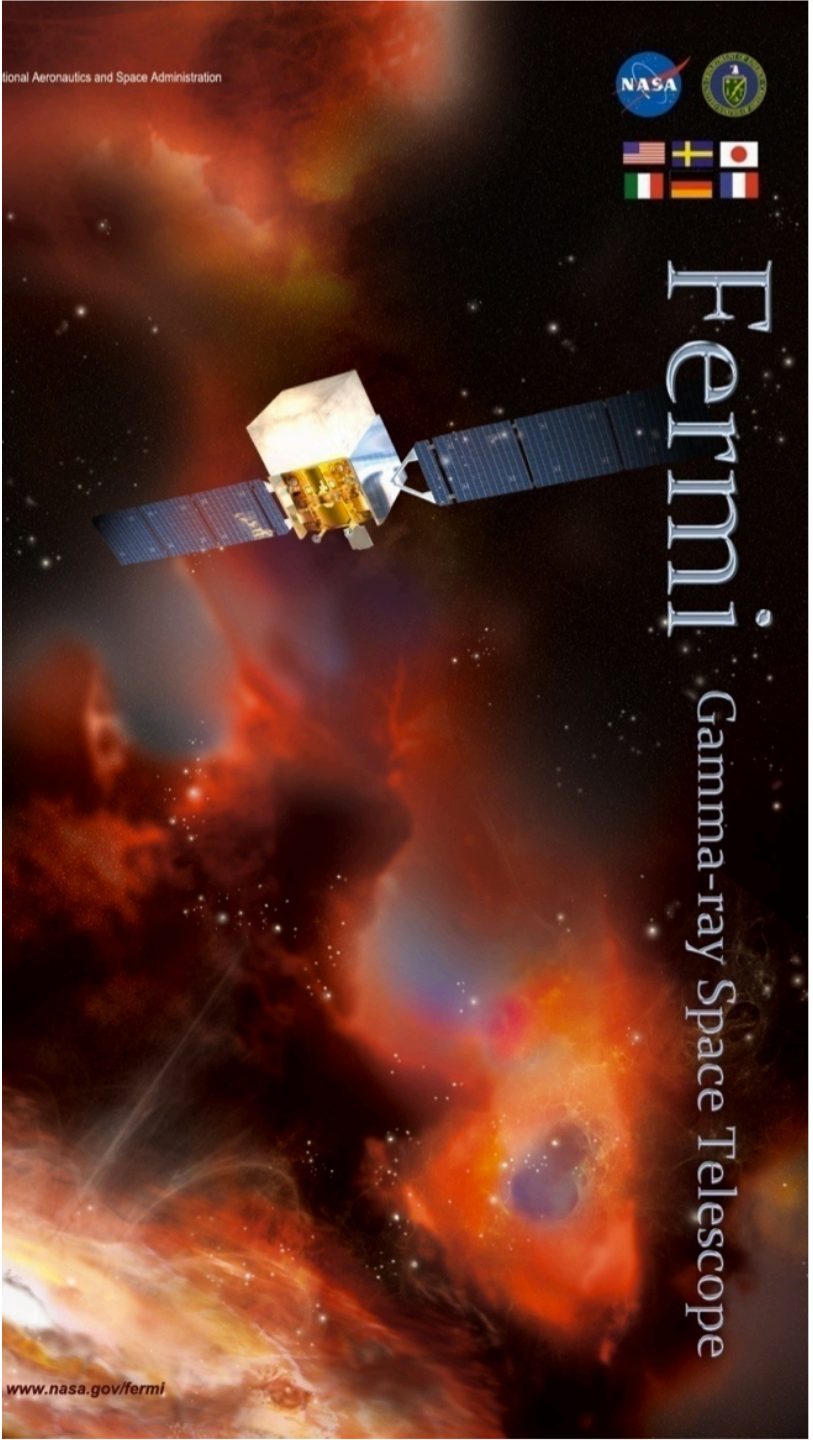

A new measurement of the Cosmic-Ray Electron Spectrum with Fermi-LAT

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on behalf of
the Fermi-LAT Collaboration

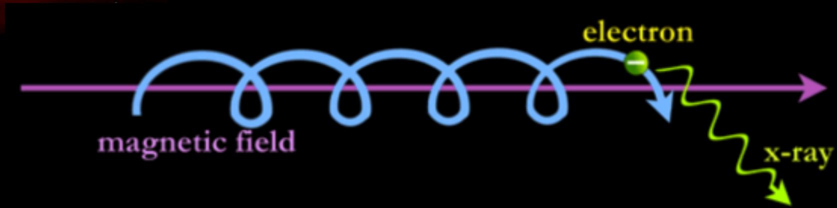
ICNFP2016, Crete

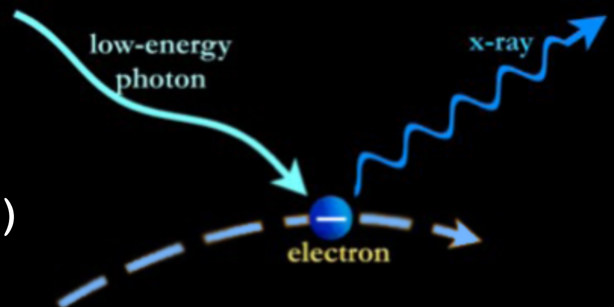
Outline

- Motivations
- The Fermi Observatory
  - Status and prospects
- CR Electrons
  - Strategy
  - Systematics
  - Results

Motivations

- While propagating throughout the Galaxy high-energy electrons and positron (CRE) rapidly lose energy by inverse Compton scattering on the interstellar radiation field and by synchrotron emission on the Galactic magnetic field



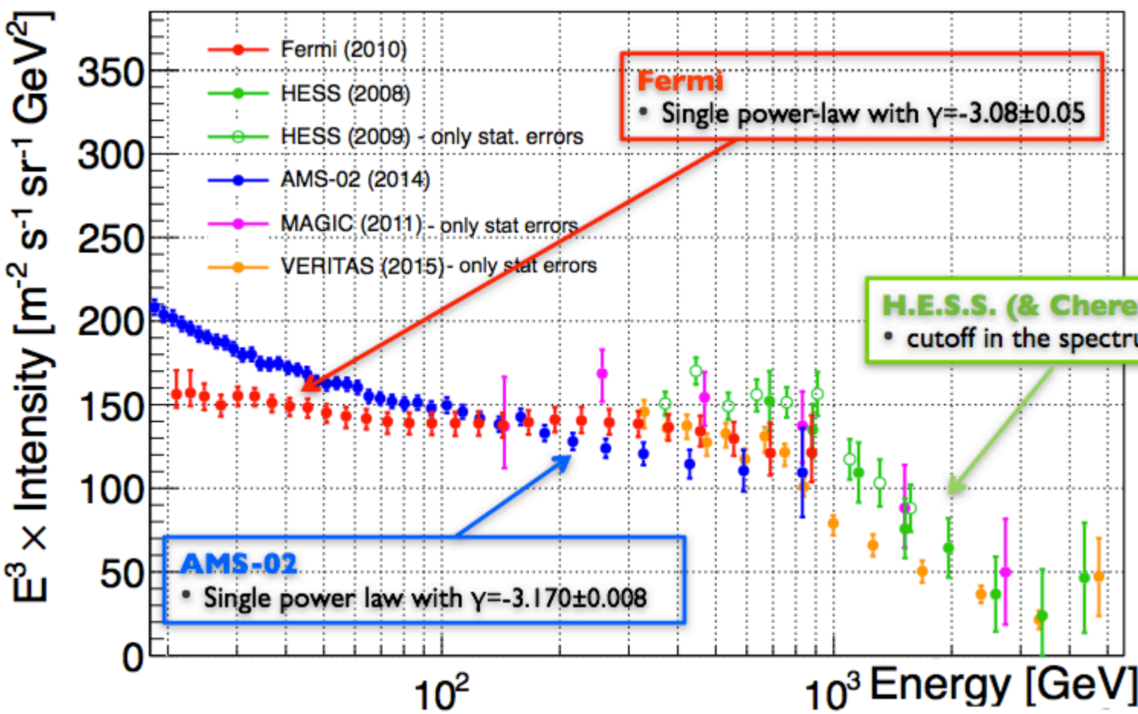


- the CRE diffusion distance is O(100 pc) at 1 TeV, much shorter than the radial scale of the Galaxy

- the shape of the CRE spectrum from ~100 GeV up to few TeV can provide evidence for local CRE sources of astrophysical or exotic nature [SNR, PWN, DM…]

Motivations

- AMS-02 and Fermi → CRE spectrum can be fit with single power law up to ~1 TeV
  - AMS-02 spectral index = −3.170 ± 0.008 [1]
  - Fermi-LAT spectral index = −3.08 ± 0.05 [2]
- H.E.S.S. → first indication of a cutoff at ~2 TeV [3,4]



[1] 2014, PRL 113, 221102
[2] 2010, PhRD 82, 092004
[3] 2008, PRL 101, 261104
[4] 2009, AsAstr 508, 561

The Fermi Observatory

Large Area Telescope [LAT]
- pair conversion
- 20 MeV - >300 GeV

Wide energy range

An International Collaboration

~ 400 Scientific Members
- NASA/DOE
- International contributors

Huge FoV (2.4 sr)
- instant 20% sky
- full sky for 30′ every 3h

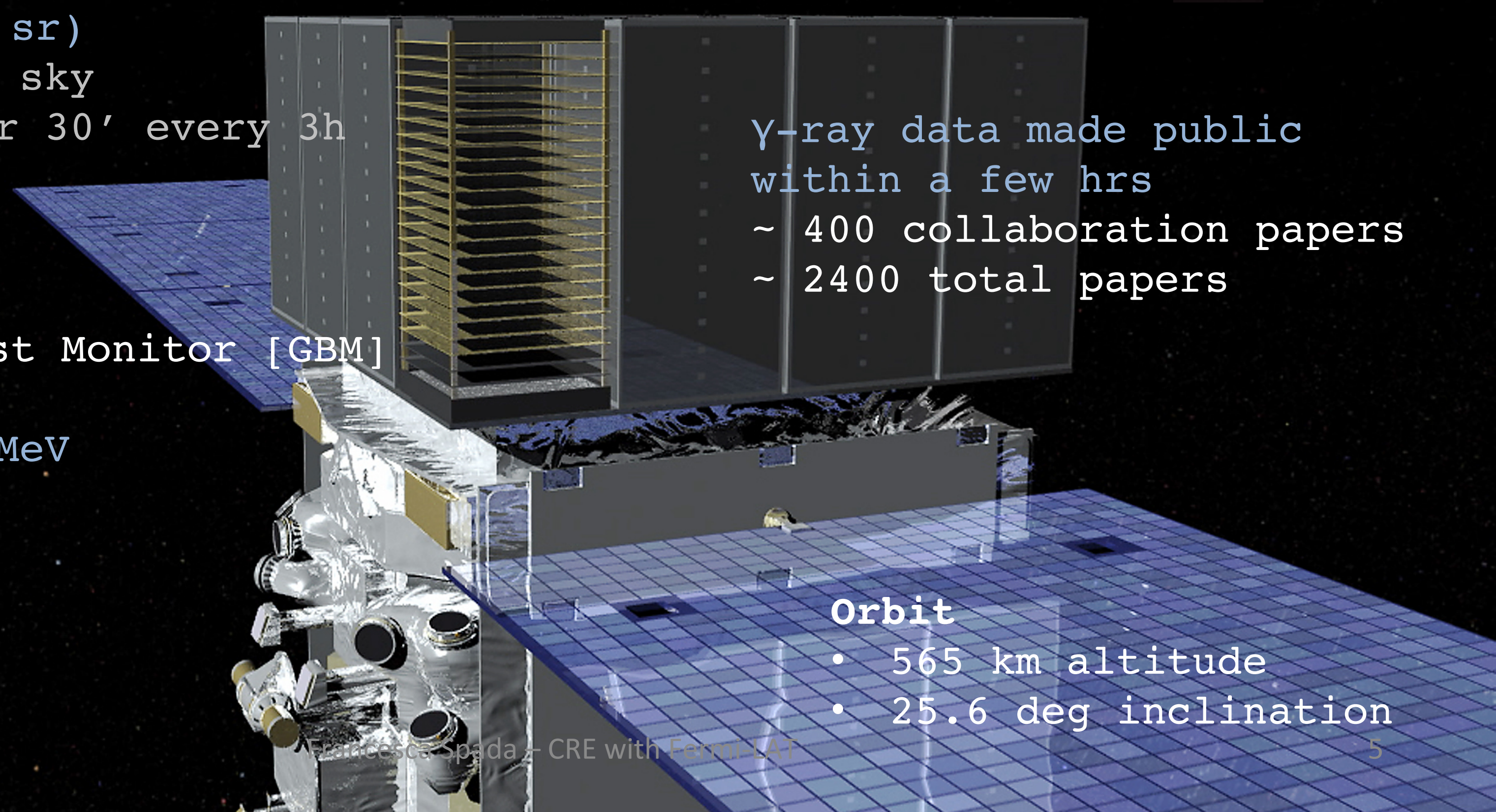
γ-ray data made public within a few hrs

~ 400 collaboration papers

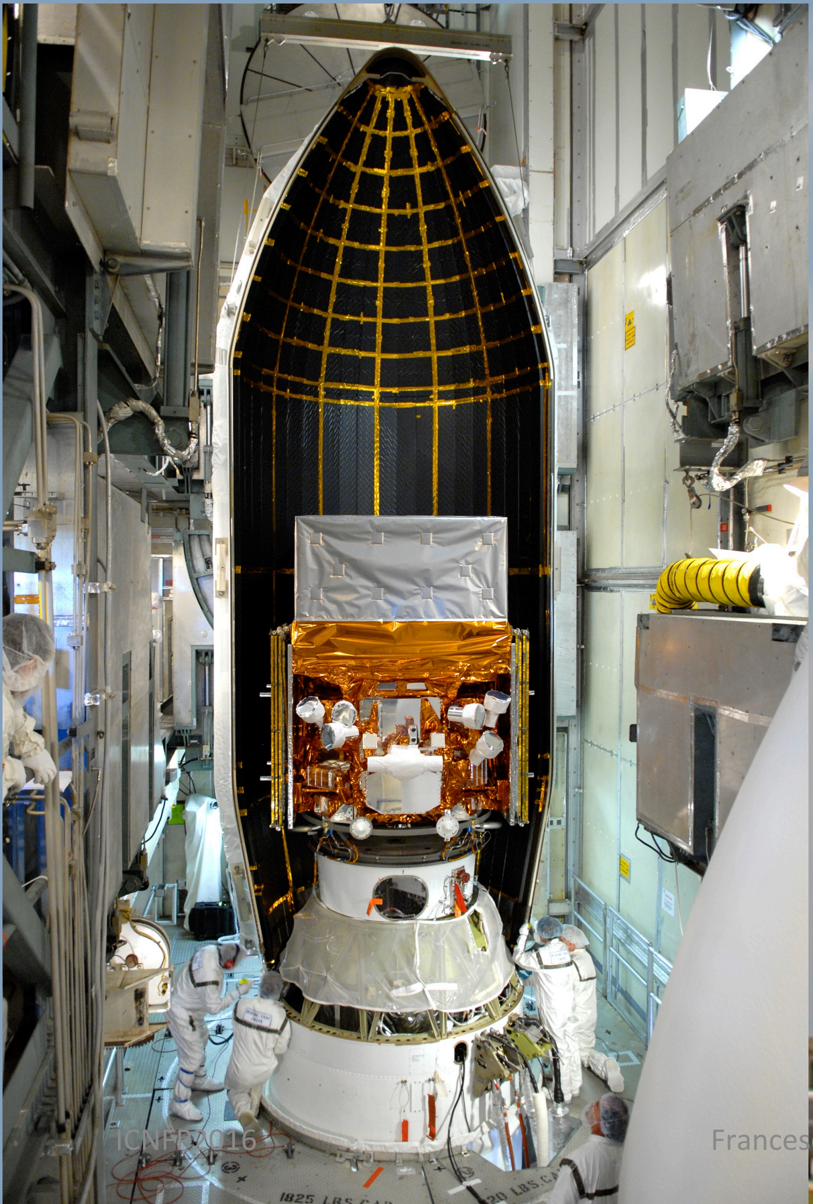
~ 2400 total papers

Gamma-ray burst Monitor [GBM]
- counters
- 8 keV – 40 MeV

Orbit
- 565 km altitude
- 25.6 deg inclination

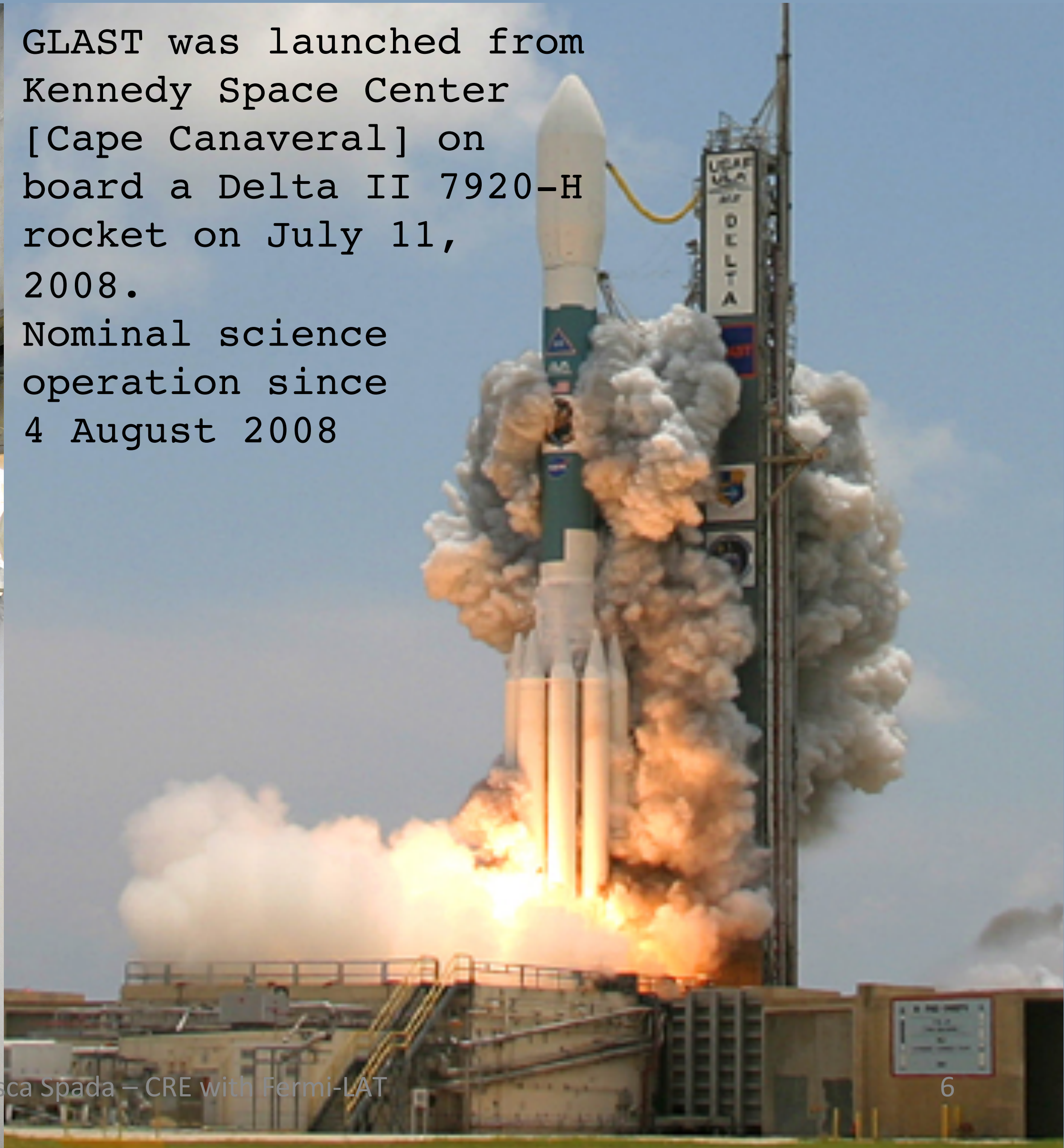


The Fermi Observatory



GLAST was launched from Kennedy Space Center [Cape Canaveral] on board a Delta II 7920-H rocket on July 11, 2008.

Nominal science operation since 4 August 2008

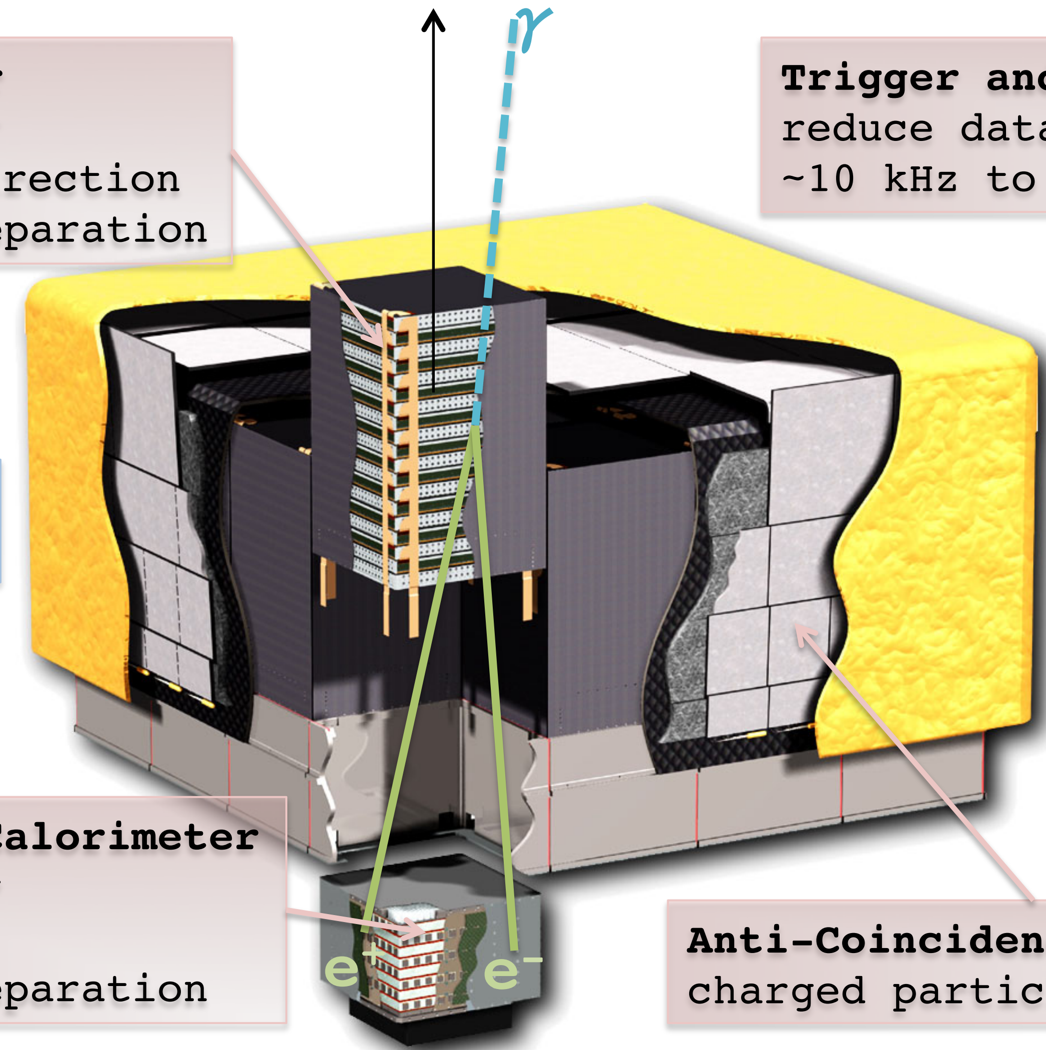


The Fermi-LAT

Si-strip Tracker
convert γ → e^+e^-
reconstruct γ direction
EM vs. hadron separation

Trigger and Filter
reduce data rate from ~10 kHz to 300-500 Hz

Modular design
4x4 towers

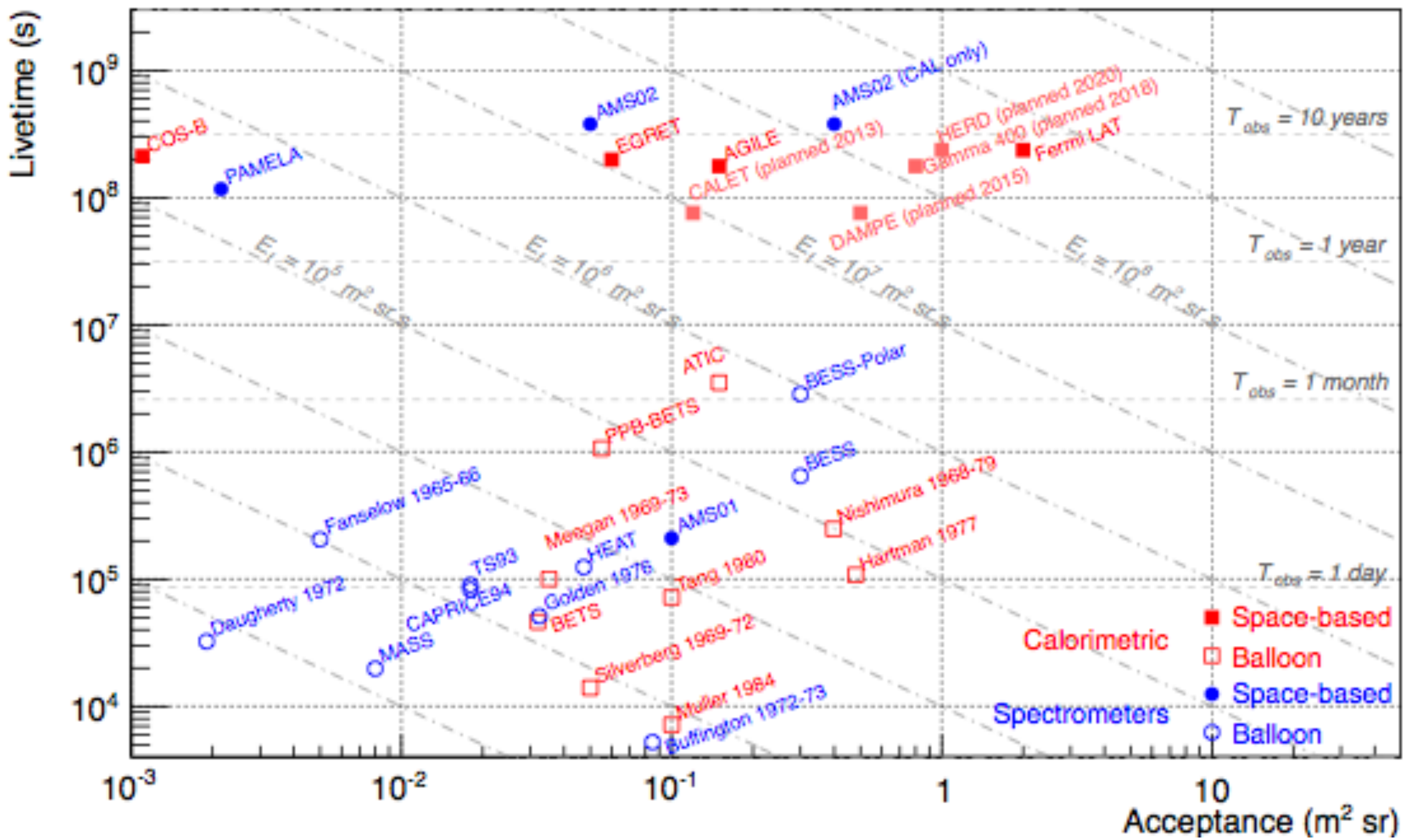


160x160 cm^2
~ 3 tons

Hodoscopic CsI Calorimeter
measure γ energy
image EM shower
EM vs. hadron separation

Anti-Coincidence Detector
charged particle separation

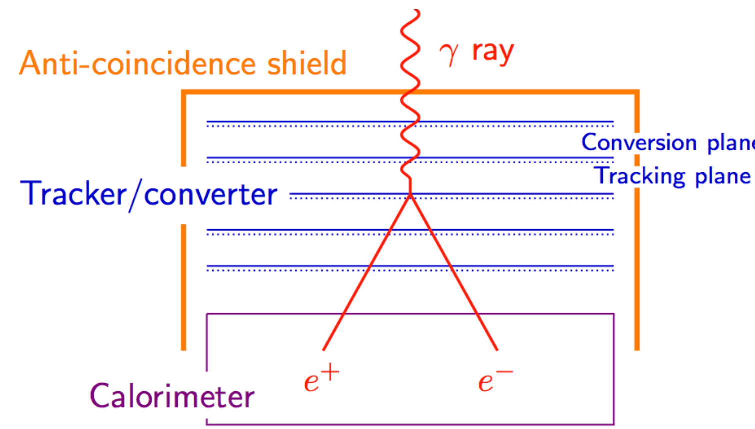
Context


Livetime (s)
Acceptance (m² sr)
COS-B
PAMELA
AMS02
EGRET
AGILE
CALET (planned 2013)
AMS02 (CAL only)
HERD (planned 2020)
Gamma 400 (planned 2018)
Fermi LAT
DAMPE (planned 2015)
$E_i = 10^5$ m² sr s
$E_i = 10^6$ m² sr s
$E_i = 10^7$ m² sr s
$E_i = 10^8$ m² sr s
T_{obs} = 10 years
T_{obs} = 1 year
T_{obs} = 1 month
T_{obs} = 1 day
ATIC
BESS-Polar
PPB-BETS
BESS
Fanselow 1965-66
Meegan 1969-73
AMS01
Nishimura 1968-79
Hartman 1977
HEAT
TS93
Golden 1976
Tang 1980
CAPRICE94
BETS
Daugherty 1972
MASS
Silverberg 1969-72
Muller 1984
Buffington 1972-73
Calorimetric
Spectrometers
Space-based
Balloon
Space-based
Balloon

CR Electrons and the LAT

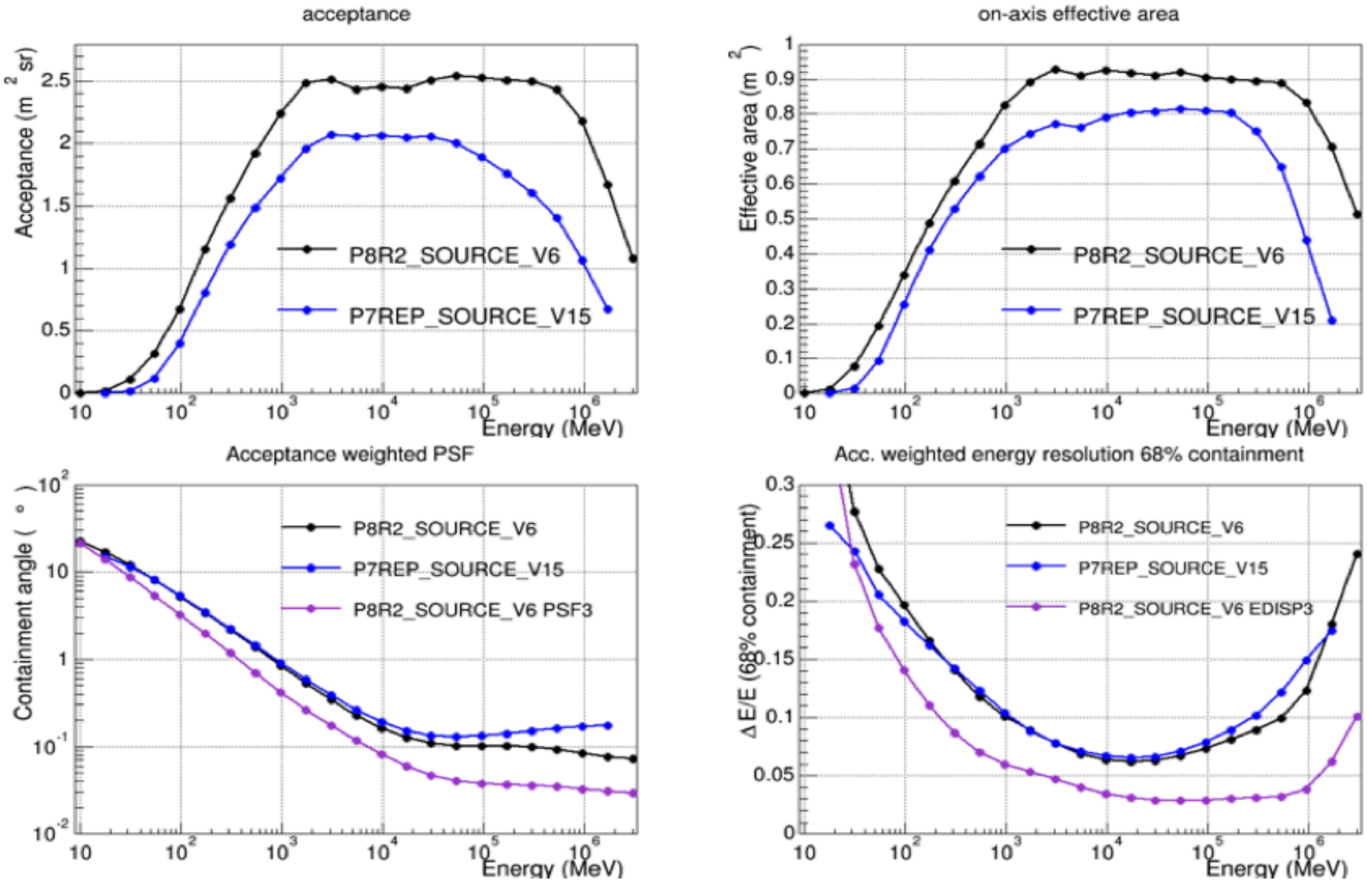
- The detector is designed for imaging the development of EM showers → naturally suitable to measure electrons
- The LAT on-board gamma filter is designed to reject charged particles but it accepts all events with a deposited energy in the CAL >20 GeV

  → **CRE are there!**



- A "trick" is needed to go to lower energies… We get down to 7 GeV
- Extending the measurement beyond 1 TeV is challenging
  - Almost 10^4 events above 1 TeV: **statistics is not an issue! But…**
  - at such high energy only ~ 35% of the shower is typically contained in the CAL
  - a significant fraction of the CAL crystals along the shower axis are saturated

Pass-8 Event Reconstruction



Public release in June 2015

Higher acceptance – wider energy range – better resolution

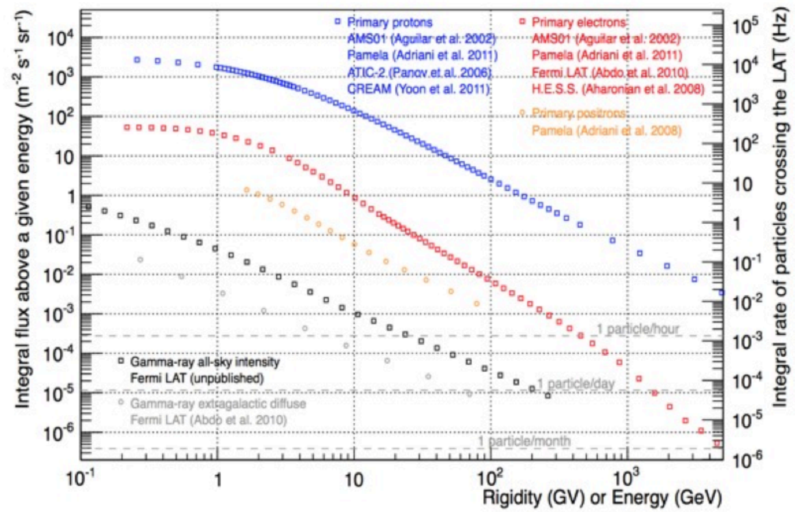
A new, improved LAT: Pass-8 was worth the huge effort!

Extending the CRE spectrum energy range

- Must discriminate **signal (e+/e-)** from the more abundant **background (mainly p)** [n_p/n_e ~ 500 for E>100 GeV]

- Improved event-level analysis performance [pass-8]
- Powerful multivariate analysis methods [BDT]

→ we achieve a residual **bg contamination < 25%** and an **energy resolution < 20%** up to 2 TeV



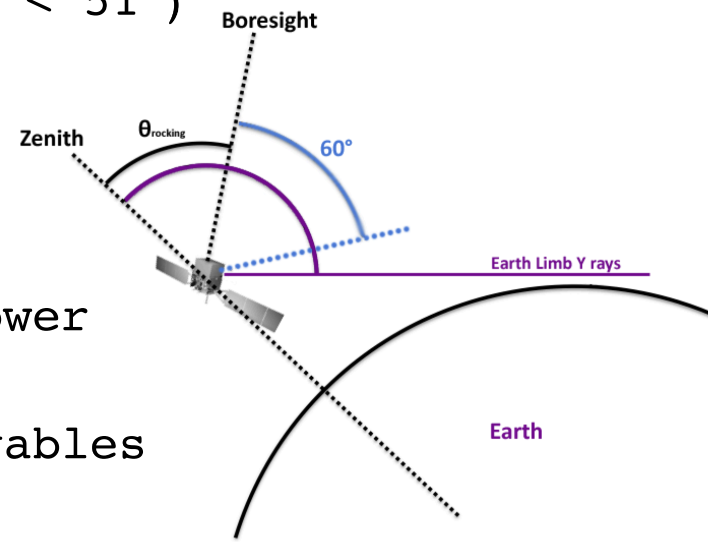
- Extending the analysis **below 20 GeV** requires the use of the **unbiased sample** of all trigger types prescaled on-board by a factor 250

  → two data samples, two independent analyses (HE & LE)

  - unified approach wherever possible
  - ad-hoc strategies when needed

Event selection

- **Data:** standard survey mode (rocking < 51°)
  livetime ~5 years
- **Precuts:**
  >60° from boresight
  → get rid of Earth Limb photons
  Require good quality track & shower
  → start from a clean sample
  Cut on ionization-related observables
  → get rid of α and heavier ions



- **We are now left with proton bg only → dedicated strategy**
- **Classification Tree:** TMVA with the BDT method
  - trained on MC signal electrons and background protons
  - 8 energy bins [HE] in $\log_{10}(E/\mathrm{GeV})$ equally spaced between 1.5 ad 3.5 + 1 [LE]
  - observables chosen according to good MC-data agreement and high separation efficiency

Proton rejection

Selection of observables

Good MC-data agreement and high separation efficiency

Boosted Decision Tree

Probability Variable

Template fitting

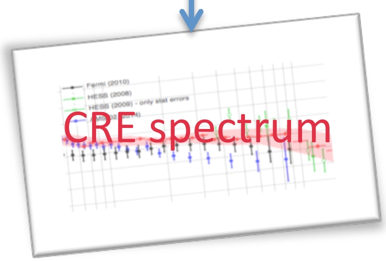
Gives bg fraction in each E bin

Output: variable p_{BDT} in the range [-1,1]
-1 → candidate proton (bg)
 1 → candidate electron (sig)

$P_{CRE} = \log_{10}(1-p_{BDT})$

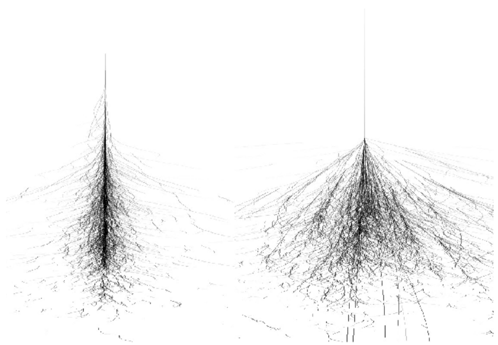
Selection Cut

Fix signal efficiency in each E bin

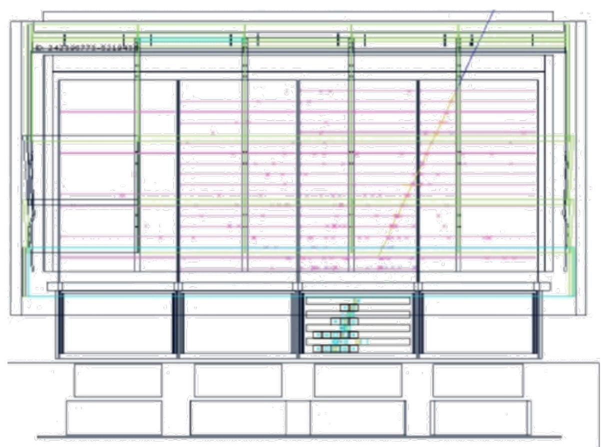


Selection of observables

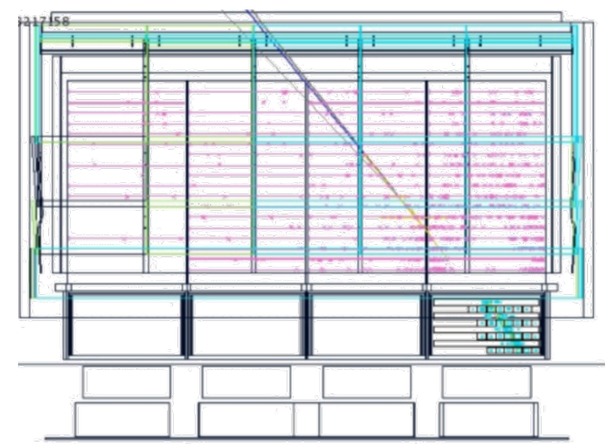
- All BDTs (8 HE + 1 LE) are built from the same 19 observables related to the event topology in TKR and CAL
- *Example: shower transverse size*



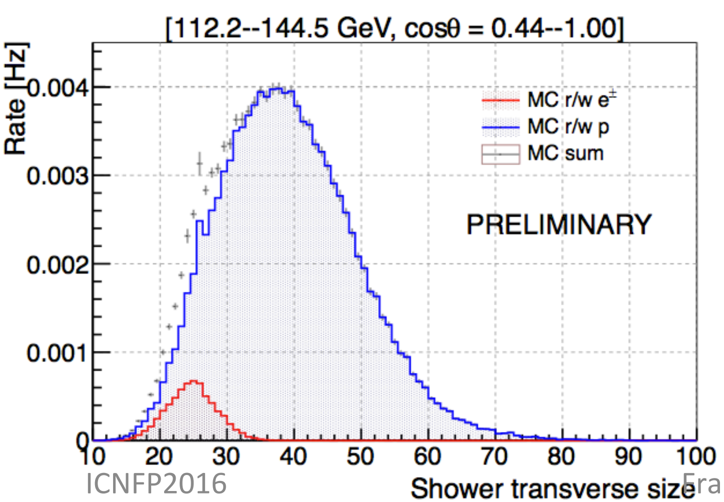
EM **HAD**



1 TeV electron



1 TeV proton

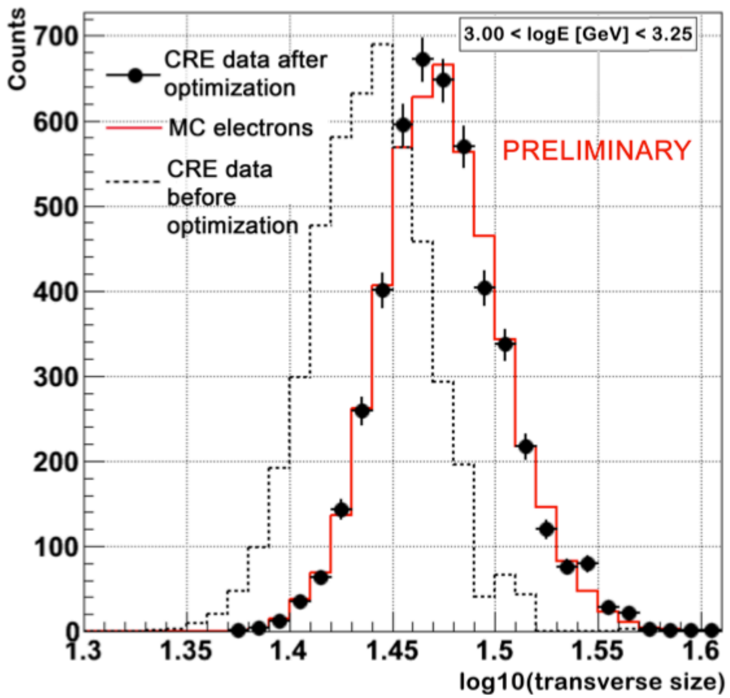


The BDT approach relies on **observables well reproduced** by the MC!

Individual variables calibration

- Systematic comparison of data/MC distributions at various **energies** and **incidence angle θ**
  - width of the distributions are in good agreement (within 15%)
  - for some observables the distributions are shifted

→ **correct** according to (E,θ) parameterization of the shift

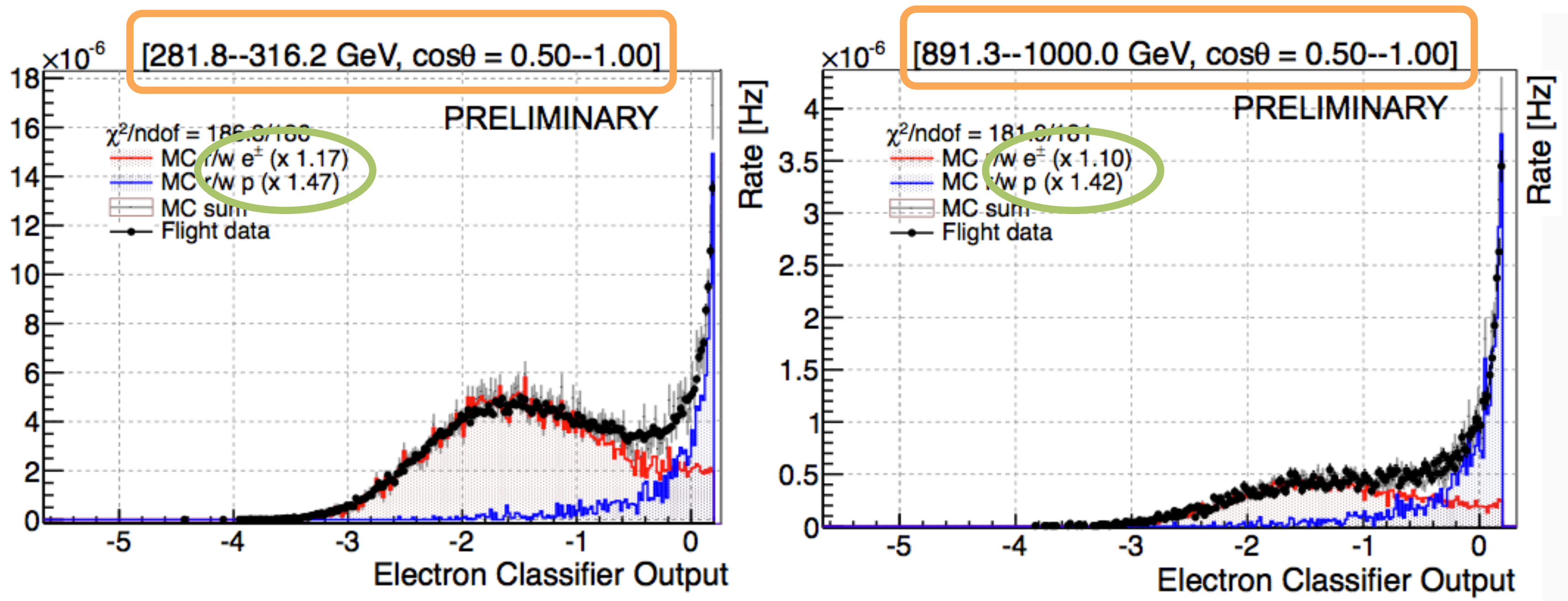


- The calibration is applied to the data:
  - equivalent but more convenient
  - no need to retrain the BDTs

- **Residual differences** used to estimate the **systematics**

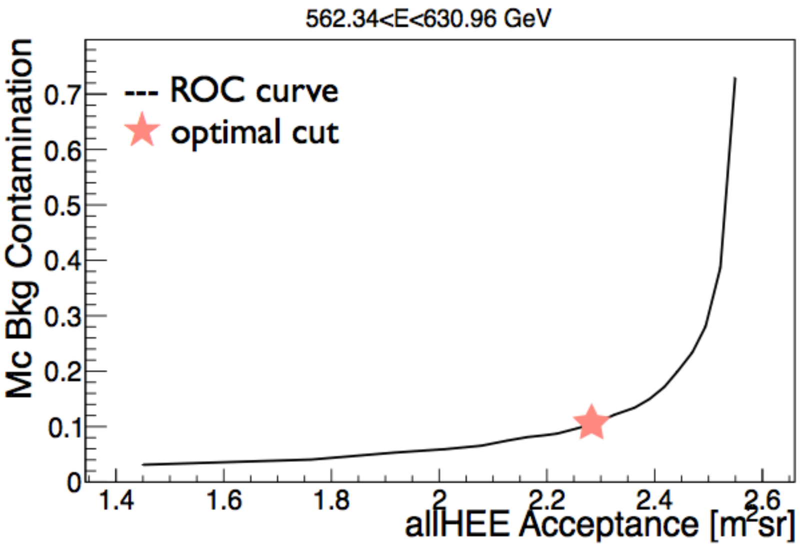
Template fitting

- The **sum** of the **signal** and the **background MC templates** are fit to the **data** by varying their **normalization** in each **energy bin**



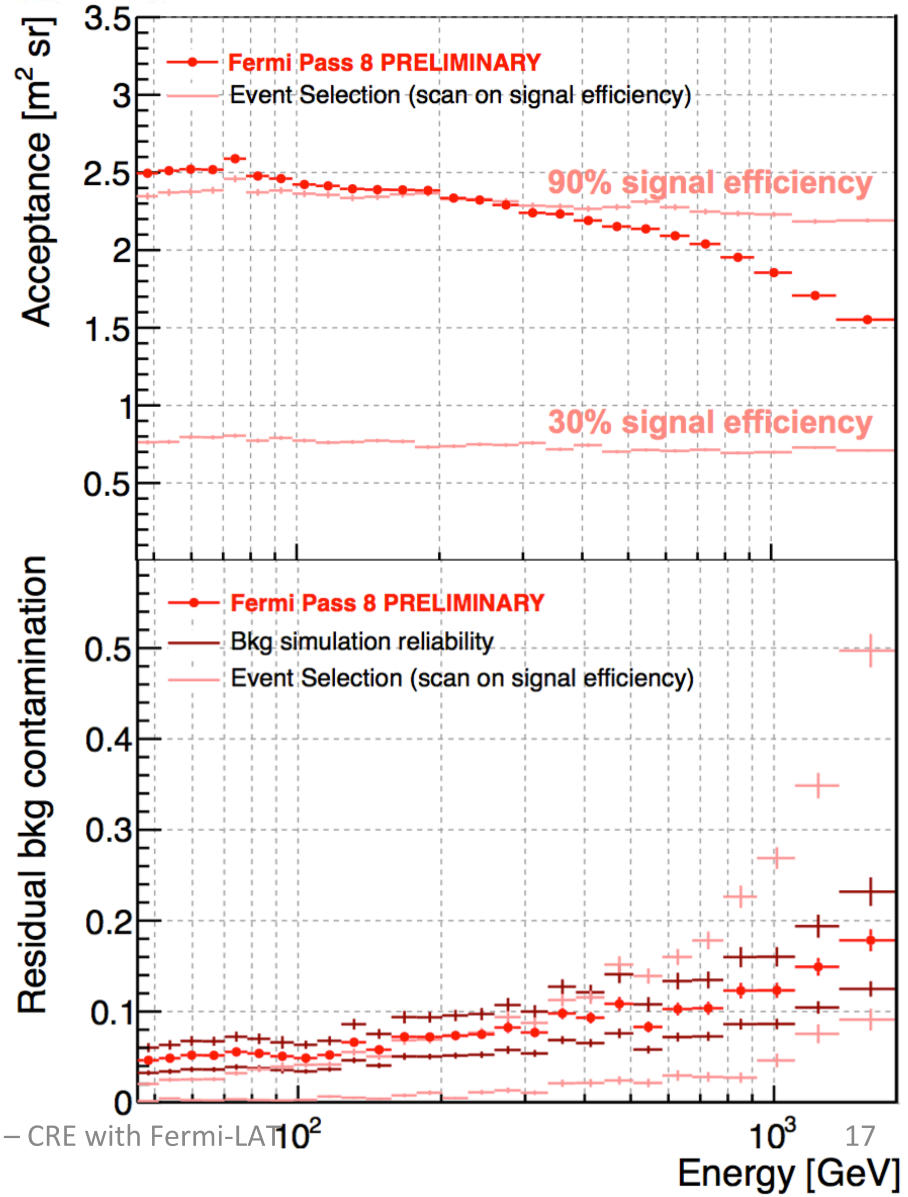
- get **number of signal and background events in the data** for any given cut on P_{CRE} integrating the distribution up to the chosen cut value

Selection cut

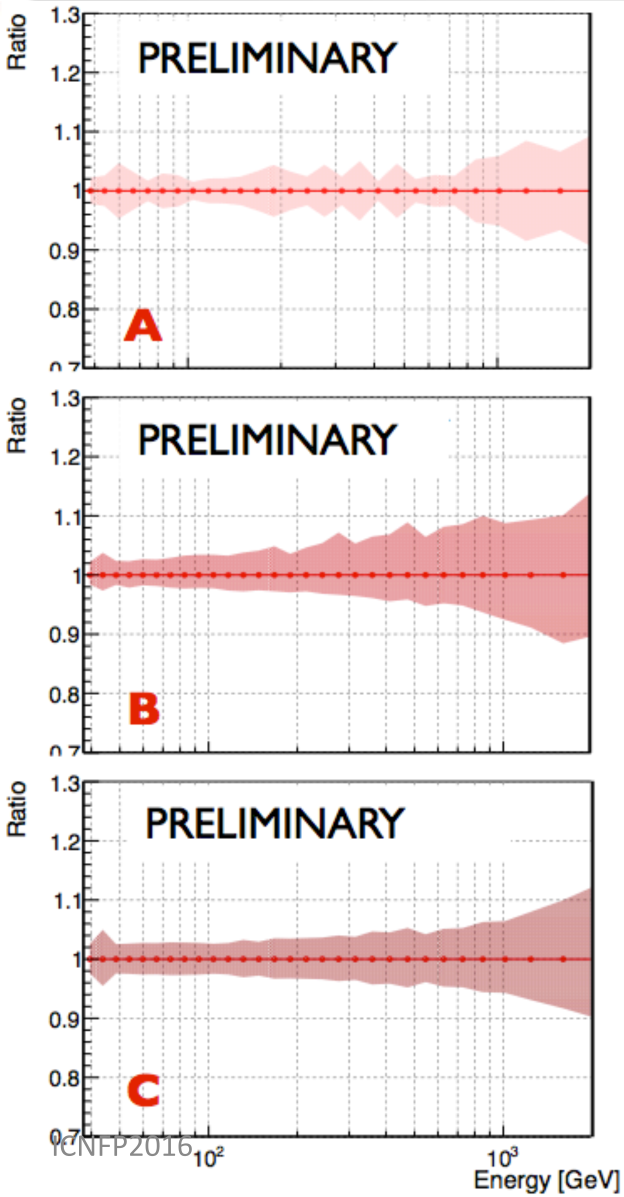


Cut criteria:

- **fix** a priori the signal **efficiency**
  - from 90% at 30 GeV to 80% at 300 GeV
  - down to 50% at 2 TeV
- stop when the **residual contamination** reaches 20%
  - occurs at 2 TeV



Systematics



A Acceptance:
main uncertainty due to the estimation of the effective area

- vary the cut ±20% in signal efficiency

→ flux variation ~2% up to 1 TeV increases to **9% at 2 TeV**

B Correction factor:

- move the correction factors by its 1-σ uncertainty

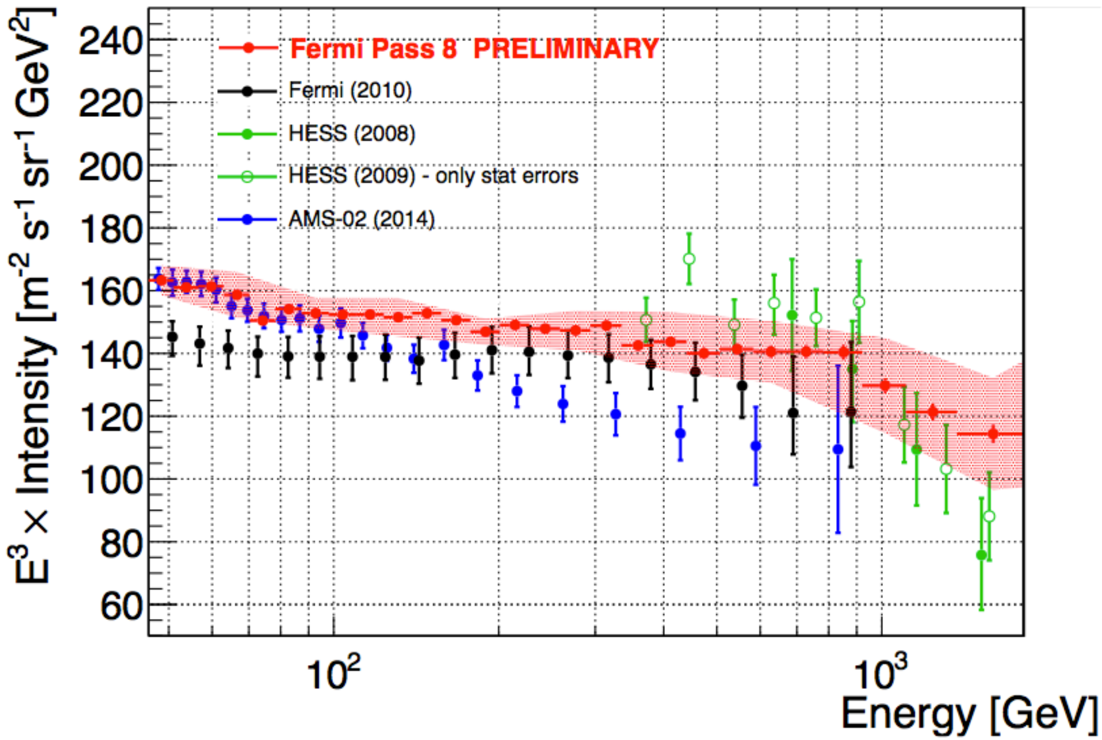
→ signal variation from 2% at 40 GeV to **12% at 2 TeV**

C Fraction of p (GEANT4 uncertainty):

- assume 20% uncertainty on bkg events

→ signal variation <2% up to 1 TeV increases to **6% at 2 TeV**

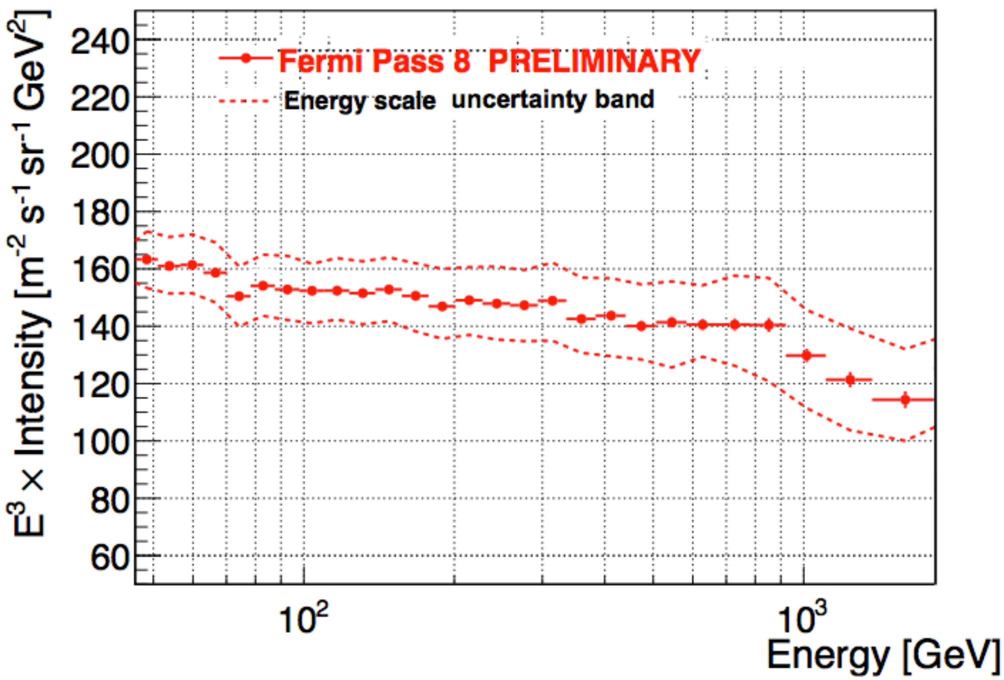
The CRE inclusive spectrum



- Between 50 GeV and 2 TeV, the CRE spectrum is compatible with a single power law with a spectral index −3.07±0.02
- Shaded band = systematics (except for the energy scale)

- Disagreement wrt published spectrum (**Fermi 2010**) due to "ghost" signals in the detector not taken into account in the acceptance in our first analysis

Energy scale systematics



The uncertainty on the absolute energy scale is the **largest source of systematics**

Pass 8 in-flight measurement of the absolute energy scale via geomagnetic cutoff study → **3.3% offset** around 10 GeV

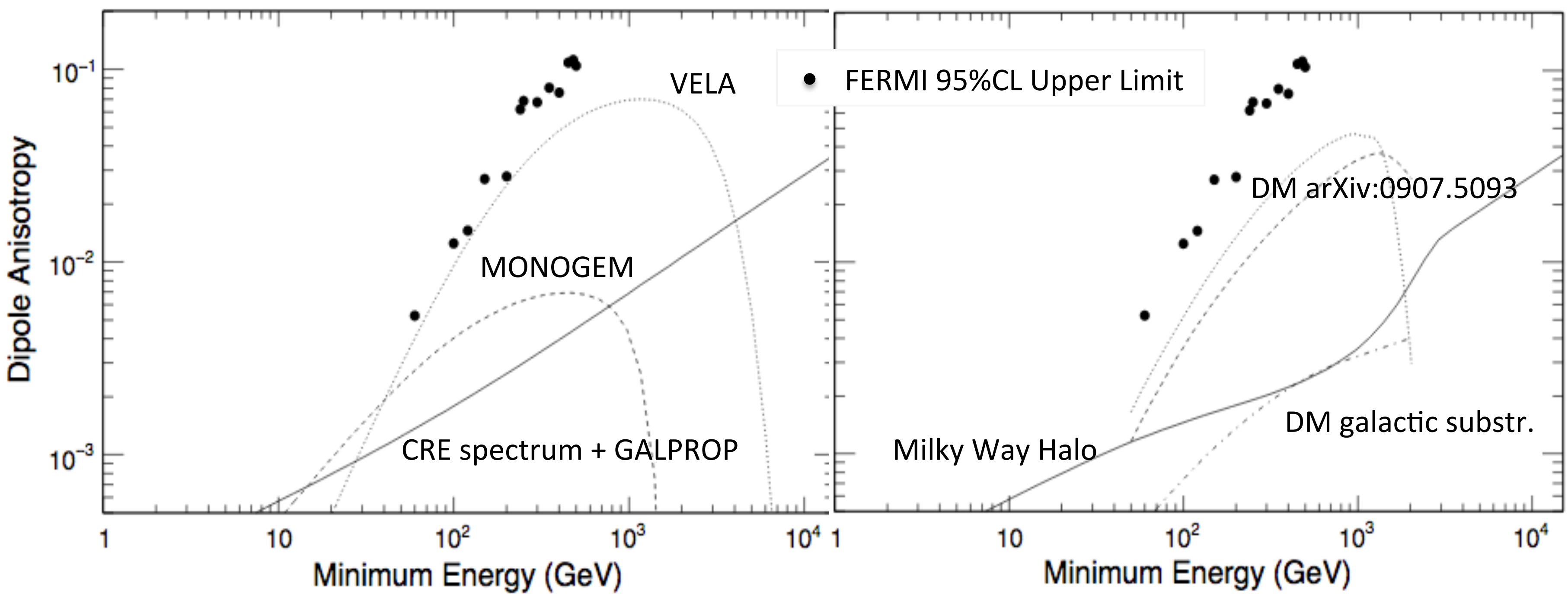
→ Rescale the whole spectrum by 3.3%

→ Estimated error on the scaling factor = **2% at 10 GeV increasing up to 5% at ~ 1 TeV**

Taking into account the uncertainties on the energy scale, **Fermi**, **AMS** and **HESS** measurements are in agreement.

Dipole anisotropies

- Search for a **steady excess** of CREs from **any direction** of the sky
- Difference with **no-anisotropy sky** maps are **considerably smaller than the smallest amplitude of a detectable signal**



Conclusions

- We performed a **new measurement of the CRE spectrum** achieving the **first direct measurement above 1 TeV**
- **Improvements** in the new analysis:
  - almost 7 years dataset
  - new event-level analysis (Pass 8)
  - new multivariate analysis tool & new selection of observables
    - variables are now "calibrated" → improved MC/data agreement
    - new CTs trained in energy bins → optimized for the whole energy range

→ **new CRE spectrum** and associated systematics

→ **Paper** to be submitted soon!

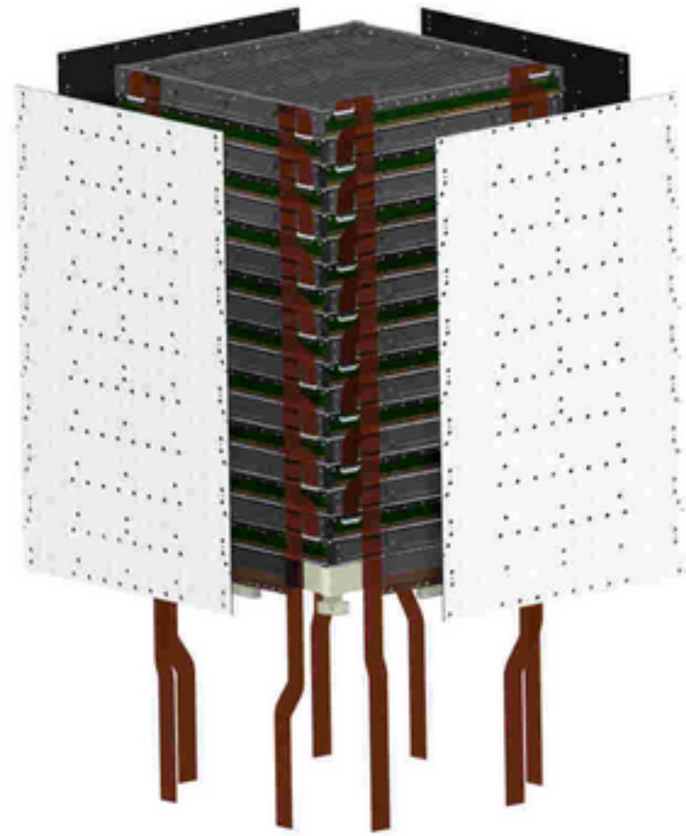
- Search for **anisotropies** in CRE arrival directions: no anisotropy observed in the *first year* of operation

→ **Pass-8 analysis** paper in preparation

BACKUP

Tracker

- 18 x,y tracking planes Si-strip detectors
  - pitch 200 μm
  - 80 m^2 silicon active area
  - 10k sensors, 1M readout channels
- 16 converter planes of tungsten
  - "FRONT" → first 12 "thin" layers of 3% radiation length
  - "BACK" → next 4 "thick" layers of 18% radiation length
- 1.5 radiation lengths on axis
- High-precision tracking
- Short dead time

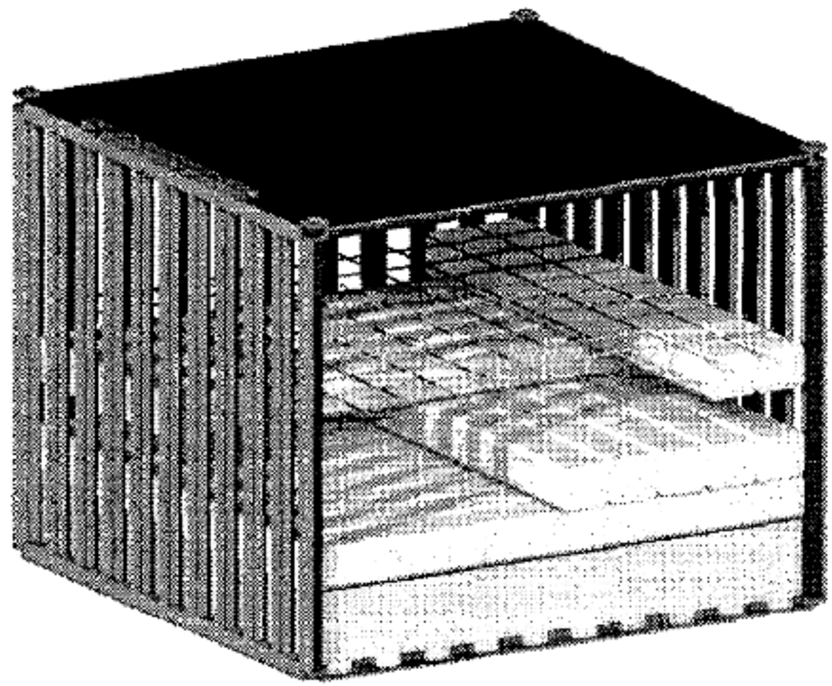


Calorimeter

- Made in a hodoscopic fashion from CsI(Tl)
  - 1536 position-sensitive crystal rods measuring 333.0 × 26.7 × 19.9 mm^3

- Each calorimeter tower contains 8 layers of crystals with 12 crystals in each layer

- Approximately 8.6 radiation lengths on axis



ACD

- Provides charged-particle bkg rejection
- 0.9997 average detection efficiency
- Plastic scintillator, wavelength shifting (WLS) fiber readout
- 89 segmented tiles
  - control backsplash
  - reduce self-veto

Pass-8

One of the the primary motivations for Pass 8 was to **mitigate the effect of 'ghost' events**, instrumental pile-up away from the gamma-ray shower that introduced errors in the measurement of the energy, and shower center and direction. The new event reconstruction features improvements in many key areas beyond that. These include:

- A **new pattern recognition algorithm in the Tracker** reconstruction that does not depend on Calorimeter information and is less sensitive to track confusion induced by the backsplash.
- A clustering stage **in the Calorimeter** reconstruction aimed at finding and **discarding** the charge deposition due to **ghost events.**
- A better energy reconstruction that improves the handling of **energy leakage and crystal saturation.**
- A better algorithm for the **association between tracks and ACD tiles** for the rejection of charged particles.
- A new event classification analysis based on **boosted decision trees** that improves the separation power between photon and cosmic-ray background events.

Precuts

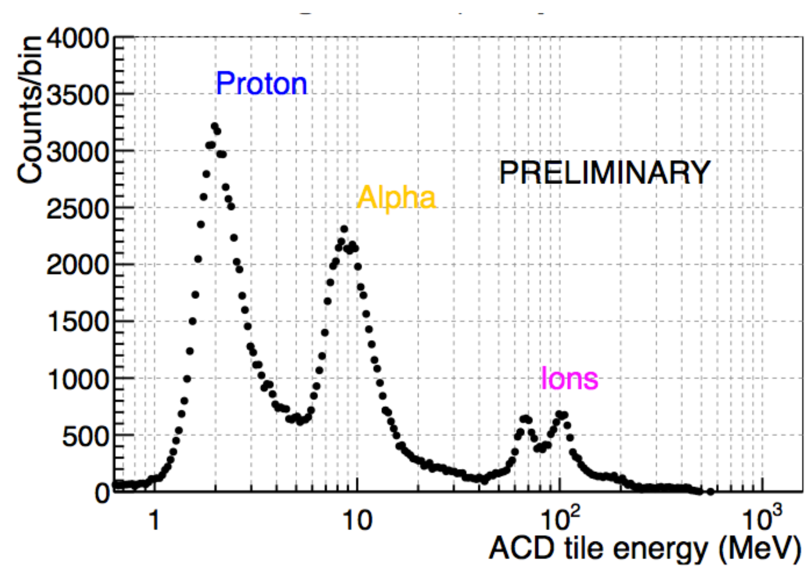
- **PRECUTS** = TRIGGER FILTER + QUALITY CUT + ALPHA CUT
  - **TRIGGER FILTER:** the event triggers the LAT and passes the on-board gamma filter

'(GltGemSummary&0x20)==0 && (GltGemSummary&0x40)==0 && FswGamState == 0'

  - **QUALITY CUT:** the event has at least a reconstructed track, a minimal PSF quality and the path length in the Cal is larger than 8 X_0

'EvtCalCsIRLn>8 && Cal1RawEnergySum>5000 && TkrNumTracks>0 && WP8CTPSFTail>0.05'

  - **ALPHA CUT:** MC doesn't reproduce accurately interactions of α and heavy ions in the LAT → cut removing the majority of α and heavies

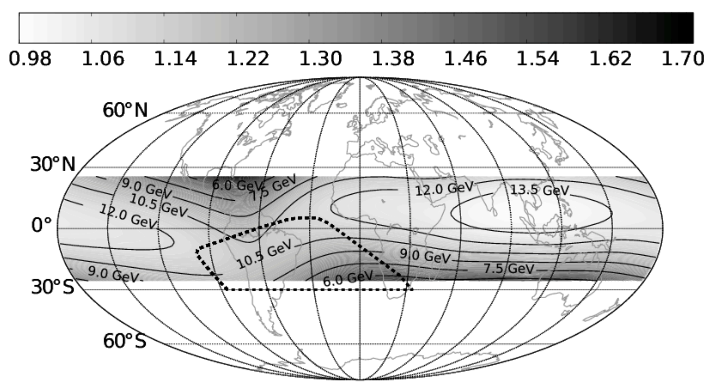


Observables for the BDT

- Five are related to the position of the shower:
  - the distance of the track head to the TKR edges
  - the depth of the track head
  - the distance of the CAL cluster centroid to the CAL edges
  - the depth of the CAL cluster centroid
  - the amount of radiation length that the incoming particle went through in the CAL
- The others describe the shower topology in the TKR and CAL:
  - the average Time Over Thresh-old (ToT) of the TKR hits
  - the number of hits in the 3 sections of the TKR
  - the fraction of TKR hits contained in a 1 cm radius cylinder around the track
  - the fraction of energy deposited in the TKR, four estimates of the shower transverse size (containing respectively 68, 90, 95 and 100% of the energy deposit)
  - the crystal-based χ^2 of the shower profile fit
  - the ratio of the energies deposited in the first and second CAL layers
  - the ratio of the number of TKR hits to the energy deposited in the first two CAL layers
  - the distance of closest approach of the CAL cluster centroid to the track

Low-energy: tracer

A dedicated Classification Tree was trained in the **low-energy region [7-70 GeV]**
Additional check: how good is the agreement with HE in the overlapping region of the spectrum



McIlwain-L describes the set of geomagnetic field lines crossing the magnetic equator at a distance of L Earth radii

Magnetically equivalent positions share the same McIlwayn-L → it is a good parameter for describing **cutoff rigidities**

After event selection:

- primary CRE [signal]
- secondary CRE [created in atmoshpere

Primary/secondary estimation:

- CRE simulation 2π str
- realistic orbital position from real FT2
- **Backtracing:** if the particle reaches 20 R_E → primary