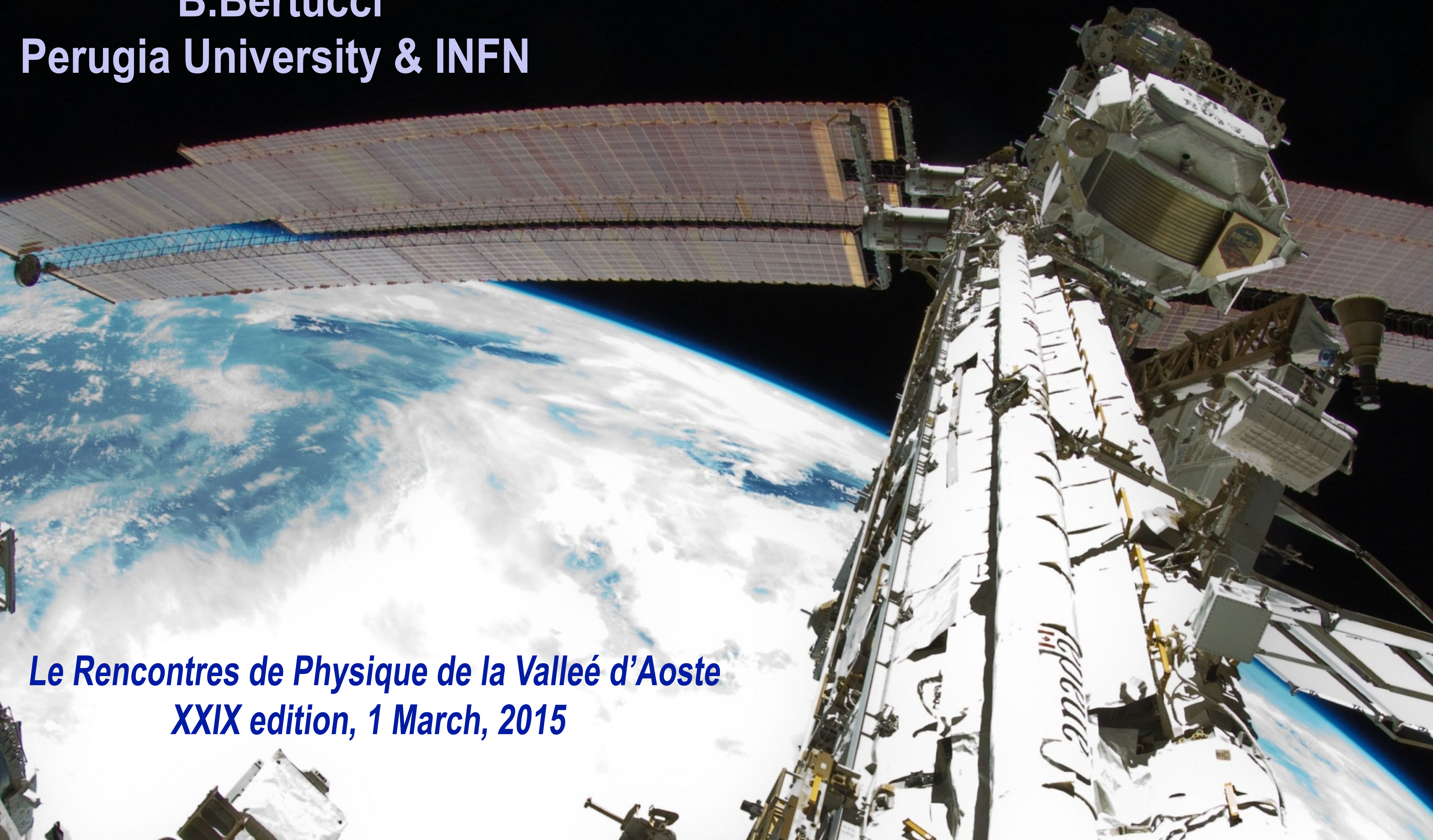
# AMS-02 on the ISS
# Results and perspectives

**B.Bertucci**
**Perugia University & INFN**

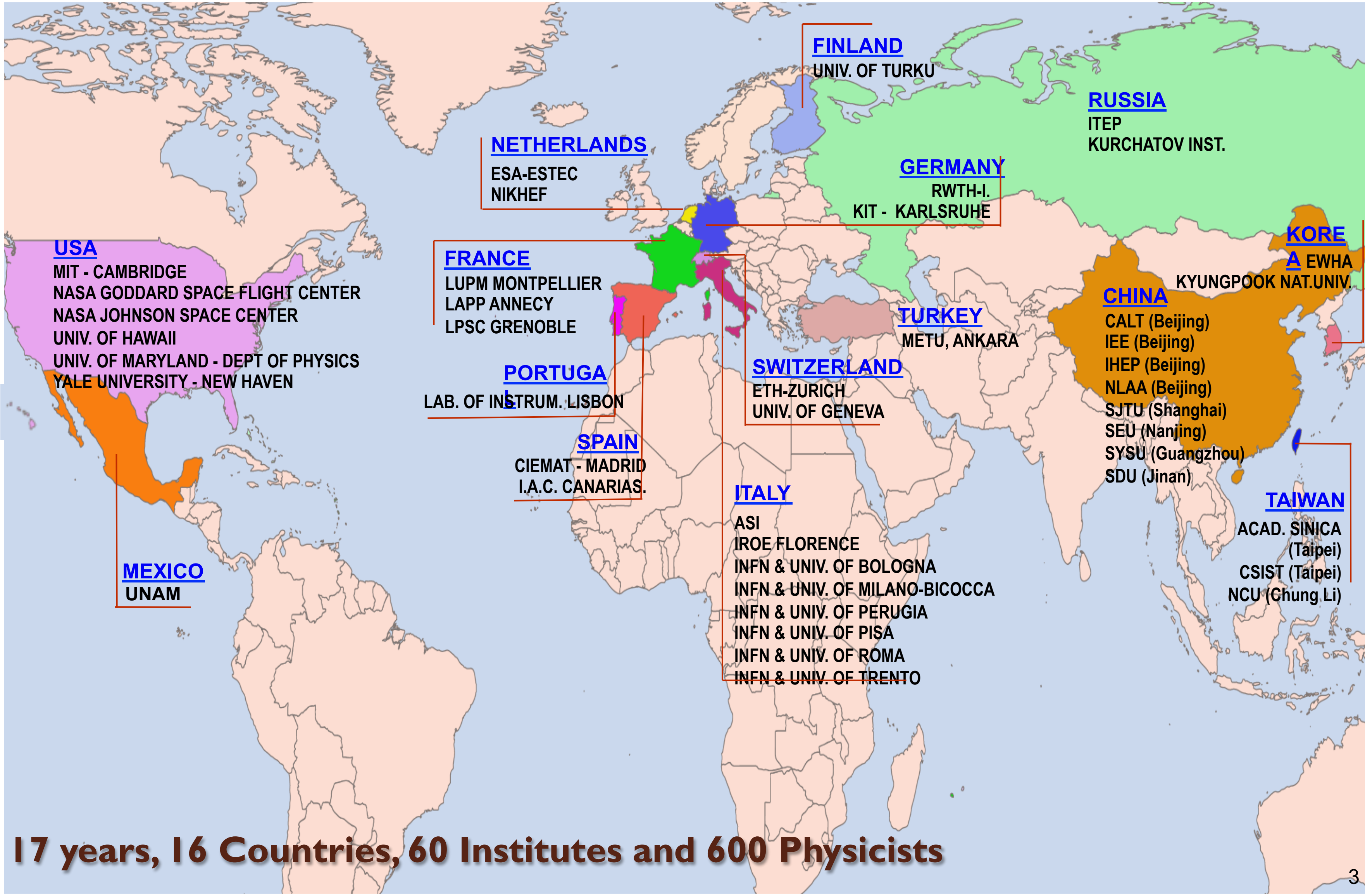


*Le Rencontres de Physique de la Valleé d'Aoste*
*XXIX edition, 1 March, 2015*

# AMS: Alpha Magnetic Spectrometer

- **AMS-02 is a particle physics detector devoted to the precision measurement of cosmic radiation in the near Earth orbit in the GeV – TeV energy range**
- **It has been installed on the International Space Station (ISS) on May 19, 2011**
- **It will take data data for the rest of the life of the ISS (2024)**

# The AMS Collaboration



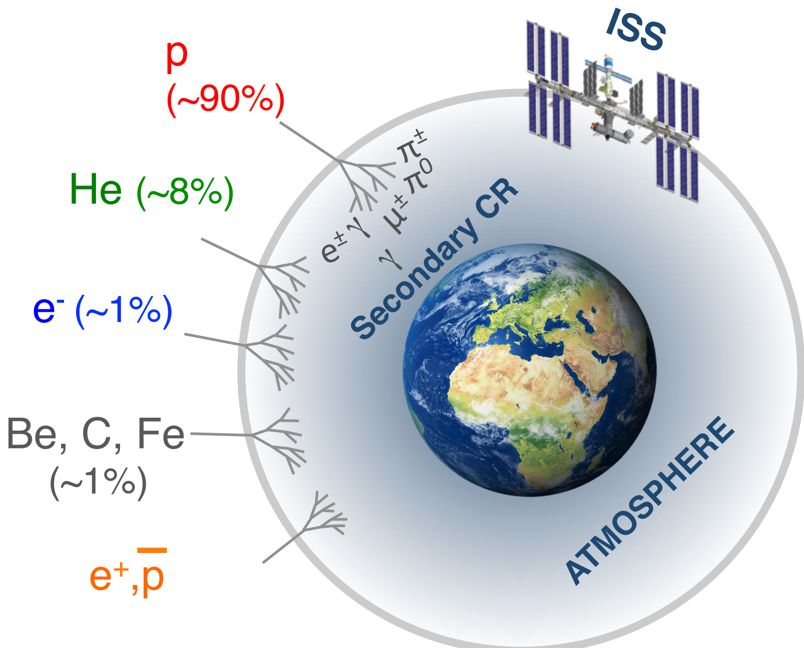
# AMS-02 :
# (part) of the Collaboration @ NASA-JSC

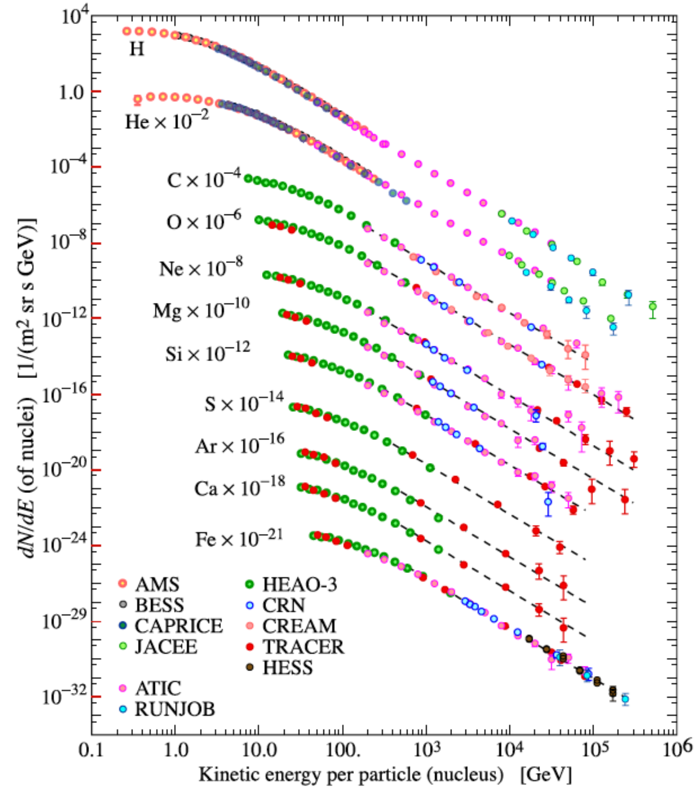
# PART 1 : The scientific objectives

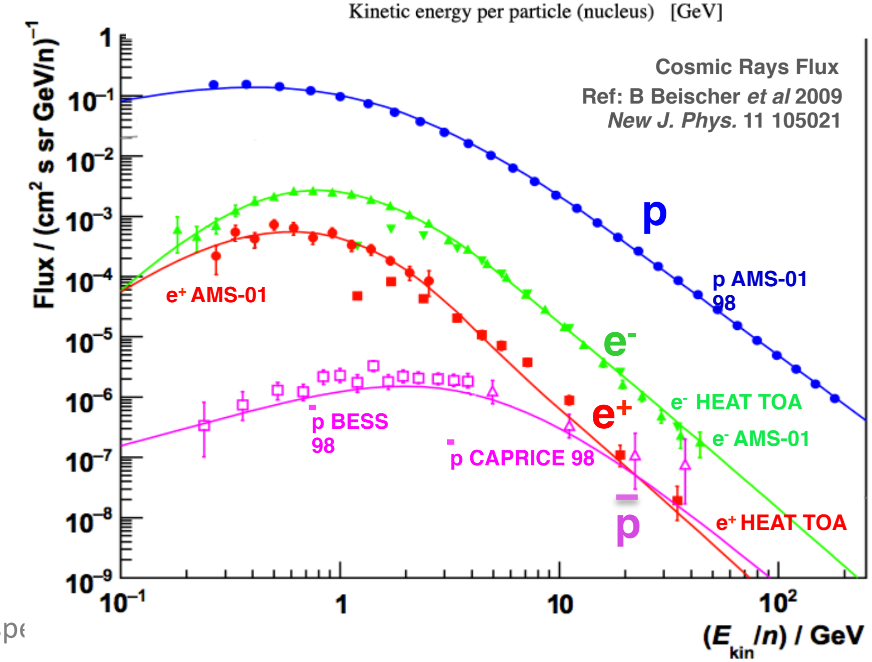
# AMS measurements

→ *charged cosmic rays* (GV-TV)

→ γ rays (E>1GeV)



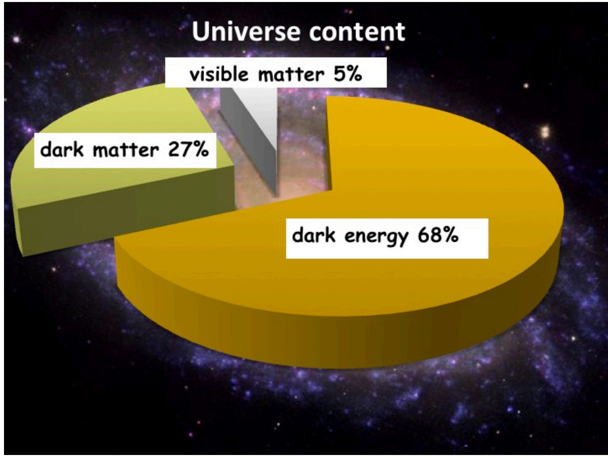
# Fundamental physics & Antimatter :

## Primordial origin ( Signal: anti-nuclei )

**Dirac's Nobel speech**

*"We must regard it rather as an accident that the Earth [...] contains a preponderance of negative electrons and positive protons. It is quite possible that for some stars it is the other way about."*

# The Quest for Dark Matter



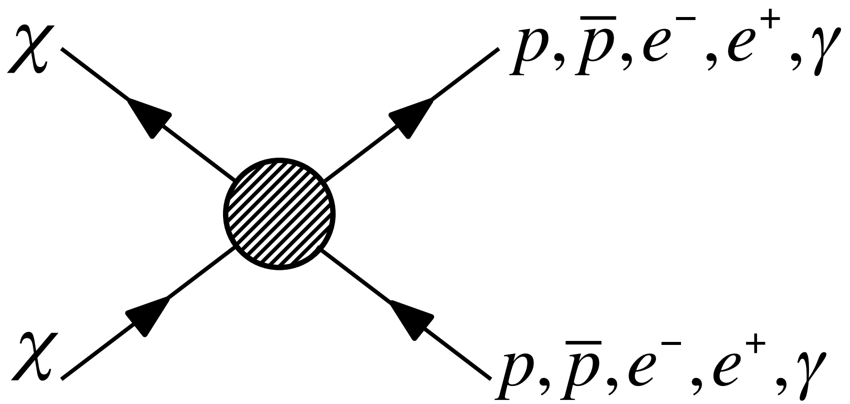

## AMS
### Annihilation (in Space)

$$\chi + \chi \rightarrow e^{+}, \bar{p}, \gamma, \ldots$$

**Scattering (Underground)**

LUX
DARKSIDE
XENON 100
CDMS II
DAMA
...

$$\chi + p \rightarrow \chi + p$$



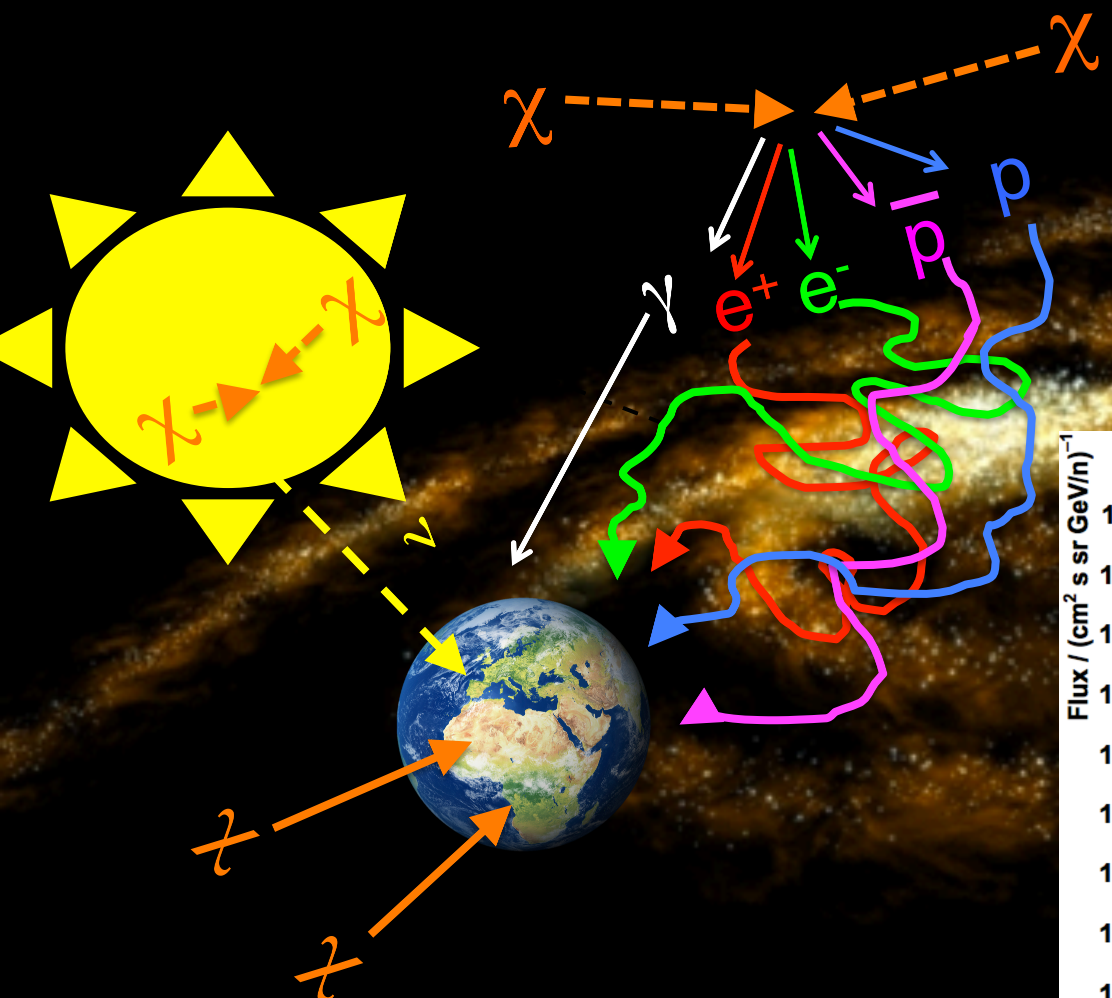

$$\chi + \chi \leftarrow p + p$$

### Production (in Accelerators)
## LHC

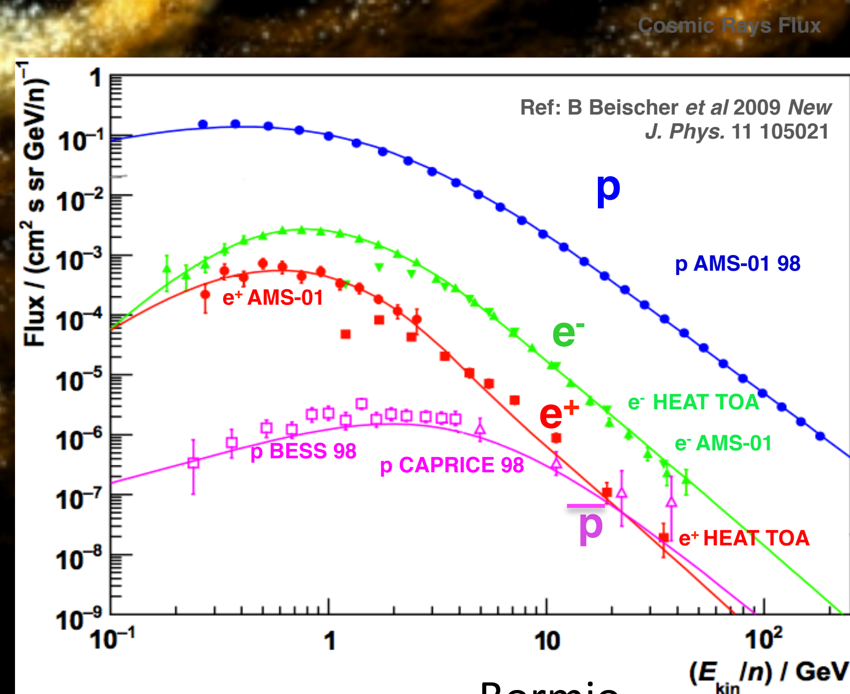
# ANTI-MATTER & DARK MATTER

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 !!

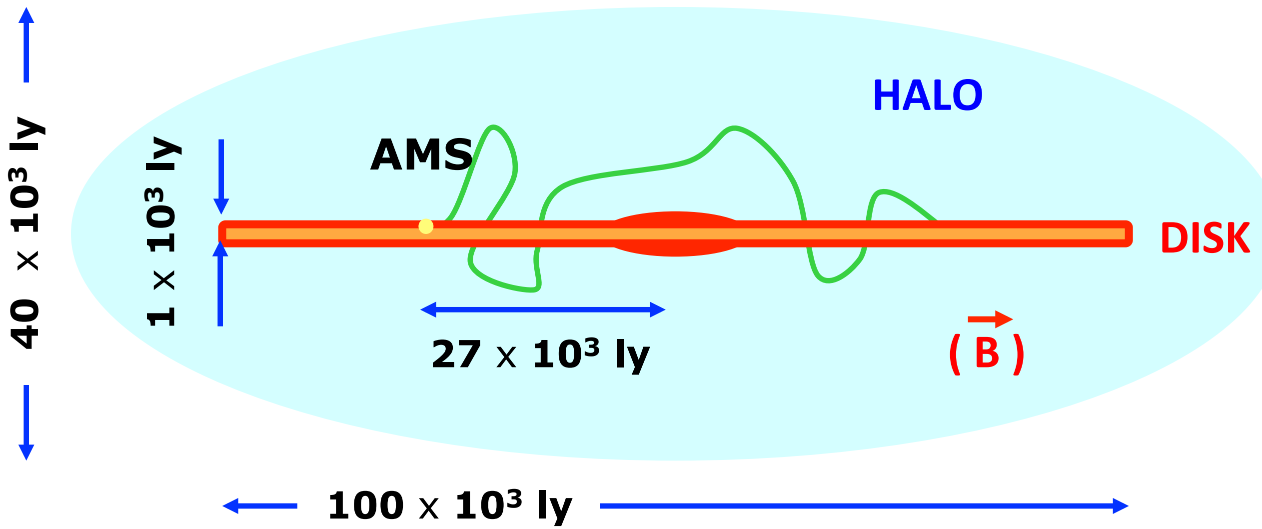



Bormio

# Knowledge of cosmic background

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

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



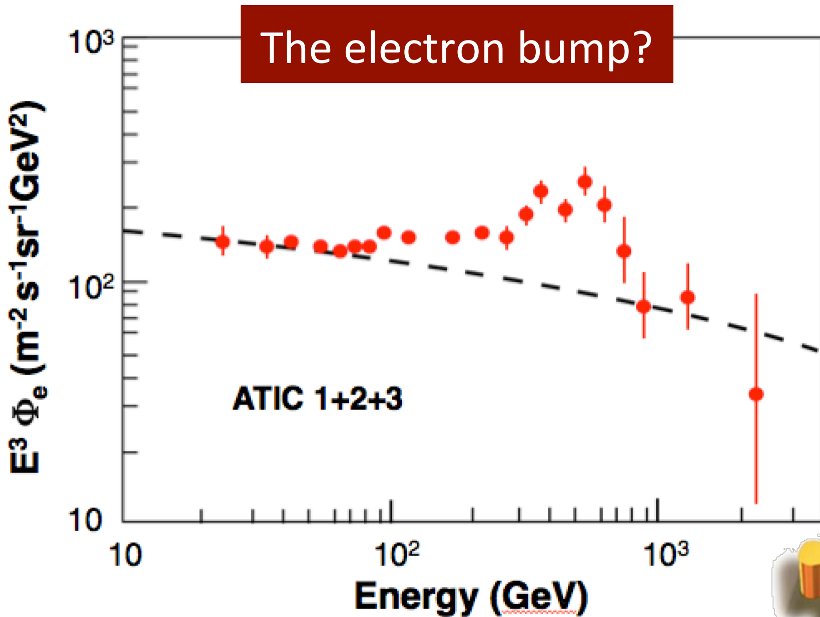

Diffusion
Convection
Reacceleration

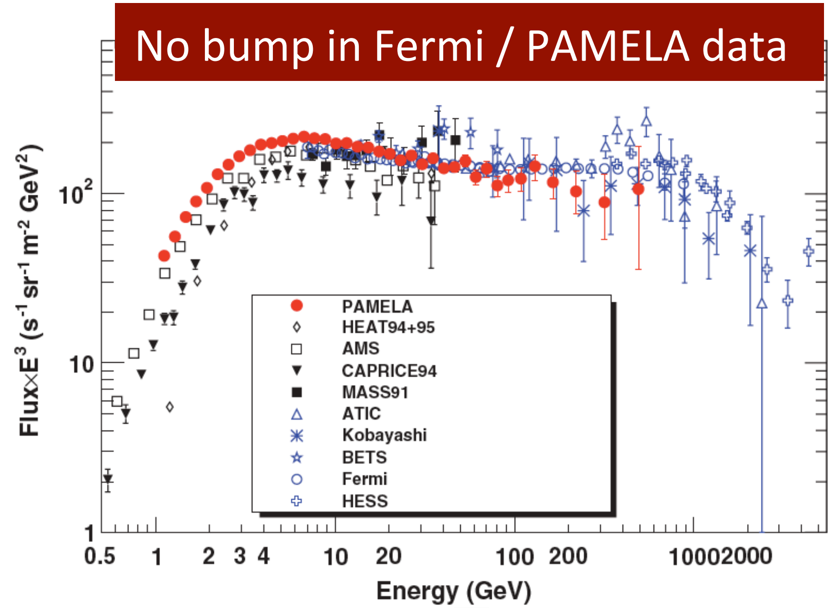
Interactions with the Interstellar Medium (ISM):
- Fragmentation
- Secondaries
- Energy loss

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

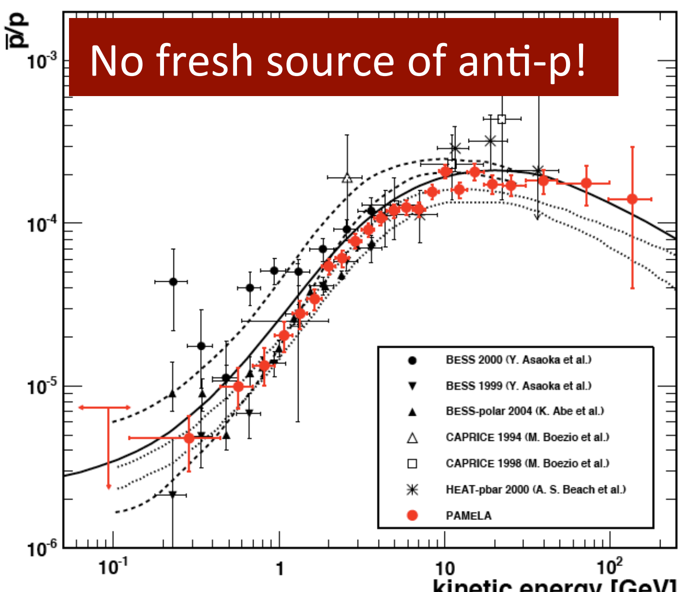
$$C + (p, He) \rightarrow B + \ldots$$

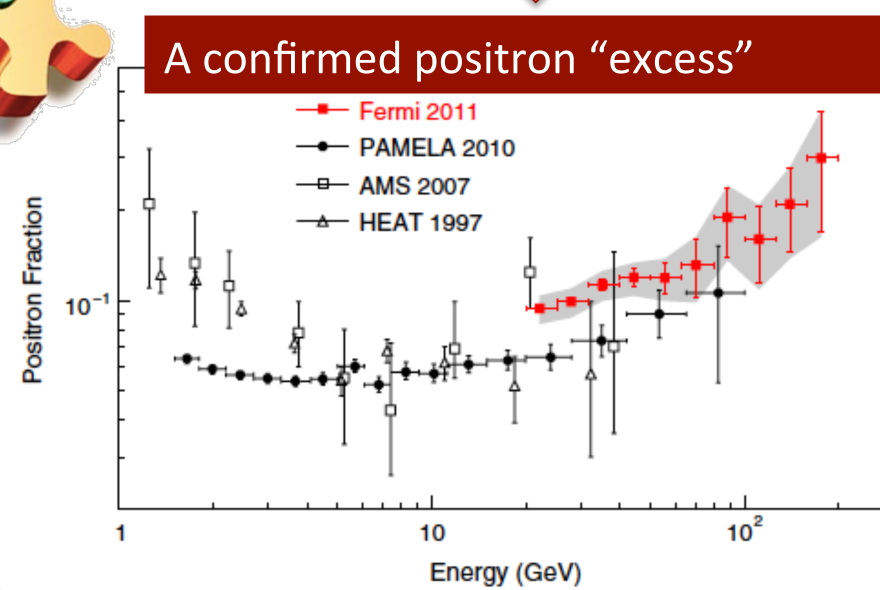
# Anti-matter & Exotic sources (DM ?)







# AMS Objectives according to some blogs…

http://www.rumormillnews.com/cgi-bin/archive.cgi?read=204750

…Shuttle Endeavor's official mission is to haul a deliberately-mislabeled "Alpha Magnetic Spectrometer" (AMS-02) to the International Space Station and install it. NASA claims that the AMS-02 is a state-of-the-art particle physics detector. In actuality the AMS-02 is an advanced extreme-energy neutral-particle-beam space weapon intended to shoot down Star Visitor craft (UFOs). And instead of the International Space Station, Shuttle Endeavor will deliver the AMS-02 Star Wars weapon to a secret military space station, also in orbit….

….

You are invited to join in a Joint Psychic Exercise to address these problems.

…

We will focus on one or both of two things. First is to direct telekinetic, electrical-pulse, disruptive-magnetic, and/or other energies to deactivate the AMS-02 neutral-particle-beam weapon and render it inoperative. Thus there will be nothing useful to deliver to the military space station.

# Objectives

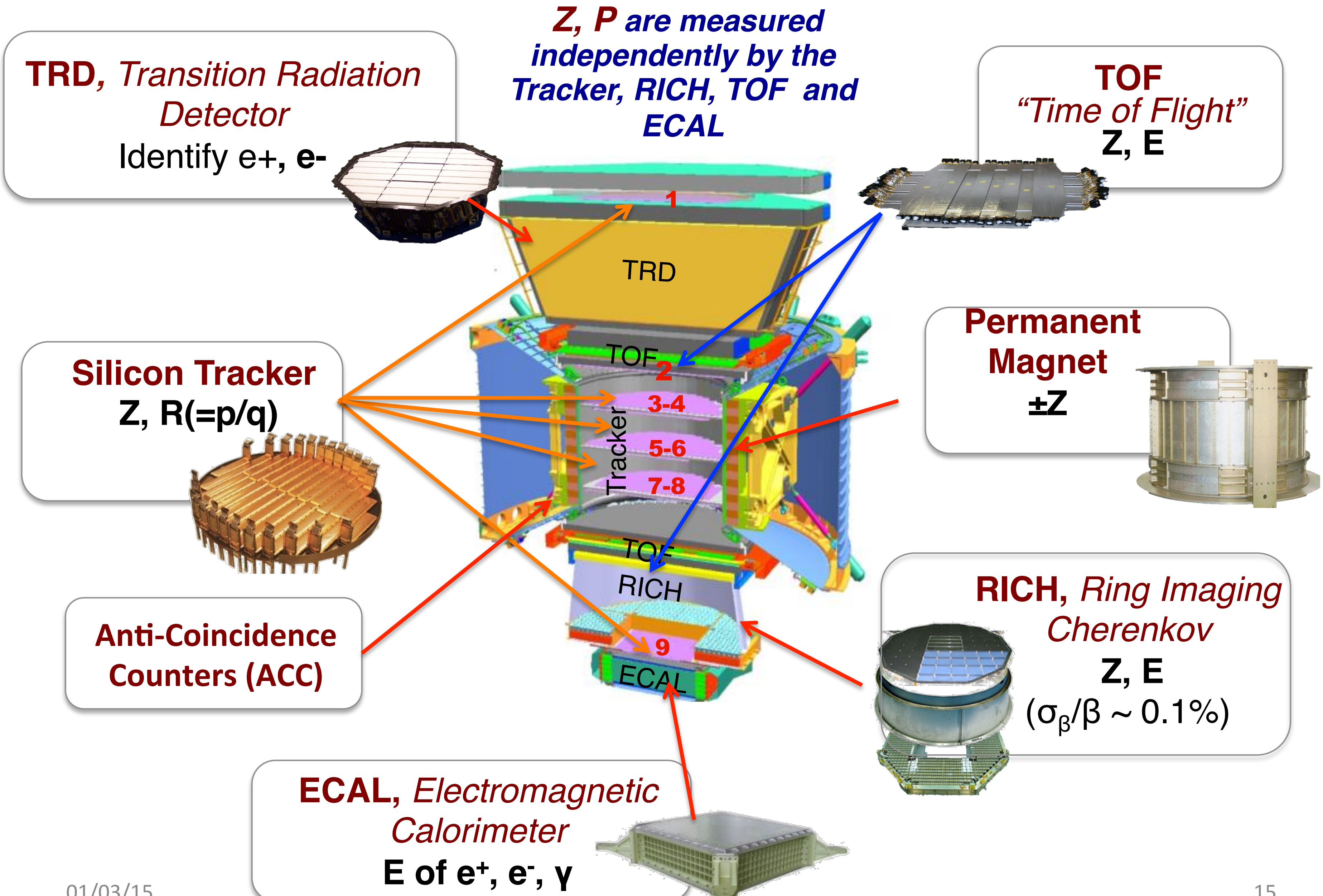
- ✓ **Fundamental physics & Antimatter :**
  - Primordial origin (anti-nuclei ?)
  - Exotic sources a.k.a DARK MATTER (positrons, anti-p, anti-D?,gammas)
- ✓ **The CR composition and energy spectrum** (how to understand the beam)
  - Sources & acceleration : Proton and He
  - Propagation in the ISM: (nuclear and isotopic composition)

# Requirements

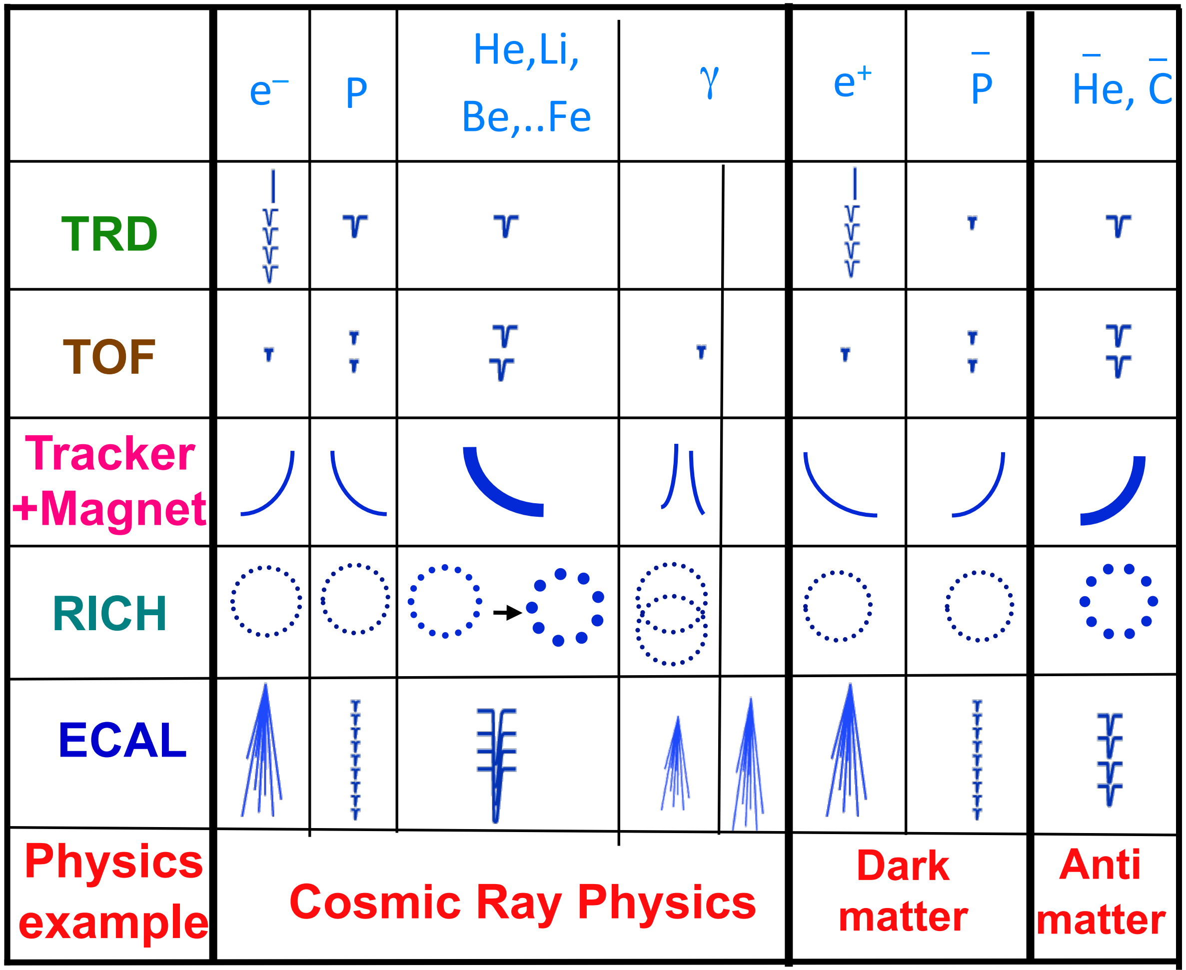
- ✓ **Particle identification and p/E measurement up to TeV:**
  - e/p separation at the $10^4$ level by means of independent detectors
  - Z : redundant measurements to evaluate fragmentation along the detector
  - Charge sign: matter to anti-matter separation (magnetic field!)
- ✓ **Statistics**
  - acceptance & efficiency
  - Exposure time

# PART 2 : The experimental challenge
## Detector & Operation

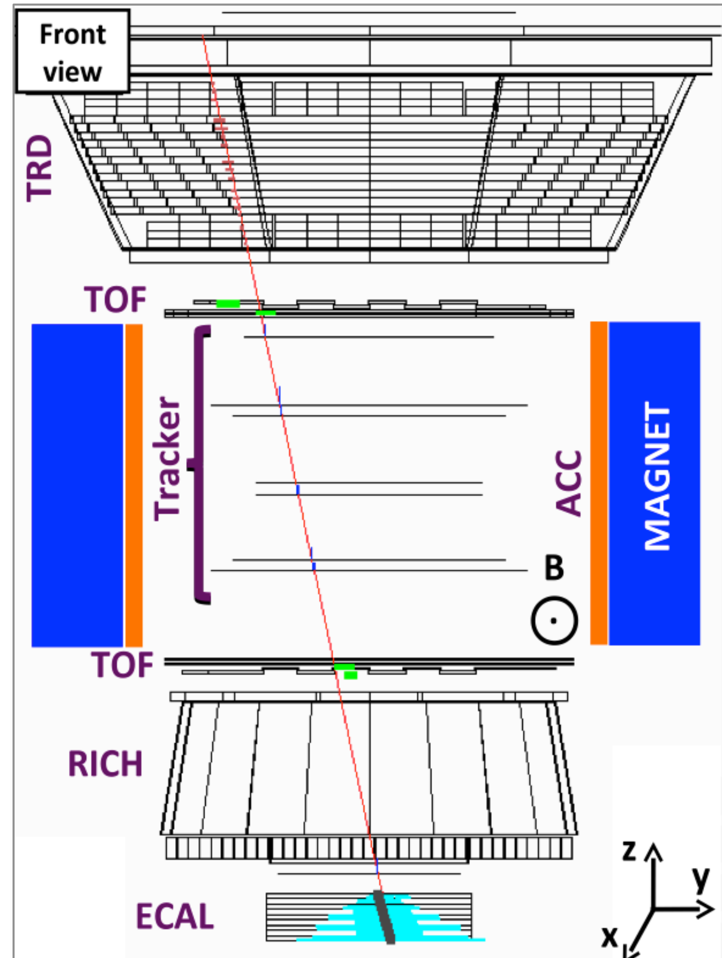
# AMS: A TeV precision, multipurpose spectrometer



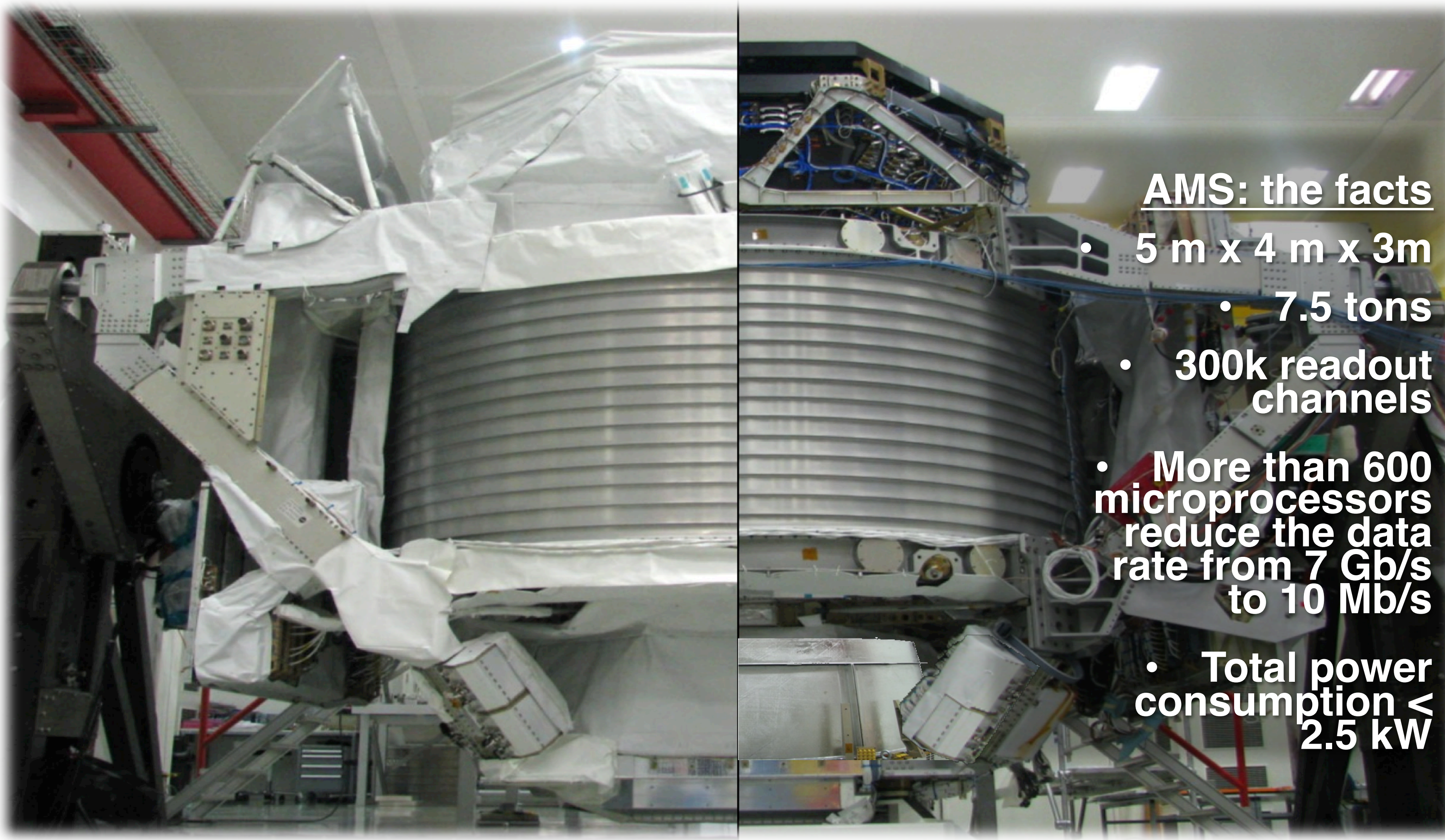
# Redundant measurements of incoming particles: full coverage of anti-matter & CR physics




600 GeV electron



# A HEP detector located in an hostile environment



**AMS: the facts**

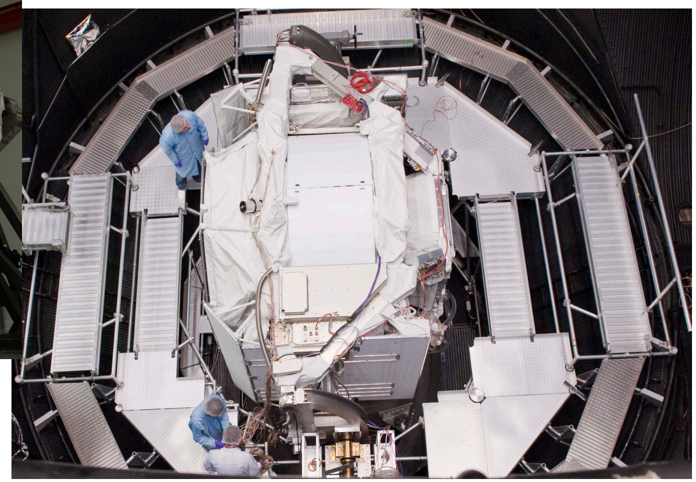
- 5 m x 4 m x 3m
- 7.5 tons
- 300k readout channels
- More than 600 microprocessors reduce the data rate from 7 Gb/s to 10 Mb/s
- Total power consumption < 2.5 kW

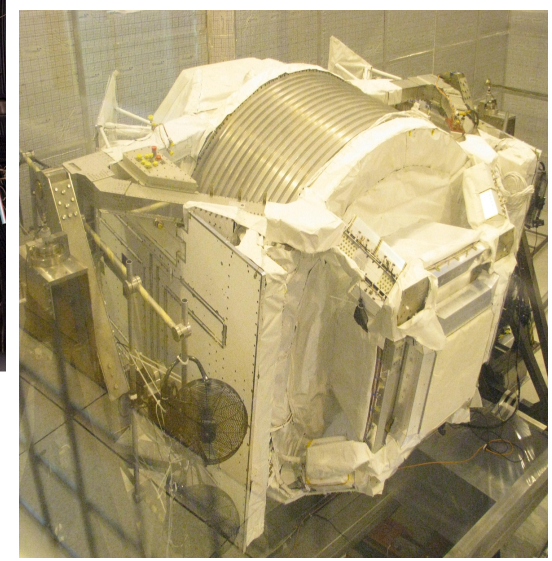
# Test….for all detectors:

## Before assembly : Beam test, Thermal, Vibration, TVT,EMI

## After assembly : EMI, TVT, Beam Test

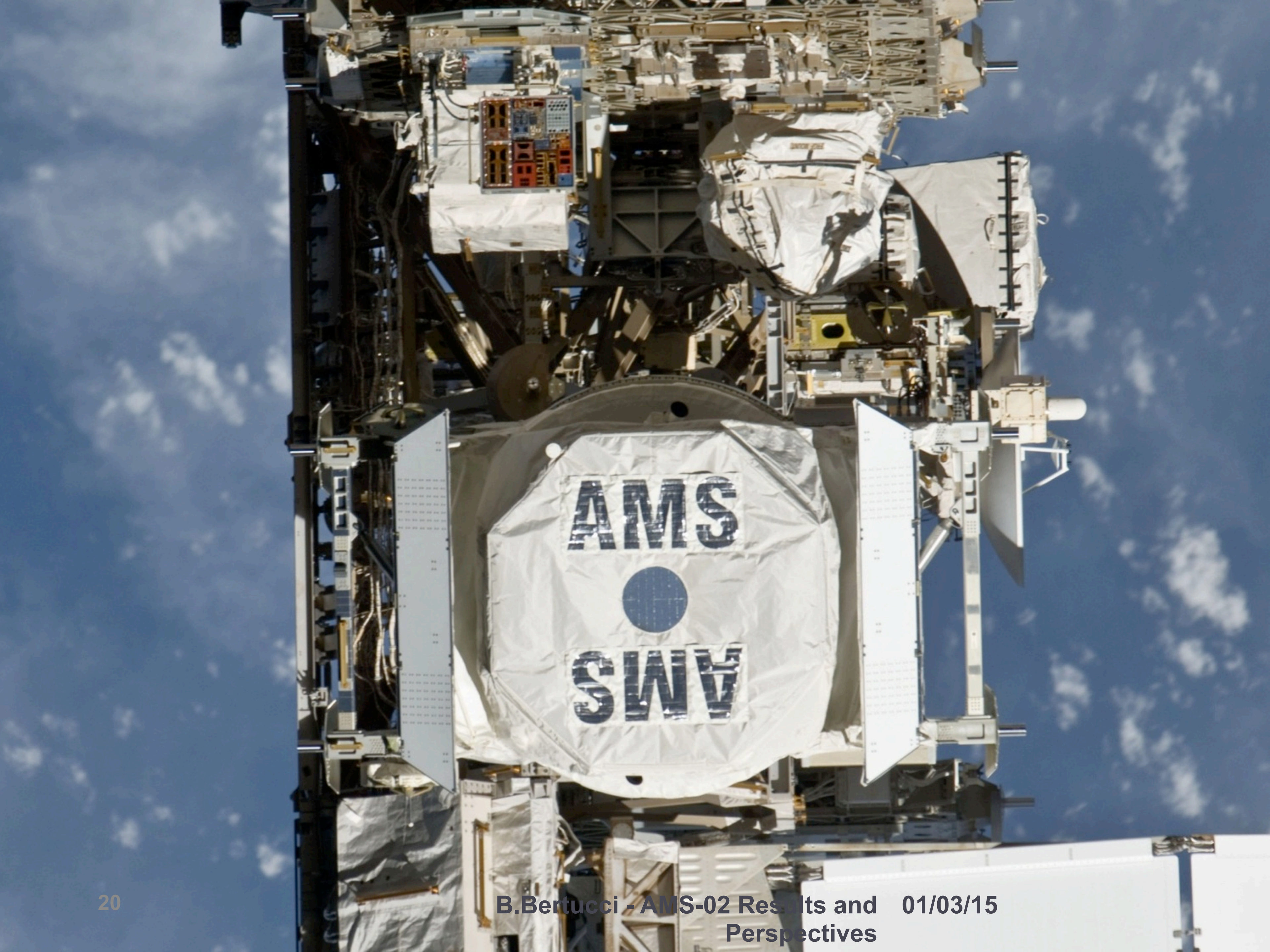

5m x 4m x 3m
7.5 tons





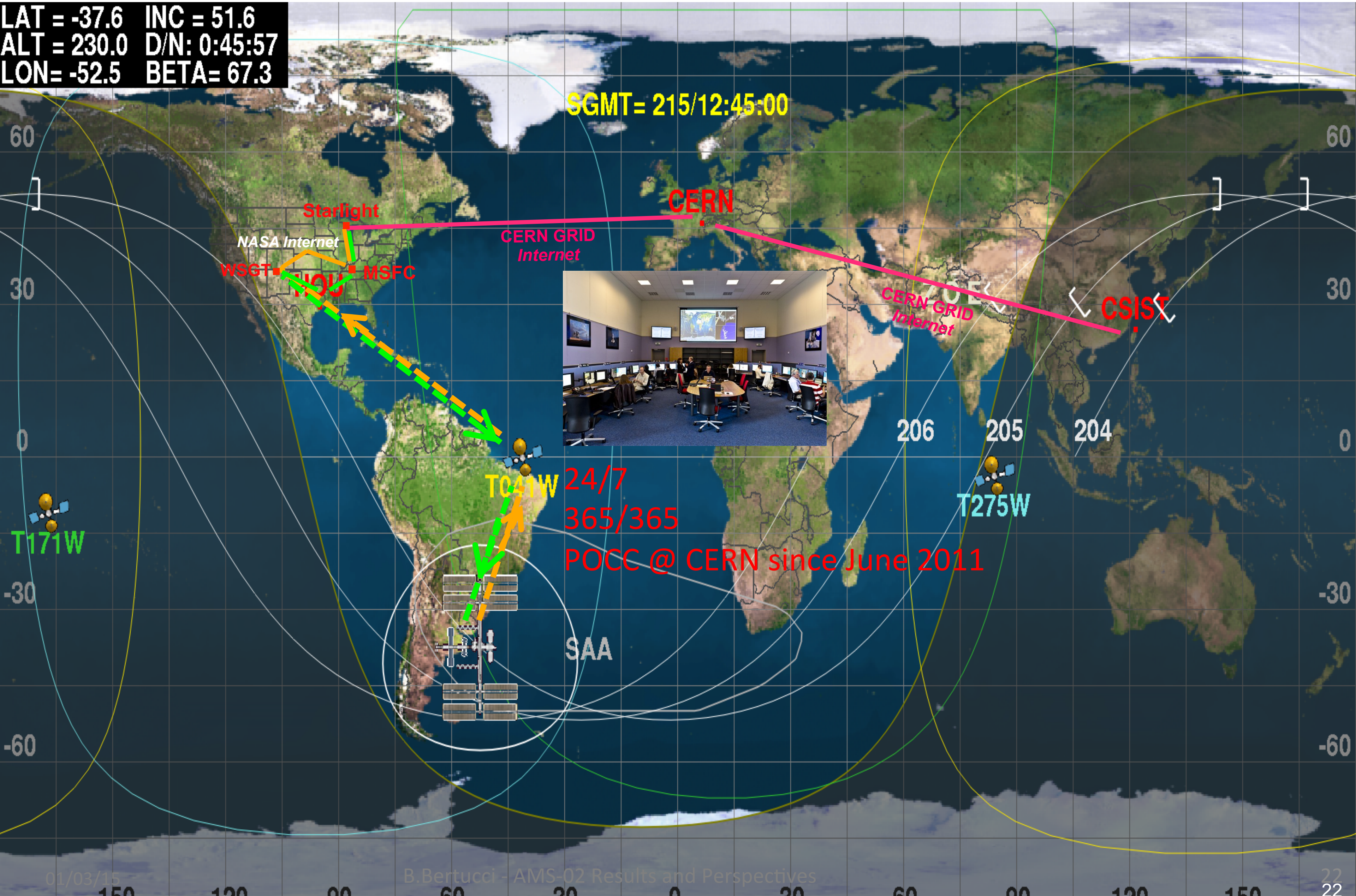
May 15, 2011

May 16, 2011


AMS
AMS

# May 19, 2011: AMS installation completed.

# AMS on ISS


LAT = -37.6 INC = 51.6
ALT = 230.0 D/N: 0:45:57
LON= -52.5 BETA= 67.3
SGMT= 215/12:45:00
CERN
Starlight
NASA Internet
WSGT
MSFC
CERN GRID Internet
CERN GRID Internet
CSIST
206
205
204
T041W
T275W
T171W
SAA
24/7
365/365
POCC @ CERN since June 2011
60
30
0
-30
-60
-150
-120
-90
-60
-30
0
30
60
90
120
150

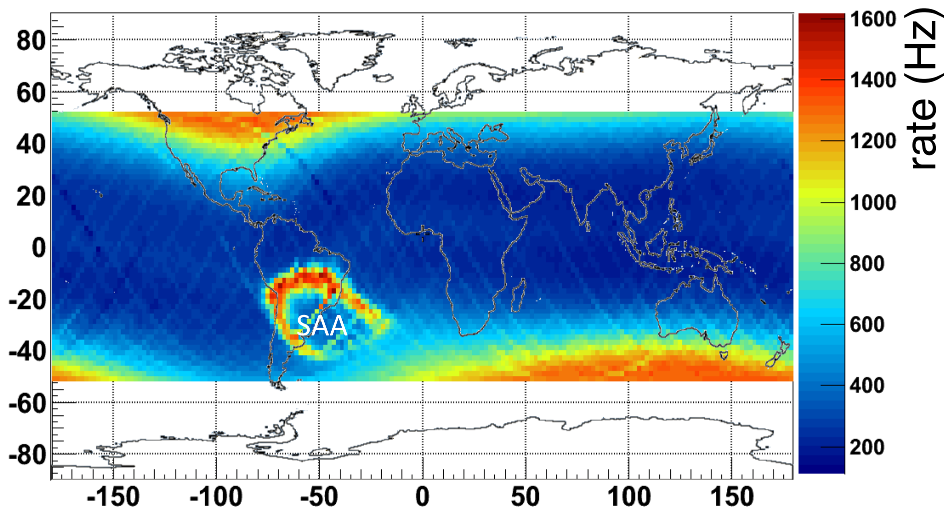
# Payload Operation Control Center (POCC) @ CERN

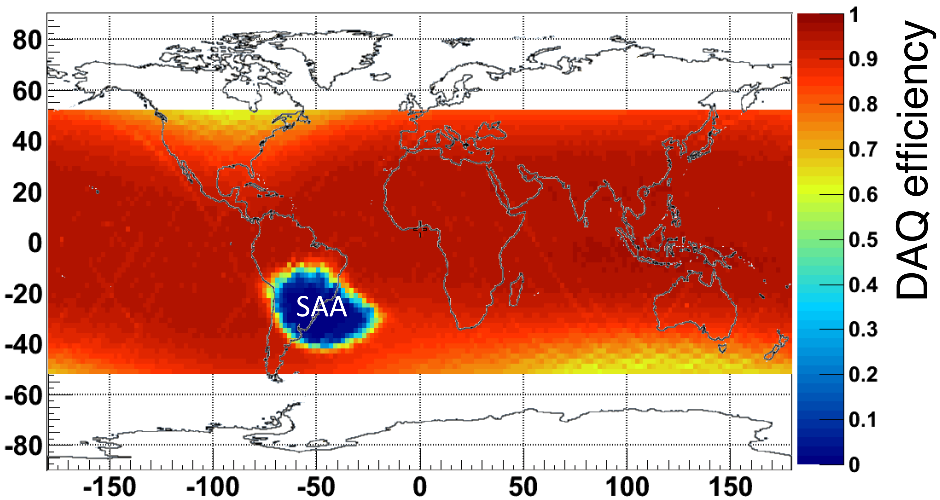
24/24 hours

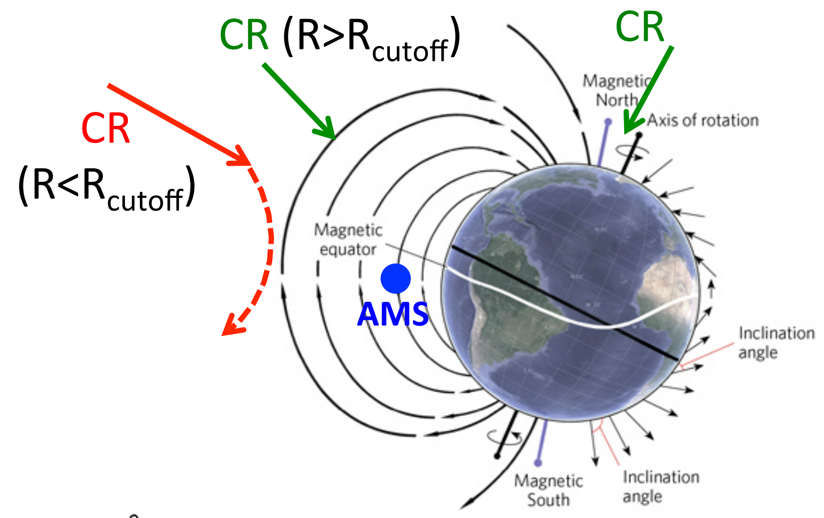
All along the year…no technical stops…

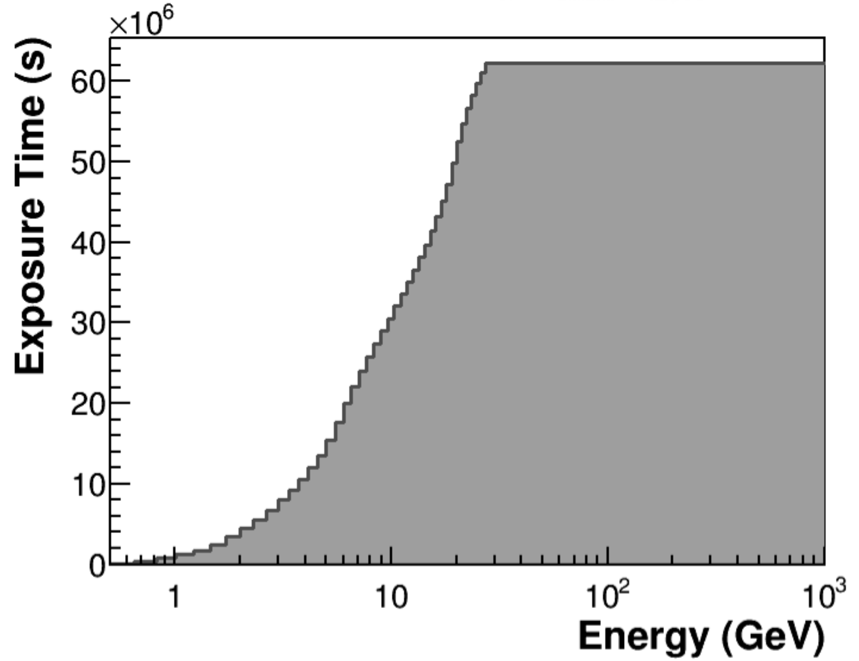
# Orbital DAQ parameters

<Acquisition rate> ≈ 500 Hz



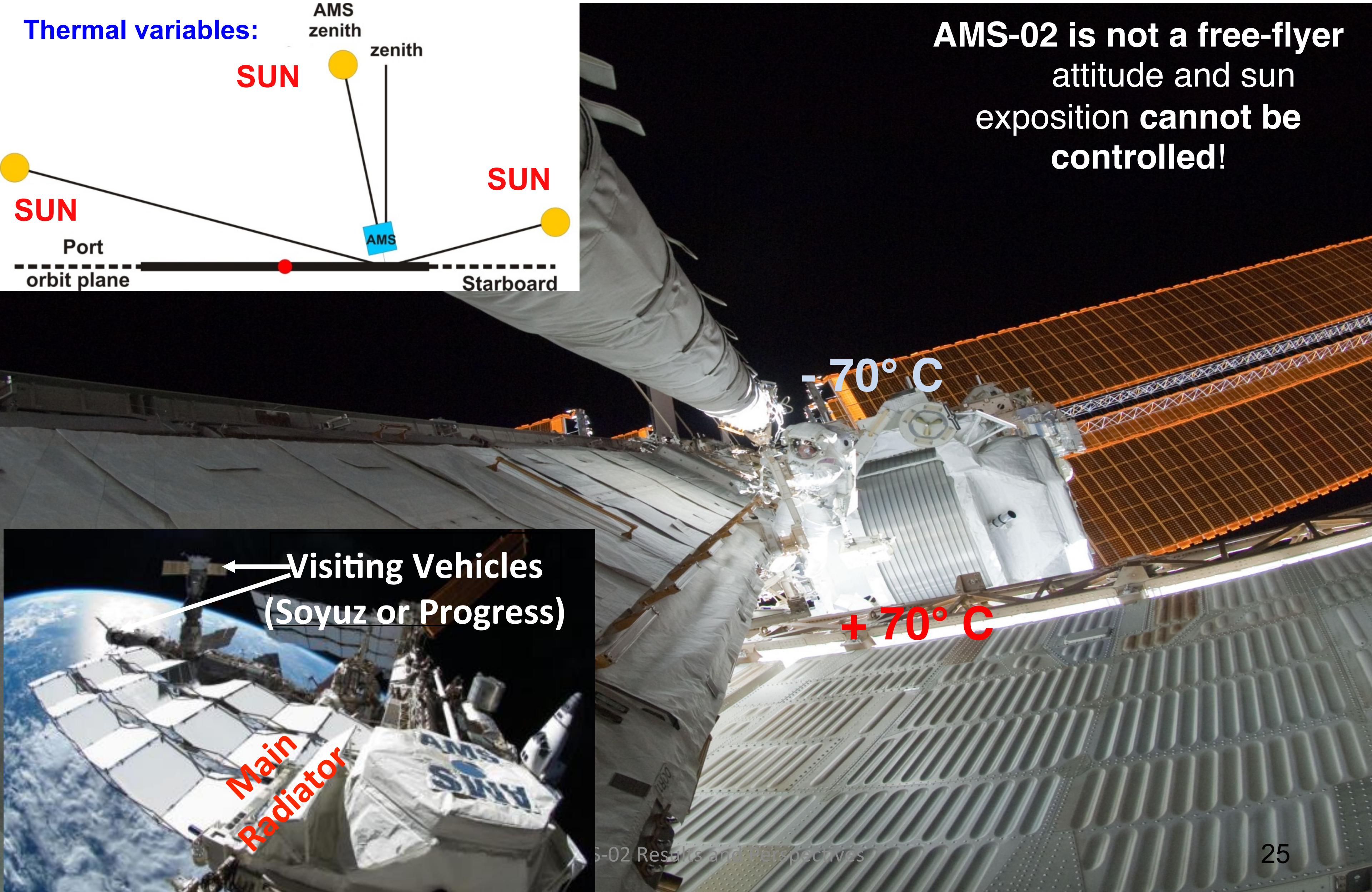




Cutoff & Orbit → Average life time fraction $T_{exp}$/44 months ~ 80 %

# The Thermal environment

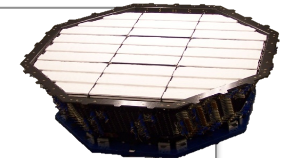


# Thermal environment

**TOF & ACC**

**64** Temperature Sensors

**TRD**

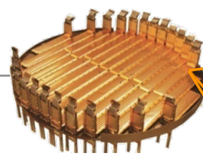


**24** Heaters

**8 Pressure Sensors**

**482** Temperature Sensors

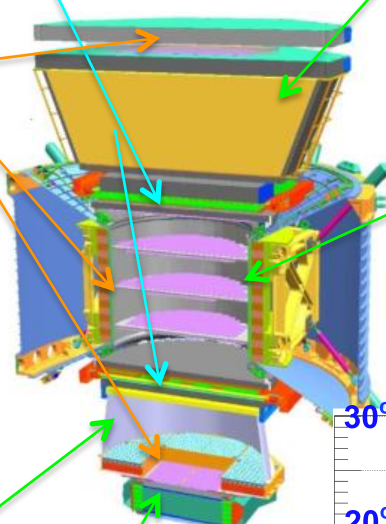
**Silicon Tracker**



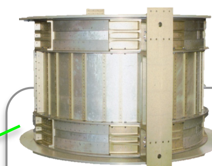
**4** Pressure Sensors

**32** Heaters

**142** Temperature Sensors

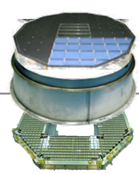


**Magnet**



**68** Temperature Sensors

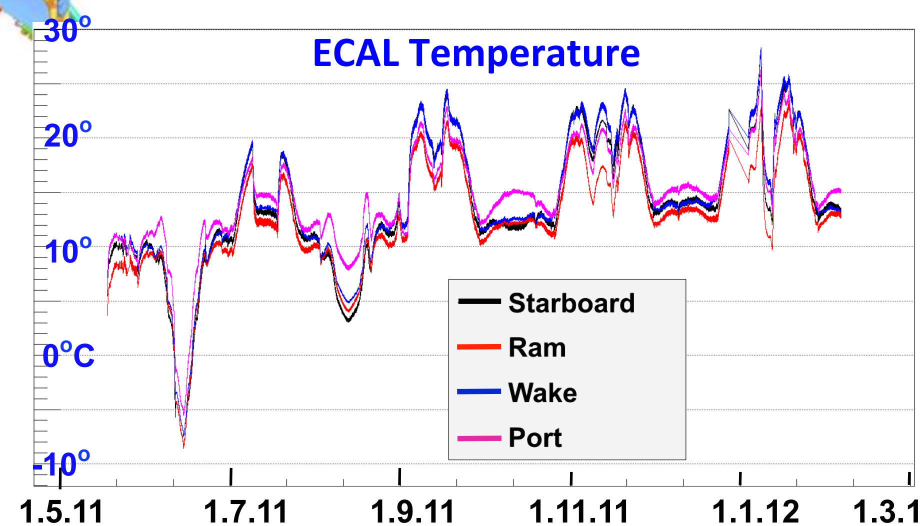
**RICH**



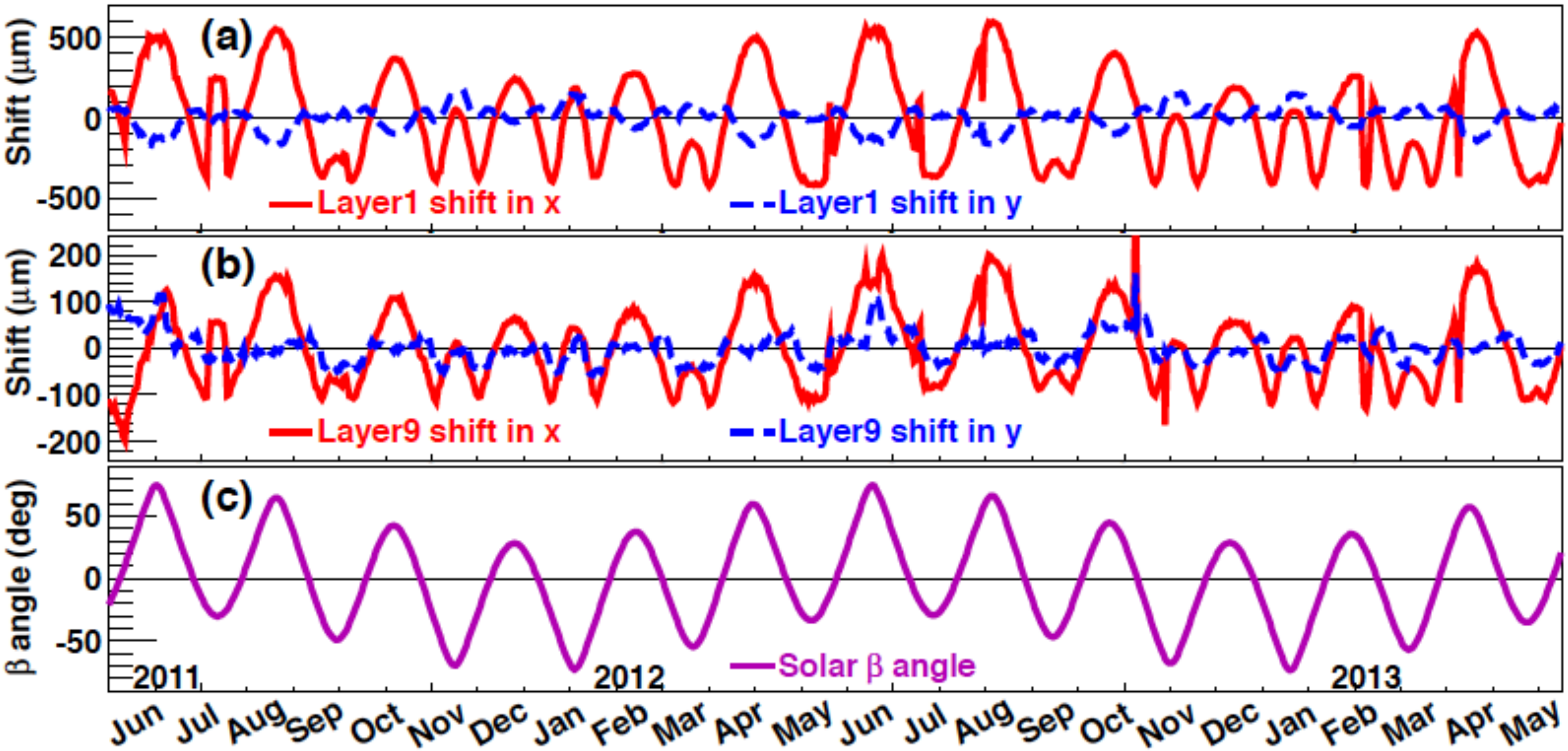
**96** Temperature Sensors

**ECAL**

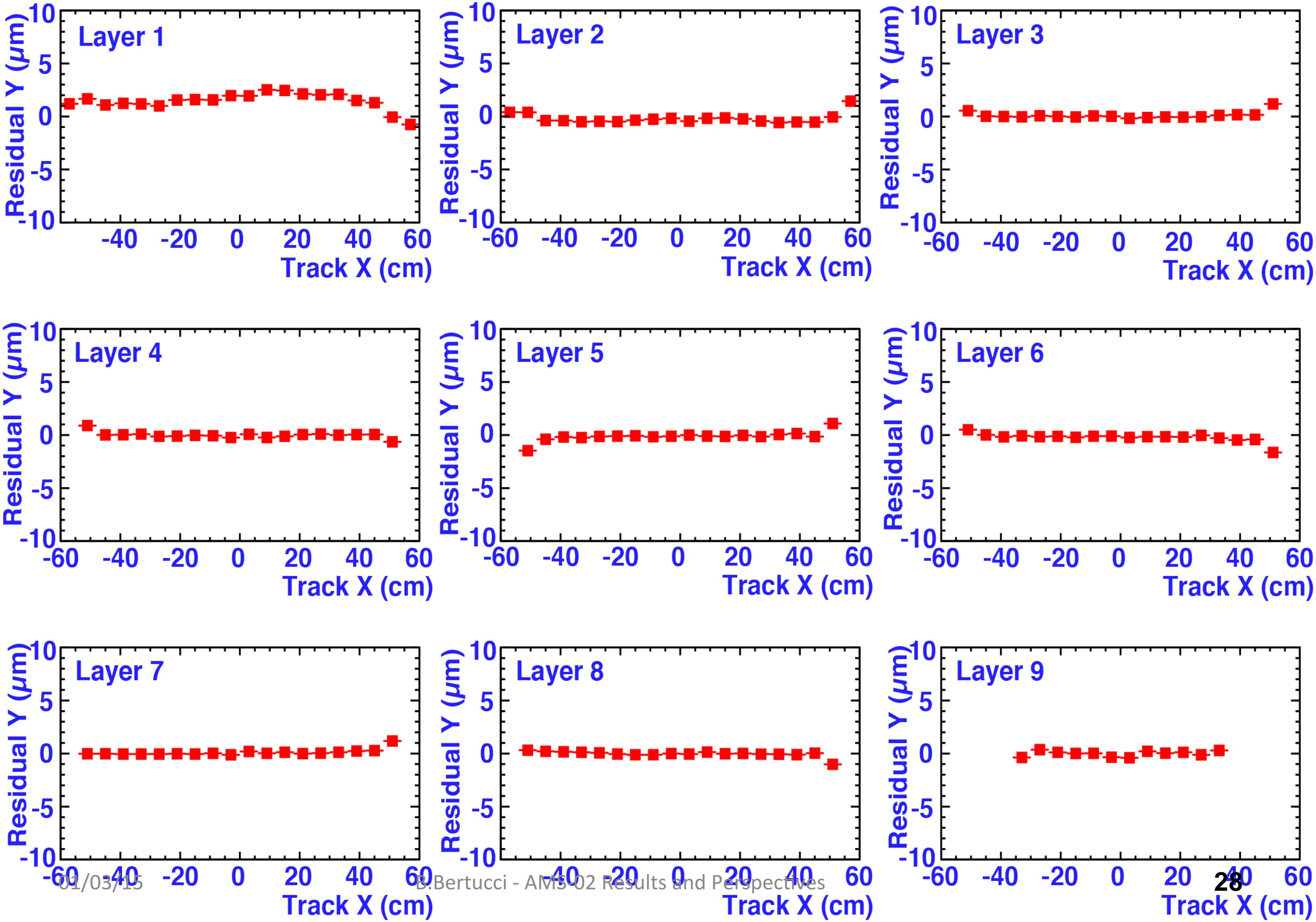
**80** Temperature Sensors



# Seasonal effects on external Tracker planes

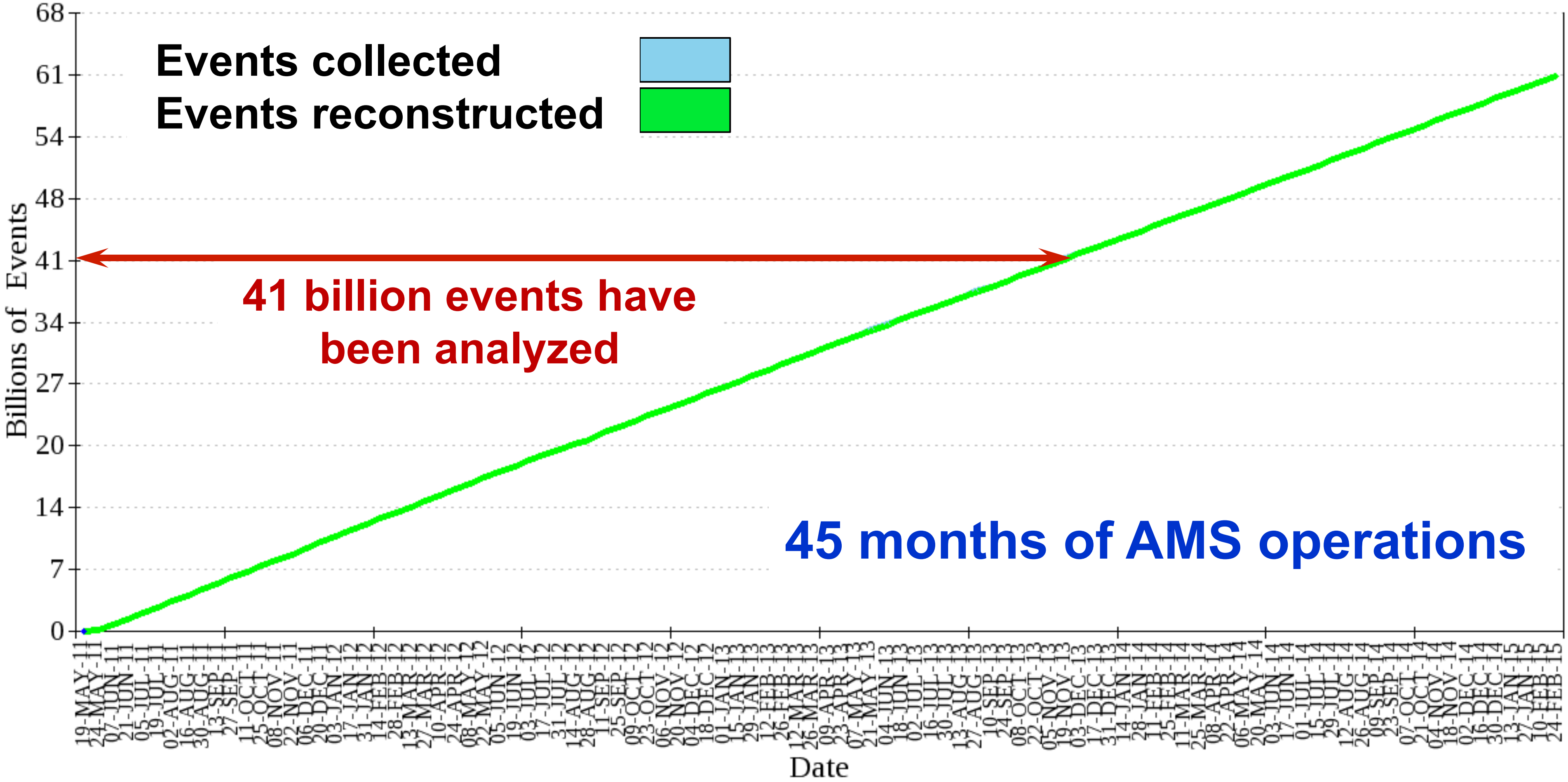


# Alignment accuracy of the 9 Tracker layers



# To date AMS collected over 60 billion events

(This is much more than all the cosmic rays collected in the last 100 years.)



# Results :

## … going to the % accuracy in CR physics

**Published**:

1. **Positron Fraction** ( 0.5–350 [2013] 0.5-500 GeV [2014])
2. **Electron** ( 0.5–700 GeV ) and **Positron Fluxes** ( 0.5–500 GeV )
3. **All electrons Flux** (0.5 GeV – 1 TeV)

**in 2015:**

1. **….proton, he fluxes**
2. **….anti-proton**
3. **….B, C, Li, O …ratio / fluxes**

# $e^-/e^+$ selection in AMS

**-TRD:**

- identify the particle as $e^+/e^-$ rejecting the hadronic hypothesis

**-TOF:**

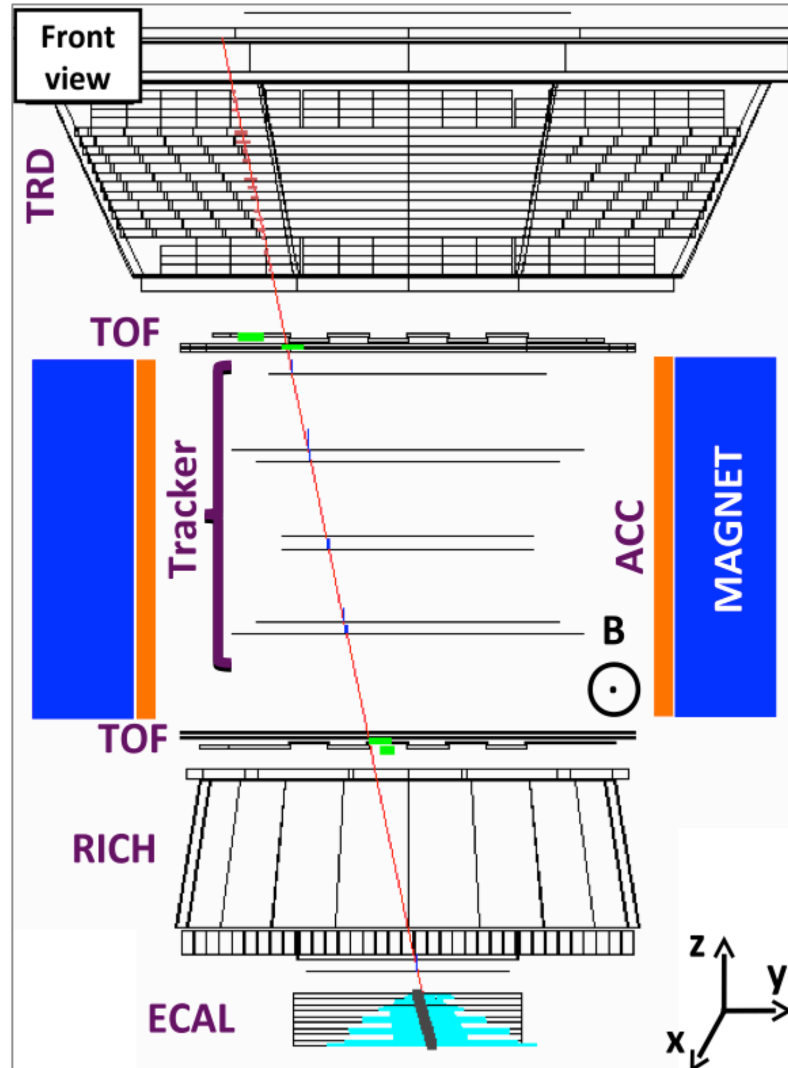
- main trigger
- down going relativistic particle
- Z=1

**-TRACKER:**

- Identify charge sign ($e^-/e^+$)
- Z=1

**-ECAL:**

- identify the particle as $e^+/e^-/\gamma$ rejecting the hadronic hypothesis
- measurement of energy

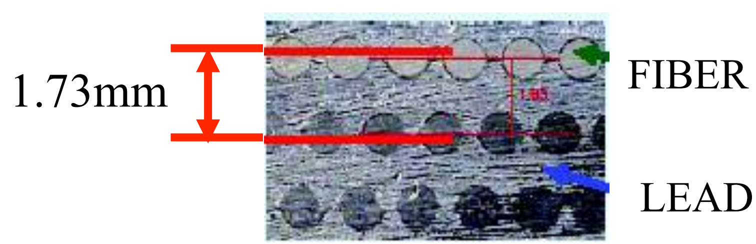


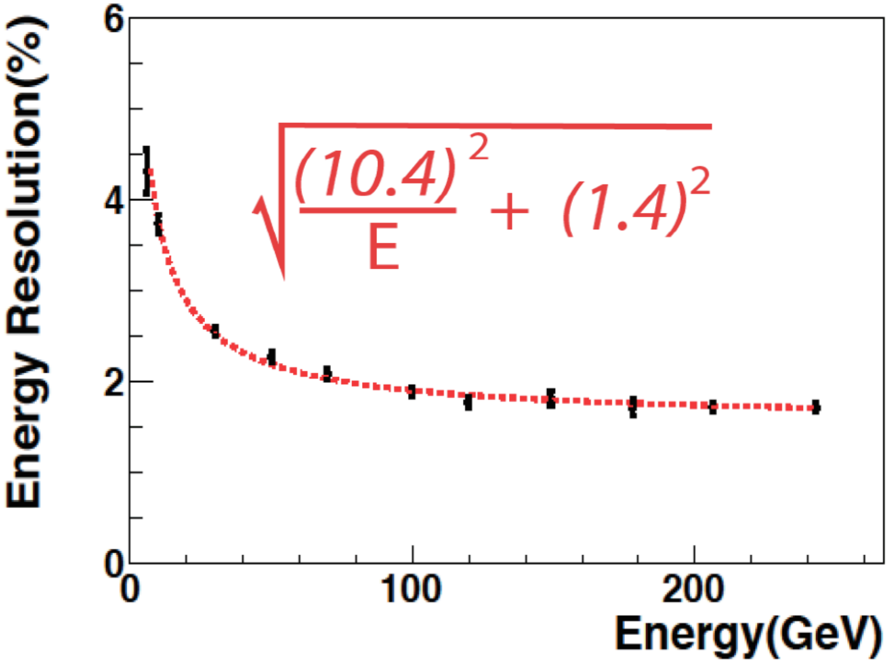
# e/p separation in ECAL

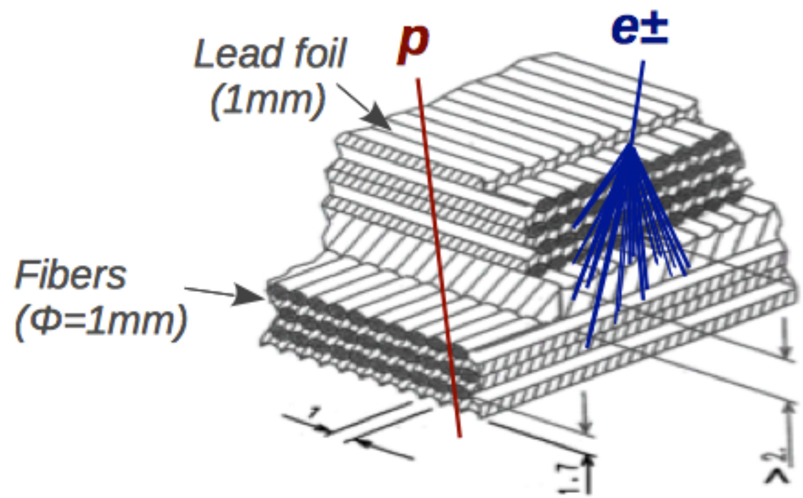
## 3D Electromagnetic Calorimeter (ECAL)

- Measurement of $e^{\pm}$ and γ energy ($\Delta E/E \sim 2\%$@100 GeV).
- *p/e rejection >$10^4$*
- 18 layers of lead and scintillating fiber

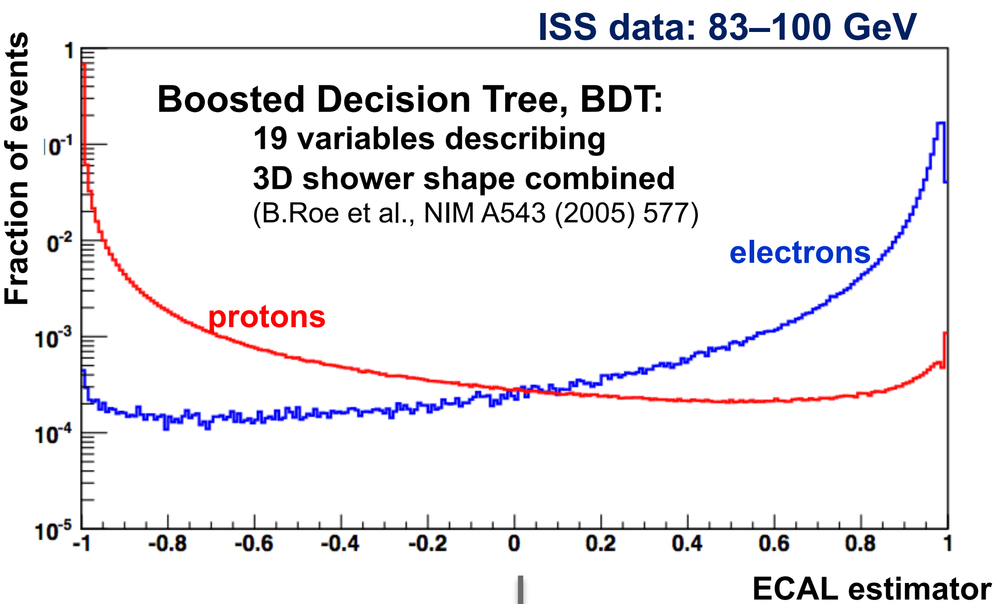
*50,000 fibers, $\phi$ = 1 mm distributed uniformly inside 600 kg of lead: Total* ***~17 $X_0$***

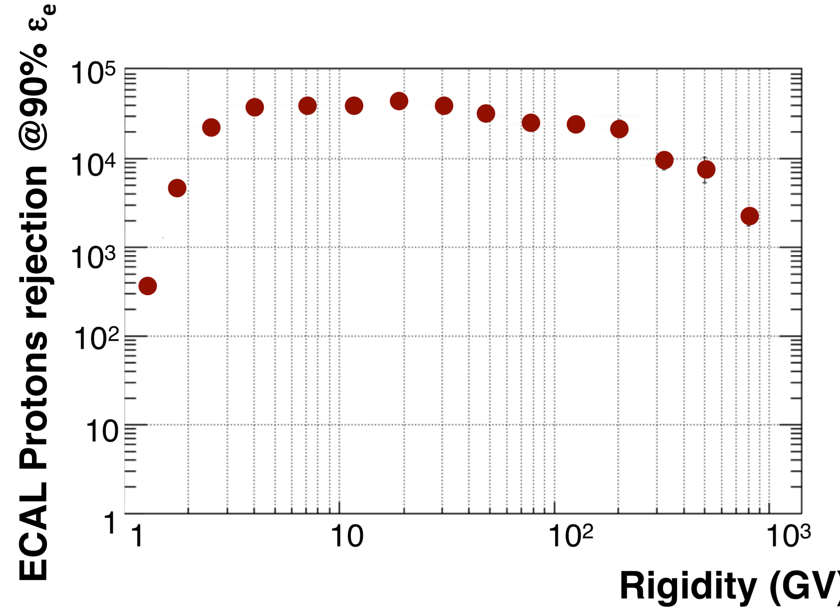


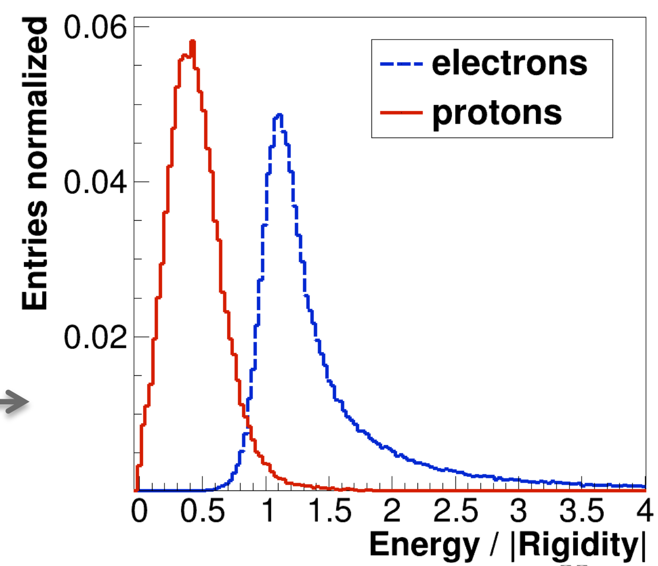
# e/p separation in ECAL



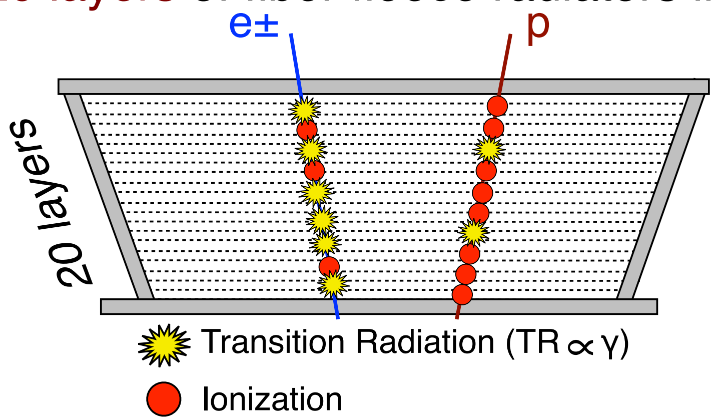

Thanks to its shower shape imaging capabilities can **discriminate** with high efficiency **eletromagnetic from hadronic showers**

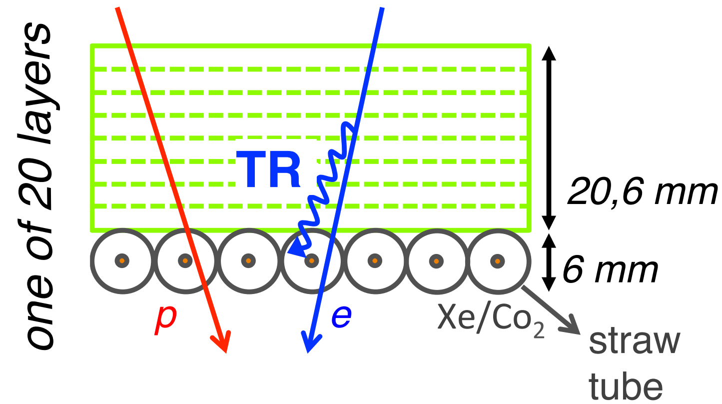
Combining the ECAL energy information with the Tracker Rigidity (E/R) the **e/p rejection** can be further **increased**

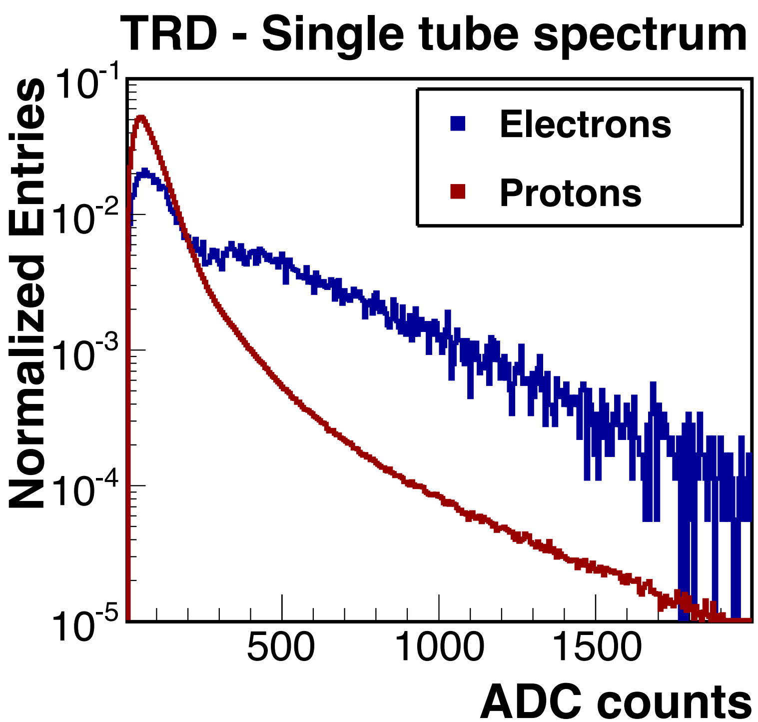


# e/p separation in TRD

20 layers of fiber fleece radiators interleaved with 80:20 $Xe/Co_2$ straw tubes.



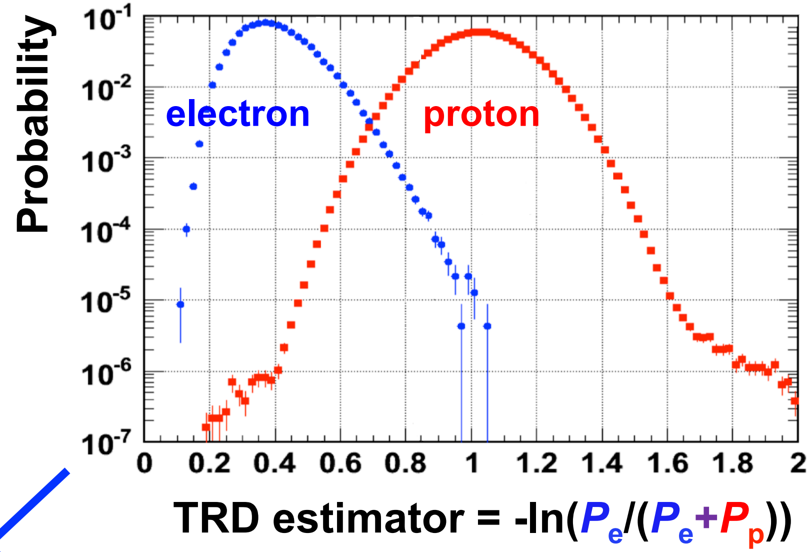




over all
20 layers

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

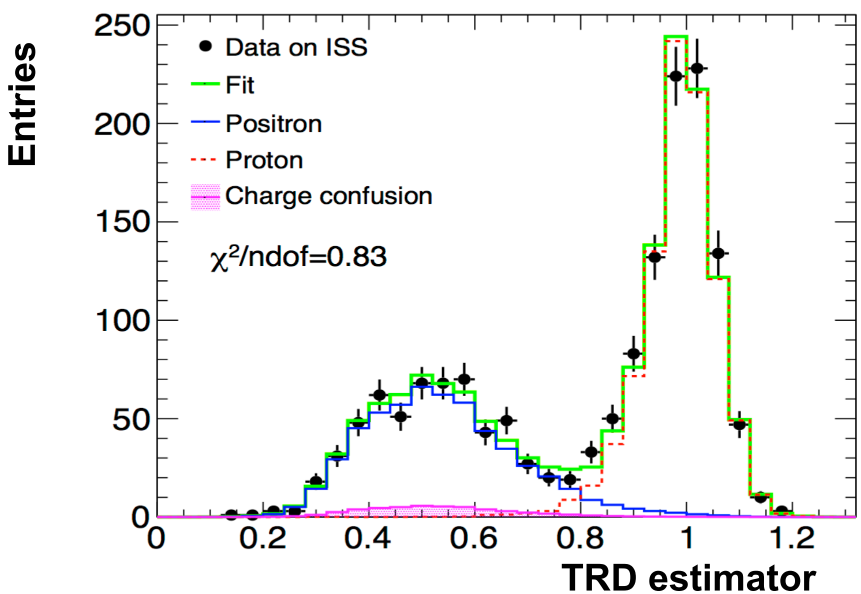
$$P_p = \sqrt[n]{\prod_i^n P_p^{(i)}(A)}$$

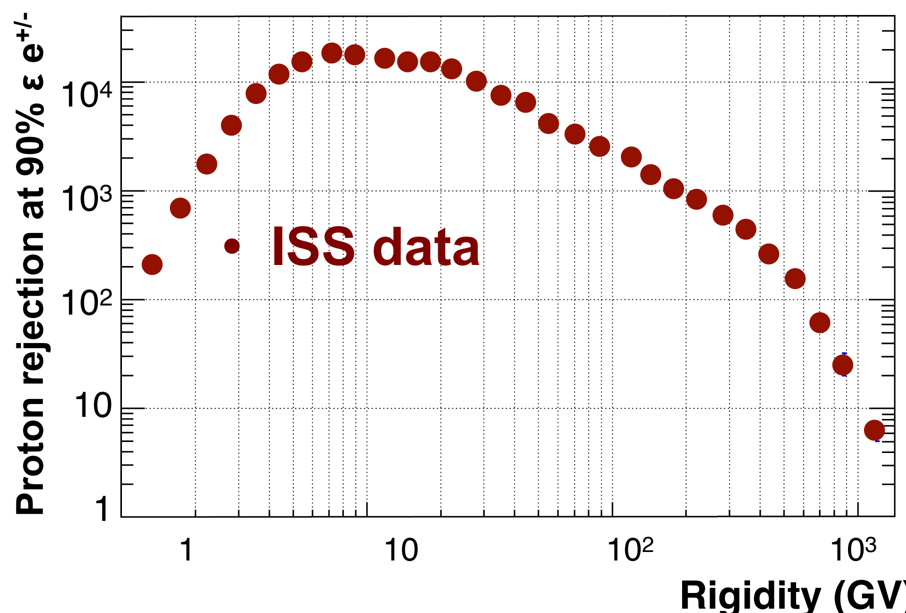
# e/p separation in TRD



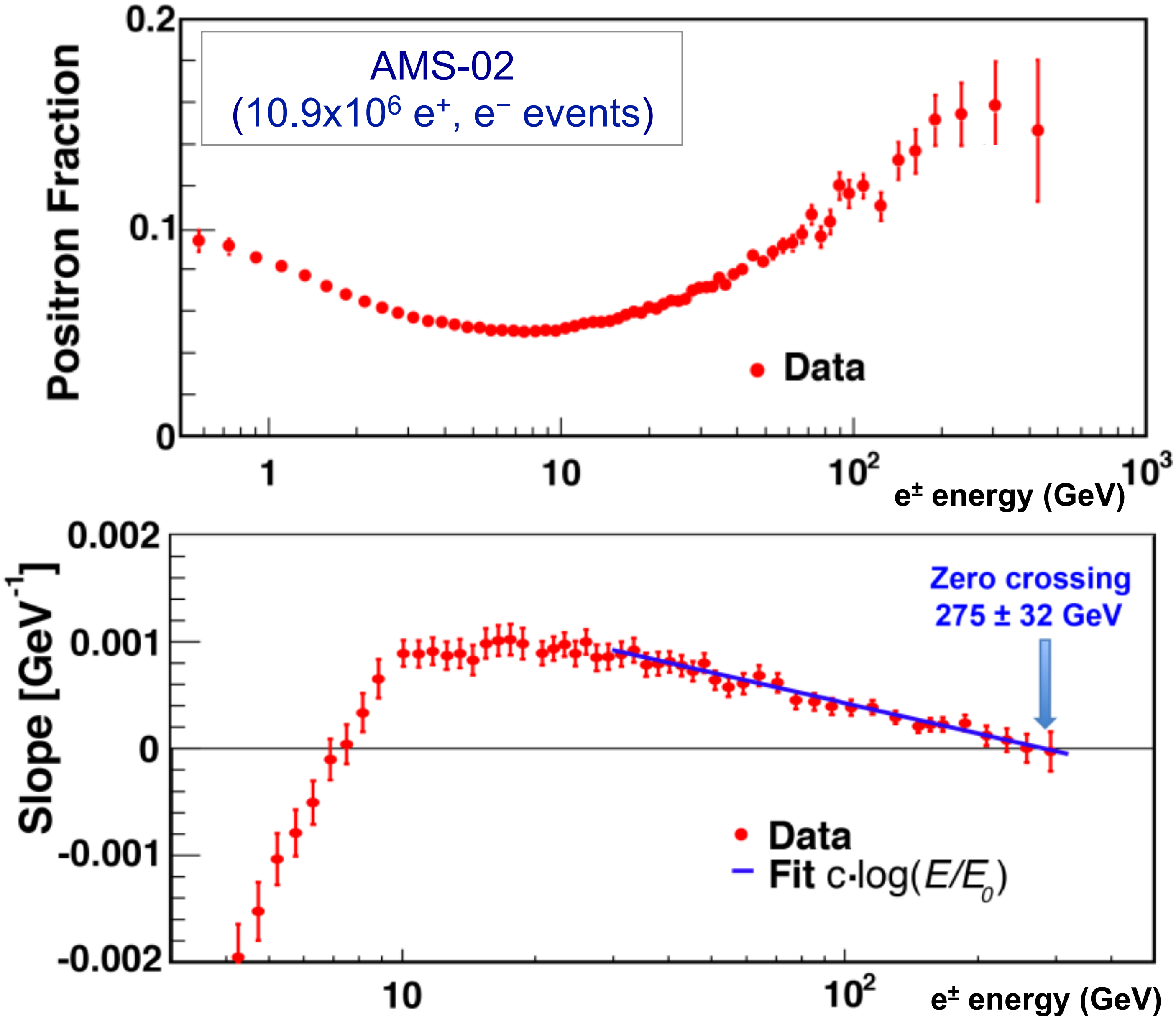

FIT

CUT



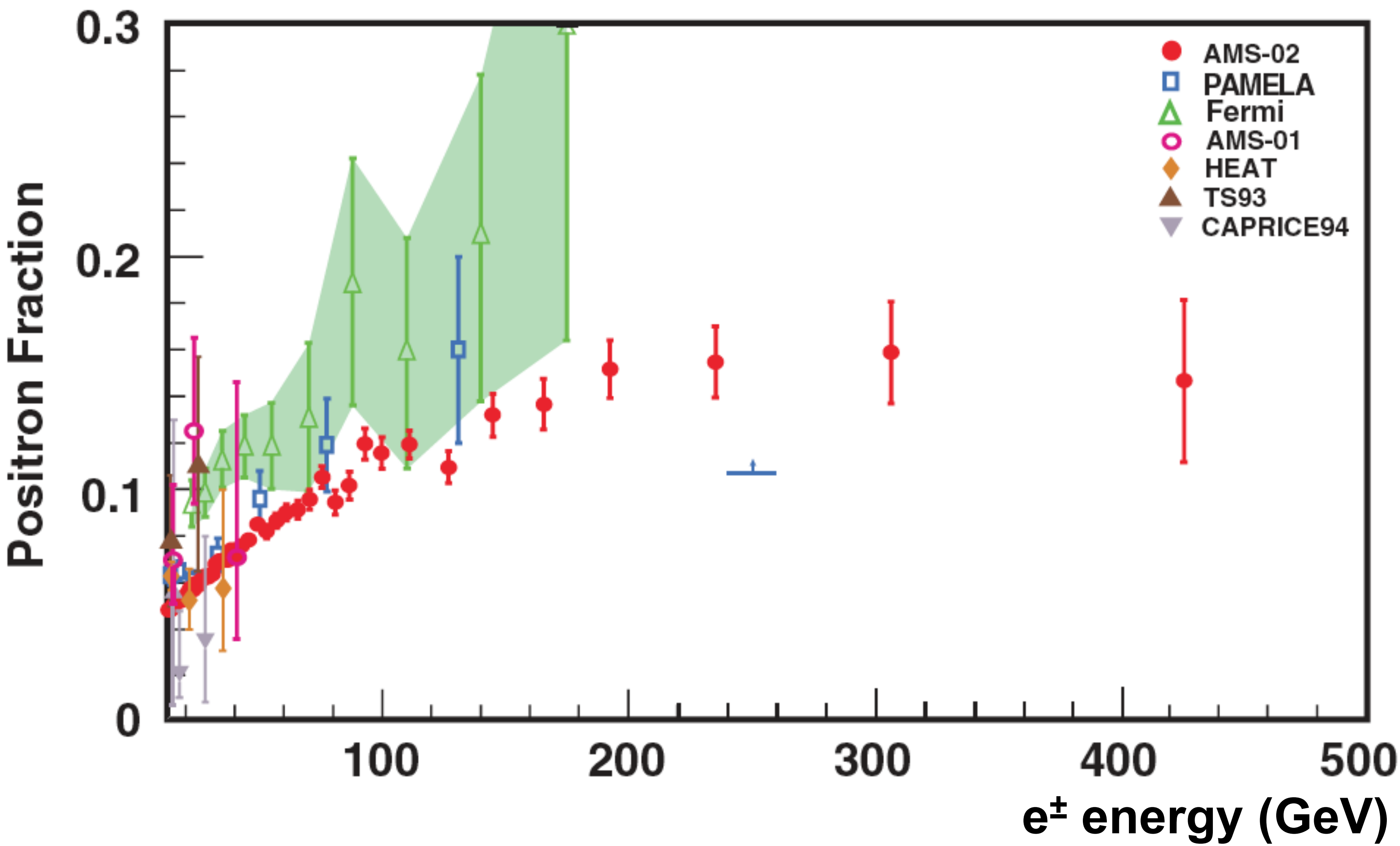



# The Positron fraction : $e^+/(e^+ + e^-)$

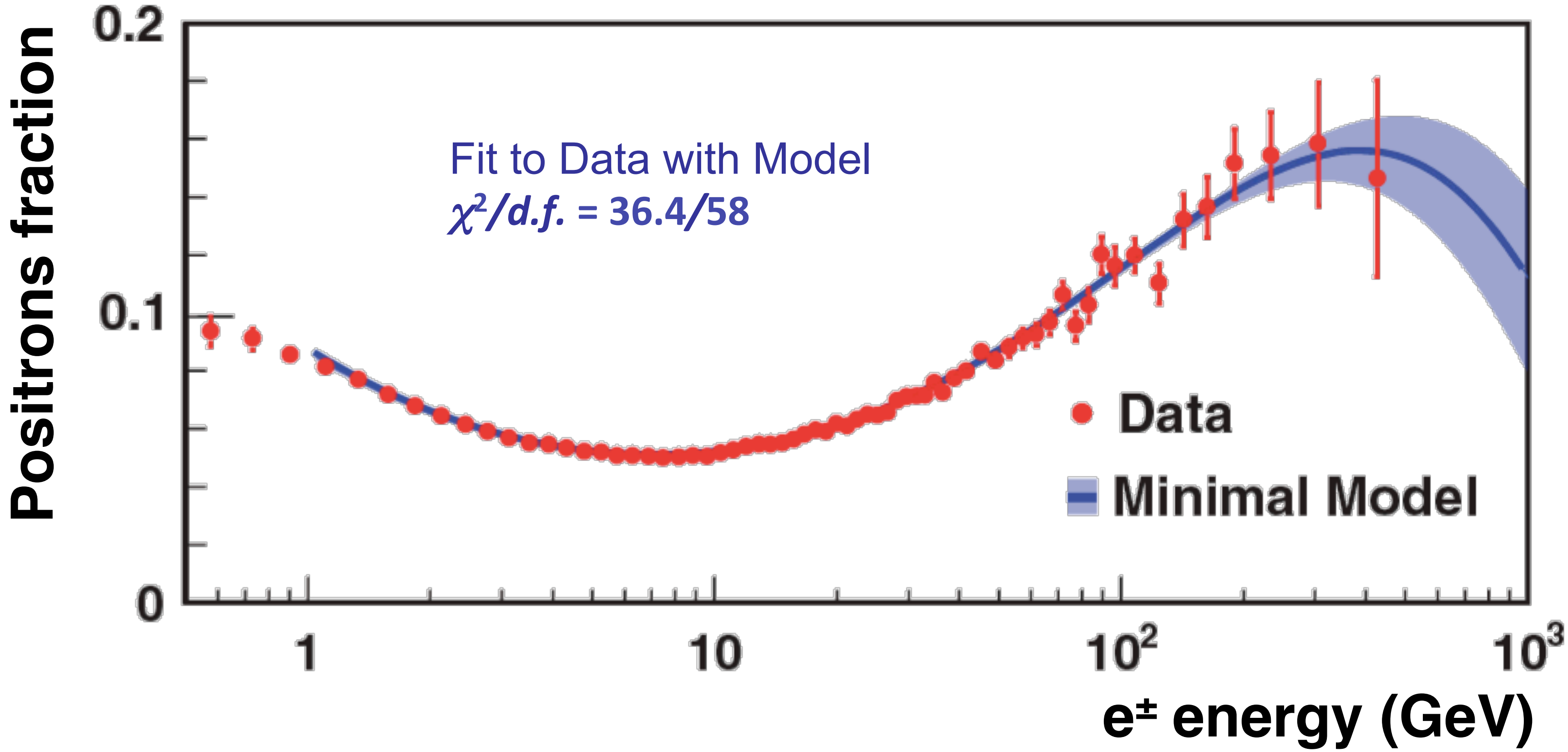



**No fine structures are observed, no anisotropies, slope suggests a maximum?**

# Positron fraction @ high energies



# Minimal empirical model




Describe electron and positron fluxes as a sum of a **diffuse component** and a **common source** with a cutoff energy :

$$\Phi_{e+} = C_{e+} E^{-\gamma_{e+}} + C_s E^{-\gamma_s} e^{-E/E_s}$$

$$\Phi_{e-} = C_{e-} E^{-\gamma_{e-}} + C_s E^{-\gamma_s} e^{-E/E_s}$$

$\gamma_{e-} - \gamma_{e+} = -0.56 \pm 0.03$

$\gamma_{e-} - \gamma_{S} = 0.72 \pm 0.04$

$C_{e+}/C_{e-} = 0.091 \pm 0.001$

$C_S/C_{e-} = 0.0061 \pm 0.0009$

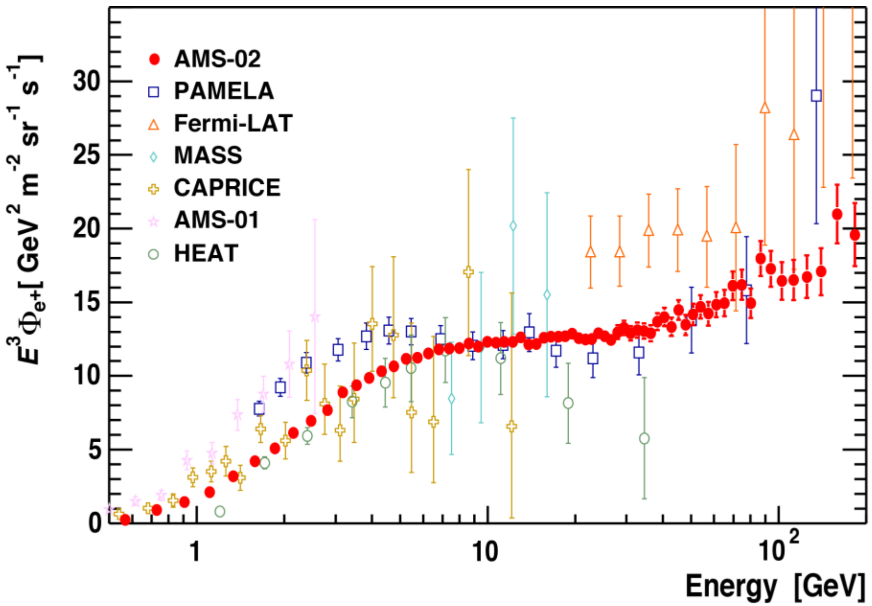
$1/E_s = 1.84 \pm 0.58\ \text{TeV}^{-1}$

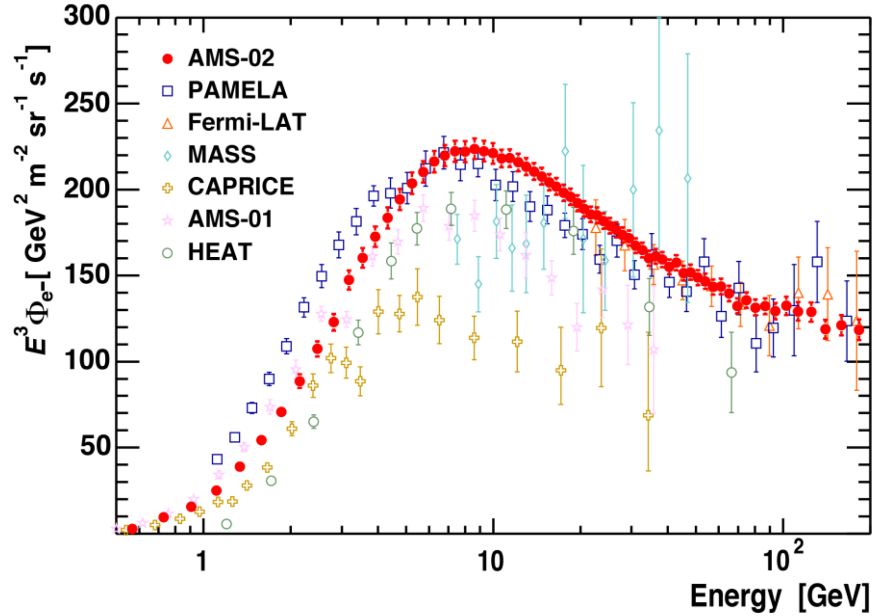
## Physics origin of the source term ?

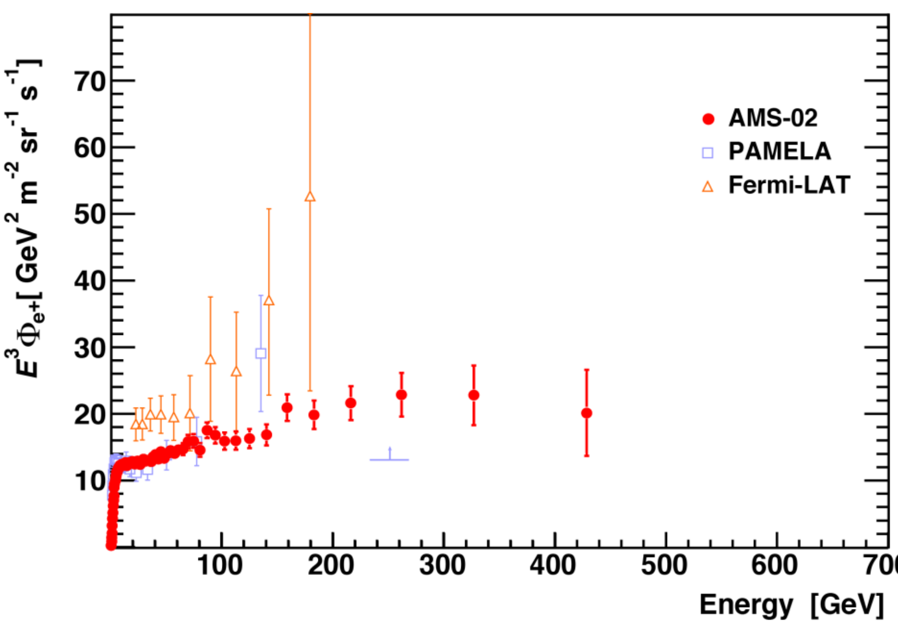
1) Particle origin: Dark Matter
2) Astrophysics origin: Pulsars, SNRs
3) Secondaries: peculiarities of propagation

**>300 references to the first AMS publication in 22 months..**

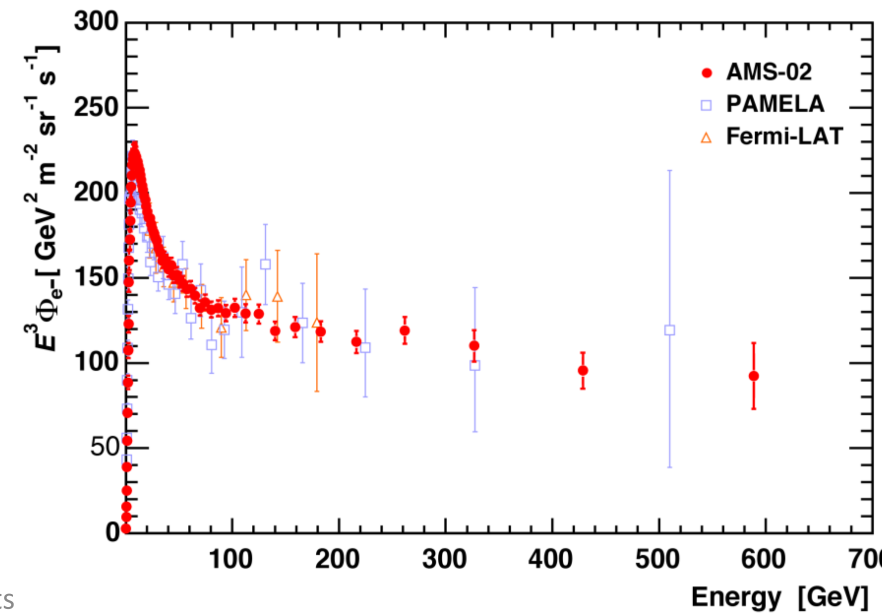
# Positron & Electron fluxes



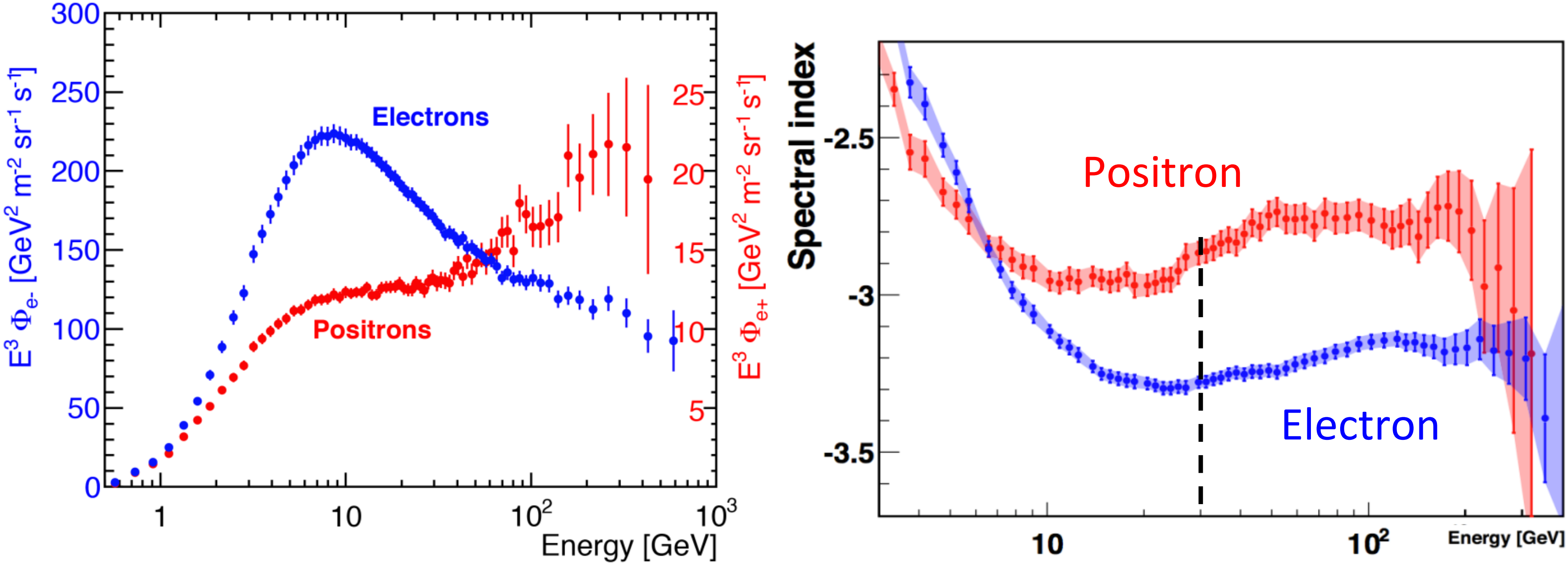




lts



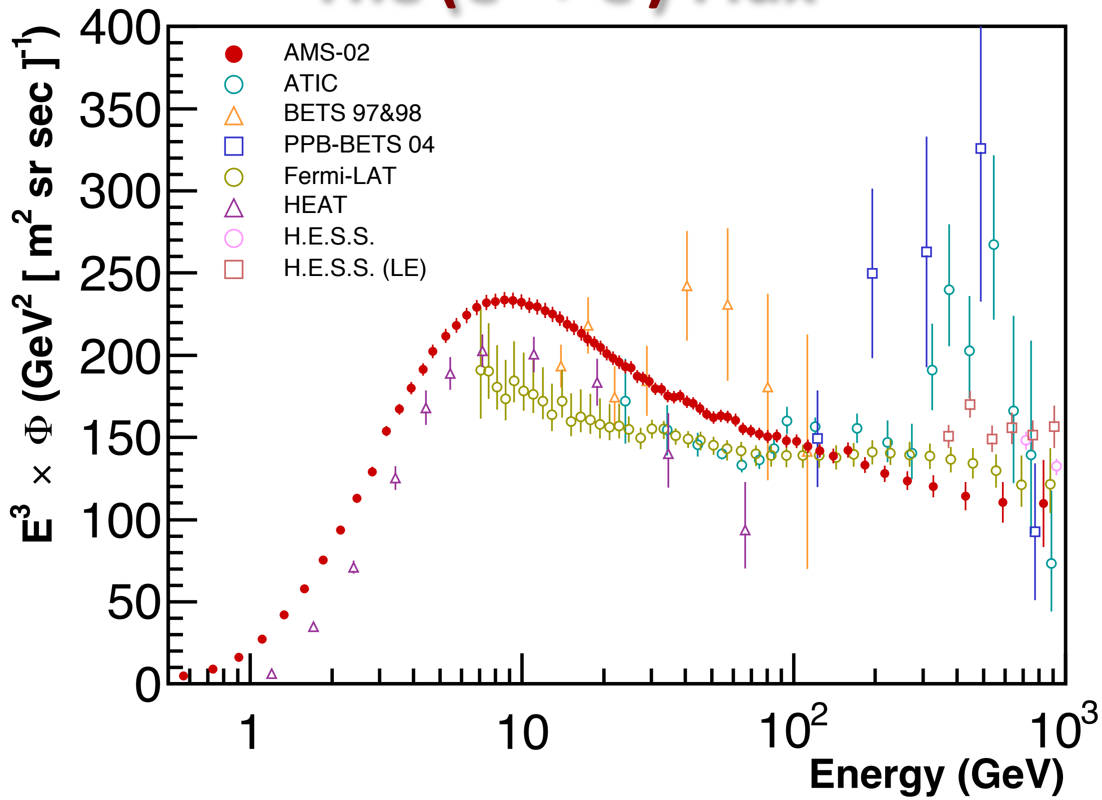
# The e$^-$ and e$^+$ fluxes

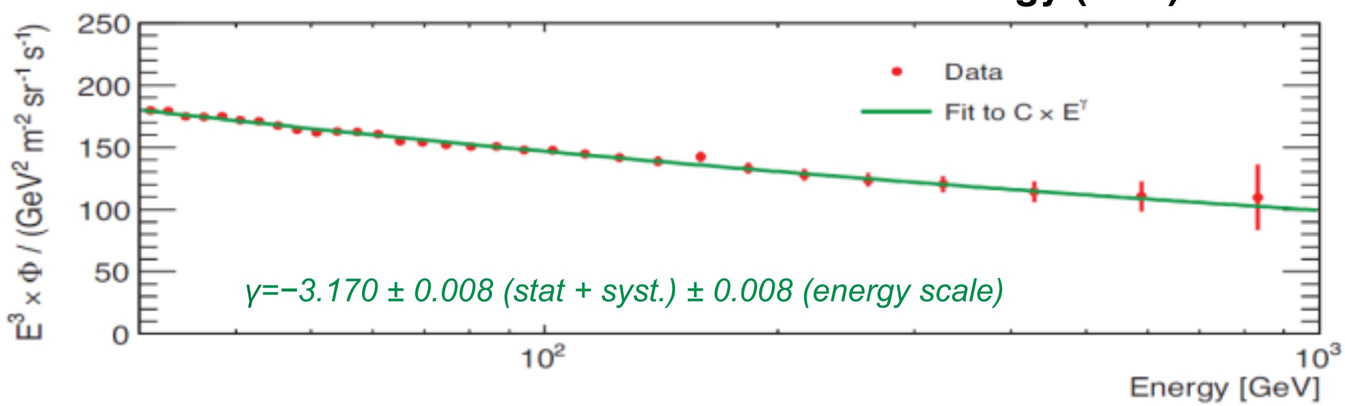



## Observations:

1. Both the electron flux and the positron flux **are significantly different in their magnitude and energy dependence**.
2. Both spectra **cannot be described by single power laws**.
3. The **spectral indices** of electrons and positrons **are different**.
4. Both change their behavior at **~30GeV**.
5. 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).

# The (e⁺ + e⁻) Flux



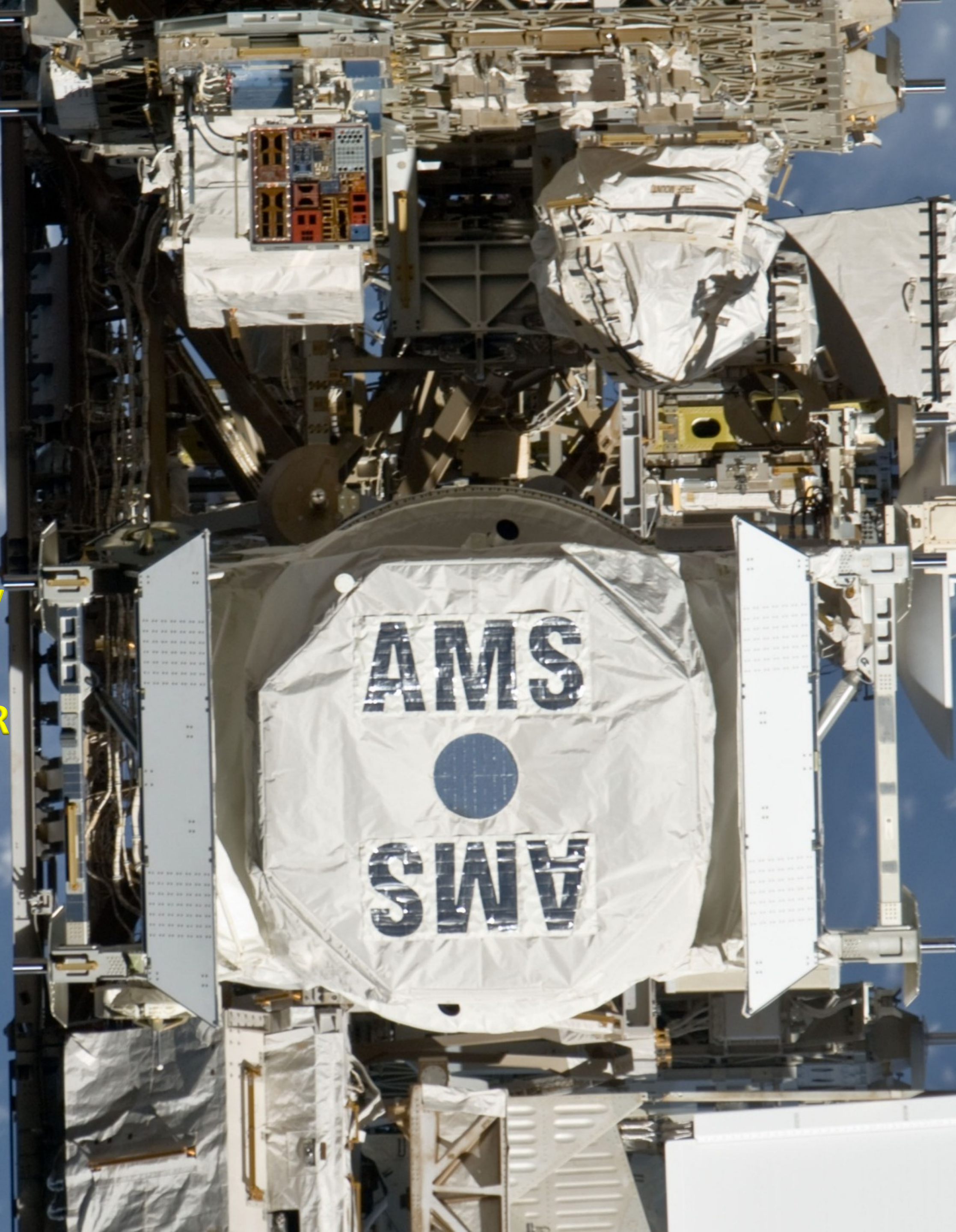




**The flux is smooth and it is consistent with a single power law above 30 GeV.**

# Conclusions

AMS is the Cosmic Rays observatory of the next decade

- The observed positron excess may imply a heavy Dark Matter WIMP particle or a new mechanism of acceleration in the pulsars: more statistics and measurements in complementary channels are needed
- Accurate measurements of the CR primary components and of anti-protons are been performed
- More data…more fun !




STAY TUNED !

# Thanks for your attention

# BACKUP

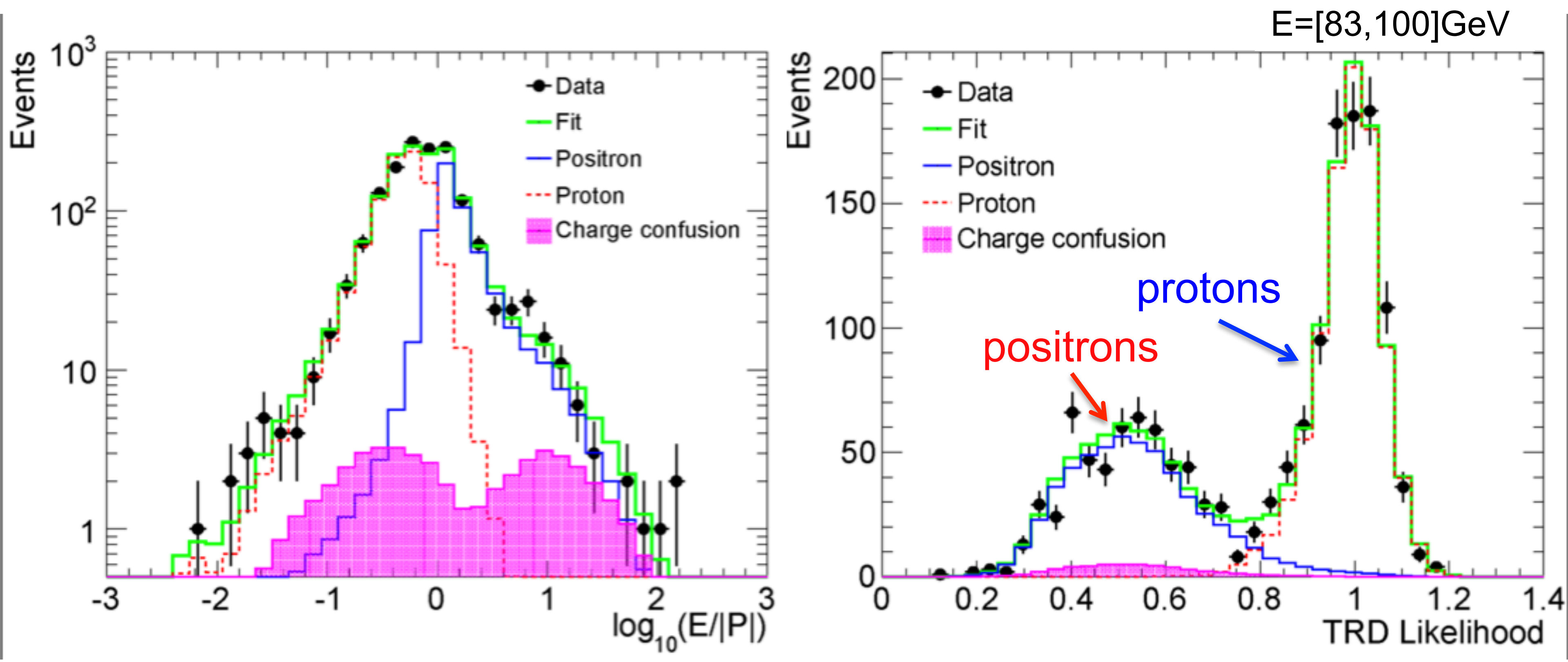
# Analysis: the template method

1. The *ecal classifier* is used to *remove most of the* ***protons*** *with high efficiency on* ***positrons***
2. *Reference spectra* (or *templates*) are built for
   - protons and electrons → from data
   - CC spillover and interactions → from MC

   in the variables **E/p** and in **TRD likelihood**
3. The templates are *fit to data* , in each energy bin, to obtain the relative contributions

- This method maximizes the signal efficiency, since no further cut is explicitely applied after ecal classifier

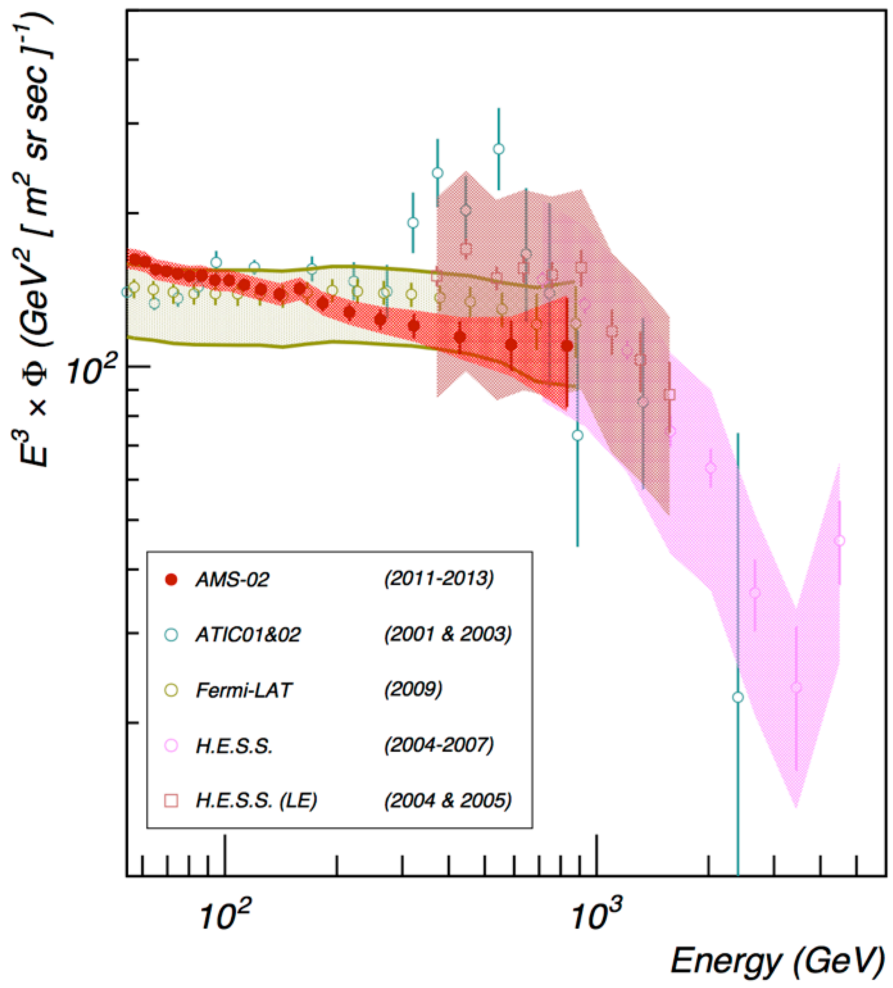
# fit to data



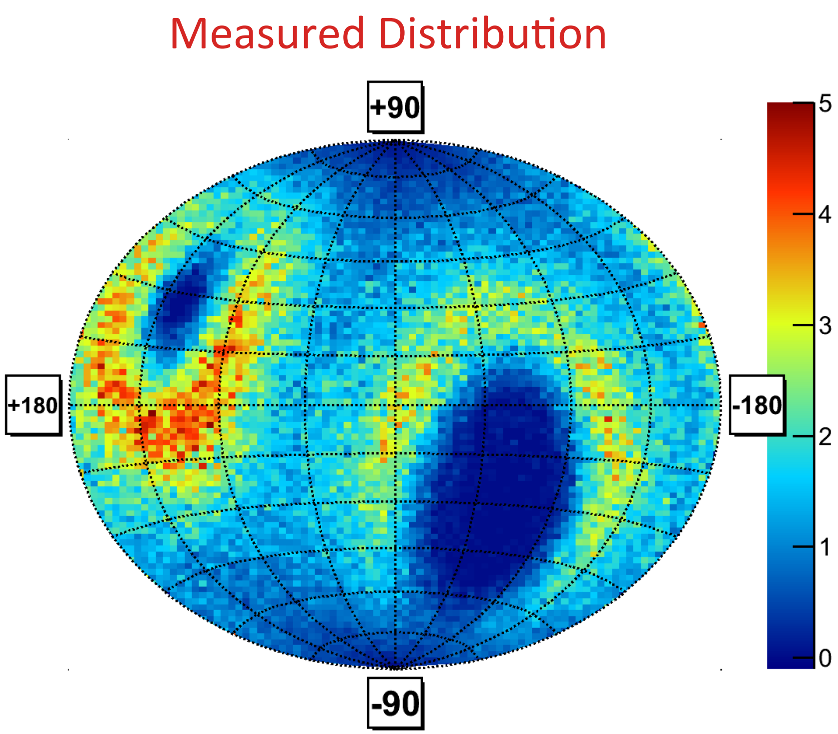

- Fit on E/p (left) and on TRD Likelihood (right)
- The fit is repeated at each energy bin

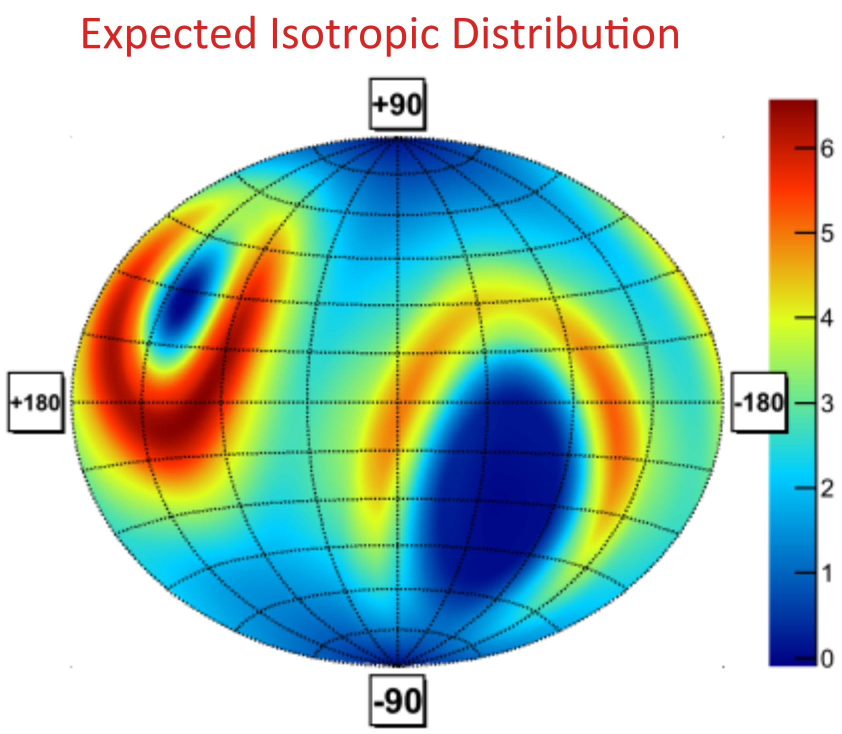
# $e^+ + e^-$ flux measurements with AMS

..Taking into account also the knowledge of the energy scale....



# Electron Anisotropy

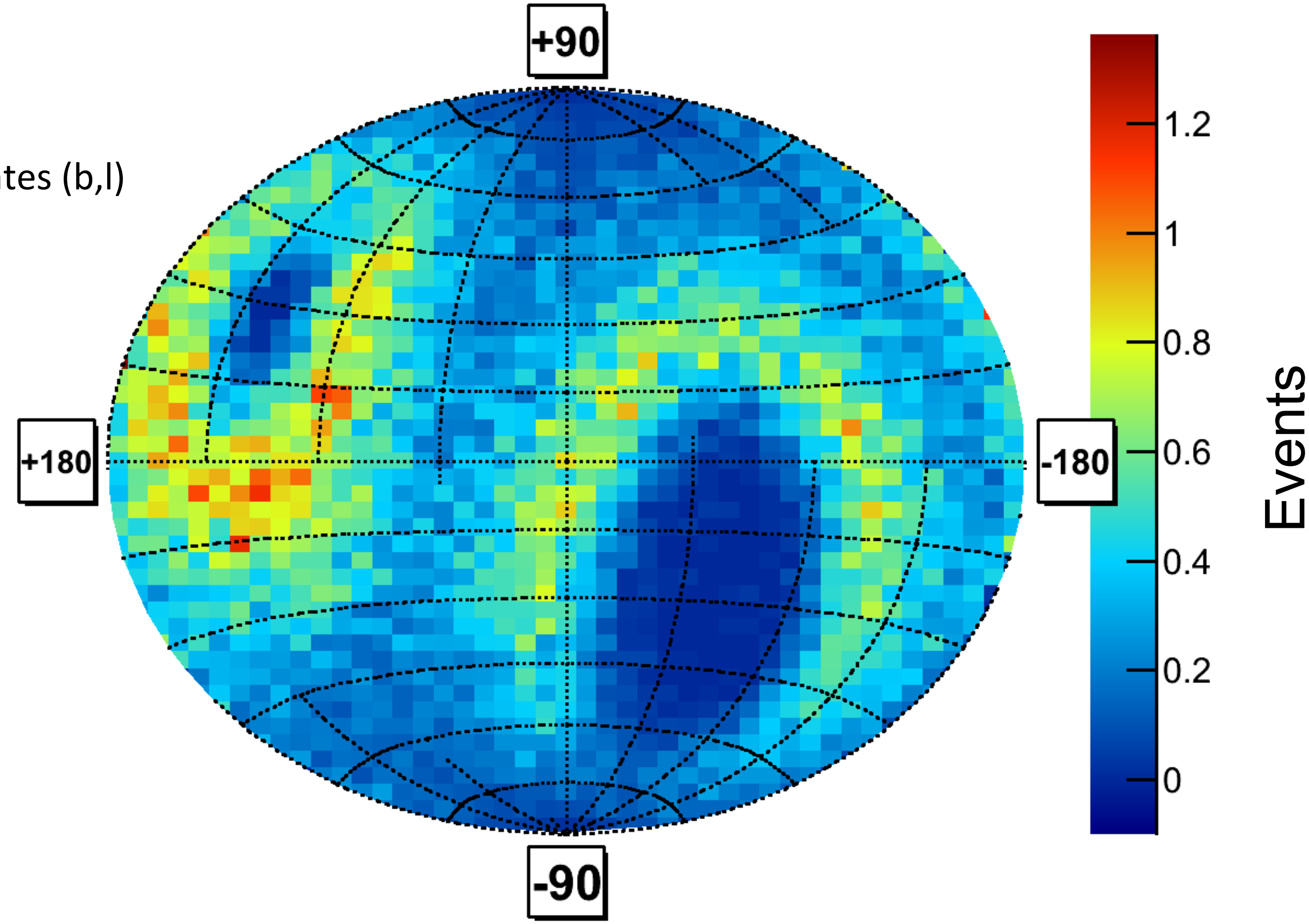



The incoming direction of electrons above 16 GeV in galactic coordinates yields **δ ≤ 0.01 at the 95% confidence level**

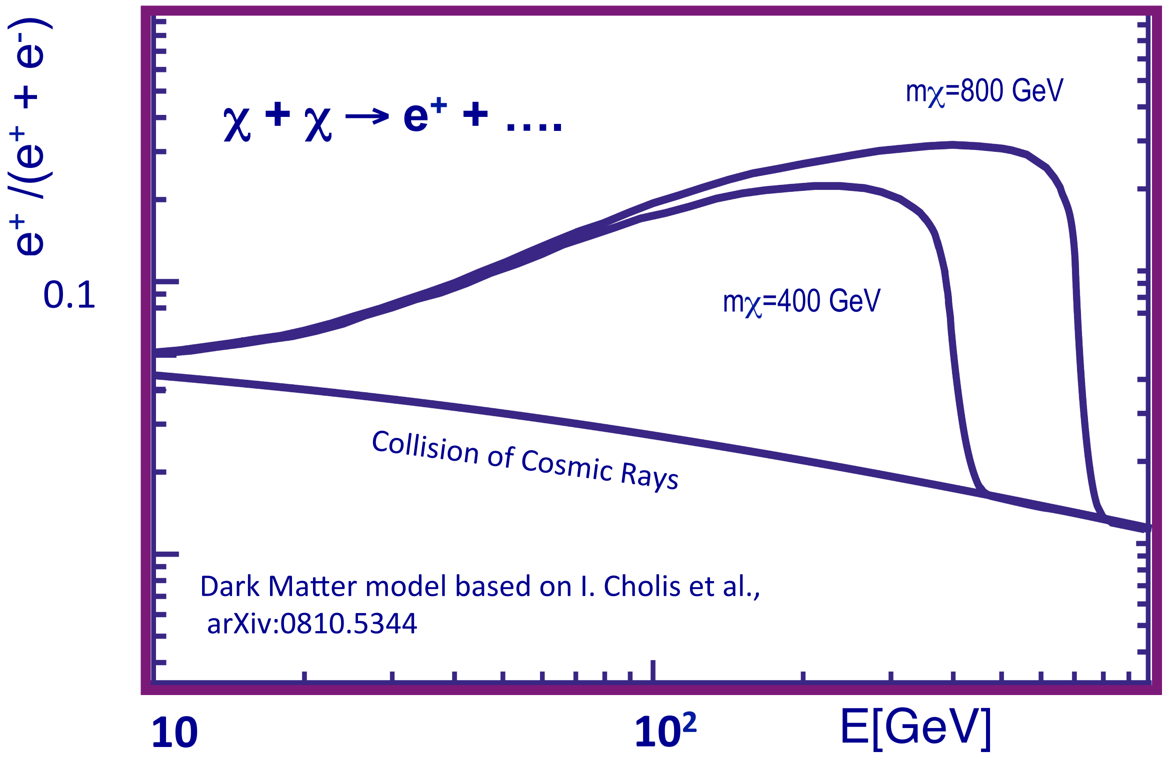
# Positron Anisotropy

Galactic coordinates (b,l)




The incoming direction of positrons above 16 GeV in galactic coordinates yields δ ≤ 0.03 at the 95% confidence level

# What is needed?

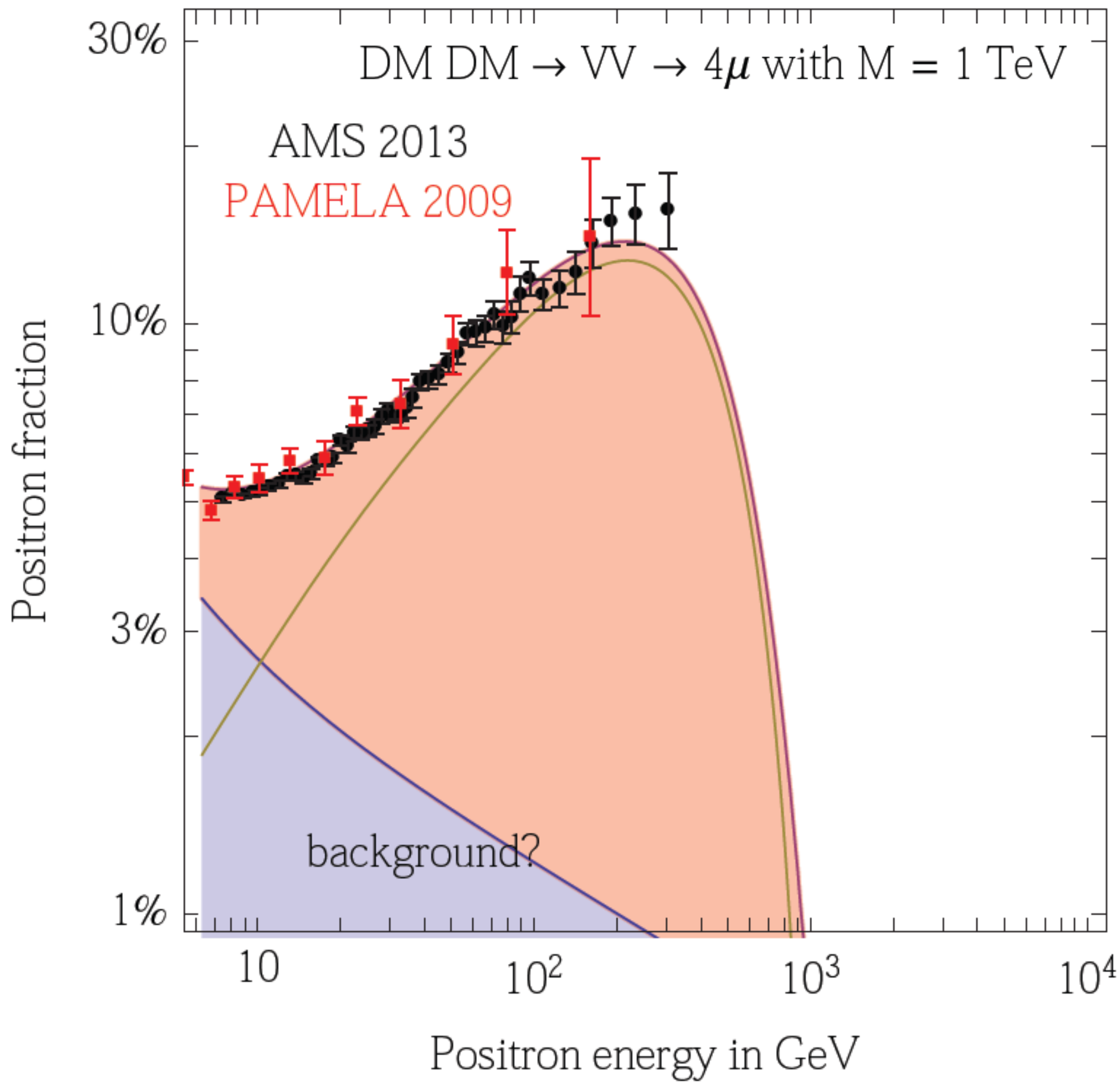



Leptophilic dark matter or astrophysical sources ??

- Shape of the excess accurately measured over an extended energy range
- Knowledge of "cosmic background"

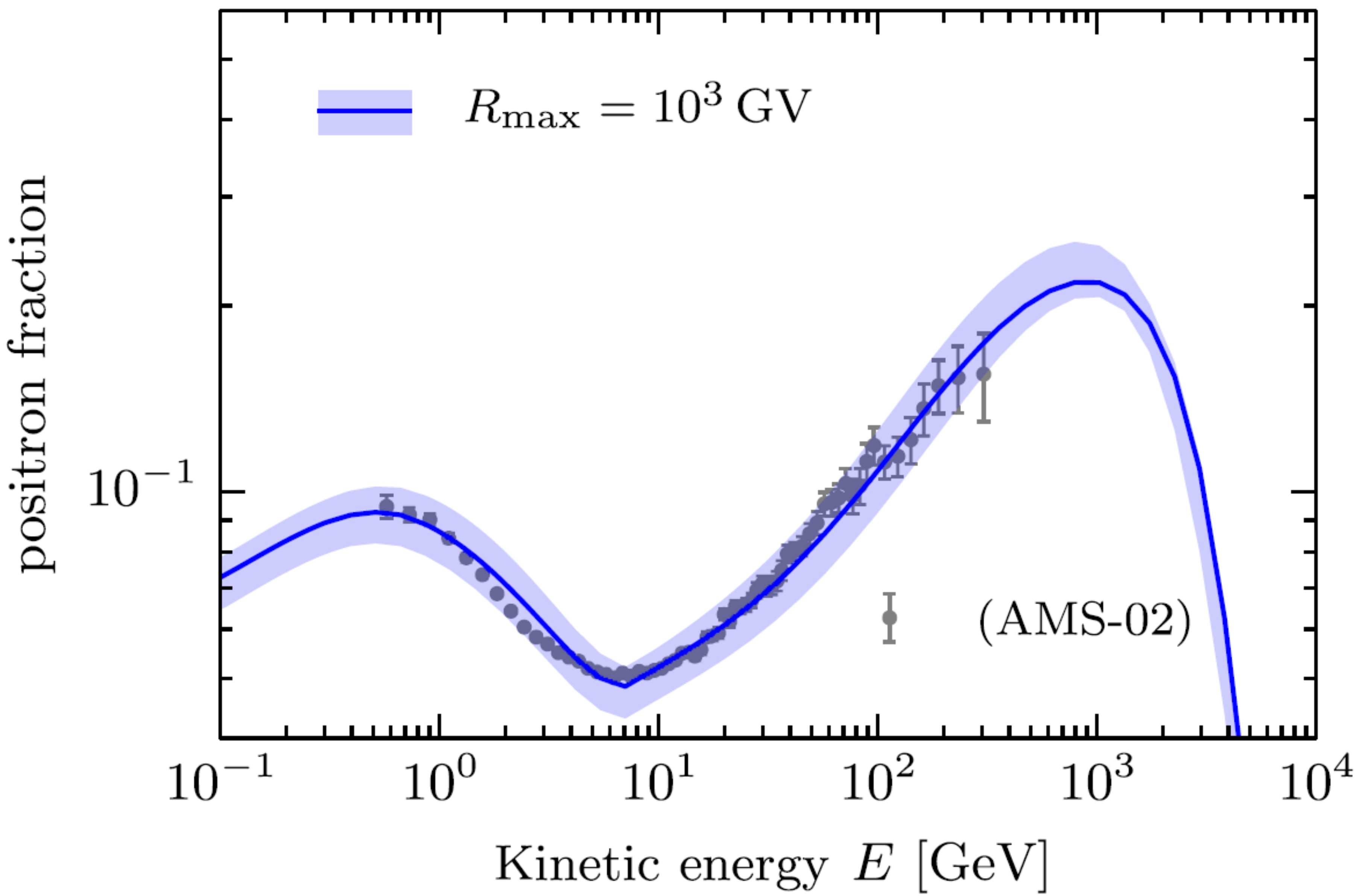
# Dark Matter model with intermediate state

**M. Cirelli, M. Kadastik, M. Raidal and A. Strumia ,Nucl.Phys. B873 (2013) 530**



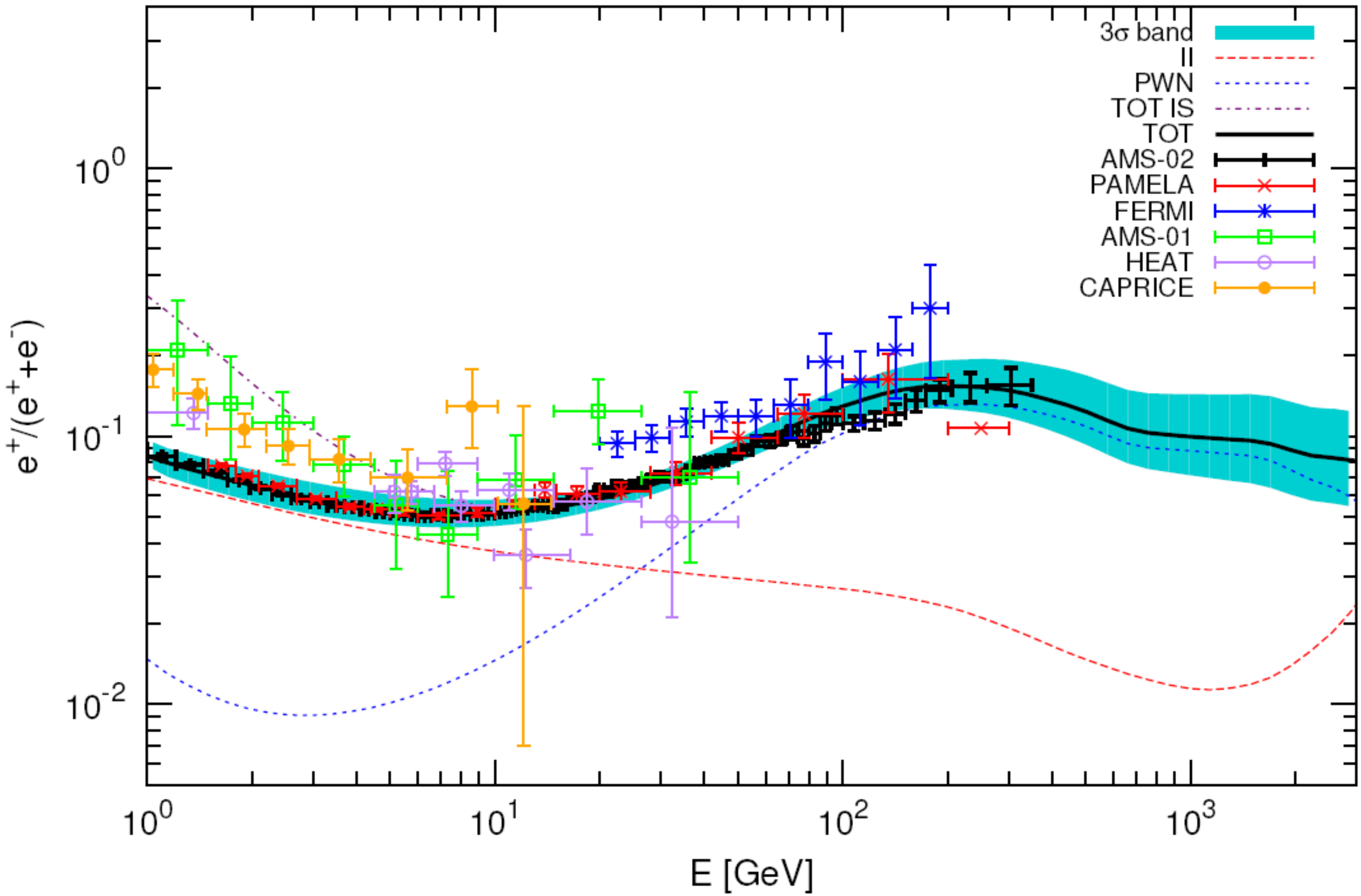
# Acceleration in SNRs

**P. Mertsch and S. Sarkar, Phys.Rev. D 90 (2014) 061301(R)**



# Production in Pulsars

**M. DiMauro, F. Donato, N. Fornengo, R. Lineros, A. Vittino, JCAP 1404 (2014) 006**



# Measurement of the flux of electrons and positrons

$$\Phi_{e^\pm}(E) = \frac{N_{e^\pm}(E)}{A_{eff}(E) \cdot \varepsilon_{trig}(E) \cdot T(E) \cdot \Delta E}$$

$N_{e\pm}$ is the number of electron or positron events

$\varepsilon_{trig}$ is the trigger efficiency

T is the exposure time

$A_{eff}$ is the effective acceptance $A_{eff} = A_{geom} \cdot \varepsilon_{sel} \cdot \varepsilon_{id} \cdot (1+\delta)$

$A_{geom}$ is the geometrical acceptance, ≃ 550 $cm^2$sr

$\varepsilon_{sel}$ is the event selection efficiency

$\varepsilon_{id}$ is the $e^\pm$ identification efficiency

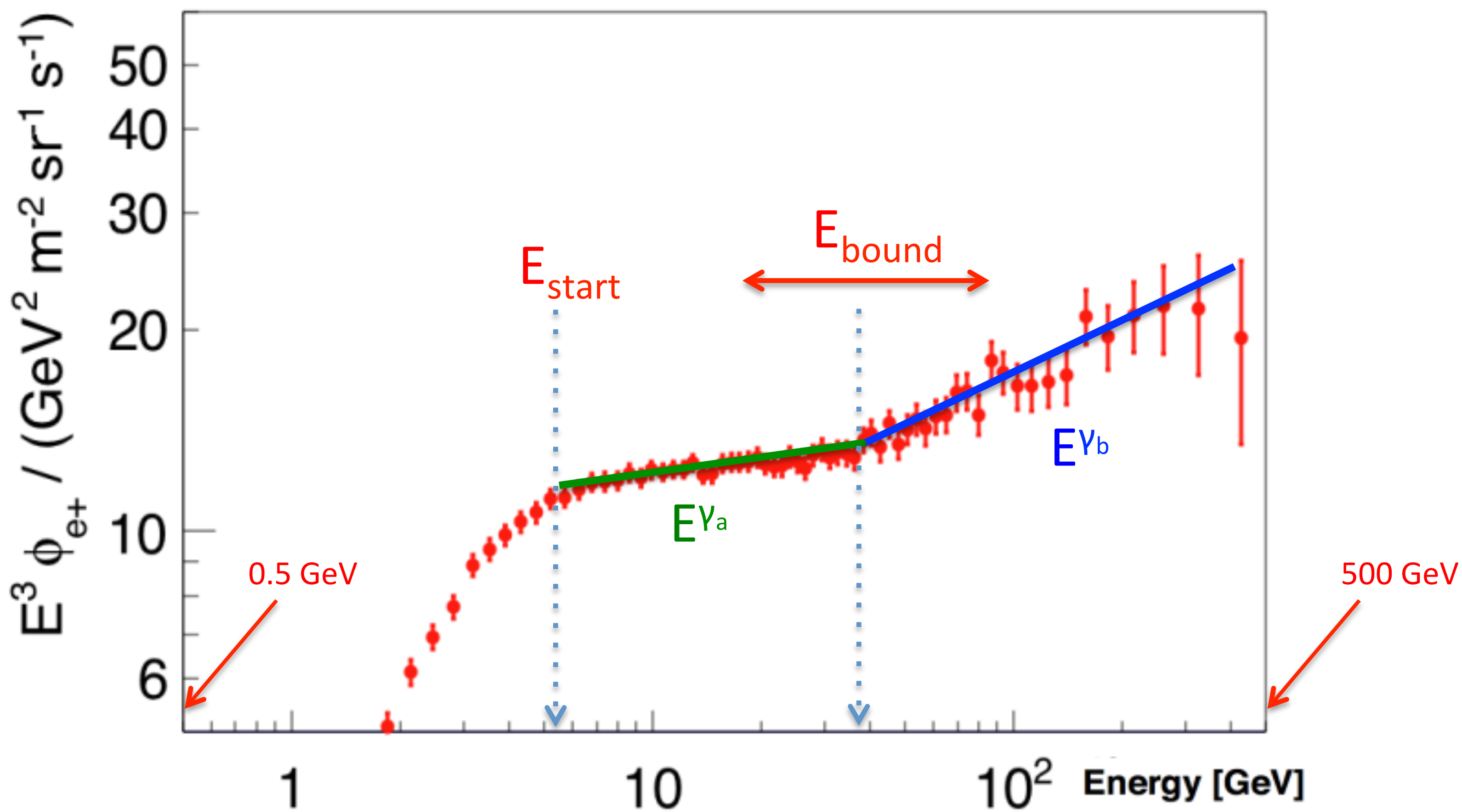
δ is a minor correction from the comparison between data and Monte Carlo (-2% at 10Gev to -6% at 700 GeV). The error on (1+δ) is ~2.5

# Lower energy limit for single power law ($E^{\gamma}$) description

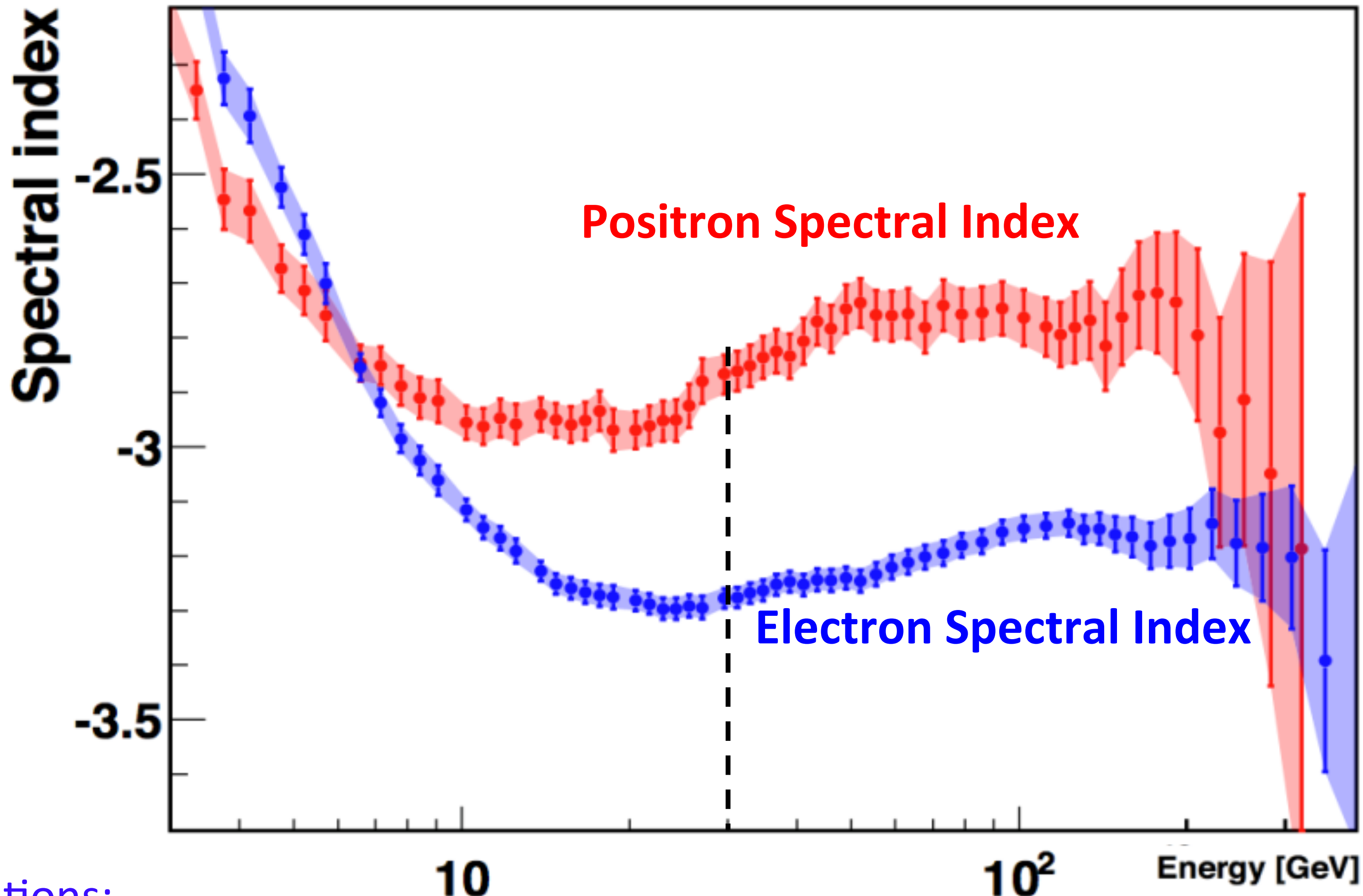
Study intervals with starting energies $E_{start}$, and ending at the highest energy.

Split a interval into two sections by any boundary $E_{bound}$ , fit with single power law for each section. Determine the significance between the difference of $\gamma_a$ and $\gamma_b$

The limit is defined by the lowest $E_{start}$ that gives consistent spectral indices at the 90% C.L. for any boundary yields Positrons: 27.2 GeV and Electron: 52.3 GeV



# Spectral indices ($E^{\gamma}$) of electron and 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.
4. 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).

# EXAMPLE:

## Minimal Model Fit to the data

**Diffuse Flux** | **Source Flux**

$$\Phi_{e^+} = C_{e^+} E^{-\gamma_{e^+}} + C_s E^{-\gamma_s} e^{-E/E_s}$$

$$\Phi_{e^-} = C_{e^-} E^{-\gamma_{e^-}} + C_s E^{-\gamma_s} e^{-E/E_s}$$

**Simultaneous fit to**

- **a) Positron Fraction from 2GeV**
- **b) Electron + Positron from 2GeV**

- **$(\gamma_{e-} - \gamma_{e+})$, $(\gamma_{e-} - \gamma_s)$, $C_{e+}$, $C_{e-}$, $C_s$, $E_s$ are constant**
- **$\gamma_{e-}$ is energy dependent below ~15 GeV.**

# Minimal Model:

**Diffuse Flux** / **Source Flux**

$$\Phi_{e^+} = C_{e^+} E^{-\gamma_{e^+}} + C_s E^{-\gamma_s} e^{-E/E_s}$$

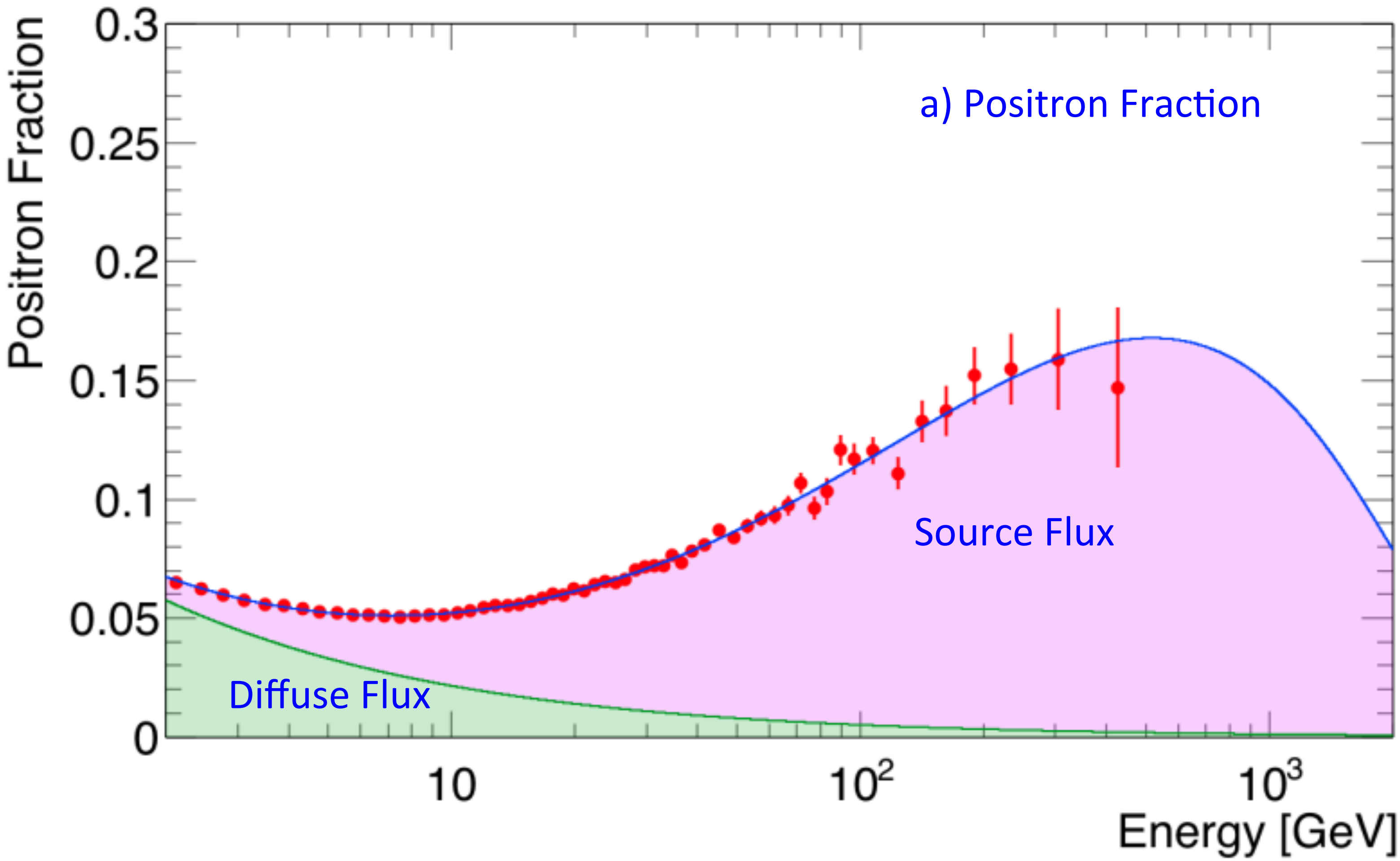
$$\Phi_{e^-} = C_{e^-} E^{-\gamma_{e^-}} + C_s E^{-\gamma_s} e^{-E/E_s}$$

Fit to a) Positron Fraction from 2 GeV determines the relations:

$\gamma_{e-} - \gamma_{e+} = -0.63 \pm 0.06$, $\gamma_{e-} - \gamma_s = 0.66 \pm 0.05$,

$C_{e+}/C_{e-} = 0.095 \pm 0.003$, $C_s/C_{e-} = 0.008 \pm 0.001$

$1/E_s = 1.3 \pm 0.6\ \text{TeV}^{-1}$



# Minimal Model:

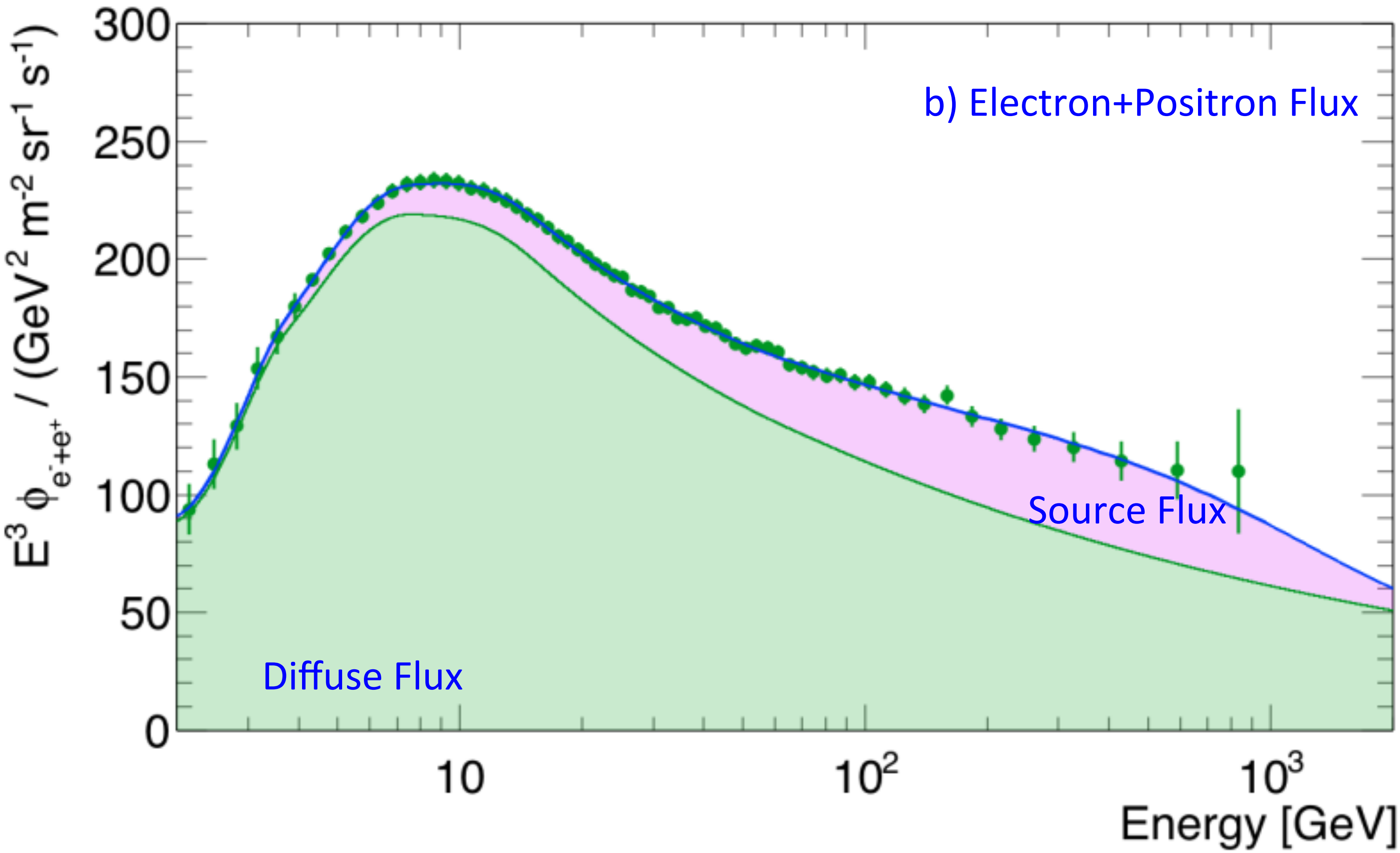
Diffuse Flux / Source Flux

$$\Phi_{e^+} = C_{e^+} E^{-\gamma_{e^+}} + C_s E^{-\gamma_s} e^{-E/E_s}$$

$$\Phi_{e^-} = C_{e^-} E^{-\gamma_{e^-}} + C_s E^{-\gamma_s} e^{-E/E_s}$$

Fit to b) Electron + Positron Flux from 2 GeV determines $\gamma_{e-}$ and $C_{e-}$

$\gamma_{e-}$ is energy dependent below ~15 GeV



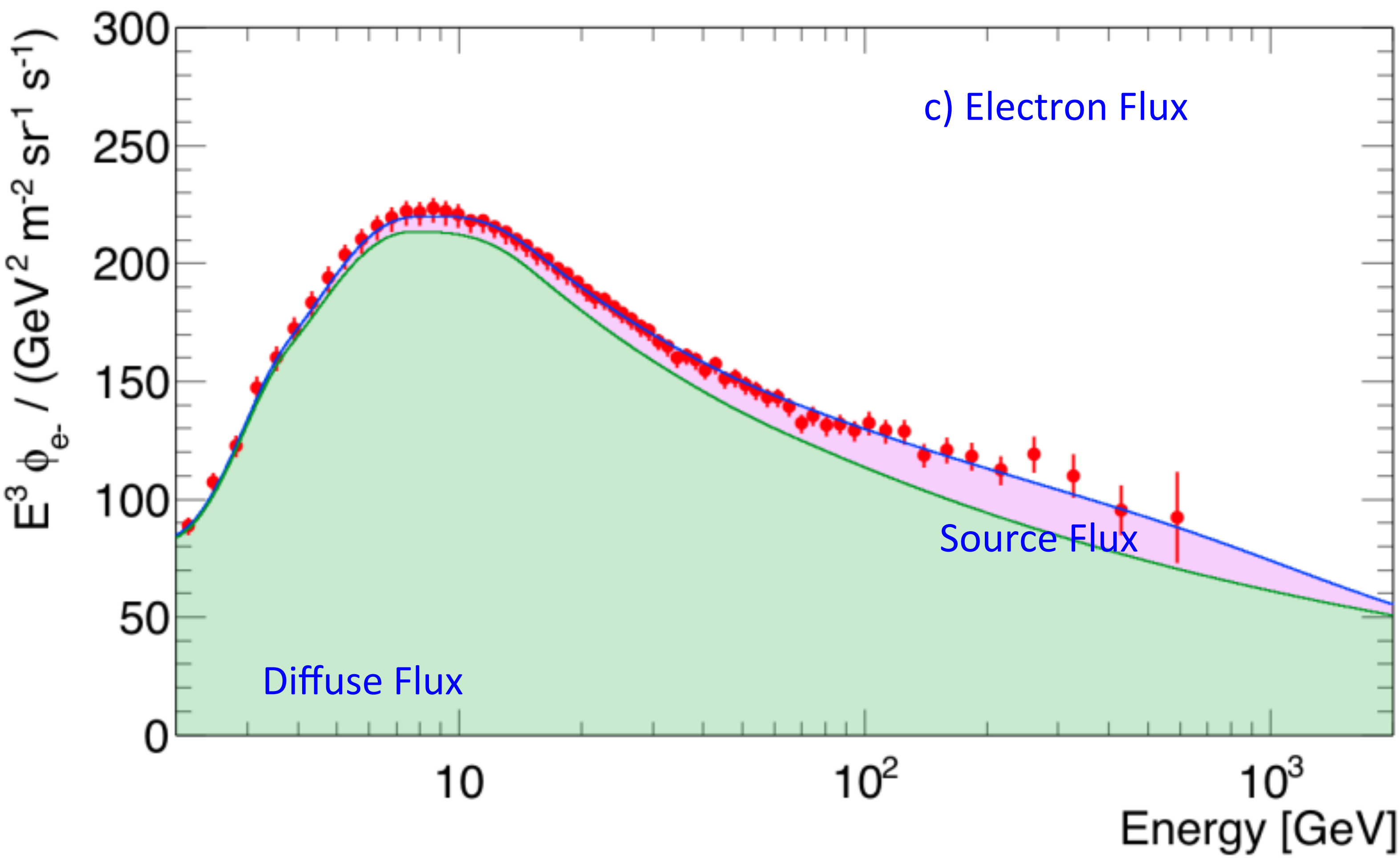
# Minimal Model:

Diffuse Flux, Source Flux

$$\Phi_{e^+} = C_{e^+} E^{-\gamma_{e^+}} + C_s E^{-\gamma_s} e^{-E/E_s}$$

$$\Phi_{e^-} = C_{e^-} E^{-\gamma_{e^-}} + C_s E^{-\gamma_s} e^{-E/E_s}$$

Prediction from fit it to a) Positron Fraction and b) Electron + Positron Flux



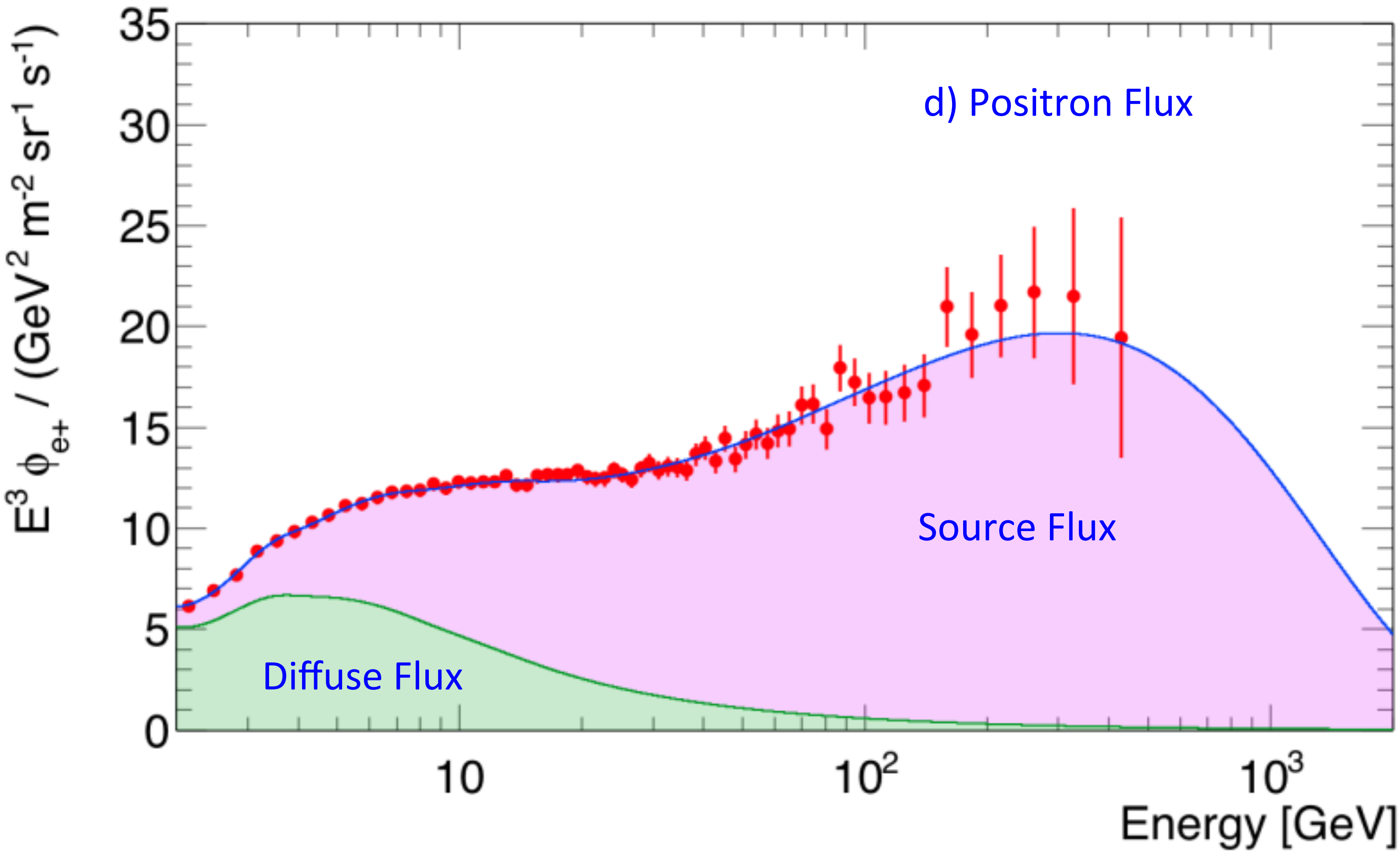
# Minimal Model:

Diffuse Flux | Source Flux

$$\Phi_{e^+} = C_{e^+} E^{-\gamma_{e^+}} + C_s E^{-\gamma_s} e^{-E/E_s}$$

$$\Phi_{e^-} = C_{e^-} E^{-\gamma_{e^-}} + C_s E^{-\gamma_s} e^{-E/E_s}$$

Prediction from fit it to a) Positron Fraction and b) Electron + Positron Flux



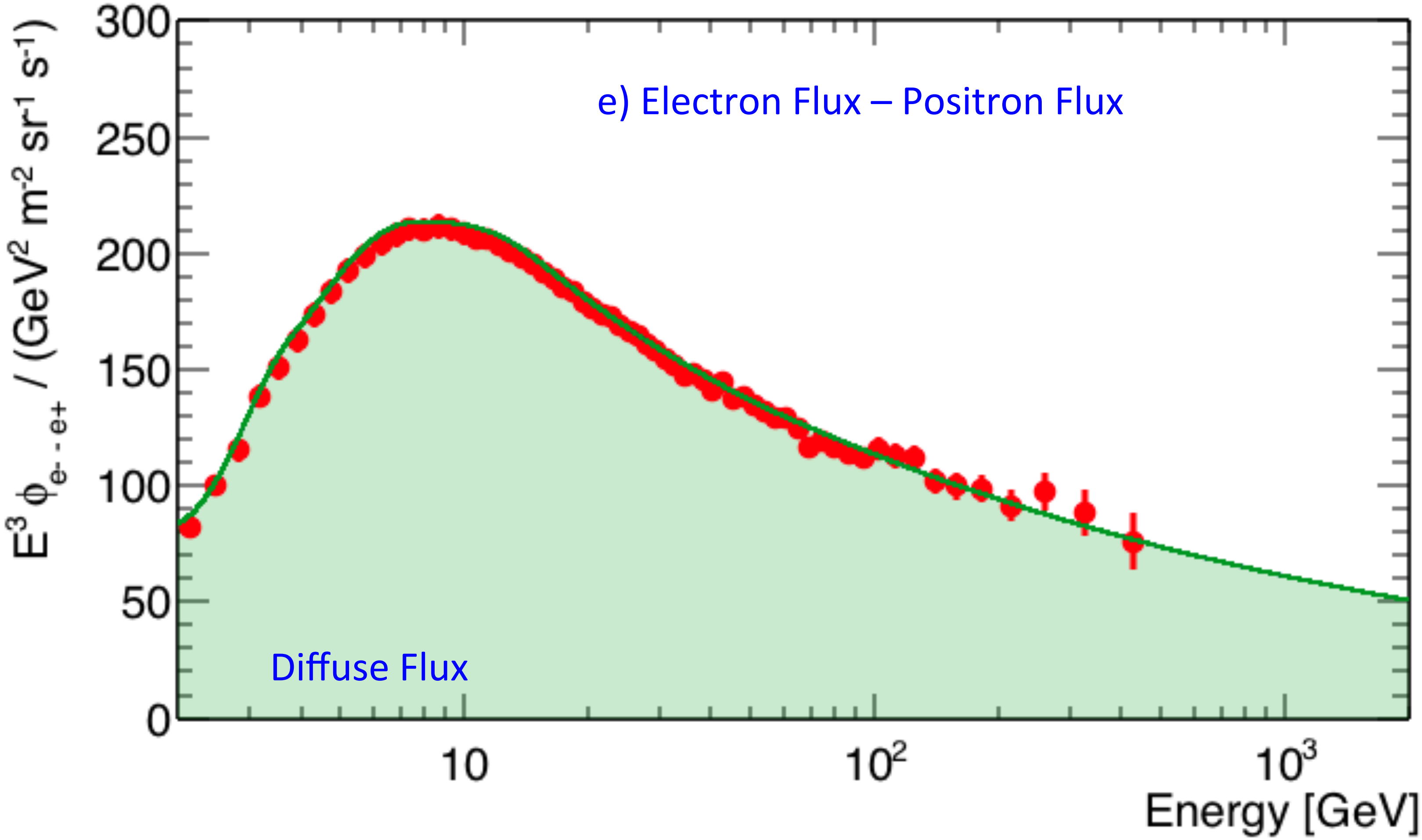
Minimal Model:

**Diffuse Flux** | **Source Flux**

$$\Phi_{e^+} = C_{e^+} E^{-\gamma_{e^+}} + C_s E^{-\gamma_s} e^{-E/E_s}$$

$$\Phi_{e^-} = C_{e^-} E^{-\gamma_{e^-}} + C_s E^{-\gamma_s} e^{-E/E_s}$$

Prediction from fit it to a) Positron Fraction and b) Electron + Positron Flux



# Dark Matter Models


1) L. Feng, R.Z. Yang, H.N. He, T.K. Dong, Y.Z. Fan and J. Chang Phys.Lett. B728 (2014) 250
2) M. Cirelli, M. Kadastik, M. Raidal and A. Strumia ,Nucl.Phys. B873 (2013) 530
3) M. Ibe, S. Iwamoto, T. Moroi and N. Yokozaki, JHEP 1308 (2013) 029
4) Y. Kajiyama andH. Okada, Eur.Phys.J. C74 (2014) 2722
5) K.R. Dienes and J. Kumar, Phys.Rev. D88 (2013) 10, 103509
6) L. Bergstrom, T. Bringmann, I. Cholis, Dan Hooper, C. Weniger, Phys.Rev.Lett. 111 (2013) 171101
7) K. Kohri and N. Sahu, Phys.Rev. D88 (2013) 10, 103001
8) P. S. Bhupal Dev, D. Kumar Ghosh, N. Okada, I. Saha, Phys.Rev. D89 (2014) 095001
9) A. Ibarra, A.S. Lamperstorfer, J. Silk, Phys.Rev. D89 (2014) 063539
10) Y. Zhao and K.M. Zurek, JHEP 1407 (2014) 017
11) ....

# Astrophysical sources

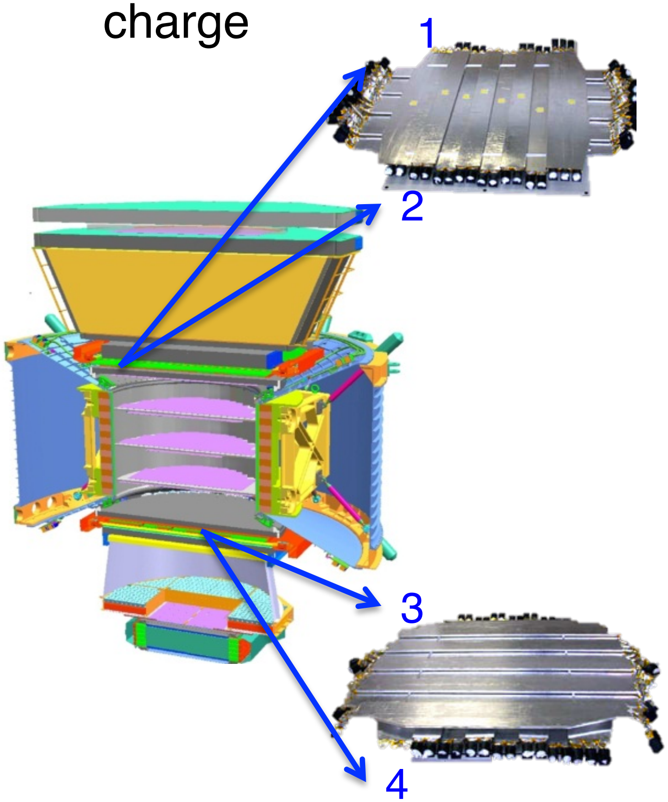
1) T. Linden and S. Profumo, Astrophys.J. 772 (2013) 18
2) P. Mertsch and S. Sarkar, Phys.Rev. D 90 (2014) 061301
3) I. Cholis and D. Hooper, Phys.Rev. D88 (2013) 023013
4) A. Erlykin and A.W. Wolfendale, Astropart.Phys. 49 (2013) 23
5) P.F. Yin, Z.H. Yu, Q. Yuan, X.J. Bi, Phys.Rev. D88 (2013) 2, 023001
6) A.D. Erlykin and A.W. Wolfendale Astropart.Phys. 50-52 (2013) 47
7) E. Amato, Int.J.Mod.Phys.Conf.Ser. 28 (2014) 1460160
8) P. Blasi, Braz.J.Phys. 44 (2014) 426
9) D. Gaggero, D. Grasso, L. Maccione, G. DiBernardo, C Evoli, Phys.Rev. D89 (2014) 083007
10) M. DiMauro, F. Donato, N. Fornengo, R. Lineros, A. Vittino, JCAP 1404 (2014) 006
11) ....

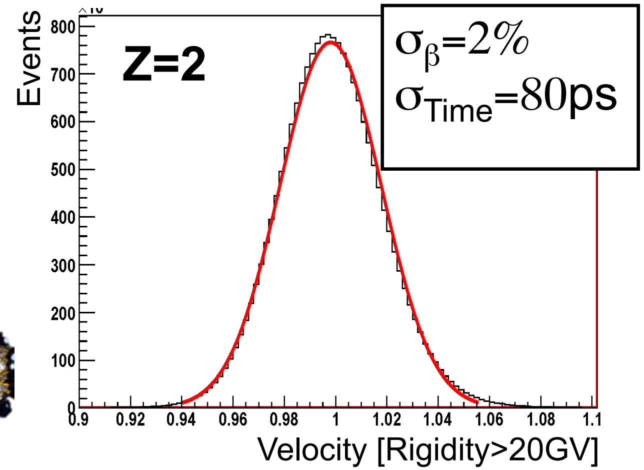
# Secondary production

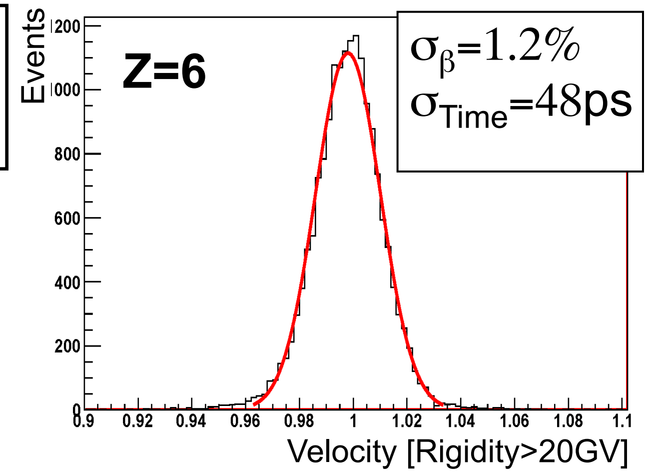
1) R.Cowsik, B.Burch, and T.Madziwa-Nussinov, Ap.J. 786 (2014) 124
2) K. Blum, B. Katz and E. Waxman, Phys.Rev.Lett. 111 (2013) 211101

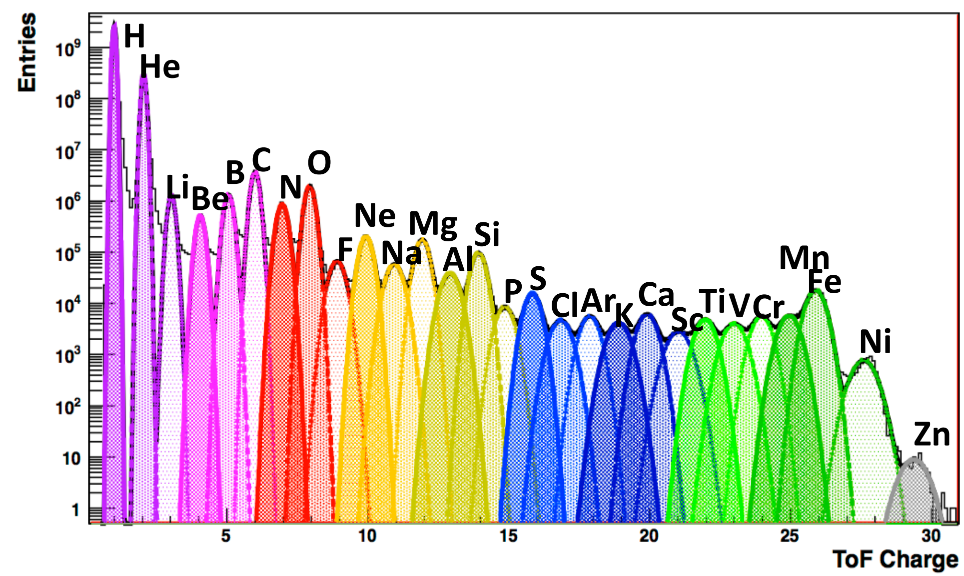
# Time of Flight System

- 4 Layers of scintillation counter
- *Main trigger*
- *Measurement of* $\beta$=v/c ($\Delta$t~180 ps)
- Measurement of charge



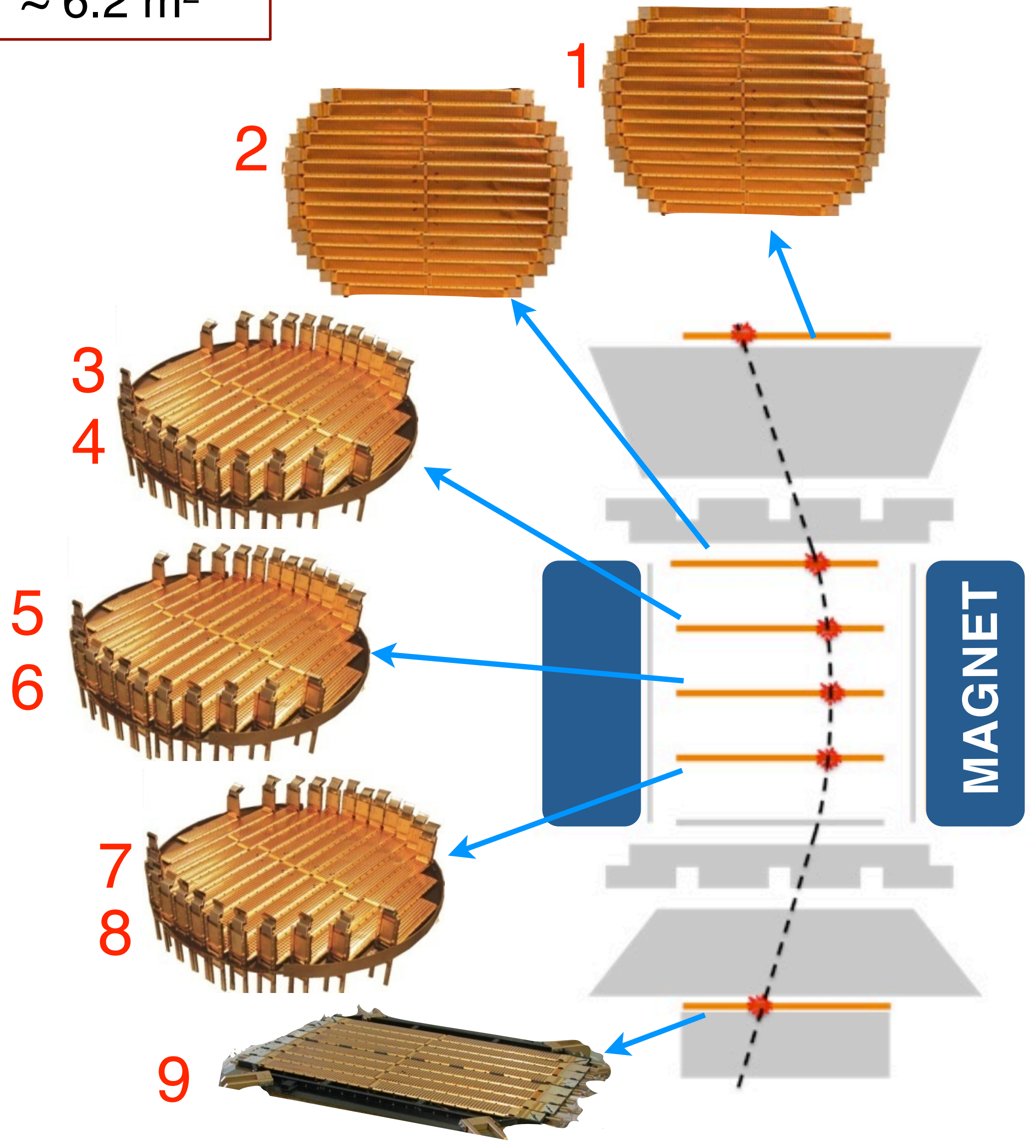



# Silicon Tracker

active area
~ 6.2 m²



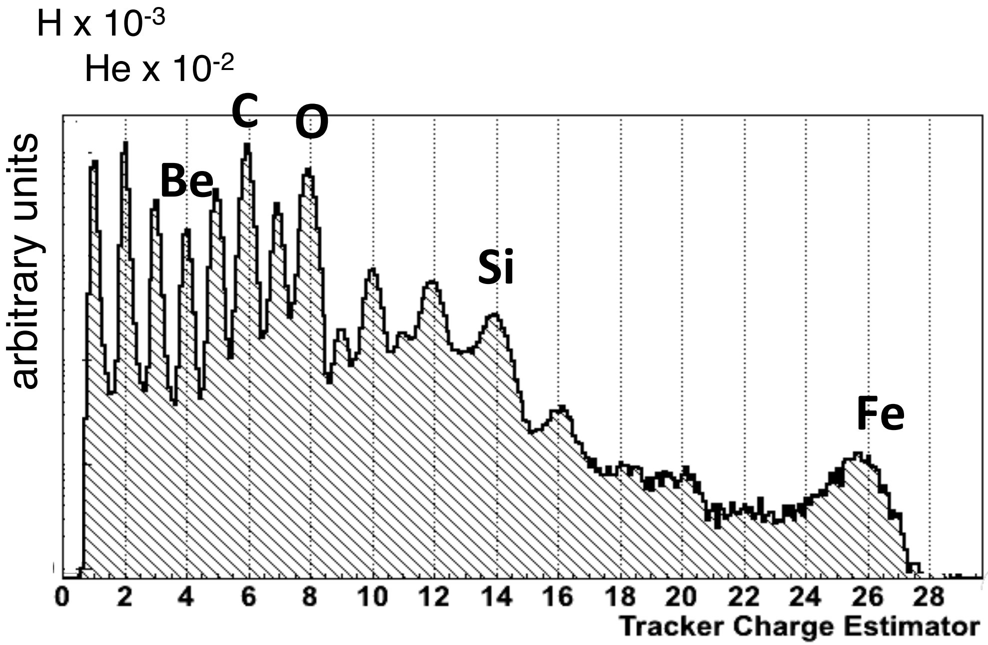

**Silicon Tracker**

- 9 layers of double-sided micro-strip silicon sensors
- Spatial accuracy in bending direction: *~10 μm*

**Purpose:**

- *Measurement of rigidity* (**R=p/q**) (MDR~2 TV)
- *Measurement of the sign of charge: **detection of anti-matter***

# Charge measurement :

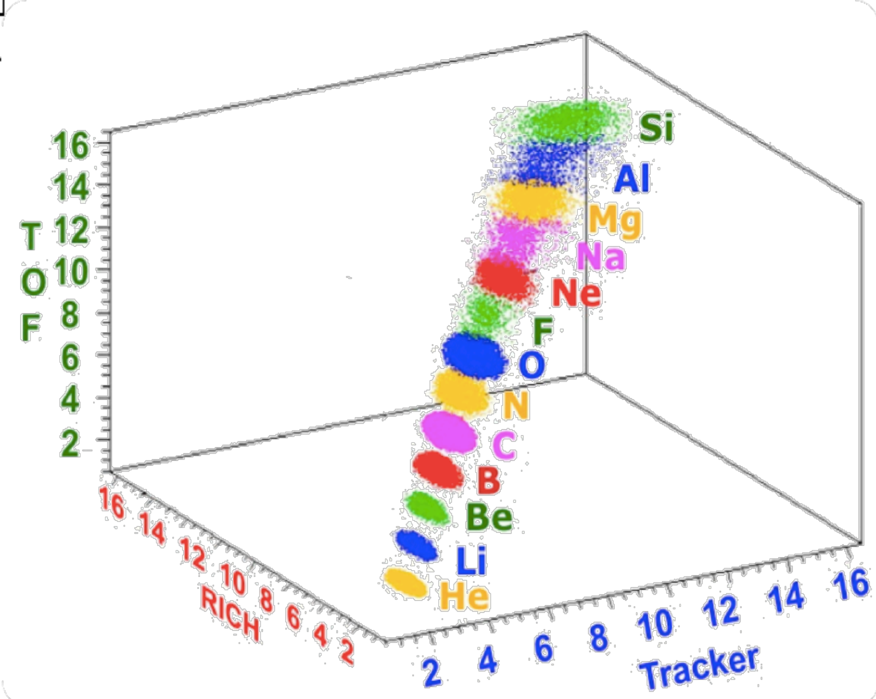



**dE/dx** in each layer →

Silicon Tracker has a very accurate charge resolution (~ 0.1 c.u.)

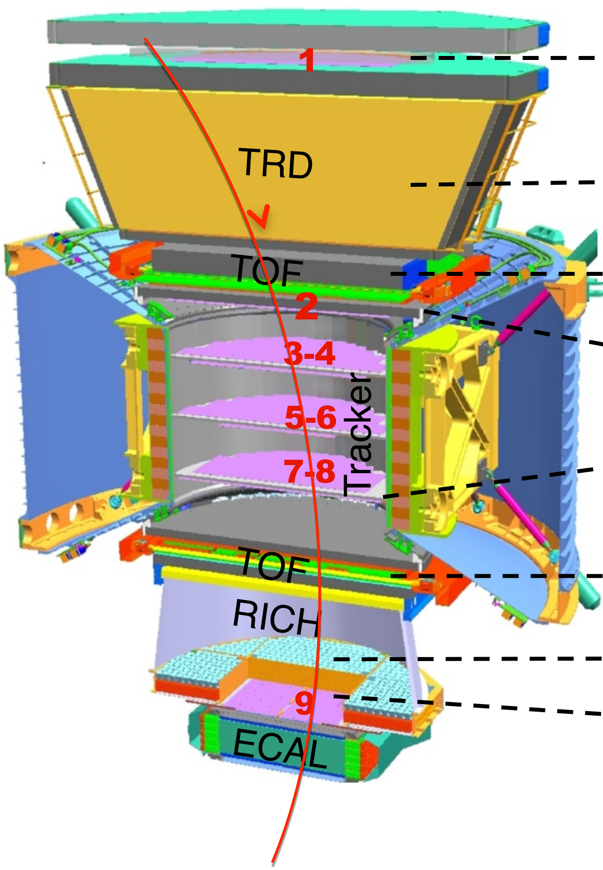
Redundant measurement of Z

→



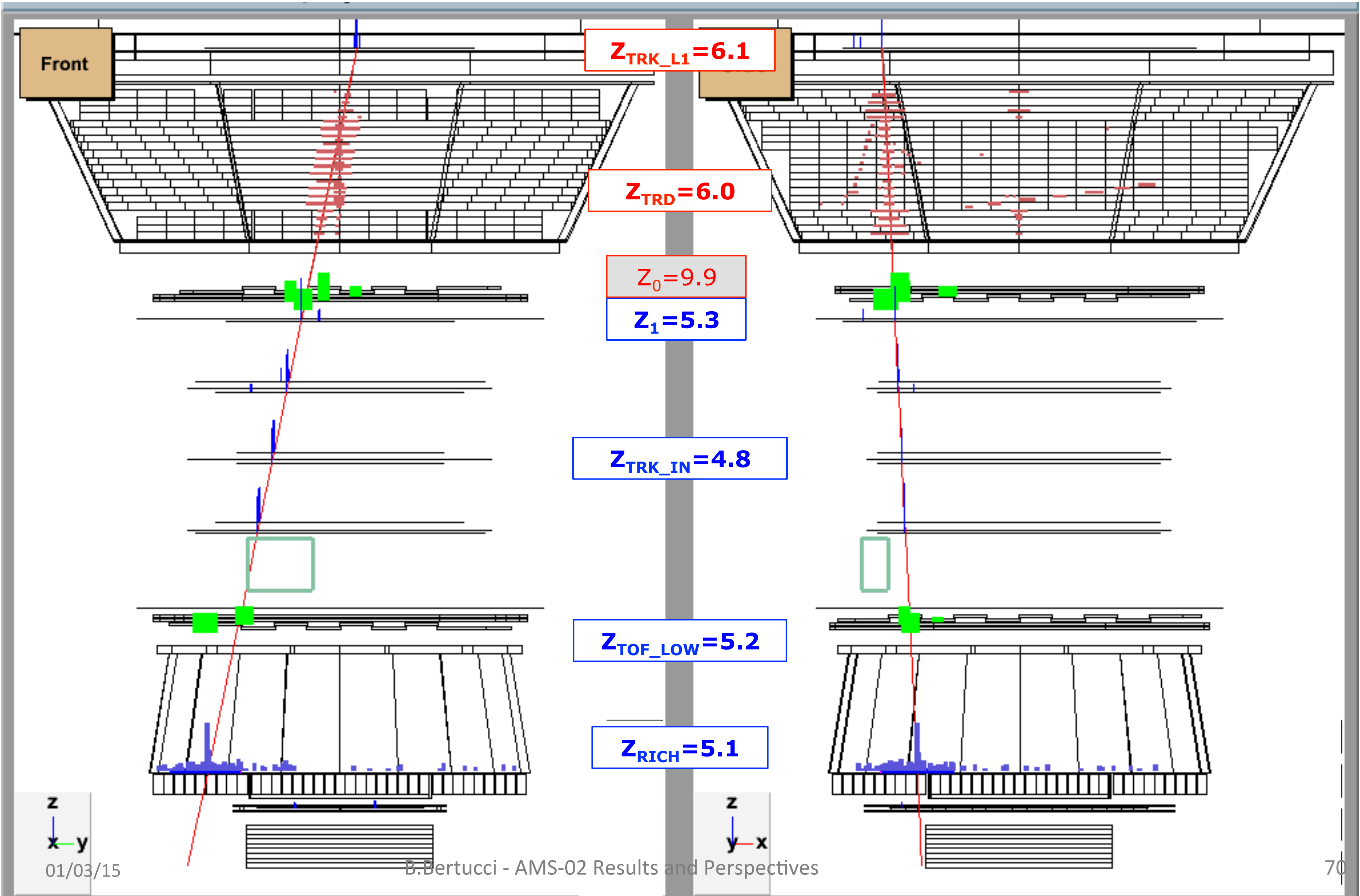
# Particle Charge Measurement

## Multiple Independent Measurements of |Z|



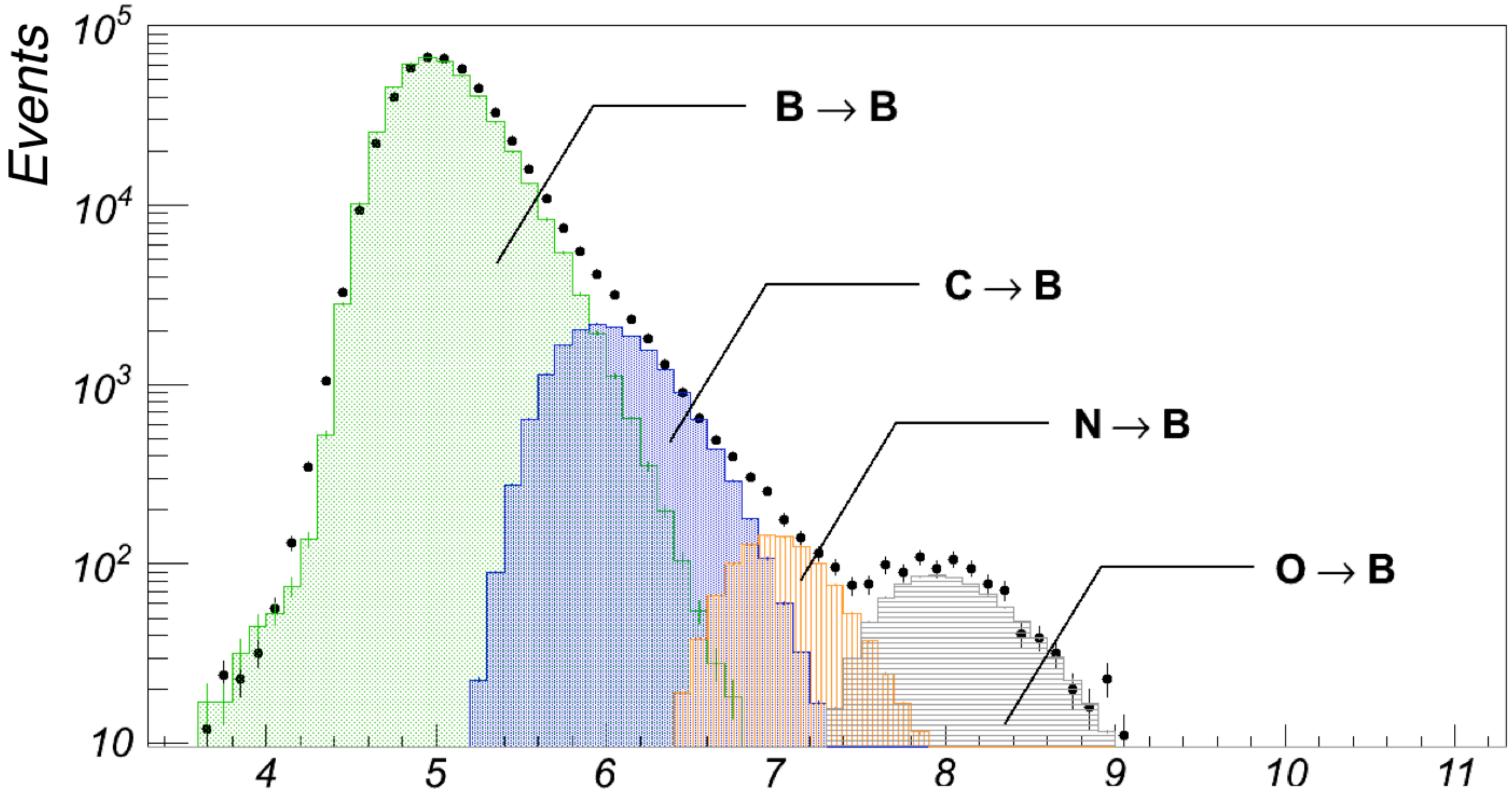

| | Carbon (Z=6) ΔZ (cu) |
|---|---|
| 1. Tracker Plane 1 | 0.30 |
| 2. TRD | 0.33 |
| 3. Upper TOF (1 counter) | 0.16 |
| 4. Tracker Planes 2-8 | 0.12 |
| 5. Lower TOF (1 counter) | 0.16 |
| 6. RICH | 0.32 |
| 7. Tracker Plane 9 | 0.30 |

# Carbon Fragmentation to Boron in Upper TOF
## Rigidity 10.6 GV



# Boron and Carbon: Sample composition

**Particles Identified as Boron in the Inner AMS show signals compatible with higher charges on the 1st**



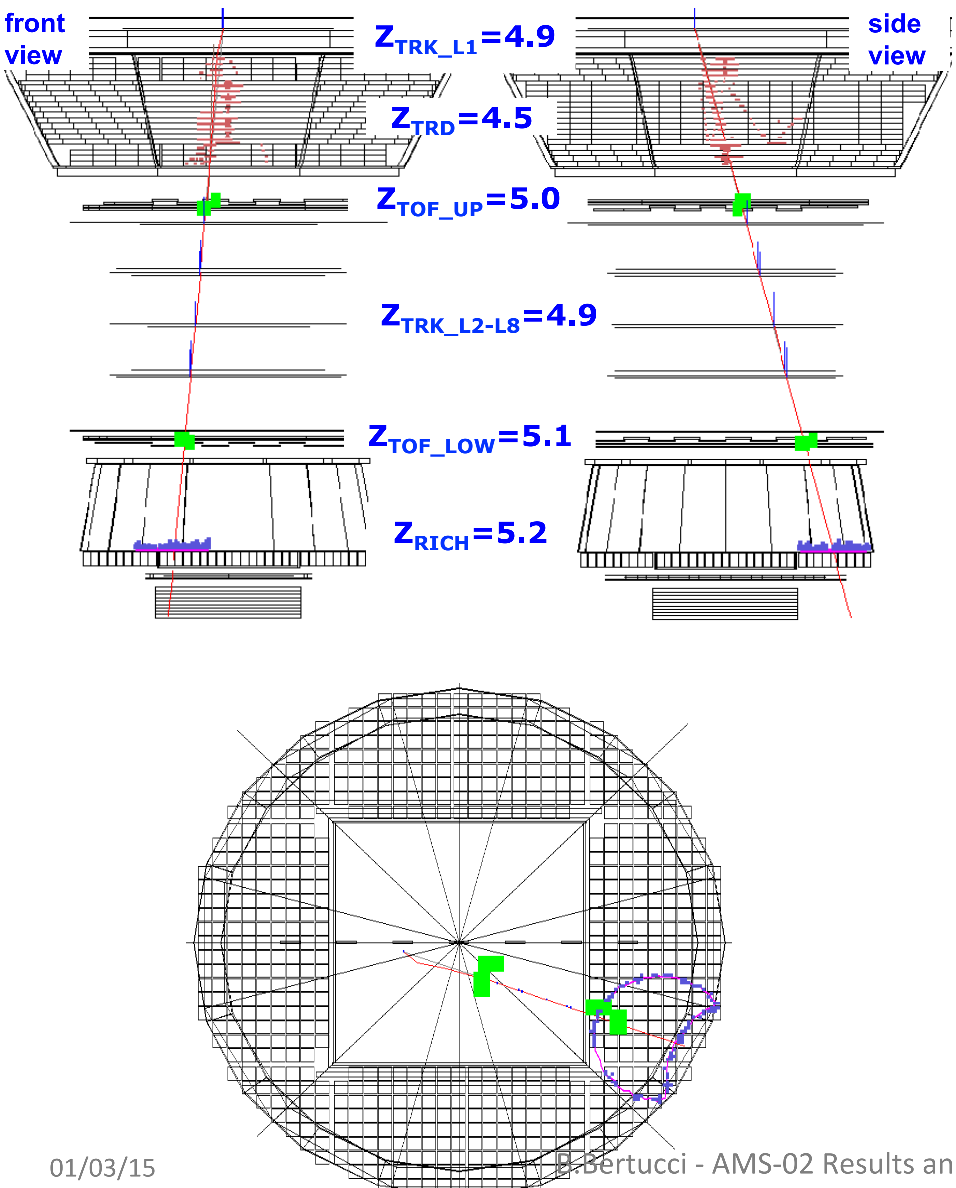

*Tracker L1 Charge measurement*

# Rigidity ~ 200 GV

## Boron

**Rigidity=187 GV**

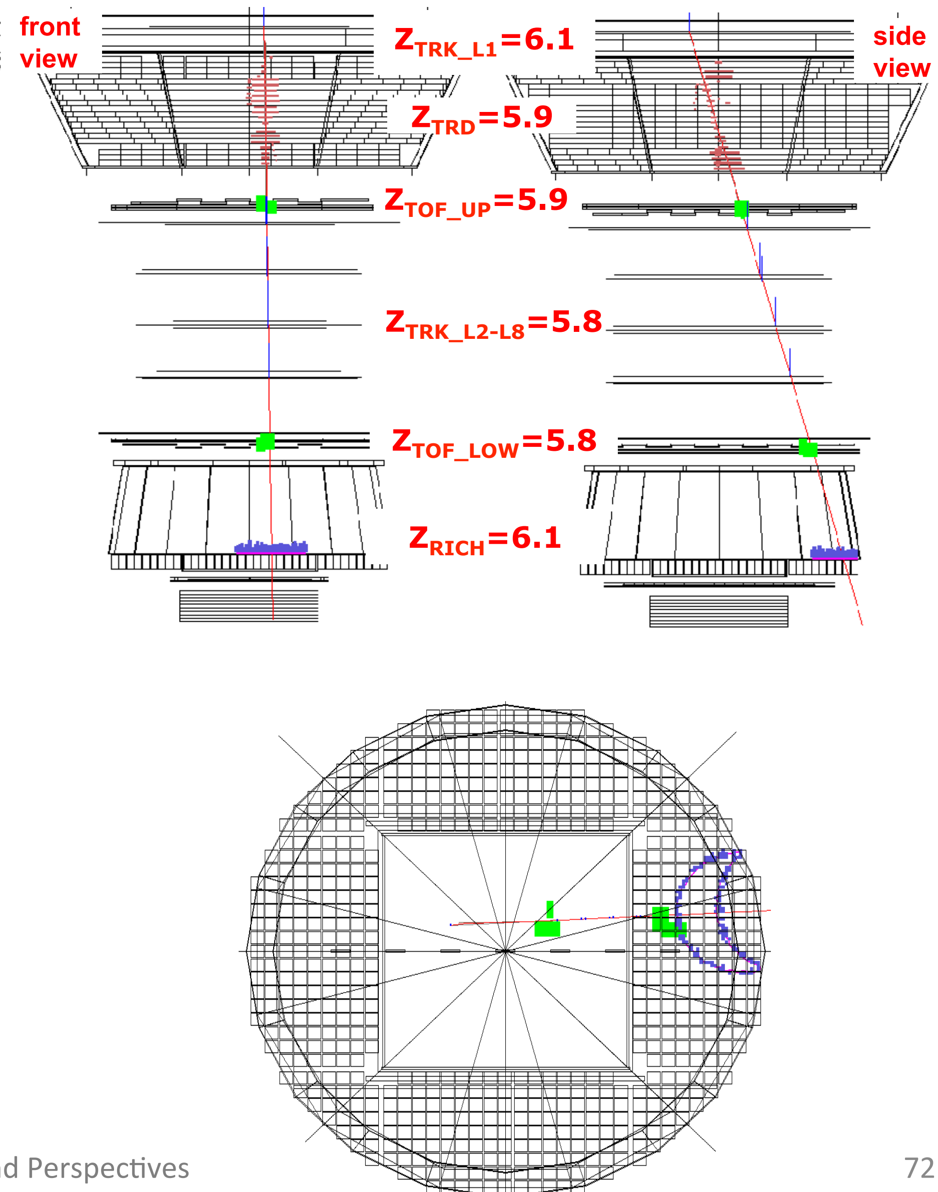
**Run/Event 1329086299/ 747549**



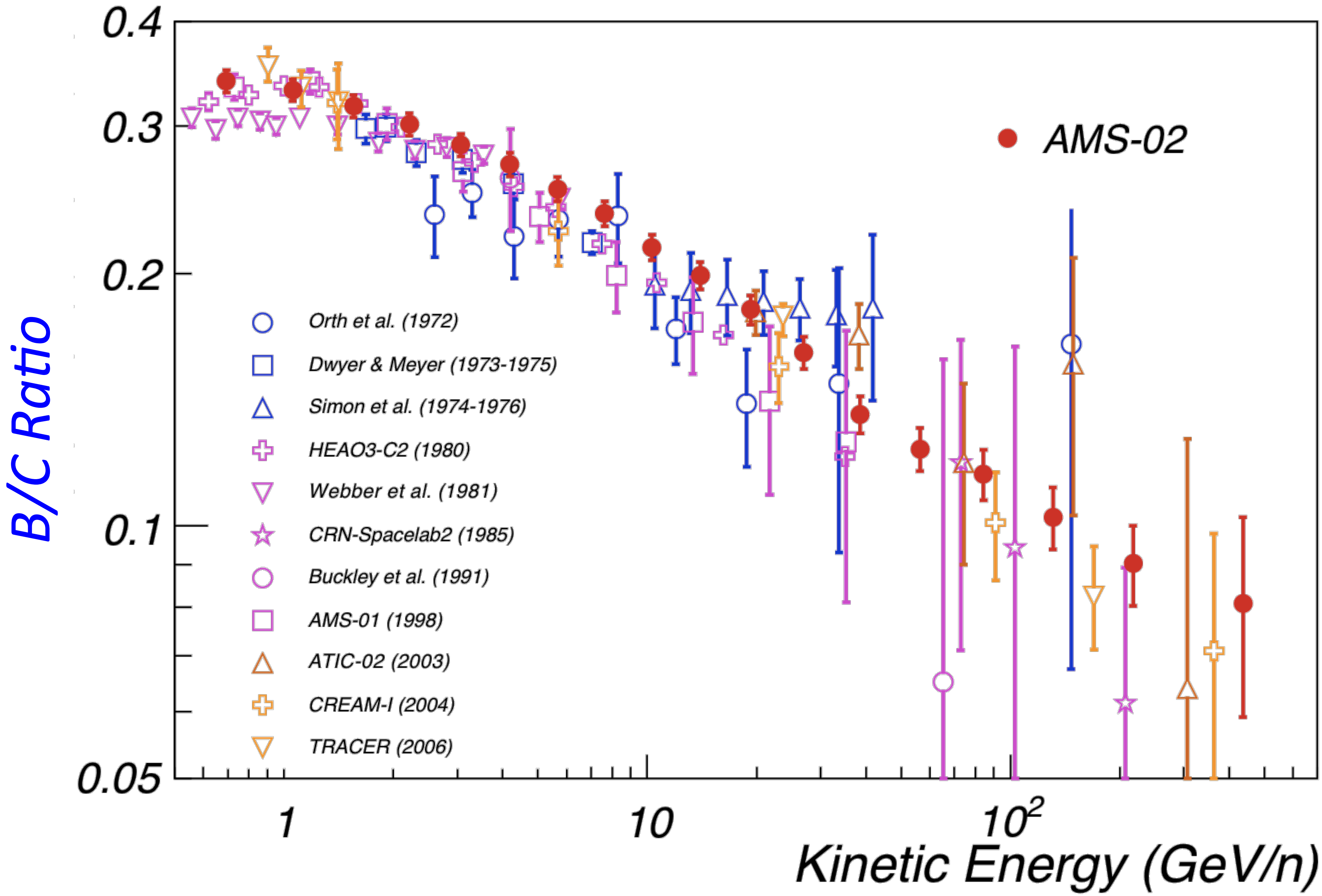

## Carbon

**Rigidity=215 GV**

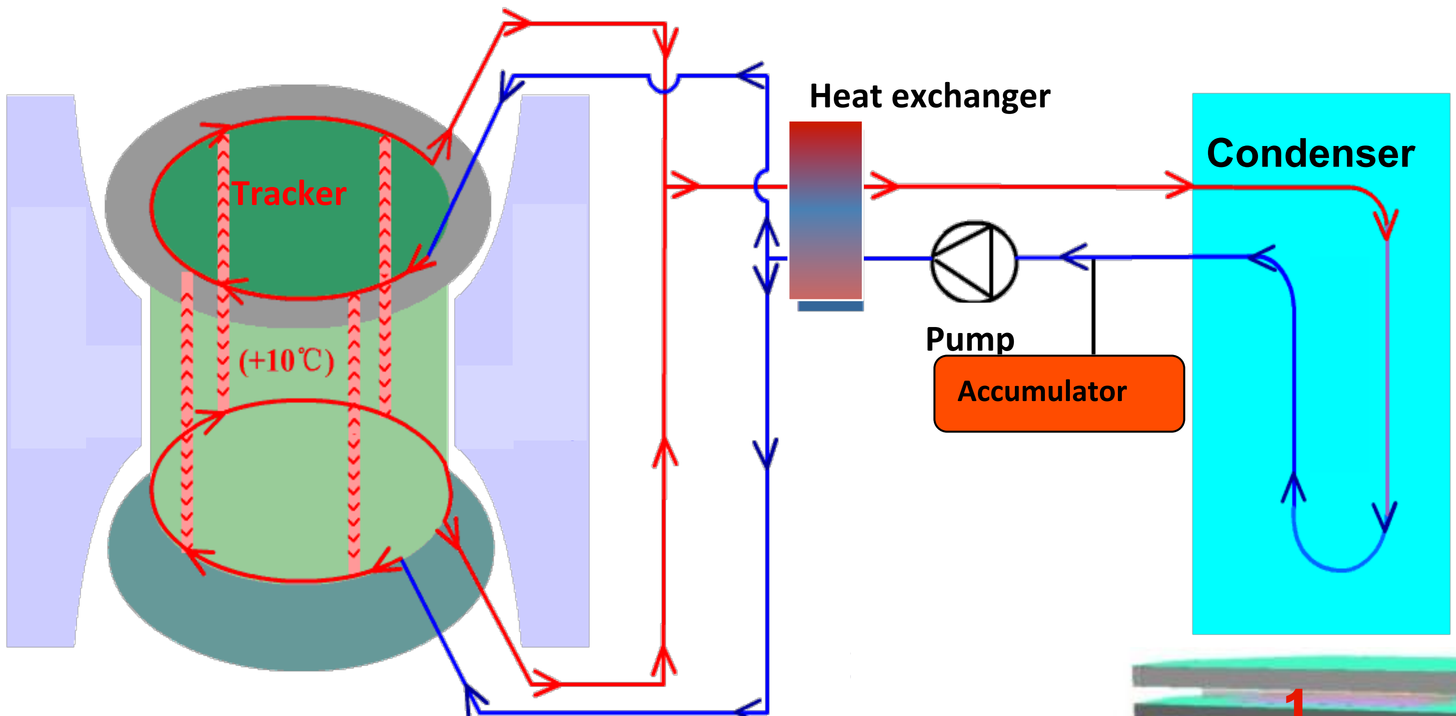
**Run/Event 132643580/ 132197**



# Boron-to-Carbon ratio

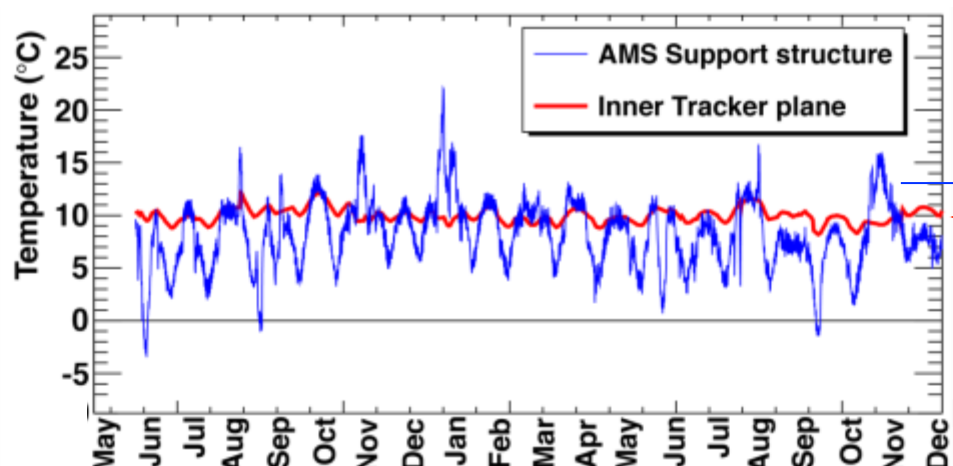


# Tracker Thermal Control System




Red line: $CO_2$ gas/liquid two phase

Blue line: $CO_2$ liquid phase




10±3°C