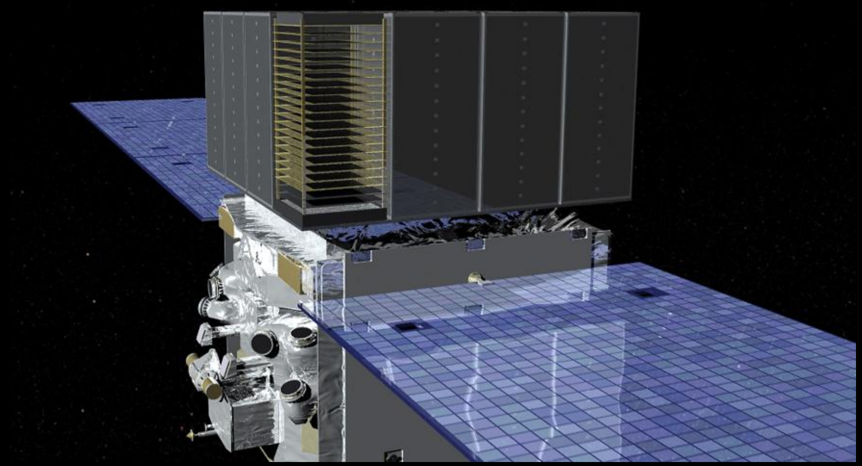
Measurement of the cosmic ray positron spectrum with the Fermi LAT using the Earth's magnetic field



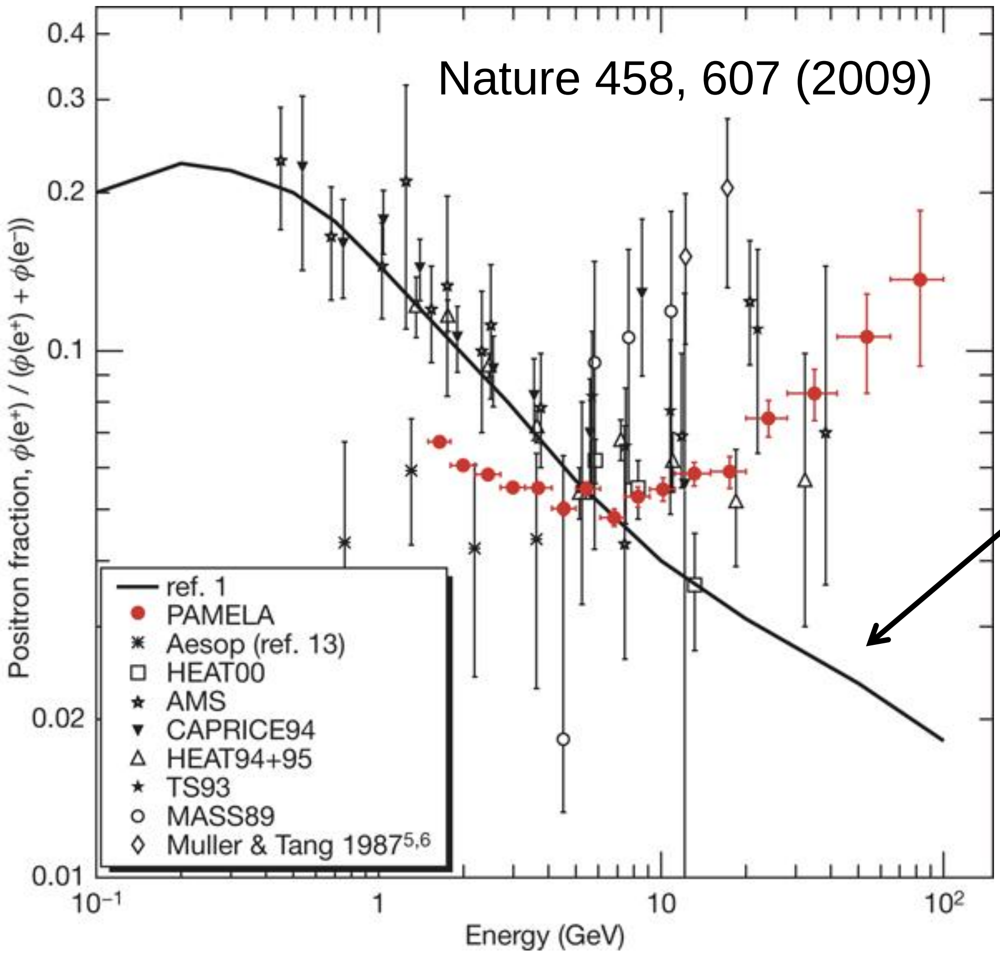
Justin Vandenbroucke
(KIPAC, Stanford / SLAC)
for the Fermi LAT collaboration

International Cosmic Ray Conference, Beijing
August 15, 2011

Outline

1. Motivation
2. The Fermi Large Area Telescope
3. Charge identification with the geomagnetic field
4. Background subtraction
5. Results

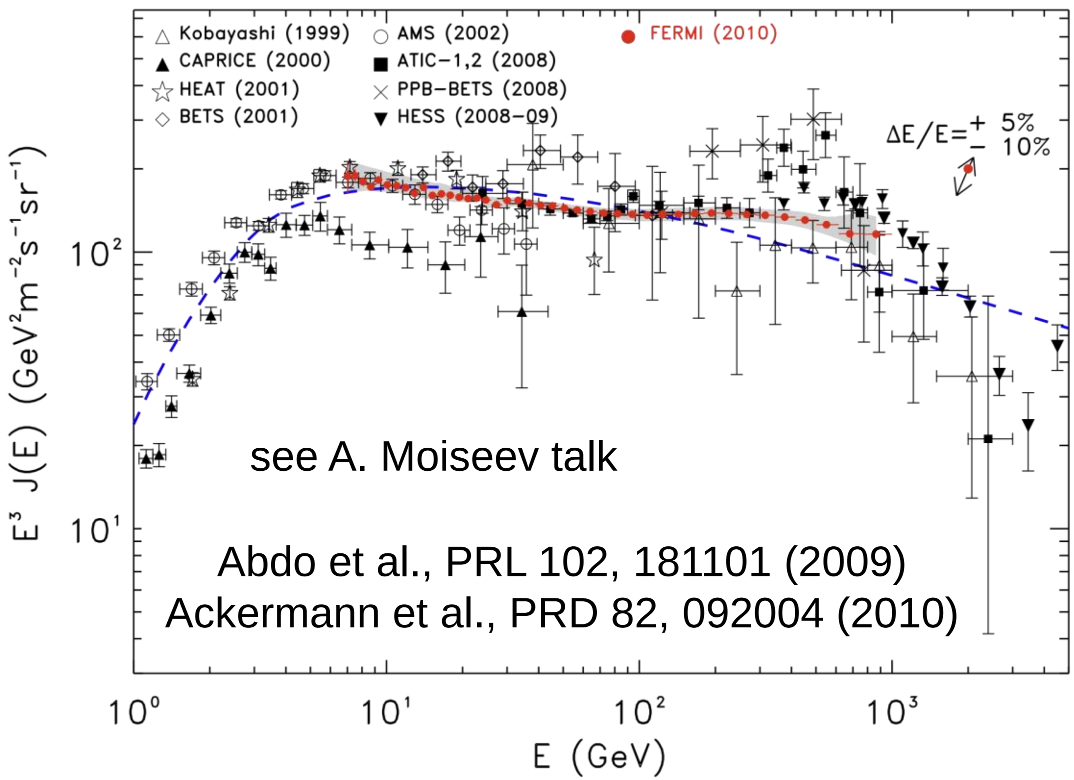
Motivation: PAMELA measurement of increasing positron fraction, 10-100 GeV



GALPROP diffuse secondary production model (Moskalenko & Strong 1998)

Possible explanations: primary astrophysical sources, dark matter, nonstandard secondary production, …

Fermi LAT measurement of combined cosmic ray electron + positron spectrum from 7 GeV to 1 TeV

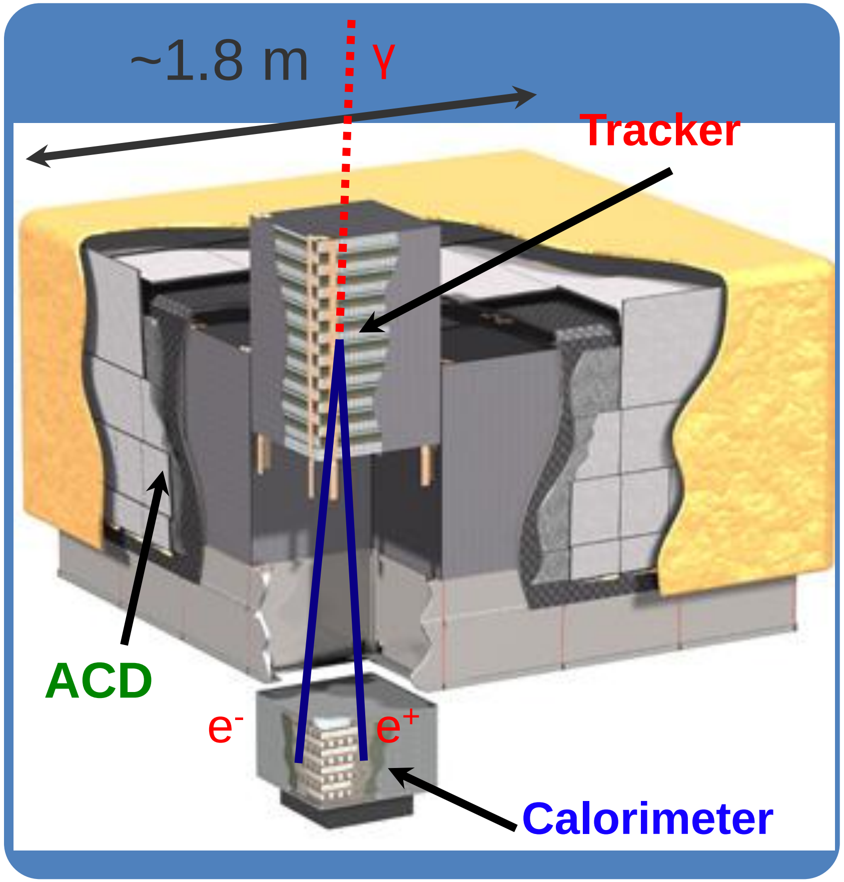


Next: can we identify positrons to check the PAMELA rising fraction? 2 challenges:

1) Suppress p^+ flux which is 3-4 order of magnitude larger than e^+: same cuts as e^+e^- analysis and estimate residual background
2) Distinguish e^+ from e^-: geomagnetic field

The Fermi Large Area Telescope (LAT): a pair-conversion telescope with ~1 m^2 effective area

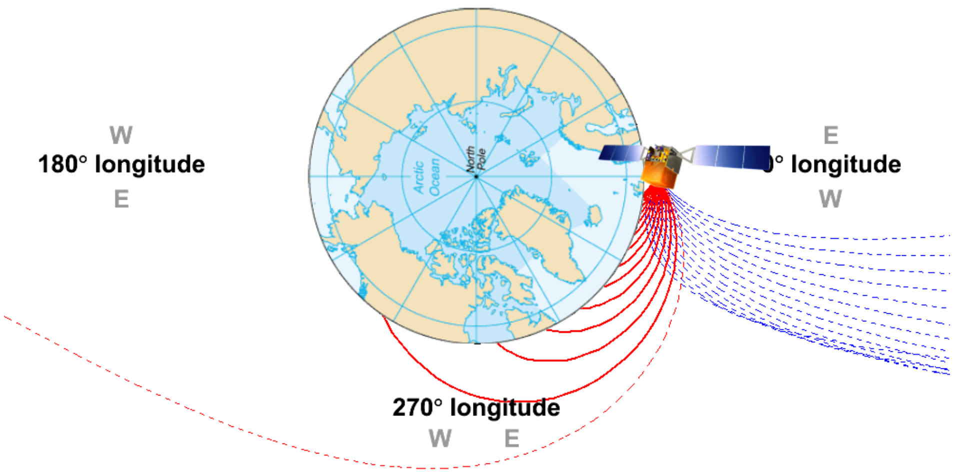
- **Anti-Coincidence Detector**: charged particle veto surrounding Tracker, 89 plastic scintillator tiles + 8 ribbons, 0.9997 efficiency for tagging singly charged particles
- **Tracker**: 16 modules: tungsten conversion foils + 80 m^2 of silicon strip detectors in 36 layers, 1.5 radiation lengths on-axis
- **Calorimeter**: 16 modules: 96 Cesium Iodide crystals per module, 8.6 radiation lengths on-axis, segmented for 3D energy deposition distribution

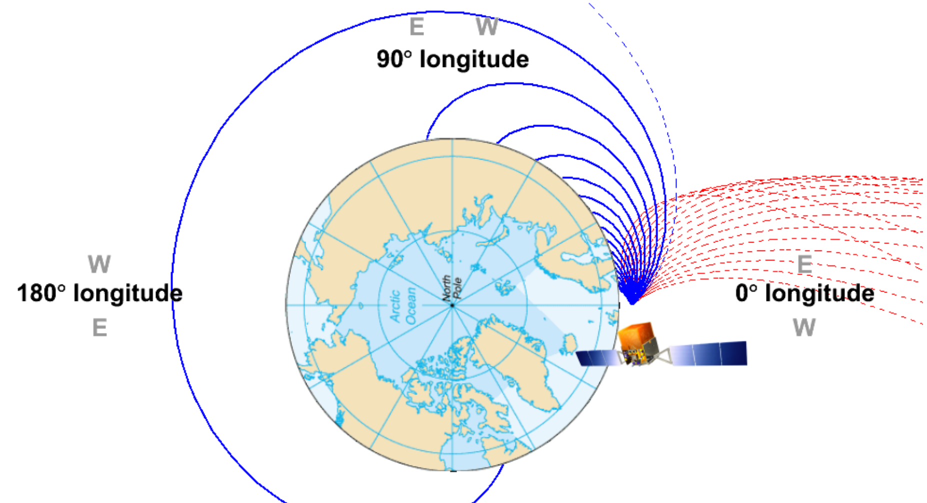


Atwood et al., ApJ 697, 1071 (2009)

Geomagnetic field + Earth shadow = directions from which only electrons or only positrons are allowed

events arriving from West:
e^+ allowed, e^- blocked



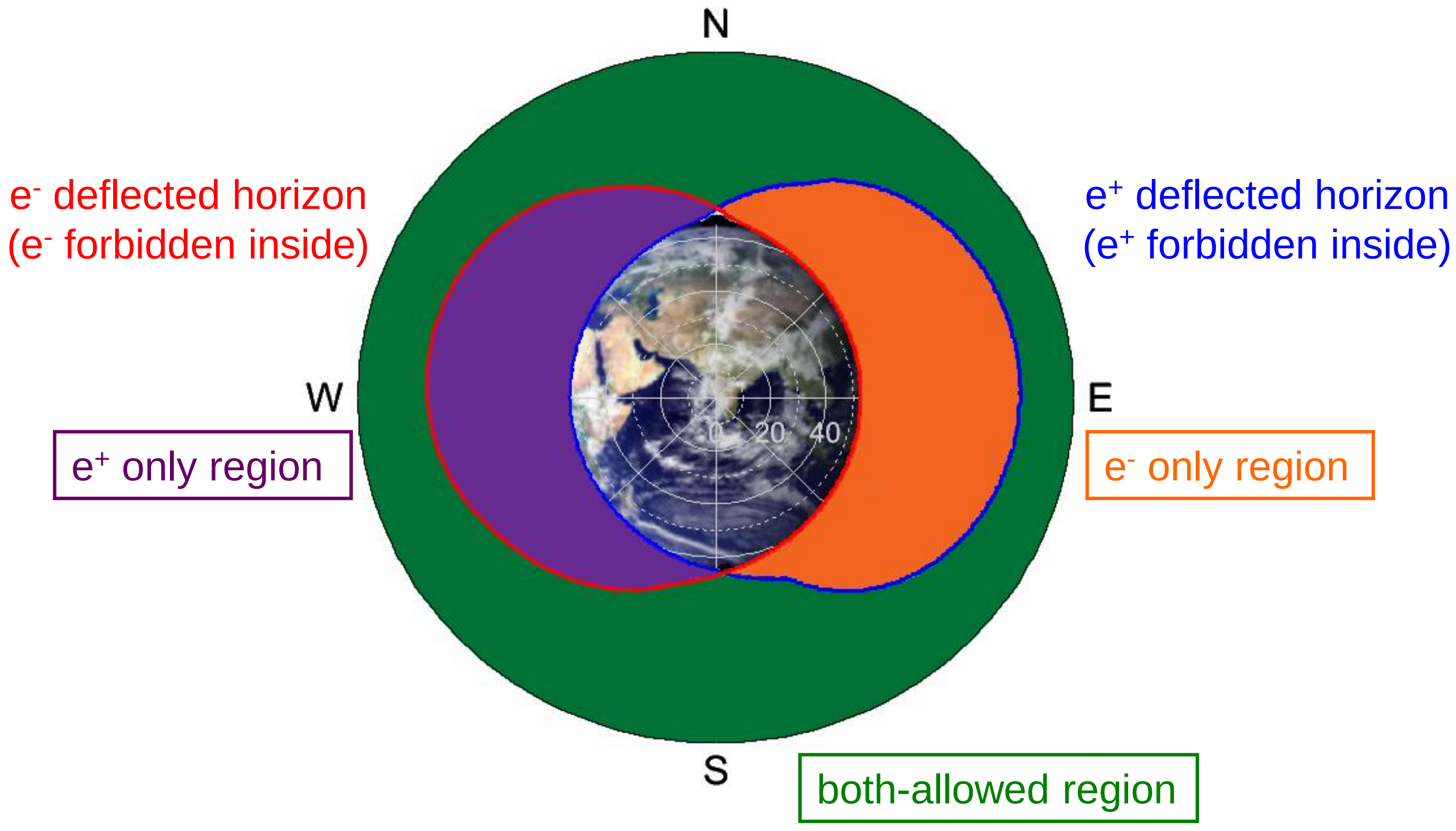


events arriving from East:
e^- allowed, e^+ blocked

- For some directions, e^- or e^+ forbidden
- Pure e^+ region looking West and pure e^- region looking East
- Regions vary with particle energy and spacecraft position
- To determine regions, use code by Don Smart and Peggy Shea (numerically traces trajectory in geomagnetic field)
- Using International Geomagnetic Reference Field for the 2010 epoch

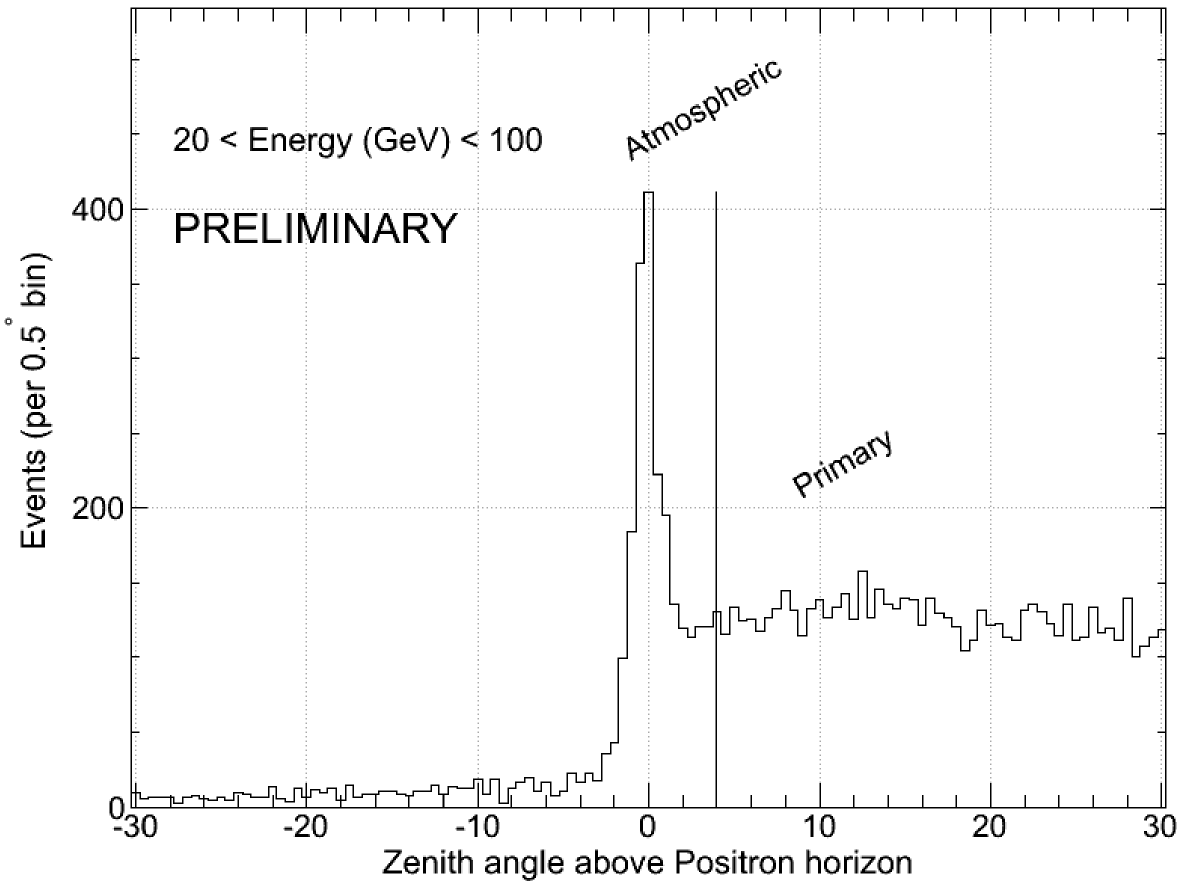
Time-dependent region selection

- "Deflected horizon" = boundary between allowed and shadowed trajectories
- Use instantaneous spacecraft position to determine two horizons for each energy
- Three regions: positron-only, electron-only, both-allowed

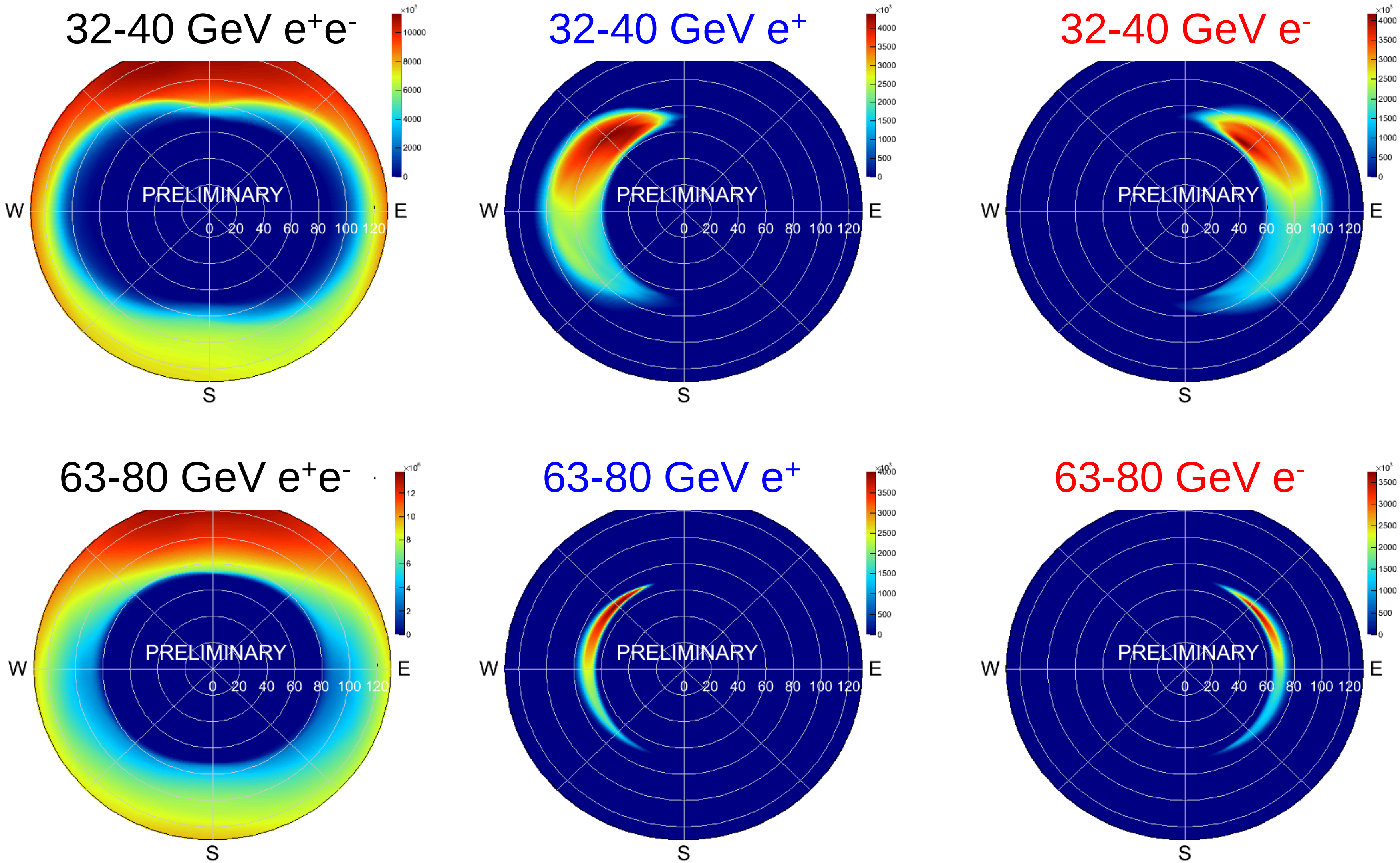


Validation of magnetic field model + tracer code

1. Geographical distribution of geomagnetic cutoffs predicted from code matches LAT data (arXiv:1108.0201)
2. Atmospheric positrons (and electrons) detected precisely from deflected direction expected from code:

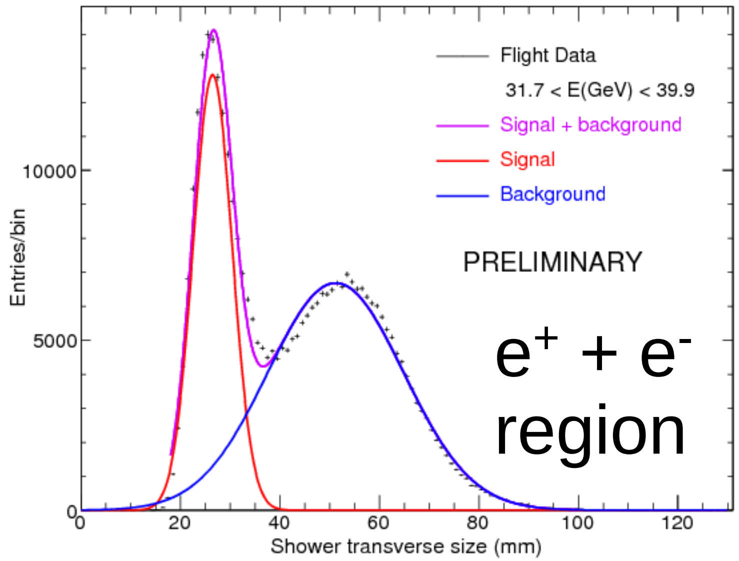


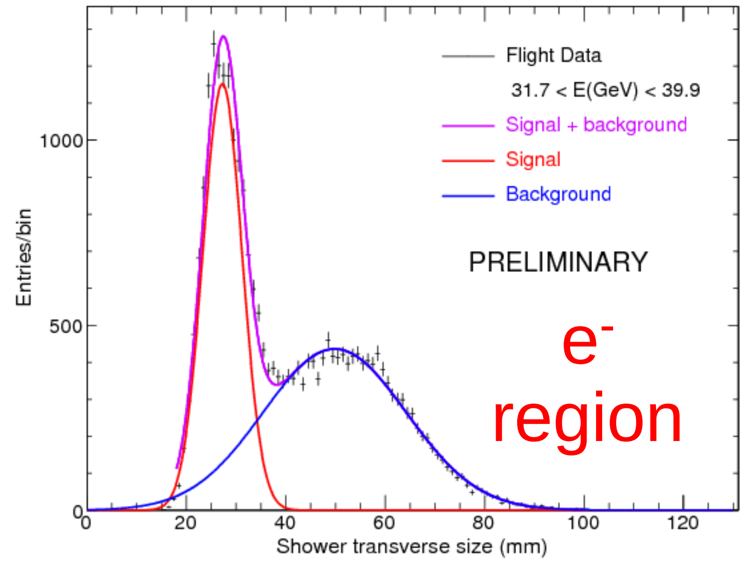
Exposure maps: 2 example energy bins for all 3 regions

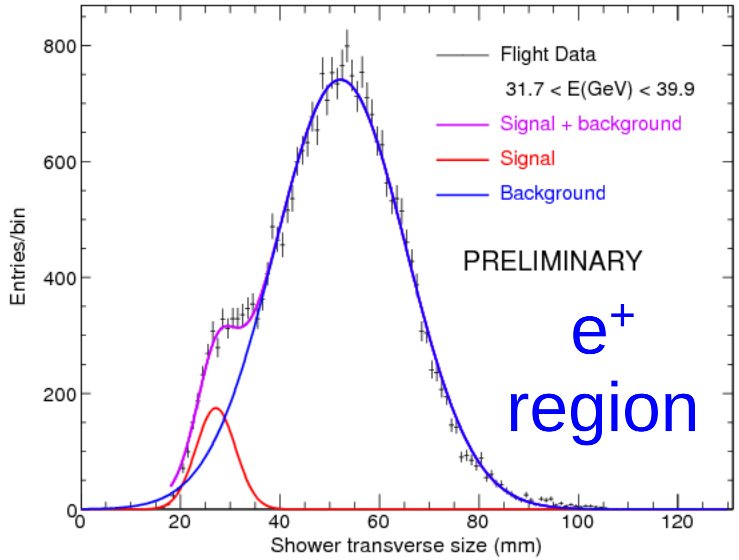


Exposure units: m^2 s

Two background subtraction methods: (1) Monte Carlo (2) fit transverse shower size in flight data



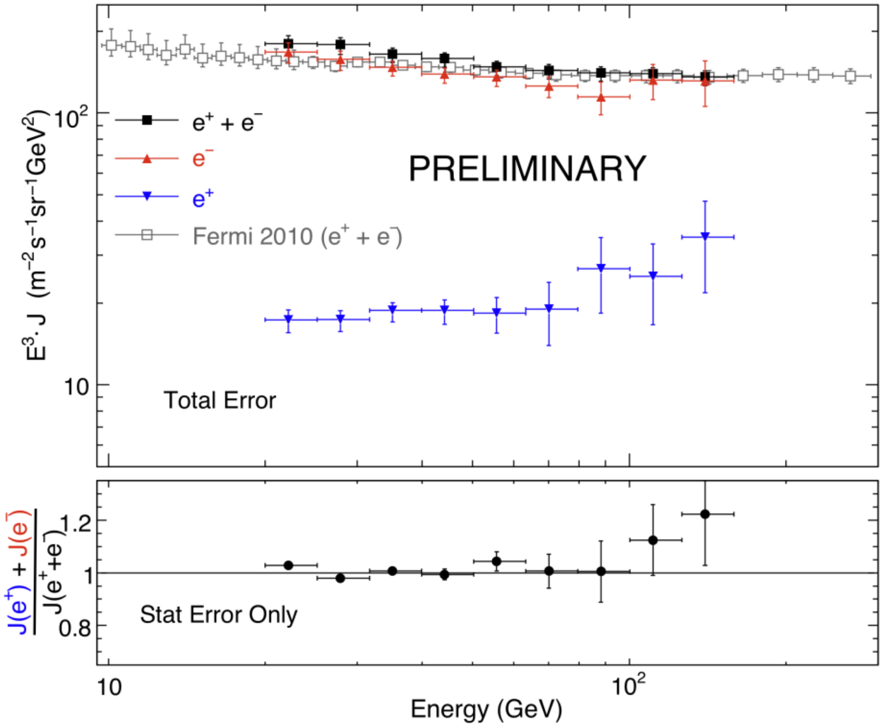




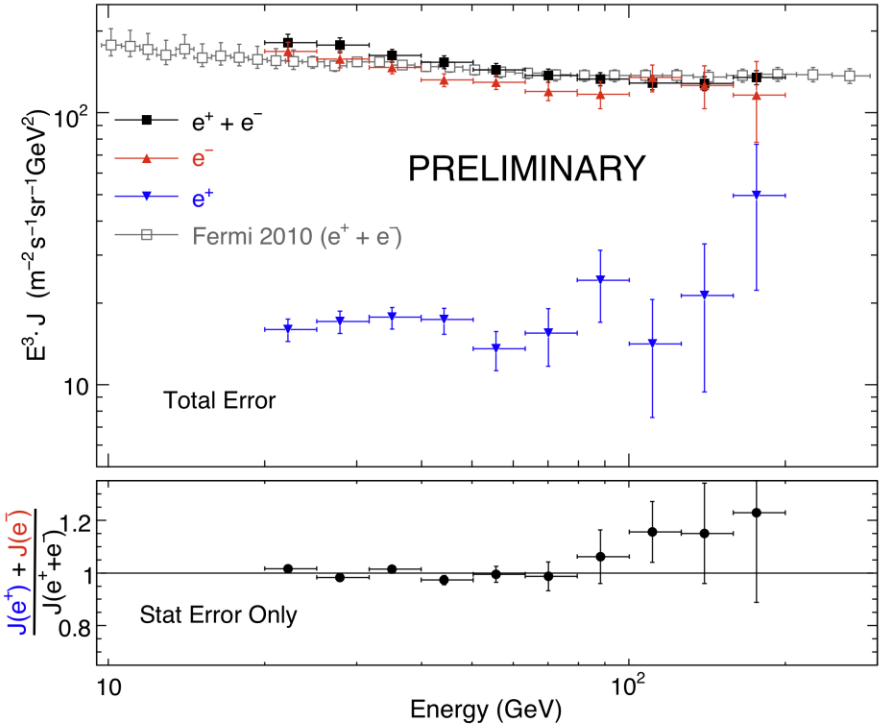
- One example energy bin
- Fit with sum of two Gaussians
- Wide hadronic + narrow electromagnetic showers

Two background subtraction methods produce consistent results

Fit-based background subtraction



MC-based background subtraction



Three cross checks:

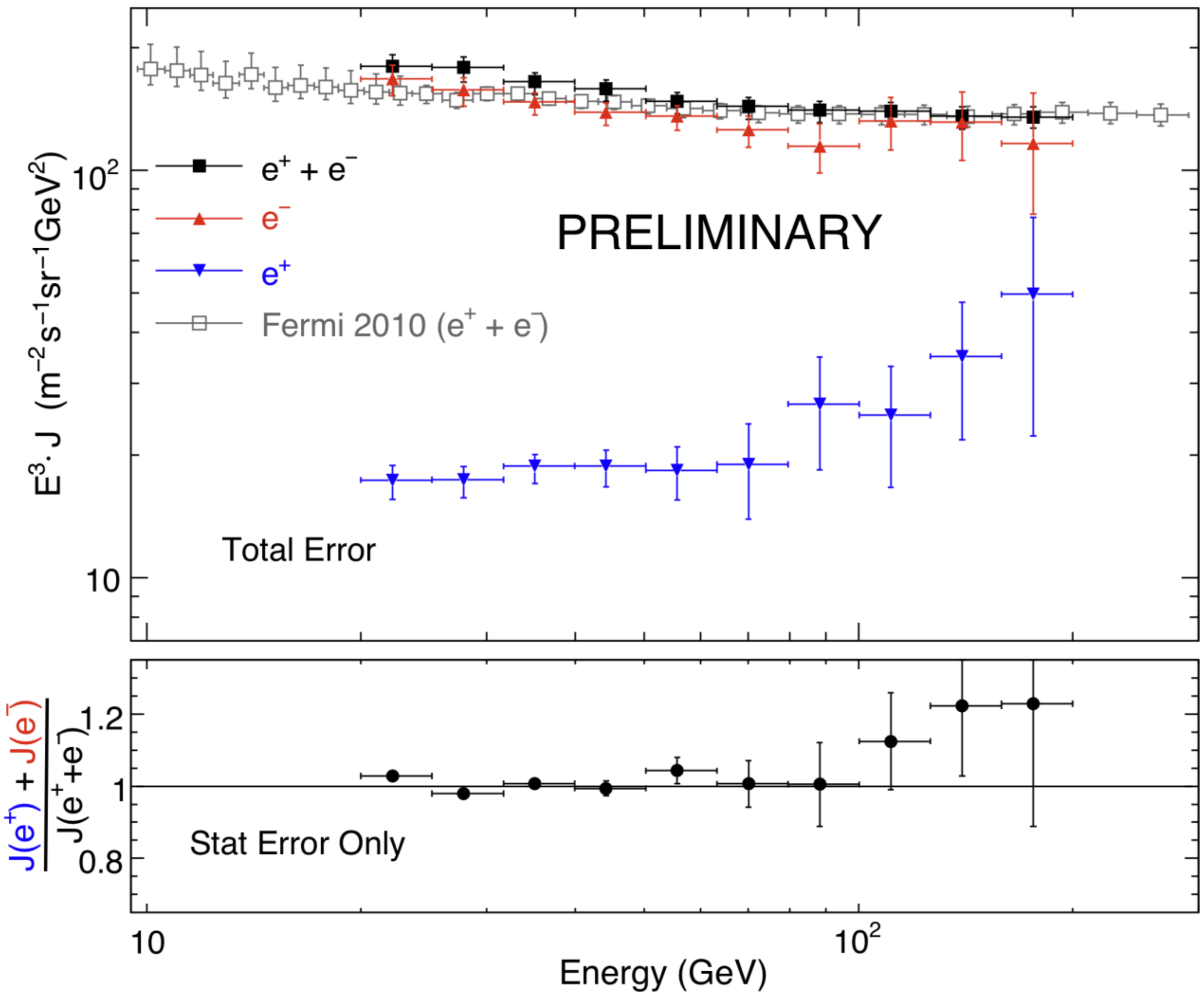
- Two background subtraction methods consistent
- Summed flux from e^- and e^+ regions matches flux from both-allowed region
- Flux from both-allowed region matches previously published e^+e^- total flux

Systematic uncertainties in spectra

Effect	**MC-based method**	**Fit-based method**
Effective area	±5%	±5%
Onboard filter efficiency	±5%	±5%
Atmospheric $e^{\pm}$ (<100 GeV)	+0%, -3%	+0%, -3%
Atmospheric $e^{\pm}$ (>100 GeV)	+0%, -10%	+0%, -10%
Data-MC p^{+} rate agreement	8%	NA
Background proton index	2-10%	NA
Fit parameterization	NA	5%
Reference θ distribution	NA	2-4%
Total	**8-19%**	**6-13%**

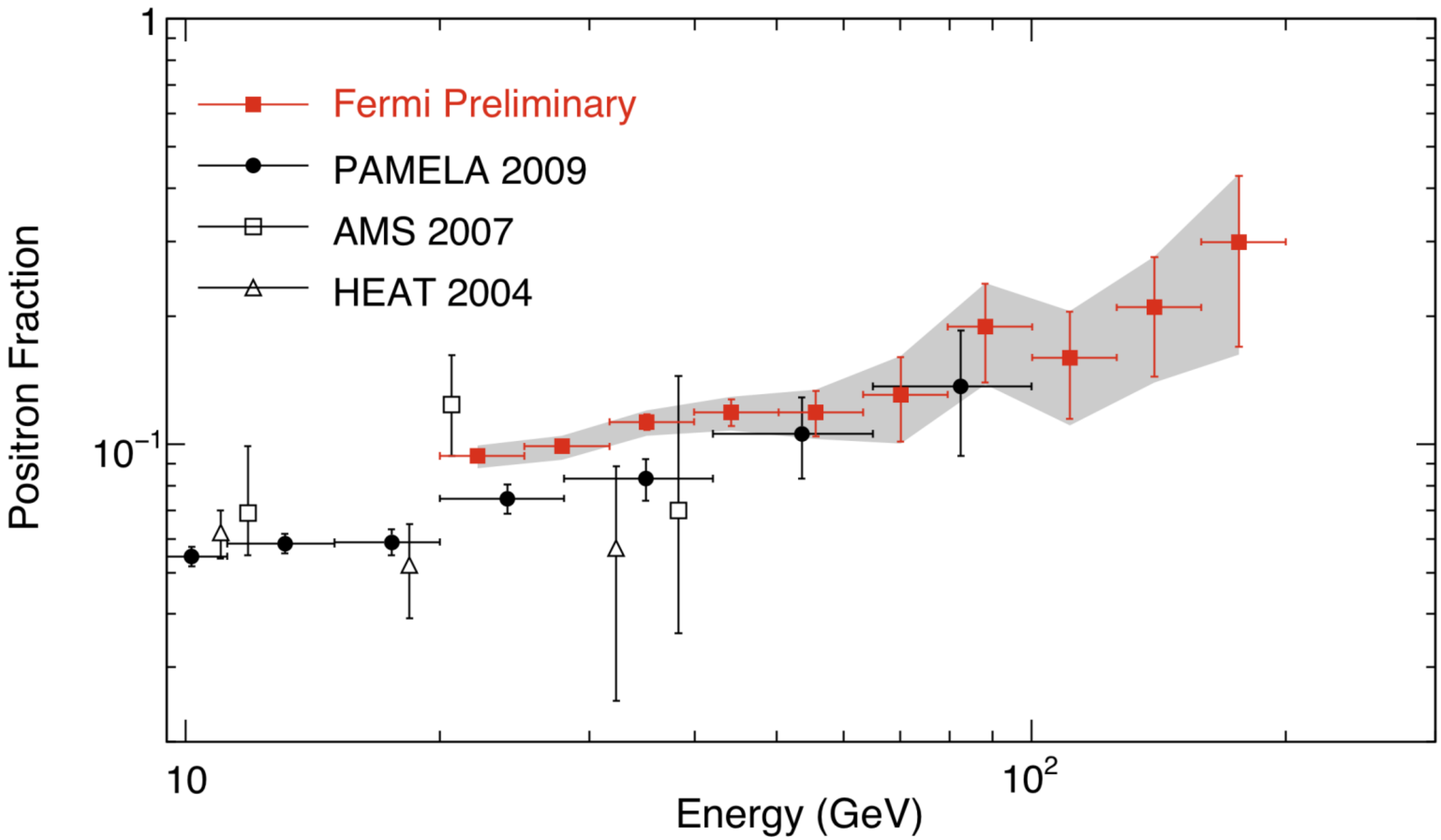
Uncertainty of positron *fraction* is smaller (A_{eff} uncertainty cancels)

Final results: electron-only, positron-only, and both-allowed spectra



Use fit-based result (lower uncertainty than MC-based) except for highest energy bin, where statistics insufficient for fitting

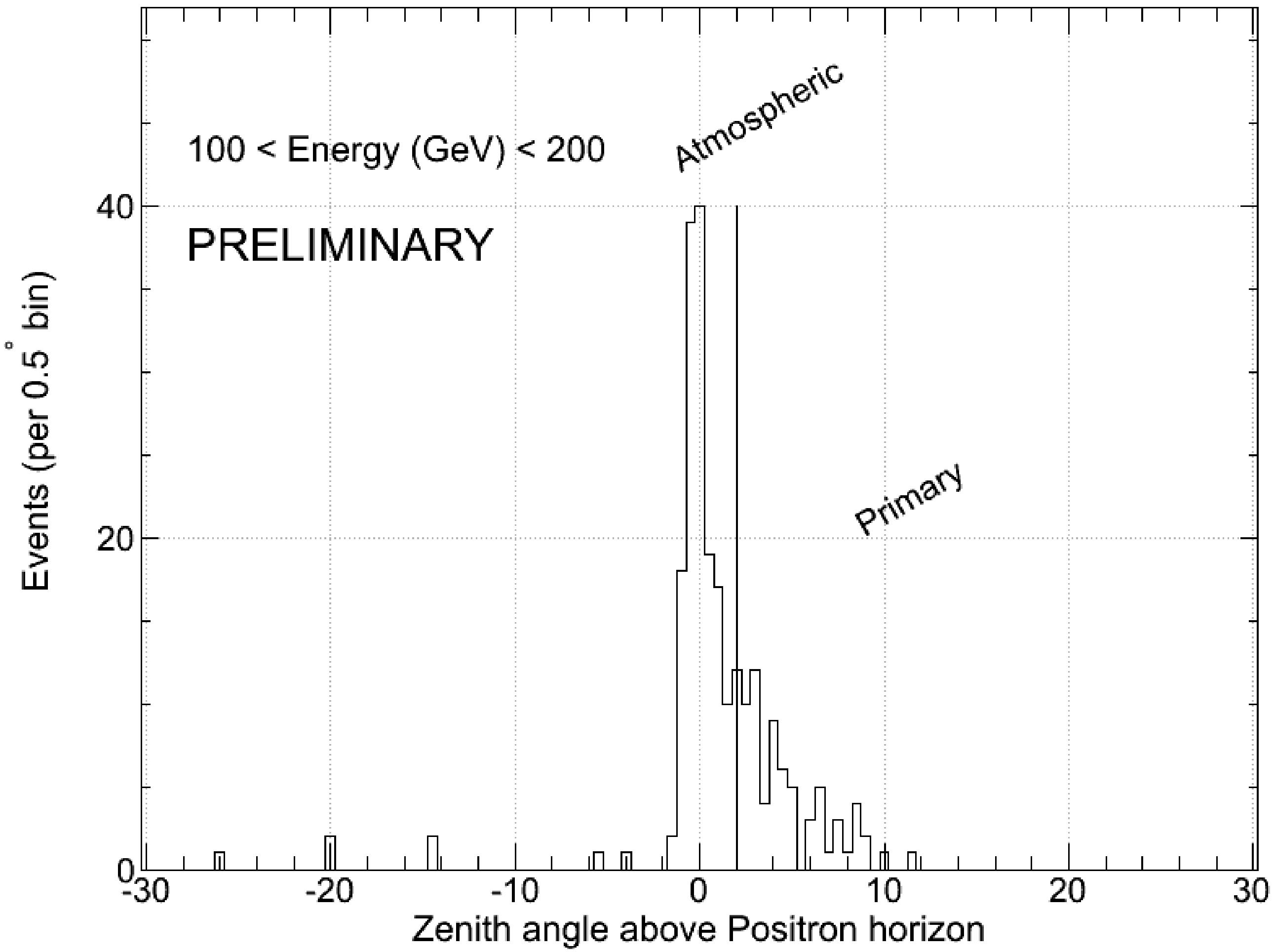
Final results: positron fraction



- Fraction = $\varphi(e^+) / [\varphi(e^+) + \varphi(e^-)]$
- We don't use the both-allowed region except as a cross check
- **Positron fraction increases with energy from 20 to 200 GeV**

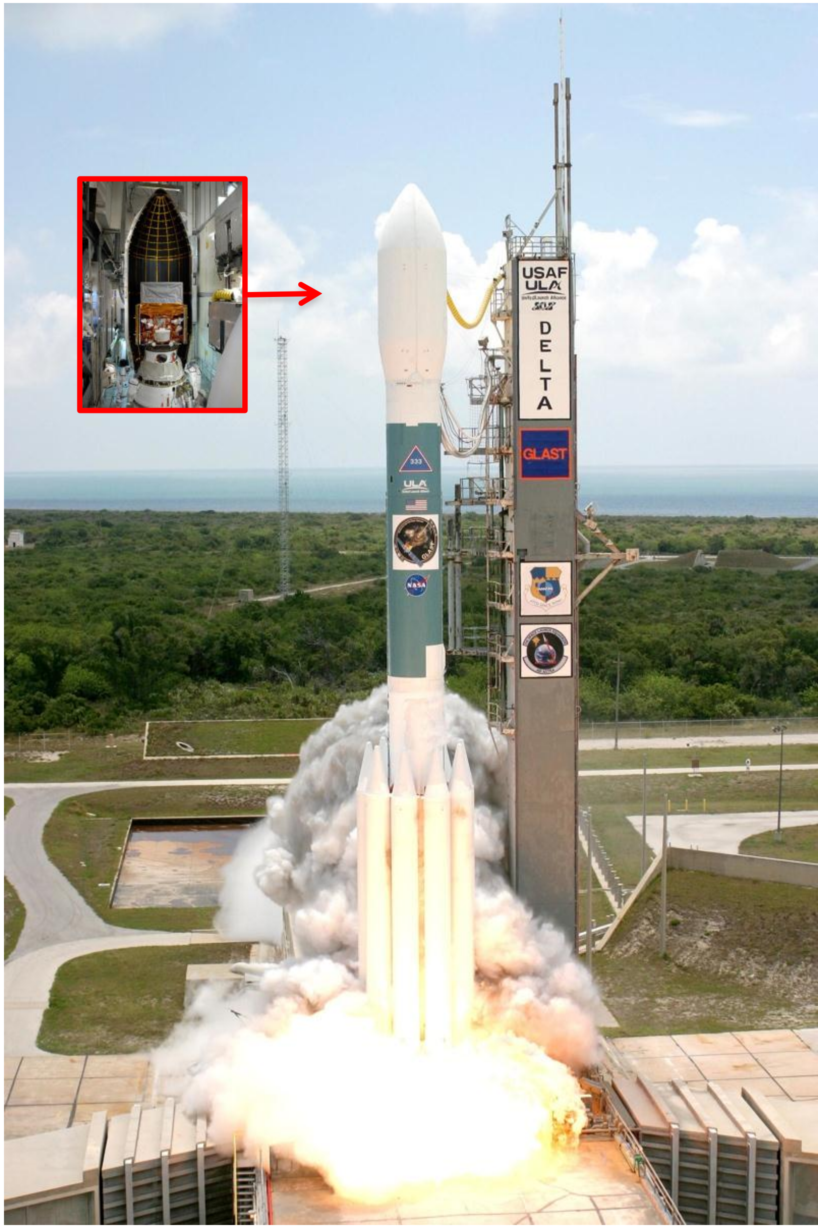
extra slides

Angular distribution of events above 100 GeV (with respect to deflected positron horizon, for events below deflected electron horizon)

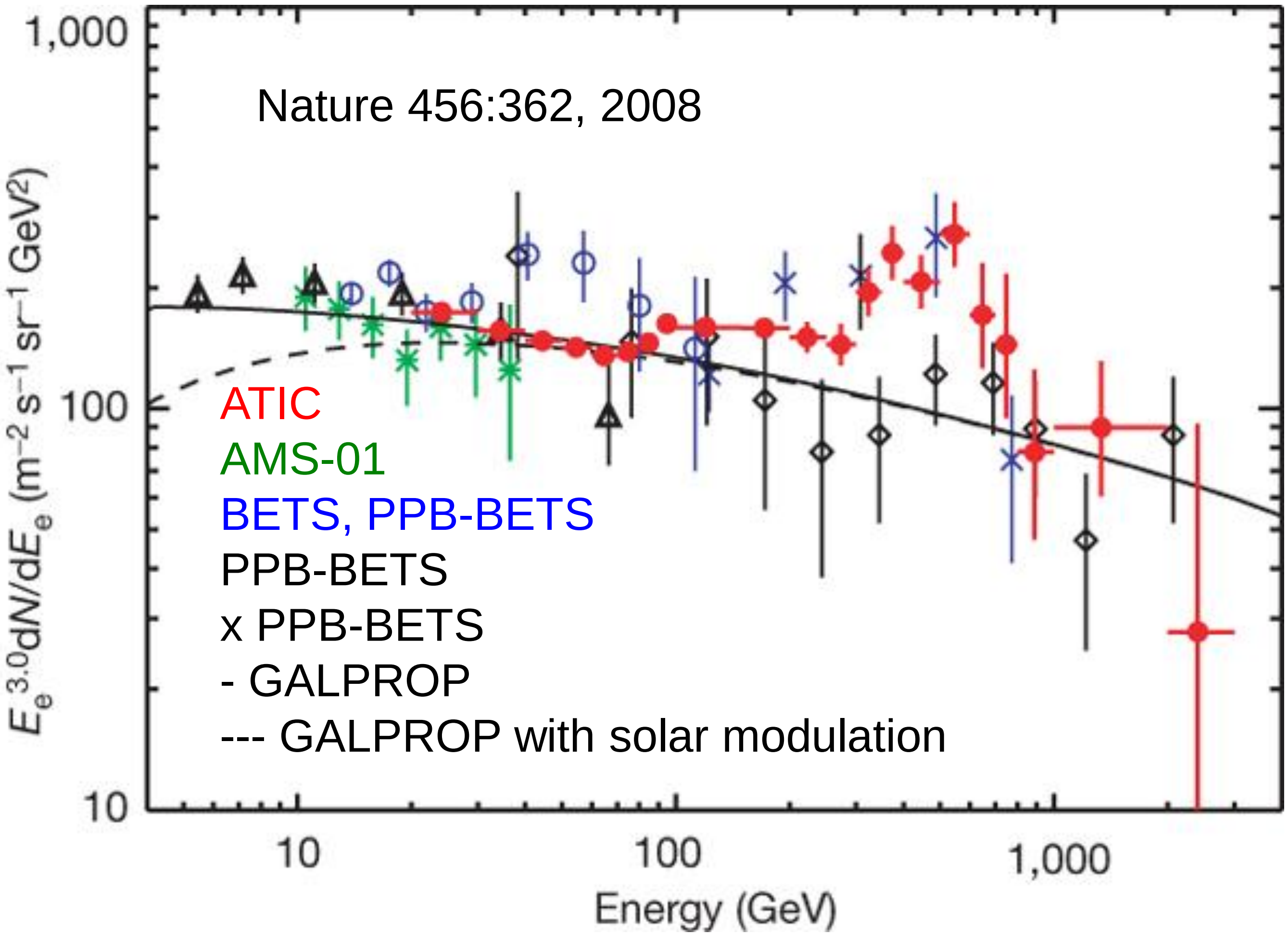


The Fermi Gamma-ray Space Telescope

- Launched by NASA at Cape Canaveral June 11, 2008
- Routine science began August 2008
- Two instruments
  - Large Area Telescope: 20 MeV – 300 GeV
  - Gamma-ray Burst Monitor: 8 keV – 40 MeV
- Data publicly available since August 2009
- Orbit: 565 km, 25.6^{o} inclination, circular
- Field of view = 2.4 sr (38% of 2π)
- Observe entire sky every 2 orbits = 3 hrs
- Expect thousands of sources, with spectra for hundreds
- ~0.1° resolution at 10 GeV, ~0.5° at 1 GeV, ~4° at 100 MeV

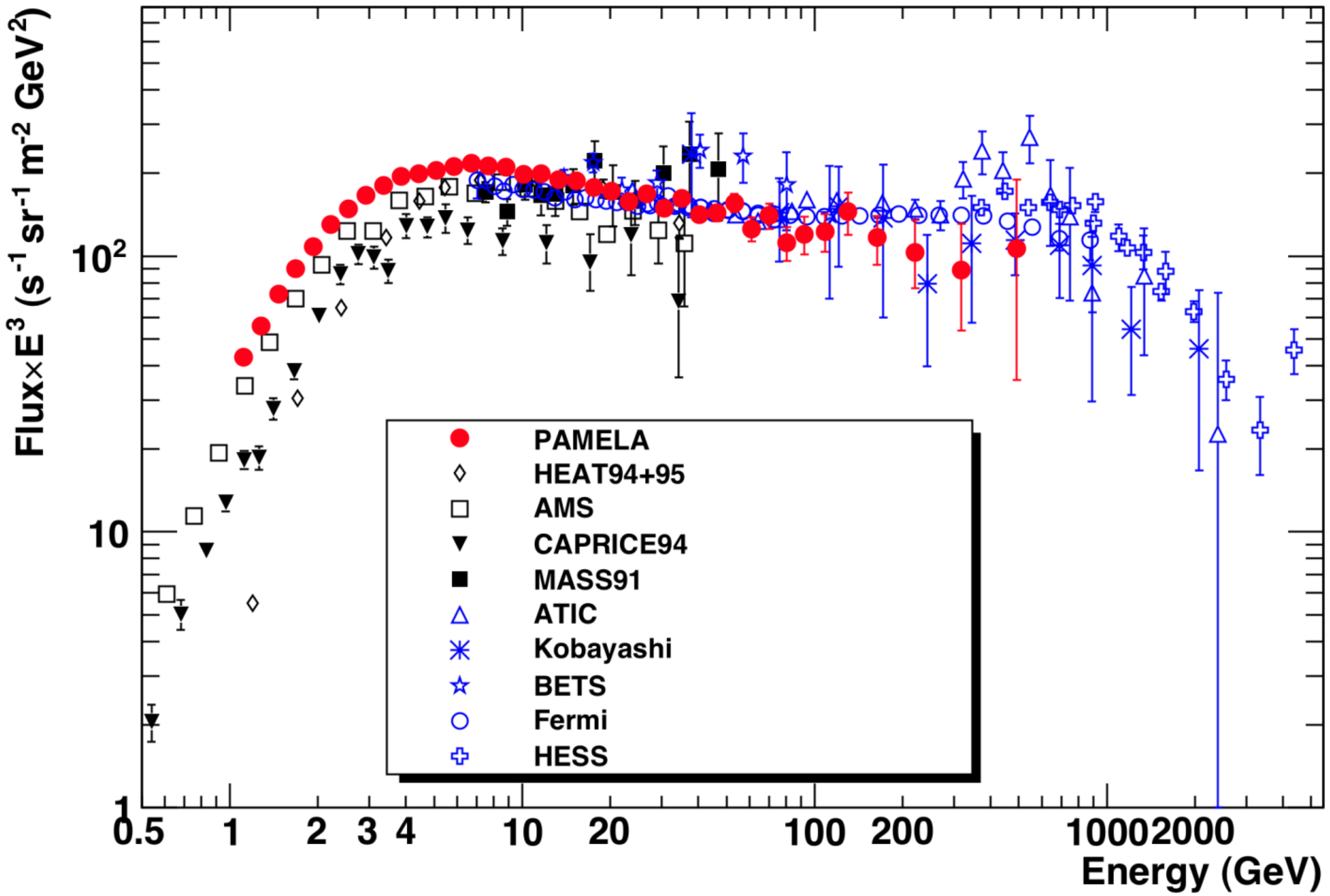


ATIC (Advanced Thin Ionization Calorimeter): bump in combined electron + positron spectrum at 300-800 GeV



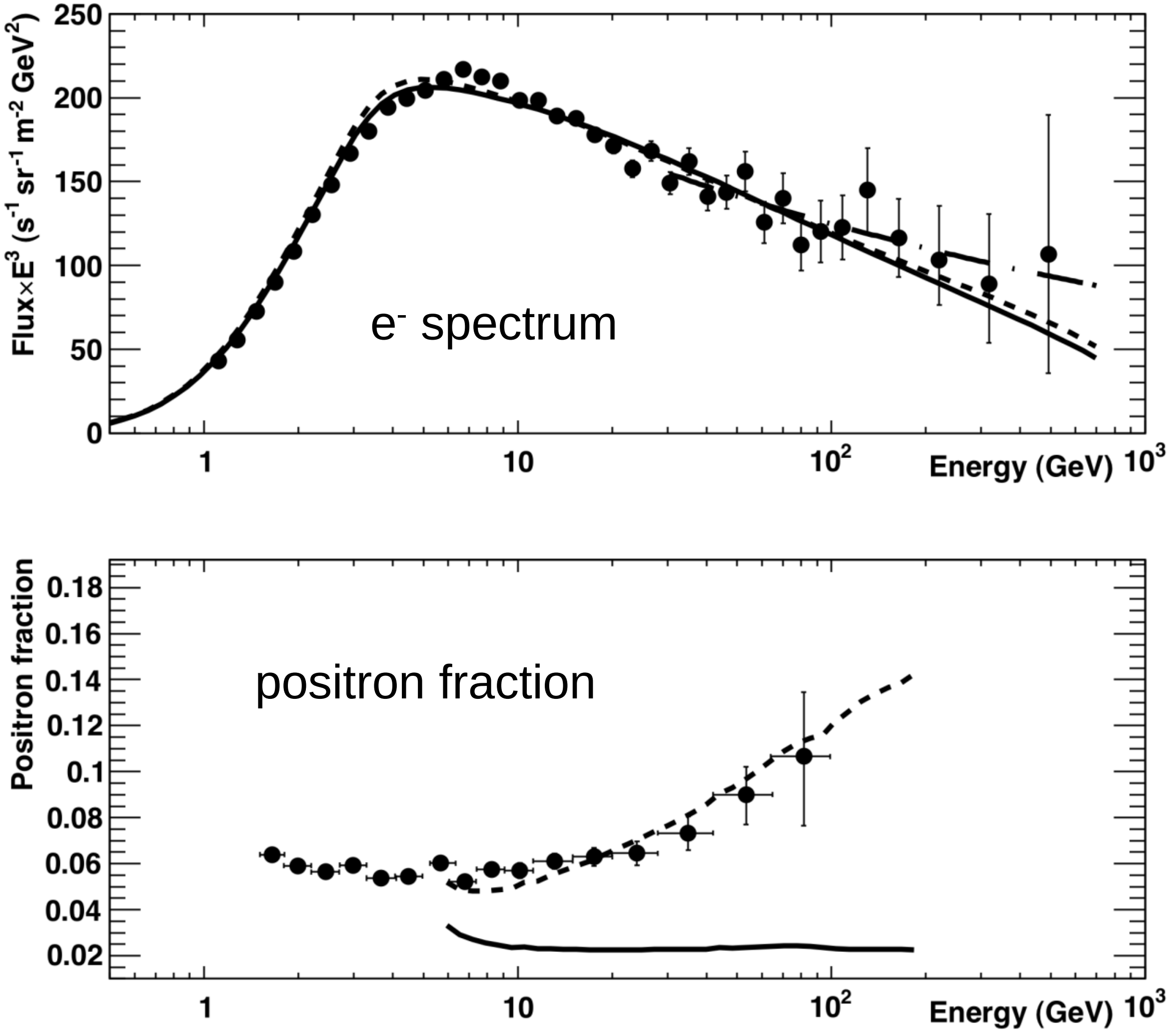
- 3 balloon flights in Antarctica, 2000-2008
- 70 events between 300 and 800 GeV

Recently updated PAMELA electron + positron analysis



PRL 106, 201101 (May 20, 2011)

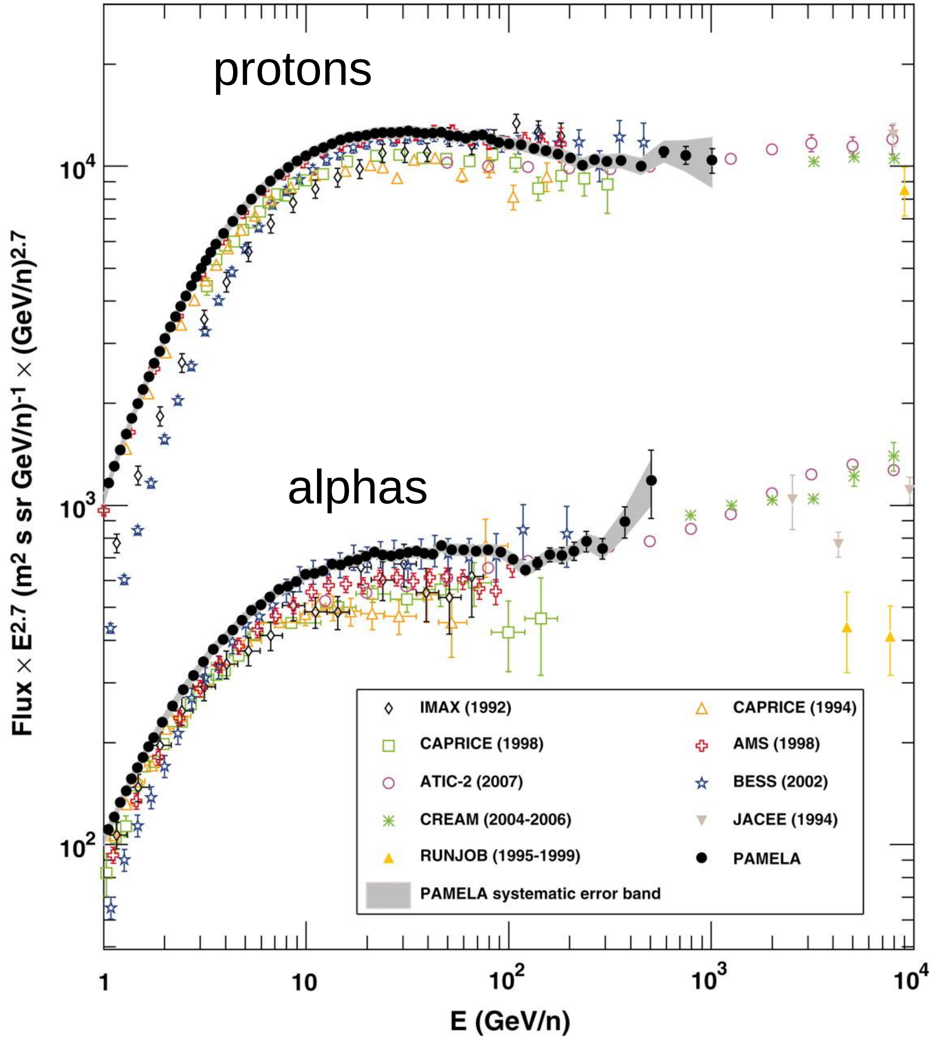
Recently updated PAMELA electron + positron analysis



PRL 106, 201101 (May 20, 2011)

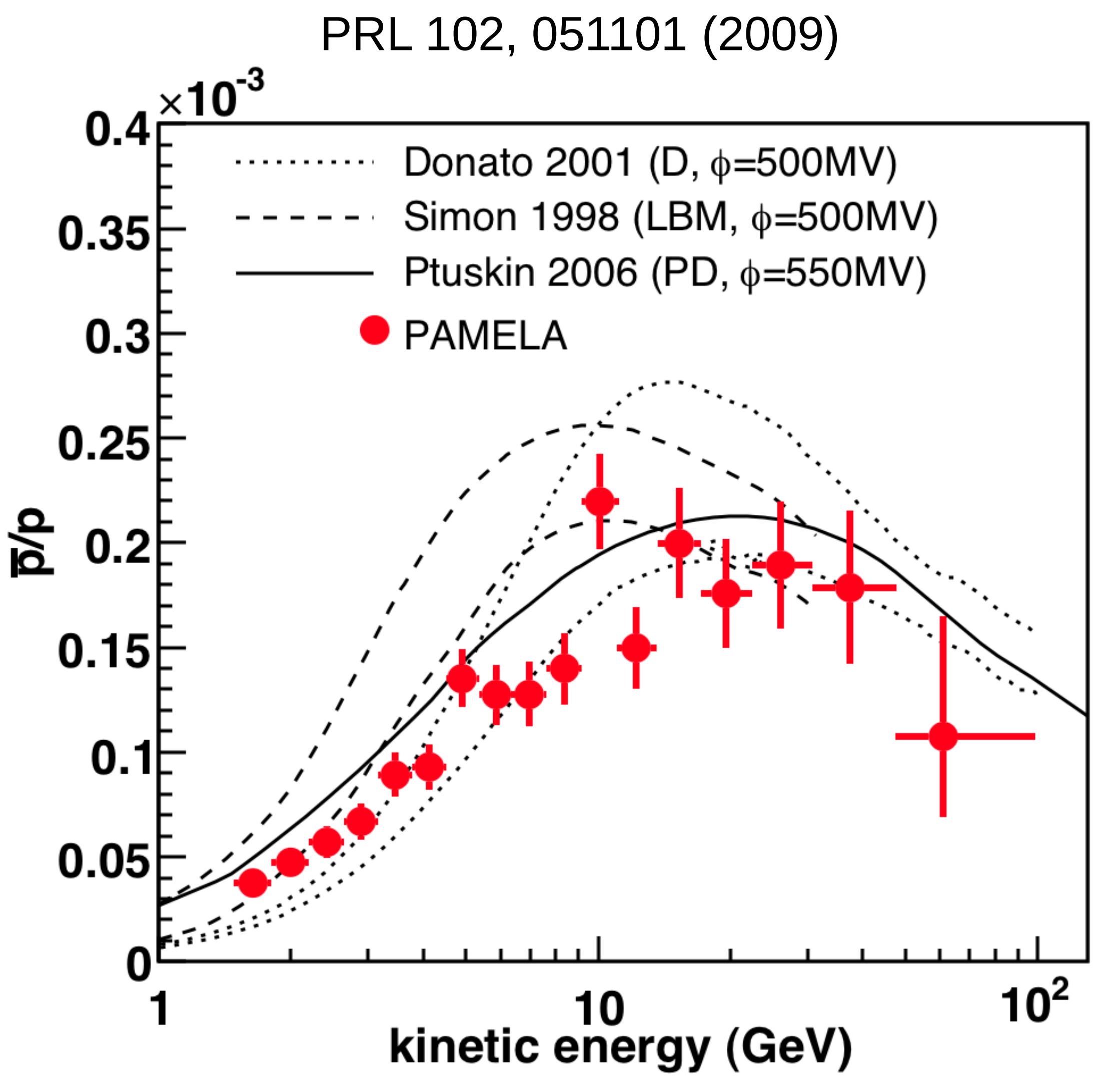
PAMELA proton and alpha spectra

Science 332 (6025): 69-72 (2011)



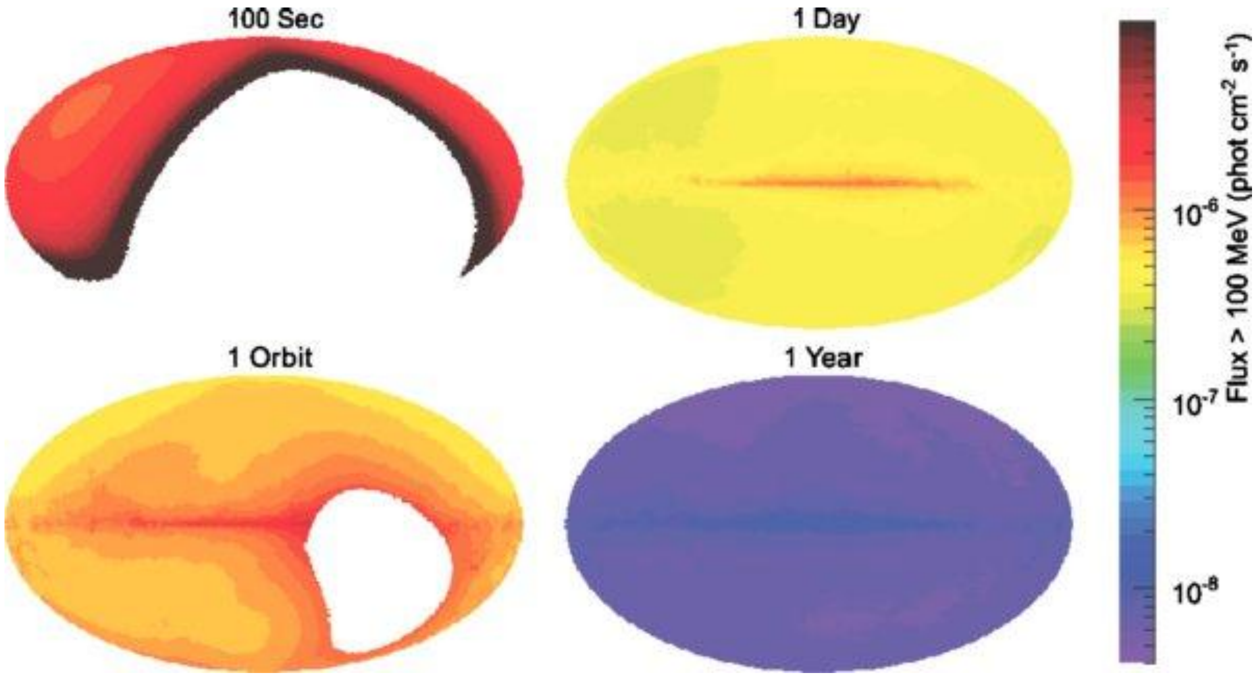
- ~E$^{-2.7}$ power law
- Proton flux an order of magnitude larger than alpha flux

PAMELA antiproton fraction



Consistent with diffuse model, unlike positron spectrum

Fermi LAT orbits and exposure



Atwood et al., ApJ 697, 1071 (2009)

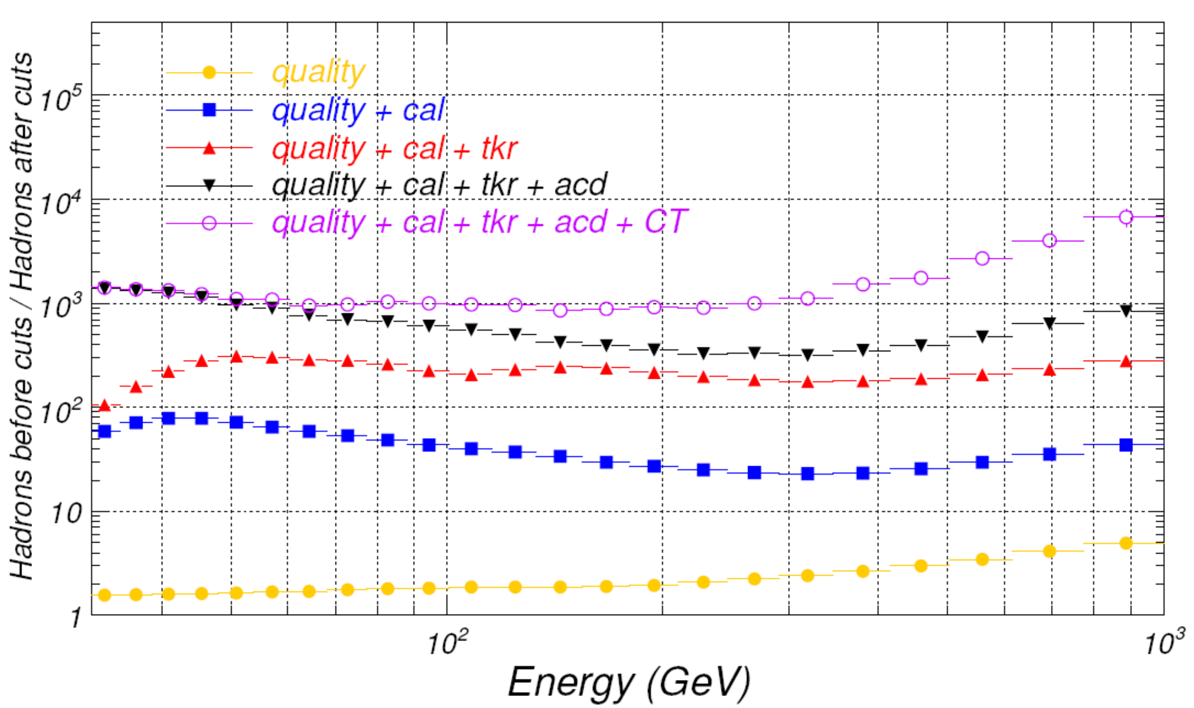
- Nearly uniform exposure every two orbits
- Typical point on sky viewed for 30 minutes every 3 hours
- Rocking: alternate North-pointing orbit with South-pointing orbit
- This survey mode has been used exclusively except for an initial pointed-mode commissioning period and several pointed-mode observations of a few days each (Crab Nebula twice, Cyg X-3 once, and very bright blazar flare – 3C 454.3 – once)

Fermi LAT data taking

- Launched June 11, 2008 (3 years old!)
- Normal data taking since August 4, 2008
- Data are publicly available, along with analysis software, from the Fermi Science Support Center (http://fermi.gsfc.nasa.gov/ssc)
- 175 billion events at trigger level as of May 10, 2011 (~2 kHz)
- 40 billion events sent from satellite to ground (after onboard filtering)
- Photons available for download, few hours after being detected
- As of May 2011, ~600 million photon events available, collected since August 4, 2008
- Detecting 6.3 gamma rays per second

Separating electrons and positrons from gammas and protons

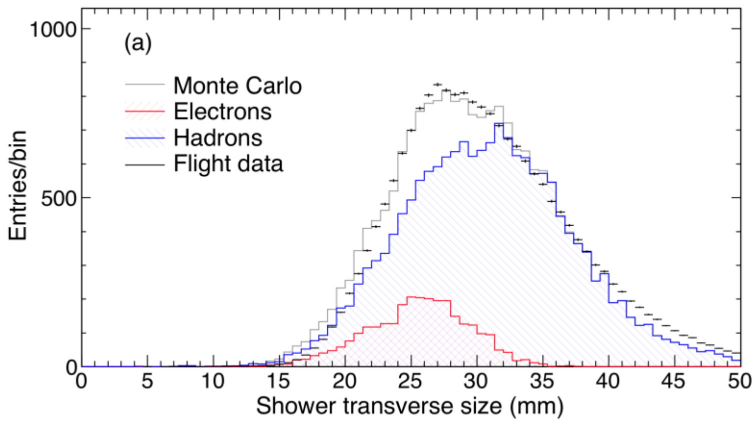
- Anti-coincidence detector (ACD = set of scintillator tiles surrounding instrument) usually required to *not* fire, to reject charged particles and keep gamma rays
- Here we require the ACD to fire, to select charged particles and reject the gamma ray "background"
- Proton rejection: require broader, clumpier shower in CAL, TKR, and ACD:



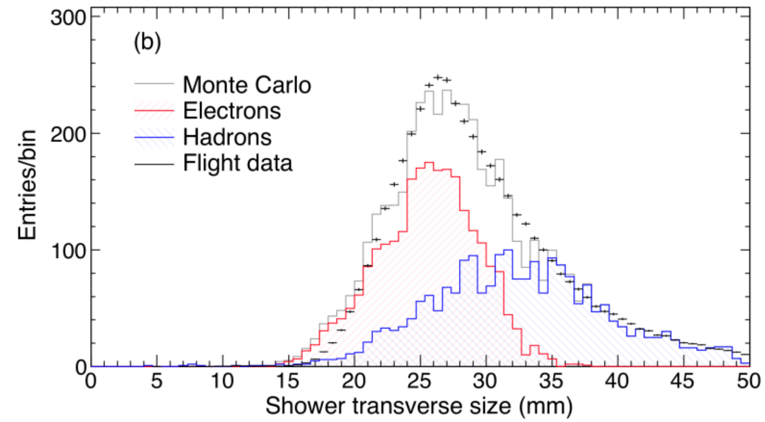
Increasing cut level and background rejection: required ~10^3 to 10^4 proton rejection achieved

Hadron-lepton separation and data – Monte Carlo comparison

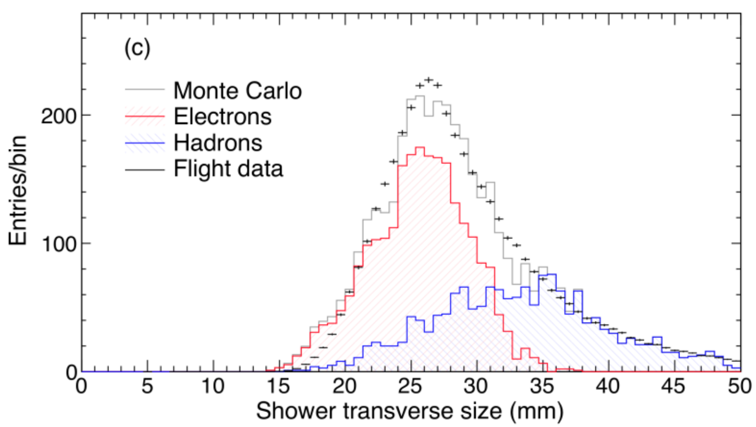
after calorimeter cuts



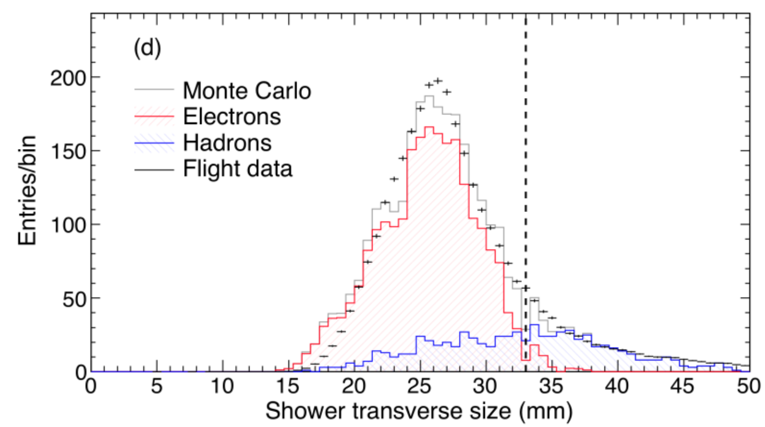
after tracker cuts



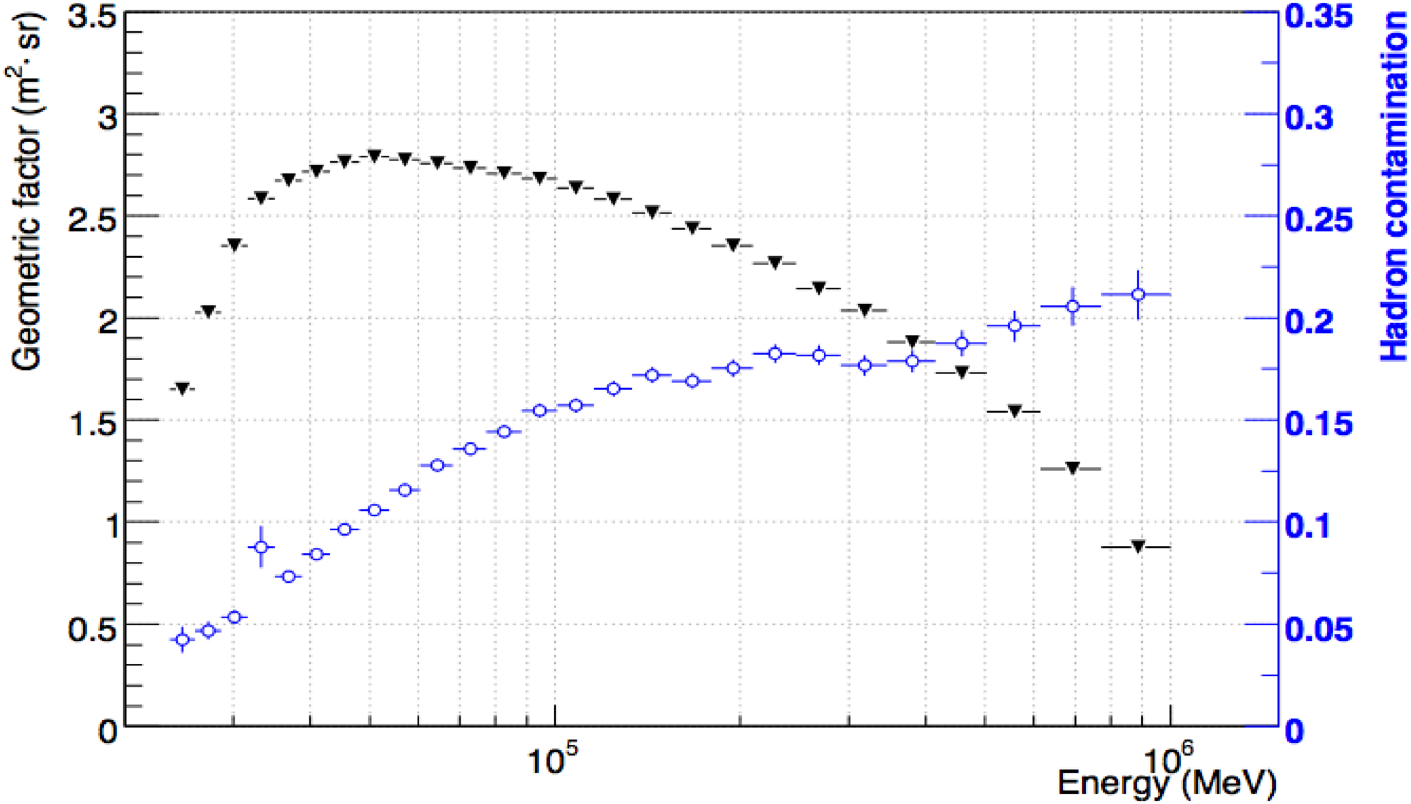
after anti-coincidence cuts



after classification tree cuts

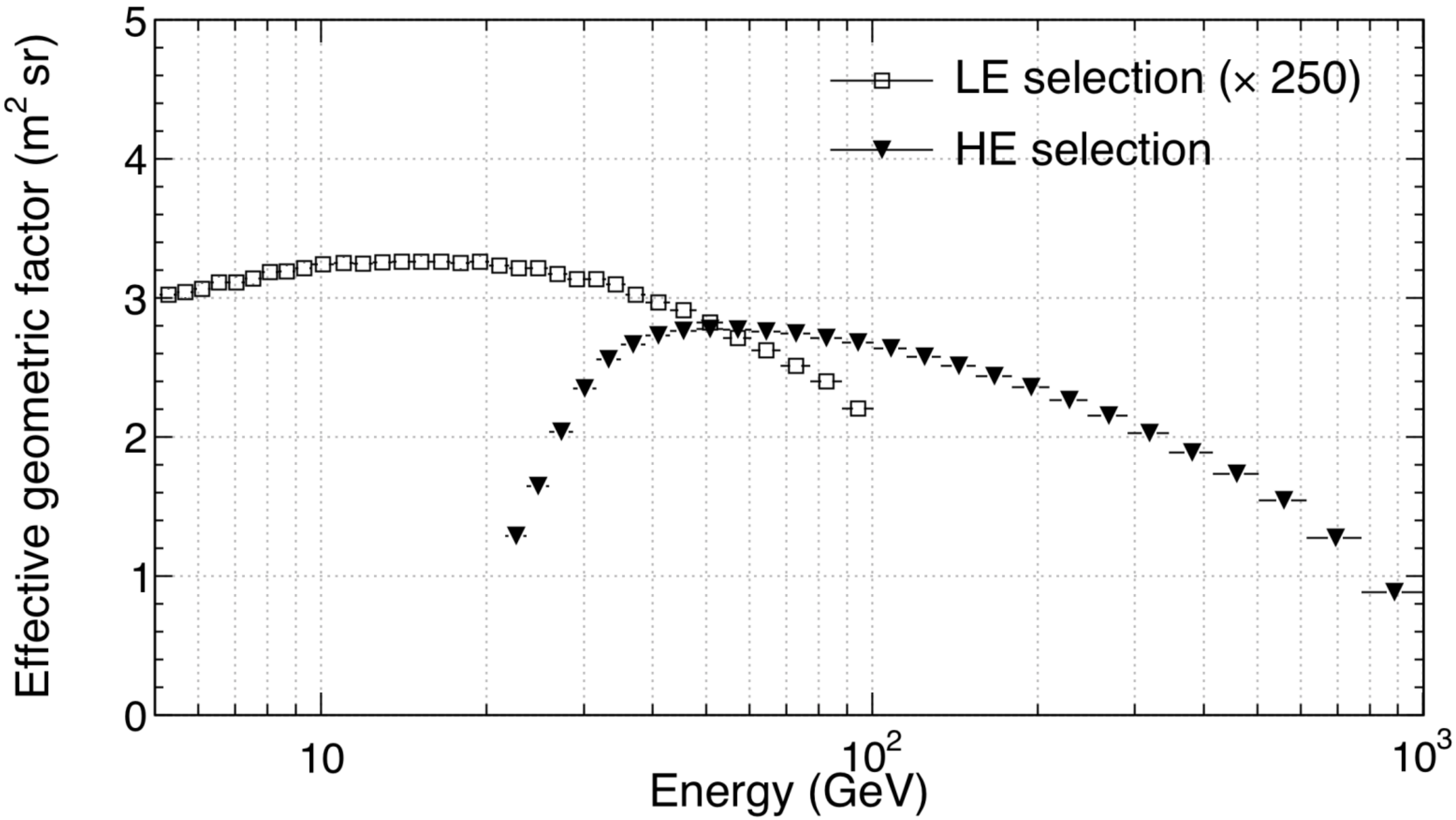


Acceptance and residual background contamination



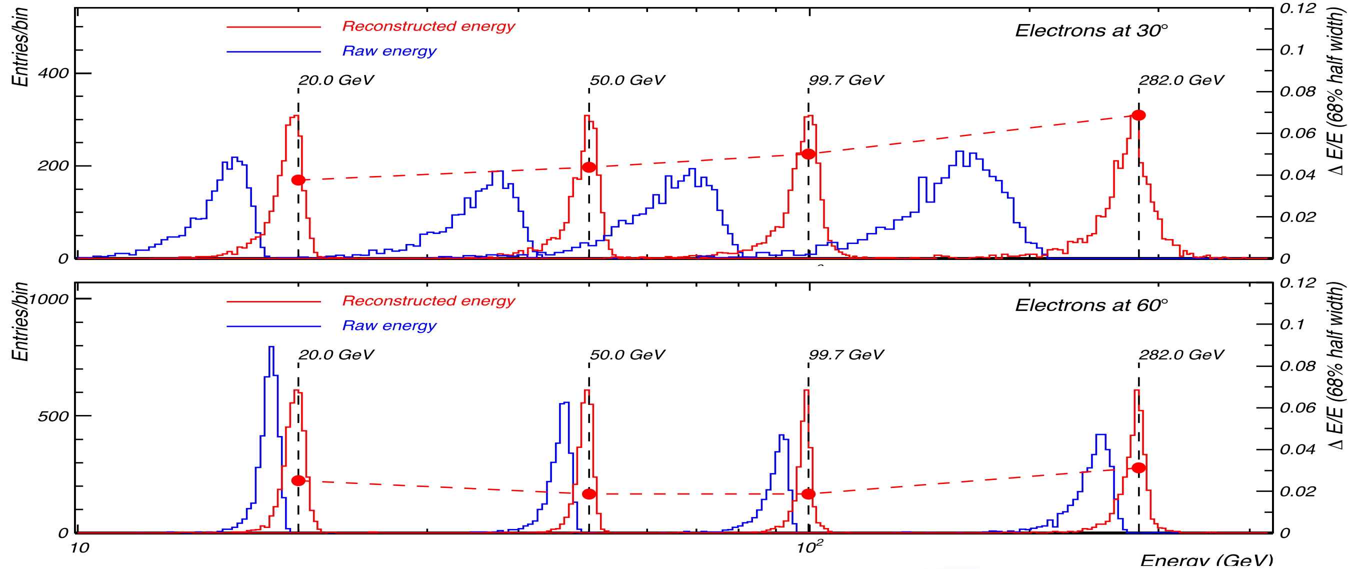
- Acceptance (“geometric factor) = 1-3 m2sr in 20 GeV to 1 TeV range
- Residual hadron contamination = 5 to 20 %

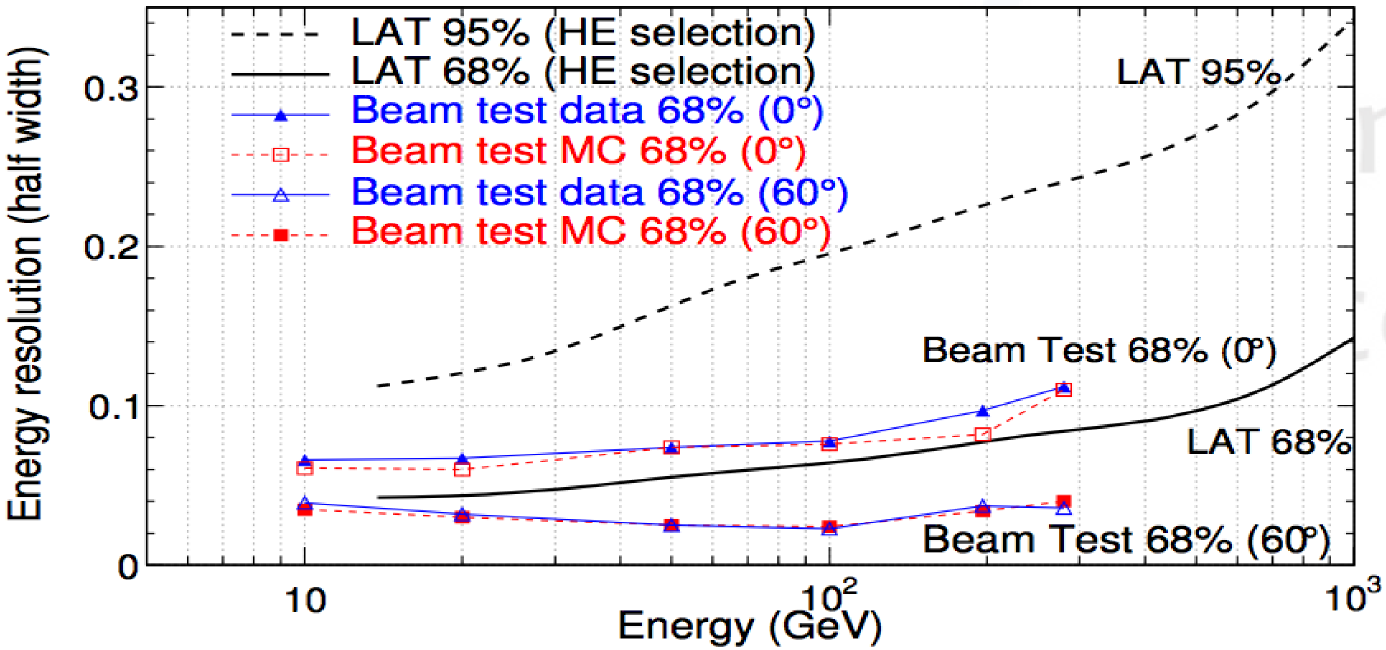
Low-energy and high-energy data streams



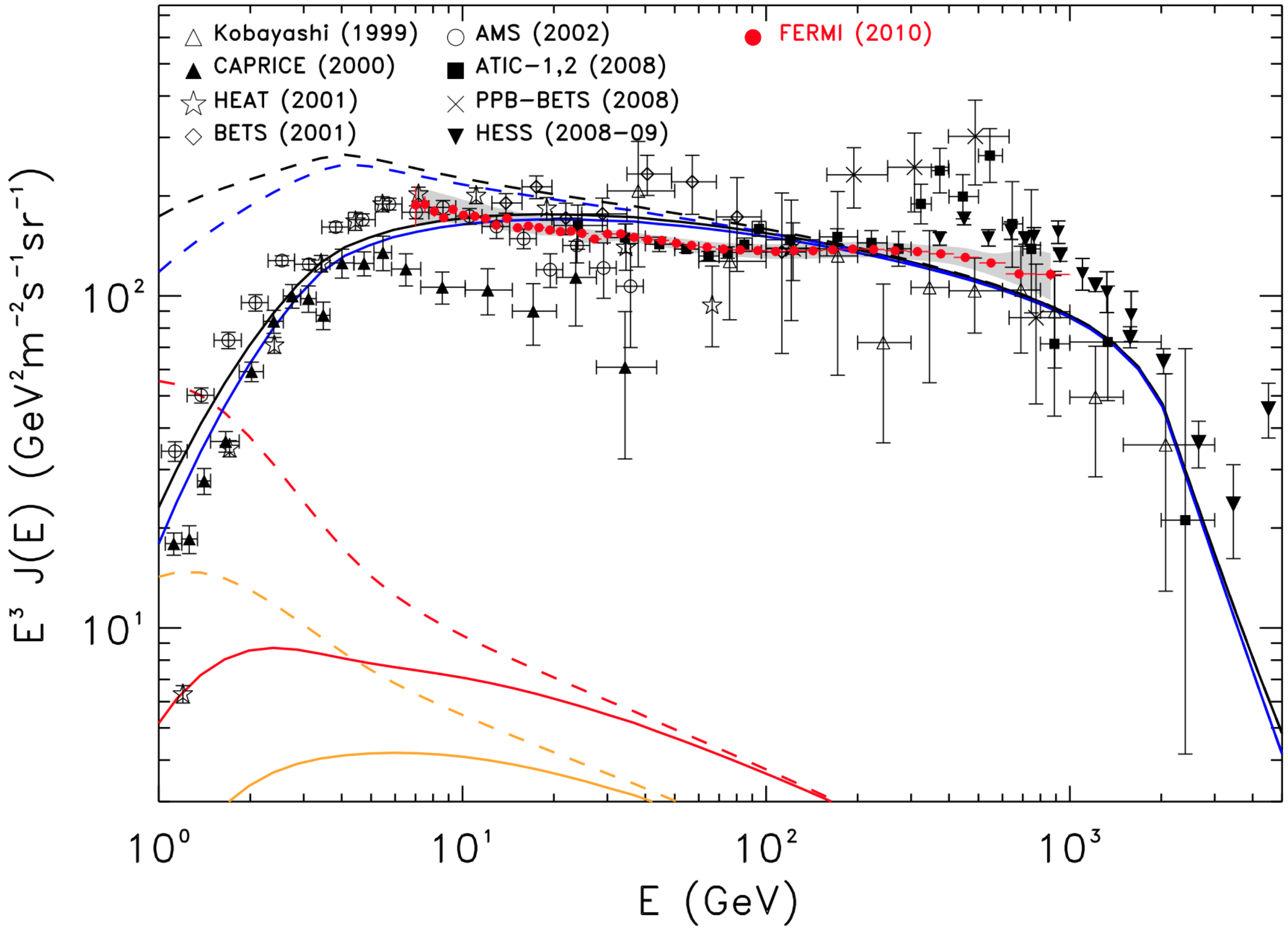
- LE: “minimum bias” set, 1 of every 250 triggered events sent to ground
- HE: any event that deposits ≥ 20 GeV in calorimeter sent to ground
- Two parallel analyses for two streams, with good consistency in overlap region

Energy resolution, measured with beam test: ~15%



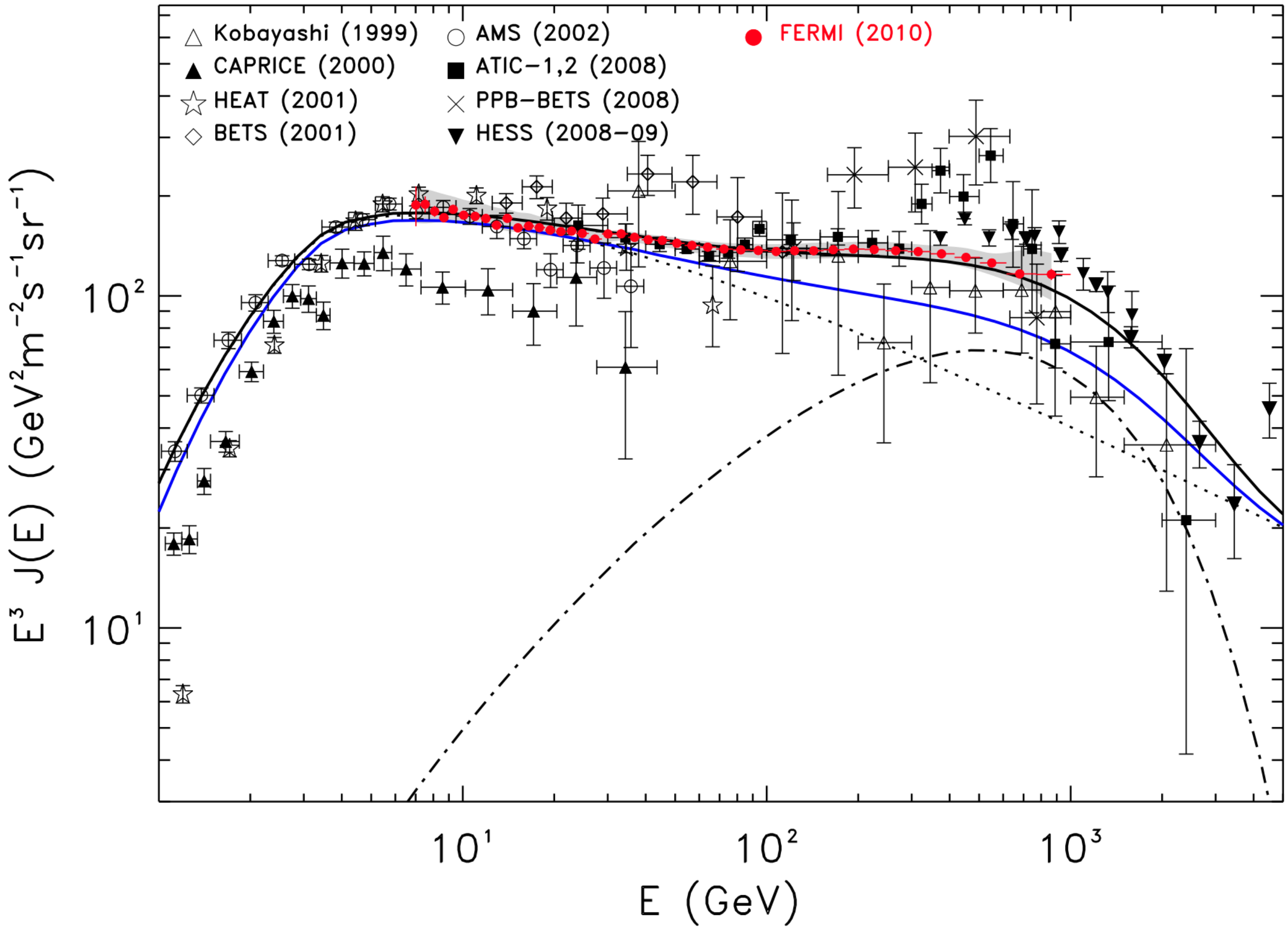


e^+e^- interpretation 1: conventional diffuse model



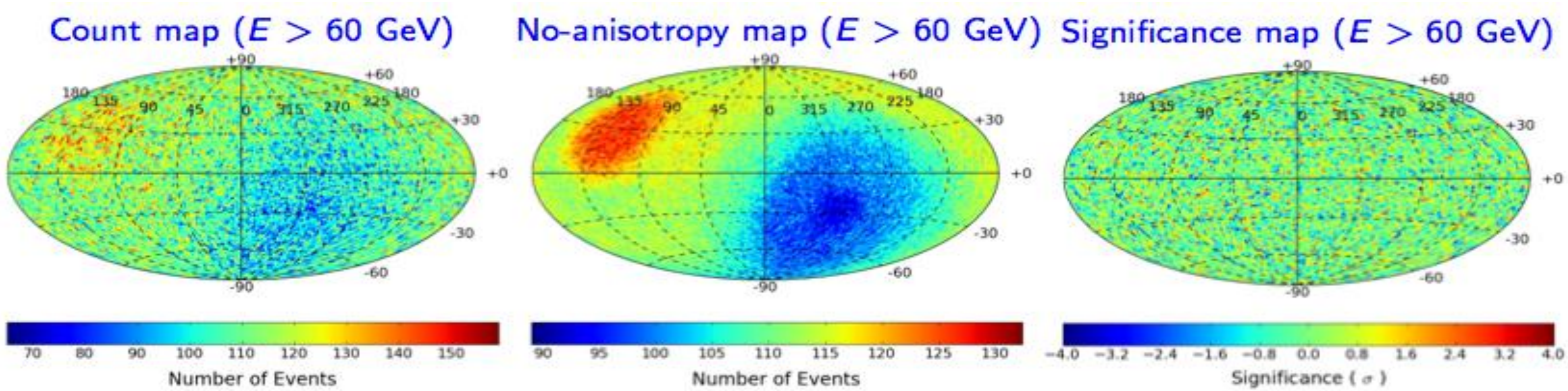
- Black: electron + positron, blue: electron only
- Dashed: without solar modulation

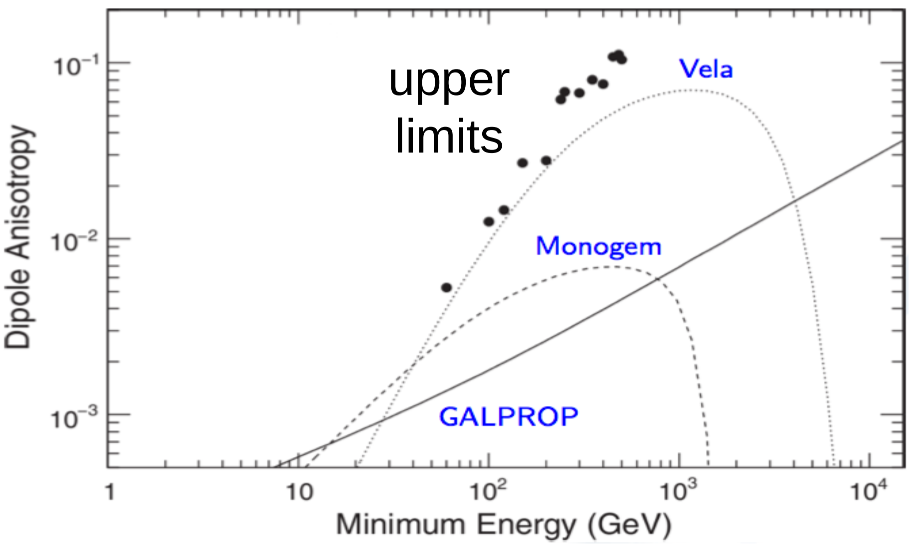
e^+e^- interpretation 2: softer diffuse secondary model, plus additional source at high energy



- Tuned to the data: softer diffuse injection spectrum, plus an additional component at high energy (pulsar? dark matter?)

Search for anisotropy in cosmic ray electron + positron flux

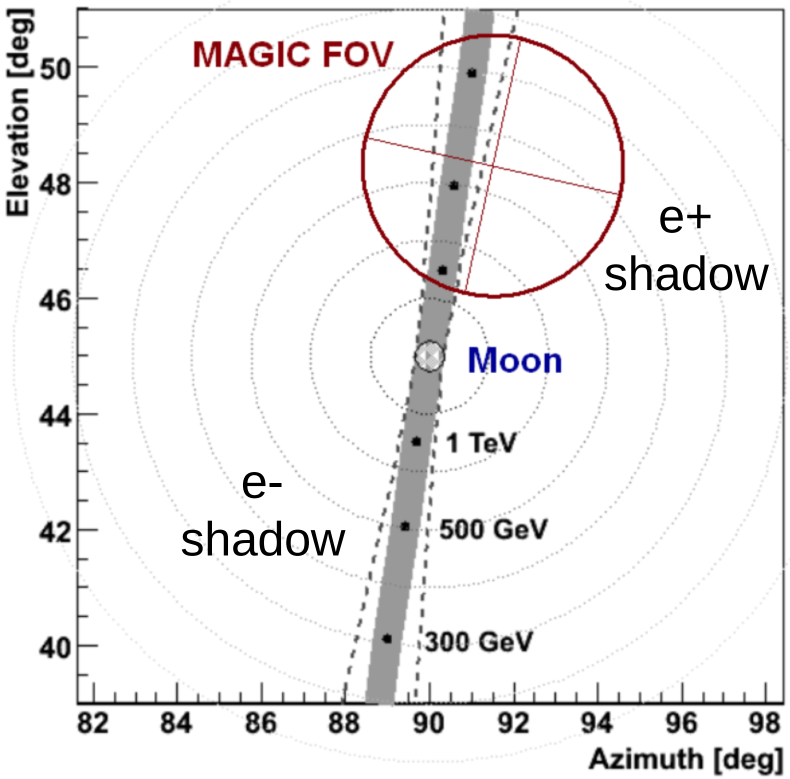




Ackermann et al, PRD 82, 092003 (2010)

- 1.6 M candidate electrons above 60 GeV in first year
- Entire sky searched for anisotropy with range of angular scales (10° to 90°) and energies
- Dipole upper limits: 0.5% to 10% (comparable to expectation for single nearby source: models are not constrained)

Cosmic ray electron/positron separation at ~ TeV with MAGIC and the Moon shadow?

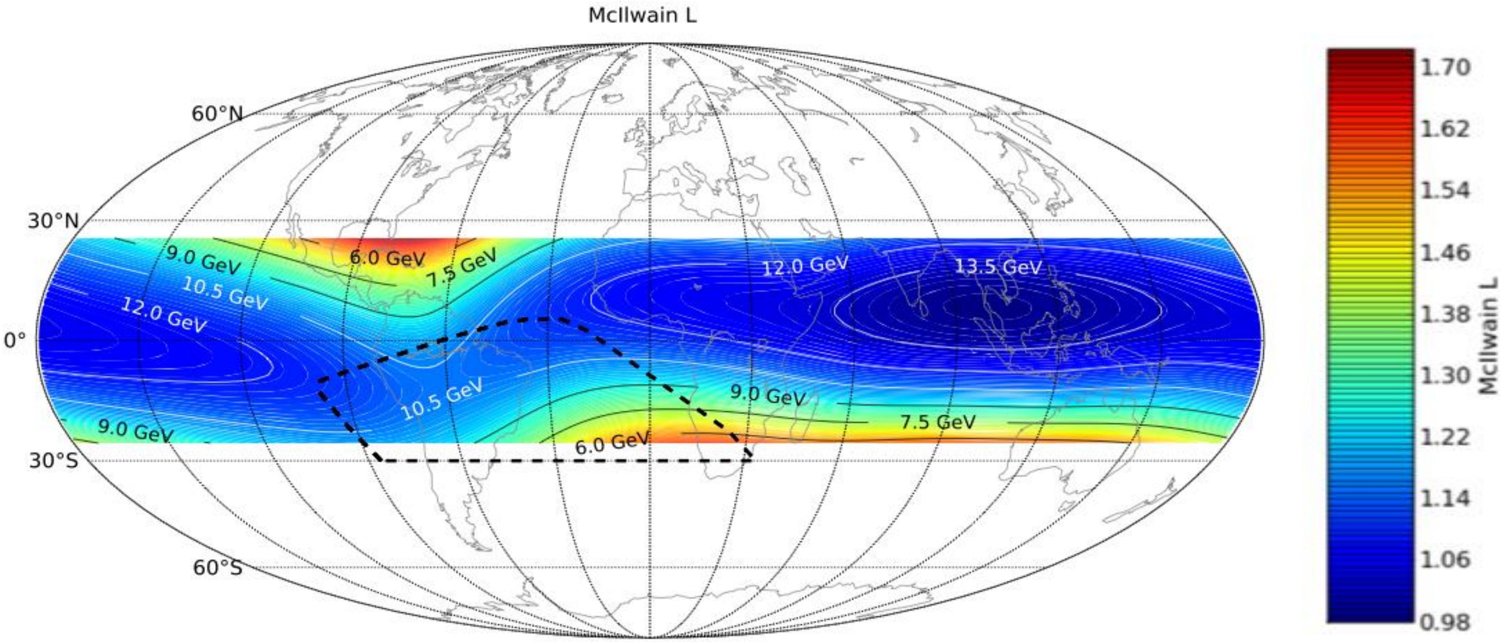


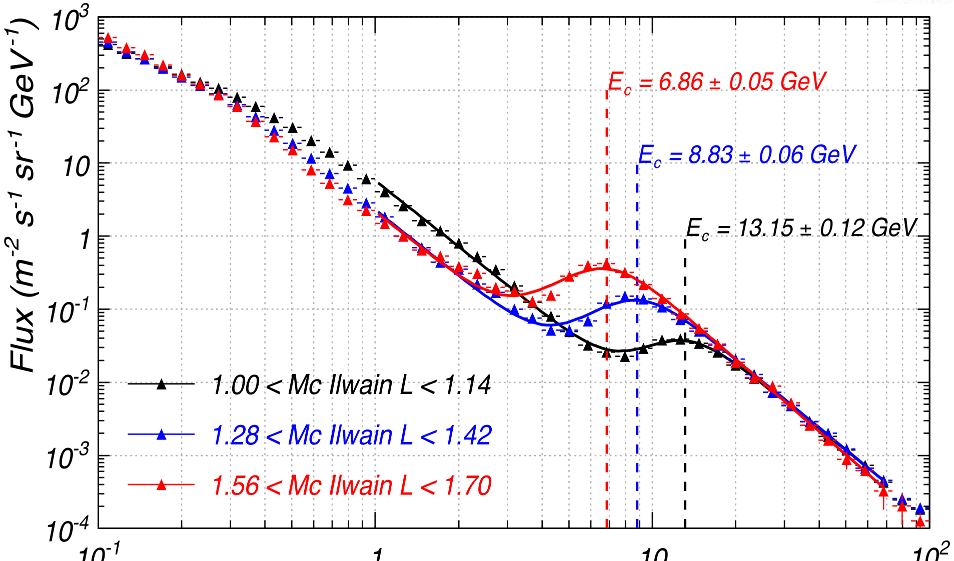
MAGIC, arXiv:0907.1026

- Measure electrons/positrons using imaging atmospheric Cherenkov telescopes like HESS, but use the Moon shadow to separate electrons and positrons (two shadows separated by ~1° at ~1 TeV)
- Moon phase must be < ~50% to avoid damaging PMTs
- They have made observations and are analyzing

Geomagnetic cutoff rigidities

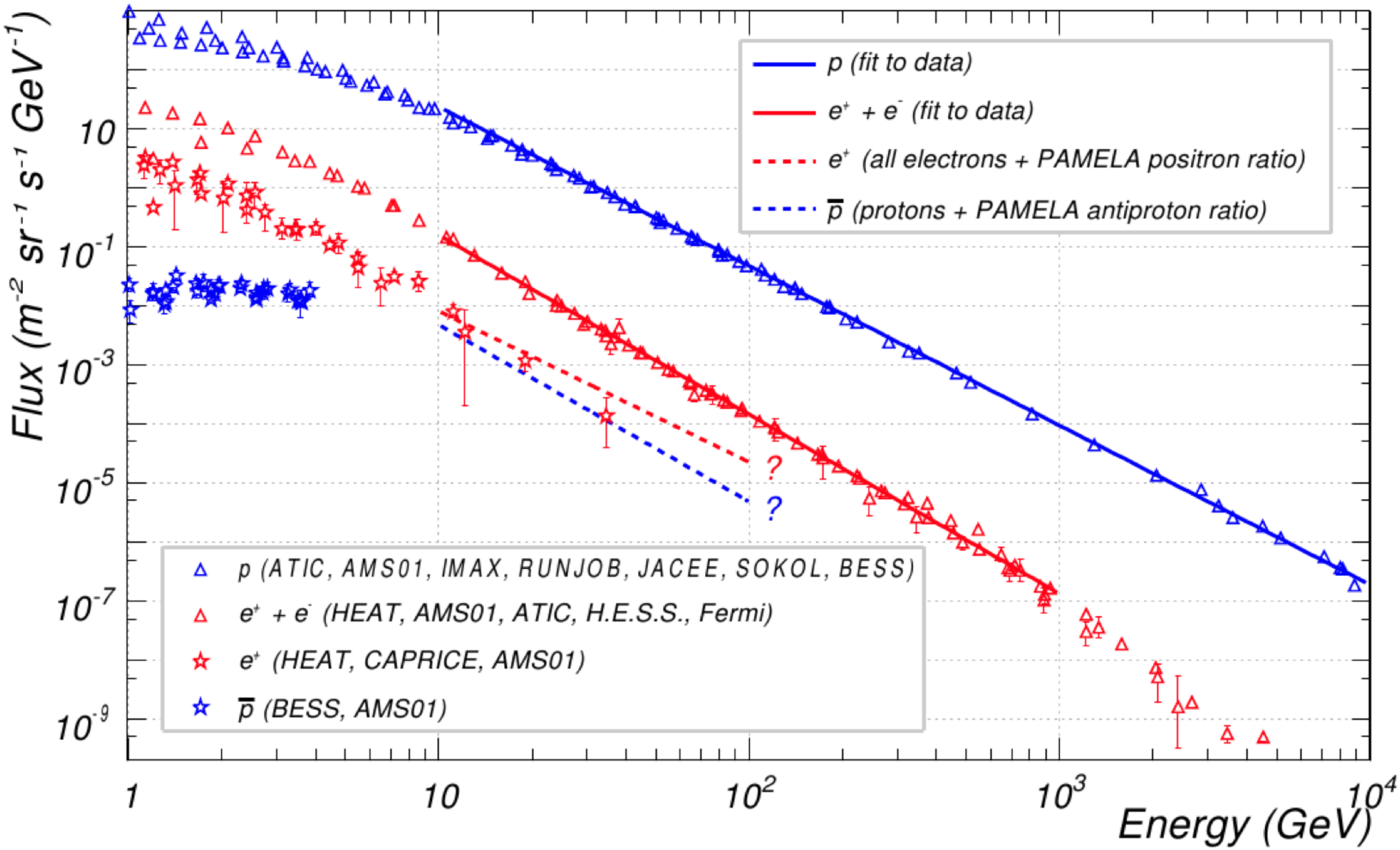
Below 20 GeV, we need to consider the shielding effect of the geo-magnetic field





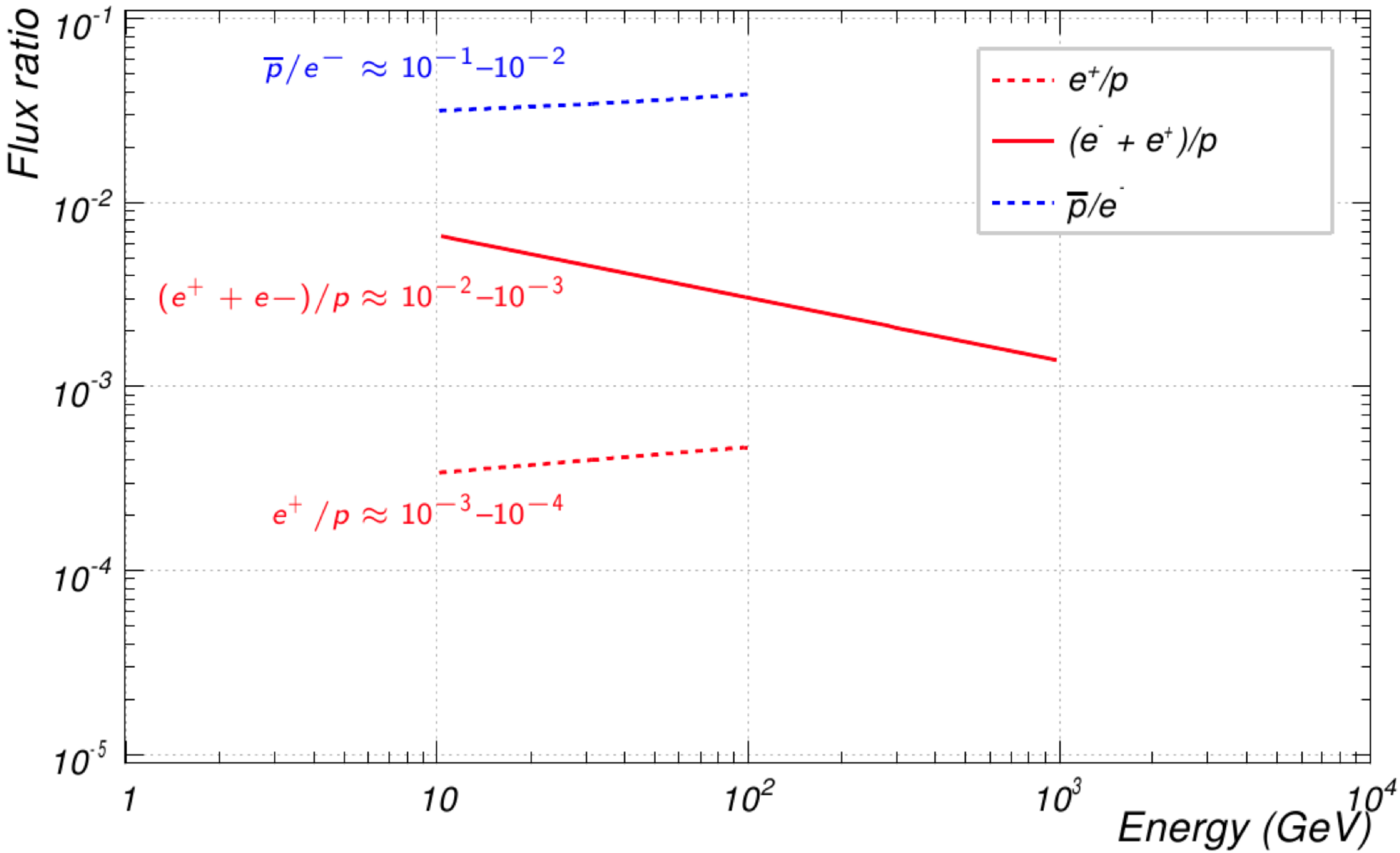
- Determine geomagnetic cutoff energy as a function of geomagnetic orbital coordinates (higher McIlwainL → lower cutoff energy)
- in each McIlwainL interval, measure spectrum for primary component above the cutoff, then recombine different spectra in the global spectrum
- BONUS: this can be used to measure the absolute energy scale of the LAT

Spectra: p^+, e^+e^-, e^+, p-bar

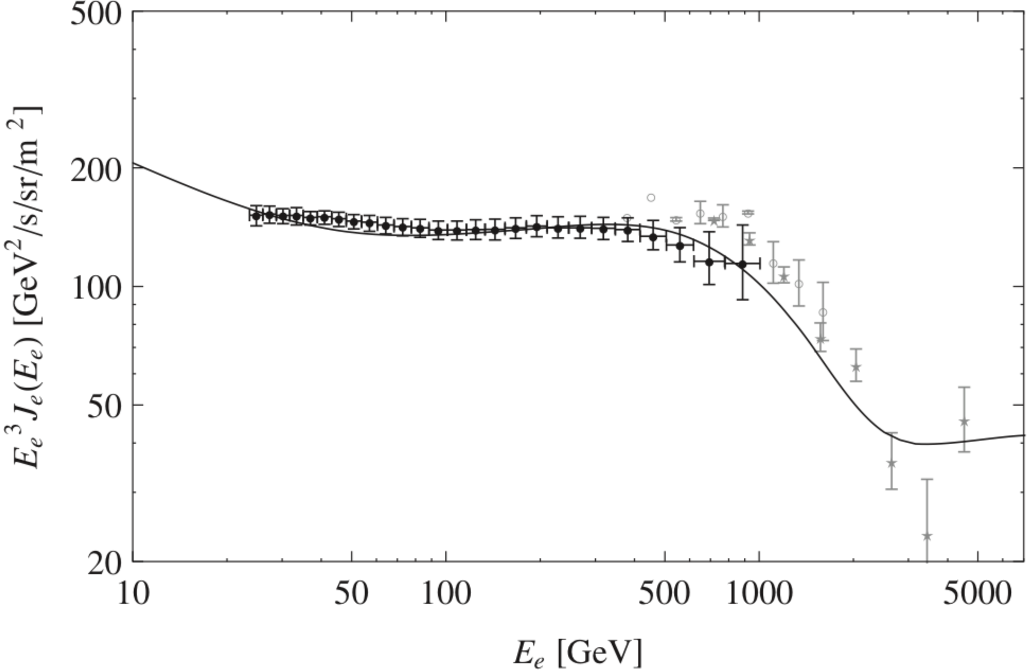


From A. Strong cosmic ray database and M. Pesce-Rollins PhD thesis

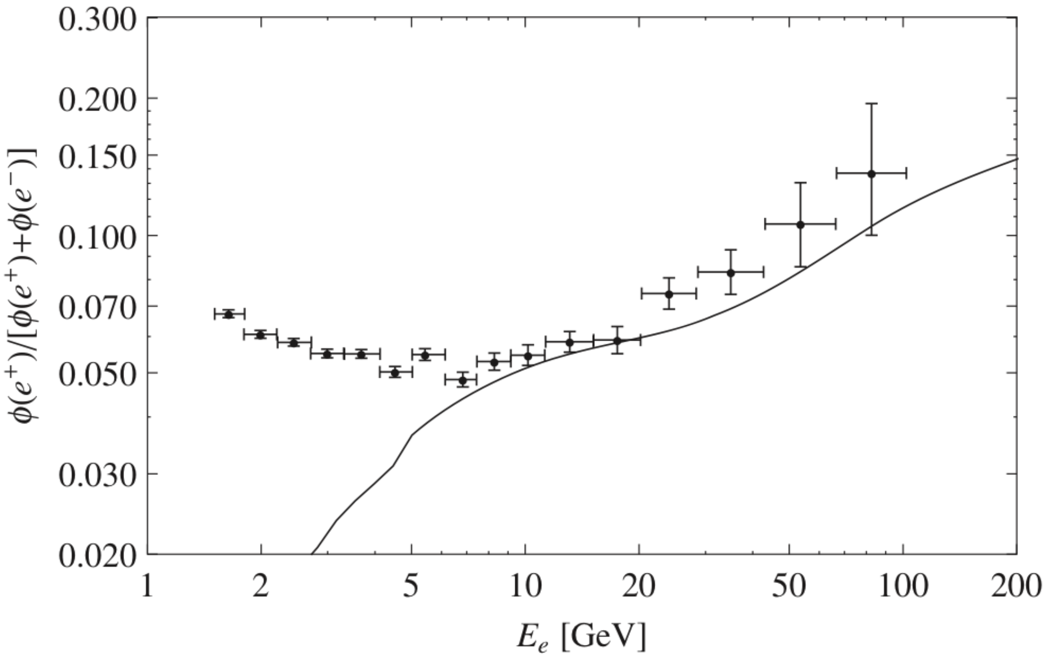
Proton flux 3-4 orders of magnitude larger than positron flux



From A. Strong cosmic ray database and M. Pesce-Rollins PhD thesis



Example interpretation with modified secondary production



- Diffuse Galactic gammas pair produce on stellar photon field
- Requires high starlight and gas densities
- Both could be high near primary sources (e.g. SNRs)

Stawarz et al., ApJ 710:236 (2010)