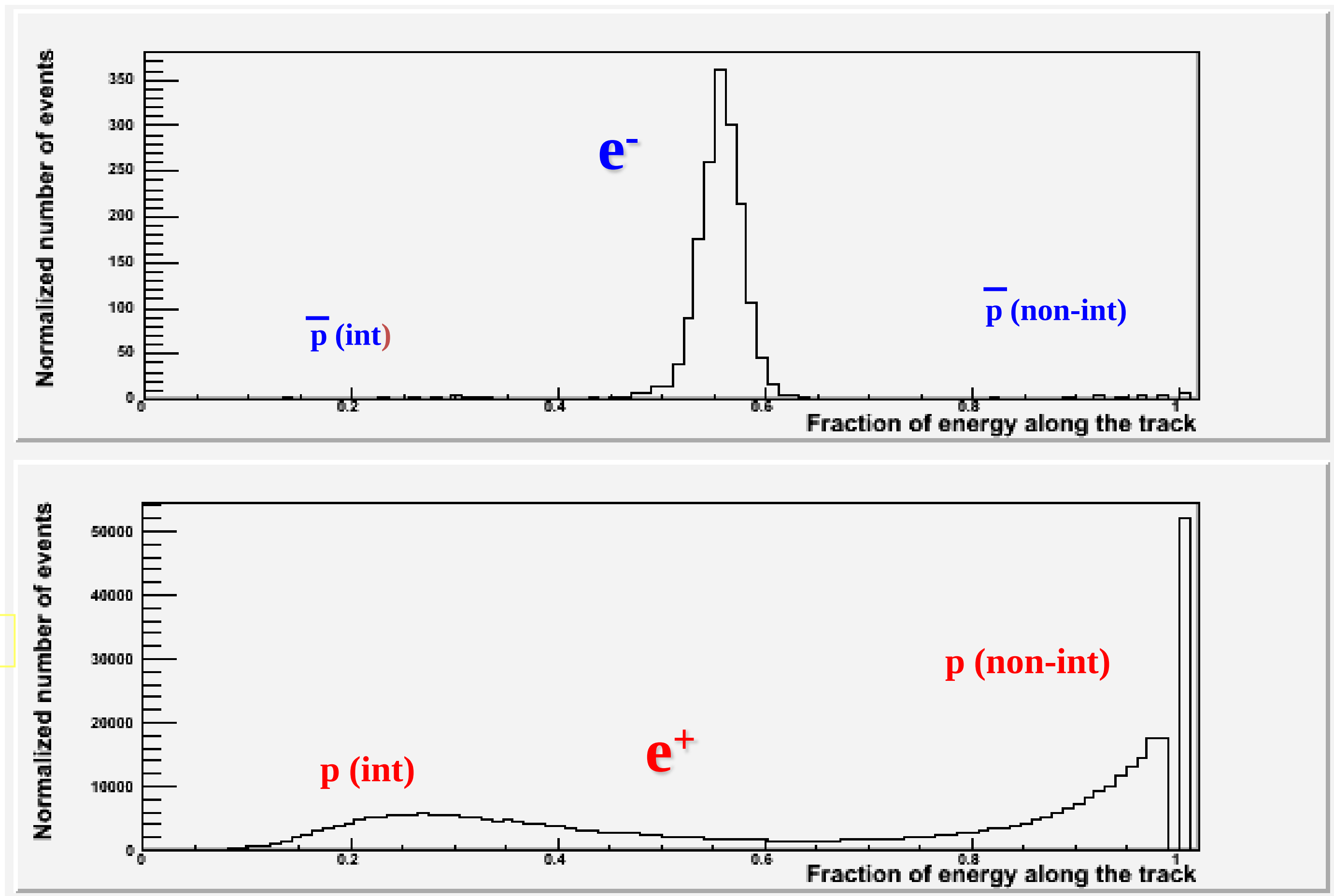


Positron

Positron selection with calorimeter

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



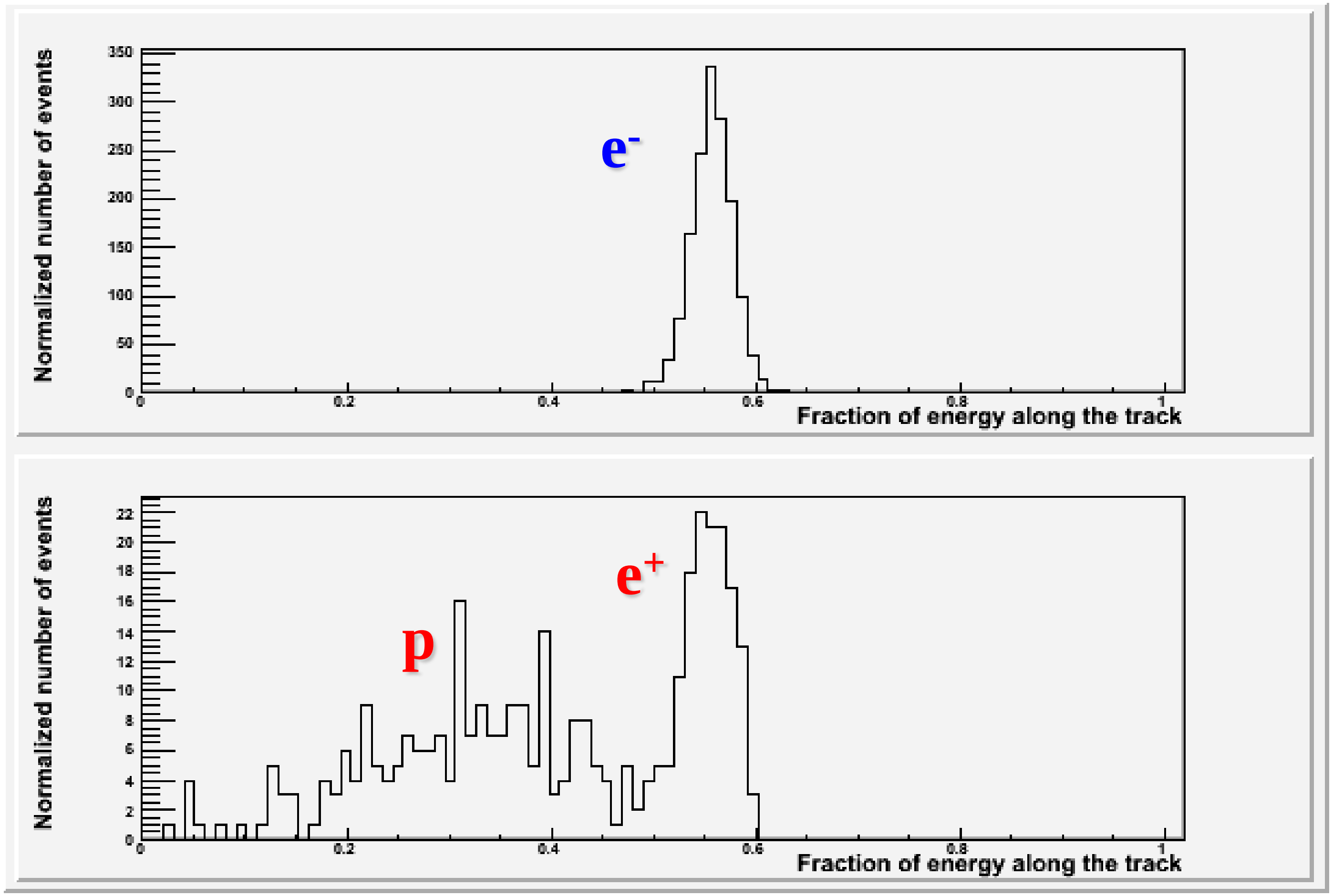


Rigidity: 20-30 GV

for em showers 90% of E contained in 1 R_M

Positron selection with calorimeter

Rigidity: 20-30 GV

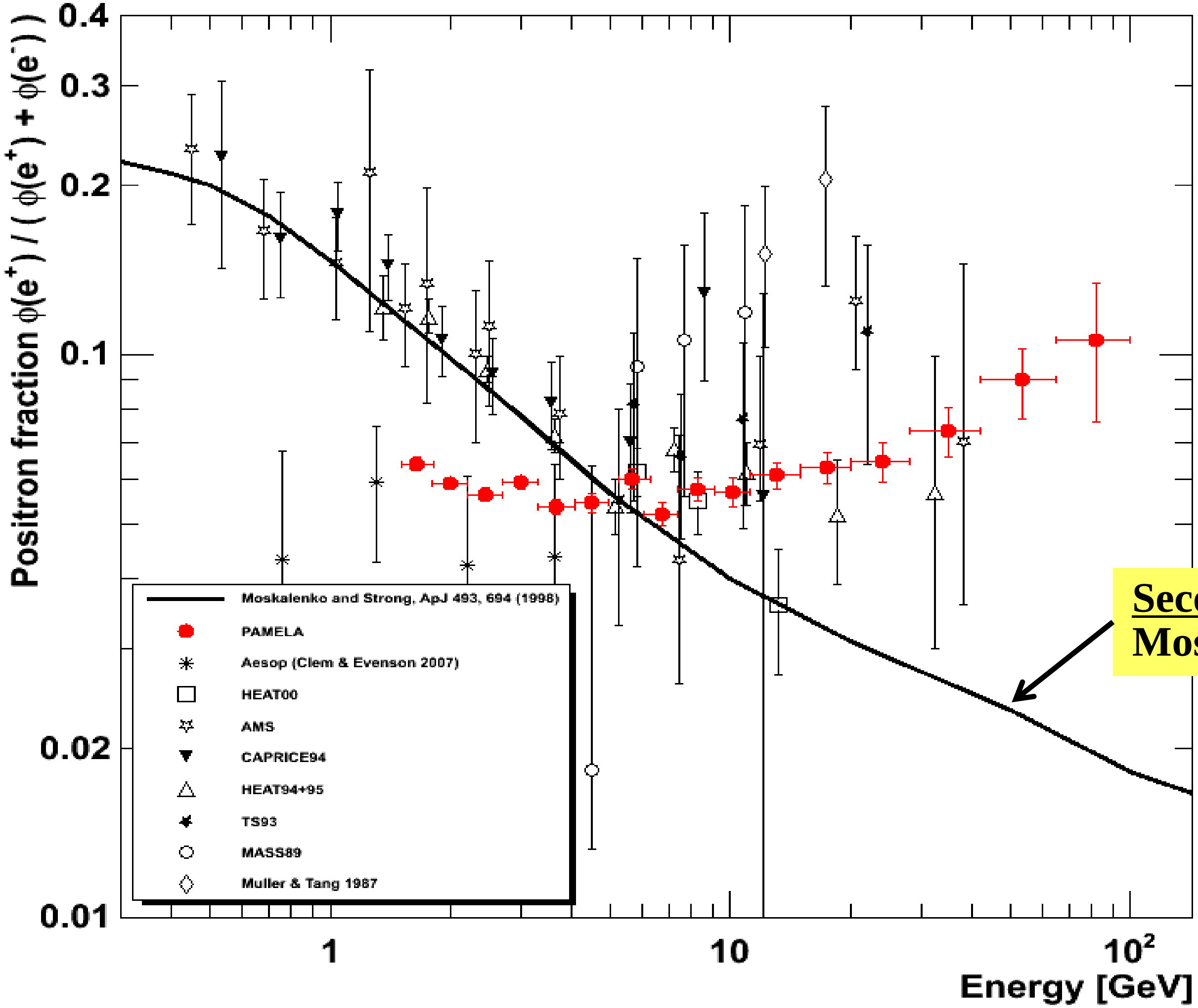


Fraction of charge released along the calorimeter track (left, hit, right)

+

- **Energy-momentum match**
- **Starting point of shower**

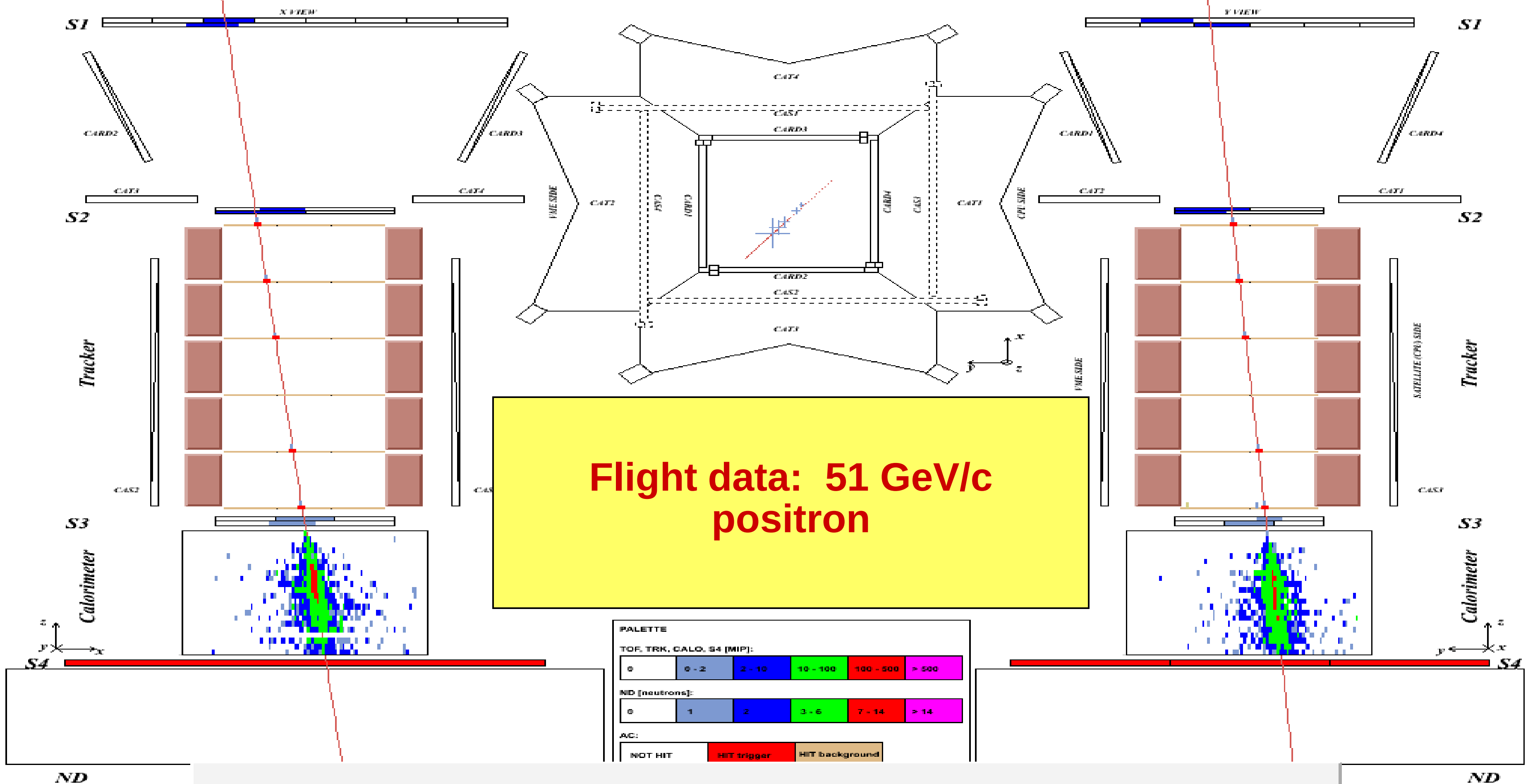
Positron to Electron Fraction

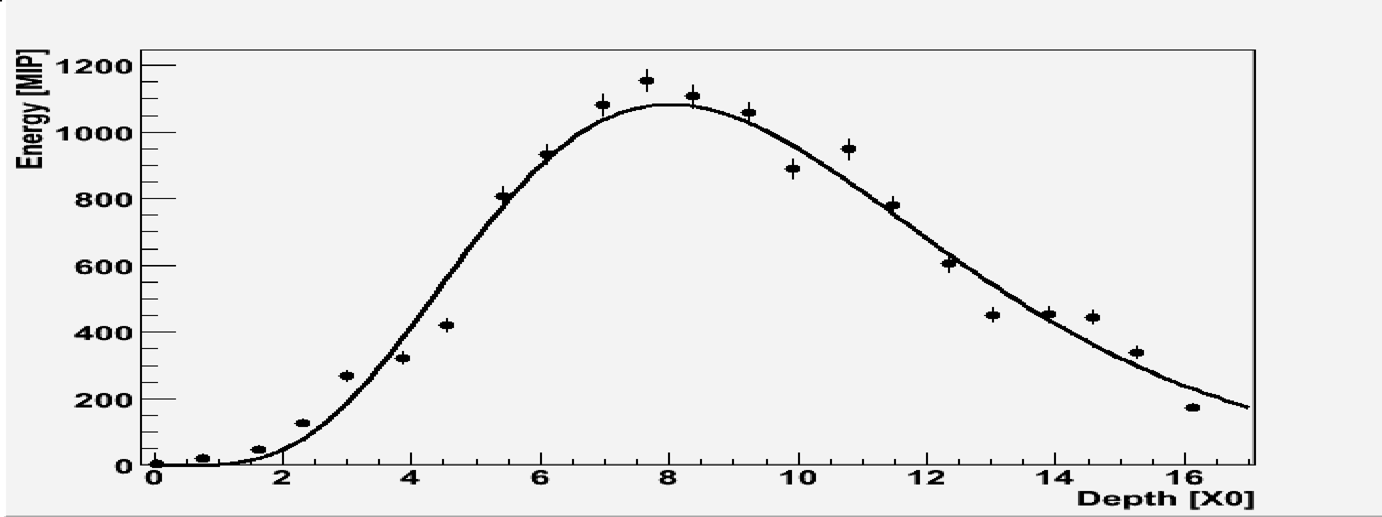


Secondary production
Moskalenko & Strong 98

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

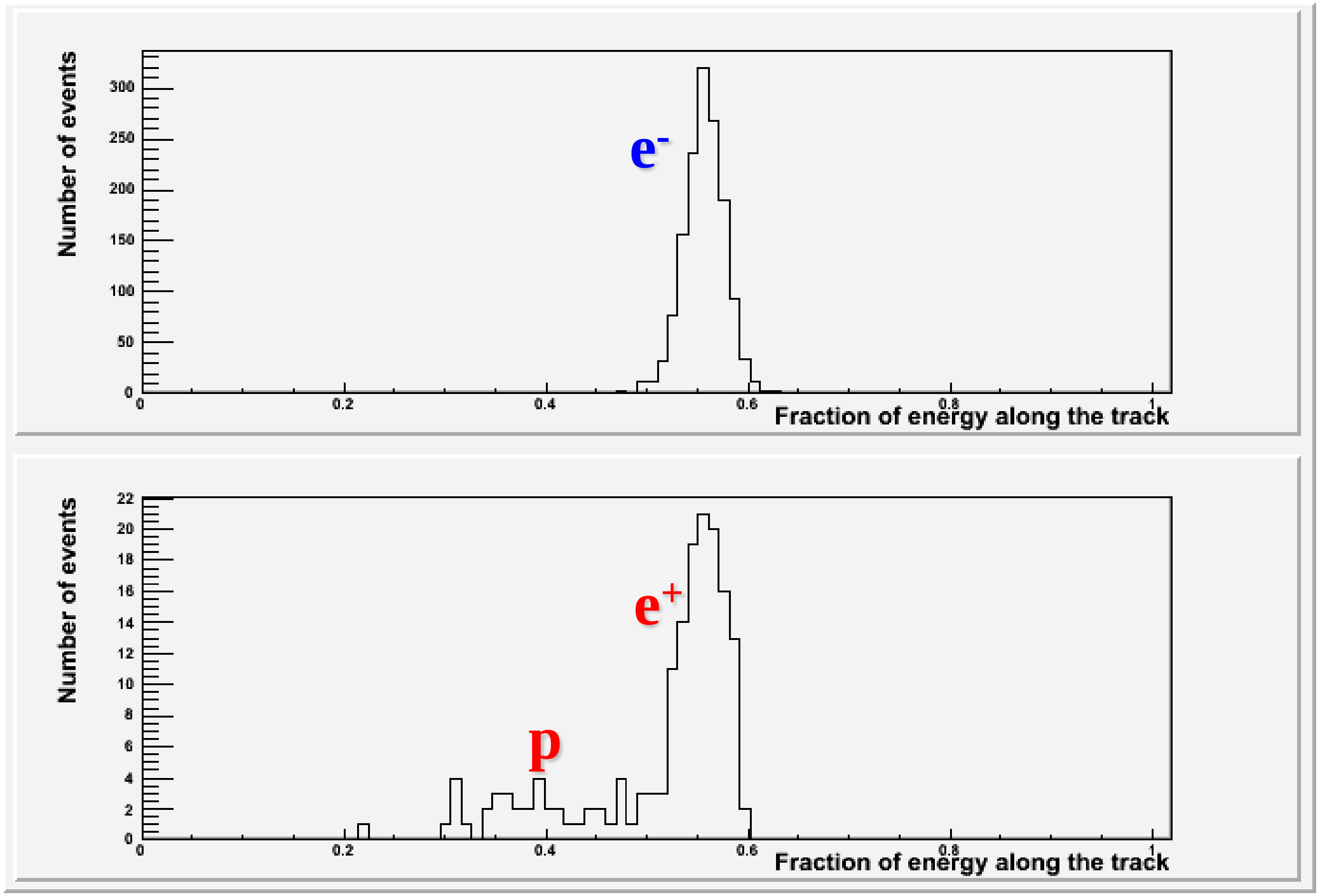
Flight data: 51 GeV/c positron





Positron selection with calorimeter

Rigidity: 20-30 GV



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

+

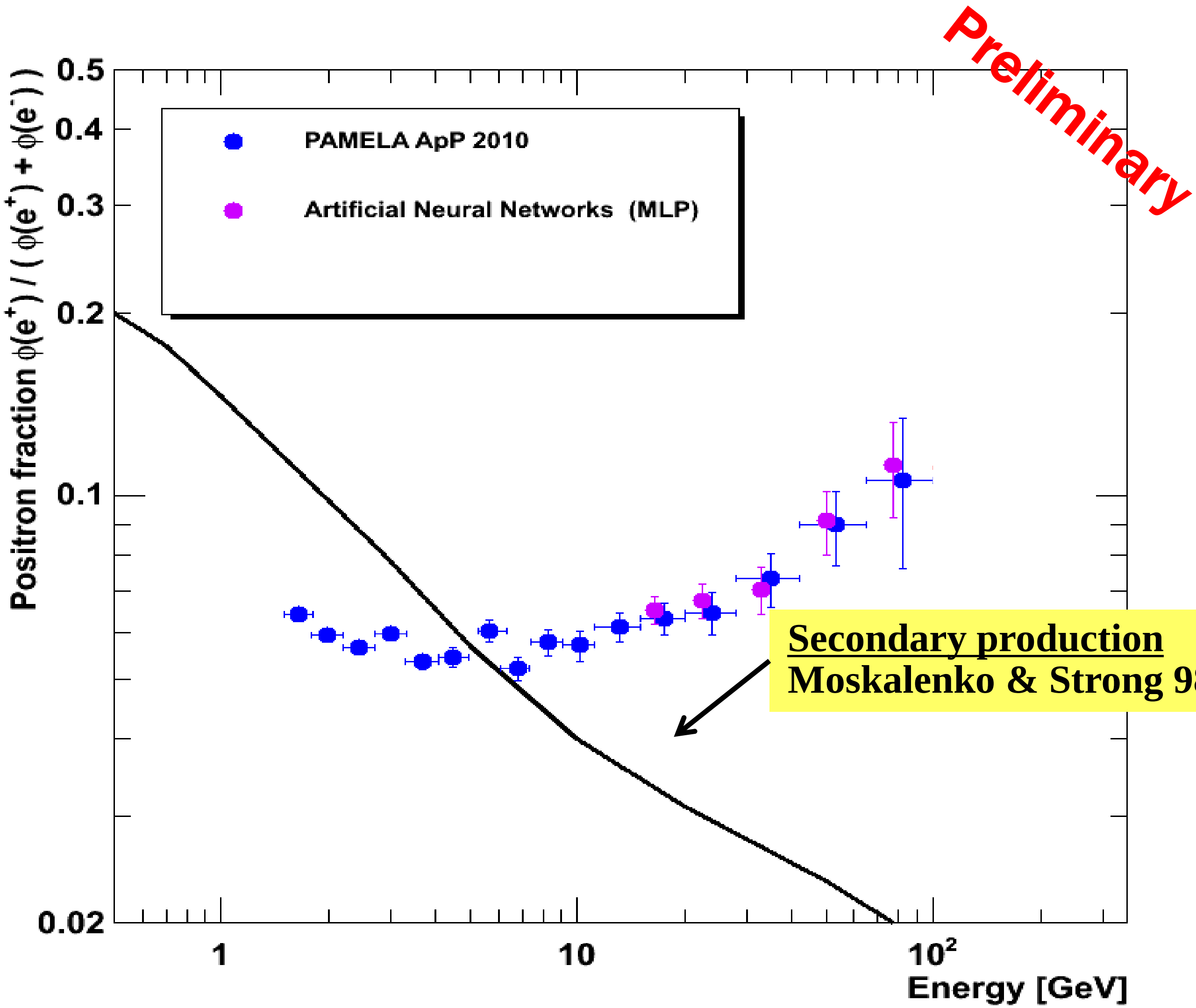
- **Energy-momentum match**
- **Starting point of shower**
- **Longitudinal profile**

PaMeLa

INFN Istituto Nazionale di Fisica Nucleare

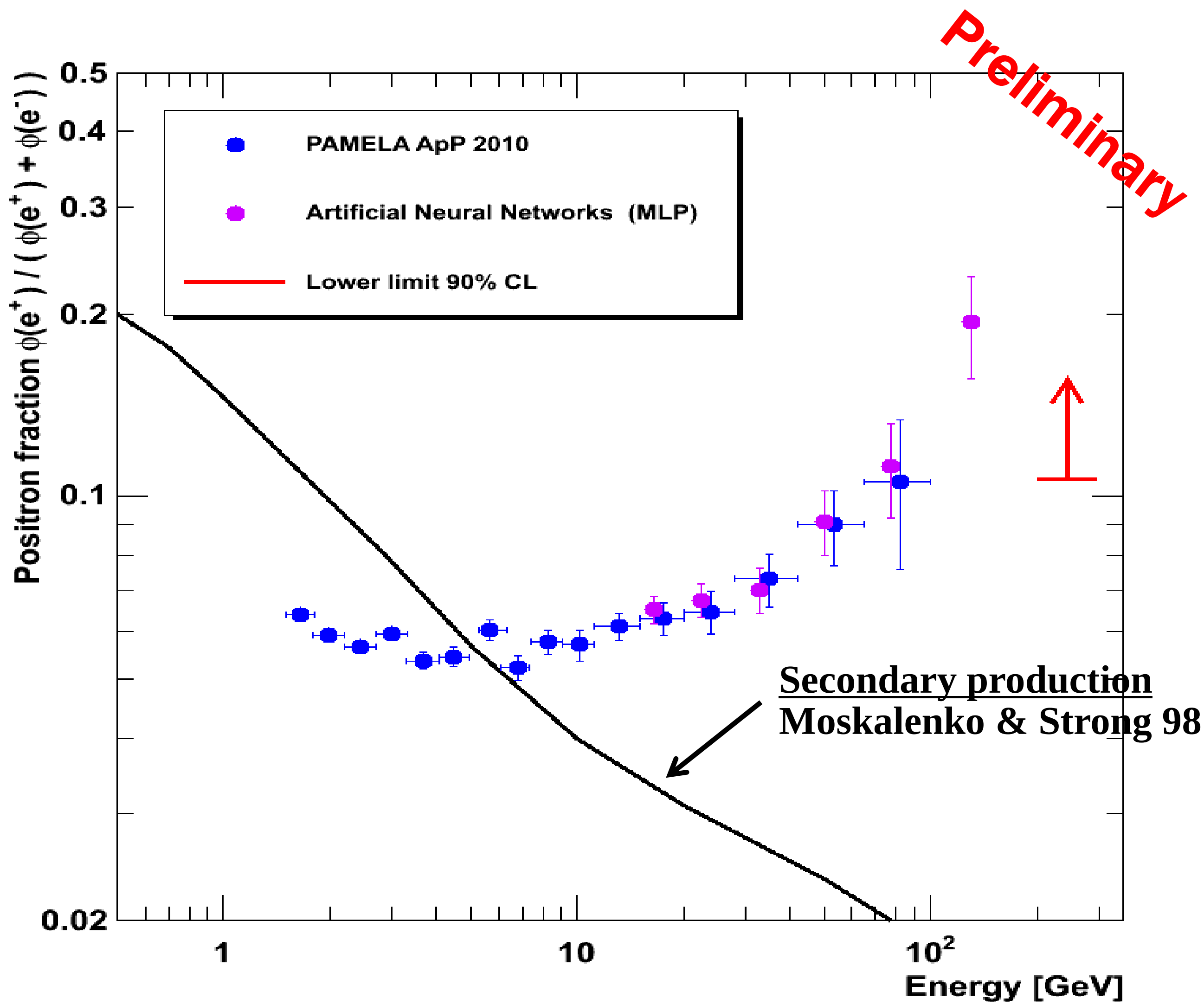
Positron to Electron Fraction

Using all data till beginning of 2010, the whole calorimeter and multivariate classification algorithms we can improve the statistical significance

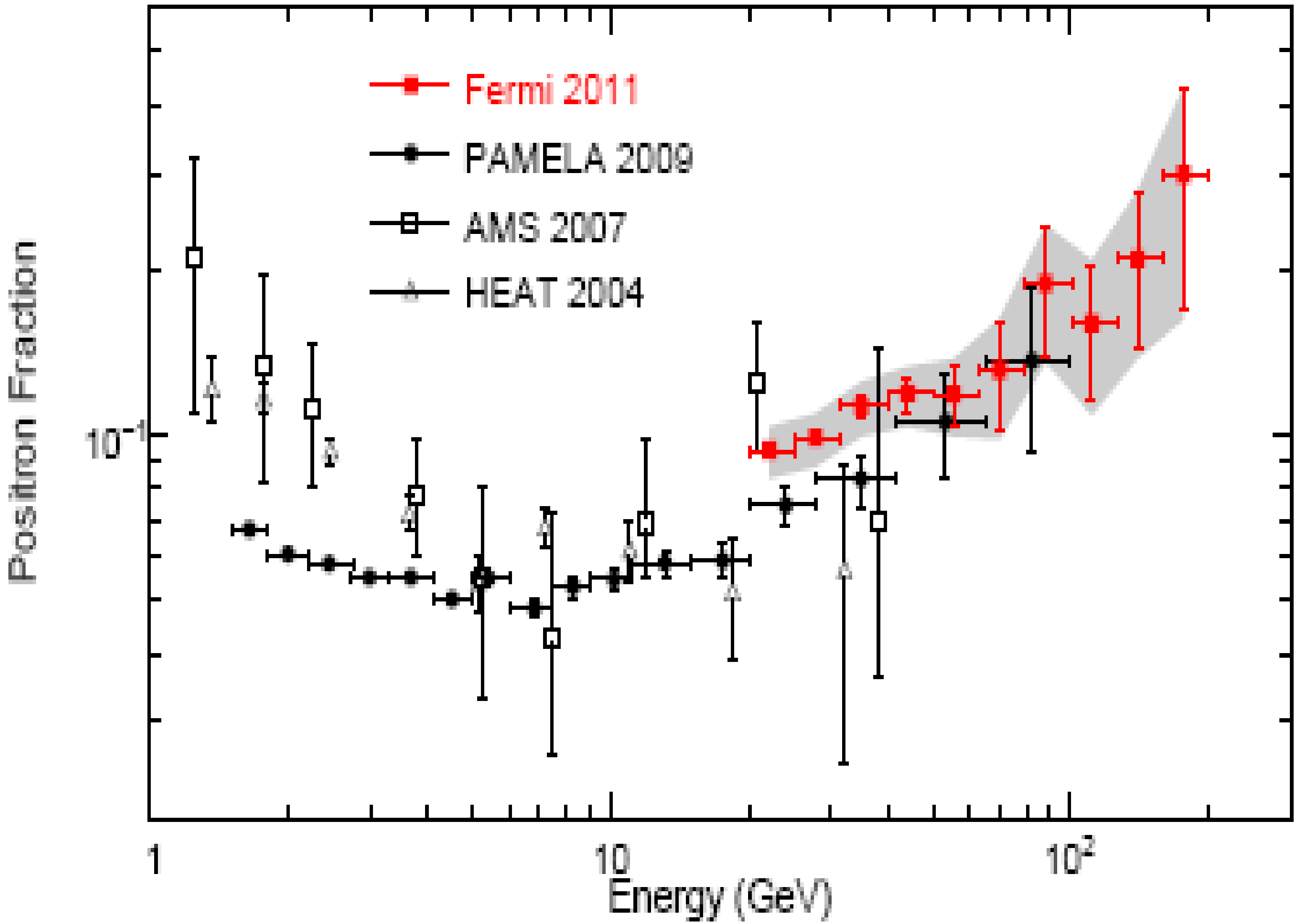


PAMELA Positron to Electron Fraction

Using all data till beginning of 2010, the whole calorimeter and multivariate classification algorithms we can improve the statistical significance and extend the measurements above 100 GeV

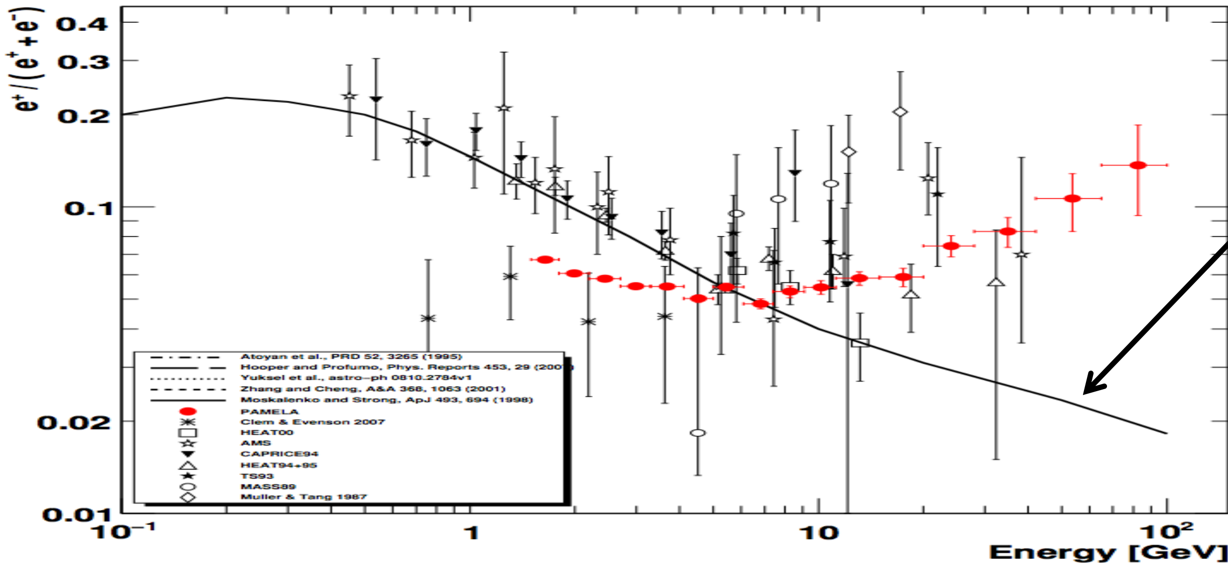


PAMELA & Fermi Positron Fraction



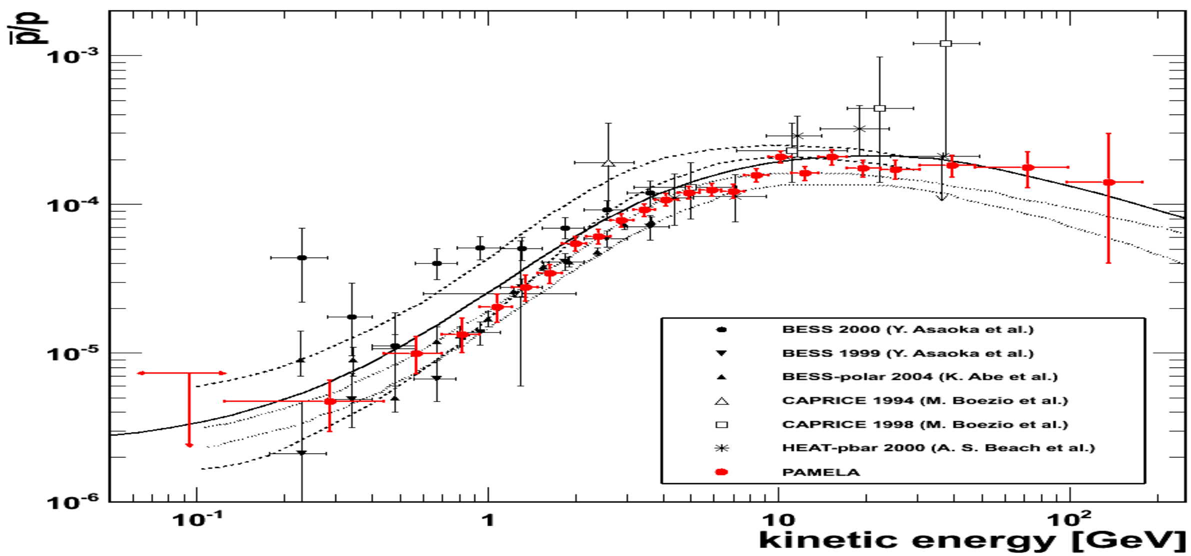
M. Ackermann, astro-ph: 1109.0521

A Challenging Puzzle for CR Physics



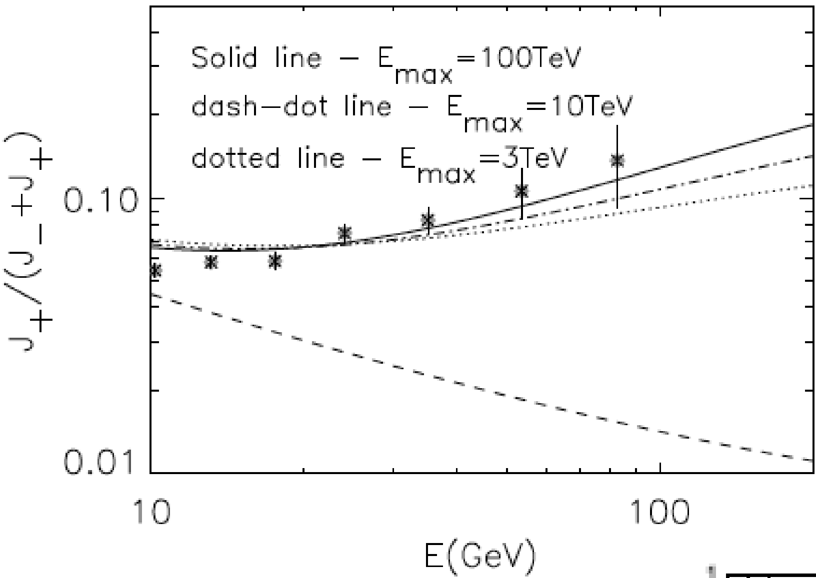
Uncertainties on:

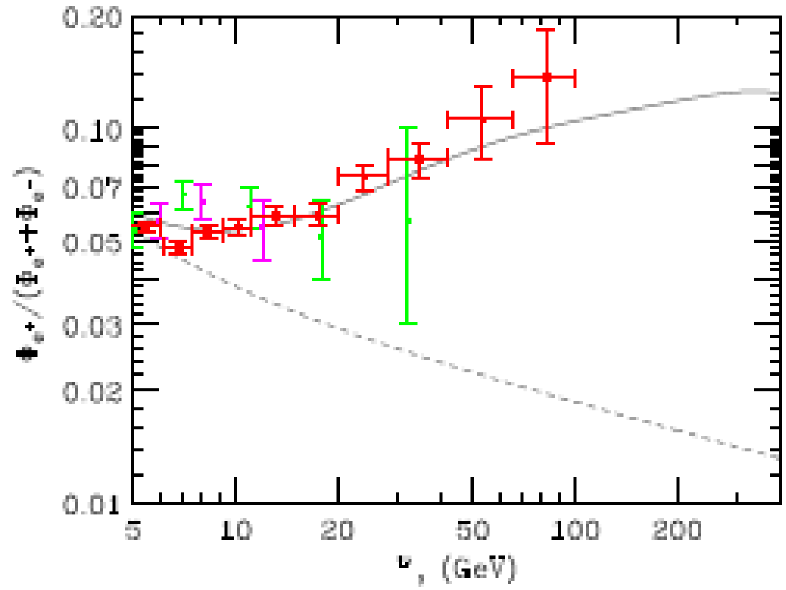
- Secondary production (primary fluxes, cross section)
- Propagation models
- Electron spectrum



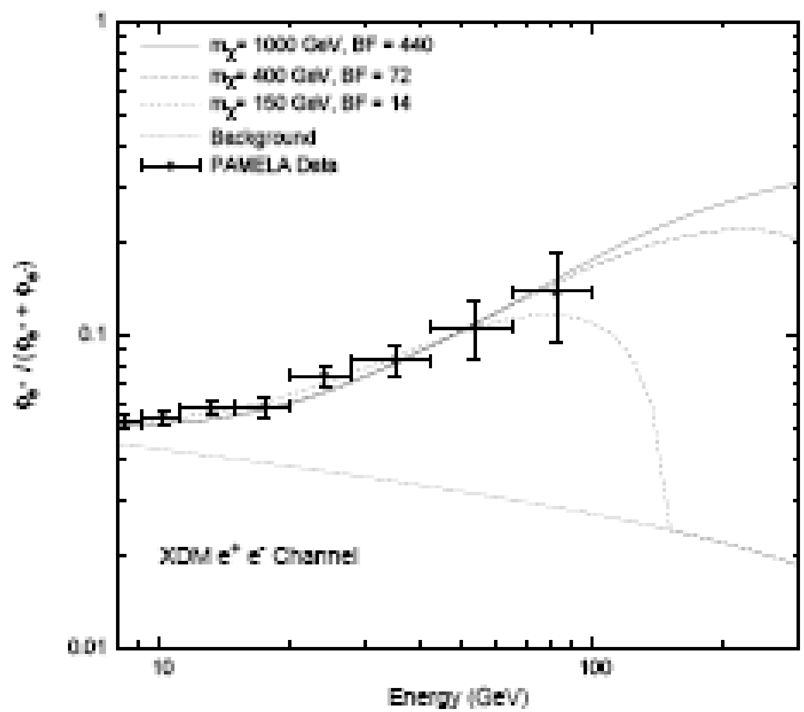
But antiprotons in CRs are in agreement with secondary production

A Challenging Puzzle for CR Physics





P.Blasi, PRL 103 (2009) 051104; arXiv:0903.2794
Positrons (and electrons) produced as secondaries in the sources (e.g. SNR) where CRs are accelerated.



i, and P. Serpico, JCAP
Xiv:0810.1527
diffuse mature &nearby

I. Cholis et al., Phys. Rev. D 80 (2009) 123518; arXiv:0811.3641v1
Contribution from DM annihilation.

ELECTRONS

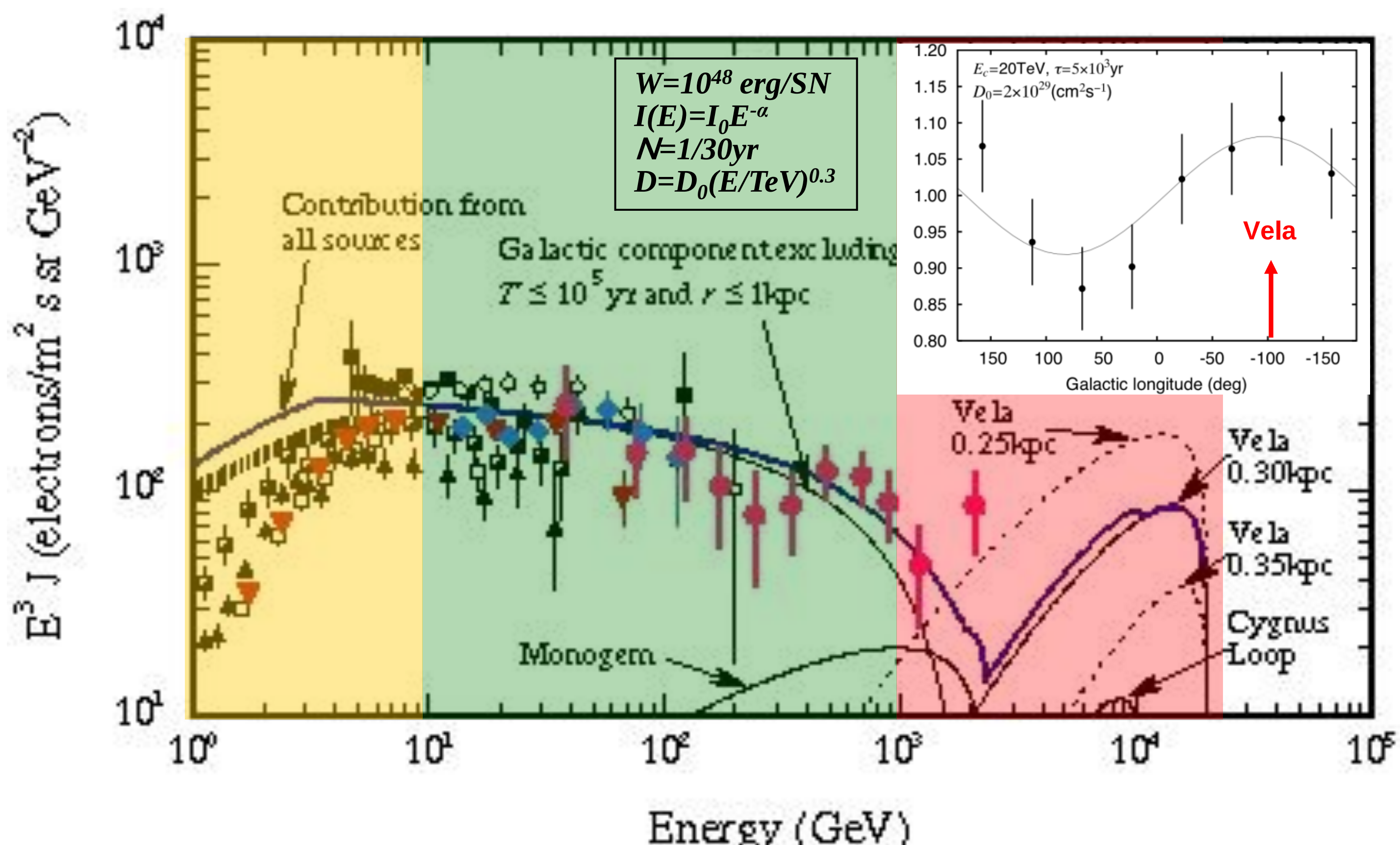
All Electron (e^- + e^+) spectra

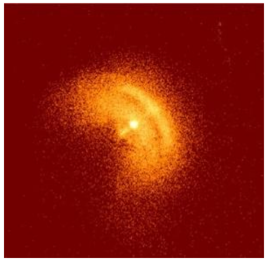
Possible Nearby Sources
- T< 10^5 years
- L< 1 kpc

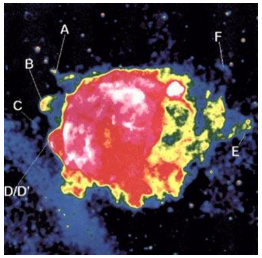
Search for the signature of nearby HE electron sources (believed to be SNR) in the electron spectrum above ~TeV

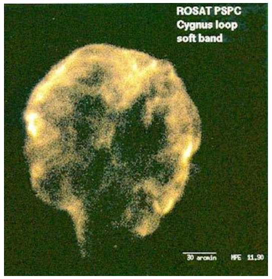
Precise measurement of electron spectrum above 10 GeV to define a model of acceleration and propagation.

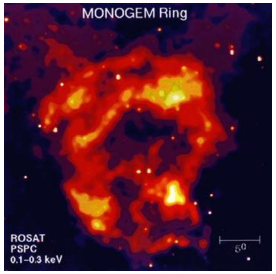
Observation of electron spectrum in 1~10 GeV for study of solar modulation




Chandra

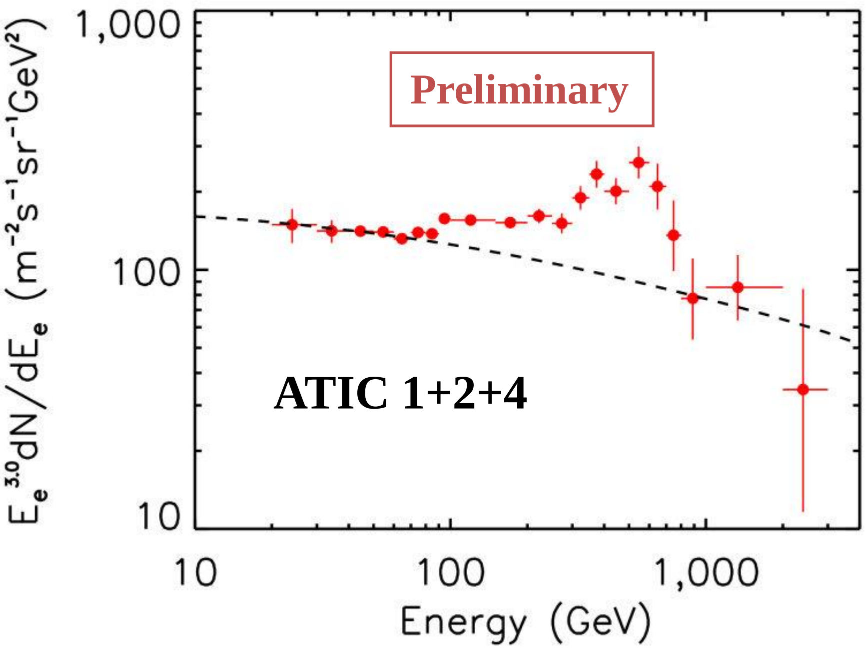
ROSAT


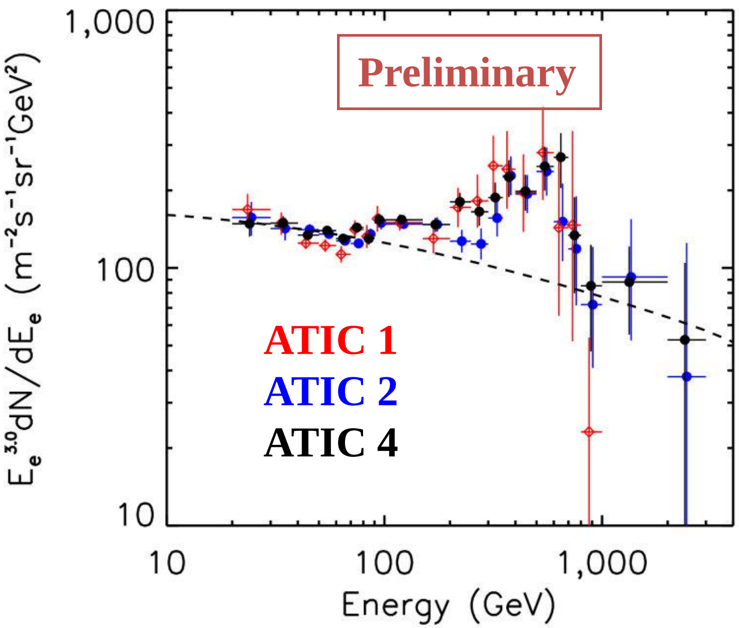




Calculations by T. Kobayashi et al, 601 (2004) 340.

All three ATIC flights are consistent





"Source on/source off" significance of bump for ATIC1+2 is about 3.8 sigma

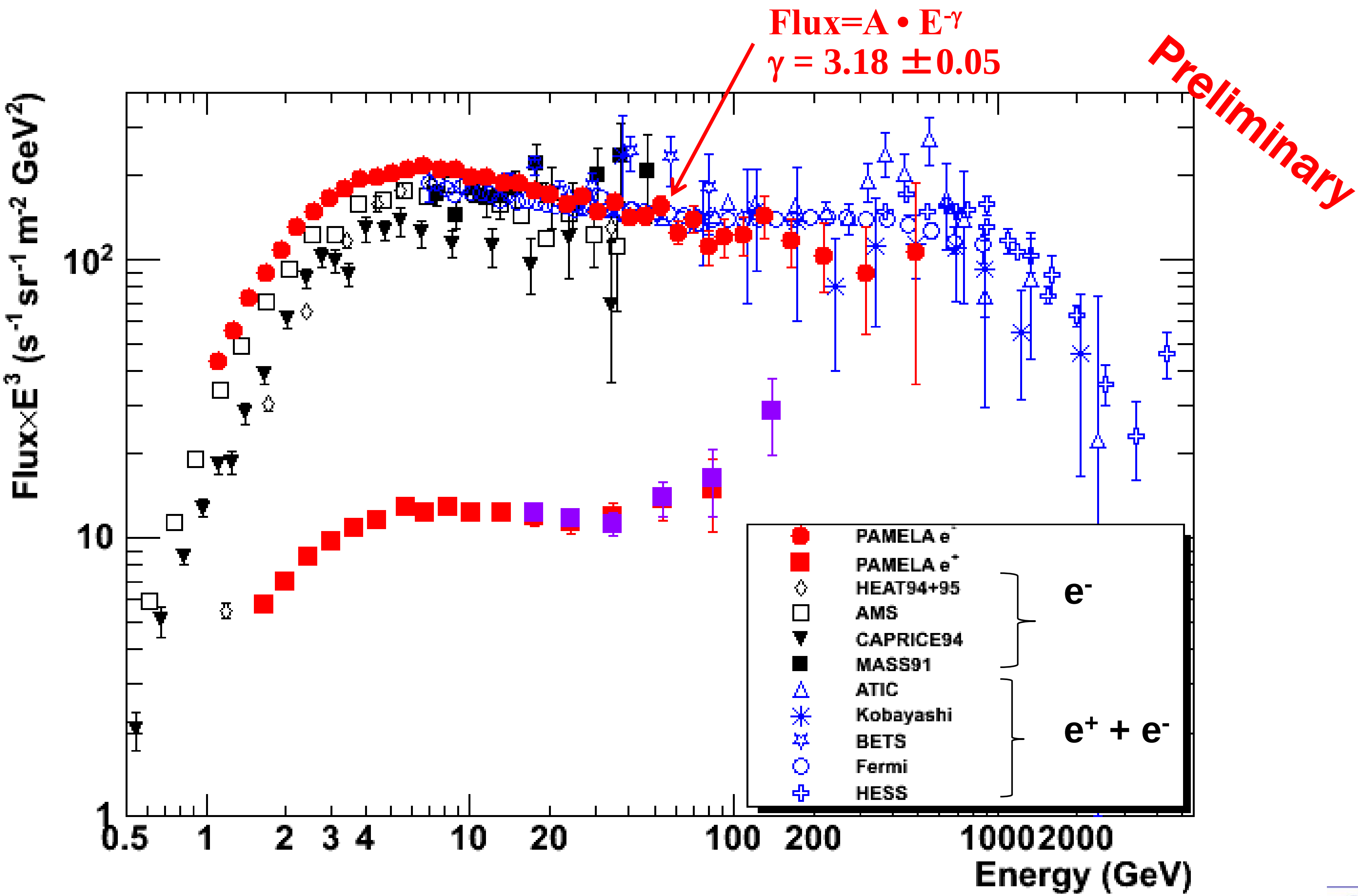
J Chang *et al. Nature* **456**, 362 (2008)

ATIC-4 with 10 BGO layers has improved e , p separation. **(~4x lower background)**

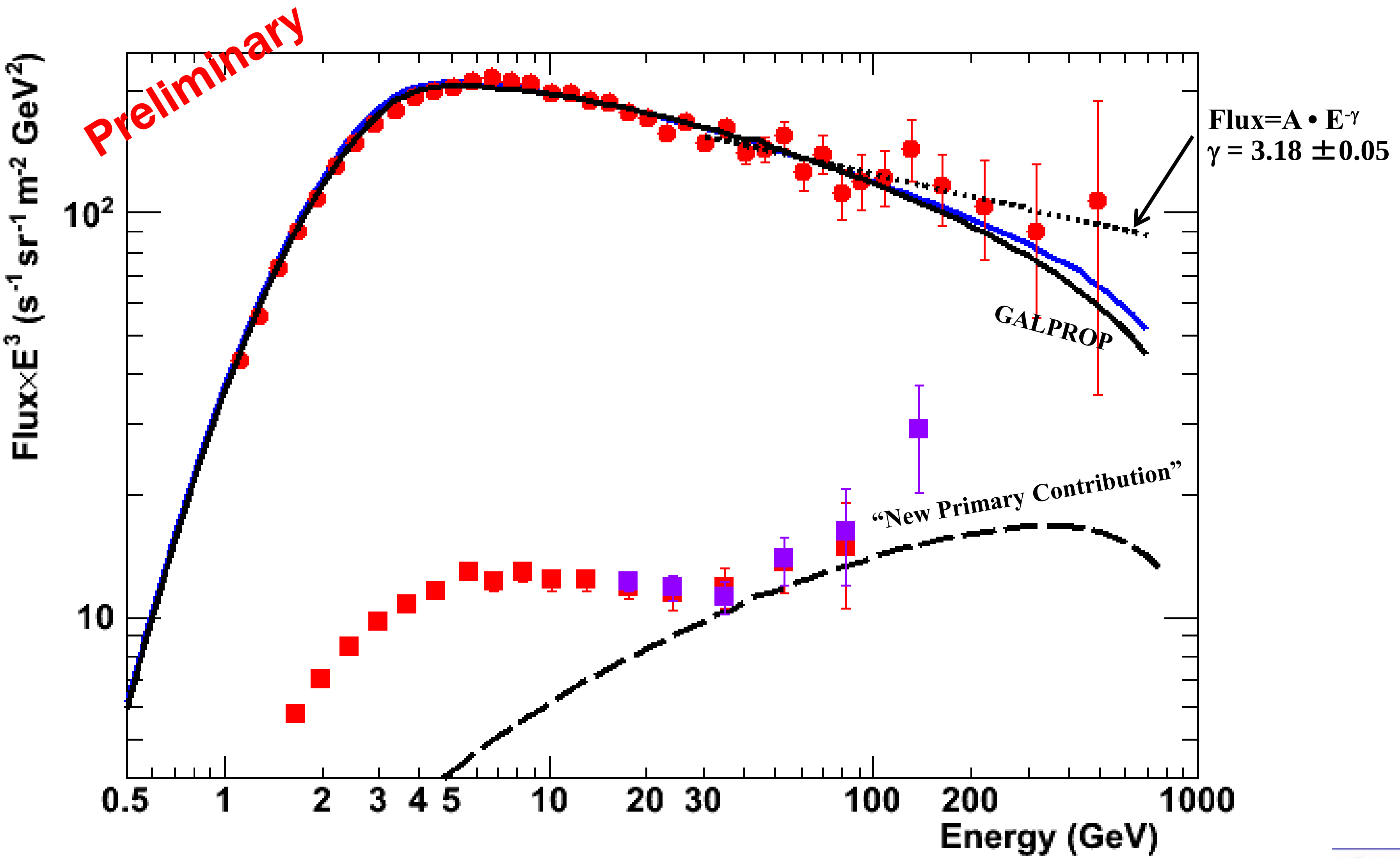
"Bump" is seen in all three flights.

Significance for ATIC1+2+4 is 5.1 sigma

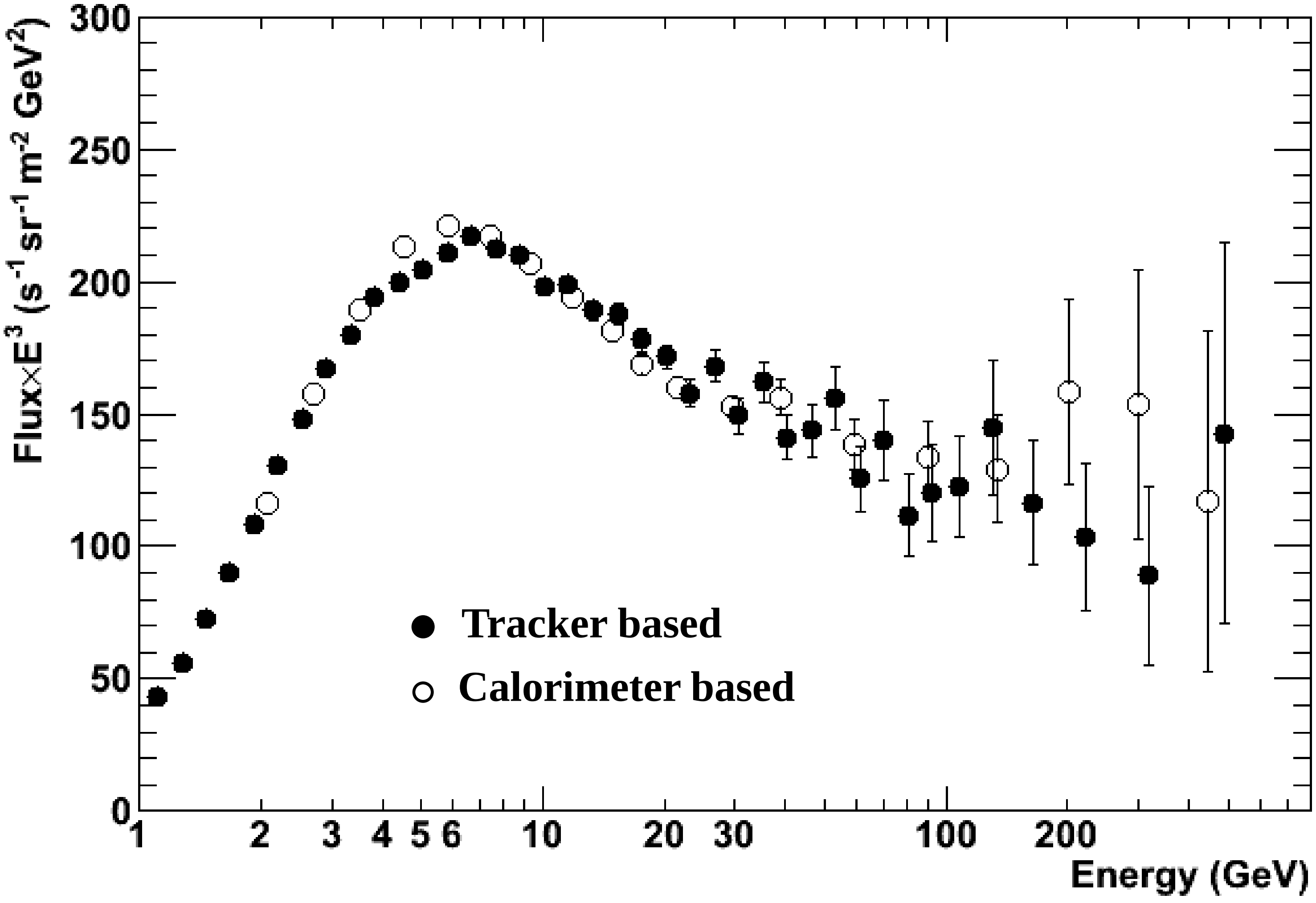
PAMELA e^- and e^+ spectra



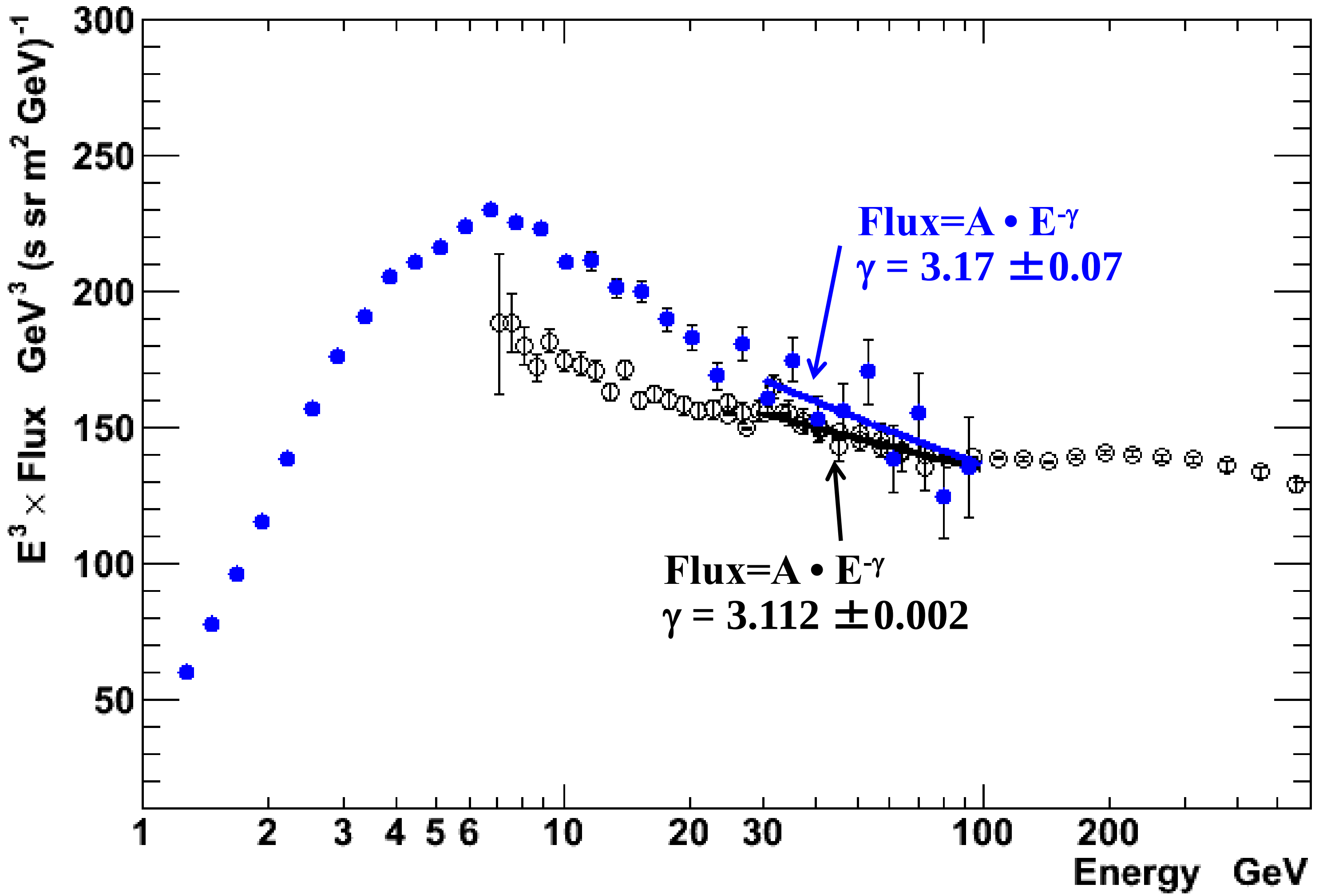
PAMELA e^- and e^+ spectra



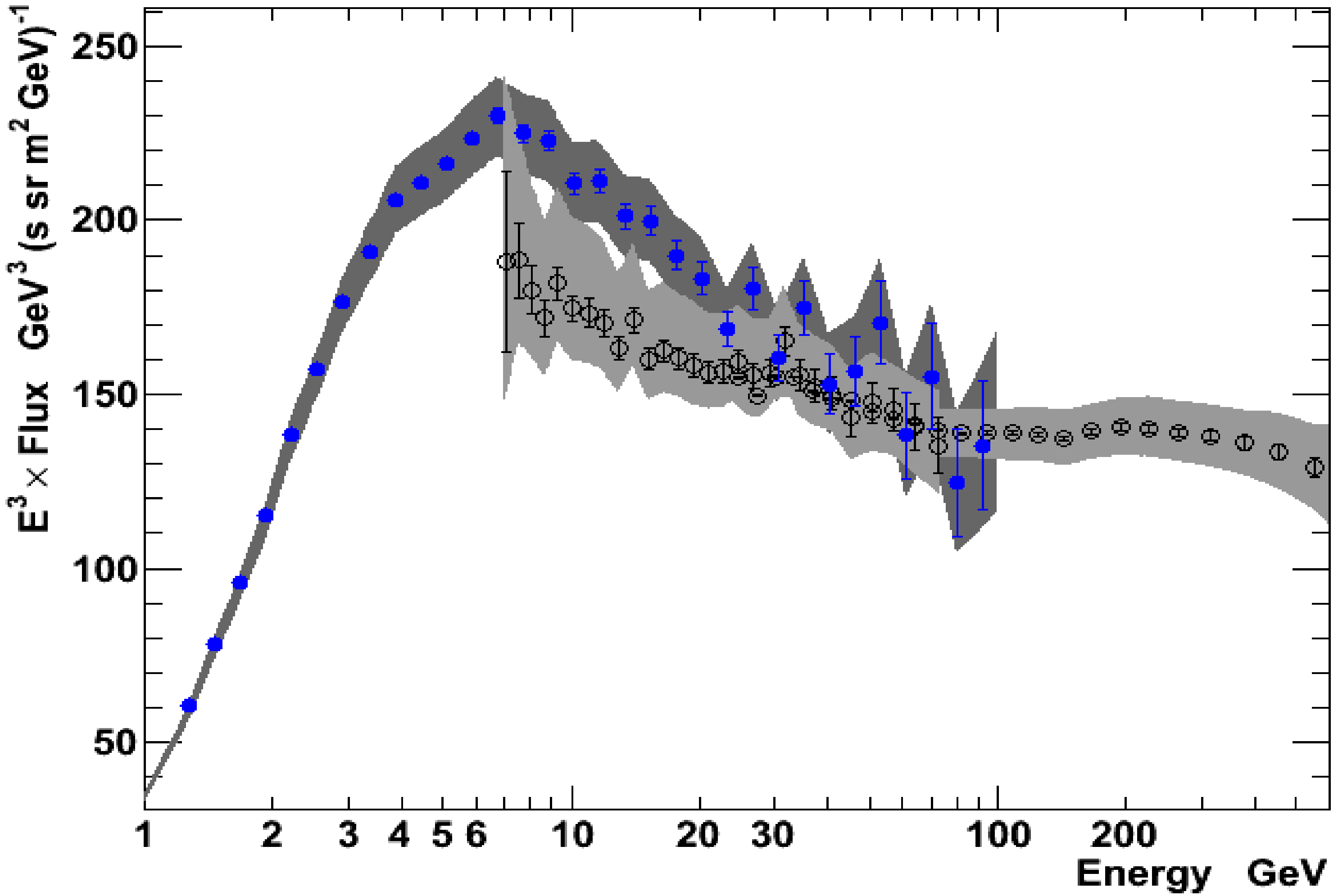
PAMELA electron (e^-) spectrum



PAMELA & Fermi electron ($e^{-}+e^{+}$) spectra



PAMELA & Fermi electron ($e^{-}+e^{+}$) spectra



Summary

- PAMELA has been in orbit and studying cosmic rays for 5 years. >10^9 triggers registered and >25 TB of data have been down-linked.

- The proton and helium nuclei spectra have been measured up to 1.2 TV. The observations challenge the current paradigm of cosmic ray acceleration and propagation.

- Antiproton-to-proton flux ratio and antiproton energy spectrum (~100 MeV - ~200 GeV) show no <u>significant</u> deviations from secondary production expectations.
- High energy positron fraction (>10 GeV) increases significantly (and unexpectedly!) with energy. Primary source?

- The e^- spectrum up to 600 GeV shows spectral features that may point to additional components.

- Waiting for AMS to compare contemporary measurements.

Thanks!