Title: Observation of the high-energy cosmic-ray electron spectrum with Fermi and implications for dark matter scenarios

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Abstract: Successfully launched on June 11, 2008, Fermi is the reference high-energy gamma-ray space observatory of the current decade. The Fermi Large Area Telescope (LAT) has been collecting data continuously in nominal operations since August 2008, providing exciting results that are contributing to changing our understanding of the extreme Universe.Being a high sensitivity gamma-ray detector, the LAT is by its nature also a powerful electron detector and has in fact delivered the first high precision measurement of the primary cosmic-ray electron spectrum between 20 GeV and 1 TeV, based on six months of data. I will present this result and discuss the implications for dark matter scenarios; possible signatures detectable by Fermi (in both electrons and gammas) that might be helpful to disentangle different models and preliminary results on selected DM searches based on the first 3 months of data will be briefly discussed

Observation of the high-energy cosmic ray electron spectrum with Fermi and implications for dark matter scenarios

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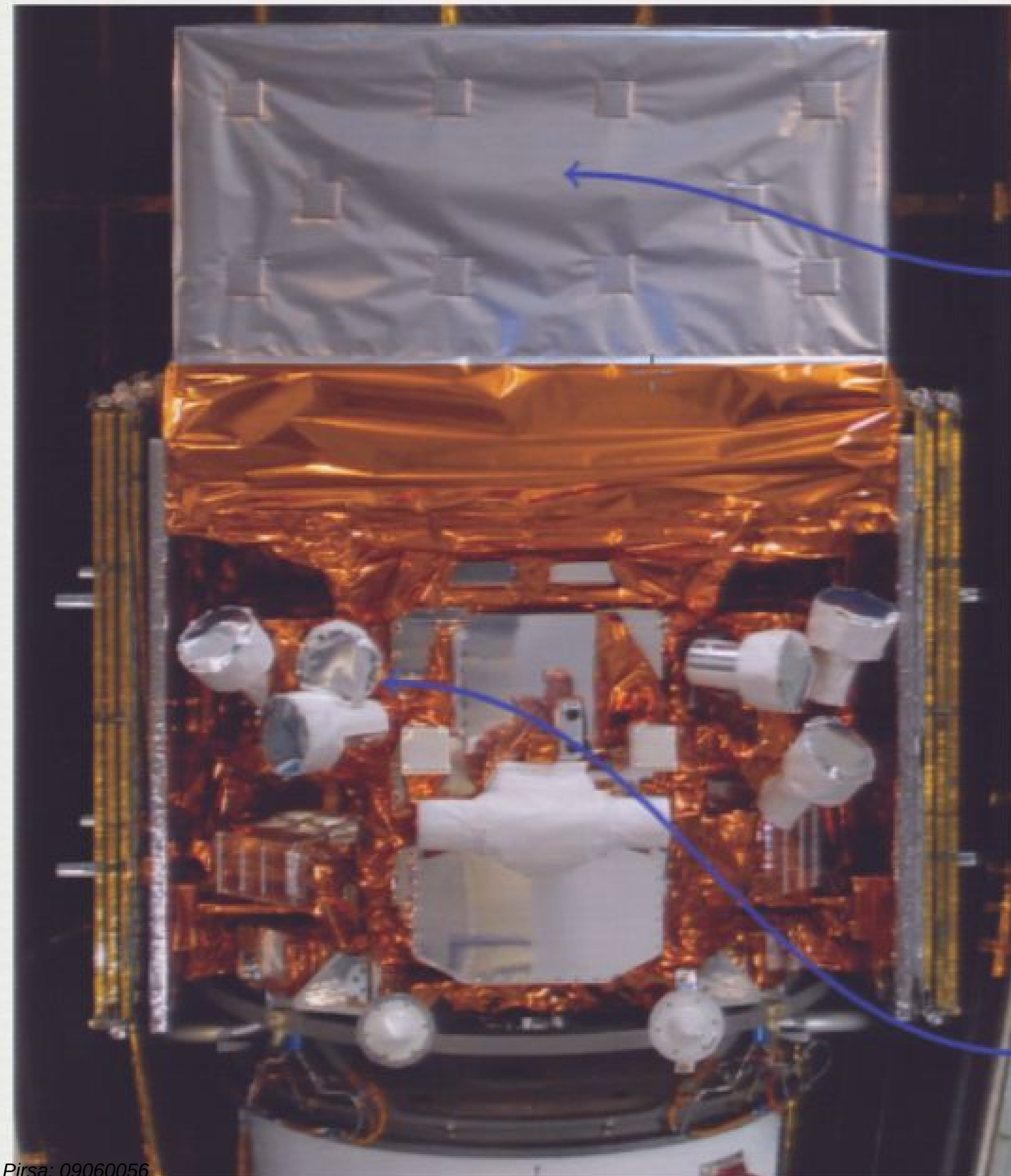
on behalf of the Fermi-LAT collaboration

New Lights on Dark Matter, Perimeter Institute, June 11, 2009

Outline

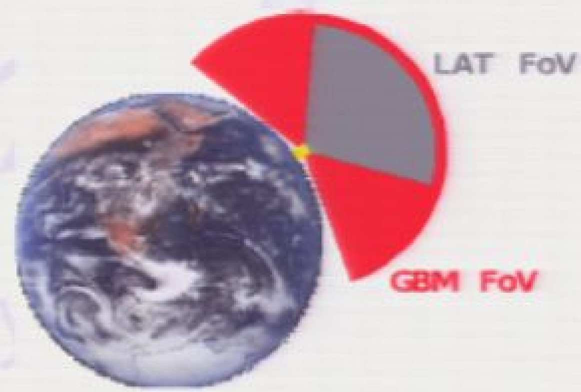
- The Fermi Large Area telescope.
- Measurement of the cosmic ray electron spectrum:
  - background rejection;
  - energy reconstruction.
- Interpretation and future perspectives.
- Dark matter signatures in gamma rays detectable by Fermi.
- Conclusions.

THE OBSERVATORY



Large Area Telescope (LAT)

- Pair conversion telescope.
- Energy range: 20 MeV–> 300 GeV
- Huge field of view ($\approx$ 2.4 sr): 20% of the sky at any time, all parts of the sky for 30 minutes every 3 hours.
- Long observation time: 5 years minimum lifetime, 10 planned 85% duty cycle.



Gamma-ray Burst Monitor (GBM)

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

The Fermi-LAT collaboration

Institutions

- **France**
  IN2P3, CEA/Saclay
- **Italy**
  INFN, ASI, INAF
- **Japan**
  Hiroshima University
  ISAS/JAXA, RIKEN
  Tokyo Institute of Technology
- **Sweden**
  Royal Institute of Technology (KTH)
  Stockholm University
- **United States**
  Stanford University (SLAC, KIPAC, and HEPL/Physics)
  University of California at Santa Cruz, Santa Cruz Institute for Particle Physics
  Goddard Space Flight Center
  Naval Research Laboratory
  Sonoma State University
  Ohio State University
  University of Washington
- Also members from Australia, Germany, Great Britain, Spain.

Sponsoring Agencies

- **France**
  IN2P3/CNRS, CEA/Saclay
- **Italy**
  INFN, ASI
- **Japan**
  MEXT, KEK, JAXA
- **Sweden**
  K. A. Wallenberg Foundation
  Swedish Research Council
  Swedish National Space Board
- **United States**
  DOE, NASA

Collaboration members

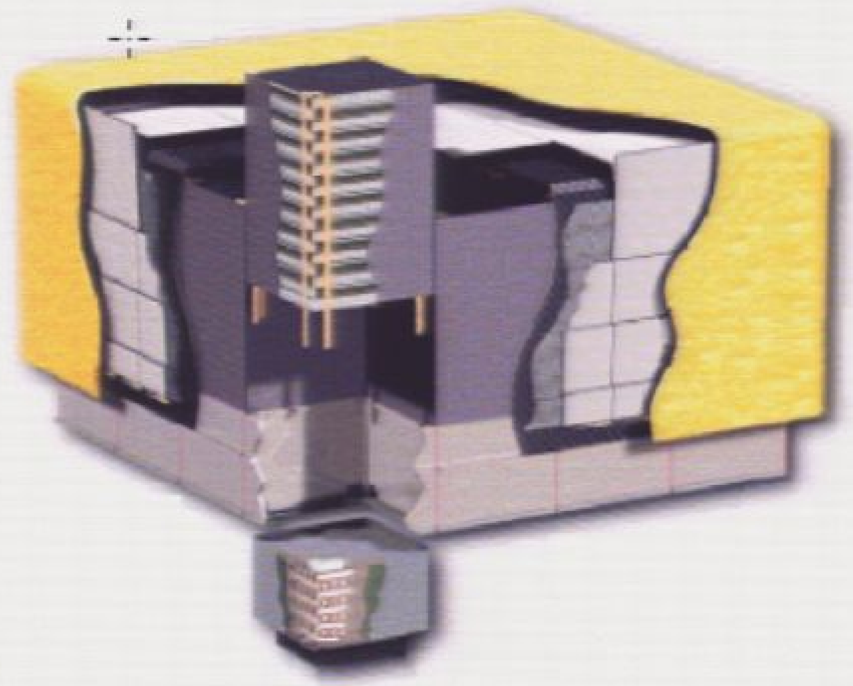
$\approx$ 390 Members ($\approx$ 95 Affiliated Scientists, 68 Postdocs, and 105 Graduate Students)

Construction and operations managed by SLAC, Stanford University

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 and Anti-Coincidence Detector (ACD)



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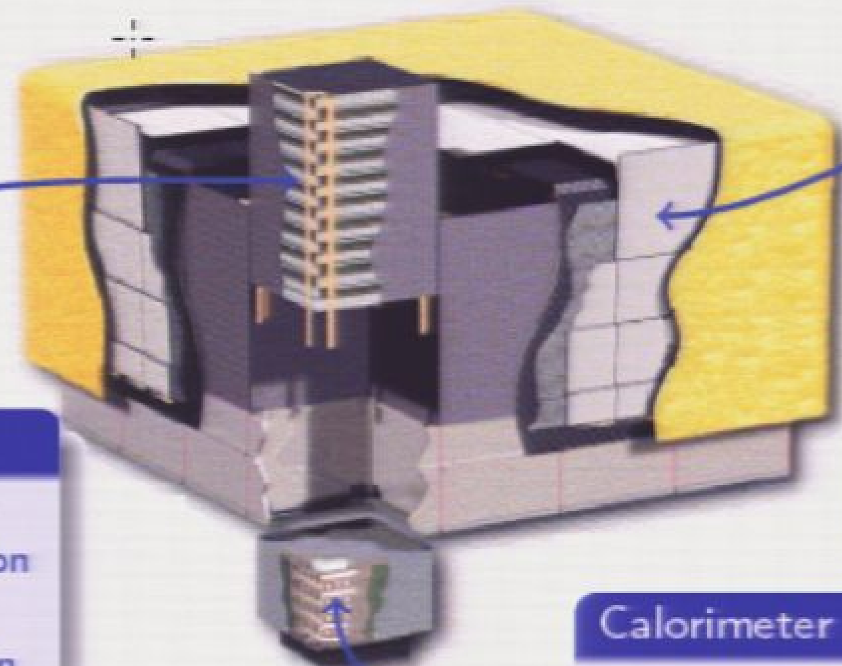


Anti-Coincidence Detector

- Segmented (89 tiles) to minimize self-veto at high energy.
- 0.9997 average efficiency (8 fiber ribbons covering gaps between tiles).

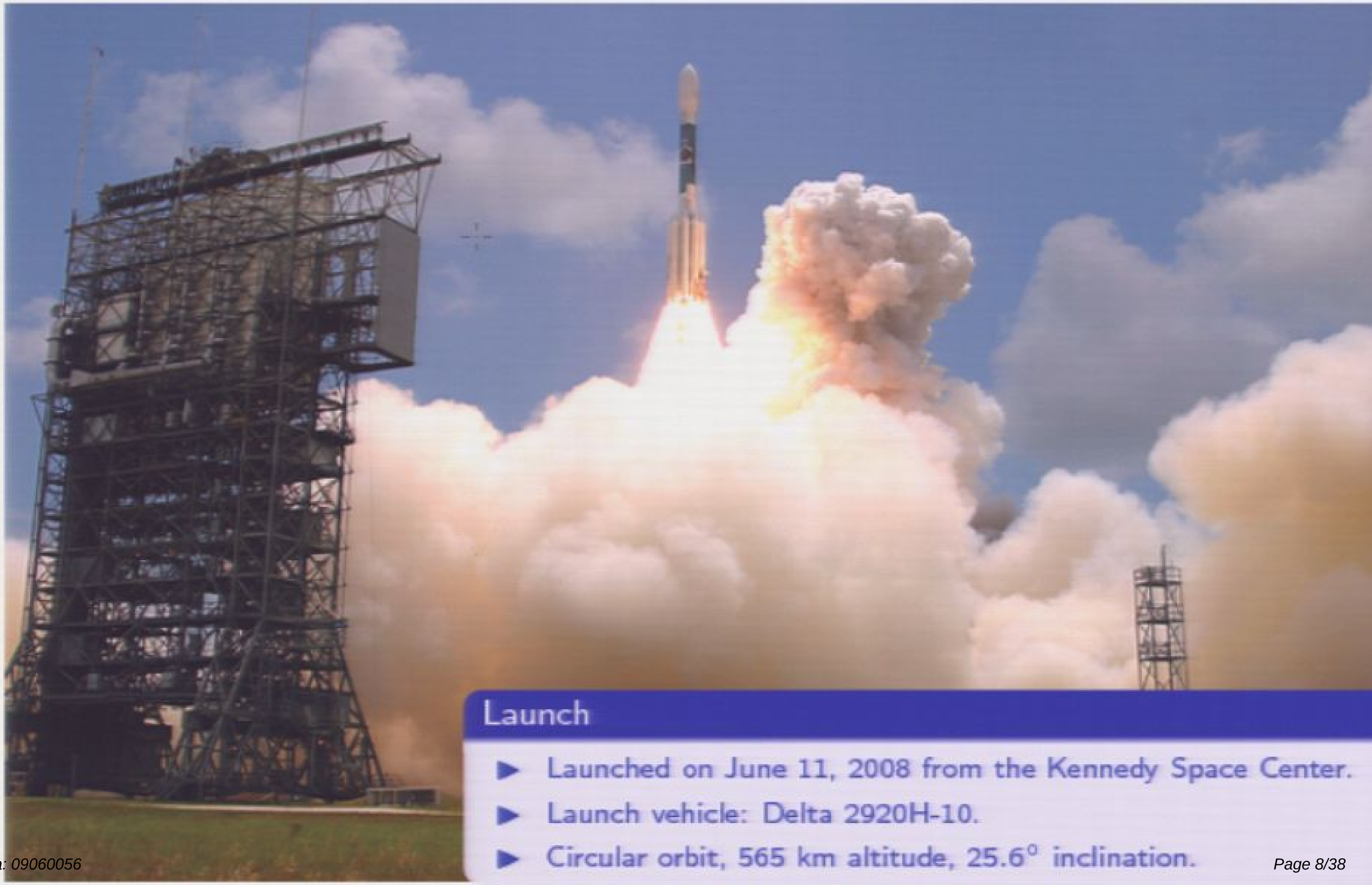
Tracker

- 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 instrumental dead time.

Calorimeter

- 1536 CsI(Tl) crystal; 8.6 radiation lengths on-axis.
- Hodoscopic, 3D shower profile reconstruction for leakage correction.

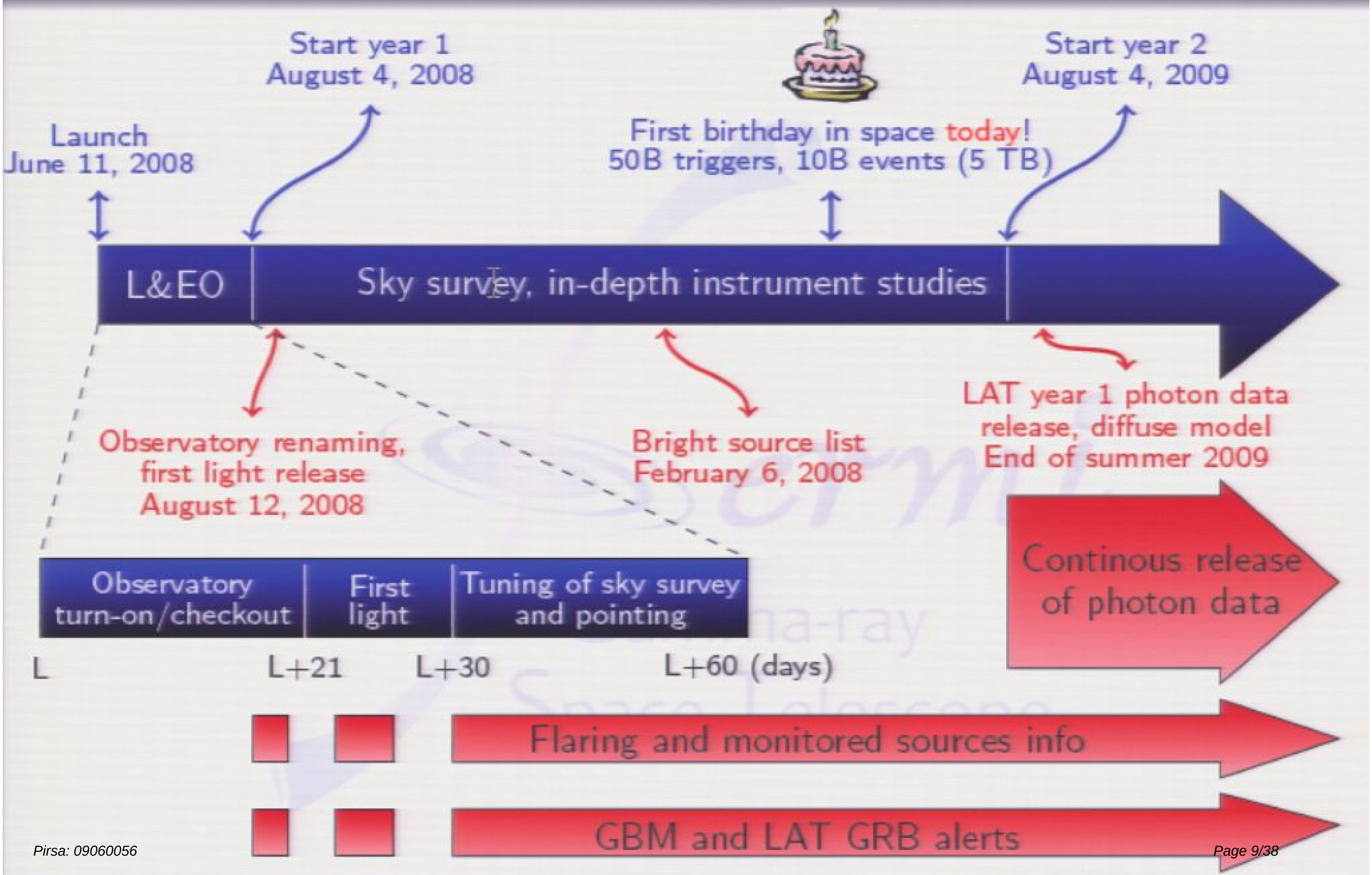
The launch
Turning one year old (in orbit) today!



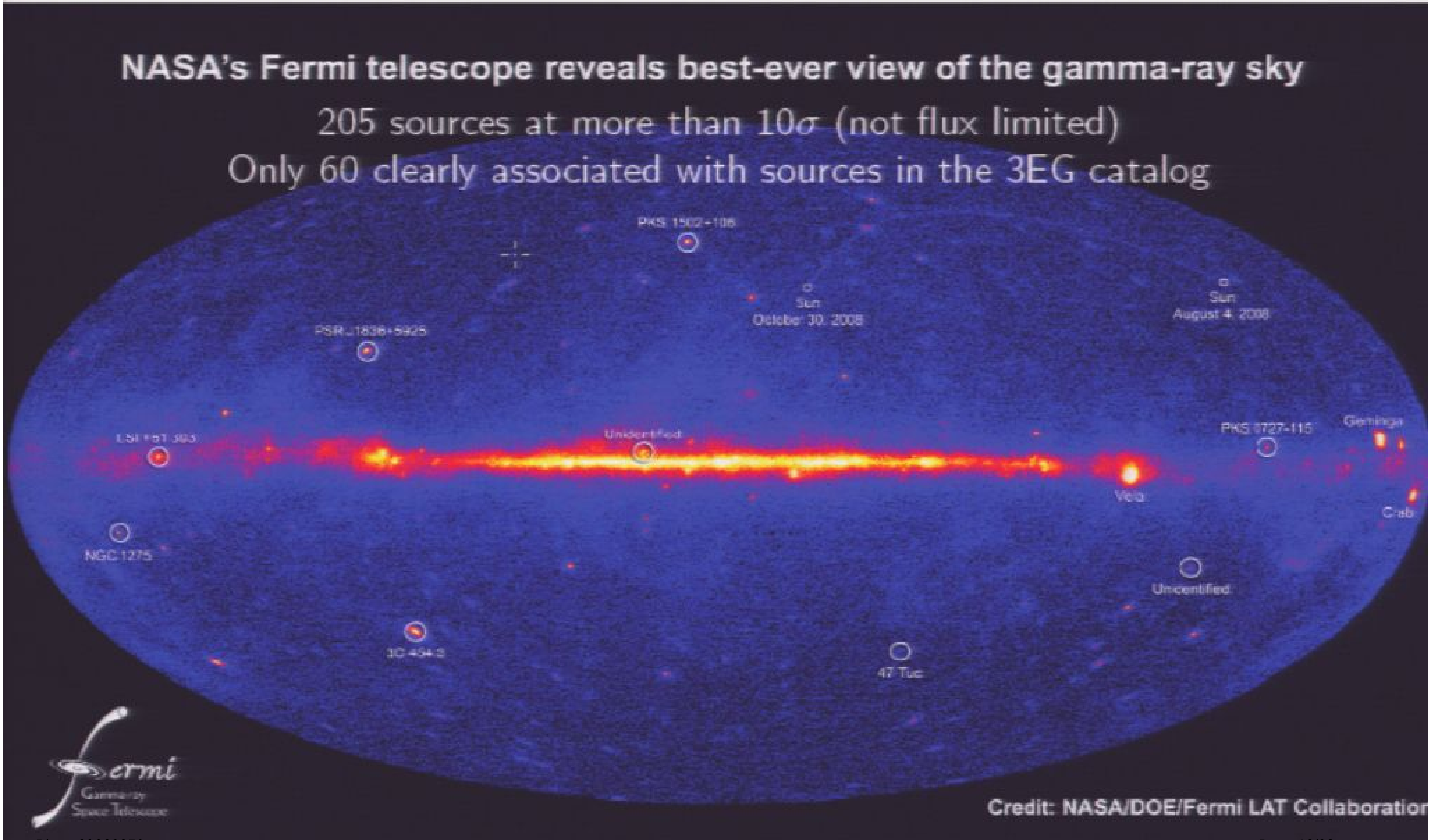
Launch

- Launched on June 11, 2008 from the Kennedy Space Center.
- Launch vehicle: Delta 2920H-10.
- Circular orbit, 565 km altitude, 25.6° inclination.

1 YEAR SCIENCE OPERATION TIMELINE



Three-months gamma-ray sky map



The LAT as an electron detector

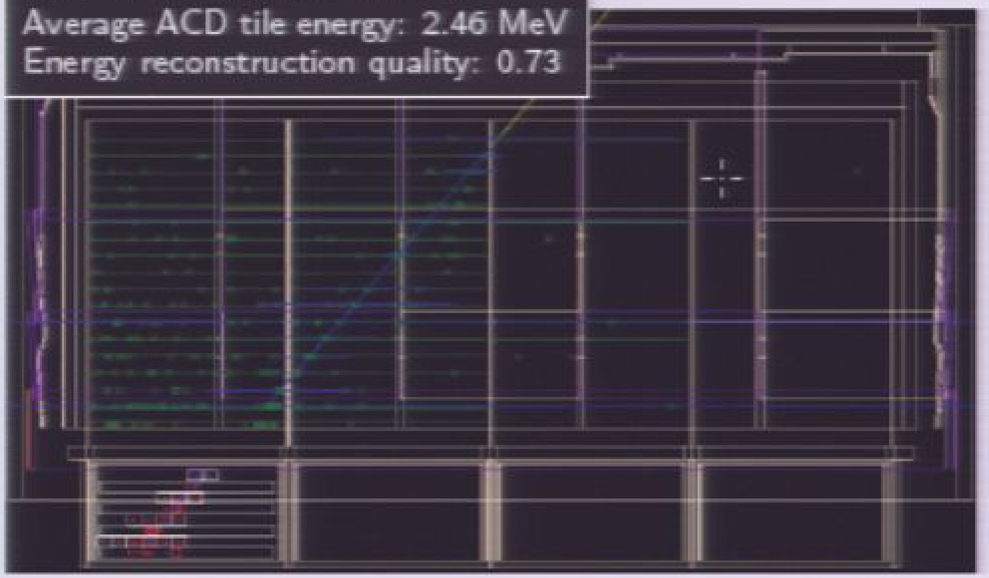
Not only gamma rays

- All events with energy (measured on board) greater than 20 GeV are down-linked to ground.
- Peak geometric factor close to 3 m^2.
- $\approx$ 10 millions of electrons per year above 20 GeV.
- Challenges connected with energy reconstruction and background rejection largely in common with the standard photon analysis.
- Cannot distinguish the charge sign (*electrons* are really $e^+ + e^-$ hereafter.)

Event topology

Candidate electron
475 GeV raw energy, 834 GeV reconstructed

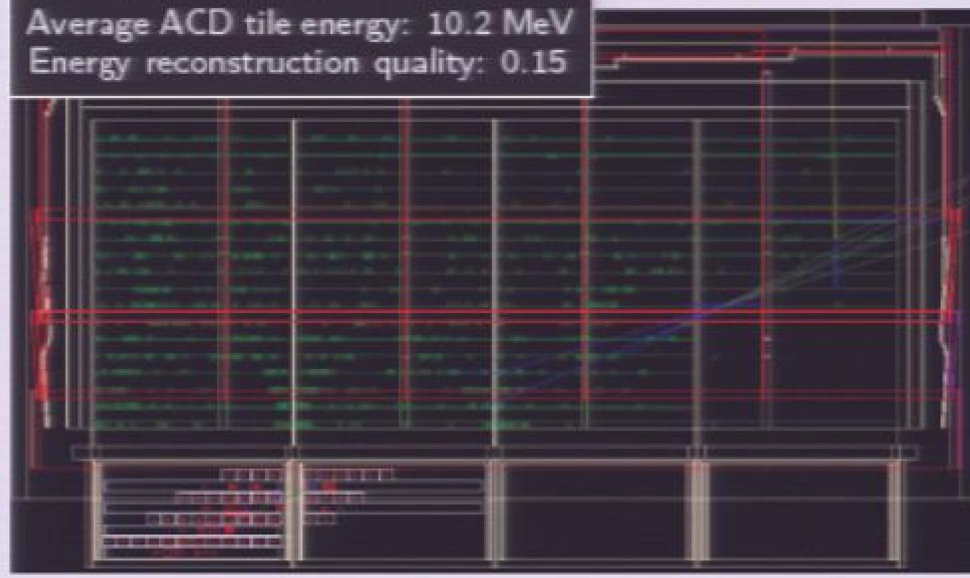
Transverse shower size: 23.2 mm
Fractional extra clusters: 1.48
Average ACD tile energy: 2.46 MeV
Energy reconstruction quality: 0.73



- Clean main track with extra clusters close to the track (note backsplash from the calorimeter).
- Relatively few ACD tile hits, mainly in conjunction with the track.

Candidate hadron
823 GeV raw energy, 1 TeV reconstructed

Transverse shower size: 34.4 mm
Fractional extra clusters: 0.17
Average ACD tile energy: 10.2 MeV
Energy reconstruction quality: 0.15



- Small number of extra clusters around main track, many clusters away from the track.
- Different backsplash topology, large energy deposit per ACD tile.

Event topology

Candidate electron
475 GeV raw energy, 834 GeV reconstructed

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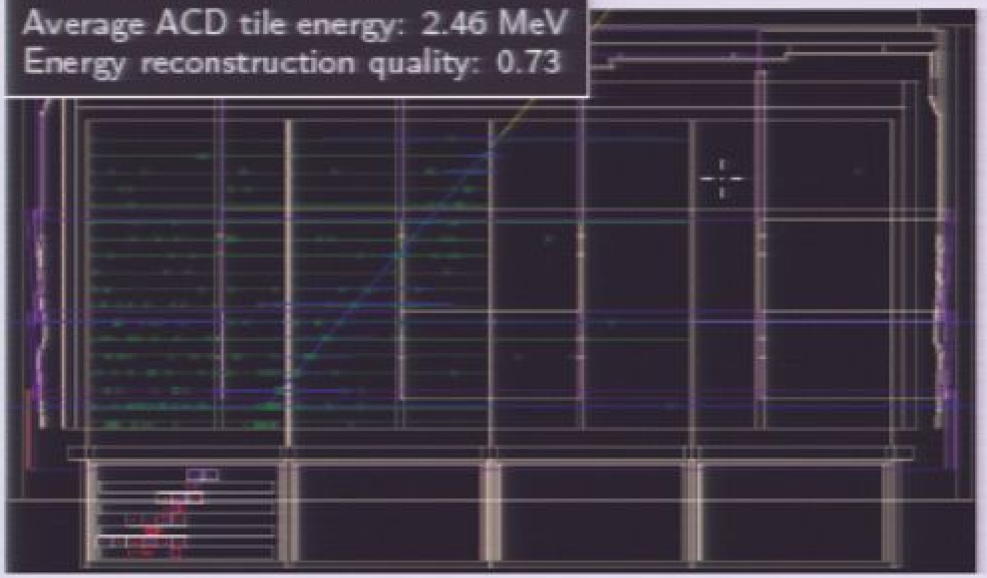

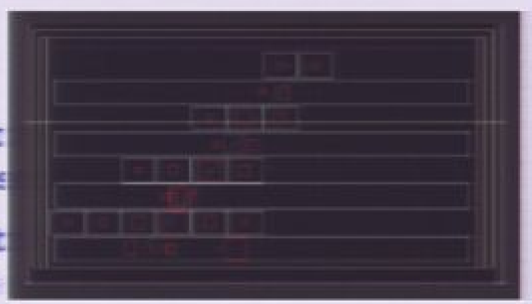

- Clean main track wit
  track (note backsplas
- Relatively few ACD t
  conjunction with the
- Well defined (not fully contained) symmetric shower in the calorimeter.

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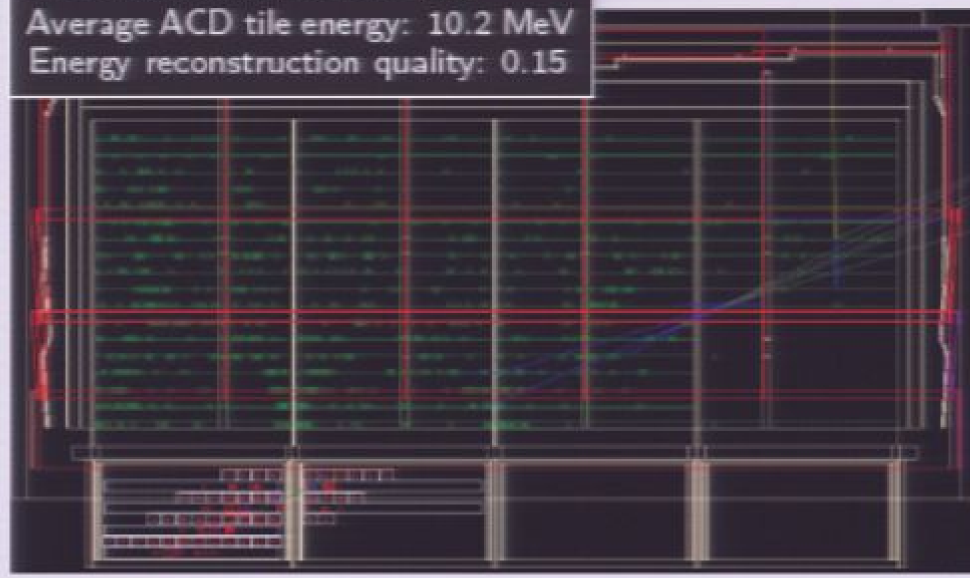
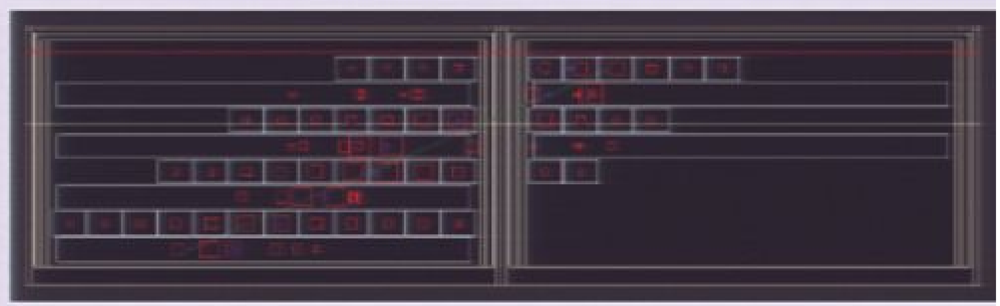
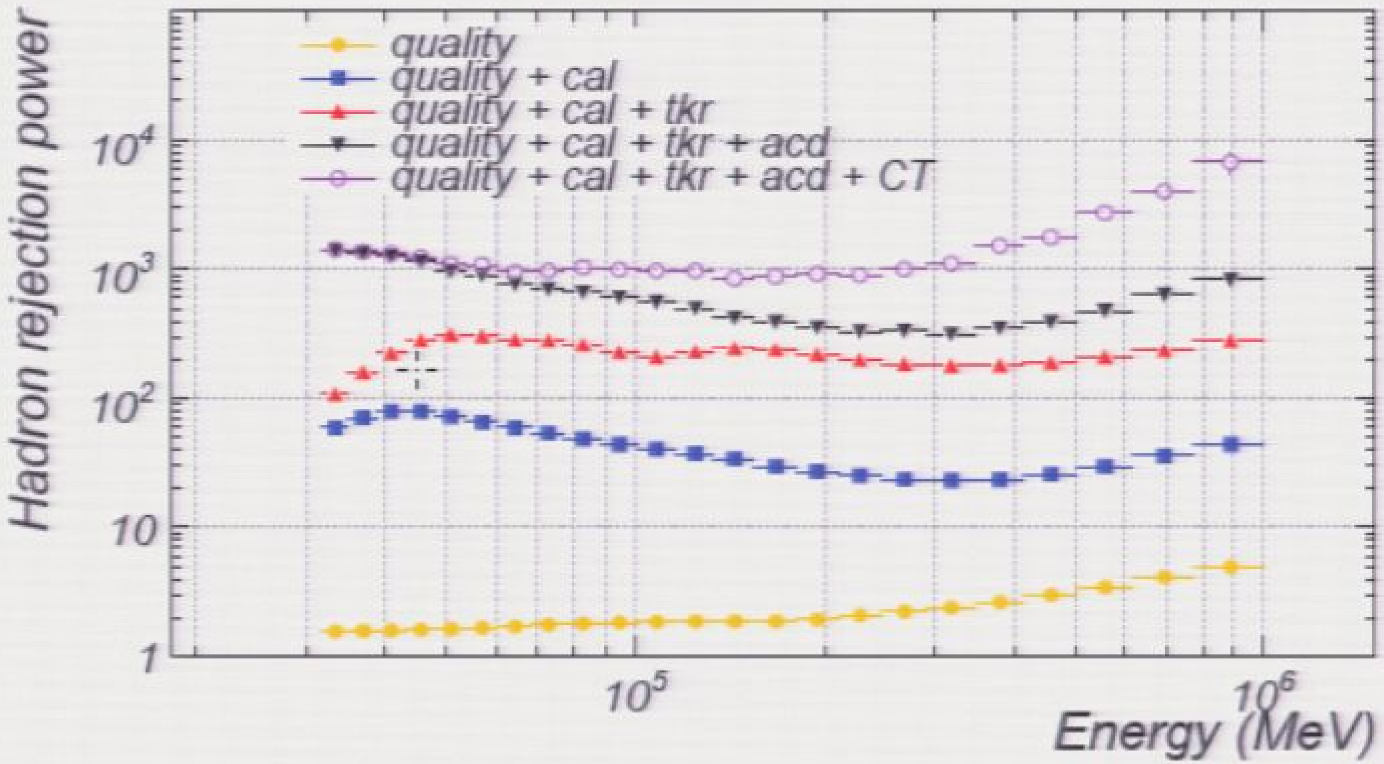




- Large and asymmetric shower profile in the calorimeter.

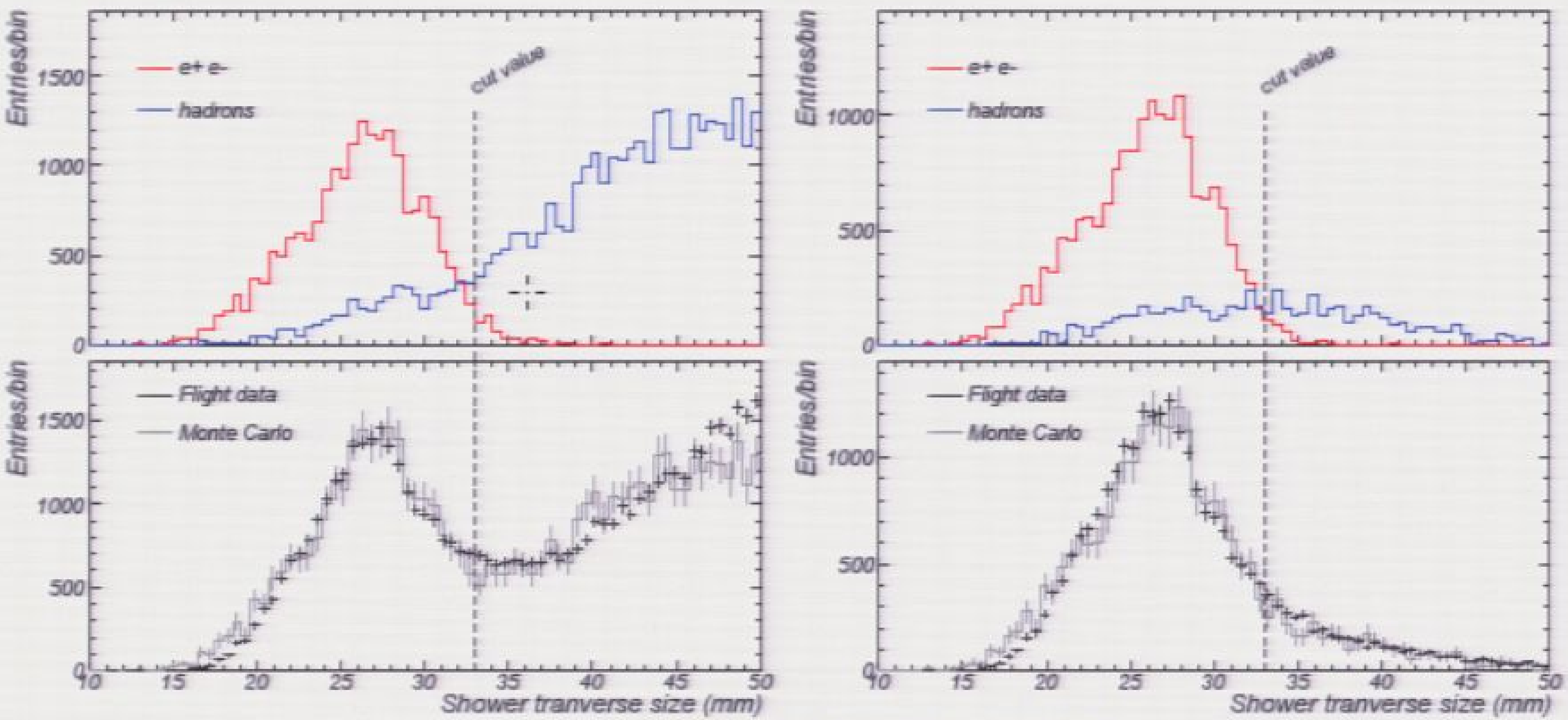
Event selection: rejection power



- Three main steps, in which *all* the subsystems contribute.
  - Basic quality cuts (requiring ACD signal to remove gammas)
  - Event topology in the tracker, calorimeter and ACD.
  - Classification tree analysis:
    - input variables for the CT analysis carefully selected;
    - boost at high energy obtained by means of an explicitly energy-dependent cut.

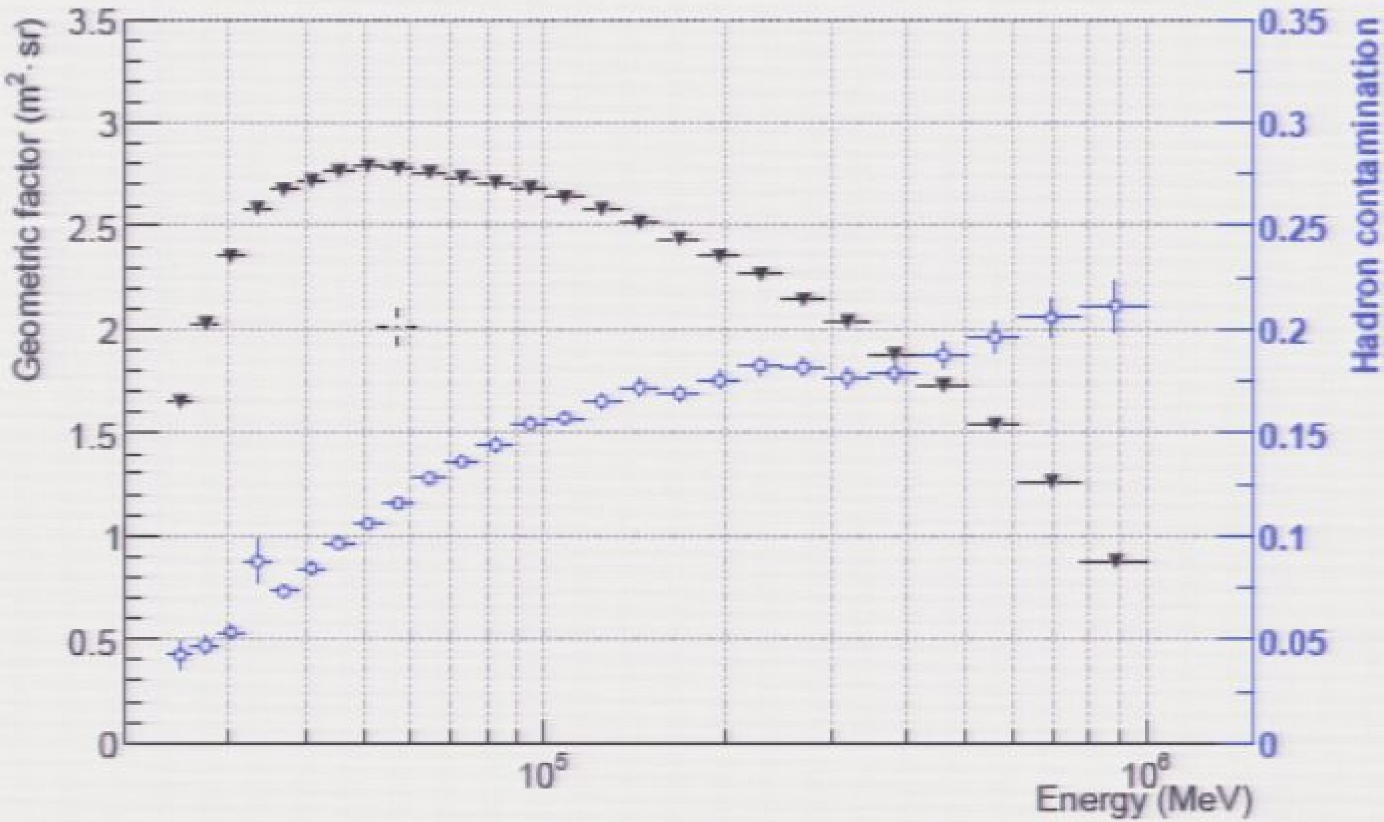
Event selection: validation with flight data

Shower transverse size above 150 GeV



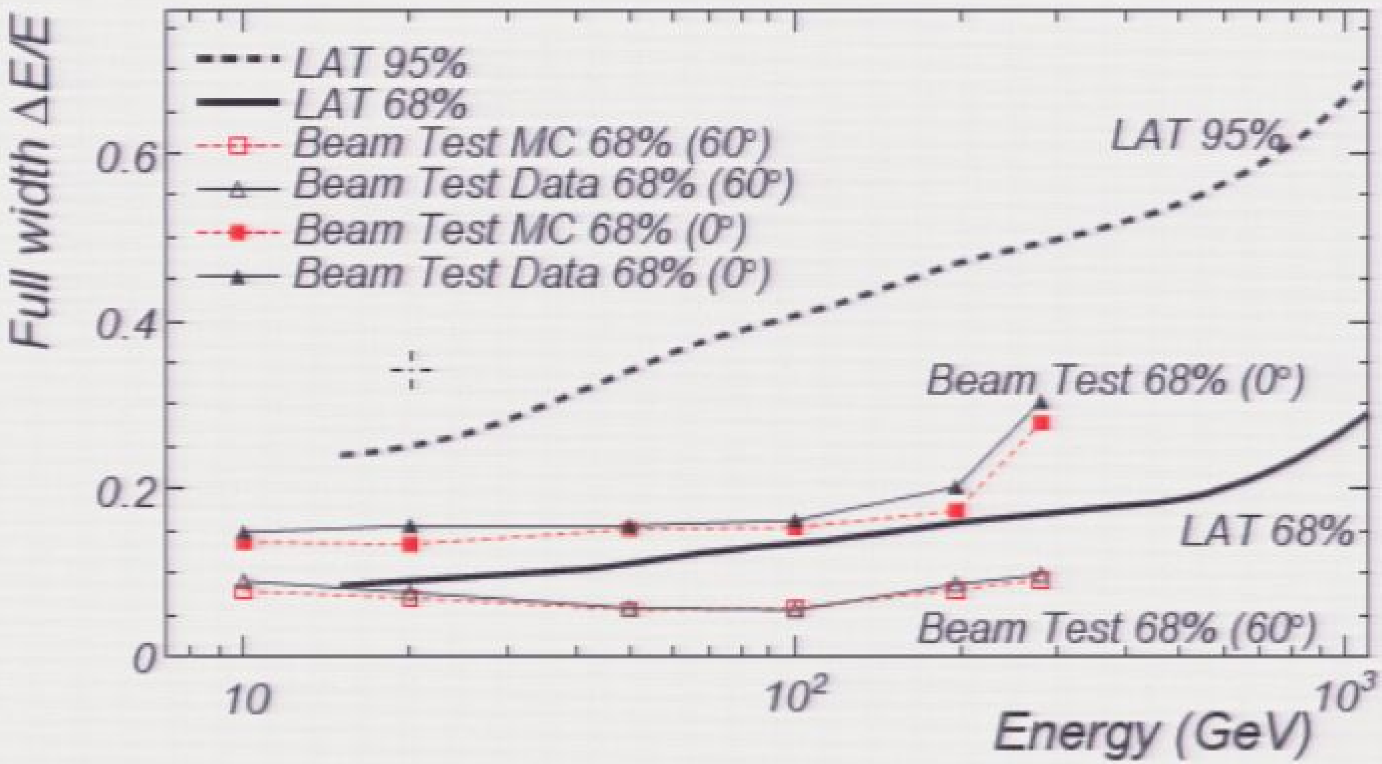
- Data/Monte Carlo comparison routinely performed for:
  - all variables involved in the selection;
  - at different stages of the selection.
- Residual discrepancies propagated to the spectrum *for each energy bin* and included into the systematics.

Event selection: figures of merit



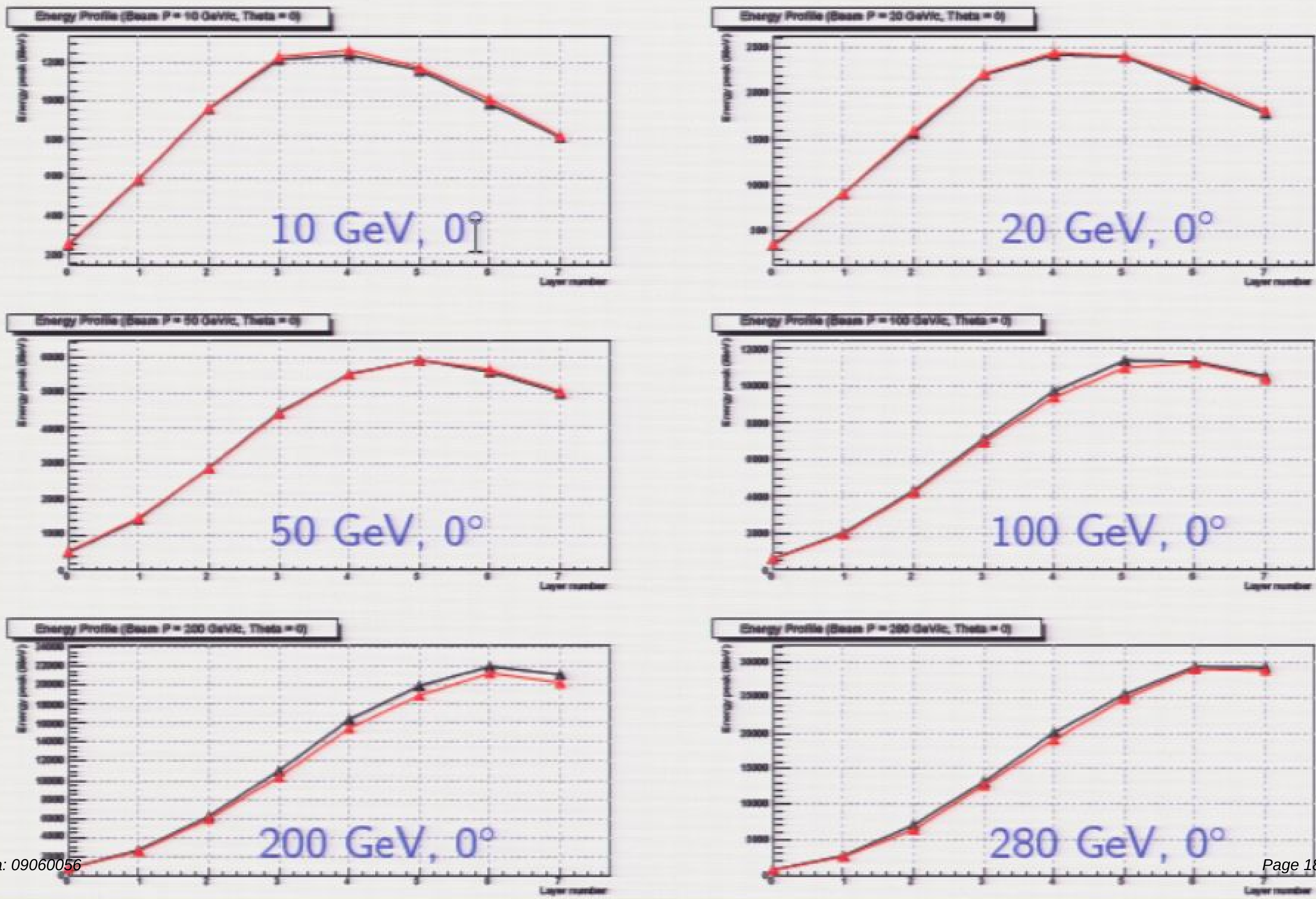
- Peak geometric factor of 2.8 m^2, 2 m^2 at 300 GeV.
- Estimated residual hadron contamination ≈ 5–20%;
  - subtracted from the candidate electrons.
- Trade-off between electron efficiency, residual contamination and control of systematic uncertainties.

Energy resolution



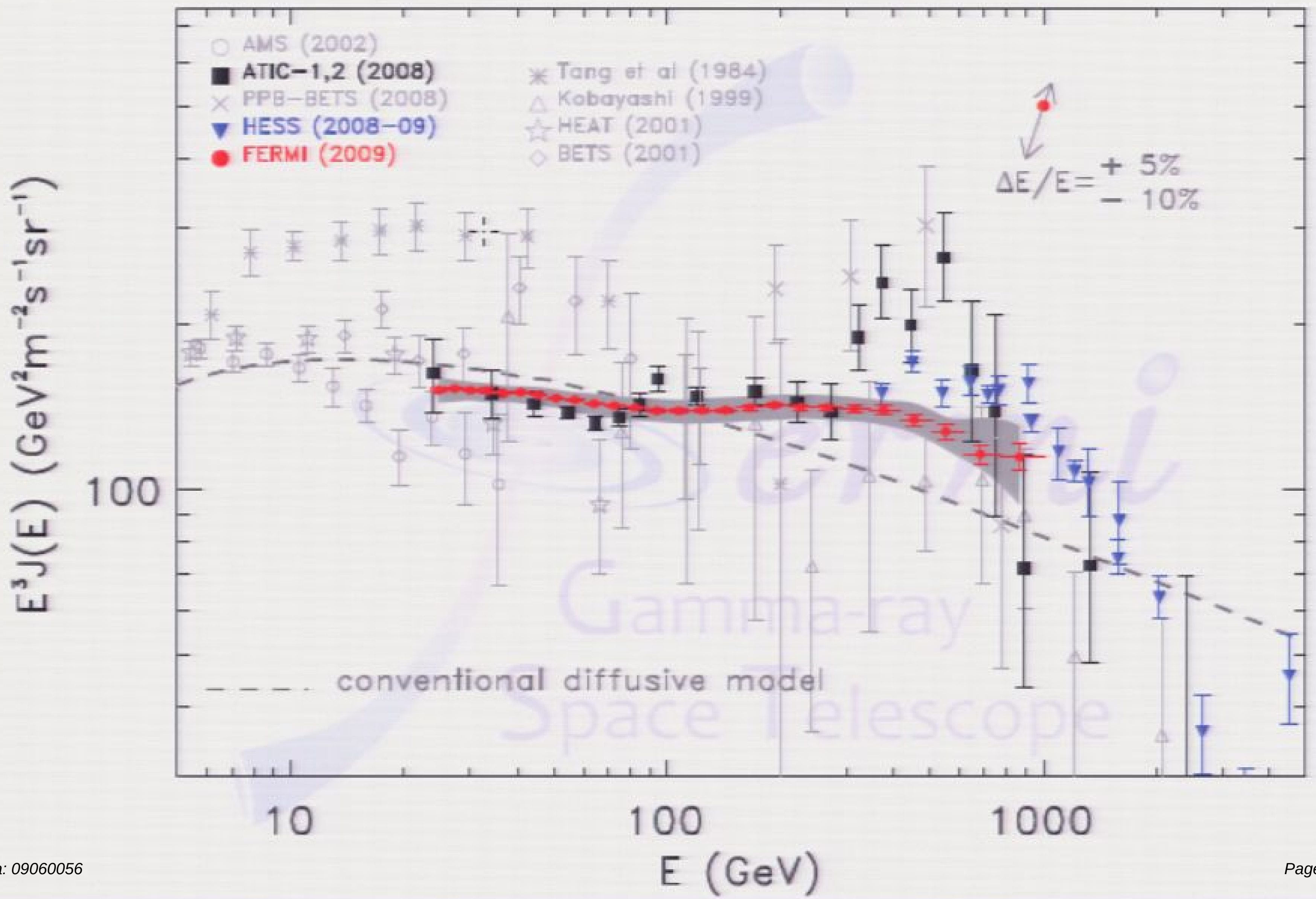
- Validated with the Calibration Unit beam tests up to 280 GeV.
  - Excellent agreement over the whole (energy, angle, position) phase space.
  - We have a solid ground in extrapolating to 1 TeV.
- Our energy dispersion is adequate for the measurement.
  - Candidate electrons traverse 12.5 X_0 on average.

Shower profile: Monte Carlo vs. beam test
Electron beams, on axis



The measured spectrum

Submitted to PRL on March 19, accepted on April 21, published on May 4



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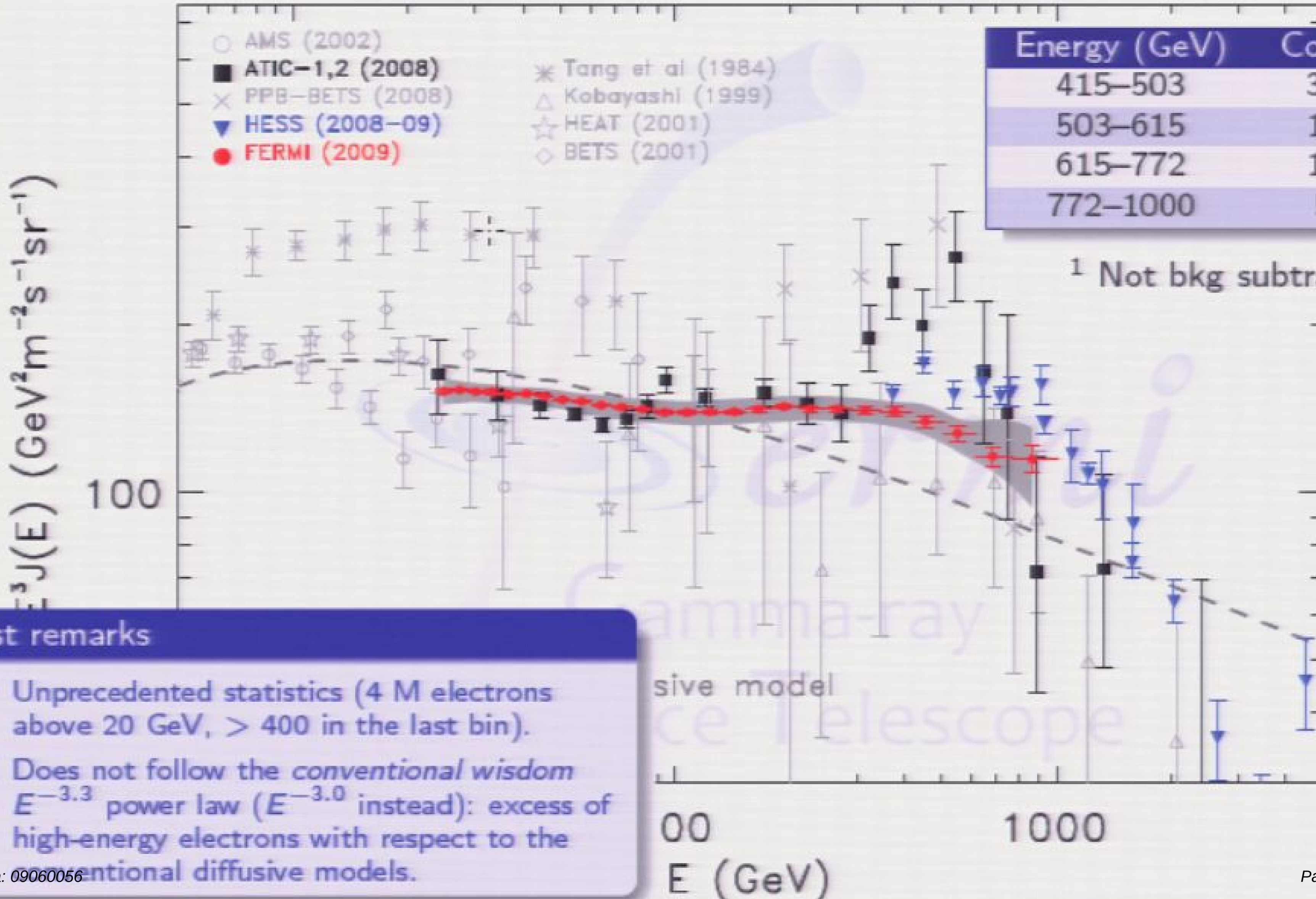


Energy (GeV)	Counts[1]
415–503	3036
503–615	1839
615–772	1039
772–1000	544

[1] Not bkg subtracted.

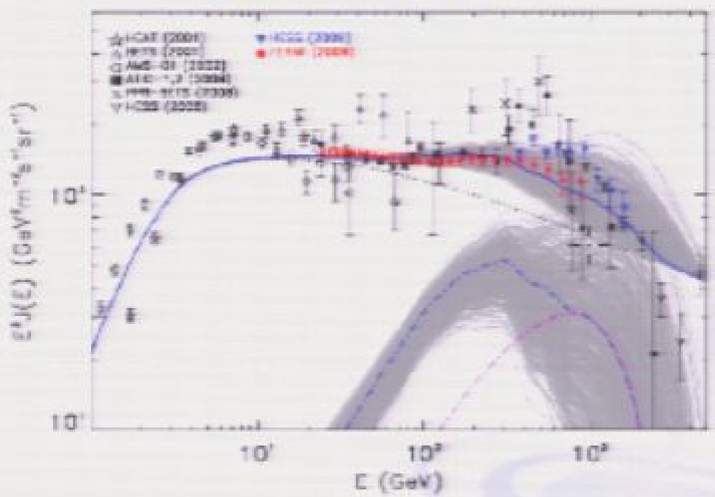
First remarks

- Unprecedented statistics (4 M electrons above 20 GeV, > 400 in the last bin).
- Does not follow the *conventional wisdom* $E^{-3.3}$ power law ($E^{-3.0}$ instead): excess of high-energy electrons with respect to the conventional diffusive models.

INTERPRETATION: QUICK REVIEW

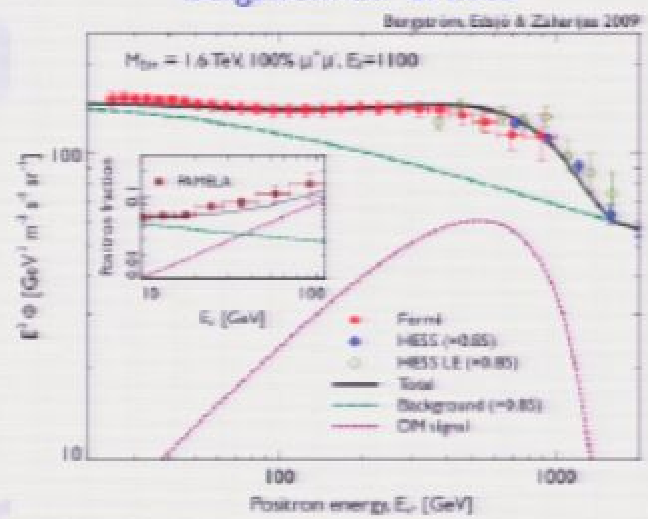
Pulsars

Grasso et. al 2009



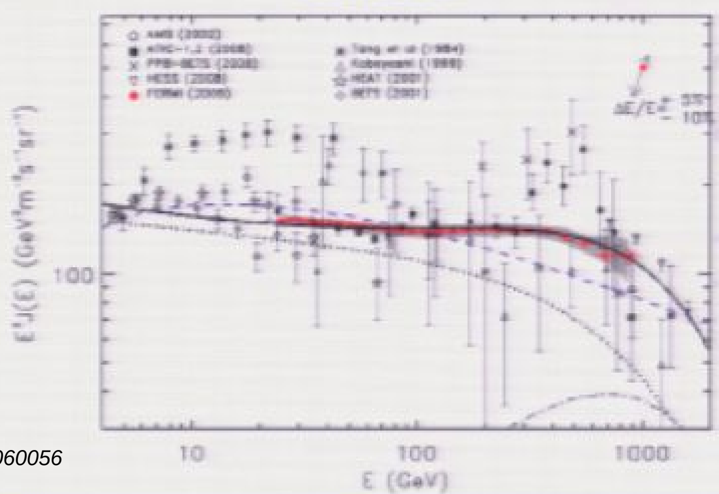
Dark matter annihilation (or decay)

Bergström et. al 2009



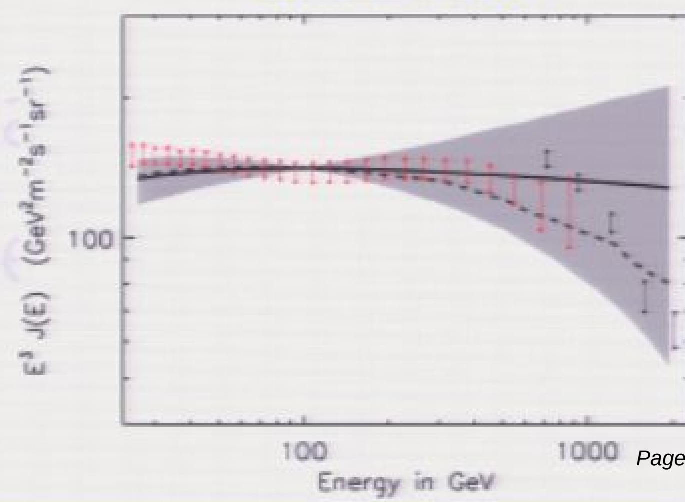
Secondary production in the CR sources

Blasi 2009



Source stocasticity

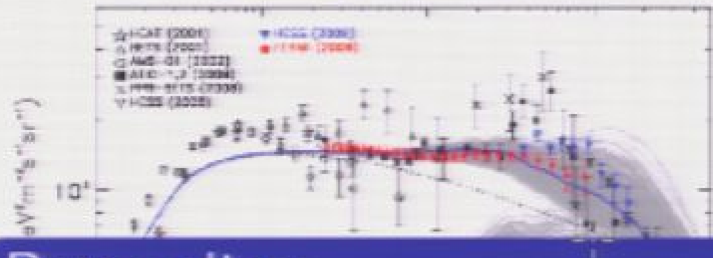
Grasso et. al 2009



Interpretation: quick review

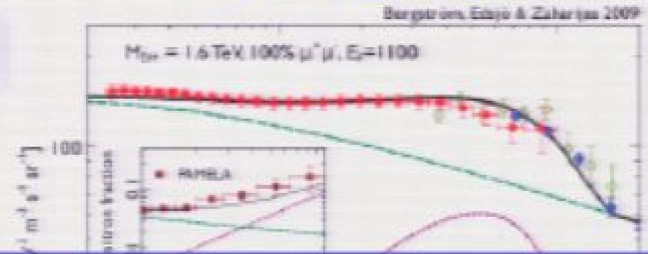
Pulsars

Grasso et. al 2009



Dark matter annihilation (or decay)

Bergström et. al 2009



Bottomline:

- No incontrovertible evidence of dark matter in the electron spectrum
  - The same holds for the other interpretations, as well.
- The CR $e^+ + e^-$ spectrum by itself is not enough to rule out any of the models.

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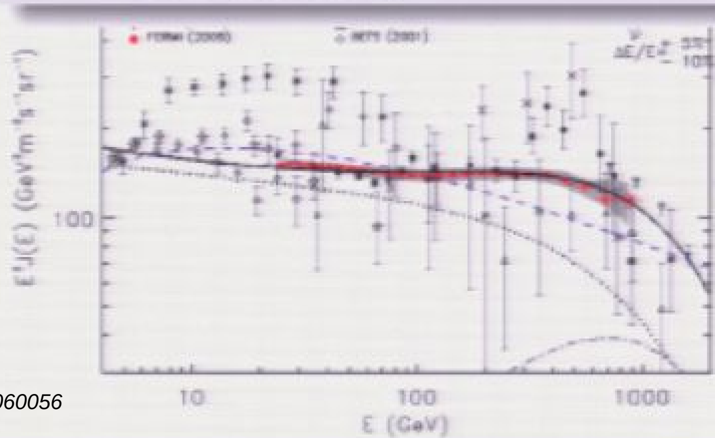
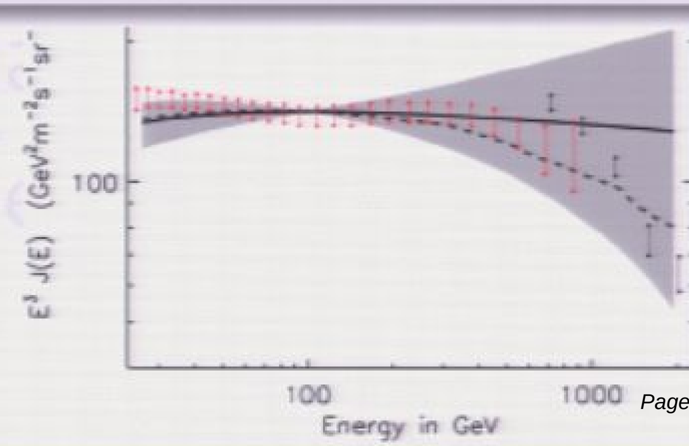
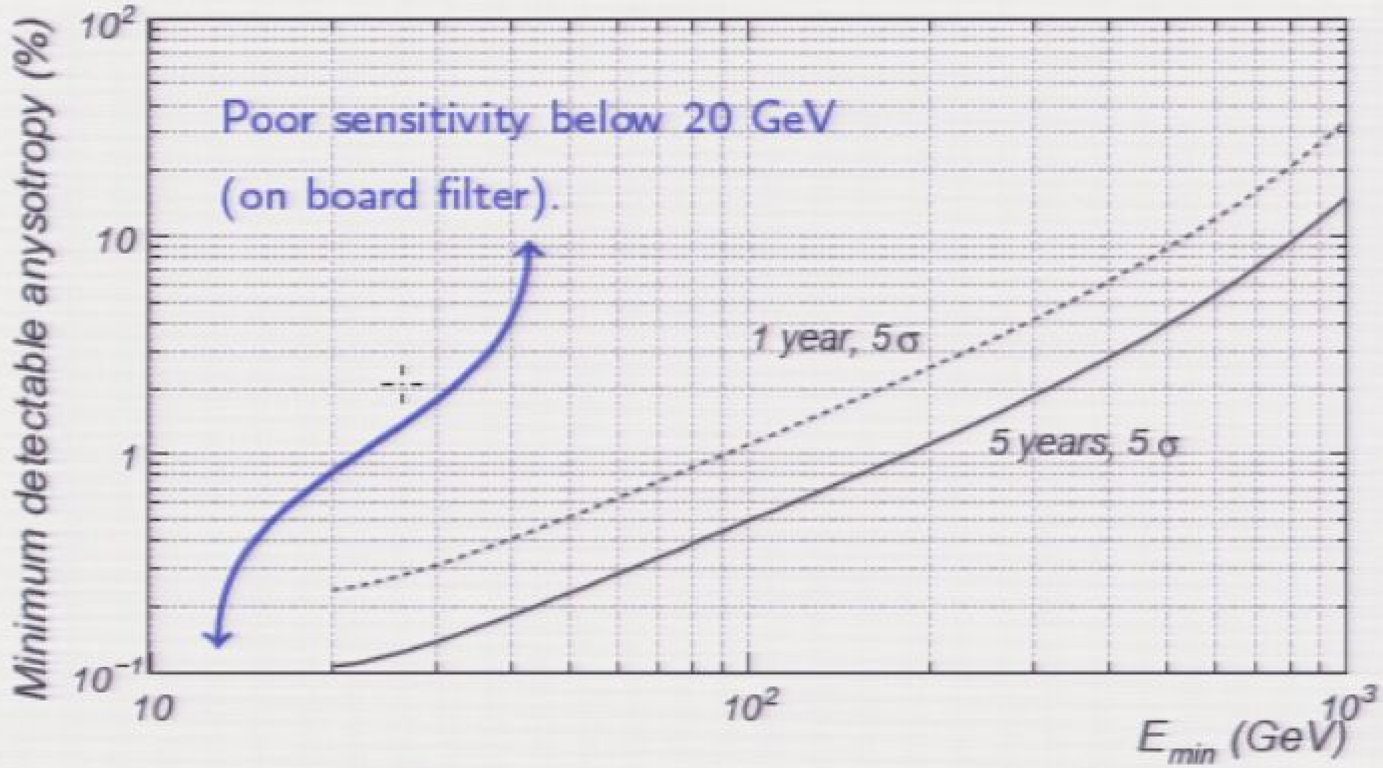




Significance of the bump around ≈ 500 GeV

- It crucially depends on the point-to-point correlation matrix between the systematic errors $C_{ij} = \left\langle \Delta_i^{\text{sys}} \Delta_j^{\text{sys}} \right\rangle$
- Two extreme (unrealistic) cases:
  - $C_{ij} \propto 1 \quad \forall i, j$: the spectrum moves up/down rigidly (i);
  - $C_{ij} \propto \delta_{ij}$: the systematic errors are bin-wise independent, i.e. can be summed in quadrature with the statistical errors (ii);
- Different sources of systematic errors in real life:
  - uncertainty in the overall energy scale: (i) to a good approximation;
  - uncertainty in the overall background flux: $C_{ij} \propto f(E) \quad \forall i, j$;
  - data/Monte Carlo discrepancies through the selection cuts: somehow in between (i) and (ii), with terms very far from diagonal presumably small.
- Detailed analysis underway (not trivial, but can be done).
  - Will not change the best values for the model parameters, but might affect the exclusion contours.

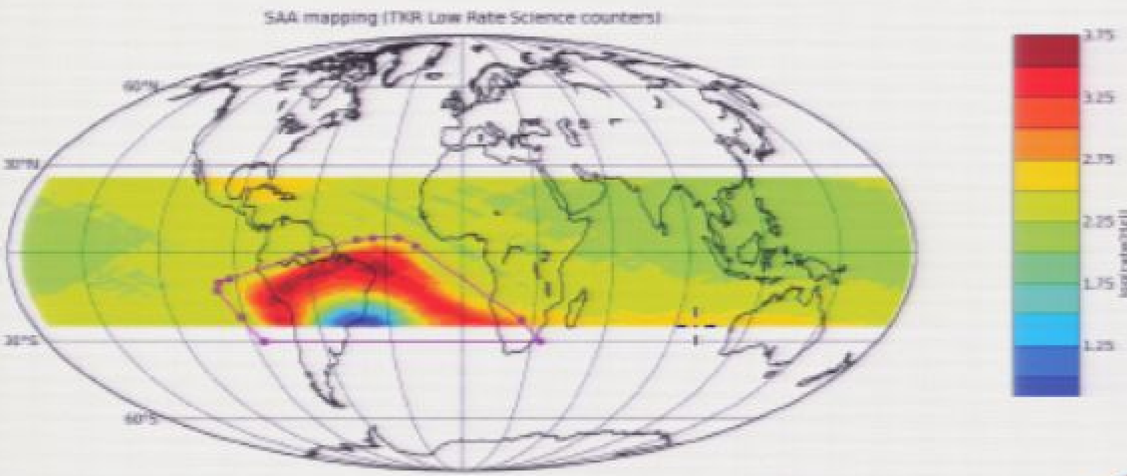
Measurement of anisotropies: statistics



- Limit for the integral dipole anisotropy set by $\delta = \frac{\sqrt{2}N_\sigma}{\sqrt{N_{\mathrm{events}}}}$
- The plot includes the main instrumental effects:
  - Energy-dependent effective geometry factor;
  - Instrumental dead time and duty cycle;
  - On board filter.
- Room for improvements with a better event selection!

Measurements of anisotropies: systematics

Far from being exhaustive

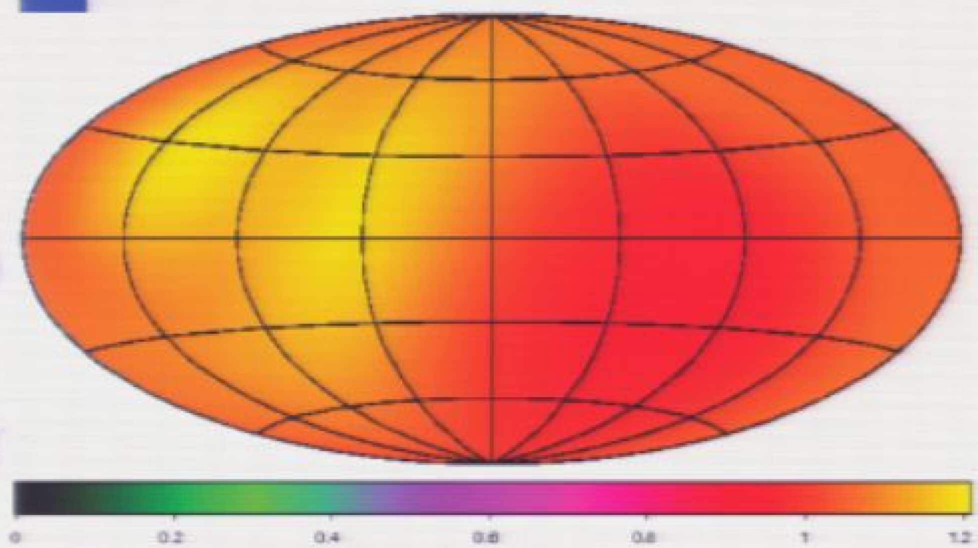


Raw TKR trigger rate

- Terrestrial coordinates (South Atlantic Anomaly clearly visible).
- Fermi does not take science data within the SAA polygon.

Exposure map

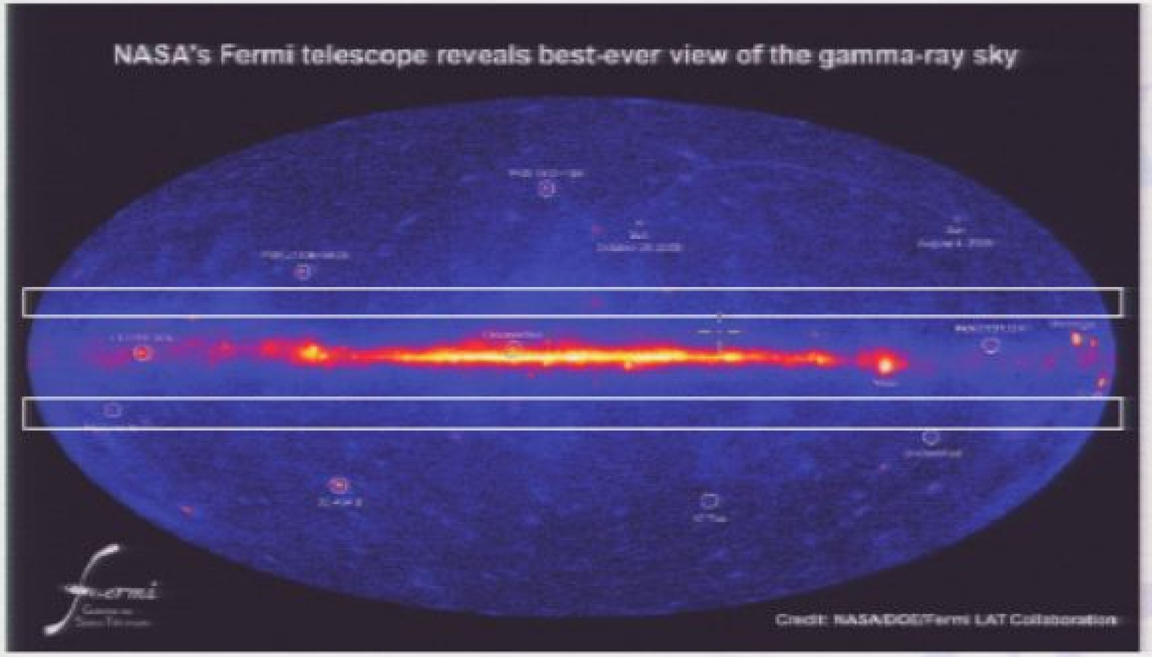
- In galactic coordinates, for gammas, after three months of mission.
- It will *not* be very different for the electrons and for longer time periods.

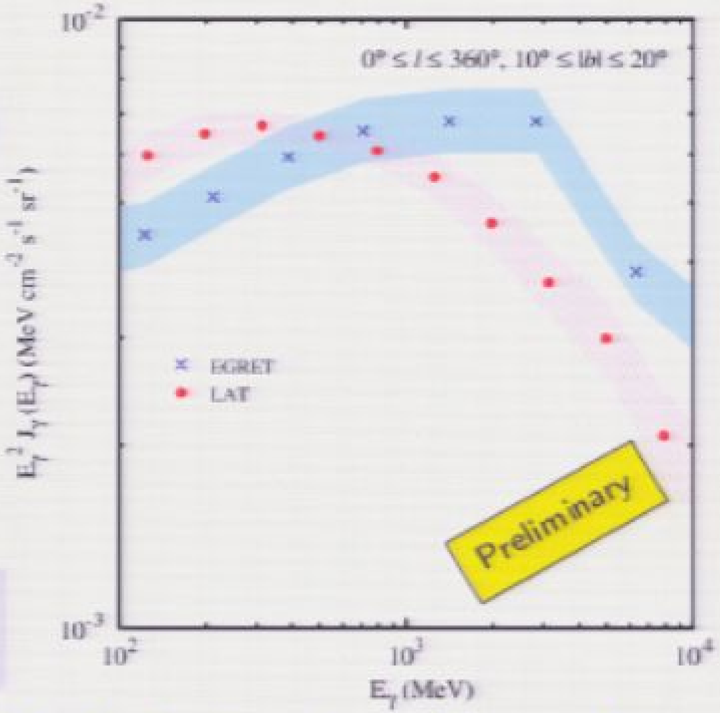


- $\approx$ 25% disuniformity in the exposure (mainly due to the SAA).
- The error on the exposure is a source of systematics for the measurement of anisotropies.

Diffuse gamma: non-GeV excess

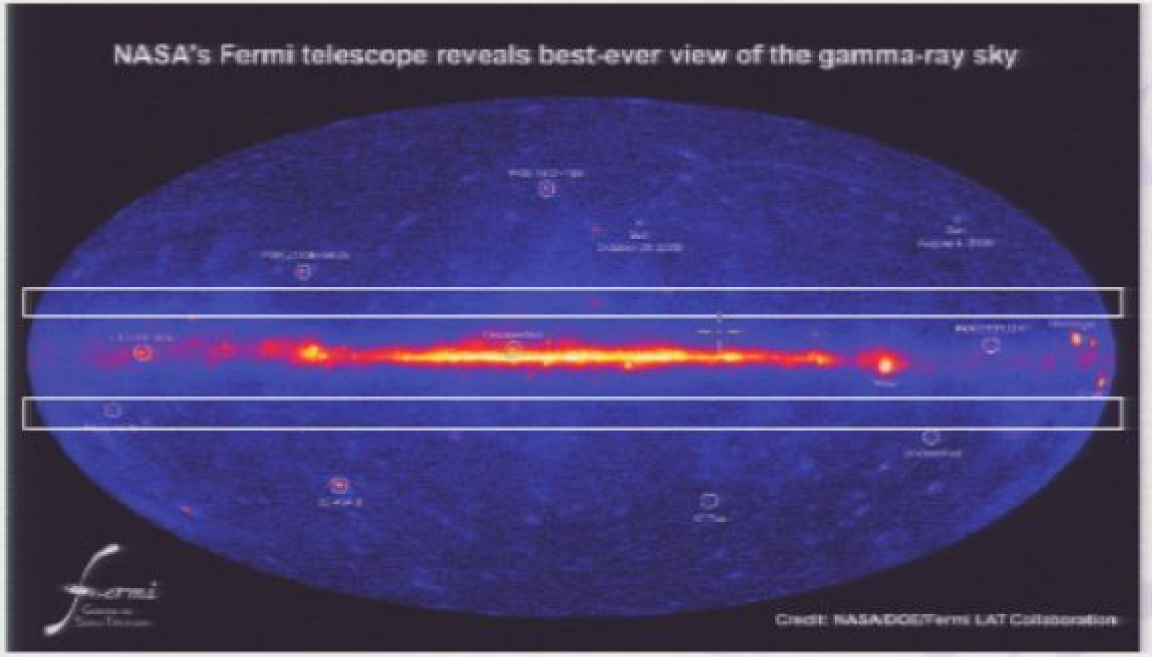
Submitted to PRL

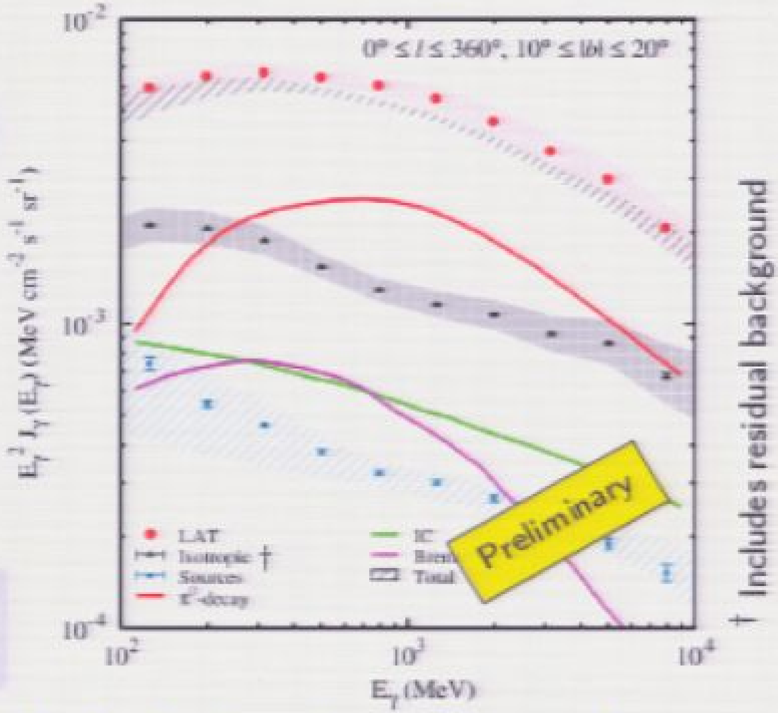




- 4.5 months of data, $10° \leq |b| \leq 20°$ (minimize the effect of uncertainties on the CR propagation and gas distribution).
  - Lower latitudes: large scale DGE.
  - Higher latitudes: instrumental background and DGE model.
- The EGRET all-sky excess is not confirmed.

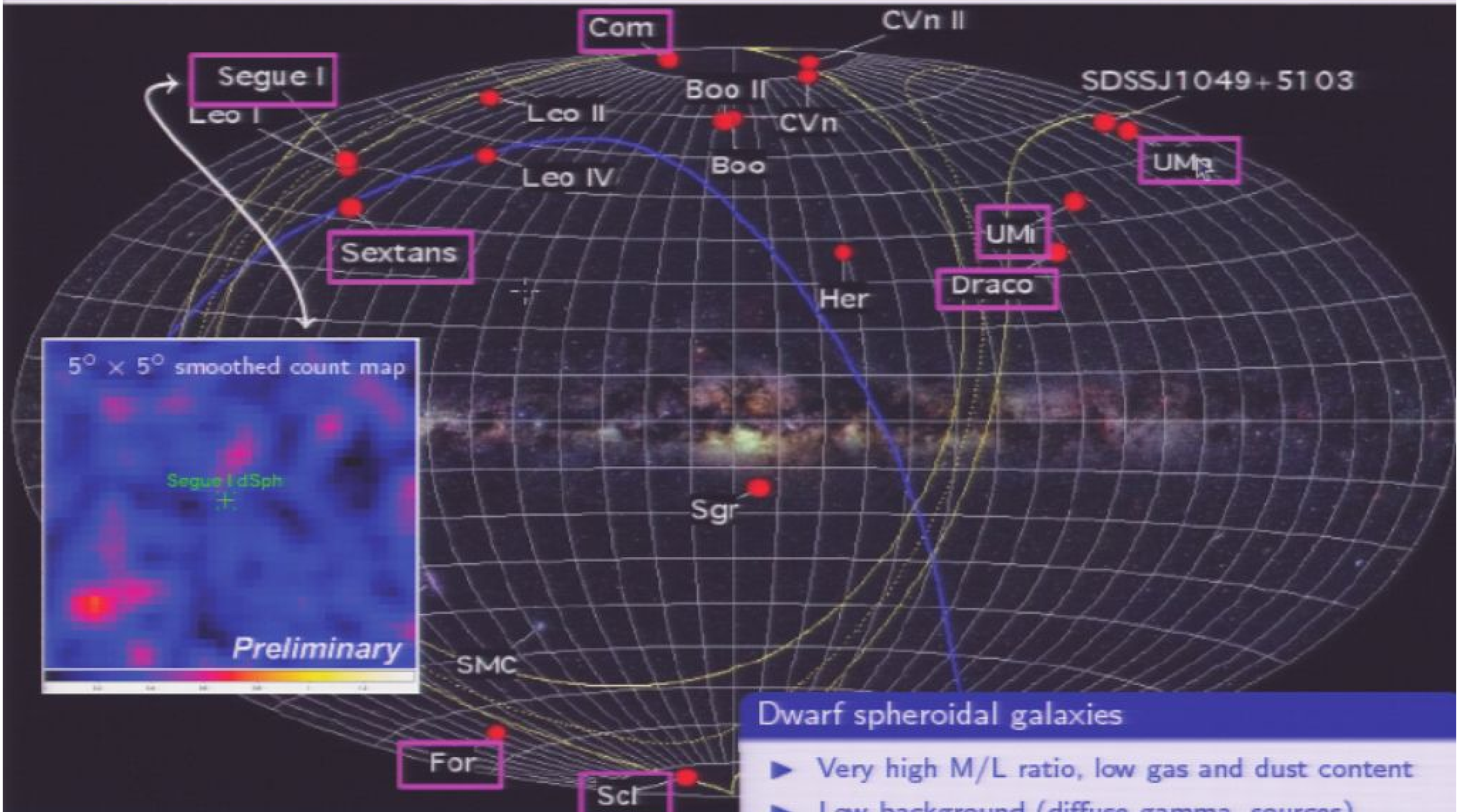
Diffuse gamma: non-GeV excess
Submitted to PRL





- 4.5 months of data, $10^\circ \leq |b| \leq 20^\circ$ (minimize the effect of uncertainties on the CR propagation and gas distribution).
  - Lower latitudes: large scale DGE.
  - Higher latitudes: instrumental background and DGE model.
- The EGRET all-sky excess is not confirmed.
- Fermi data well reproduced by an a-priori DE model.

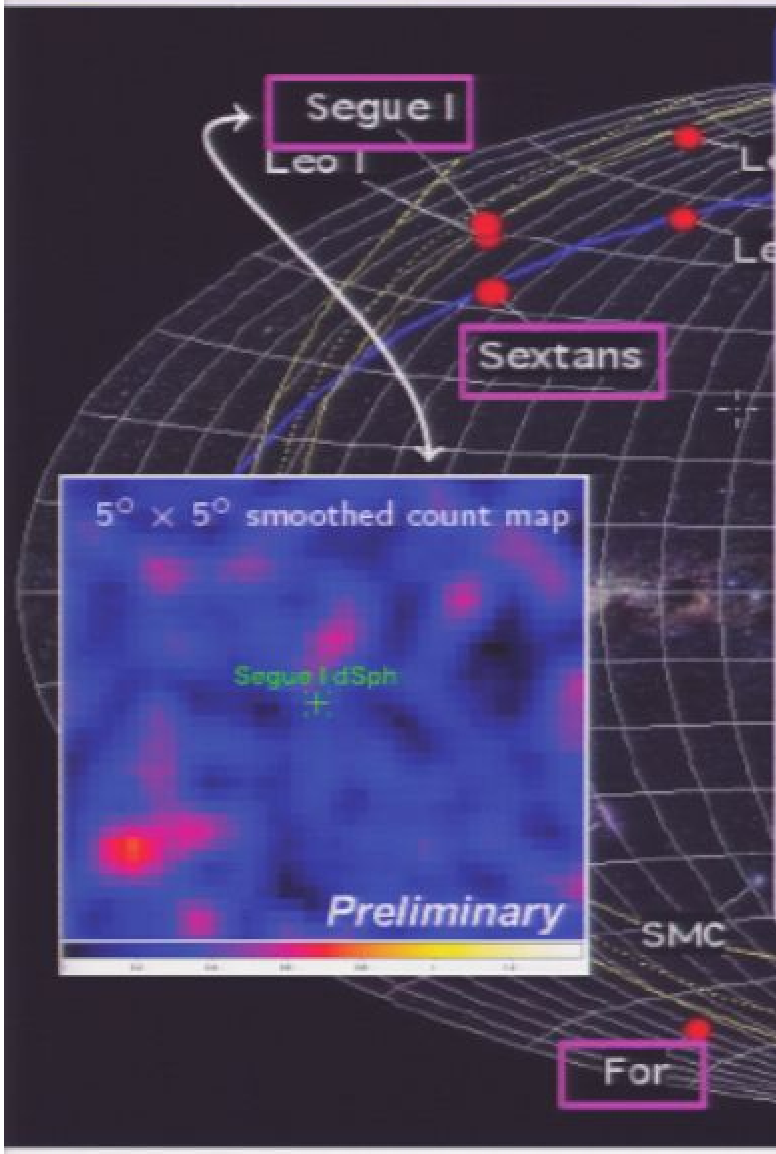
Dwarf spheroidal galaxies



Dwarf spheroidal galaxies

- Very high M/L ratio, low gas and dust content
- Low background (diffuse gamma, sources).
- 10 candidate DSph galaxies (nearby, far from the galactic plane, known kinematic parameters).

Dwarf spheroidal galaxies



Upper limits with three-months data†

Source	U. L. flux > 100 MeV (95% C. L.)
Segue 1	$0.4 \times 10^{-9} \mathrm{cm}^{-2} \mathrm{s}^{-1}$
Ursa Major II	$0.4 \times 10^{-9} \mathrm{cm}^{-2} \mathrm{s}^{-1}$
Segue 2	$0.3 \times 10^{-9} \mathrm{cm}^{-2} \mathrm{s}^{-1}$
Willman 1	$0.3 \times 10^{-9} \mathrm{cm}^{-2} \mathrm{s}^{-1}$
Coma Berenices	$0.3 \times 10^{-9} \mathrm{cm}^{-2} \mathrm{s}^{-1}$
Ursa Minor	$0.3 \times 10^{-9} \mathrm{cm}^{-2} \mathrm{s}^{-1}$
Sculptor	$0.5 \times 10^{-9} \mathrm{cm}^{-2} \mathrm{s}^{-1}$
Draco	$0.3 \times 10^{-9} \mathrm{cm}^{-2} \mathrm{s}^{-1}$
Sextans	$0.4 \times 10^{-9} \mathrm{cm}^{-2} \mathrm{s}^{-1}$
Fornax	$0.4 \times 10^{-9} \mathrm{cm}^{-2} \mathrm{s}^{-1}$

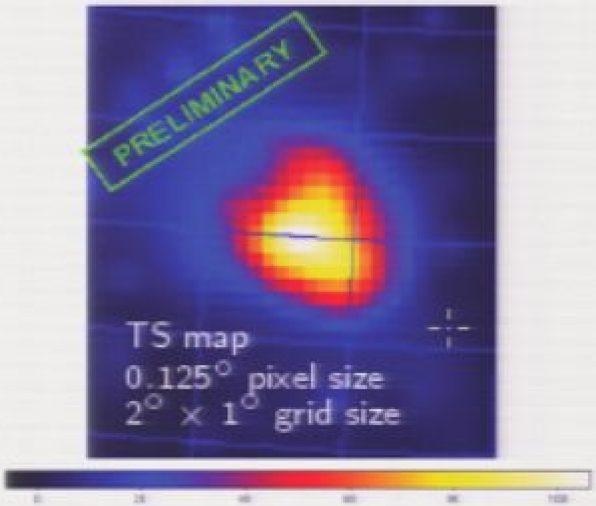
† Assuming $\Gamma = -1$ (reasonable approximation of the FSR spectrum from leptonic final states).

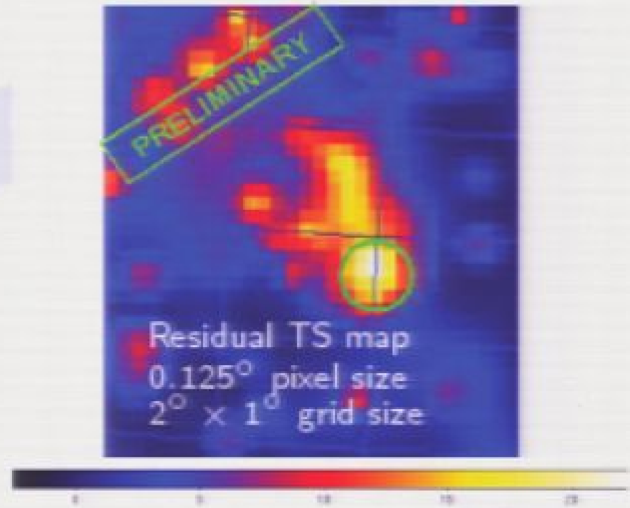
Dwarf spheroidal galaxies

- Very high M/L ratio, low gas and dust content
- Low background (diffuse gamma, sources).
- 10 candidate DSph galaxies (nearby, far from the galactic plane, known kinematic parameters).

Dark matter galactic satellites

Blind search





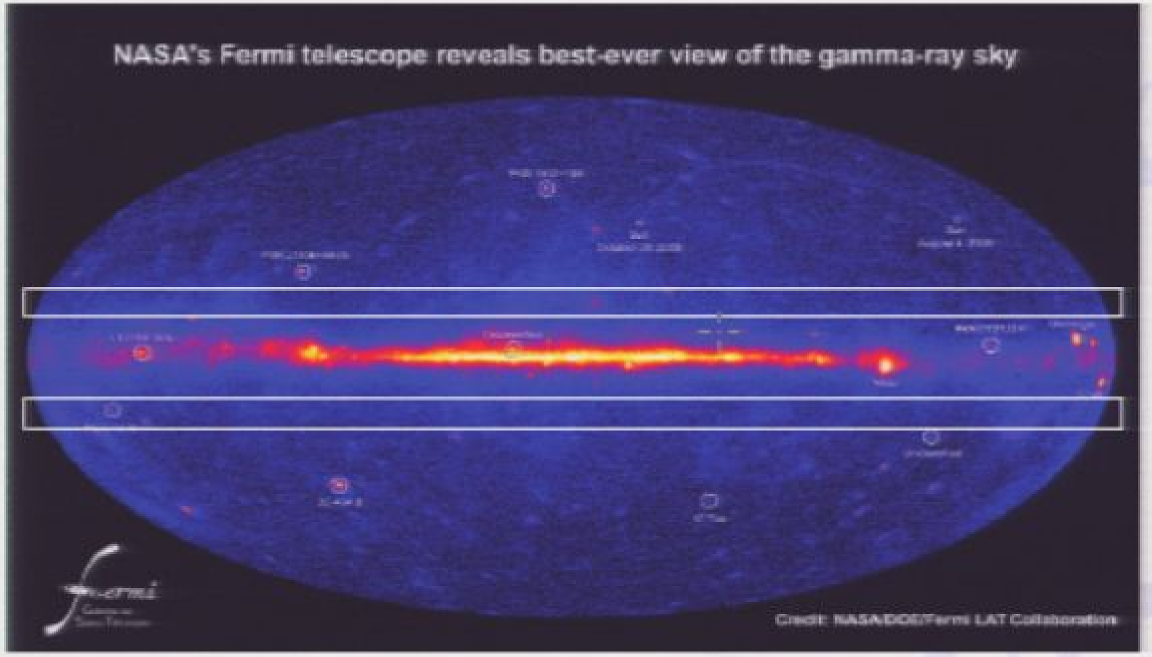
- Search for DM subhalos:
  - no counterpart at other wavelengths;
  - extended (order of $\approx 1^\circ$), not variable;
  - no power-law energy spectrum.
- No evidence for DM satellites, based on 3 months of data.
  - One potential candidate, most likely two sources very close to each other.
- Consistent with the results of pre-launch sensitivity studies.
  - Analysis of first-year data ongoing.

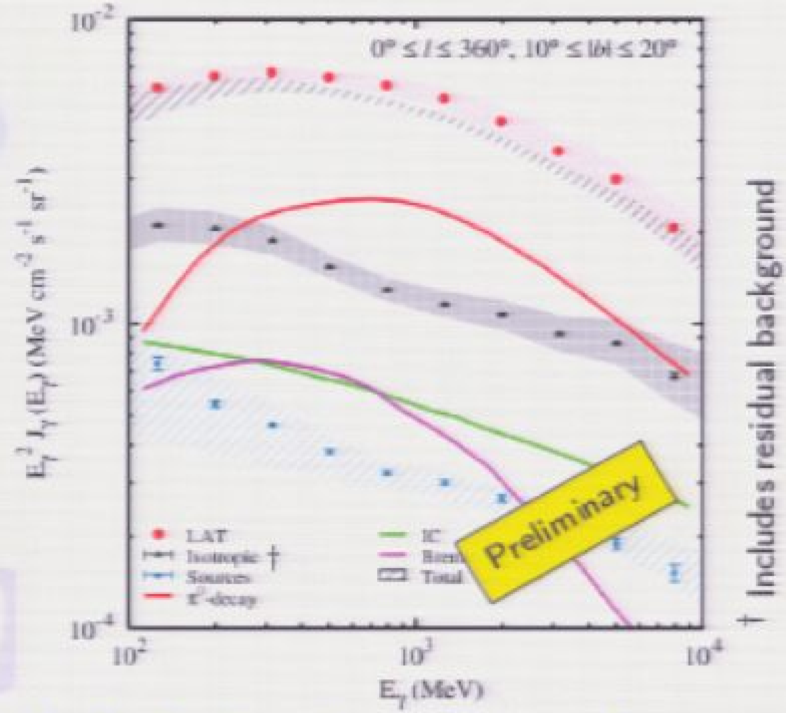
Conclusions

- The last two years have been very exciting:
  - Fermi has provided the first high-statistic measurement of the $e^+ + e^-$ spectrum;
  - Measurements by two other experiments: ATIC, HESS.
- $e^+ + e^-$ not enough to really constrain models, other pieces of the puzzles being positron and antiproton ratios, gammas (at different wavelengths), neutrinos.
- More exciting years yet to come:
  - more data from several experiments in the near future.
- Fermi will play a crucial role:
  - improvements in the analysis ongoing: extend energy reach, reduce systematics;
  - an anisotropy of 1–few% at $\approx$ hundreds of GeV (predicted by realistic models) definitely within reach if present;
  - many more data in gammas: diffuse at different energies and latitudes, line search, galactic center, dwarf galaxies, dark matter satellites.

Diffuse gamma: non-GeV excess

Submitted to PRL





- 4.5 months of data, $10^\circ \leq |b| \leq 20^\circ$ (minimize the effect of uncertainties on the CR propagation and gas distribution).
  - Lower latitudes: large scale DGE.
  - Higher latitudes: instrumental background and DGE model.
- The EGRET all-sky excess is not confirmed.
- Fermi data well reproduced by an a-priori DE model.

Diffuse gamma: non-GeV excess

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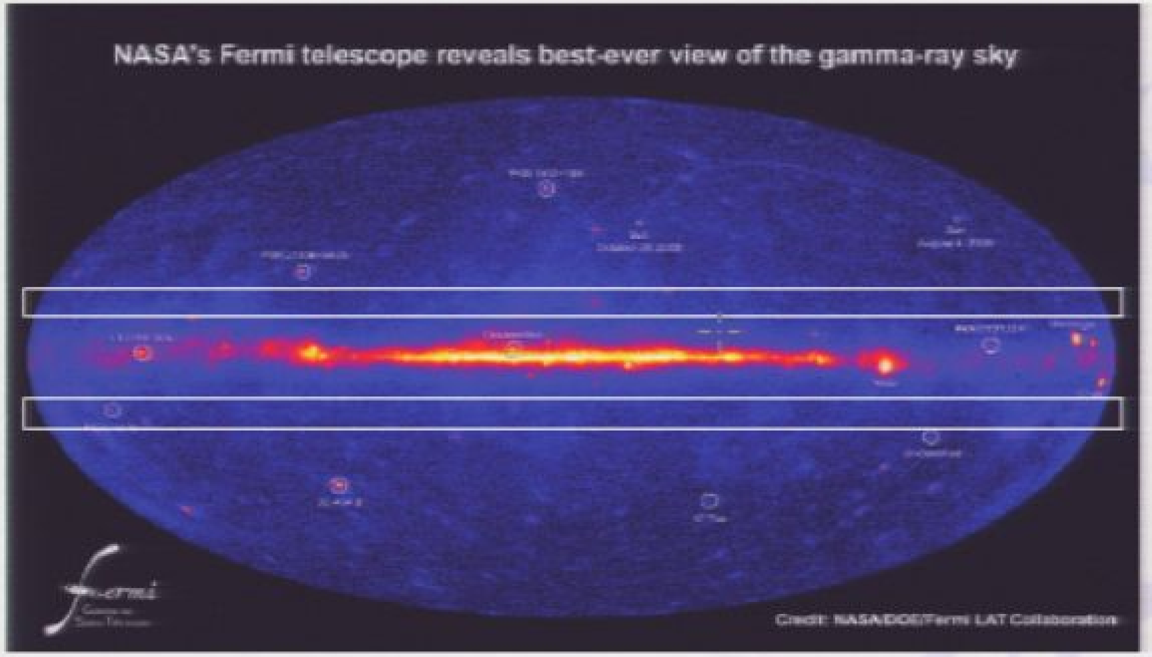

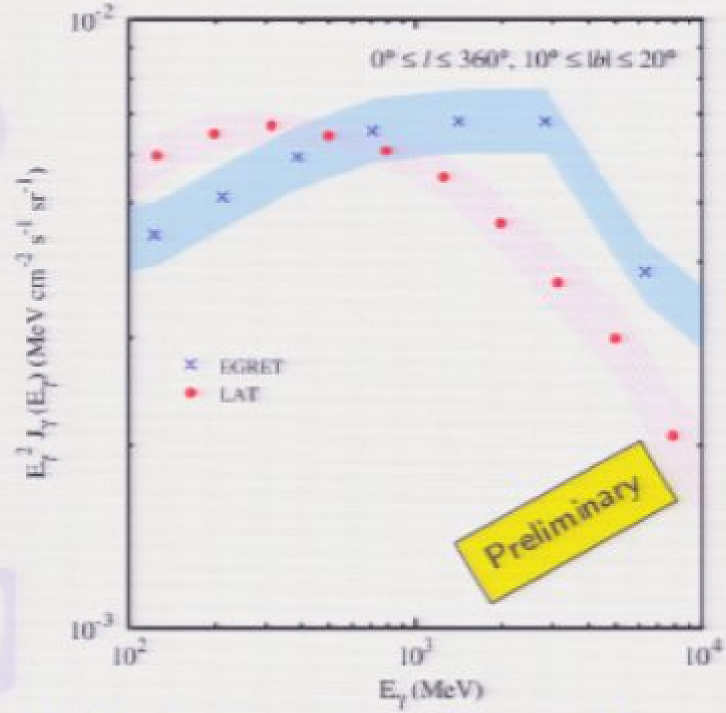

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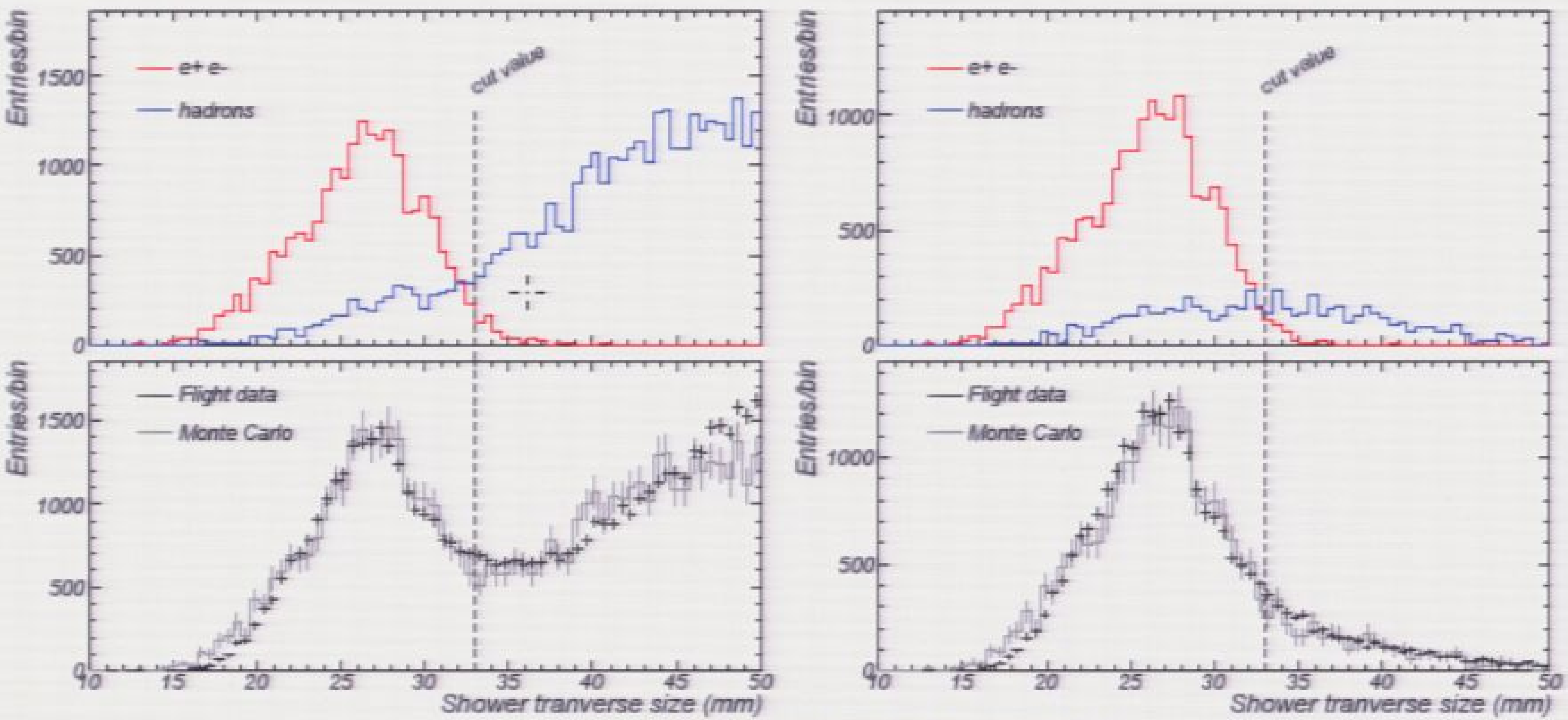
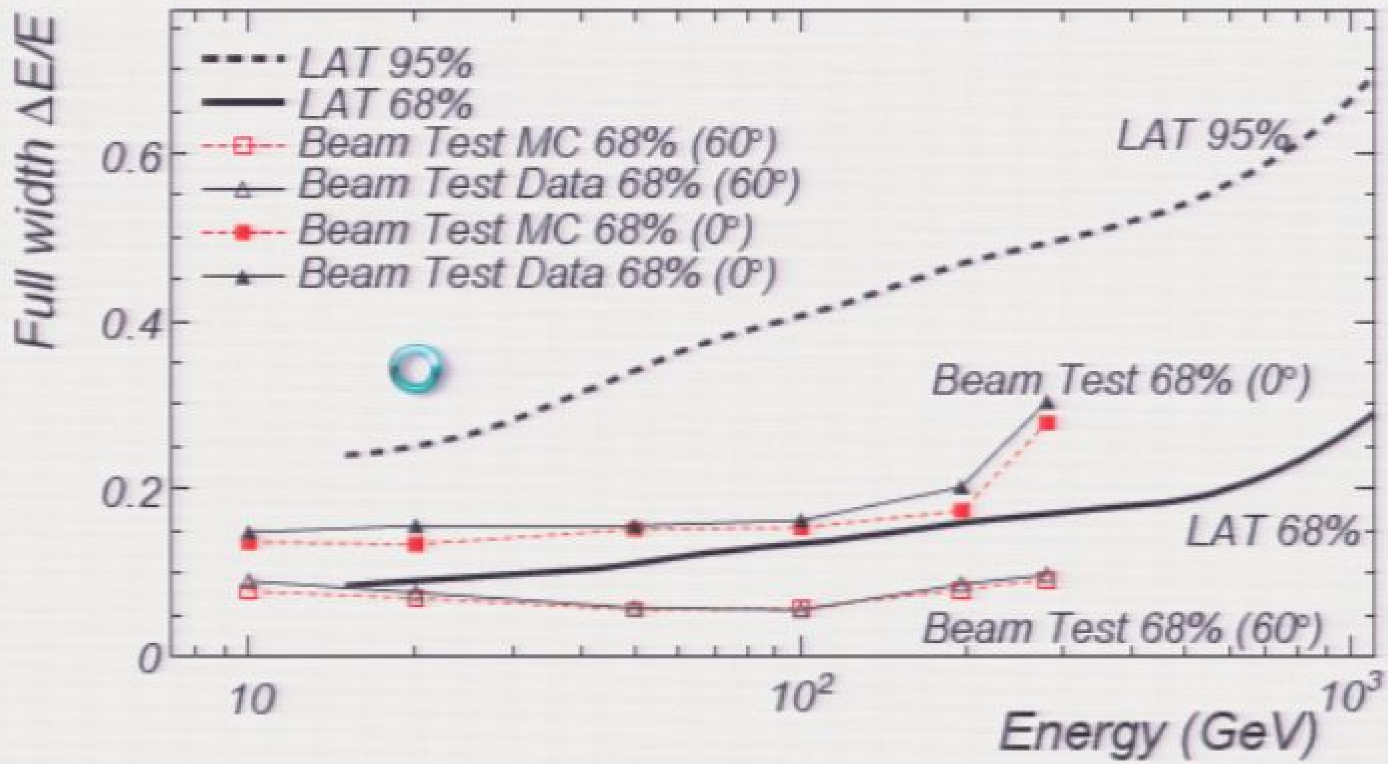
Event selection: validation with flight data

Shower transverse size above 150 GeV



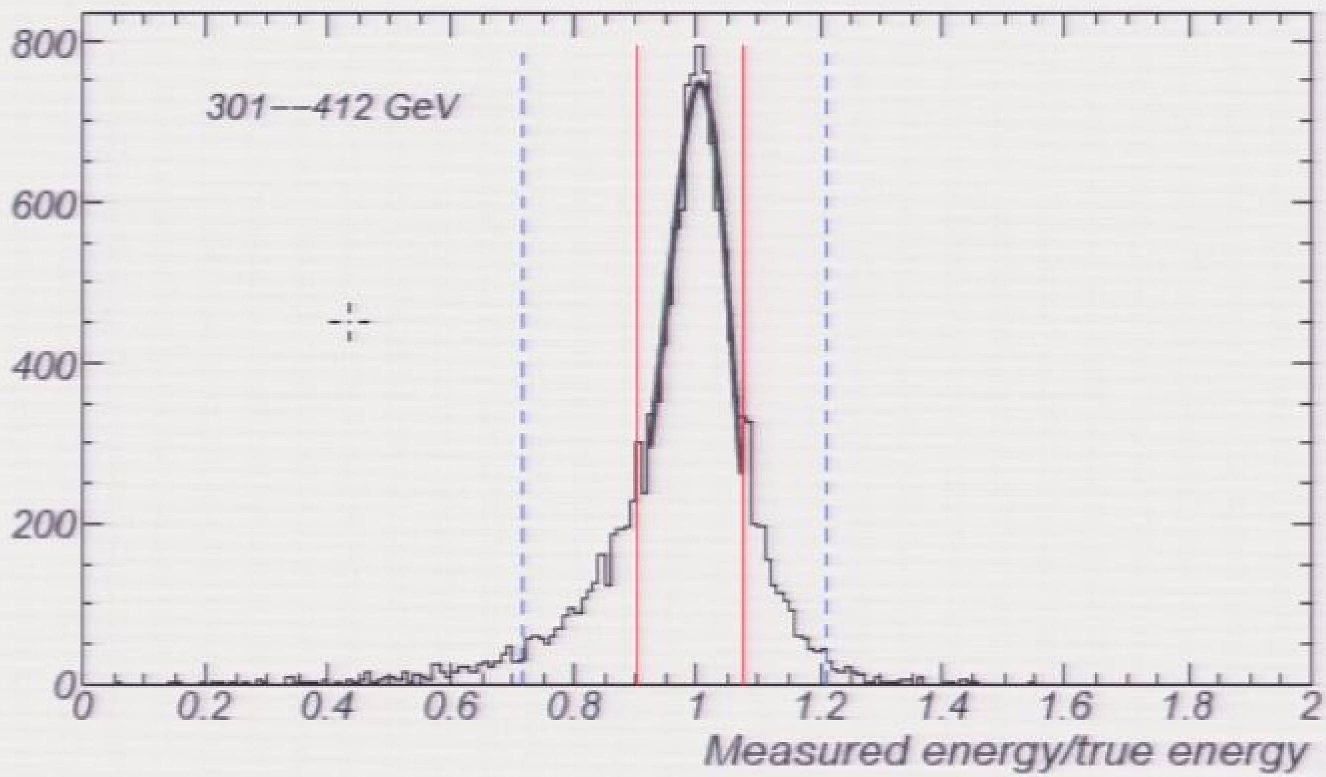
- Data/Monte Carlo comparison routinely performed for:
  - all variables involved in the selection;
  - at different stages of the selection.
- Residual discrepancies propagated to the spectrum *for each energy bin* and included into the systematics.

Energy resolution



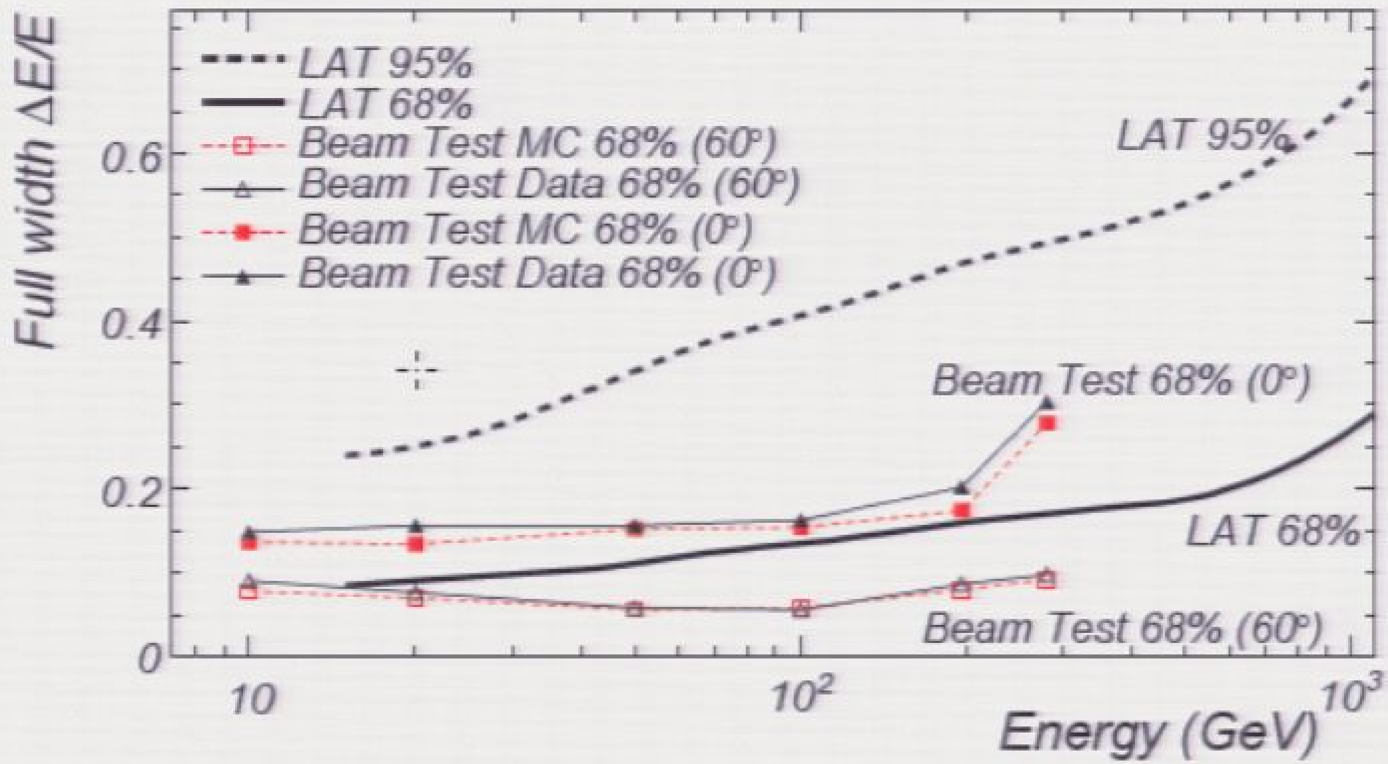
- Validated with the Calibration Unit beam tests up to 280 GeV.
  - Excellent agreement over the whole (energy, angle, position) phase space.
  - We have a solid ground in extrapolating to 1 TeV.
- Our energy dispersion is adequate for the measurement.
  - Candidate electrons traverse 12.5 X_0 on average.

Energy reconstruction quality



- *Probability of good energy reconstruction*: diagnostic output of our energy analysis.
  - A CT is trained to identify events in the core of the energy dispersion.

Energy resolution



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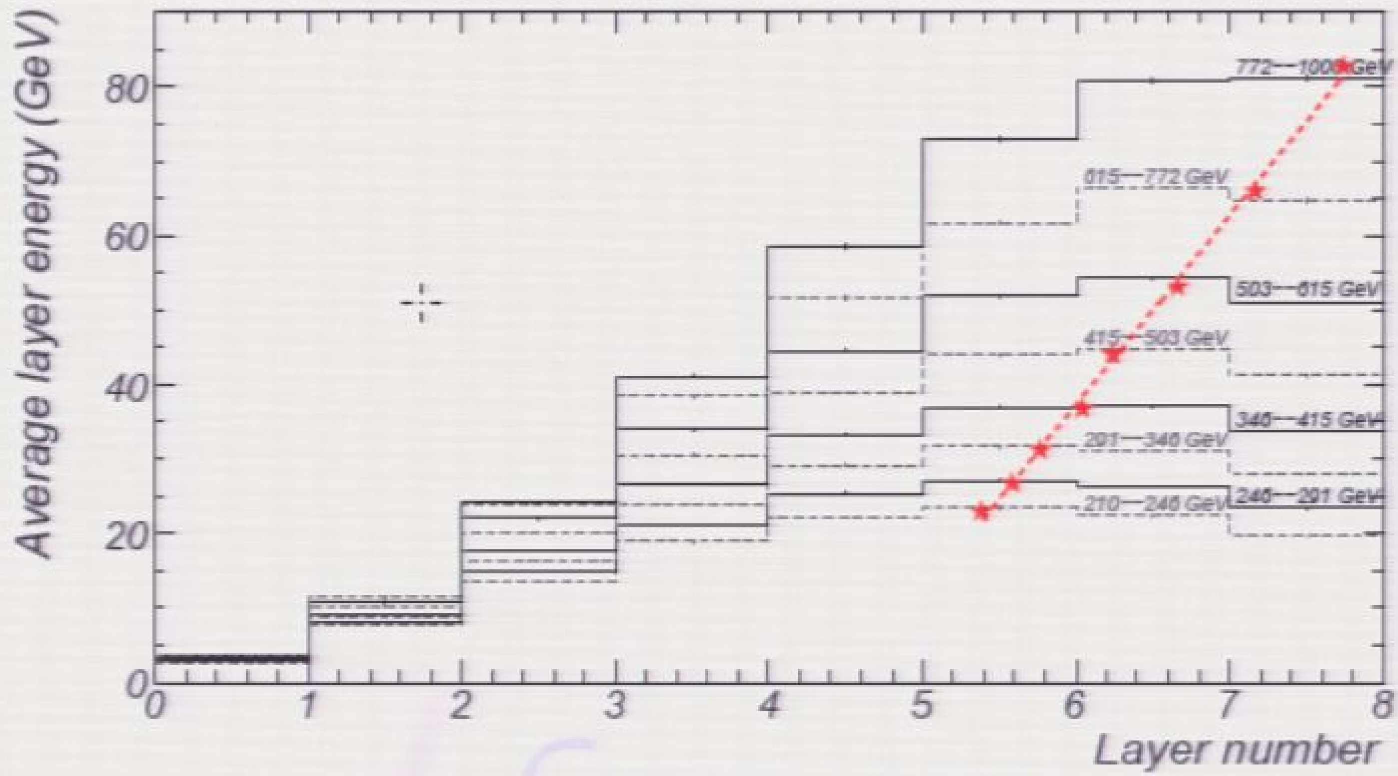
Shower profile: flight data

After the electron selection, integrated over all angles



- Showers of different energies look different in the detectors (i.e. can be distinguished).
- The shower maximum at 1 TeV is at 11.5 X_0 (candidate electrons traverse ≈ 12.5 X_0).