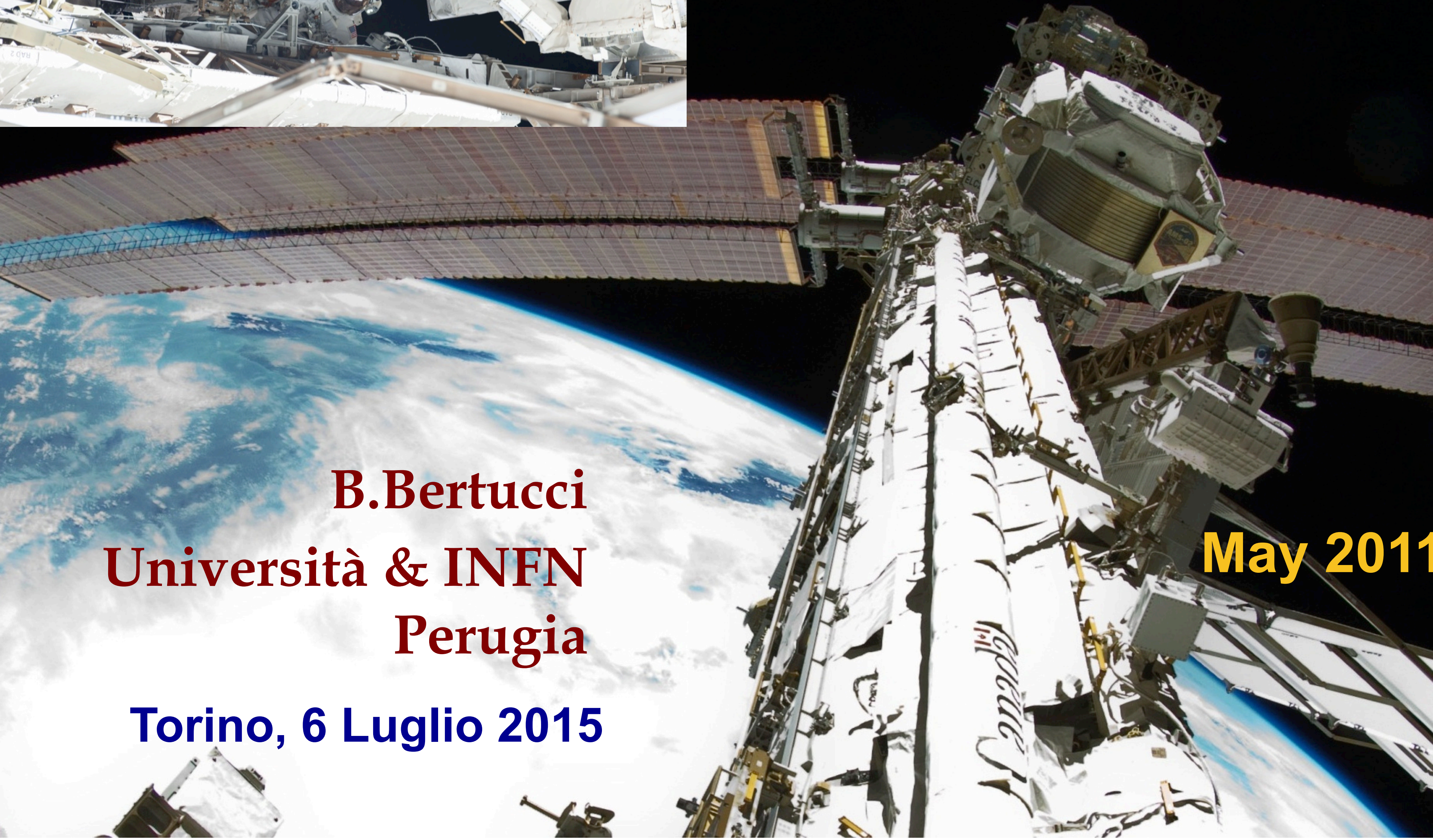
# Recent results from AMS-02

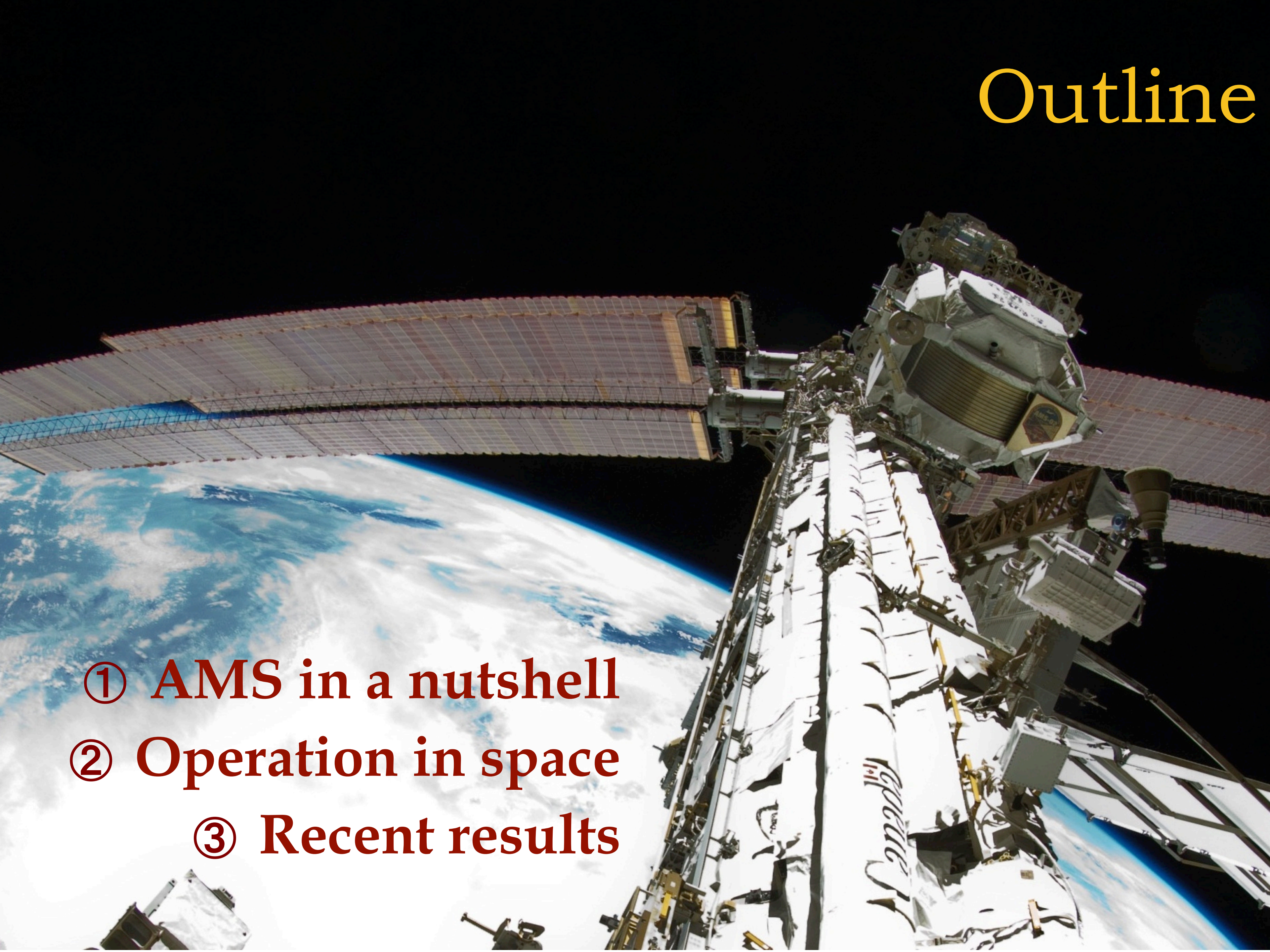


B.Bertucci

Università & INFN Perugia


Torino, 6 Luglio 2015

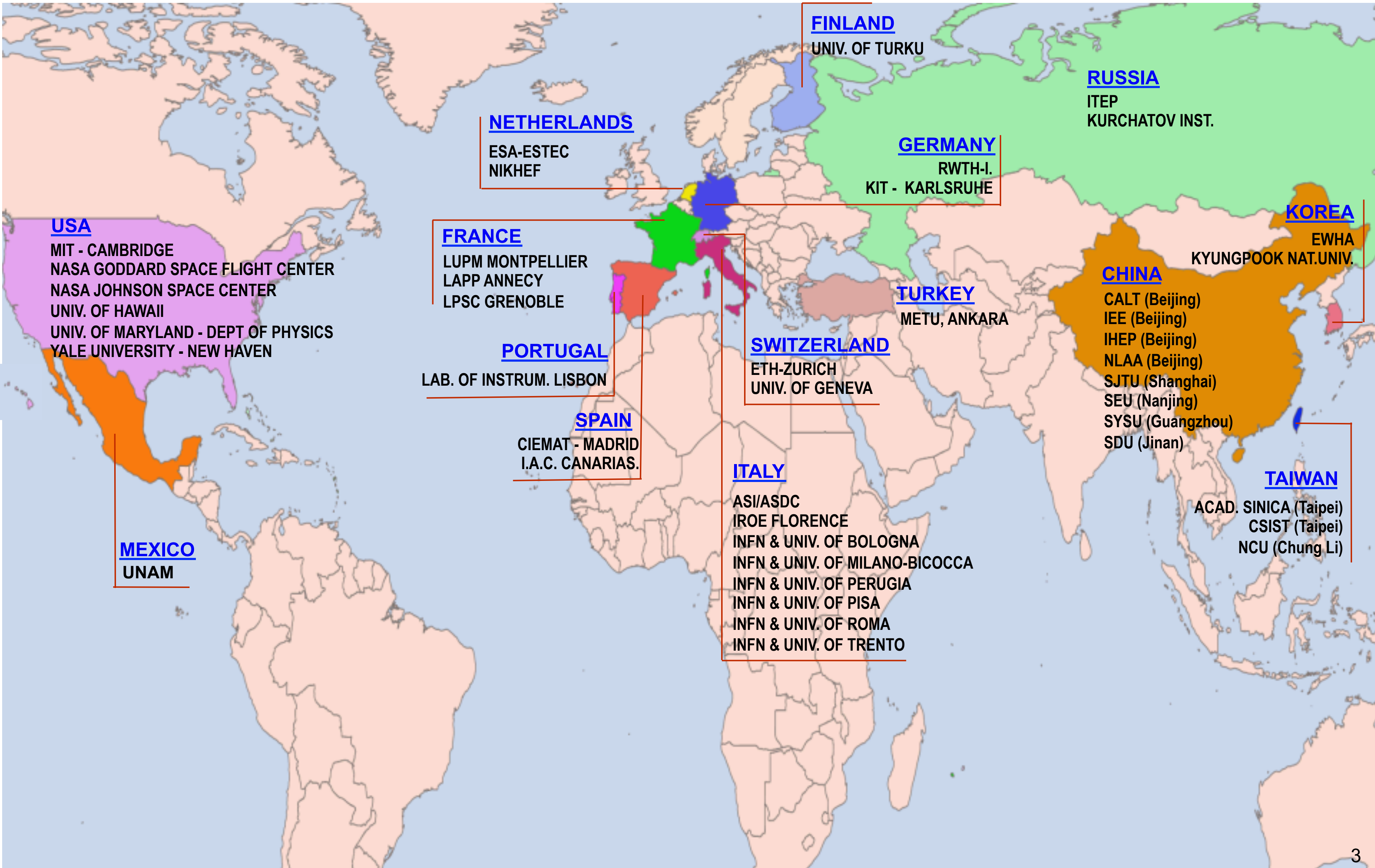
# Outline



① AMS in a nutshell
② Operation in space
③ Recent results

# Alpha Magnetic Spectrometer :

## 16 Countries, 57 Institutes and 600 Physicists



# AMS Objectives

- **Fundamental physics & Antimatter :**
  - **Primordial origin (anti-nuclei ?)**
  - **Exotic sources a.k.a DARK MATTER (positrons, anti-p, anti-D?)**

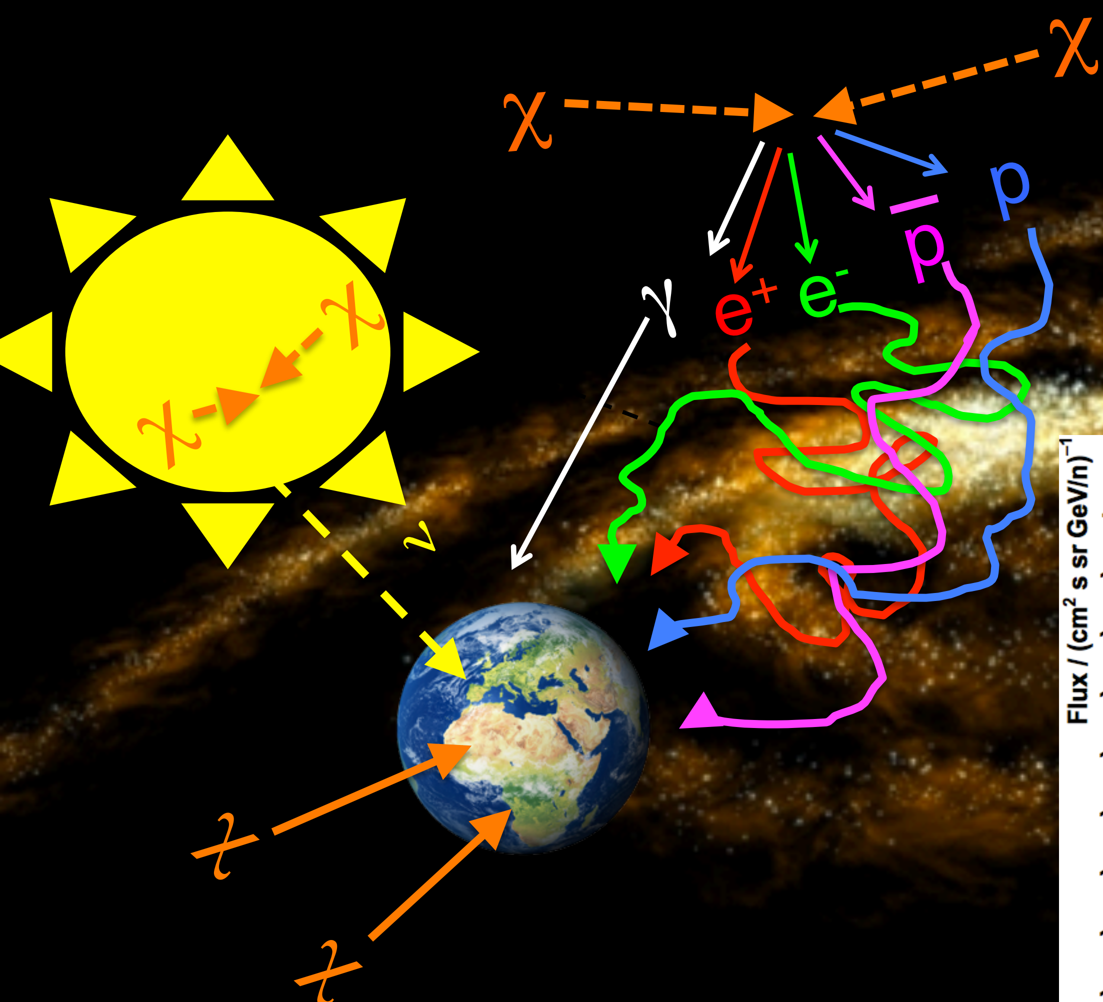
- **The CR composition and energy spectrum**

  **(how to understand the beam)**
  - **Sources & acceleration : Proton and He, electrons**
  - **Propagation in the ISM: (nuclear and isotopic composition)**

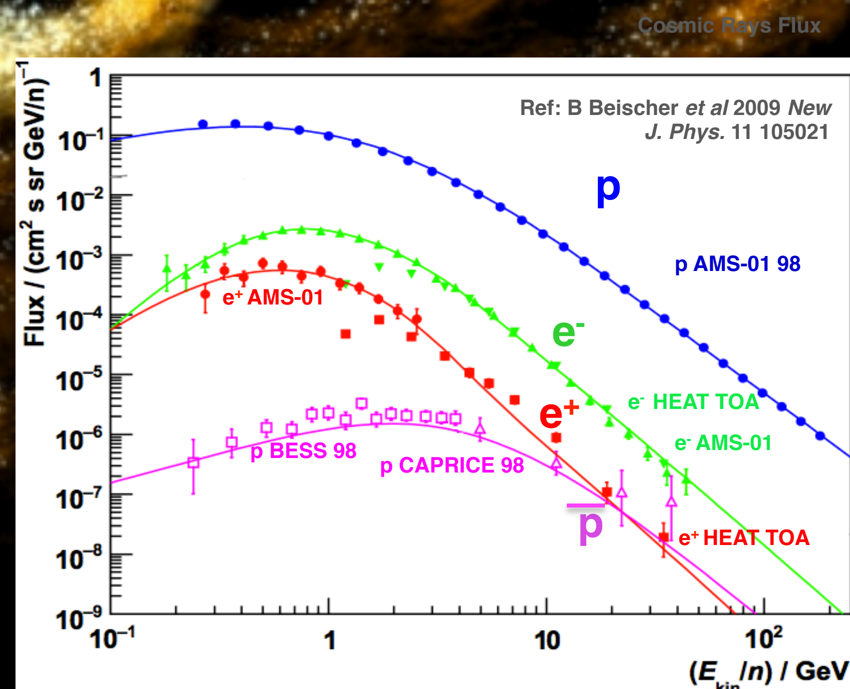
# ANTI-MATTER & DARK MATTER

WIMP as the responsible of Dark Matter (?)

Indirect DM search → search for (RARE IN CR) products from their annhilation….



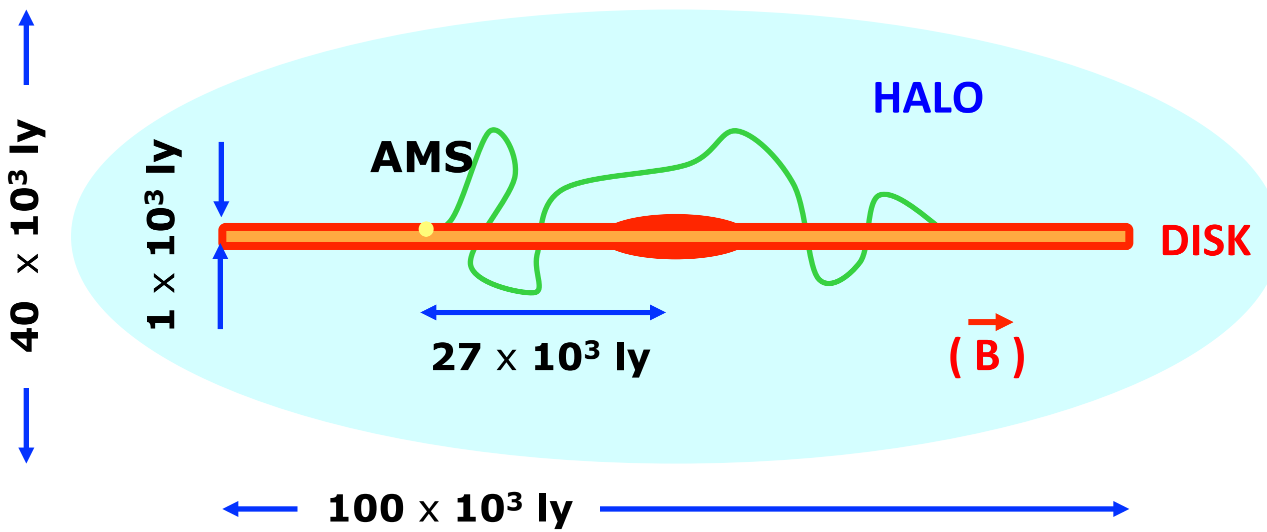

But you should know what you expect in the ISM !!



# Knowledge of cosmic background

## $e^+$, $\bar{p}$ are produced in the CR interactions with the ISM

$$P+H_{ISM} \,/\, P+He_{ISM} \rightarrow \bar{P} + ..., e^+ .....$$
$$He+H_{ISM} \,/\, He+He_{ISM}$$




Diffusion
Convection
Reacceleration

Interactions with the Interstellar Medium (ISM):
- Fragmentation
- Secondaries
- Energy loss

**Information on Cosmic Ray Interactions and Propagation can be provided by the accurate measurement of nuclear species e.g. B/C**

$$C + (p,He) \rightarrow B + ...$$

# AMS Objectives

- **Fundamental physics & Antimatter :**
  - **Primordial origin (anti-nuclei ?)**
  - **Exotic sources a.k.a DARK MATTER (positrons, anti-p, anti-D?)**

- **The CR composition and energy spectrum**

  **(how to understand the beam)**
  - **Sources & acceleration : Proton and He, electrons**
  - **Propagation in the ISM: (nuclear and isotopic composition)**

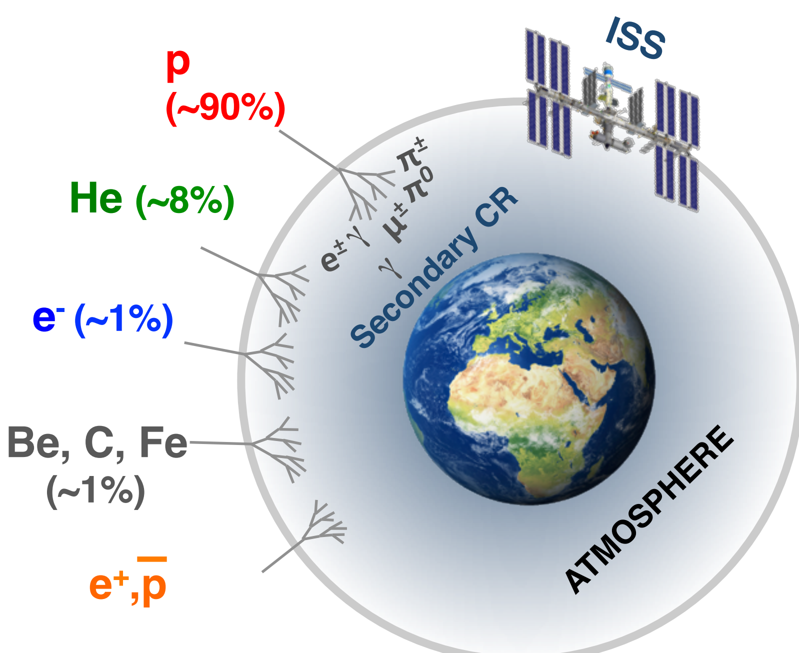
**The experimental challenge: hunt rare signals & provide accurate flux measurements to interpret them !**

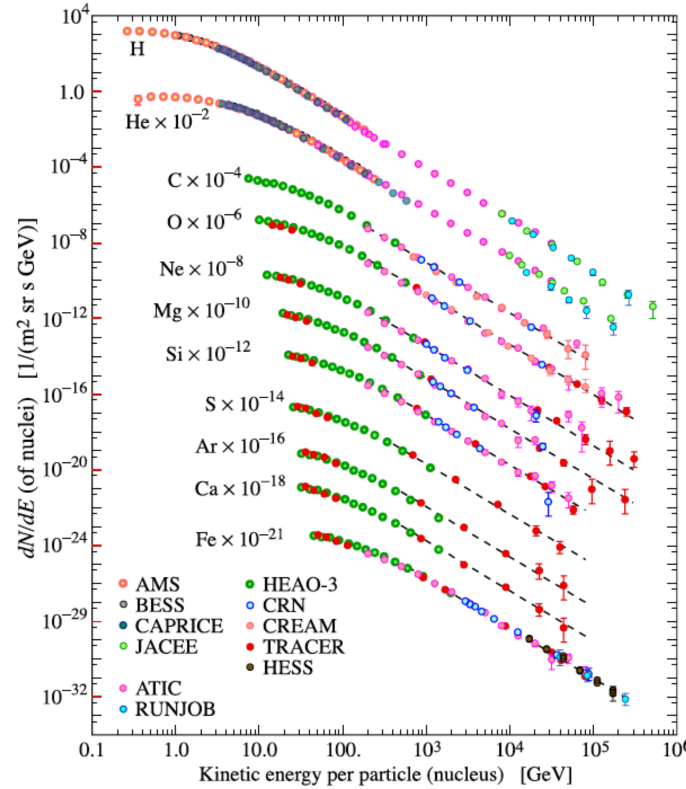
- **DESIGN : state of the art detectors providing redundant measurements of particle properties**
- **TEST: test and calibration on ground**
- **MONITORING on ISS : calibration on flight**
- **Data analysis**

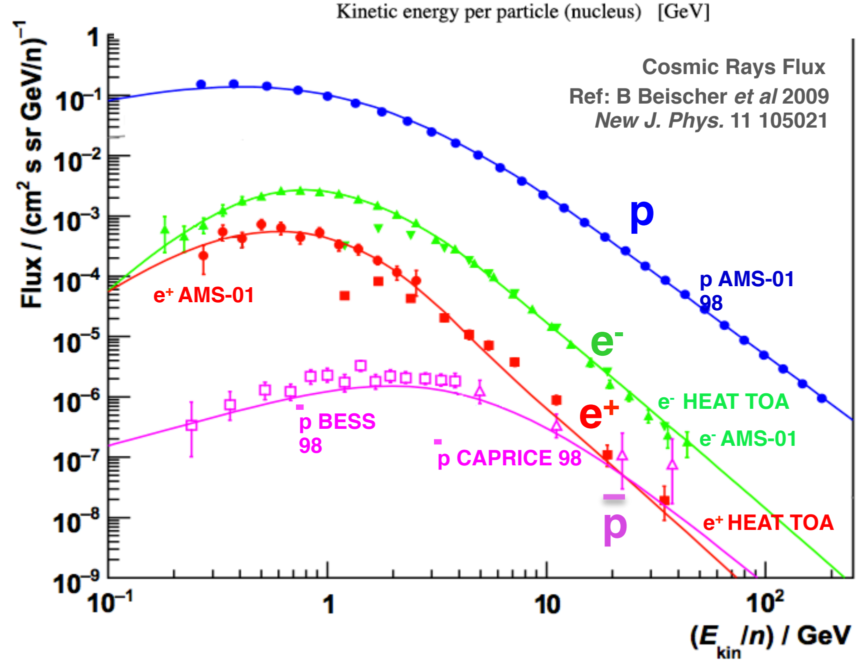
# AMS measurements

→ *charged cosmic rays* (GV-TV) & their variation in time

→ γ rays (E>1GeV)

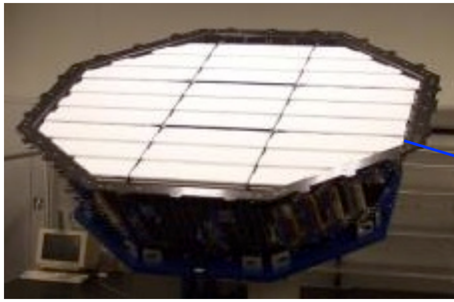


# AMS: A TeV precision, multipurpose spectrometer

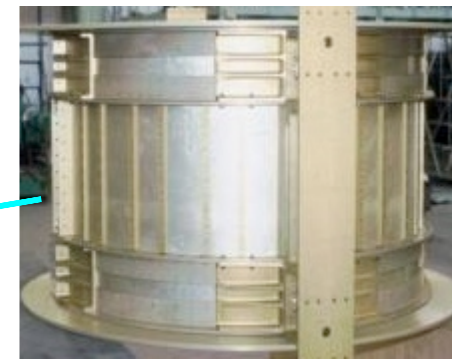
**Transition Radiation Detector (TRD)**
Identify $e^+$, $e^-$



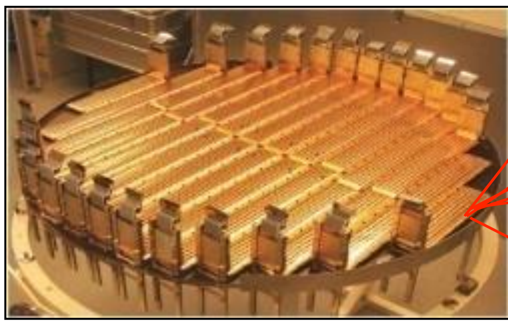
**Particles and nuclei are defined by their charge (Z) and energy (E)**

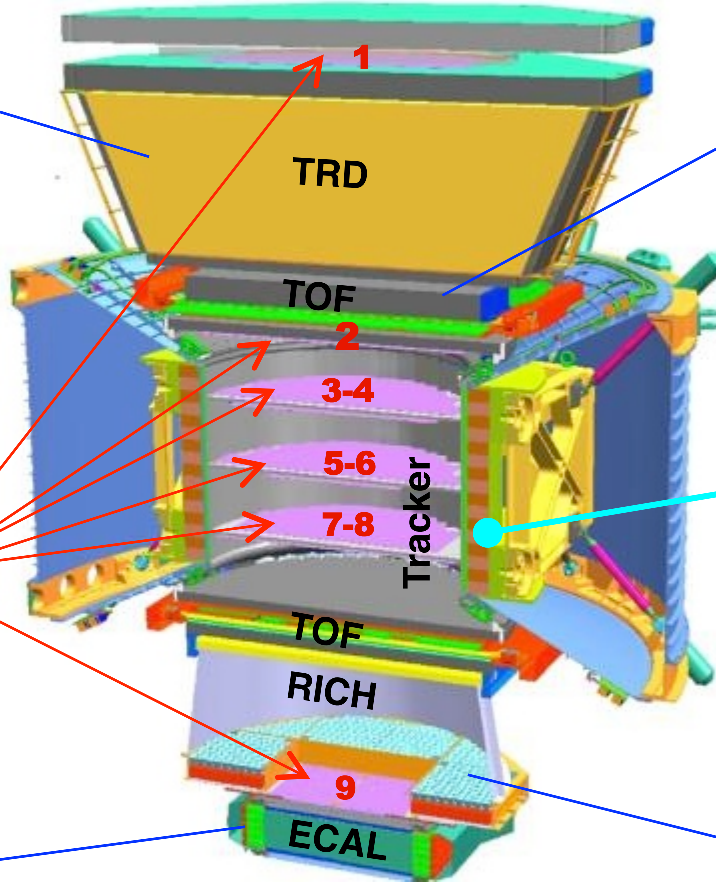
**Time of Flight (TOF)**
Z, E

**Magnet (0.15 T)**
±Z



**Silicon Tracker**
Z, P



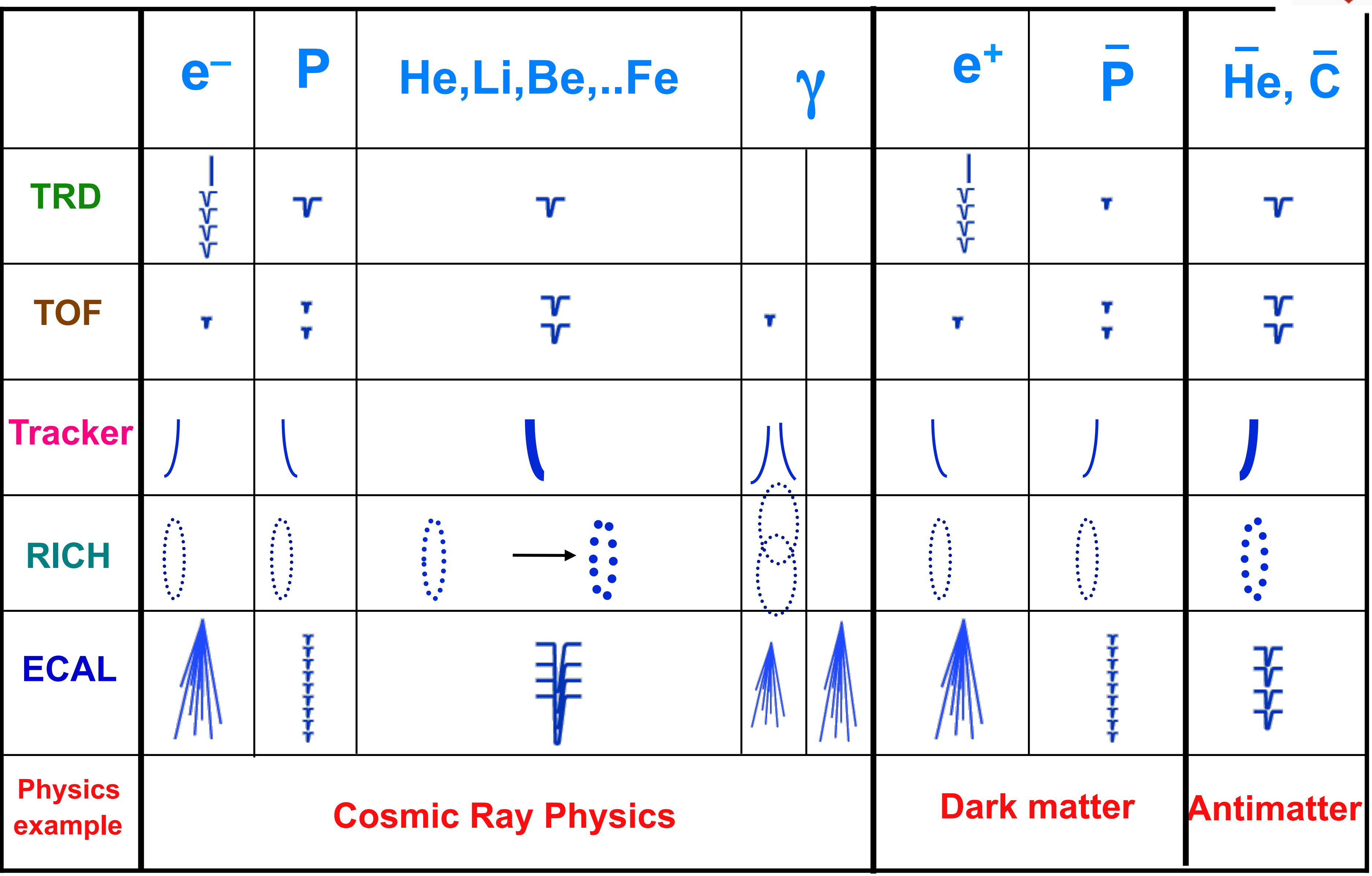


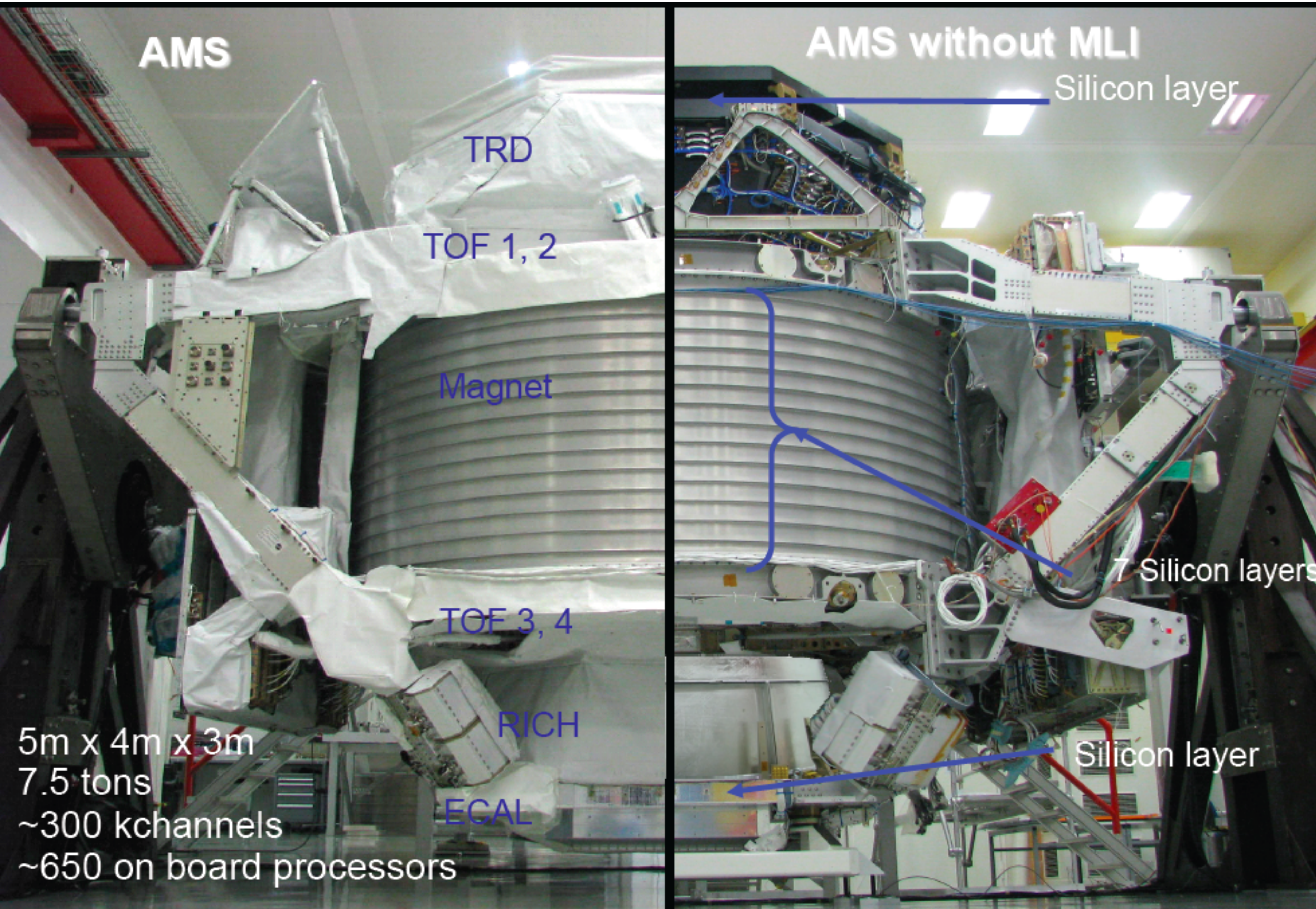

**Ring Imaging Cherenkov (RICH)**
Z, E

**Electromagnetic Calorimeter (ECAL)**
E of $e^+$, $e^-$, γ

***Z, E are measured independently by the Tracker, RICH, TOF and ECAL***

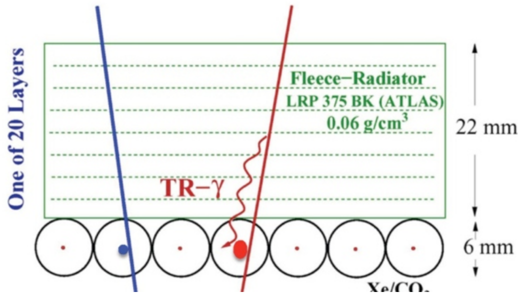
# Full coverage of anti-matter & CR physics



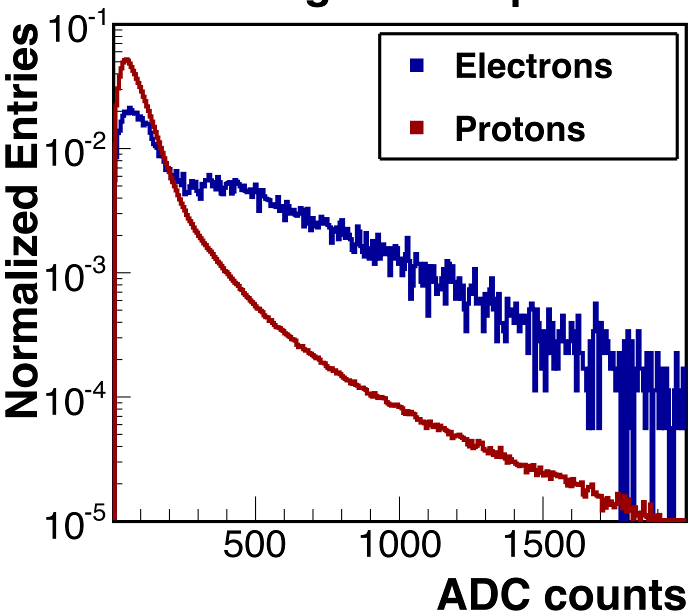

AMS
TRD
TOF 1, 2
Magnet
TOF 3, 4
RICH
ECAL
5m x 4m x 3m
7.5 tons
~300 kchannels
~650 on board processors
AMS without MLI
Silicon layer
7 Silicon layers
Silicon layer

# TRD

**20 layers of fiber fleece radiators interleaved with 80/20 Xe/Co2 straw tubes.**



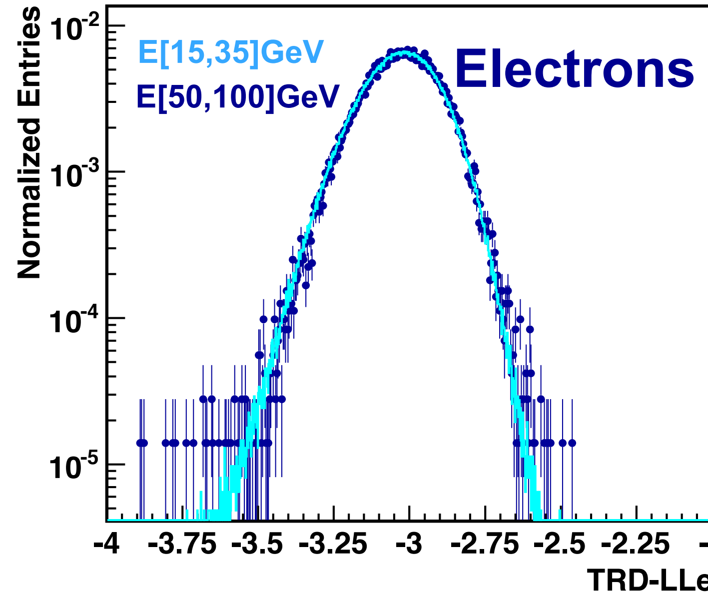

**TRD - Single tube spectrum**

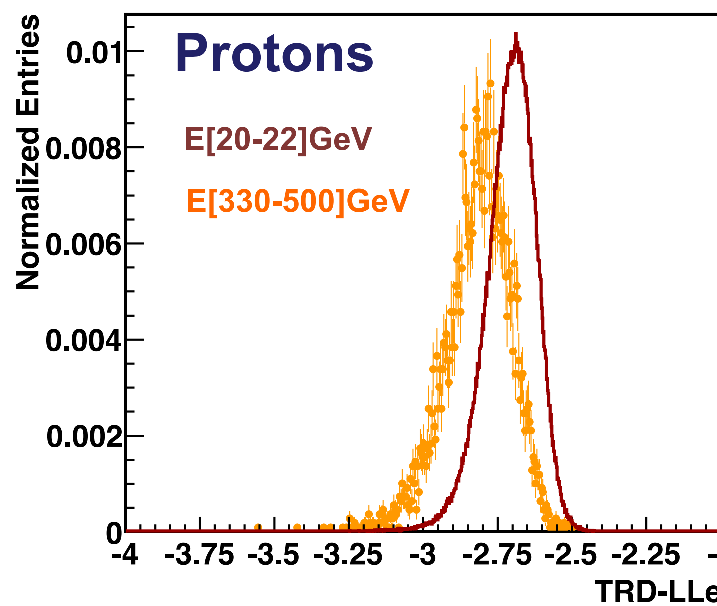



$$P_p = \sqrt[n]{\prod_i^n P_p^{(i)}(A)}$$

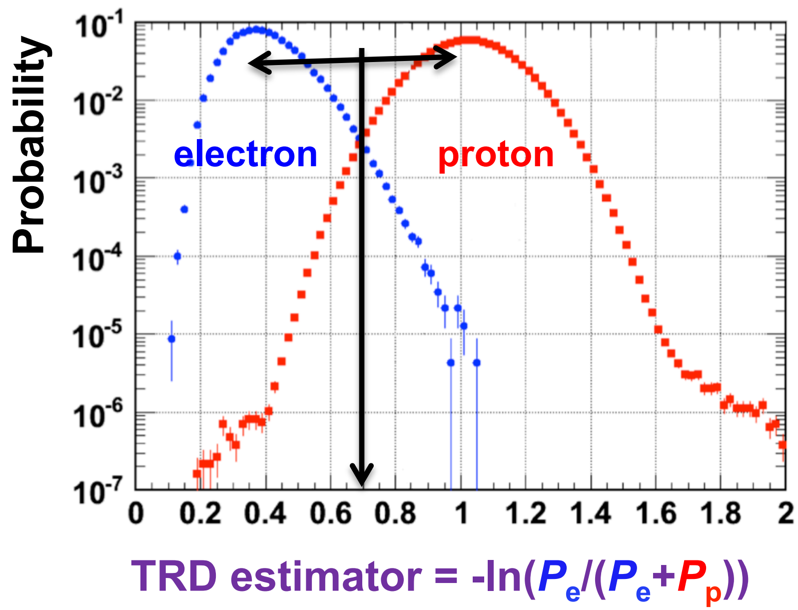
$$P_e = \sqrt[n]{\prod_i^n P_e^{(i)}(A)}$$

**TRD-LLe = $\text{Log}_{10}(P_e)$**



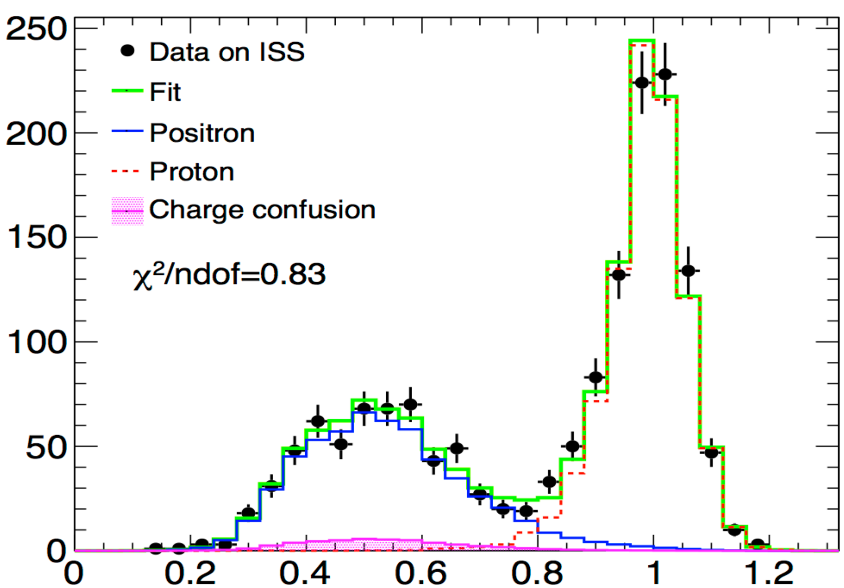



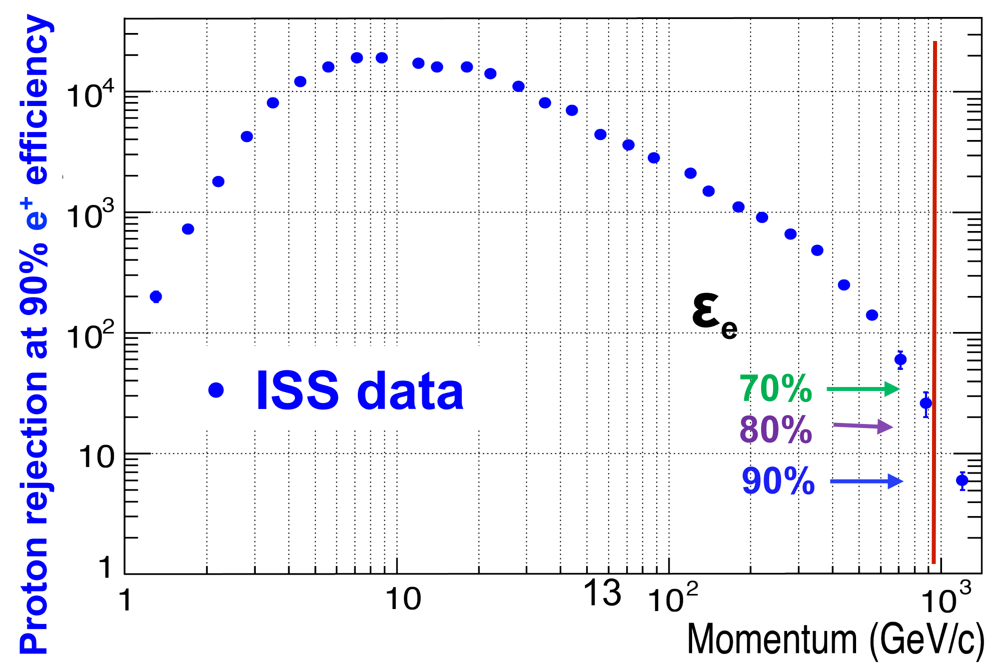
# TRD e/p separation




FIT

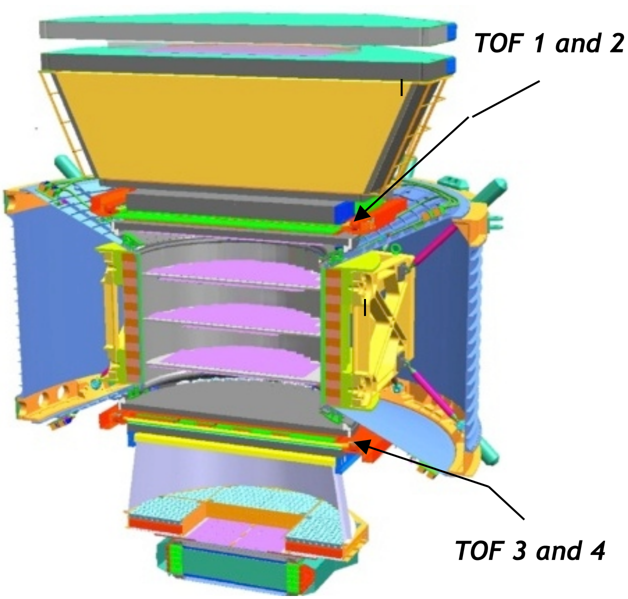
CUT

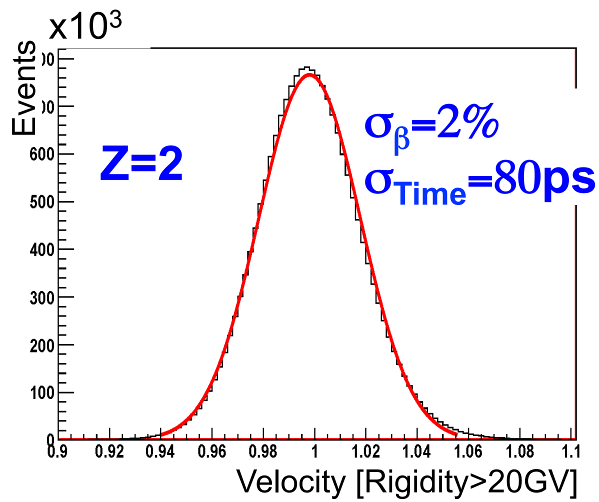


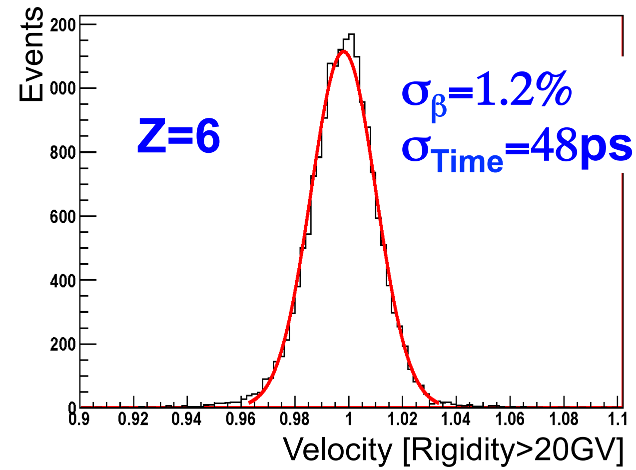



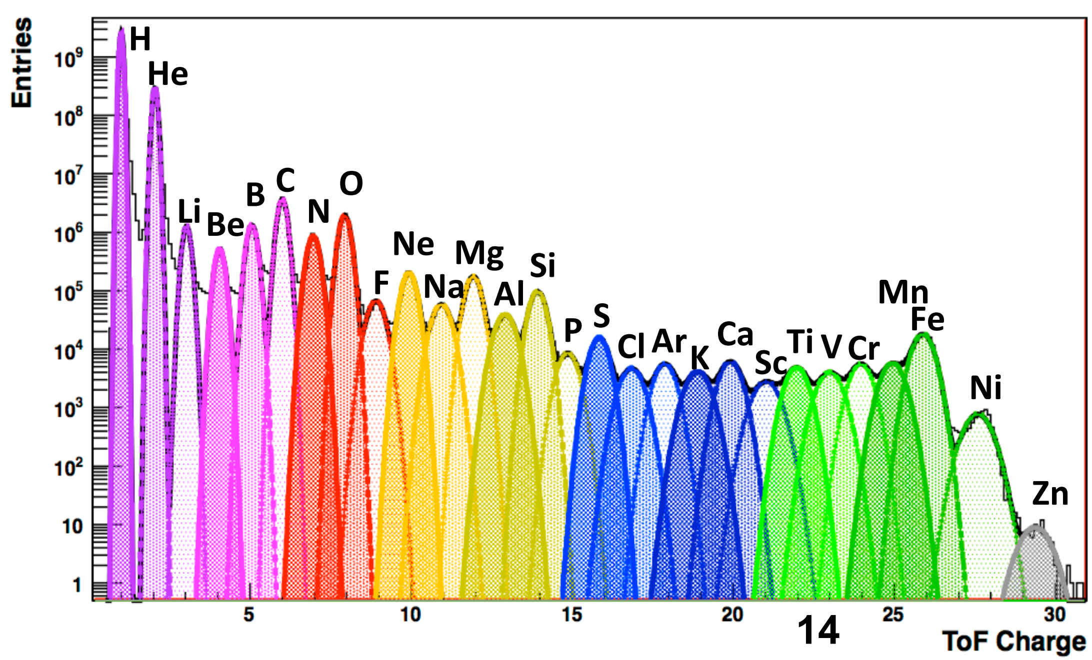
# Time of Flight System

## Measures Velocity and Charge of particles



# Tracker:

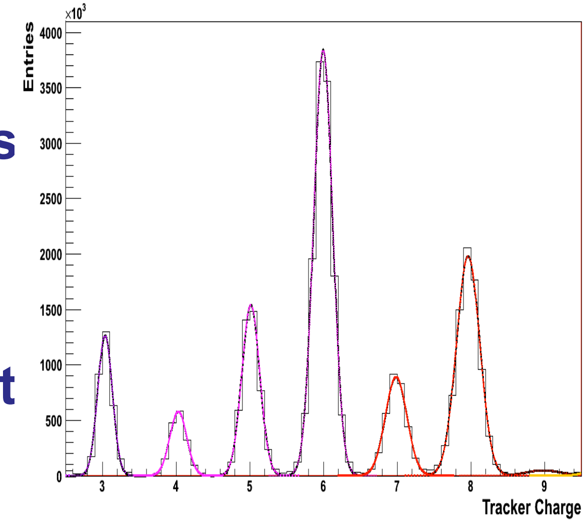
9 layers of double sided silicon microstrip detectors

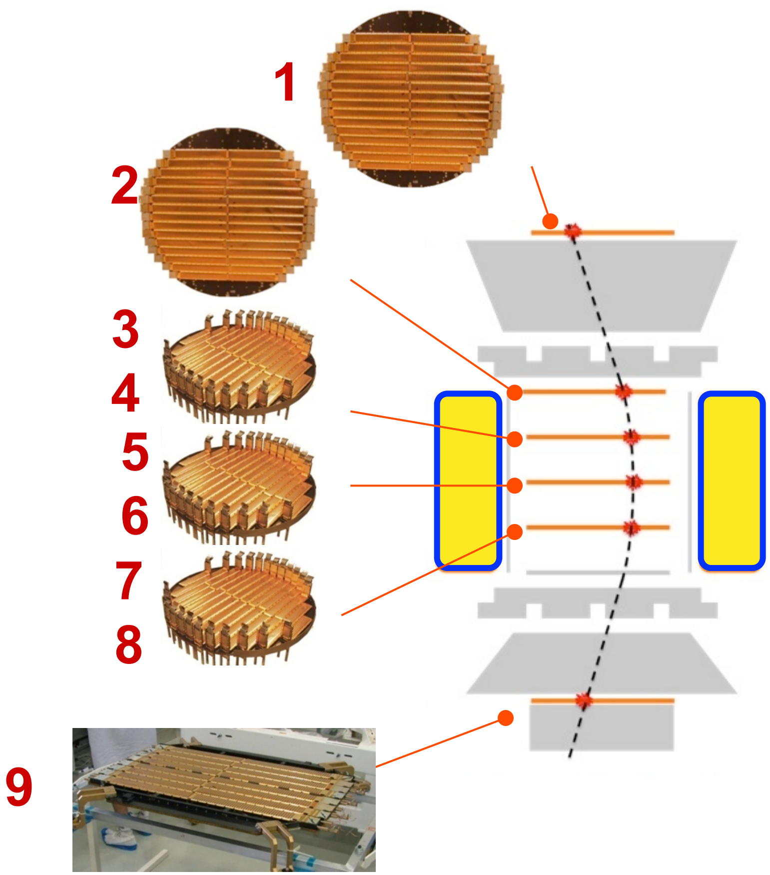
192 ladders / 2598 sensors/ 200k readout channels

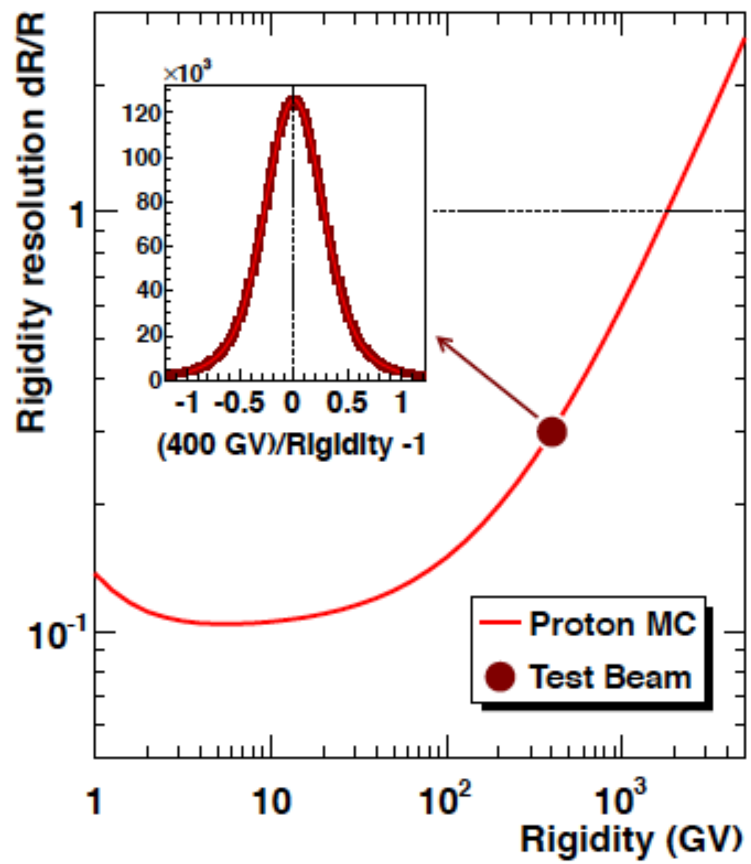
Coordinate resolution 10 μ

→ 20 –UV Lasers to monitor inner tracker alignment

→ Cosmic rays to monitor outer tracker alignment

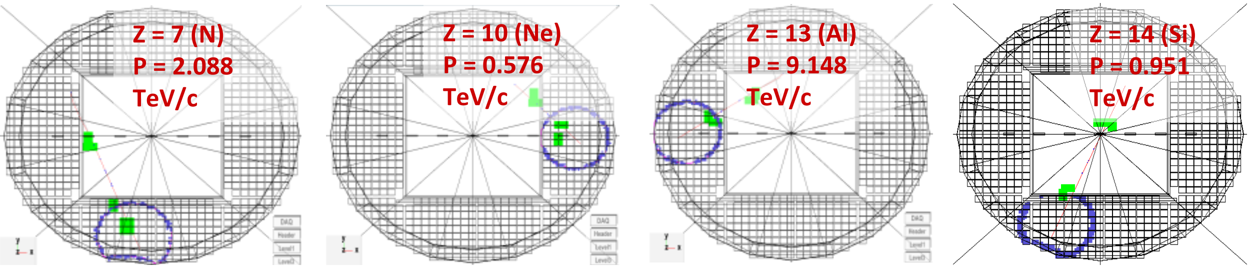


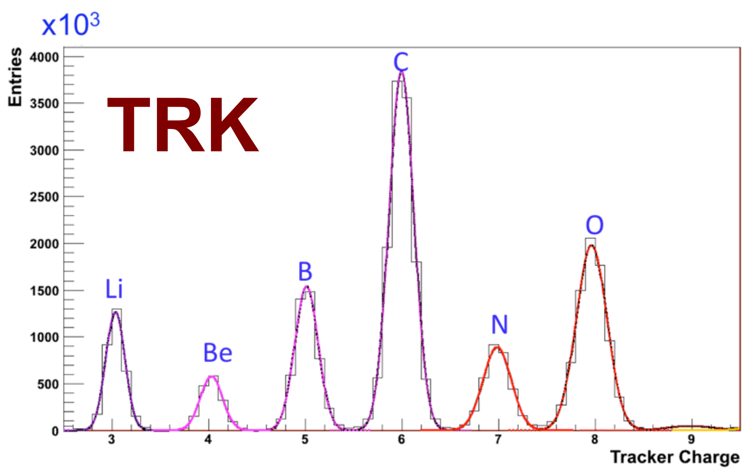



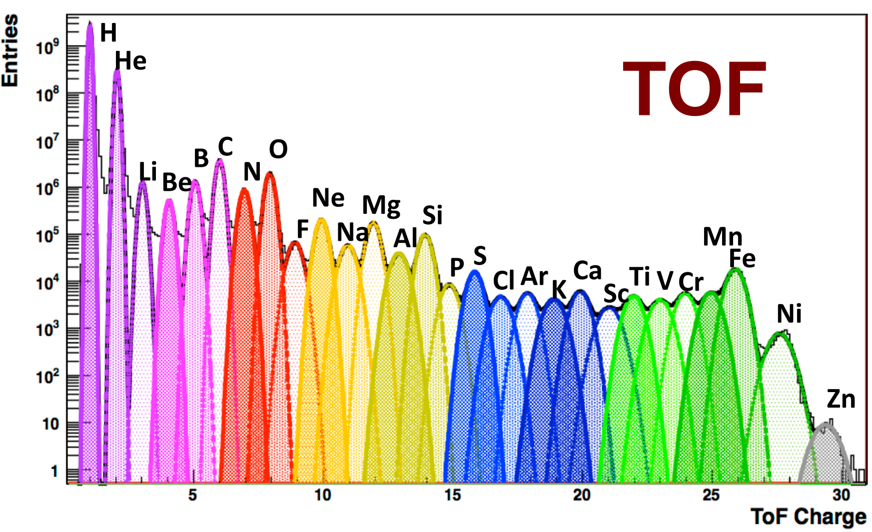



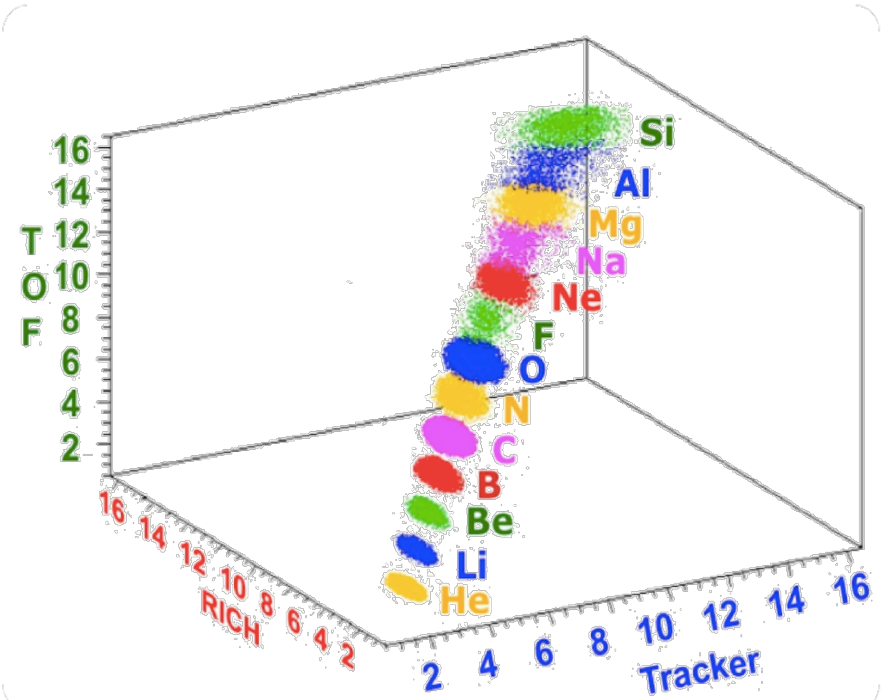
# RICH

# Z measurement



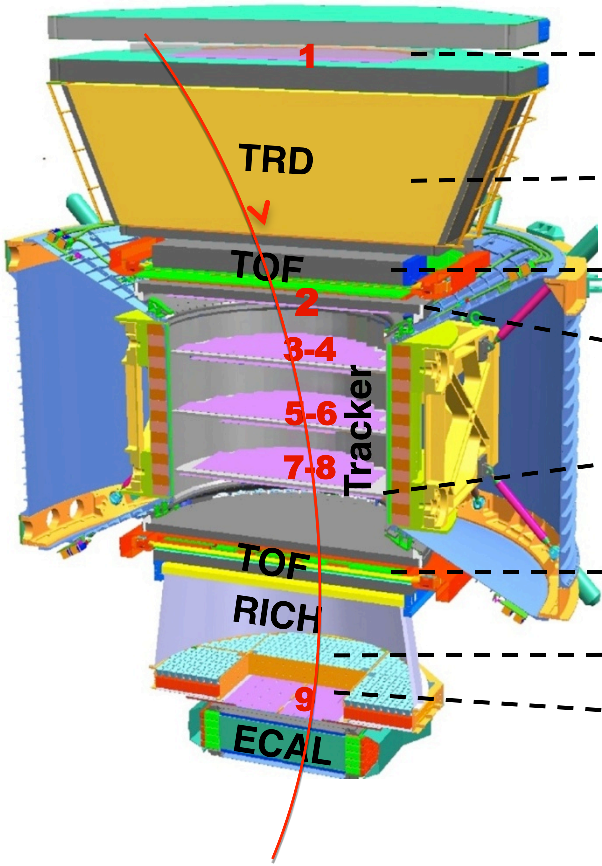



# Particle Charge Measurement

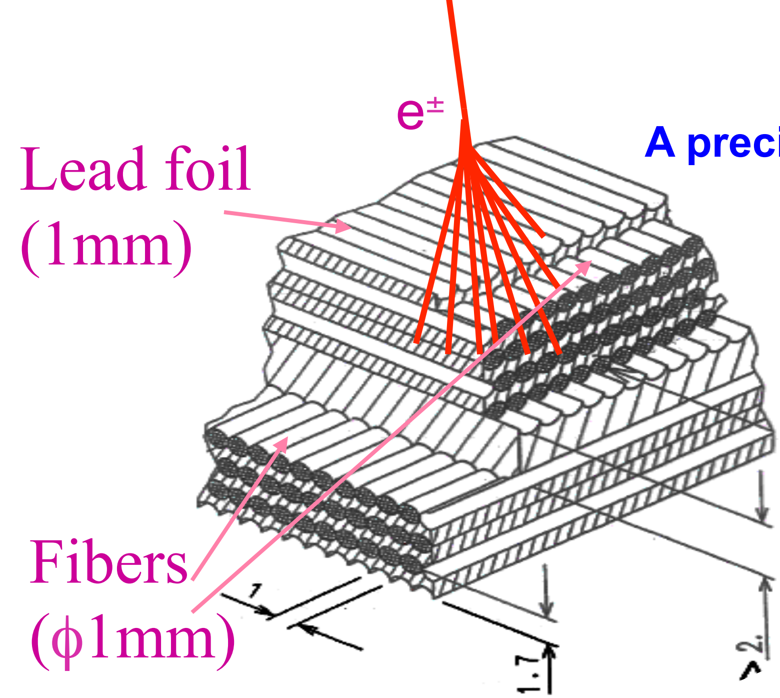
## Multiple Independent Measurements of |Z|

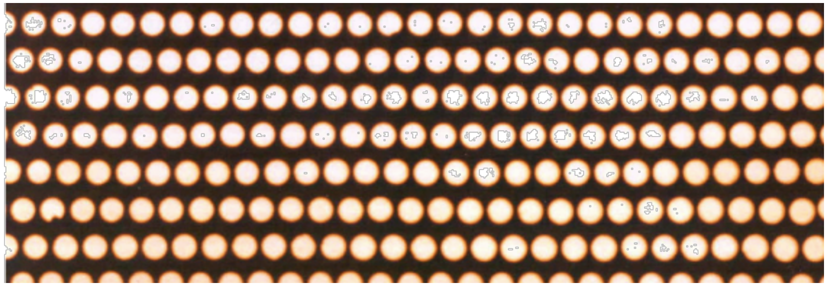



| | Carbon (Z=6) ΔZ (cu) |
|---|---|
| 1. Tracker Plane 1 | 0.30 |
| 2. TRD | 0.33 |
| 3. Upper TOF (1 counter) | 0.16 |
| 4. Tracker Planes 2-8 | 0.12 |
| 5. Lower TOF (1 counter) | 0.16 |
| 6. RICH | 0.32 |
| 7. Tracker Plane 9 | 0.30 |

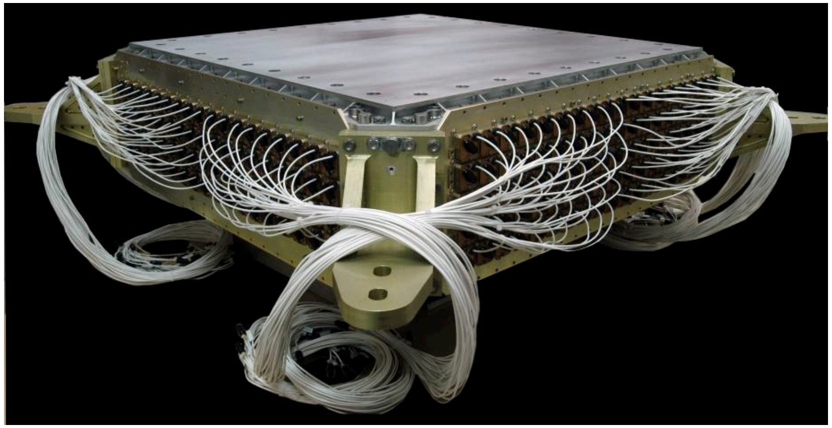
# Calorimeter (ECAL)

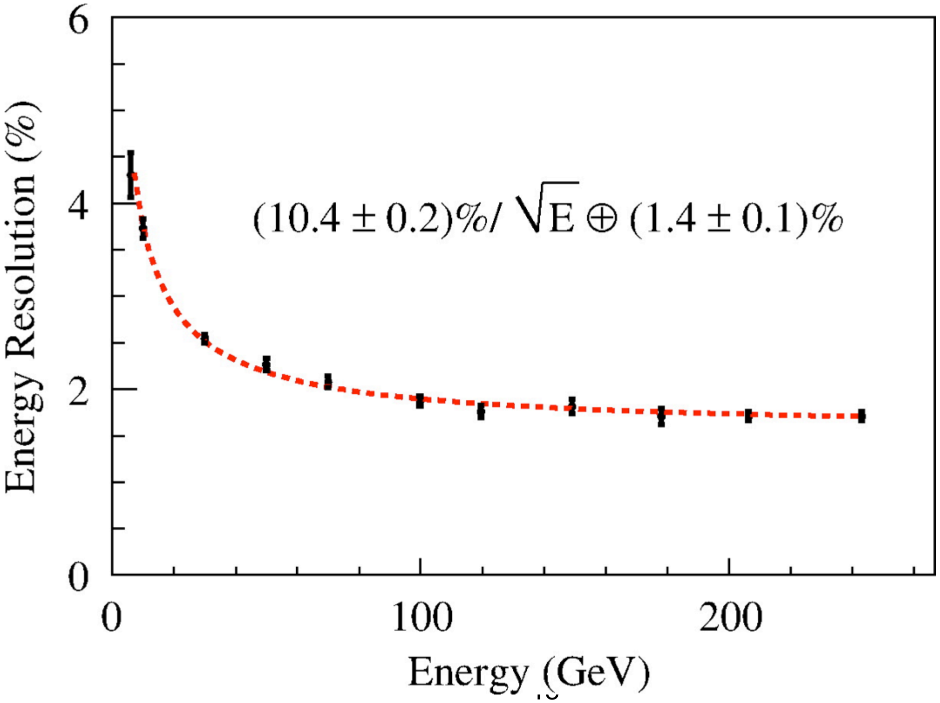
**A precision, 3-D measurement of the directions and energies of gammas and electrons up to 1 TeV**



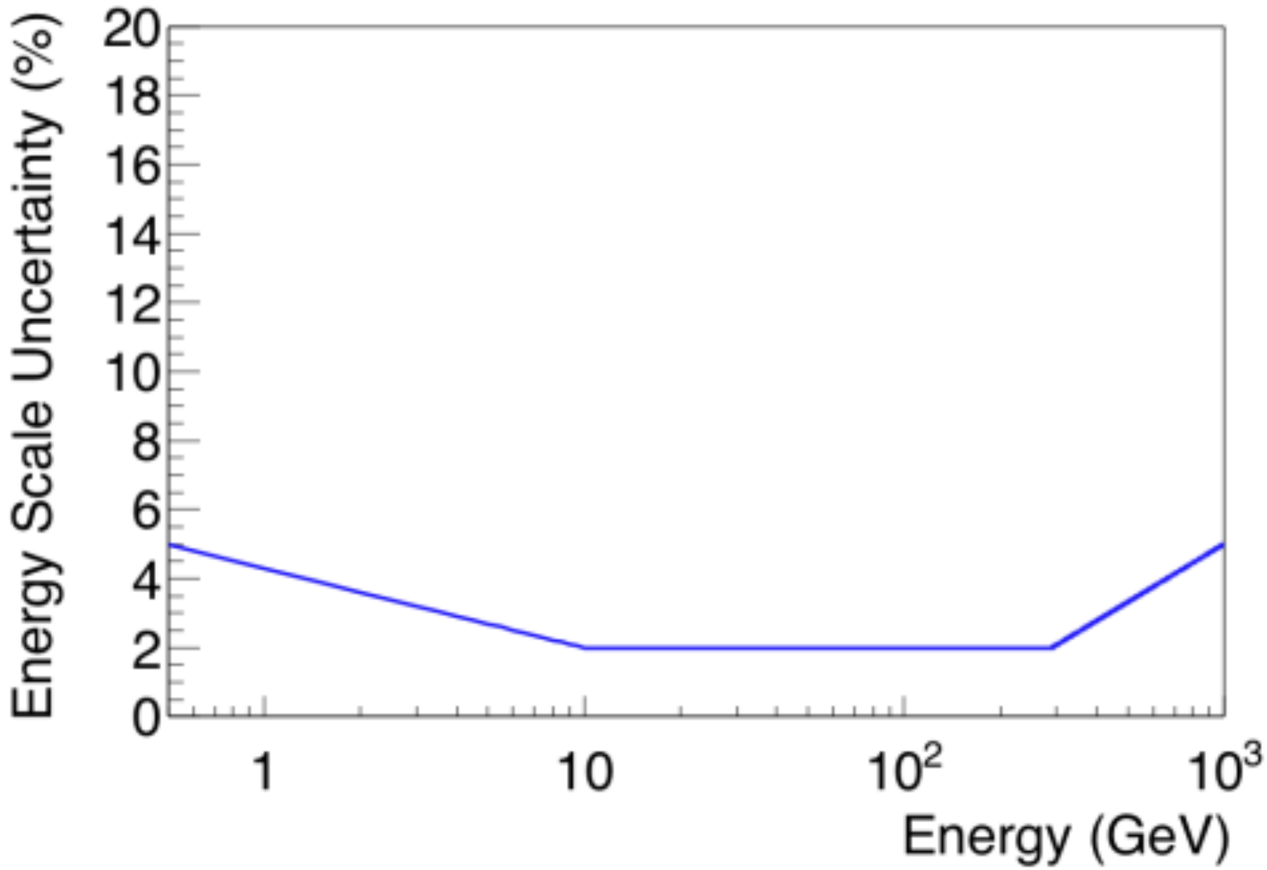
**50,000 fibers, ϕ = 1 mm**
**distributed uniformly Inside 600 kg of lead**



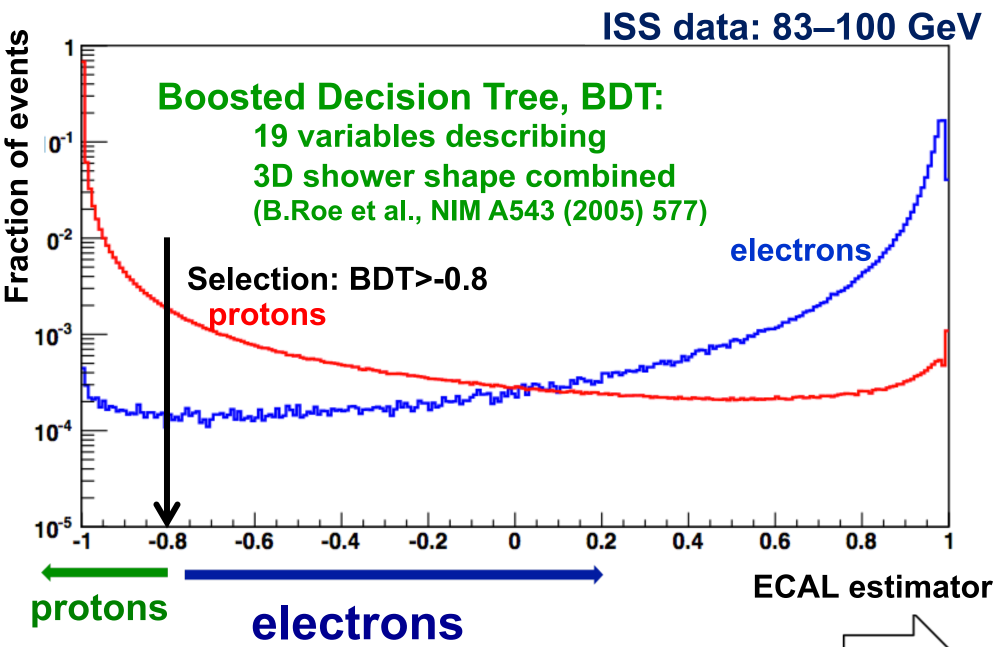


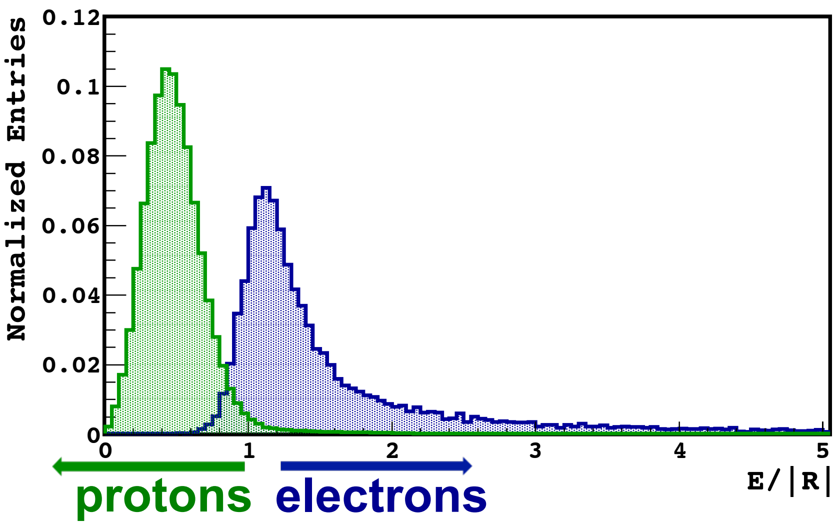
# Absolute Energy Scale for $e^{\pm}$ (at the top of AMS)

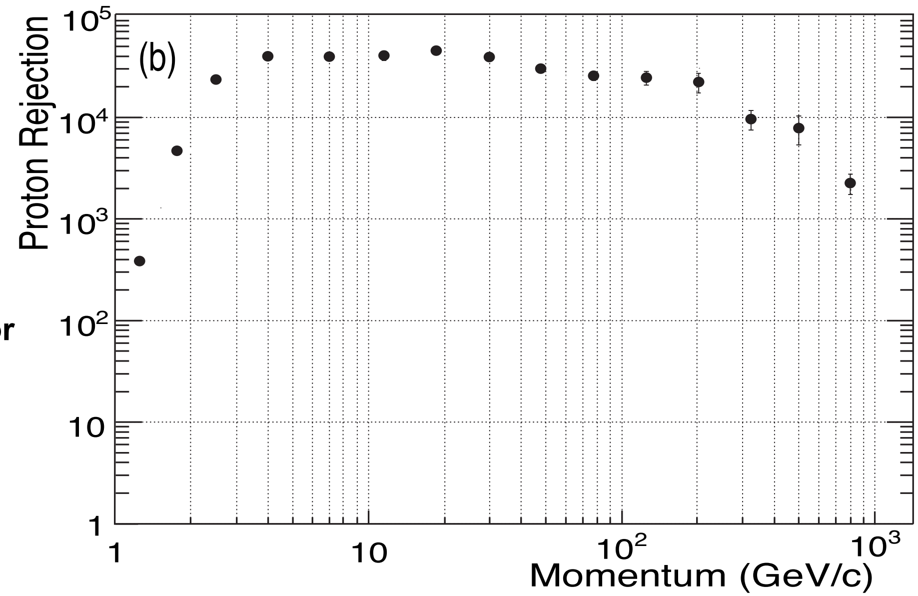
**Verified using MIPs and E/p; compared to the test beam.**
**In the test beam range (10-290 GeV) the uncertainity is 2%.**
**It increases to 5% at 0.5 GeV and 1 TeV.**



# e/p separation with ECAL+trk

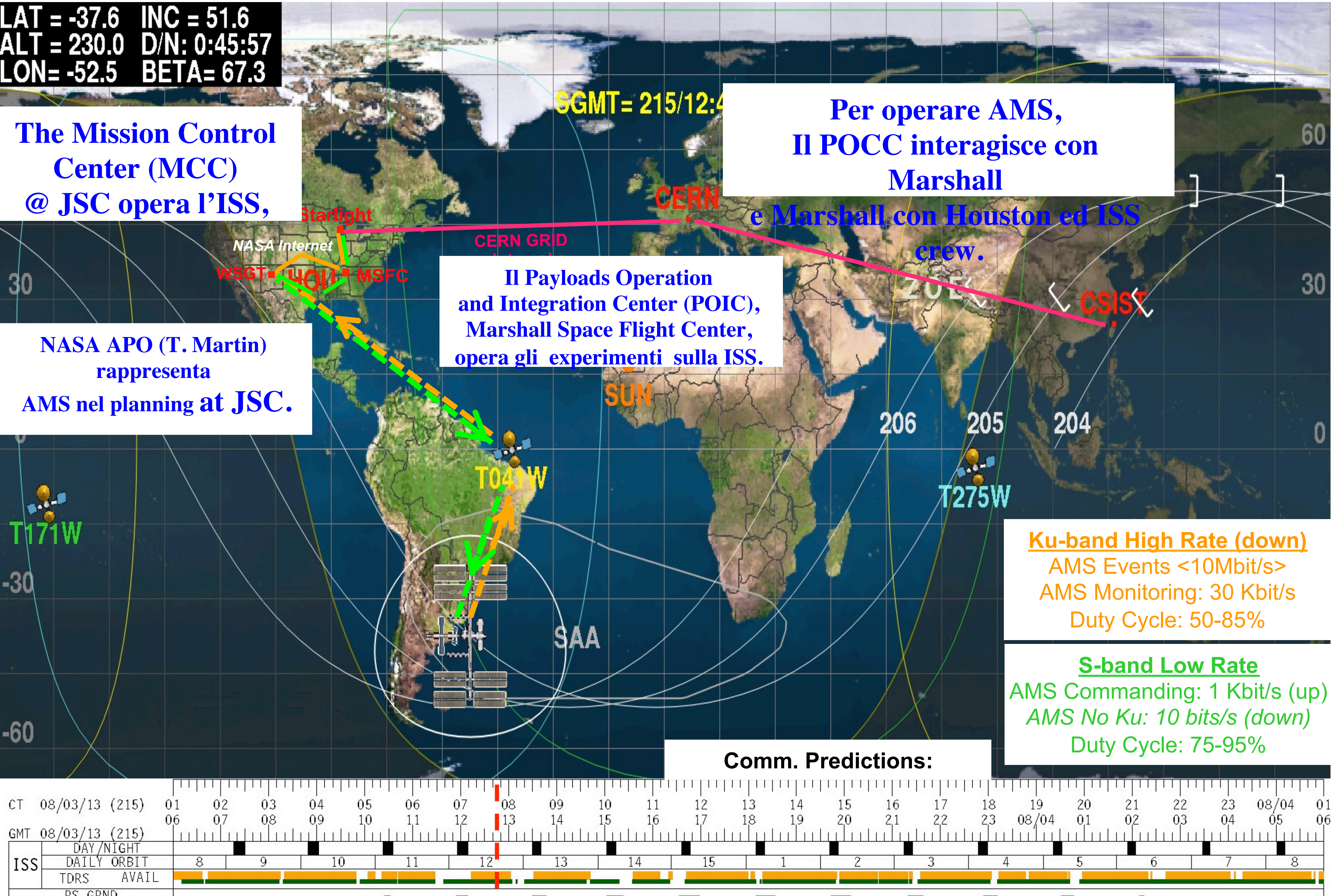


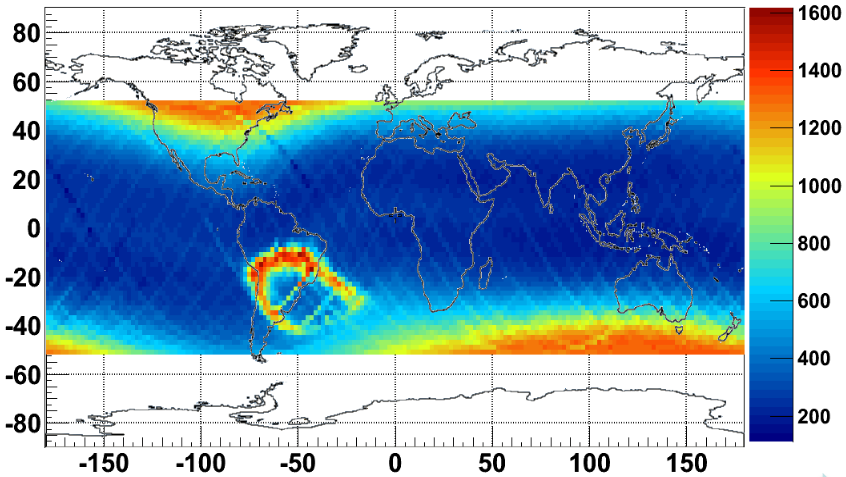
# AMS-Operation

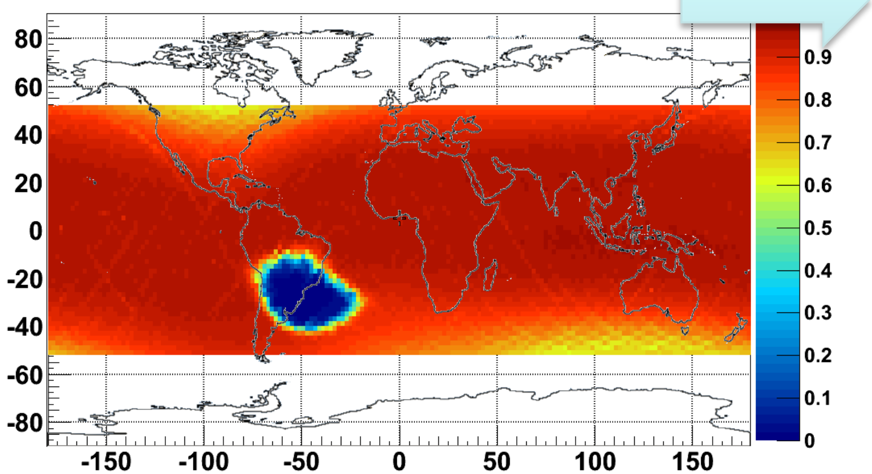
# From space to ground..

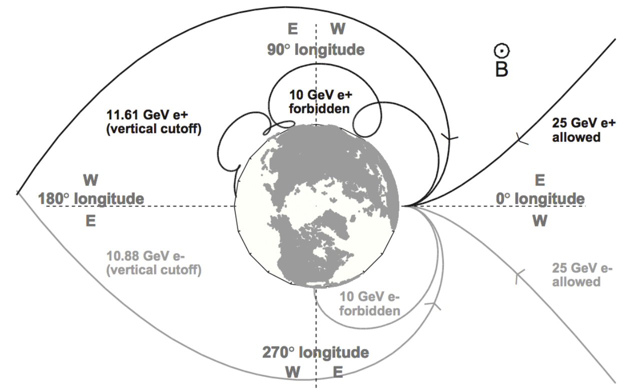


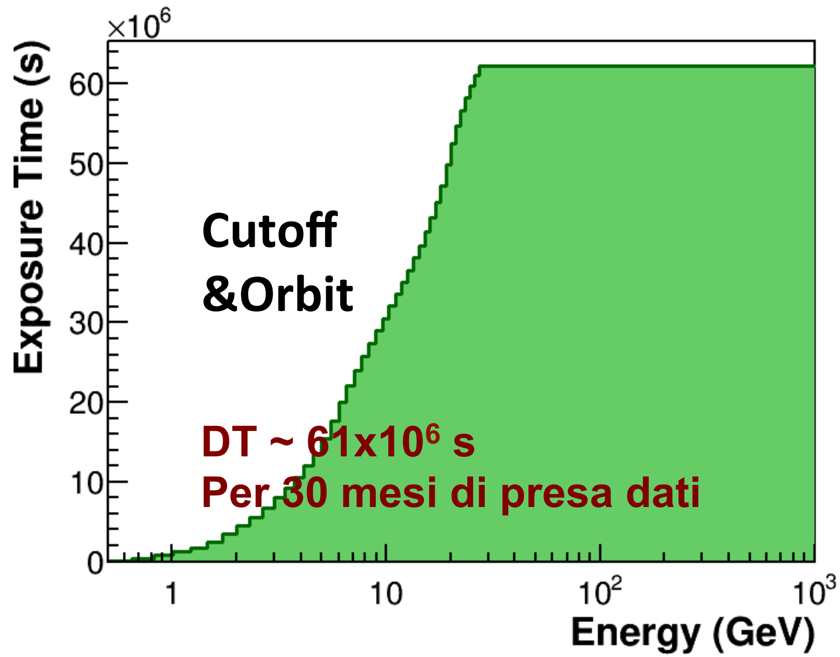
# Orbital DAQ parameters

<Acquisition rate> ≈ 600 Hz



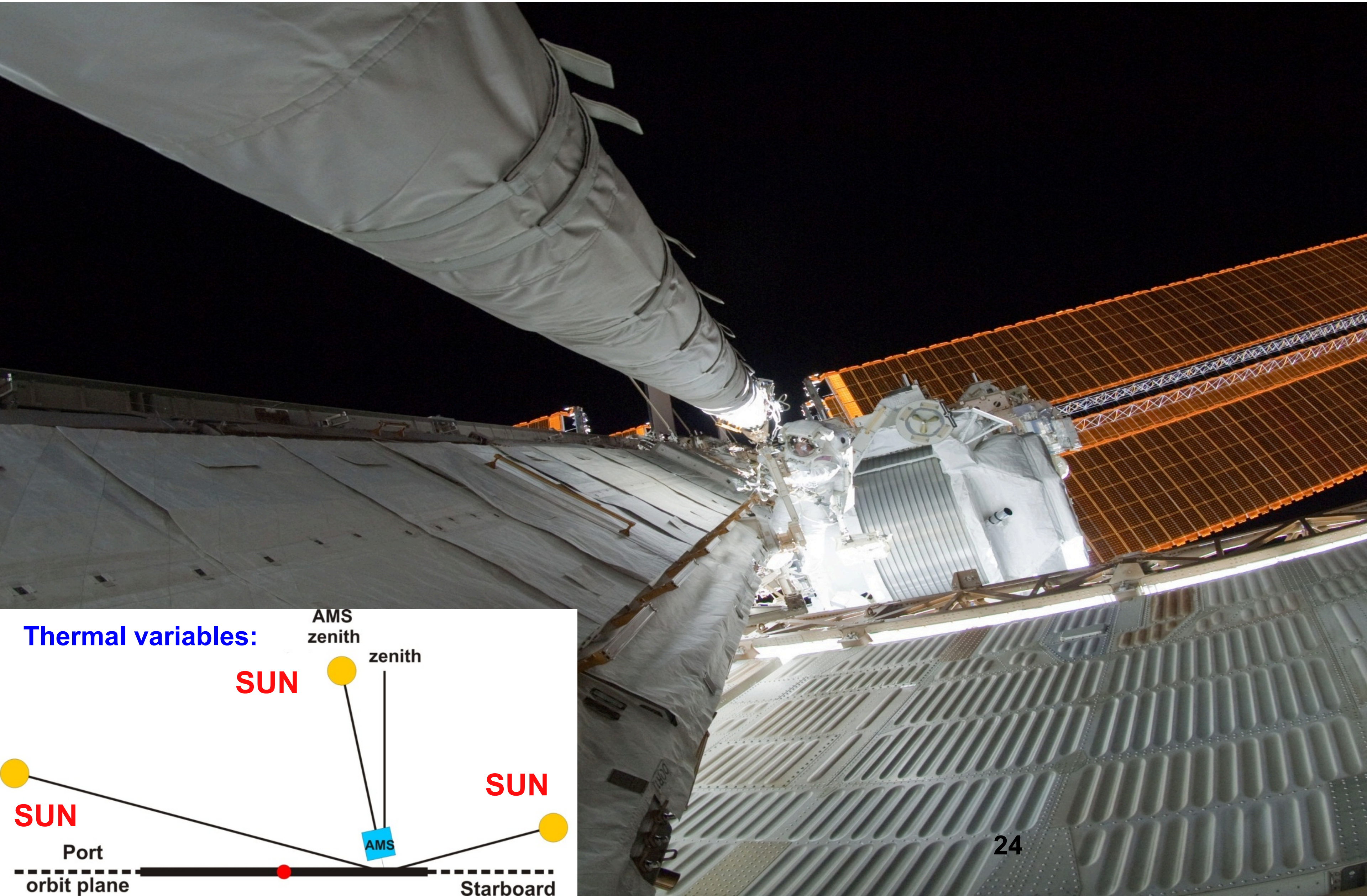




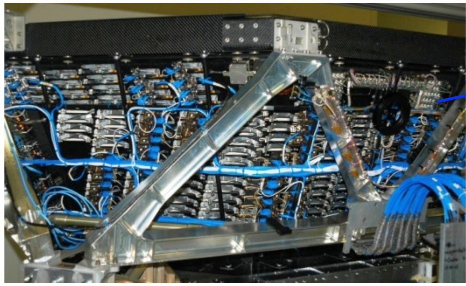

**Average life time fraction $T_{exp}$/3 years = 80.6 %**

# The Thermal environment

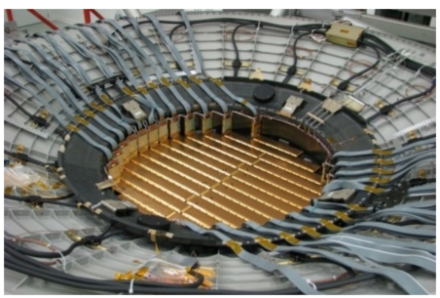


# AMS Flight Electronics for Thermal Control

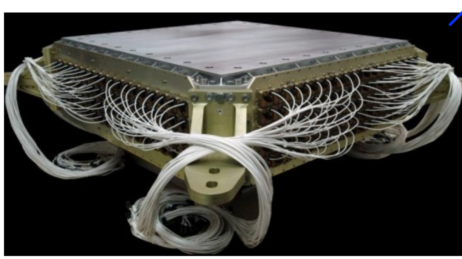
**TRD**
**24 Heaters**
**8 Pressure Sensors**
**482 Temperature Sensors**

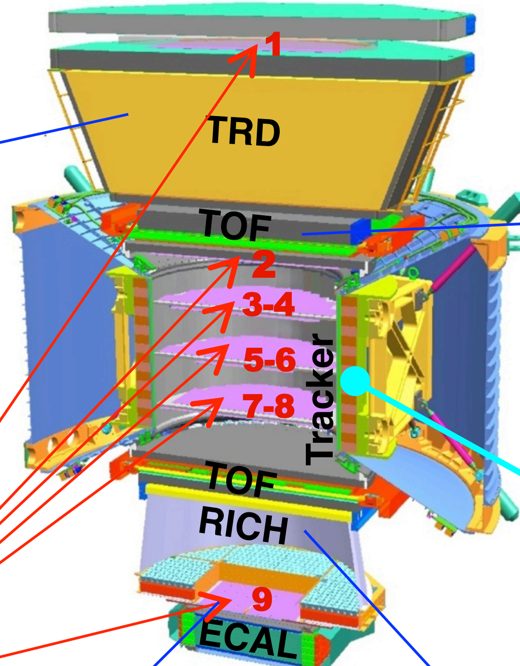


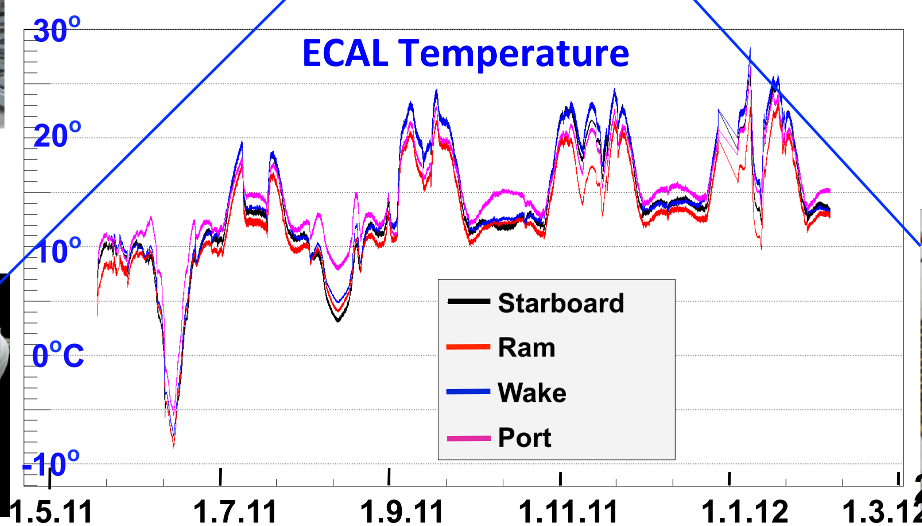
**Silicon Tracker**
**4 -Pressure Sensors**
**32 Heaters**
**142 Temperature Sensors**



**ECAL**
**80 Temperature Sensors**

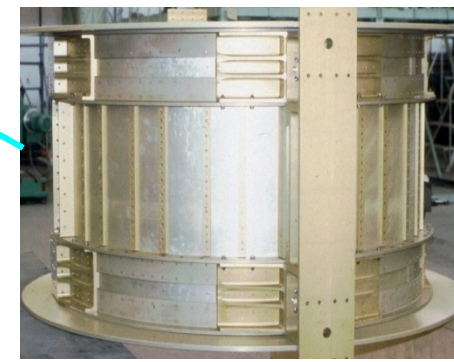





**TOF & ACC**
**64 Temperature Sensors**

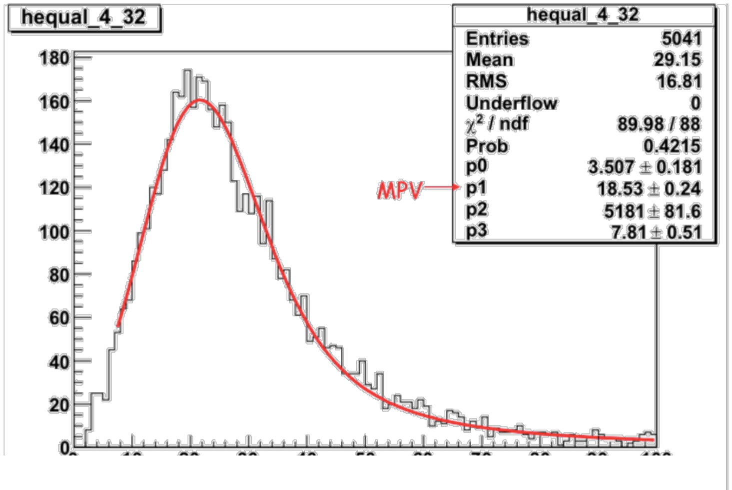
**Magnet**
**68 Temperature Sensors**

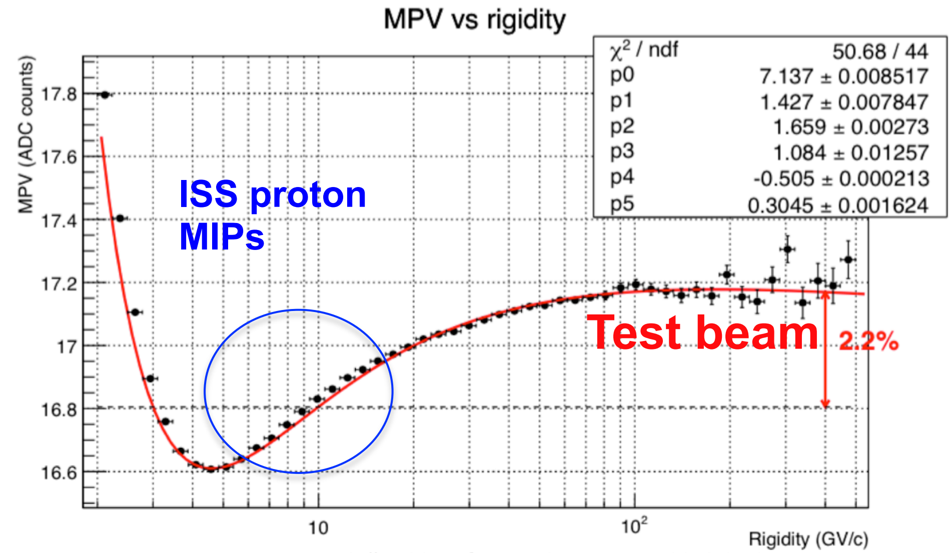


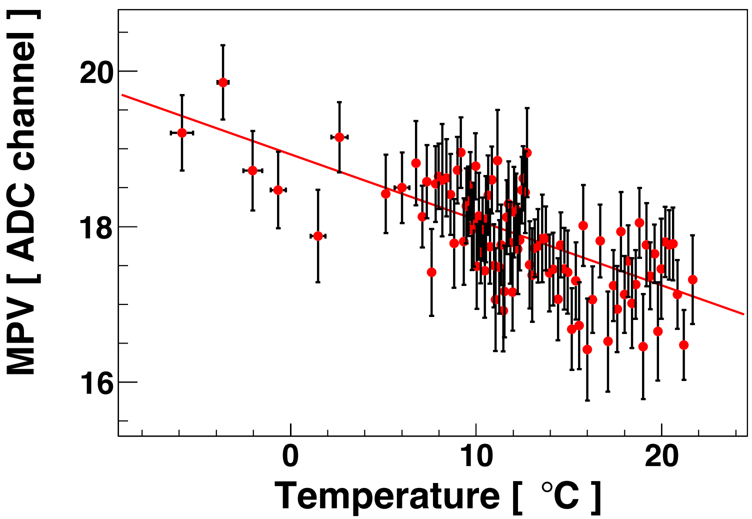
**RICH**
**96 Temperature Sensors**

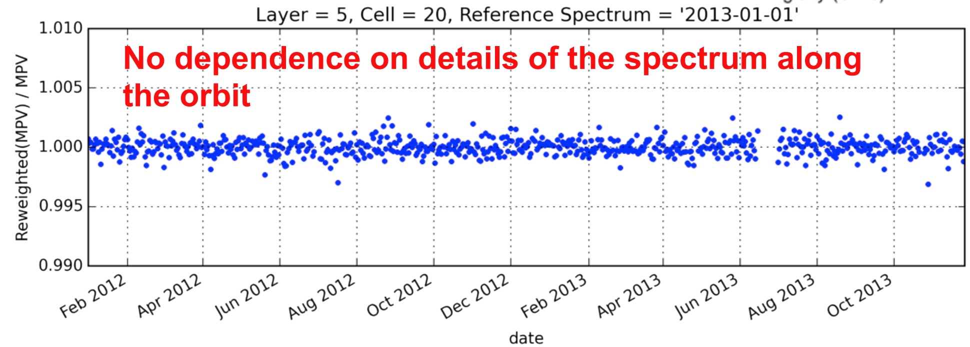
# Response depending on time/temperature :

## Equalization of the electronic gains → per cell → Daily with protons



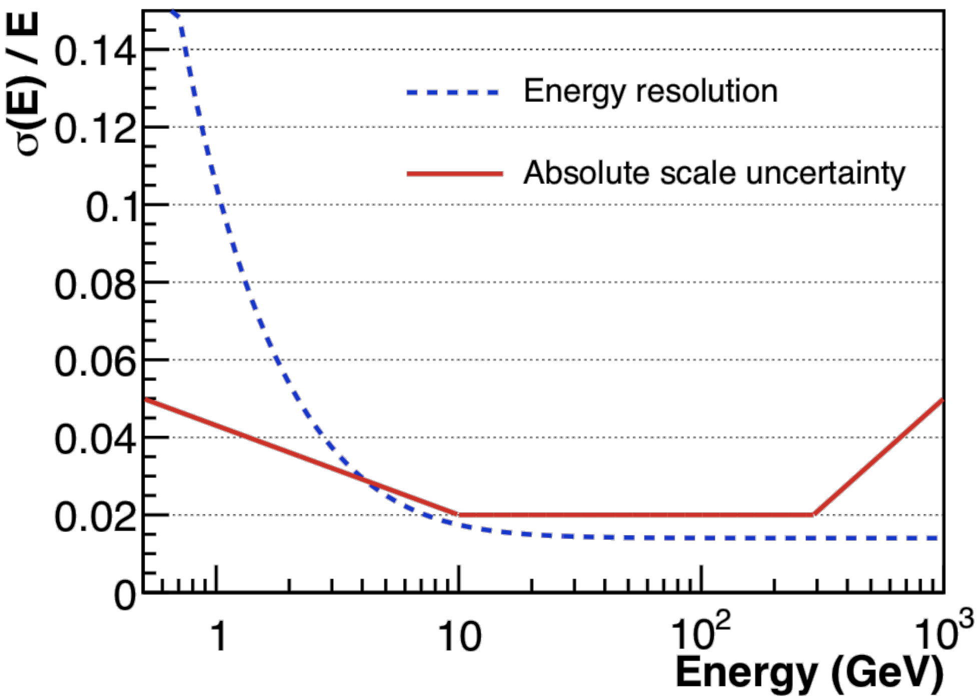



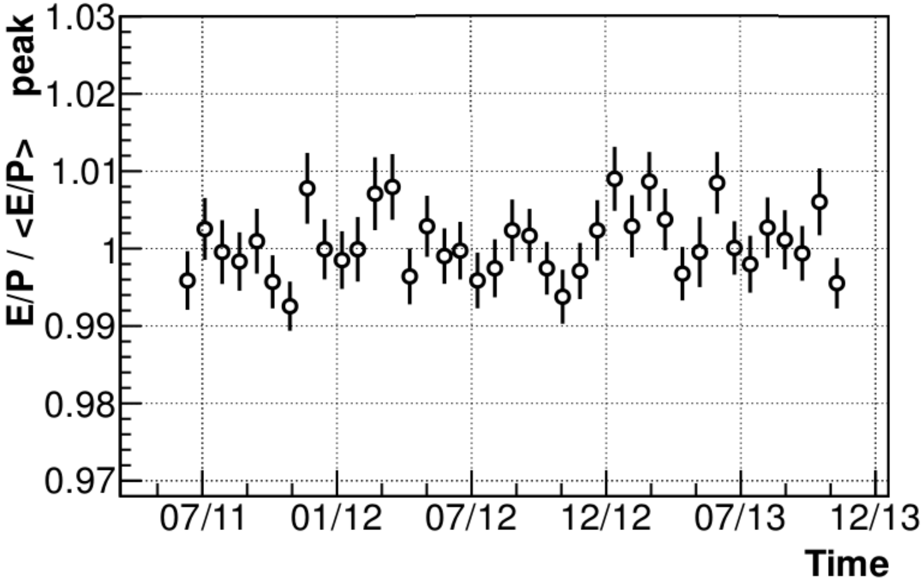




- **Normally, equalization in flight is performed with proton MIPs**
- **In 24h (= 16 orbits = 64 runs) ~2000 MIPs/day/cell**
- **Use He MIPs for problematic cells (3 days..)**

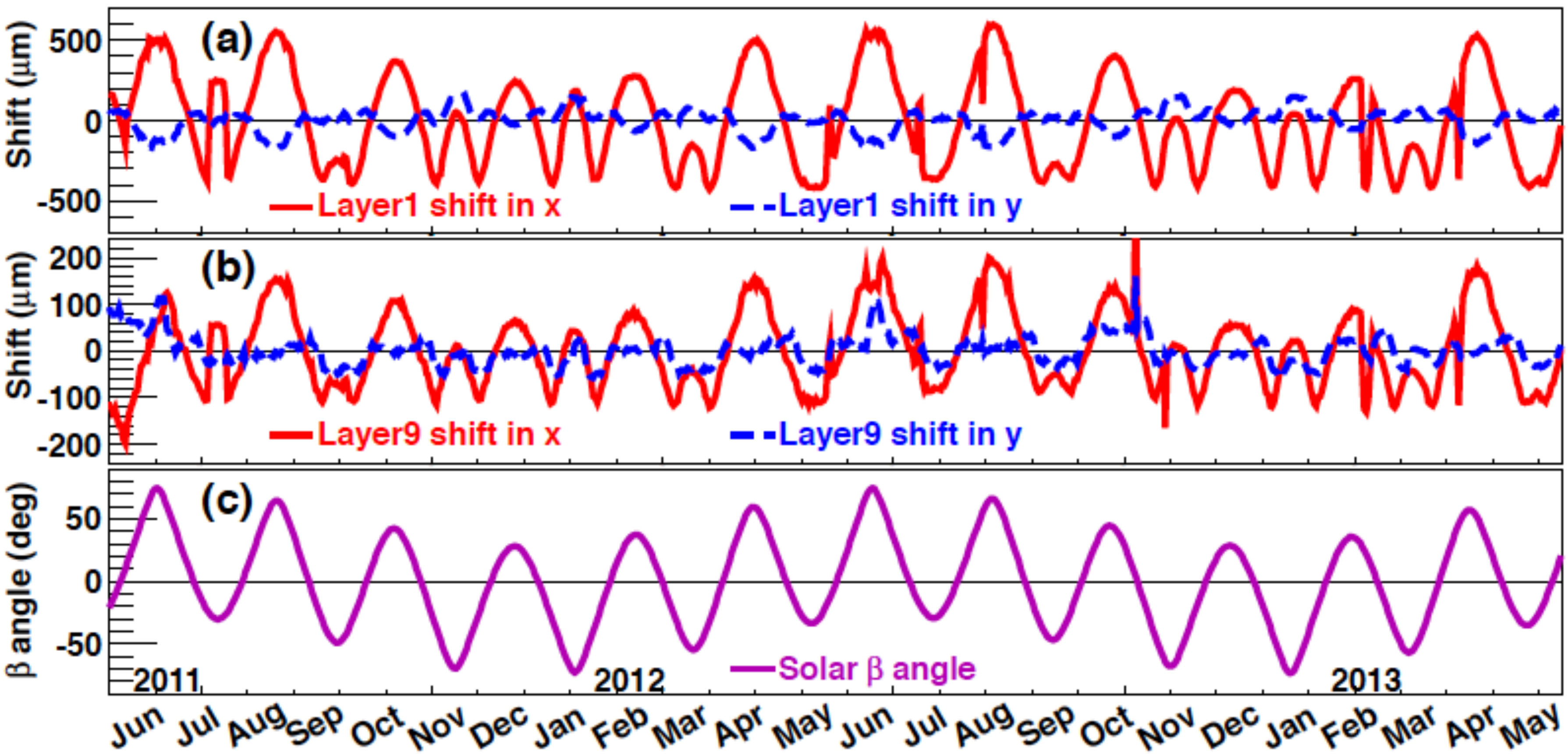
# Time independent behaviour after calibration:



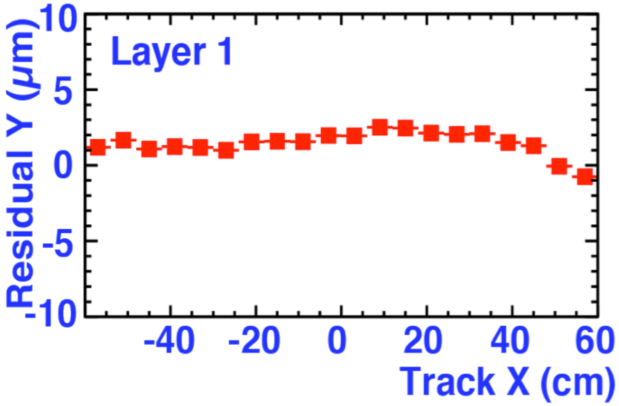



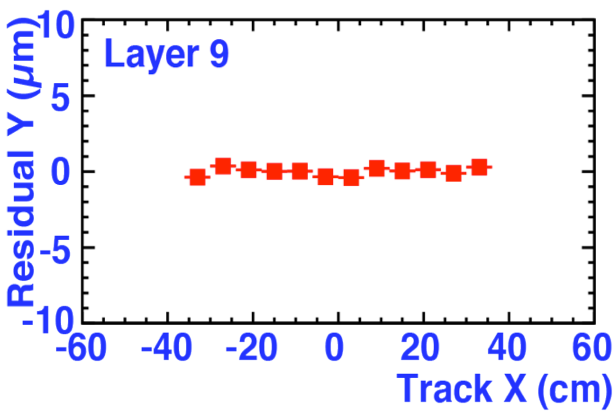

Energy scale & resolution used in e+/e- analyses
No time dependence within calibration accuracy
→ Still improving …

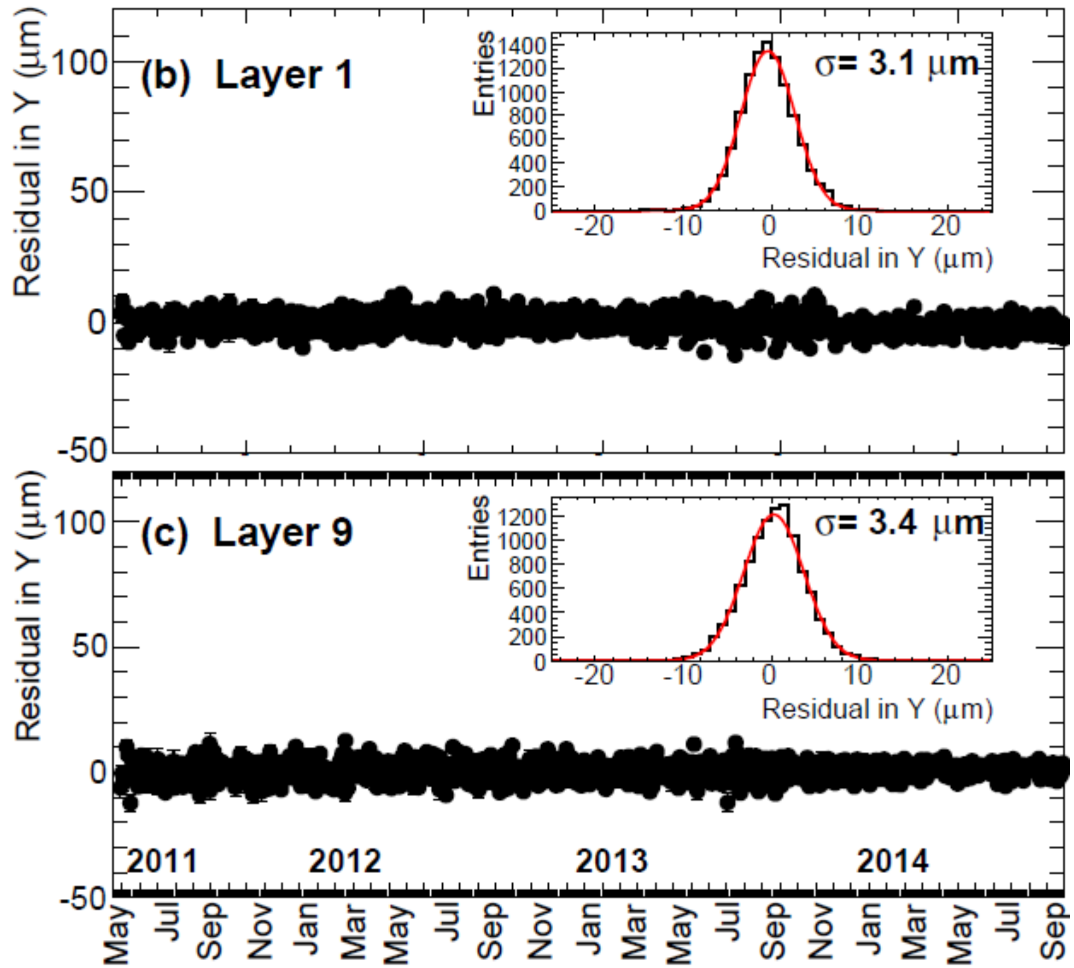
# Seasonal effects on Tracker



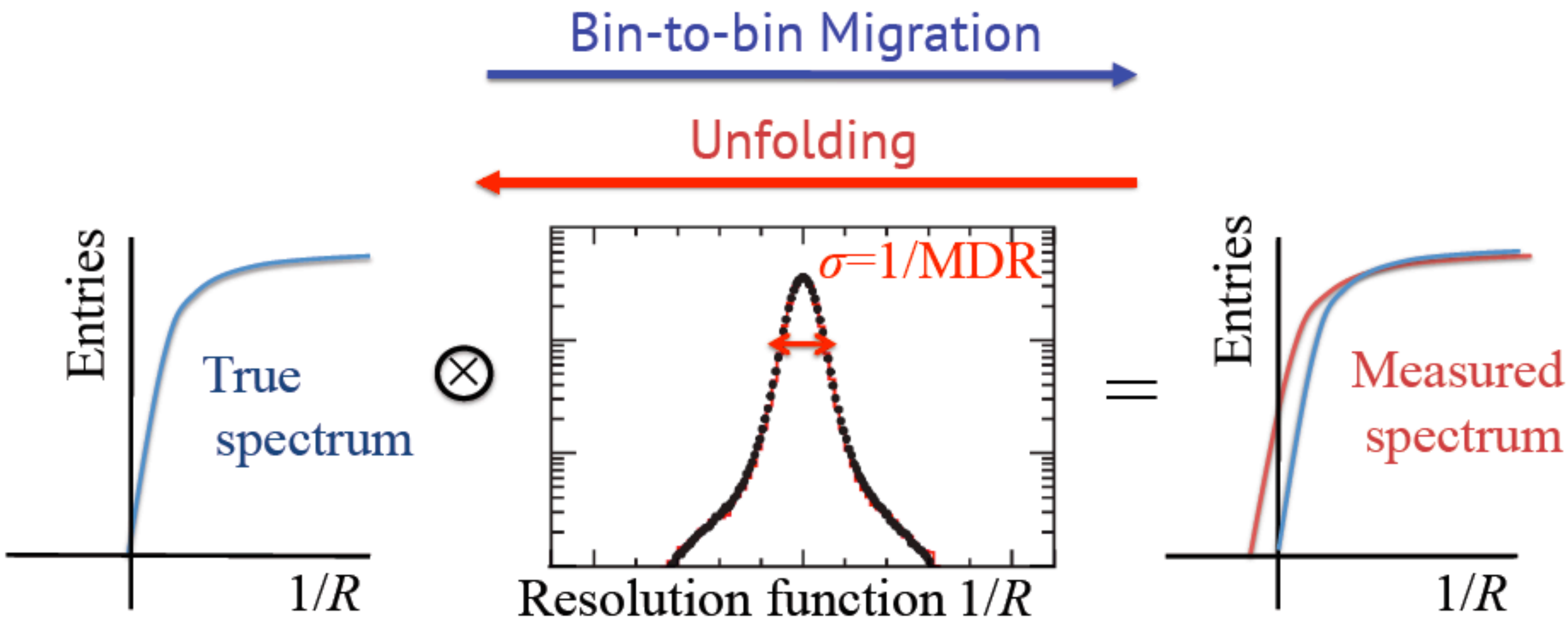
# Post-alignment accuracy



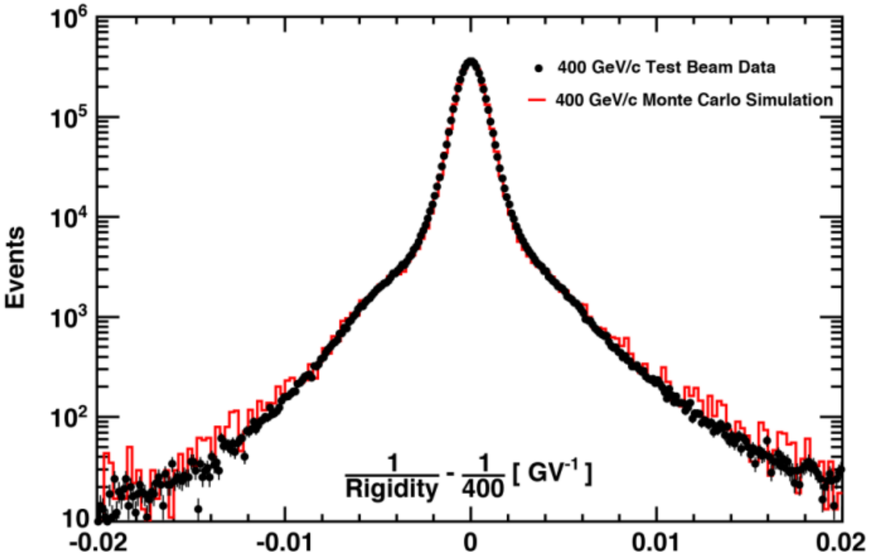
# Can we trust the alignment ?
# A key point for p, He, nuclear spectra…



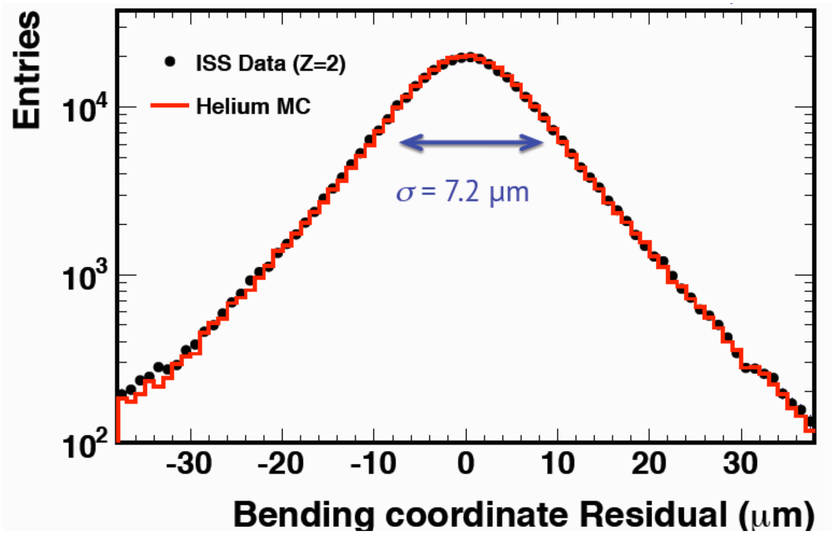

- **Tracker resolution**: verified from residual distributions (ISS-Data/TB for protons, ISS-Data/MC for p and nuclei)
- **Rigidity scale**: verified from E/R in $e^+/e^-$ samples
- *Consistency of flux results for different regions in the tracker*
- *Consistency of flux results for different lever arms in the tracker*

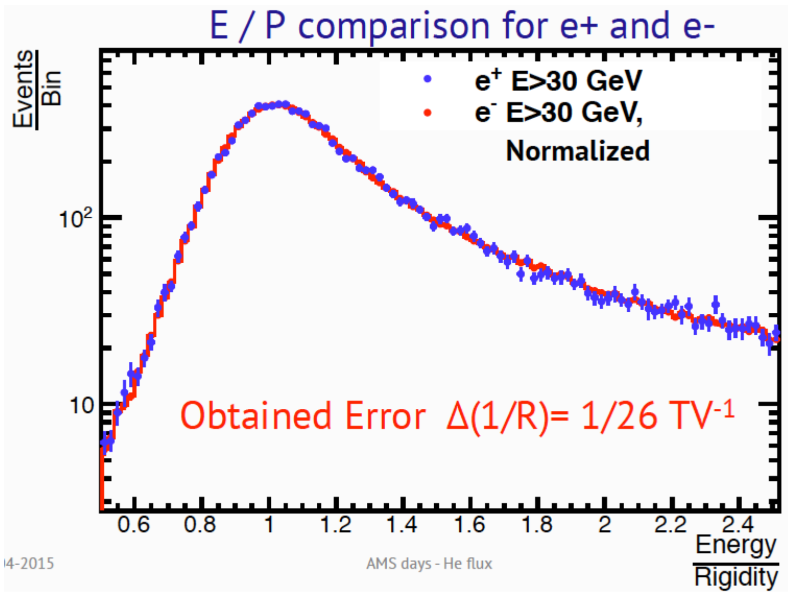
# Different kind of crosschecks...

## P - Data-beam test



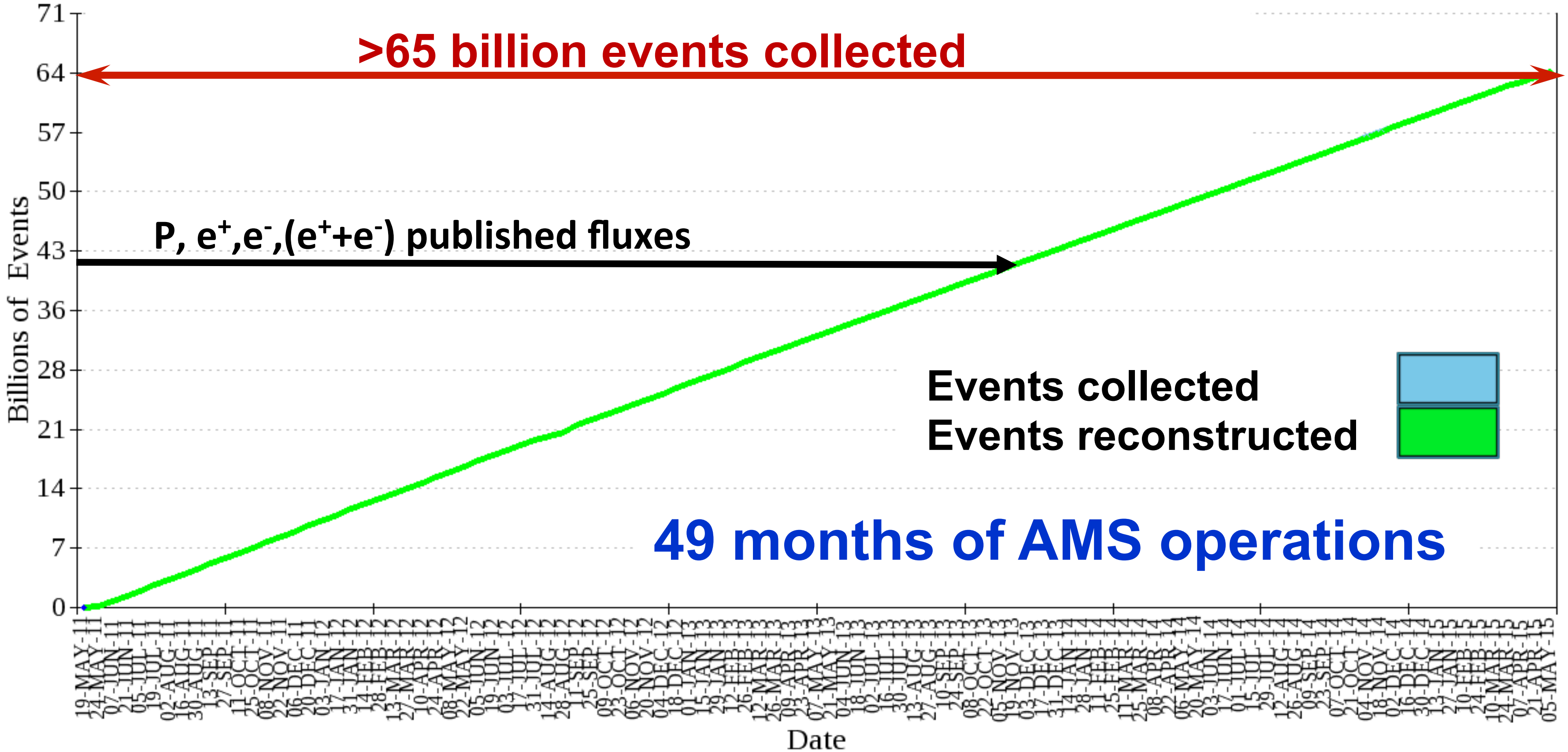

## He – ISS Data/MC



# Data analysis
# & Results

# Statistics



>65 billion events collected
P, e+,e-,(e++e-) published fluxes
Events collected
Events reconstructed
49 months of AMS operations
Billions of Events
Date
0
7
14
21
28
36
43
50
57
64
71

# Results

## "Rare" channels:

- ✓ Positron fraction $e^+/(e^+ + e^-)$ (0.5 GeV- 500 GeV)
  *PRL, 110, 141102 (2013), PRL 113, 121101 (2014)*
- ✓ $e^+$ (0.5-500 GeV) , $e^-$ flux (0.5 – 700 GeV)
  *PRL 113, 121102 (2014)*
- ✓ $e^+ + e^-$ flux (0.5-1 TeV)
  *PRL 113, 221102 , (2015)*

30 months of data
≈ $10^6$ $e^-$ / 5 $10^5$ $e^+$

- ✓ pbar/p (450 GV) [ status report]

40 months of data:≈ 290k pbar

## Nuclear components:

- ✓ Proton flux (1 GV – 1.8 TV)
  *PRL, 114, 171103 , (2015)*
- ✓ Helium flux (2GV -3TV, He/P ratio) [submission to PRL in the next weeks]

30 months of data
≈ 30 $10^7$ p / 5 $10^7$ He

- ✓ B,C,Li,O,…ongoing analyses

40 months of data
≈ 2 $10^6$ B / 7 $10^6$ C / 5 $10^5$ Li ..

## CR fluxes time dependence (solar modulation effects):

- ✓ Proton
- ✓ $e^+/e^-/e^+/(e^+ + e^-)$

…ongoing analyses

# Electron/Positron measurements

## *(simplified analysis flow..)*

**Step 1:**
**clean Z=1 event selection traversing all AMS**
**Step 2 :**
**efficient $e^{\pm}$ selection from the p background**
**Step 3 :**
**e+/e- separation (charge confusion effects)**
**Step 4 :**
**Normalization: acceptance and energy resolution effects**

**A minimum of two independent analyses (yes data and detector are the same !) carried in parallel as internal crosscheck before data release.**

# Step 1: clean Z=1 event selection traversing all AMS

**DAQ:**
- efficient data periods (no SAA, TRD gas refills, AMS z-axis more than 40° w.r.t. local zenith)

**Geomagnetic effects:**

E>1.20 max geomagnetic cutoff

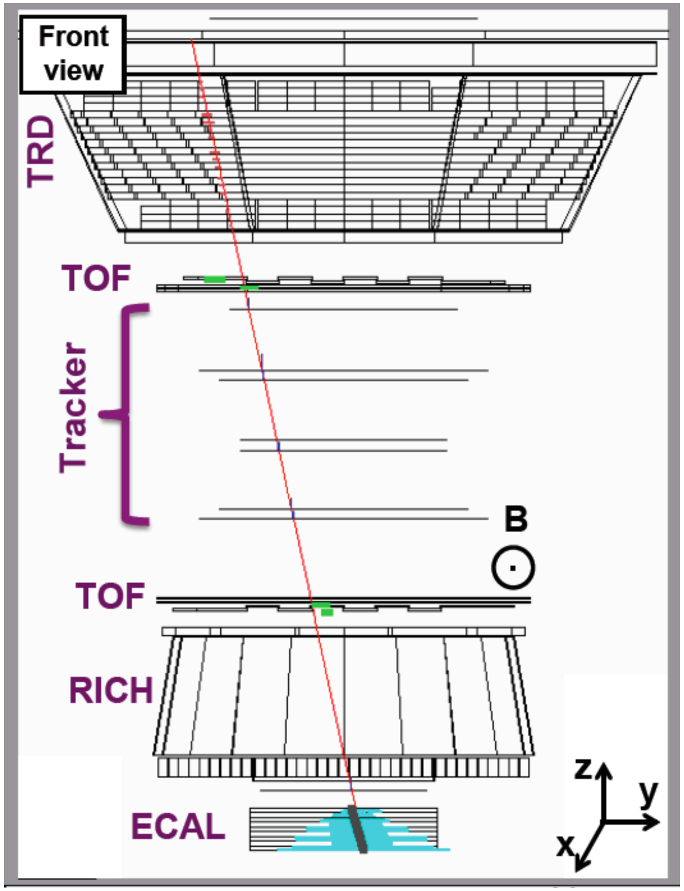
**TRD:**
- Minimum 8 hits used for e/p identification
- |Z| = 1

**TOF:**
- relativistic down-going particle (β>0.83)

**TRACKER:**
- |Z| = 1
- track/ECAL matching to define fiducial volume

**ECAL:**
- Shower axis within the fiducial volume
- Not MIP in the first $5X_0$
- Electromagnetic shape of the shower (ECAL estimator)

**600 GeV electron**



# Step 2: efficient $e^{\pm}$ selection from p background

a) Define a clean sample of electrons/protons based on Tracker/ ECAL detectors in order to study the TRD signals for electrons/ protons

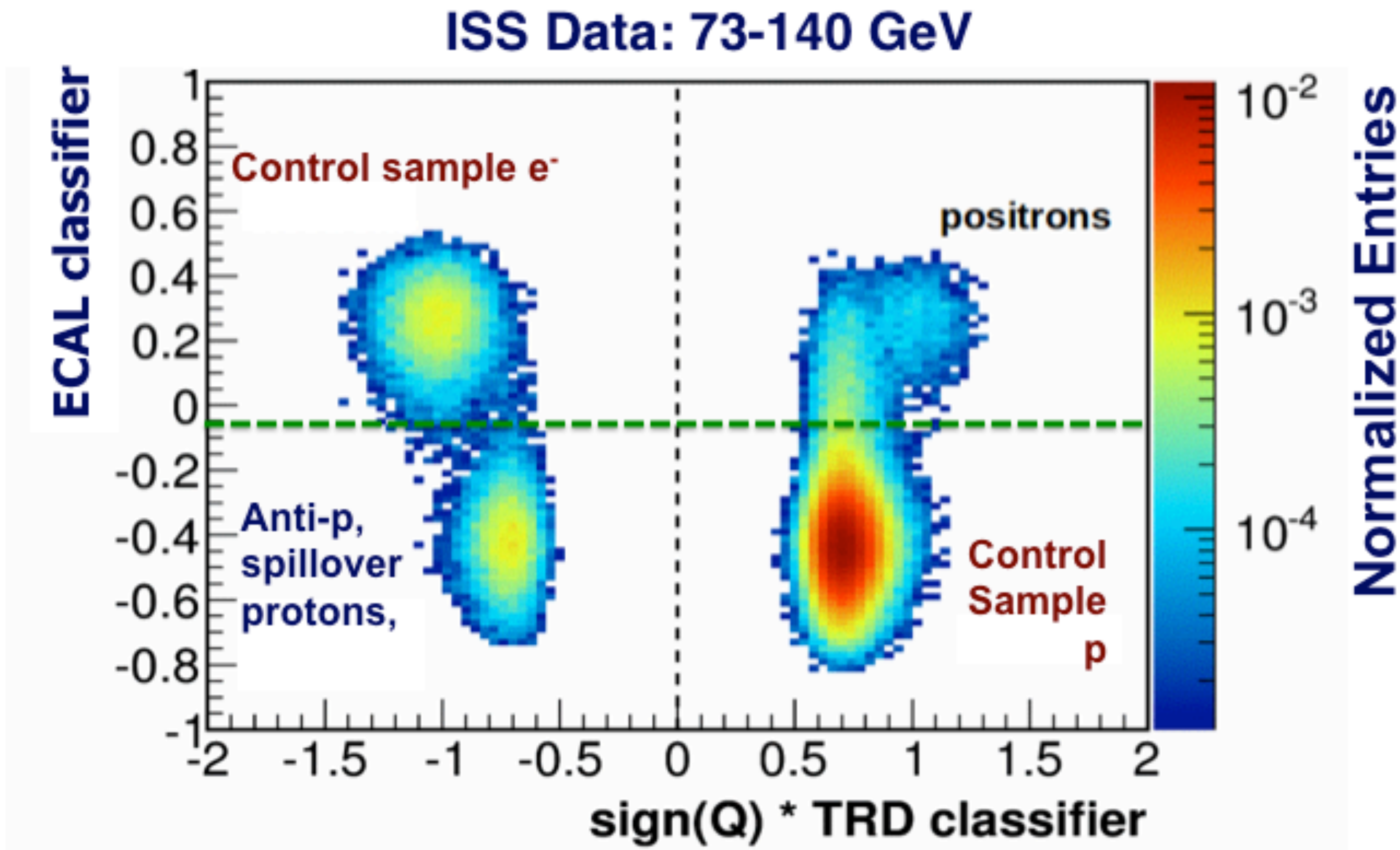
b) Define a clean sample of electron/protons based on TRD/Tracker detectors in order to study the ECAL signals for electrons/protons

c) Efficiently select a sample of ISS data enriched in ($e^{+}$+$e^{-}$) signal based on ECAL

d) Measure the number of $e^{+}$/$e^{-}$ by a fit of the TRD classifier distribution of the selected sample to the reference distributions in TRD for signal and background

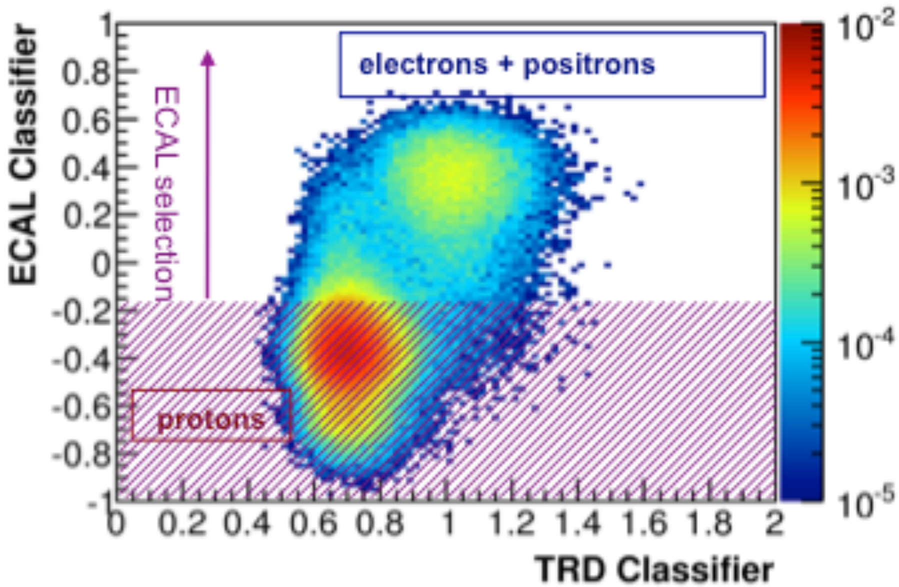
*Following examples from $e^{+}$+ $e^{-}$ measurement, but similar logic in other measurements: each analysis has its own optimization.*

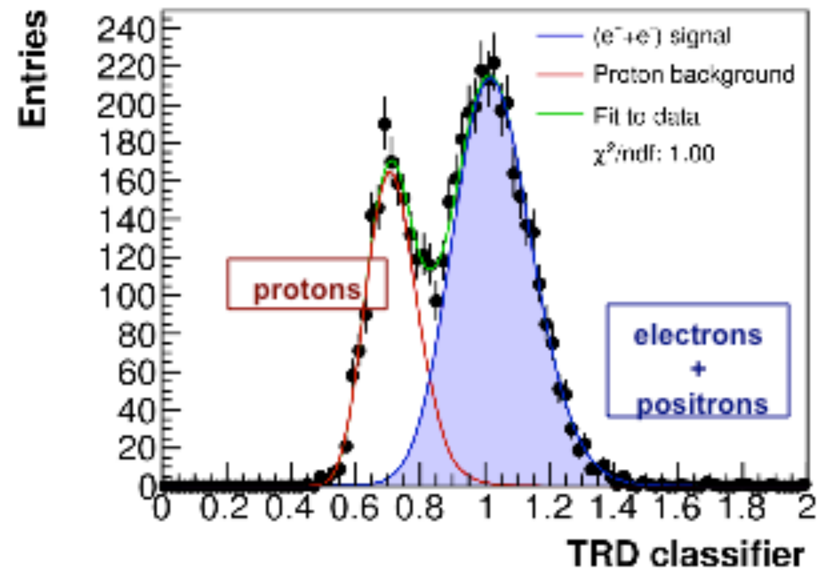
# Step 2: e/p separation : ($e^{+}+e^{-}$) flux measurement



# Step 2: e/p separation : ($e^{+}$+$e^{-}$) flux measurement

**Reference spectra for the signal and the background are fitted to data as a function of the TRD classifier for different cuts on the ECAL BDT estimator**



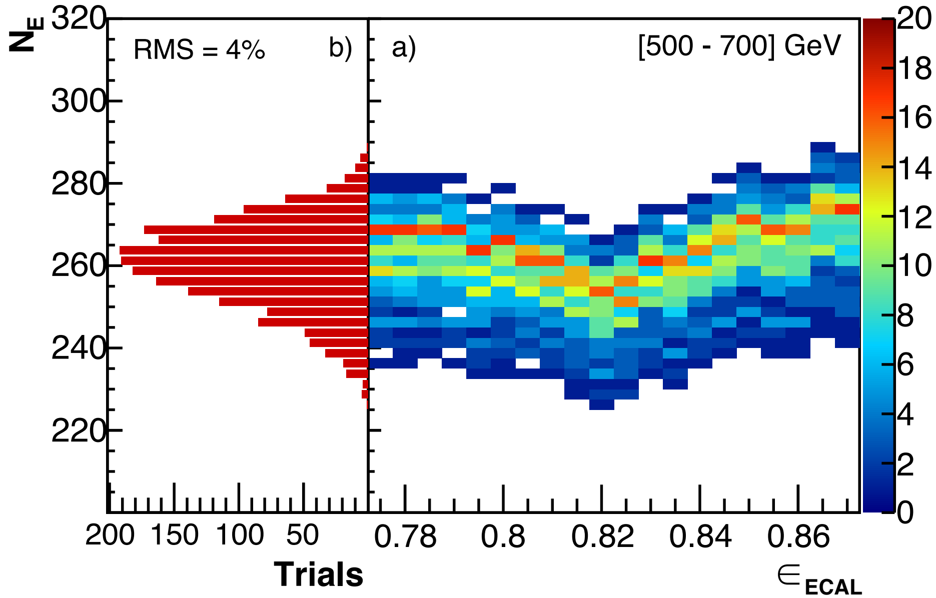




**Measurement is performed for the cut on the ECAL classifier that minimizes the overall statistical + systematic uncertainty ( → $\varepsilon_{BDT}$)**

# Step 2: e/p separation : ($e^+ + e^-$) flux measurement

Dominating systematic uncertainties on $N_{e^+ + e^-}$

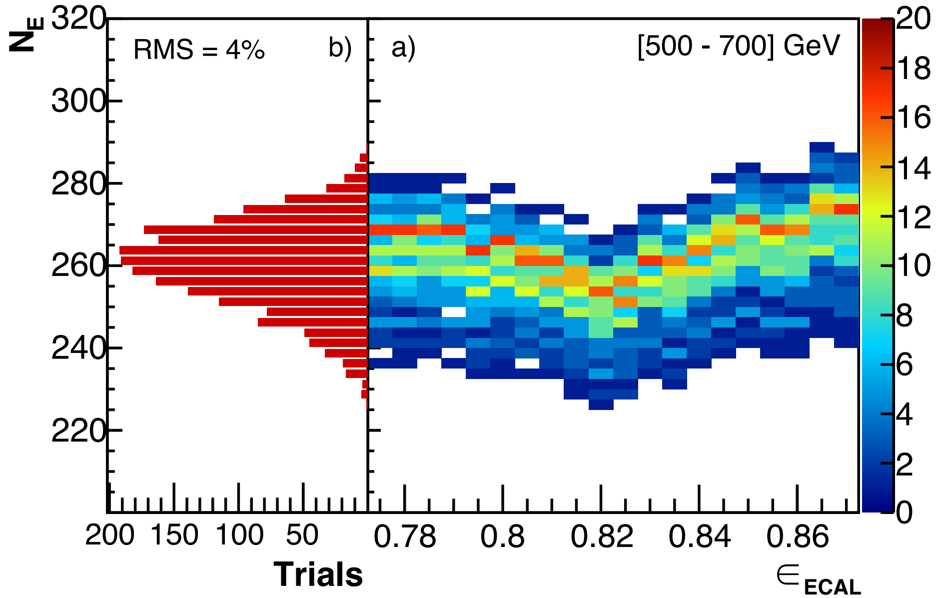
- Knowledge of the TRD reference distributions
- Stability of the fit result for different background levels, e.g. ECAL classifier cuts




**The analysis was repeated 2000 times in each energy bin varying the ECAL classifier cut and different values of selection cuts used to construct the templates and the stability of the results verified within a 5% window in ECAL classifier cut efficiency**

# Step 2: e/p separation : ($e^{+}$+$e^{-}$) flux measurement

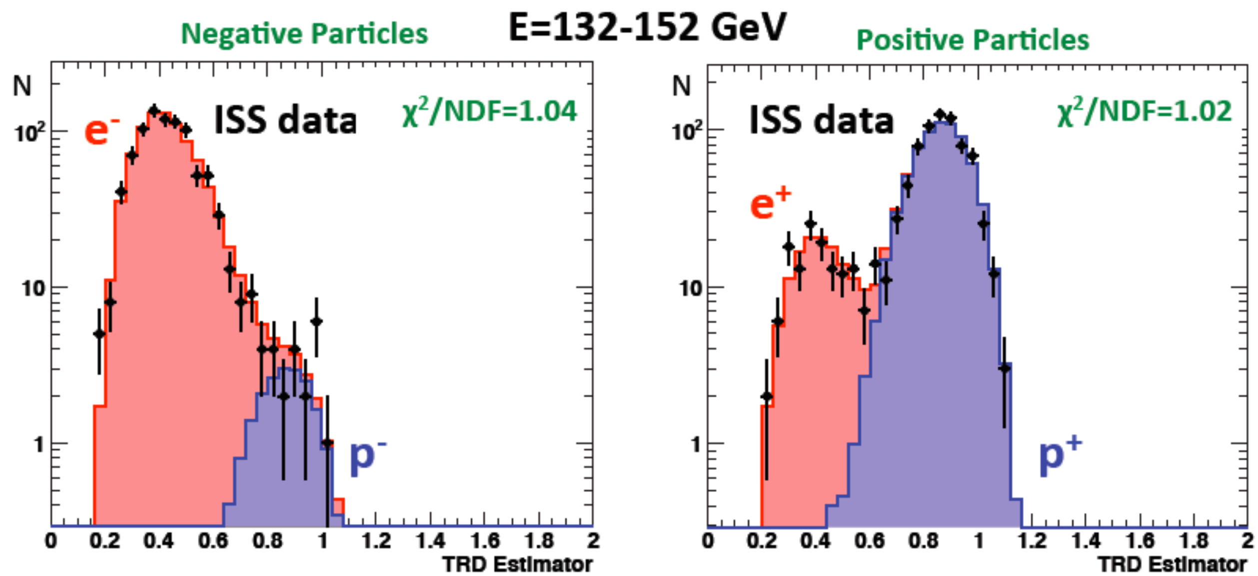
The RMS of the $N_e$ as been used as systematics uncertainty, the effect of purely statistical contributions were taken into account and subtracted estimated from a dedicated simulation.



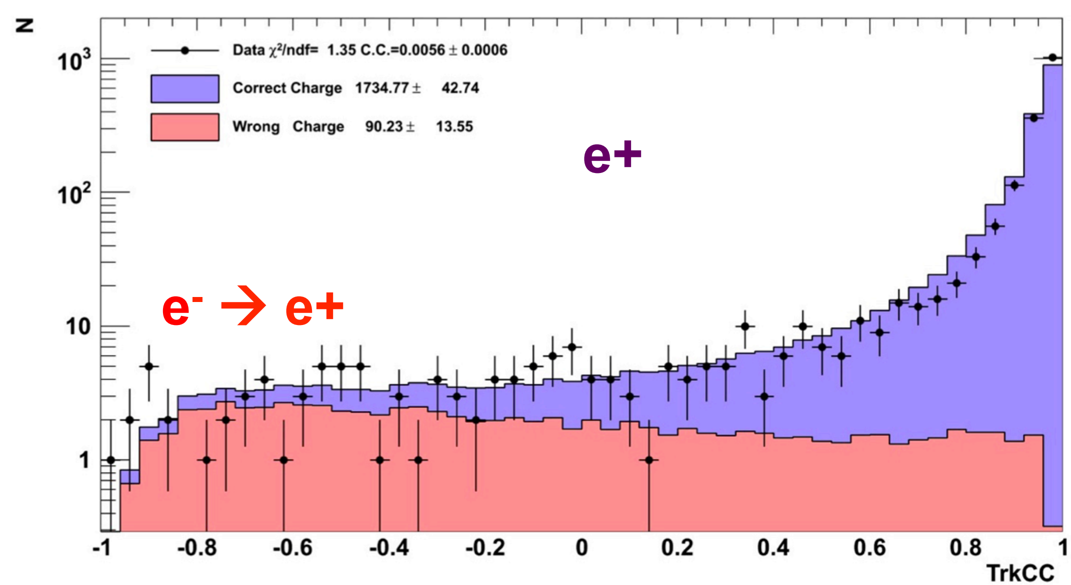

**Negligible contribution to the measurement error below ≈ 200 GeV**
**Dominant source of systematic error at higher energies (> 500 GeV)**

# e+/e- fluxes

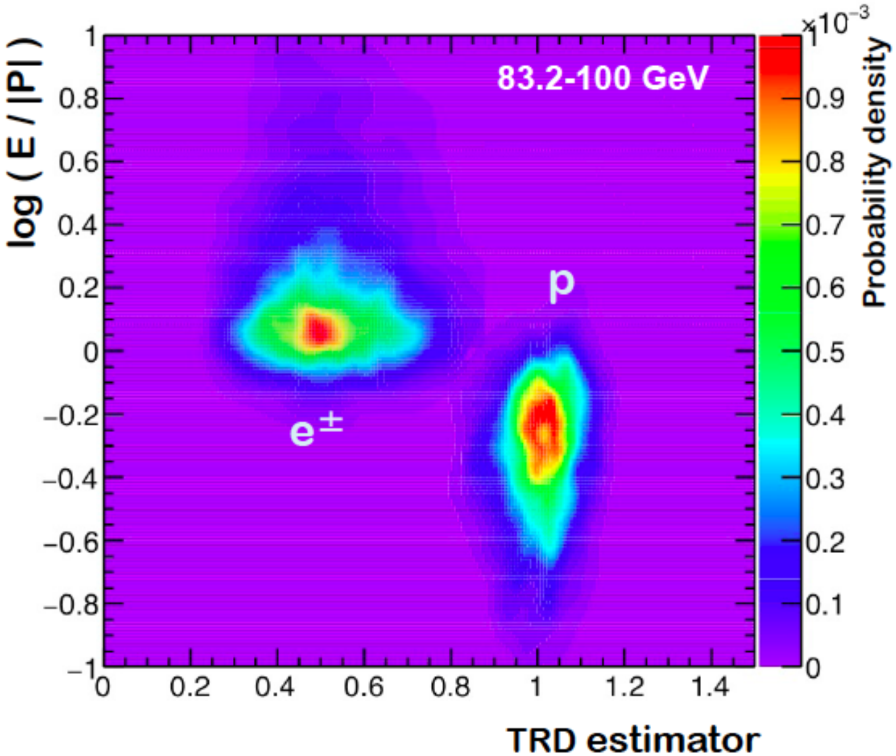
**Step 2: separate e± with a fit to reference e/p distribution in TRD Estimator**

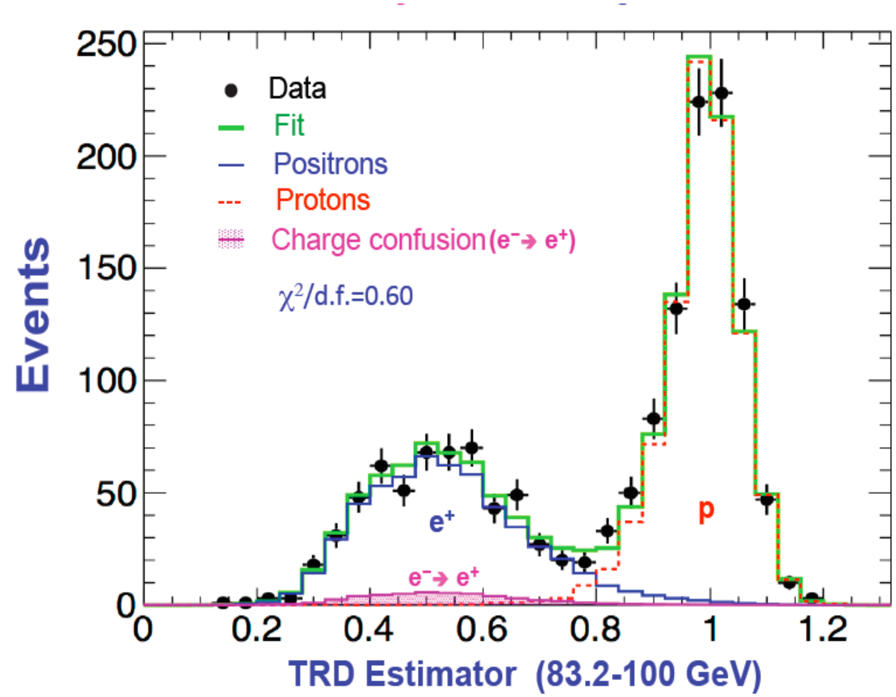


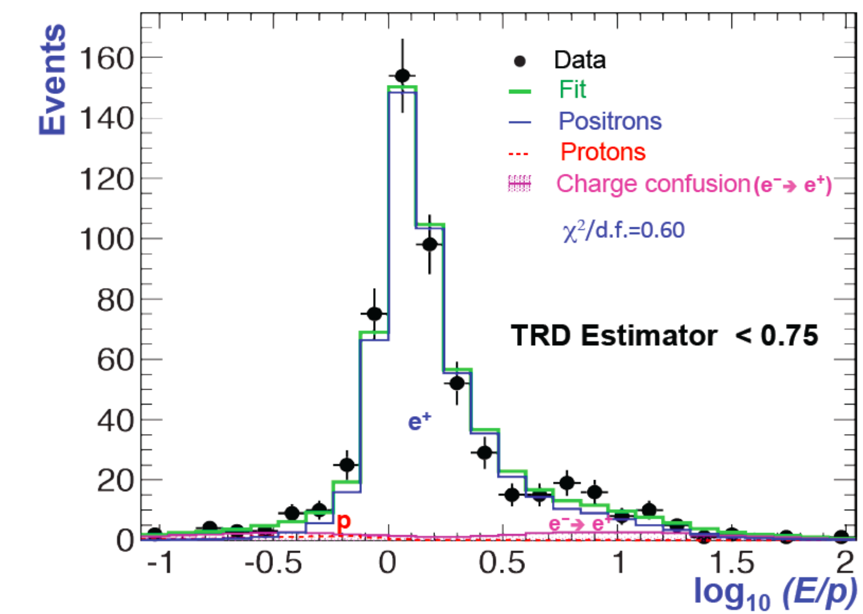

**Step 3: Define a TrkCC estimator by means of a BDT based on track quality parameters & activity in the detector: extract charge confused events from fit of ISS data to reference distribution for good and cc events**



# Positron fraction




**Number of Charge confused events evaluated taking reference distribution of interacting events in log(E/P) – TRD plane and leaving background events to fluctuate within their statistical uncertainty.**

# Step 4: normalization and acceptance effects

**Flux** $$\mathbf{\Phi}(E, E+\Delta E) = \frac{\mathbf{N}(E, E+\Delta E)}{\mathbf{A}(E)\epsilon_{trig}\mathbf{T}(E)\mathbf{\Delta E}}$$

**$e^-/e^+/(e^++e^-)$ fluxes**:

trigger efficiency measured from data

Acceptance: $A_{eff}(E) = A_{geom} \times \epsilon_{sel} \times (1+\delta)$

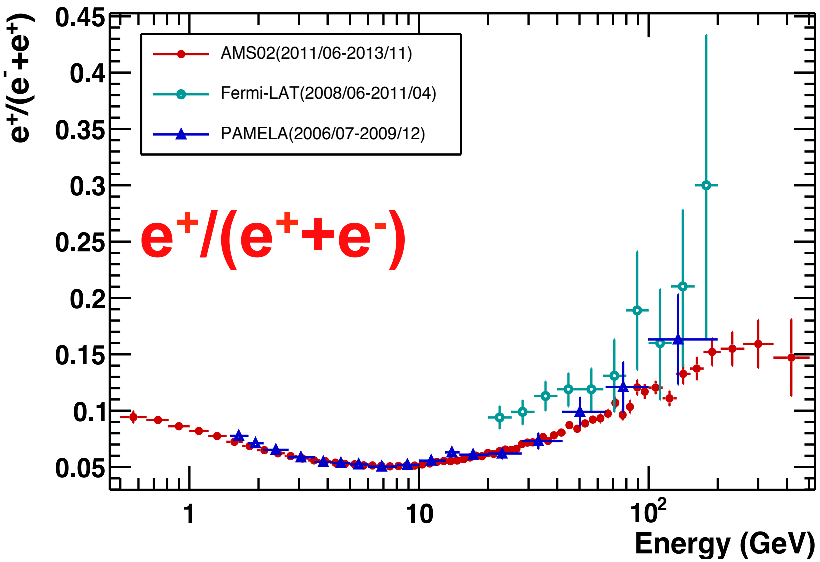
- Ageom: geometrical acceptance from MC
- $\varepsilon_{sel}$ : selection efficiency from MC
- $(1+\delta)$ : correction coming from ISS/MC selection efficiency comparison .

**Positron Fraction** $$\frac{\phi(\mathbf{e}^+)}{\phi(\mathbf{e}^-)+\phi(\mathbf{e}^-)} = \frac{\mathbf{N_{e^+}}}{\mathbf{N_{e^+}} + \mathbf{N_{e^-}}\frac{\mathbf{A_{e^-}}}{\mathbf{A_{e^+}}}}$$

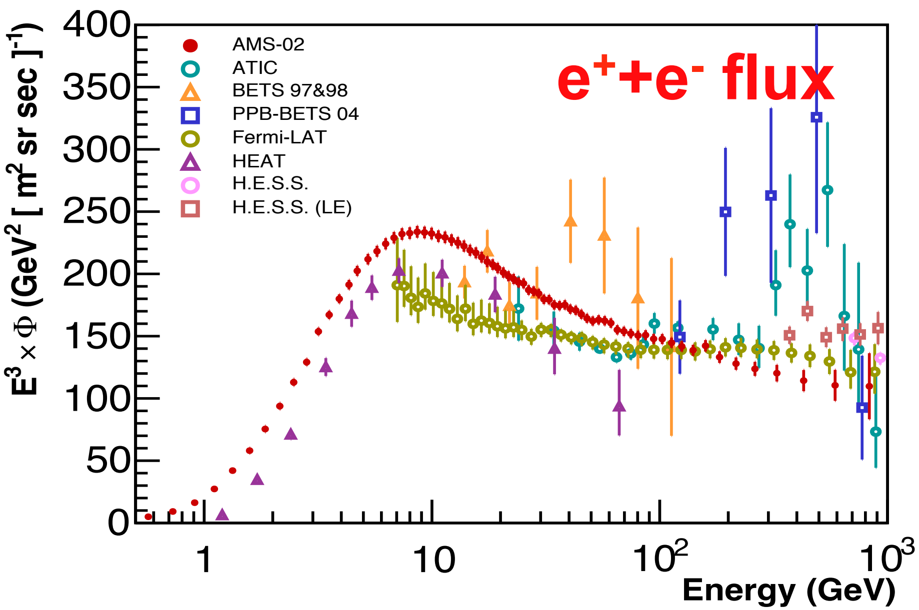
only e+/e- acceptance ratio matters, small asymmetry at low energy

**Energy resolution effects**: binning optimized to have a small effect below few GeV, minor source of uncertainty.

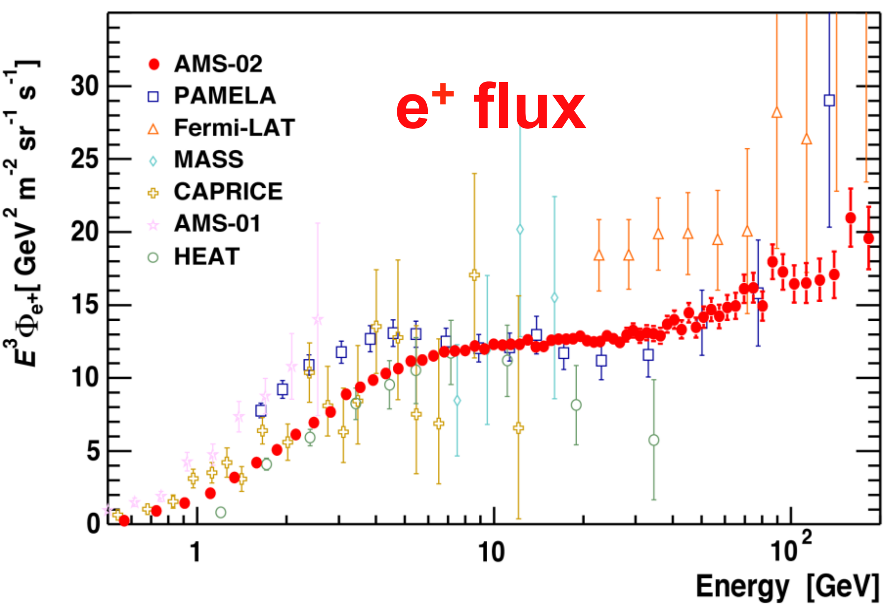
# Results



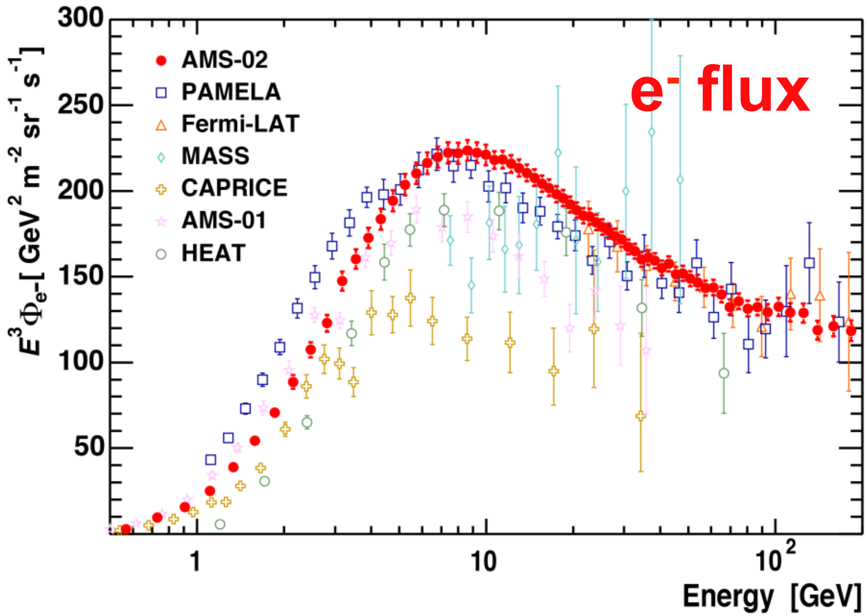
e+/(e-+e+)
AMS02(2011/06-2013/11)
Fermi-LAT(2008/06-2011/04)
PAMELA(2006/07-2009/12)
e+/(e++e-)
Energy (GeV)

AMS-02
ATIC
BETS 97&98
PPB-BETS 04
Fermi-LAT
HEAT
H.E.S.S.
H.E.S.S. (LE)
e++e- flux
E3 × Φ (GeV2 [ m2 sr sec ]-1)
Energy (GeV)

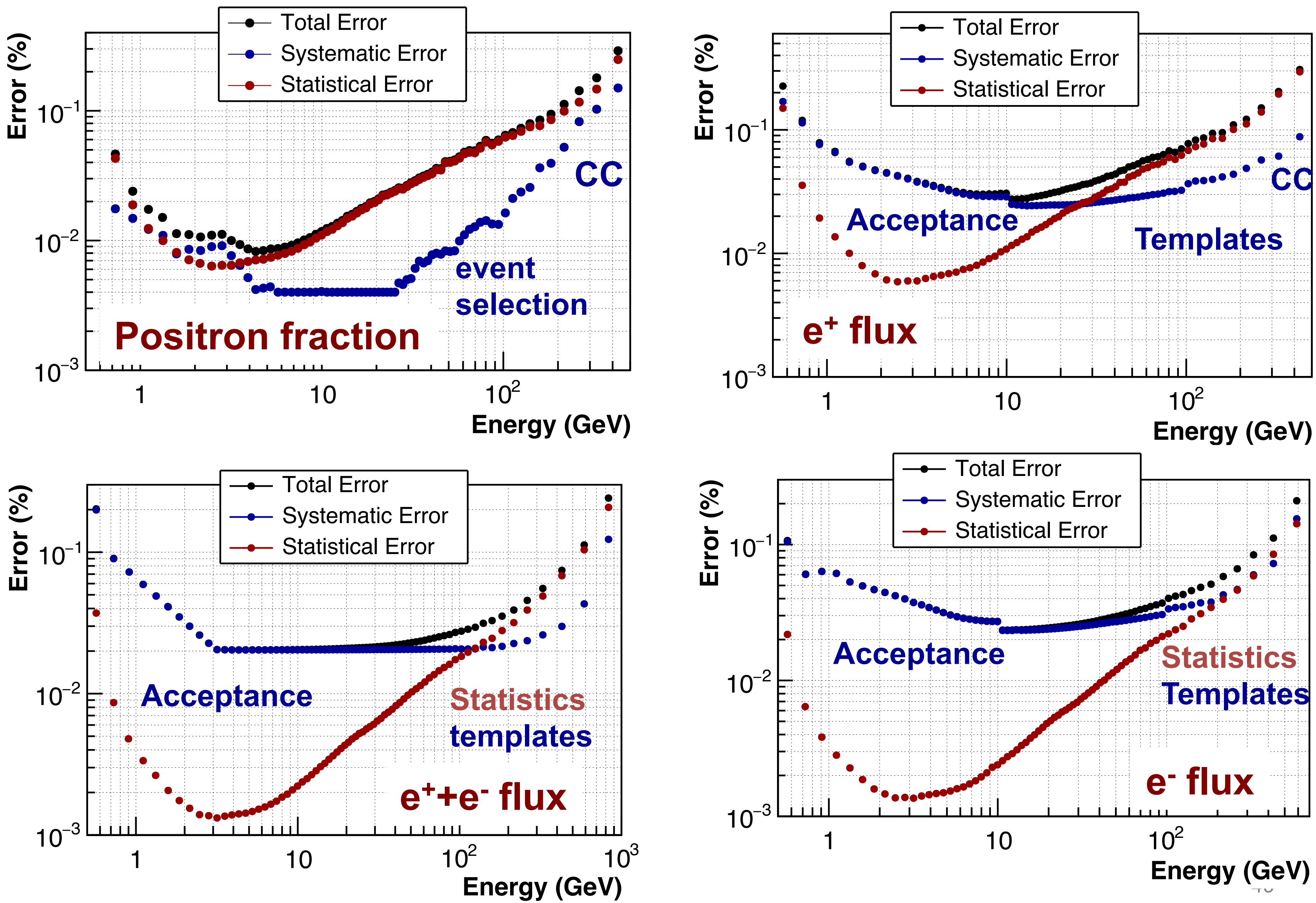



AMS-02
PAMELA
Fermi-LAT
MASS
CAPRICE
AMS-01
HEAT
e+ flux
E3Φe+[ GeV2 m-2 sr-1 s-1]
Energy [GeV]

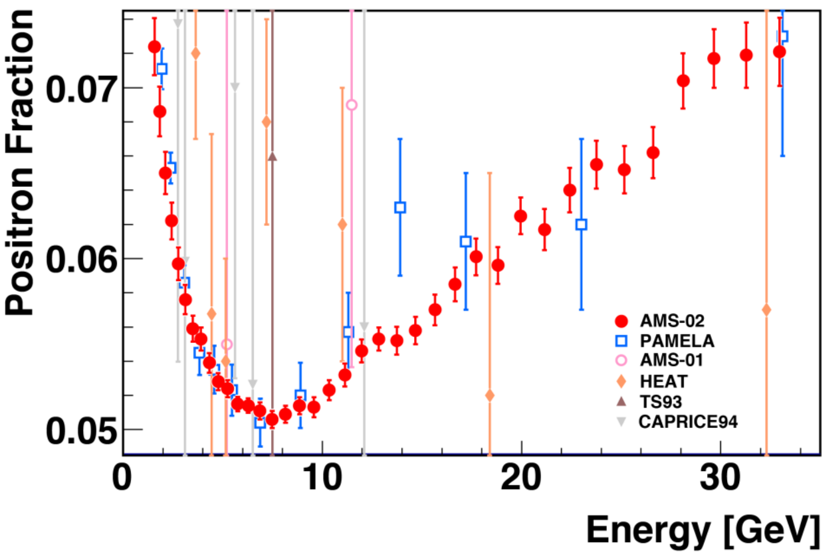



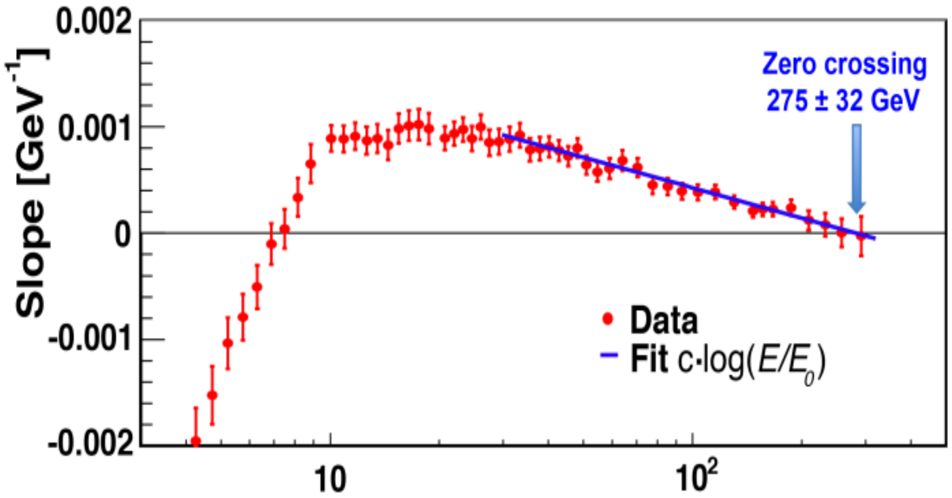
AMS-02
PAMELA
Fermi-LAT
MASS
CAPRICE
AMS-01
HEAT
e- flux
E3Φe-[ GeV2 m-2 sr-1 s-1]
Energy [GeV]

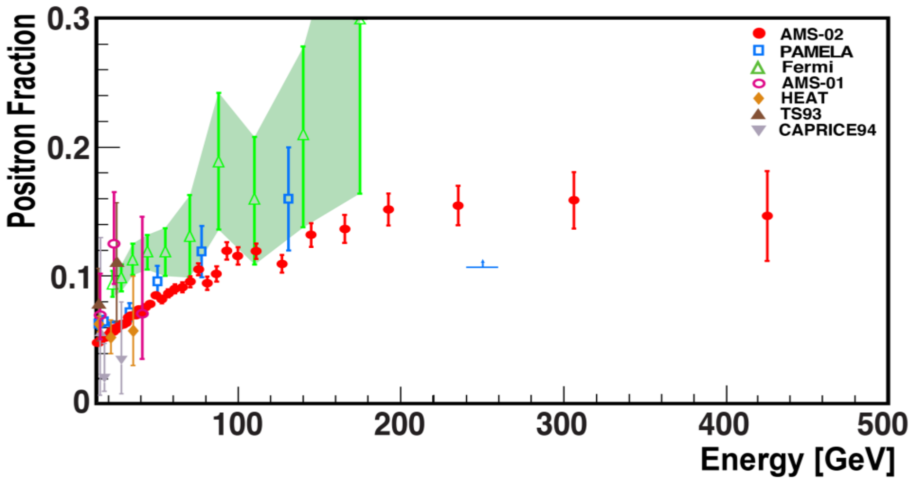
# Measurement errors

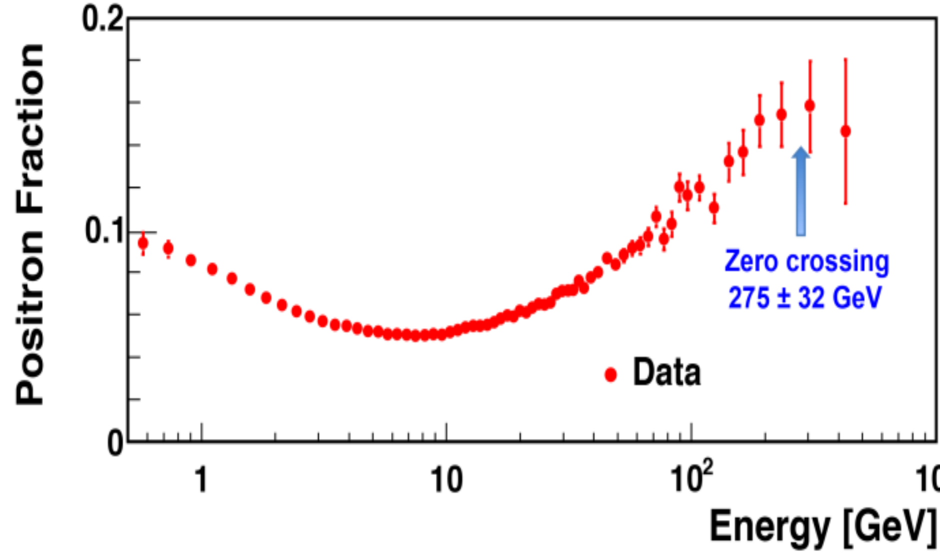


# Positron fraction

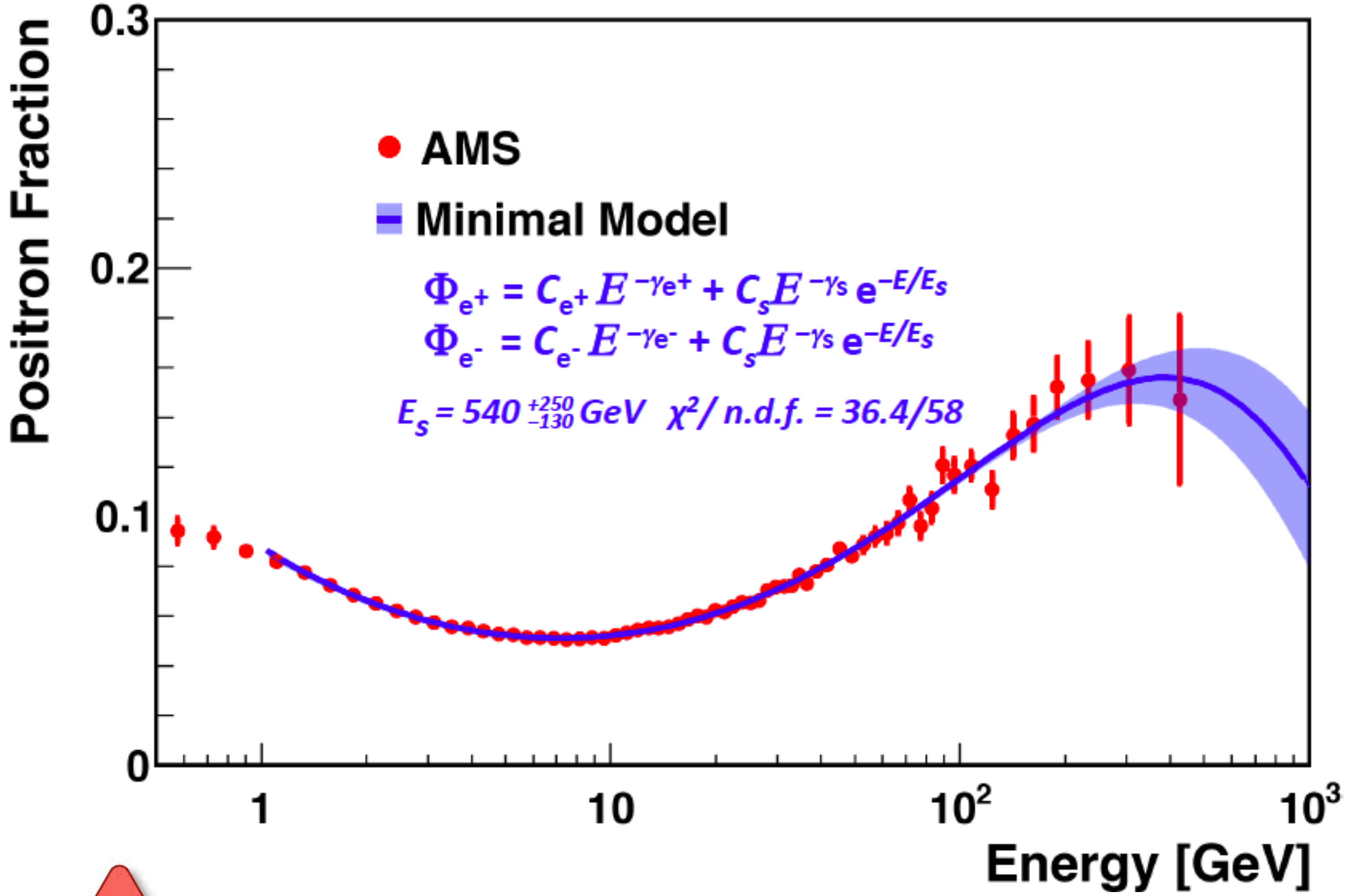


# Effective description of data..

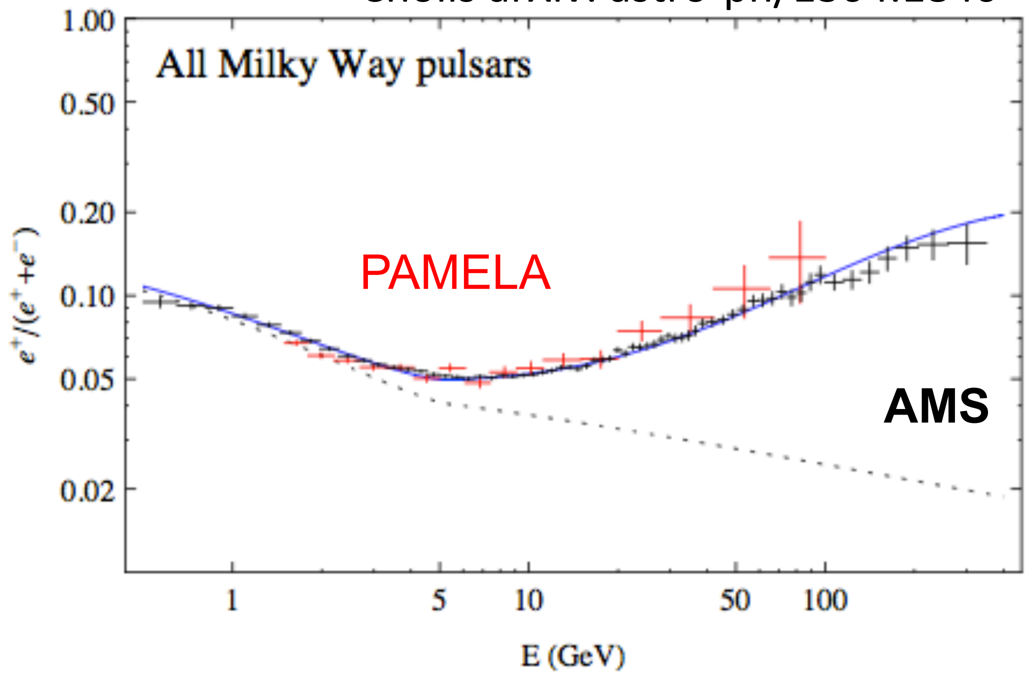



**IT IS NOT A REAL MODEL !**

# What is AMS observing?

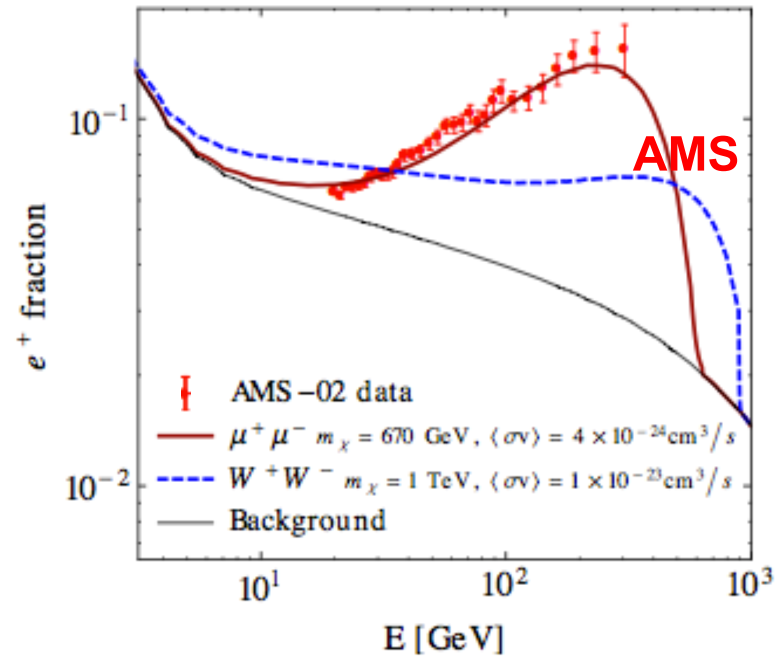
## Astrophysical objects

Cholis arXiv: astro-ph/1304.1840




## Dark Matter

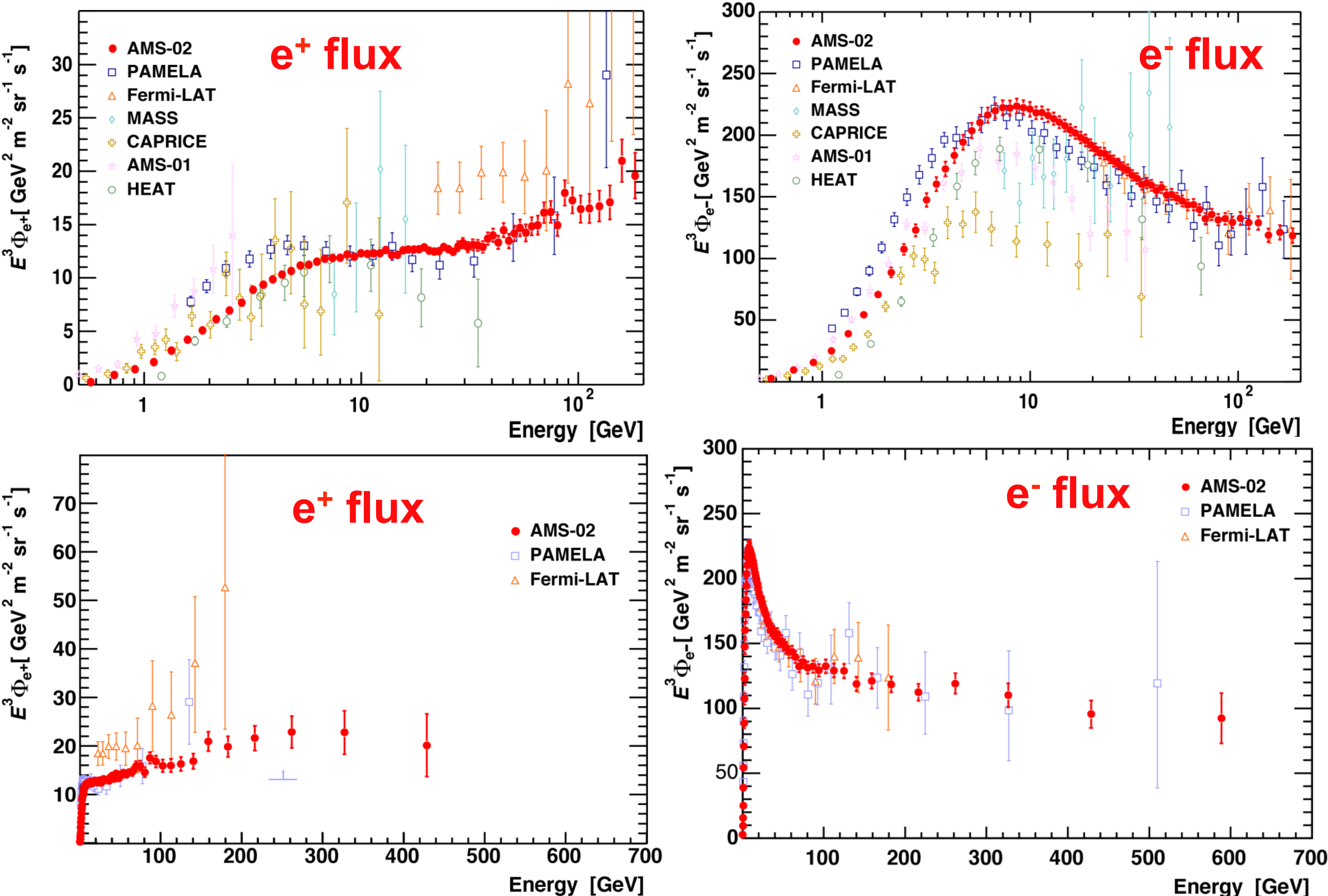
Kopp hep-ph/1304.1184



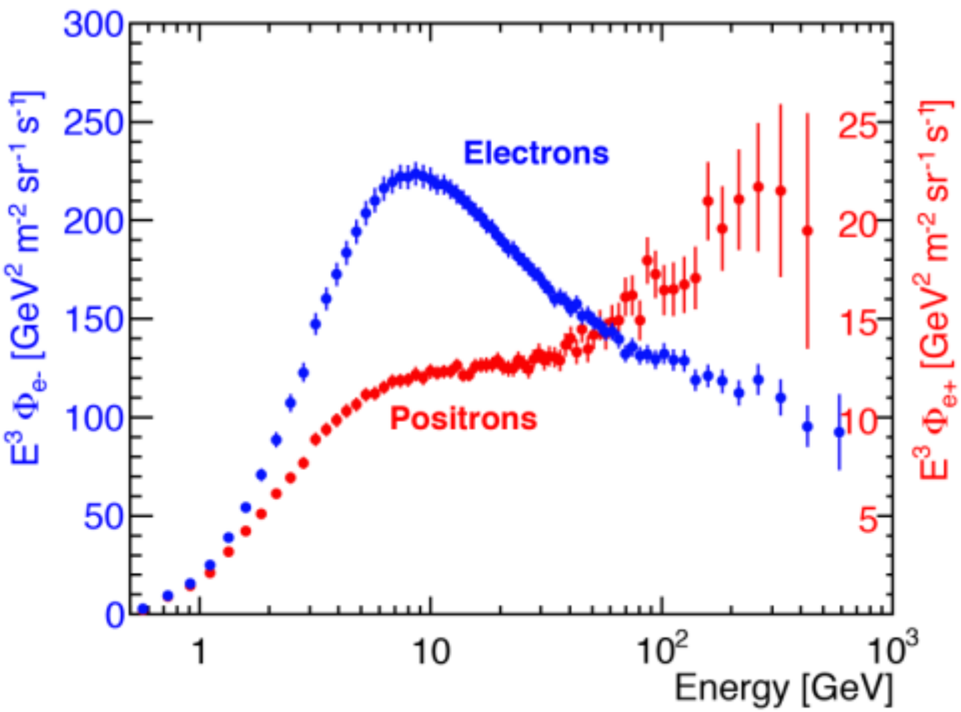

**Different energy behavior of the positron fraction:**

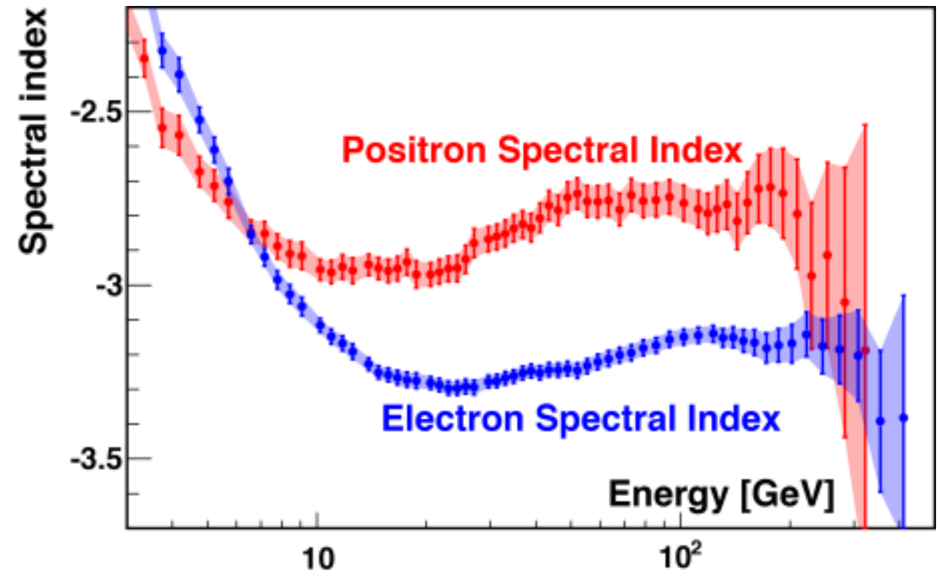
- **Pulsars predictions:**
  - **slow fall at high energies**
  - **anisotropic positron flux**
- **Dark Matter prediction:**
  - **steeper fall at high energies**
  - **isotropic positron flux**

# Electron/positron fluxes



# Electron/positron fluxes



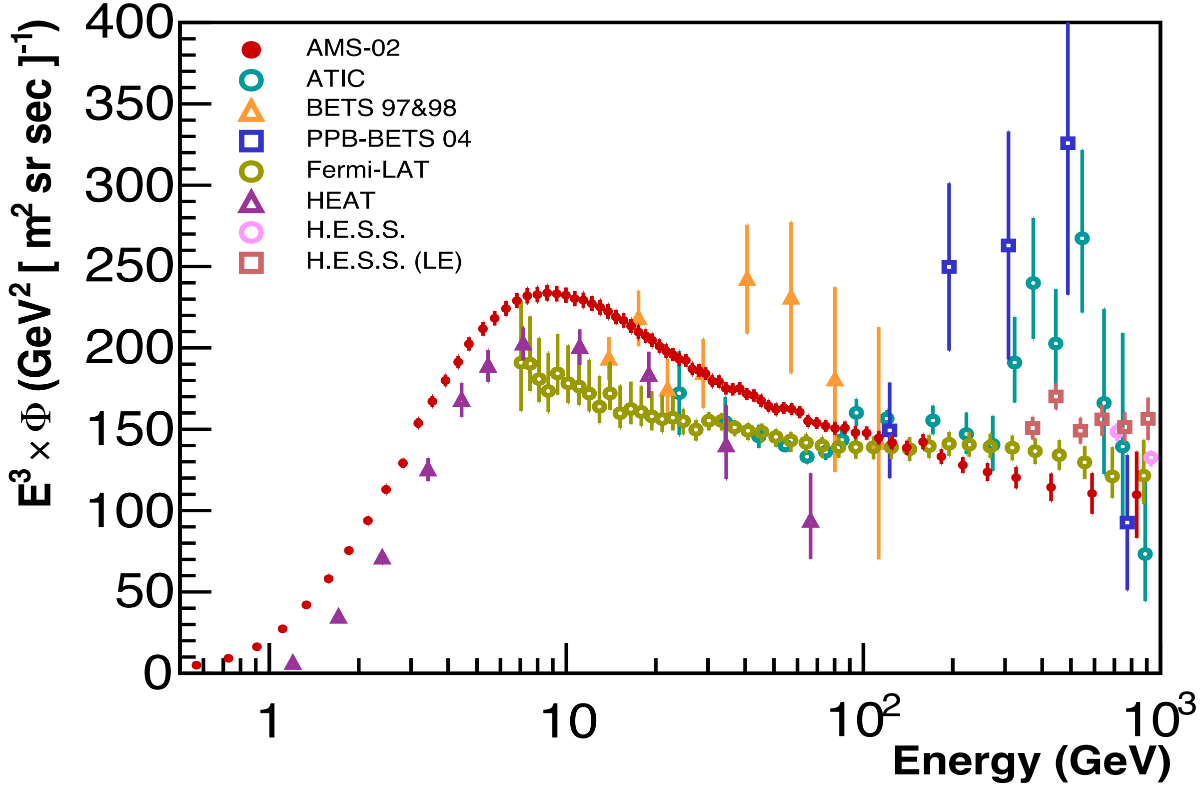




**Observations:**

1. Both spectra cannot be described by single power laws.
2. The spectral indices of electrons and positrons are different.
3. Both change their behavior at ~30GeV.

[ The rise in the positron fraction from 20 GeV is due to an excess of positrons, not the loss of electrons (the positron flux is harder) ]

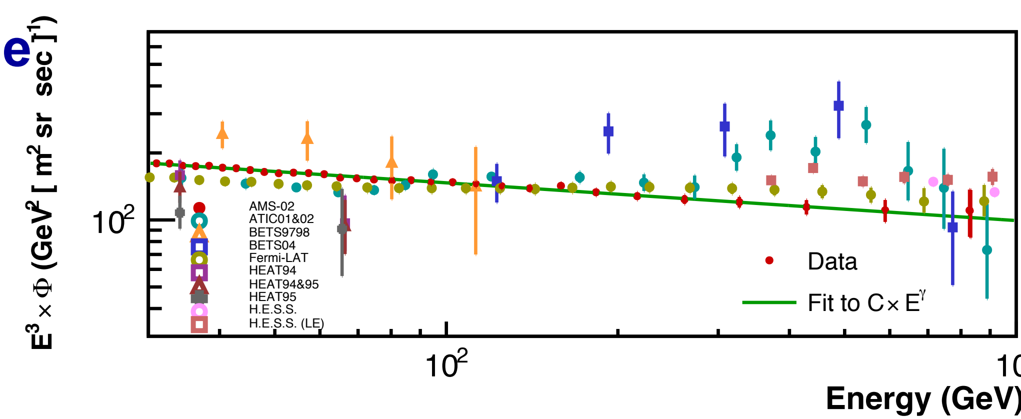
# electron + positron flux



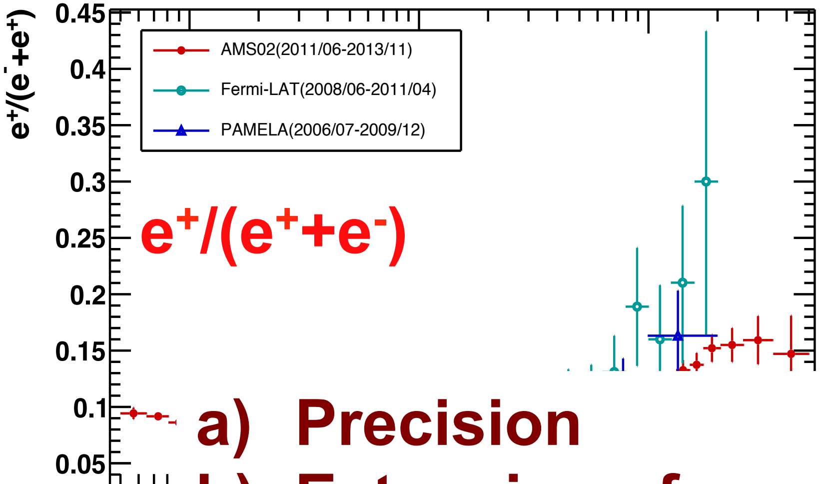

**A single power law describes the spectrum for E>30.2 GeV**

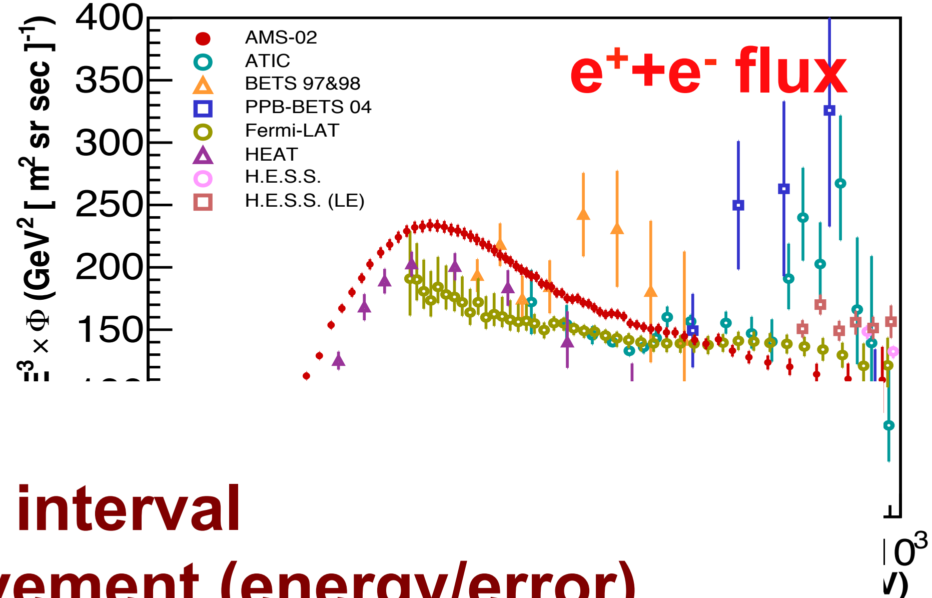
***d log (Φ)/ d log (E) =***

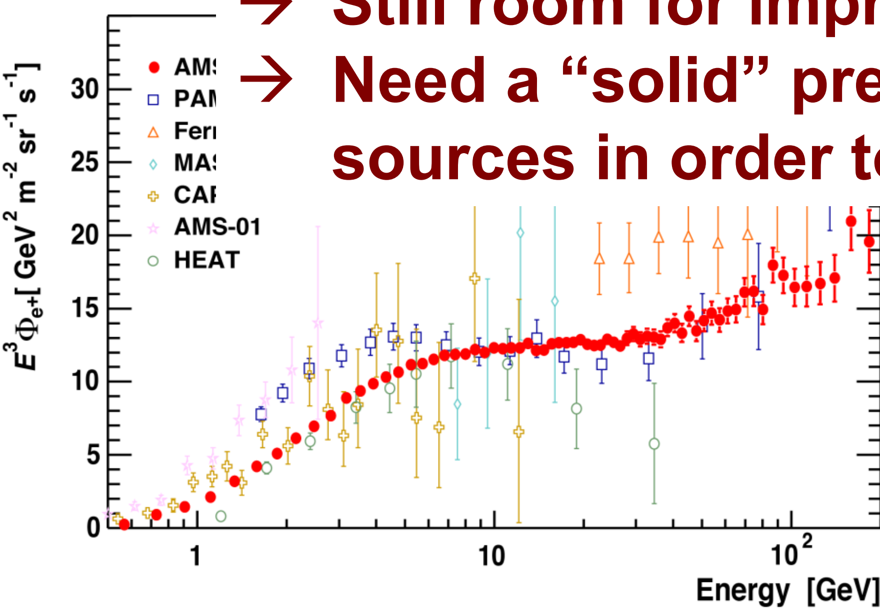
**-3.170 ±0.008 (stat+sys) ±0.008 (E scale)**

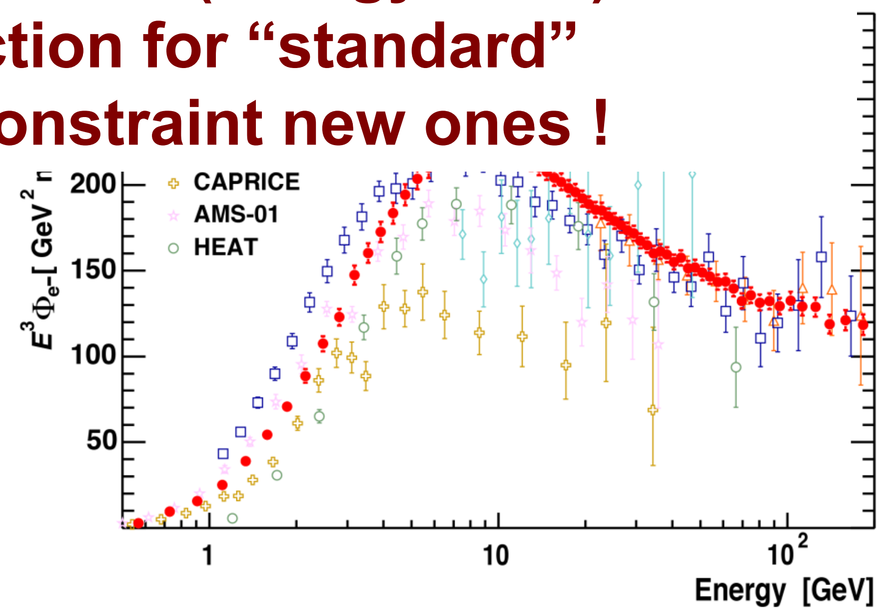


# Results




a) **Precision**

b) **Extension of energy interval**

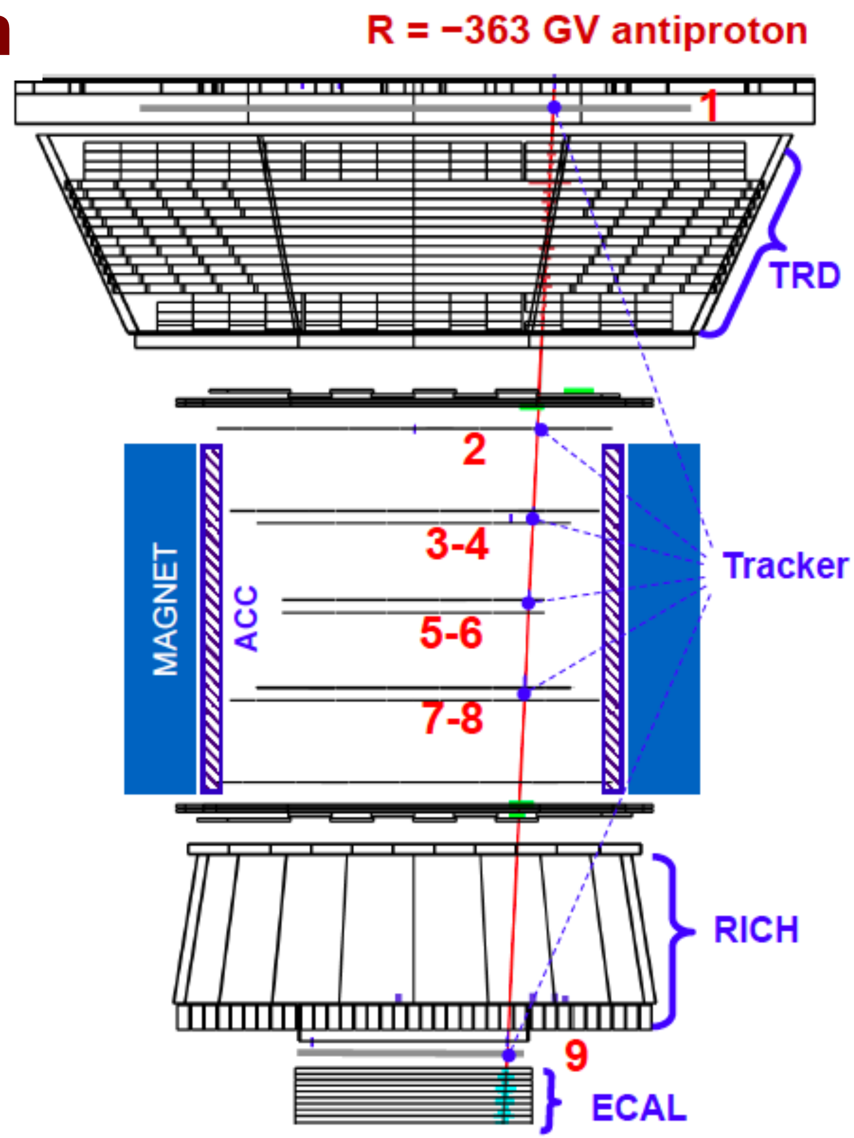
→ **Still room for improvement (energy/error)**

→ **Need a "solid" prediction for "standard" sources in order to constraint new ones !**

# Pbar/p measurement: status report

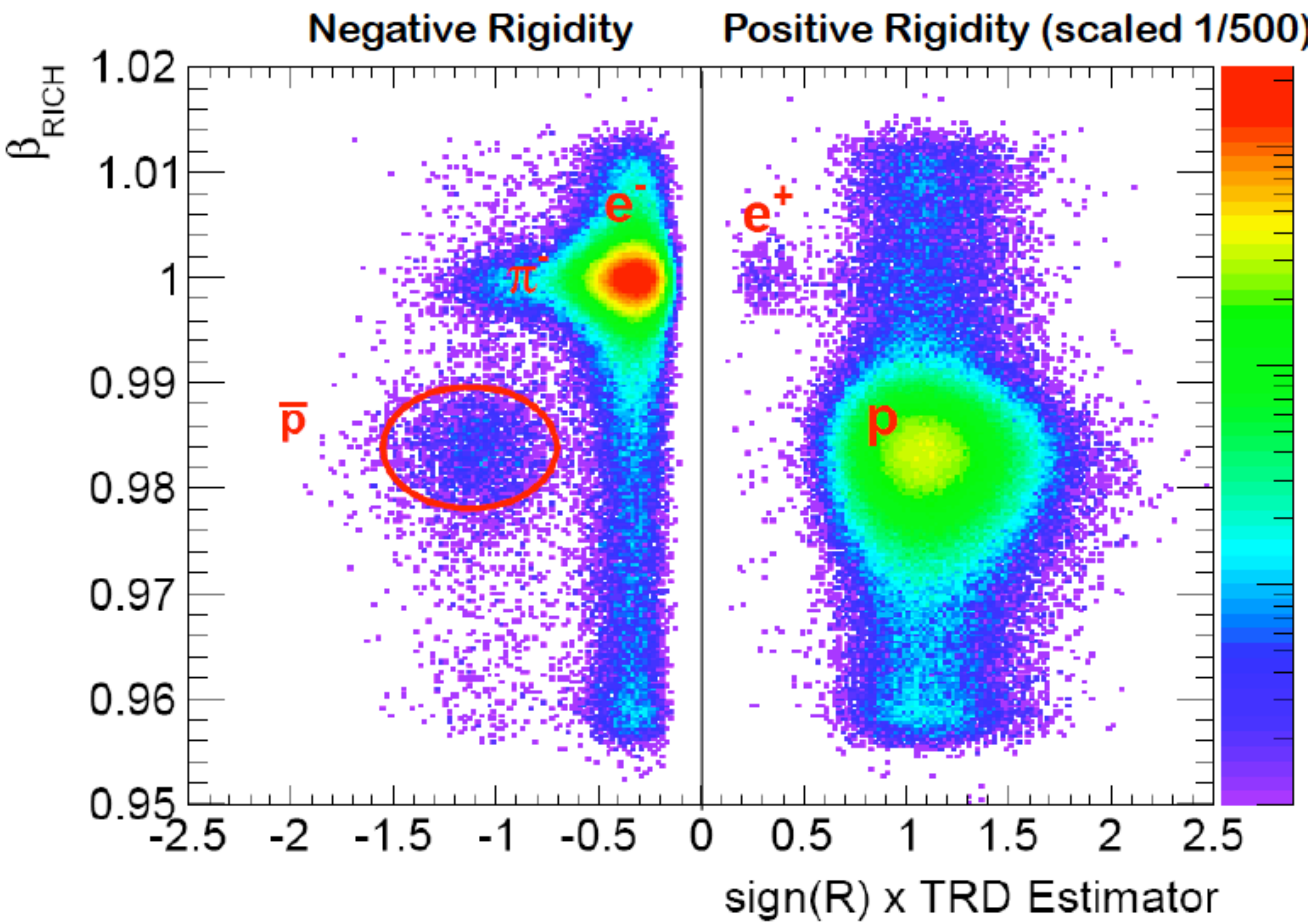
## Step 1: Event Selection

- DAQ:
  - livetime > 50% (no SAA)
- Geomagnetic cutoff:
  |R| > 1.2·max cutoff
- TOF:
  - downgoing particle
  - β>0.3
- TRD:
  at least 12 hits
- TRACKER:
  - Track quality
  - 0.8 < |Q| < 1.2
- ECAL:
  - Hadron shower shape

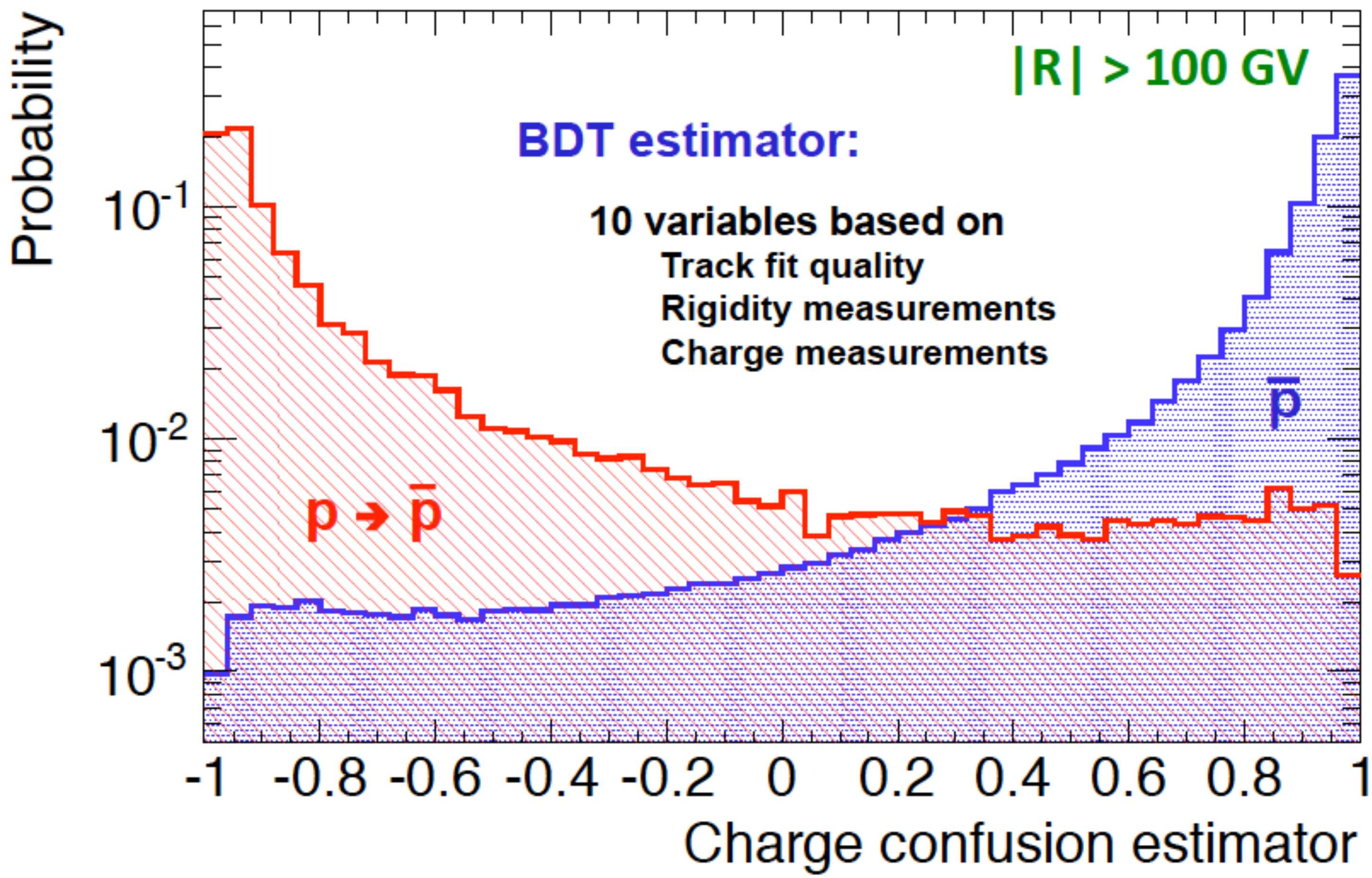



(both MIP / showering events are analyzed)

# Step 2: at low energy p/e/π background rejection



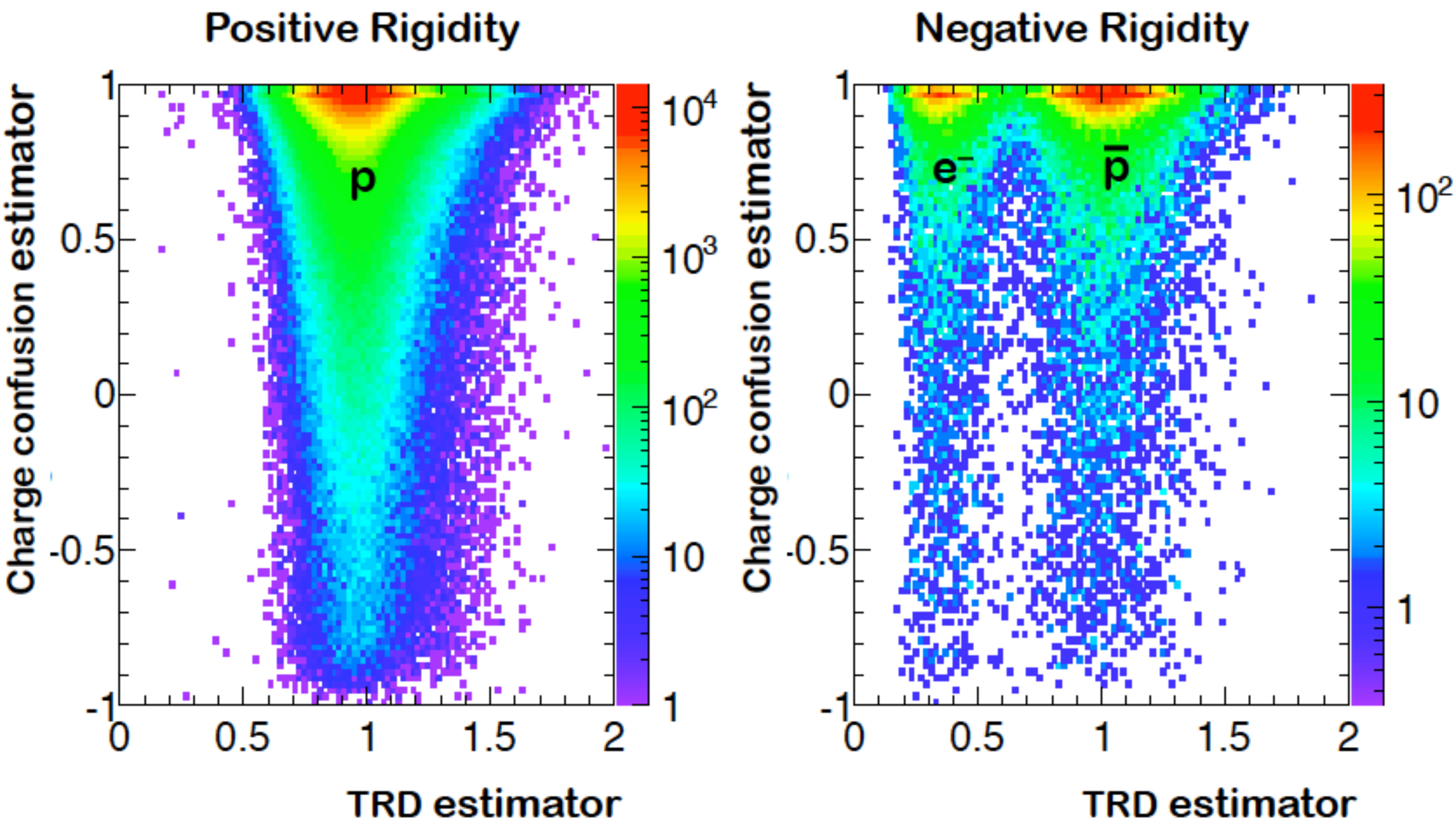
# Step 3: at high energy fight against charge confused protons




**Different estimators are being evaluated within independent analyses:**

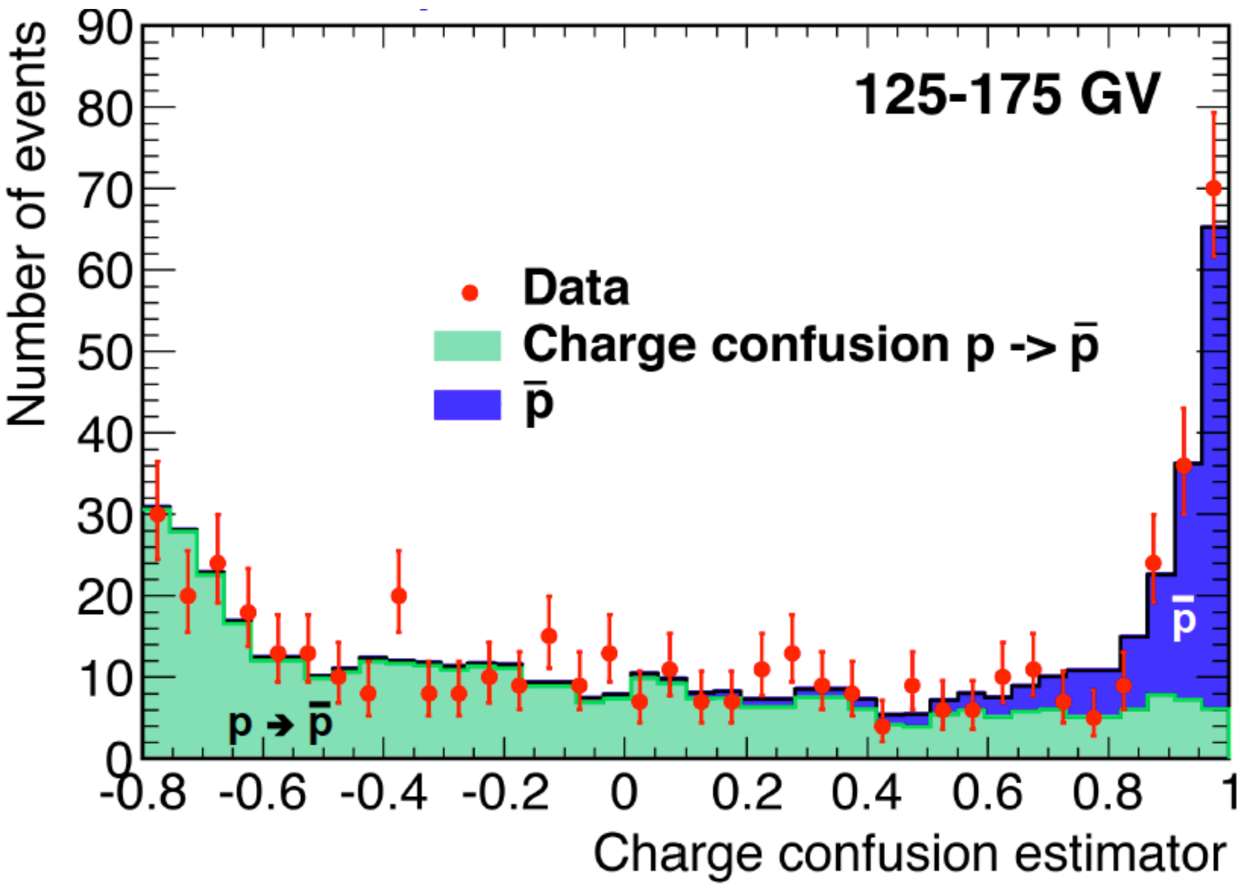
- **Different set of variables**
- **Different statistical methods to combine them**
- **Different trainings for the BDT**

# Step 3: at high energy fight against charge confused protons




**Most of the $e^-$ background easily removed by TRD estimator**

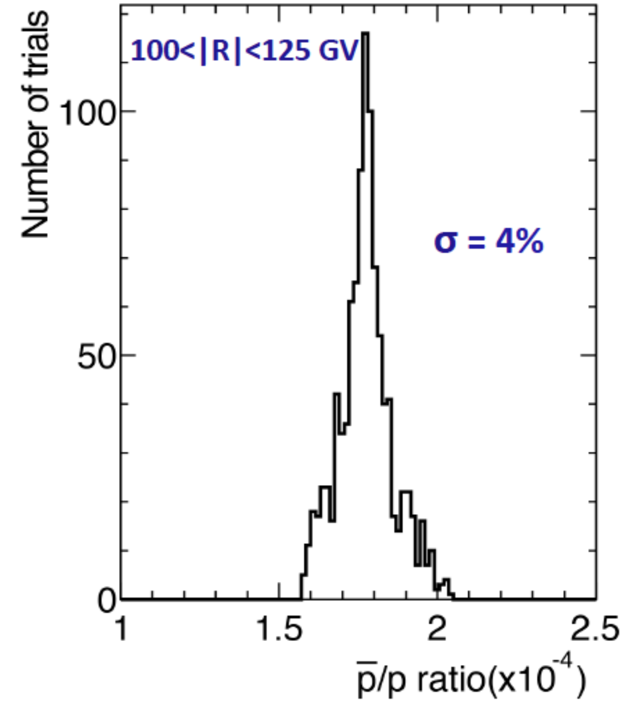
# Step 3: at high energy fight against charge confused protons




Number of anti-protons evaluated from the fit to the reference distributions for well reconstructed protons (from ISS data) and from charge confused protons (from MC)

# Systematic uncertainties

**Selection:**
Vary the selection cuts (in analysis and to define the TRD templates) and perform the full analysis.

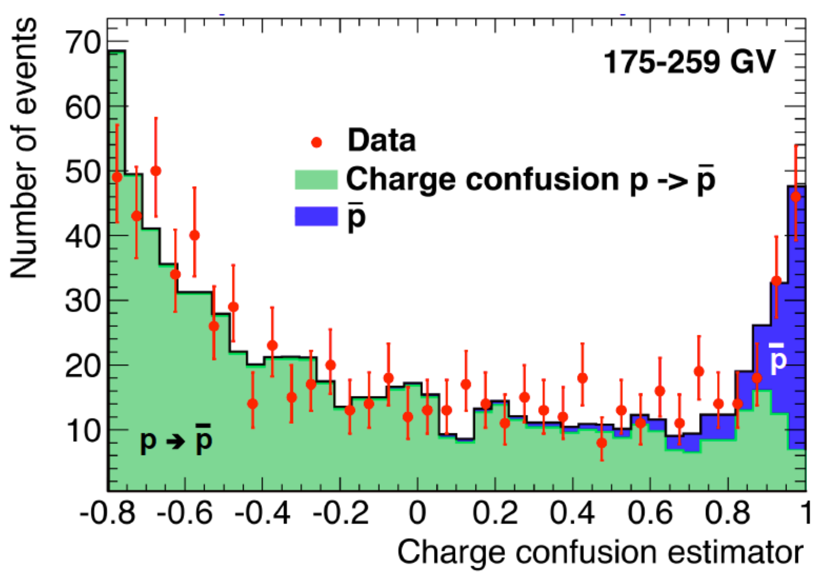



**Charge confusion:**
Shapes of the reference spectra: detailed verification of DATA/MC agreement

**Acceptance asymmetry**
**& bin-to-bin migration effects**

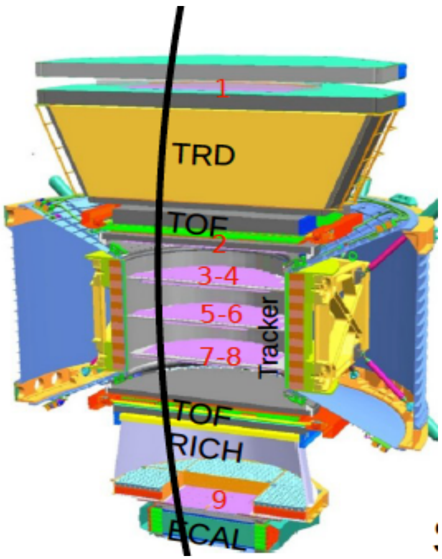
Bin-to-bin migration effects not really relevant to optimized binning / tracker resolution

***Acceptancy asymmetry → xsections !***



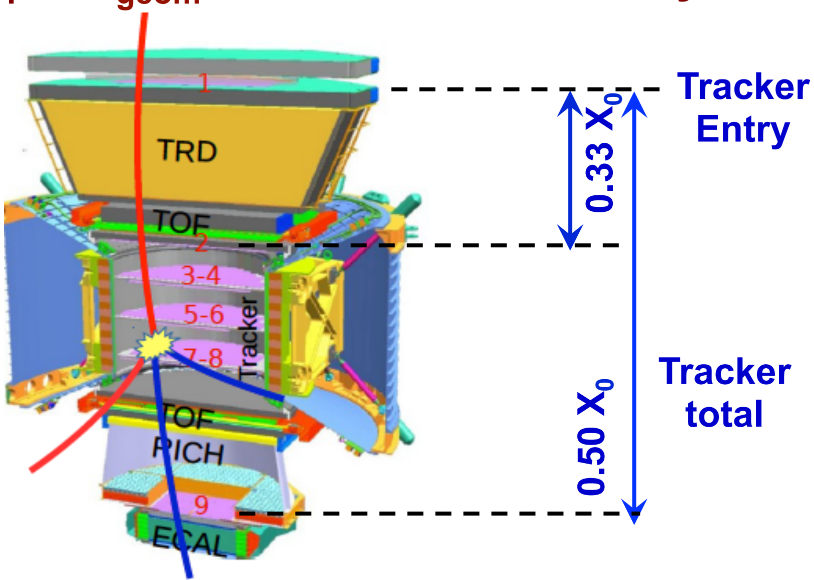
For a "Geantino" $\sigma = 0$

$A = A_{geom}$

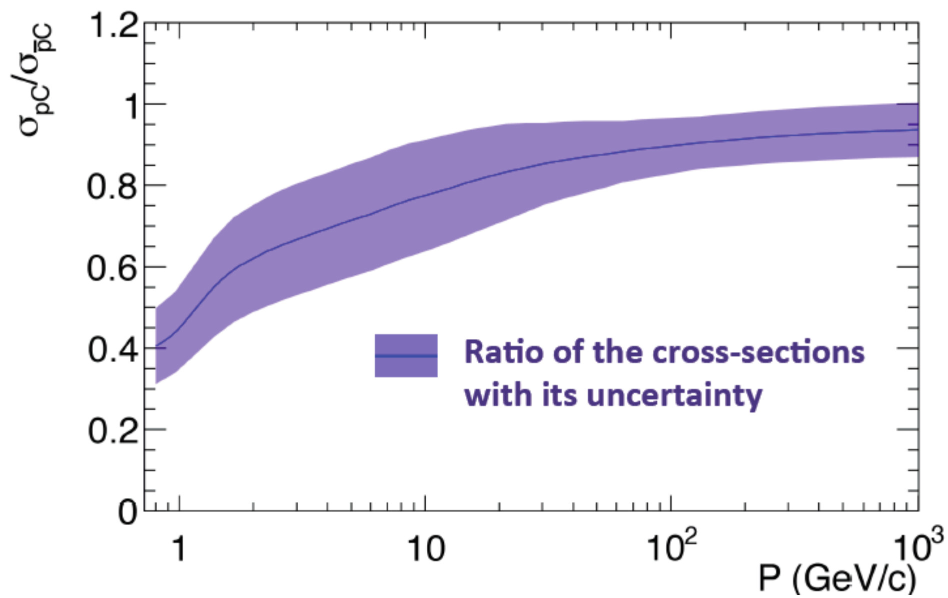



For a real particle $\sigma_{anel} \neq 0$

$A_P = A_{geom}$ x Survival Probability



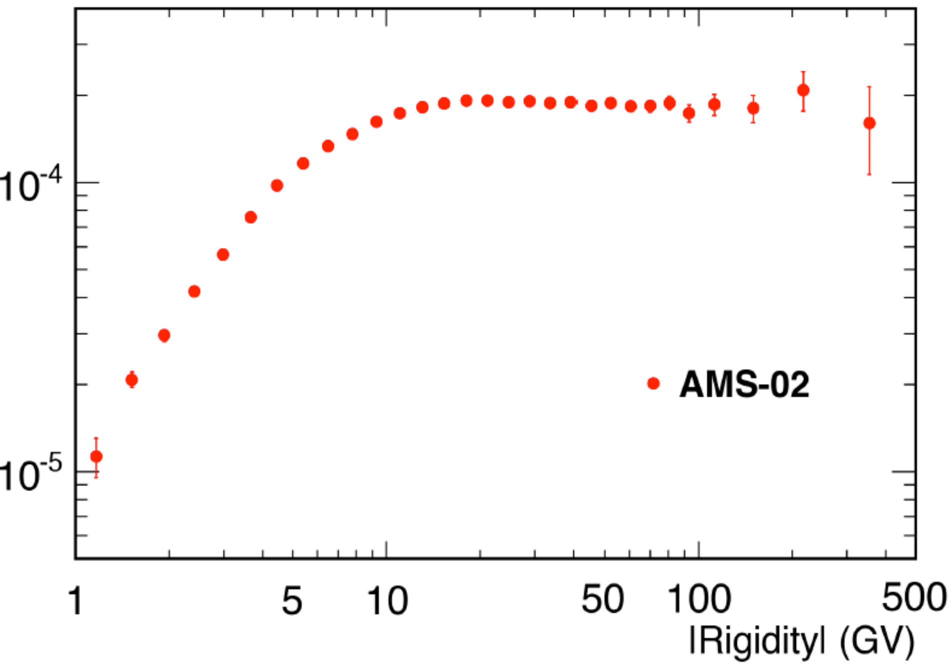

SP is different for p/anti-p due to different $\sigma$ with detector material (C, Al):

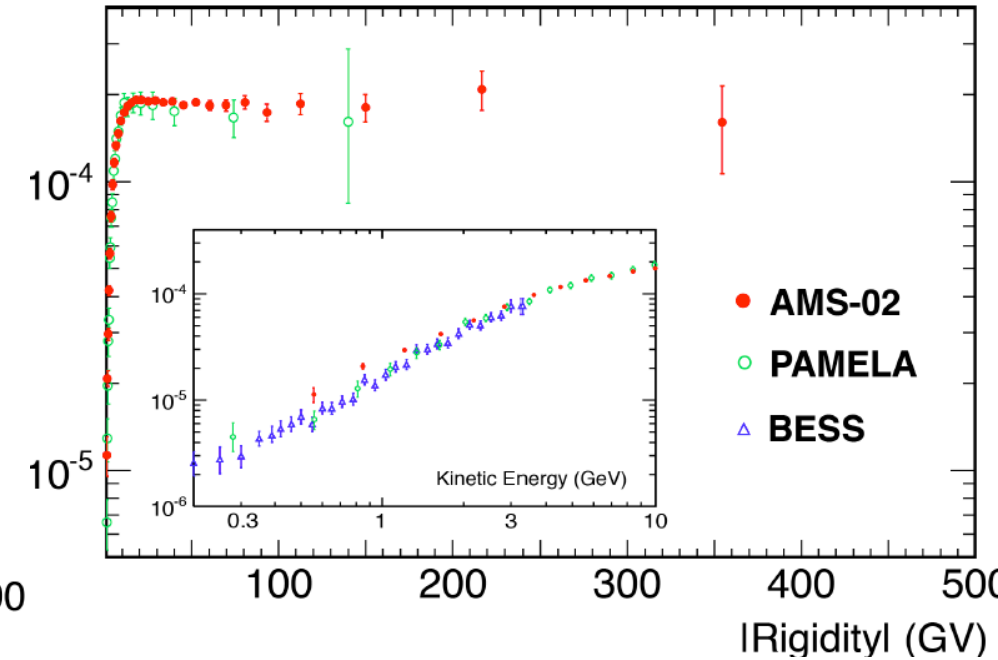



The effective uncertainty on A due to the knowledge of $\sigma$ depends on the amount of traversed material:

$$\mathrm{SP} \propto \mathrm{e}^{-\alpha\sigma}$$

# Status of pbar/p measurement



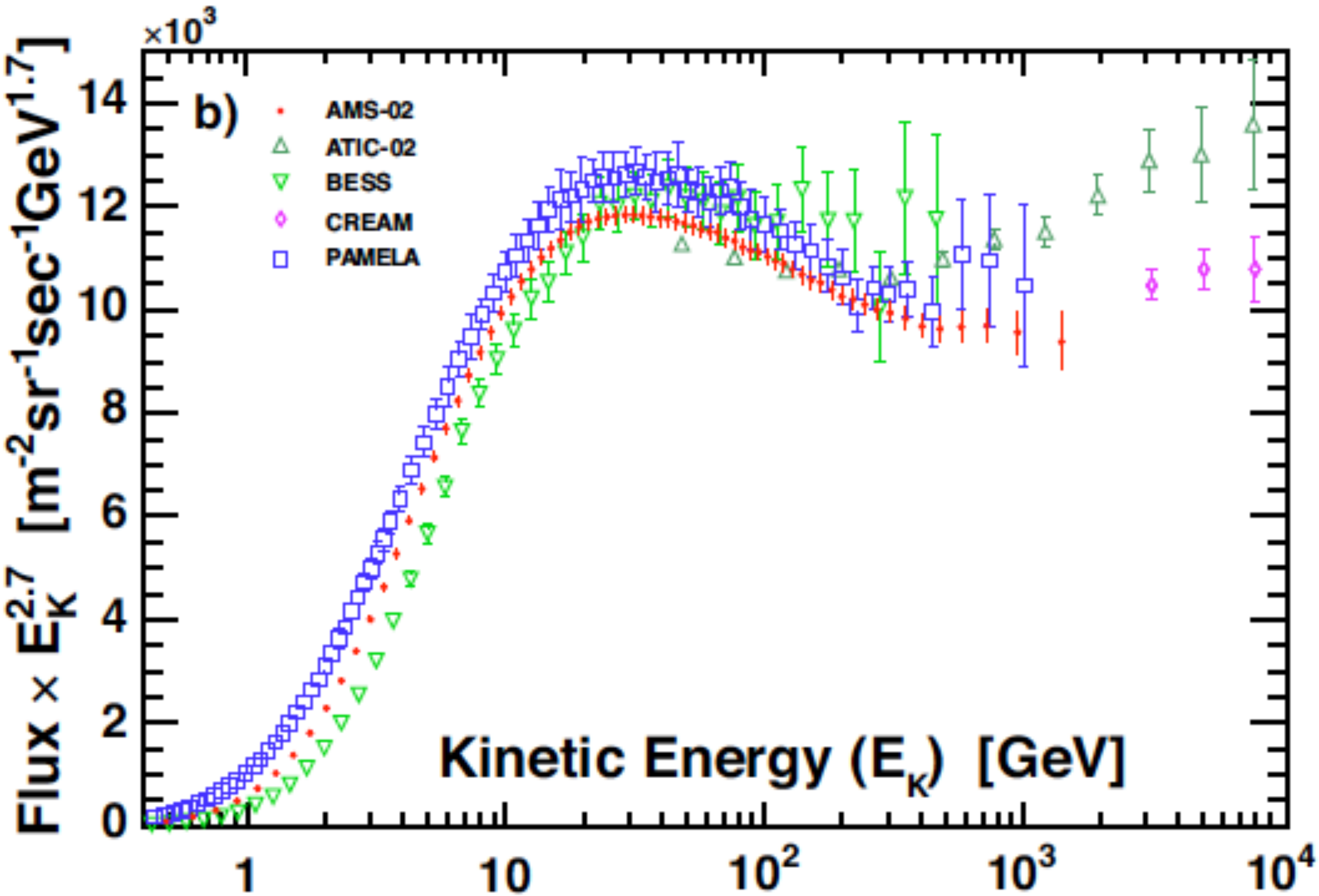




**Statistical and systematic uncertainties @ [175-259] GV : pbar/p ratio 2x10$^{-4}$**

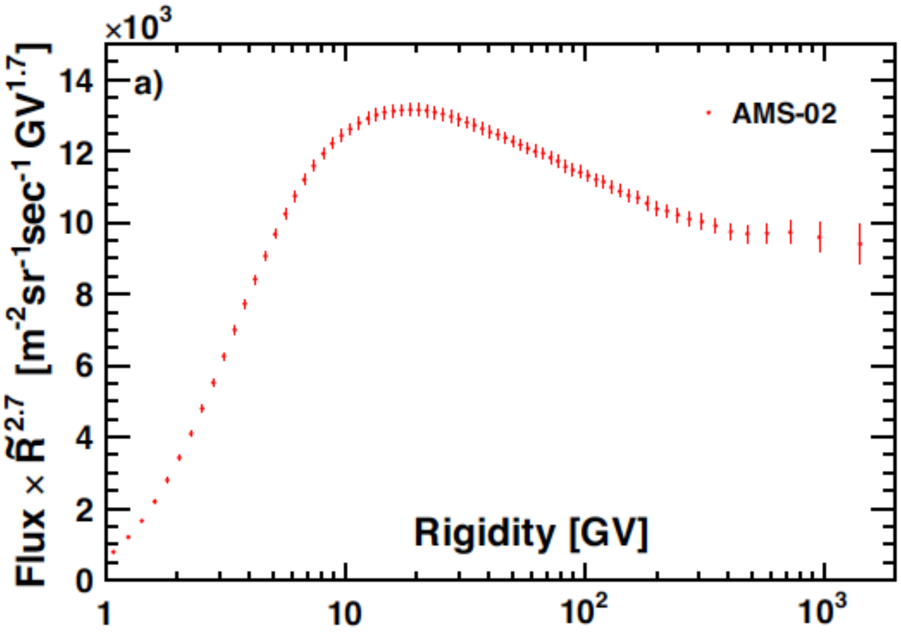
**Statistical error: 14.4%**
**Systematic error: 7.3%**
- **Acceptance 1.4%**
- **Selection 2.1%**
- **Ref. spectra 6.9%**

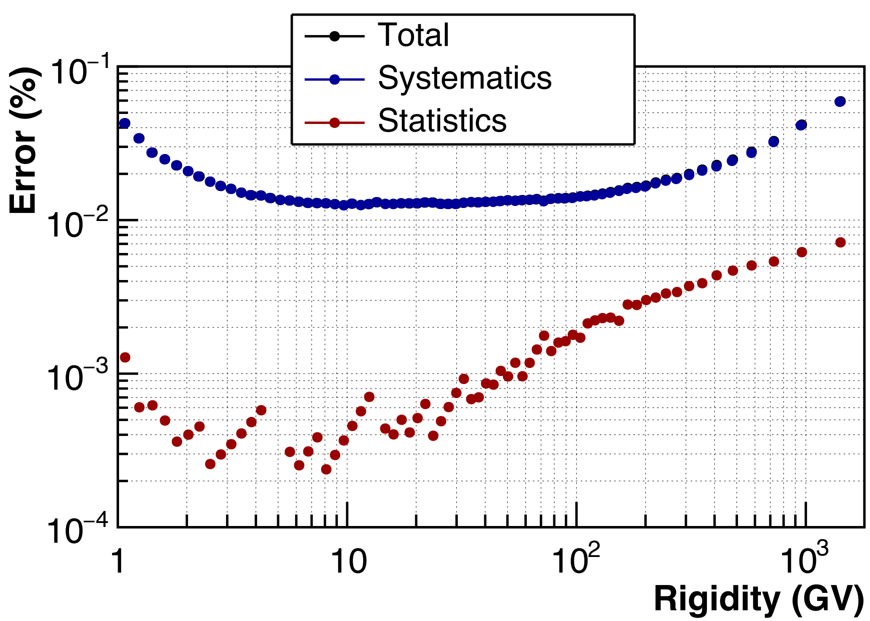
**Total error: ≈16%**

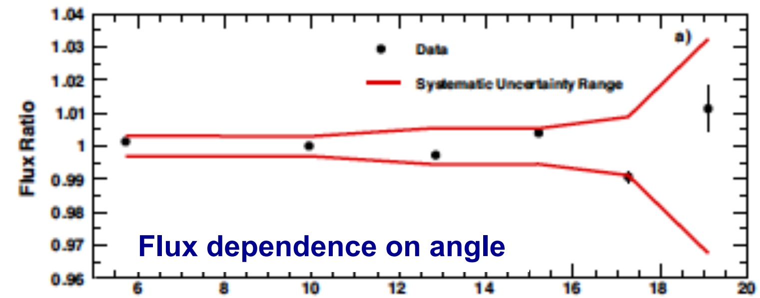
# Nuclear fluxes: proton

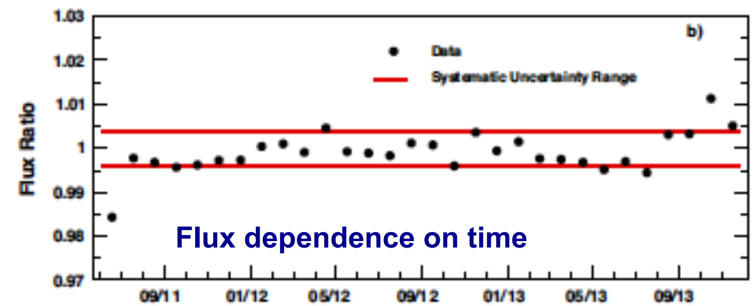


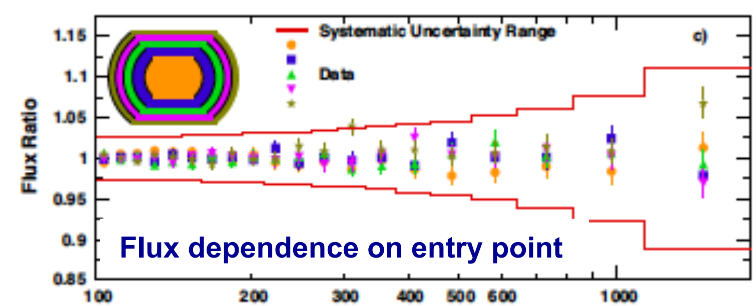
# Nuclear fluxes: proton

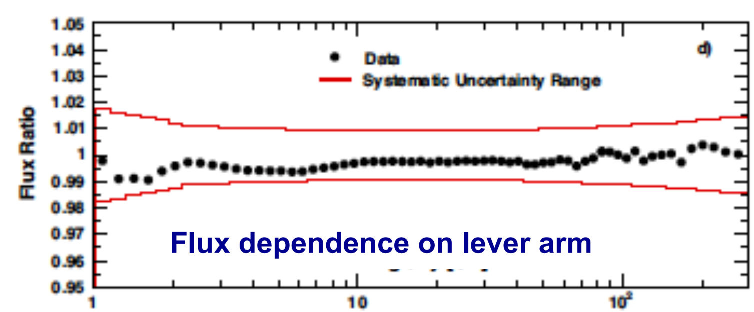


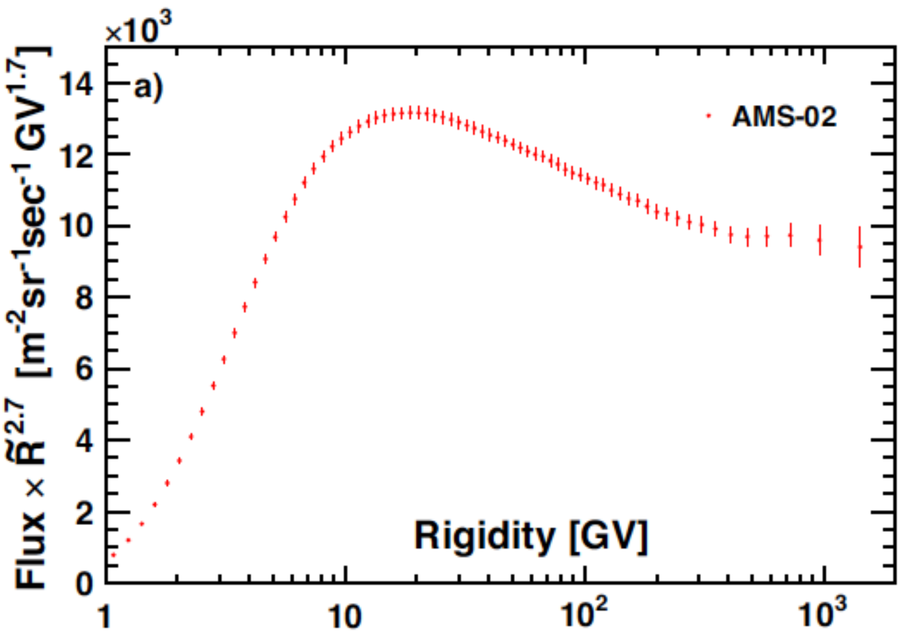



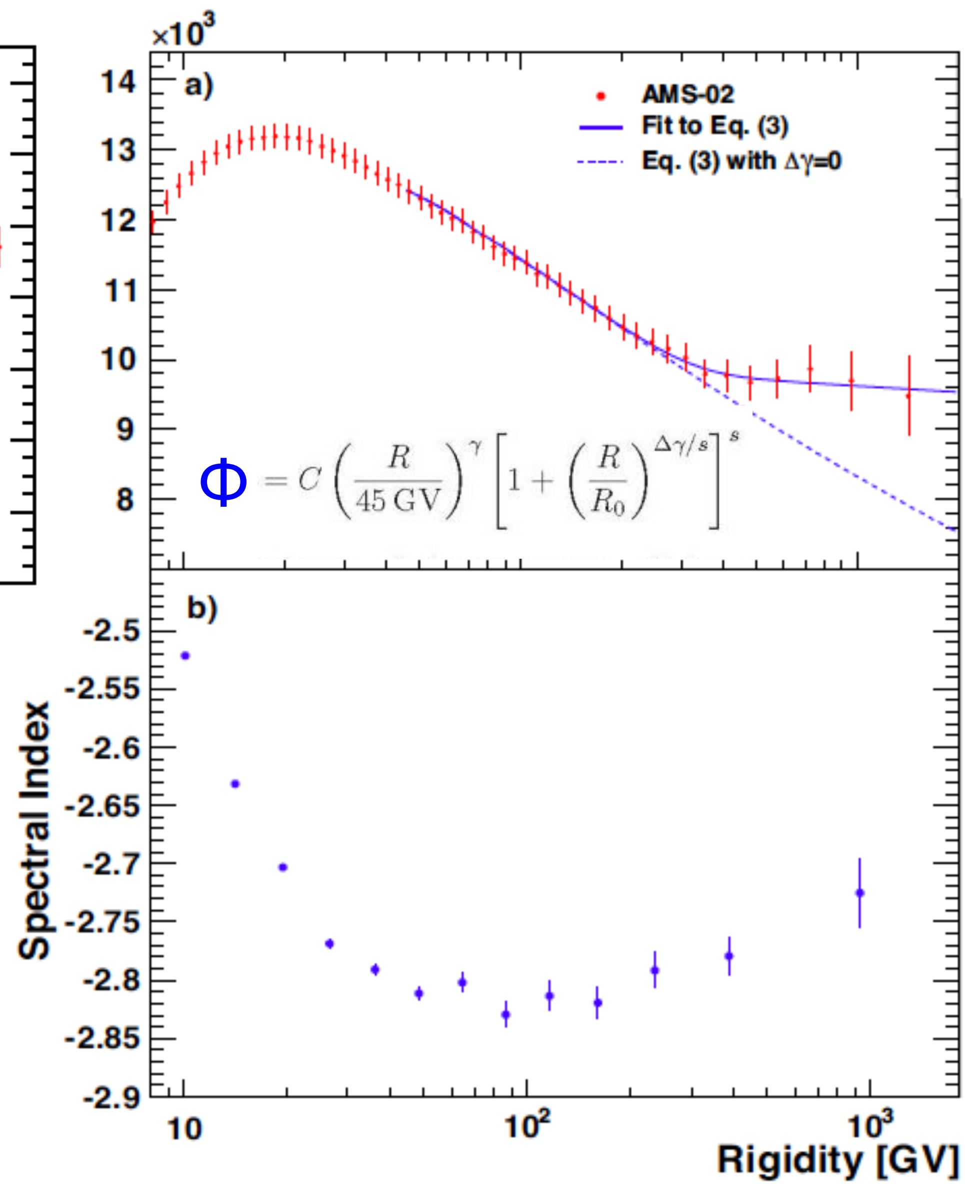



# Nuclear fluxes: proton



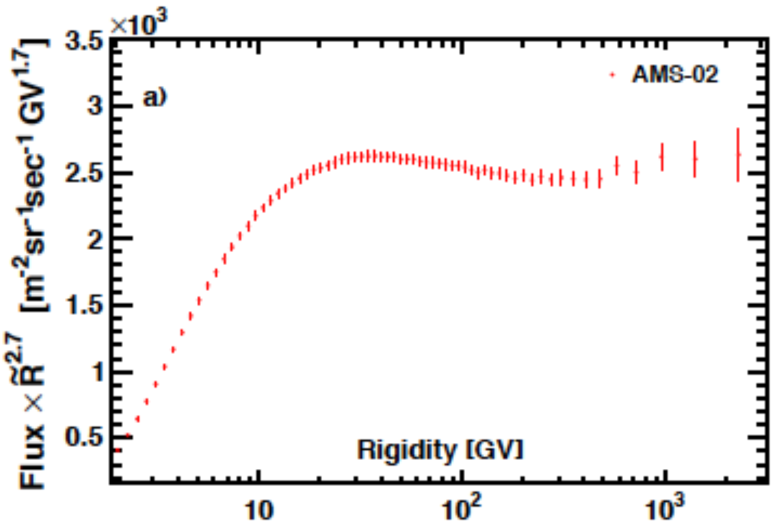

$\gamma$ = -2.849 ± 0.002 + 0.004/-0.003

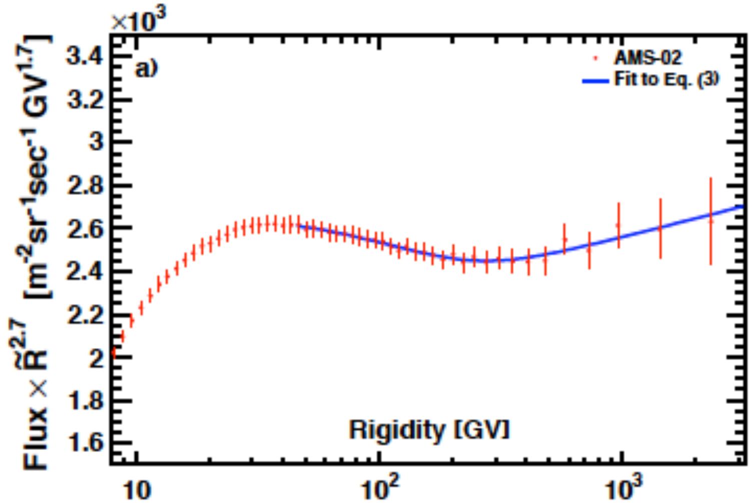
s = 0.024 +0.020/-0.013+0.027/-0.016

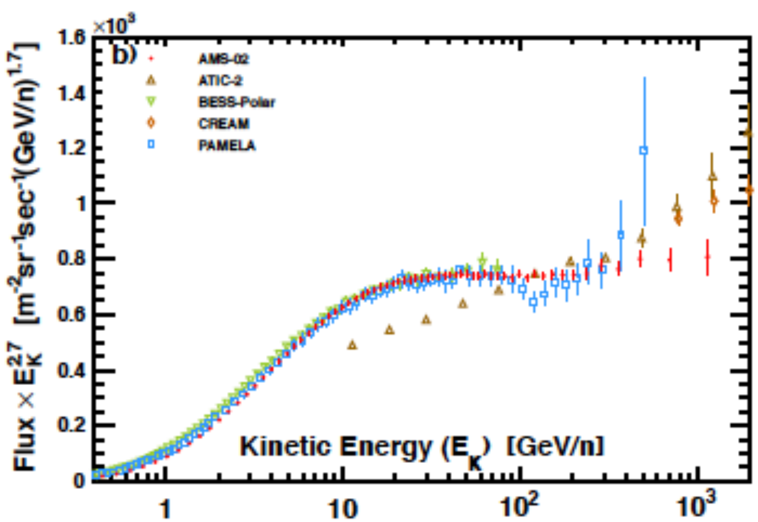
$\Delta\gamma$ = 0.133 + 0.032/-0.021 +0.046/-0.030

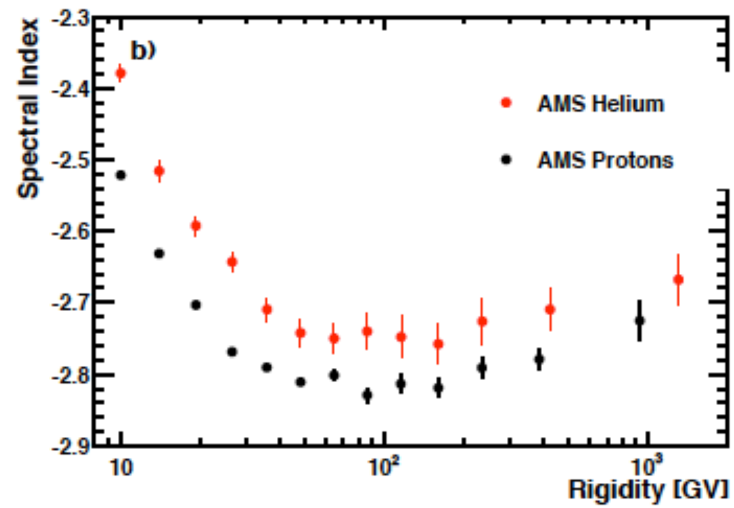
$R_0$ = 336 +68/-44 + 66/-28 GV

# Nuclear fluxes: He….(coming soon!)

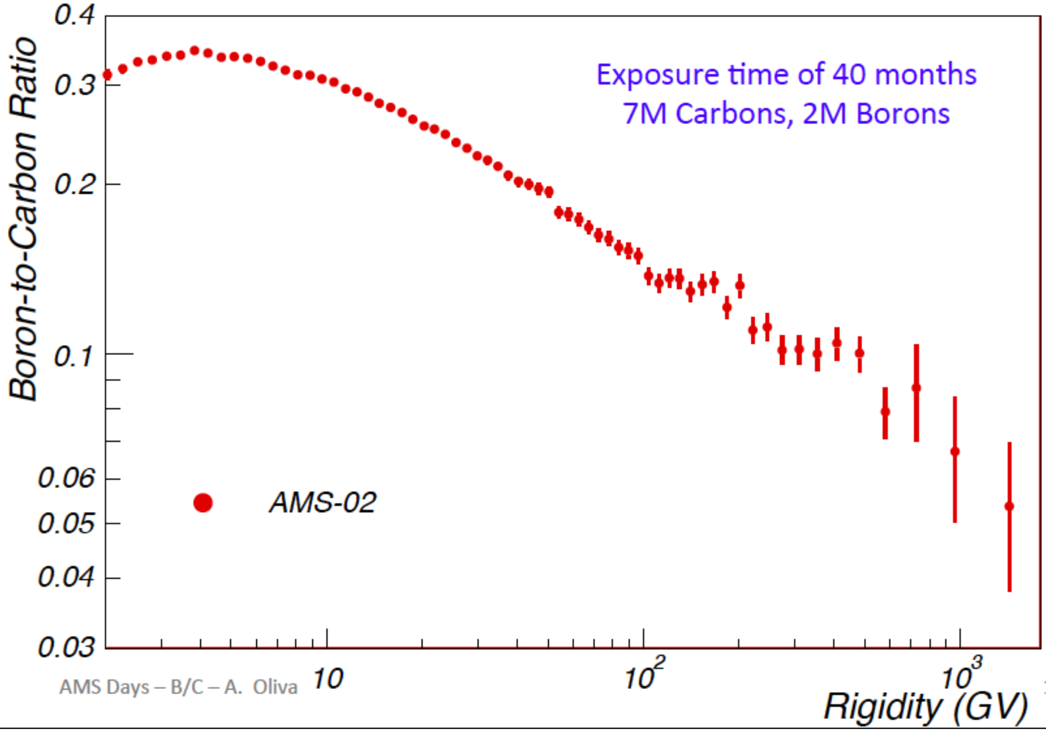


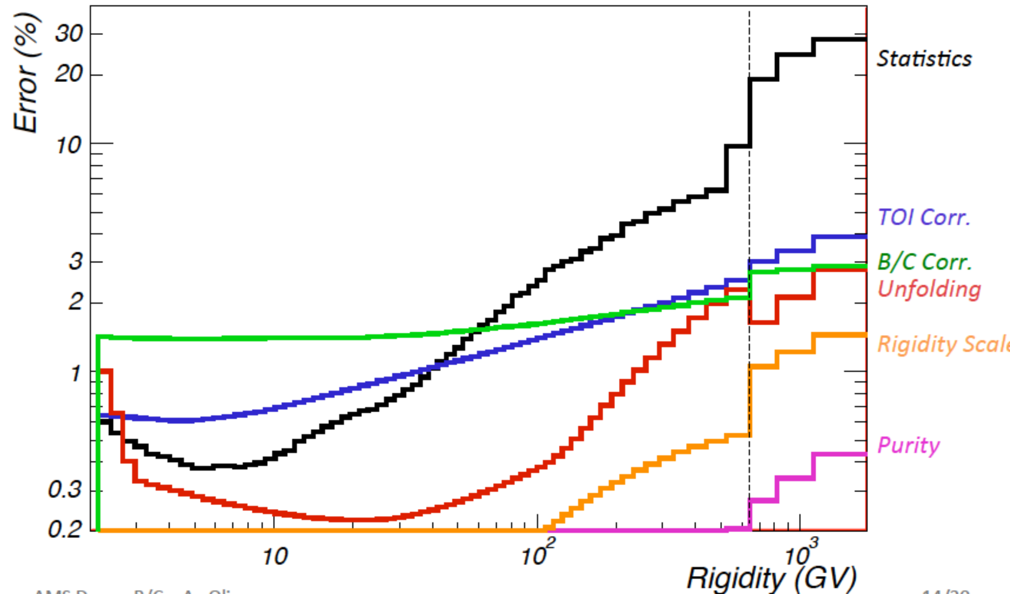



# B/C Ratio



Boron-to-Carbon Ratio
Exposure time of 40 months
7M Carbons, 2M Borons
AMS-02
Rigidity (GV)



Error (%)
Statistics
TOI Corr.
B/C Corr.
Unfolding
Rigidity Scale
Purity
Rigidity (GV)

# Summary..

The era of "precision" CR measurement has started …

- ✓ Thanks to the high collected statistics and detector performances AMS has extended the energy interval and the of $e^+$/$e^-$/anti-p and details can be studied with unprecedented accuracy

- ✓ Detailed spectral behaviour of nuclear CR ( P, He, B, C…) in the GV-TV ridigity range are also studied in AMS: tight constraints on models for origin and propagation models

- ✓ Looking for exotic sources with AMS-02 (and to plan future CR spectrometers) requires a detailed knowledge of "standard" CR


**Thanks for your attention …**
**and (most important)**
**to Fiorenza for organizing this workshop !**