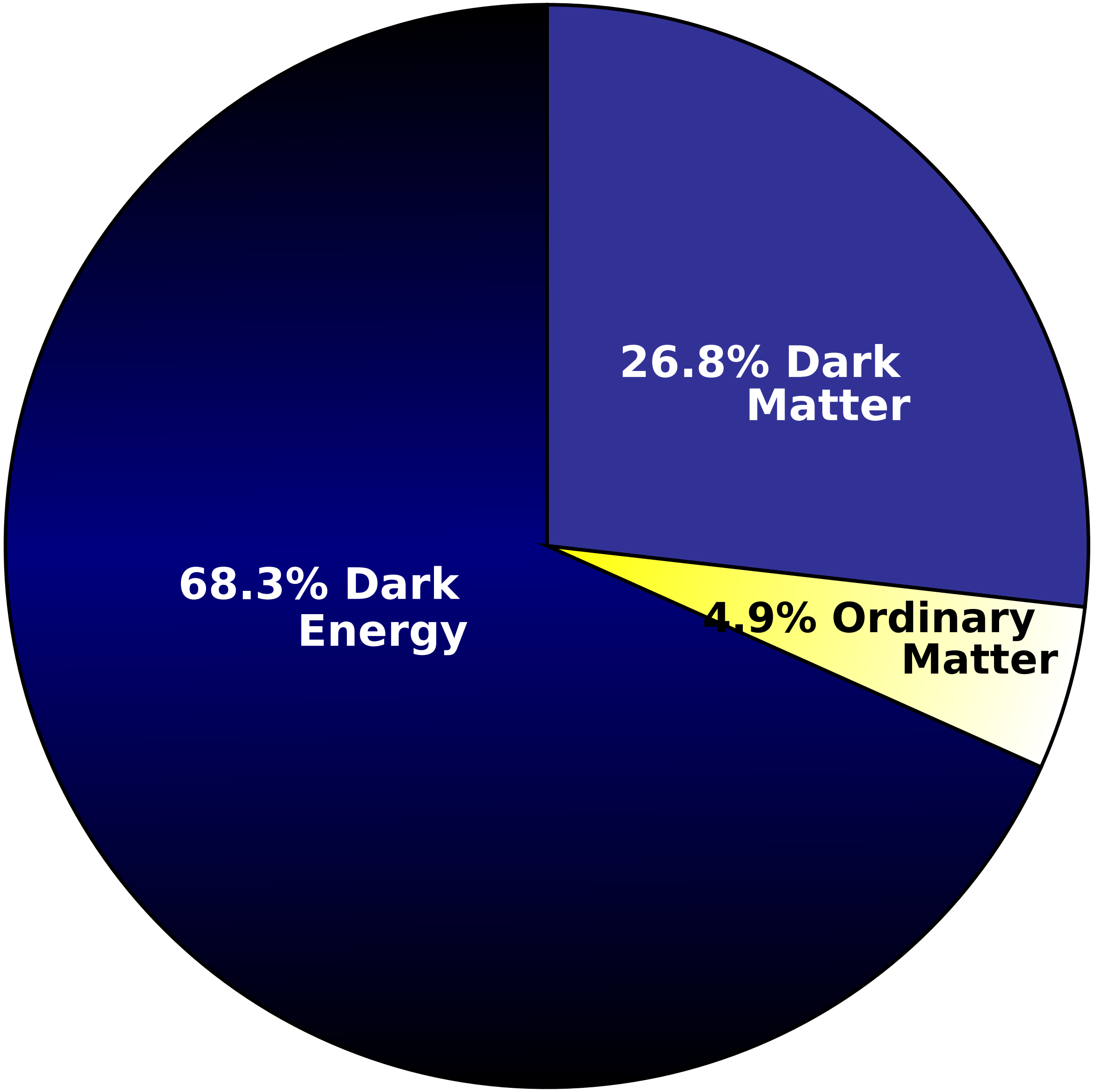
Performance of the Electromagnetic CALorimeter of the AMS-02 experiment on the International Space Station and measurement of the positron fraction in the 1.5 – 350 GeV energy range

Laurent Basara

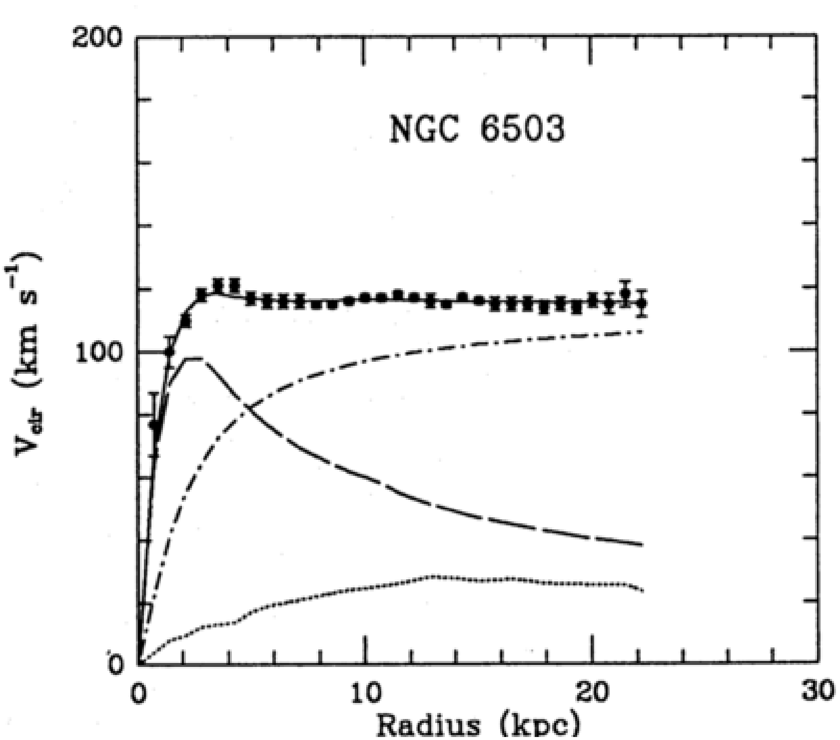
Overview

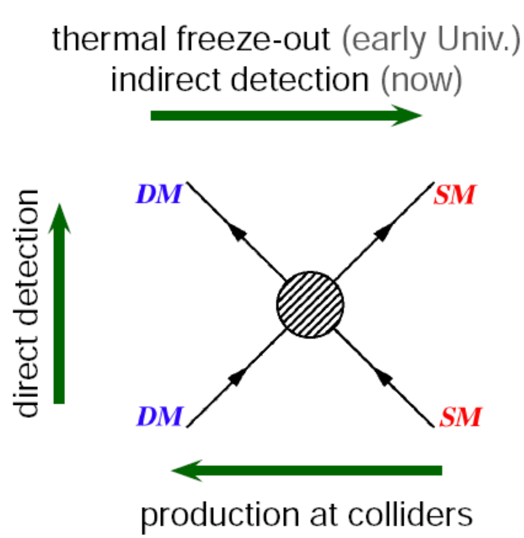
- Performances of the AMS-02 detector
- Lepton / proton discrimination
- Positron fraction

What is the Universe made of?

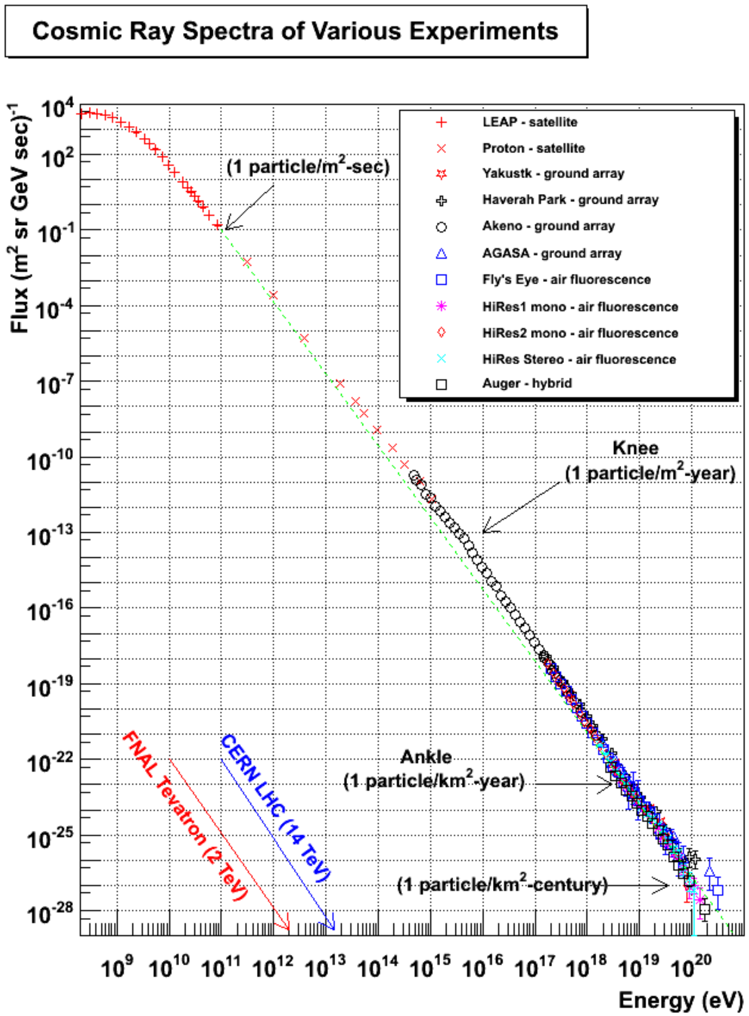


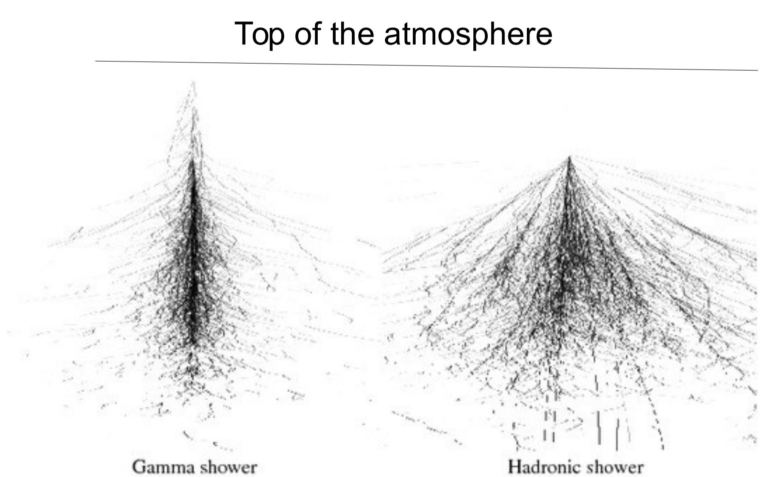
Dark matter





- Evidences
  - Galaxy rotation curves
  - Bullet cluster
  - CMB
- What it could be
  - Not standard matter
  - MOND ?
  - SuSy particles, axions, ...
- Detection
  - Production
  - Direct
  - Indirect

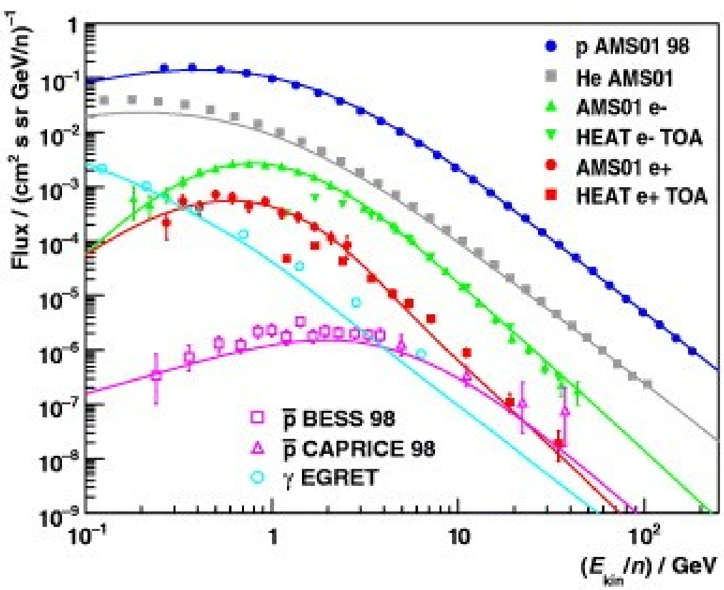


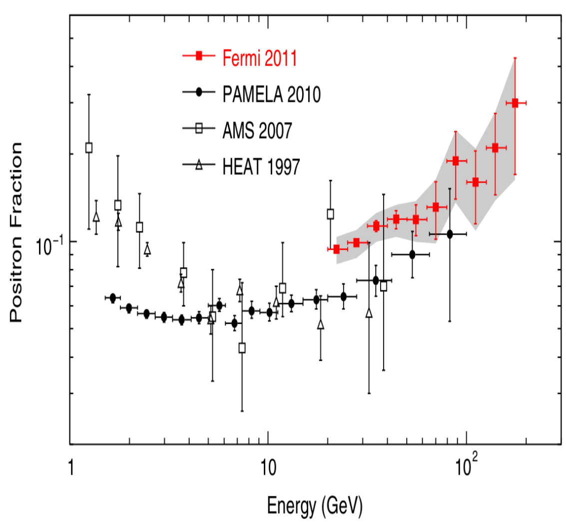


Standard matter

- Stars, planets, us…
- Probed with astroparticles
- 10^8 up to 10^{20} eV
- Interact with the atmosphere
  - Go above for direct detection
  - Reduced energy range: 0.1 to 1000 GeV

Composition of cosmic rays

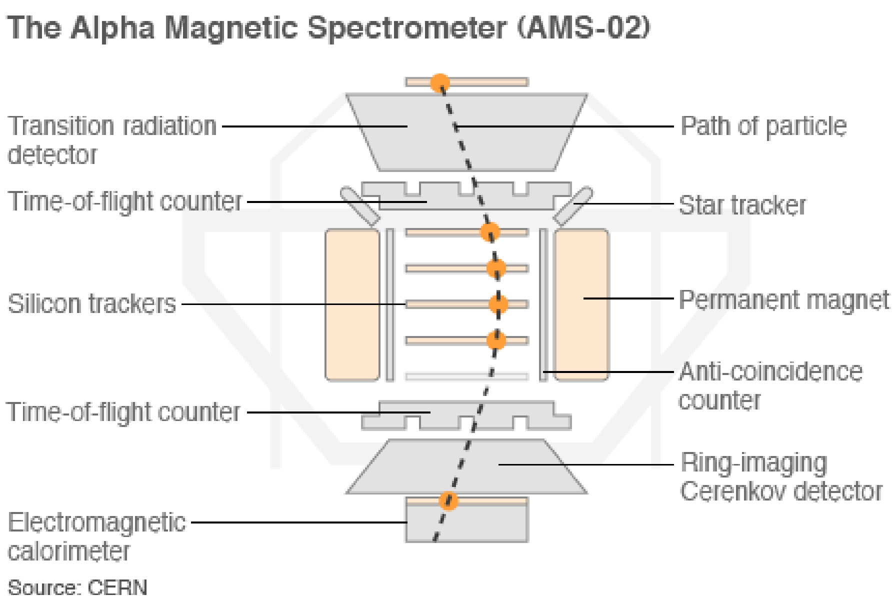




- Spectrum composition
  - 87 % protons
  - 11 % helium
  - 1 % higher nuclei
  - 1 % electron
  - 0.1 % positrons
  - 0.01 % antiprotons
- Expected types of particles
  - Primary : matter (protons, electrons, ...)
  - Secondary : antimatter (positrons, ...)
- $e^+ / (e^+ + e^-)$: expected to decrease
  - Fermi, PAMELA, ... : increases above 10 GeV
  - Primary source of antiparticles ? Propagation ?
  - From now on: increase the precision of the measurement

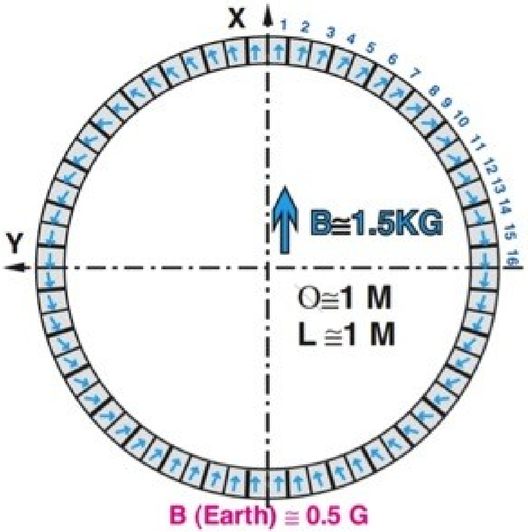
Part I
The AMS-02 detector

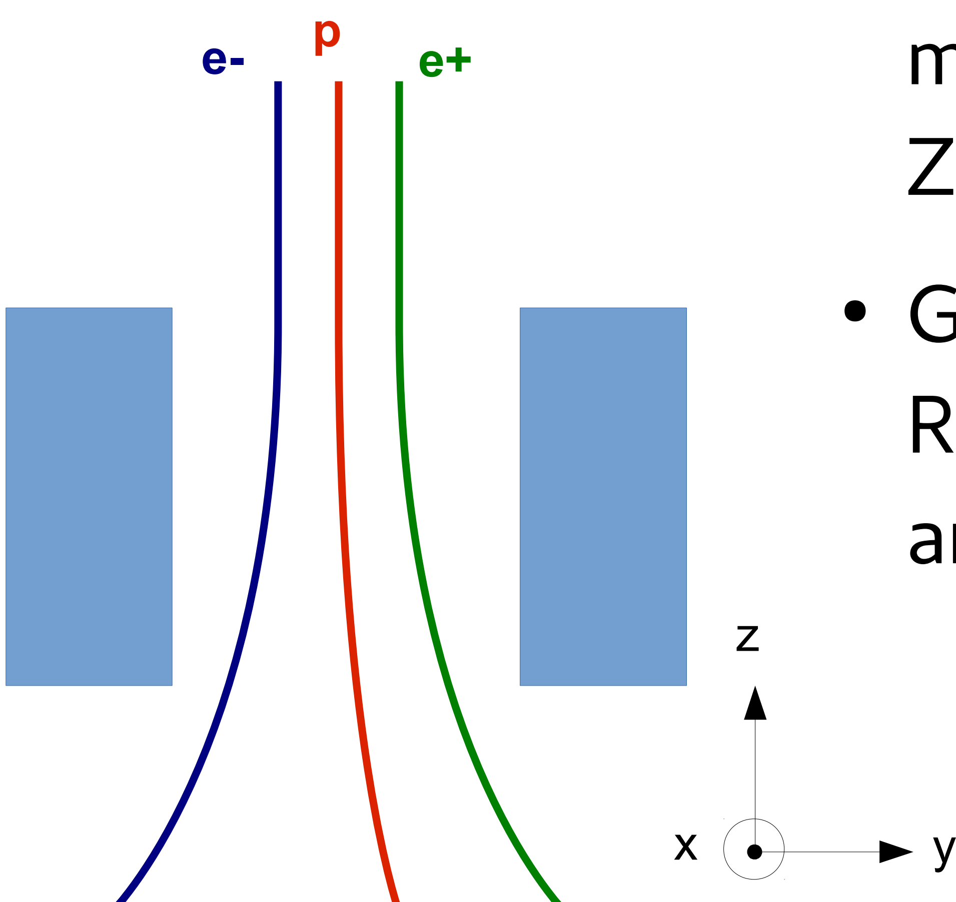
The AMS-02 experiment



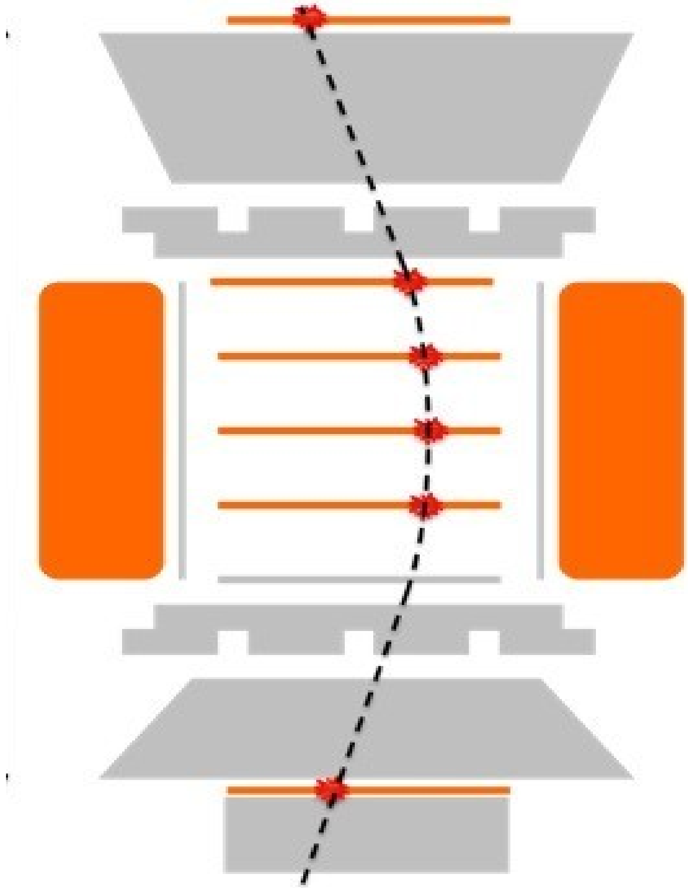
- Magnetic spectrometer installed on the International Space Station since May 2011
- GeV to TeV (anti)particles, nuclei up to Z=26
- 17.10^9 particles / year
- Objectives :
  - Dark matter studies
  - Primordial antimatter
  - Production / propagation models

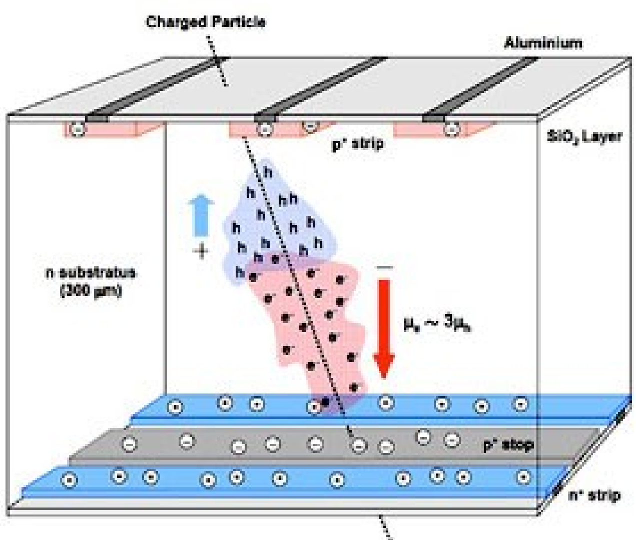
Permanent magnet





- Field B = 0.15 T curves with radius r particles of momentum p and charge Z
- Gives rigidity R=p/Z = Br and the sign of the charge

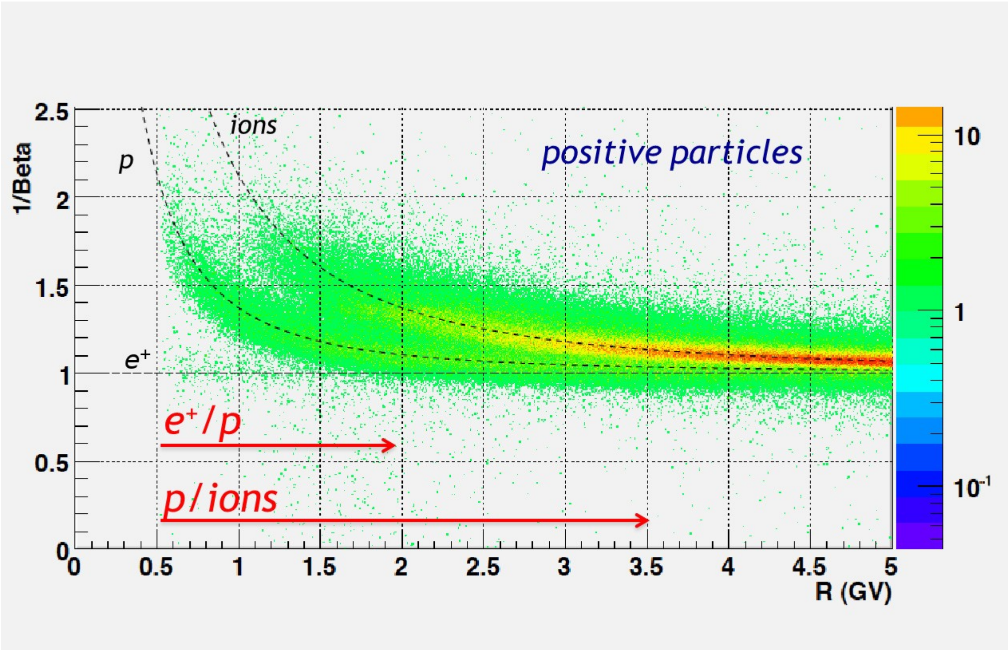


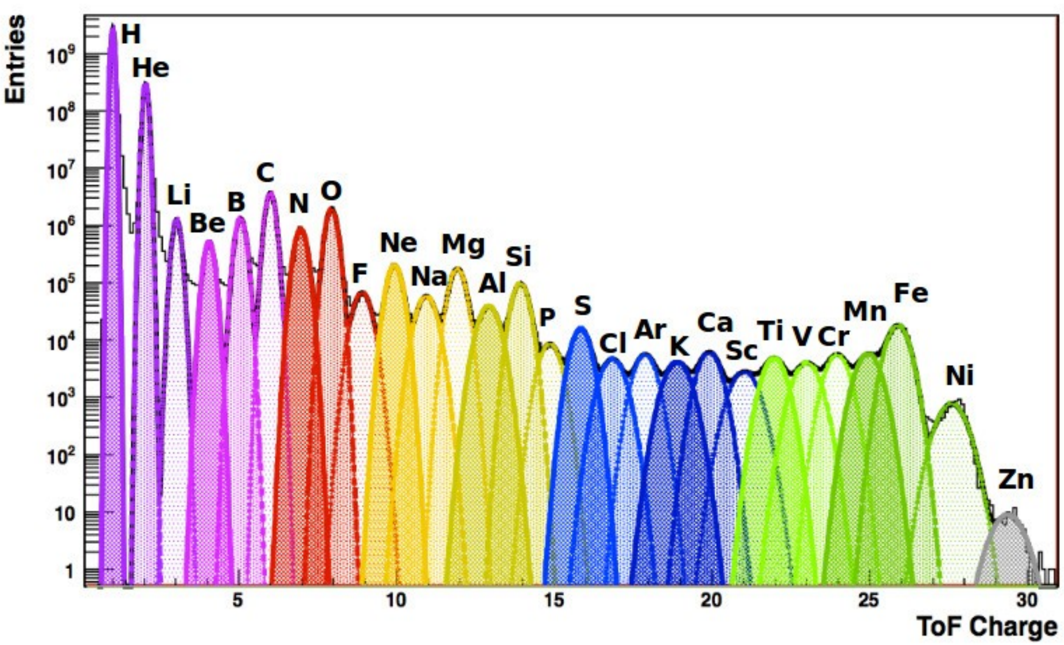


Tracker

- Reconstructs the trajectory of particles
- 9 layers
- 10μm in the curvature plane, 30μm in the other direction
- MDR : 2 TeV
- Incoming direction, absolute charge up to Z=26

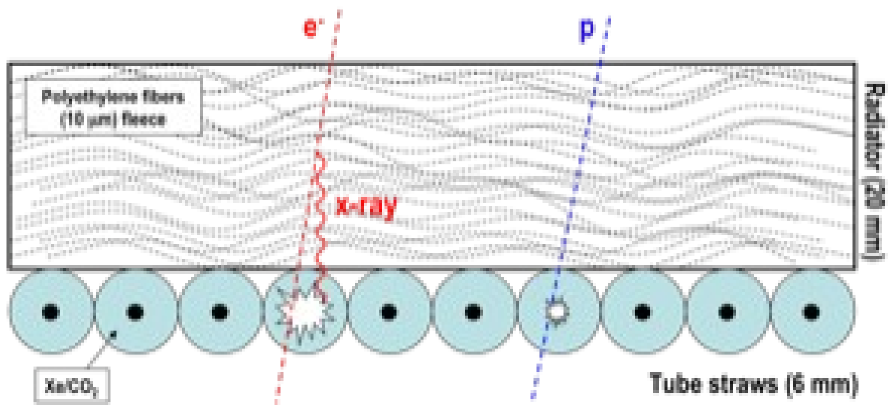
ToF

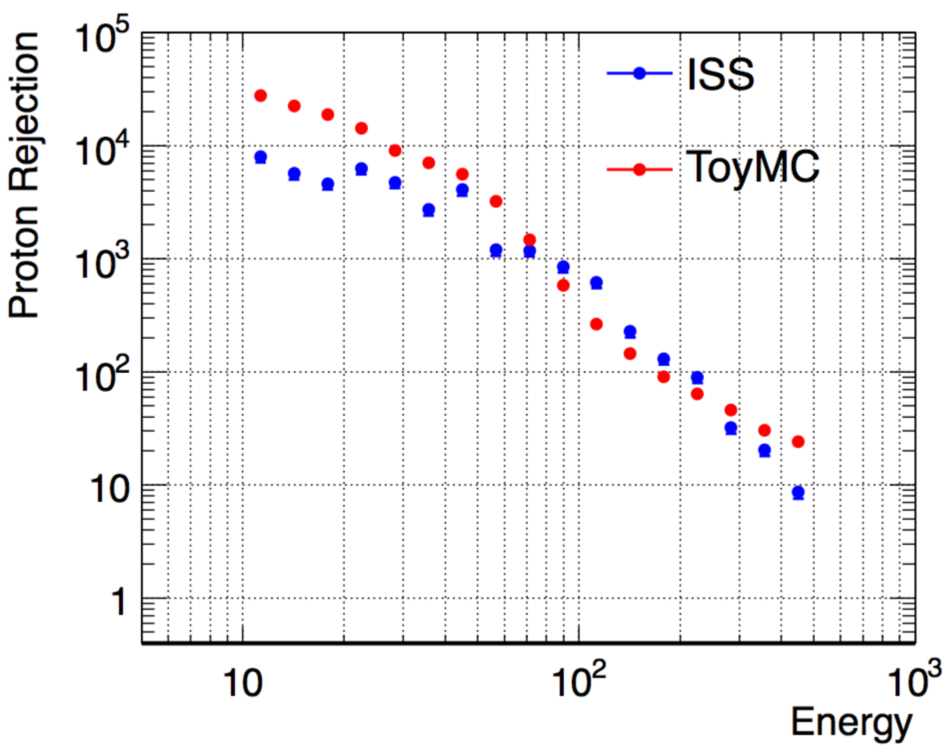




- First level trigger
- Direction of particles (10^9 rejection)
- Separate leptons/protons up to 2 GeV.
- Absolute charge of the incident particle.

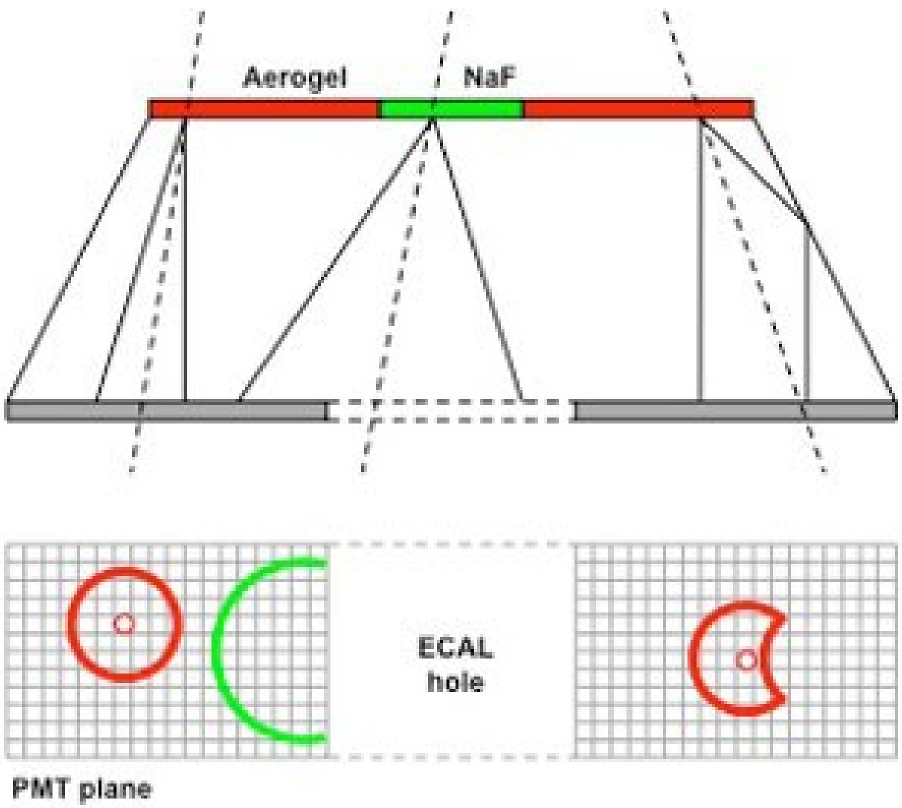
Transition Radiation Detector (TRD)





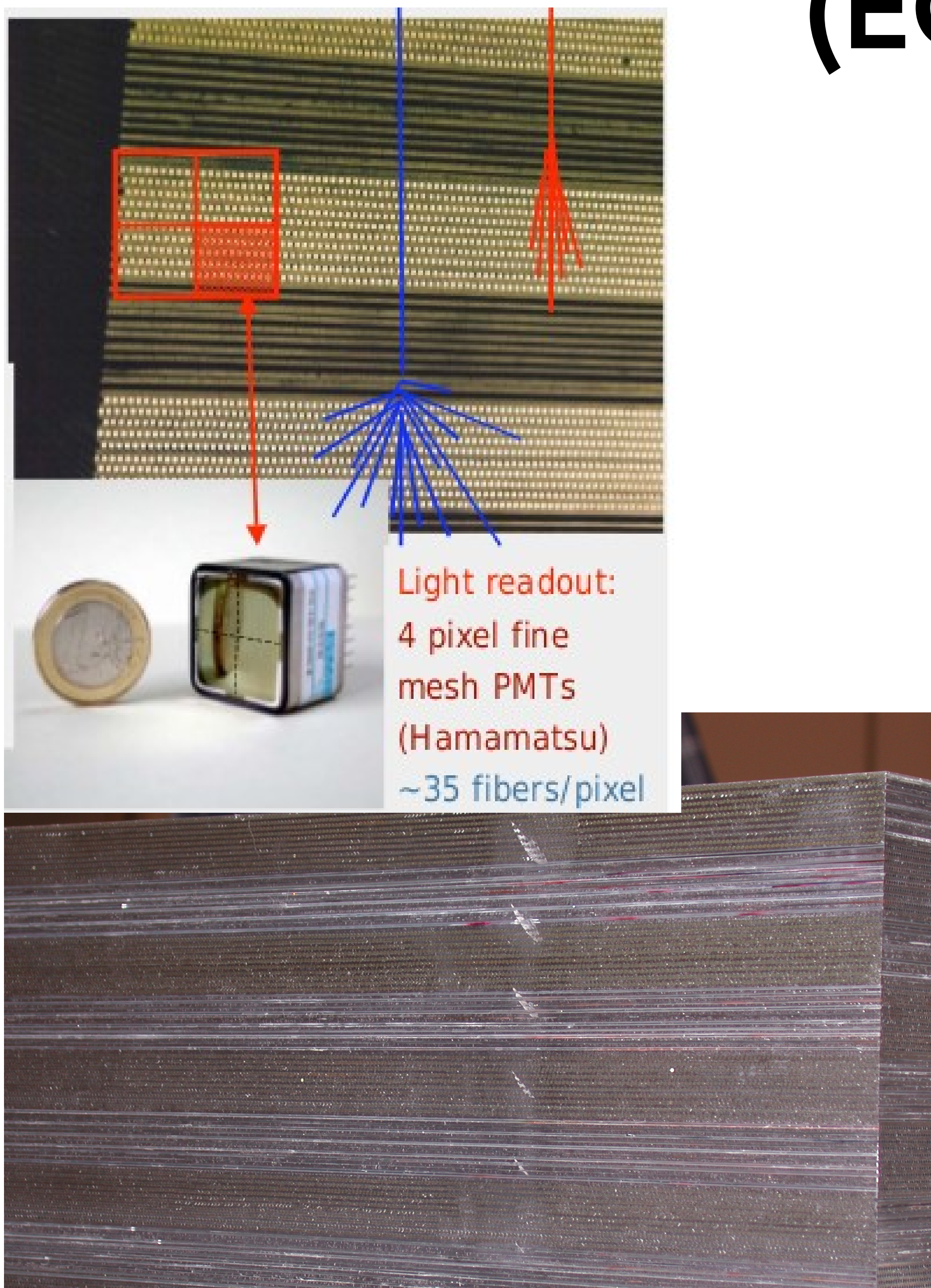
- Identify particles through detection of the X-rays emitted by electrons and protons
- Emitted energy increases with Lorentz factor: electrons radiate more than hadrons (above 300 GeV)
- Discrimination in 1-100 GeV range, rejection 100 to 1000 for a 90 % efficiency

Ring Imaging Cherenkov (RICH)



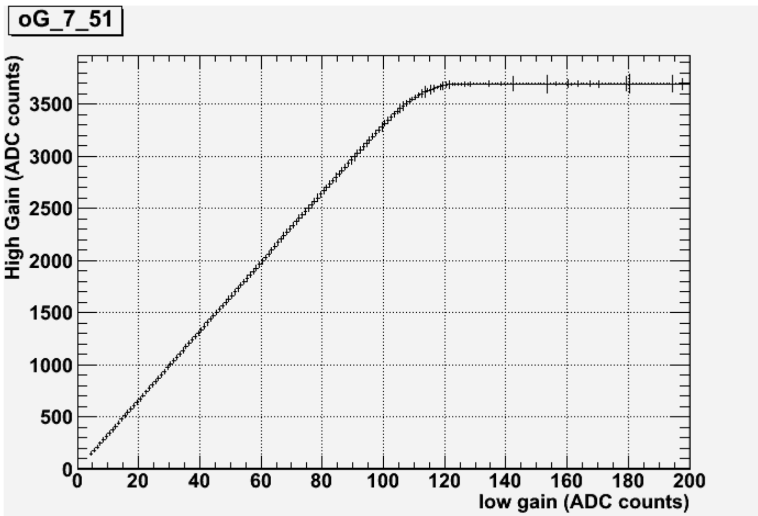
- Identify elements until the iron (Z = 26) with an energy per nucleon up to the TeV
- Measure the velocity, β
- Separate electrons and protons up to 15 GeV

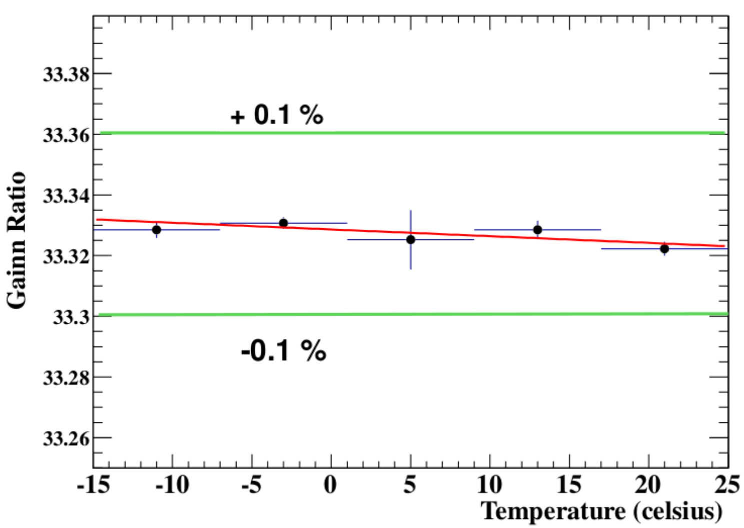
Electromagnetic CALorimeter (ECAL)



- 3D imaging electromagnetic calorimeter, sandwich of 9 superlayers of 72 cells
- Measure the energy
- Leptons / hadrons discrimination at high energy
- Performances important for our goal

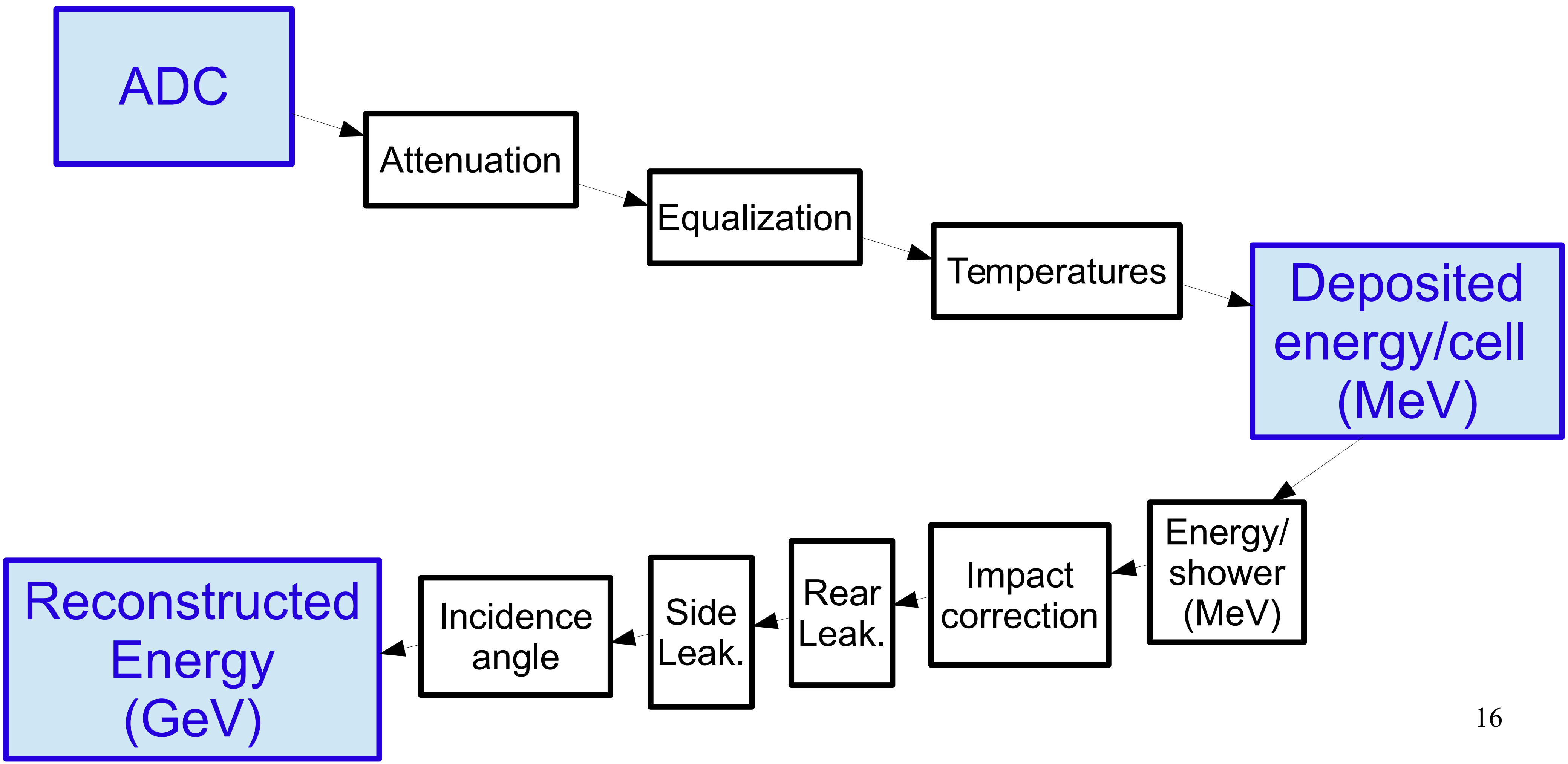
Electronic readout : Retrieving the numeric signal



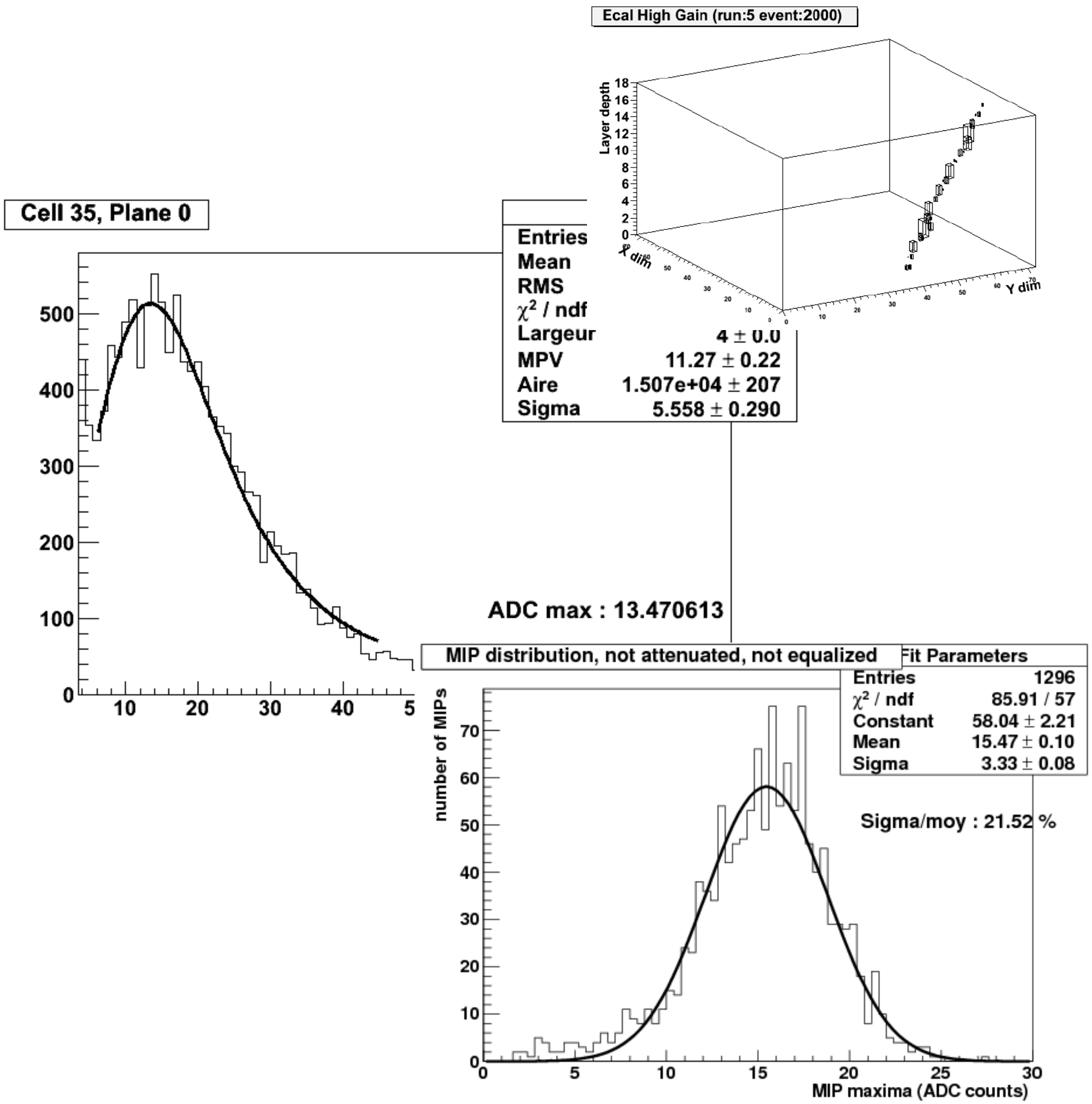


- PMTs converts number oh photons to electric charge
- HG and LG channels convert to (usable) ADC
- Pedestals recomputed (and substracted) every 45 mn ; stable.
- Gain ratio between HG and LG stable through time and temperature.

Energy reconstruction in the ECAL

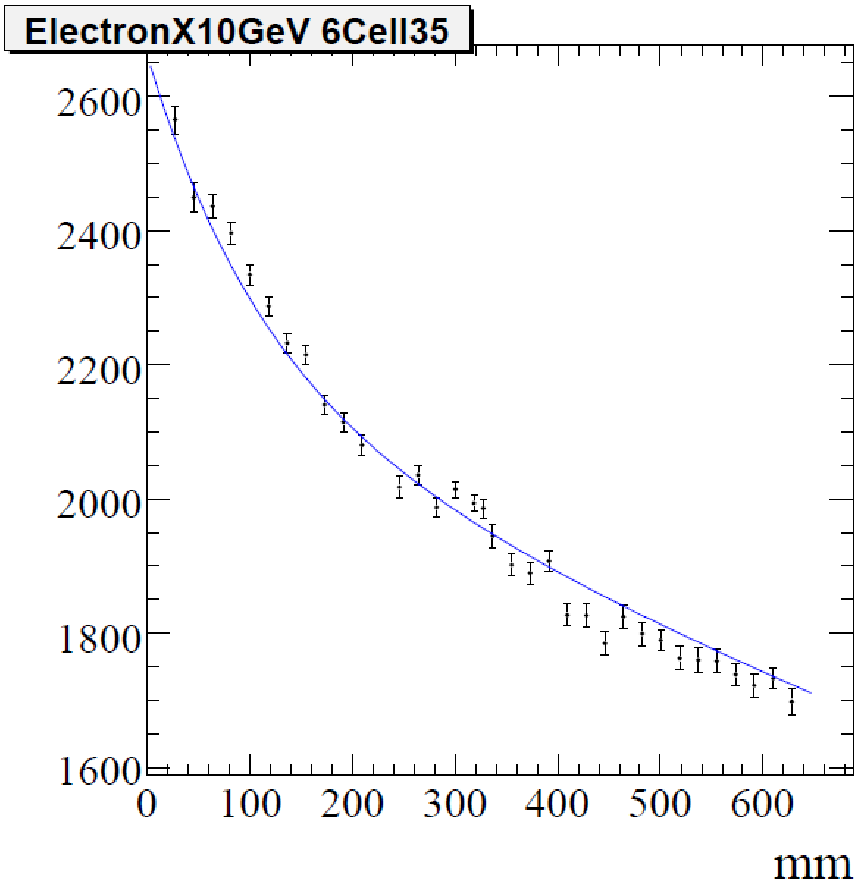


Interaction of particles in the ECAL



- Shower development :
  - Leptons almost contained.
  - Protons :
    - Rear leakage
    - 50 % minimum ionization particles (MIPs)
- MIP Distribution
  - Landau (th) x Gaussian (inst. Resol.), fitted
  - Distribution of maxima : gaussian
  - Objectives: reduce Gaussian spread (sigma/mean)

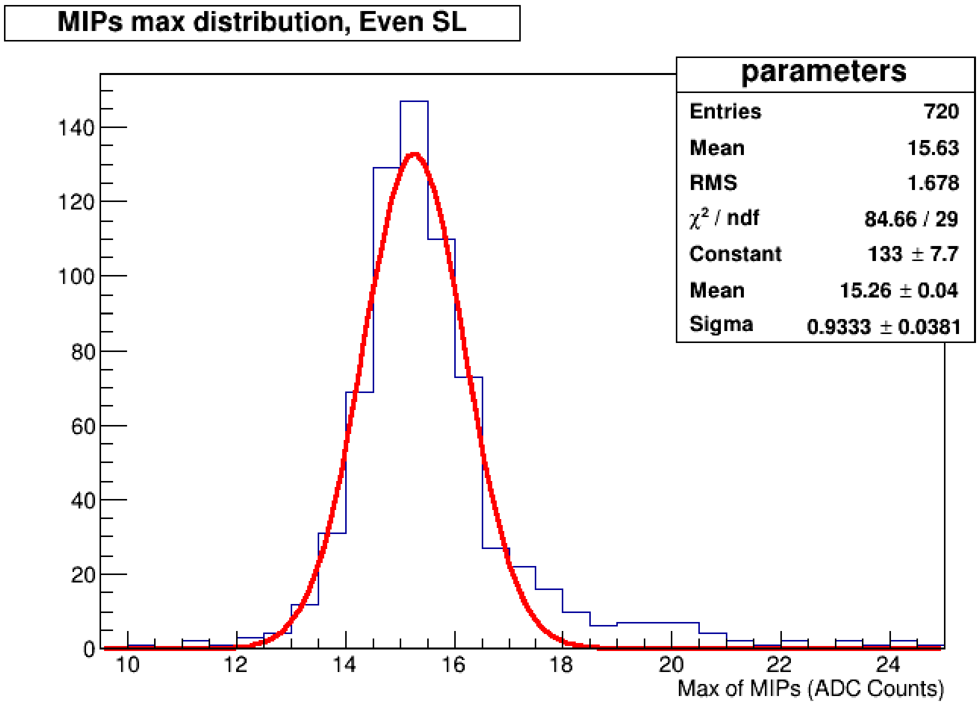
Attenuation

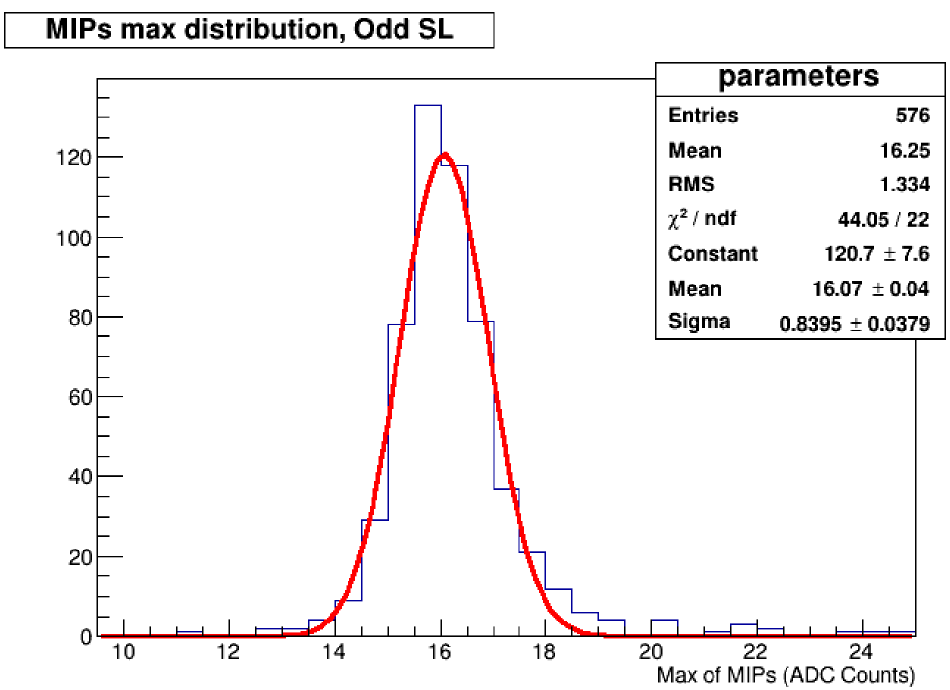


- Inside cells : fibers
- Energy attenuated along length of fibers
- Scanned in BT, assumed homogeneous for all cells
- Direct collection (fast) + reflexion on other end (slow):

$$\mathsf{AttCor}(\mathsf{x}) = \mathsf{N}\left[\mathsf{k}\exp\left(-\frac{\lambda_{\mathsf{fast}}}{\mathsf{X}}\right) + (1-\mathsf{k})\exp\left(-\frac{\lambda_{\mathsf{slow}}}{\mathsf{X}}\right)\right]$$

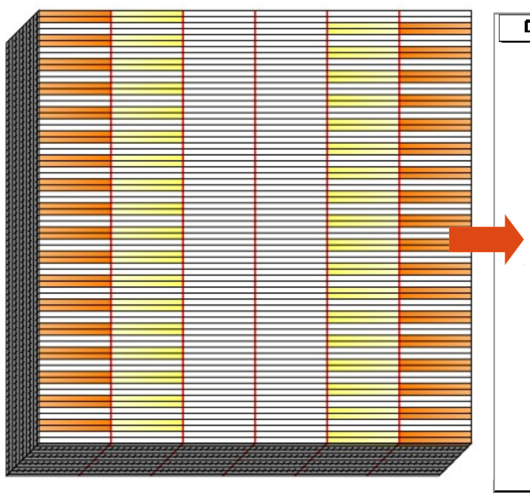
X and Y fit

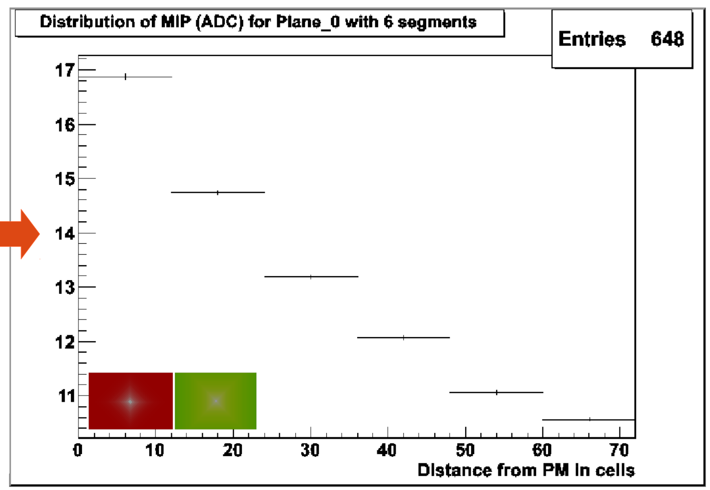


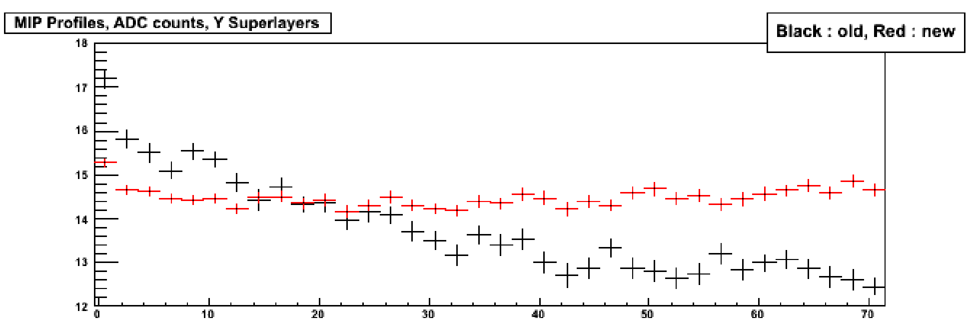


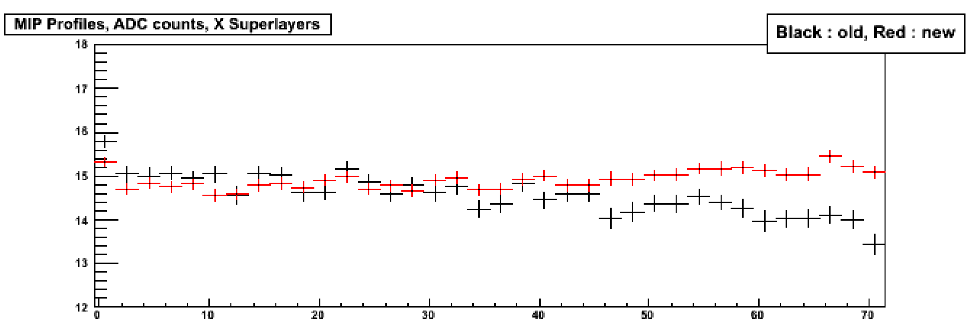
- Homogeneity probed against the direction of the cells.
- Sigma/mean of 5.2 % in X, 6.1 % in Y.
- Do certain directions / layers / cells behave differently ?

Cell binning



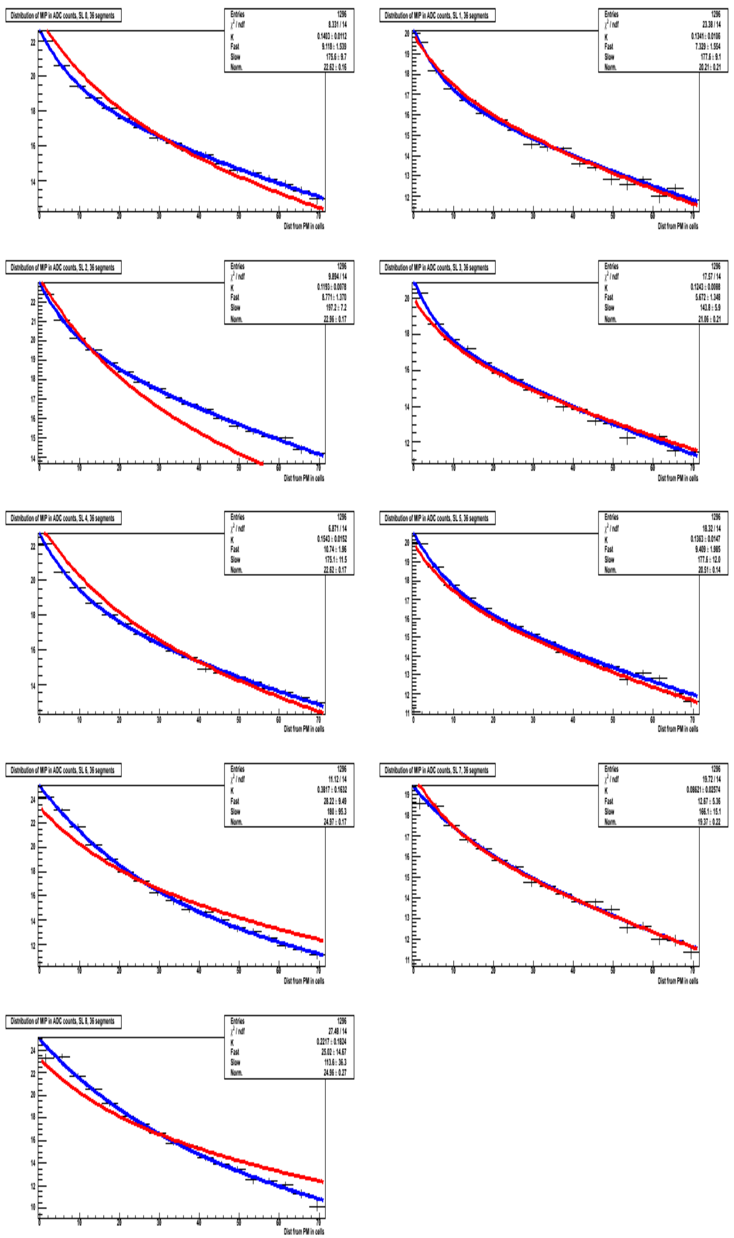




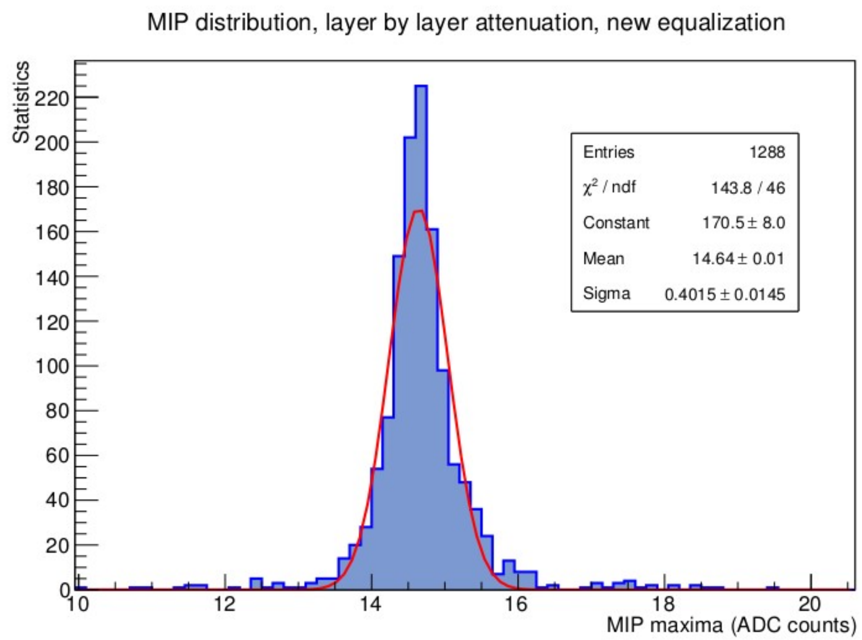


- For each cell, interpolation to estimate hit position
- Binning along the fiber
- Summed according to direction and fit for each bin
- Difference for the two directions

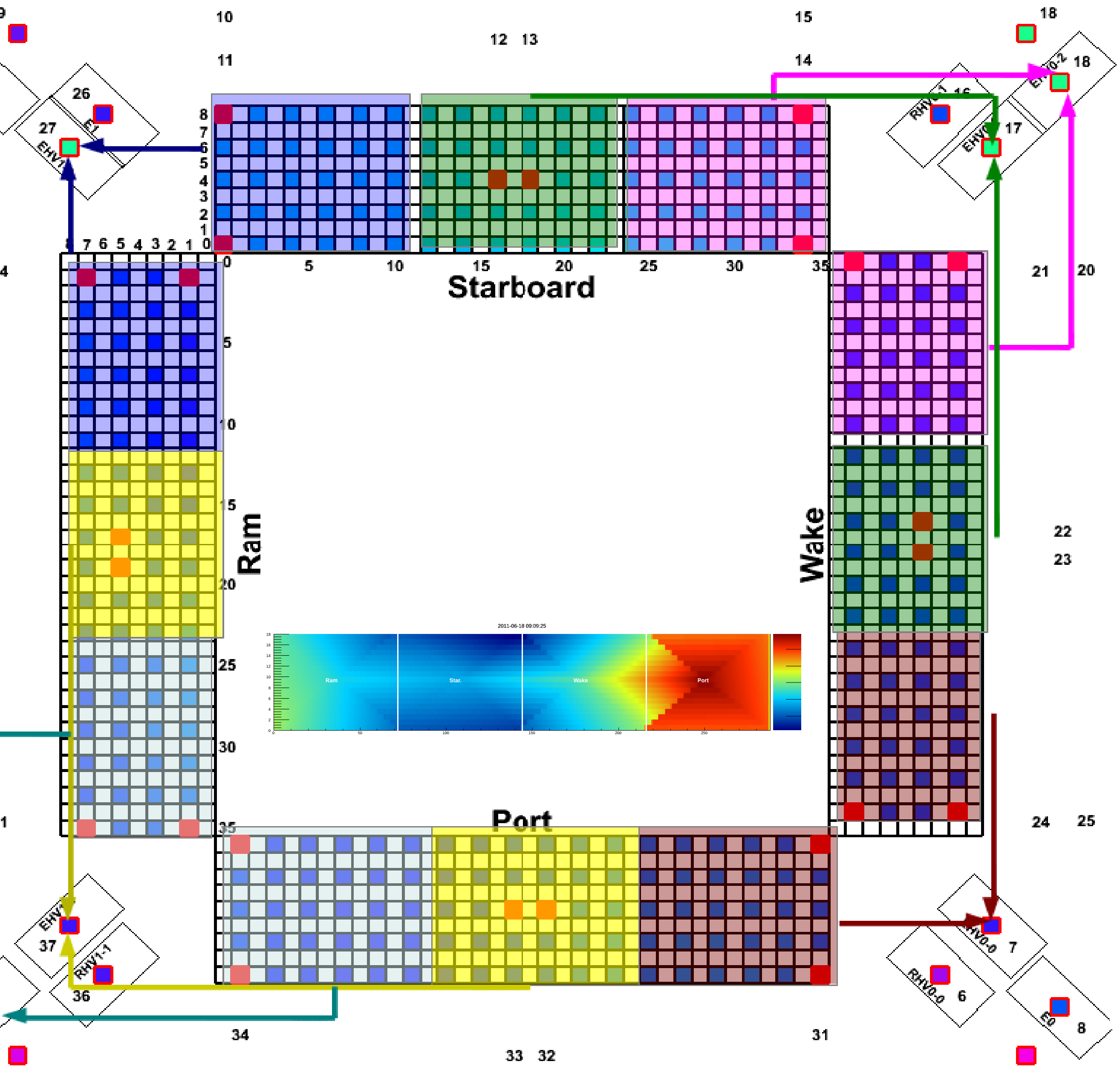
Equalization



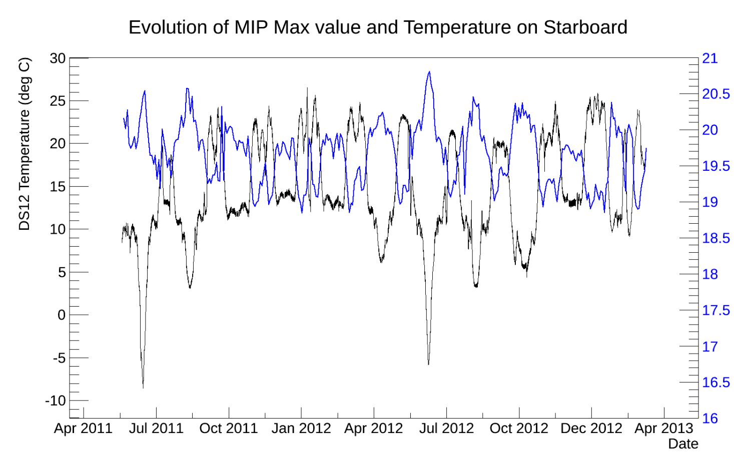
- Finally done for each superlayer → differences
- New intercell equalization
- After the equalization new spread of 2.7 % (8 % before)
- Could the differences found be due to aging effects ?
- Monitor MIP evolution through time



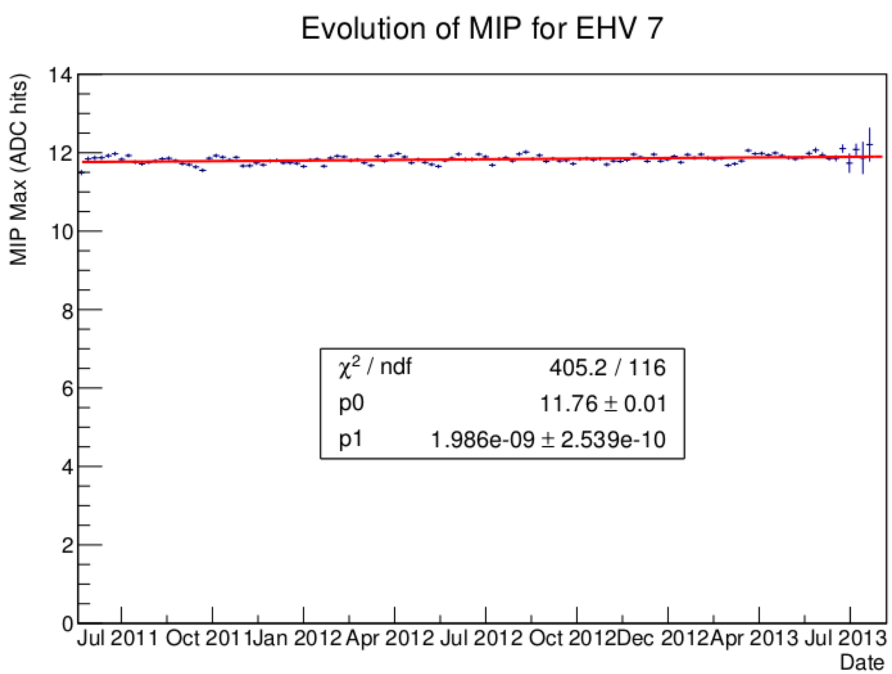
Temperature decorrelation



- 30 temperature sensors
  - 6 / face (angles + middle)
  - 6 for the electronic boards
- Evolution due to orbit, beta angle, umbra.
- Temperature interpolated for each cell, compared to MIP
- High (negative) correlation

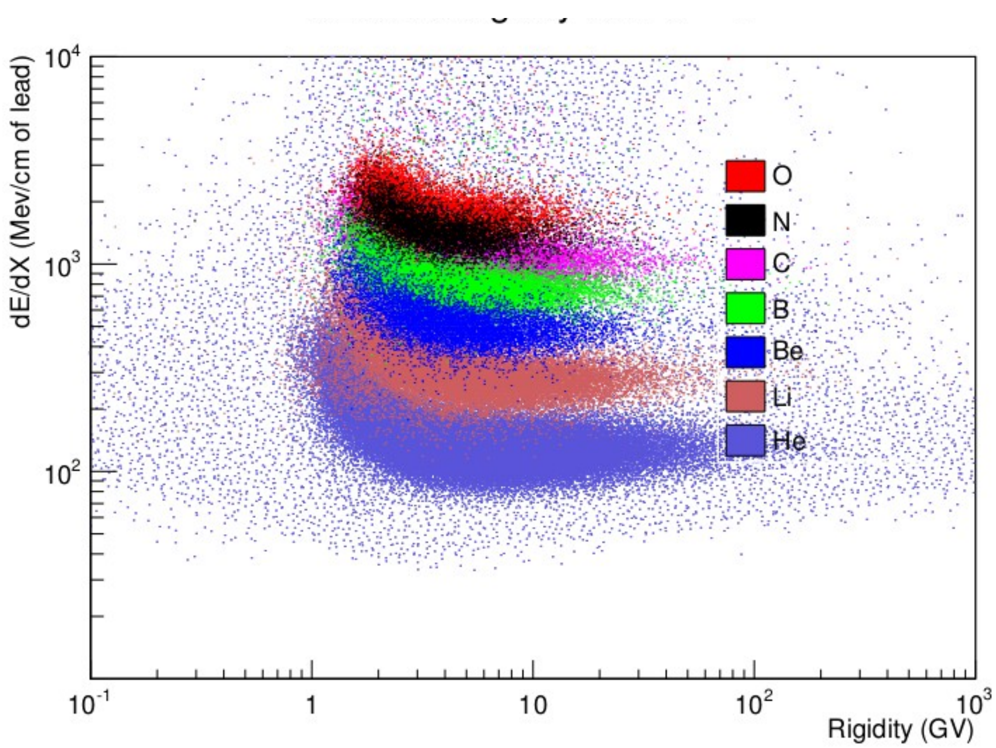


MIP evolution



- MIP correlated to EHV rather than face sensors (electronic effects)
- Decorrelated, then evolution through time
- No aging
- Performances ok for the lower energies (proton MIP ~ 6 MeV)
- What happens for higher energies ?

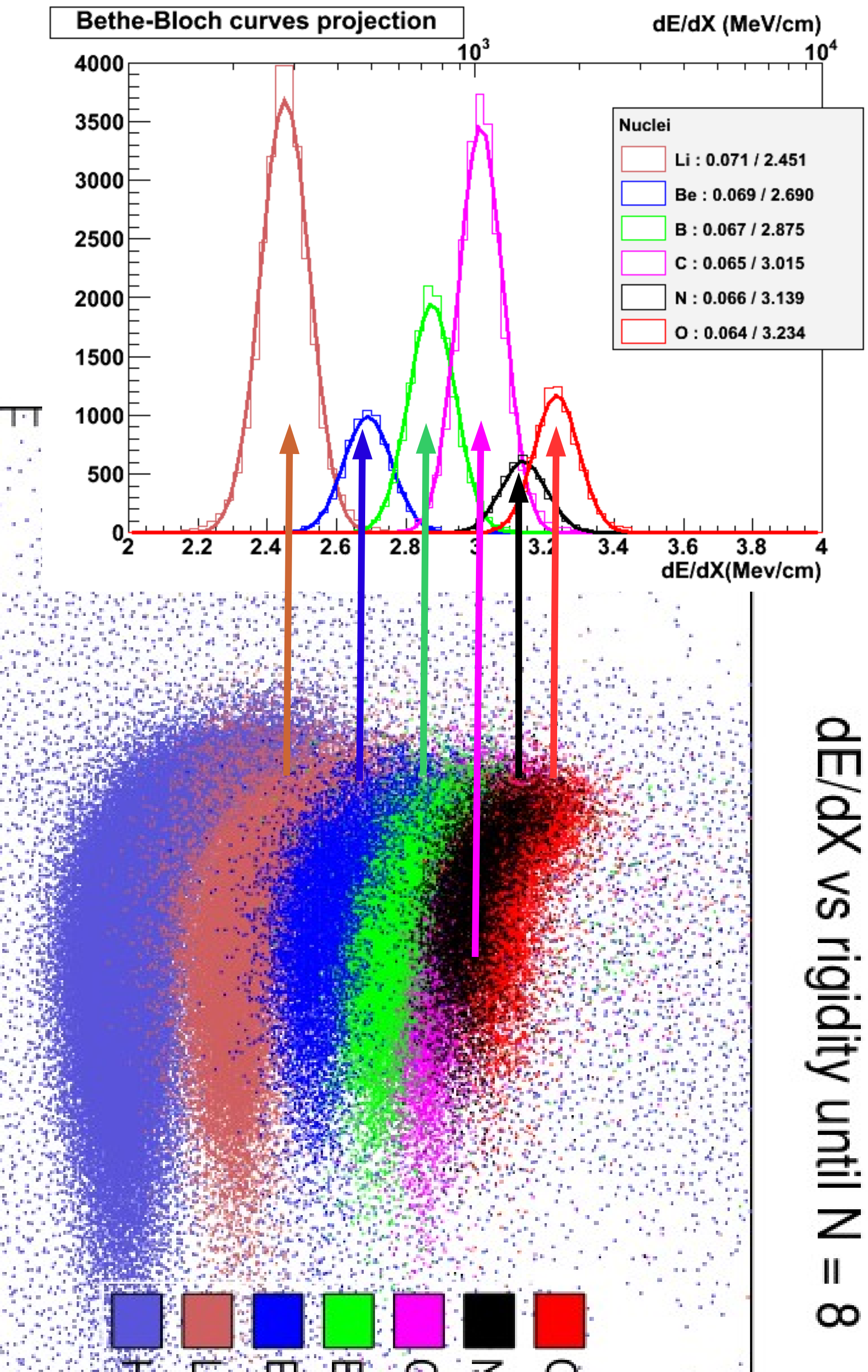
Bethe–Bloch formula



- For ionization losses :

$$-\frac{\mathrm{d}E}{\mathrm{d}\xi} = z^2 f(v)\frac{Z}{m}$$

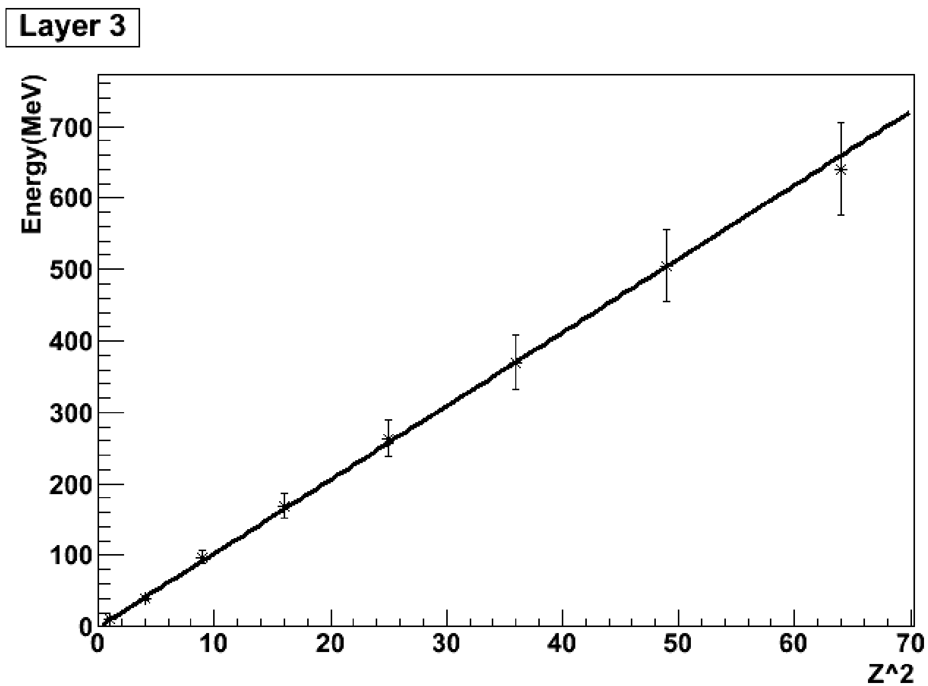
- Rigidity + Energy known: single point (z^2)
- Tracker used to :
  - Identify nuclei
  - Compute rigidity
- dE/dX from ECAL allow to identify charge ?



Estimator building

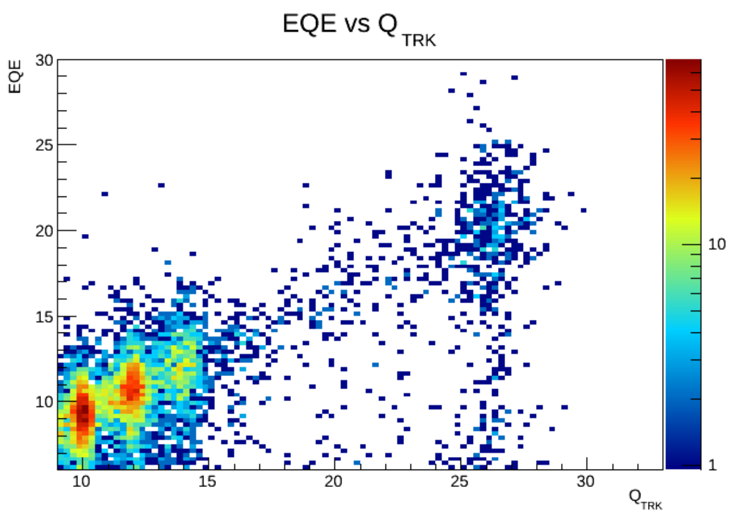
- Check linearity, formula in Z^2 → logarithmical scale
- Peaks of same width, equireparted
- Simple estimator building :
  - For each layer at MIP, compute
    - dE (deposited energy)
    - dX (geometrical length crossed)
  - Multivariate event
  - Estimate most probable charge of a nuclei depositing that energy
  - Log-likelihood estimator

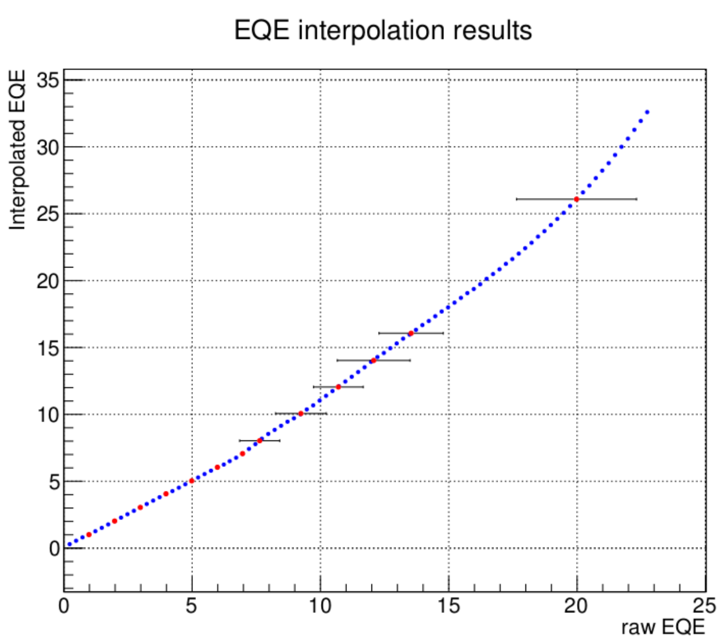
Linearity for most abundant nuclei



- Nuclei up to Z=8 (O) more abundant
- Excellent linearity up to Z=7
- Drop for Z=8 ?

Nuclei of higher charge





- Drop, and the re-increase
- Known effects (GLAST, ToF...)
  - Quenching
  - Antiquenching
- Effect due to nuclei charge, not lack of linearity.
- Use of splines between Z=8 and Z=26
- Implemented in the software

Conclusions on the performances of the detector

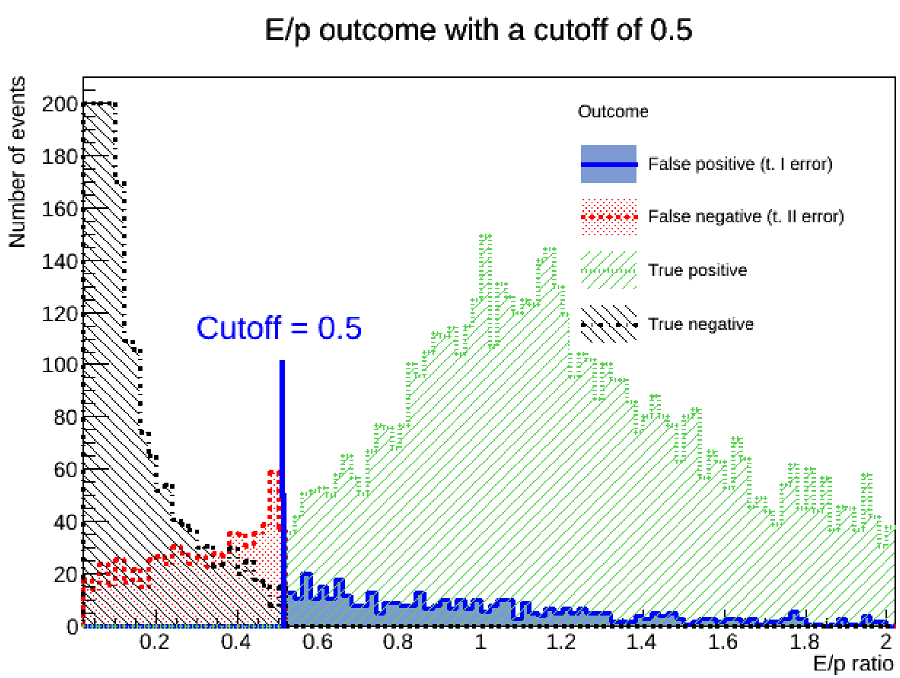
- Global AMS-02 performances as expected
- For ECAL :
  - Excellent electronic performances.
  - Stable through time.
  - Stable in energy up to GeV.

Part II.
Leptonic / hadronic discrimination

Objectives

- e+ / e+e- ratio
  - Only select leptons
  - Protons 100 times more abundant than electrons, 1000 than positrons (and same charge sign)
  - Carefully discriminate protons
- TRD up to ~ 100 GeV, above: ECAL
  - *Electromagnetic* cal.: difference of behaviour between EM and hadronic showers.
  - Find a way to take advantage of those differences

First example: E/P ratio

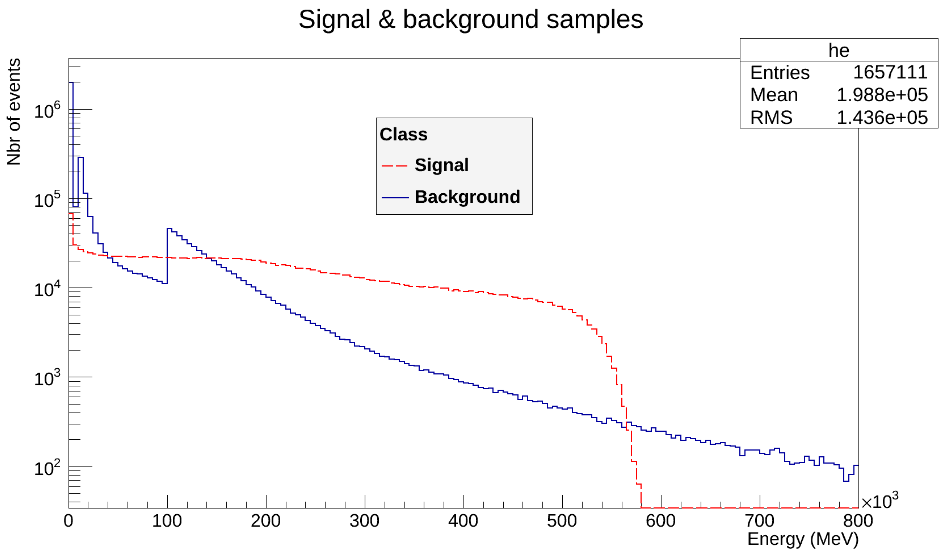


- E/P discrimination
  - For β = 1: E=P, for Z=1: R=P
  - Electromagnetic showers: E=P(=R)
  - Hadronic showers: E<P(=R)
  - Compare R with E
- Discrimination quantification:
  - Number of particle correctly identified (or not)
  - *Efficiency* = leptons seen as such (above the cut) / number of leptons
  - *Rejection* = total number of hadrons / hadrons falsely seen as leptons (above the cut)

Multivariate analysis

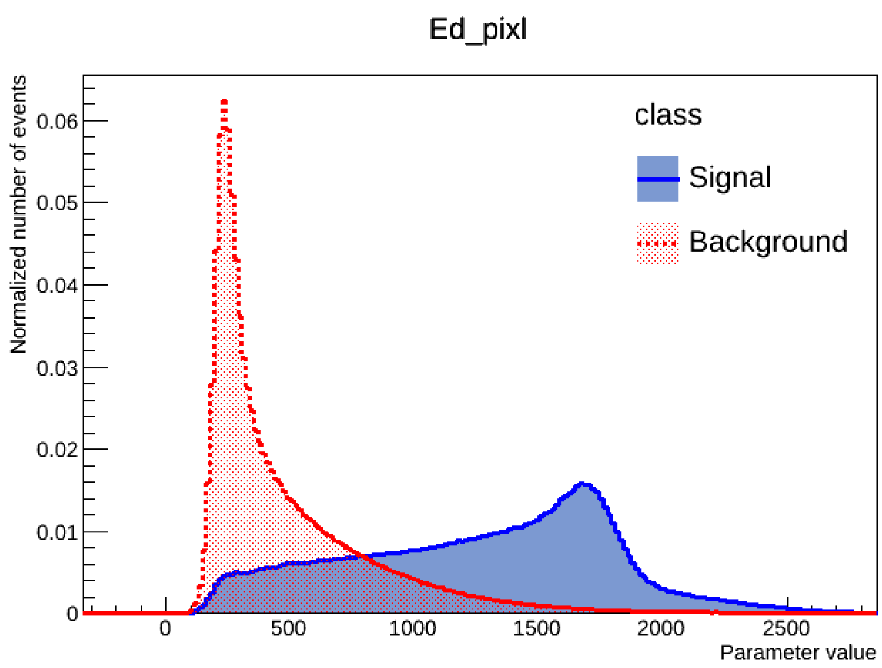
- *Get pure samples* of electrons and protons
- *Identify variables* behaving differently for each sample
- *Optimally combinate* all variables to get a relevant estimator
- *Assess* the performance of the estimator
- *Estimate* whether an event is a proton or lepton given its variables.

Get ``pure" electrons and protons samples



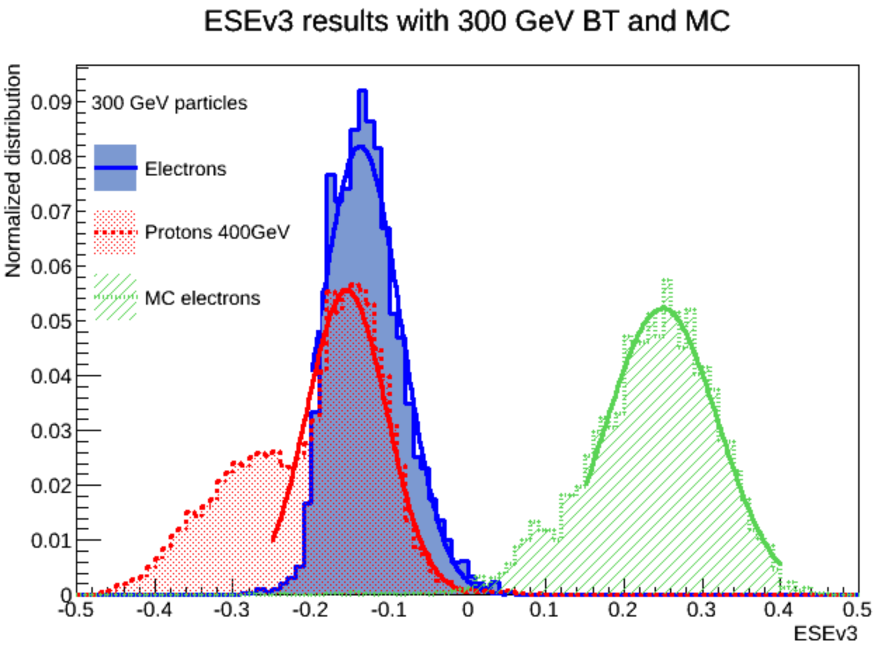
- Beam tests
  - True, identified data...
  - ... but beams can be polluted
  - Low statistics, only for some energies
- Monte-Carlo simulations
  - Huge statistics
  - Do the simulations reproduce the data ?
- ISS Data (selected by TRD, E/P...)
  - Contamination
  - Low energy (we need high energy)

Which variables ?



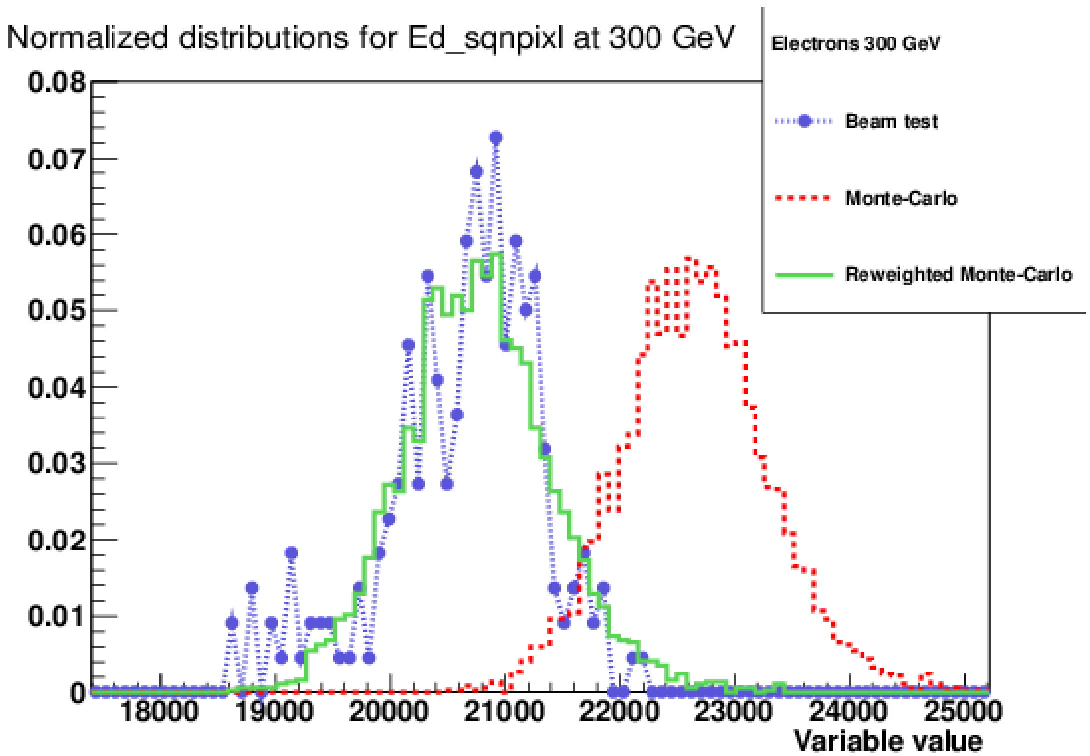
- Shape-related variables
  - Longitudinal dispersion
  - Number of layers at MIP
- Fit to the longitudinal profile
  - Chi^2
  - Rear leakage
- Energy-deposited variables
  - Energy / number of cells hit

First results



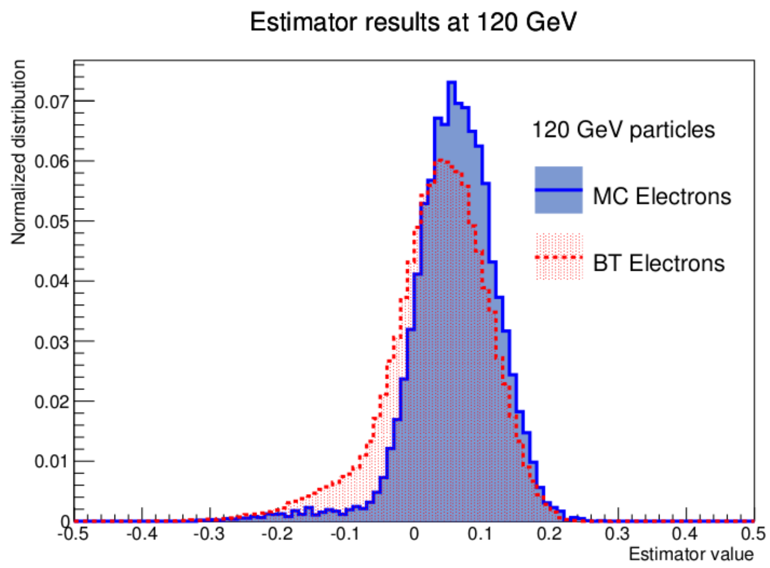
- MC / Data: poor match
- Find a way to adjust simulation to data

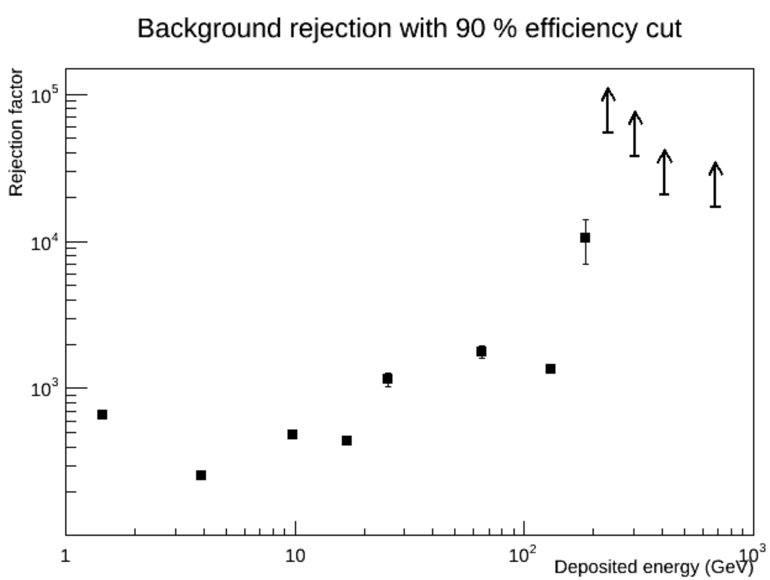
Smearing



- Differences MC/BT at the variables level
- Compare, for each common energy (100, 120, 180, 300 GeV), the variables distributions
- Smear the variables :
  - Shift the mean
  - Add a gaussian noise
  - Interpolate between energies

Results after smearing





- Estimator distributions almost the same
- Use half the statistics (test sample) to assess the rejection power.
- For a 90 % efficiency, increases with energy, $>10^4$ above 200 GeV

Conclusions on part II

- A Leptons / hadrons estimator was built
- Only ECAL variables
- Combined (E/P + MIPs + Estimator) rejection of 10^4 obtained for a 90 % efficiency above 200 GeV
- → Compute the positron fraction

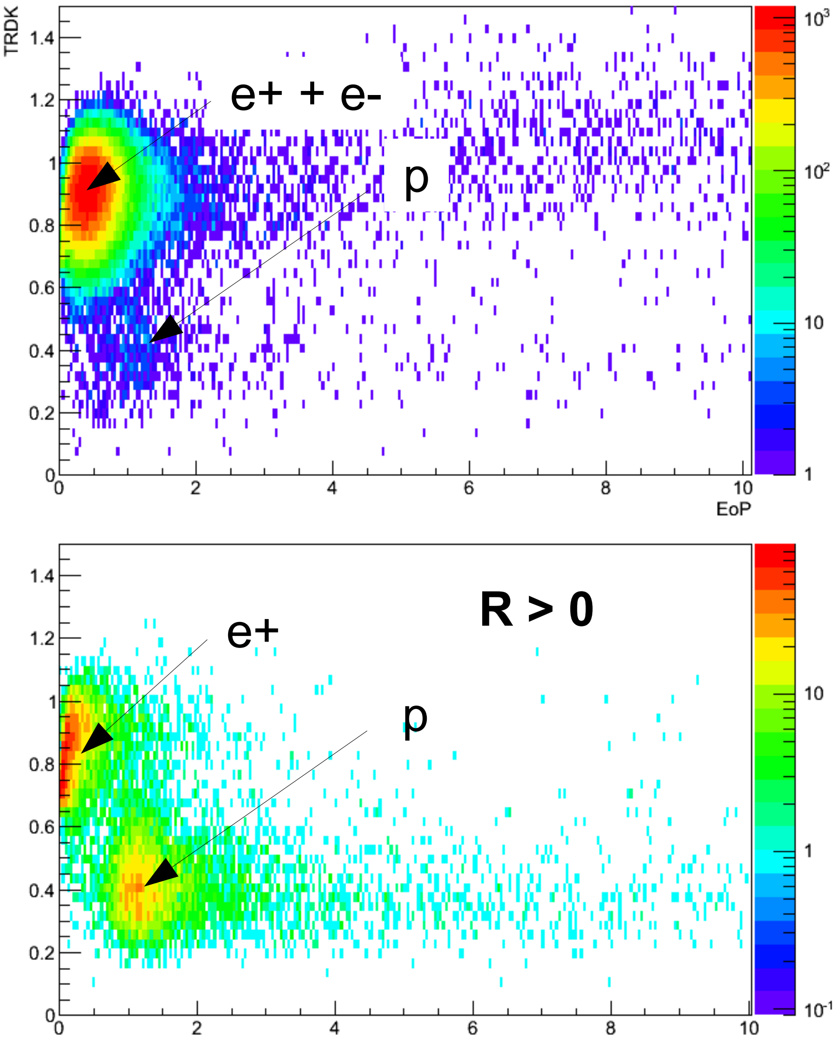
Part III.
The positron fraction

Definition of the positron fraction

$$R \equiv \frac{\Phi_{e^+}}{\Phi_{e^+} + \Phi_{e^-}} \approx \frac{n_{e^+}}{n_{e^+} + n_{e^-}}$$

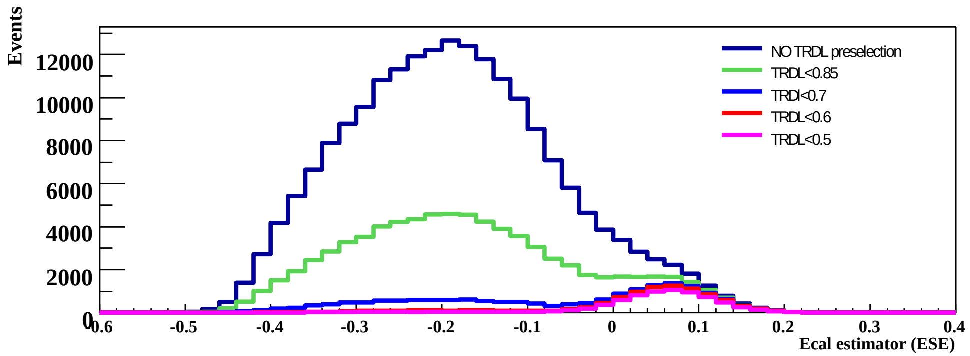
- The positron fraction
  - Does not (a priori) depend on the acceptance
  - Direct ratio of the number of particles (positive leptons / total leptons)
- Methodology
  - Only keep leptons (E/P estimator)
  - Estimate their charge along with possible confusion (tracker)

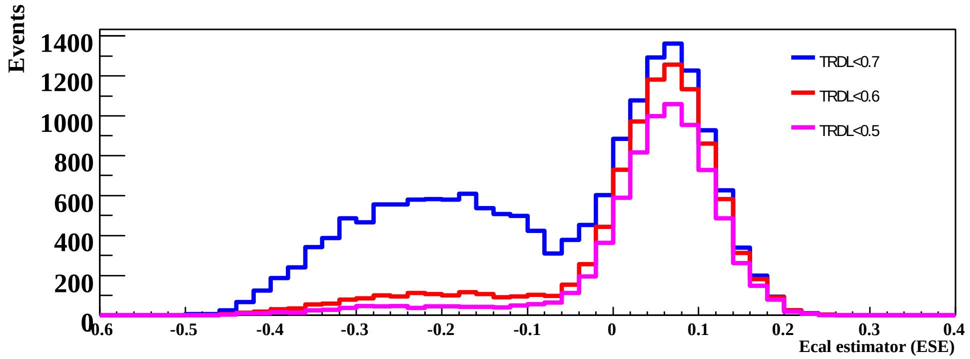
Leptons selection



- 65 energy bins from 1.5 to 350 GeV
- Events selection : primary events, track quality, particle estimators...
- 3 estimators :
  - TRD log-likelihood
  - E/P rejection
  - ECAL Estimator
- Use the first two to select pure samples
- Determine the shape of the third on those samples

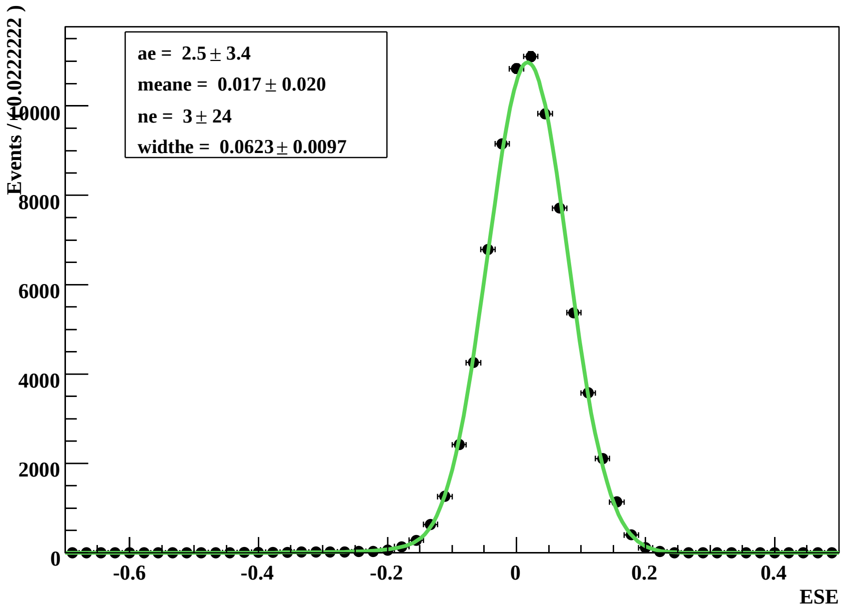
Lepton selection 2





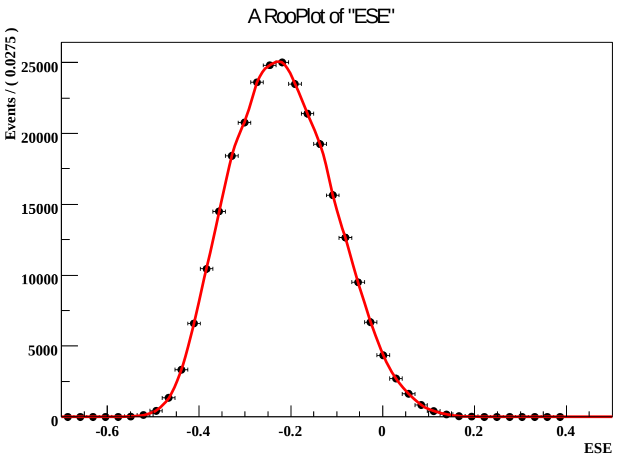
- Effect of various TRD cuts on ESE around 100 GeV
- Discard hadrons while keeping leptons.
- Done for all energies.
- Optimal selections

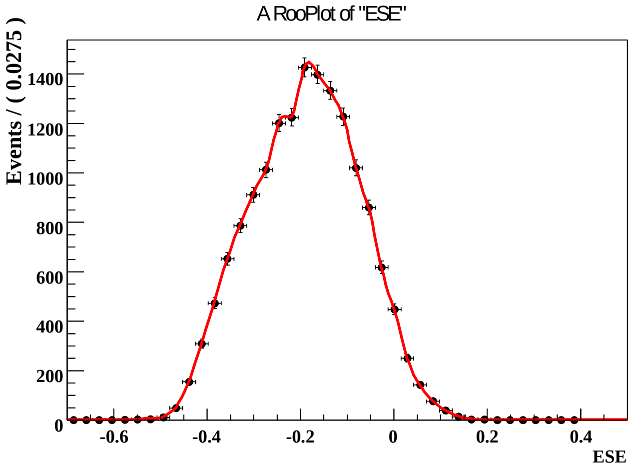
Leptons templates



- Preselection
  - R<0
  - E/P>0.9
  - TRDL<0.45
- Good fit through analytical function
  - Crystal Ball
  - Gaussian core portion
  - Power law low-end tail

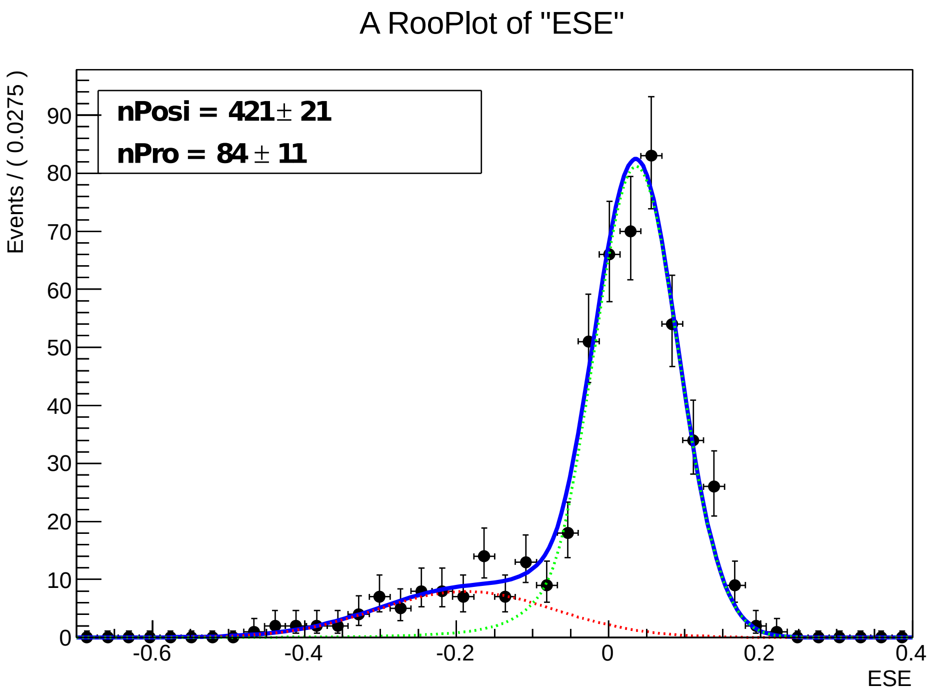
Protons templates





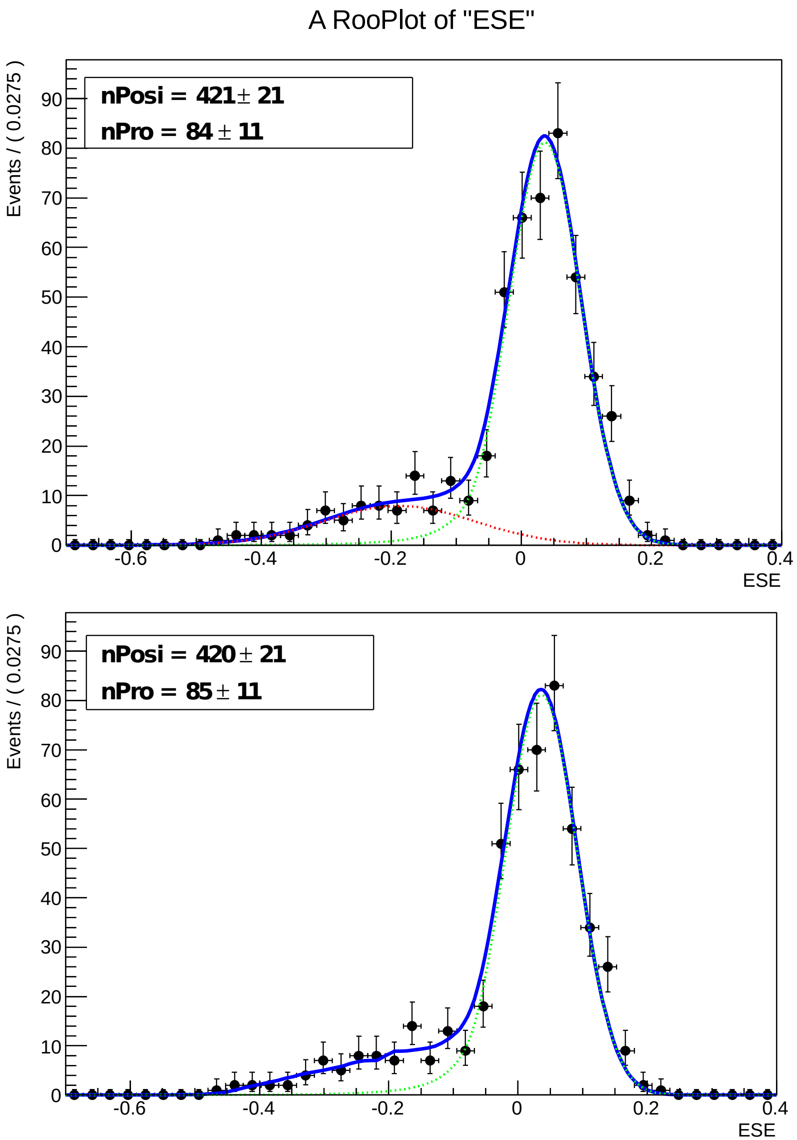
- Preselection :
  - R > 0
  - E/P < 0.4
  - TRD > 0.9 for E<115GeV, 0.85 above.
- Crystal ball does not reproduce well data
  - Novosibirsk (analytical)
  - Histograms (direct) fits

Application of the templates



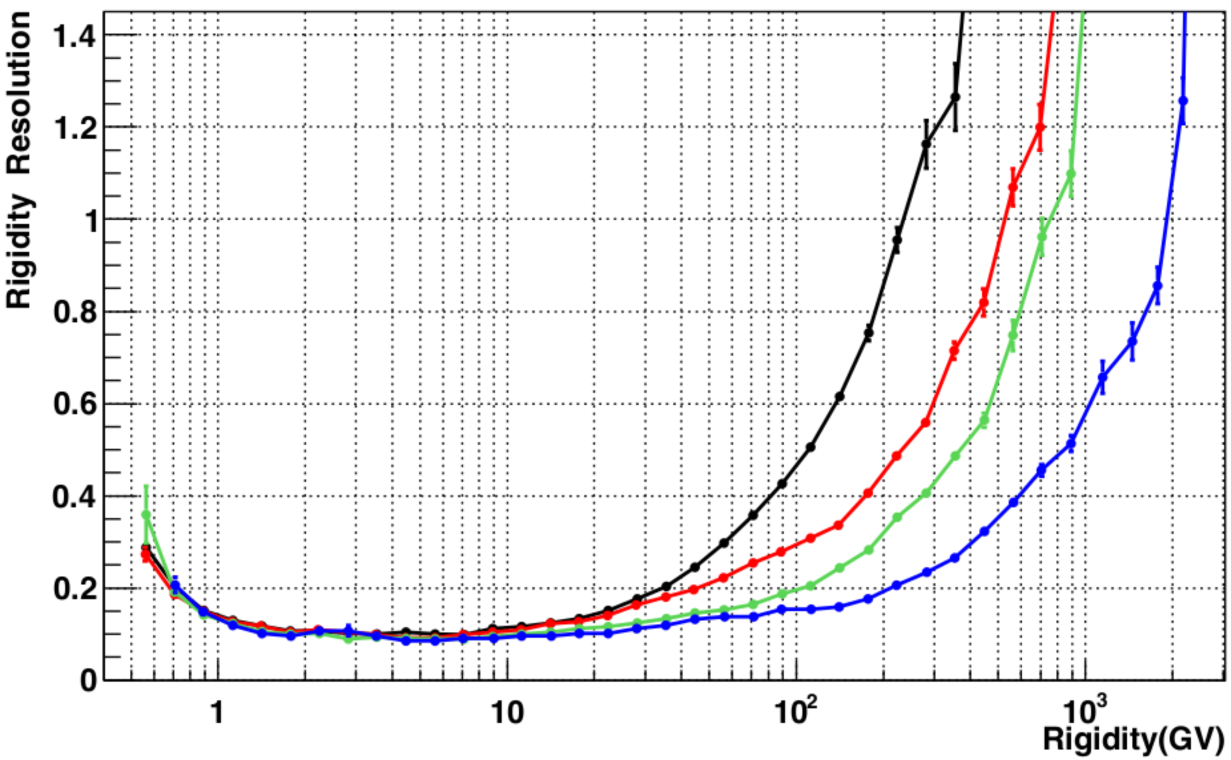
- Apply to preselected "real" data for each bin
- A histogram = a unique linear combination of leptons and protons template.
- Area = number of each species
- Done for all events ($e^+ + e^-$) and ones with positive rigidities (e^+).

Comparison between proton templates



- Top: Novosibirsk, bottom: histograms
- Differ only by one event
- Seen for all bins of high energies
- Histograms taken for all bins

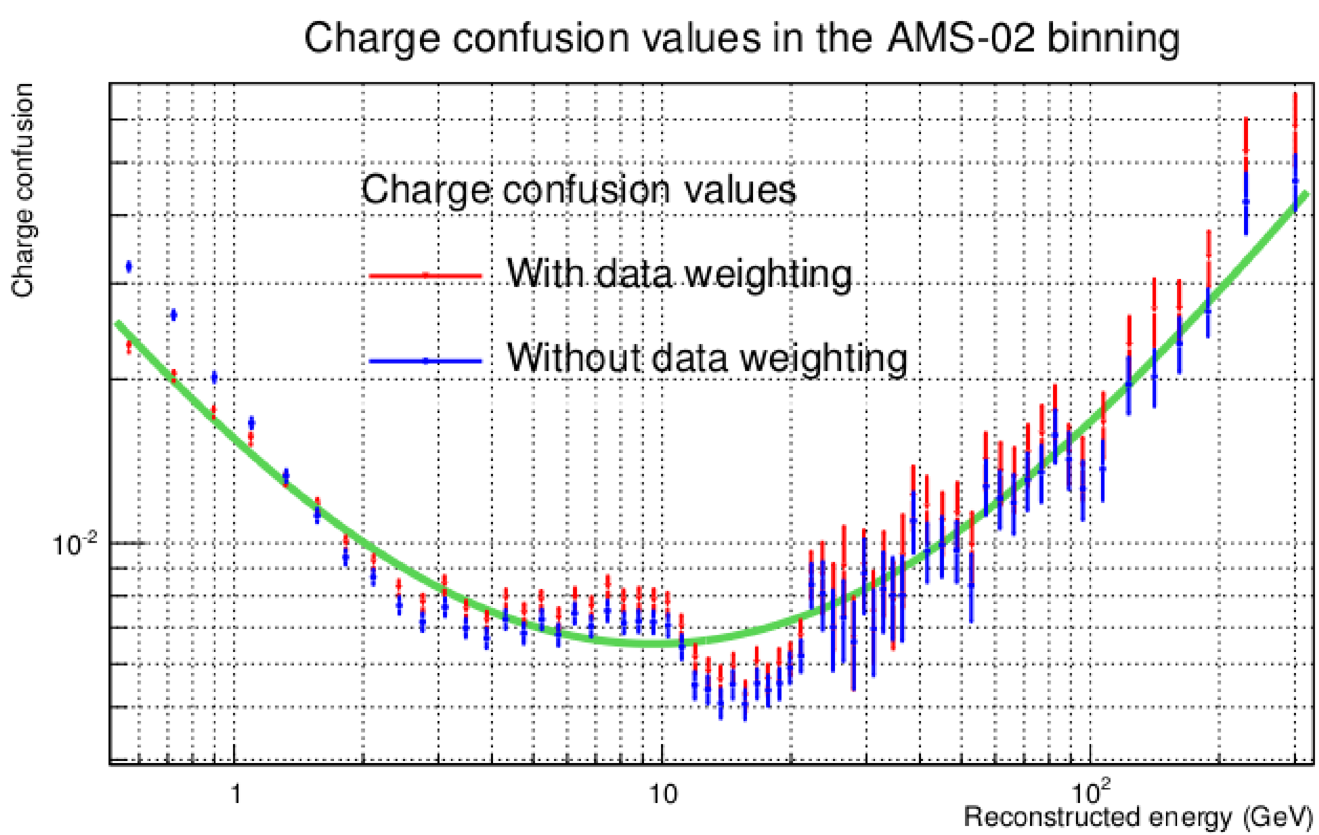
Charge confusion



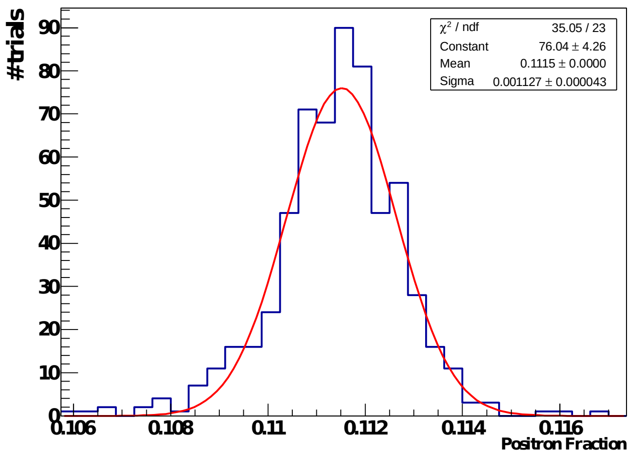
- Sign of charge: only given through magnet + tracker
- Limited granularity
  - Maximum detectable rigidity 2TV
  - Some charge signs are wrong
- Estimate the fraction of charge misidentified (charge confusion)
- Monte-Carlo simulations

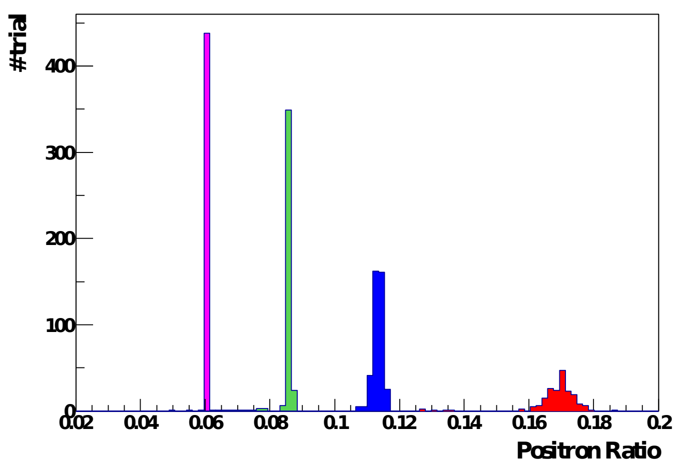
Assessing the charge confusion

$$f_{cc} \equiv \frac{n_{cc}}{n_{e^-}} \qquad R = \frac{1}{1-2f_{cc}}\left(\frac{n_+}{n_+ + n_-} - f_{cc}\right)$$



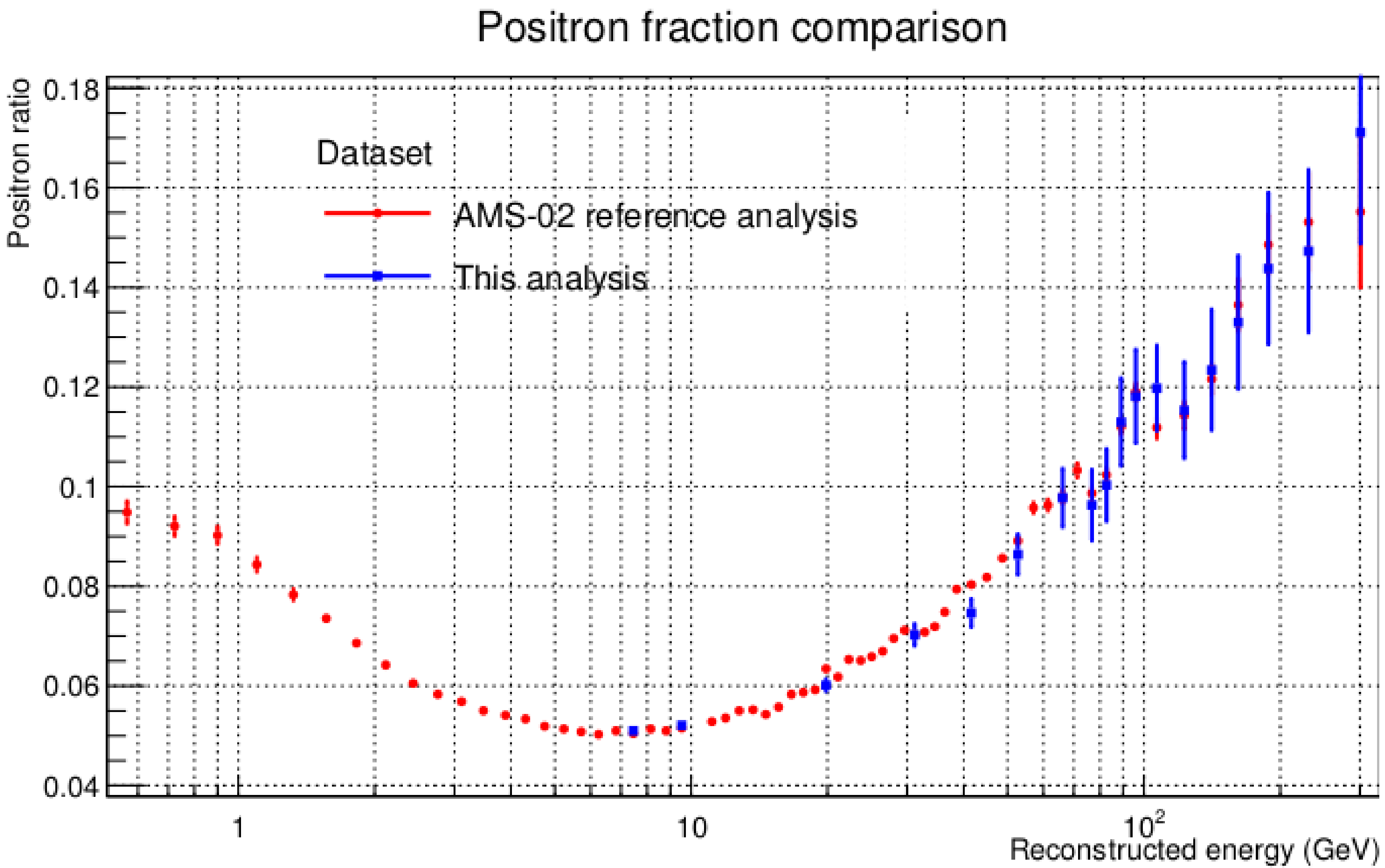
Uncertainty sources





- Acceptance asymmetry (neglected)
- Bin-to-bin migration (neglected)
- Charge confusion (stat.)
- Reference spectra (seen)
- Effect of the number of leptons selected by TRDL, E/P on ratio
- Added in squares to give the squared total uncertainty

Final positron ratio



Conclusions and prospectives

- Results from the paper are reproduced, using different method and estimator
- Crucial point: what happens after 350 GeV (plateau ? stiff drop?)
- More statistics ($\sqrt{t}$)
- Improve ESEv3
  - New MC simulations
  - More smeared variables
  - More ISS Data
- 2D fits
- Other spectra from AMS-02
- Other experiments
  - ISS-CREAM
  - CALET