Fermi-LAT electron+positron spectrum from 7 GeV to 2 TeV

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Introduction

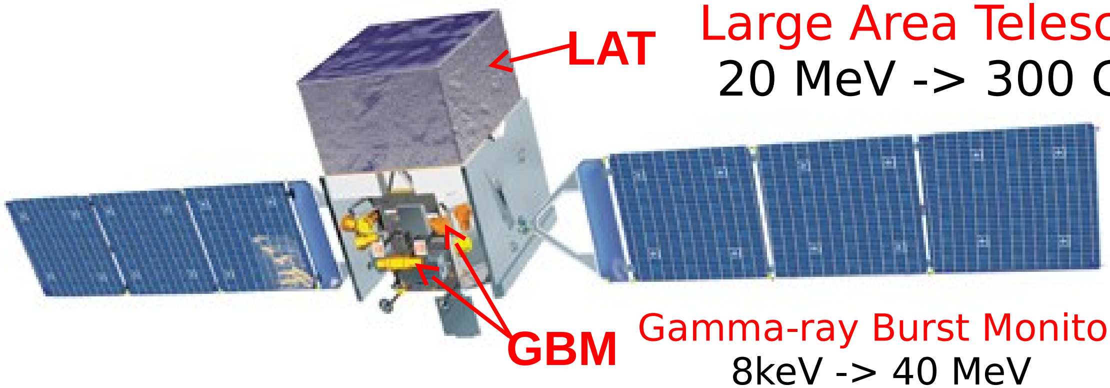
- First LAT electron+positron spectrum analyses:
  - Abdo+2009: 20 GeV → 1 TeV, 6 months of Pass 6 data
  - Ackermann+2010: 7 GeV → 1 TeV, 1 year of Pass 6 data

- Other results:
  - Ground: H.E.S.S. (Aharonian+2008 & 2009): 340 GeV → 5 TeV
    - break at ~1 TeV
  - Space: AMS-02 (Agilar+2014): 0.5 GeV → 1 TeV
    - power law up to 1 TeV

- New LAT analysis (Abdollahi et al. 2017, PRD 95, 082007)
  - the goal was to provide the first space based measurement above 1 TeV
    - more and better data: 7 years of Pass 8 data
    - extending the energy range: 7 GeV → 2 TeV (target was 3 TeV)

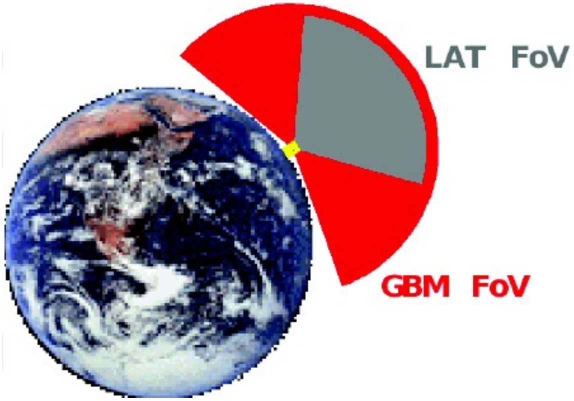
- Since then:
  - H.E.S.S. (Kerszberg+2017) → 20 TeV, Veritas (Archer+2018) → 5 TeV
  - DAMPE (Ambrosi+2017) → 4.6 TeV, CALET (Adriani+2018) → 4.8 TeV, AMS-02 (Ting @CERN 2018) → 2 TeV

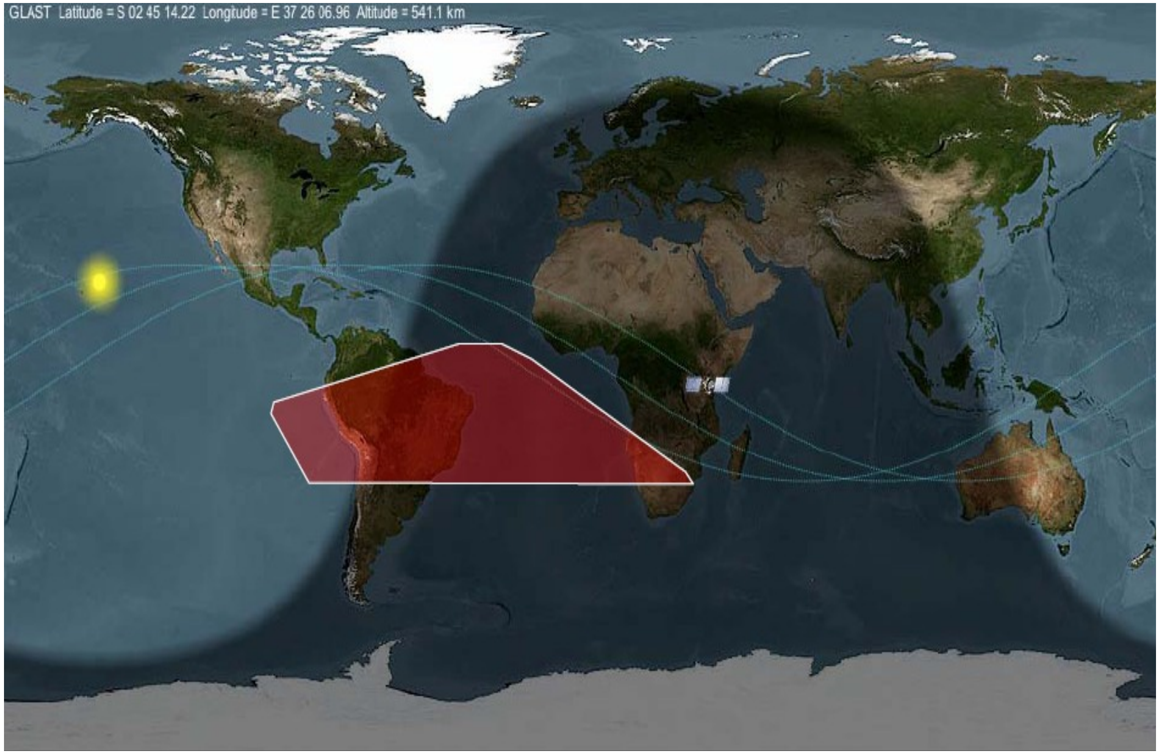
Fermi Gamma-ray Space Telescope



Large Area Telescope
20 MeV -> 300 GeV

Gamma-ray Burst Monitor
8keV -> 40 MeV

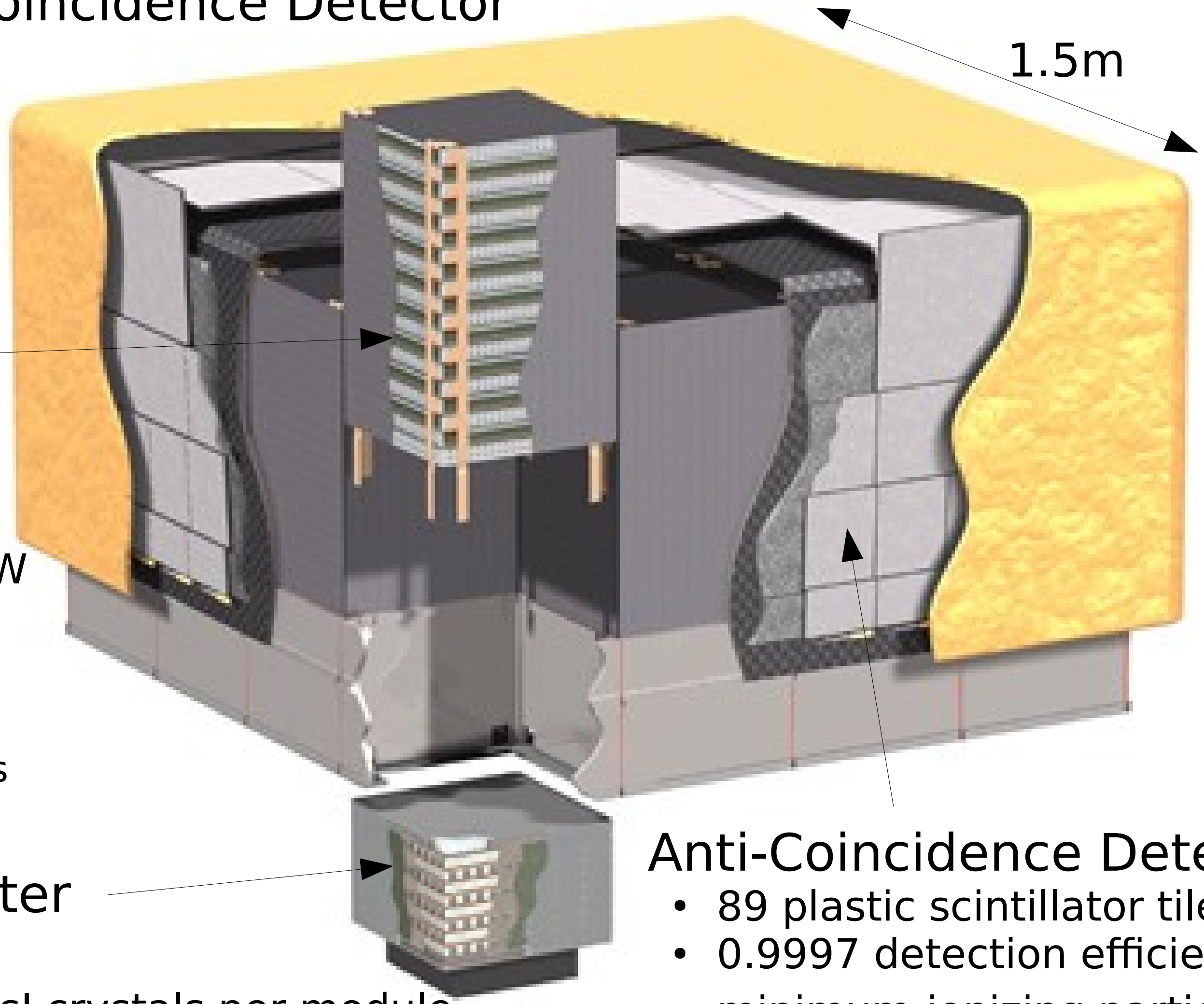




- Launched in June 2008
- Altitude : 565 km
- Inclination : 25.6deg
- Period : 1.5h
- Survey mode
- Lifetime >10 years

Fermi-LAT

4x4 array of identical towers (tracker + calorimeter) surrounded by an Anti-Coincidence Detector



Tracker

- 18 layers (x-y) with silicon strip detectors + tungsten conversion foil
- 2 sections (depending on W thickness):
  - Thin (front) : 12x0.03X_o
  - Thick (back) : 4x0.18X_o
  - No W in the 2 bottom layers
- 1.4 X_o on axis

Calorimeter

- 8.6 X_o
- 8x12 CsI crystals per module
- 2 diodes at each crystal end

Anti-Coincidence Detector

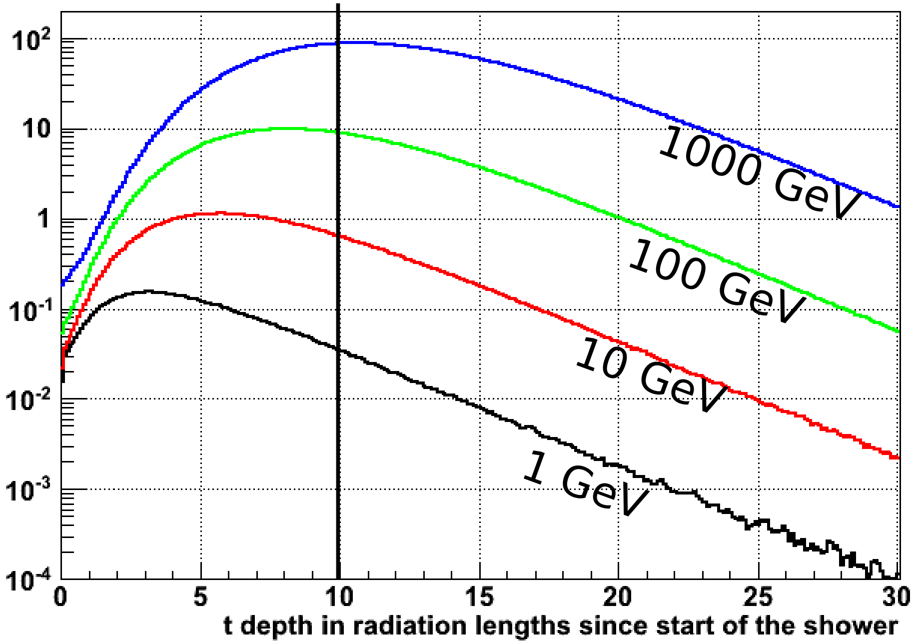
- 89 plastic scintillator tiles
- 0.9997 detection efficiency for minimum-ionizing particles

Energy measurement >1 TeV

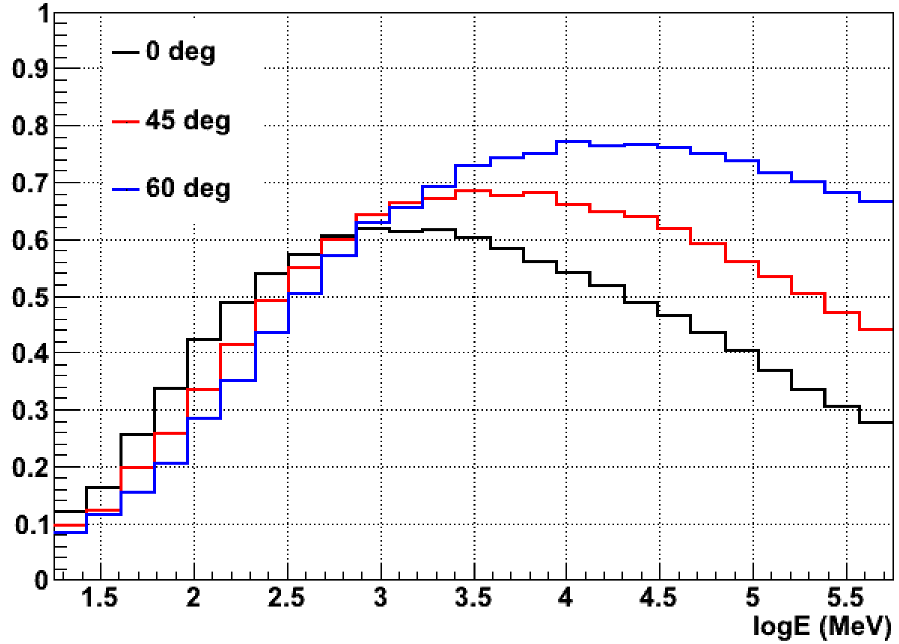
- Instrument relevant quantities:

AMS-02	0.7x0.7 m^2	17 X_o
CALET	0.4x0.4 m^2	30 X_o
DAMPE	0.6x0.6 m^2	32 X_o
Fermi-LAT	1.5x1.5 m^2	**10 X_o**

Average shower profile



Containment fraction



LAT energy measurement

- The calorimeter comprises 8 layers:
  - → longitudinal shower profile fit

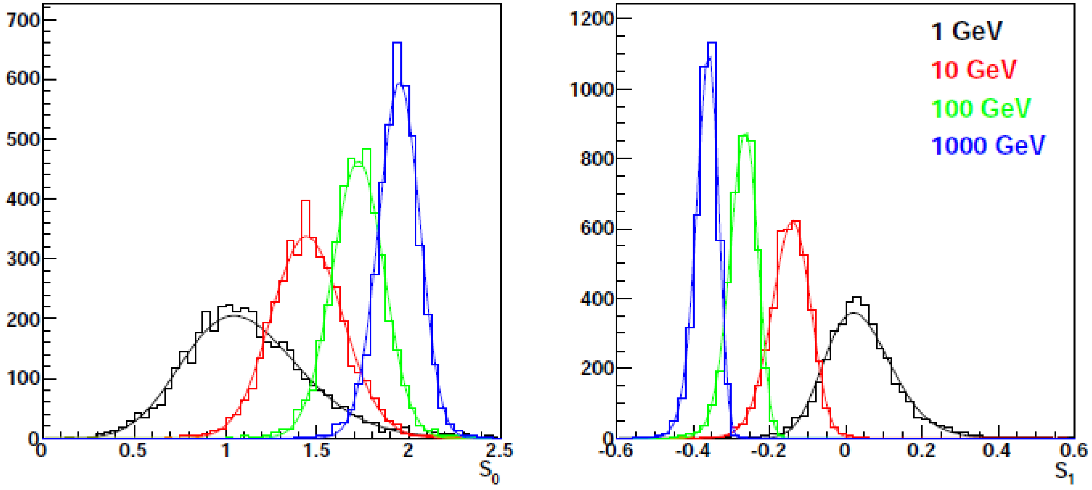
- Two main ingredients:
  - general knowledge of electromagnetic shower development
    - energy dependence of the longitudinal profile (average and fluctuation) and the transverse profile
  - detailed description of the shower development in the LAT
    - energy fraction deposited in each layer/crystal
    - shower leakage at the rear of the CAL, through the gaps
    - on an event by event basis

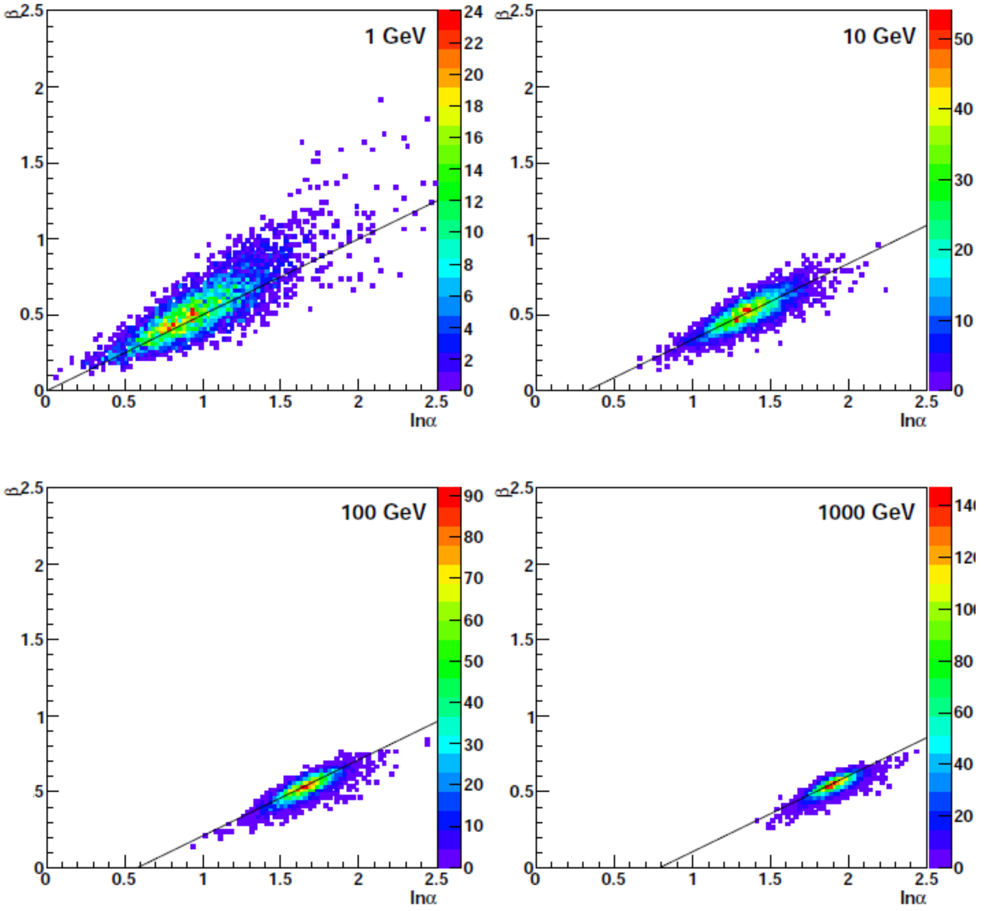
Electromagnetic showers (1)

$$\left\langle \frac{dE(t)}{dt} \right\rangle = E \times \frac{(\beta t)^{\alpha-1}\beta e^{-\beta t}}{\Gamma(\alpha)}$$

- Besides E, we have 2 parameters: α and β
- We choose log α and β, because they are more gaussian.
- Taking into account their correlation:

$$\begin{aligned} S_0 &= \ln\alpha\cos\theta_c + \beta\sin\theta_c \\ S_1 &= -\ln\alpha\sin\theta_c + \beta\cos\theta_c \end{aligned}$$





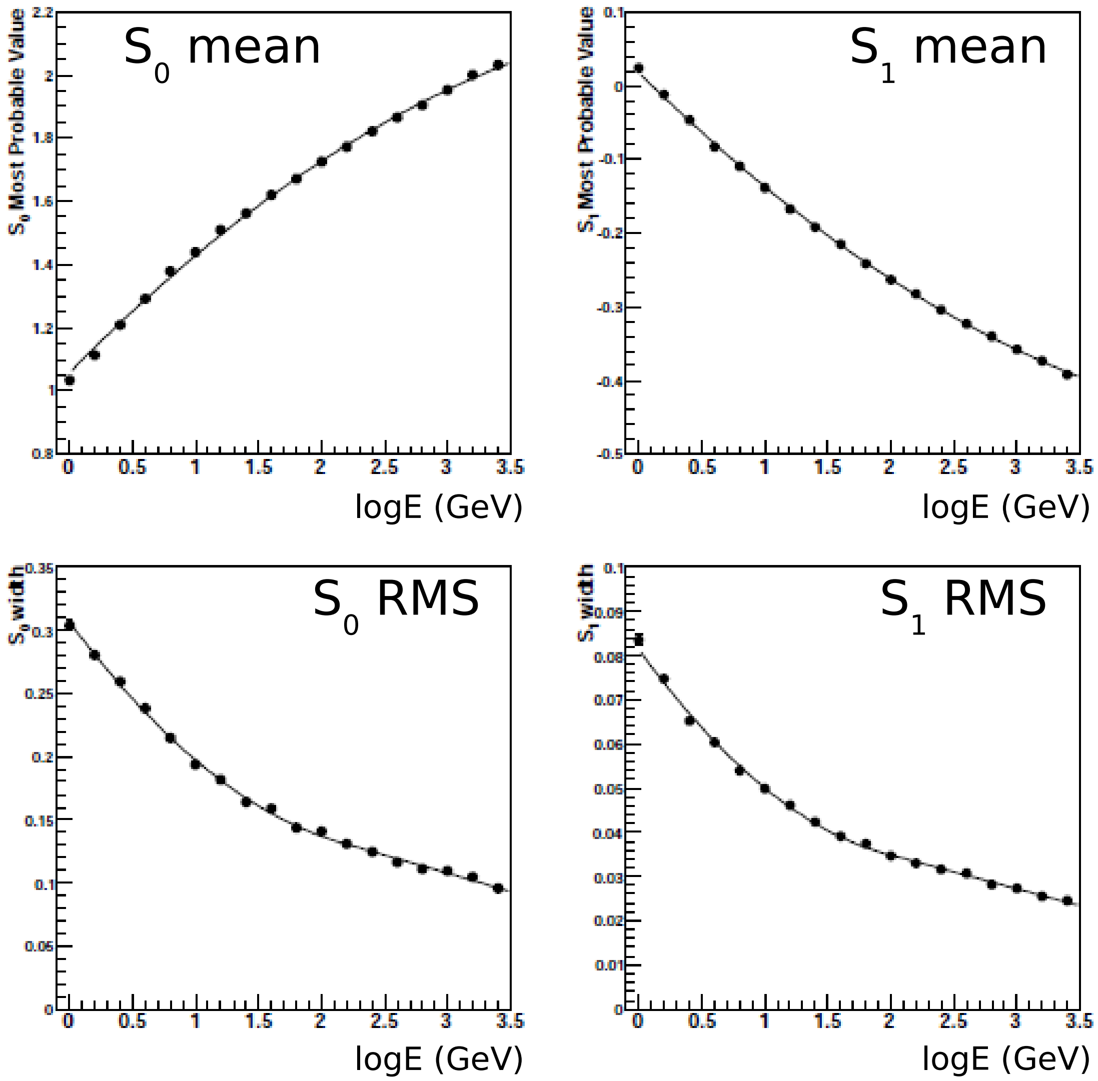
Based on Geant 4 simulations

Electromagnetic showers (2)

- Full description of S_0 and S_1 : parameterization of their mean and RMS as a function of logE

- In order to help the fit convergence, the fit parameters are the reduced variables (bound to be in [-5,5] during the fit):

$$s_0 = (S_0 - \mu_{S_0})/\sigma_{S_0}$$
$$s_1 = (S_1 - \mu_{S_1})/\sigma_{S_1}$$

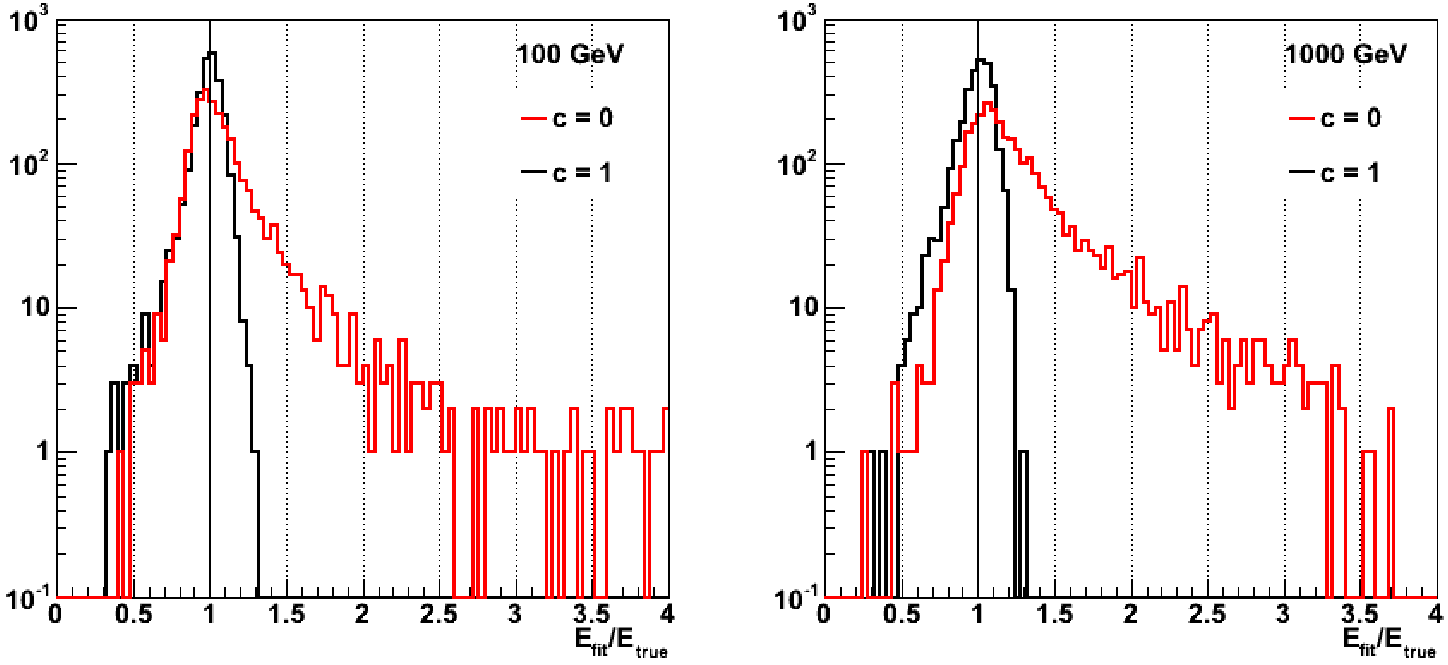


Shower profile fit

- Using the knowledge on the e.m. showers during the fit by constraining the parameters to be close to their expected values
- → we add a simple term to the chi2 :

$$\chi^2(S_0, S_1, E) = \sum_{i=1}^{8} \frac{\left(e_{m,i} - e_{p,i}(E)\right)^2}{\delta e^2(E)} + c\left(s_0^2(E) + s_1^2(E)\right)$$

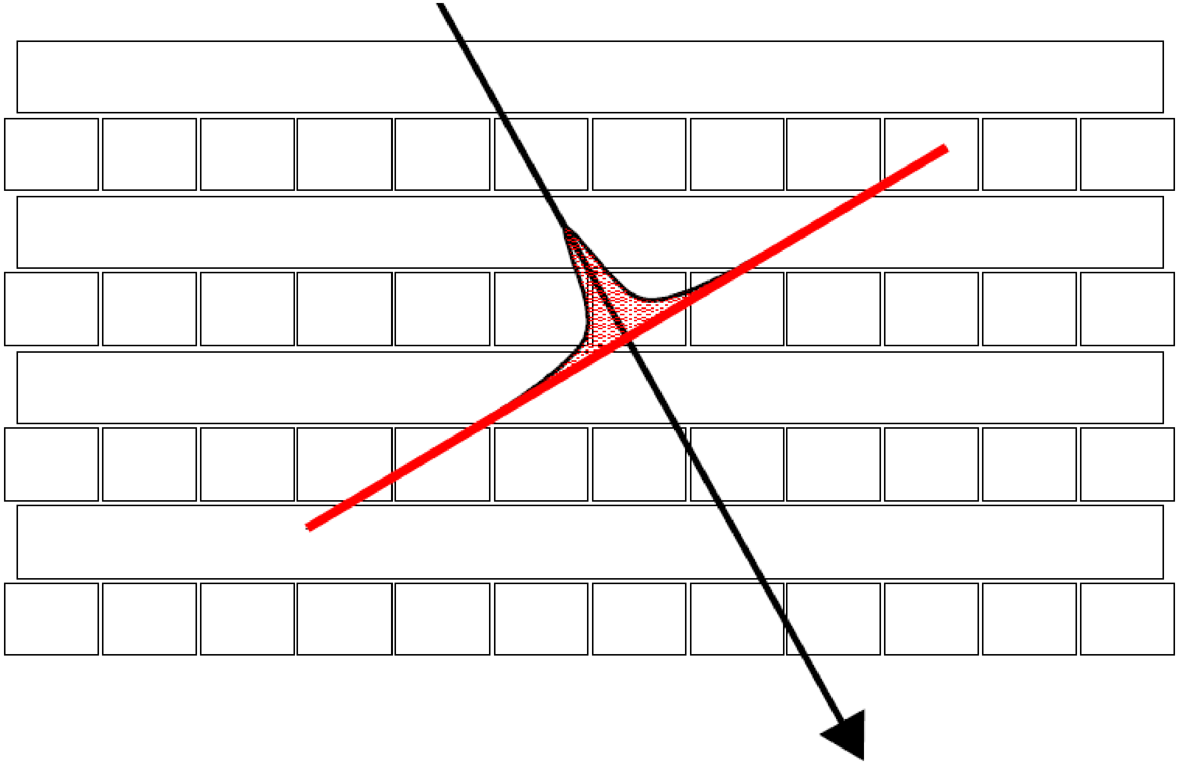
- Using c=1 improves the resolution and avoids large overestimation of the energy
- c is increased when the shower maximum lies outside the CAL



Showers in the LAT CAL (1)

- **For each event**, in order to be able to predict the energy in the layers/crystals, we need to know at each position of the shower what fraction of energy is deposited in each layer/crystal

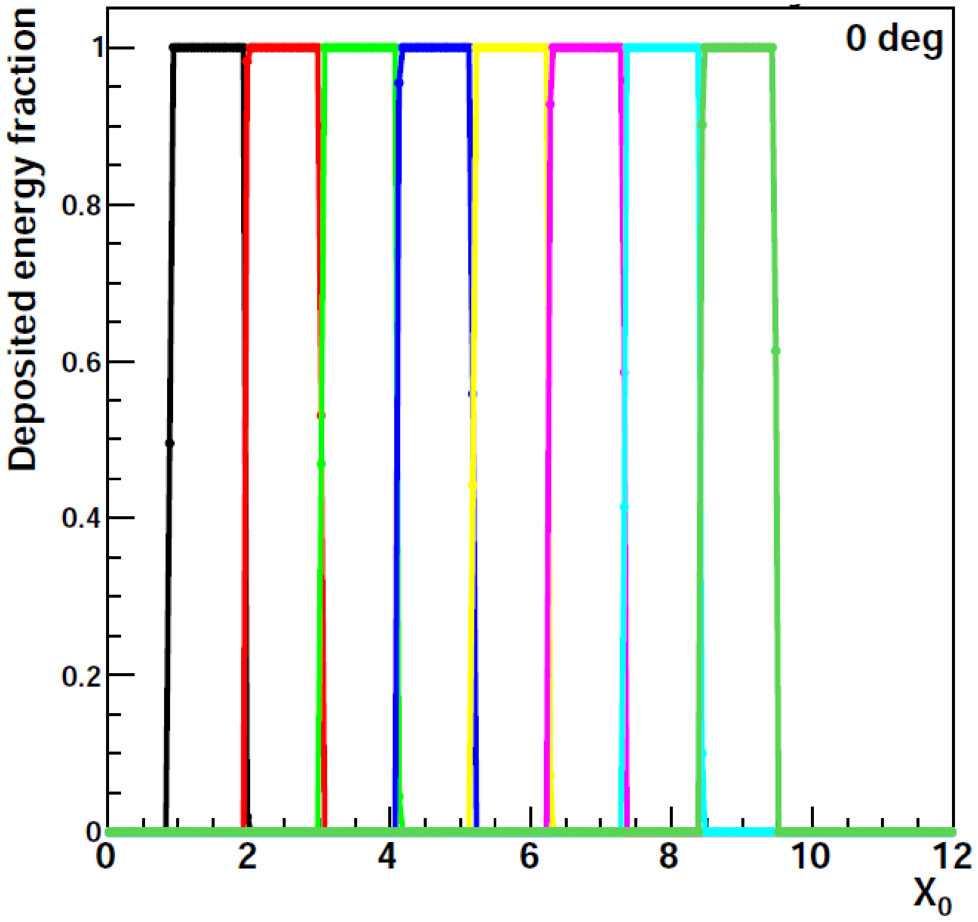
- We divide the trajectory into 1.85mm steps. At each step, corresponding to a depth t in radiation lengths, we use the **radial profile** to compute the fraction of energy deposited by the shower slice in each layer/crystals.

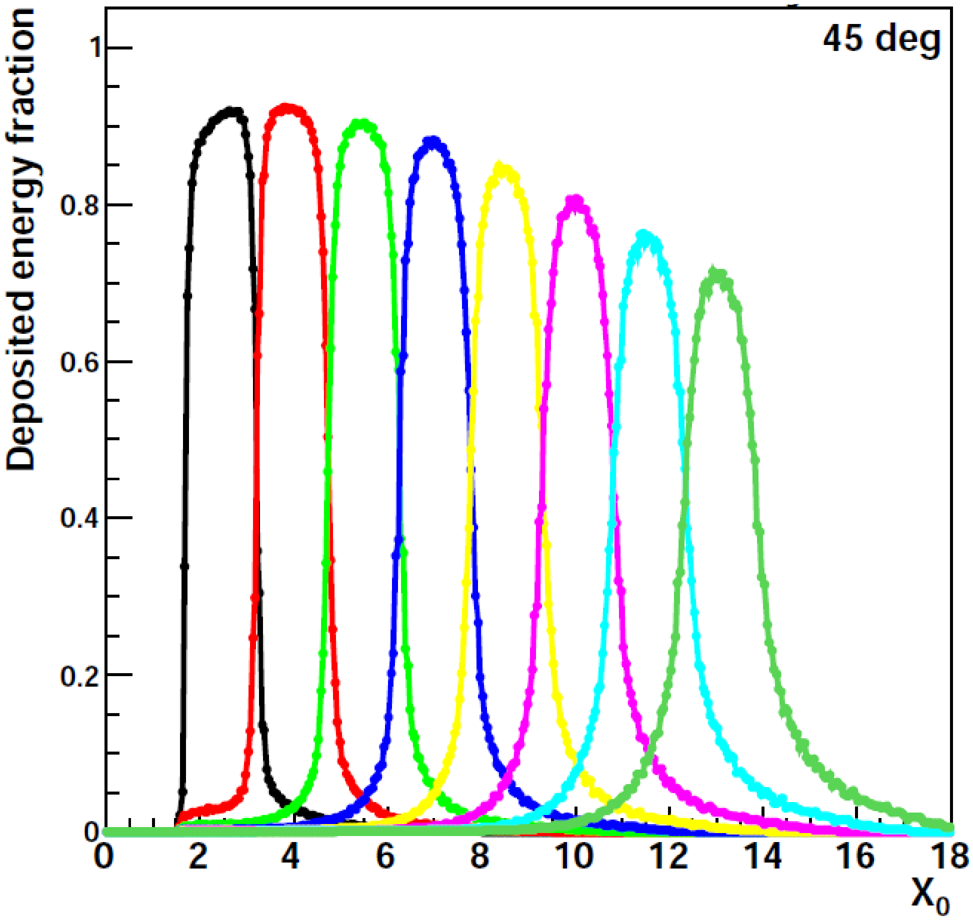


one CAL
tower module
8 layers
12 xtals/layer

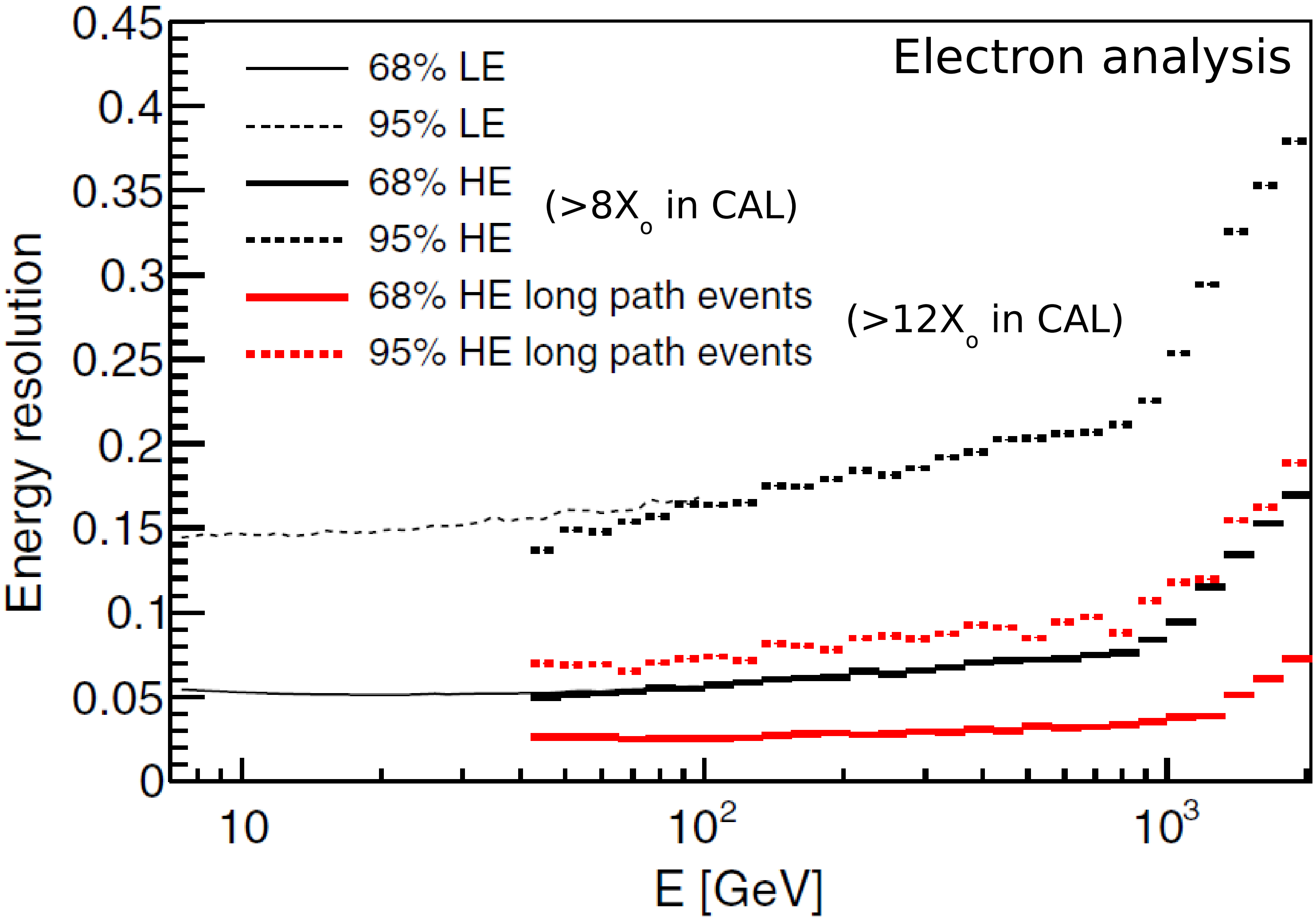
Showers in the LAT CAL (2)

$$E_{\text{pred},i}(\alpha,\beta,E) = \int_0^\infty f_i(t)\times E\frac{(\beta t)^{\alpha-1}\beta e^{-\beta t}}{\Gamma(\alpha)}\mathrm{d}t$$



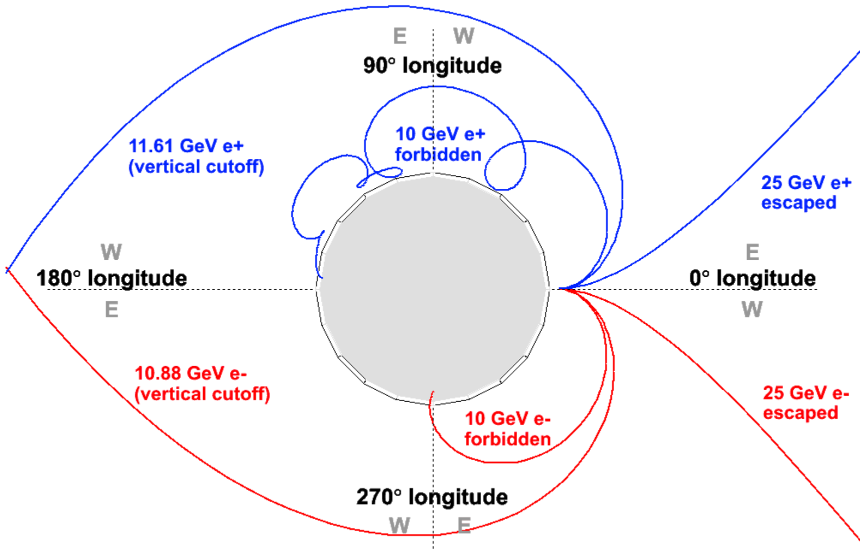


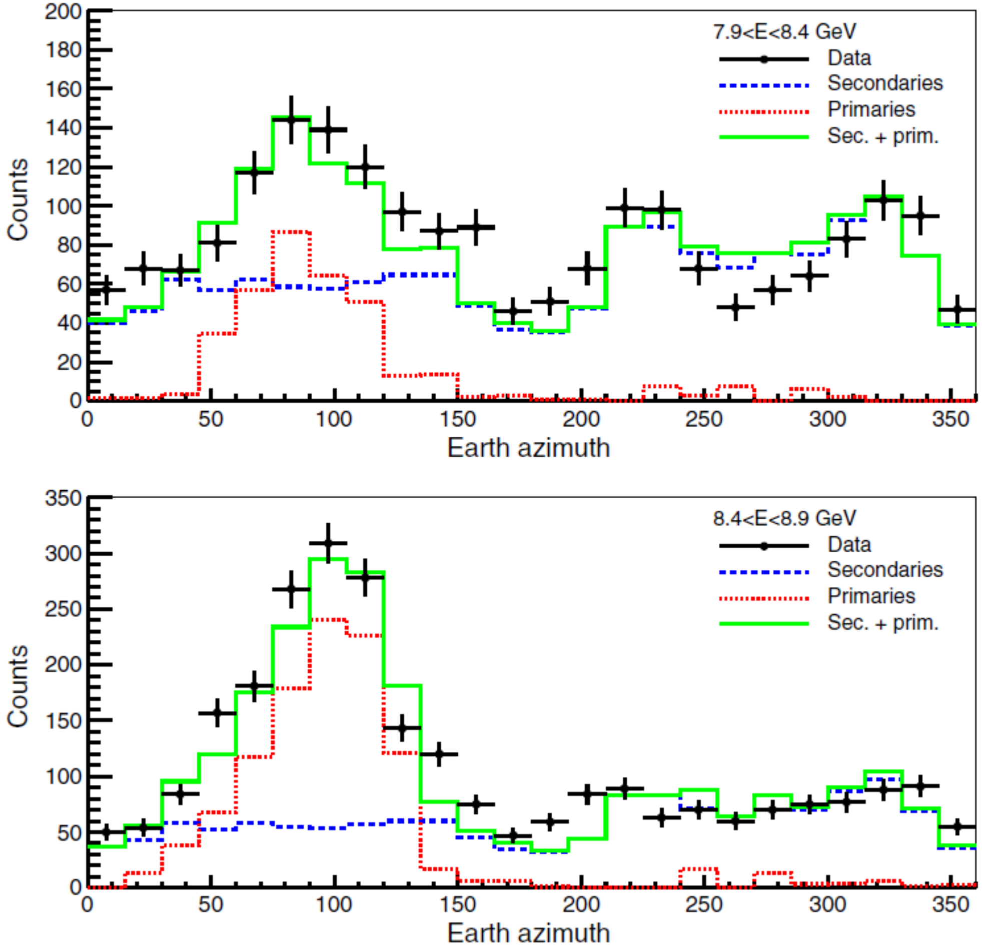
Energy resolution



Absolute energy scale (1)

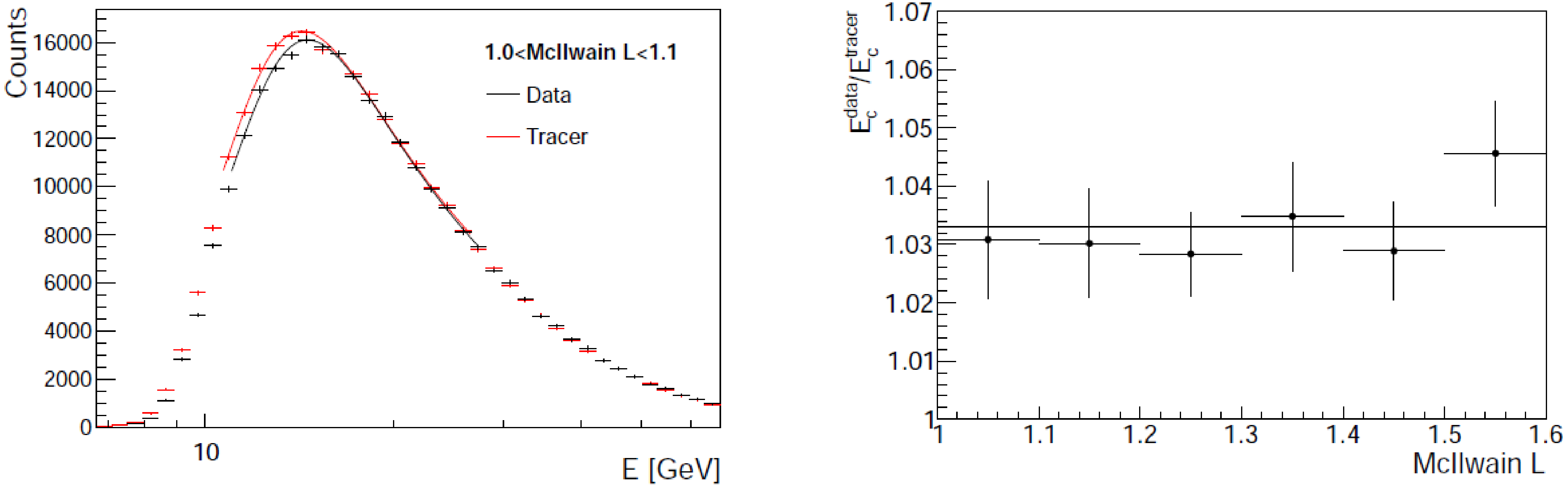
- We use the cutoff of the electron spectrum at ~10 GeV due to the Earth's magnetic field (as in Ackermann+2012)
  - template fit of the azimuthal distribution
  - estimate the secondaries fraction
  - get the primary spectrum





Absolute energy scale (2)

  - We use the cutoff of the electron spectrum at ~10 GeV due to the Earth's magnetic field (as in Ackermann+2012)
  - fit the primary spectrum
  - compare with the tracer prediction
- Result: data/tracer ratio = 1.033 +- 0.004 (stat) +- 0.020 (syst)
- Charge-injection calibration ensures linearity better than 1% up to saturation level
- We assume light-yield linearity up to 2 TeV
  - → we rescale the energy in data by -3.3%



Electron analysis

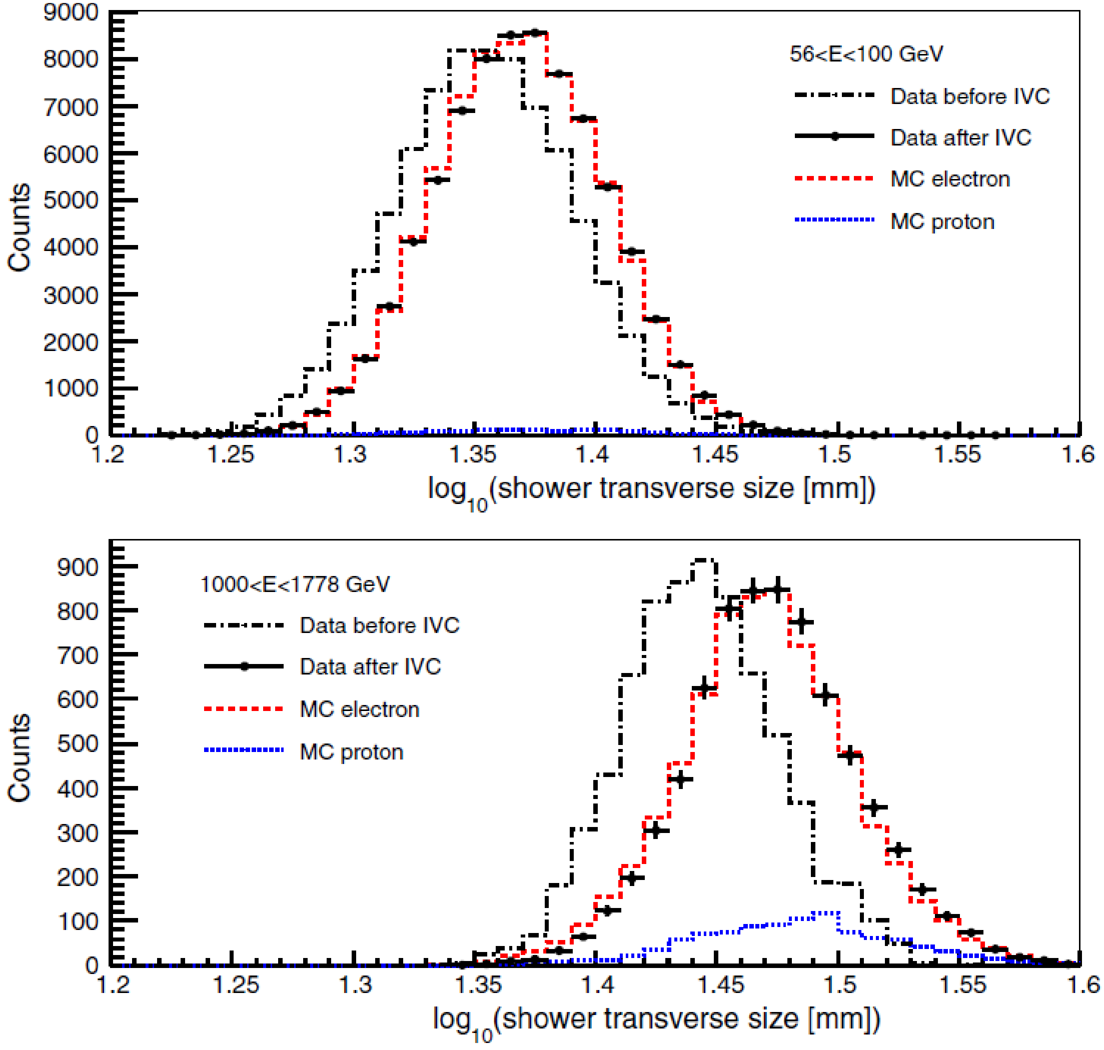
- 2 analyses:
  - HE analysis: E>42 GeV, events passing the onboard gamma filter
  - LE analysis: 7<E<70 GeV, events passing the unbiased trigger prescaled by 250

- Analysis precuts:
  - rocking angle<51deg
  - incoming angle < 60deg
  - we use the ACD signal and the TKR Time over Threshold (ToT) to remove alphas and heavy ions
  - more than 8 X_o in the CAL

- The rest of the selection is performed thanks to a multivariate analysis:
  - using the ROOT TMVA package (as for the Pass 8 standard photon selection)
  - 8 Boosted Decision Trees in 8 logE bins from 31 GeV to 3.1 TeV (to account for the changes in event topology in the LAT between few GeVs and few TeVs)

Data/MC agreement

- Data/MC agreement is important in multivariate analyses
- We found some disagreements that had a big impact on the BDT output
- We performed a systematic data/MC comparison of the variables used for the BDT training and derived additive corrections as a function of energy and angle = Individual Variable Corrections (IVC)



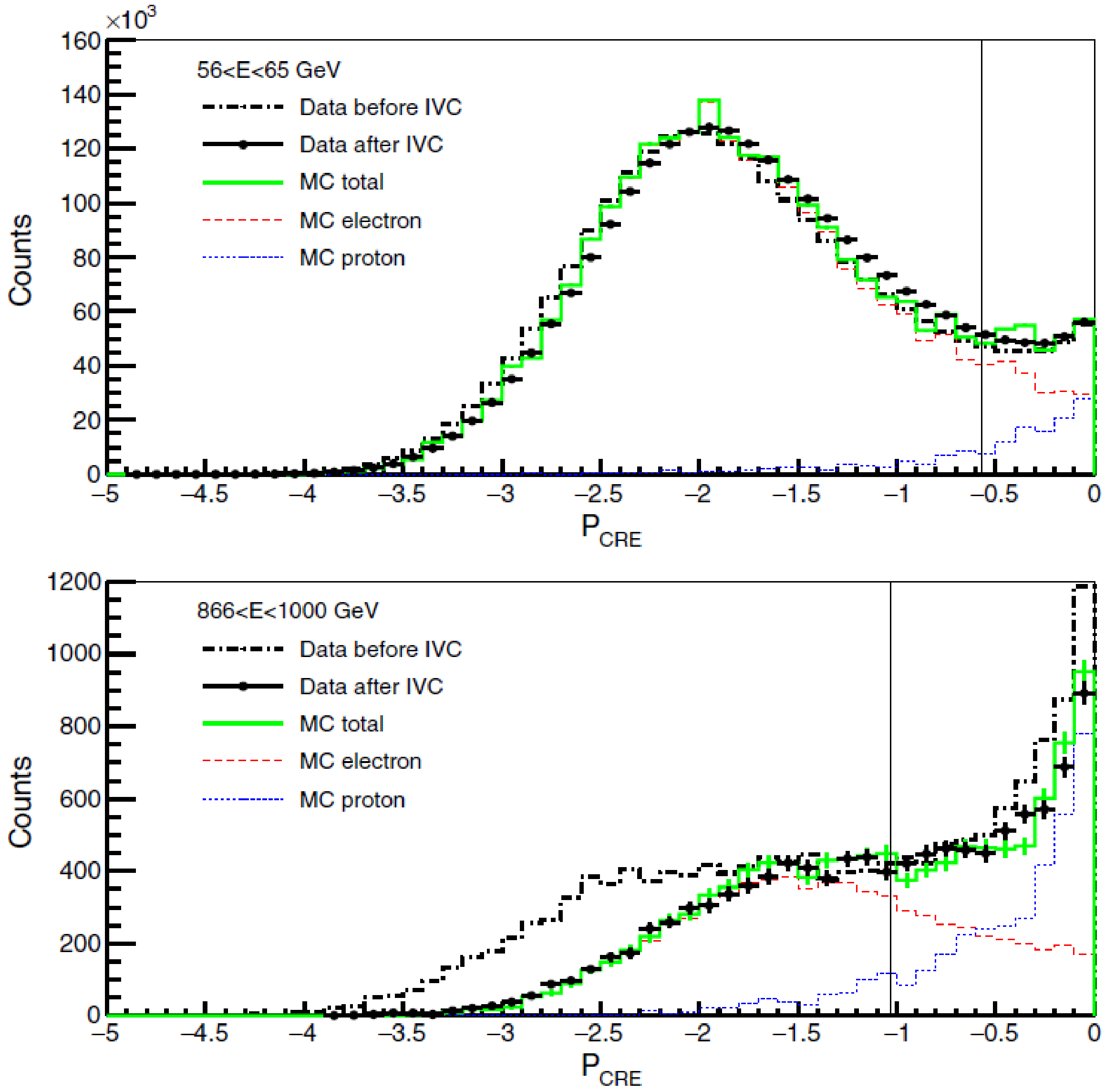
Event selection

- Electron estimator:

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

- In each energy bin, we perform a template fit using MC predicted electron and proton distributions

- Find the energy dependent cut that minimizes the flux uncertainty (taking into account systematics)
  - → number of electrons
  - → proton contamination

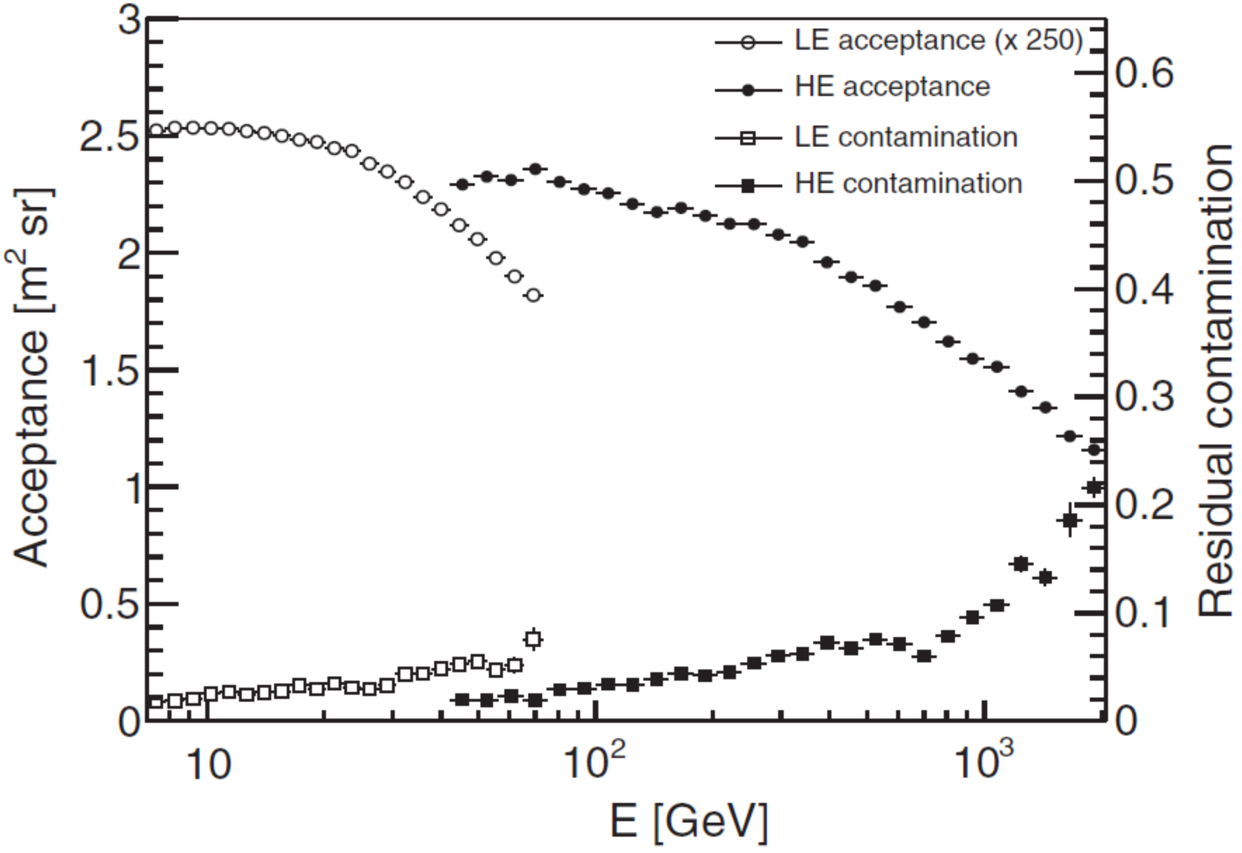


Performance

- We stop the analysis when the proton contamination reaches 20%
  - → 2 TeV

Performance at 1 TeV:

	2010	2017
acceptance (m^{2}sr)	1.0	1.5
contamination	20%	10%
E resolution	14%	10%



Systematic uncertainties (1)

1) Acceptance: we scan the selection cut around the nominal one such that the cut efficiency varies by +-20%:
   - → 2 to 6%

2) Residual contamination: we rely on the GEANT4 prediction. We assume a 20% uncertainty
   - → 2 to 7%

3) Data/MC agreement: we use 2 bracketing sets of corrections in which each correction is displaced by +- the maximum of the residual data/MC differences
   - → 2 to 14%

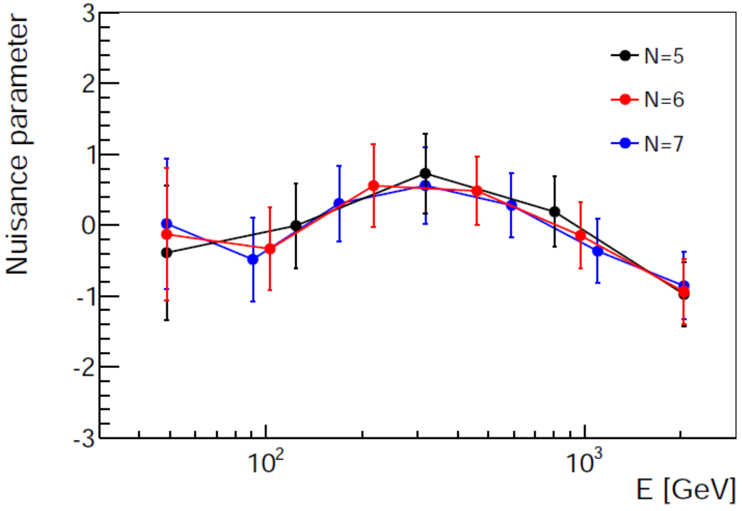
- (2) and (3) are modeled by adding 6 nuisance parameters in the spectrum fit:

$$\chi^2 = \sum_{i=1}^{n} \left(\frac{N_i - (1 + s(E_i;\mathbf{w}) S(E_i))\mu_i(\boldsymbol{\theta})}{\delta N_i} \right)^2 + \sum_{j=1}^{\mathcal{N}} w_j^2$$

piecewise function
with nuisance param w_i

systematics
amplitude

gaussian prior
on w_i

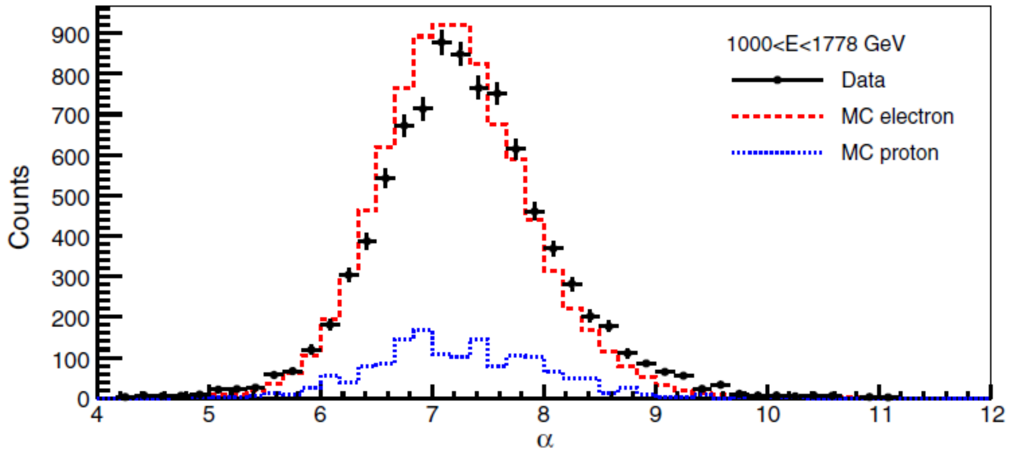


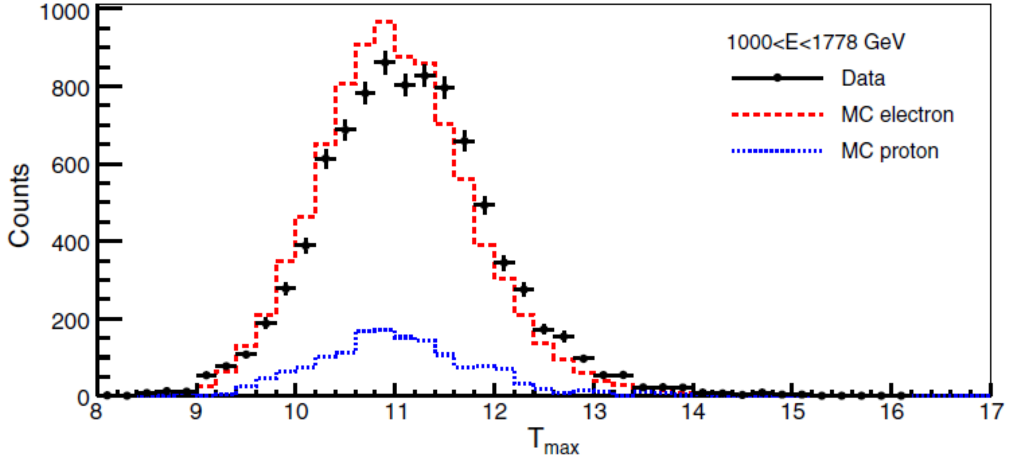
Systematic uncertainties (2)

- Energy systematic uncertainty:
  - energy scale at 10 GeV: 2%
  - energy measurement: 0% at 10 GeV to 5% at 1 TeV

- The E reconstruction basically corrects for the shower leakage (that increases linerlay with logE) thanks to the shower parameter estimation
- Data/MC difference of α and Tmax
  - $\delta\alpha(E) = 0.05 \log(E/10\mathrm{GeV})$
  - $\delta T_{max}(E) = 0.10 \log(E/10\mathrm{GeV})$
- Energy variation = $0.025 \log(E/10\mathrm{GeV})$
  - → 5% at 1 TeV

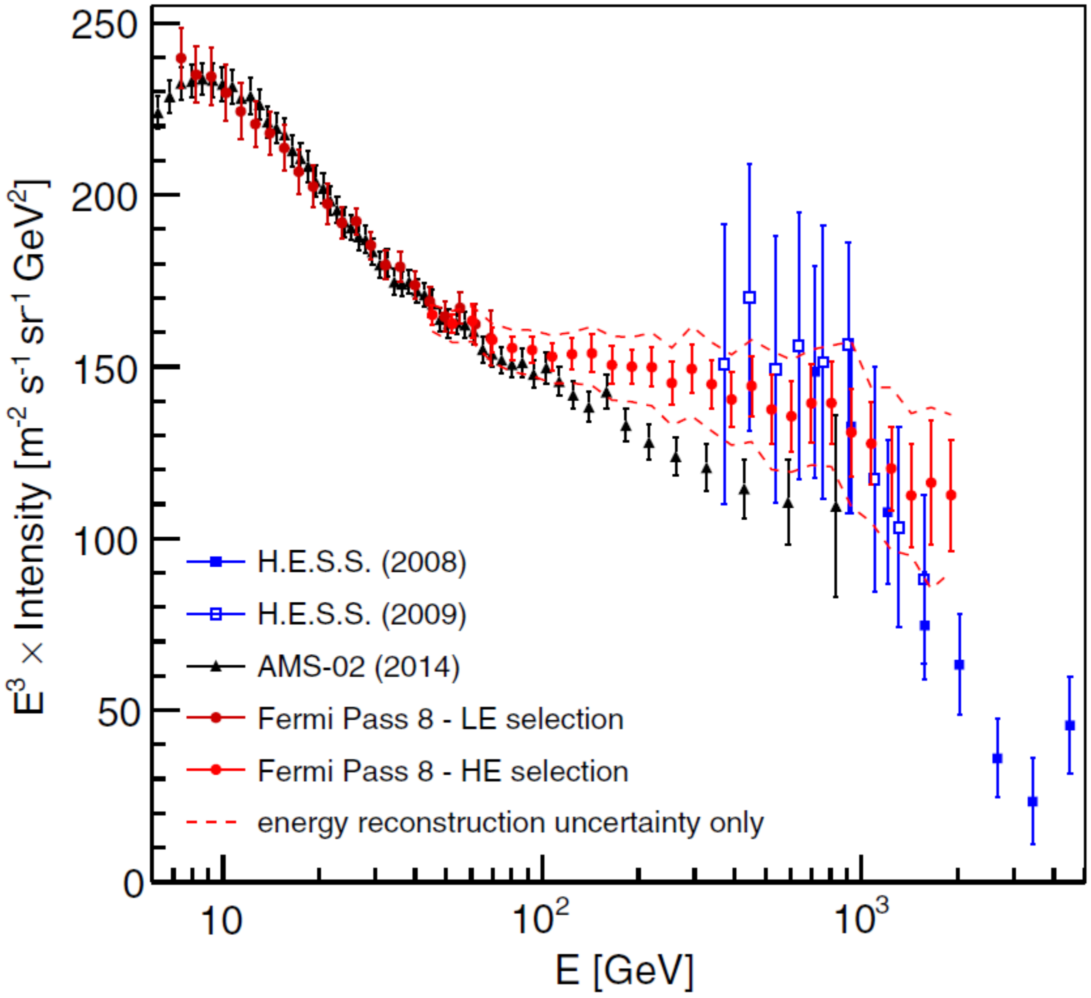
- The energy systematic uncertainty is taken into account with worst case scenari in the spectrum fit

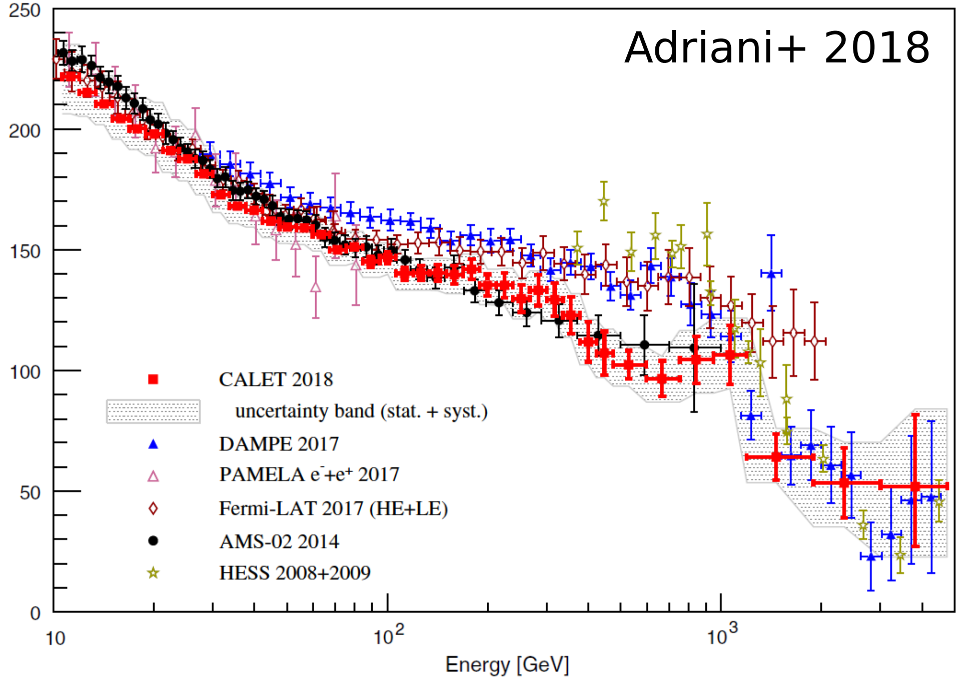




Electron+positron spectrum

- We fit the count spectrum by forward folding the predicted flux using the Detector Response Matrix (to take into account energy resolution)
- Energy break at 50±10 GeV (spectral index 3.21±0.02 and 3.07±0.06)
- 95%CL lower limit on exponential cutoff: E_c>2.1 TeV




Adriani+ 2018

Conclusions

- Fermi-LAT was able to measure the electron+positron spectrum up to 2 TeV

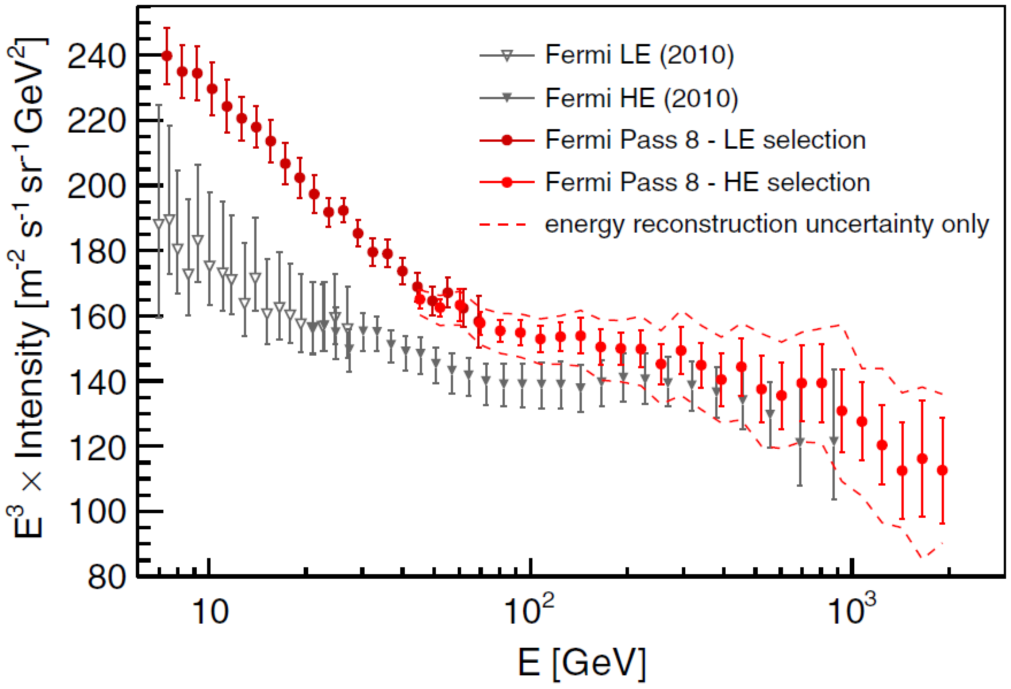
- Measurement limitations:
  - low shower containment
    - energy measurement
    - background rejection
  - data/MC disagreements

- No plan to update the analysis (unless data/MC disagreements are fixed)

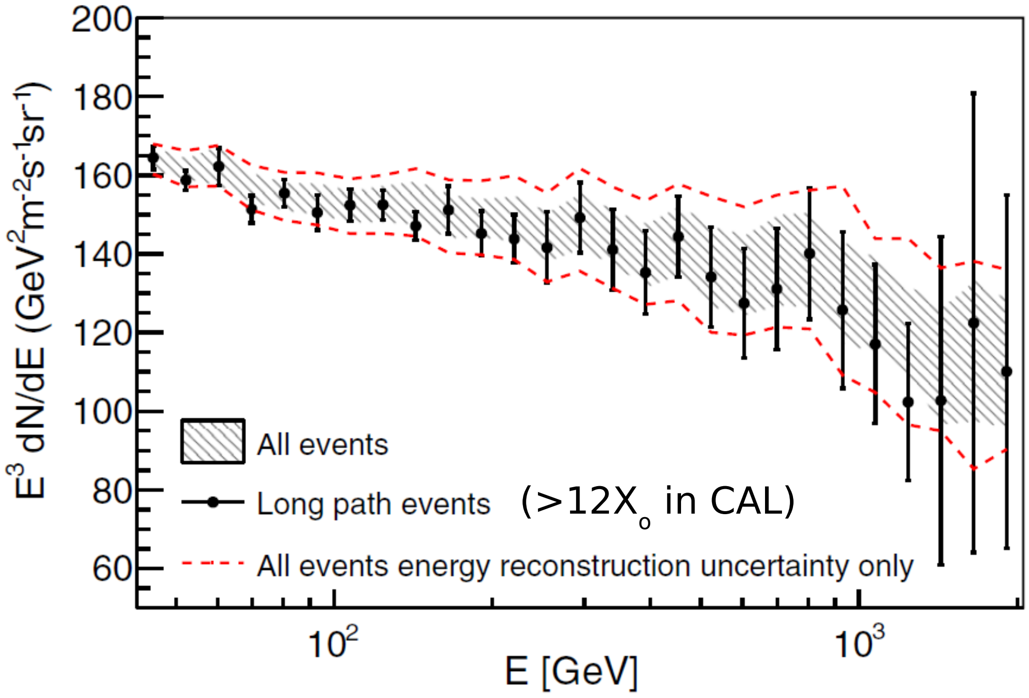
- Puzzling differences among space-based results AMS/CALET/DAMPE/Fermi

Backup

Results

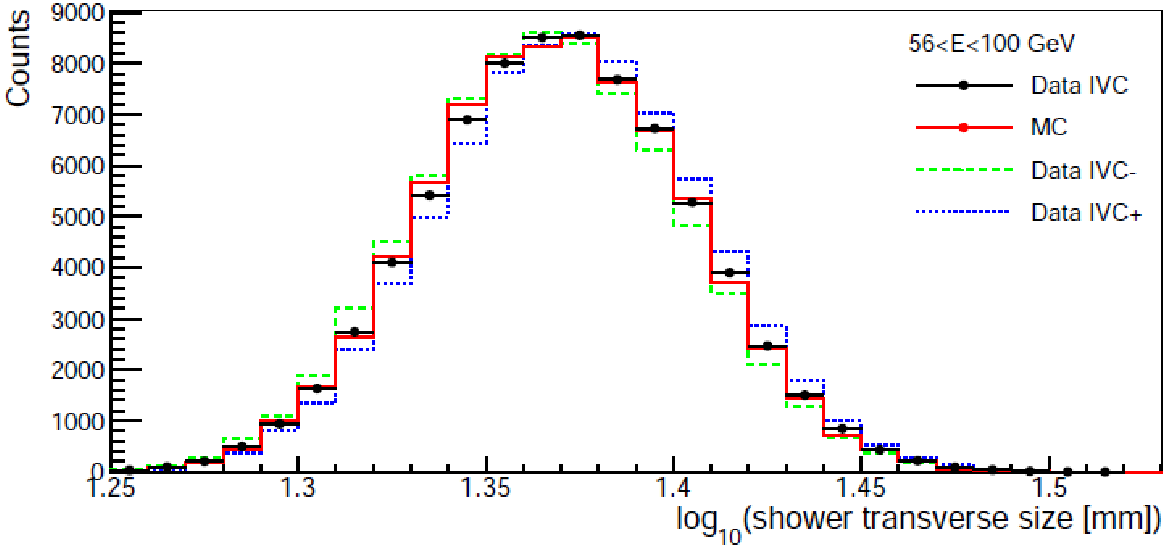


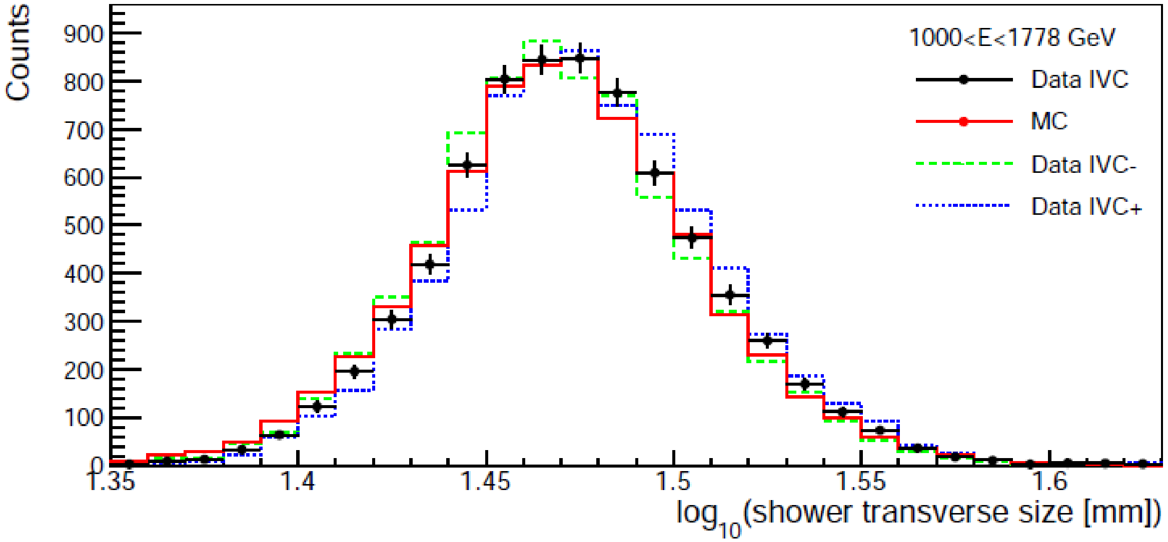
Fermi LE (2010)
Fermi HE (2010)
Fermi Pass 8 - LE selection
Fermi Pass 8 - HE selection
energy reconstruction uncertainty only
$E^3 \times$ Intensity [$m^{-2} s^{-1} sr^{-1} GeV^2$]
240
220
200
180
160
140
120
100
80
10
10^2
10^3
E [GeV]



All events
Long path events
(>$12X_o$ in CAL)
All events energy reconstruction uncertainty only
E^3 dN/dE ($GeV^2 m^{-2} s^{-1} sr^{-1}$)
200
180
160
140
120
100
80
60
10^2
10^3
E [GeV]

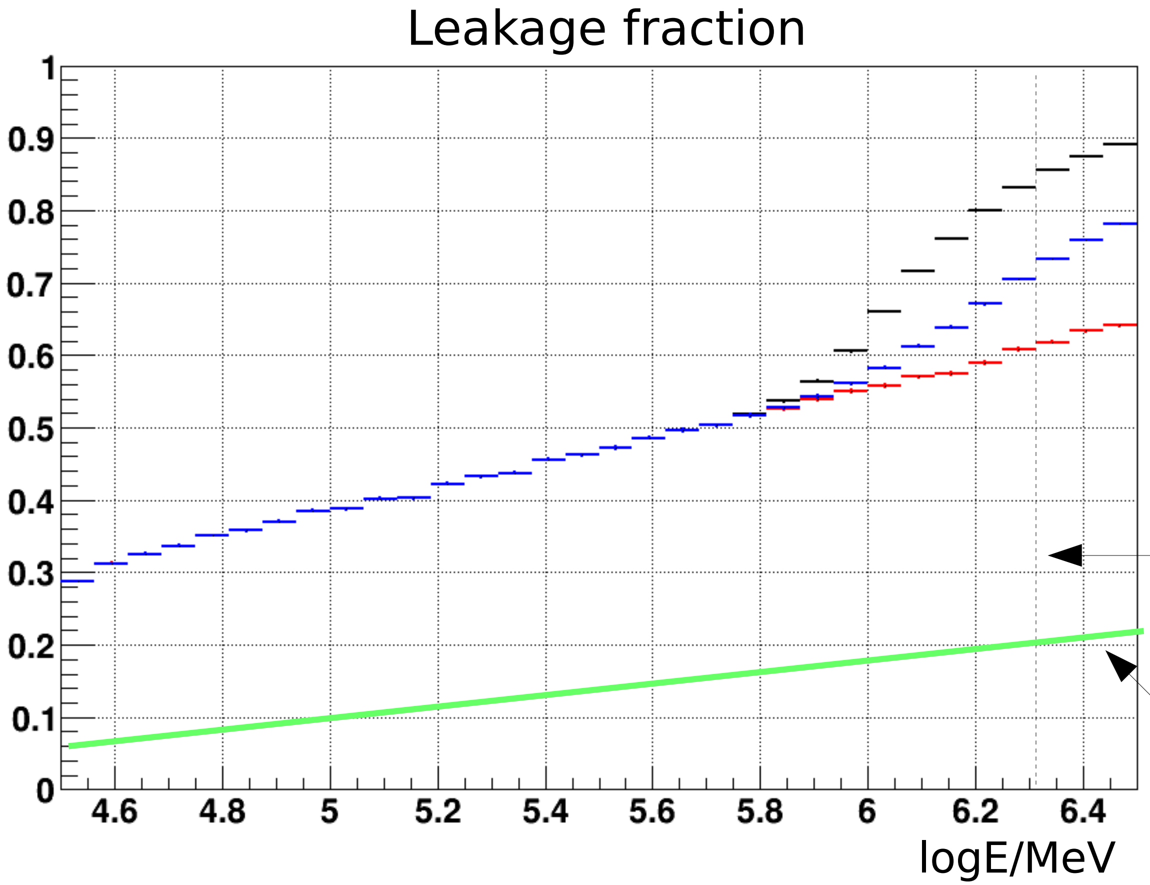
IVC systematics





Leakage and saturation

- Leakage = front + rear leakage (mostly rear at high energy)
- Crystal saturation (70 GeV/crystal) starts for electrons of ~600 GeV
- Saturated crystals are discarded in the shower fit: we only take into account the non-saturated layer energies



information used in the fit

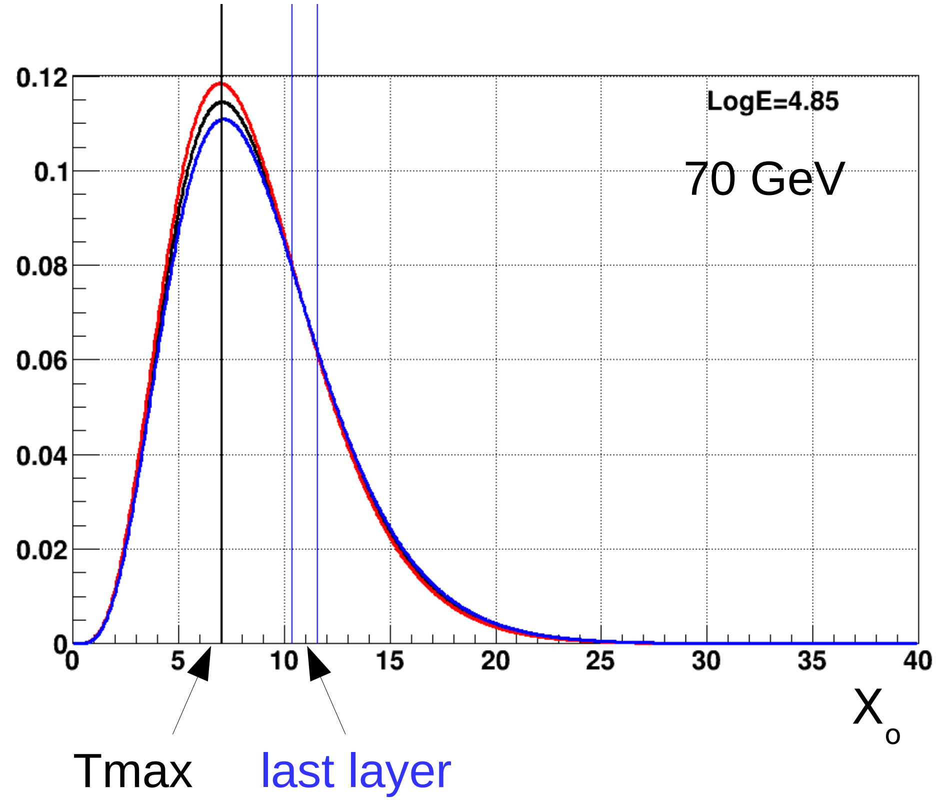
leakage w/o saturation

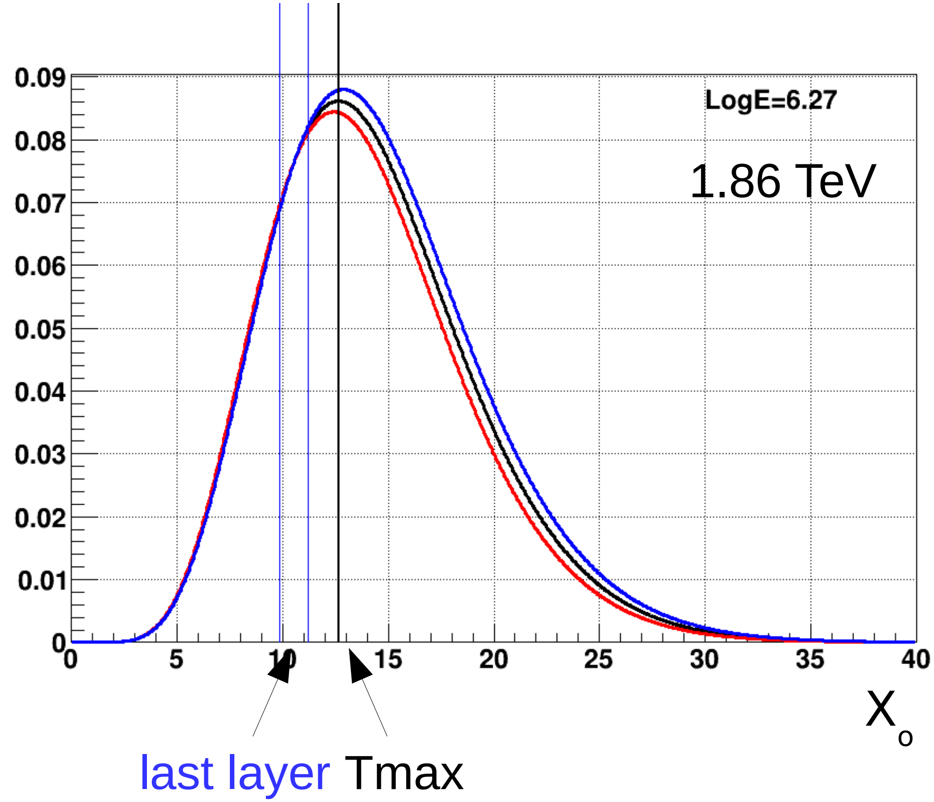
end of the energy range (2TeV)

AMS leakage with 17 X_o

Leakage uncertainty

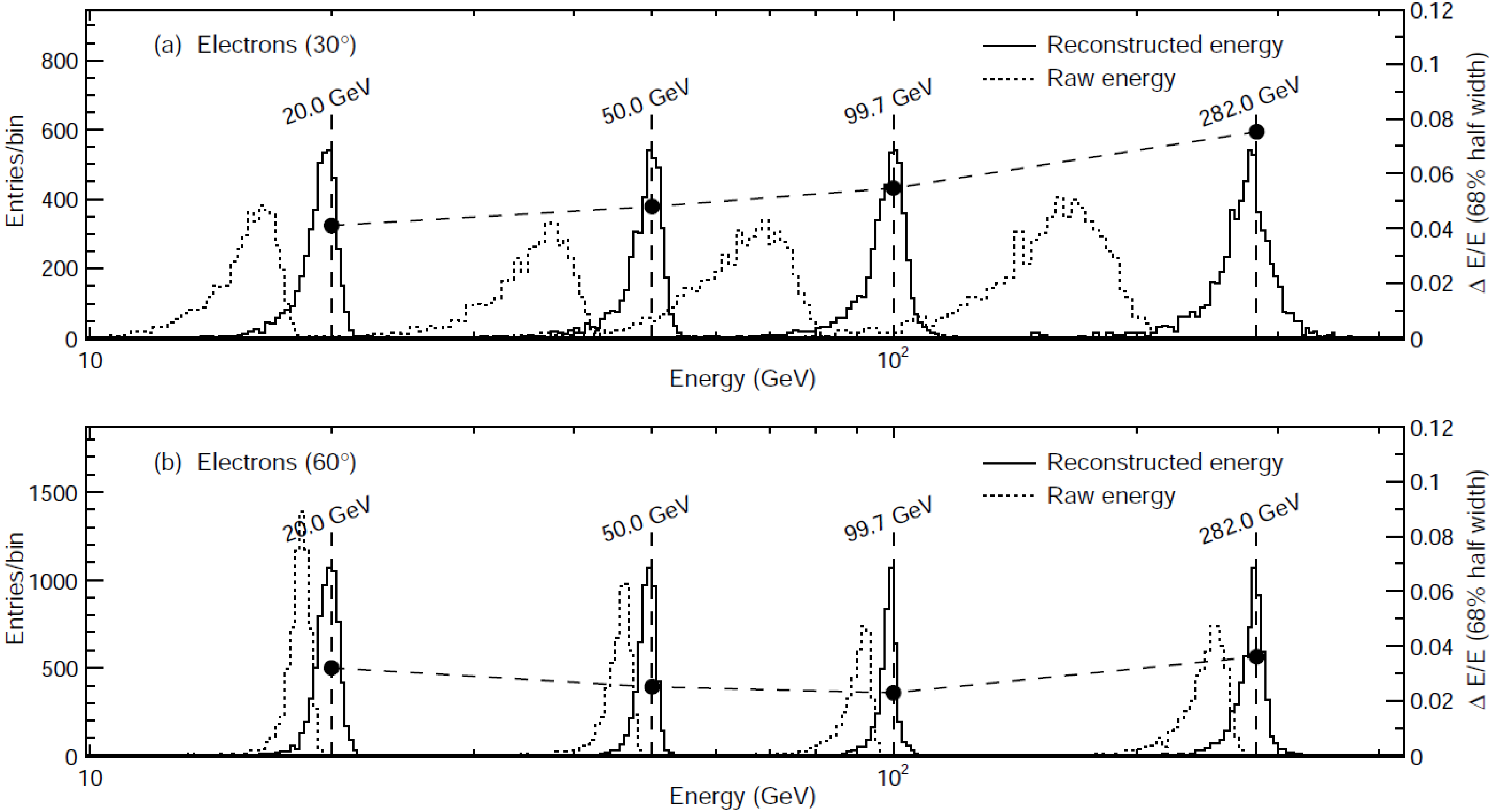
- Estimate the uncertainty on the leakage and derive the total E undertainty:
  - E = E_contained + E_leaked → δE = δE_leaked
- To estimate the uncertainty of the leakage, use data/MC difference for the fit parameters α and Tmax:
  - vary α within ±δα and and Tmax within ±δTmax
    - rescale the energy in layer 7 so that it matches the nominal layer 7 one
    - compute the change in leaked energy





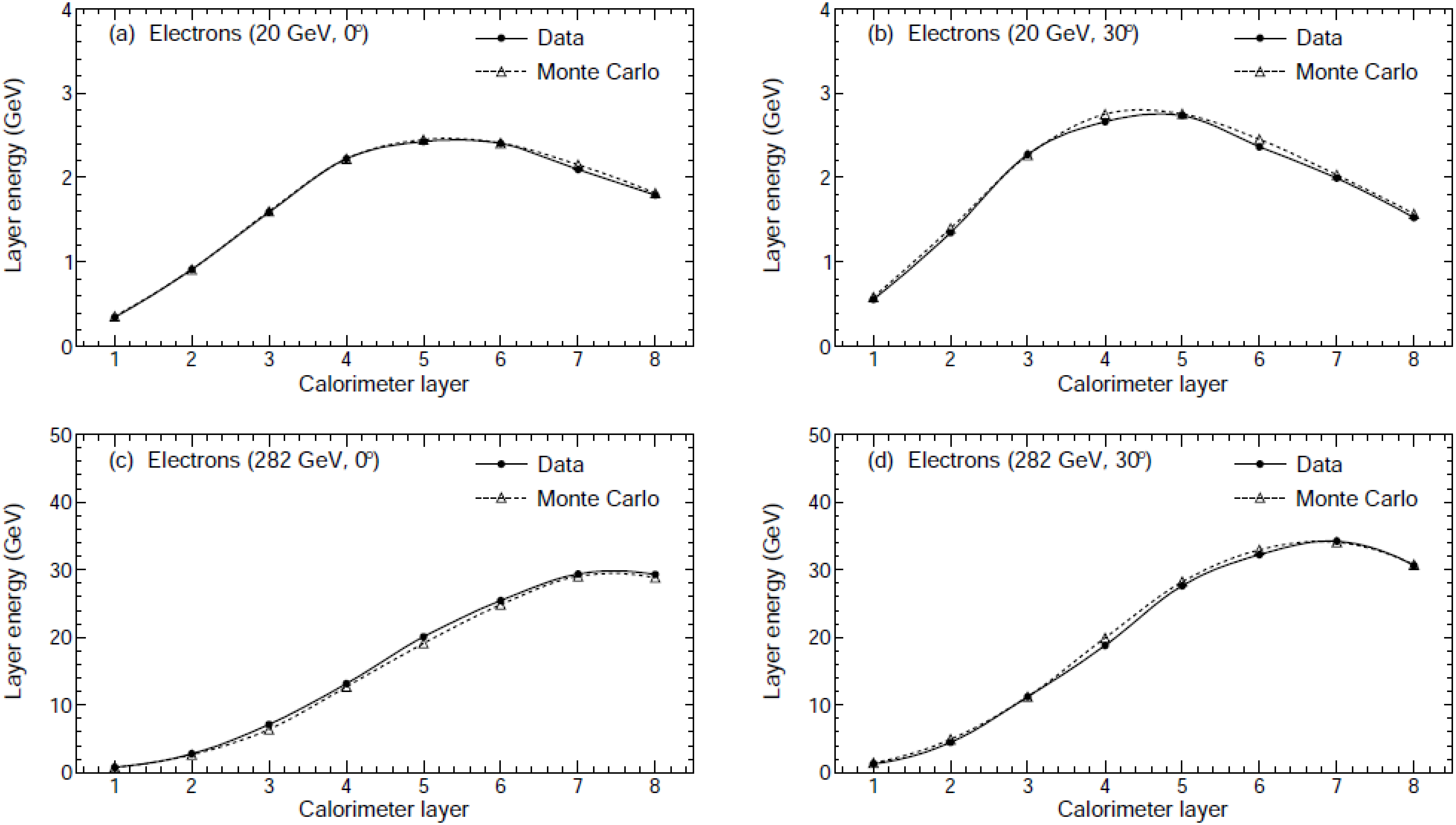
Beam tests (1)

- LAT calibration unit (2.5 towers) at CERN PS+SPS in 2006



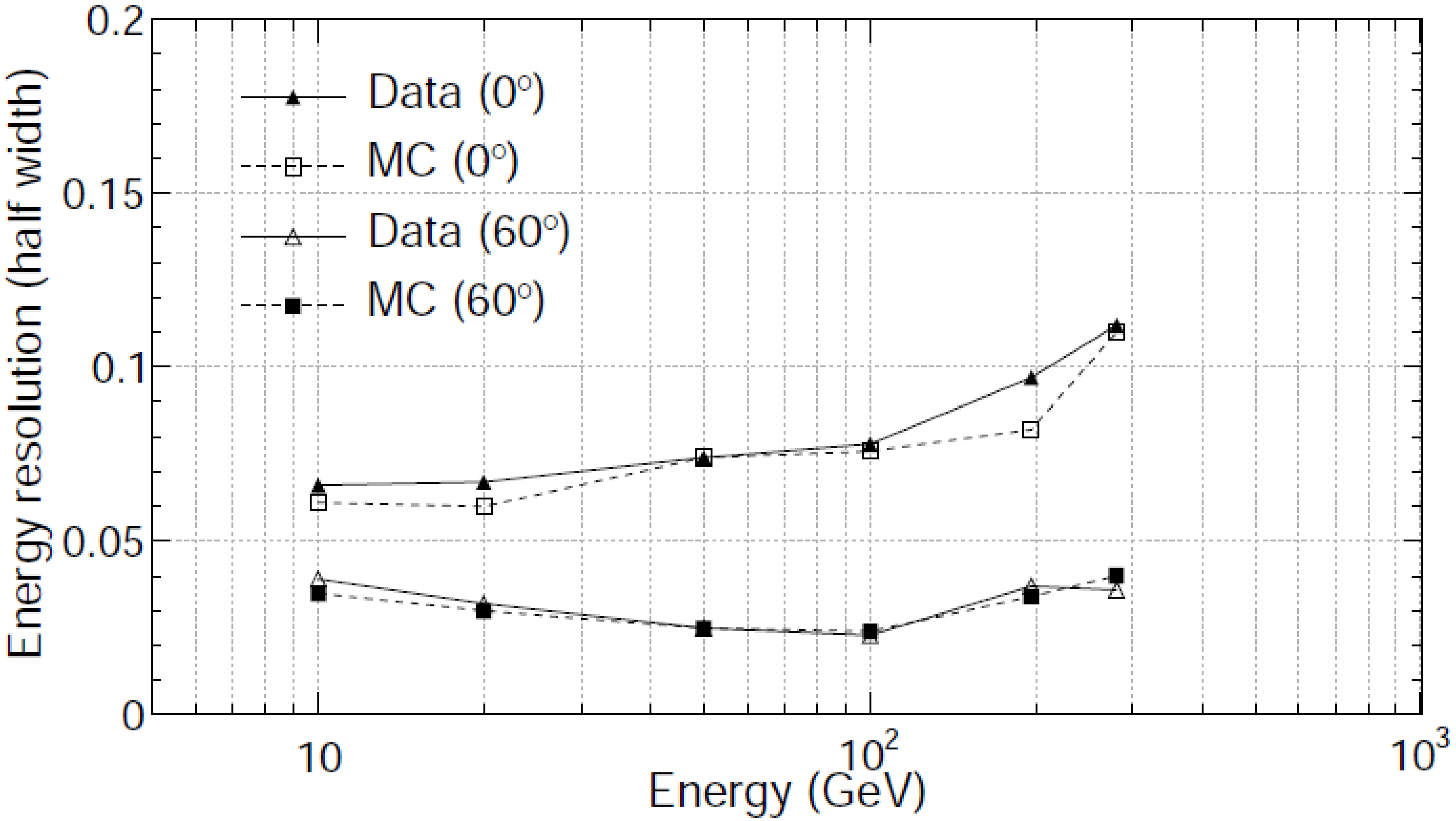
Beam tests (2)

- LAT calibration unit (2.5 towers) at CERN PS+SPS in 2006



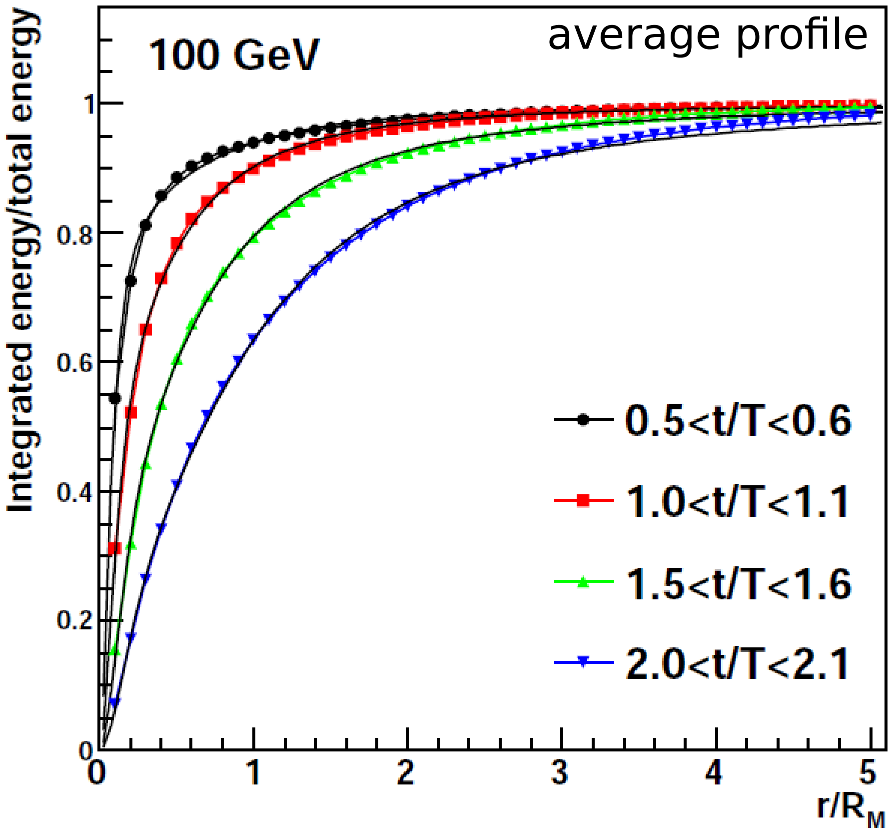
Beam tests (3)

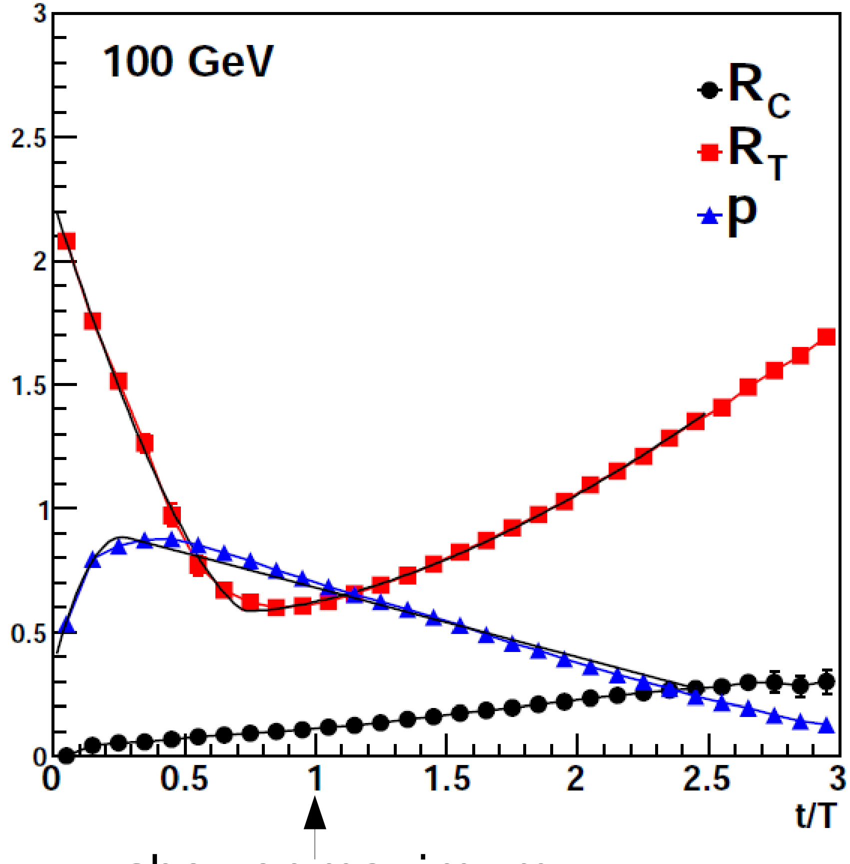
- LAT calibration unit (2.5 towers) at CERN PS+SPS in 2006



Shower transverse profile

$$f(t/T,r) = \frac{1}{dE(t)}\frac{dE(t,r)}{dr} = p\frac{2rR_C^2}{(r^2+R_C^2)^2} + (1-p)\frac{2rR_T^2}{(r^2+R_T^2)^2}$$





shower maximum