Measurement of Cosmic-Ray Positrons & Electrons

An Experimentalist's Point of View

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ENTApP Dark Matter Workshop

CERN 2009

Electrons & Positrons in Cosmic Rays

- Electrons from SN
- Positrons / electrons from Secondary Production (p-ISM $\rightarrow \pi^+ \rightarrow \mu^+ \rightarrow e^+$)

- $e^\pm$ lose energy rapidly ($dE/dt \propto E^2$)
  - IC scattering on interstellar photons
  - synchrotron radiation (interstellar B field ~ few μG)

  $\rightarrow$ high energy electrons (and positrons) are "local."

- $e^\pm$ produced in pairs (in ISM).
- $e^+/(e^+ + e^-)$ fraction is small (≈10%)

  $\rightarrow$ substantial primary e^- component.

Cosmic Ray Electrons

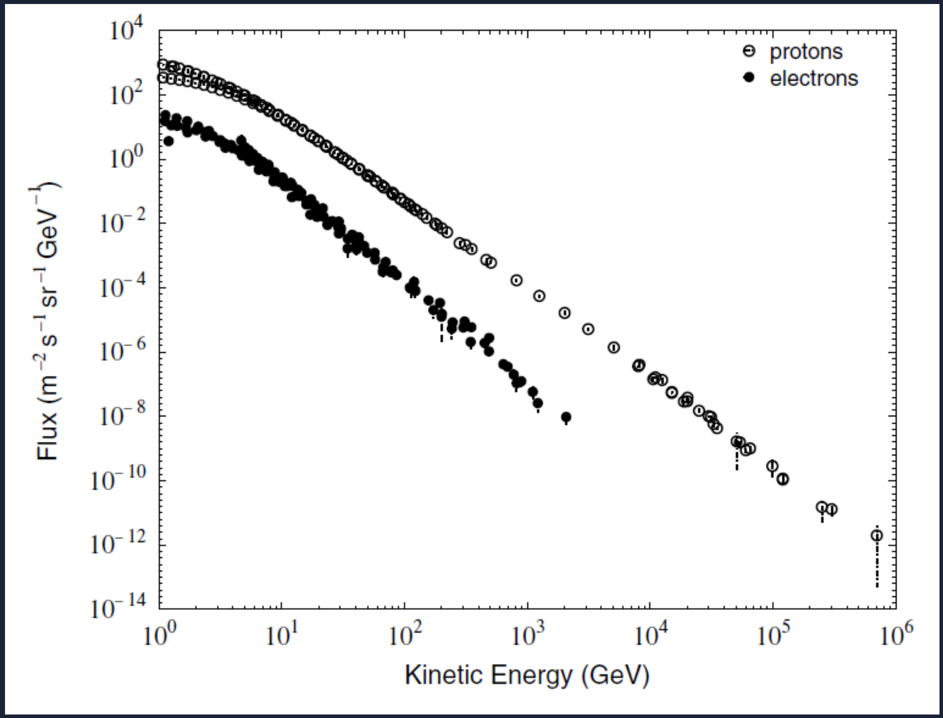
- Electron intensity ~ 1% Proton intensity (at 10 GeV)

- Power-law energy spectrum for CR protons and CR electrons

  At GeV-TeV energies:

  Protons: $I(E) \sim E^{-2.7}$

  Electrons: $I(E) \sim E^{-3.4}$

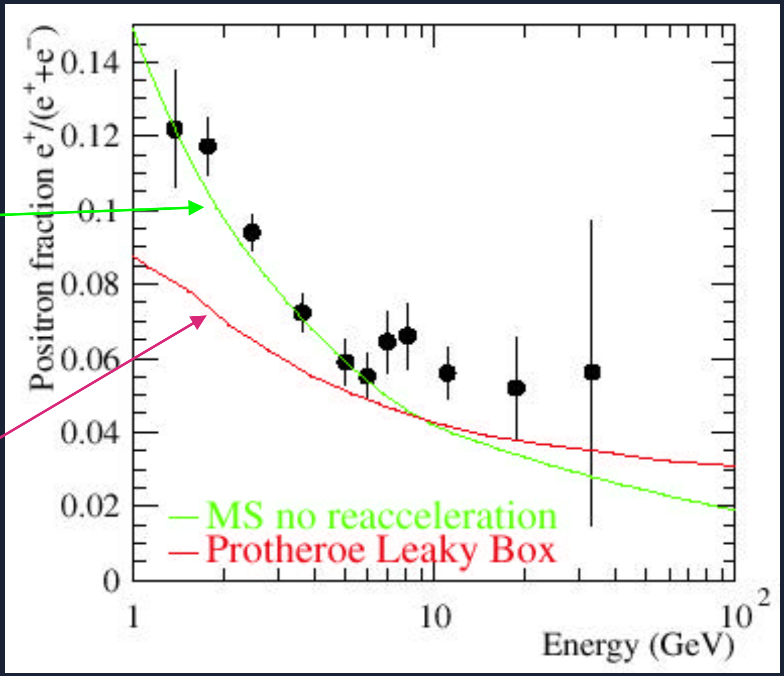


Why do we care?

Structure in the CR Positron fraction
- as first observed by HEAT instrument –
could be DM signature* (or nearby pulsars or...?**)

Galactic diffusion model (no re-acceleration)
[Moskalenko & Strong, ApJ 493, 694 (1998)]

leaky-box propagation
[Protheroe, ApJ 254, 391 (1982)]



* M. Kamionkowski and M. Turner, Phys. Rev. D 43, 1774 (1991)
** S. Coutu *et al.*, Astropart. Phys. 11, 429 (1999).

CR Positron measurements are challenging

- Flux of CR protons in the energy range 1 – 50 GeV exceeds that of positrons by a factor of ~ 5×10^4

- Proton rejection of 10^6 is required for a positron sample with less than 1% proton contamination.

Remember: The single largest challenge in measuring CR positrons is the discrimination against the vast proton background!

CR positron measurements
The early years: 1965 - 1984

1963: Manitoba

(De Shong, Hildeband, Meyer, 1964)

1965, 1966: Manitoba

(Fanselow, Hartman, Hildebrand, Meyer, 1969)

1967: Italy

(Agrinier et al. 1969)

1972: Manitoba

(Daugherty, Hartman, Schmidt, 1975)

1972: Texas

(Buffington, Orth, Smoot, 1974)

1974: Manitoba

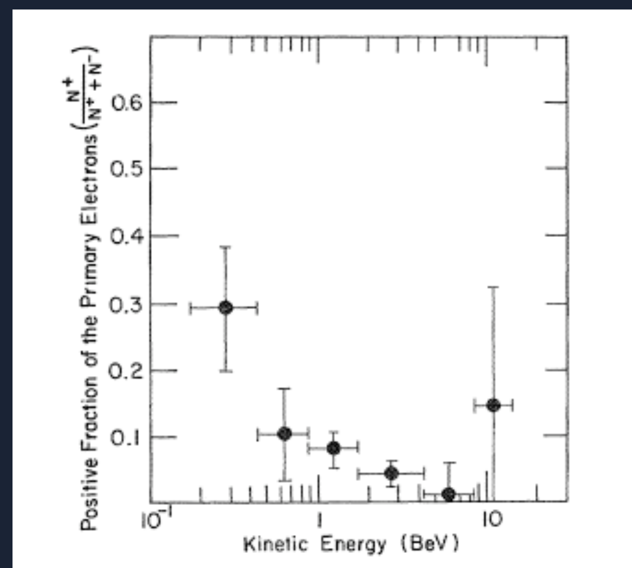
(Hartman and Pellerin, 1976)

1976: Texas

(Golden et al., 1987)

1984: Hawaii

(Müller and Tang, 1987)



Fanselow, Hartman, Hildebrand, Meyer
ApJ 158 (1969)

CR positron measurements
The early years: 1965 - 1984

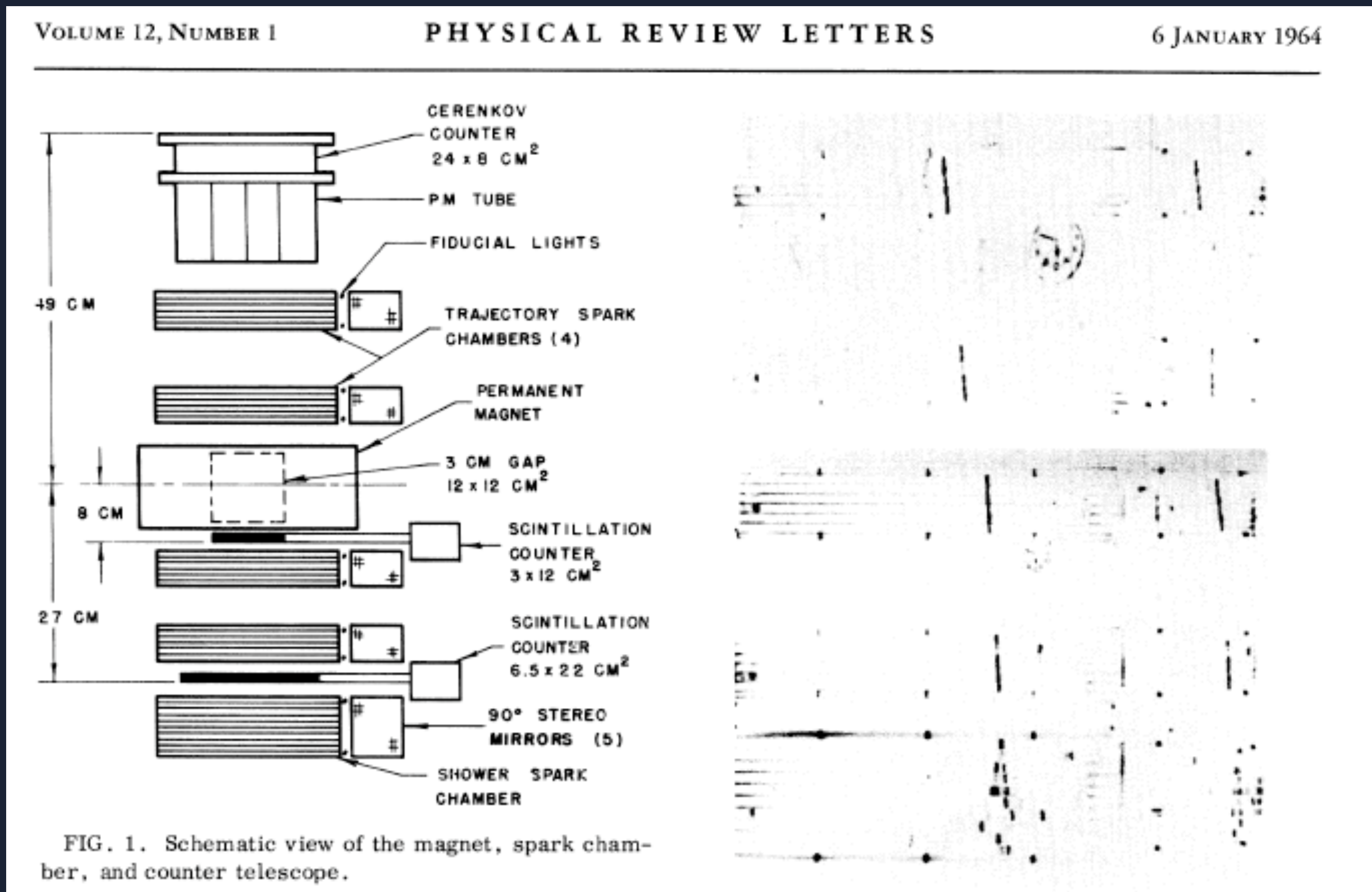

VOLUME 12, NUMBER 1 PHYSICAL REVIEW LETTERS 6 JANUARY 1964

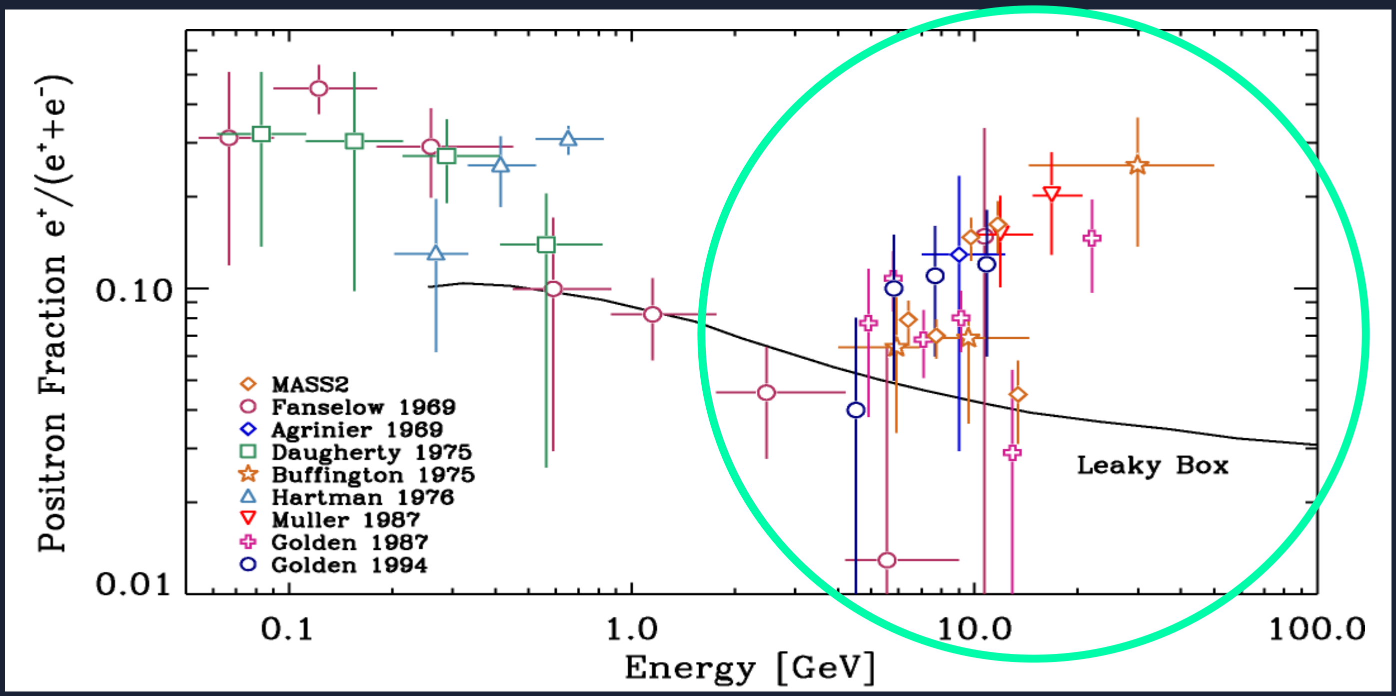
FIG. 1. Schematic view of the magnet, spark chamber, and counter telescope.

De Shong, Hildeband, Meyer, Phys. Rev. Let. 12 (1964)

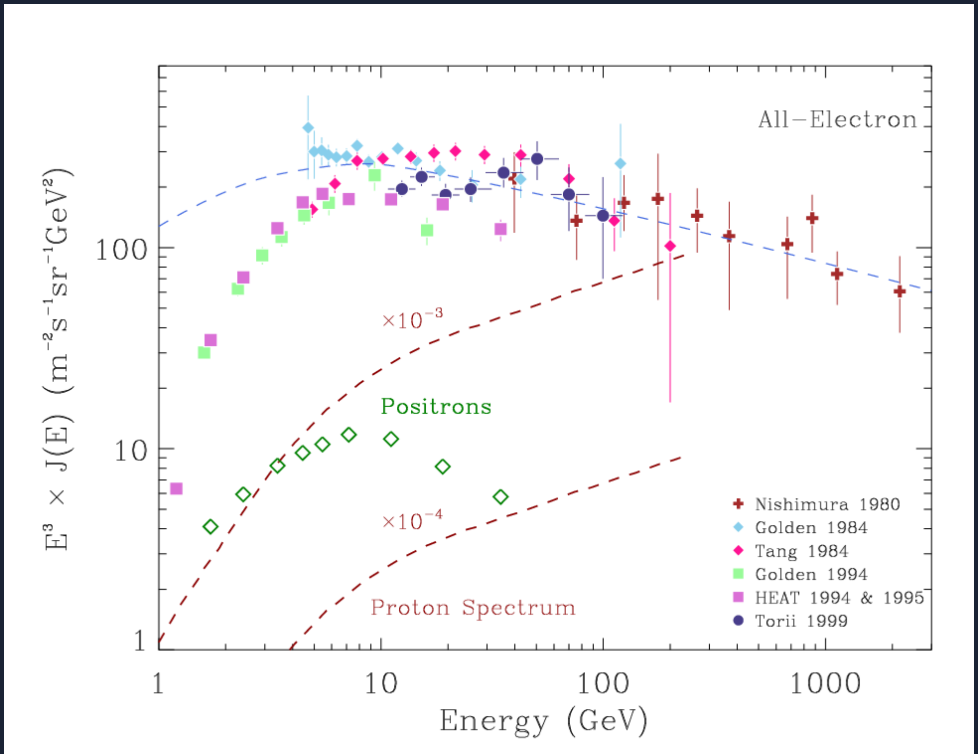
CR positron measurements
The early years: 1965 - 1984

What causes the dramatic rise at high energies?

Interesting physics or ... ?



CR electron (and positron) spectrum much harder than proton spectrum



Above 10 GeV:
- decreasing flux
- increasing p background

Need:
- large geometrical factor
- long exposure
- excellent p rejection

- Proper particle ID becomes more important at higher energies
- Spillover from tails in lower energy bins can become problematic

Particle ID

Positron flux measurements require

- excellent particle identification for background discrimination
- sufficient MDR to separate positive and negative charged particles at high energy.

Primary sources of background for positrons:

protons and positively charged muons and pions produced in the atmosphere and material above the detector.

HEAT- $e^{\pm}$ was first to employ powerful particle ID (rigidity vs. TRD vs. EM shower development) resulting in improved hadron rejection ($\geq 10^{-5}$).

CR positron measurements: The 90s

1989: Saskatchewan
(MASS - Golden et al., 1994)

1991: New Mexico
(MASS - Grimani et al., 2002)

1993: New Mexico
(Golden et al., 1996)

1994: New Mexico
(Heat – Barwick et al., 1995)

1994: Manitoba
(CAPRICE - Barbiellini et al., 1996;
Boezio et al 2002)

1994: Manotoba
(AESOP – Clem & Evanson 1996)

1995: Manitoba
(HEAT – Barwick et al., 1997)

1998: New Mexico
(CAPRICE – Boezio et al., 1999)

1999: Manitoba
(AESOP – Clem & Evanson, 2002)

2000: New Mexico
(HEAT – Beatty et al, 2004)

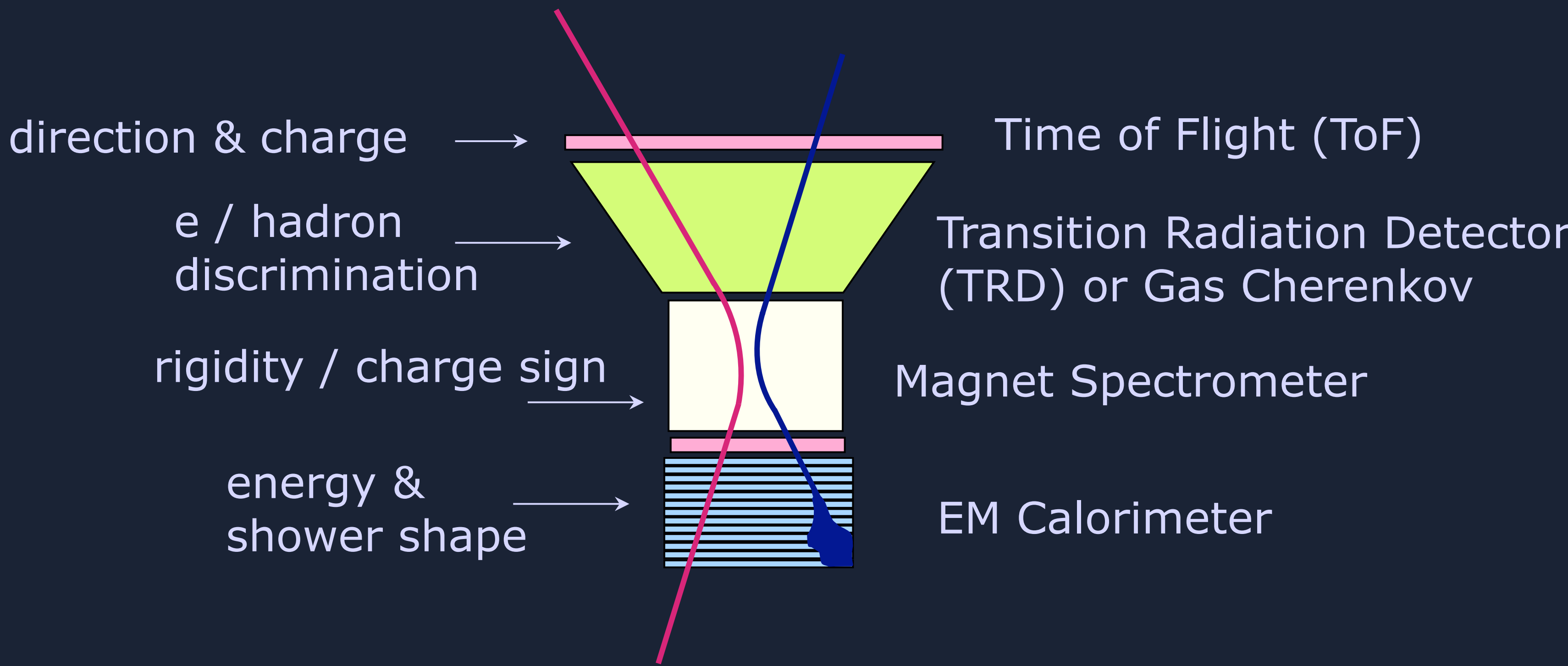
2000: Manitoba
(AESOP – Clem & Evanson, 2002)

2002: Manitoba
(AESOP – Clem & Evanson, 2004)

e^+ and e^- Instruments

Need magnet spectrometer for e^+ and e^- separation

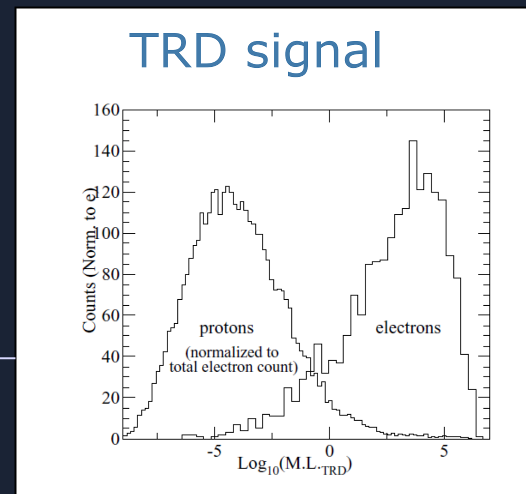
<u>Typical Instrument:</u>

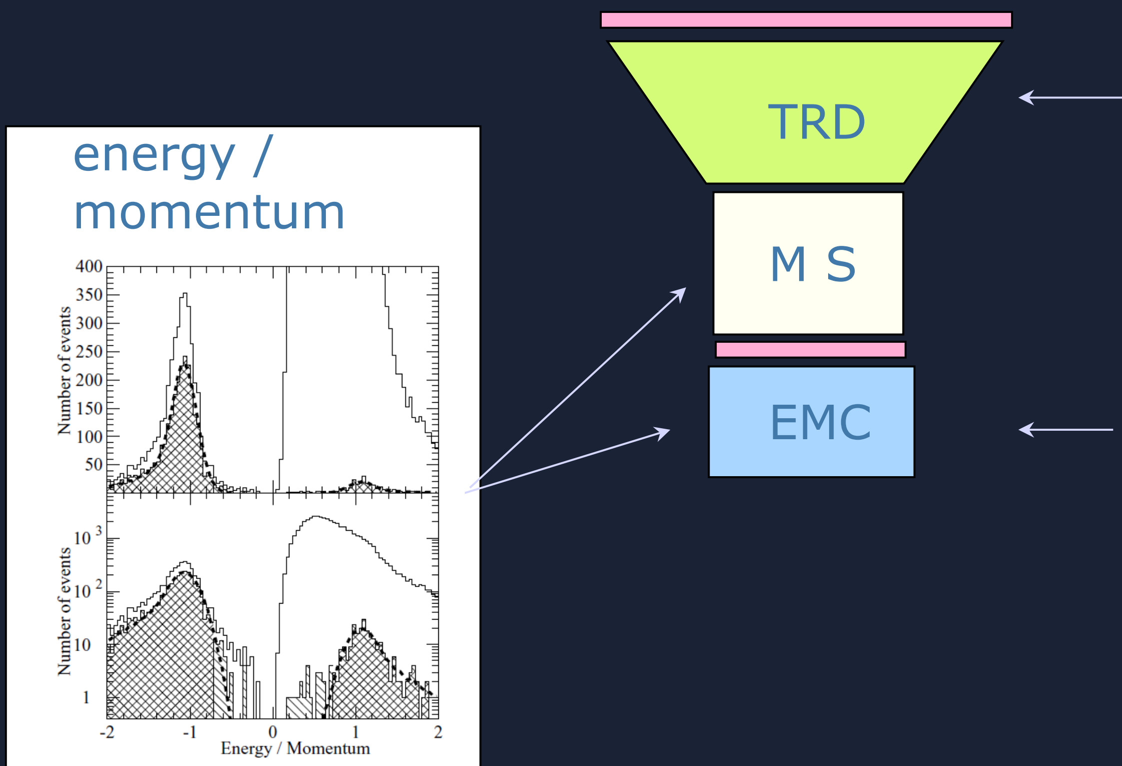


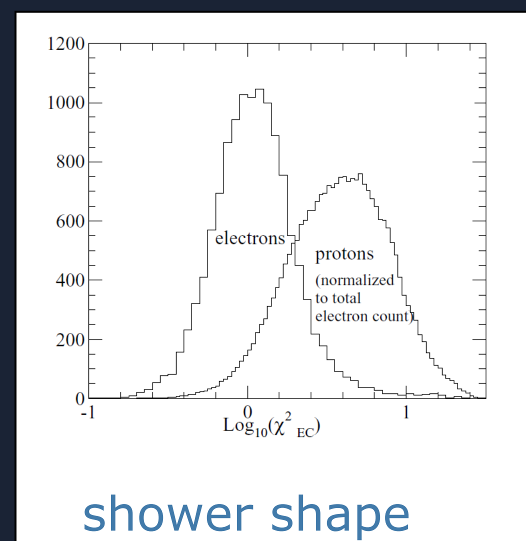
Proton Rejection

Combination of multiple independent techniques:

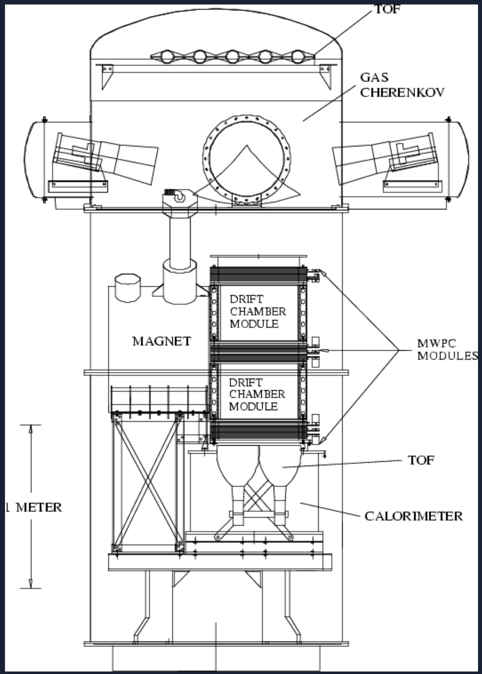
- results in large rejection factor (>10^5)
- allows cross check



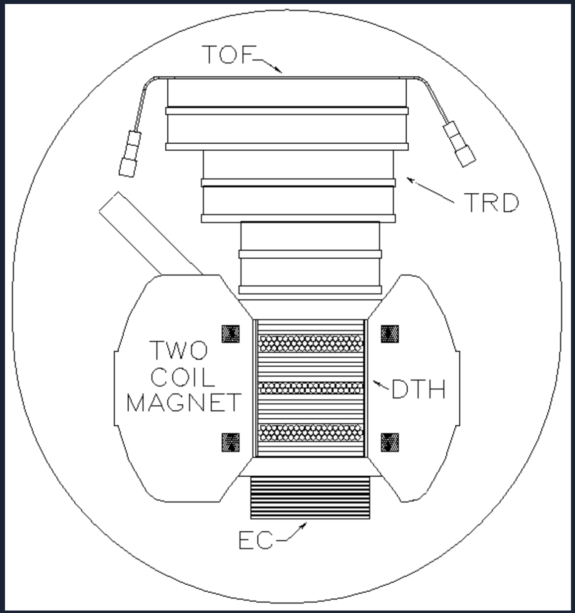




Examples of e^+ / e^- capable Instruments

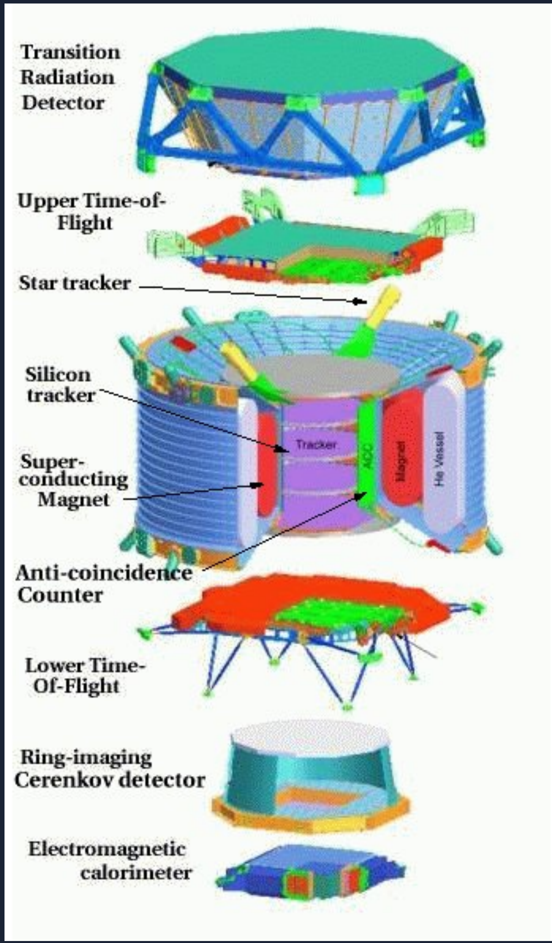


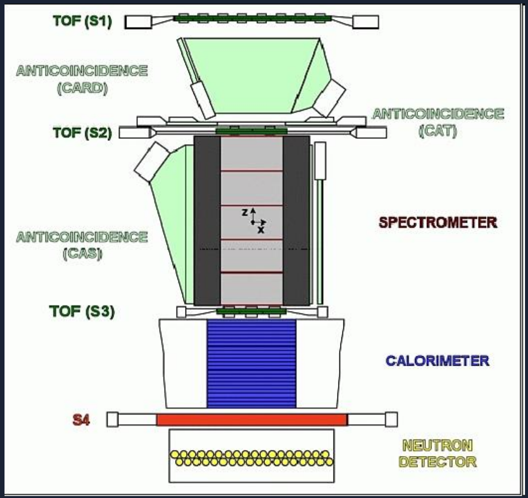
MASS-91



HEAT $e^{\pm}$

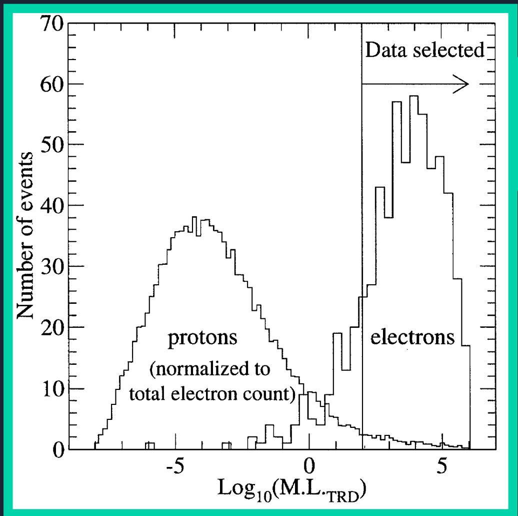
AMS-2 (planned)



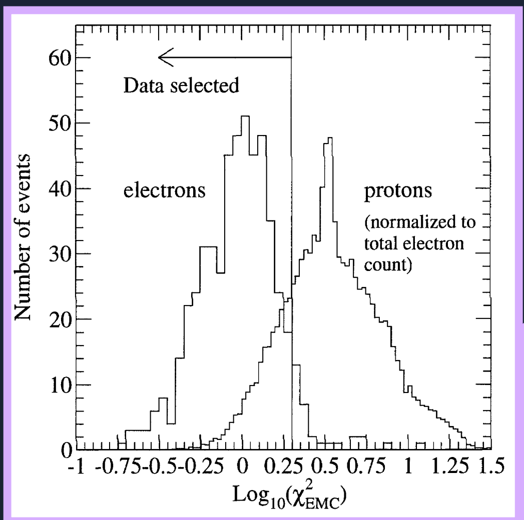


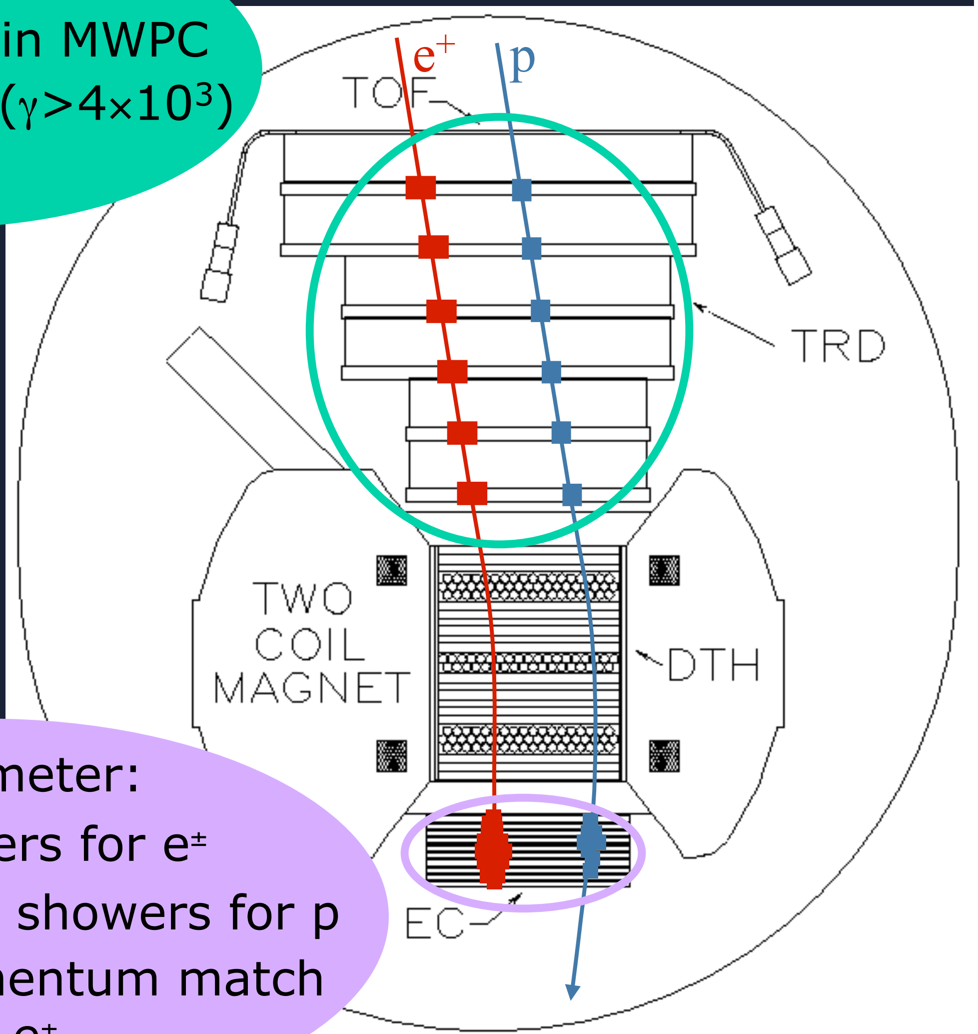
PAMELA

HEAT Instrument



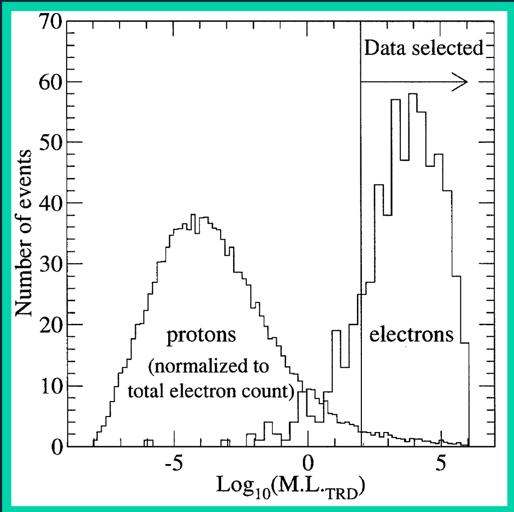
TRD:
dE/dx losses in MWPC
TR only for e± ($\gamma > 4\times10^3$)



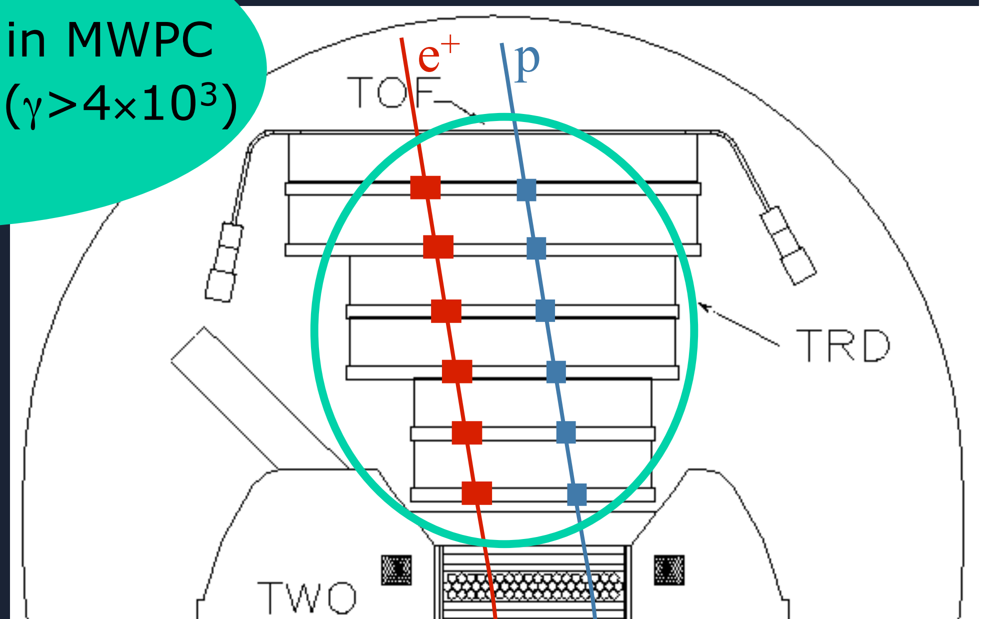


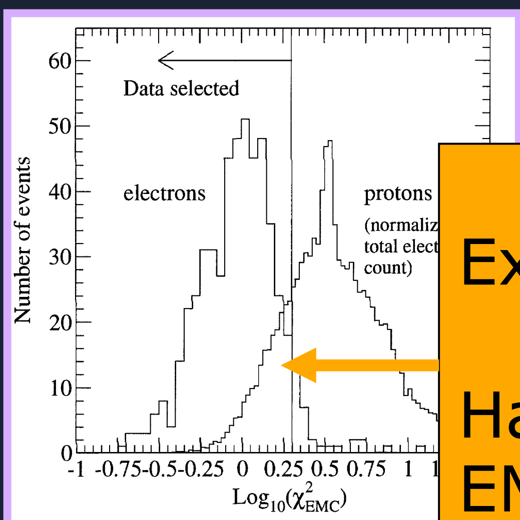
Calorimeter:
EM showers for e±
Hadronic or no showers for p
Energy – Momentum match for e±

HEAT Instrument



TRD:
dE/dx losses in MWPC
TR only for e± ($\gamma > 4 \times 10^3$)



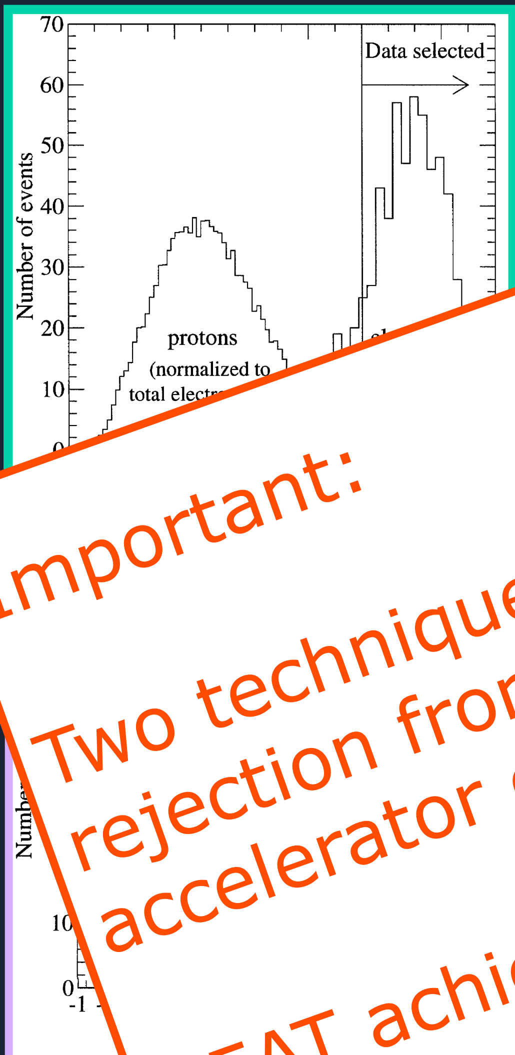


Extreme Caution Required!

Hadronic showers can occasionally mimic EM showers (early $\pi^0 \rightarrow \gamma \rightarrow$ EM showers)

HEAT-e± Collaboration U. Chicago, Indiana U., UCI, PSU, U. of Michigan

HEAT Instrument



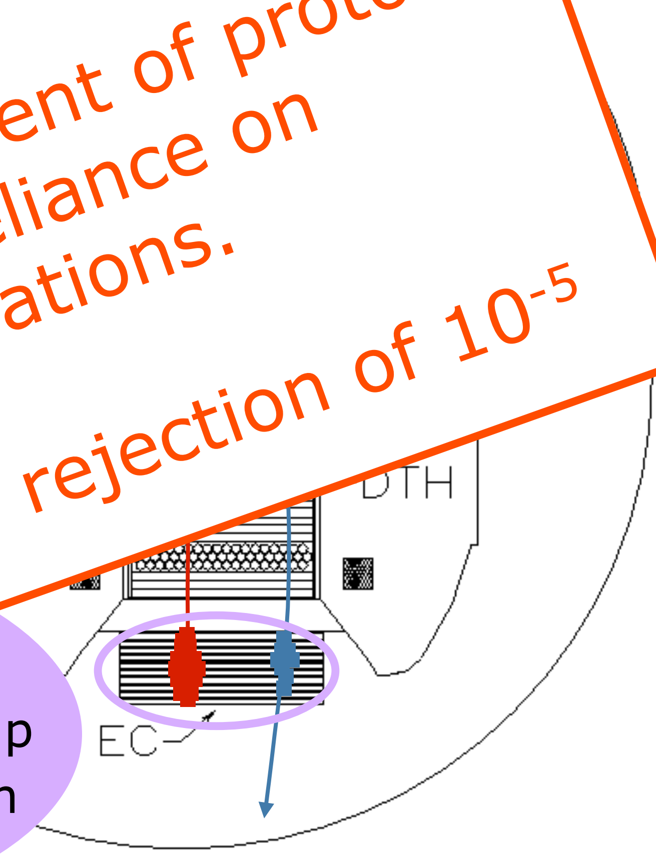
TRD:
dE/dx losses in MWPC
TR only for e± (

Important:

Two techniques allow measurement of proton rejection from flight data. No reliance on accelerator calibration or simulations.

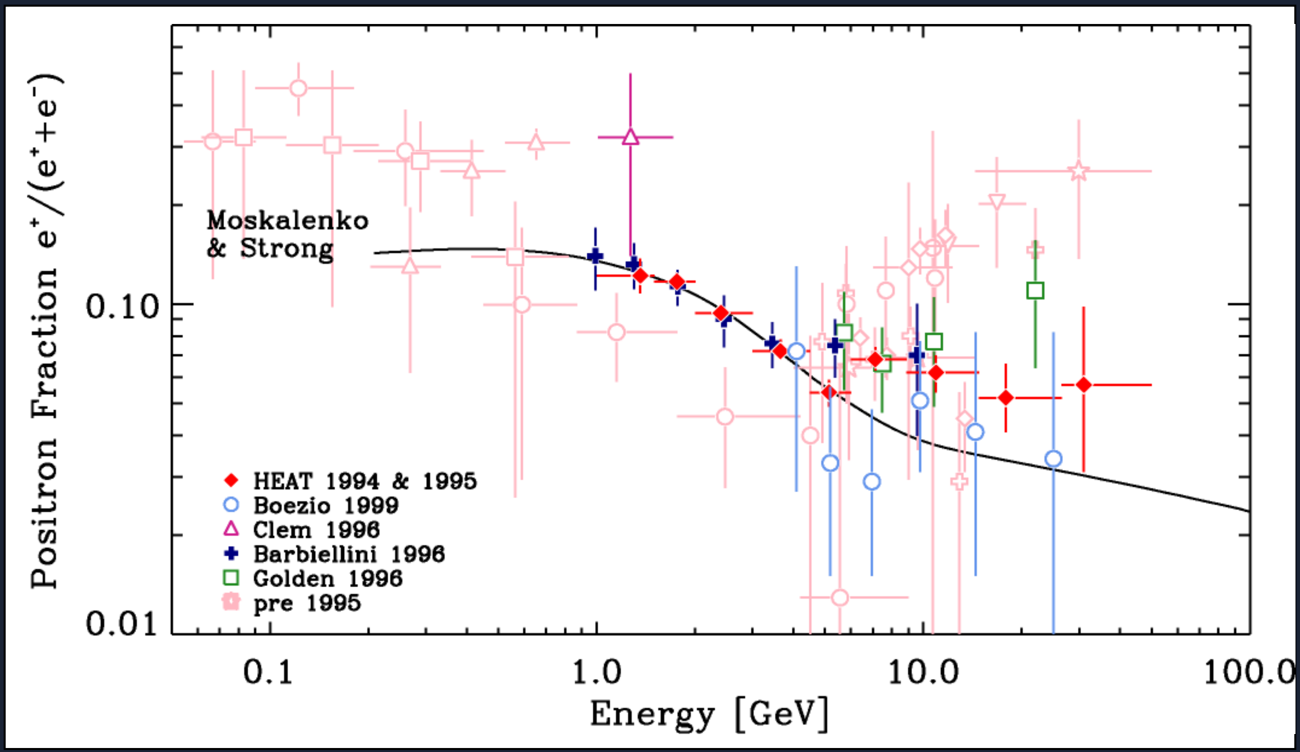
HEAT achieved a measured p rejection of 10^{-5}

e±
no showers for p
rgy – Momentum match for e±



A *feature* presentation

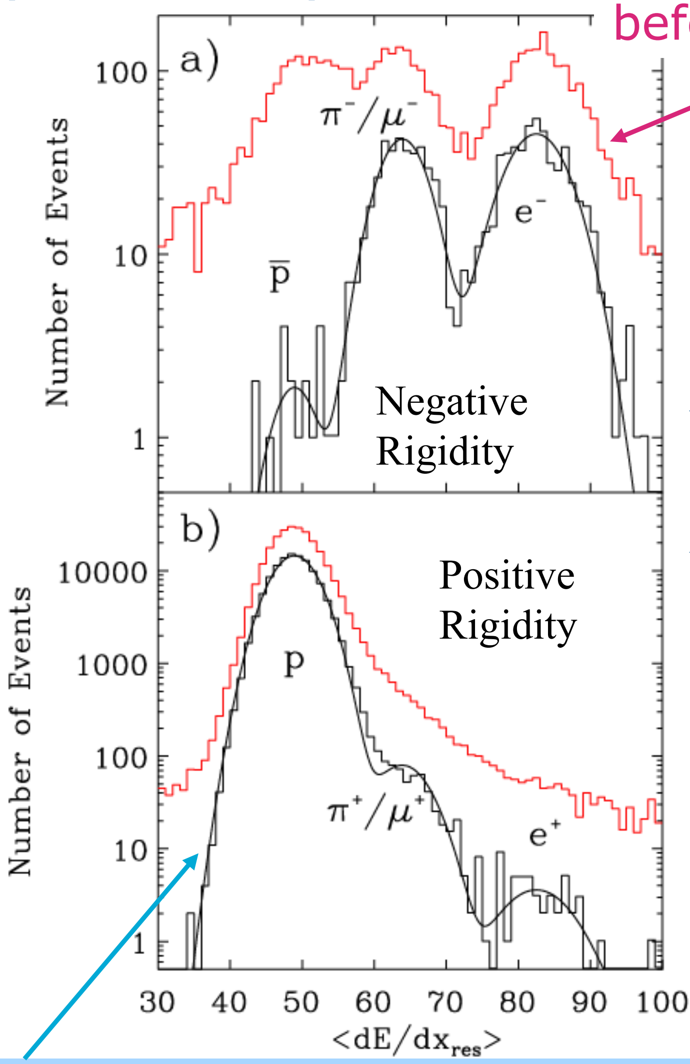
- Trend consistent with secondary production [Moskalenko & Strong ApJ 493, 694 (1998)] but high energy data lies above the curve.
- Solar modulation only affects low energy.



HEAT-e$^\pm$ Collaboration:
U. Chicago, Indiana U., UCI, PSU, U. of Michigan

Particle ID with HEAT-pbar

Select Rigidity bands and fit restricted average dE/dx distributions (4.5 – 6 GV):



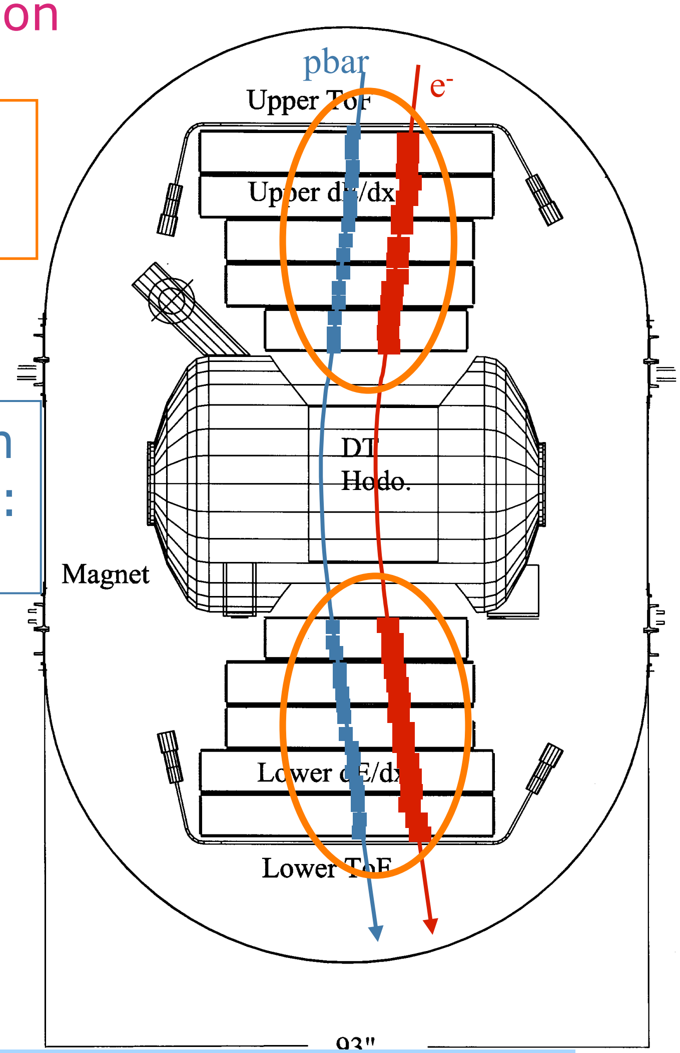
before event selection

Multiple dE/dx: p / π-μ / e separation

18 Antiprotons

'bending' in Hodoscope: rigidity

1.19×10^5 Protons

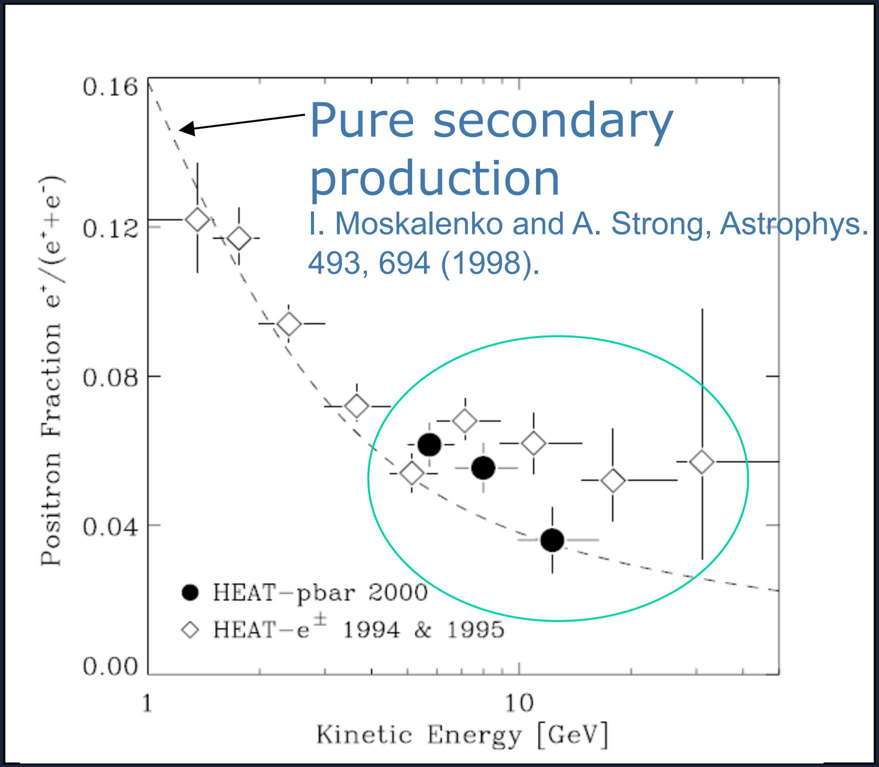


Highly Gaussian shape allows for good particle separation/count.

HEAT Positron Fraction

3 flights, 2 instruments, 2 geomagnetic cutoffs, 2 solar epochs: Trend consistent with secondary production at low energy but all show excess positrons at high energy.

Structure in e^+ fraction as first observed by HEAT could be DM signature (or nearby pulsars or...?)

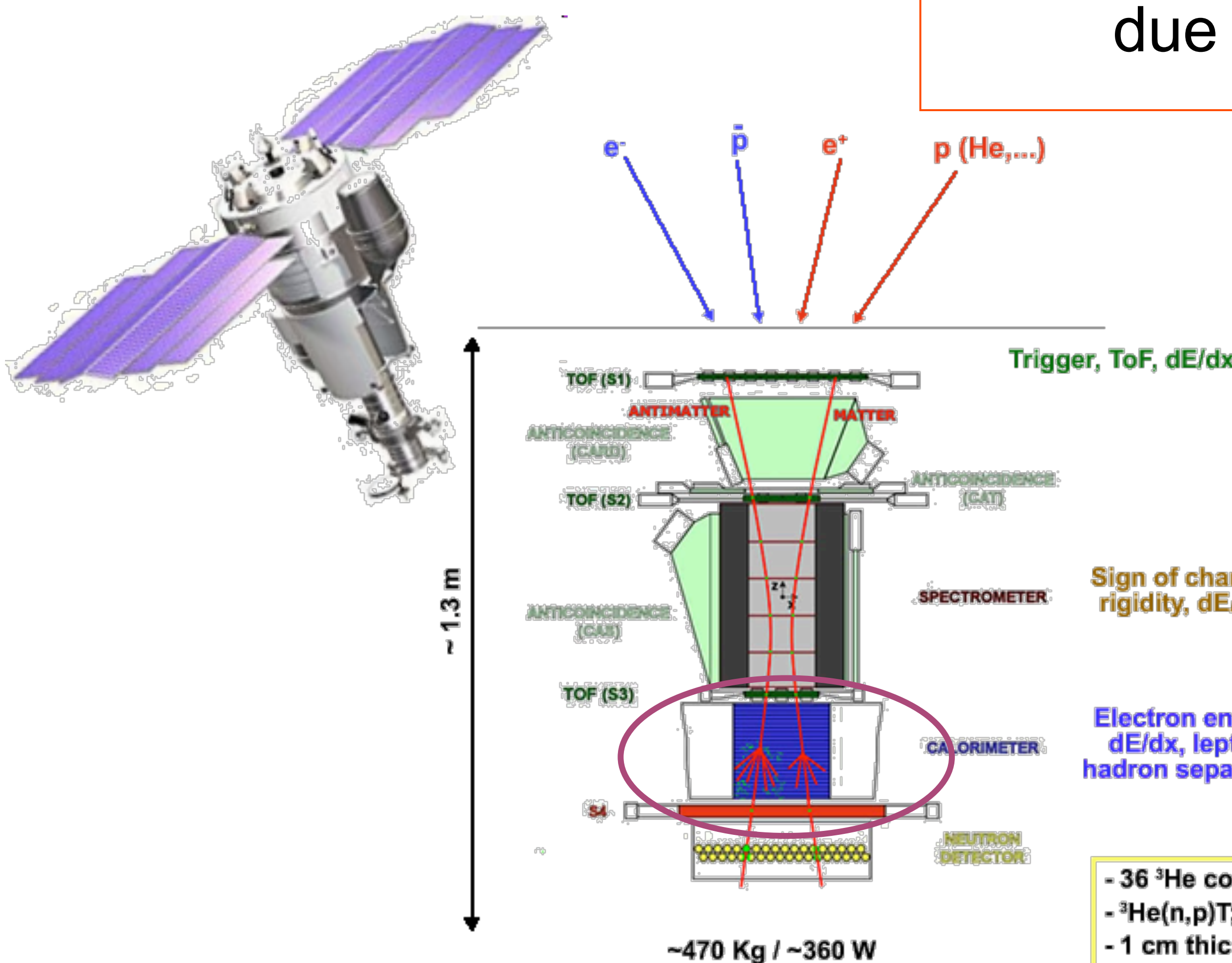


HEAT results
PRL **75**, 390 (1995)
Ap.J. Lett. **482**, L191-L194(1997)
Ap. J. **498**, 779-789 (1998)
Astropart. Phys. **11,** 429-435 (1999).
Ap. J. **559**, 296-303 (2001)
PRL **93**, 241102-1 (2004).

	HEAT- $e^{\pm}$		HEAT-pbar
Flight	May 1994	August 1995	May 2000
Geomagnetic cutoff rigidity	~ 4 GV	~ 1 GV	~ 4 GV
Solar cycle epoch	near minimum		near maximum

PAMELA

☹ Originally PAMELA had a TRD but had to drop it due to technical issues.



- S1, S2, S3; double layers, x-y
- plastic scintillator (8mm)
- ToF resolution ~300 ps (S1-3 ToF >3 ns)
- lepton-hadron separation < 1 GeV/c
- S1.S2.S3 (low rate) / S2.S3 (high rate)

Sign of charge, rigidity, dE/dx

- Permanent magnet, 0.43 T
- 21.5 cm² sr
- 6 planes double-sided silicon strip detectors (300 μm)
- 3 μm resolution in bending view → MDR ~800 GV (6 plane) ~500 GV (5 plane)

Electron energy, dE/dx, lepton-hadron separation

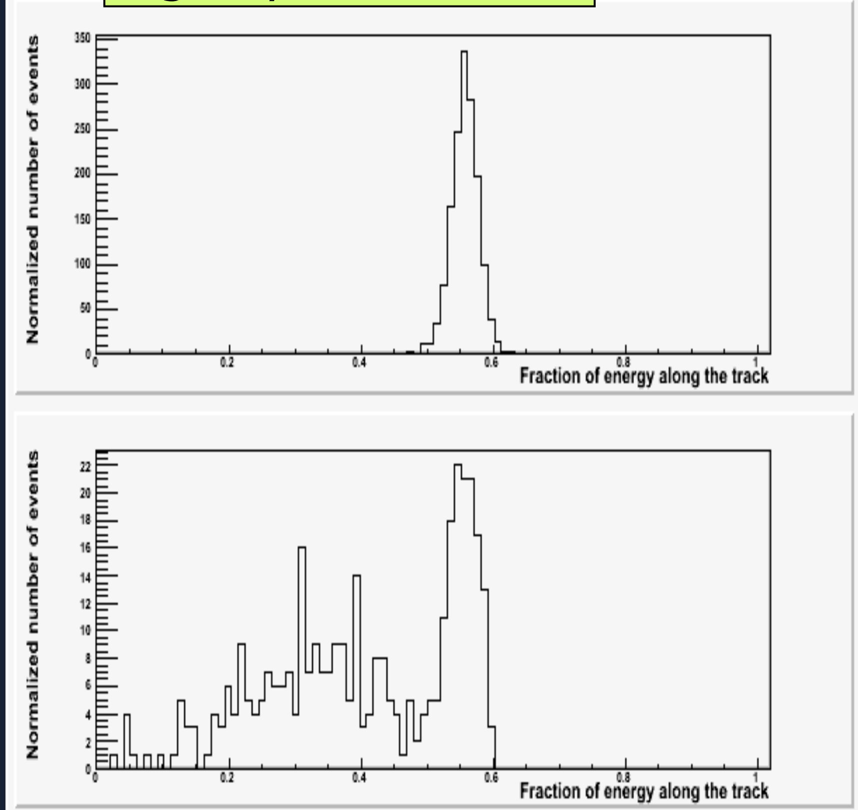
- 44 Si-x / W / Si-y planes (380)
- 16.3 X0 / 0.6 L
- dE/E ~5.5 % (10 - 300 GeV)
- Self trigger > 300 GeV / 600 cm² sr

- 36 ^{3}He counters
- ^{3}He(n,p)T; E_p = 780 keV
- 1 cm thick poly + Cd moderator
- 200 μs collection

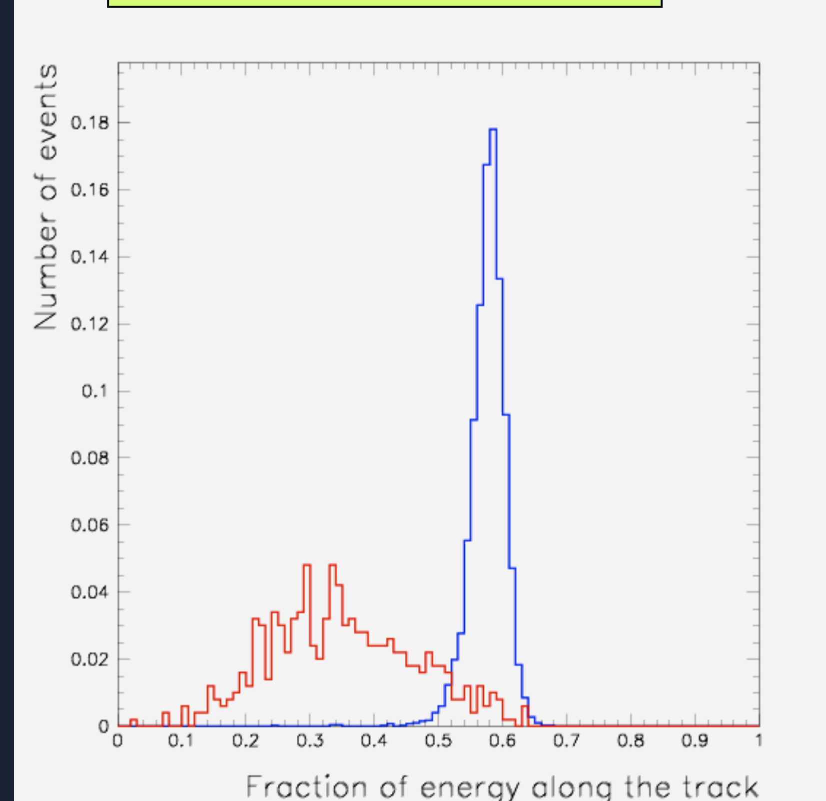
Caution: Particle ID solely dependent on calorimetry.
No in-flight verification of proton rejection.

PAMELA e^+ Selection with Calorimeter

Flight data:
Rigidity: 20-30 GeV



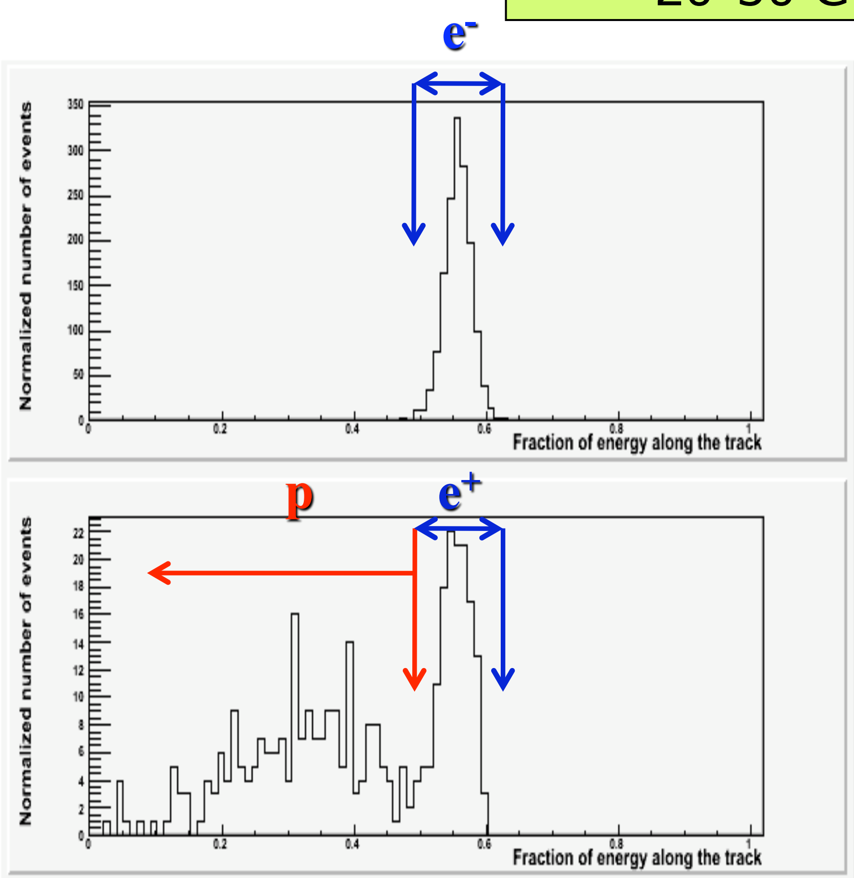
Test beam data:
Momentum: 50 GeV/c



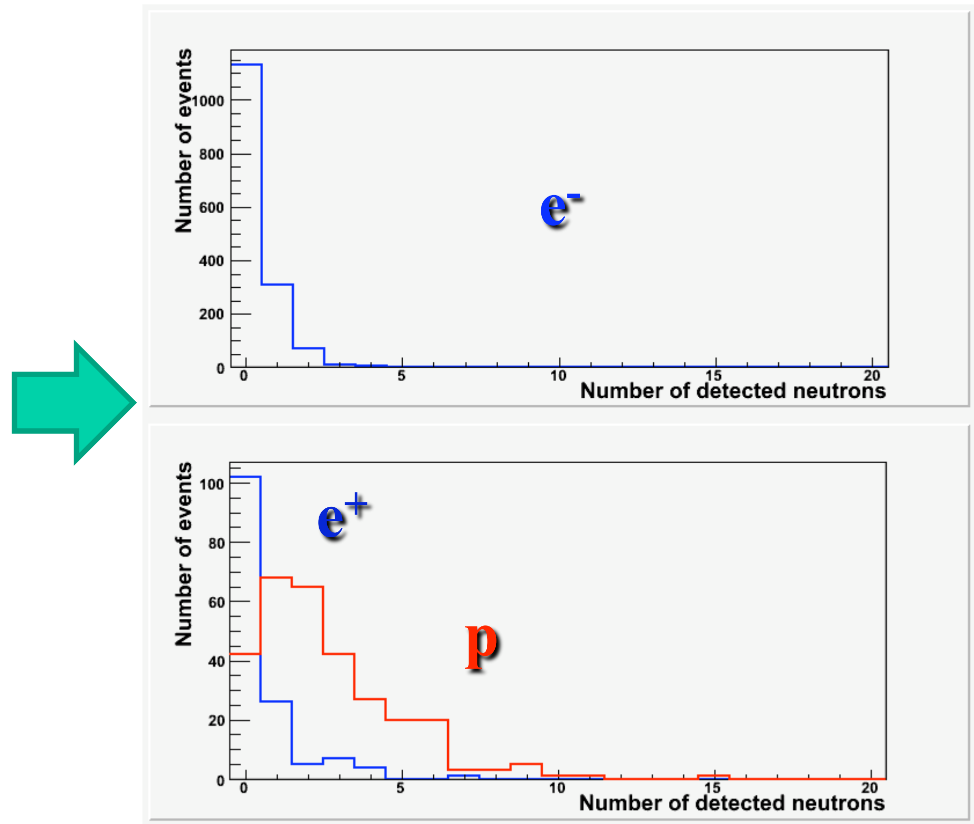
Thanks to Piergiorgio Picozza,
Spokesman, PAMELA Collaboration

Selecting e+ with PAMELA's n Detector

Rigidity:
20-30 GeV



Neutrons detected by ND

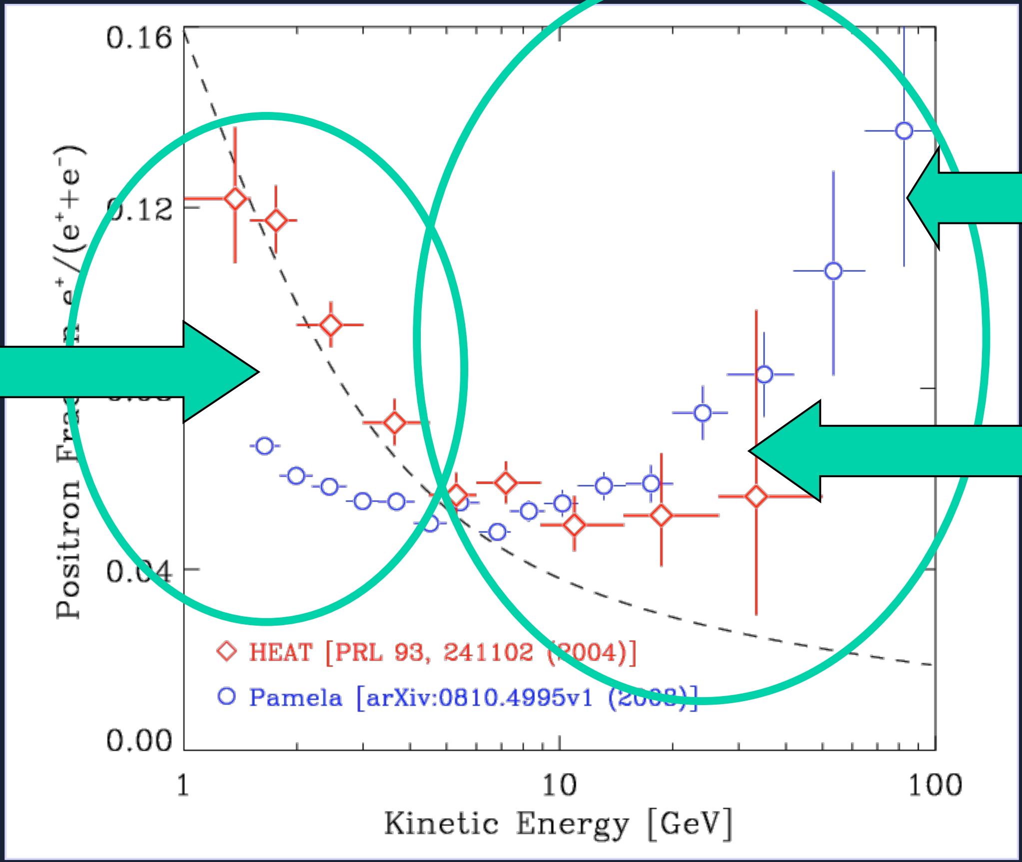


Caution: n detector efficient for E > 100 GeV

Thanks to Piergiorgio Picozza,
Spokesman, PAMELA Collaboration

Comparison HEAT & Pamela

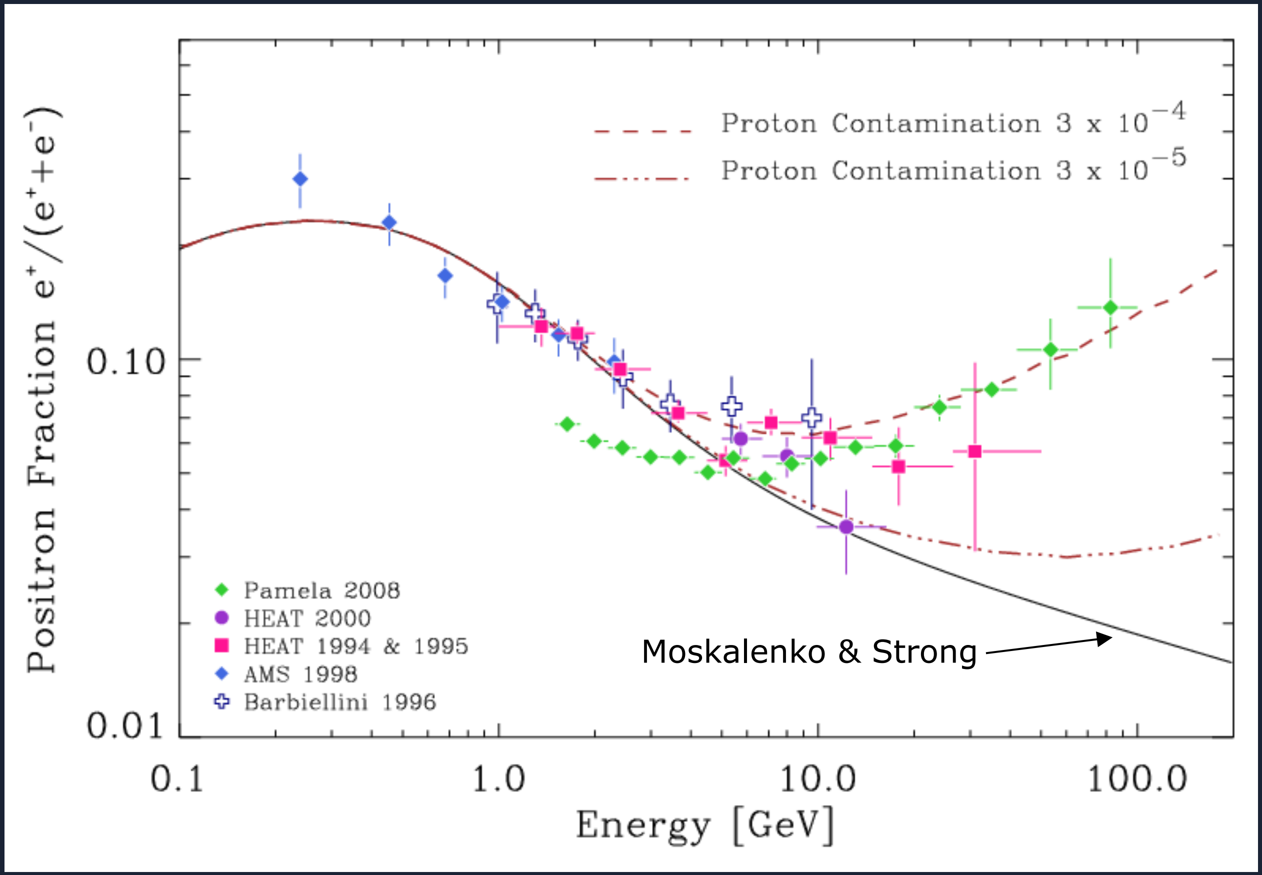
Don't worry about this. Completely consistent with charge sign dependent solar modulation.



Dramatic rise is reminiscent of an earlier era when particle ID was insufficient

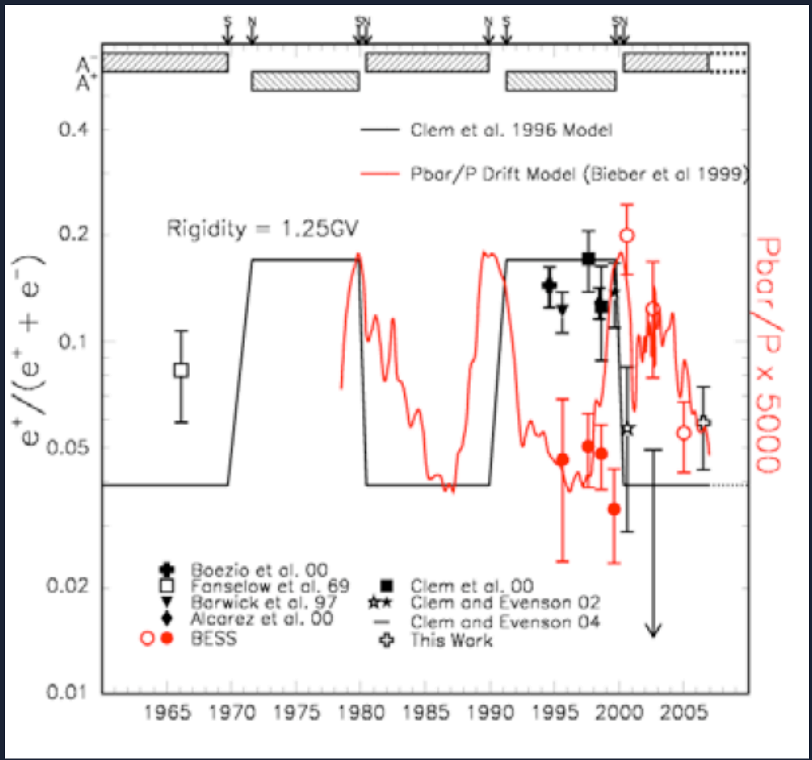
In the region of interest PAMELA and HEAT are completely consistent with each other.

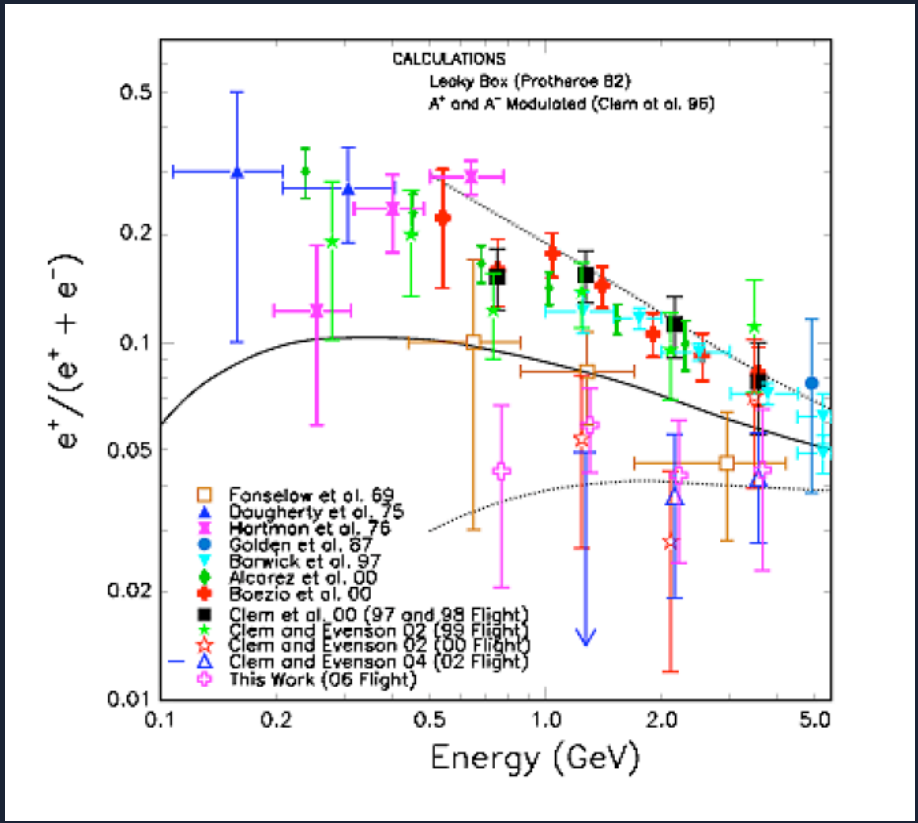
What a *little* dash of protons can do!



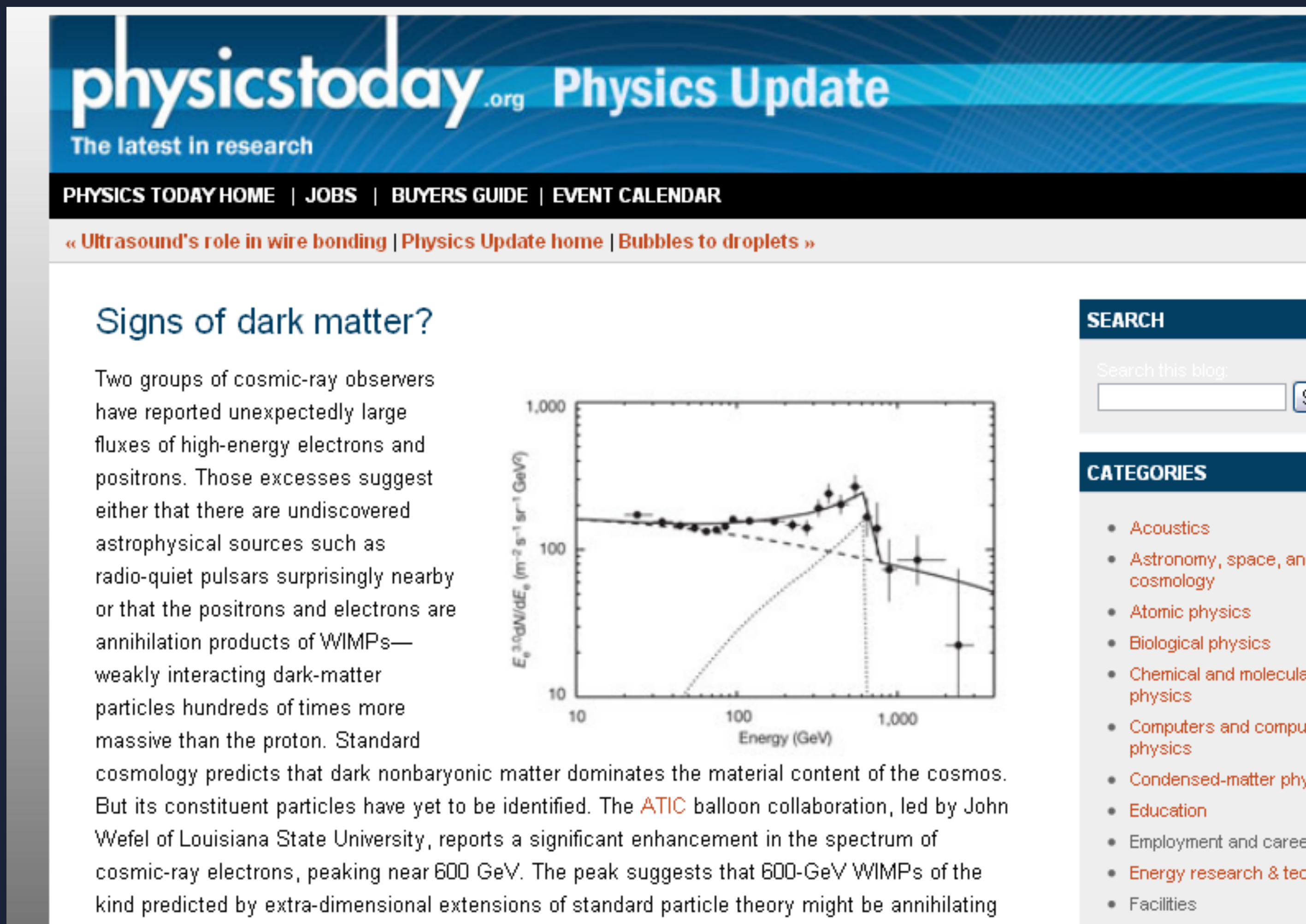
PAMELA claims p rejection of $^{10-5}$. CAUTION! This is not verified using independent technique in flight.

Clem and Evanson: Low energy (< a few GeV) data is affected by solar modulation





What about ATIC?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Signs of dark matter?

Two groups of cosmic-ray observers have reported unexpectedly large fluxes of high-energy electrons and positrons. Those excesses suggest either that there are undiscovered astrophysical sources such as radio-quiet pulsars surprisingly nearby or that the positrons and electrons are annihilation products of WIMPs—weakly interacting dark-matter particles hundreds of times more massive than the proton. Standard cosmology predicts that dark nonbaryonic matter dominates the material content of the cosmos. But its constituent particles have yet to be identified. The ATIC balloon collaboration, led by John Wefel of Louisiana State University, reports a significant enhancement in the spectrum of cosmic-ray electrons, peaking near 600 GeV. The peak suggests that 600-GeV WIMPs of the kind predicted by extra-dimensional extensions of standard particle theory might be annihilating

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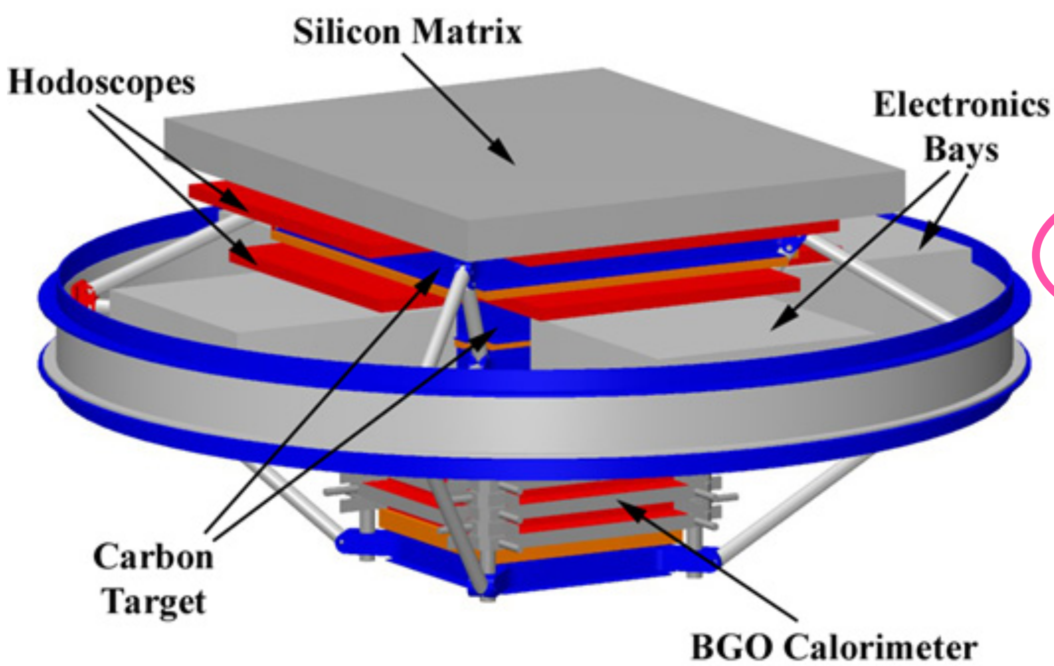


Advanced
Thin
Ionization
Calorimeter

CERN calibration configuration:

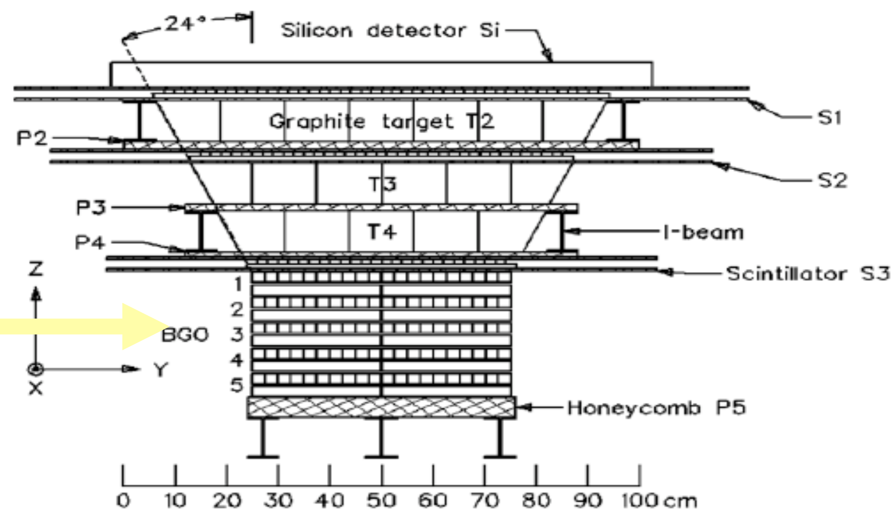
5 layers of 5 cm BGO
(2.5 cm in x and 2.5 cm in y)

~ 22 rad length ~ 1 interaction length

Flight config:

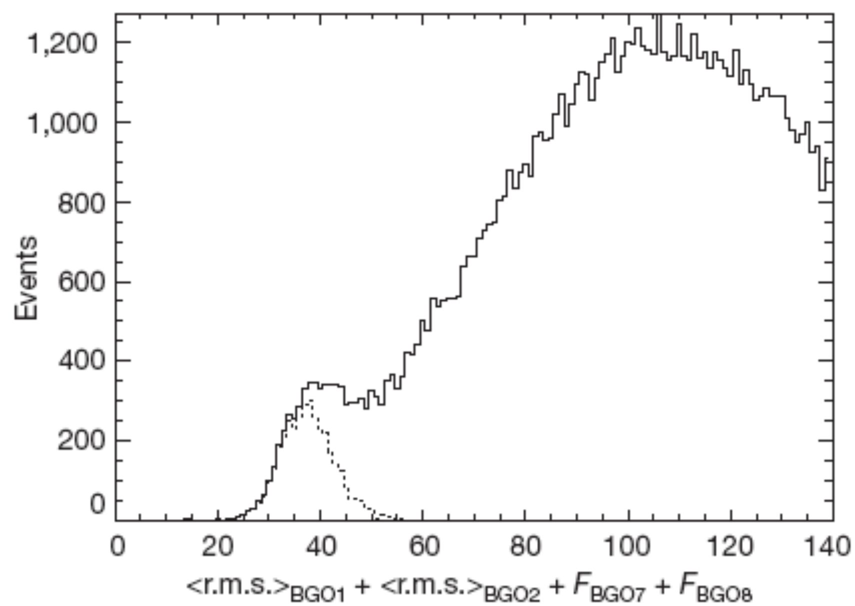
4 layers:

~ 18 rad length ~ .8 interact. length

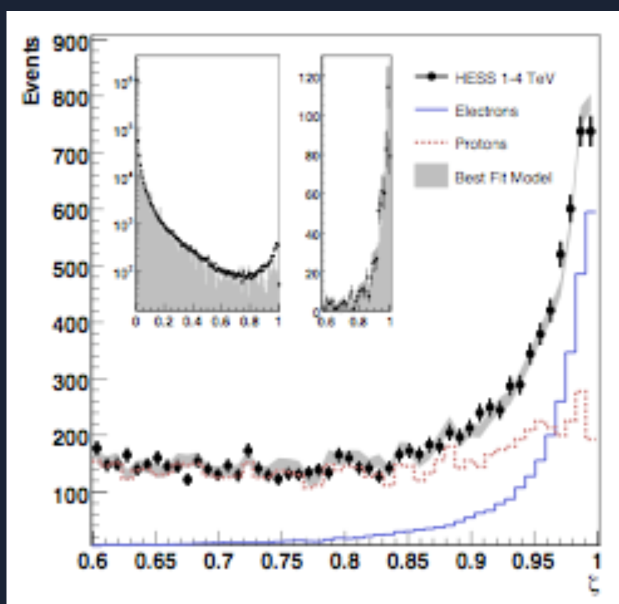


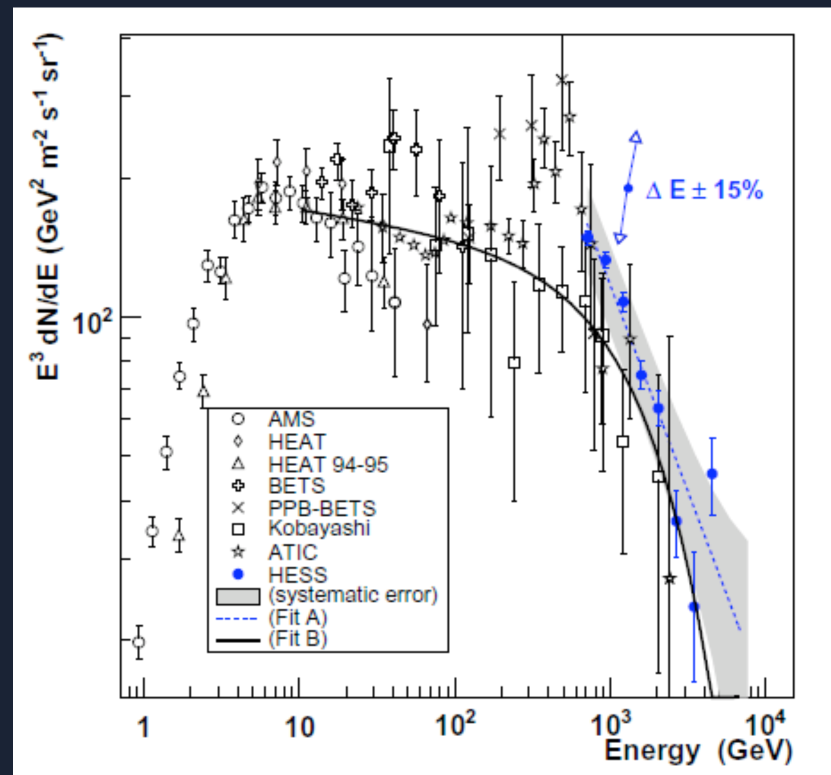
- Designed to measure nuclei, not $e^{\pm}$
- Uses 22 rad.length EM calorimeter with a 0.75 interaction length C target. Caution: Use of a low Z target is good for detecting nuclei but increases probability of hadronic contamination of electron spectra.
- Caution: Leakage out the back of calorimeter can lead to pileup at lower energy. Common problem with mis-calibrated calorimeters
- No magnet, no $e^{\pm}$ separation.

Advanced
Thin
Ionization
Calorimeter

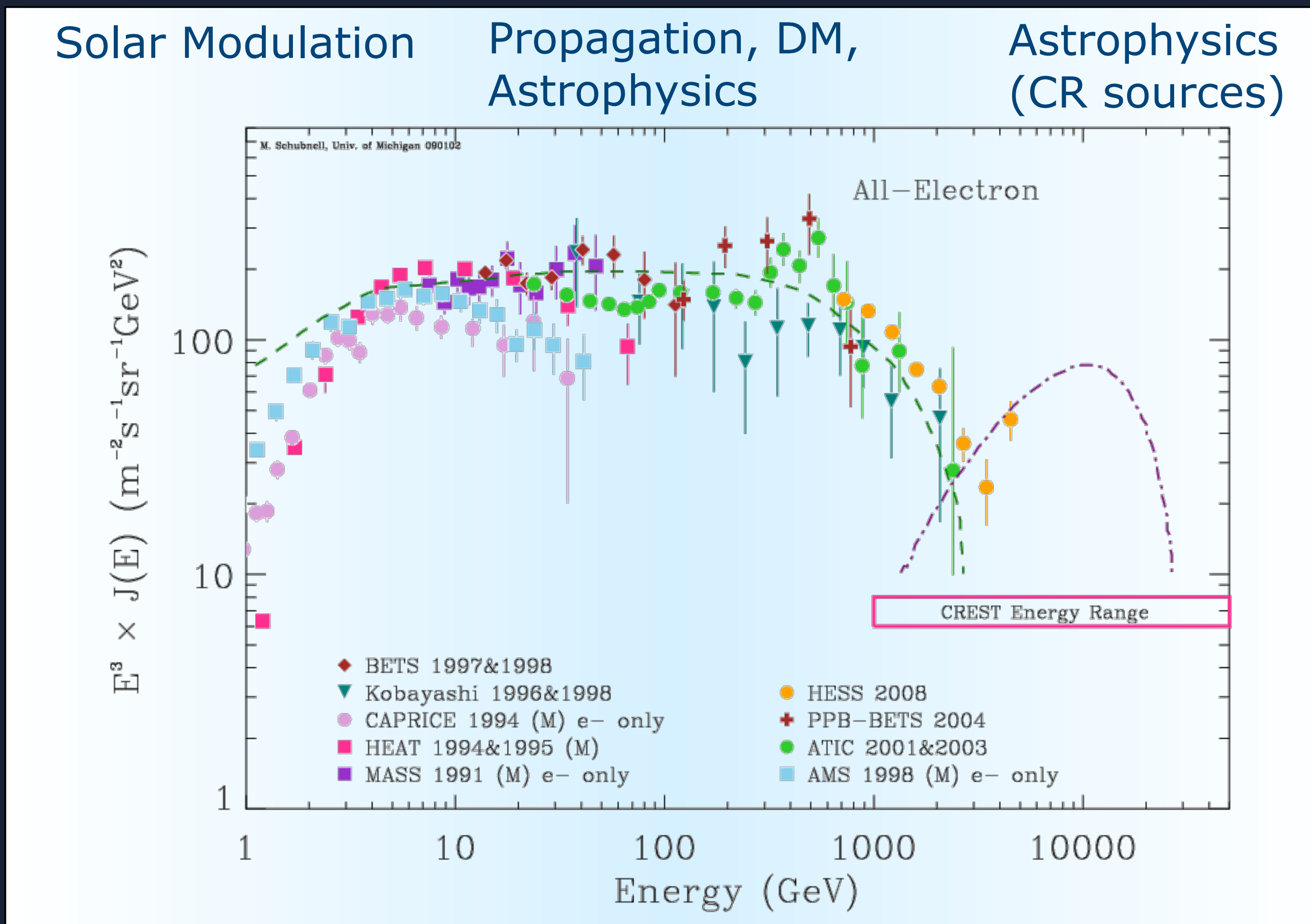


What about HESS?





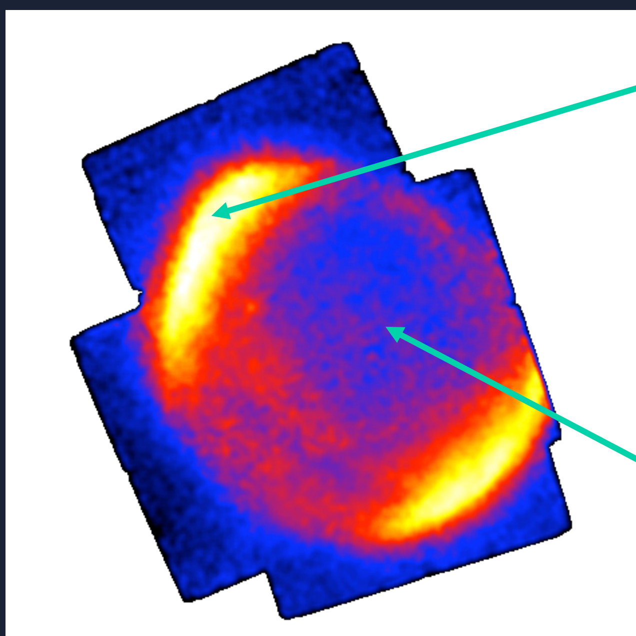
Cosmic Ray Electron/Positron Observations



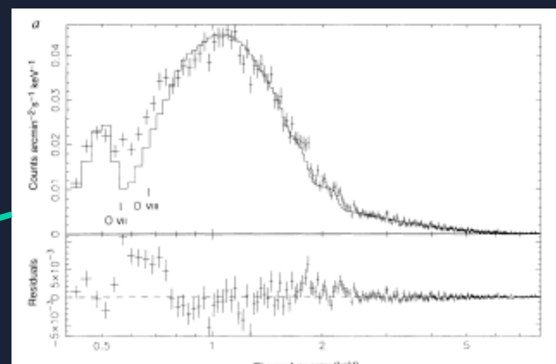
Galactic Cosmic Ray Electrons

Evidence for supernova shock acceleration of galactic CR electrons through observations of non-thermal X-rays and TeV gamma rays from SN remnants.

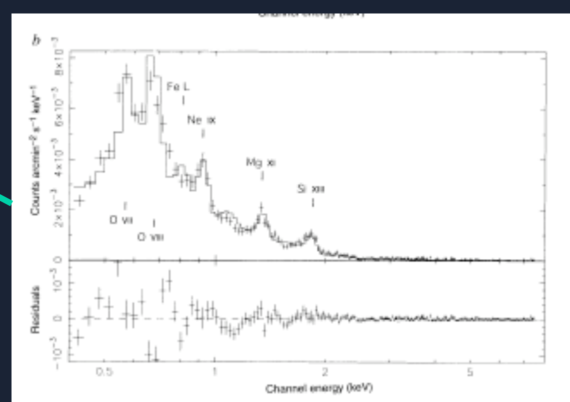
Synchrotron emission from SN1006



Koyama et al (1995)

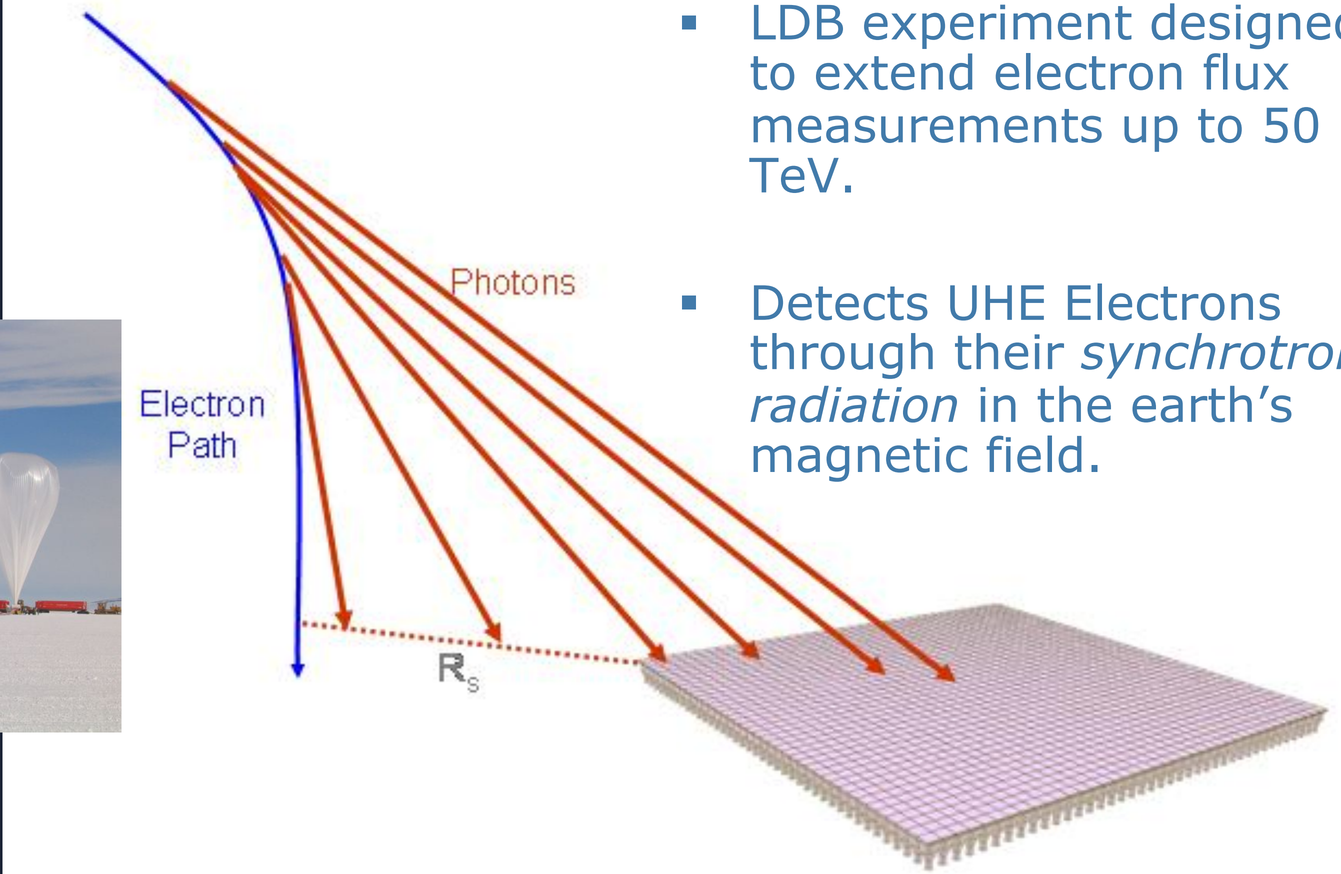


Non-thermal emission from rim.
Morphology correlates well between x-ray and radio bands



Thermal emission from core

CREST: Cosmic Ray Electron Synchrotron Telescope



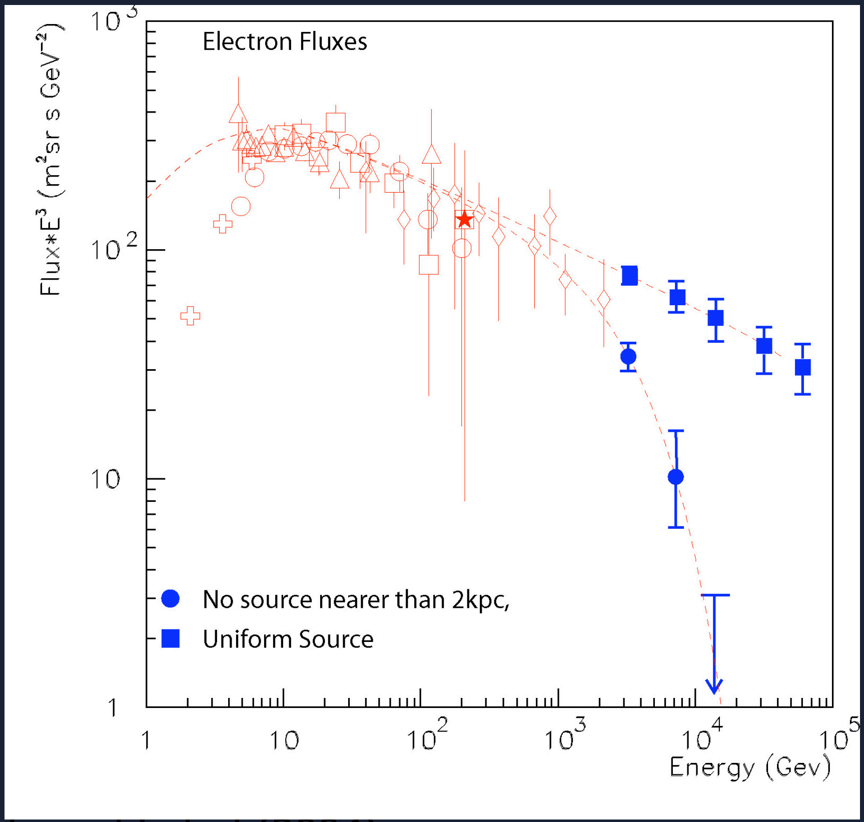
- LDB experiment designed to extend electron flux measurements up to 50 TeV.
- Detects UHE Electrons through their *synchrotron radiation* in the earth's magnetic field.

Technique first described in 70's by Prilutskiy, and fully developed in 80's by Stephens & V.K. Balasubrahmanran

Predicted Electron Spectrum & Current Experimental Status

- Spectral shape of HE electrons should be strongly affected by the number of nearby sources, and their distance distribution.

- If no such features in the high-energy electron spectrum are observed it will call into question our understanding of CR sources and propagation



Kobayashi et al (2004)

Conclusions

- PAMELA e^+ data, if correct, is very exciting.
- Confirmation of earlier HEAT e^+ excess.
- Possible DM signature but could also be due to an astrophysical source (nearby pulsar)
- Caution should be exercised when interpreting this data because of possible proton contamination.
- ATIC results are suspicious and not likely to survive for more than a few months (Fermi/ GLAST).
- Message to theorists: Go and have fun but exercise caution when interpreting positron spectra.