Fermi

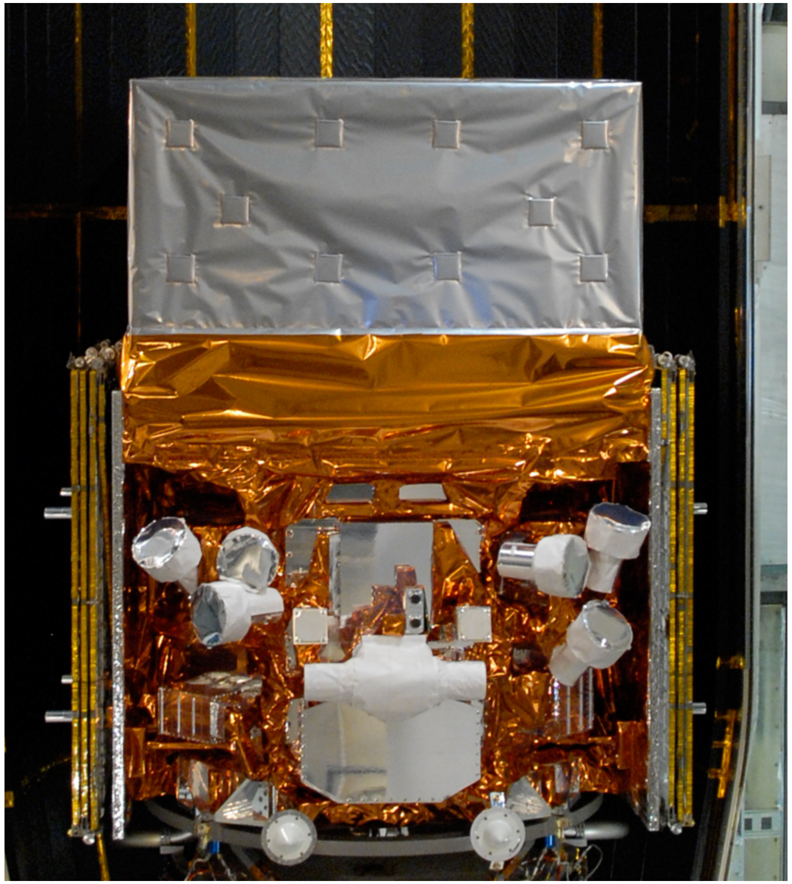
Gamma-ray Space Telescope

Studies of Cosmic Ray Electrons with the Fermi-LAT

L. Latronico
INFN-Pisa
On behalf of the Fermi Mission Team

Les Rencontres de Physique de la Vallèe d'Aoste
La Thuile, March 1 2010

The Fermi observatory



- Satellite gamma-ray telescope
  - Large Area Telescope (LAT)
    - 20 MeV – > 300 GeV
  - Gamma Burst Monitor (GBM)
    - 8 KeV – 40 MeV
- Key features
  - Huge field of view
    - 30 mins full sky every 3hrs
  - Huge energy range
- Milestones
  - 11 jun 2008 : launch
  - 04 aug 2008 : science ops start
  - 13 aug 2009 : γ data go public
  - 18 feb 2010 : 100B triggers

Fermi-LAT scientific highlights

- ❑ **Gamma-ray sky catalog**
  - **>1400 sources > 100 MeV**
  - **Known classes plus UNID**
- ❑ **Pulsar catalog**
  - **>60 γ-ray PSR, ~20 γ-ray only**
- ❑ **Active Galactic Nuclei**
  - **TeV cosmic accelerators**
- ❑ **Gamma-ray Bursts**
  - **Cosmological probes**
  - **Fundamental physics (LIV)**
- ❑ **Diffuse emission** ***(Knoedelseder talk)***
  - **Galactic model**
  - **EGB**
- ❑ **Cosmic Rays Electrons** ***(this talk)***

Science, 325 (2009)

Nature, 462 (2009)

65 refereed papers

66 Atels / 21 GCN circulars

Importance of a direct CRE measurement

- Probe CR models
  - Sources (including DM), interactions, propagation, diffusion
- Probe CR targets (ISM, ISRF)
  - Propagation and diffusion
  - Strong connection with diffuse gamma-ray radiation
- Probe nearby sources
  - limited electron lifetime within Galaxy
- Answers to long-standing questions and vast literature

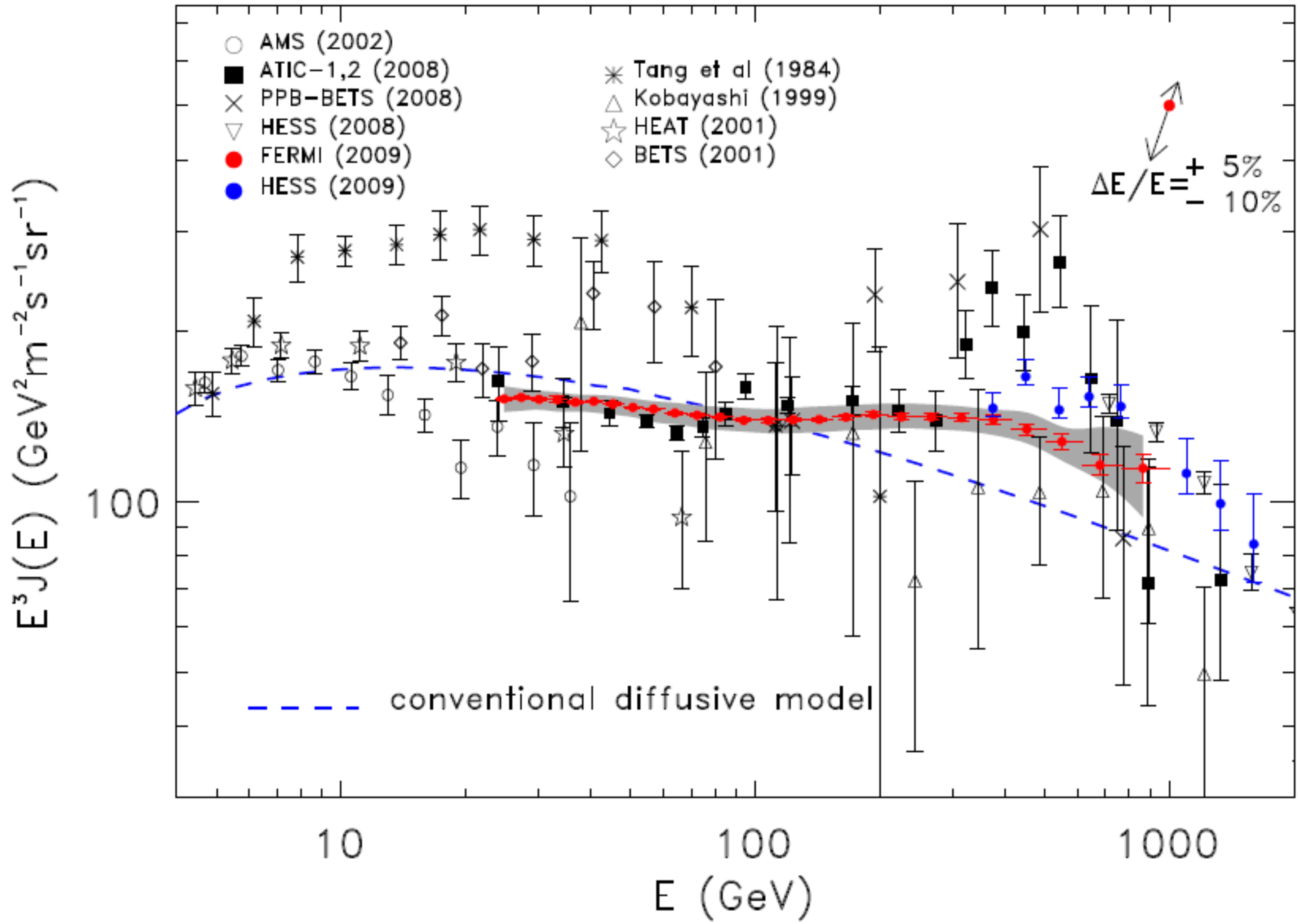
THE ASTROPHYSICAL JOURNAL, 162:L181–L186, December 1970

PULSARS AND VERY HIGH-ENERGY COSMIC-RAY ELECTRONS

C. S. SHEN*
Department of Physics, Purdue University, Lafayette, Indiana 47907
Received 1970 June 8; revised 1970 September 19

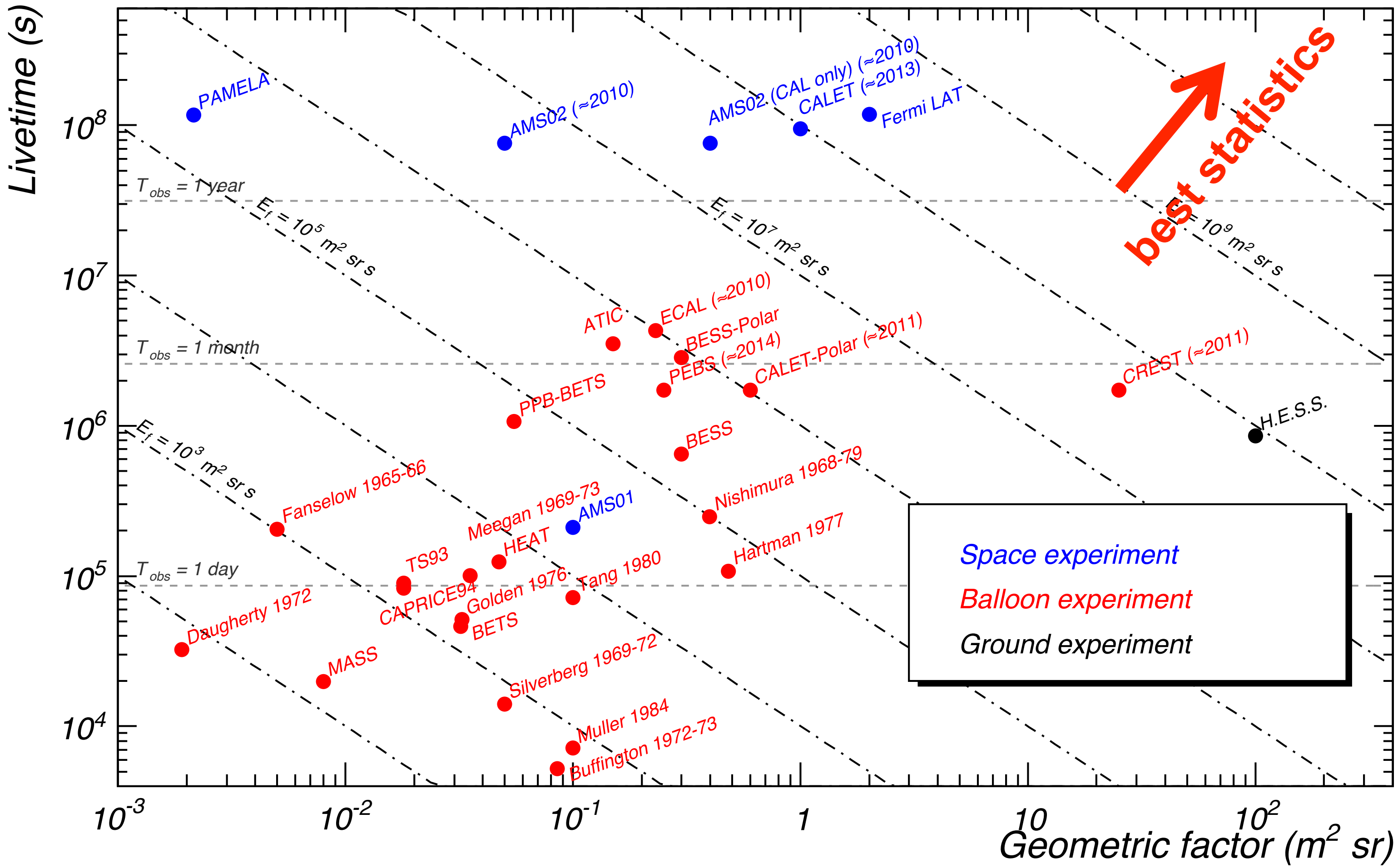
Selected for a Viewpoint in *Physics*
PRL **102,** 181101 (2009) PHYSICAL REVIEW LETTERS week ending 8 MAY 2009

Measurement of the Cosmic Ray $e^+ + e^-$ Spectrum from 20 GeV to 1 TeV



Fermi → hard CRE spectrum
PAMELA → positron excess → ***Cosmic Ray Lepton puzzle*** → **Several 100s articles**

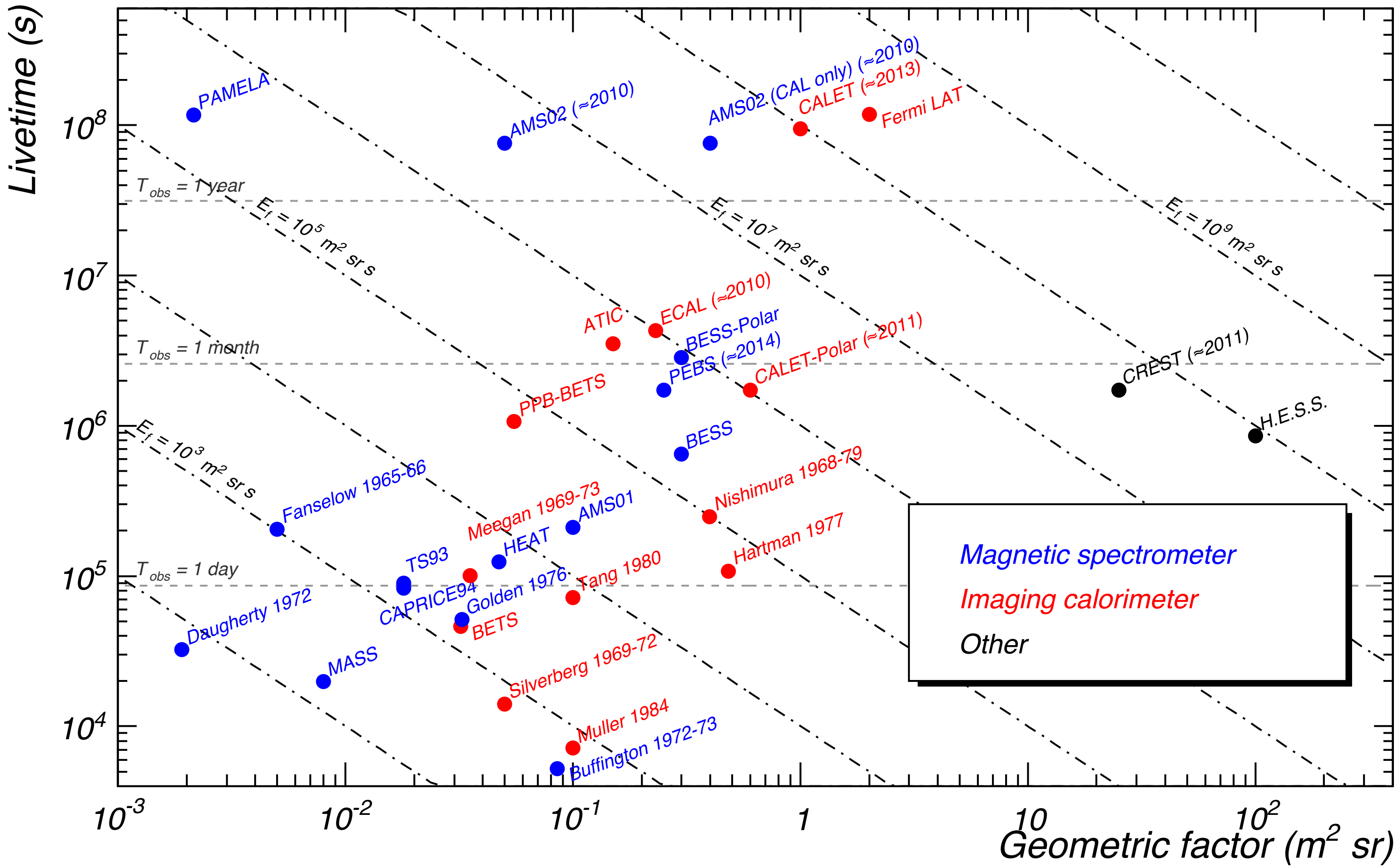
Fermi and the others



caveat1 – illustrative - 2x corrections possible

caveat2 - statistics is not enough

Fermi and the others



different techniques have different systematics

How the LAT detects electrons

Trigger and downlink

Very versatile and configurable

- **Triggering on ~ all particles that cross the LAT**
  - **Including electrons (8M/yr)**

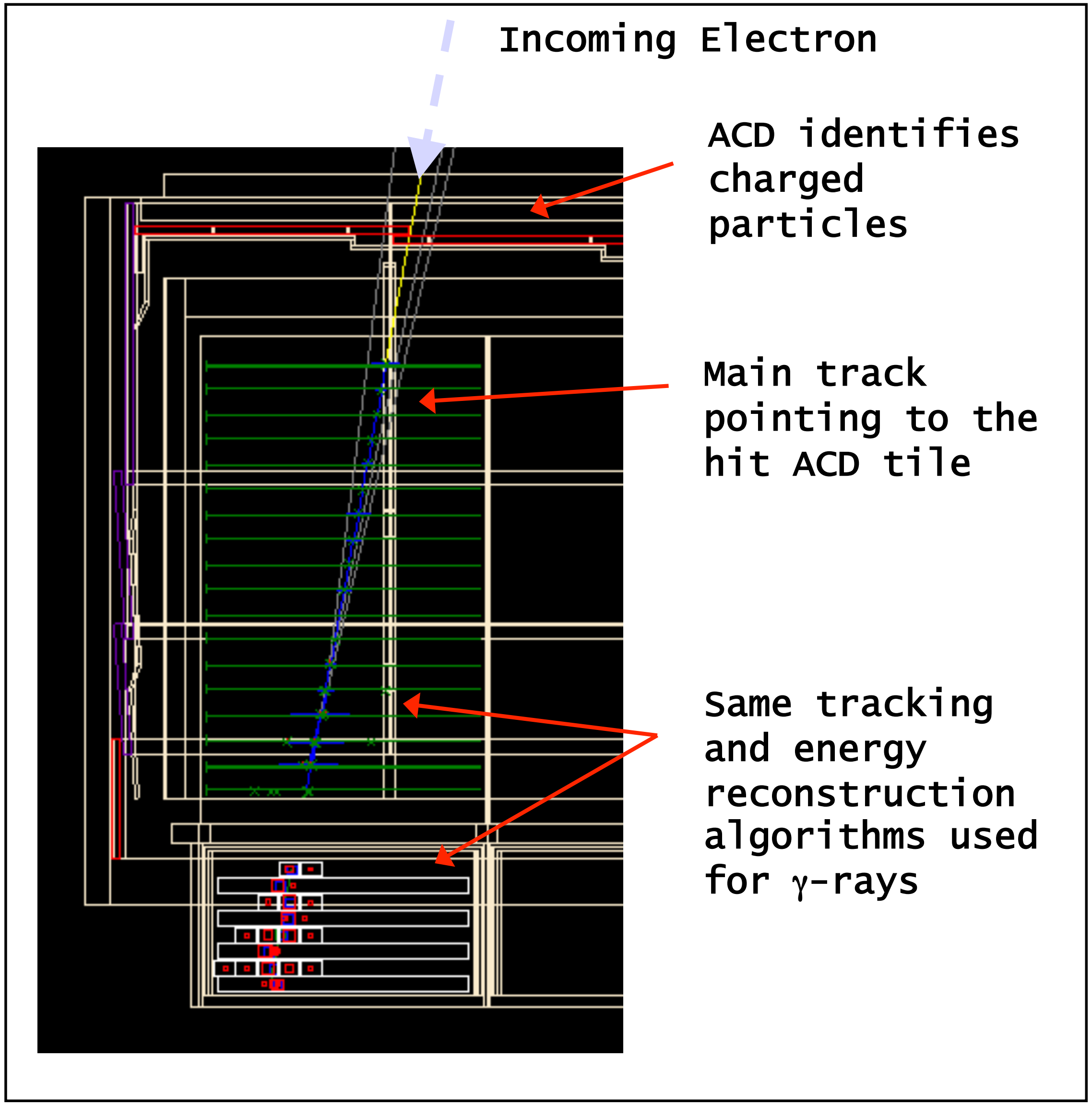
On board filtering to fit bandwidth

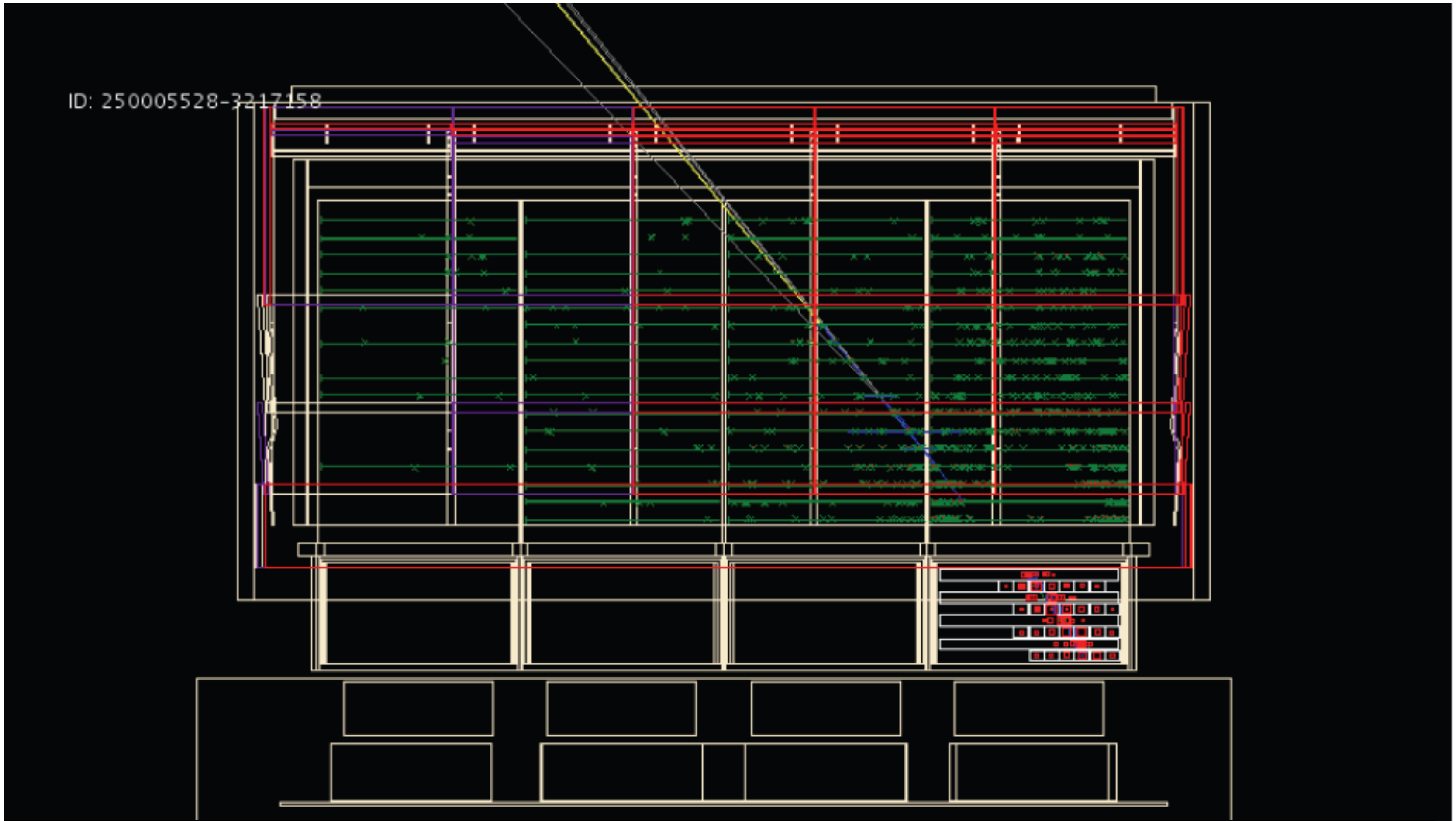
- **Remove many charged particles**
- **Keeps all events with more than 20 GeV in the CAL (HE)**
- **Prescaled (1:250) sample of unfiltered triggers (LE)**

Electron identification

The challenge is large proton background

- **Rejection power of $10^3 - 10^4$ required**
- **Can not separate electrons from positrons**
- **→ Dedicated high energy electron event selection**

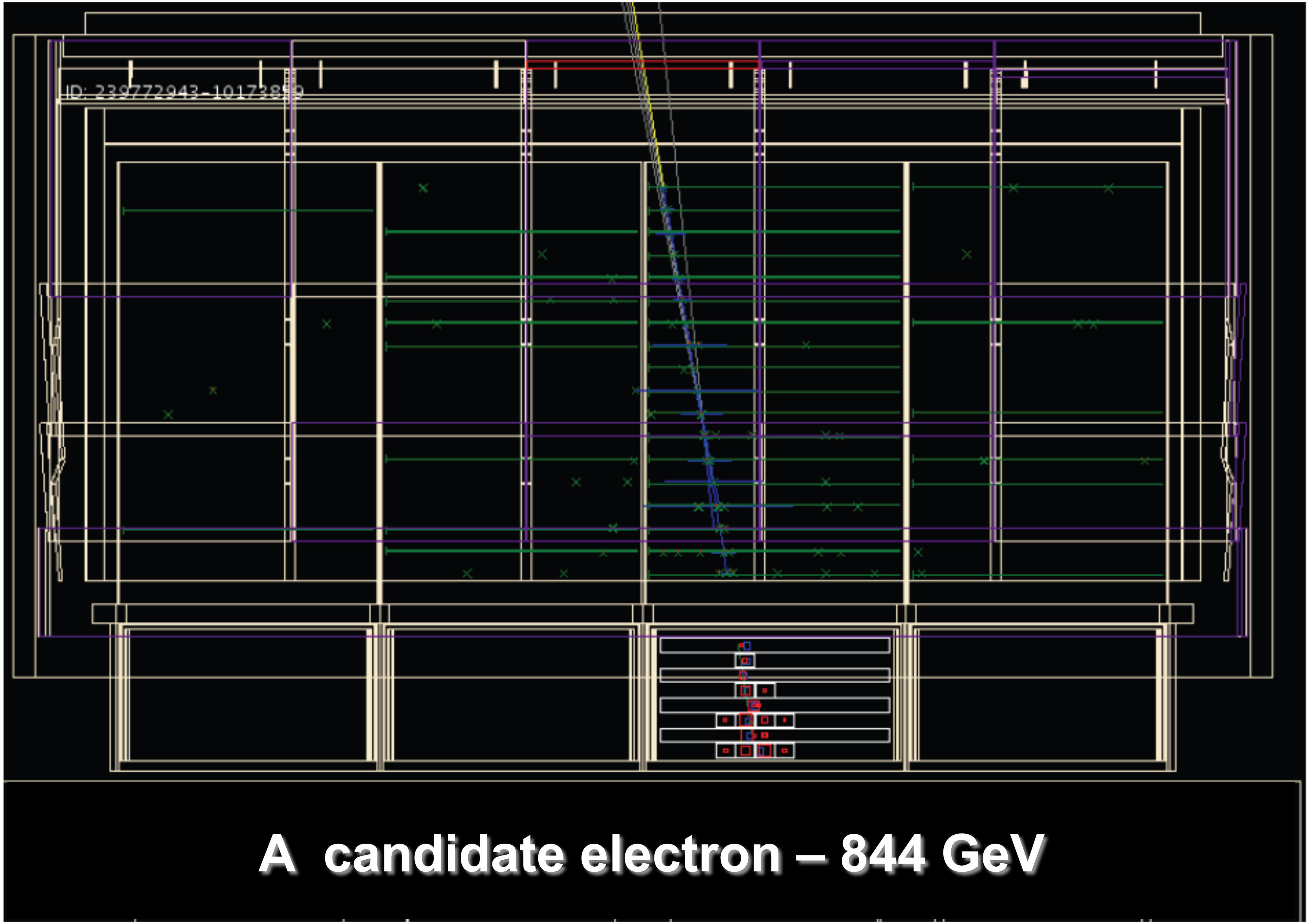




A candidate hadron event – raw energy > 800 GeV

CalEnergyRaw	8.228e+05
CTBBestEnergy	1.026e+06
CTBBestEnergyProb	0.146
TkrNumTracks	5
CalCsIRLn	10.9
CTBBestZDir	-0.387
CTBTKRHEEProb	N/A
CTBCALHEEProb	N/A
CalLRmsAsym	0.00419
CalTrSizeTkrT95	1022.6
CalTransRms	34.4
Tkr1CoreHC	1
Tkr1Hits	6
Tkr1ToTTrAve	0
AcdTotalEnergy	660.7
AcdTileCount	65

- **ACD: large energy deposit per tile**
- **TKR: small number of extra clusters around main track, large number of clusters away from the track**
- **CAL: large shower size, low probability of good energy reconstruction**



CalEnergyRaw
2.501e+05

CTBBestEnergy
8.443e+05

CTBBestEnergyProb
0.531

TkrNumTracks
5

CalCsIRLn
8.49

CTBBestZDir
-0.986

CTBTKRHEEProb
0.924

CTBCALHEEProb
0.733

CalLRmsAsym
0.0656

CalTrSizeTkrT95
9.73

CalTransRms
23.8

Tkr1CoreHC
29

Tkr1Hits
35

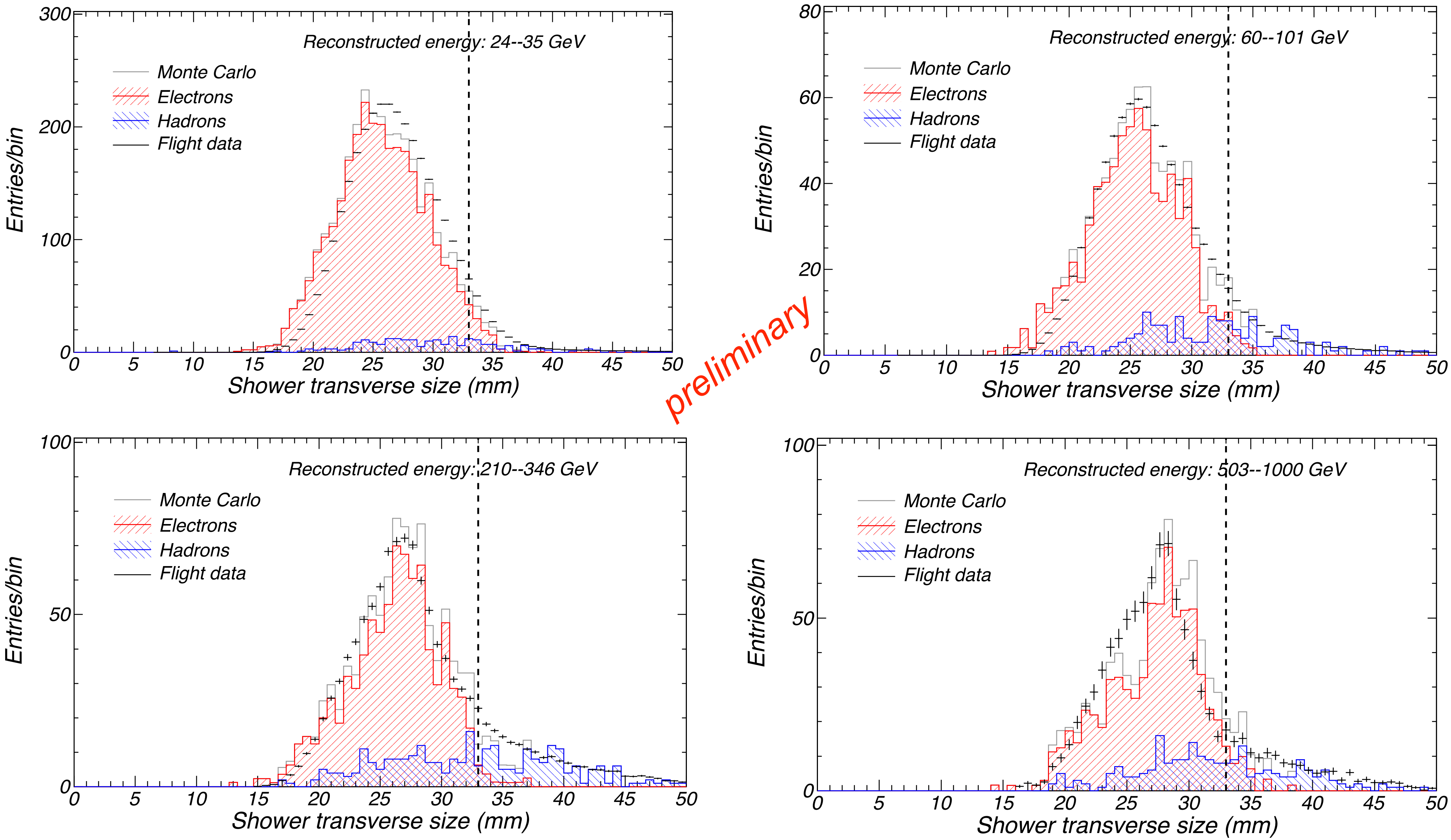
Tkr1ToTTrAve
5.40

AcdTotalEnergy
8.99

AcdTileCount
20

- **ACD: few hits in conjunction with track**
- **TKR: single clean track, extra clusters around main track clusters (preshower)**
- **CAL: clean EM shower not fully contained in CAL**

Shower size data-MC comparison vs energy

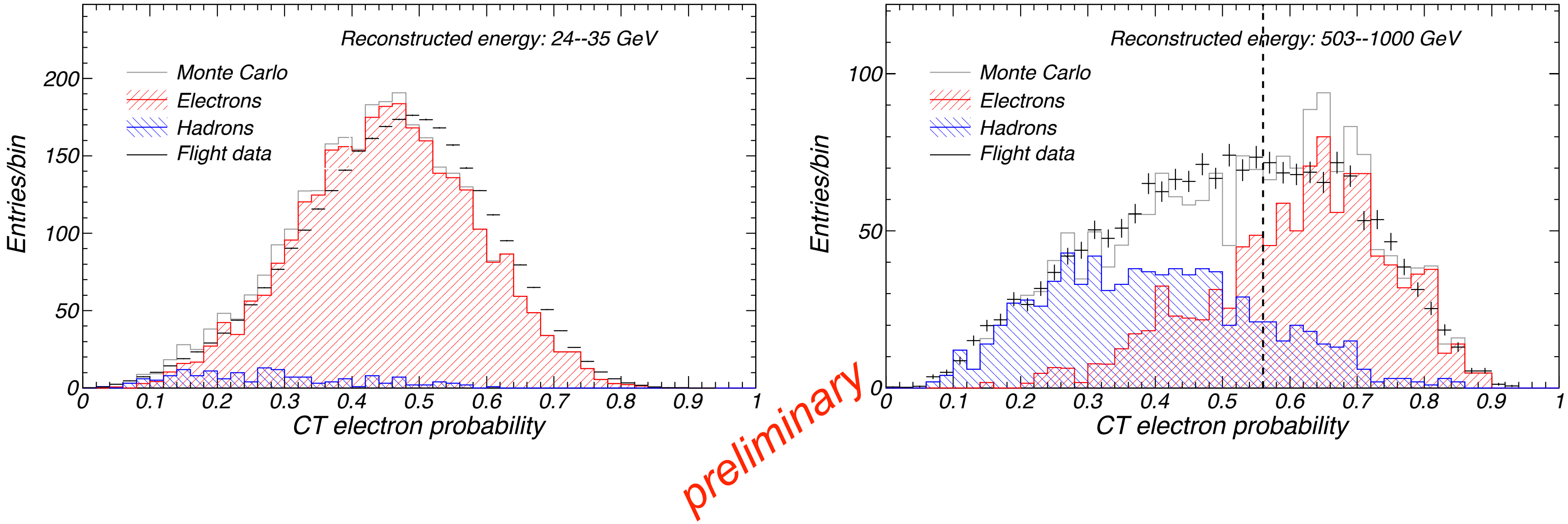


Good agreement over whole spectrum
Trade-off residual background with systematics

HE event selection – cutting on CT variable

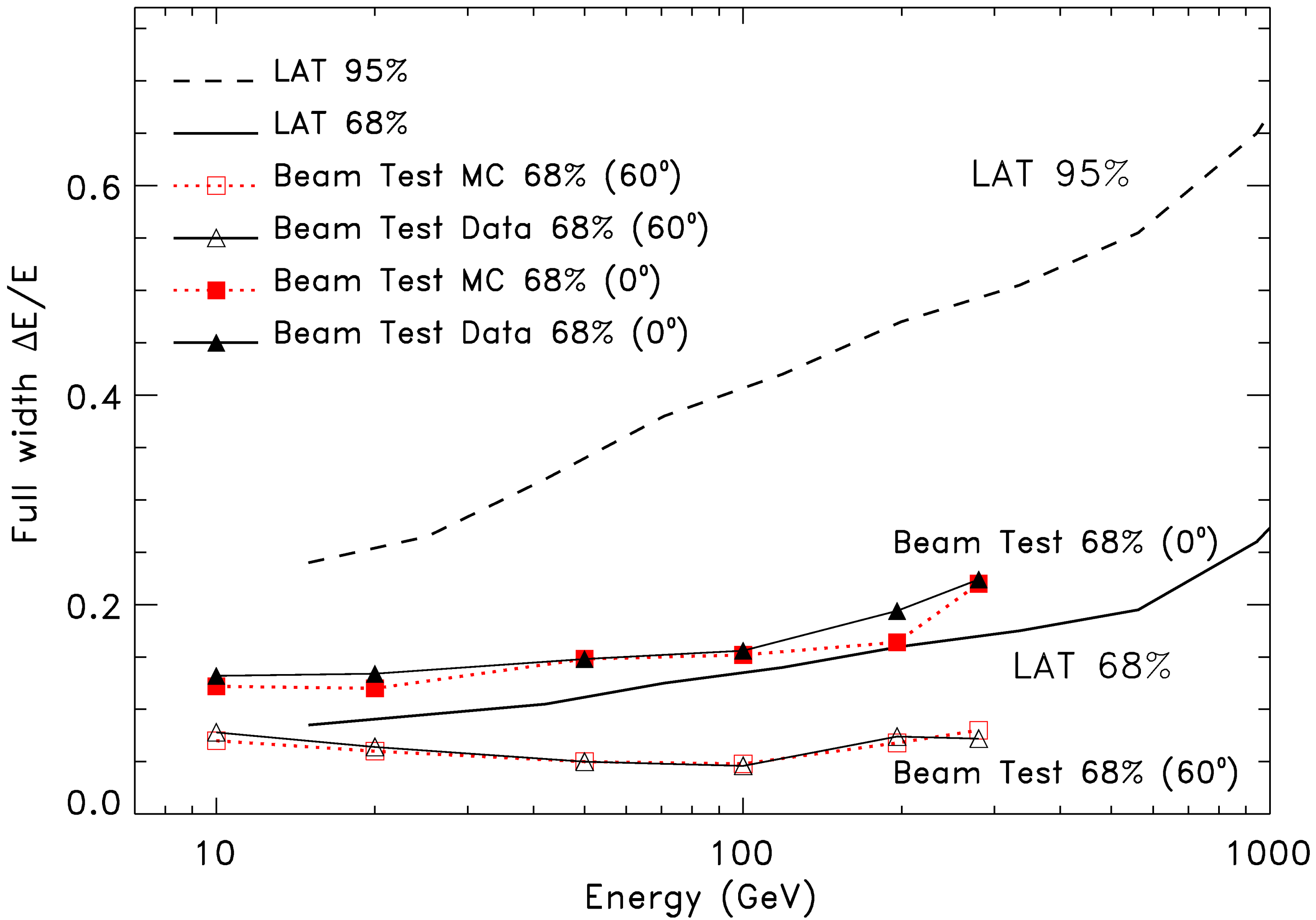
Energy dependent selection on combined electron probability from CAL and TKR probabilities

$$P^e_{comb} = sqrt(p^e_{tkr} \times p^e_{cal})$$



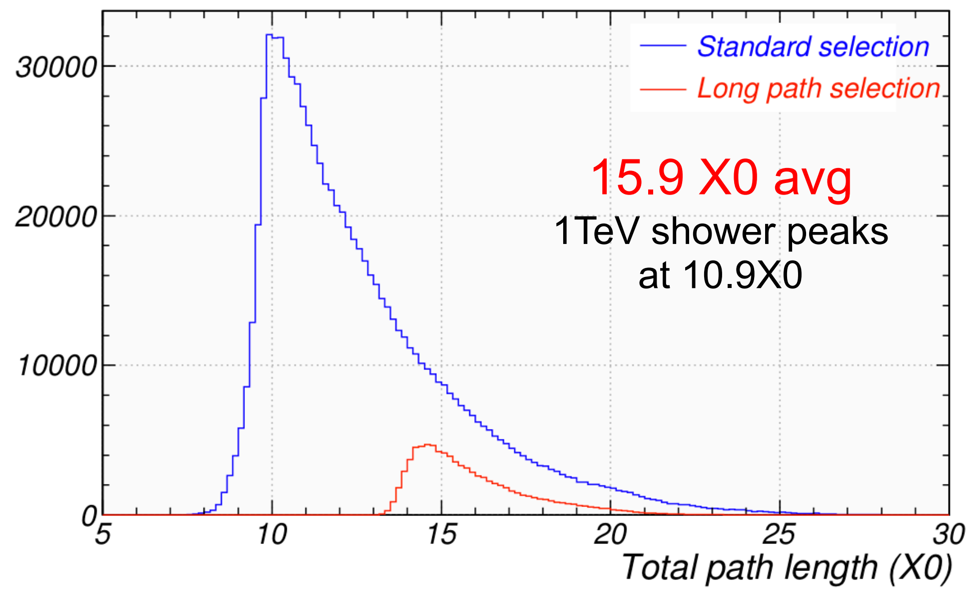
Good agreement over whole spectrum no CT cut need at low energies

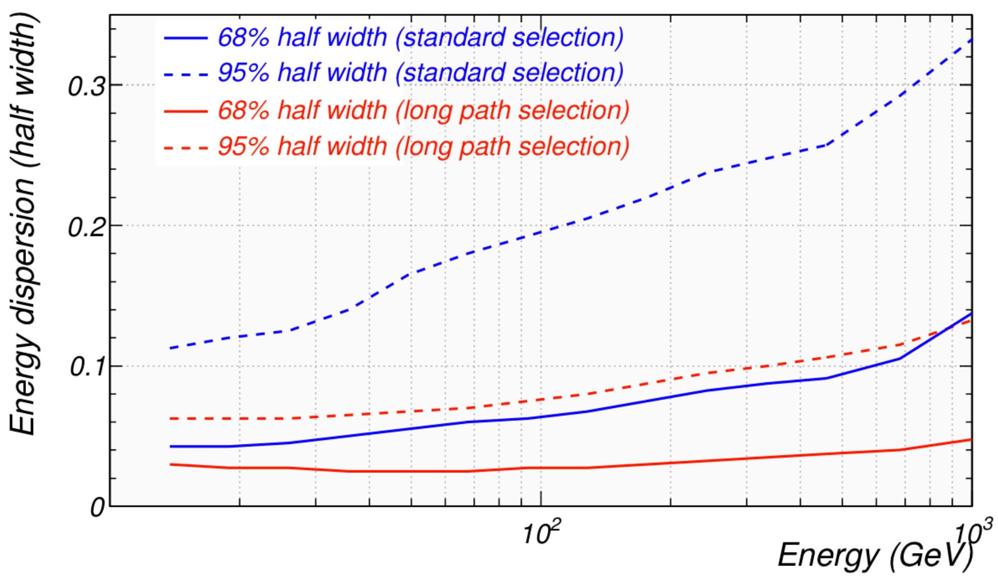
Energy resolution – MonteCarlo vs BT electron data



Energy resolution checks – High X0 events

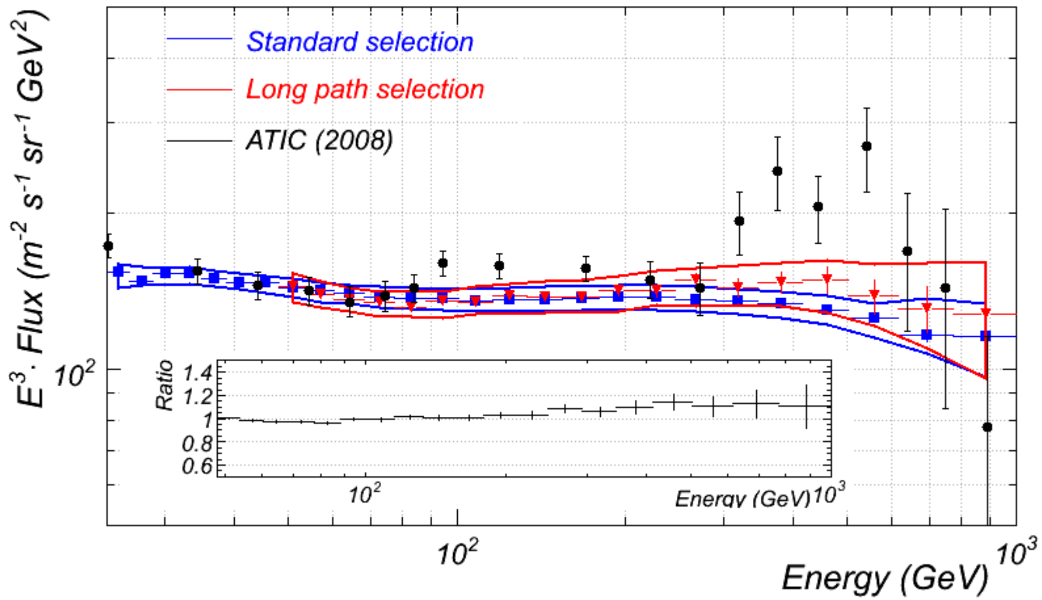
- ❑ Critical for high energies
  - – Shower leakage from CAL
- ❑ Select subsample of events with long path-length (HI-X0)
  - – X0>13
    - – 12 in CAL + minimum track length in TKR + events contained in a single CAL module
- ↑ Energy resolution X ~ 2 – 4
  - – Down to 5% at 1 TeV (68% containment half-width)
- ↓ Instrument acceptance to ~ 5% of standard and limited to a specific portion of instrument phase space
  - – Much higher systematics



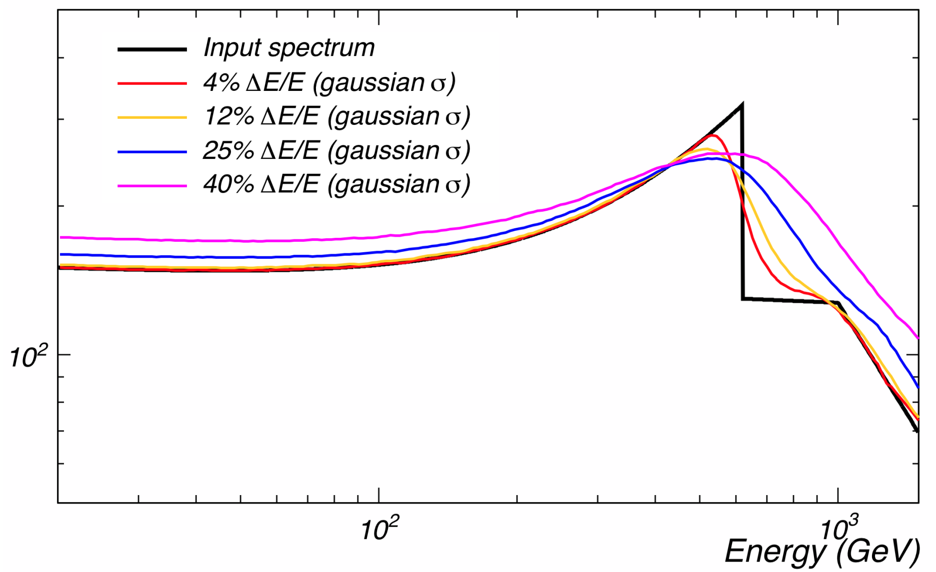


Comparison of standard and High-X0 spectra

- Consistent within their own systematics



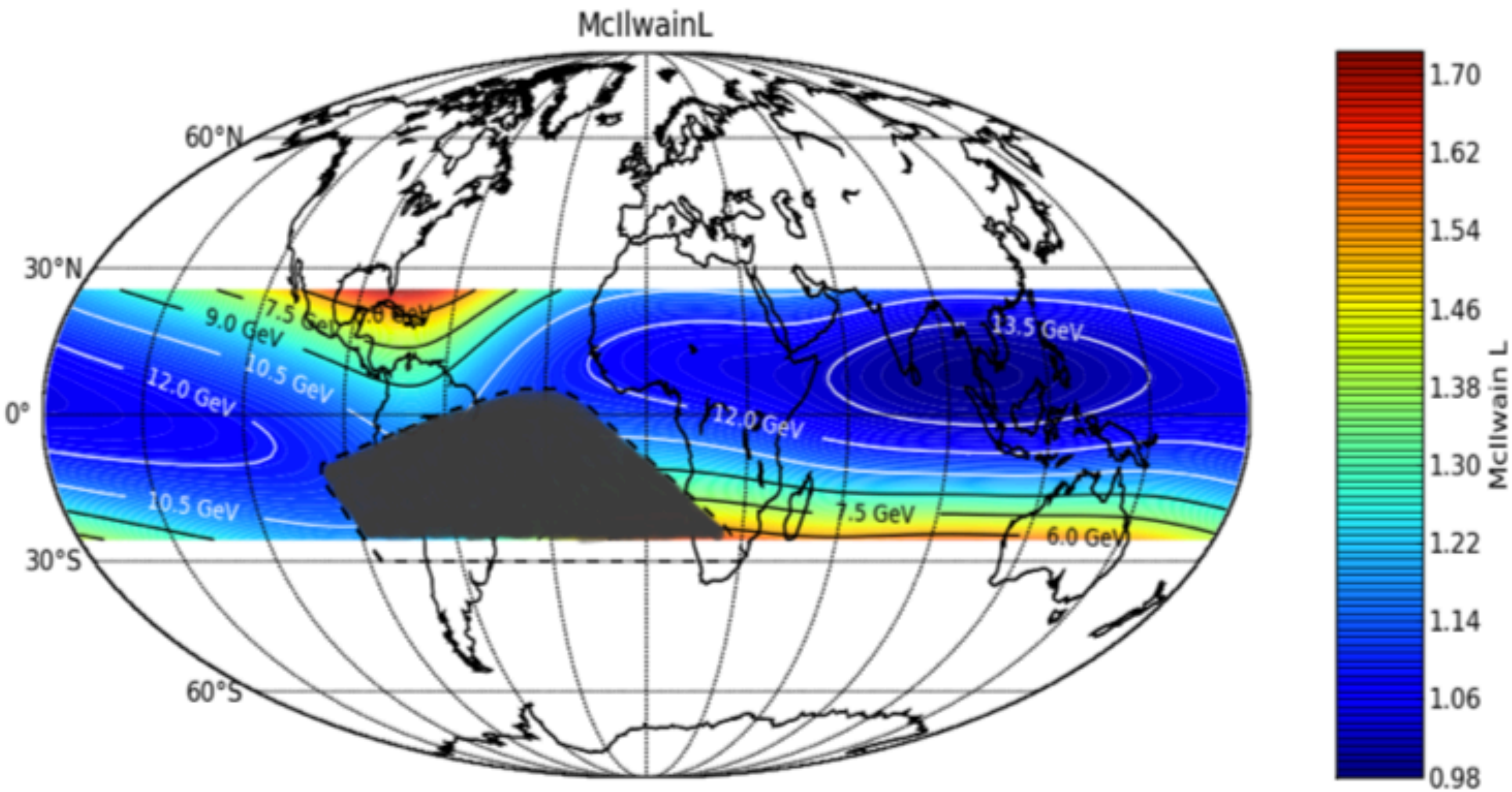
- already demonstrated by simulation of LAT response to spectral features with artificially worsened resolution



➔ the LAT energy resolution is adequate to detect prominent spectral features

➔ the Fermi spectrum is NOT dependent on the energy resolution of the bulk of the events

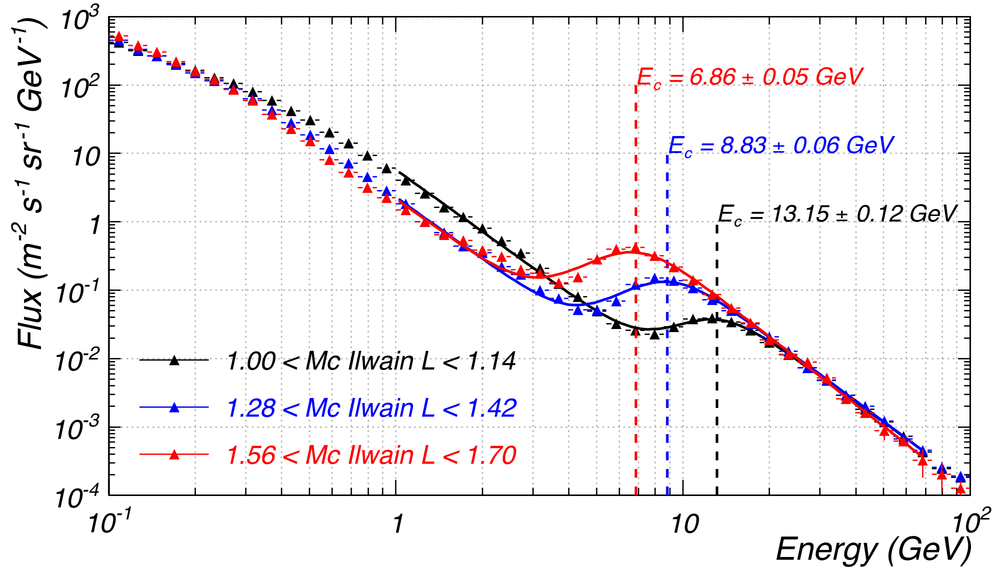
Extension to low energy measurements

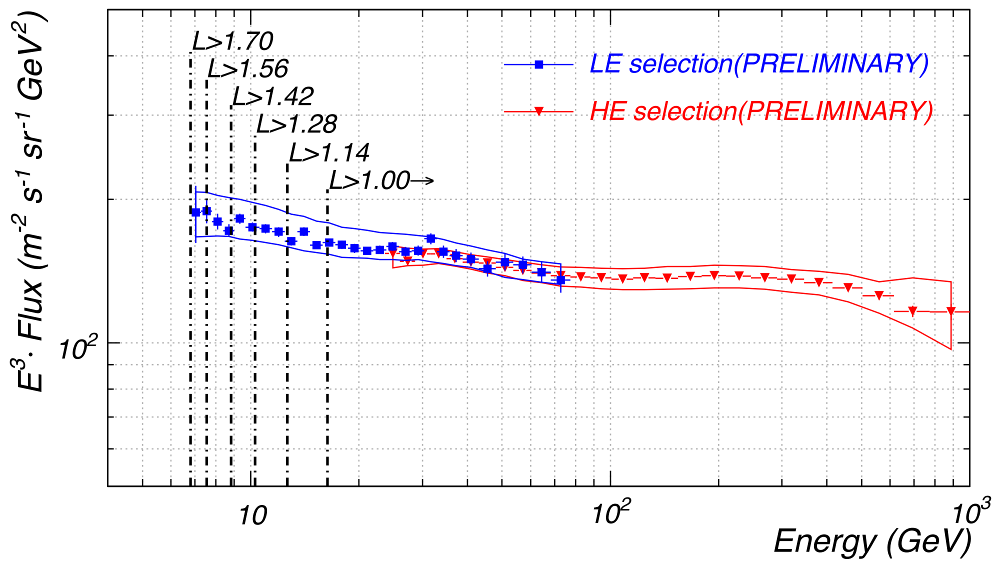


~ 7 GeV is the natural lower limit

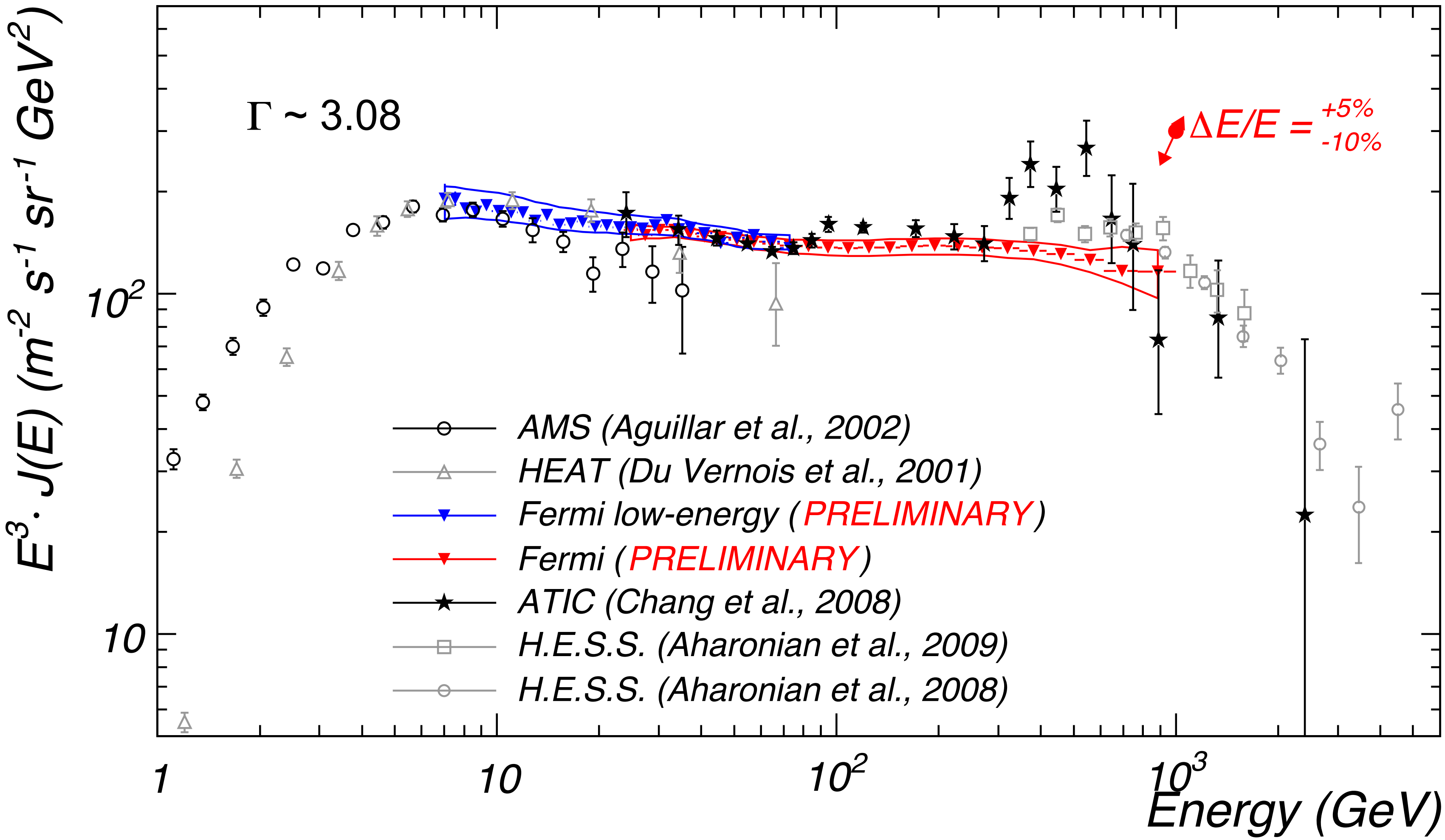
Extension to low energy measurements

- Determine geomagnetic cutoff energy as a function of geomagnetic orbital coordinates
  - Higher McIlwainL, lower cutoff energy
- Measure spectrum for primary component above cutoff
- Recombine spectra into global spectrum

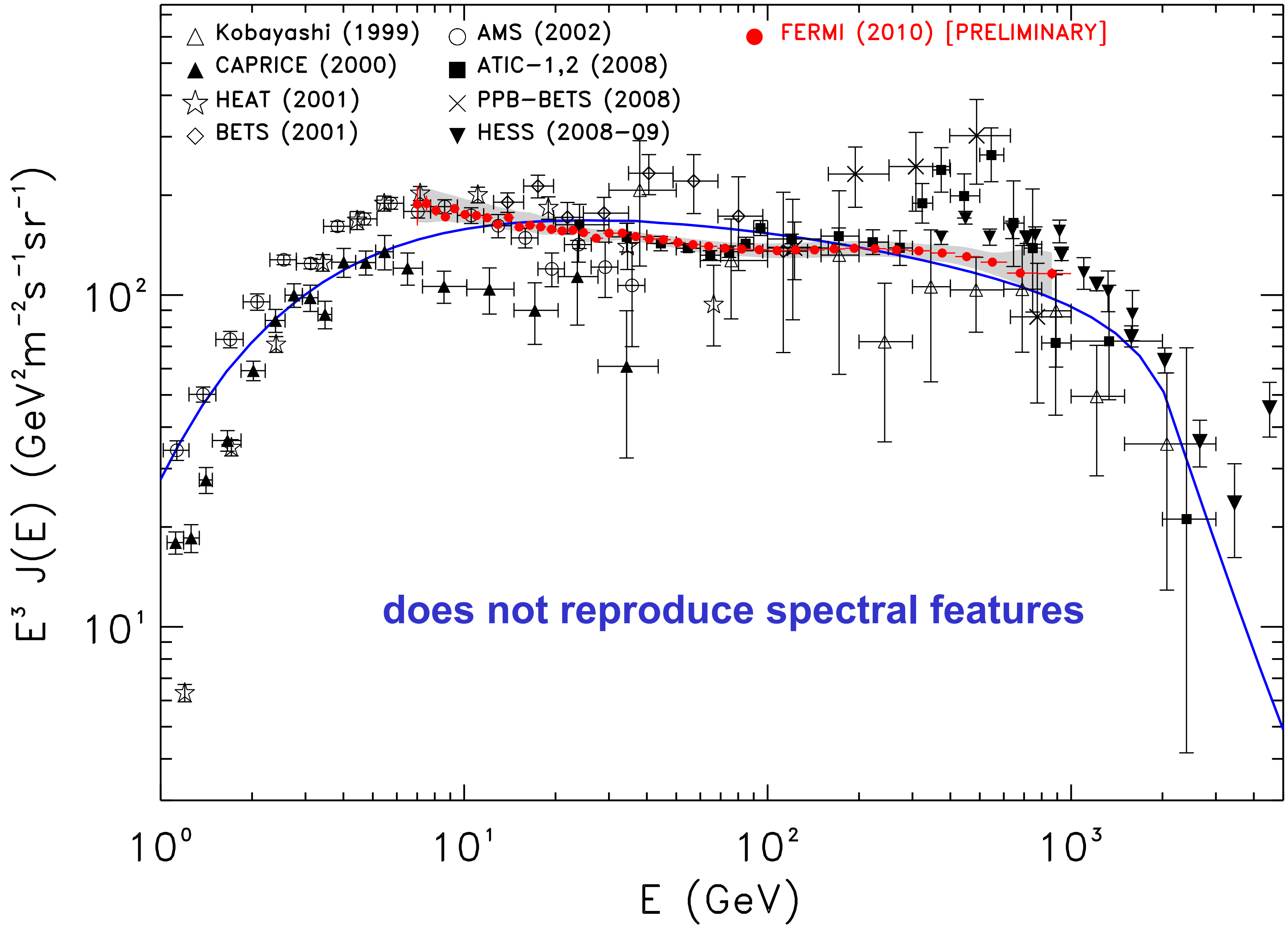




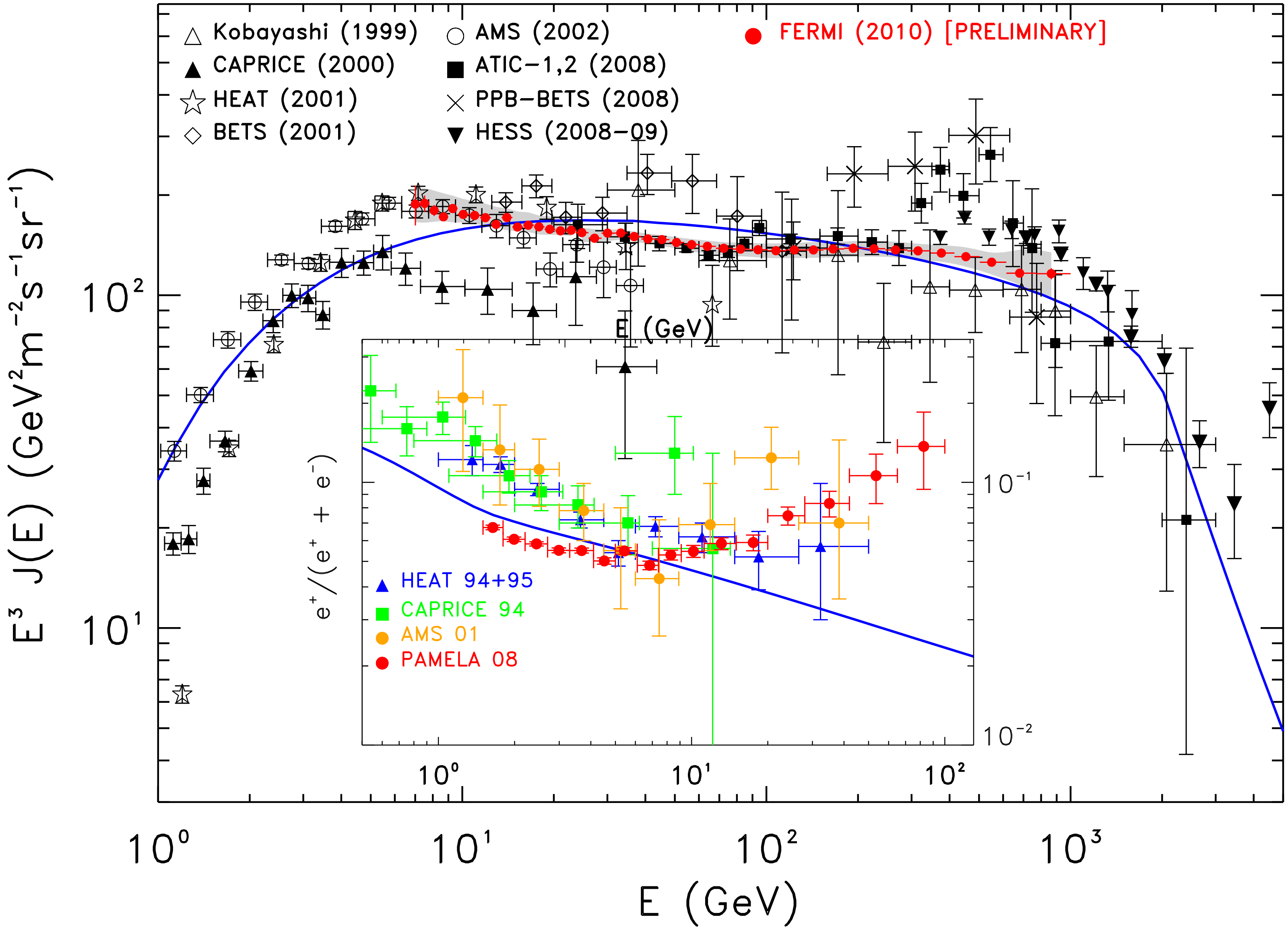
The Fermi CRE spectrum as of Nov. 2009



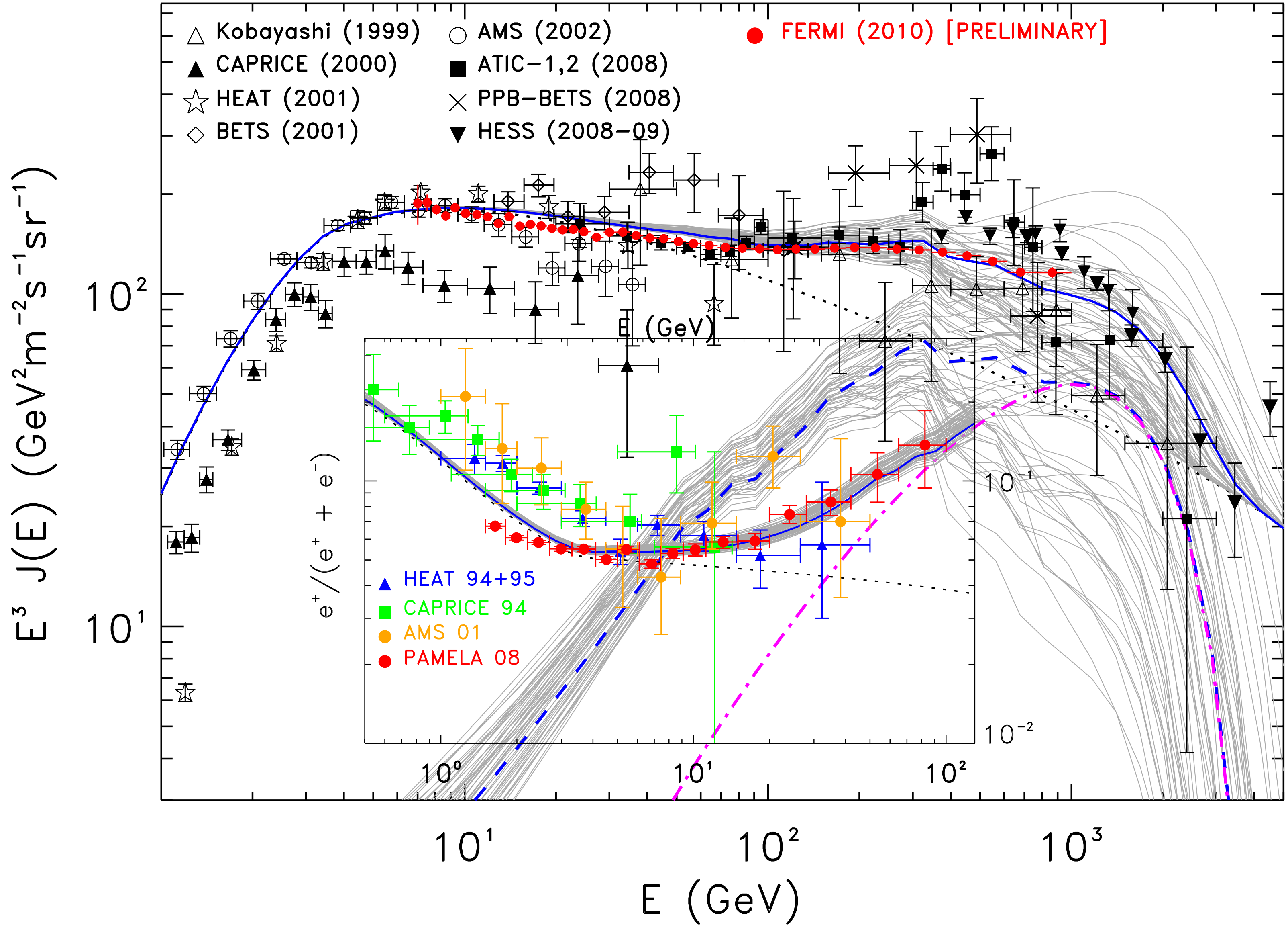
Possible interpretations – diffusive scenario



Diffusive scenario, CRE and positron fraction

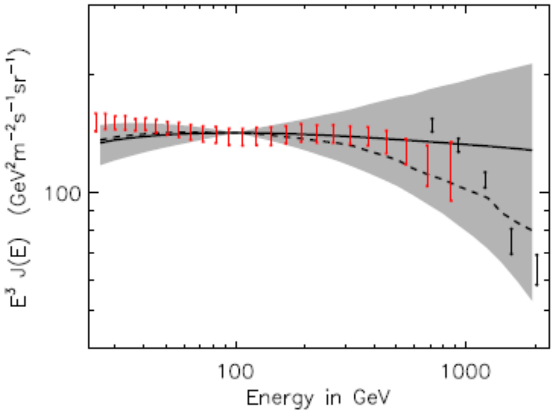


A secondary local CRE source? Pulsar?



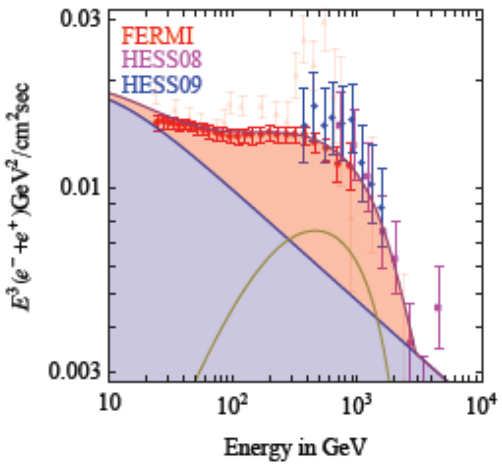
Other possible interpretations? Many !

1) Source stochasticity



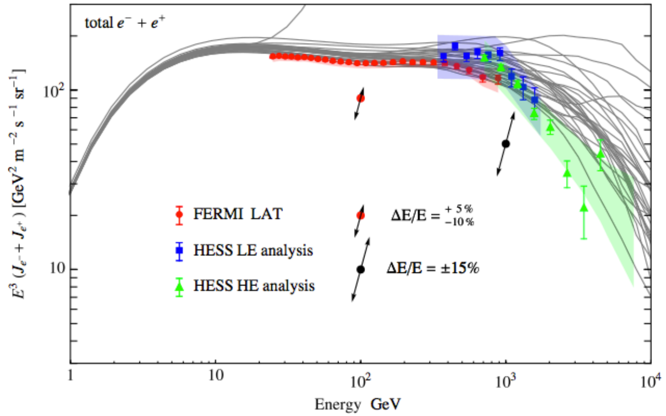
Grasso et al. arXiv 0905.0636

2) Dark Matter



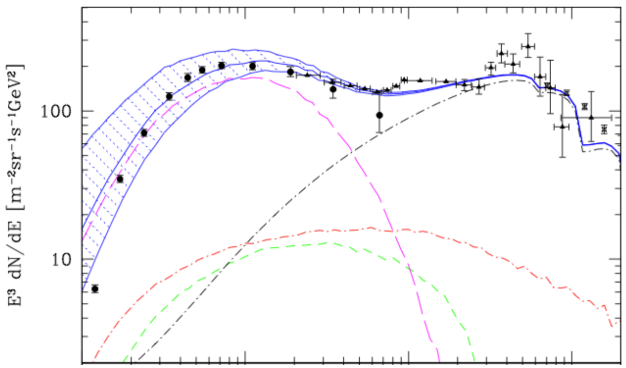
Strumia et al. arXiv 0905.0480

3) Secondary CR acc.



Blasi arXiv 0903.2794
Ahlers et al. arXiv 0909.4060

4) SNR inhomogeneity



Piran et al. arXiv 0902.0376

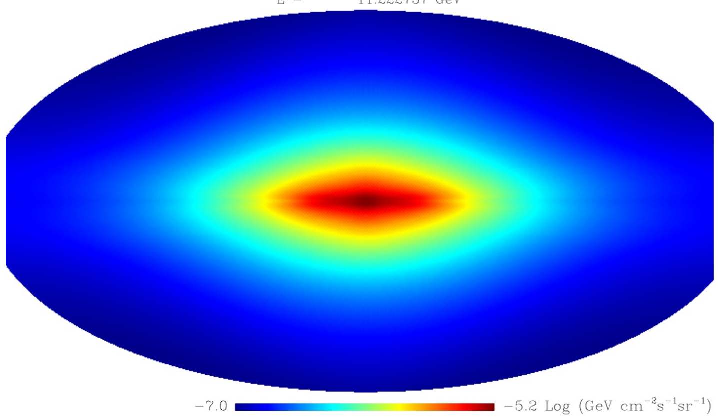
But with specific signatures

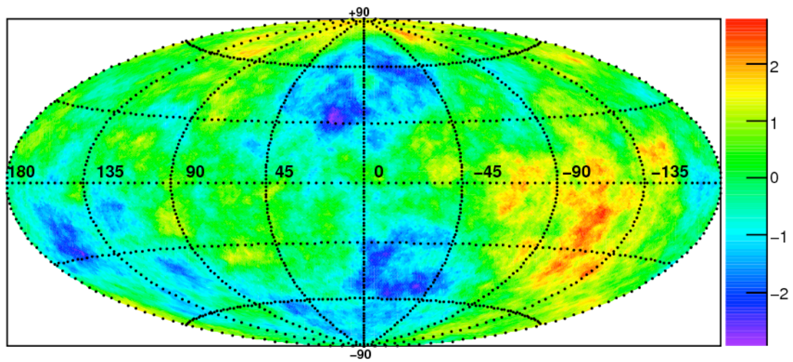
1. Spectral features
2. Excess in diffuse gamma ray emission
3. Rising nuclei ratio (i.e. B/C)
4. Falling positron ratio above 100 GeV

Models Discriminants from Fermi

- **Diffuse gamma-ray emission**
  - **Spectrum**
    - **IC excess from lepton excess**
  - **Shape**
    - **More spherical distribution for DM wrt PSR**
- **Measure CRE anisotropies**
  - **Tracer of local sources of electrons**
    - **Currently no evidence for anisotropy**

IC diffuse gammas from DM halo – GALPROP sim





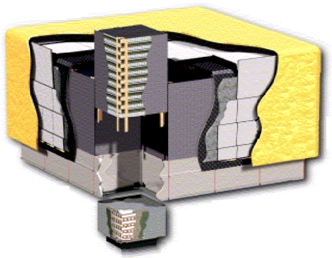
CRE anisotropy pre-trial significance map

Conclusions and prospects

- Fermi measures CR electrons from 7 GeV to 1 TeV
  - Robust event selection
  - Adequate energy resolution
- Spectral index is hard ($\Gamma \sim -3$) and requires revision of simplistic diffusive scenarios
  - Focus on source
    - Primary distribution
    - Extra component viable: PSR, DM
    - Acceleration of secondaries
- Additional observables are crucial
  - Fermi
    - diffuse gamma-ray, anisotropies
  - Spectrometers (PAMELA, AMS)
    - Positron, proton, nuclei ratios

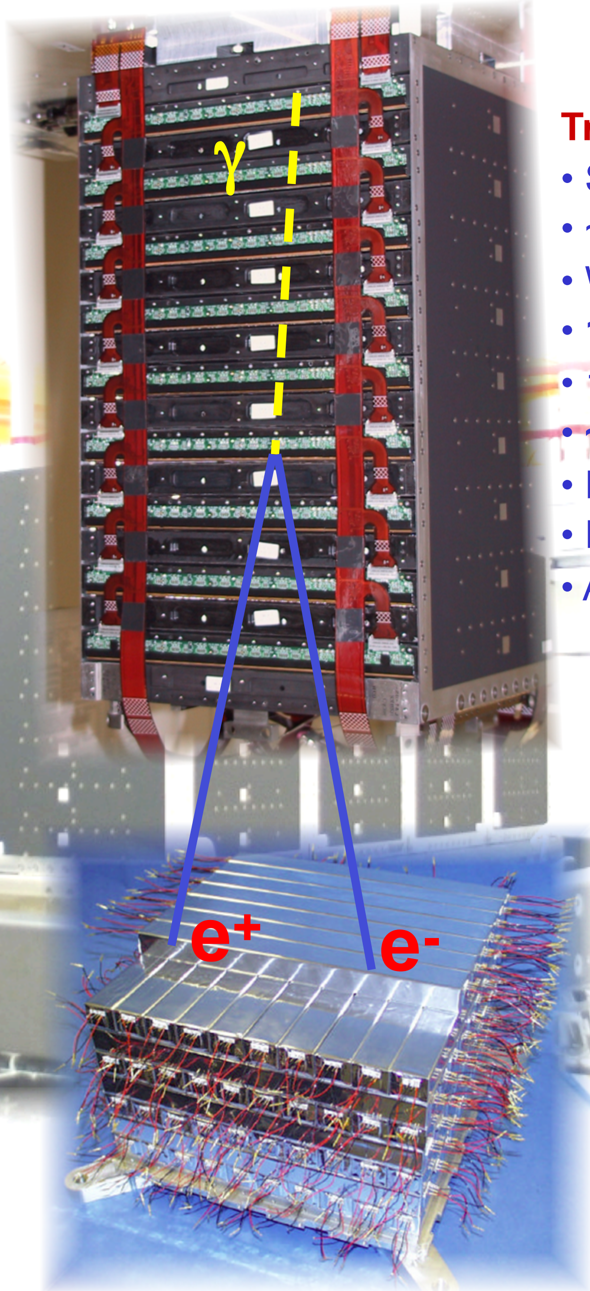
BACKUP

Overview of the Large Area Telescope



LAT:
- modular - 4x4 array
- 3ton – 650watts

Anti-Coincidence (ACD):
- Segmented (89 tiles + 8 ribbons)
- Self-veto @ high energy limited
- **0.9997 detection efficiency**

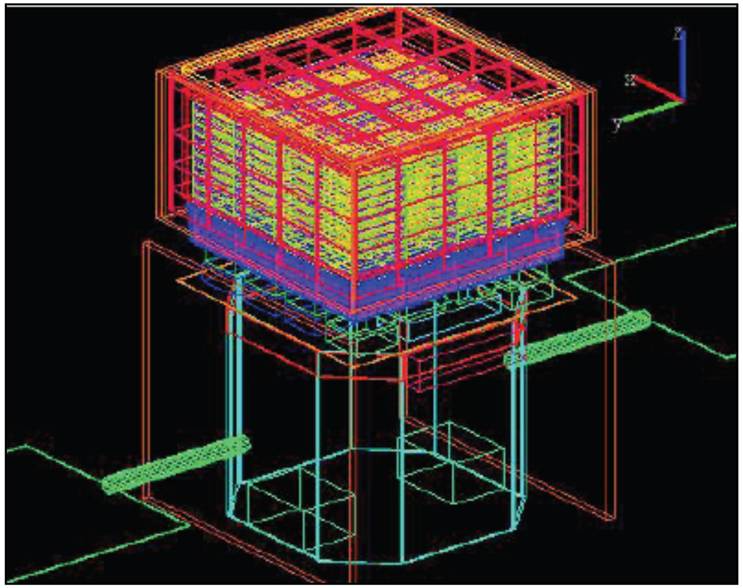


Tracker/Converter (TKR):
- Si-strip detectors
- ~80 m^2 of silicon (total)
- W conversion foils
- **1.5 X0 on-axis**
- 18XY planes
- **~10^6 digital elx chans**
- Highly granular
- High precision tracking
- Average plane PHA

Calorimeter (CAL):
- 1536 CsI(Tl) crystals
- **8.6 X0 on-axis**
- large elx dynamic range (2MeV-60GeV per xtal)
- **Hodoscopic (8x12)**
- Shower profile recon
- leakage correction
- EM vs HAD separation

Event Simulation and Reconstruction

- Very accurate Monte Carlo
  - >45k active volumes
  - Geant4 optimized physics
- Simulation is key for
  - Reconstruction tuning
  - Event selection and performance
  - Estimate residual contamination

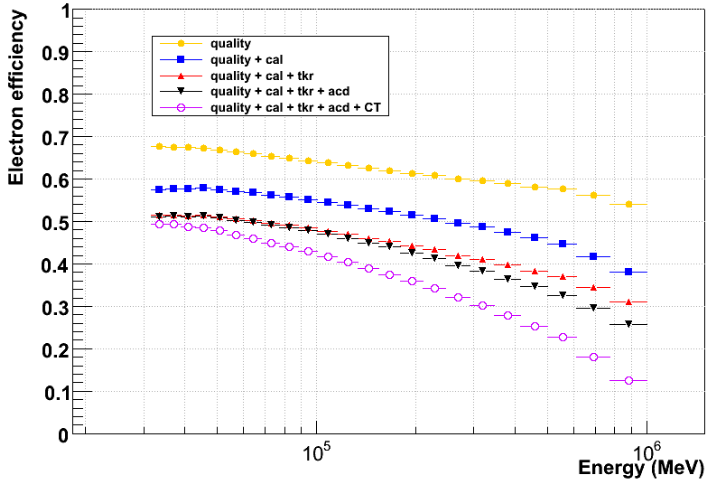


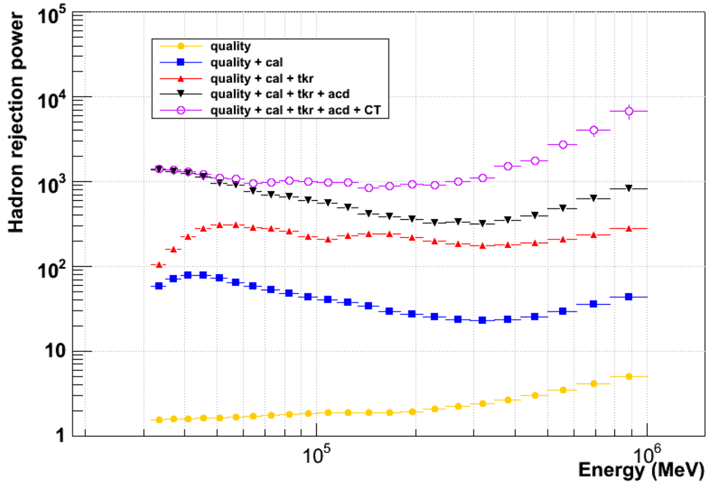
- Full subsystems reconstruction
  - ACD - PH analysis
  - TKR - powerful tracking
  - CAL - 3D shower profile recon, handles cracks and saturation

Event Selection, Global Performance and Systematics

- Event selection tuned on simulation and validated with real data
  - 100s variables describing key event topology in each subsystems
    - Prefilters +
    - Classification Trees (CT) optimizing electron efficiency and hadron rejection
- Peak geometry factor 2.8 m^2sr at 50 GeV, rejection power up to $1:10^4$ at 1 TeV
- Systematic uncertainties kept below 20%
  - Data-MC disagreement and event selection effect on acceptance <20%
  - Proton spectrum <20%
  - Energy calibration uncertain (+5%,-10%)→ rigid shift of the spectrum

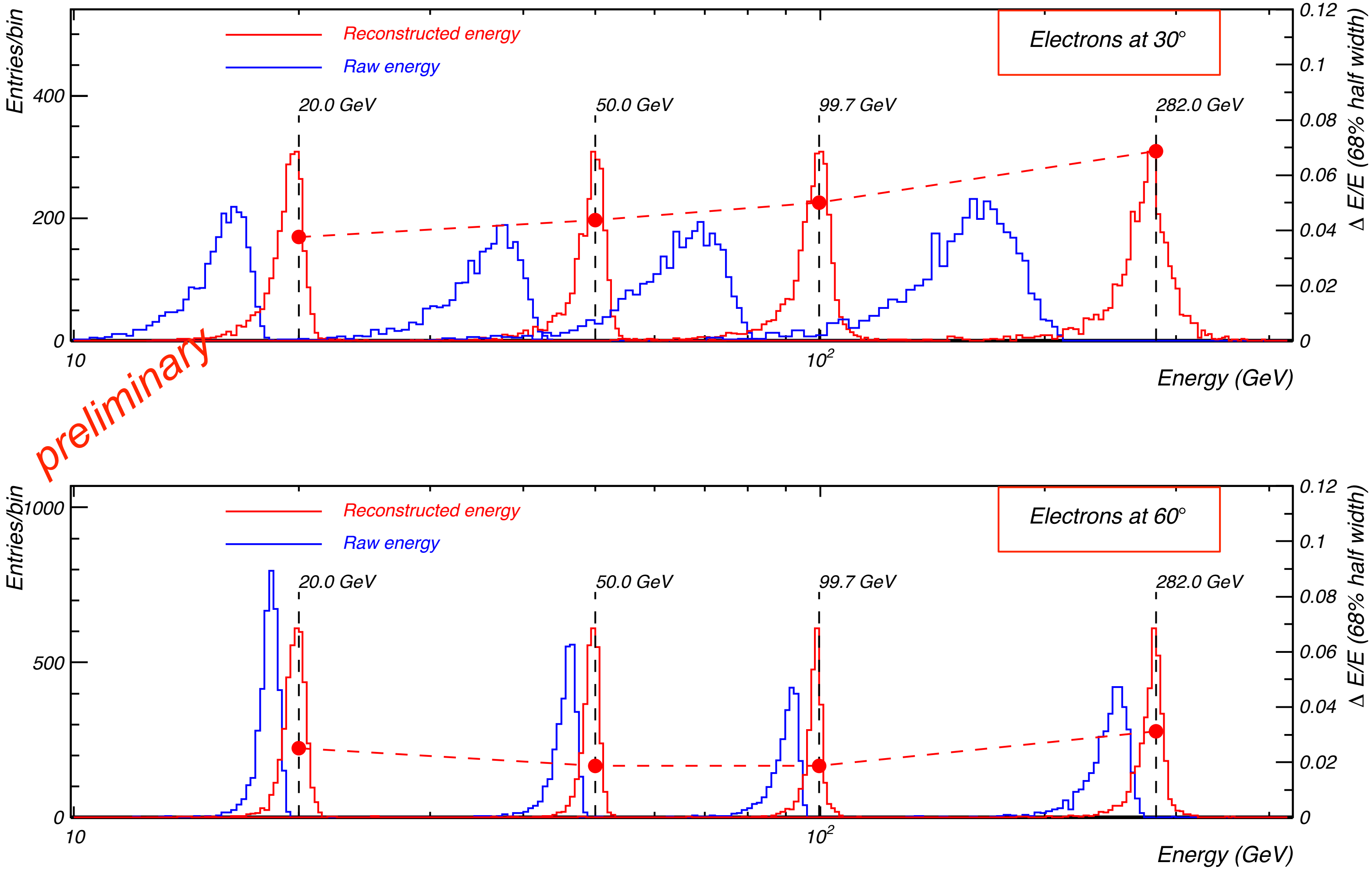
LAT Electron performance



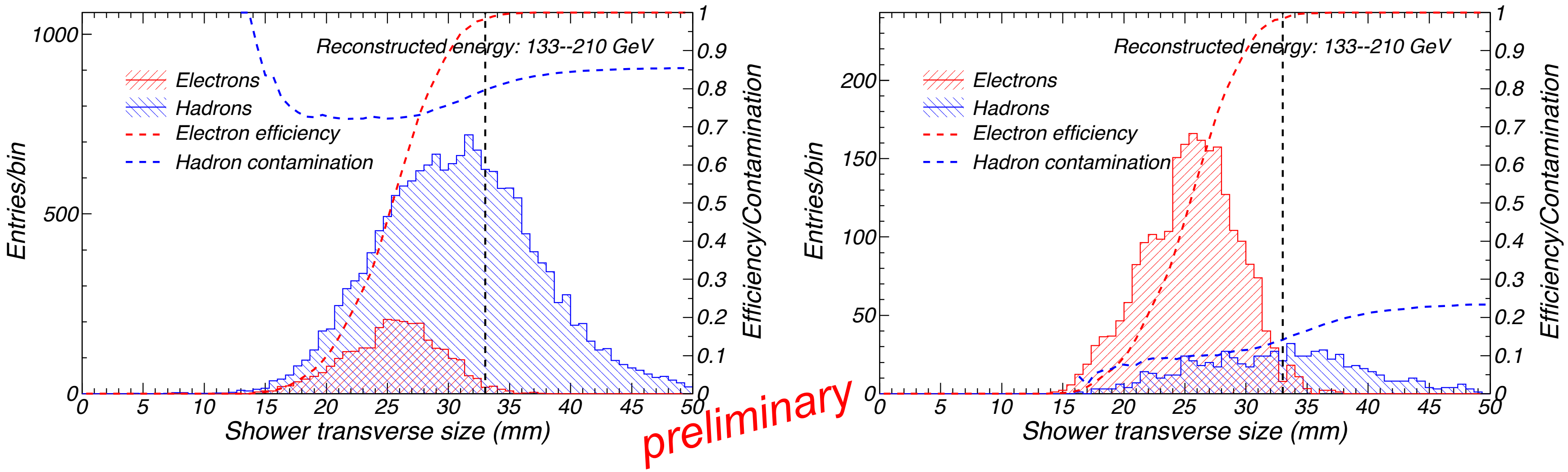


- Performance is a trade-off among:
  - electron-acceptance – hadron contamination - systematics
- Geometry factor
  - ~ 3 m^2sr (50 GeV) to ~ 1 m^2sr (1 TeV)
  - > 10x wrt previous experiments
- Rejection power: ~ 1:10^3 (20 GeV) to ~ 1:10^4 (1 TeV)
- Maximum residual contamination ~ 20% (1 TeV)
- Maximum systematic uncertainty ~ 20% (1 TeV)

Energy resolution validations with BT electrons



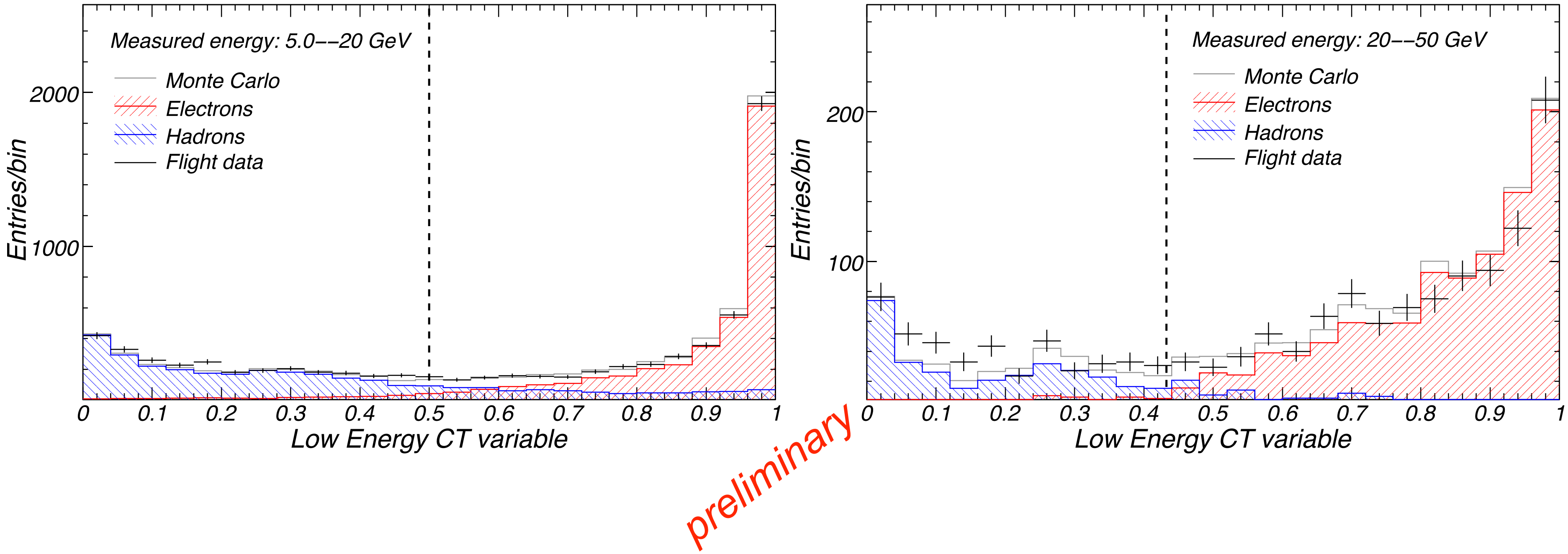
Shower size at different selection steps



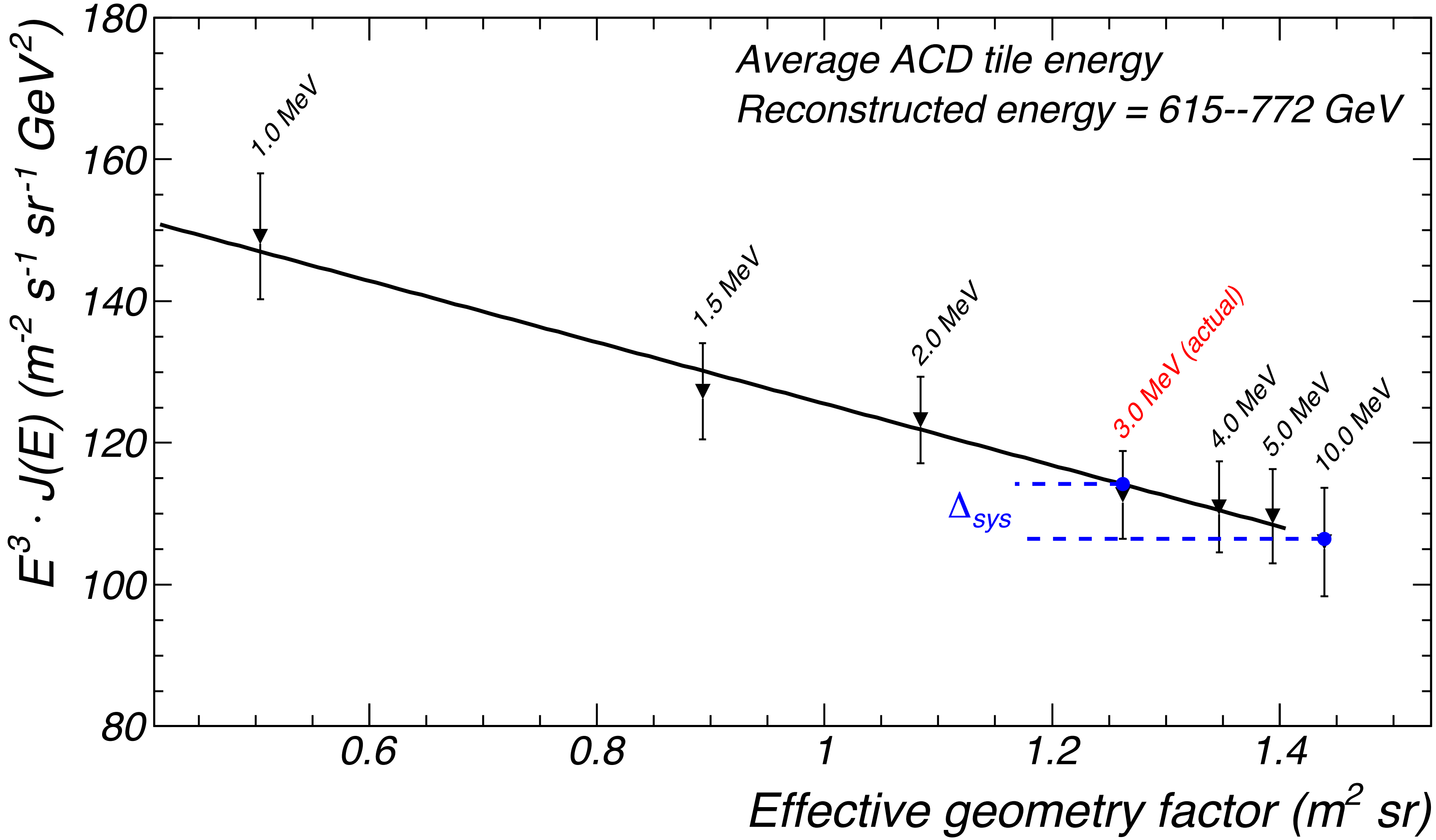
- **CAL variables cuts only**
  - **High electron efficiency**
  - **Large hadron contamination**

- **All cuts**
  - **acceptable hadron contamination**

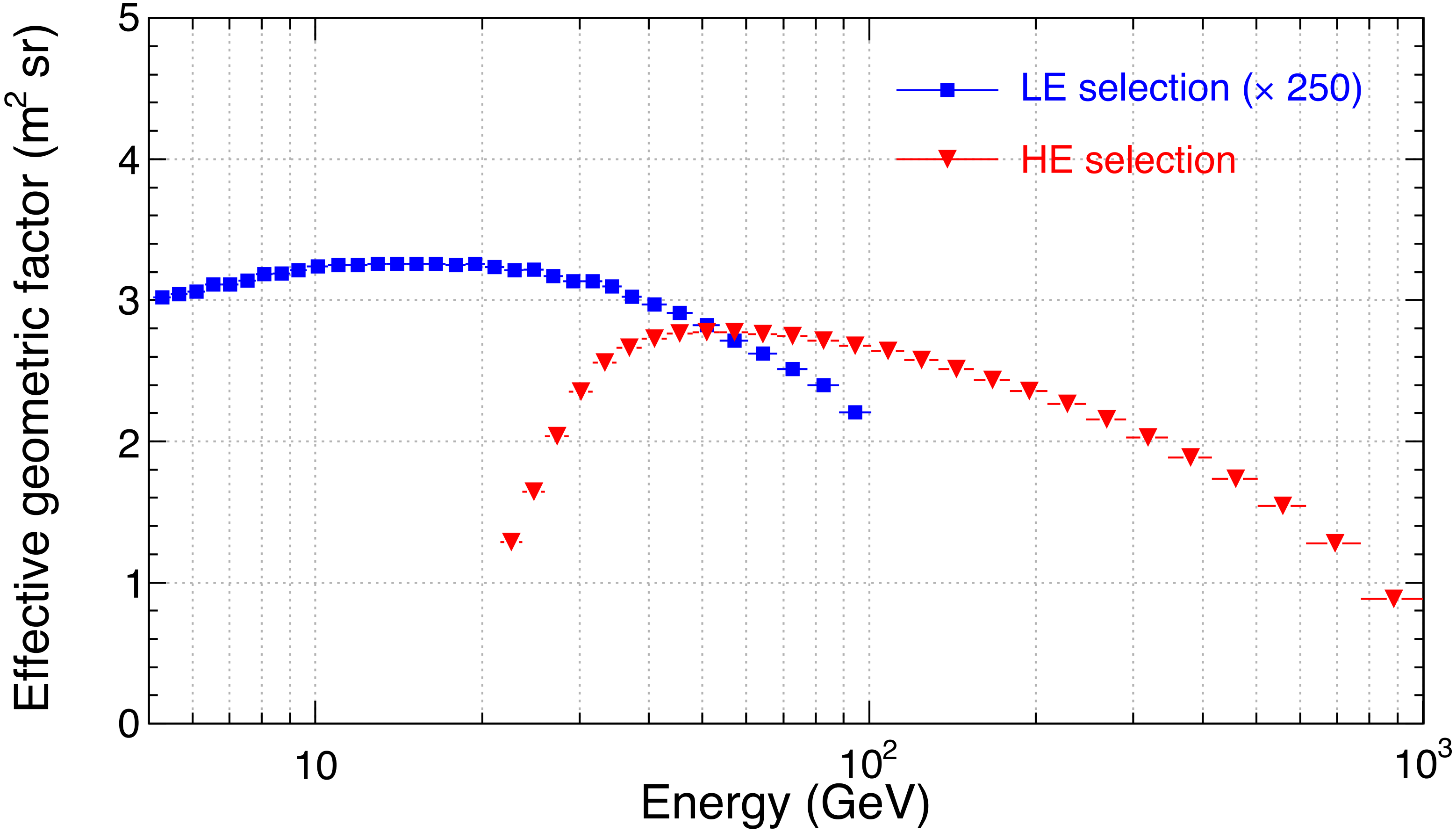
LE selection variables validation



Systematic uncertainties

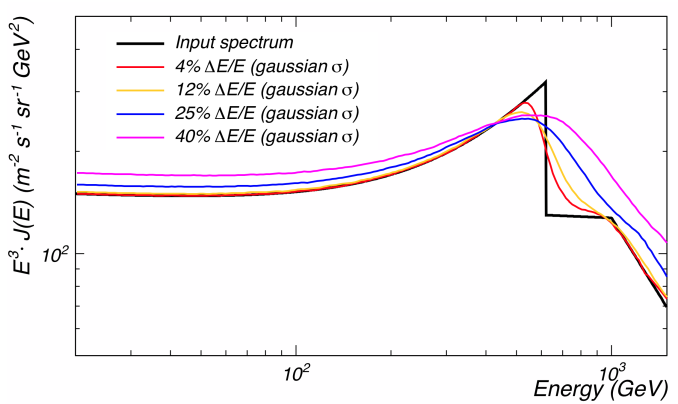


Extension to low energy measurements

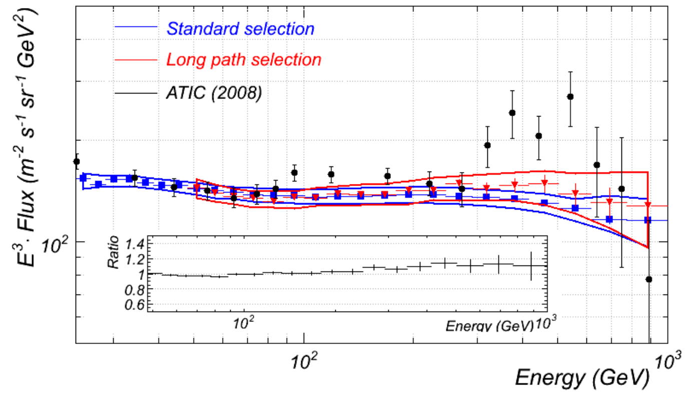


Absence of high energy features

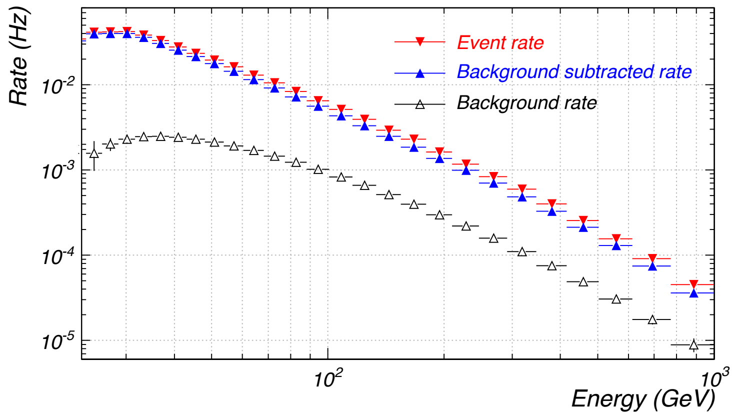
- Sensitivity to spectral features demonstrated



- Spectrum with best possible energy resolution compatible with main spectrum



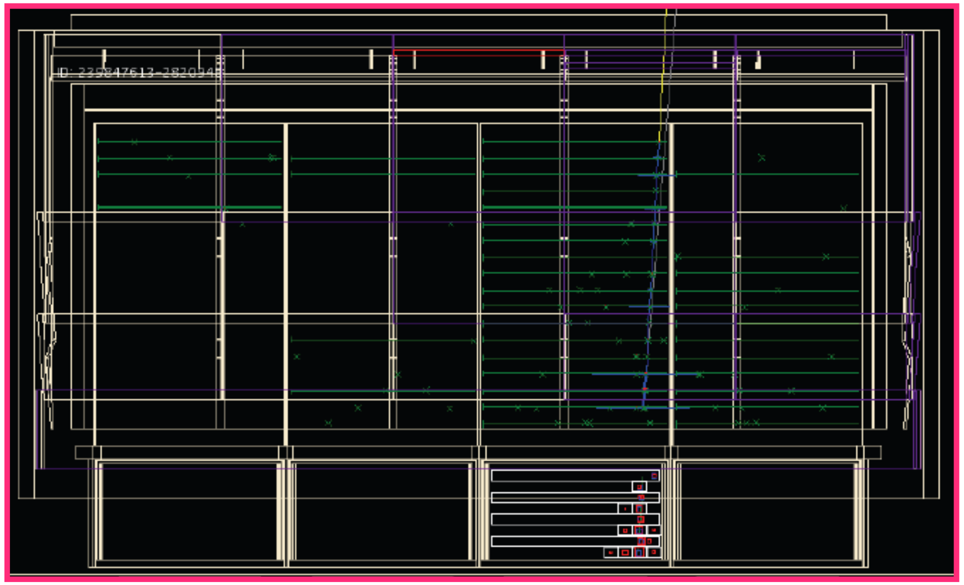
- Event rate before background subtraction does not show any feature

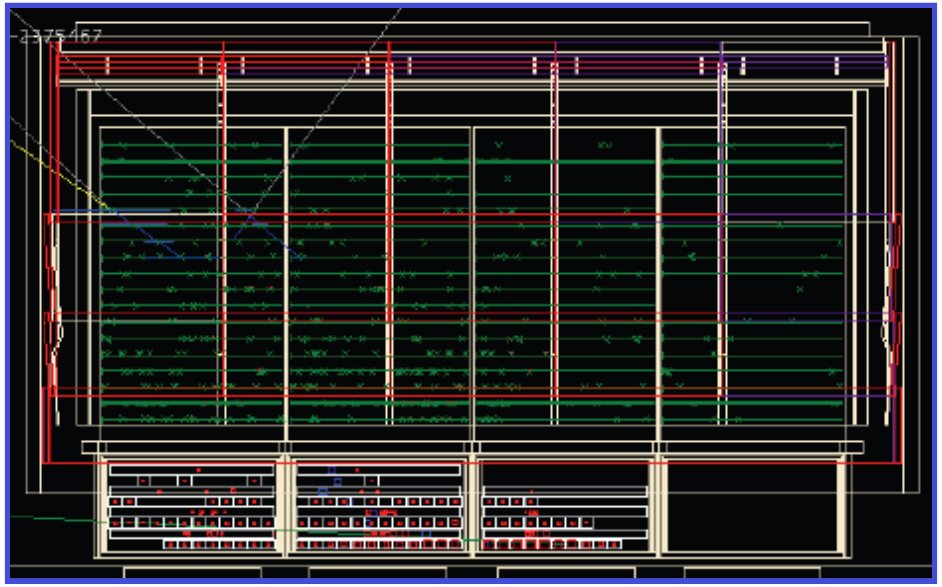


Latronico

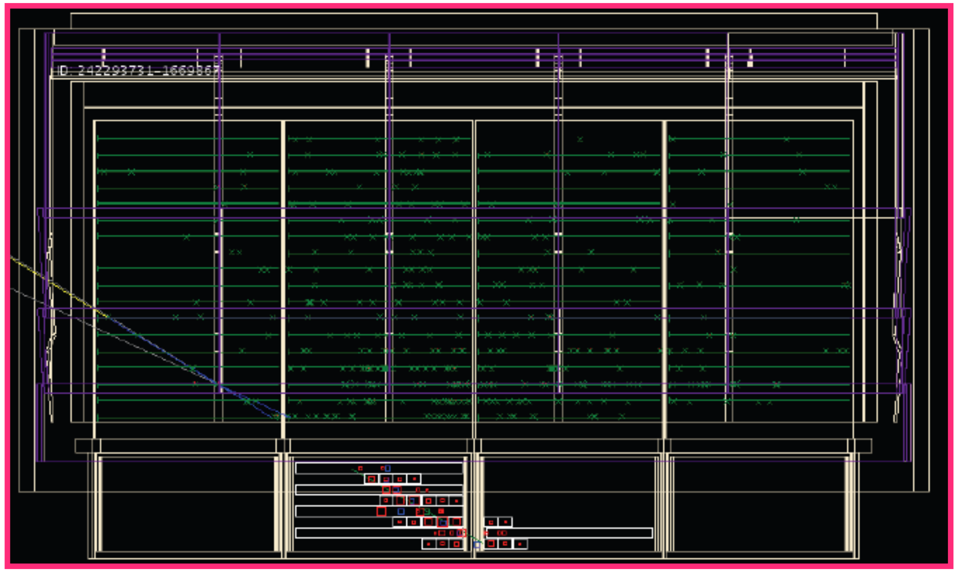
Electrons

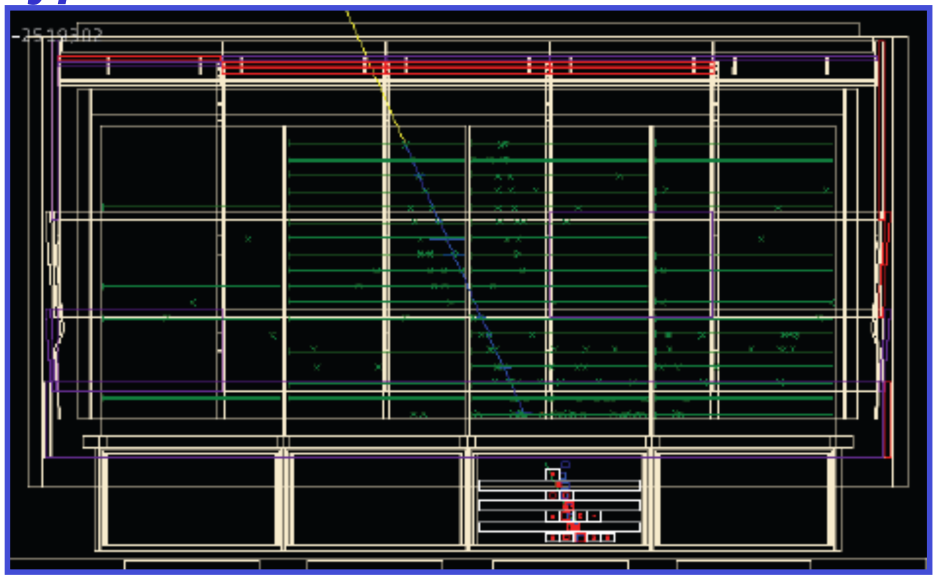
Hadrons





more simple type events





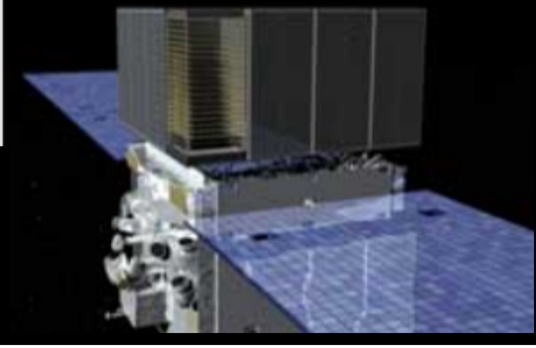
Examples of less obvious events well tagged

Science impact by citation (Nov 2009)

- "Measurement of the Cosmic Ray $e^{+}+e^{-}$ Spectrum from 20 GeV to 1 TeV with the Fermi Large Area Telescope" (05/2009) ~190
  - Cited across a broad range - cosmic-ray, astronomy, particle physics (D0, BABAR)
- "Fermi/Large Area Telescope Bright Gamma-Ray Source List" (07/2009) ~85
- "Fermi Observations of High-Energy Gamma-Ray Emission from GRB 080916C" (03/2009) ~74
- "Bright Active Galactic Nuclei Source List from the First Three Months of the Fermi Large Area Telescope All-Sky Survey" (07/2009) ~62
- "The Fermi Gamma-Ray Space Telescope Discovers the Pulsar in the Young Galactic Supernova Remnant CTA 1" (11/2008) ~41

NASA's Fermi Explores High-energy *Space Invaders*

Since its launch last June, NASA's Fermi Gamma-ray Space Telescope has discovered a new class of pulsars, probed gamma-ray bursts and watched flaring jets in galaxies billions of light-years away. Today at the American Physical Society meeting in Denver, Colo., Fermi scientists revealed new details about high-energy particles implicated in a nearby cosmic mystery.



Physics: Cosmic light matter probes heavy dark matter

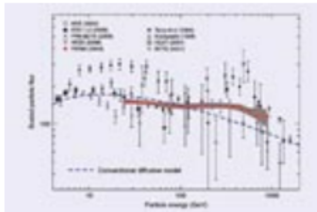
May 4, 2009

New results from the Fermi Gamma-Ray Space Telescope, the most precise to date in the energy range 20 GeV to 1 TeV, should help resolve whether cosmic rays composed of the lightest charged particles, i.e., electrons and positrons, come from dark matter or some other astrophysical source.
[Viewpoint on Phys. Rev. Lett. **102,** 181101 (2009)]

CERN COURIER

Jun 8, 2009

Fermi measures the spectrum of cosmic-ray electrons and positrons



Spectrum

The Fermi Gamma-Ray Telescope can find out about more than gamma rays. It has now provided the most accurate measurement of the spectrum of cosmic-ray electrons and positrons. These results are consistent with a single power-law, but visually they suggest an excess emission from about 100 GeV to 1 TeV. The additional source of electrons and positrons could come from nearby pulsars or dark-matter annihilation.

SLAC today

High-energy Electrons Could Come from Pulsars—or Dark Matter

by Michael Wall

Something in our galactic neighborhood seems to be producing large numbers of high-energy electrons, according

An artist's conception of the Fermi Gamma-ray Space Telescope. (Image: NASA.)

Lights Out for Dark Matter Claim?

By Adrian Cho
*Science*NOW Daily News
2 May 2009

Last November, data from a balloon-borne particle detector circling the South Pole revealed a dramatic excess of high-energy particles from space--a possible sign of dark matter, the mysterious substance whose gravity seems to hold our galaxy together. But satellite data reported today stick a pin in that

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