First results on the high energy cosmic ray electron spectrum with the Fermi-LAT

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on behalf of the Fermi–LAT collaboration

TANGO in Paris - May 4^{th}, 2009

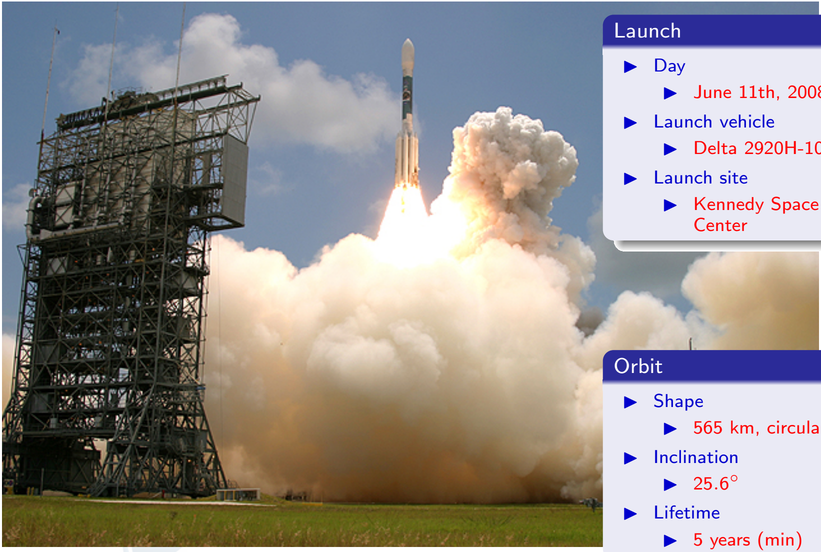
Outline...

The Fermi Gamma-ray Space Telescope
- Observatory: LAT and GBM
- The Large Area Telescope

Measuring the CRE spectrum with the LAT
- Energy resolution
- Electrons selection and hadron rejection
- Geometry factor and rejection power
- Residual background
- MC validation and systematics
- CRE spectrum from 20 GeV to 1 TeV

Interpretation of the CRE spectrum
- Conventional GCRE models
- Nearby pulsars
- Dark matter

Fermi Launch !



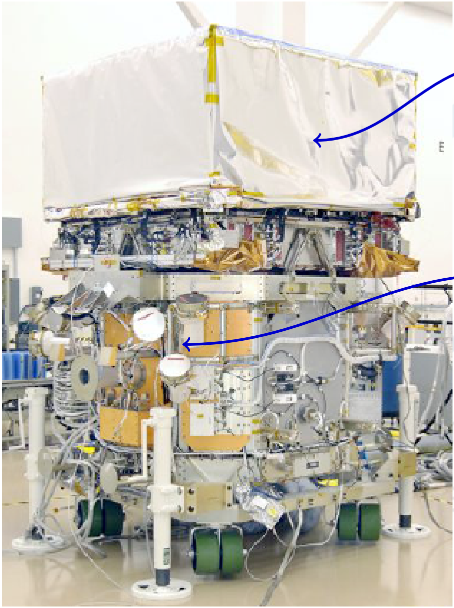
Launch

- Day
  - June 11th, 2008
- Launch vehicle
  - Delta 2920H-10
- Launch site
  - Kennedy Space Center

Orbit

- Shape
  - 565 km, circular
- Inclination
  - 25.6°
- Lifetime
  - 5 years (min)

The observatory

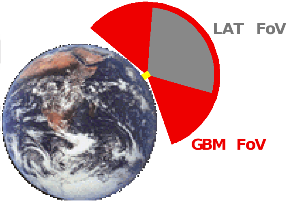


Large Area Telescope (LAT)

- Pair conversion telescope.
- Energy range: 20 MeV–300 GeV.

Gamma-ray Burst Monitor (GBM)

- 12 NaI and 2 BGO detectors.
- Energy range: 8 keV–40 MeV.



The Fermi-LAT collaboration

United States

- California State University at Sonoma
- University of California at Santa Cruz
- Goddard Space Flight Center
- Naval Research Laboratory
- Ohio State University
- Stanford University (SLAC and HEPL/Physics)
- University of Washington
- Washington University, St. Louis

PI: Peter Michelson (Stanford & SLAC)

- 390 Members (including 96 Affiliated Scientists, plus 68 Postdocs, and 105 Graduate Students)
- Cooperation between NASA and DOE, with key international contributions from France, Italy, Japan and Sweden
- Managed at Stanford Linear Accelerator Center (SLAC)

Sweden

- Kalmar University
- Royal Institute of Technology
- Stockholm University

France

- IN2P3
- CEA/Saclay

Japan

- Hiroshima University
- ISAS/JAXA, RIKEN
- Tokyo Tech.

Spain

- ICREA
- Inst de Ciencies de l'Espi

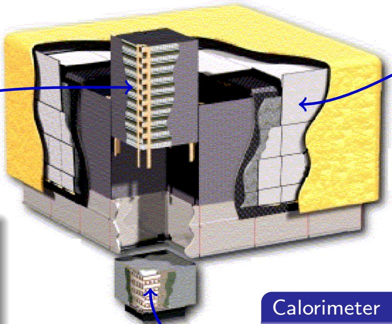
Italy

- INFN
- ASI

The Large Area Telescope

Large Area telescope

- Overall modular design
- 4×4 array of identical towers (each one including a tracker and a calorimeter module)
- Tracker surrounded by an Anti-Coincidence Detector (ACD)



Tracker

- Silicon strip detectors, W conversion foils; 1.5 radiation lengths on-axis
- 10k sensors, 80 m^2 of silicon active area, 1M readout channels
- High-precision tracking, short dead time

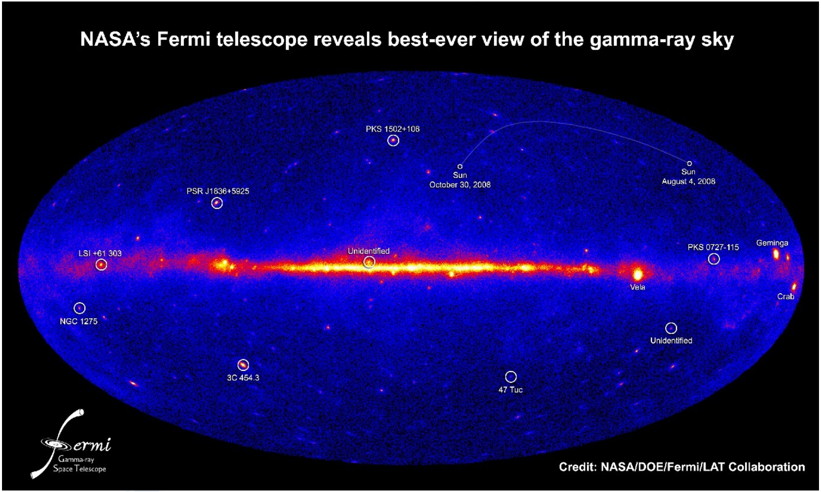
Anti-Coincidence Detector

- Segmented (89 tiles) as to minimize self-veto at high energy
- 0.9997 average detection efficiency

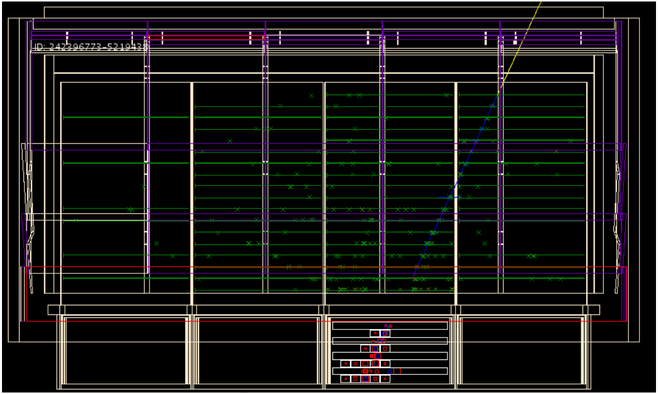
Calorimeter

- Hodoscopic tower of 1536 CsI(Tl) crystals; 8.6 radiation lengths on-axis
- 3D shower profile reconstruction for leakage correction and hadron rejection

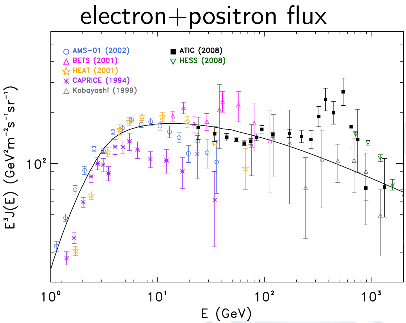
THE LAT, A γ-RAY TELESCOPE...
3 MONTHS γ-RAY SKY MAP

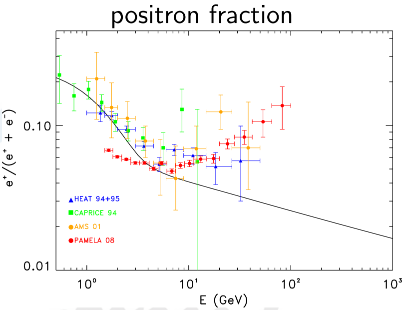


900 GeV electron candidate - flight data



- *All* events with on-board energy greater than 20 GeV are sent to ground for offline analysis
- The LAT cannot distinguish between electrons and positrons
  - ⇒ hereafter, electrons will mean *electrons+positrons*





- Spectral features in the $(e^+ + e^-)$ spectrum
  - possible excess around 600 GeV reported by ATIC and PPB-BETS
  - spectral cutoff measured by H.E.S.S. around 1 TeV
- Pamela reports an excess in the positron fraction

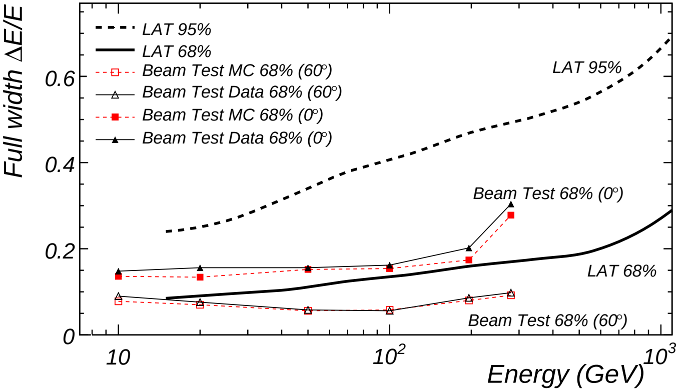
$\Rightarrow$ $>$ 30 papers mentioned these results the past few months

$\Rightarrow$ Nearby sources expected ? astrophysical or exotic origin ?

Measuring the CRE spectrum with the LAT

- Energy resolution
- Electrons selection and hadron rejection
- Geometry factor and rejection power
- Residual background
- Monte-Carlo validation and systematics
- CRE spectrum from 20 GeV to 1 TeV

Energy resolution

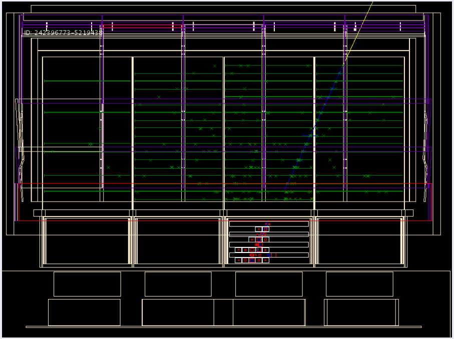


- Validated with the Calibration Unit beam test up to 282 GeV
  - excellent agreement over the whole phase space
  - reasonable to trust the Monte-Carlo up to 1 TeV

⇒ The energy dispersion is adequate to measure the CRE spectrum up to at least 1 TeV

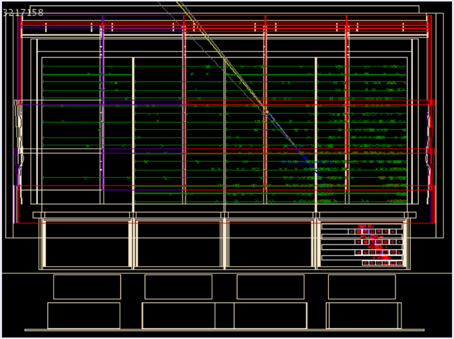
Electromagnetic vs hadronic cascades
events in the last energy bin 772 GeV - 1 TeV

Electron candidate



- few ACD tile hits in conjunction with the track
- clean main track with extra-clusters very close to the track - note backsplash from the calorimeter
- well defined symmetric shower in the calorimeter, not fully contained

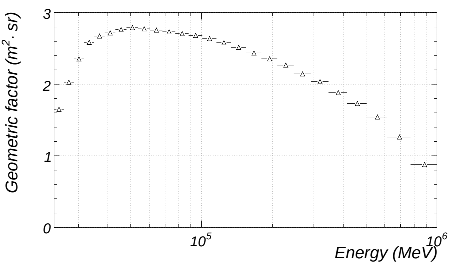
Hadron candidate



- large energy deposit per ACD tile
- small number of extra clusters around main track, large number of clusters away from the track
- large and asymmetric shower profile in the calorimeter

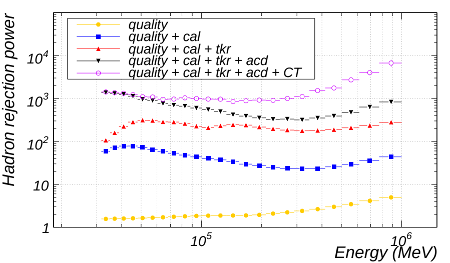
Geometry factor and rejection power

CRE geometry factor



- 2.8 m^2 peak geometry factor
- 2 m^2 at 300 GeV
- almost 1 m^2 at 1 TeV
- an order of magnitude larger than previous experiments

Hadron rejection power

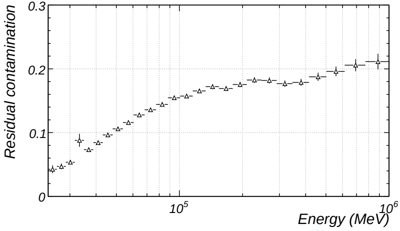


- rejection power with respect to what triggers
- pre-filter : all three sub-systems (ACD, TKR and CAL) contribute
- 2 classification trees combined, based on TKR and CAL variables

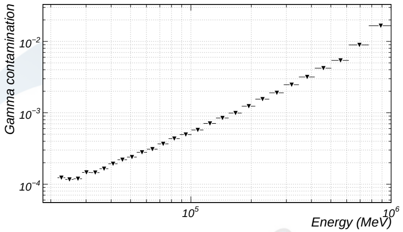
$\rightarrow$ boost of the rejection power at high energy

$\Rightarrow$ Find the best trade-off between electron selection efficiency, hadron rejection power and reasonable systematic uncertainties

Residual hadronic contamination



Expected γ-ray contamination

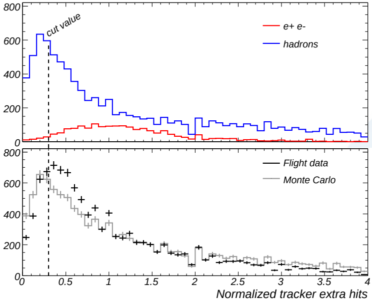


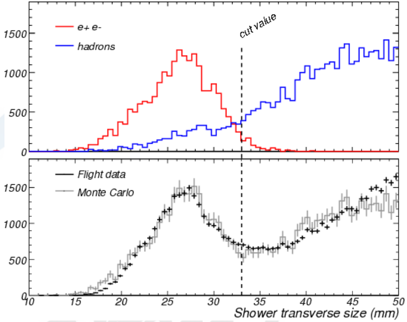
- Hadronic contamination rises from few percent to $\simeq 20\%$ over the whole energy range
  - estimated from a large Monte-Carlo simulation, using *standard* cosmic ray models from 10 MeV to 10 TeV
  - subtracted from the candidate electrons
- γ-ray contamination is less than 2% in the highest energy bin
  - conservative estimation extrapolating EGRET total γ-ray flux measurement

  → not subtracted from the candidate electrons

Sources of systematic errors

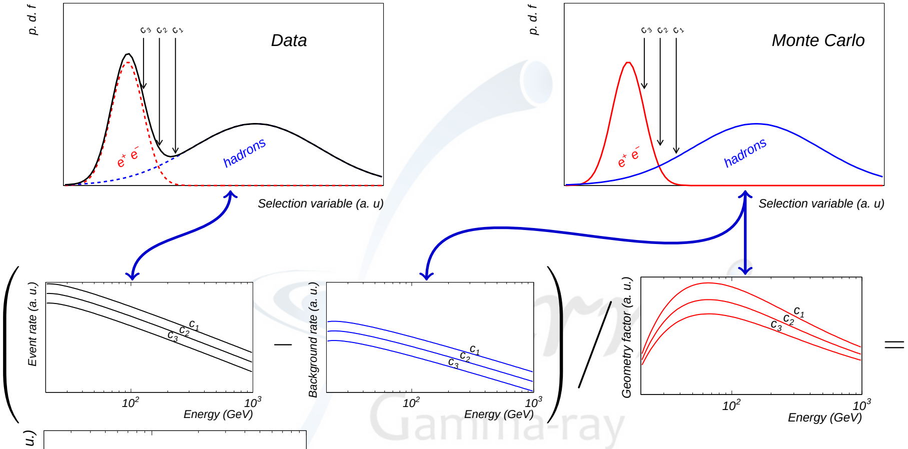
1. Uncertainty in our knowledge of the geometry factor
   - data/Monte Carlo agreement extensively studied for each single variable involved in the selection (bin by bin)
   - all the residual discrepancies mapped and propagated to the actual spectrum.
   - ranging from a few % to $\simeq$ 20% depending on energy
2. Normalization of the primary proton spectrum
   - the uncertainty on the proton cosmic ray model ranges from few % to $\simeq$ 20% around 1 TeV
   - affecting the electron spectrum through the subtraction of the residual hadron contamination
3. LAT absolute calibration of the energy scale
   - unlike the other terms does not introduce energy-dependent modifications of the spectrum
   - from beam test data, calibration and flight data, the systematic uncertainty on the absolute energy is (+5%, -10%)

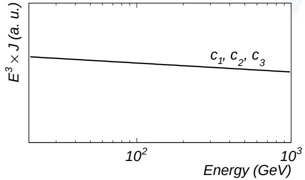




- A tracker and a calorimeter variable at an intermediate stage of the analysis
  - good overall agreement between data and simulations
  - Monte-Carlo validation started from beam test data
  - analysis variables carefully check over the energy range with flight data

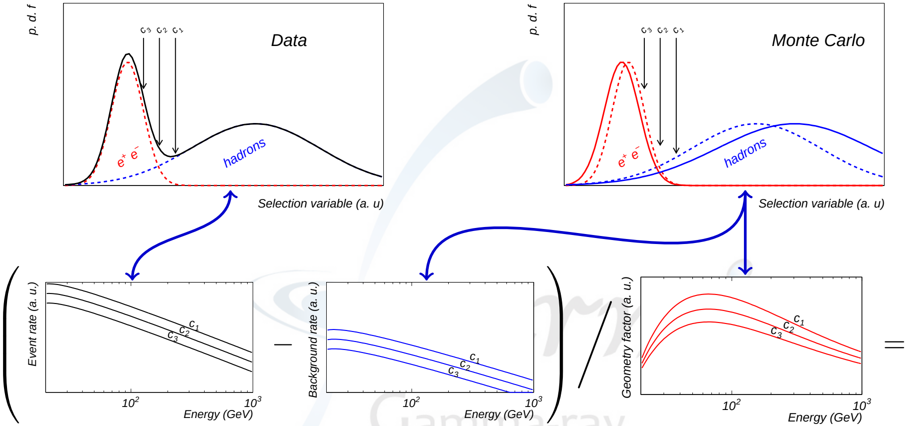
$\Rightarrow$ Residual discrepancies studied and included in the systematic uncertainties

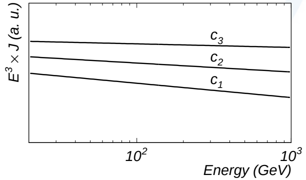




Evaluating the systematics

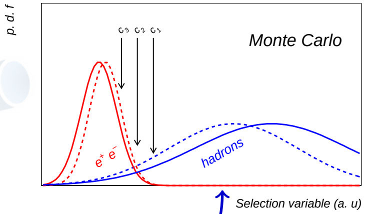
- If the data/MC agreement was perfect, the actual spectrum would not depend on the cut values.

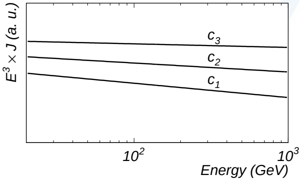




Evaluating the systematics

- In real life data/MC discrepancies introduce such a dependence.



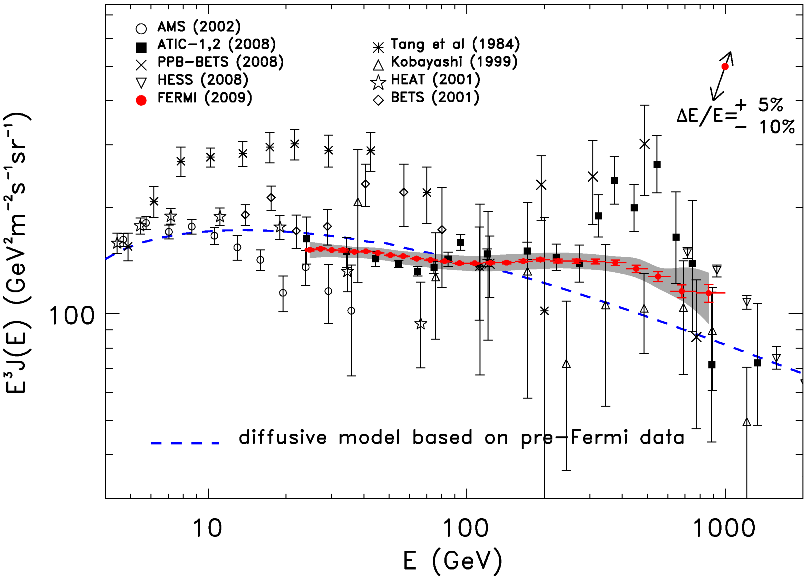


Evaluating the systematics

- The induced variations in the spectrum effectively map the data/MC discrepancies.

CRE spectrum from 20 GeV to 1 TeV

submitted to PRL on March, 19th and accepted April, 21st 2009



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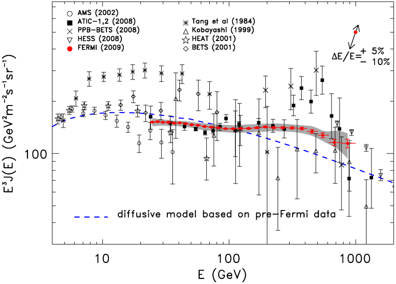
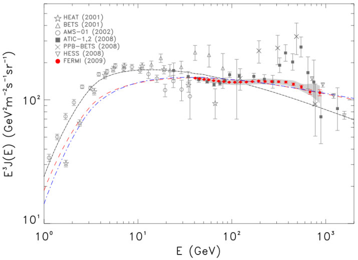


Energy (GeV)	GF (m^2sr)	Residual contamination	Counts
...	...	...	...
291–346	2.04	0.18	7207
346–415	1.88	0.18	4843
415–503	1.73	0.19	3036
503–615	1.54	0.20	1839
615–772	1.26	0.21	1039
772–1000	0.88	0.21	544

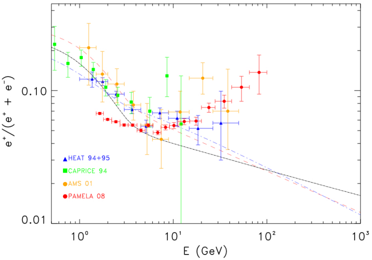
more than 400 electrons in the last energy bin 772 GeV - 1TeV

- High statistics : ∼4.5 millions of events in 6 months
  - errors dominated by systematic uncertainties
- Not compatible with the the pre-Fermi data diffusive model ($E^{-3.3}$ whereas we measured $E^{-3.0}$)
- No evidence of a prominent spectral feature
  - ATIC excess: 70 electrons between 300 and 800 GeV
  - → we would have seen an excess of 7000 electrons

electron+positron



positron fraction



- Conventional models (produced using GALPROP)
  - black: with re-acceleration, $\gamma_0 = 2.54$ as *Strong et al. 2004* [1]
  - red: with re-acceleration, $\gamma_0 = 2.42$ ($\delta = 0.33$)
  - blue: plain diffusion, $\gamma_0 = 2.33$ ($\delta = 0.6$)

$\Rightarrow$ Fermi data are well matched with a slight change of γ_0 but:
  - not so good under 20 GeV with respect to other data
  - an extra-component is needed to interpret the PAMELA data

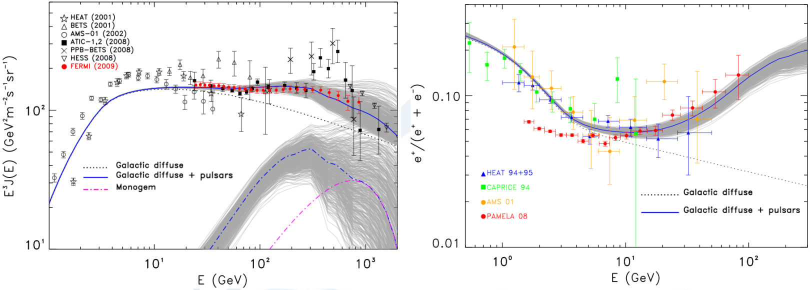
[1] and also in the Fermi GeV no-excess paper (see talk by A. Strong)

Interpretation – Nearby pulsars (1)

- Pulsars are candidate sources of relativistic electrons and positrons (see e.g. Shen 1970, Harding & Ramaty 1987)
  - $e^{\pm}$ pairs are believed to be produced in the magnetosphere and re-accelerated in the wind
- Characteristics needed to explain Fermi/Pamela excesses with respect to conventional models
  - nearby: because of synchrotron energy losses
  - mature: because electrons remain confined in the Pulsar Wind Nebula until it merges with ISM
  - but not too old: because old electrons are already diluted in space

⇒ Considering distributions of pulsars from the ATNF catalog

  - with $d < 3kpc$ with age $5.10^4\ yr < T < 10^7\ yr$
  - randomly varying the parameters within acceptable ranges
    - injection index, cutoff energy, $e^{\pm}$ conversion efficiency, delay between pulsar birth and electron release
  - create different possible summed contribution of *all* pulsars

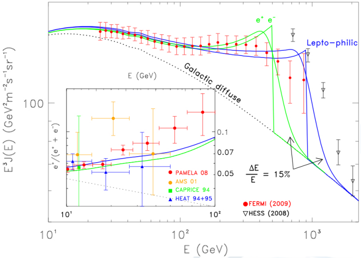


- CRE spectrum with a nearby pulsars extra-component
  - dotted line: a conventional model with re-acceleration $\gamma_0 = 2.54$ as in Strong et al. 2004 rescaled by a factor ~ 0.95
  - dotted-dashed blue: average spectrum over *all* pulsars
    - $\rightarrow$ each gray line is a particular combination of the parameters
  - blue continuous: the sum, conventional+extra component

$\Rightarrow$ Reasonable interpretation for Fermi, Pamela and HESS data
  - slightly better under 20 GeV than conventional models
  - the diffuse $\gamma - ray$ emission should be hardly affected with respect to the GeV no-excess paper

Interpretation – Dark matter (quick look)

preliminary



- 2 best fits among 2 classes
  - green line: $e^{\pm}$ model, annihilation into a light gauge boson that kinematiccaly decays into $e^{\pm}$
  - blue line: leptophilic model, annihilation into charged lepton species ($\frac{1}{3}e^{\pm}, \frac{1}{3}\mu^{\pm}, \frac{1}{3}\tau^{\pm}$)

- The impact of the new Fermi CRE data
  - Much weaker rationale to postulate a DM mass in the 0.3–1 TeV range ("ATIC bump") motivated by the CRE spectrum
  - If the Pamela positron excess is from DM annihilation or decay, Fermi CRE data set constraints on such interpretation
  - Even neglecting Pamela, Fermi CRE data are useful to put limits on rates for particle DM annihilation or decay
  - A DM interpretation to the Pamela positron fraction data consistent with the new Fermi-LAT CRE is a viable possibility

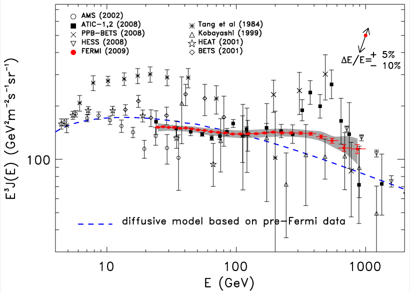
Conclusions and further analysis

Conclusions

- high statistics spectrum
- errors are dominated by systematics
- not compatible with pre-Fermi data conventional diffuse model
- adjusting the conventional diffuse model is fair and fits well Fermi data
- possibility of an extra-component
  - pulsars as nearby sources of $e^{\pm}$ offer a natural explanation for Fermi, Pamela and HESS data
  - dark matter models cannot be ruled out

* See David Smith's talk about Fermi horde of γ-ray pulsars !

Fermi-LAT CRE spectrum



Further analysis

- Search anisotropy in the electron flux
- Reduce systematic errors in instrument response and energy determination
- Expand energy range down to ∼5 GeV (lowest possible for Fermi orbit) and up to ∼2 TeV, revealing spectral shape above 1 TeV and providing more overlap with the H.E.S.S. data
- Increase the statistics at high energy end. Each year Fermi-LAT will collect ∼400 electrons above 1 TeV with the current selections if the spectral index stays unchanged
- Pursue the work started on the interpretation of our data

Conclusions

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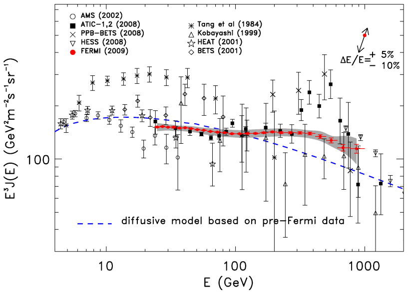
Fermi-LAT CRE spectrum



- Publications
  - Measurement of the CRE spectrum: published on PRL today
    http://prl.aps.org/#tabcontent-highlights
  - Spectrum interpretation: article to be submitted soon

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- American Physical Society *Viewpoints* today
  http://physics.aps.org

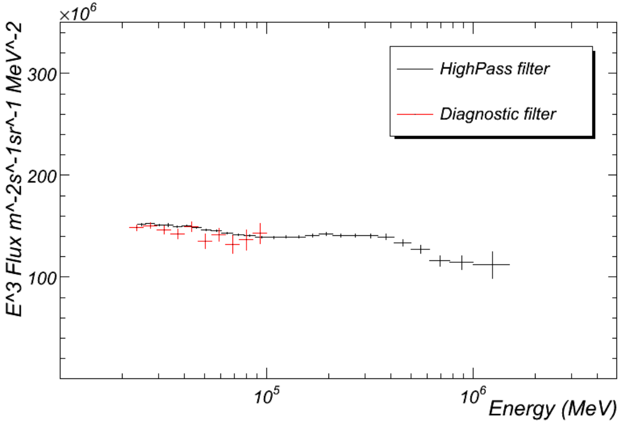
Special thanks to Luca Baldini for the Fermi Beamer LaTeX template

Extra Slides

Trigger, filter and data source

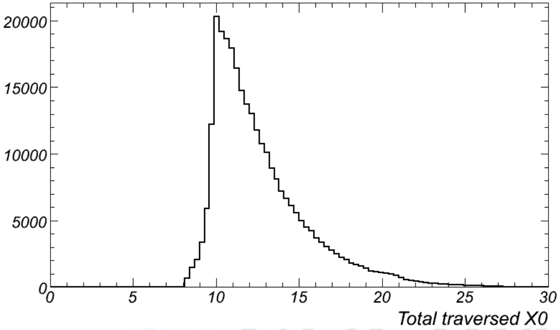
- All events with uncorrected energy greater than 20 GeV pass the gamma filter.
  - primary data source of high-energy electrons (20 GeV–1 TeV)
- The diagnostic filter provides a prescaled sample of all trigger types at all energies
  - 250 prescale factor
  - adequate for studying the electron spectrum at relatively low energies (up to 100 GeV)
- Two different sources of events
  - allow to compare different analysis approaches in the overlap region (20 GeV–100 GeV)

Diagnostic versus High-Pass filter

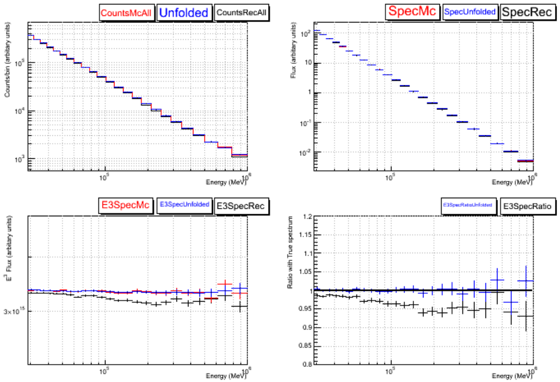


- Independent analysis at lower energy in good progress
  - different physics involved at low energies
  - separate and completely different analysis
- Perfect agreement between the two approaches in the overlap

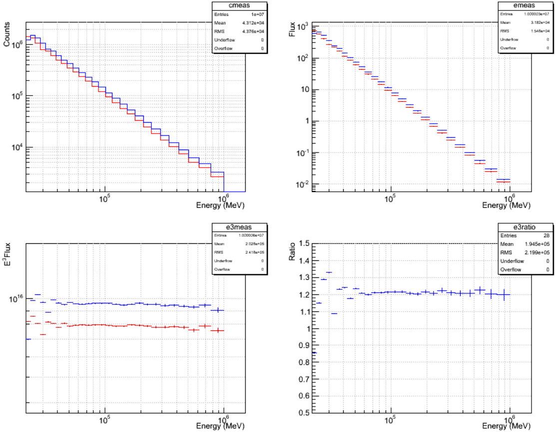
Energy resolution



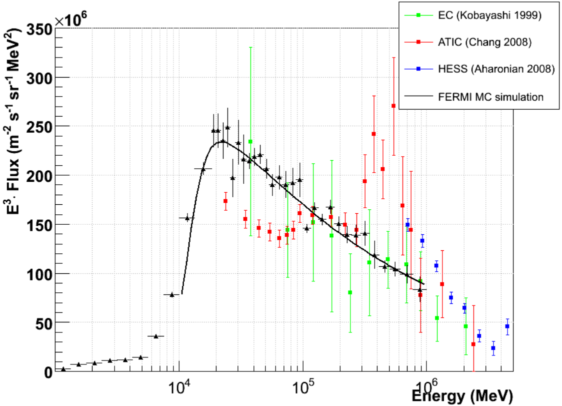
- Our calorimeter is 8.6 $X0$ deep
- The tracker adds up 1.5 $X0$ of material
  - 1.5 $X0$ of *finely segmented active* material, providing additional rejection power
- The LAT is a wide-FOV instrument
- More than 12 $X0$ traversed on average by candidate electrons



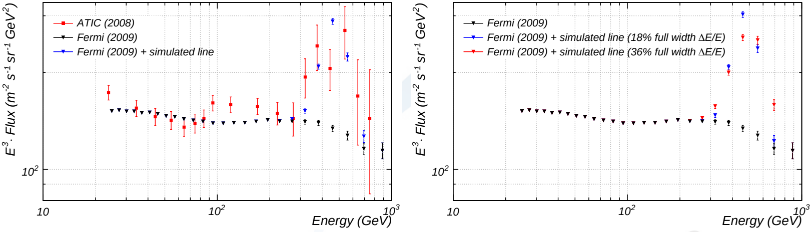
- Folding a test power law through the parametrized energy response
  - the effect is at the level of a 5% percent, see black (measured) vs. red (simulated)
  - this effect is cured by the unfolding (blue)



- Folding a test power law through the parametrized energy response and change the energy scale by 10%
  - increasing the energy scale by 10% induces an increase of the flux normalization in $E^3.J(E)$ of 20%



- The analysis chain is applied to MC as if it was flight data
  - our model is very different from what we measure.
  - getting the statistics with the MC simulation is not nearly as easy as with flight data



- Given our energy resolution we would have seen a proeminent feature such as the "ATIC bump"
  - ATIC excess: 70 electrons between 300 and 800 GeV

  $\longrightarrow$ we would have seen an excess of 7000 electrons
- Test by adding a simple gaussian signal (450 Gev$\pm$50) to our spectrum
  - even if we worsen our energy resolution by a factor of 2, the feature is clearly seen