New PAMELA Results

Mirko Boezio
INFN Trieste, Italy

On behalf of the PAMELA collaboration

Dmatter Workshop, KITP, Santa Barbara

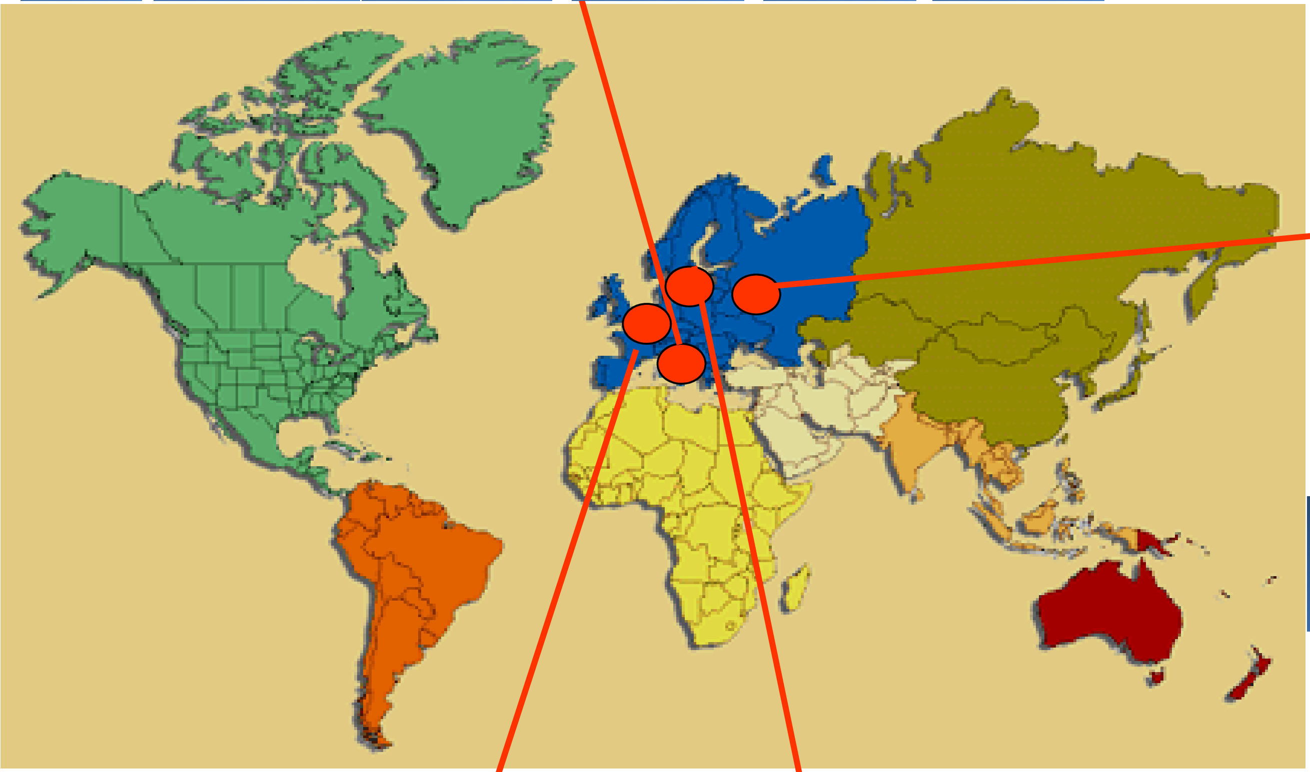
December 8th 2009

PAMELA

Payload for Antimatter Matter Exploration and Light Nuclei Astrophysics

PAMELA Collaboration

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



Russia:

Ioffe Physico-Technical Institute

Moscow
St. Petersburg

Germany: Universität Gesamthochschule Siegen

Siegen

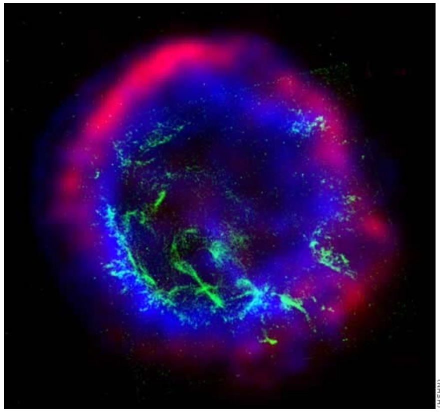
Sweden: Kungl Tekniska Högskolan

KTH, Stockholm

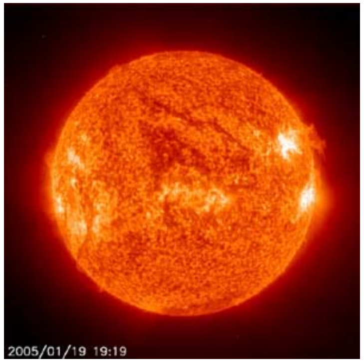
INFN Istituto Nazionale di Fisica Nucleare

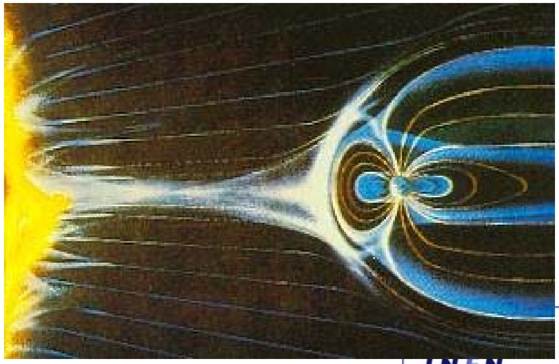
Scientific goals

- Search for dark matter annihilation
- Search for antihelium (primordial antimatter)



- Study of cosmic-ray propagation (light nuclei and isotopes)
- Study of electron spectrum (local sources?)
- Study solar physics and solar modulation
- Study terrestrial magnetosphere





PAMELA apparatus

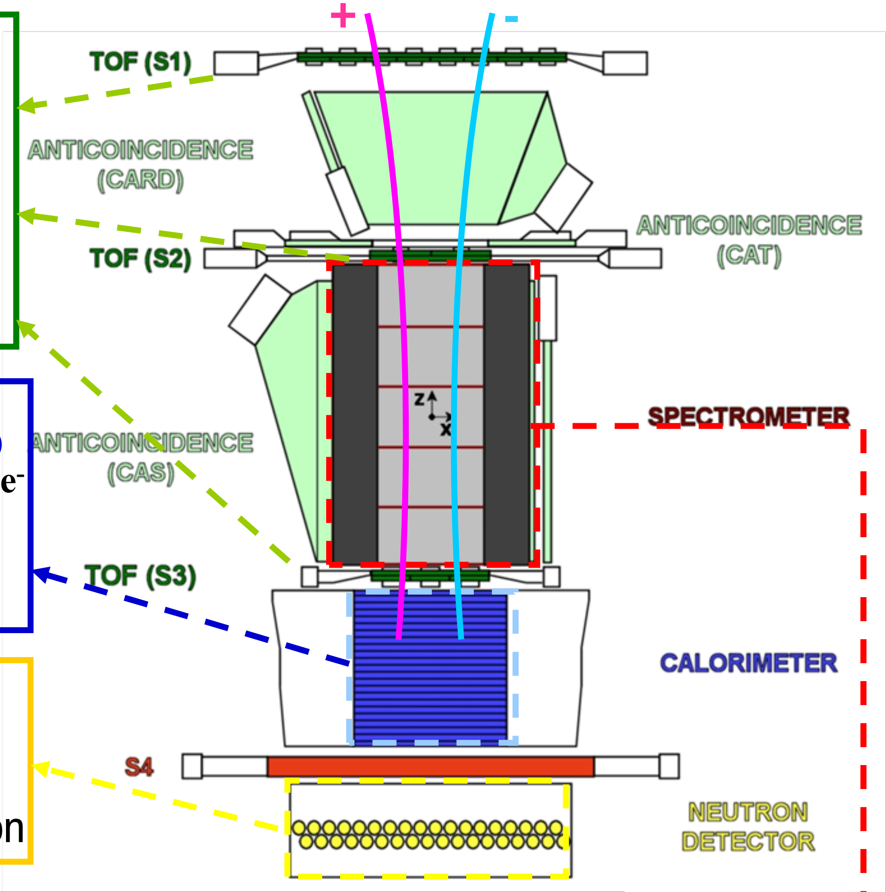
PAMELA detectors

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

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



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

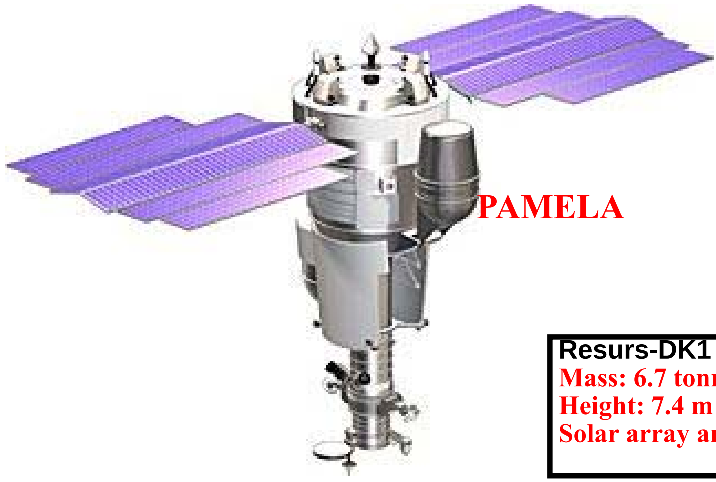
Spectrometer
microstrip silicon tracking system + permanent magnet
It provides:
- *Magnetic rigidity* → R = pc/Ze
- *Charge sign*
- *Charge value from dE/dx*

Design Performance

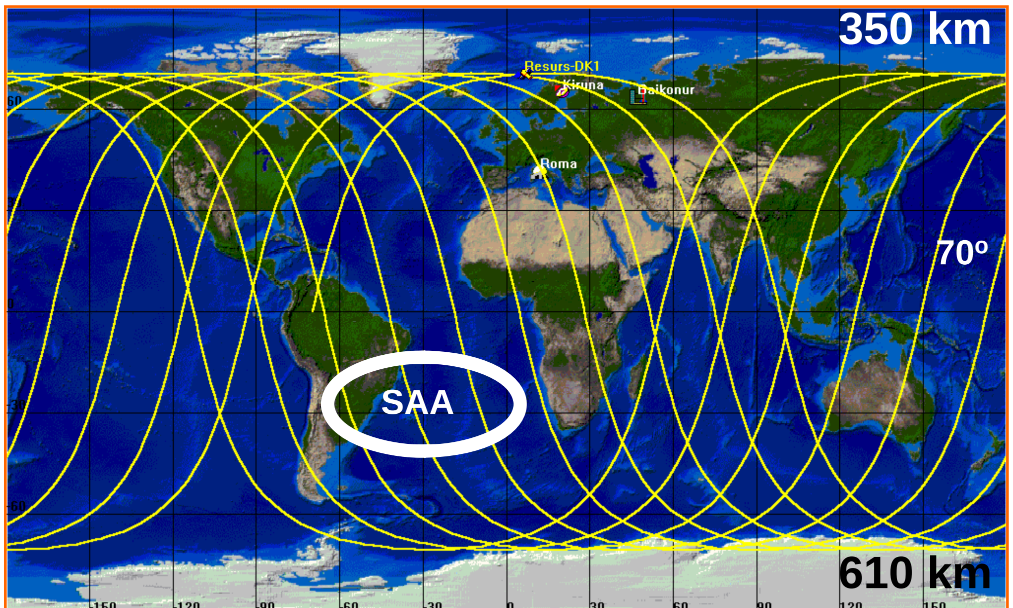
	energy range
• Antiprotons	80 MeV - 190 GeV
• Positrons	50 MeV – 300 GeV
• Electrons	up to 500 GeV
• Protons	up to 700 GeV
• Electrons+positrons	up to 2 TeV (from calorimeter)
• Light Nuclei (He/Be/C)	up to 200 GeV/n
• AntiNuclei search	sensitivity of $3x10^{-8}$ in $\overline{\mathrm{He}}$/He

→ Simultaneous measurement of many cosmic-ray species
→ New energy range
→ Unprecedented statistics

Resurs-DK1 satellite + orbit



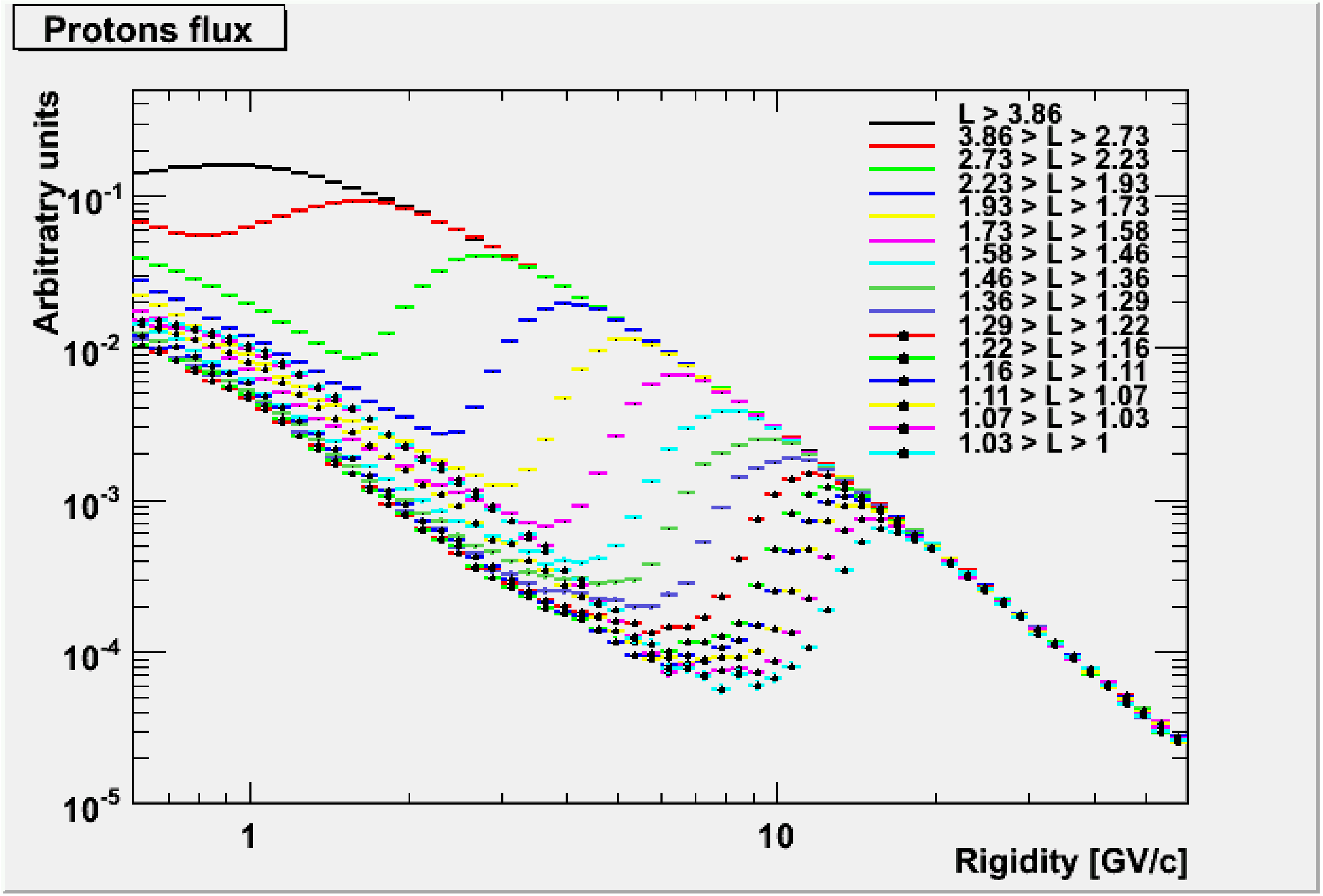
Resurs-DK1
Mass: 6.7 tonnes
Height: 7.4 m
Solar array area: 36 m^2



~90 mins

- **Resurs-DK1: multi-spectral imaging of earth's surface**
- **PAMELA mounted inside a pressurized container**
- **Lifetime >3 years (assisted, first time last February). Expected till end 2011.**
- **Data transmitted to NTsOMZ, Moscow via high-speed radio downlink. ~16 GB per day**
- **Quasi-polar and elliptical orbit (70.0°, 350 km - 600 km)**
- **Traverses the South Atlantic Anomaly**
- **Crosses the outer (electron) Van Allen belt at south pole**

Subcutoff particles



PAMELA milestones

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

Main antenna in NTsOMZ

‘First light’ → June 21st 2006, 0300 UTC.

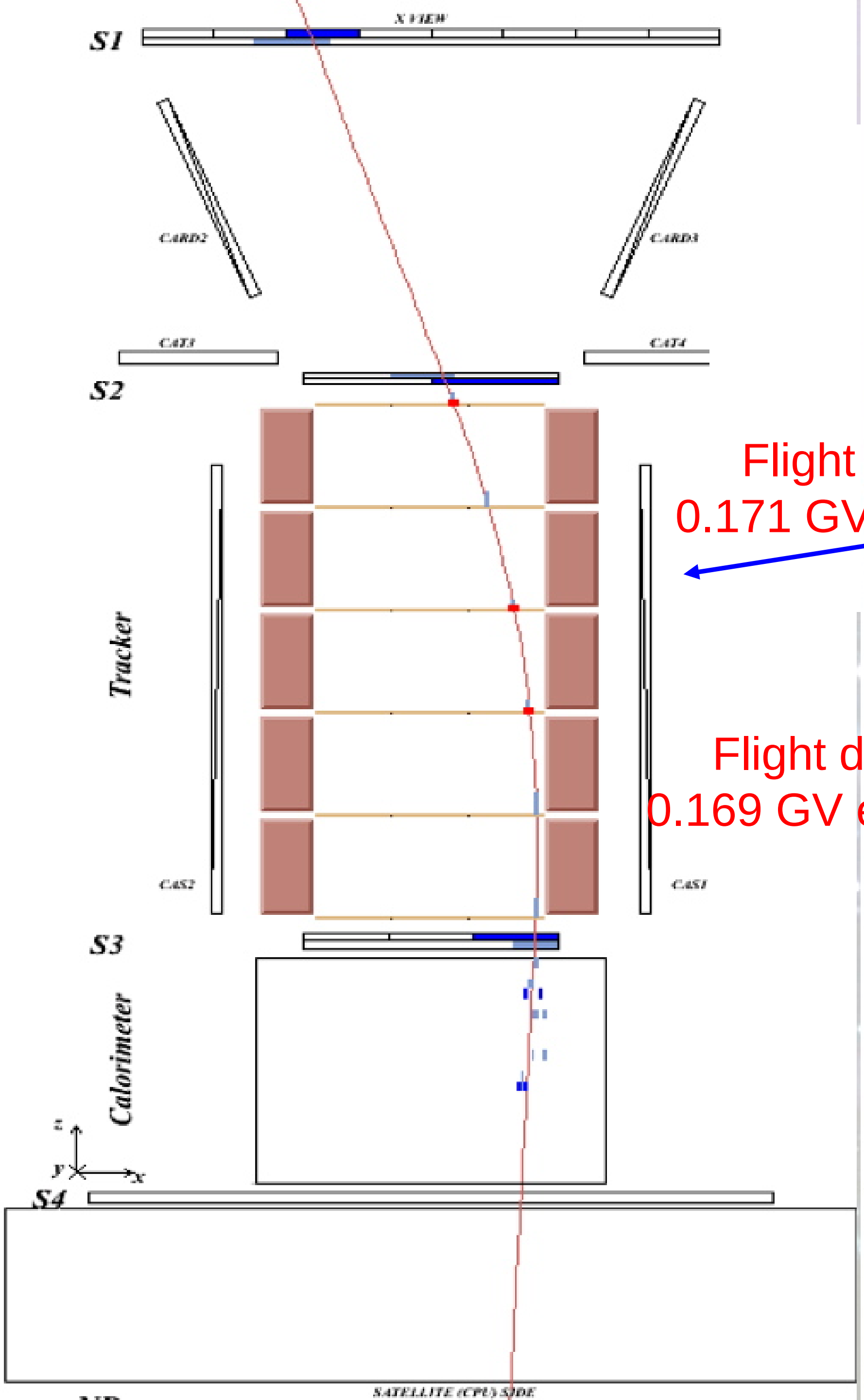
- Detectors operated as expected after launch
- Different trigger and hardware configurations evaluated

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

Trigger rate* ~25Hz
Fraction of live time* ~ 75%
Event size (compressed mode) ~5kB
25 Hz x 5 kB/ev → ~ 10 GB/day
(*outside radiation belts)

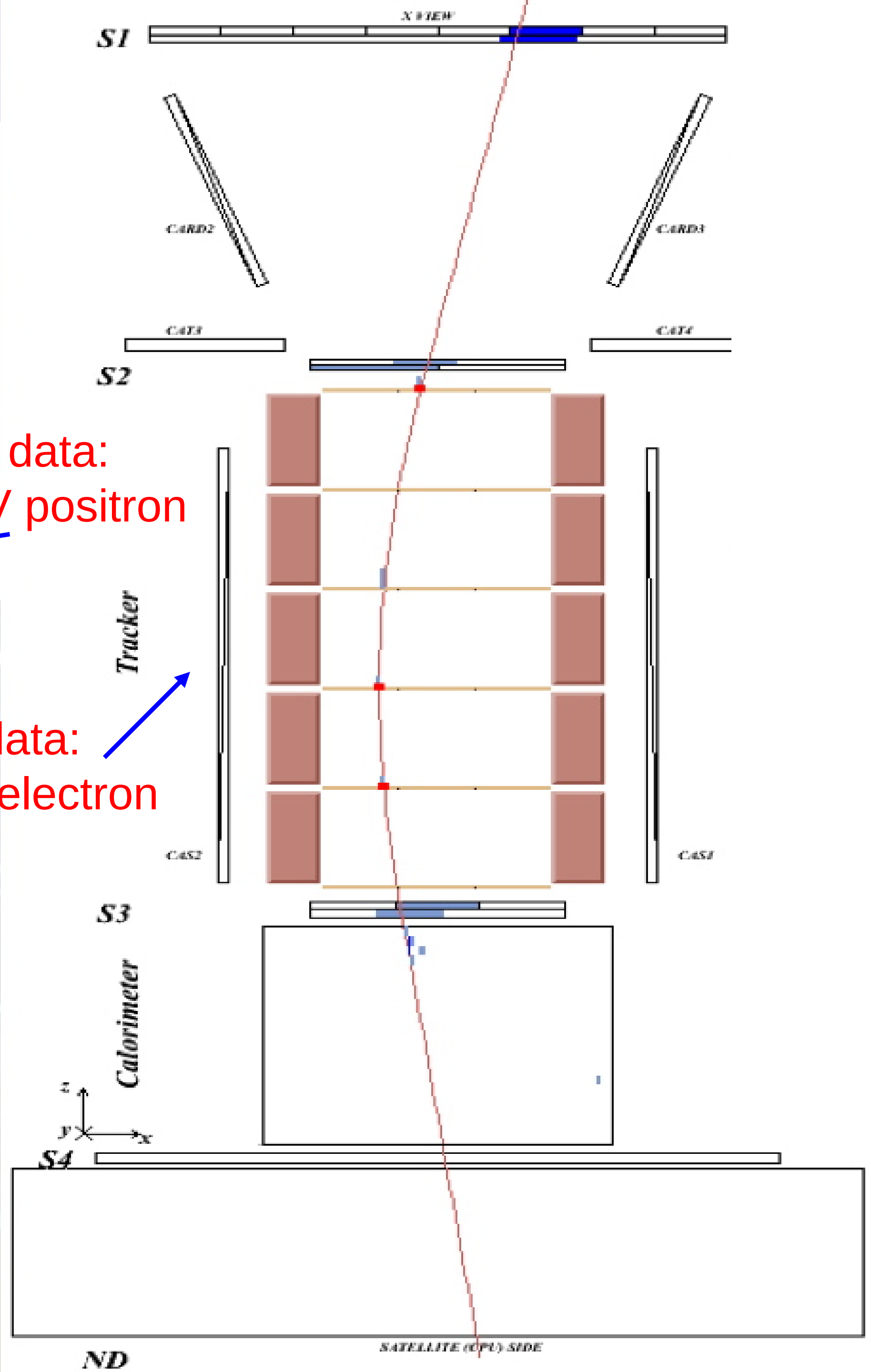
Till ~now:
~1200 days of data taking
~18 TByte of raw data downlinked
$>10^9$ triggers recorded and analyzed
(Data from April till December 2008 under analysis)

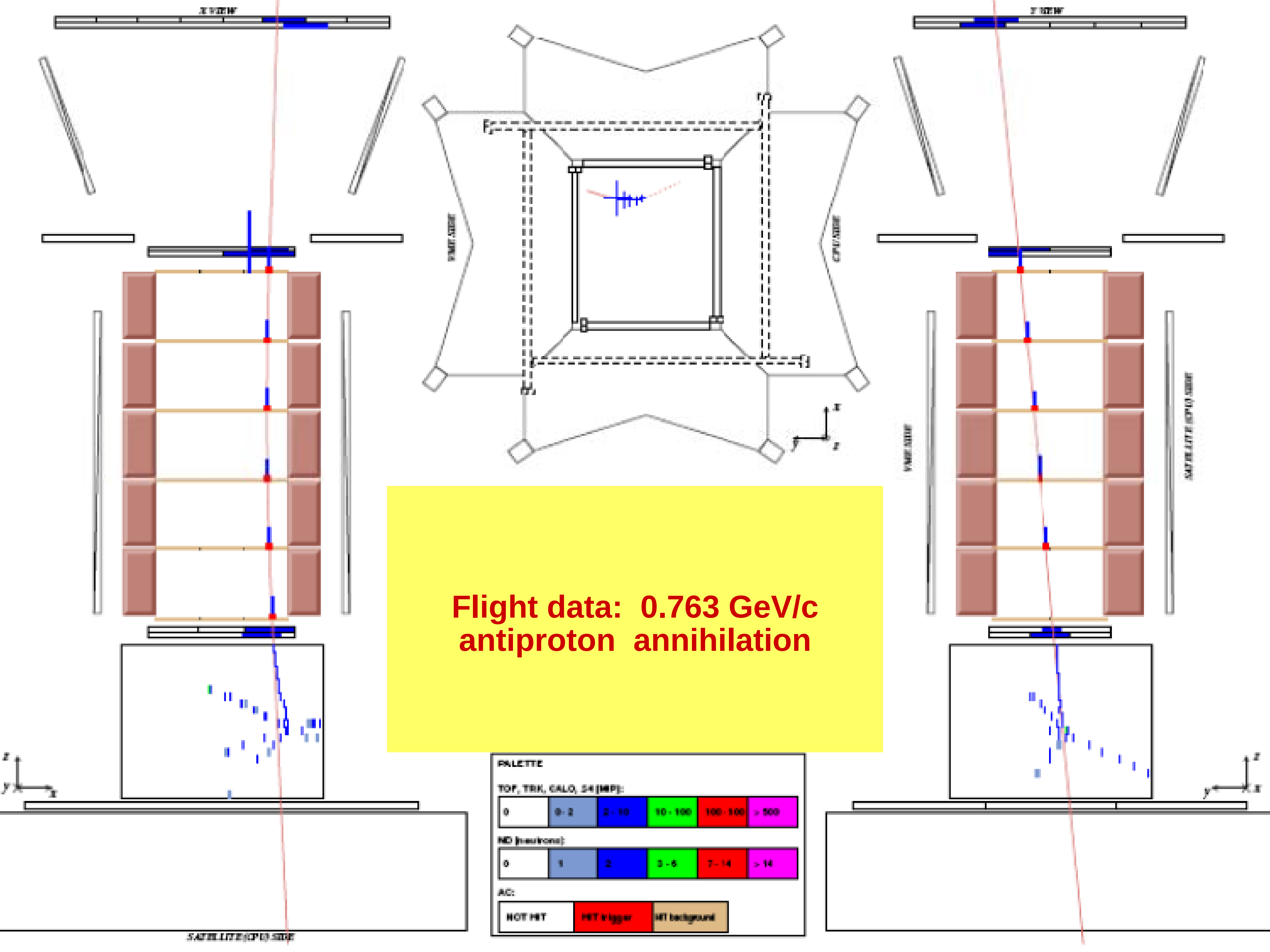
Antiparticles with PAMELA



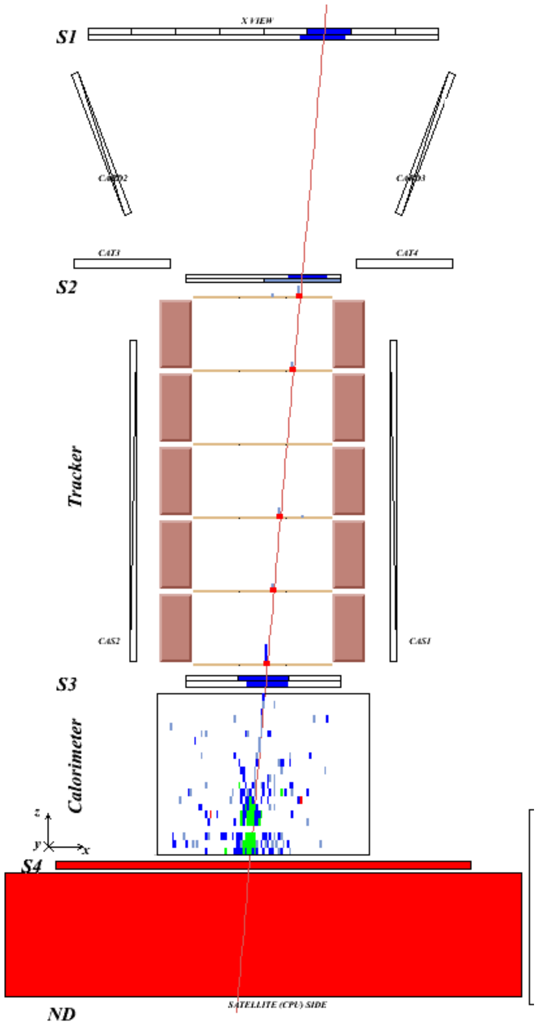
Flight data:
0.171 GV positron

Flight data:
0.169 GV electron




X VIEW
Y VIEW
VME SIDE
CPU SIDE
SATELLITE (CPU) SIDE
Flight data: 0.763 GeV/c
antiproton annihilation
PALETTE
TOF, TRK, CALO, S4 [MIP]:
0
0 - 2
2 - 10
10 - 100
> 500
ND [neutrons]:
0
1
2
3 - 6
7 - 14
> 14
AC:
NOT HIT
HIT trigger
HIT background

Antiproton / positron identification



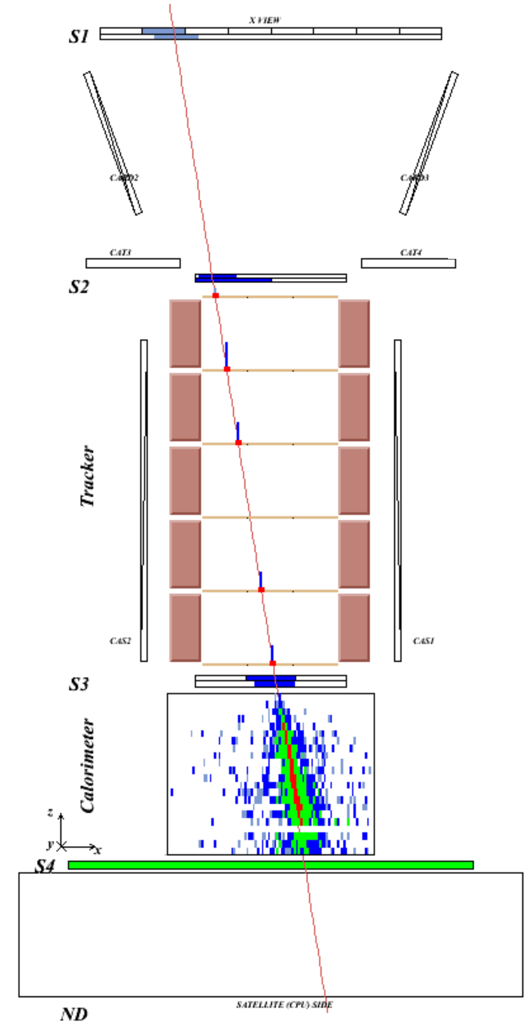
Antiproton
(NB: $e^-/\bar{p}$ ~ 10^2)

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

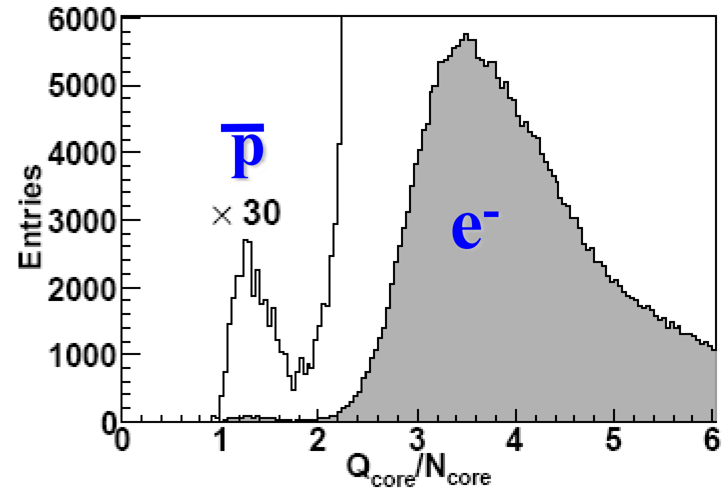
Interaction pattern in calorimeter:
electron-like or proton-like, electron energy

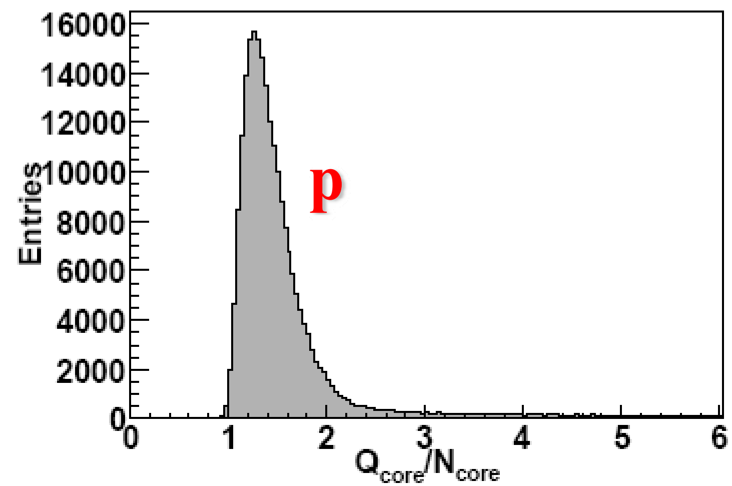


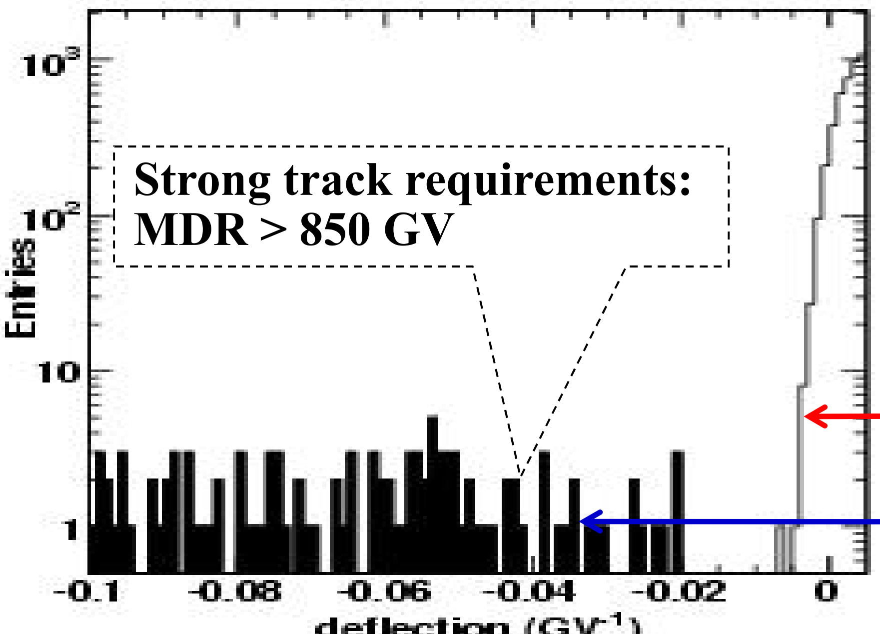
Positron
(NB: p/e^+ ~10^{3-4})

ANTIPROTONS

Calorimeter selection







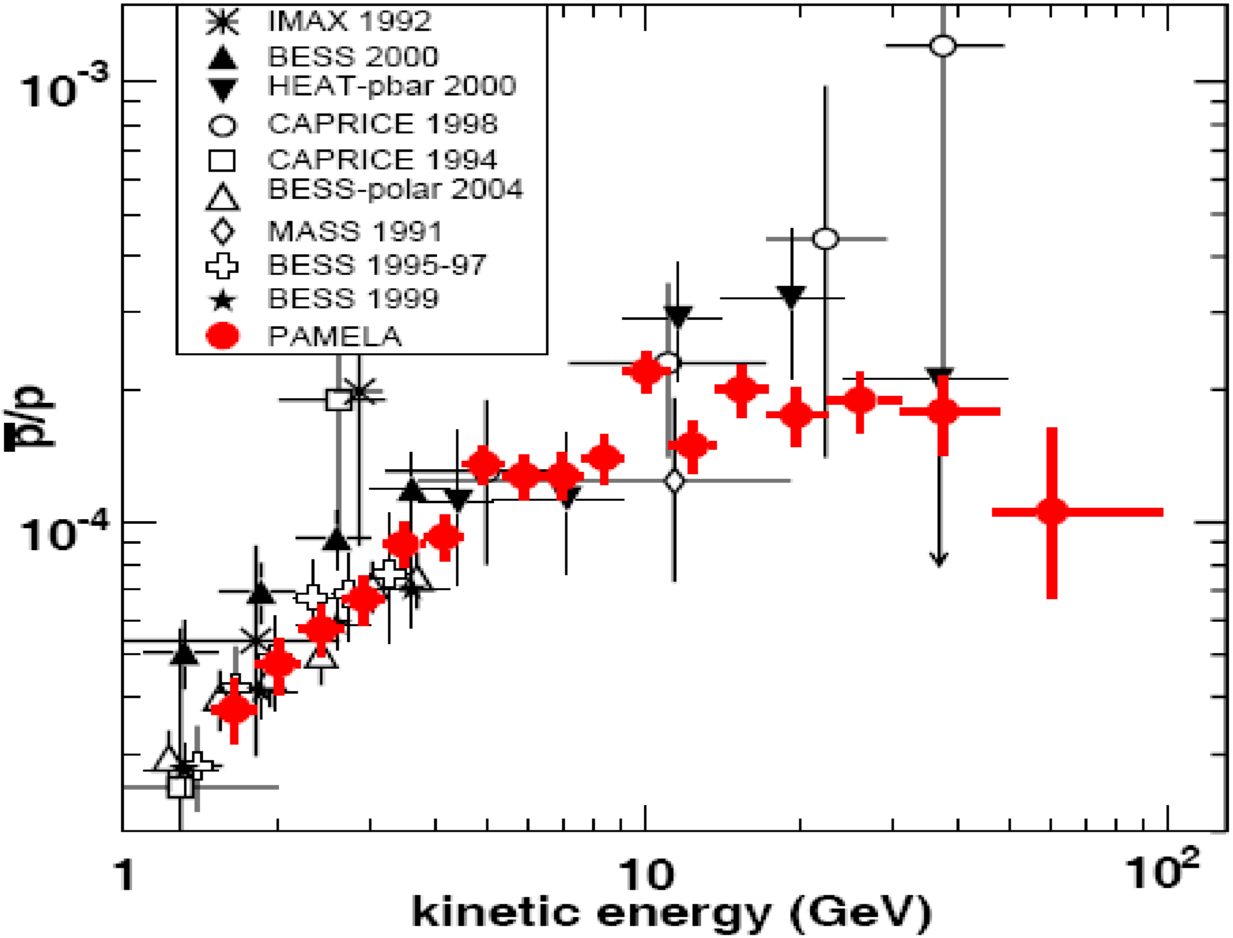
Tracker Identification

Protons (& spillover)

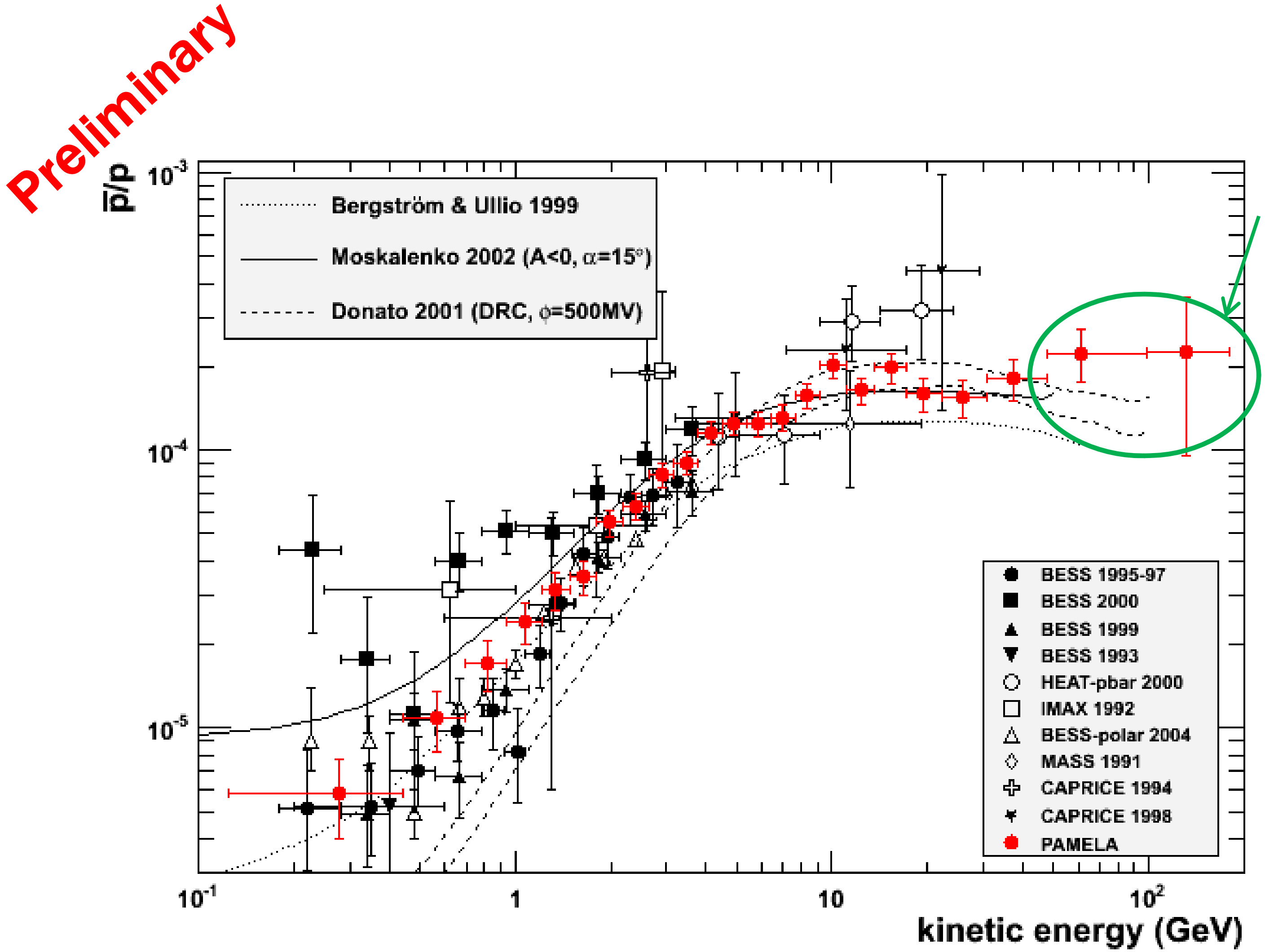
Antiprotons

Antiproton to proton flux ratio

PRL 102, (2009) 051101, Astro-ph 0810.4994

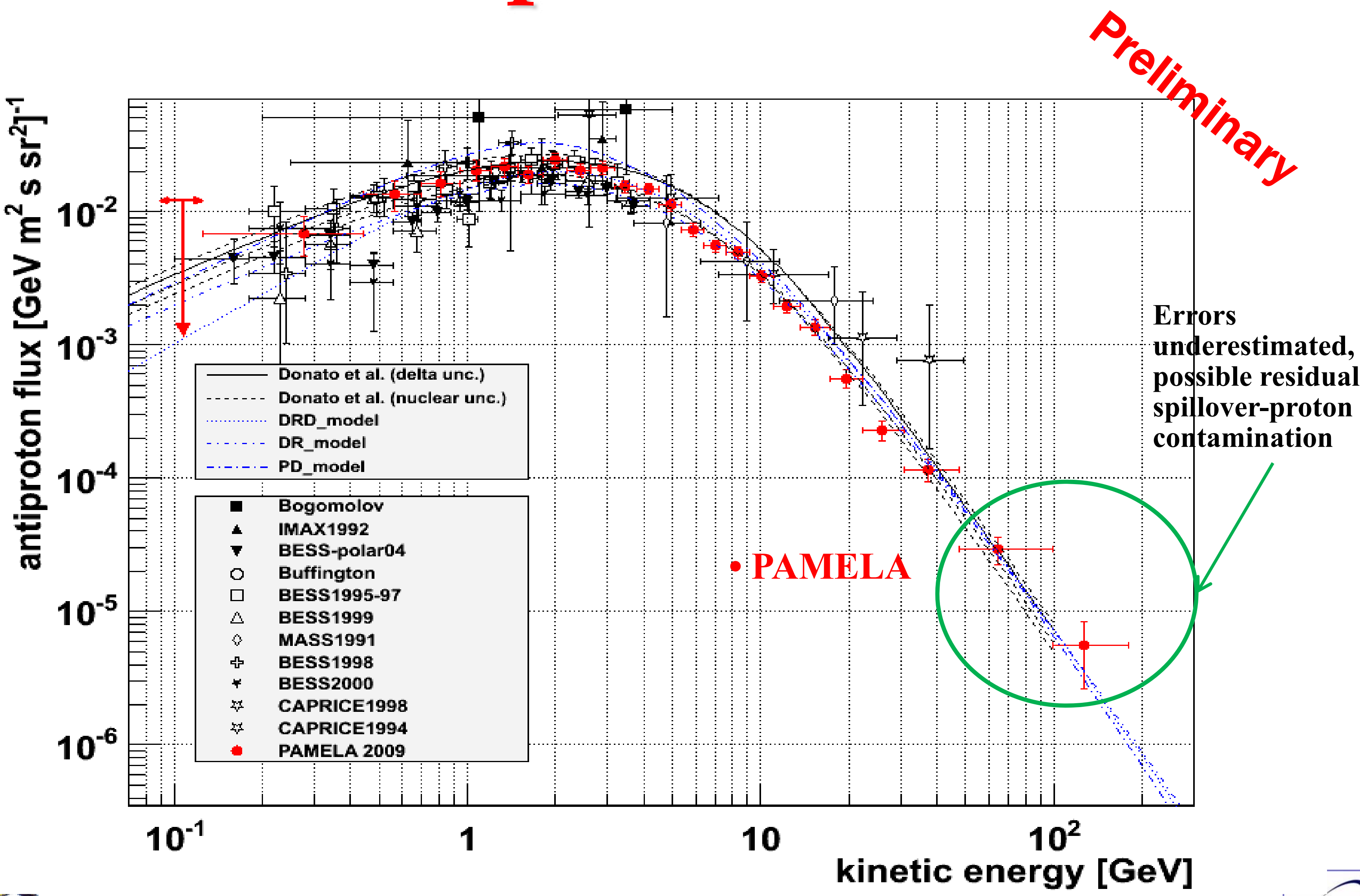


Antiproton to proton flux ratio



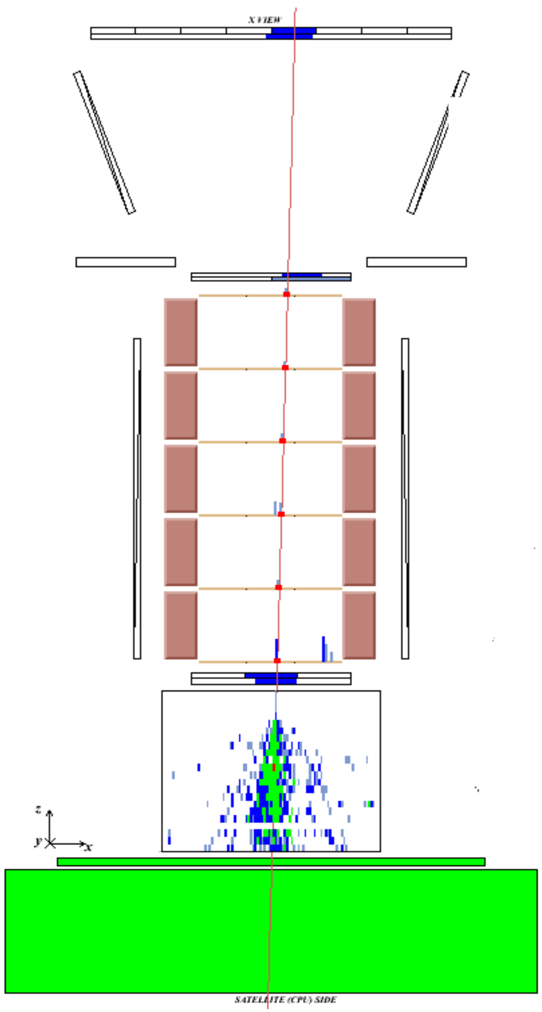
Errors might be underestimated, possible residual spillover-proton contamination

Antiproton Flux



POSITRONS

Proton / positron discrimination

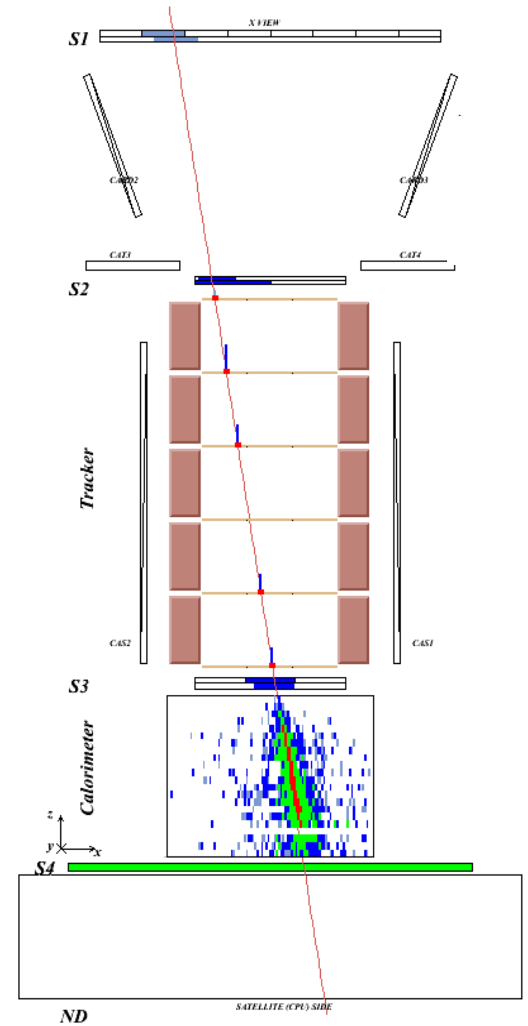


Time-of-flight:
trigger, albedo rejection, mass determination (up to 1 GeV)

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

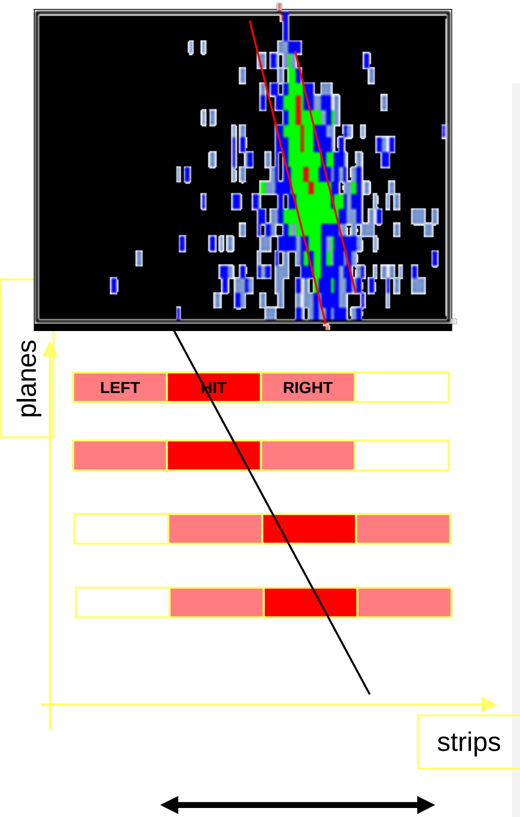


Proton

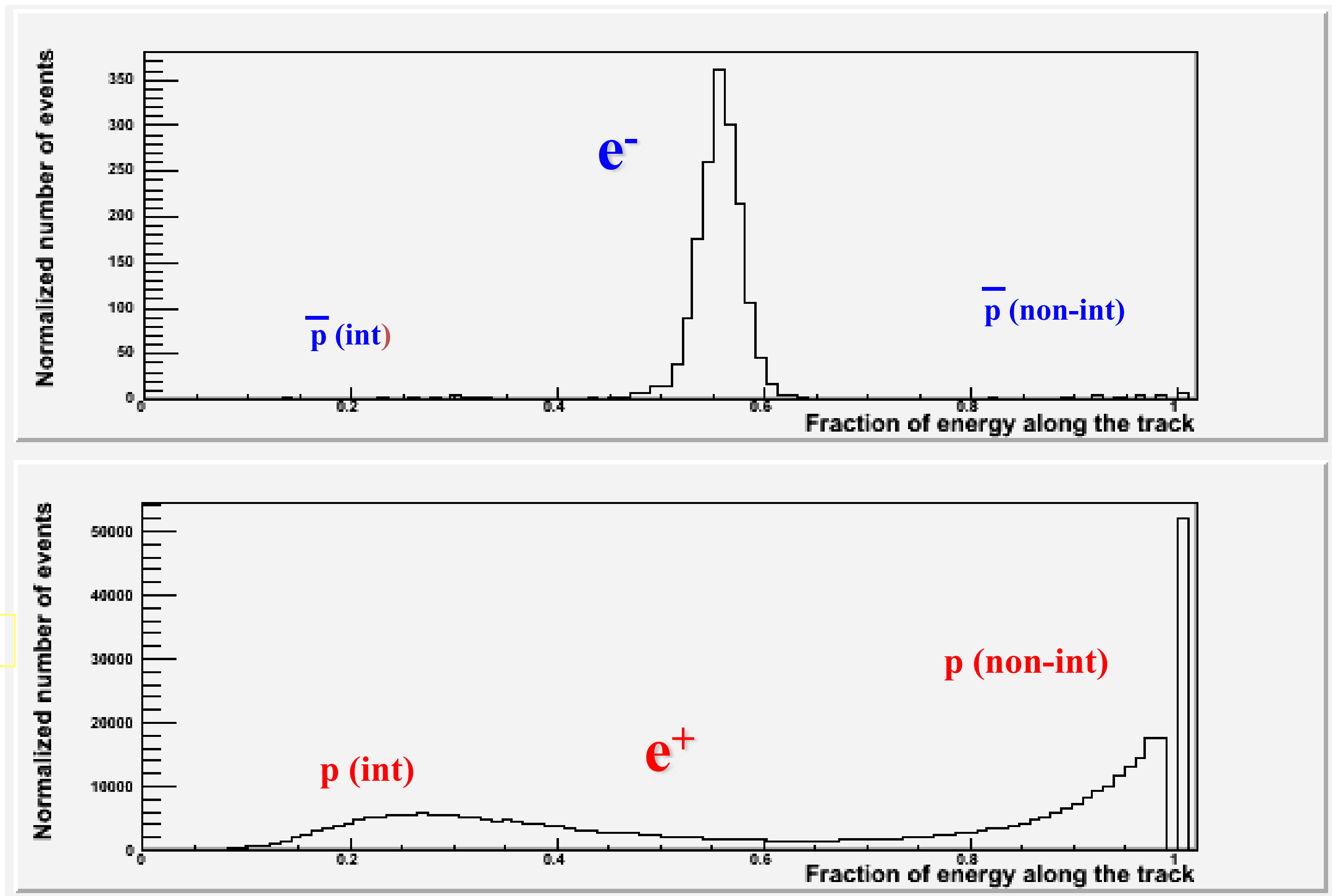
Positron

Positron selection with calorimeter

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



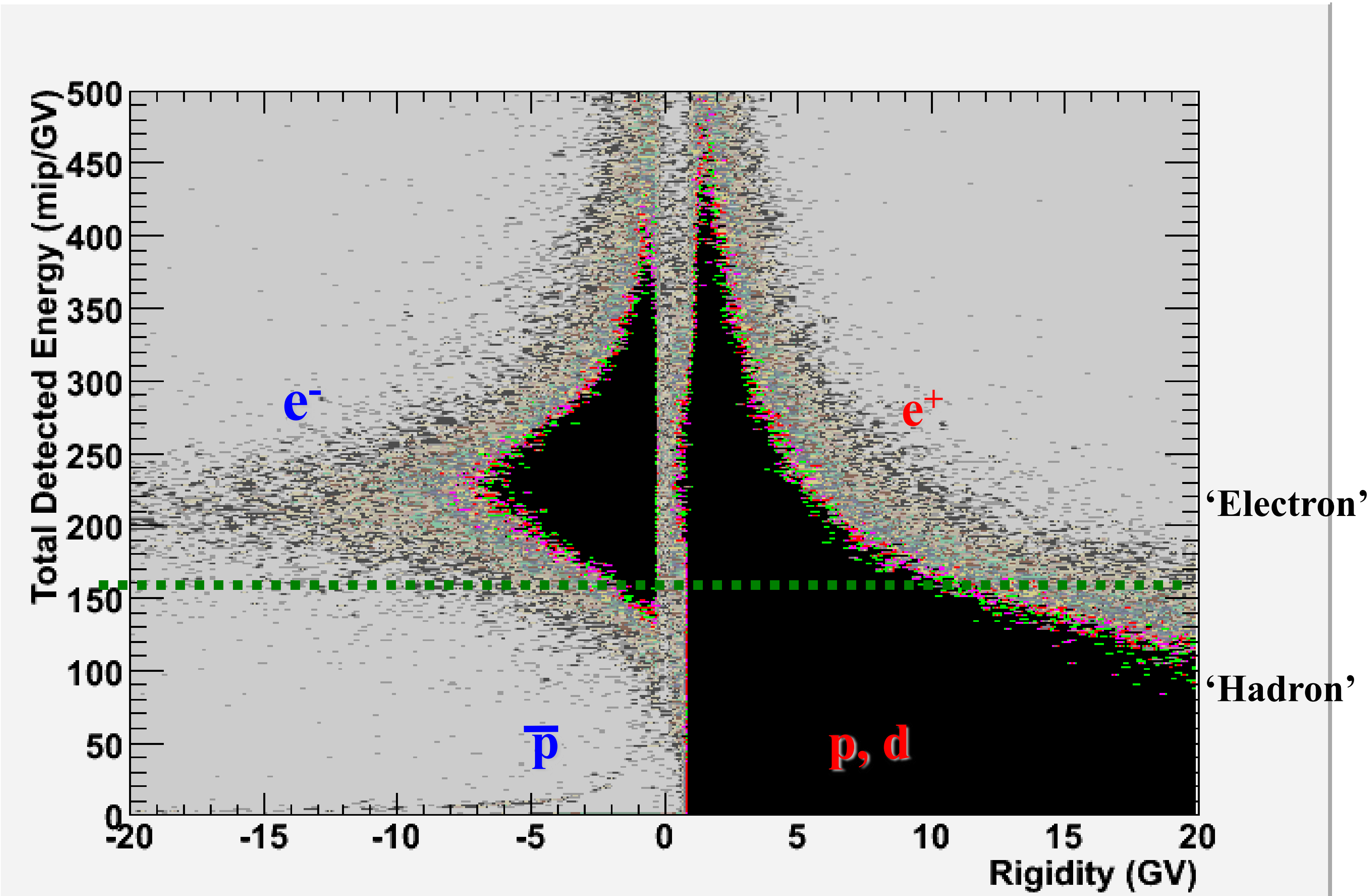
$0.6\ R_M$



for em showers 90% of E contained in 1 R_M

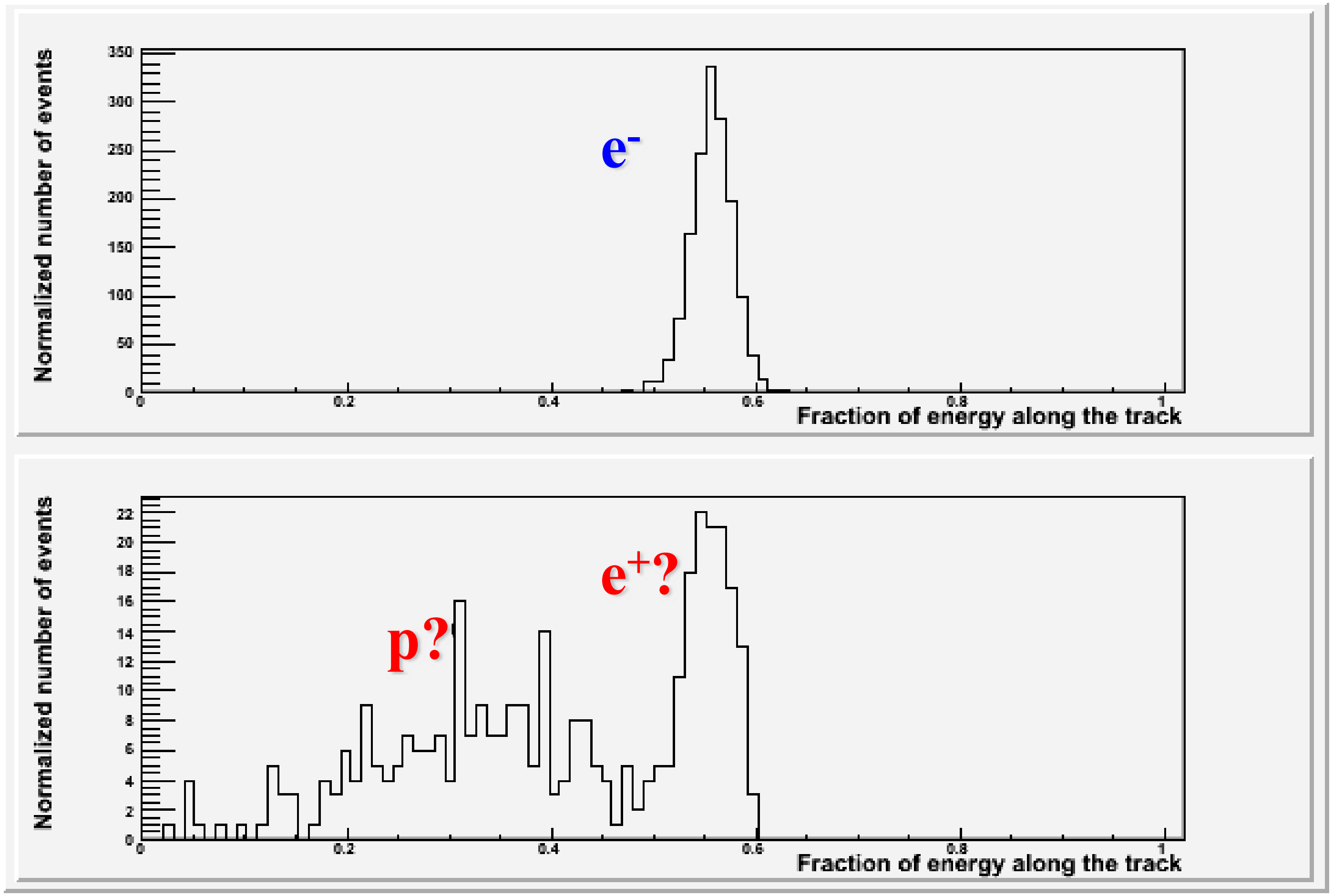
Rigidity: 20-30 GV

Antiparticle selection



Positron selection with calorimeter

Rigidity: 20-30 GV



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

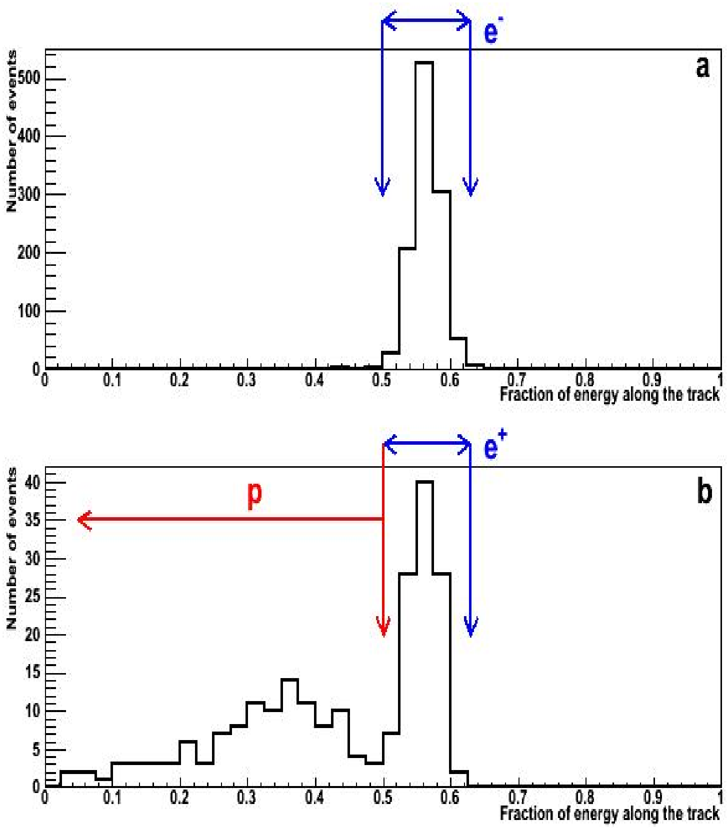
+

•Energy-momentum match
•Starting point of shower

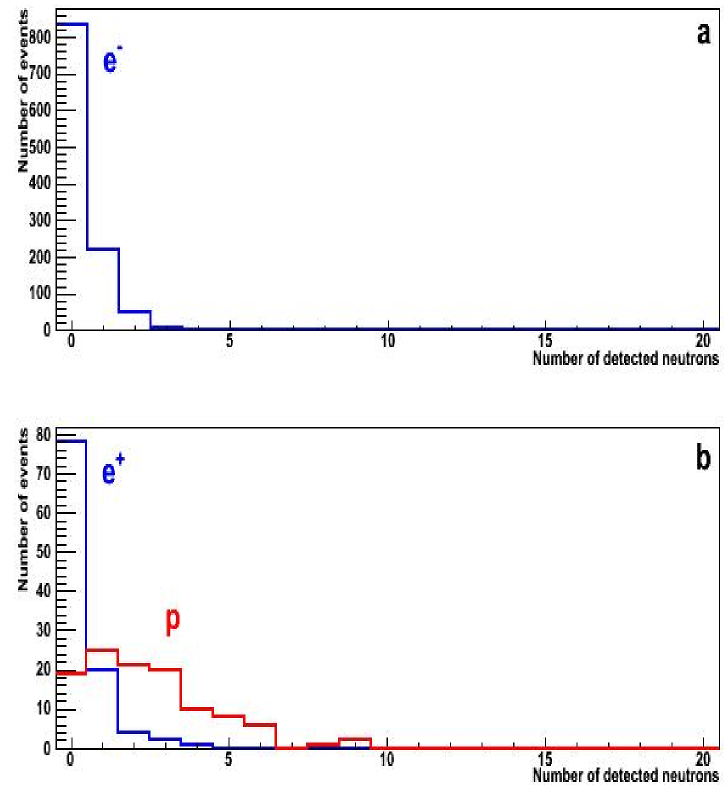
Positron selection with "pre-sampler"

Rigidity: 20-28 GV

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



Neutrons detected by ND

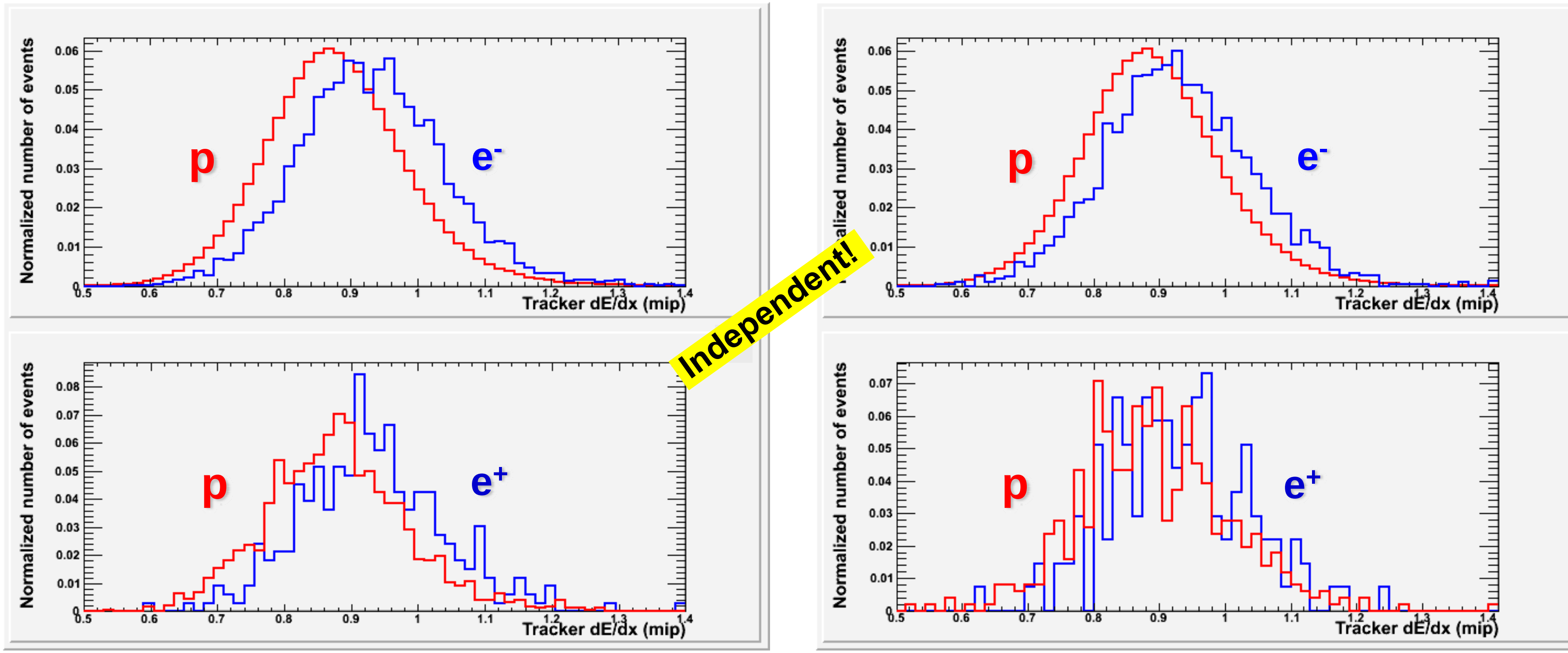


- Energy-momentum match
- Starting point of shower

Positron selection with dE/dX

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

TOP: positive (mostly p) and negative events (mostly e^-)



BOTTOM: positive events identified as p and e^+ by transverse profile method

Rigidity: 10-15 GV

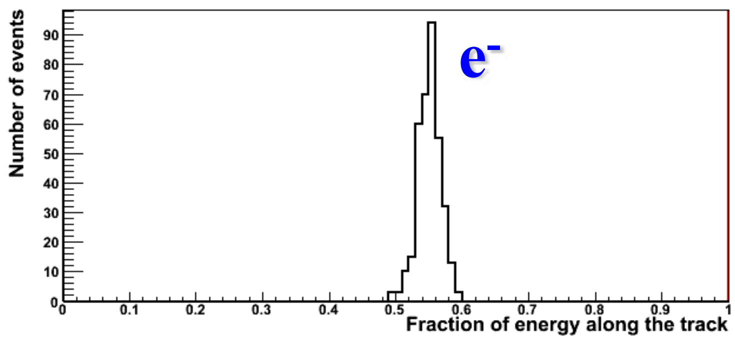
Rigidity: 15-20 GV

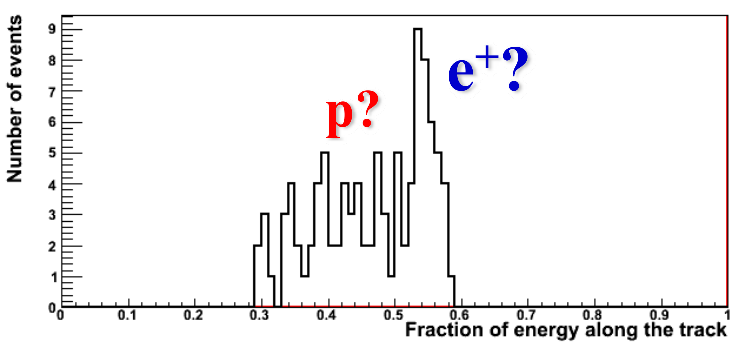
Positron selection with calorimeter

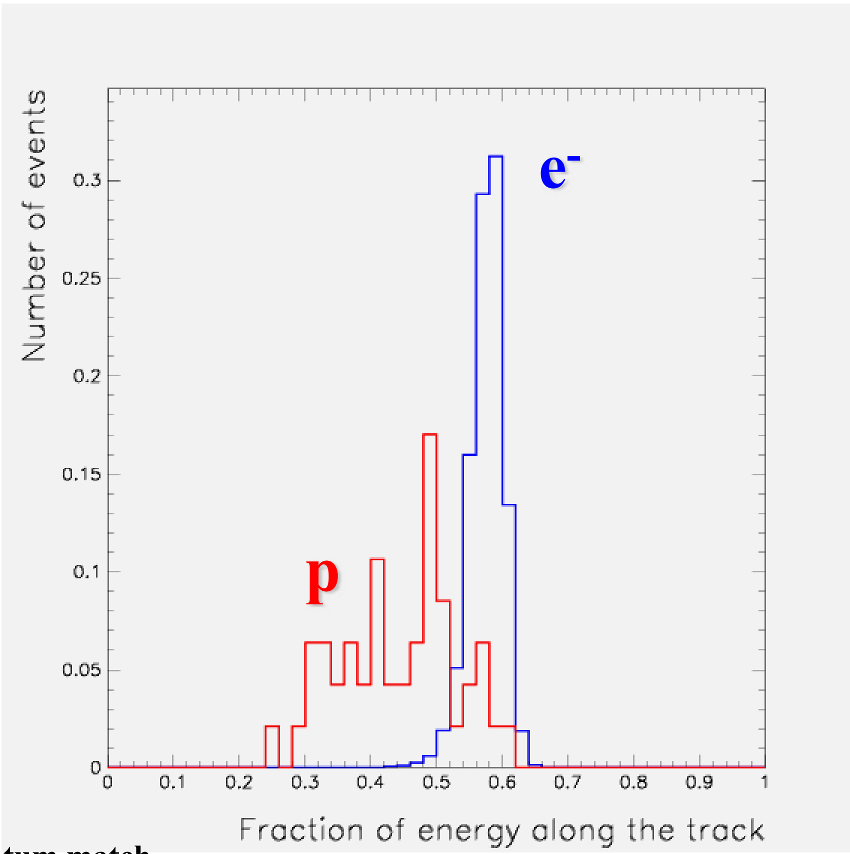
Fraction of charge released along the calorimeter track (left, hit, right)

Flight data: rigidity: 42-65 GV

Test beam data: momentum: 50GeV/c

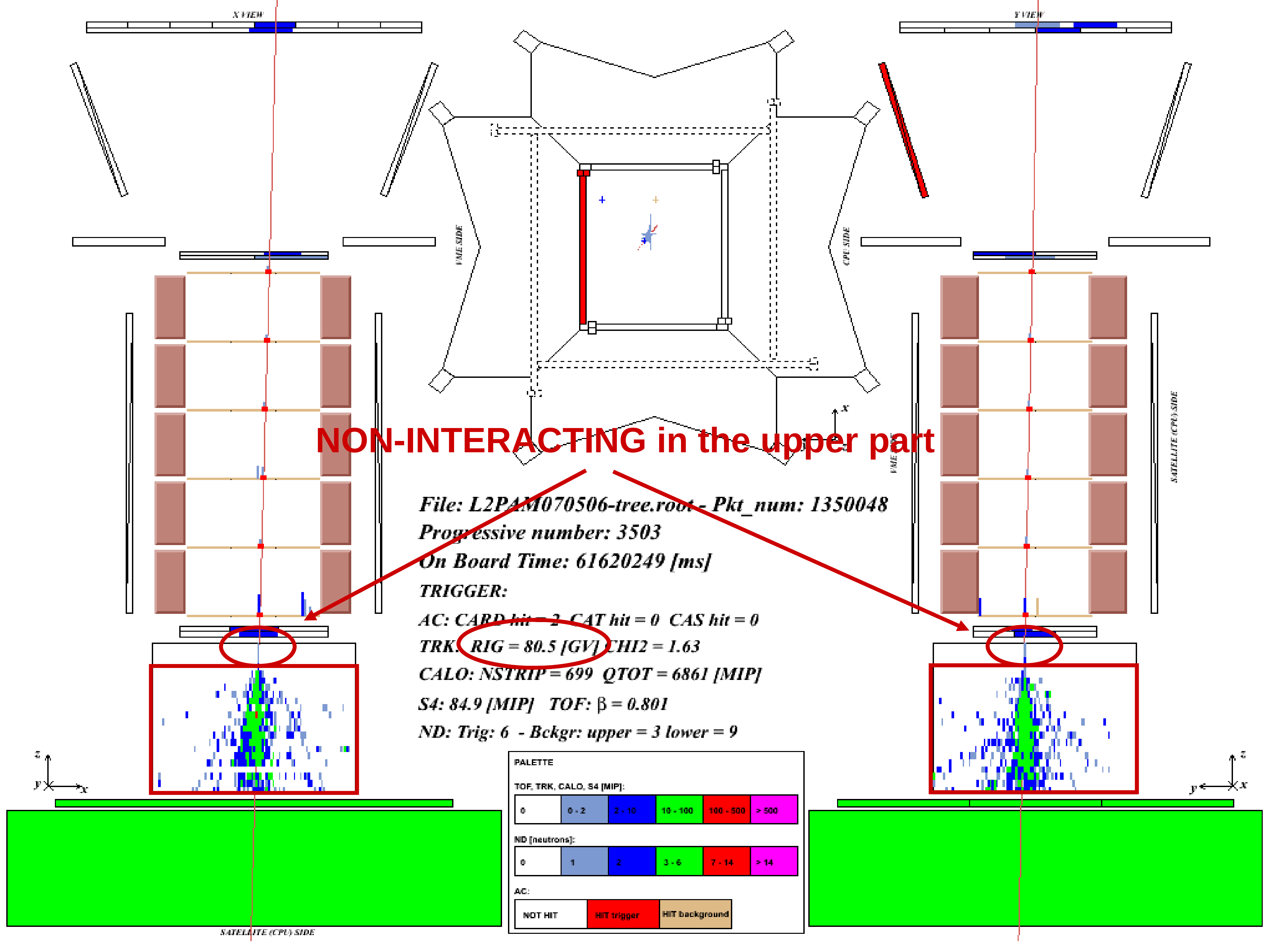


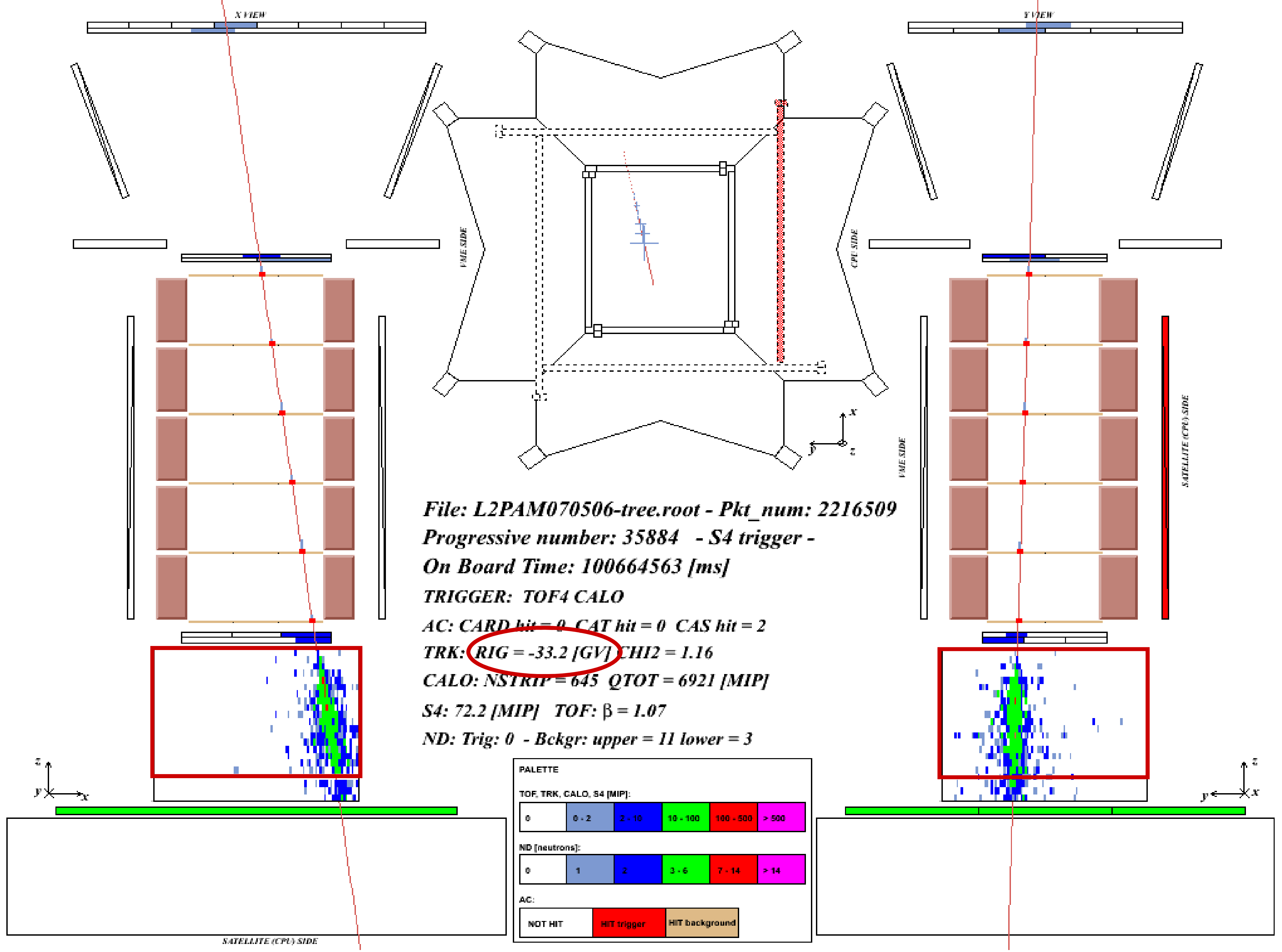




- Energy-momentum match
- Starting point of shower

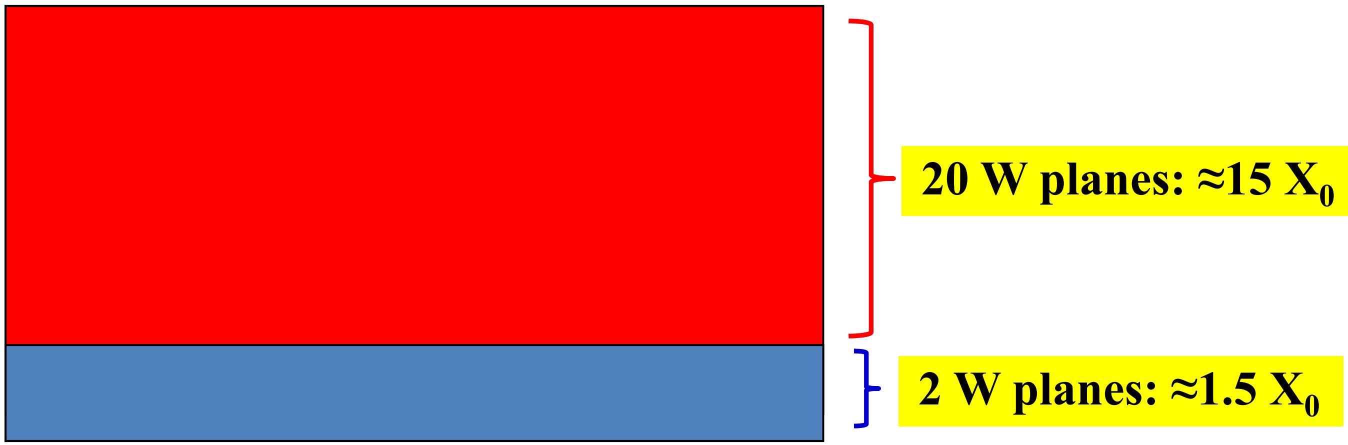
Can we create a sample of protons from the flight data themselves?
Yes with the “pre-sampler” method!


NON-INTERACTING in the upper part
File: L2PAM070506-tree.root - Pkt_num: 1350048
Progressive number: 3503
On Board Time: 61620249 [ms]
TRIGGER:
AC: CARD hit = 2 CAT hit = 0 CAS hit = 0
TRK: RIG = 80.5 [GV] CHI2 = 1.63
CALO: NSTRIP = 699 QTOT = 6861 [MIP]
S4: 84.9 [MIP] TOF: β = 0.801
ND: Trig: 6 - Bckgr: upper = 3 lower = 9
PALETTE
TOF, TRK, CALO, S4 [MIP]:
0
0 - 2
2 - 10
10 - 100
100 - 500
> 500
ND [neutrons]:
0
1
2
3 - 6
7 - 14
> 14
AC:
NOT HIT
HIT trigger
HIT background
X VIEW
Y VIEW
VME SIDE
CPU SIDE
SATELLITE (CPU) SIDE

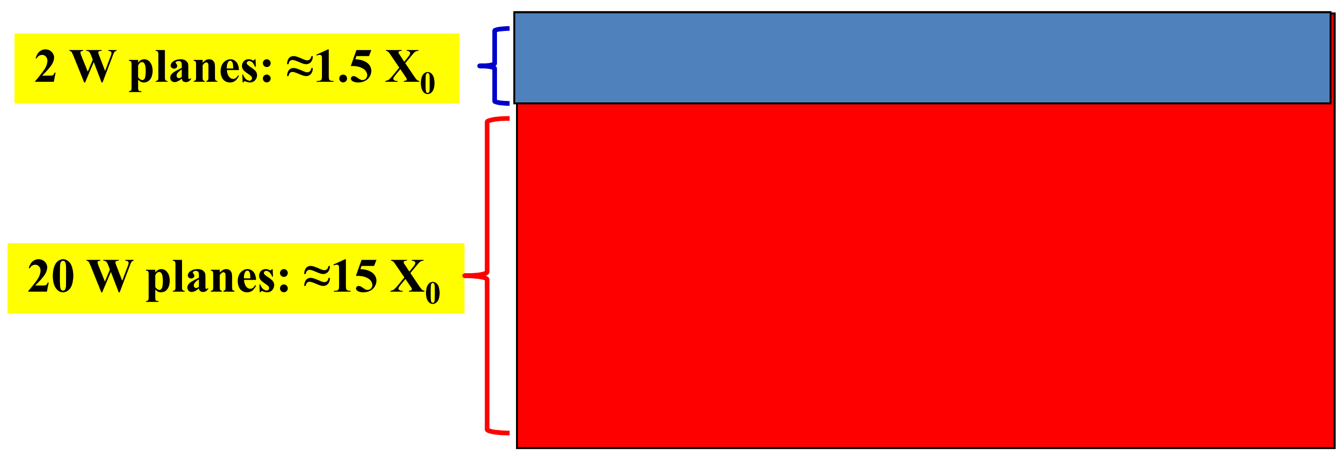

X VIEW
Y VIEW
VME SIDE
CPU SIDE
SATELLITE (CPU) SIDE
File: L2PAM070506-tree.root - Pkt_num: 2216509
Progressive number: 35884 - S4 trigger -
On Board Time: 100664563 [ms]
TRIGGER: TOF4 CALO
AC: CARD hit = 0 CAT hit = 0 CAS hit = 2
TRK: RIG = -33.2 [GV] CHI2 = 1.16
CALO: NSTRIP = 645 QTOT = 6921 [MIP]
S4: 72.2 [MIP] TOF: β = 1.07
ND: Trig: 0 - Bckgr: upper = 11 lower = 3
PALETTE
TOF, TRK, CALO, S4 [MIP]:
0
0 - 2
2 - 10
10 - 100
100 - 500
> 500
ND [neutrons]:
0
1
2
3 - 6
7 - 14
> 14
AC:
NOT HIT
HIT trigger
HIT background

The "pre-sampler" method

POSITRON SELECTION

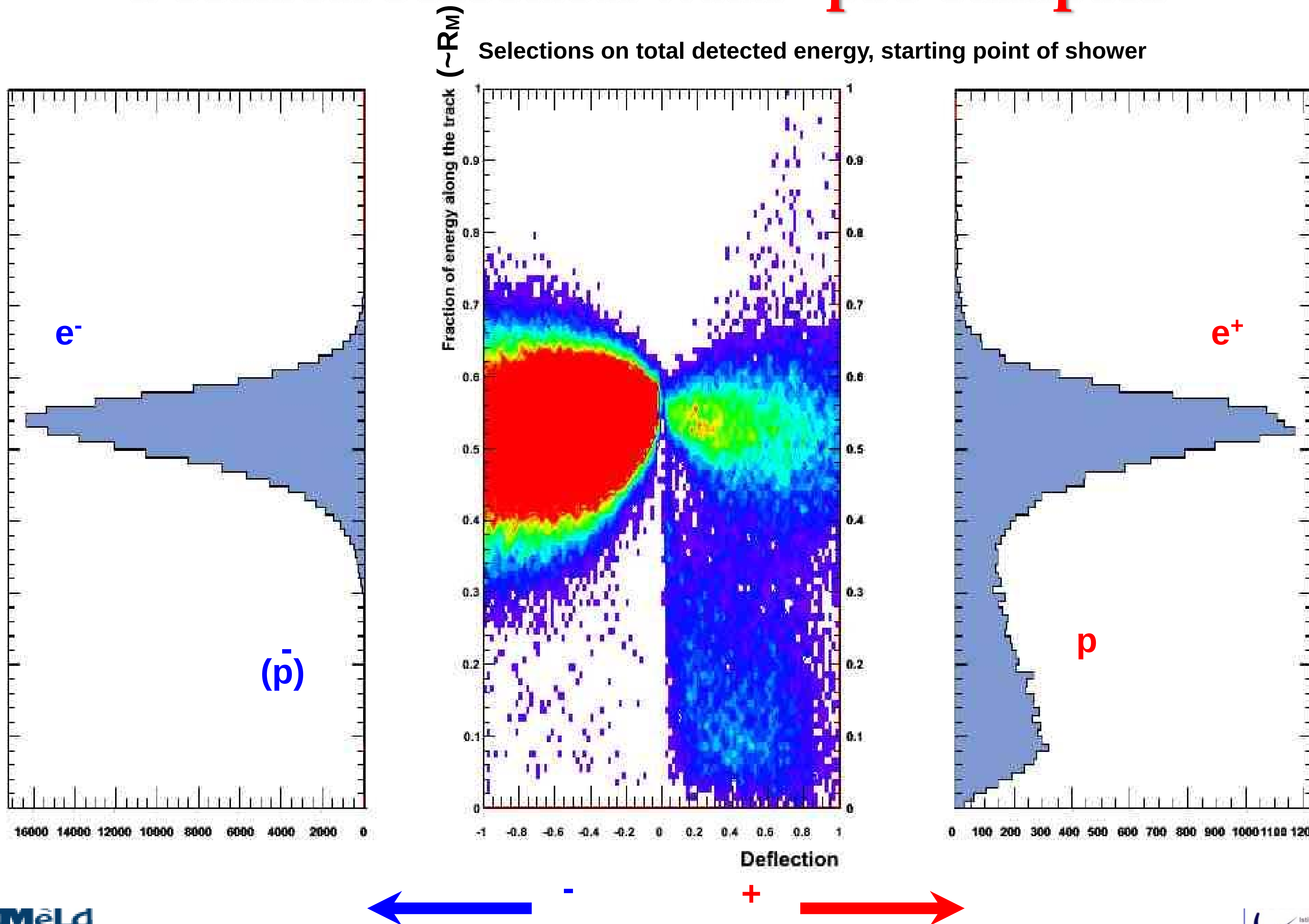


PROTON SELECTION



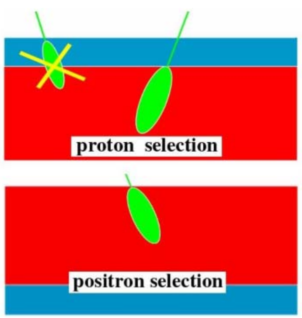
Positron selection with "pre-sampler"

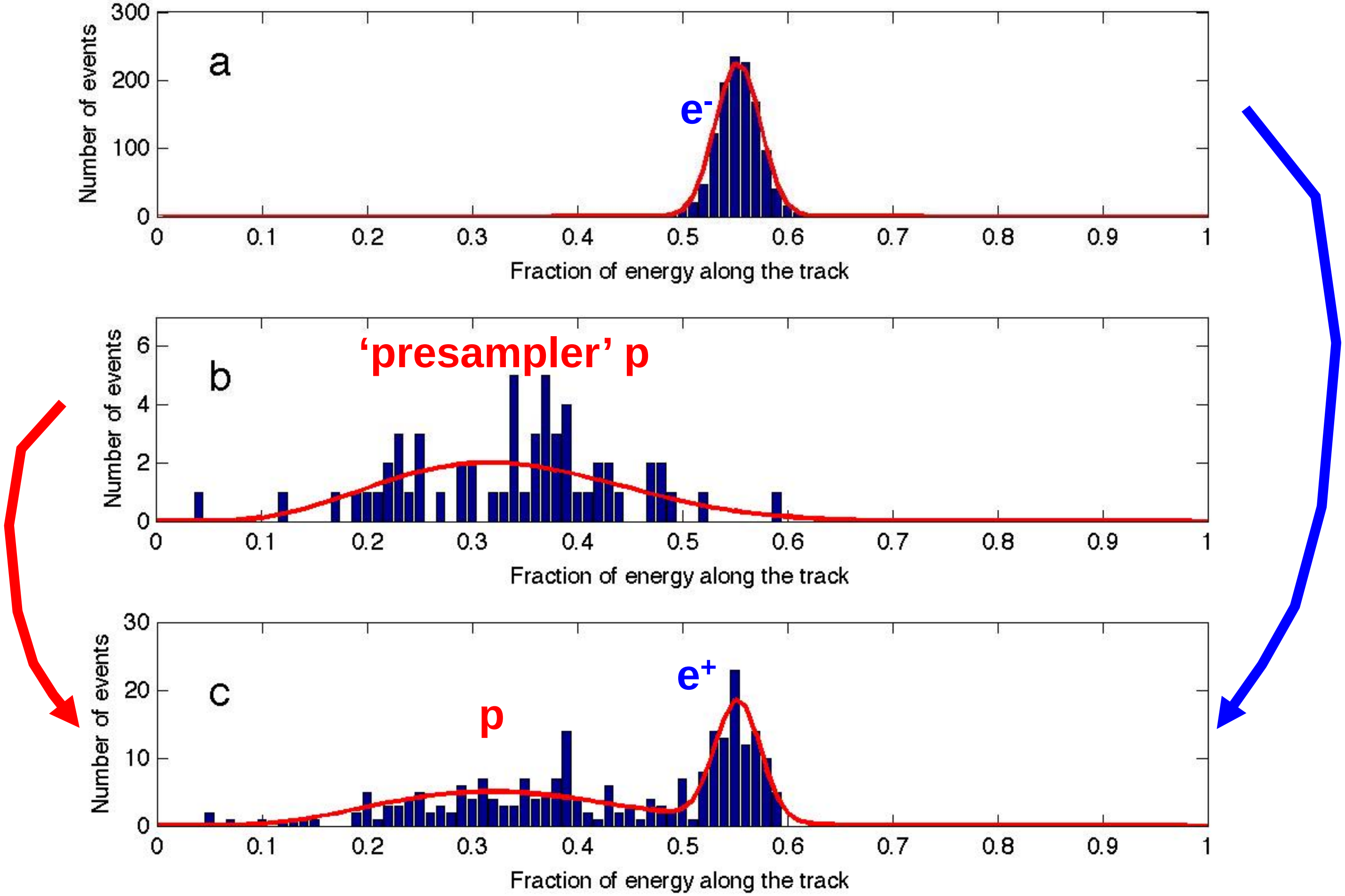
Selections on total detected energy, starting point of shower



e^+ background estimation from data

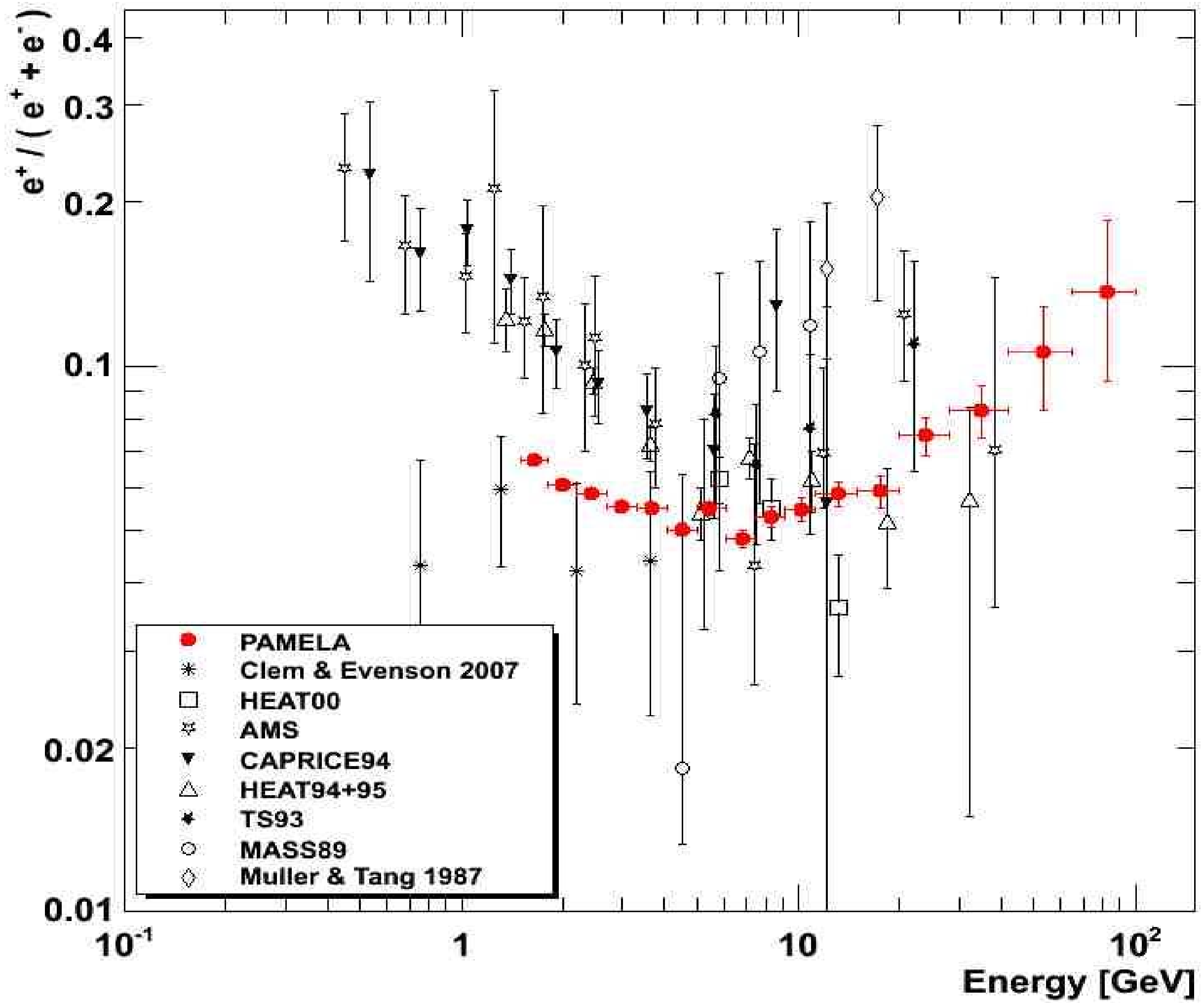
Rigidity: 20-28 GV





+ • Energy-momentum match
• Starting point of shower

Positron to Electron Fraction



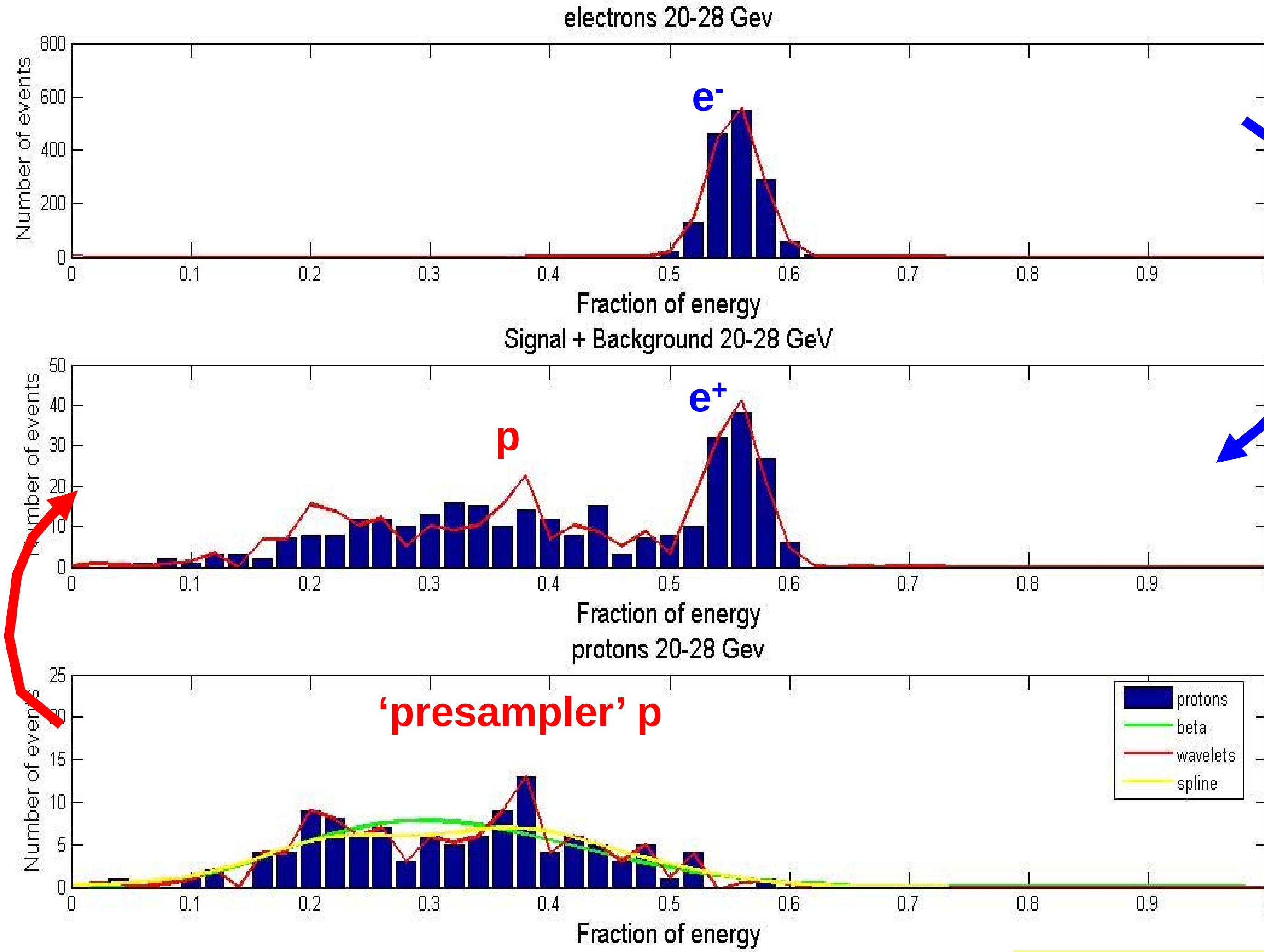
End 2007:
~10 000 e^+ > 1.5 GeV

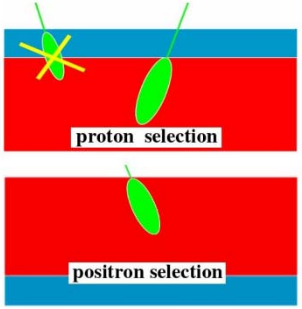
~2000 > 5 GeV

Nature 458 (2009) 607,
Astro-ph 0810.4995

e^+ background estimation from data

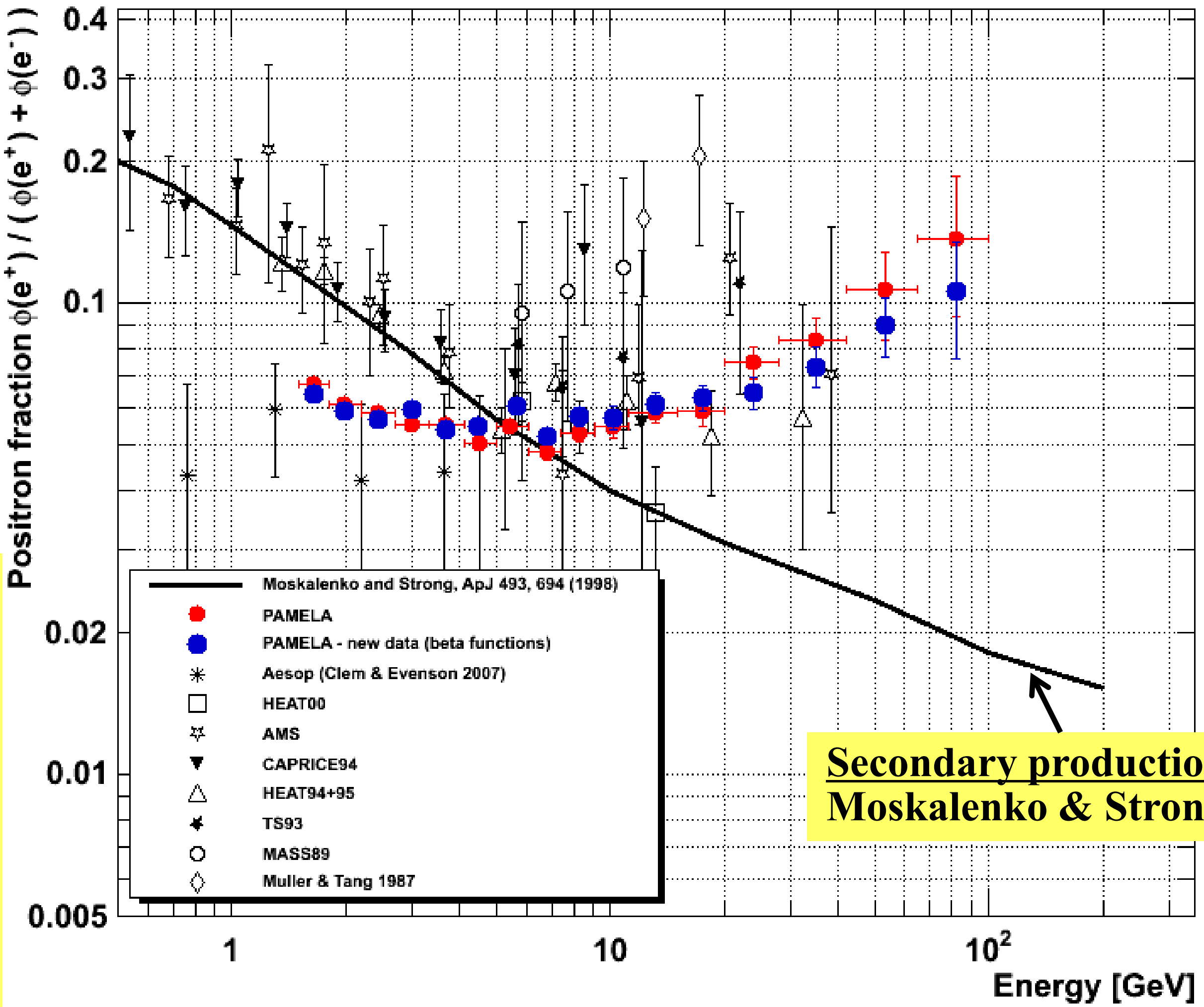
Data till end of 2008.Rigidity: 20-28 GV





+ • Energy-momentum match
• Starting point of shower

Positron to Electron Fraction



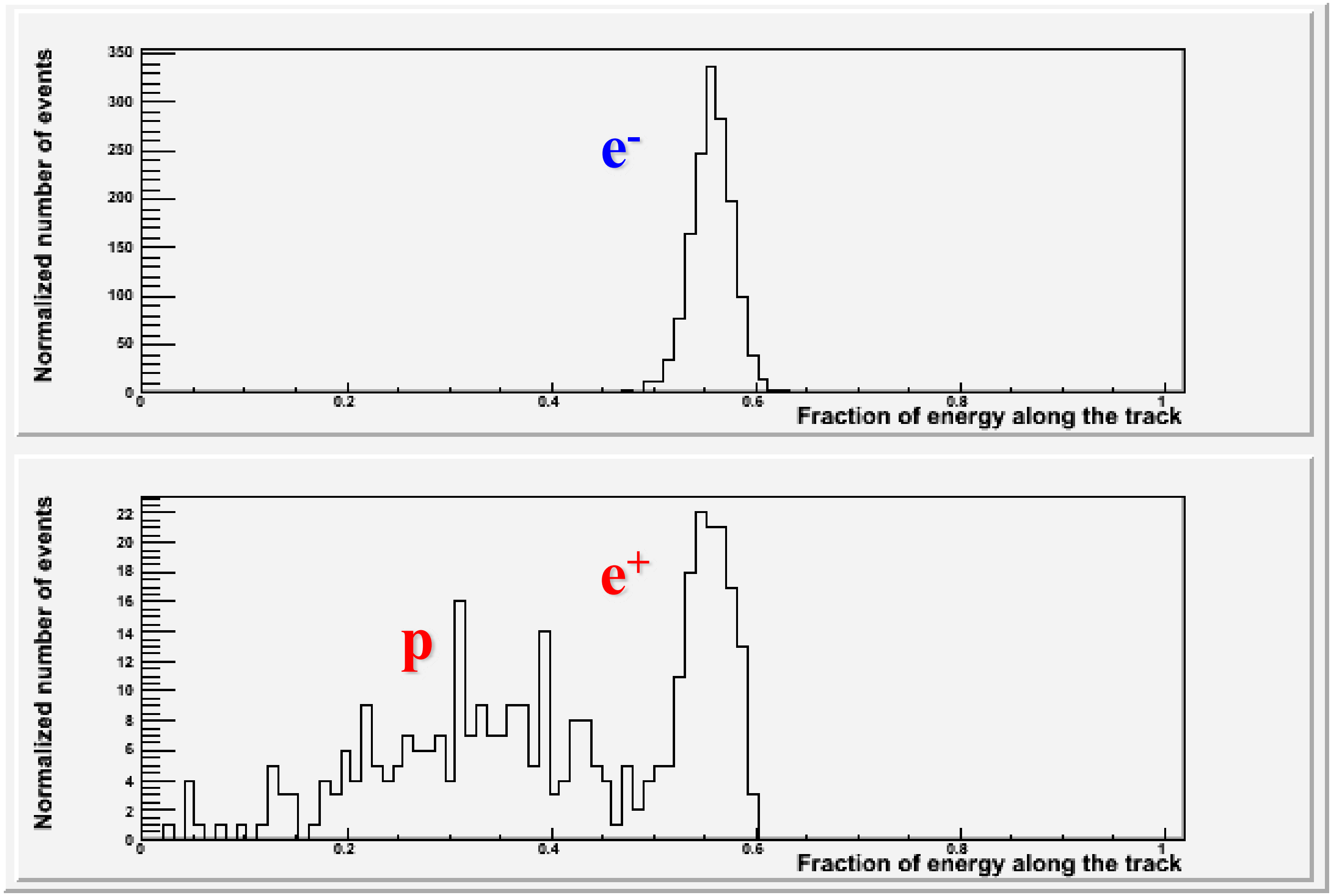
Secondary production
Moskalenko & Strong 98

In Nature article published data acquired till February 2008

New data reduction: data till end of 2008. With same approach of Nature paper ~30% increase in statistics better understanding of systematics.

But can we use the whole calorimeter?

Rigidity: 20-30 GV

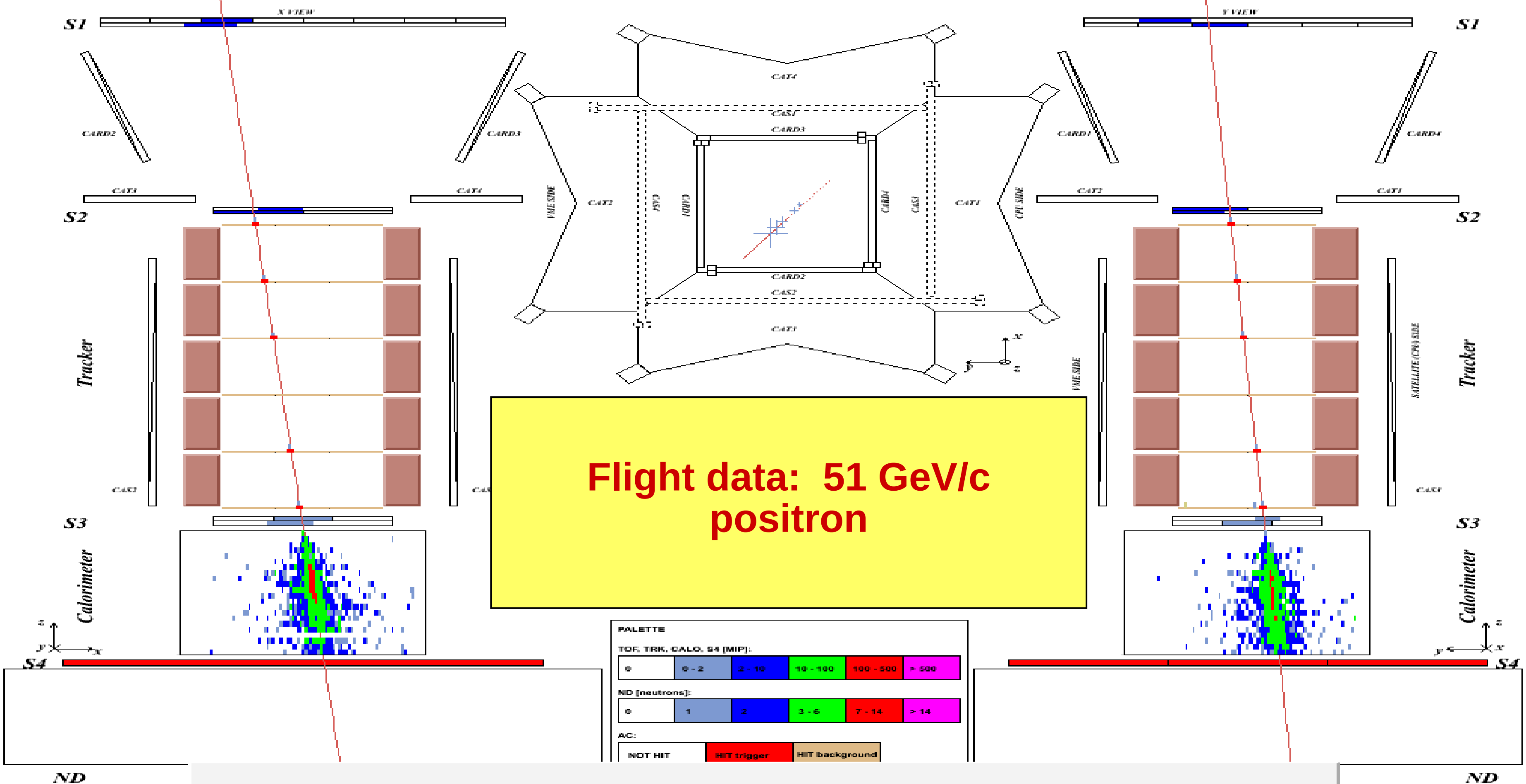


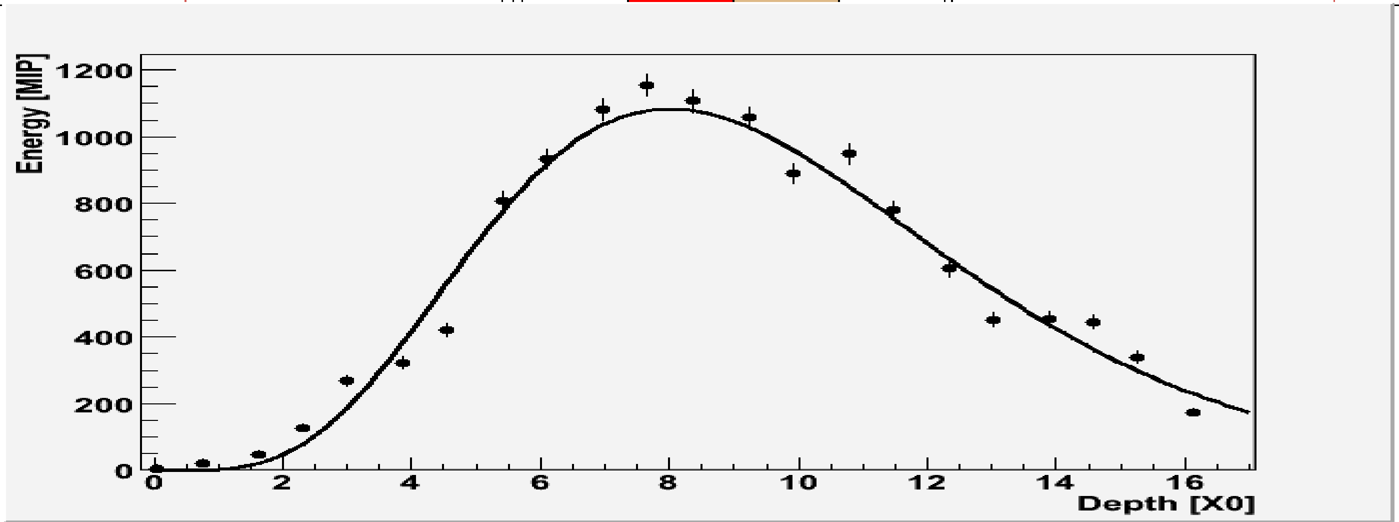
Fraction of charge released along the calorimeter track (left, hit, right)

+

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

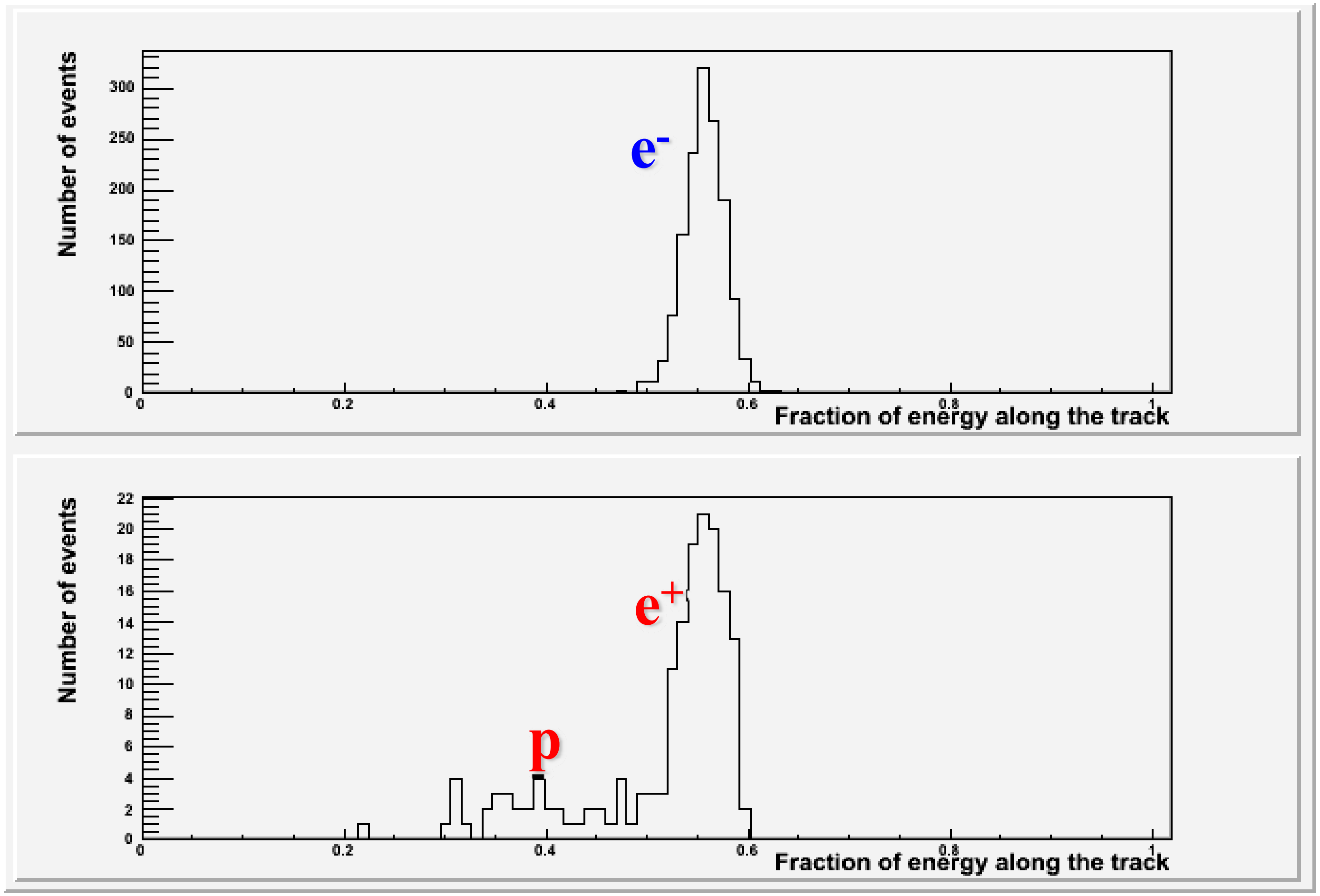
Flight data: 51 GeV/c positron





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**

Positron selection with calorimeter

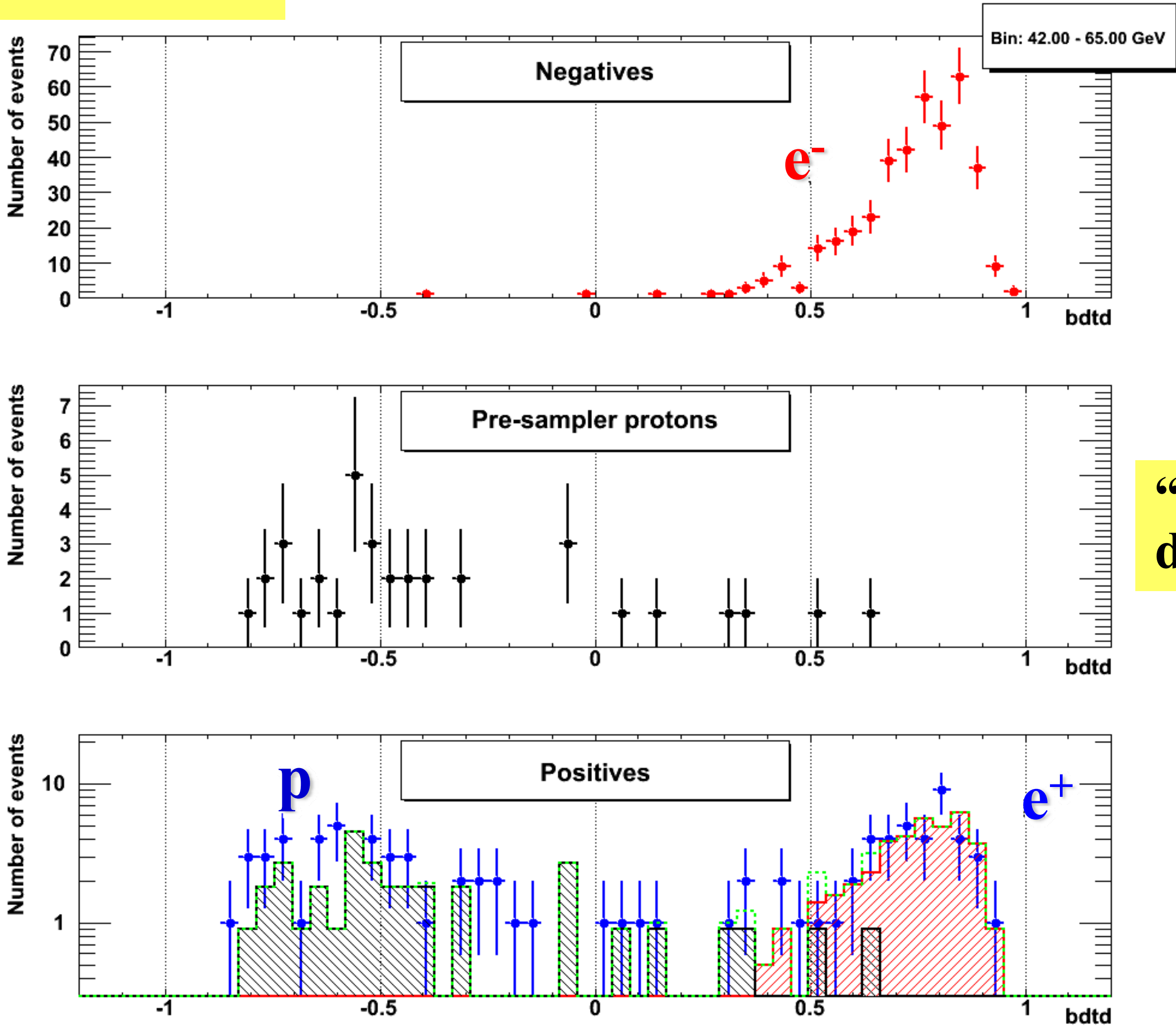
TMVA: Toolkit for MultiVariate data Analysis
http://tmva.sourceforge.net/

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

Training with "pre-sampler" data and simulation for the whole calorimeter.

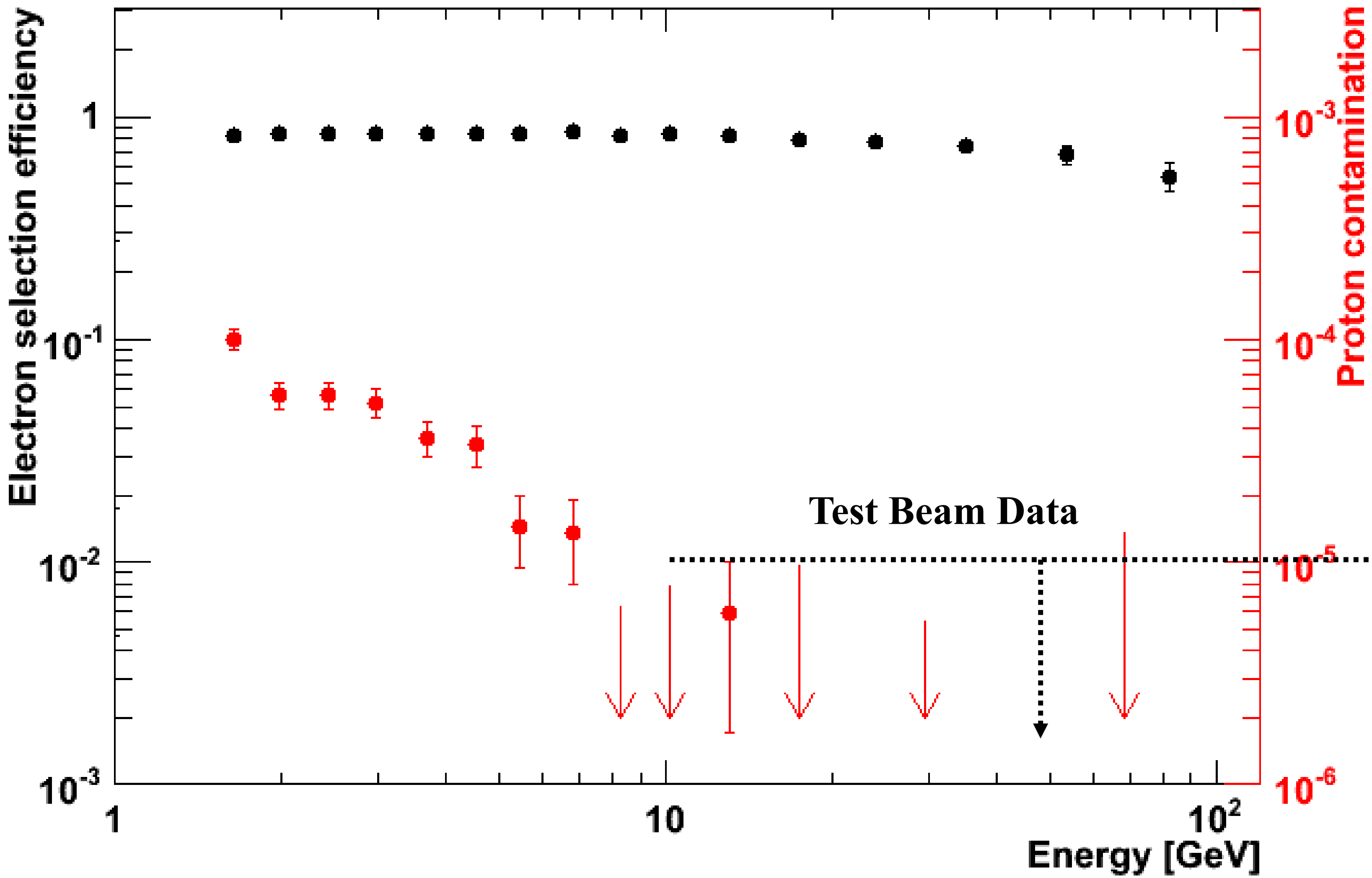
Positron selection with calorimeter

Rigidity: 42-65 GV
Boosted Decisional Trees



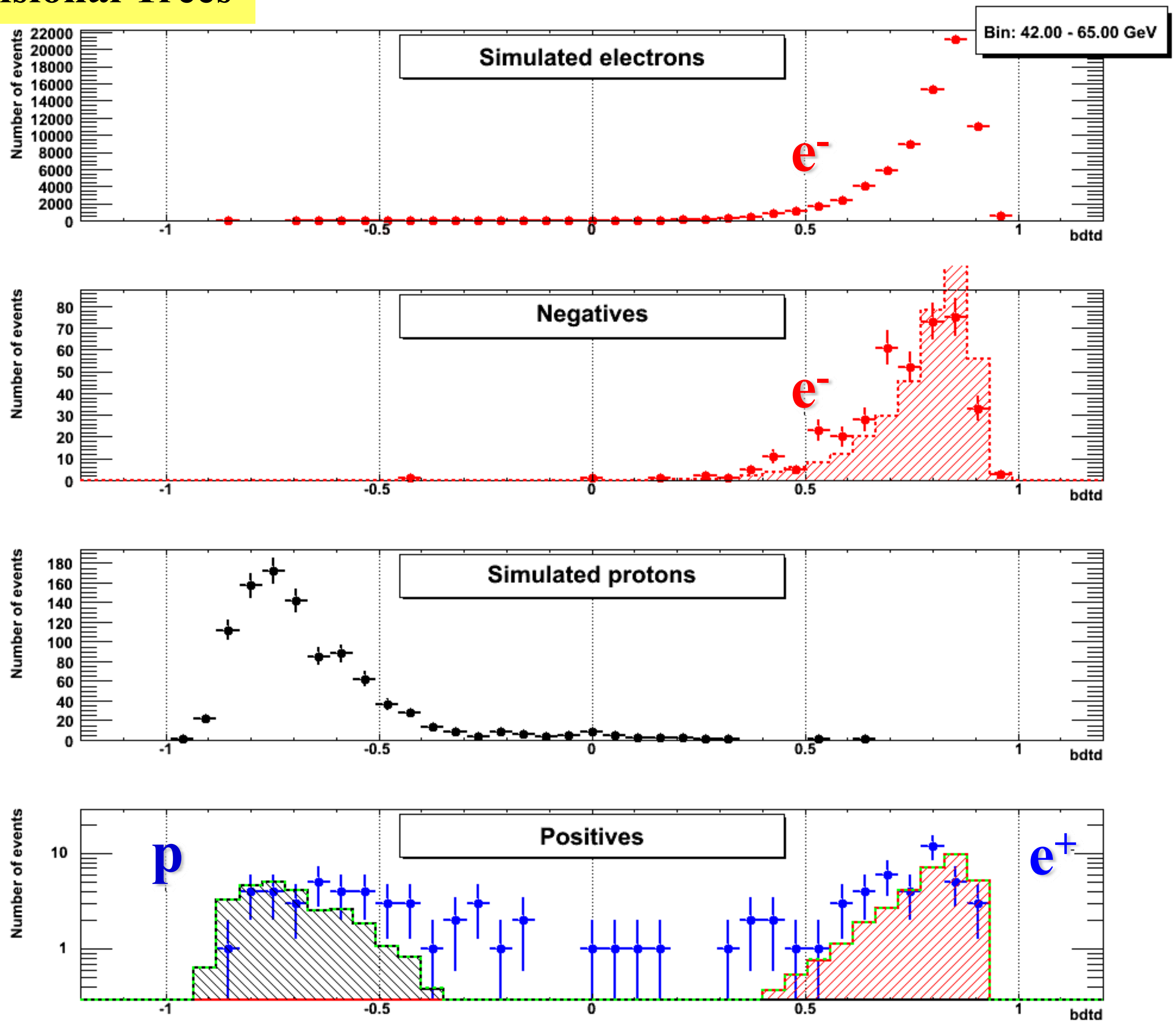
"Pre-sampler" data

Estimated proton contamination with "pre-sampler" method



Positron selection with calorimeter

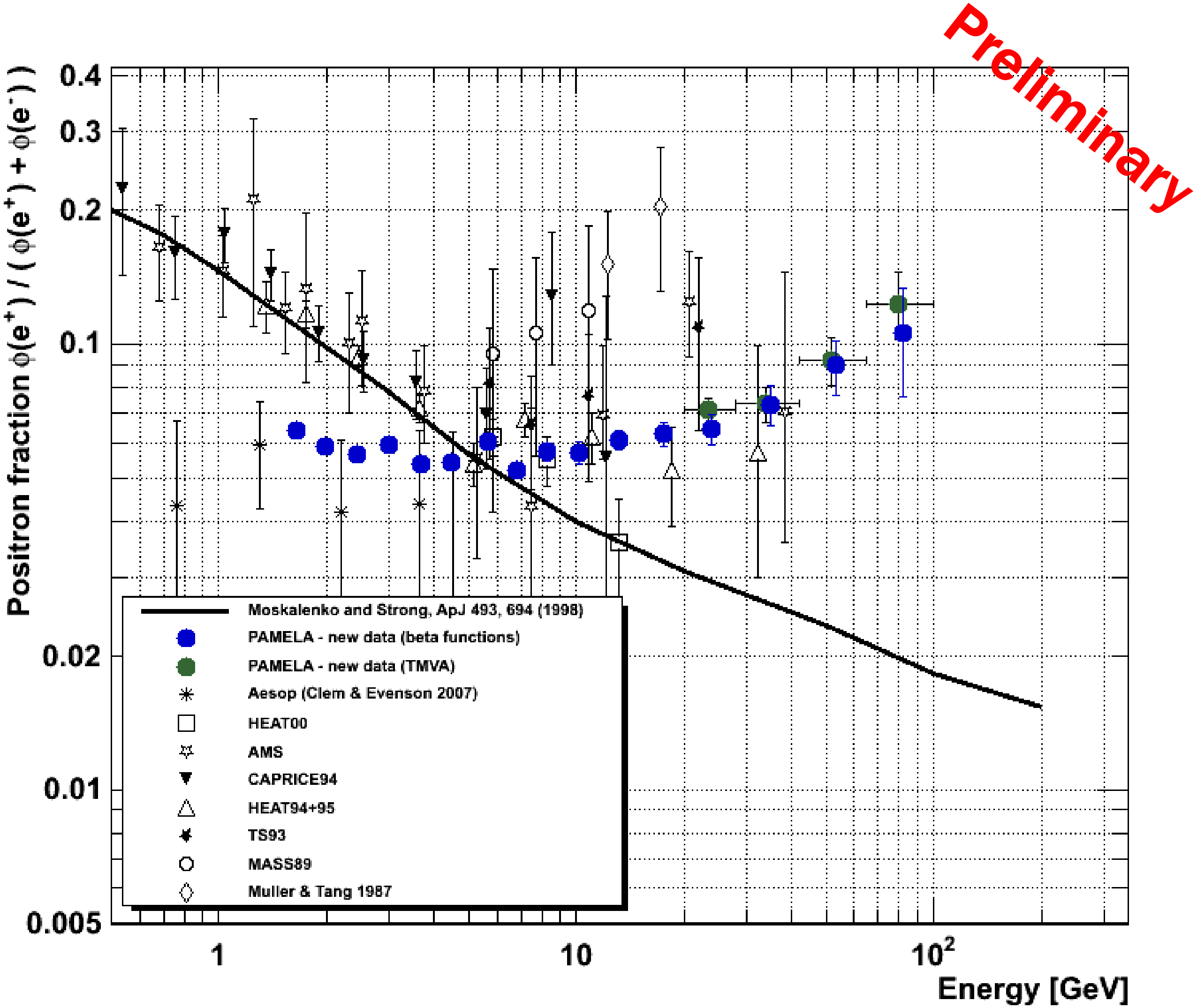
Rigidity: 42-65 GV
Boosted Decisional Trees



What about simulation?

Rather good but better to combine two methods: BDT and NN!

Positron to Electron Fraction



We use the whole calorimeter and train the multivariate algorithms with simulation.

Using all data till end of 2008, the whole calorimeter and multivariate classification algorithms about factor 2.5 increase in statistics (factor 3 in the highest energy bin)

Solar Modulation of galactic cosmic rays

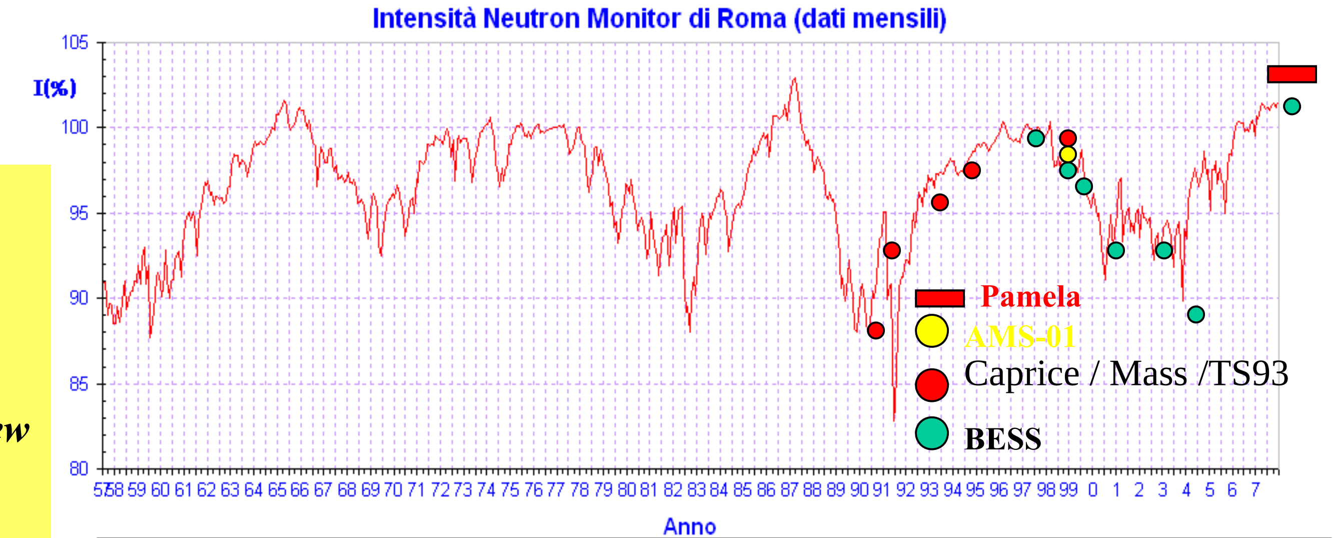
- **Study of charge sign dependent effects**

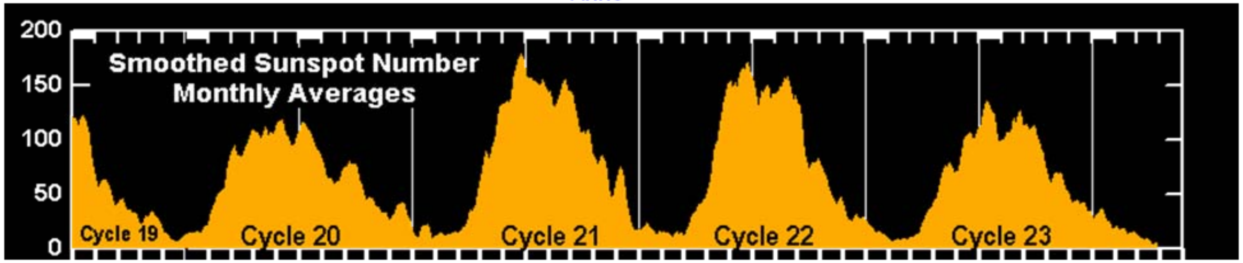
Asaoka Y. et al. 2002, Phys. Rev. Lett. 88, 051101),

Bieber, J.W., et al. Physi-cal Review Letters, 84, 674, 1999.

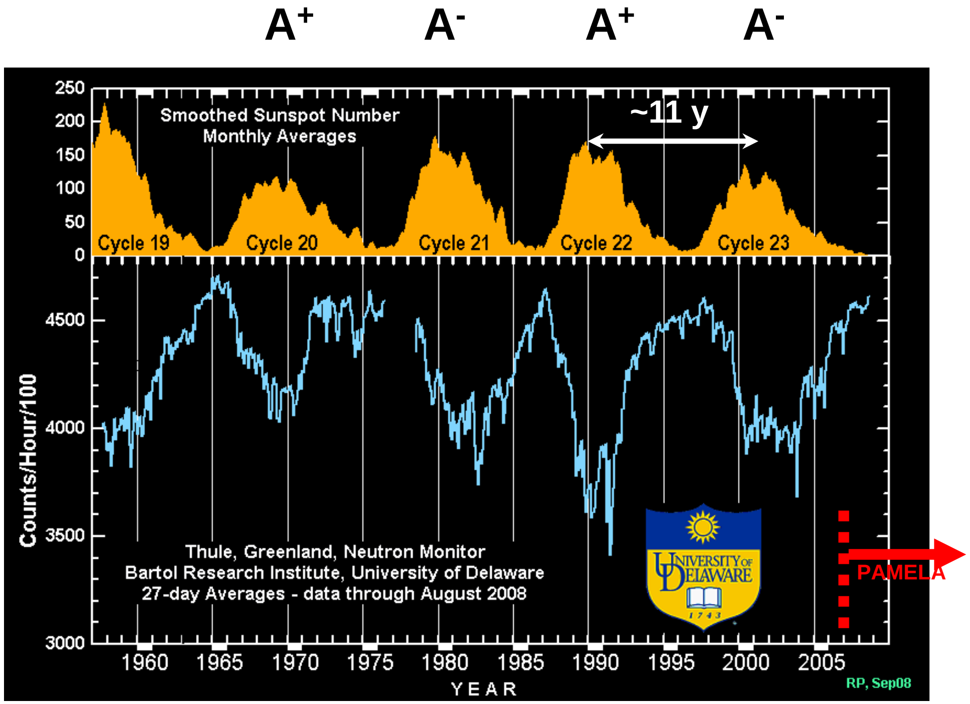
J. Clem et al. 30th ICRC 2007

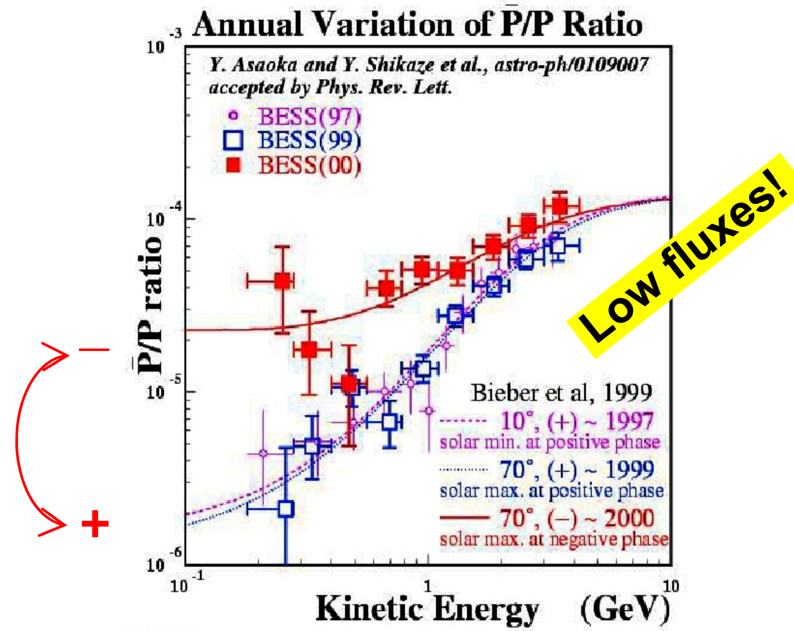
U.W. Langner, M.S. Potgieter, Advances in Space Research 34 (2004)

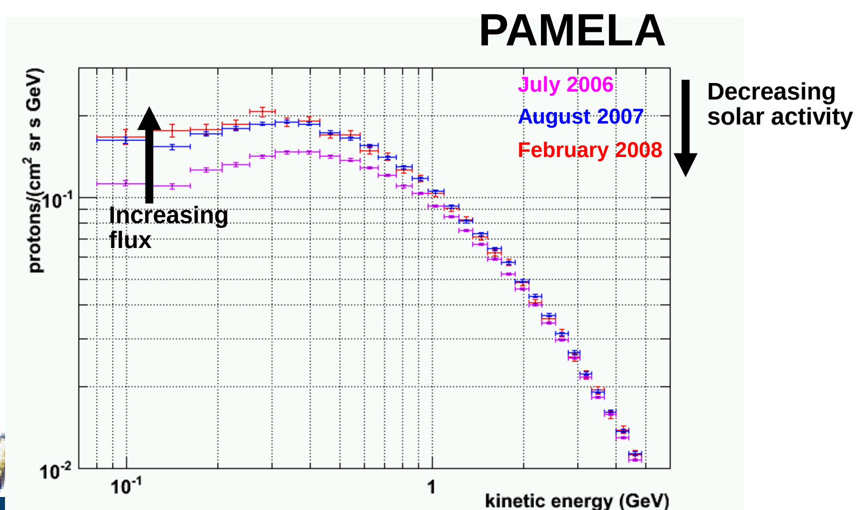


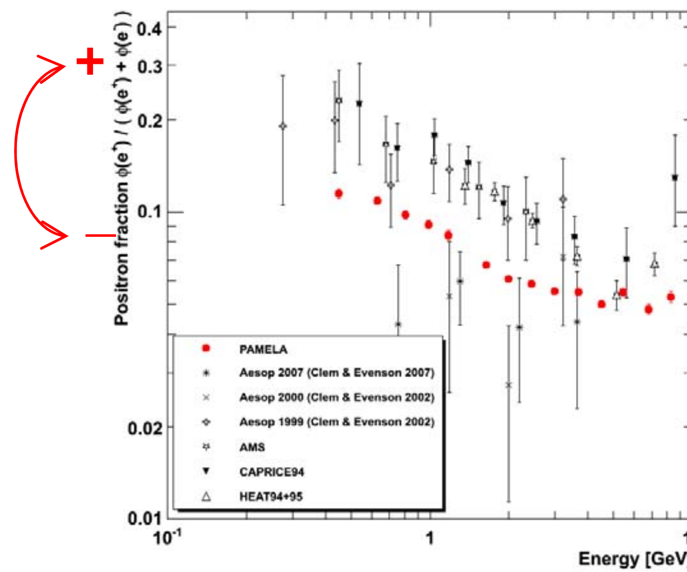


Solar modulation

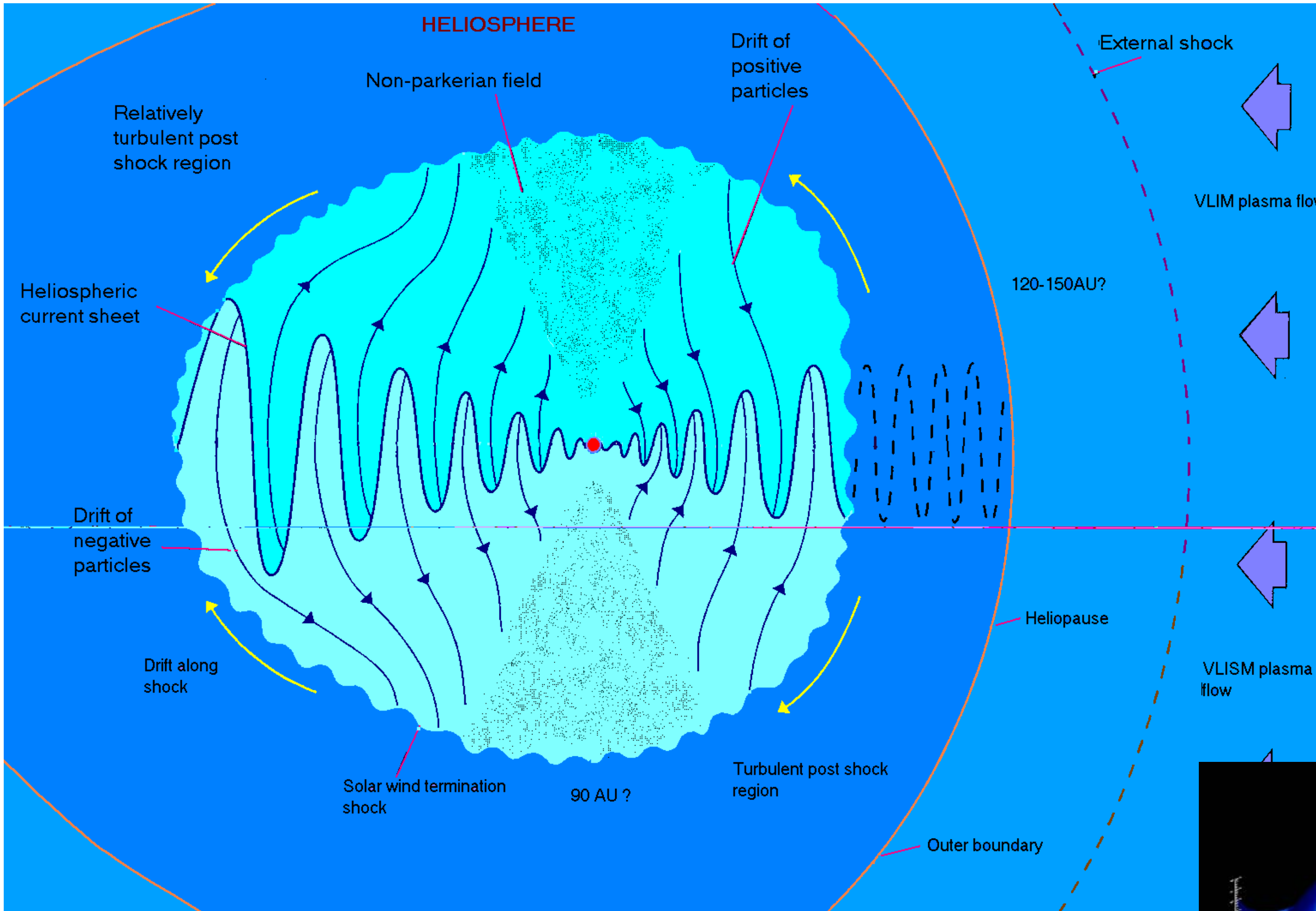


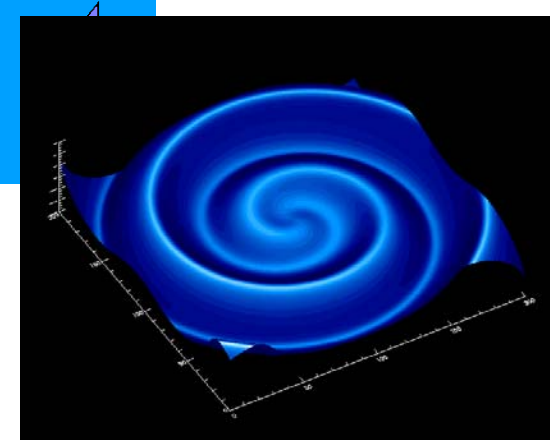




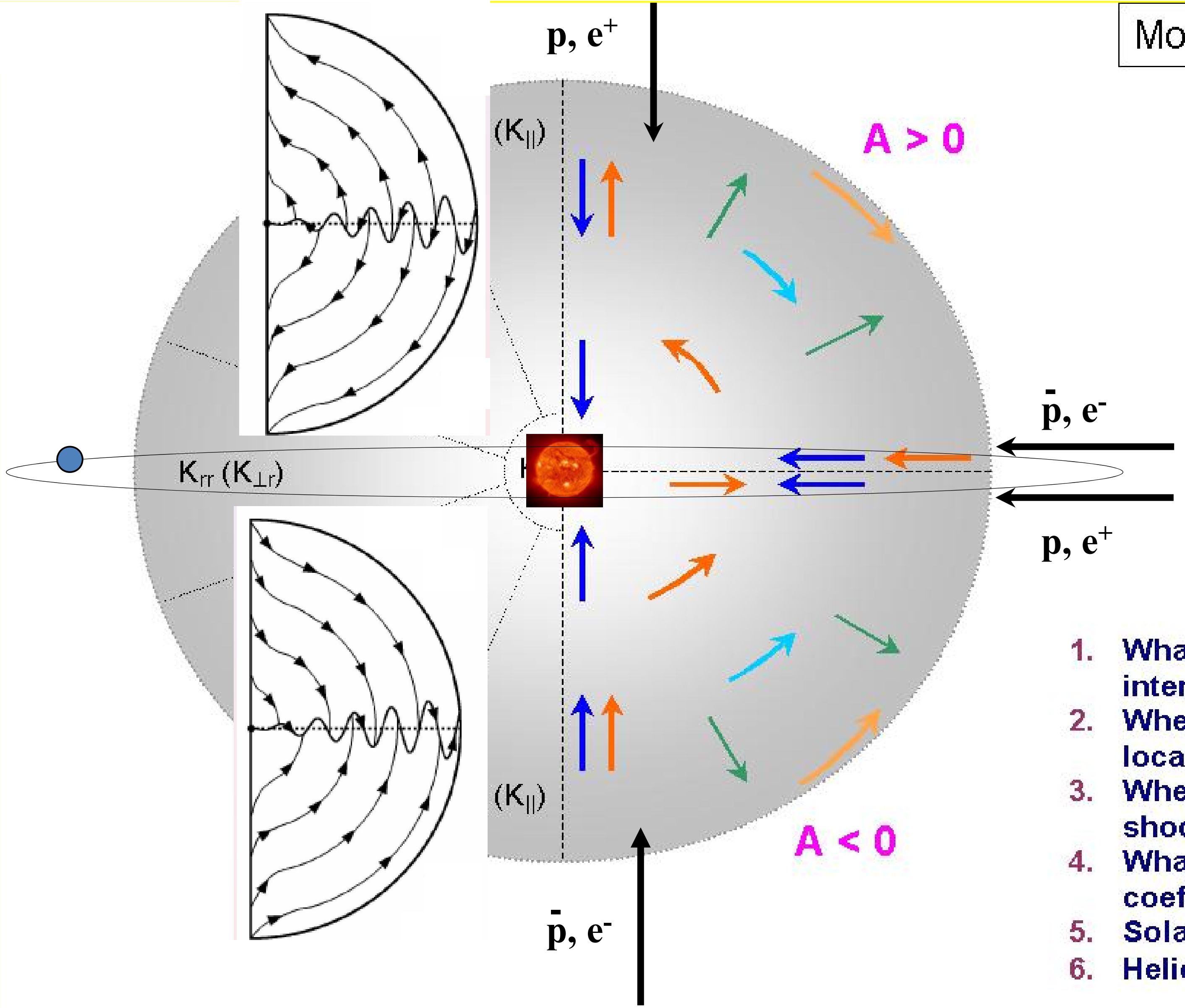


Heliosphere & Cosmic Ray Modulation Mechanisms





Charge dependent solar modulation

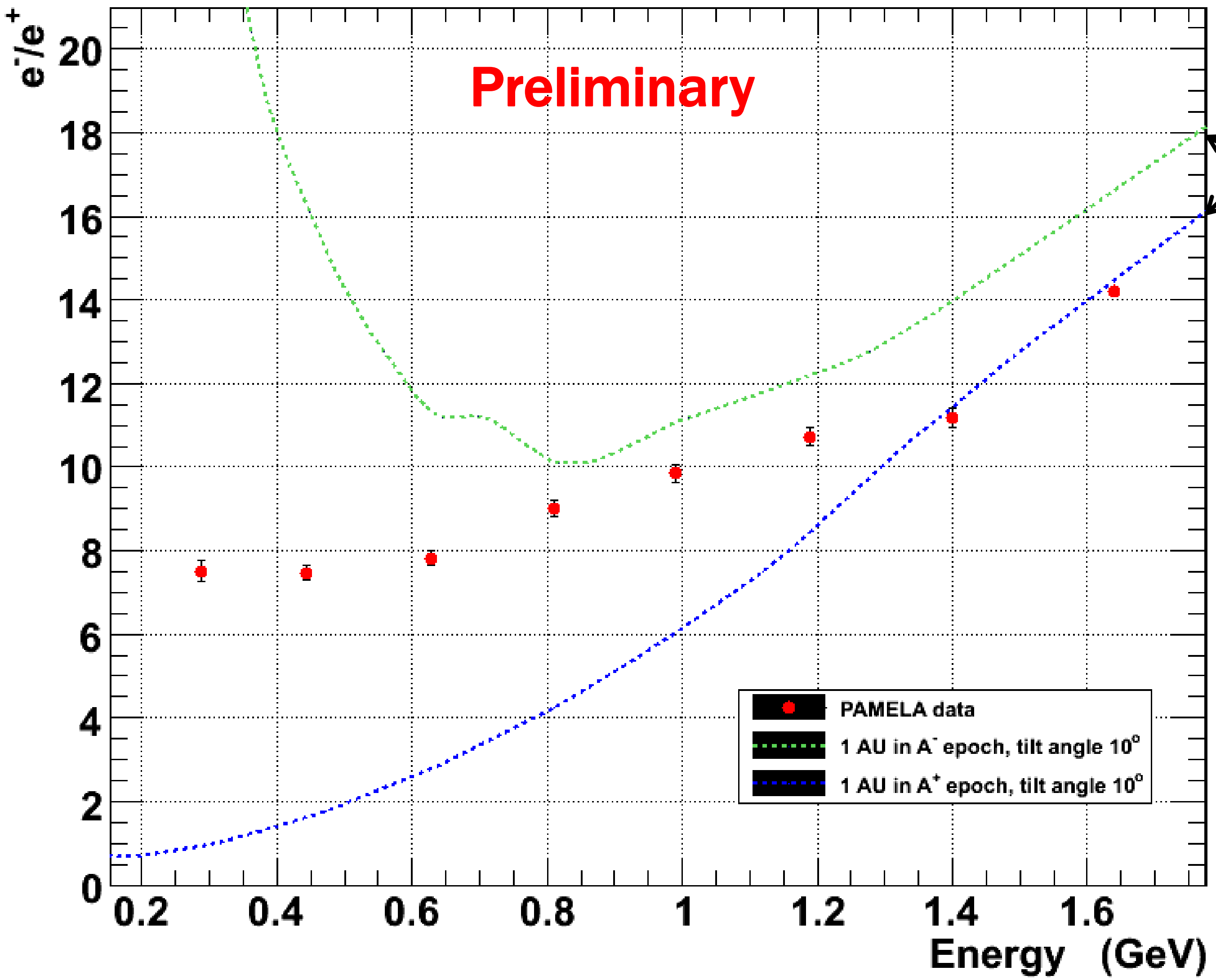


Modulation mechanisms

- Convection
- Diffusion
- Perpendicular diffusion
- G,C & NS Drifts
- Shock-drift

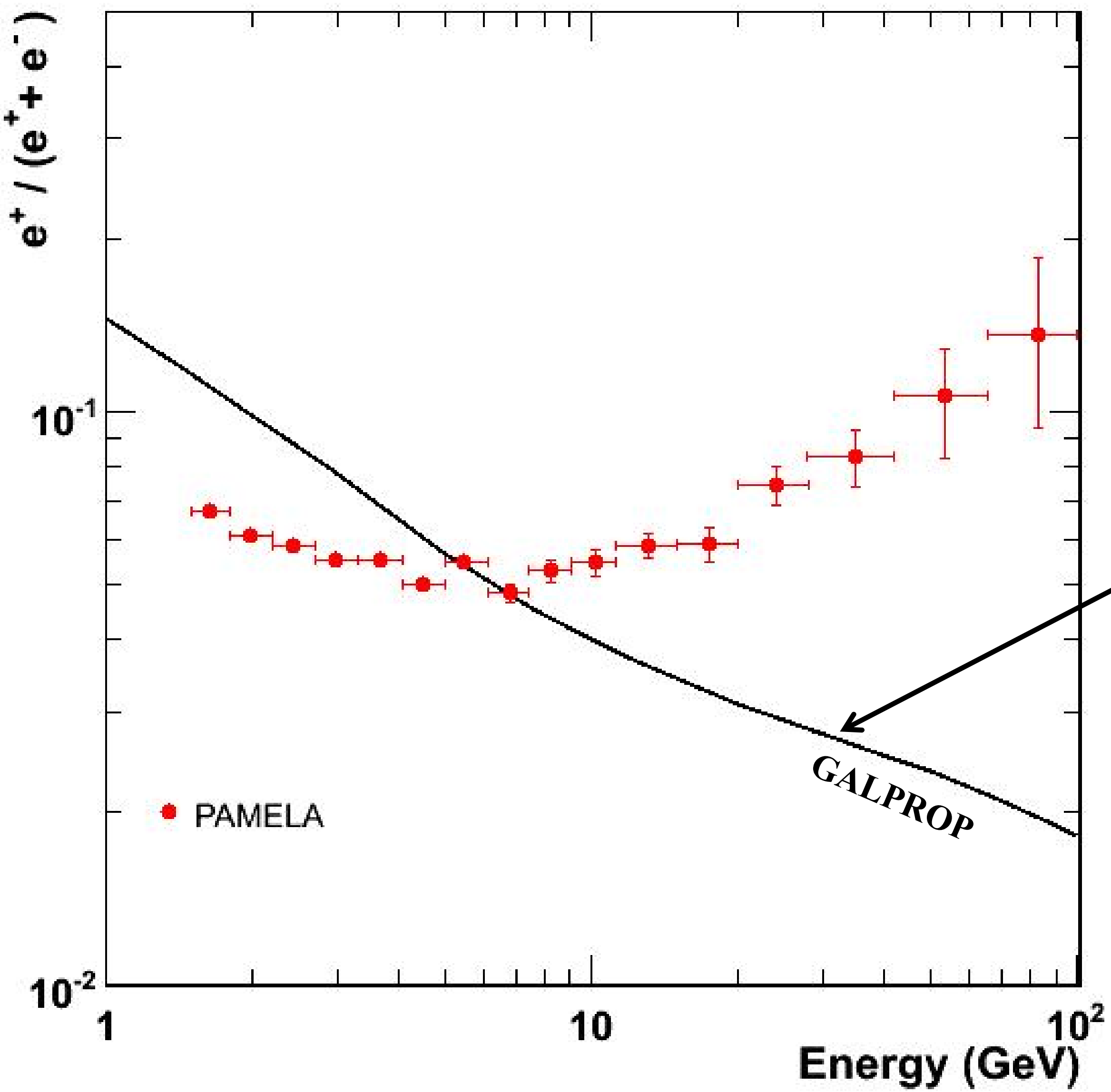
1. What are the local interstellar spectra?
2. Where is the outer boundary located?
3. Where is the termination shock located?
4. What are the diffusion coefficients? (r, t)
5. Solar wind profile?
6. Heliospheric magnetic field?

PAMELA electron to positron ratio and theoretical models



U.W. Langner, M.S. Potgieter, Advances in Space Research 34 (2004)

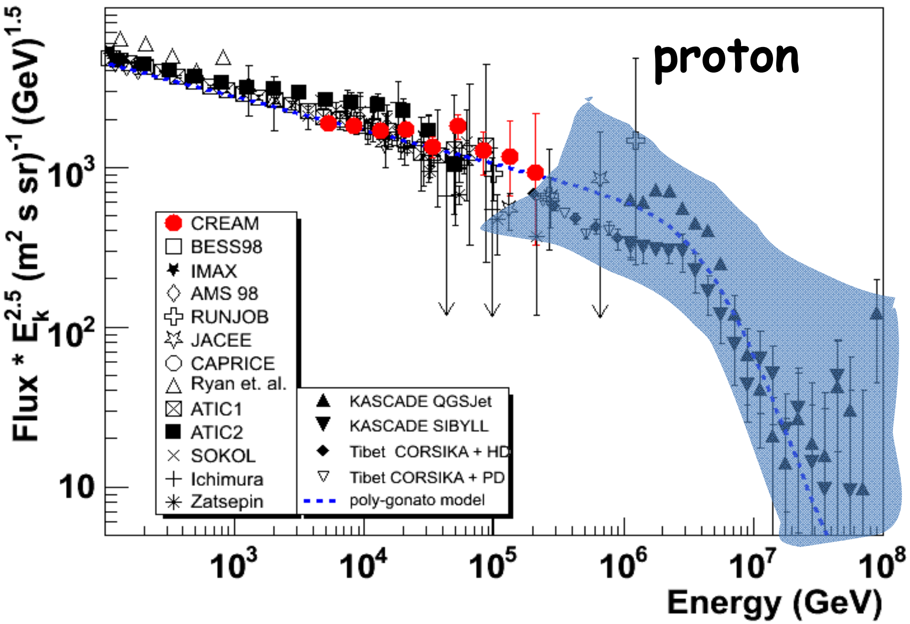
PAMELA Positron Fraction

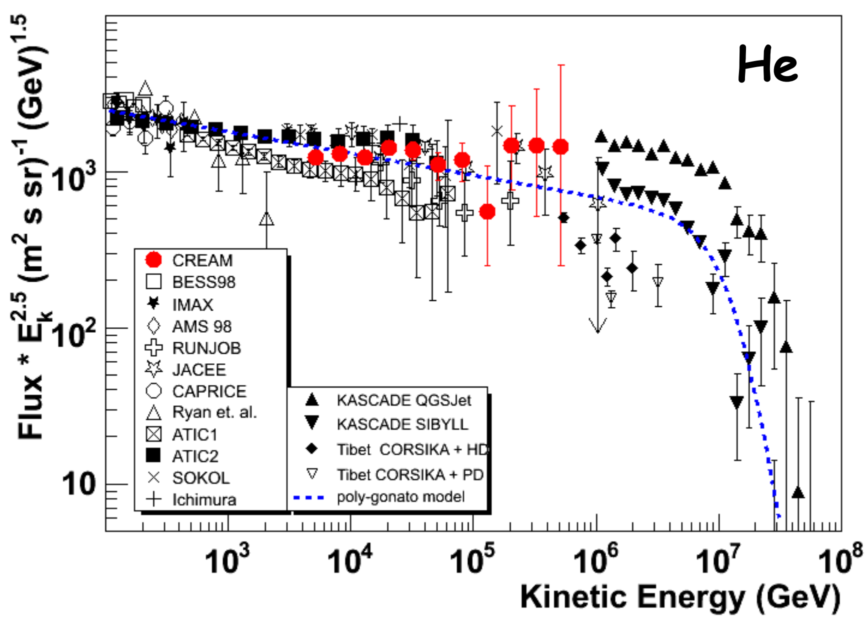


<u>Secondary production</u>
Moskalenko & Strong 98

But uncertainties on:
- **Secondary production (primary fluxes, cross section)**

Galactic H and He spectra

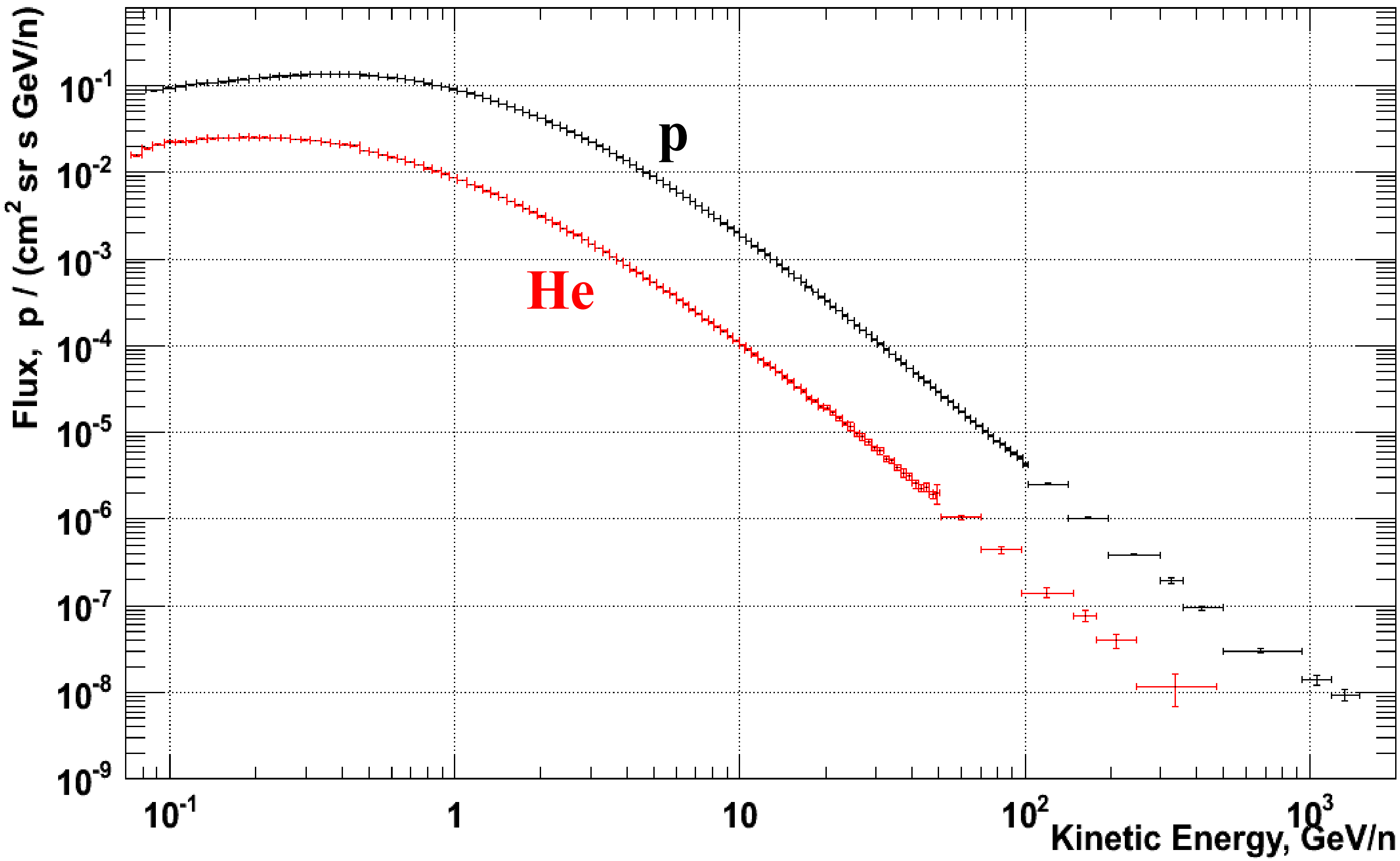




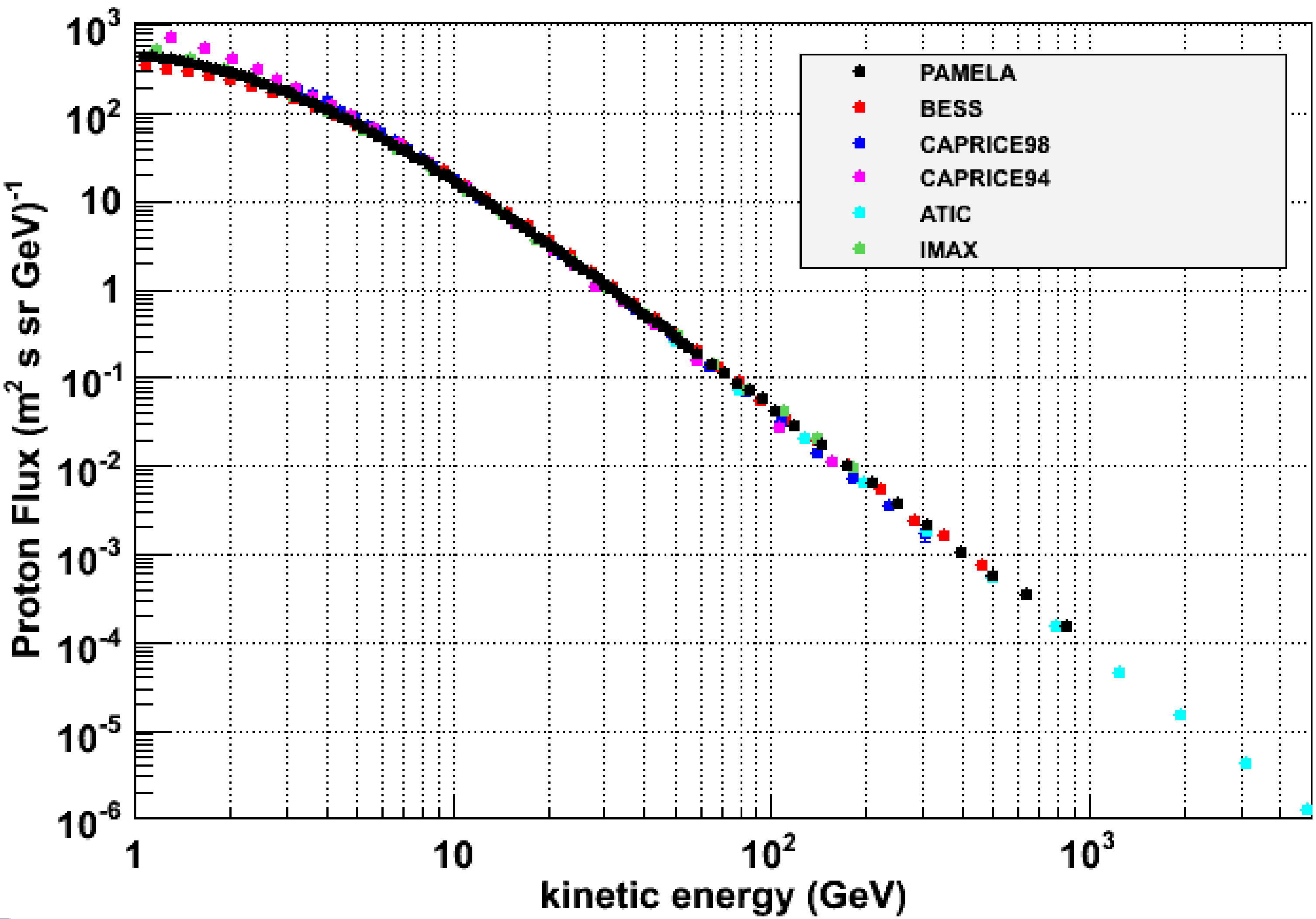
PaMeLa

di Fisica Nucleare

PAMELA Galactic Proton and Helium Spectra

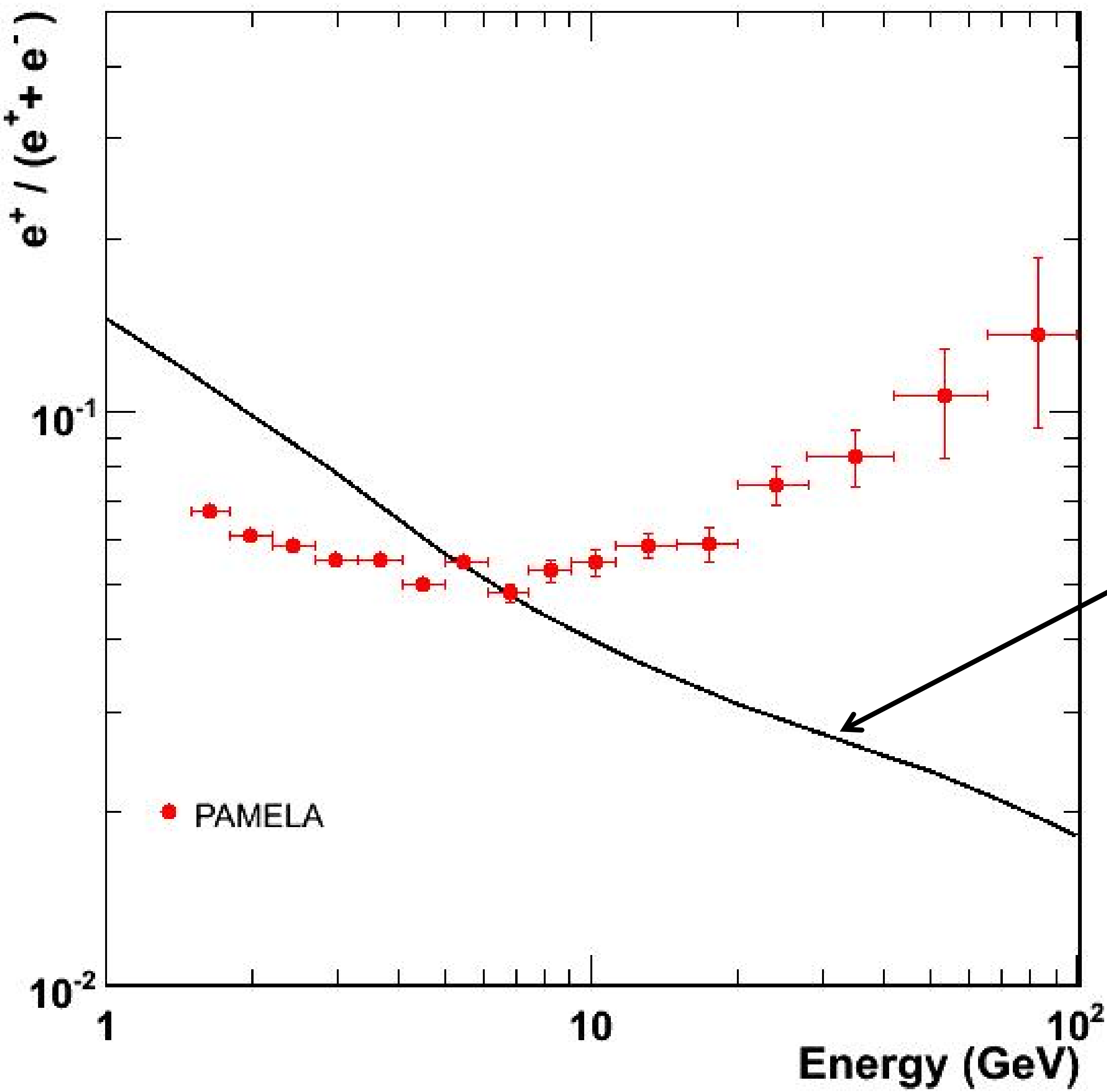


Proton flux



PAMELA
BESS
CAPRICE98
CAPRICE94
ATIC
IMAX
Proton Flux (m^2 s sr GeV)$^{-1}$
kinetic energy (GeV)
10^3
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
1
10
10^2
10^3

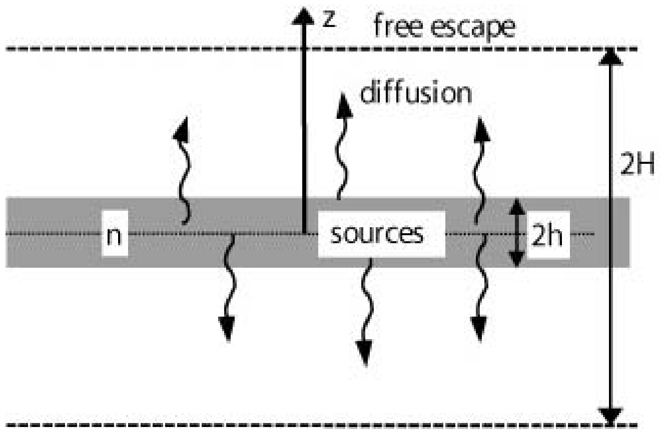
PAMELA Positron Fraction



Secondary production
Moskalenko & Strong 98

But uncertainties on:
- **Secondary production (primary fluxes, cross section)**
- **Propagation models**

Diffusion Halo Model

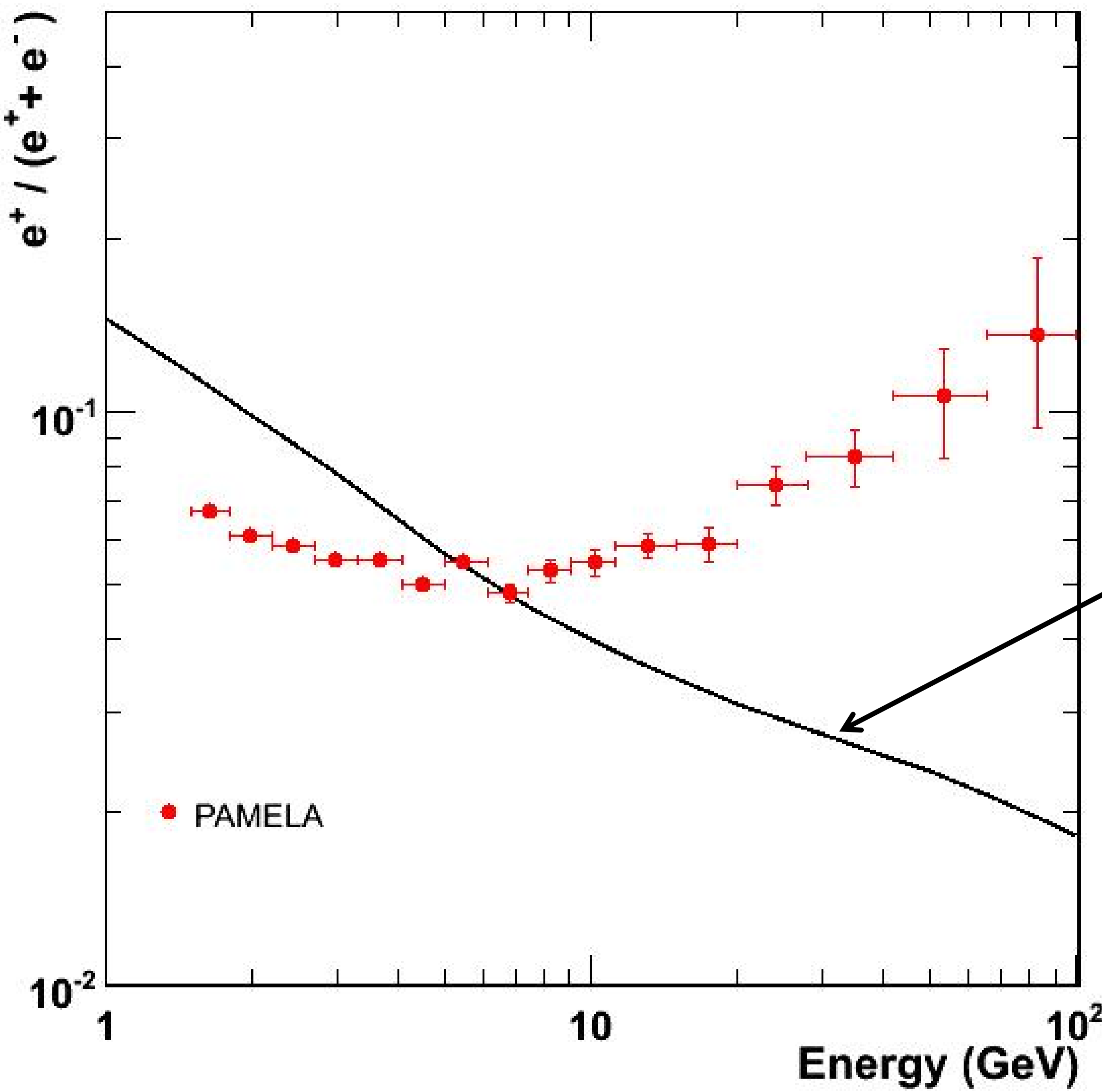


$$\frac{\partial N_i(E,z,t)}{\partial t} = \underbrace{D(E)\cdot\frac{\partial^2}{\partial z^2}N_i(E,z,t)}_{\text{diffusion}} \underbrace{- N_i(E,z,t)\left\{\frac{1}{\tau_i^{\text{int}}(E,z)}+\frac{1}{\gamma(E)\tau_i^{dec}}\right\}}_{\text{interaction and decay}}$$

$$+ \underbrace{\sum_{k>i}\frac{N_k(E,z,t)}{\tau_{\text{int}}^{k\to i}(E,z)}}_{\text{secondary production}} + \underbrace{Q_i(E,z)}_{\text{primary sources}}$$

$$\underbrace{-\frac{\partial}{\partial E}\left\{\left\langle\frac{\partial E}{\partial t}\right\rangle\cdot N_i(E,z,t)\right\}+\frac{1}{2}\frac{\partial^2}{\partial E^2}\left\{\left\langle\frac{\Delta E^2}{\Delta t}\right\rangle\cdot N_i(E,z,t)\right\}}_{\text{energy changing processes (ionisation, reacceleration)}}$$

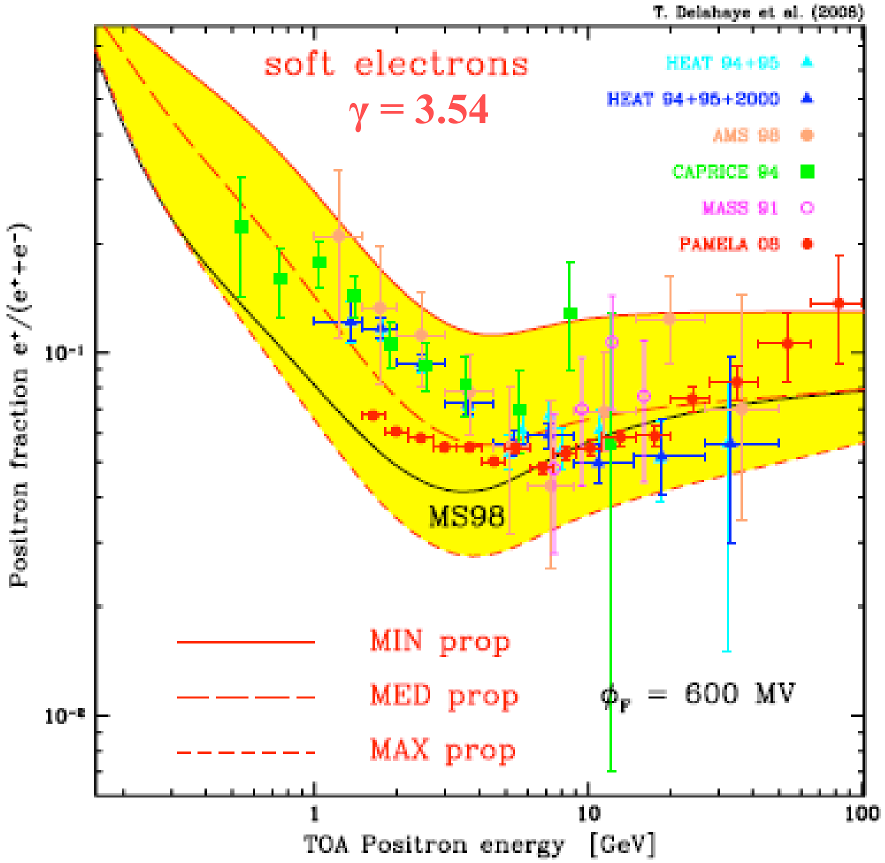
PAMELA Positron Fraction

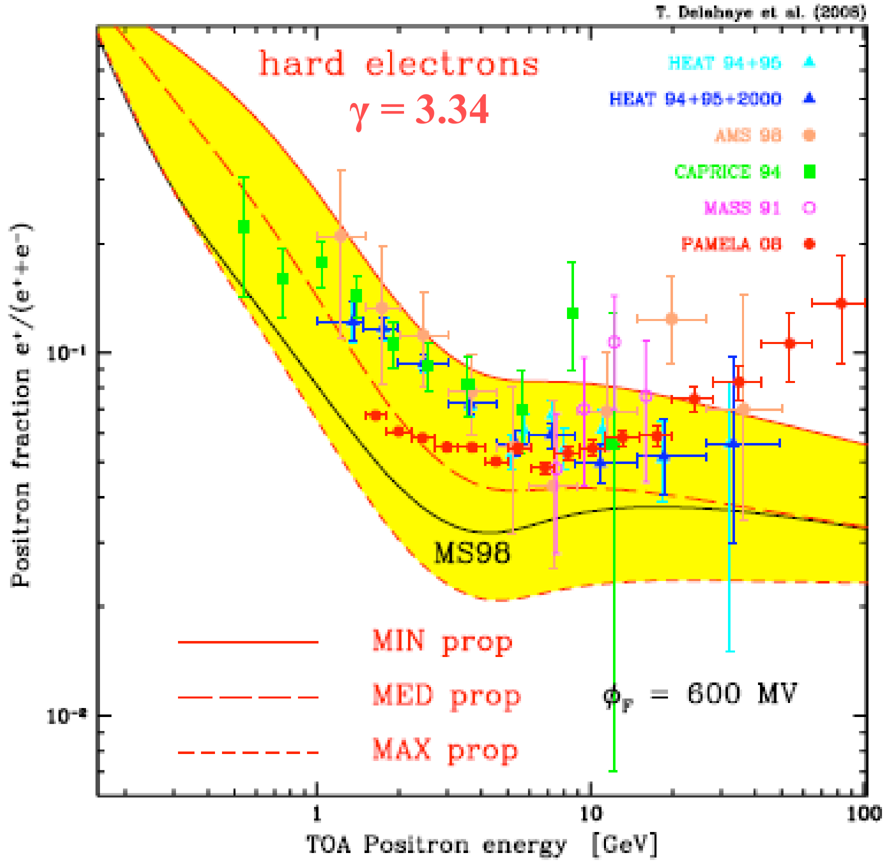


Secondary production
Moskalenko & Strong 98

But uncertainties on:
- **Secondary production (primary fluxes, cross section)**
- **Propagation models**
- **Electron spectrum**

Theoretical uncertainties on "standard" positron fraction





T. Delahaye et al., arXiv: 0809.5268v3

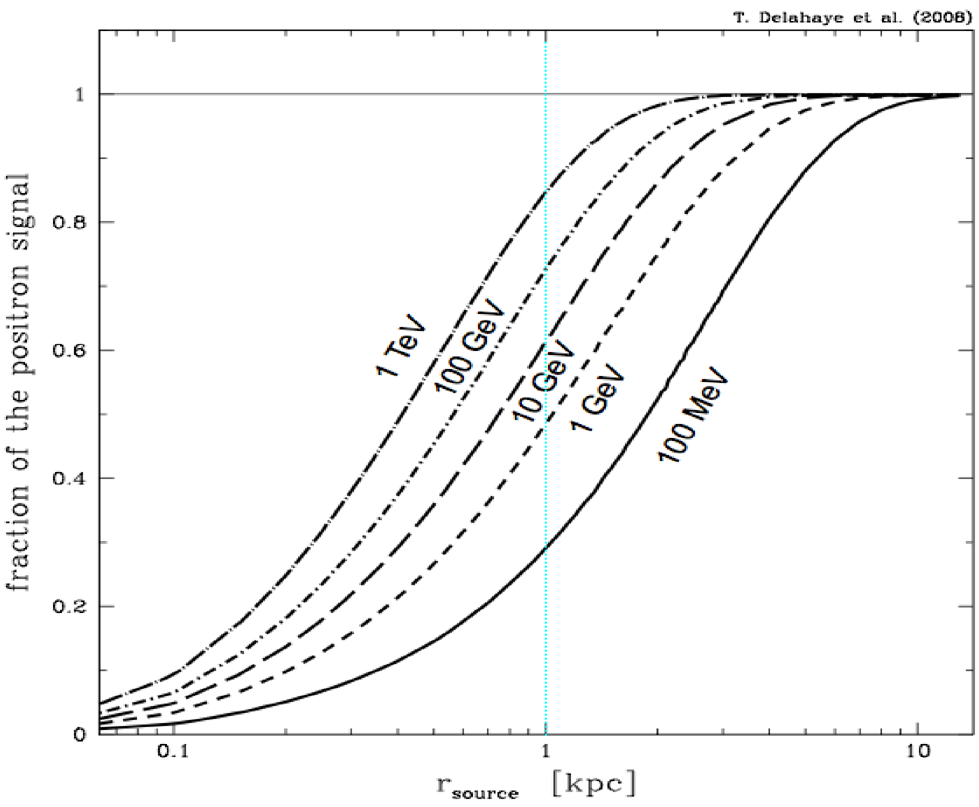
Positrons detection

Where do positrons come from?

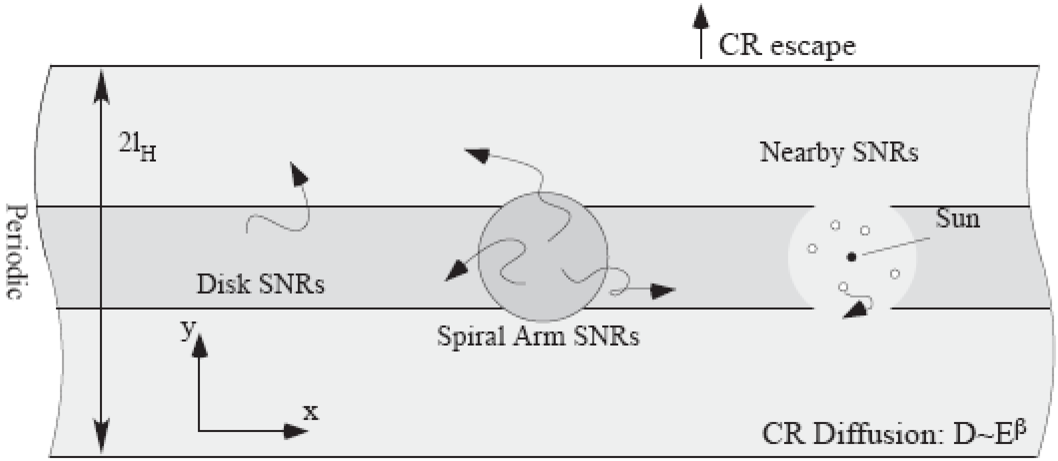
Mostly locally within 1 Kpc, due to the energy losses by Synchrotron Radiation and Inverse Compton

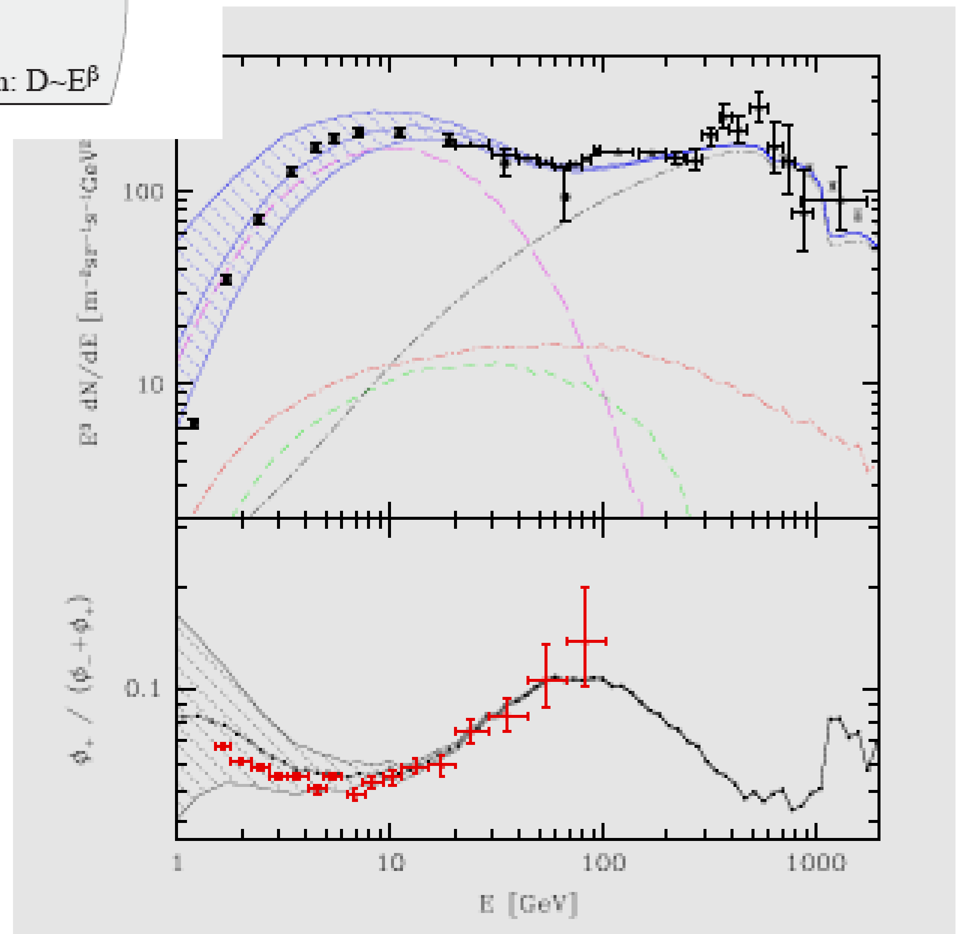
Typical lifetime

$$\tau \simeq 5 \cdot 10^5 \mathrm{yr} \left(\frac{1\,\mathrm{TeV}}{E} \right)$$



Astrophysical Explanation: SNR

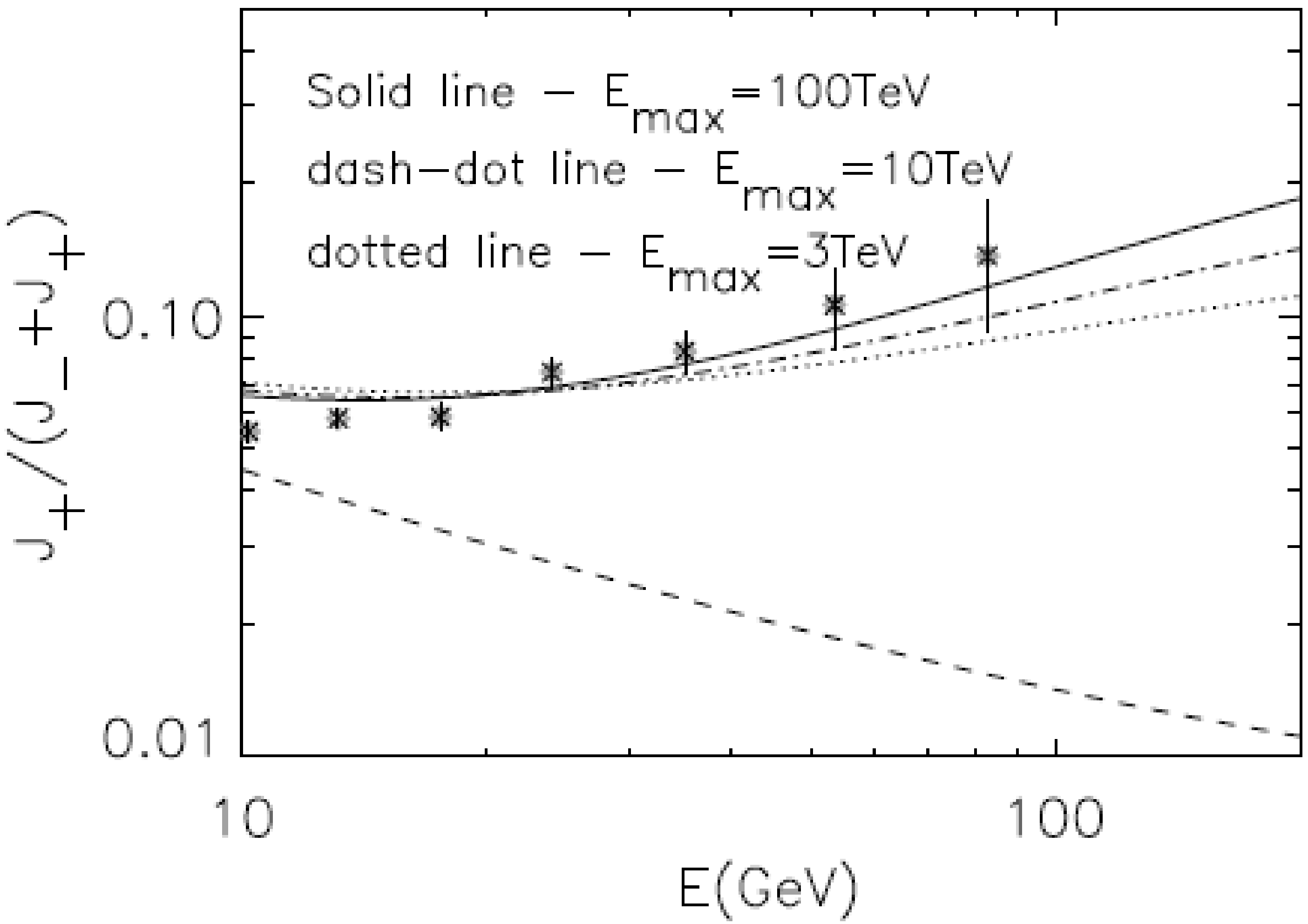




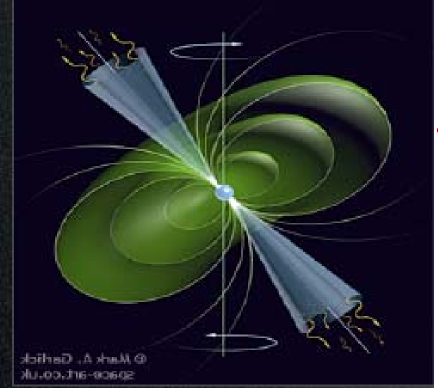
N.J. Shaviv et al., arXiv:0902.0376v1

Astrophysical Explanation: SNR

Positrons (and electrons) produced as secondaries in the sources (e.g. SNR) where CRs are accelerated



P.Blasi, arXiv:0903.2794 [astro-ph]



Astrophysical Explanation: Pulsars

- Mechanism: the spinning $\vec{B}$ of the pulsar strips e^- that accelerated at the polar cap or at the outer gap emit γ that make production of $e^\pm$ that are trapped in the cloud, further accelerated and later released at $\tau \sim 10^5$ years.

- Young ($T < 10^5$ years) and nearby (< 1kpc)
- If not: too much diffusion, low energy, too low flux.

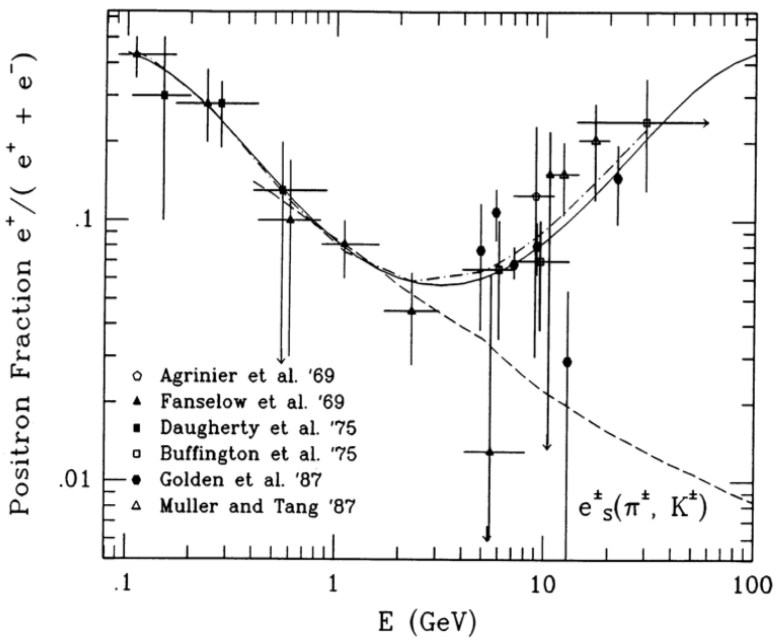
- Geminga: 157 parsecs from Earth and 370,000 years old
- B0656+14: 290 parsecs from Earth and 110,000 years old.

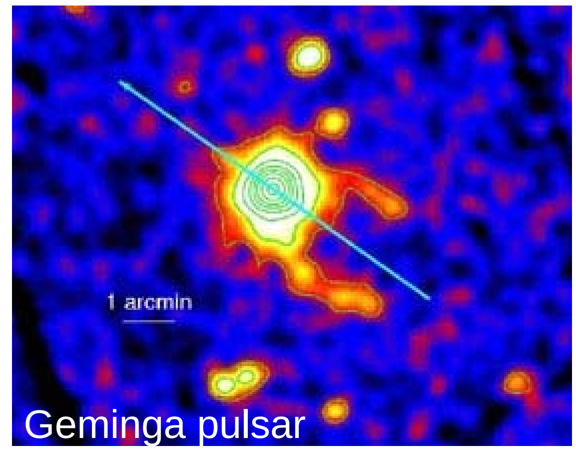
- Diffuse mature pulsars

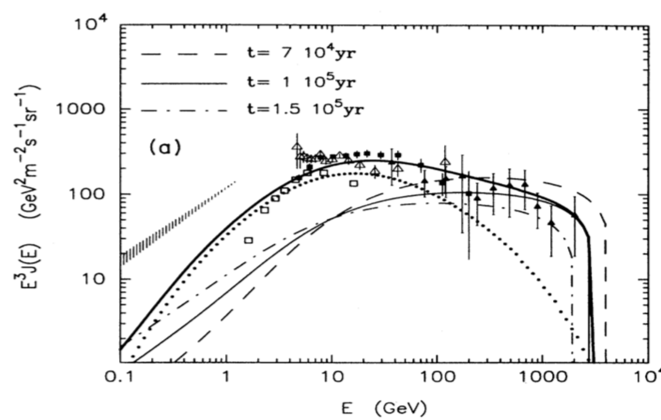
Astrophysical Explanation: Pulsars

Are there "standard" astrophysical explanations of the PAMELA data?

Young, nearby pulsars

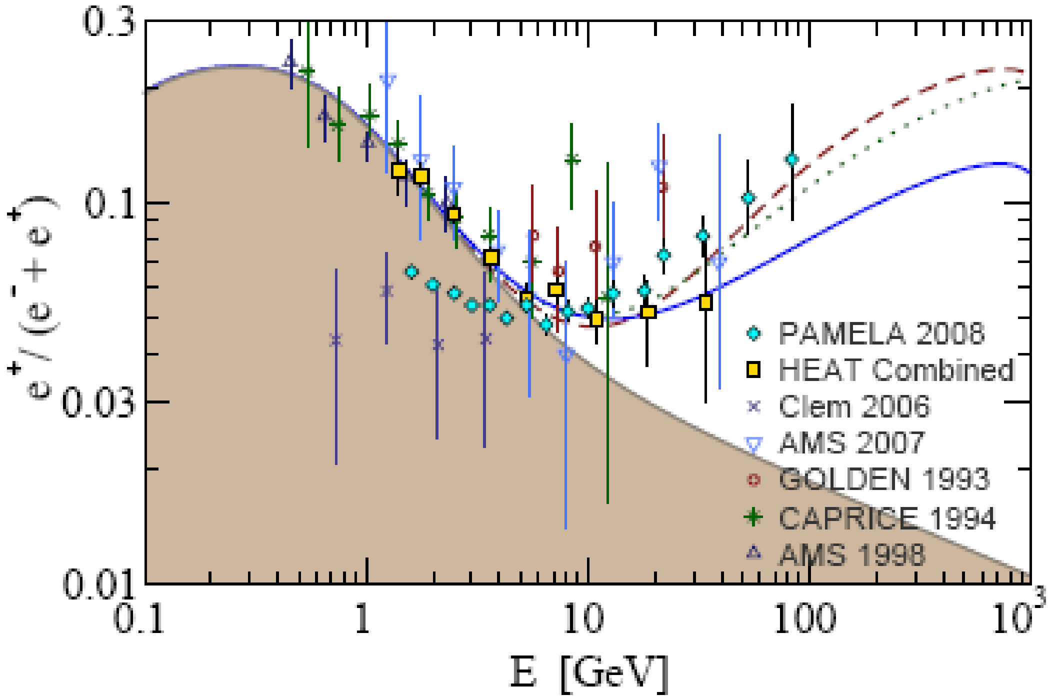




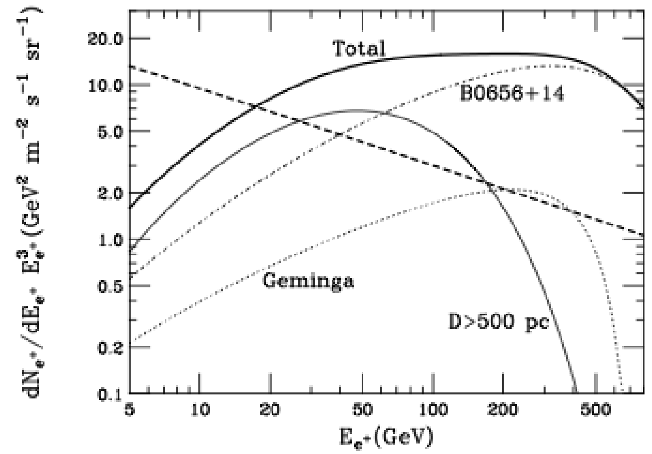


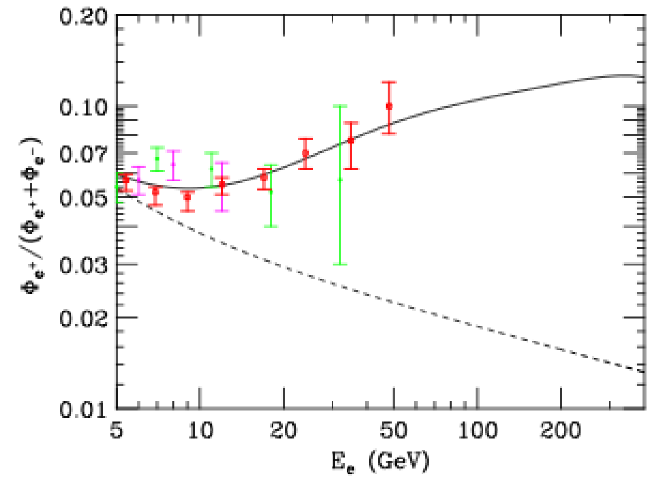
Not a new idea: Boulares, ApJ 342 (1989), Atoyan et al (1995)

Astrophysical Explanation: Pulsars



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





diffuse mature &nearby young pulsars
Hooper, Blasi, and Serpico
arXiv:0810.1527

ELECTRONS

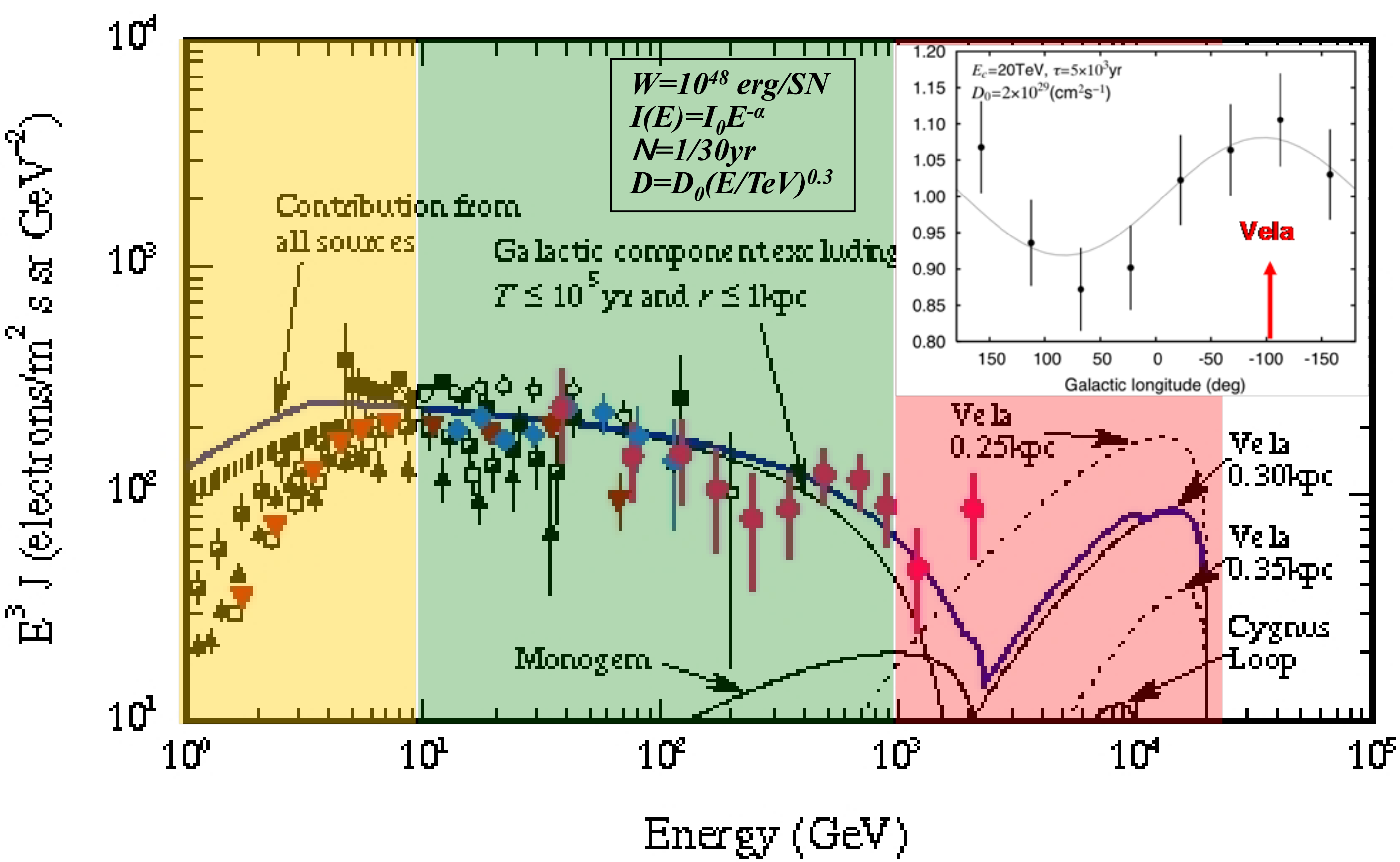
All Electron (e^- + e^+) spectra

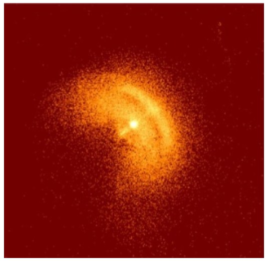
Possible Nearby Sources
- $T < 10^5$ years
- $L < 1$ kpc

Search for the signature of nearby HE electron sources (believed to be SNR) in the electron spectrum above 1 TeV

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

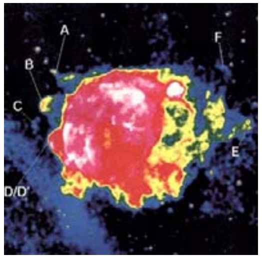
Observation of electron spectrum in 1~10 GeV for study of solar modulation

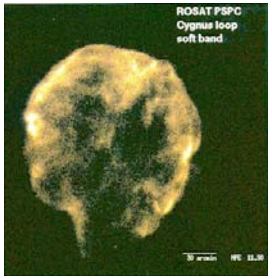


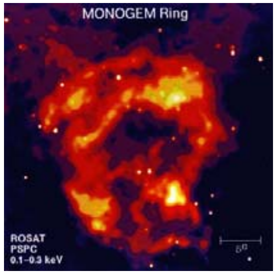


Chandra

ROSAT







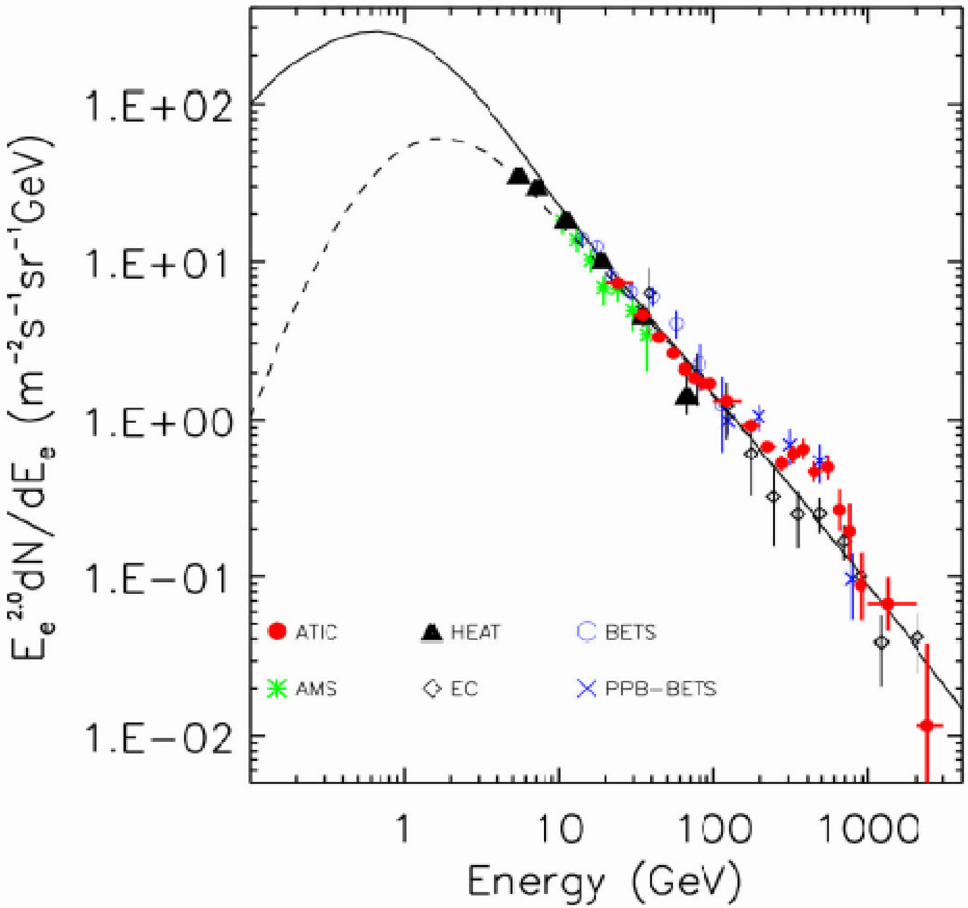
The ATIC electron results exhibits a feature

Curves are from GALPROP diffusion propagation simulation code

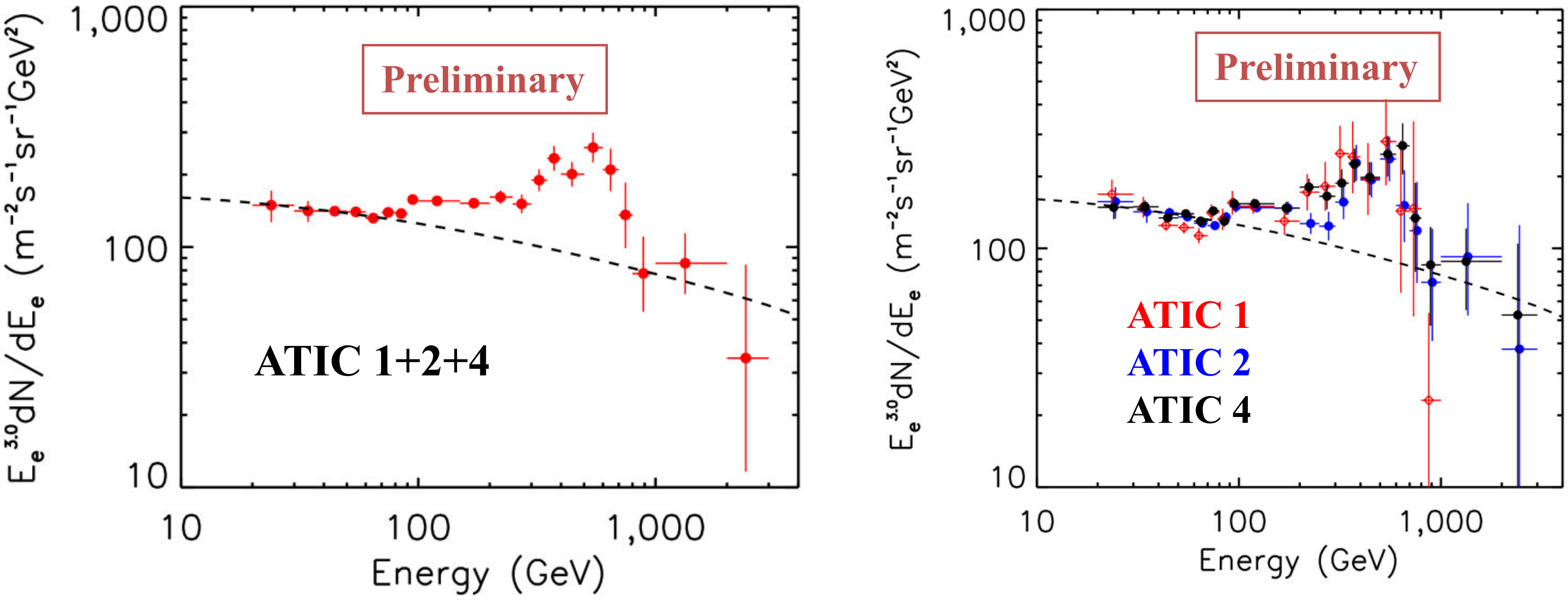
- Solid curve is local interstellar space
- Dashed curve is with solar modulation (500 MV)

"Excess" at about 300 – 600 GeV

Also seen by recent PPB-BETS



All three ATIC flights are consistent



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

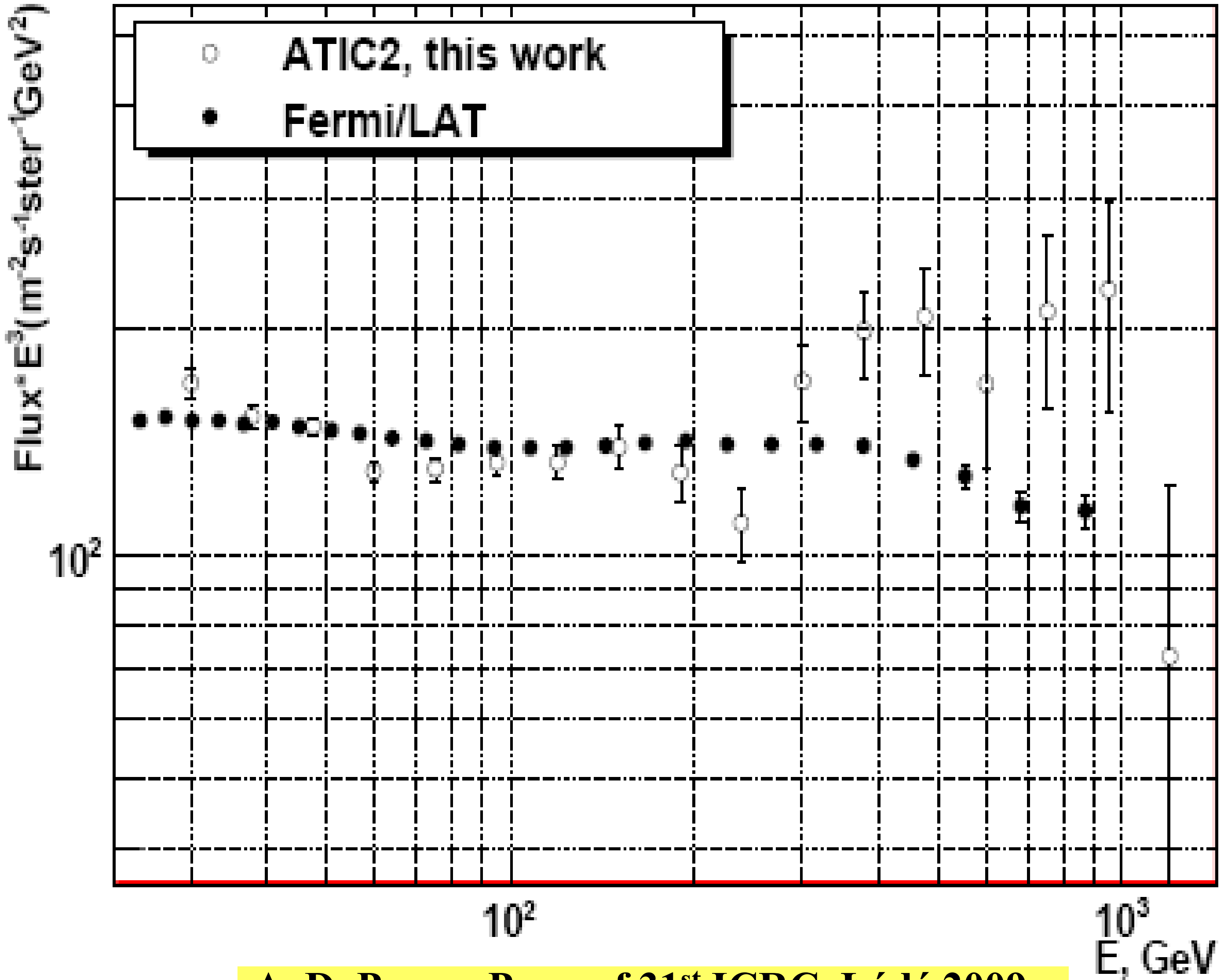
J Chang *et al. Nature* **456**, 362 (2008)

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

"Bump" is seen in all three flights.

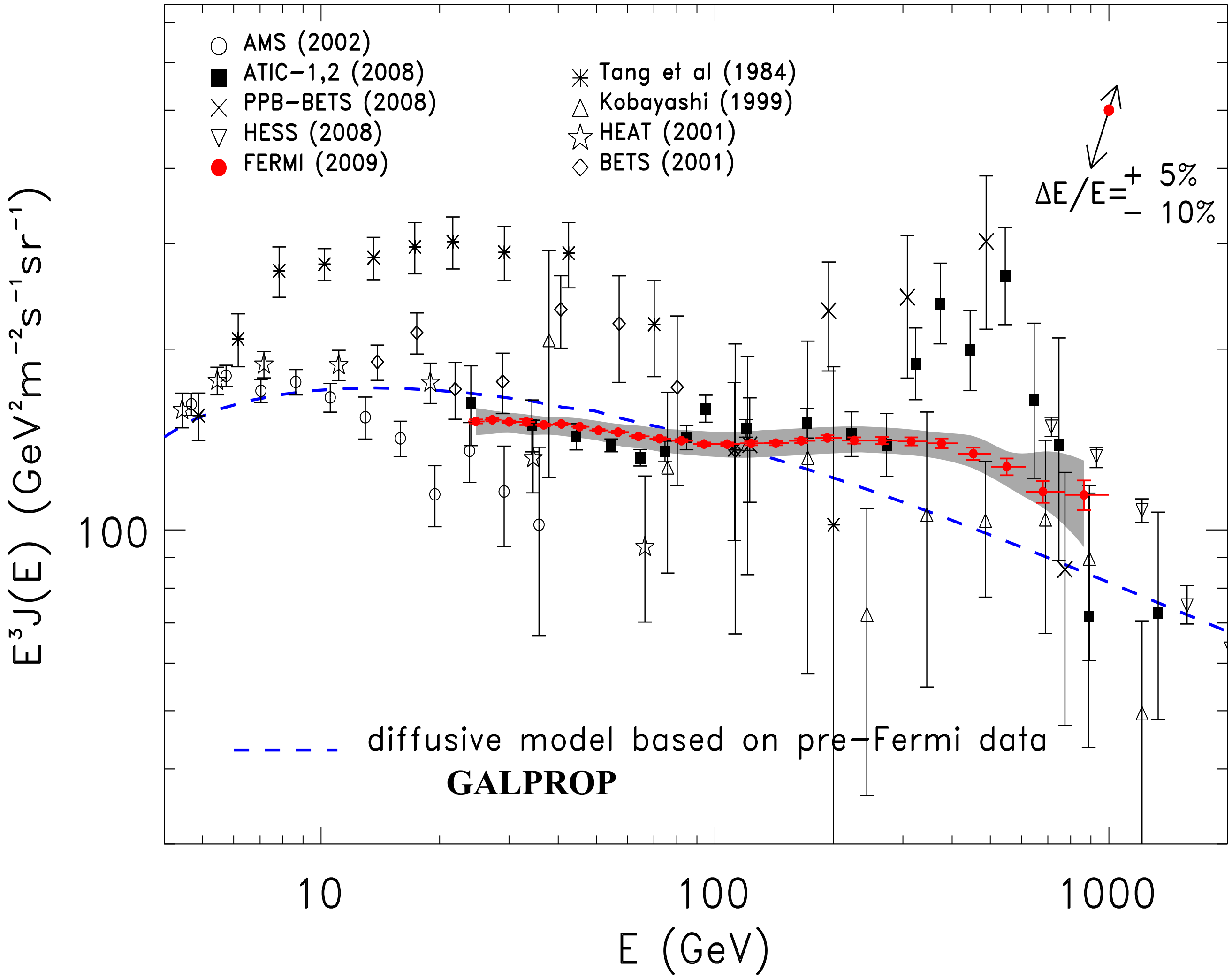
Significance for ATIC1+2+4 is 5.1 sigma

New ATIC Analysis?



A. D. Panov, Proc. of 31st ICRC, Łódź 2009

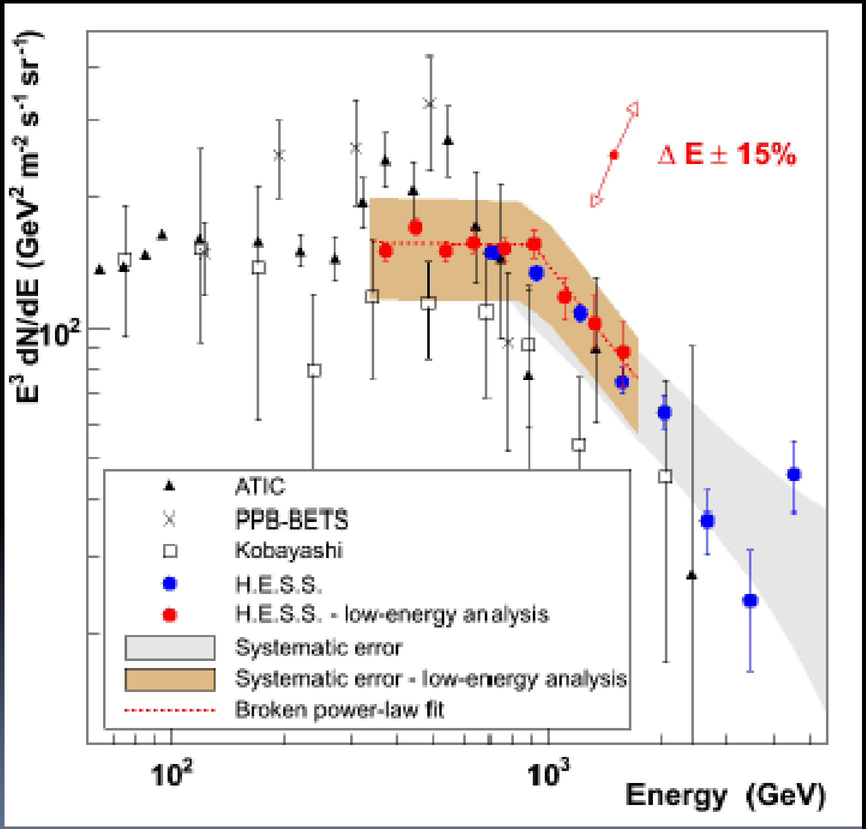
FERMI all Electron Spectrum



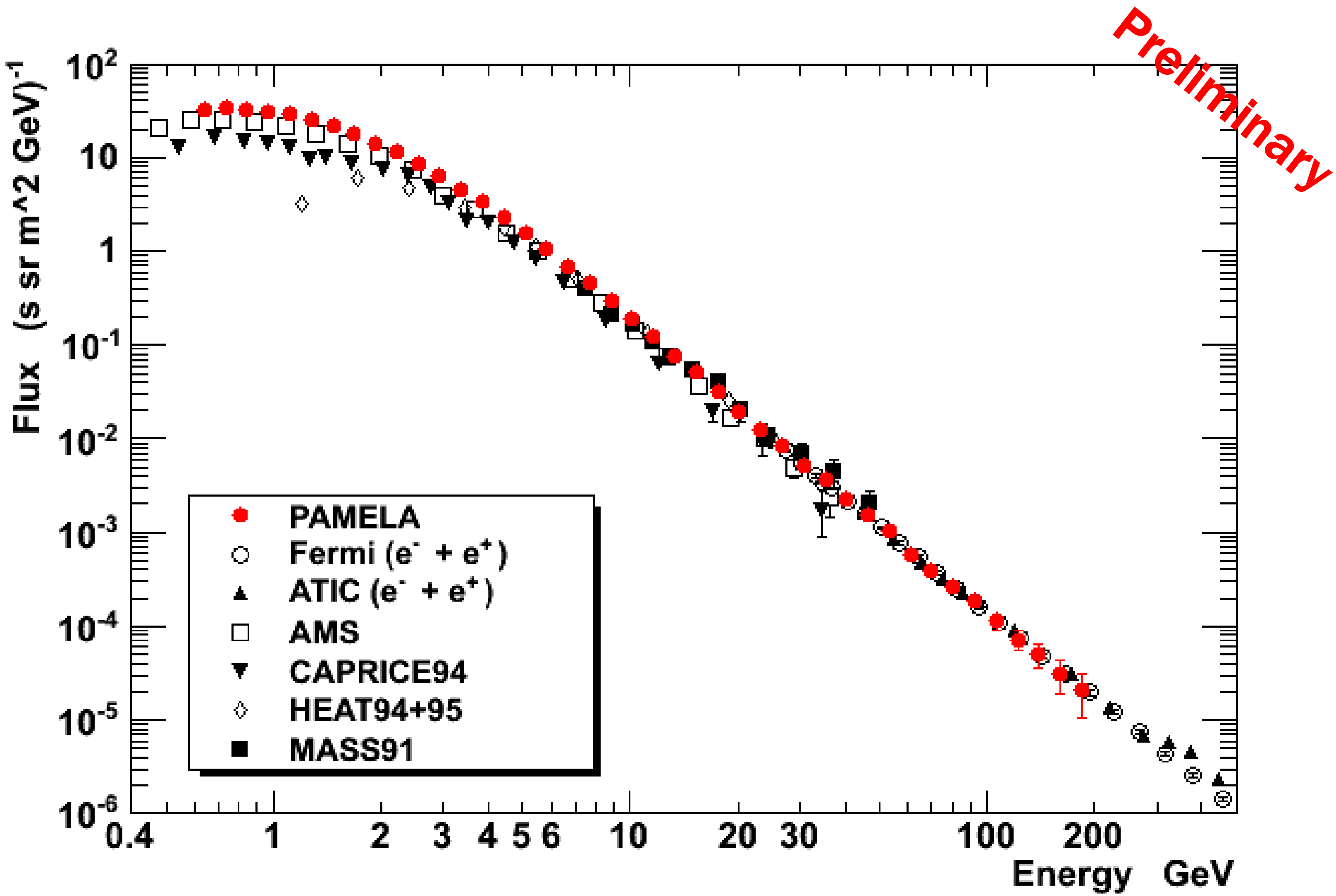
Electrons measured with H.E.S.S.

Results: Low-Energy Spectrum

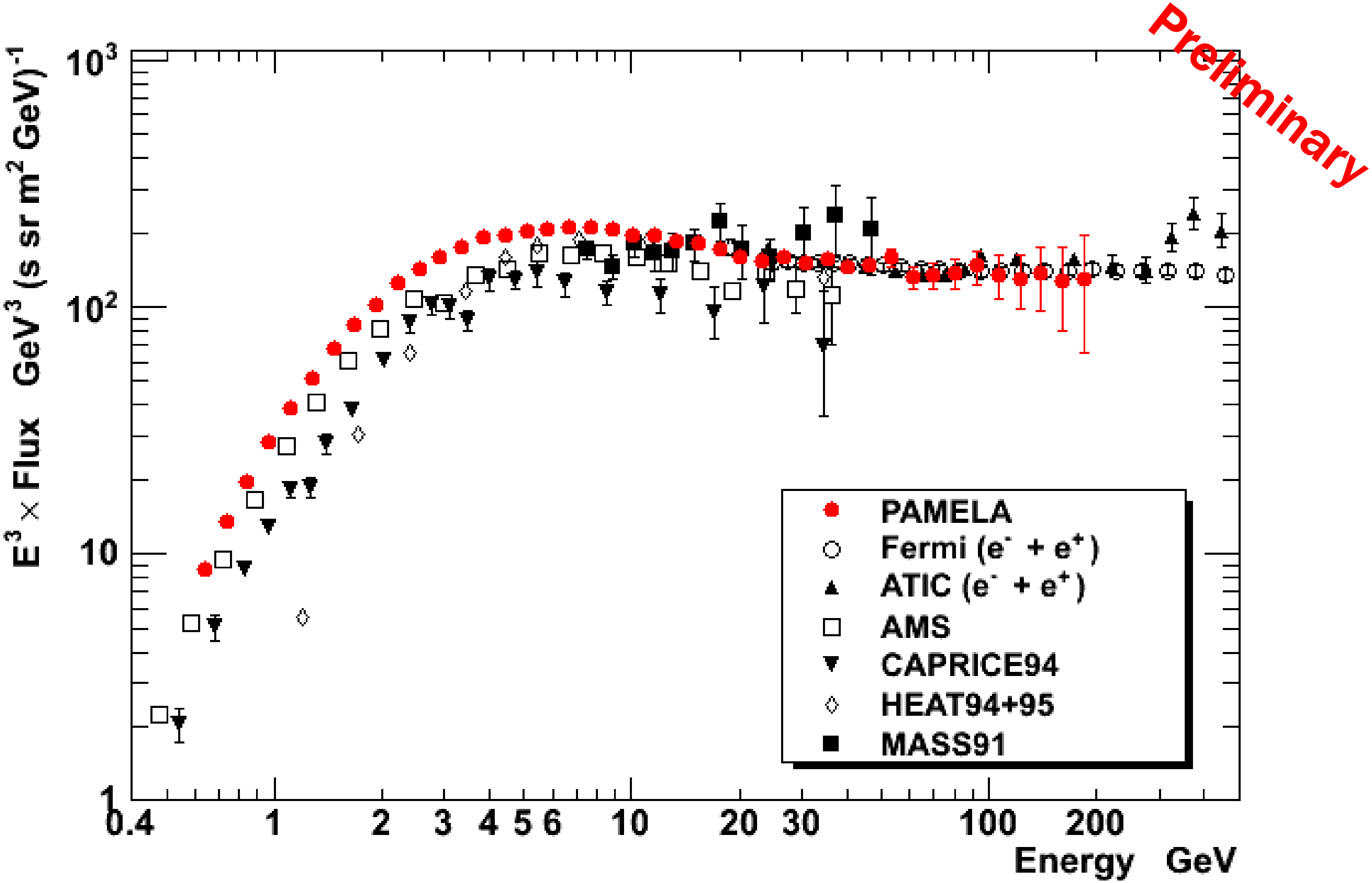
- Cuts:
  - impact distance < 100 m
  - image size in each camera > 80 photo electrons
  - Data set of 2004/2005
- Syst. uncertainty: atmospheric variations + model dependence of proton simulations (SIBYLL vs. QGSJET-II)
- Spectral index:
  $\Gamma_1 = 3.0 \pm 0.1(stat) \pm 0.3(syst.)$
  $\Gamma_2 = 3.9 \pm 0.1(stat) \pm 0.3(syst.)$



PAMELA Electron (e^-) Spectrum



PAMELA Electron (e^-) Spectrum



Summary

- PAMELA has been in orbit and studying cosmic rays for ~42 months. >10^9 triggers registered and >18 TB of data has been down-linked.

- Antiproton-to-proton flux ratio and antiproton energy spectrum (~100 MeV - ~200 GeV) show no significant deviations from secondary production expectations.

- High energy positron fraction (>10 GeV) increases significantly (and unexpectedly!) with energy. Primary source?
Data at higher energies might help to resolve origin of rise (spillover limit ~300 GeV).

- e^- spectrum up to ~200 GeV shows spectral features that may point to additional components. Analysis is ongoing to increase the statistics and expand the measurement of the e^- spectrum up to ~500 GeV and e^+ spectrum up to ~300 GeV (all electrum ($e^- + e^+$) spectrum up to ~1 TV).

- Furthemore:
  - PAMELA is going to provide measurements on elemental spectra and low mass isotopes with an unprecedented statistical precision and is helping to improve the understanding of particle propagation in the interstellar medium
  - PAMELA is able to measure the high energy tail of solar particles.
  - PAMELA is going to set a new lower limit for finding Antihelium

http://pamela.roma2.infn.it

INFN Istituto Nazionale di Fisica Nucleare

Thanks!