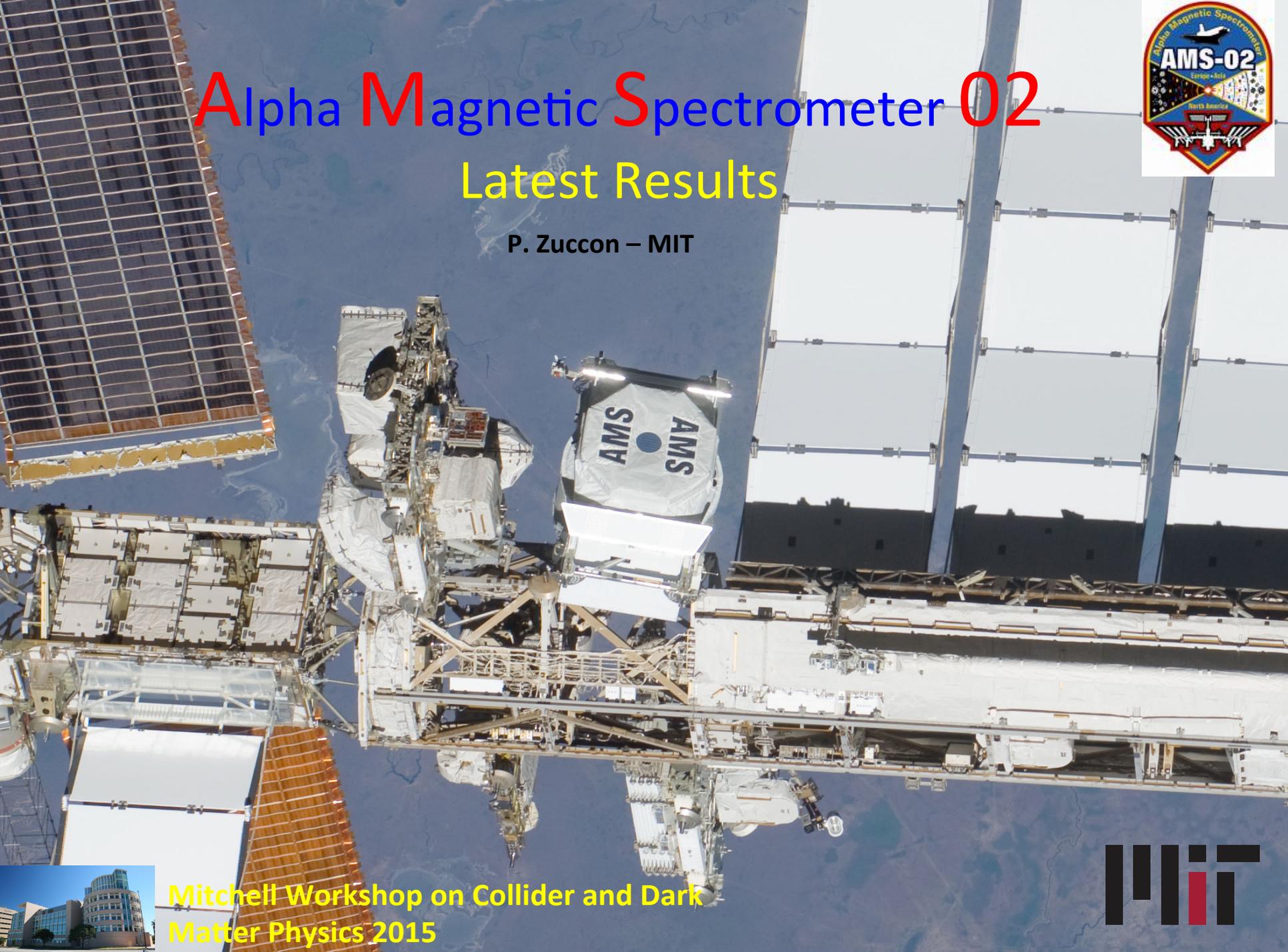


Alpha Magnetic Spectrometer 02

Latest Results

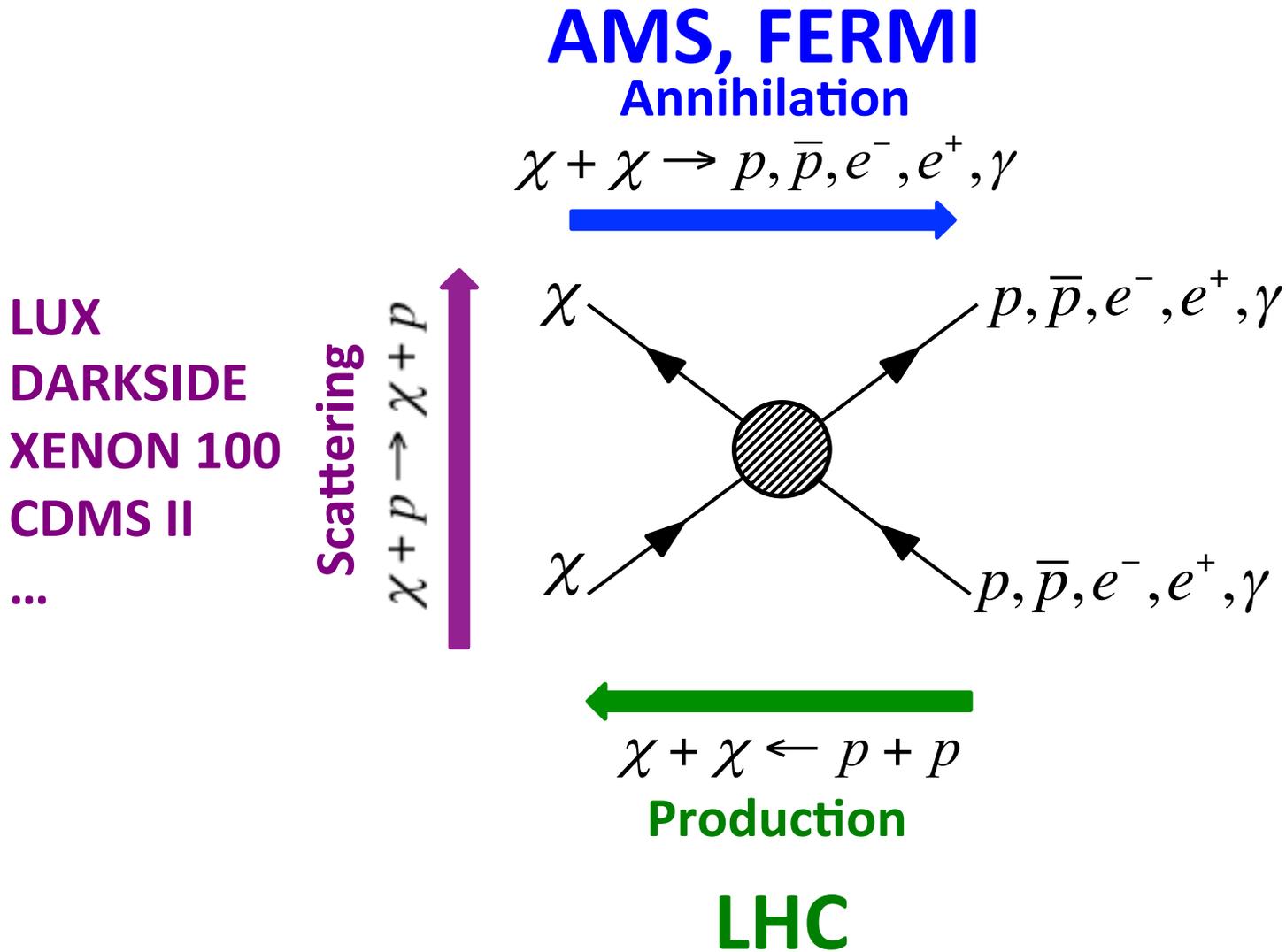
P. Zuccon – MIT



Mitchell Workshop on Collider and Dark Matter Physics 2015



Independent methods to search for Dark Matter





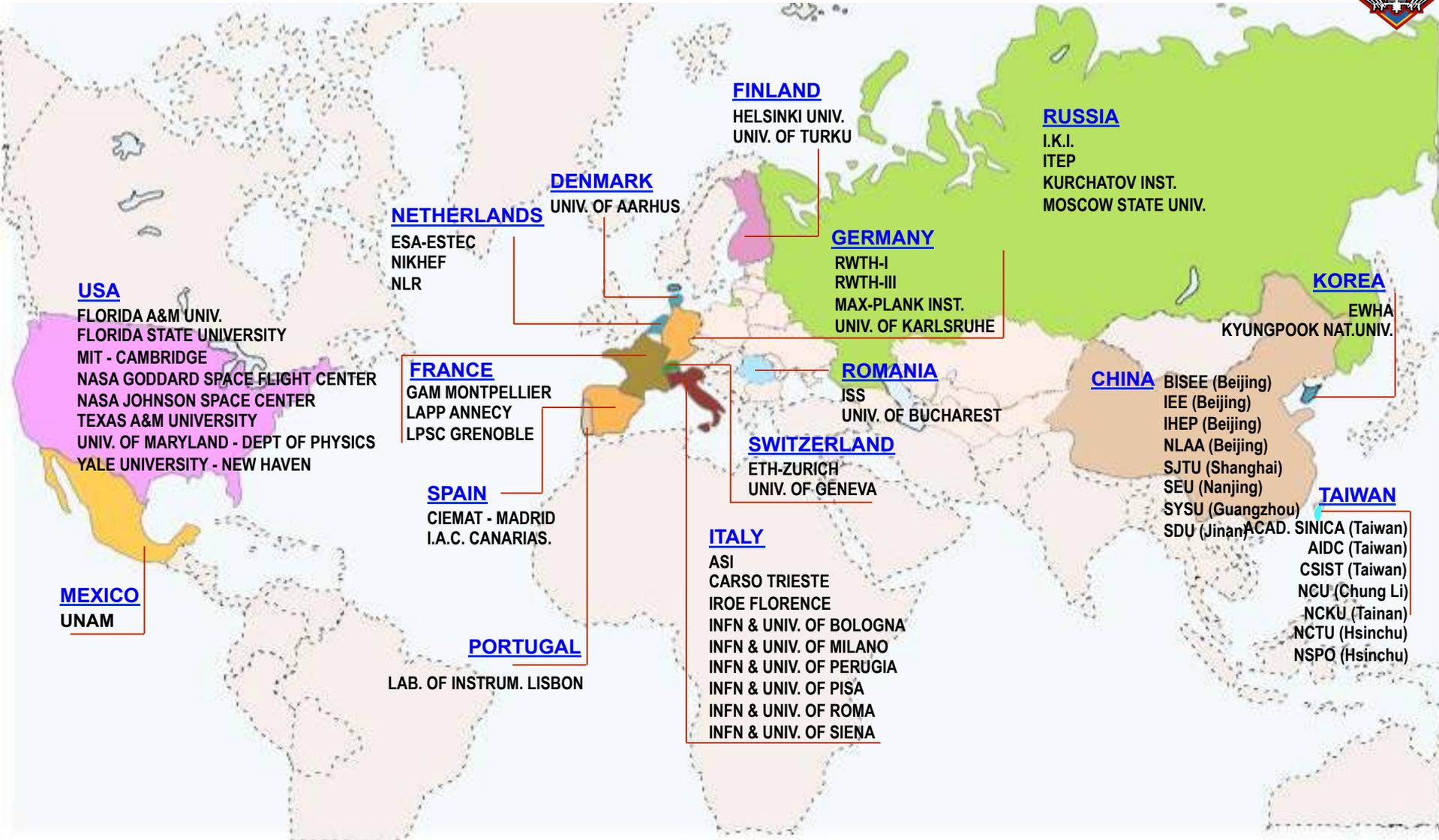
Alpha **M**agnetic **S**pectrometer

- AMS-02 is a particle physics detector devoted to the measurement of cosmic rays fluxes in the near Earth orbit in the range 0.1 GV – 2 TV
- 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 (recently extended to 2024)



AMS is MIT led International Collaboration

16 Countries, 60 Institutes and 600 Physicists, 17 years



**The detectors were built all over the world
 and assembled at CERN, Geneva, Switzerland**

AMS Physics Goals

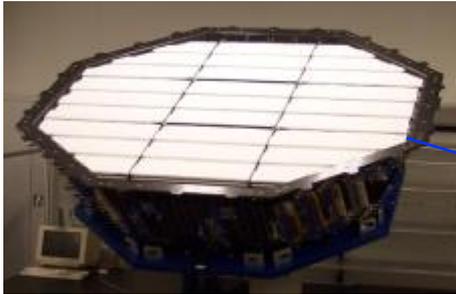


- **Searches for primordial antimatter:**
 - Anti-nuclei: **He**, ...
- **Dark Matter searches:**
 - e^+ , e^\pm , \bar{p} , ...
 - simultaneous observation of several signal channels.
- **Measuring CR spectra – refining propagation models;**
 - Nuclei spectra from p, He -> Fe
- **Identification of local sources of high energy photons (\sim TeV):**
 - SNR, Pulsars, PBH, ...
- **Study effects of solar modulation on CR spectra over 11 year solar cycle**
- **Search for Strangelets**
- ...

AMS: A TeV precision, multipurpose spectrometer

Transition Radiation Detector
(TRD)

Identify e^+ , e^-

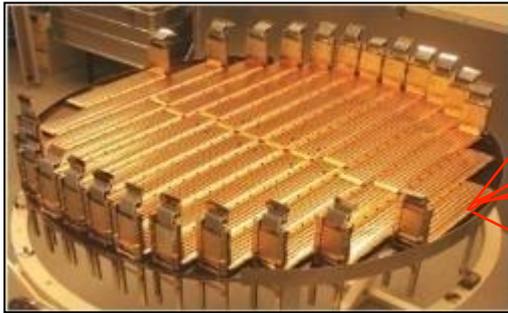


Particles and nuclei are defined by their charge (Z) and energy (E)

Time of Flight
(TOF)
 Z, E

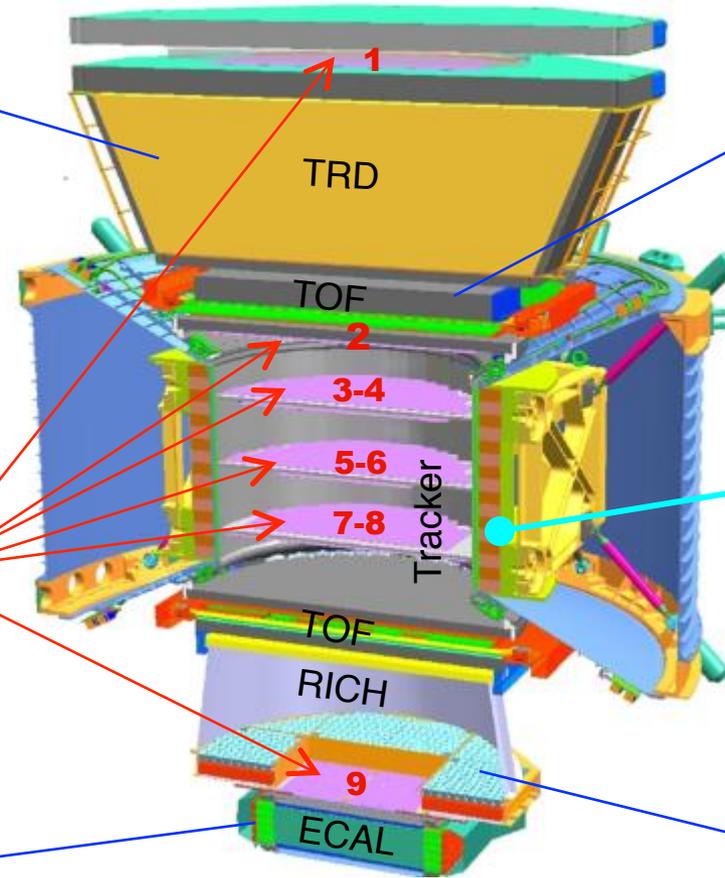


Silicon Tracker
 Z, P



Electromagnetic Calorimeter
(ECAL)

E of e^+ , e^- , γ



Magnet
 $\pm Z$



Ring Imaging Cherenkov
(RICH)
 Z, E



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

Transition Radiation Detector:



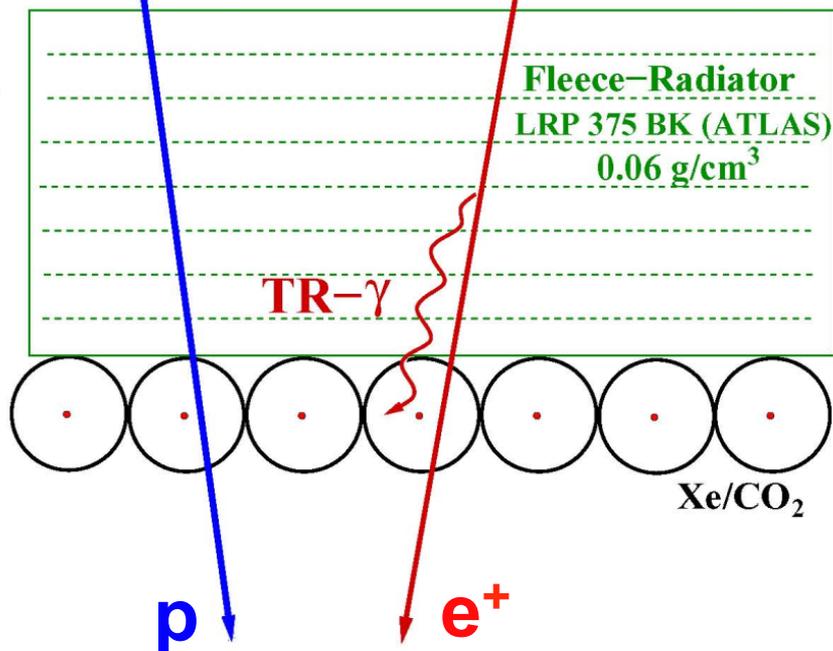
Prof. U. Becker

Prof. P. Fisher

TRD

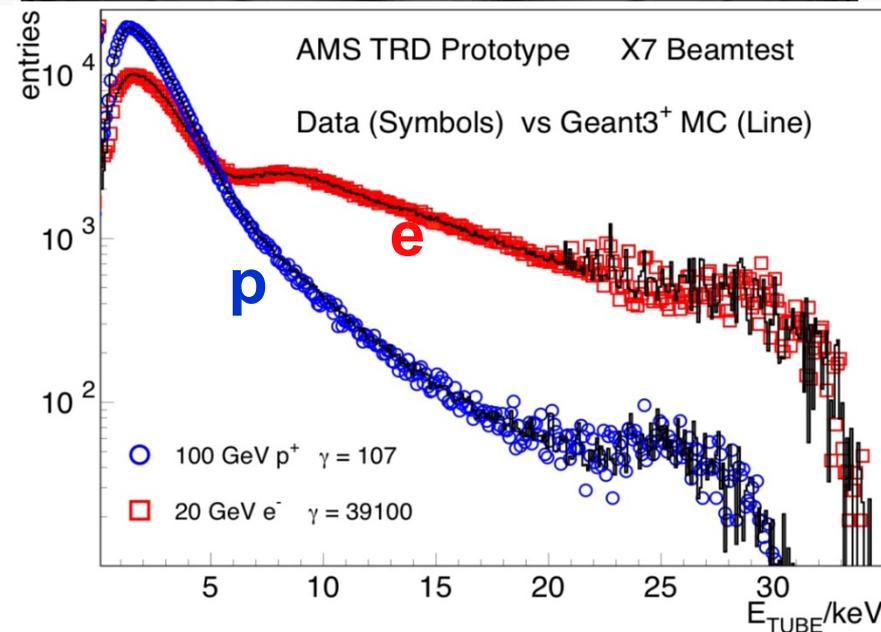
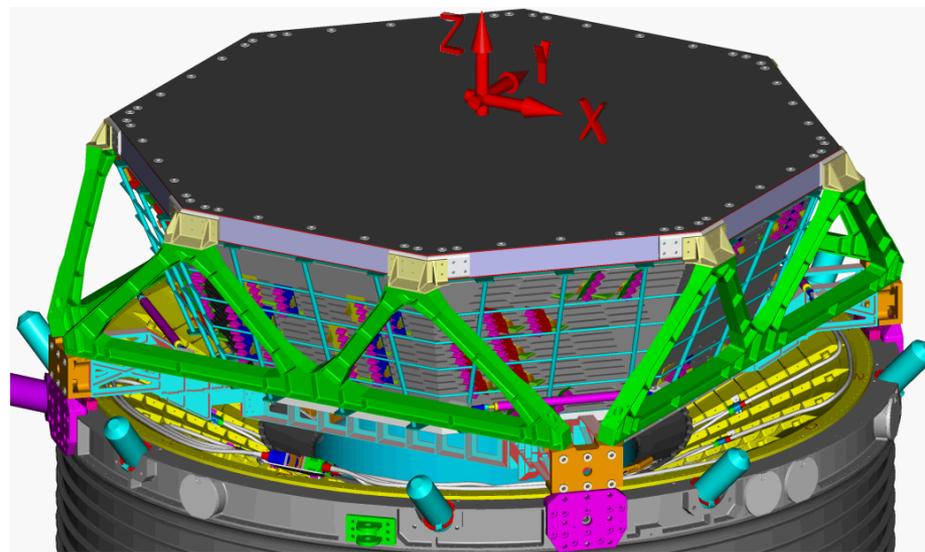
Identify e^+ , reject P

One of 20 Layers



Leak rate: $\text{CO}_2 \approx 5 \mu\text{g/s}$

Storage: 5 kg, >20 years lifetime

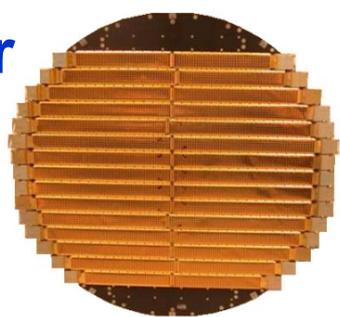
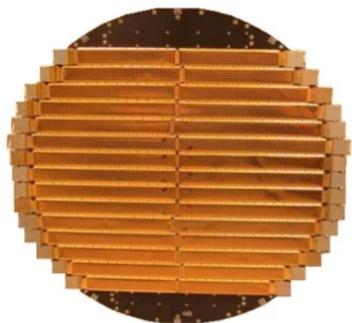


Silicon Tracker

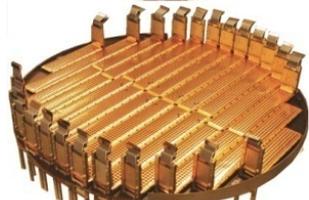
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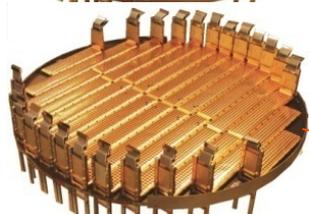
2



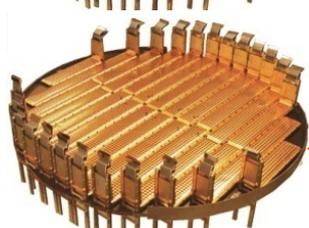
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4



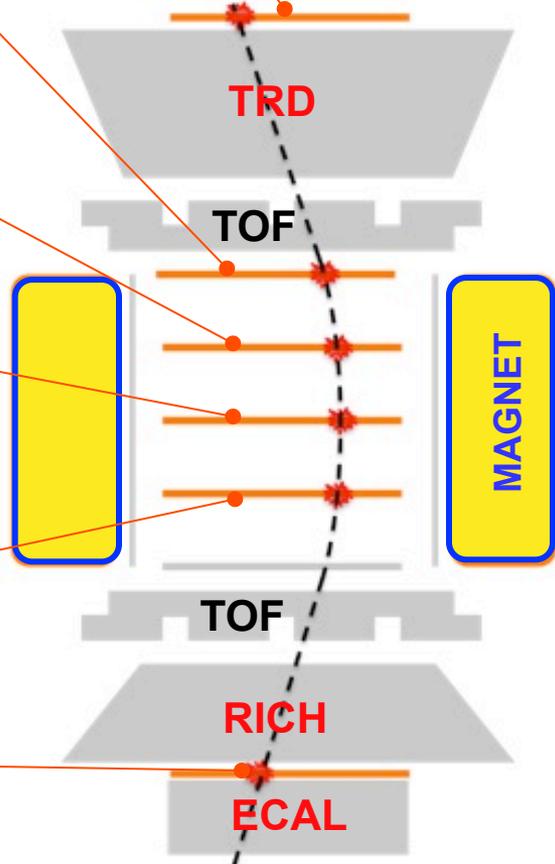
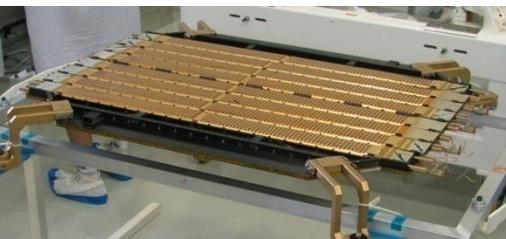
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6



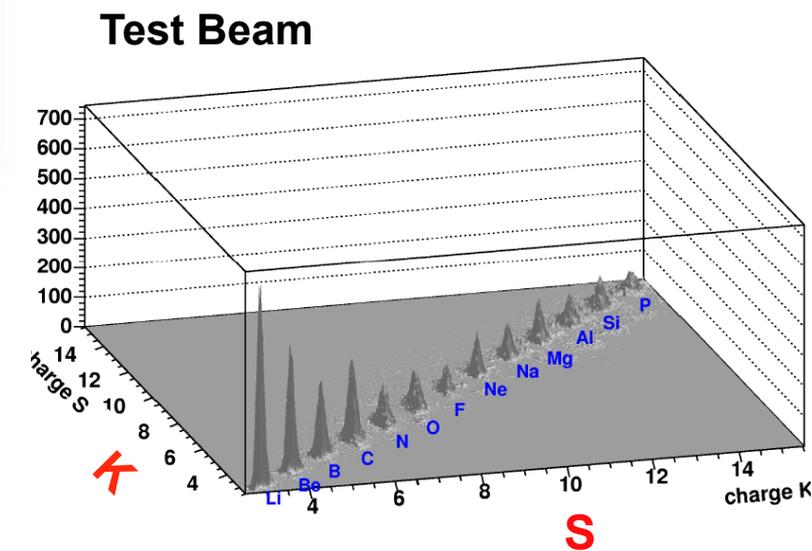
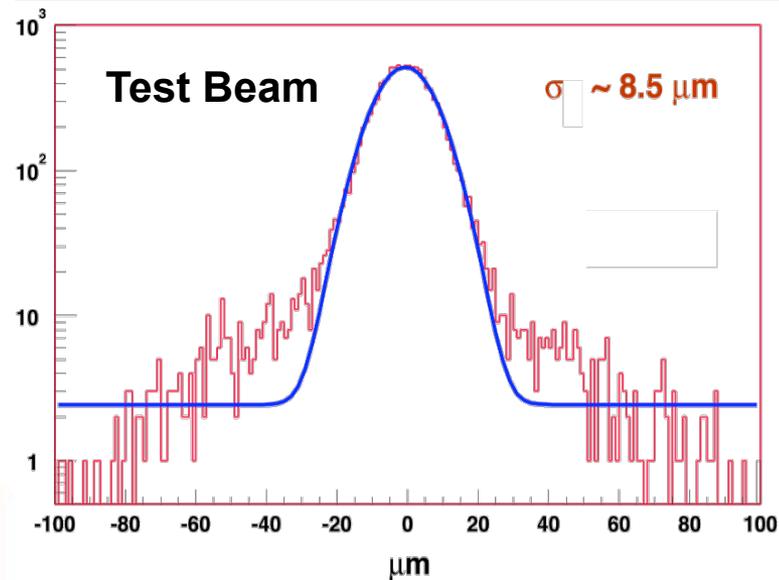
7
8



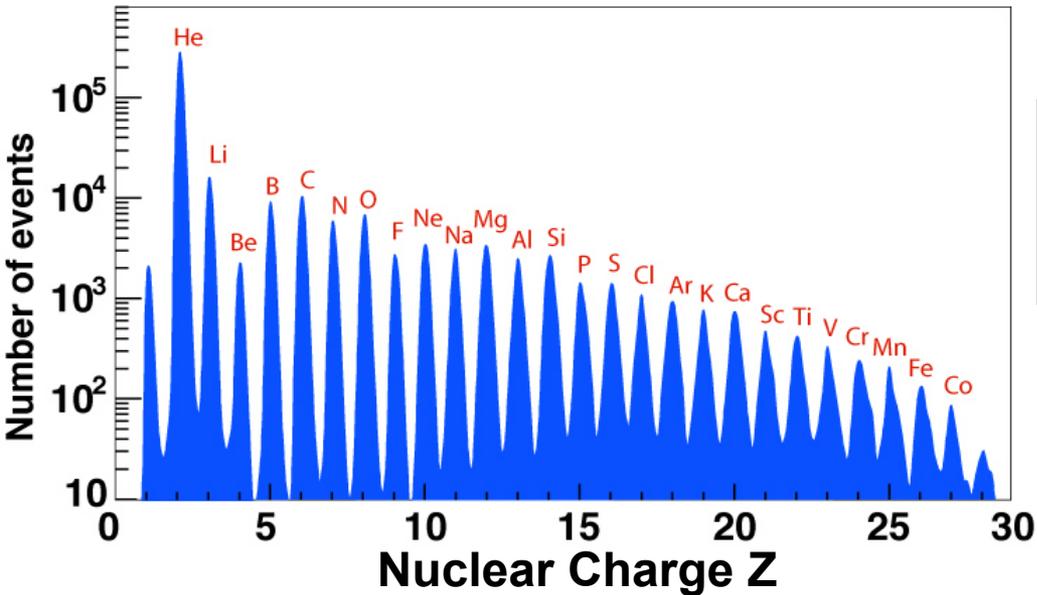
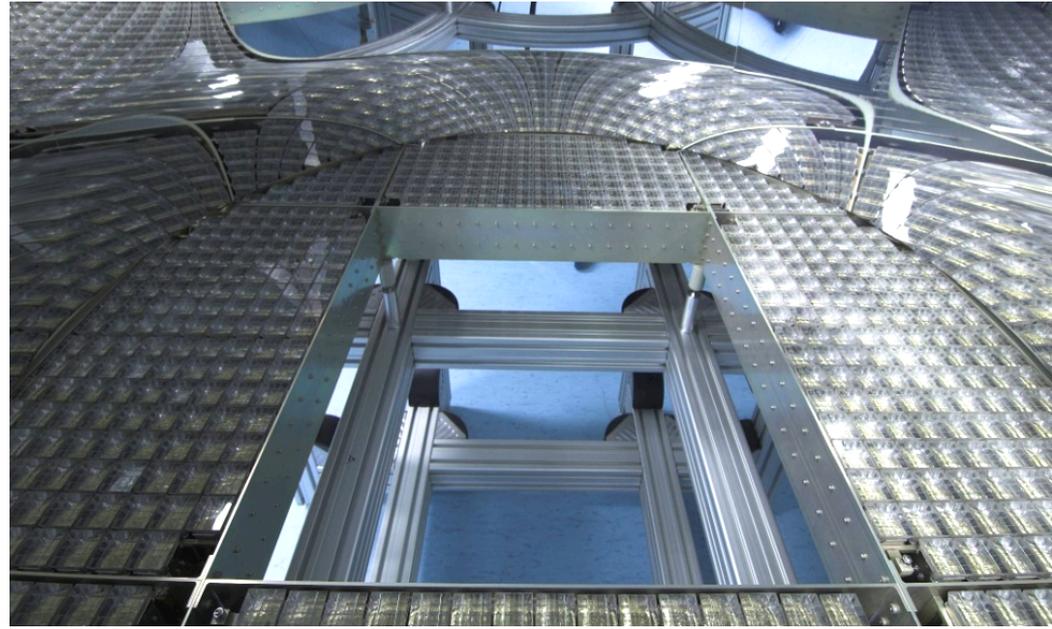
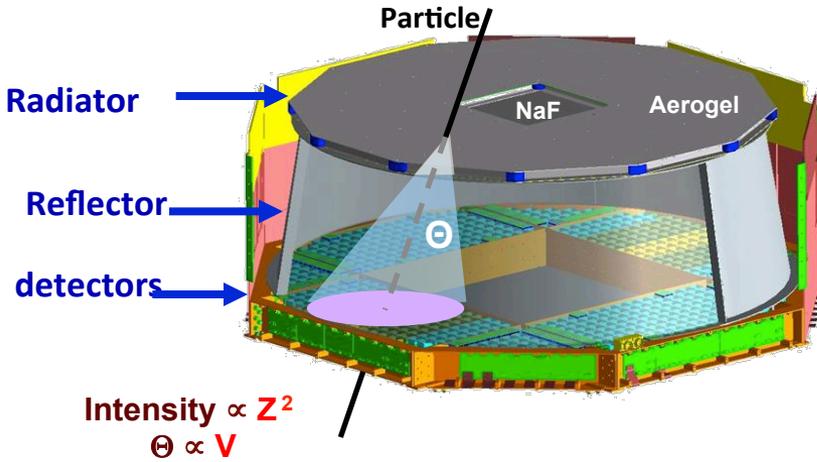
9



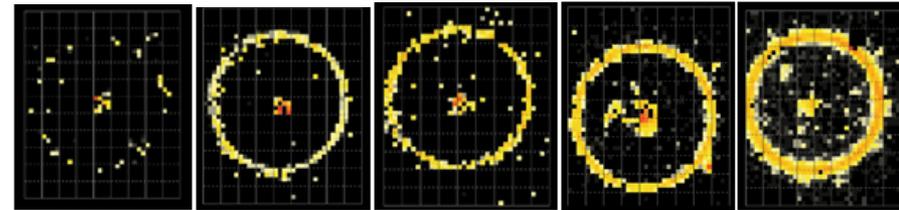
$MDR_p = 2.0 \text{ TV}$
 $MDR_{He} = 3.2 \text{ TV}$



Ring Imaging Cherenkov Detector (RICH)



10,880 photosensors



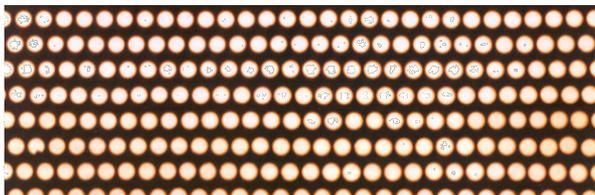
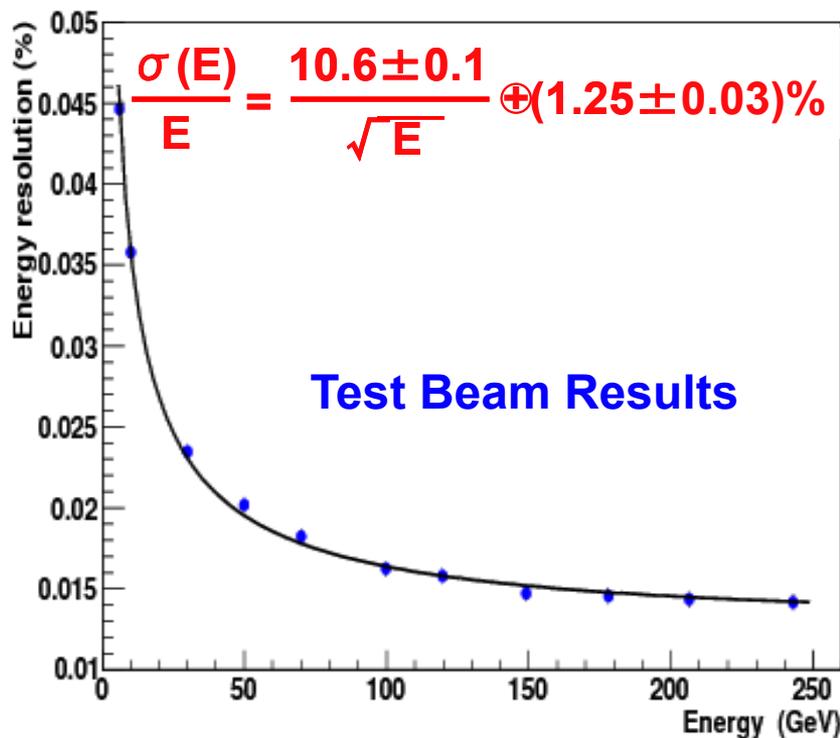
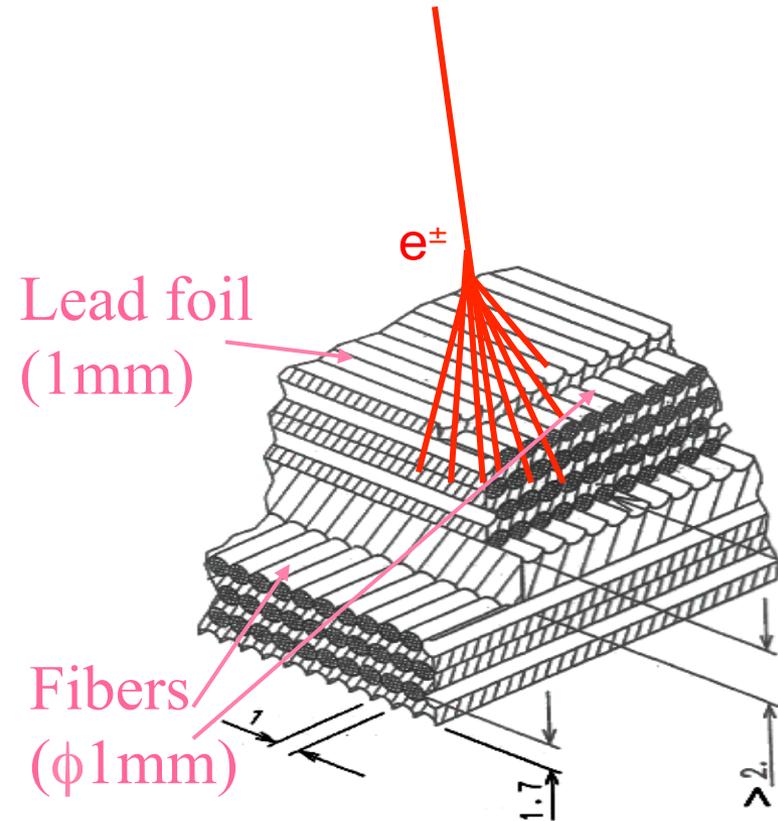
Single Event Displays

RICH test beam E=158 GeV/n



Calorimeter (ECAL)

A precision, $17 X_0$, TeV, 3-dimensional measurement of the directions and energies of light rays and electrons

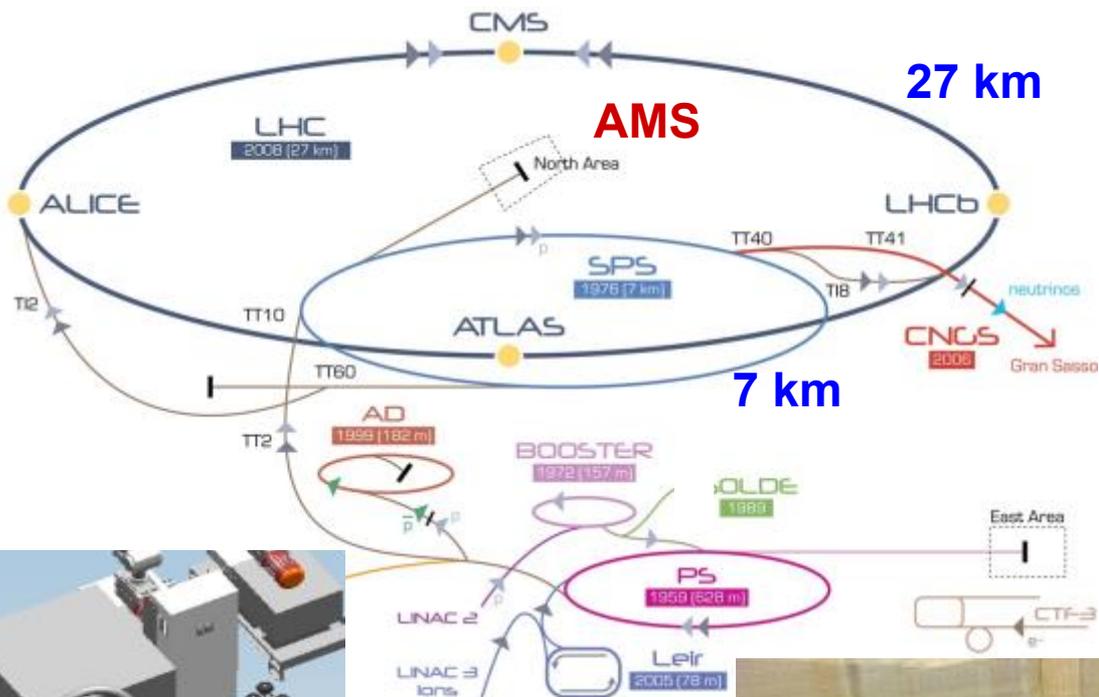


50 000 fibers, $\phi = 1\text{ mm}$
distributed uniformly
Inside 1,200 lb of lead

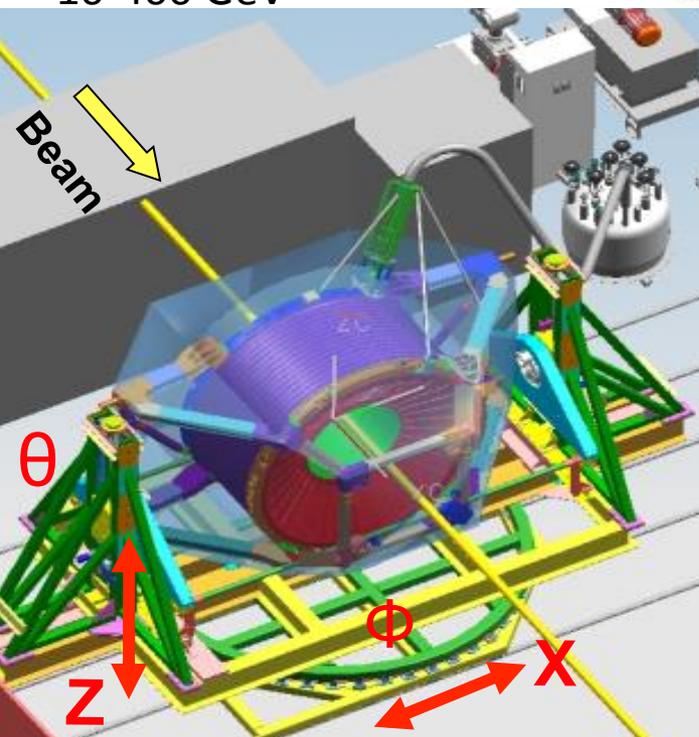


Tests at CERN

AMS in accelerator test beams Feb 4-8 and Aug 8-20, 2010



p, e+, e-, π
10-400 GeV



2000 positions



AMS in SPS Test Beam, August 2010

Particle	Momentum (GeV/c)	Positions	Purpose
Protons	400 + 180	1,650	Full Tracker alignment, TOF calibration, ECAL uniformity
Electrons	100, 120, 180, 290	7 each	TRD, ECAL performance study
Positrons	10, 20, 60, 80, 120, 180	7 each	TRD, ECAL performance study
Pions	20, 60, 80, 100, 120, 180	7 each	TRD performance to 1.2 TeV

May 16, 2011, 08:56 AM

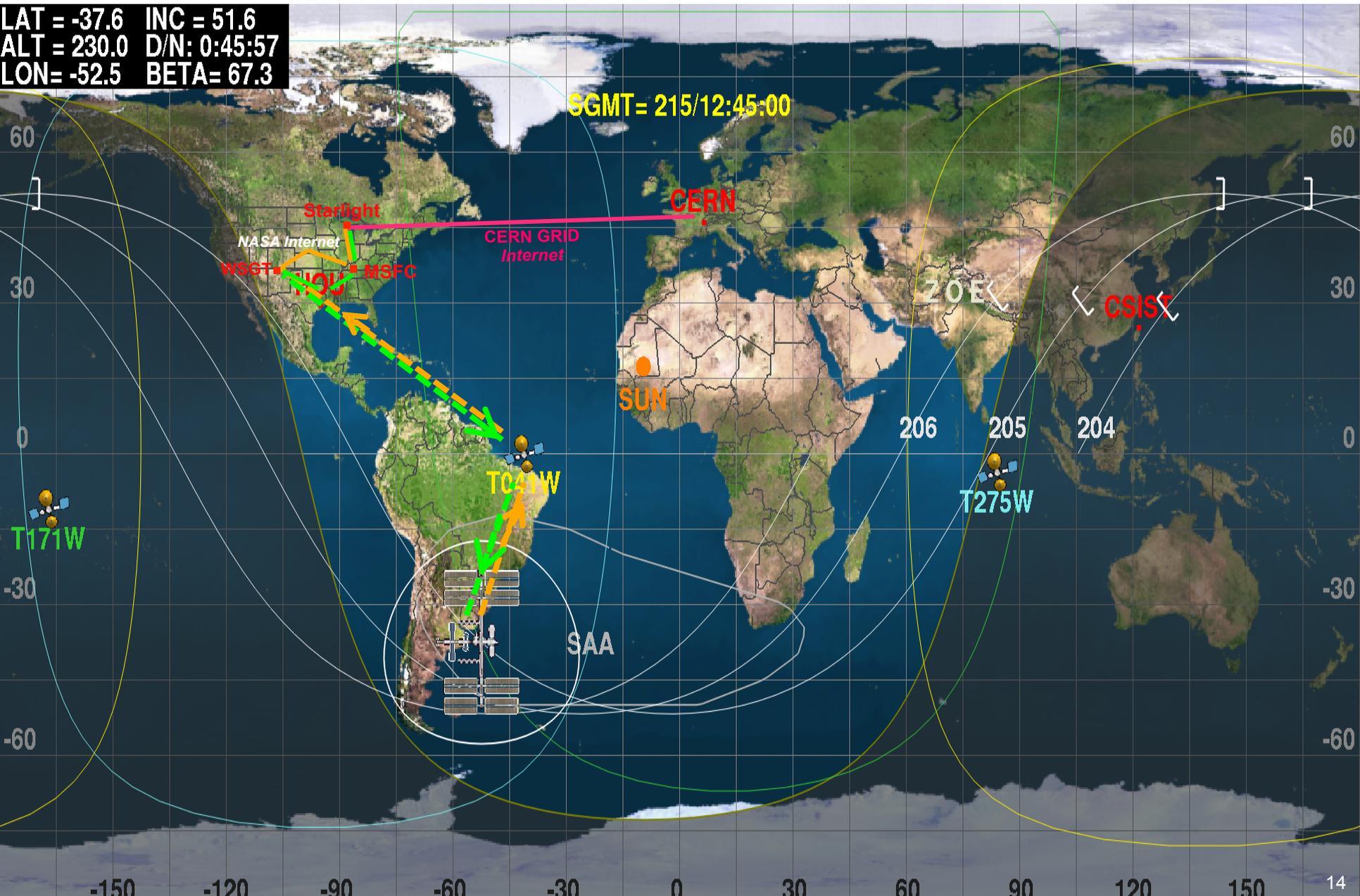
Total weight: 2008 t
AMS weight: 7.5 t



AMS on ISS

LAT = -37.6 INC = 51.6
ALT = 230.0 D/N: 0:45:57
LON = -52.5 BETA = 67.3

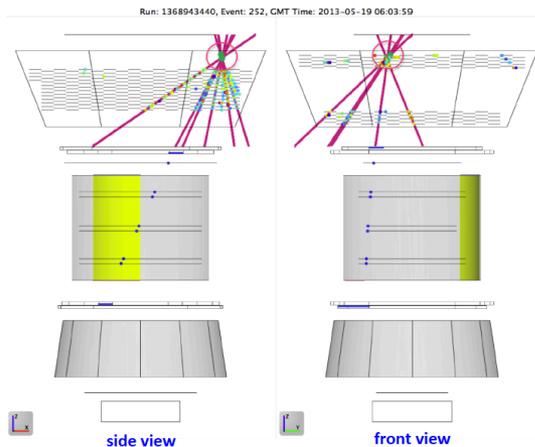
SGMT = 215/12:45:00



POCC at CERN in control of AMS since 19 June 2011

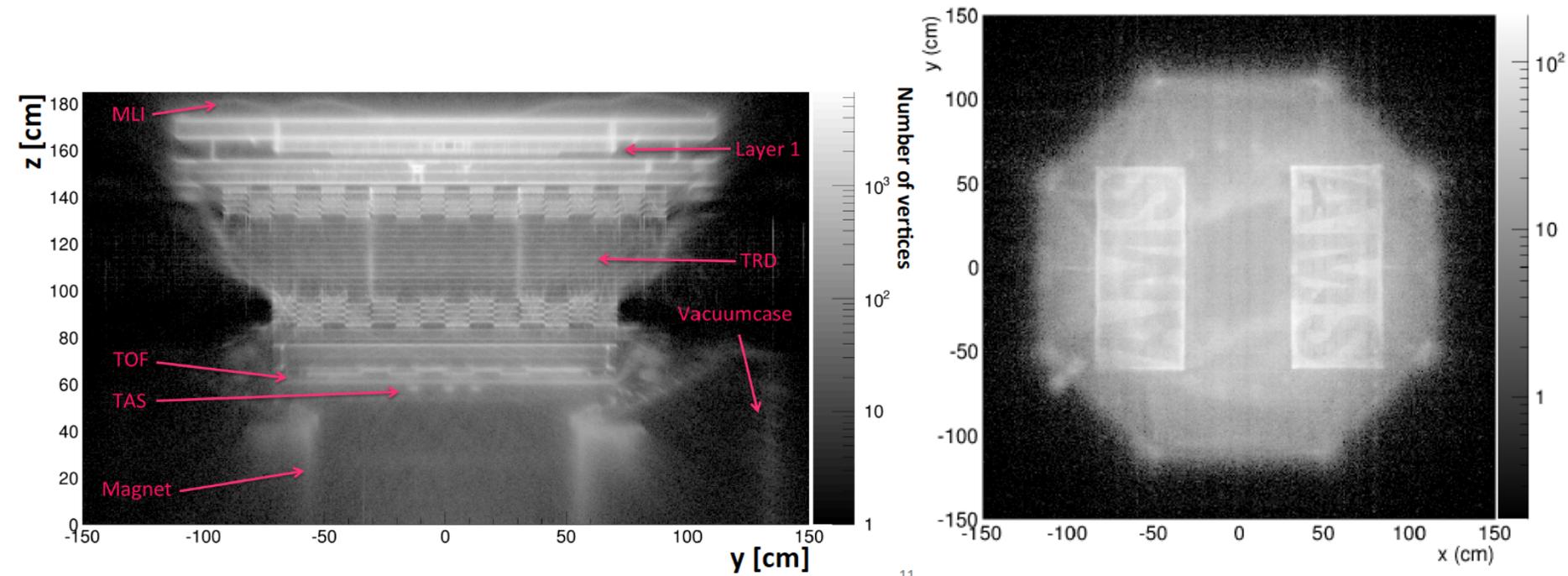


AMS “tomography” using rare nuclear interaction events

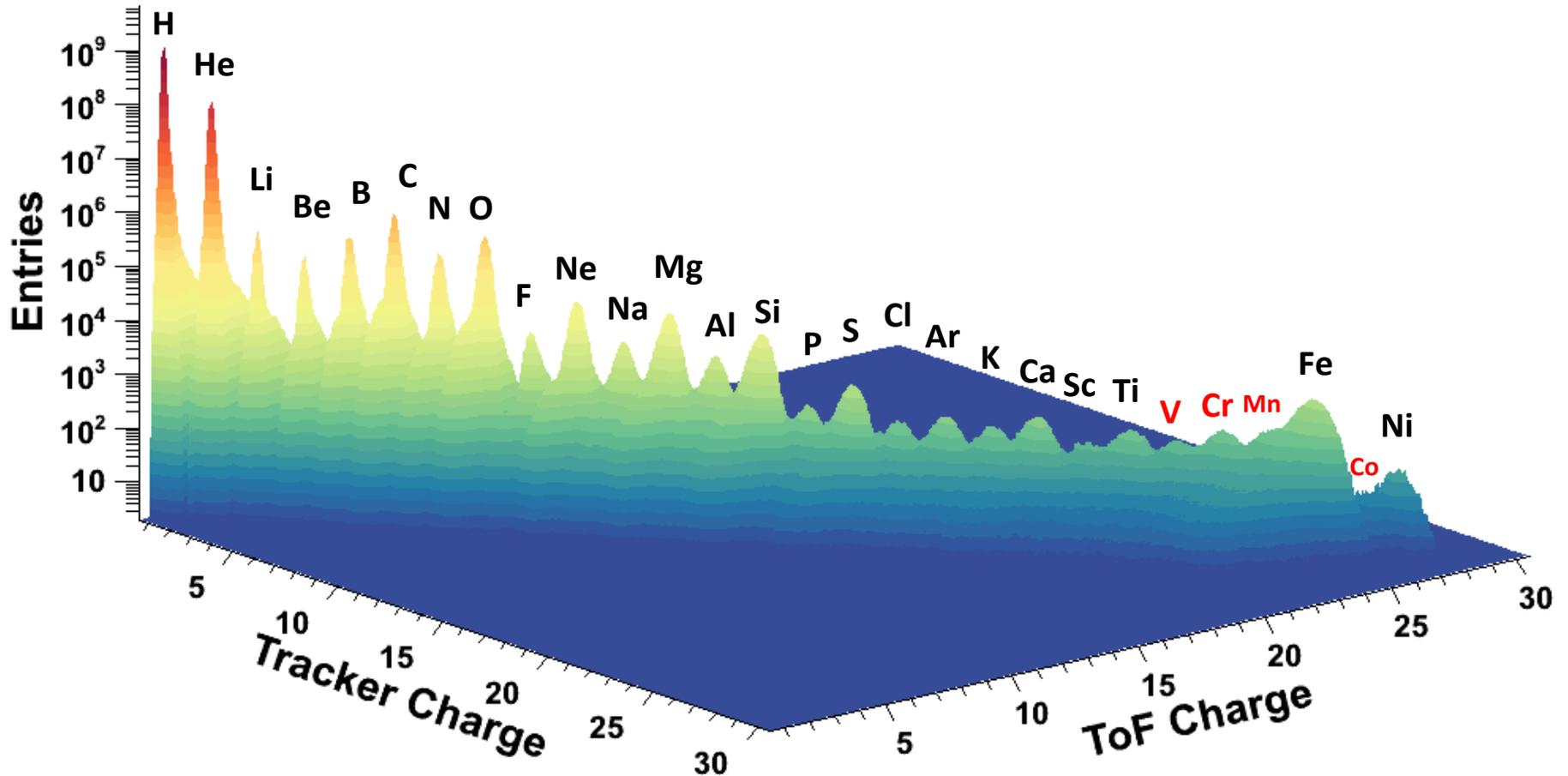


The gray scale is proportional to the the number of found vertices

Z=178.5 cm



Event selection: charge

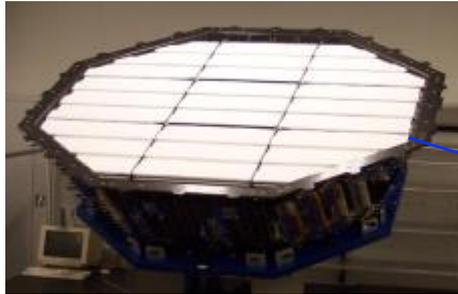


Resolution: $\Delta Z \approx 0.05$ for $Z = 1$

AMS: A TeV precision, multipurpose spectrometer

Transition Radiation Detector
(TRD)

Identify e^+ , e^-

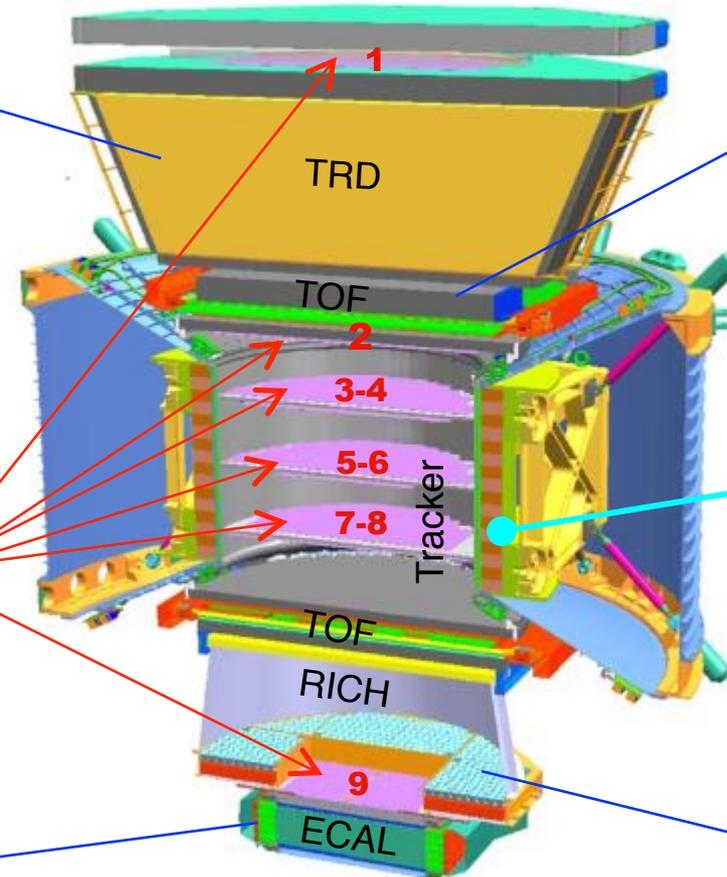
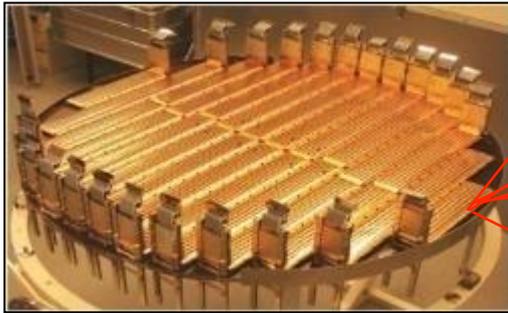


Particles and nuclei are defined by their charge (Z) and energy (E)

Time of Flight
(TOF)
 Z, E



Silicon Tracker
 Z, P



Magnet
 $\pm Z$



Electromagnetic Calorimeter
(ECAL)

E of e^+ , e^- , γ

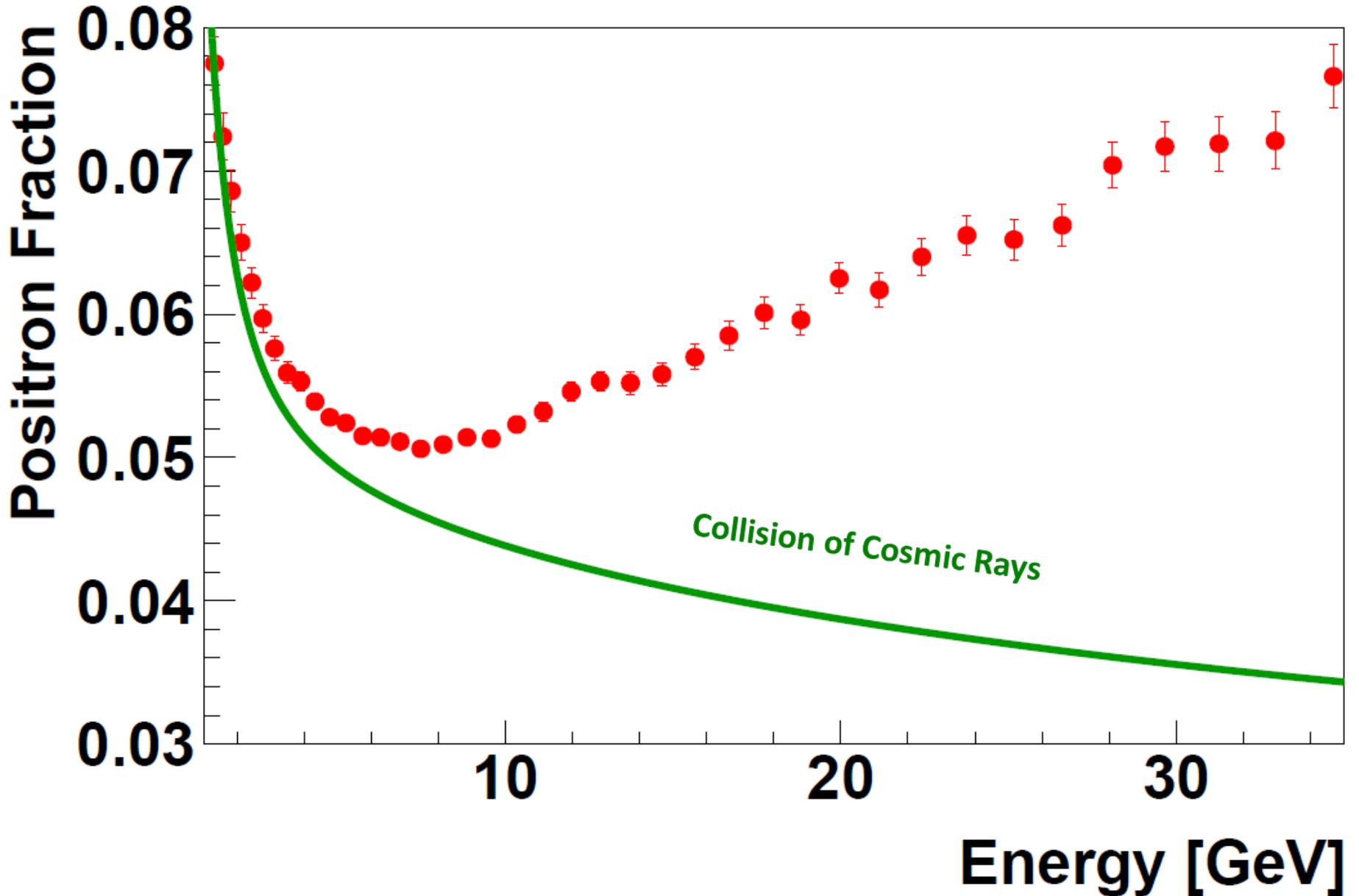


Ring Imaging Cherenkov
(RICH)
 Z, E

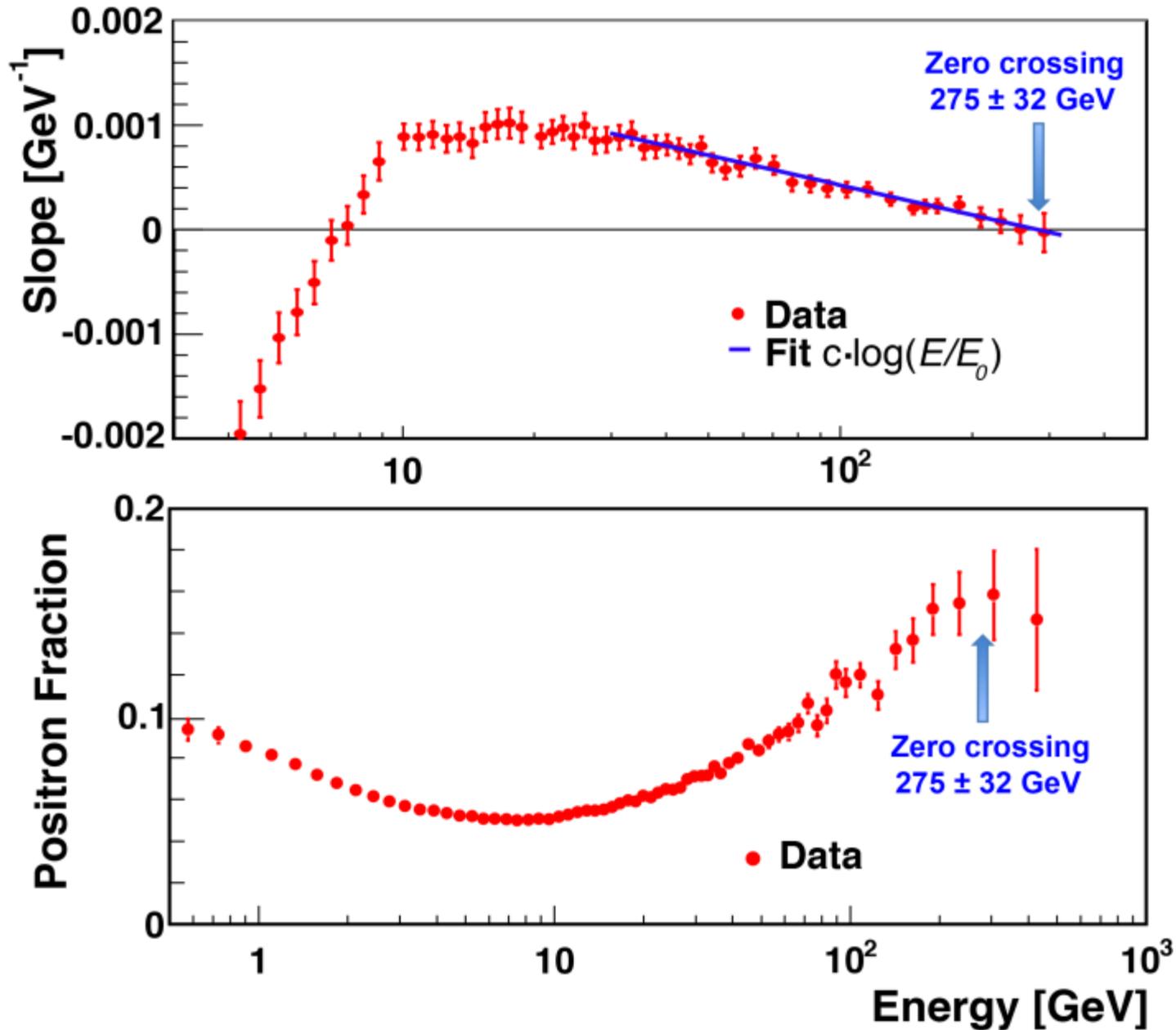


Z, E are measured independently by the Tracker, RICH, TOF and ECAL

The energy at which it begins to increase.



The energy beyond which it ceases to increase.



Measurement of the flux of electrons and positrons

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

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

ϵ_{trig} is the trigger efficiency

T is the exposure time

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

A_{geom} is the geometrical acceptance, $\approx 550 \text{ cm}^2\text{sr}$

ϵ_{sel} is the event selection efficiency

ϵ_{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).

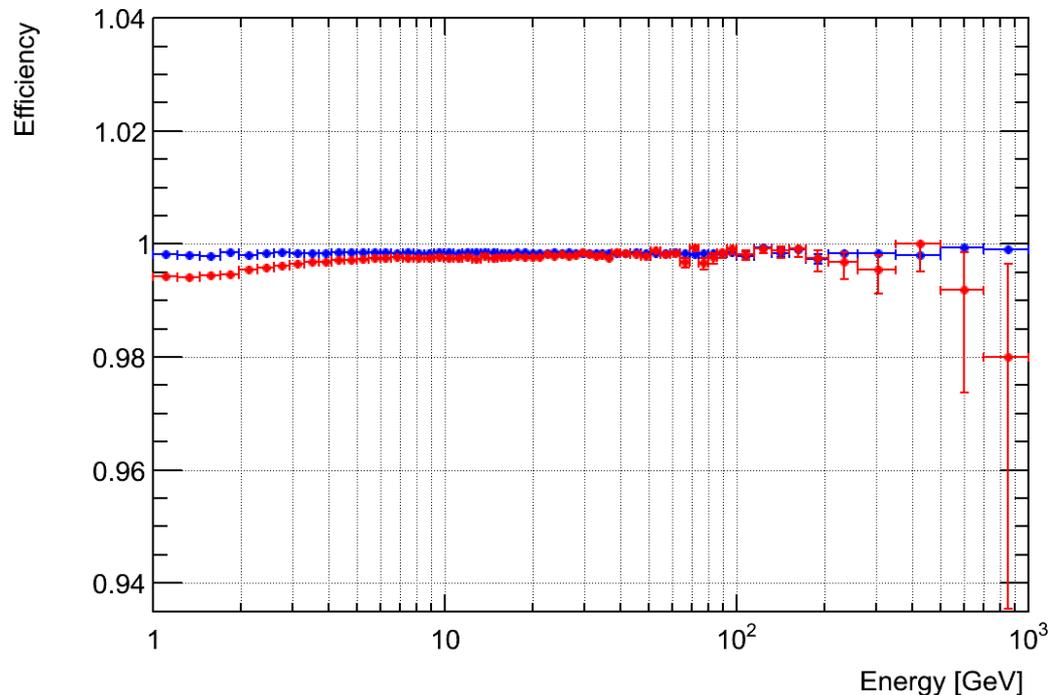
The error on $(1 + \delta)$ is $\sim 2.5\%$.

In order to determine the correction, δ , a negative rigidity sample is selected for every cut (i) using information from the detectors unrelated to that cut.

$$(1+\delta) = \prod_{\text{Cuts}} (1+\delta_i)$$

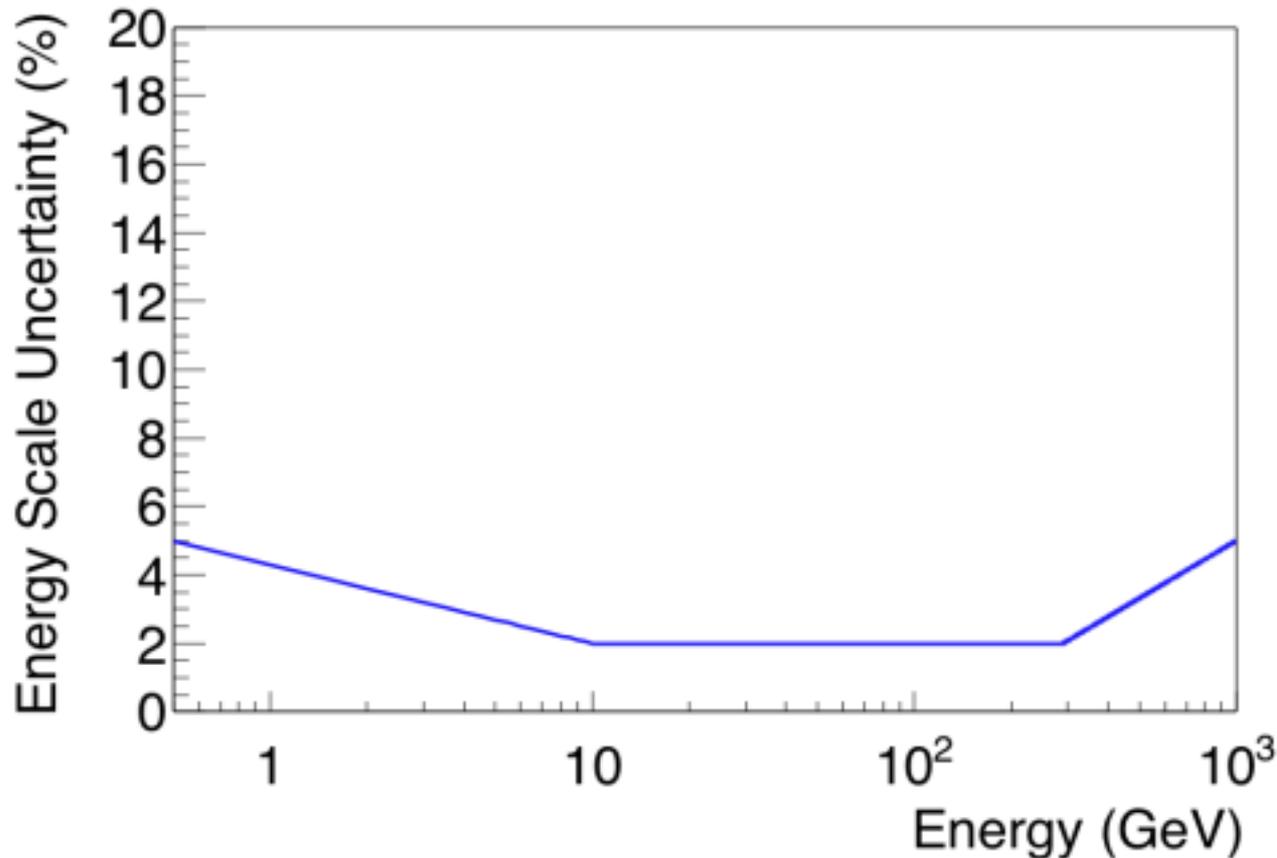
Example: TRD Track reconstruction

- Select electron candidate events using information from Tracker, TOF and ECAL.
- Calculate the efficiency of a **matching** TRD Track being reconstructed.
- The difference between **Monte Carlo** and **Data** determines the correction δ_i .

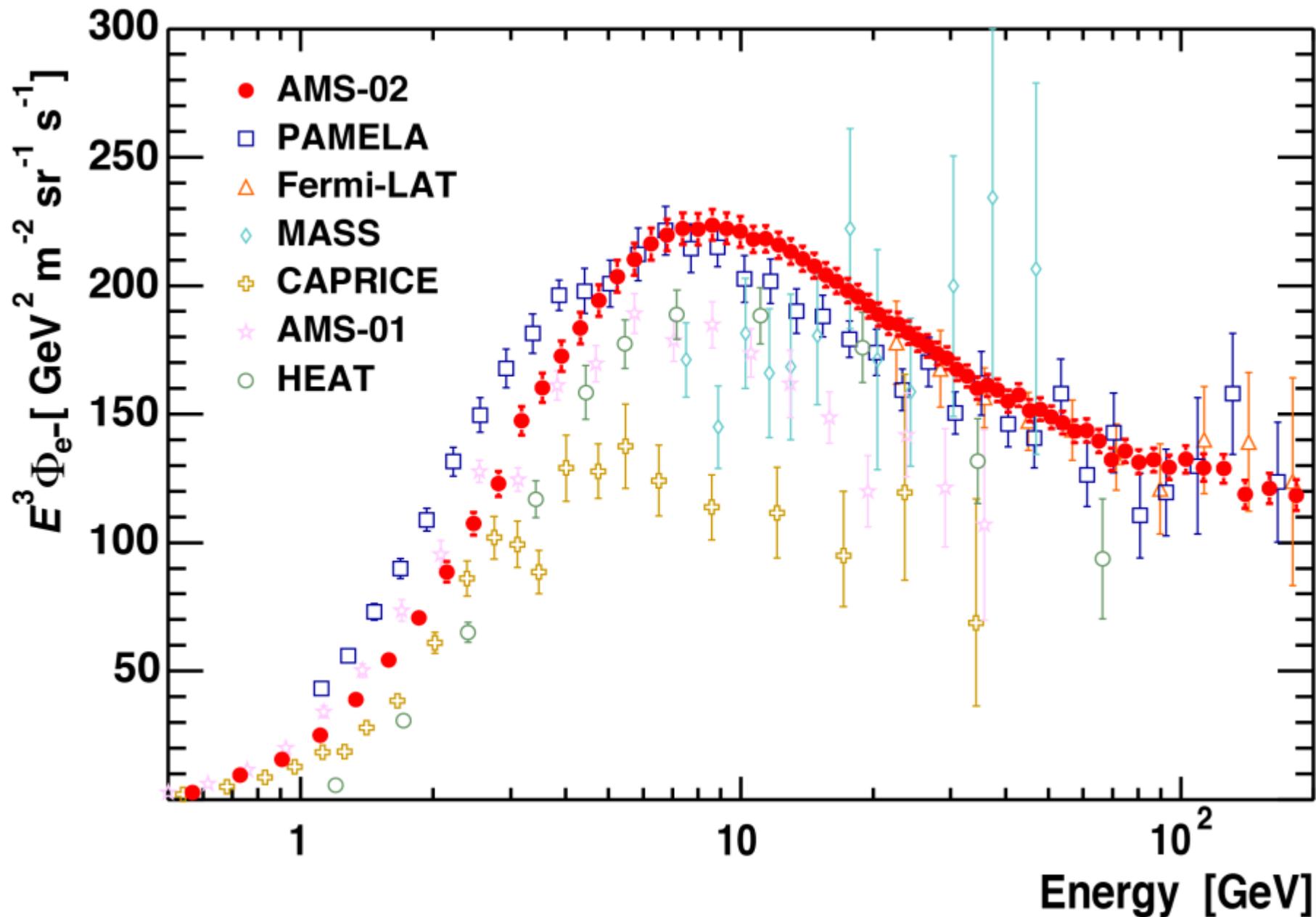


Absolute Energy Scale for e^\pm (at the top of AMS)

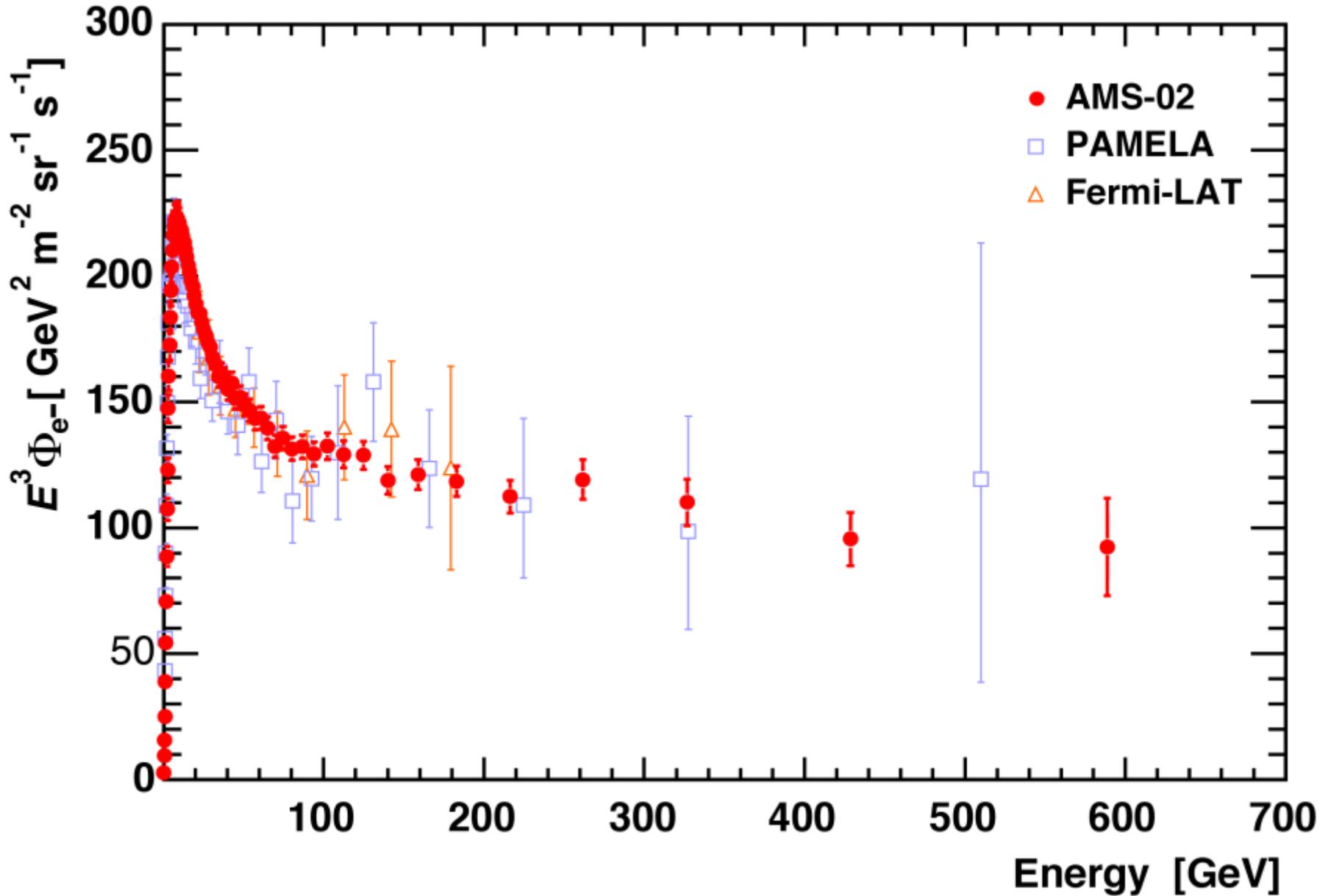
Verified using MIPs and E/p; compared to the test beam.
In the test beam range (10-290 GeV) the uncertainty is 2%.
It increases to 5% at 0.5 GeV and 1 TeV.



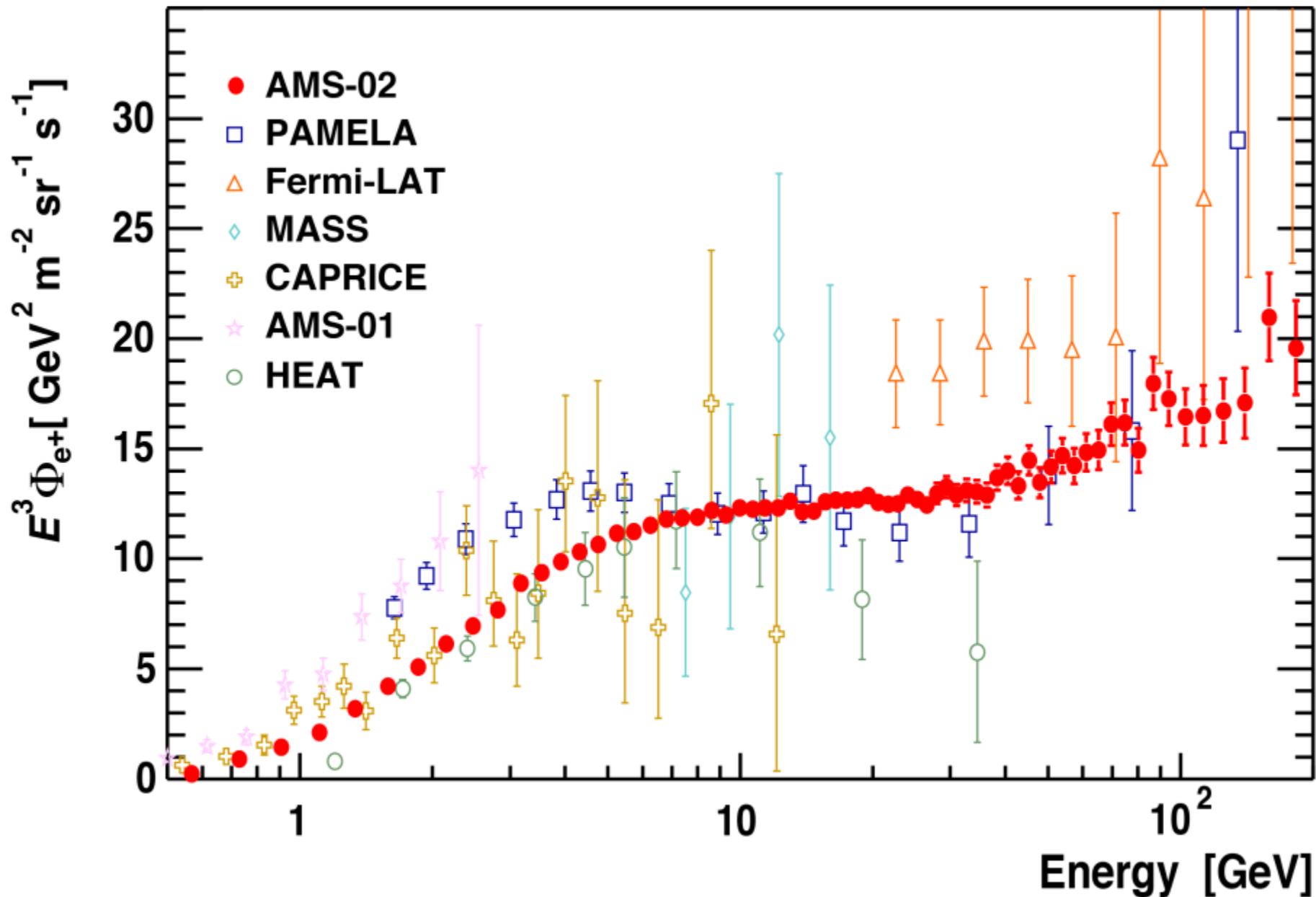
Electron Flux



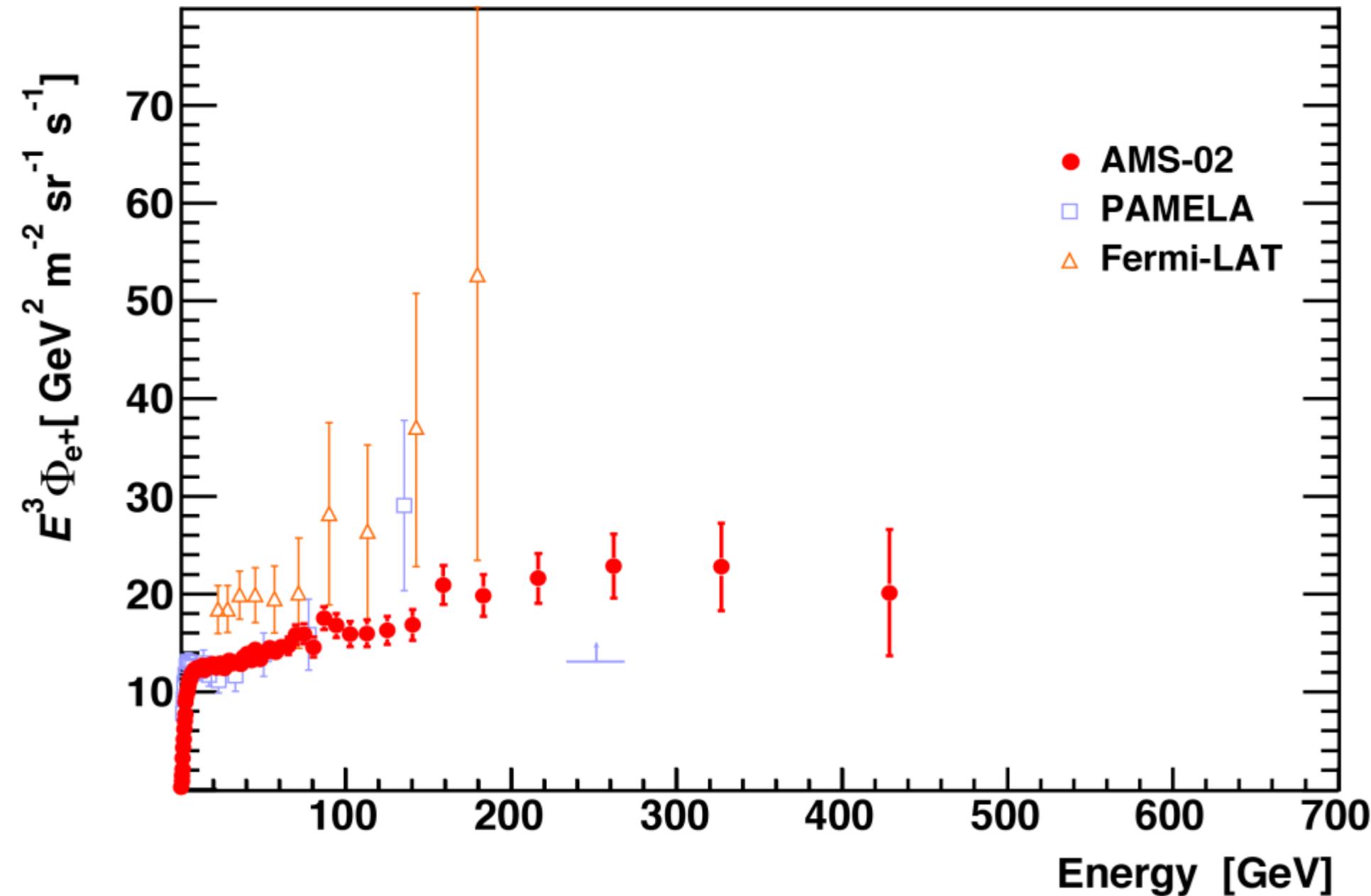
Electron Flux

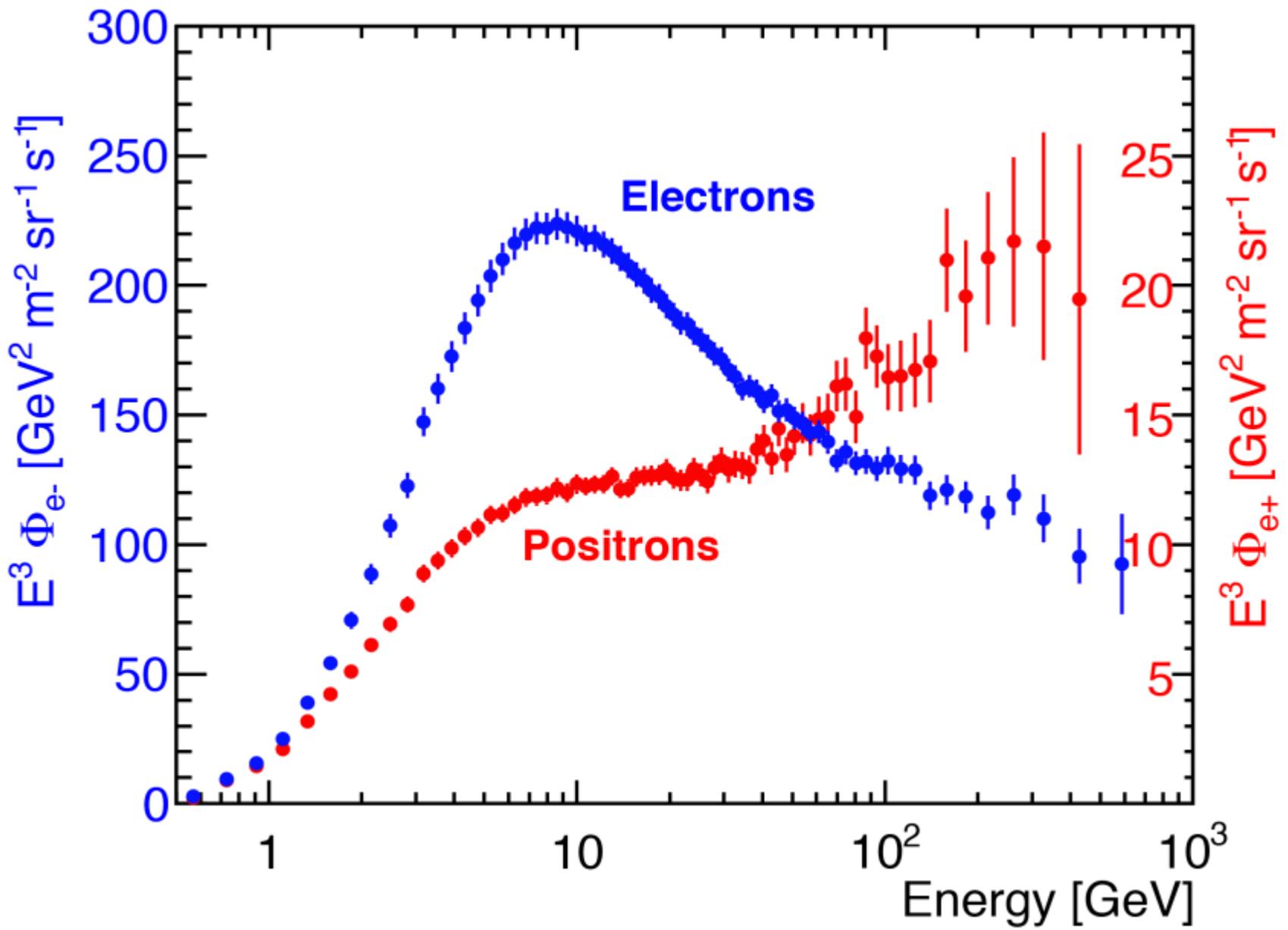


Positron Flux



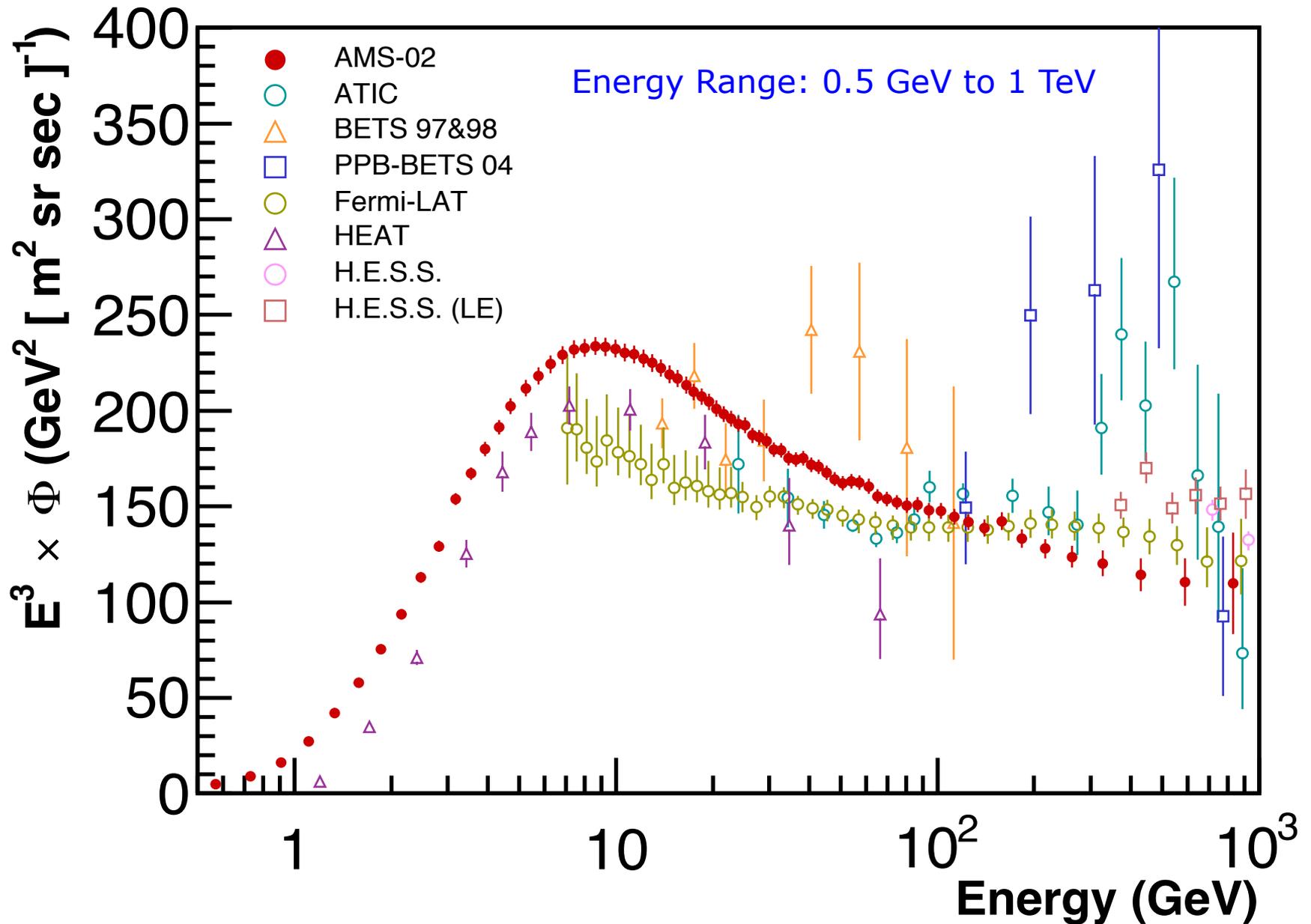
Positron Flux





Conclusion: The electron flux and the positron flux are different in their magnitude and energy dependence.

AMS Results: ($e^+ + e^-$) flux



The flux is smooth and reveals new and distinct information.

EXAMPLE:

Minimal Model Fit to the data

$$\begin{aligned}\Phi_{e^+} &= \underbrace{C_{e^+} E^{-\gamma_{e^+}}}_{\text{Diffuse Flux}} + \underbrace{C_s E^{-\gamma_s} e^{-E/E_s}}_{\text{Source Flux}} \\ \Phi_{e^-} &= \underbrace{C_{e^-} E^{-\gamma_{e^-}}}_{\text{Diffuse Flux}} + \underbrace{C_s E^{-\gamma_s} e^{-E/E_s}}_{\text{Source Flux}}\end{aligned}$$

Simultaneous fit to

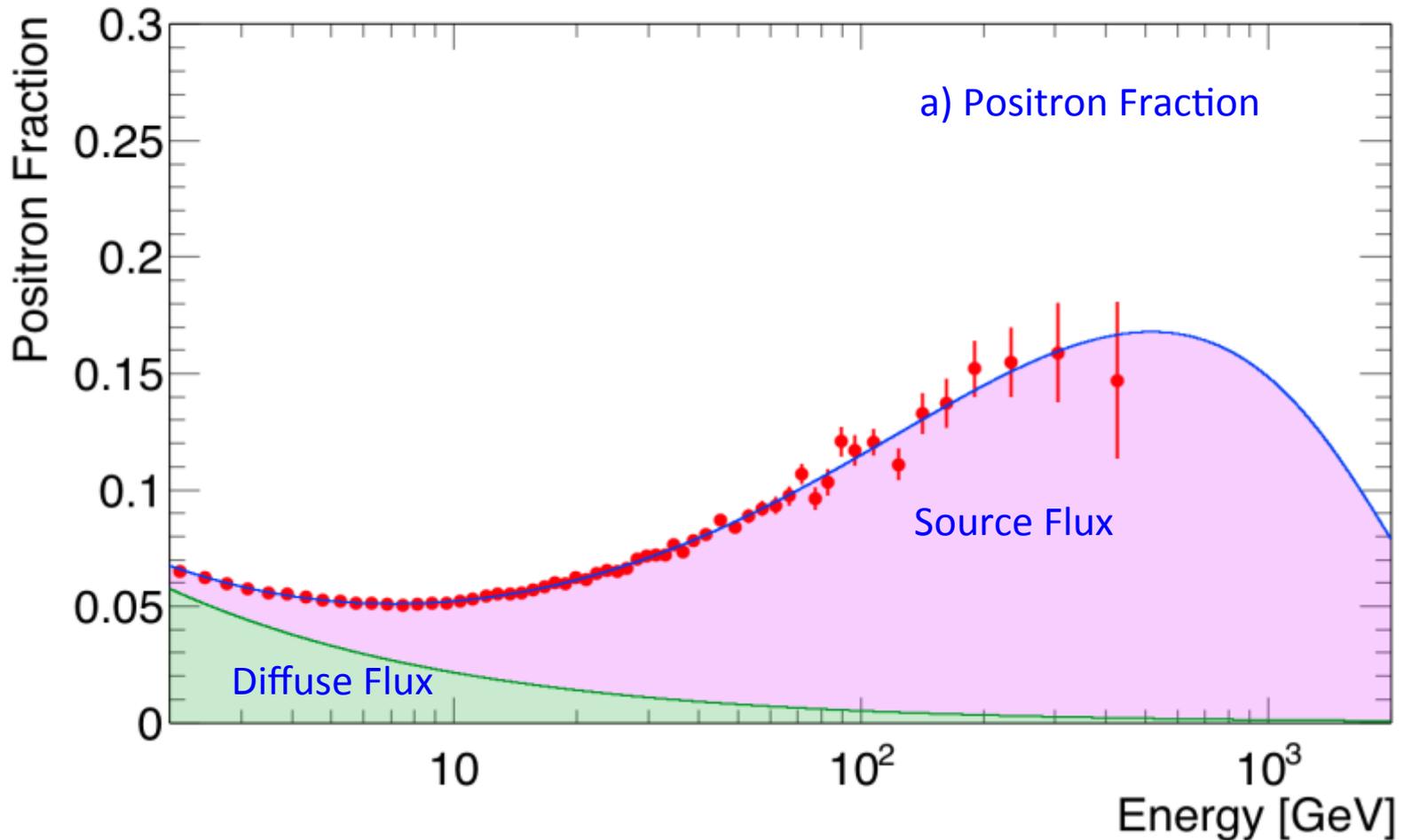
- a) Positron Fraction from 2GeV
- b) Electron + Positron from 2GeV
- $(\gamma_{e^-} - \gamma_{e^+}), (\gamma_{e^-} - \gamma_s), C_{e^+}, C_{e^-}, C_s, E_s$ are constant
- γ_{e^-} is energy dependent below ~ 15 GeV.

Minimal Model:

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

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

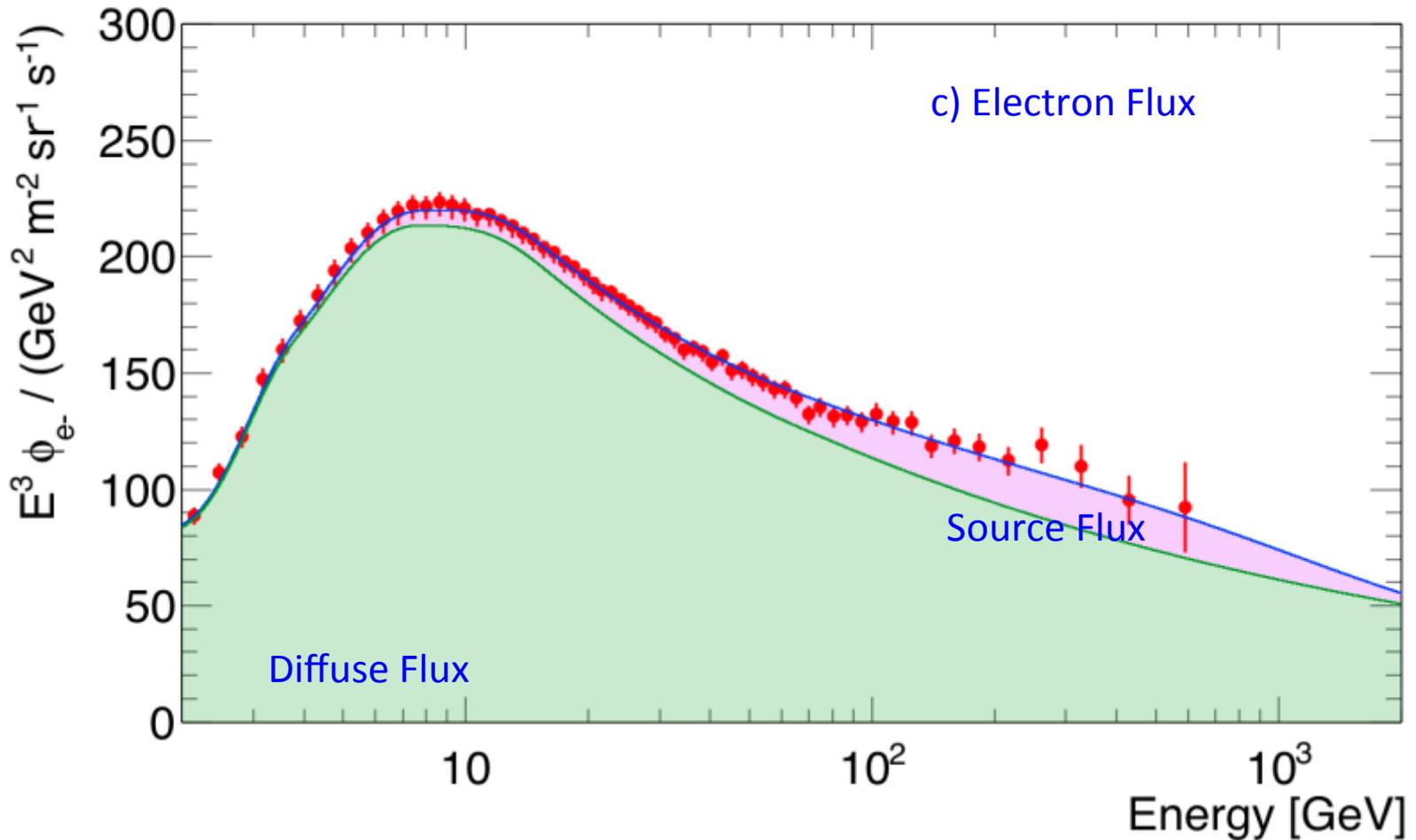
$$\begin{aligned}\gamma_{e^-} - \gamma_{e^+} &= -0.63 \pm 0.06, & \gamma_{e^-} - \gamma_s &= 0.66 \pm 0.05, \\ C_{e^+}/C_{e^-} &= 0.095 \pm 0.003, & C_s/C_{e^-} &= 0.008 \pm 0.001 \\ 1/E_s &= 1.3 \pm 0.6 \text{ TeV}^{-1}\end{aligned}$$



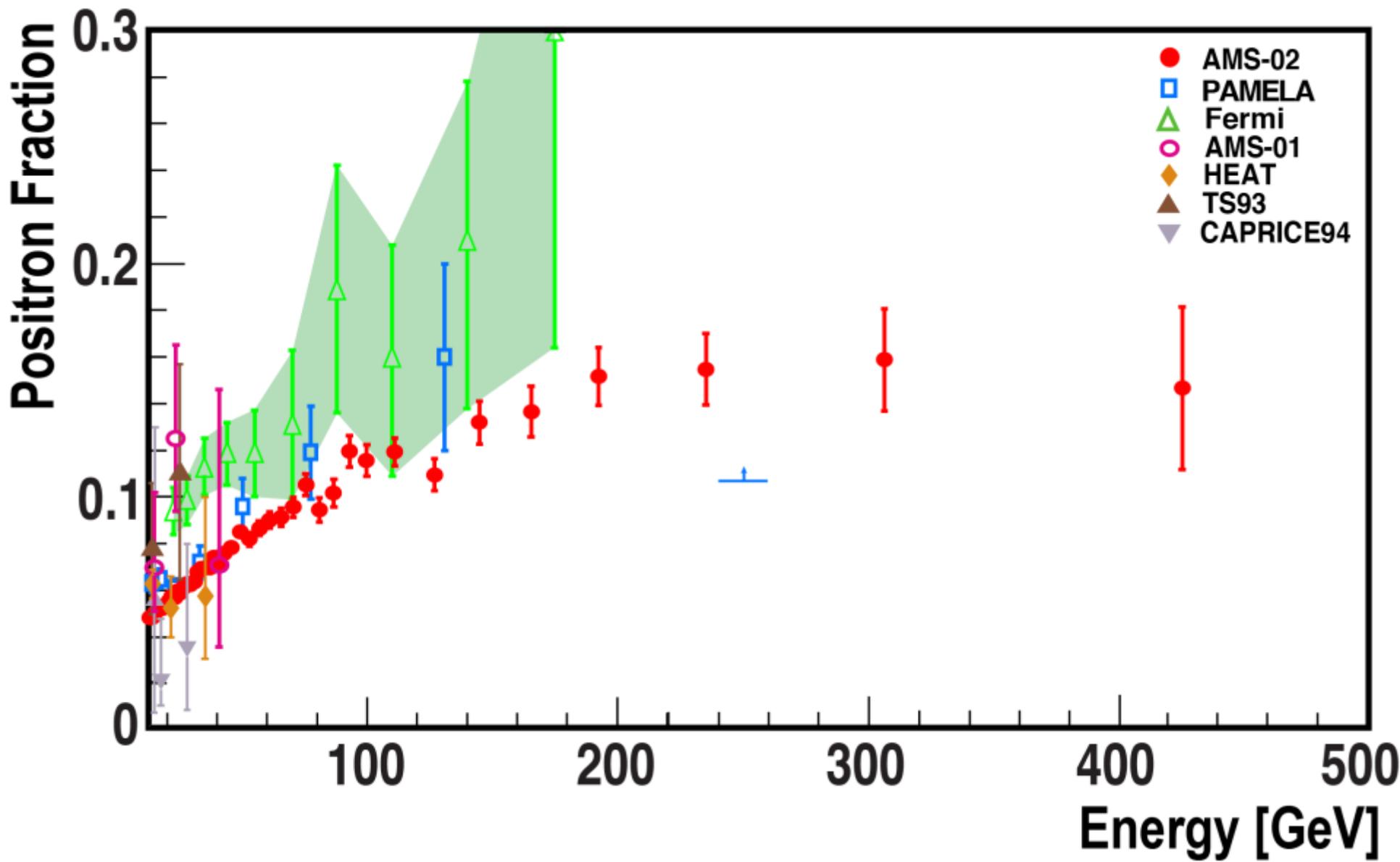
Minimal Model:

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

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



AMS Positron Fraction



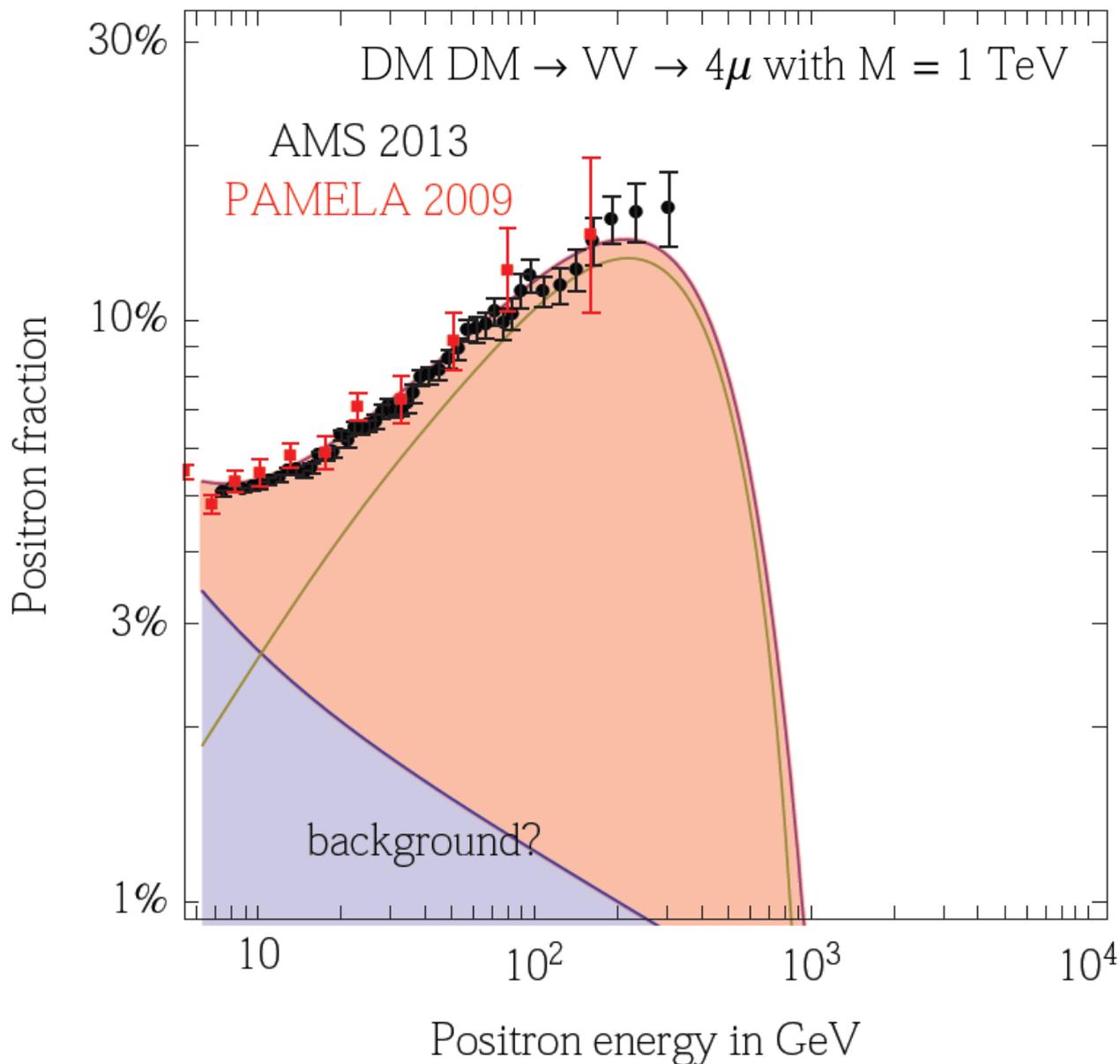
Physics origin of the source term:

- 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**

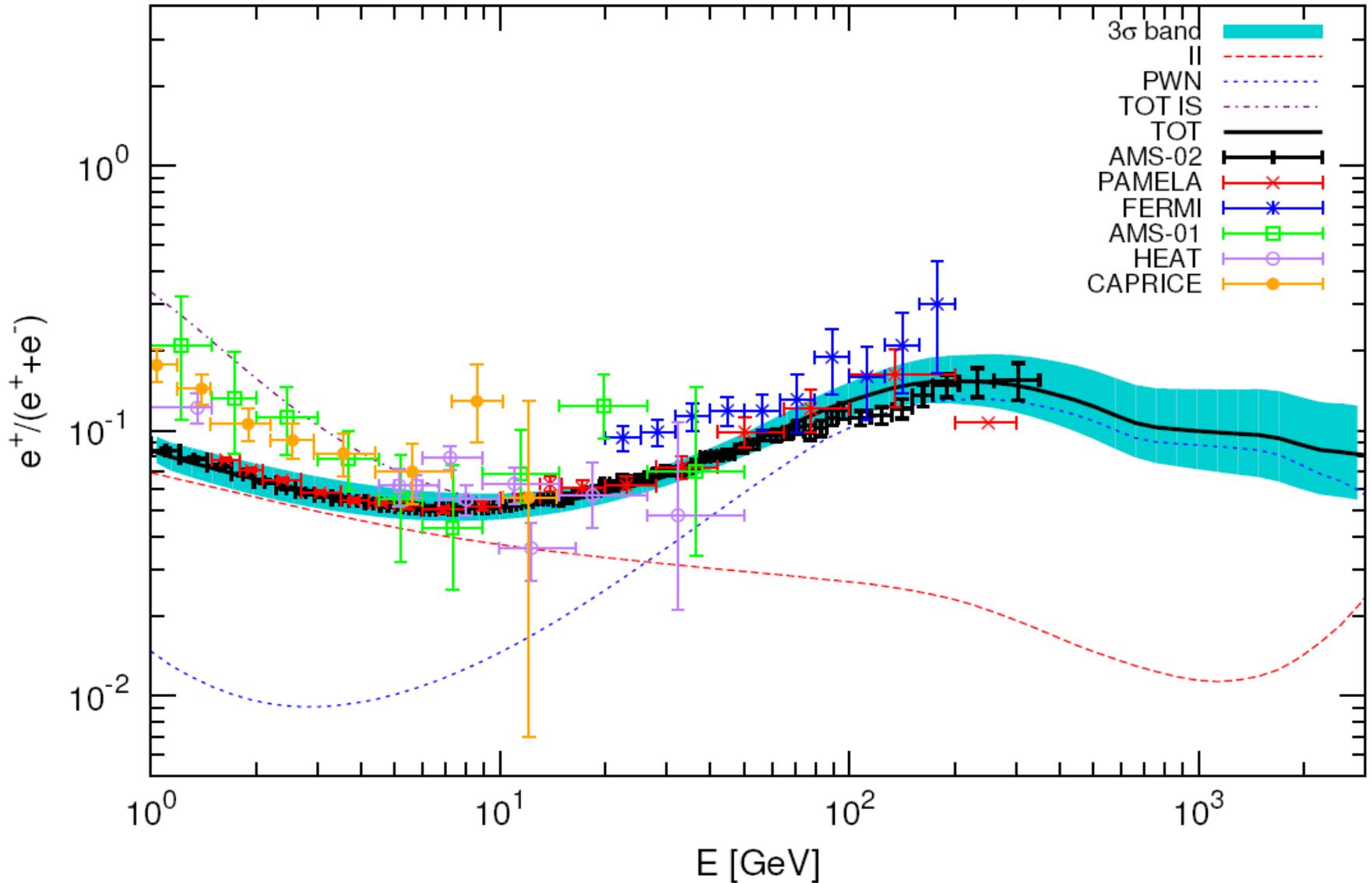
Dark Matter model with intermediate state

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



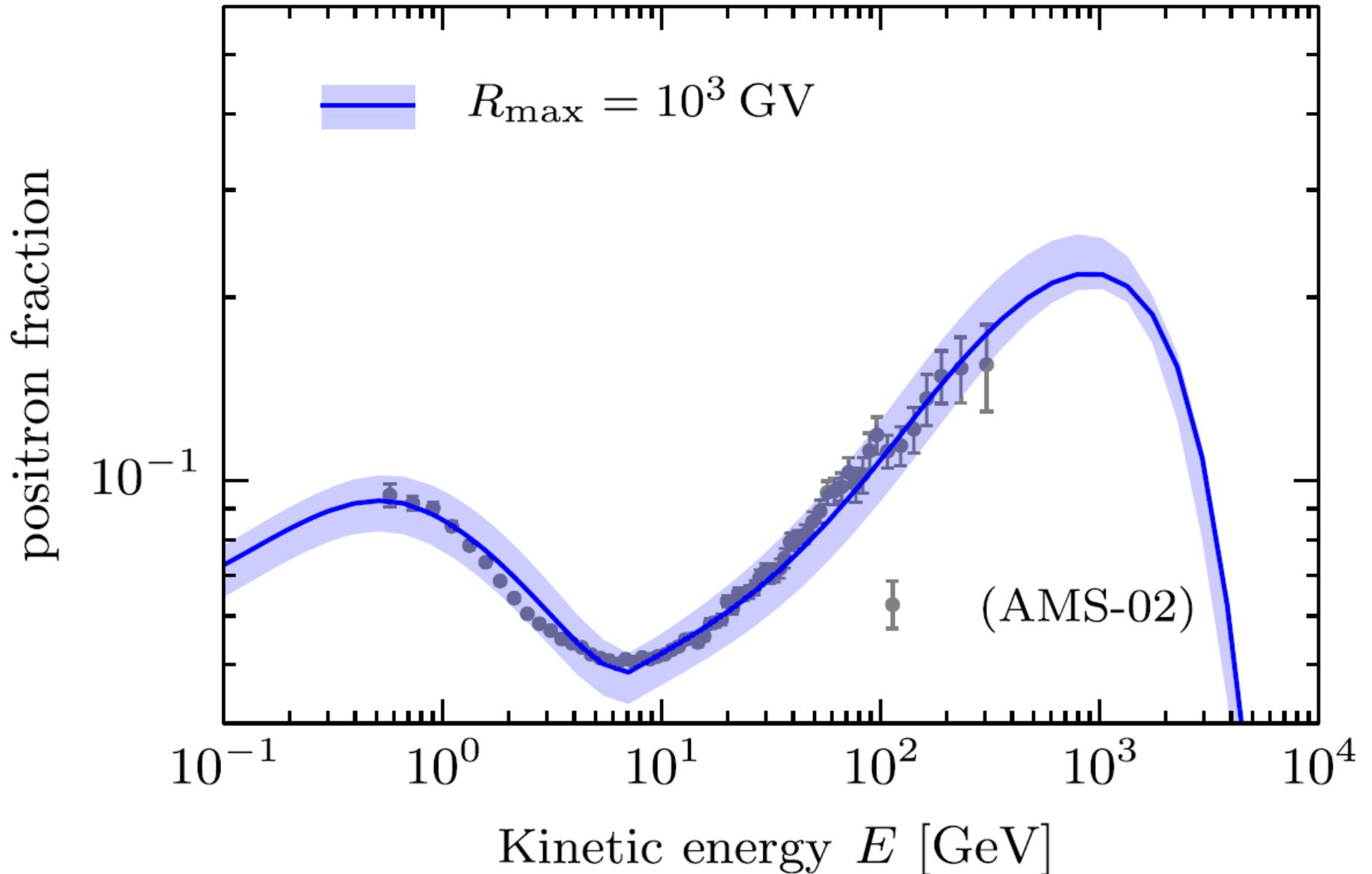
Production in Pulsars

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



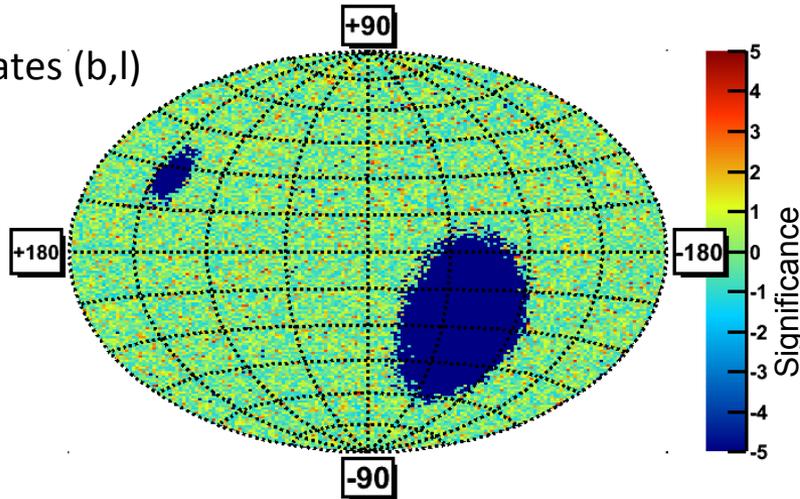
Acceleration in SNRs

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



The isotropy.

Galactic
coordinates (b,l)



The fluctuations of the positron ratio e^+/e^- are isotropic.

The anisotropy in galactic coordinates:
 $\delta \leq 0.030$ at the 95% confidence level

$$\delta = 3\sqrt{C_1/4\pi} \quad C_1 \text{ is the dipole moment}$$

Arrival directions of electrons and positrons are used to build a sky map in galactic coordinates, (b, l) , containing the number of observed positrons and electrons. The fluctuations of the observed positron ratio are described using a spherical harmonic expansion

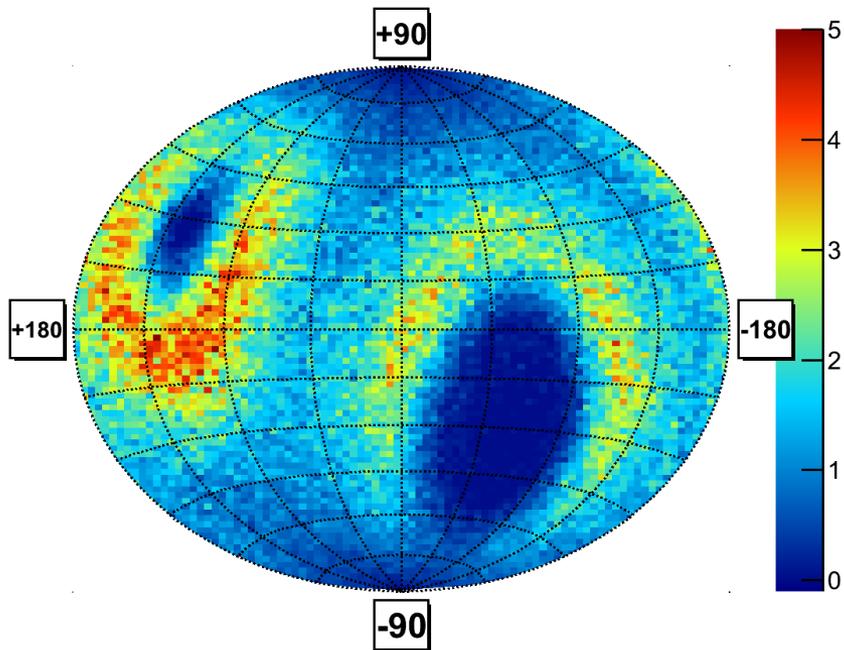
$$\frac{r_e(b, l)}{\langle r_e \rangle} - 1 = \sum_{l=0}^{\infty} \sum_{m=-l}^l a_{lm} Y_{lm}(\pi/2 - b, l),$$

where $r_e(b, l)$ denotes the positron ratio at (b, l) ; $\langle r_e \rangle$ is the average ratio over the sky map; Y_{lm} are spherical harmonic functions and a_{lm} are the corresponding weights. The coefficients of the angular power spectrum of the fluctuations are defined as

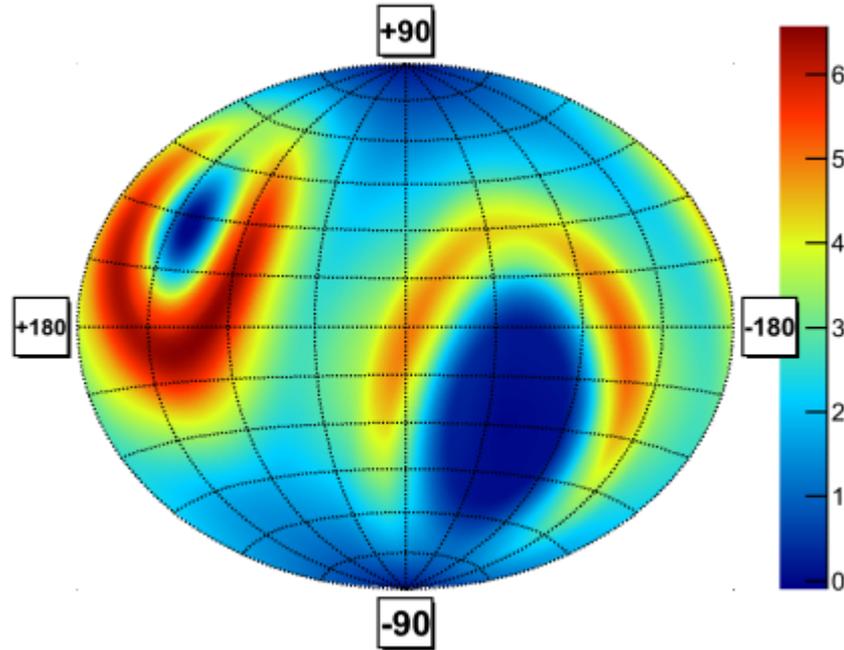
$$C_l = \frac{1}{2l+1} \sum_{m=-l}^l |a_{lm}|^2. \quad \delta = 3\sqrt{C_1/4\pi}$$

Electron Anisotropy

Measured Distribution

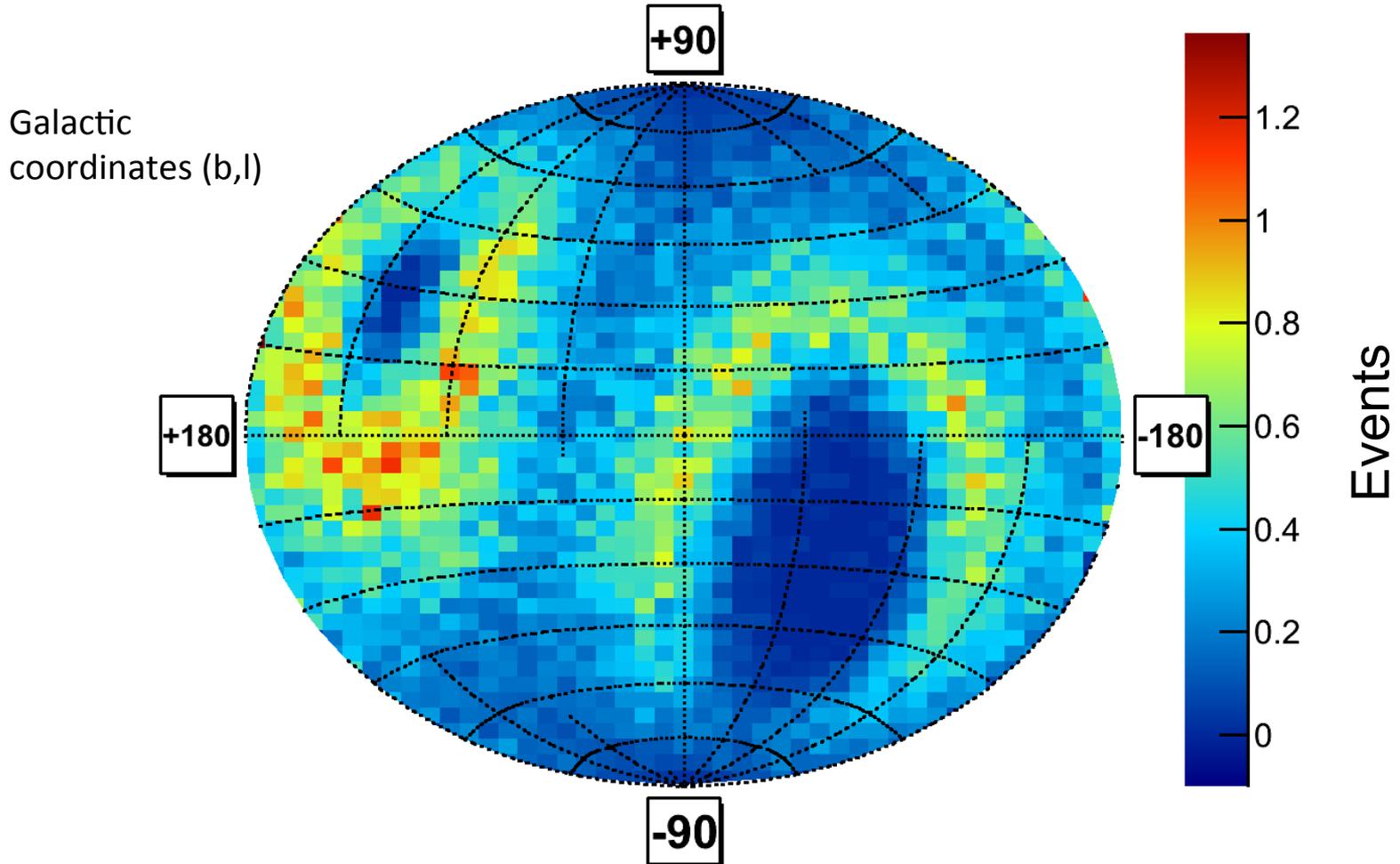


Expected Isotropic Distribution



The incoming direction of **electrons** above 16 GeV in galactic coordinates yields $\delta \leq 0.01$ at the **95% confidence level**

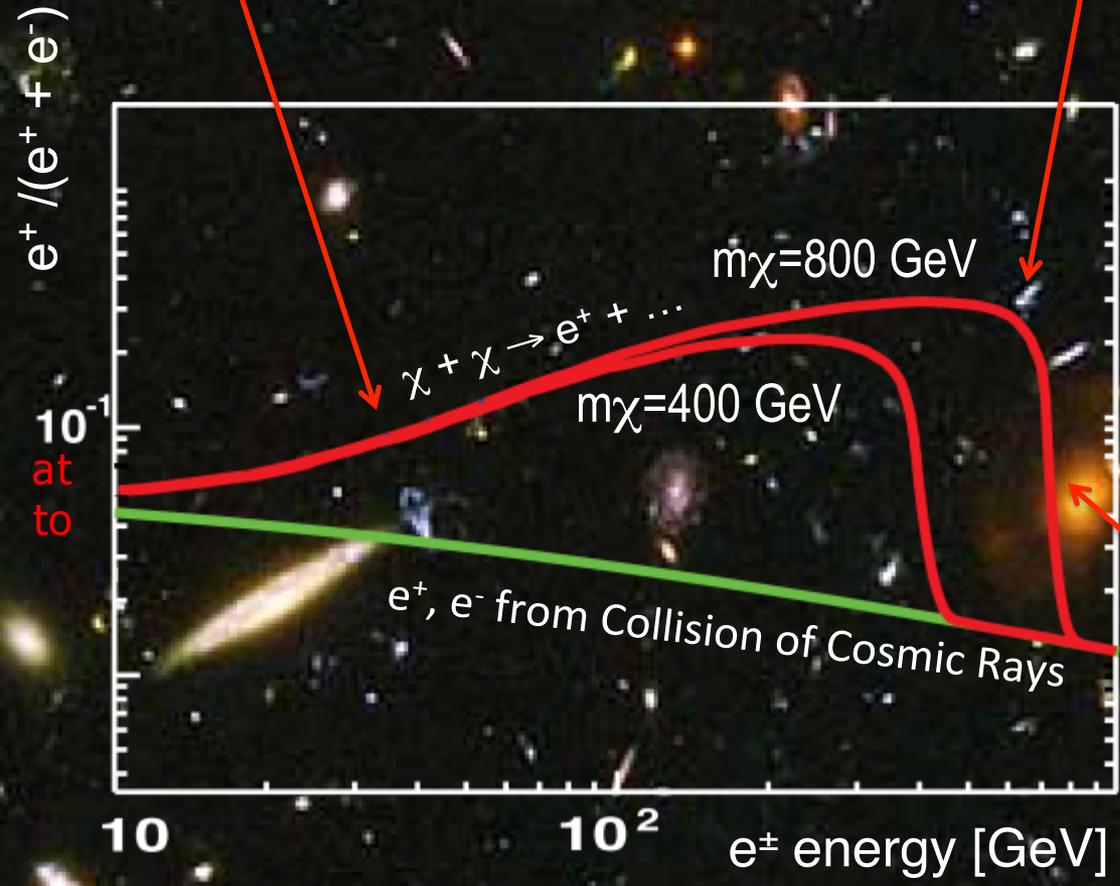
Positron Anisotropy



The incoming direction of **positrons** above 16 GeV in galactic coordinates yields $\delta \leq 0.03$ at the 95% confidence level

- 2. The rate of increase with energy
- 3. The existence of sharp structures.

- 4. The energy beyond which it ceases to increase.

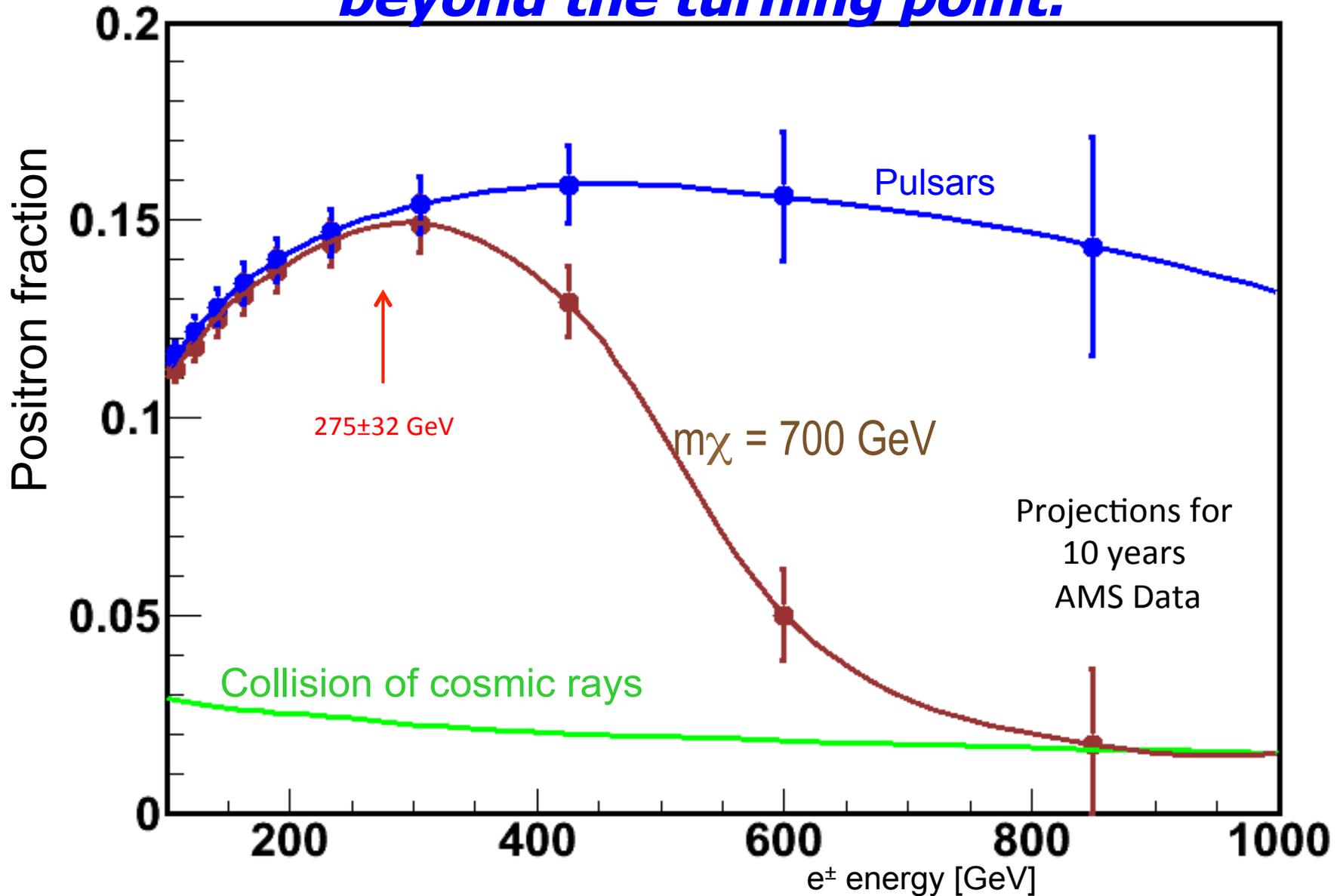


5. Isotropy.

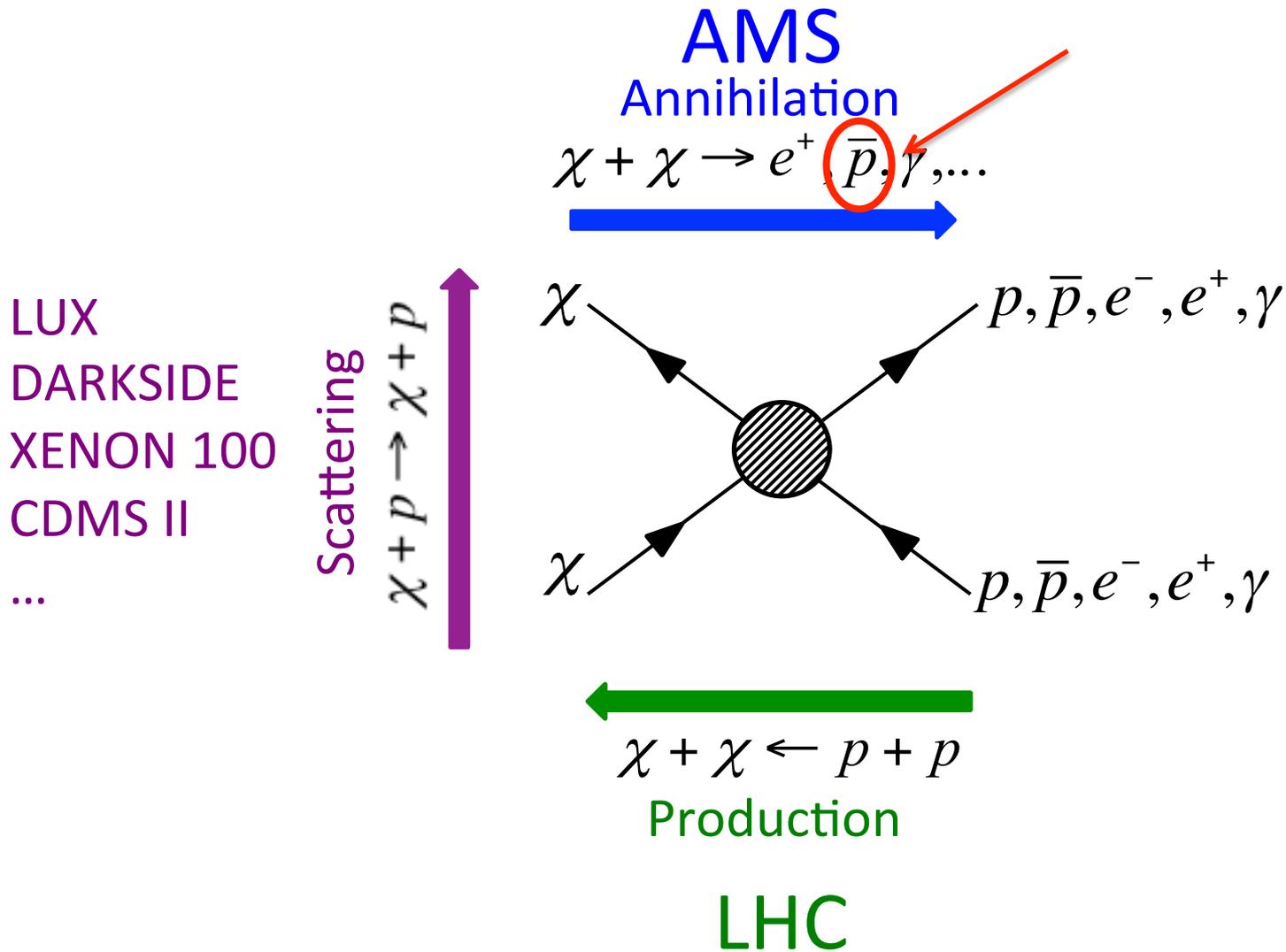
- 1. The energy at which it begins to increase.

- 6. The rate at which it falls beyond the turning point.

***The expected rate at which it falls
beyond the turning point.***

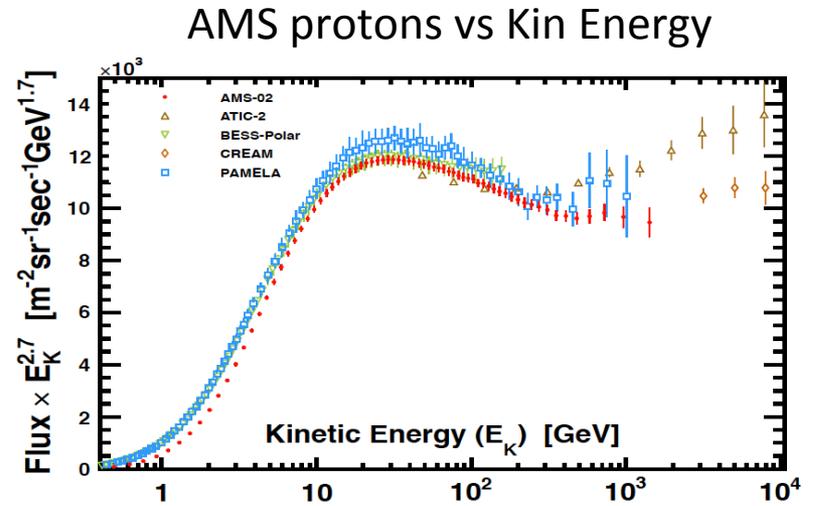
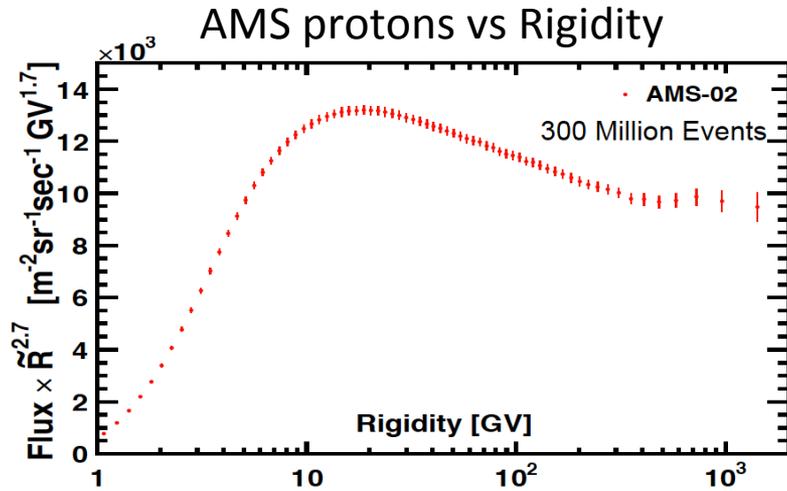


Three independent methods to search for Dark Matter

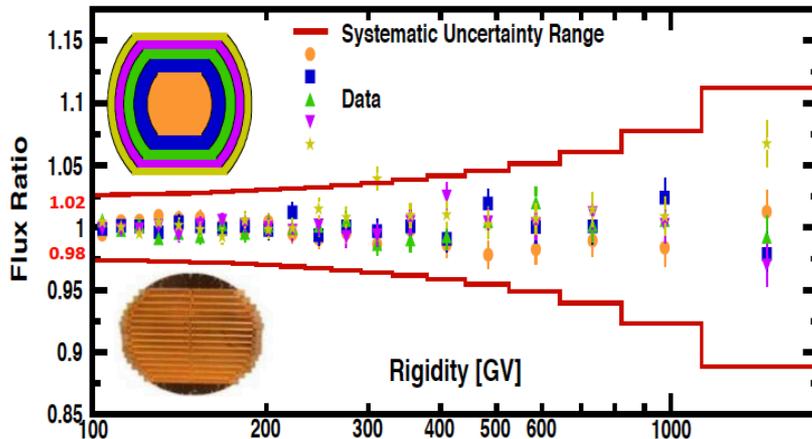




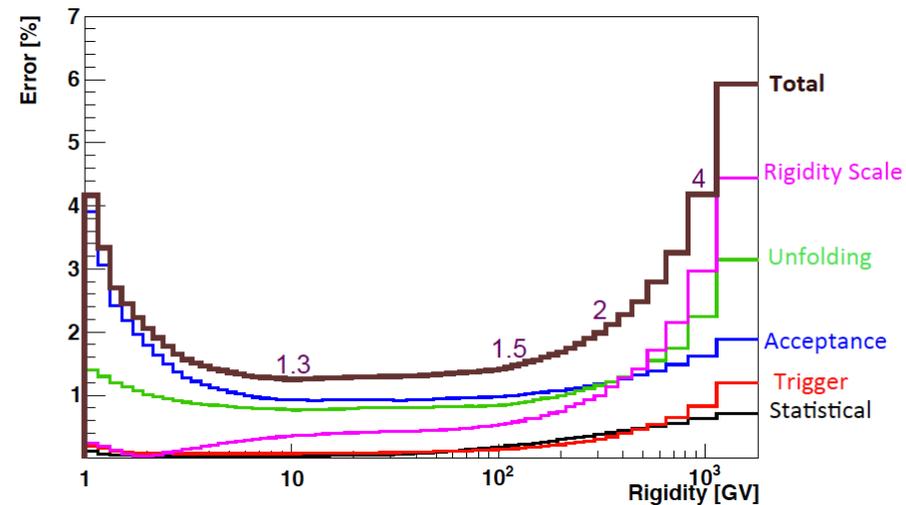
Proton Spectrum



Flux vs different entry points in the detector



Proton Flux errors breakdown

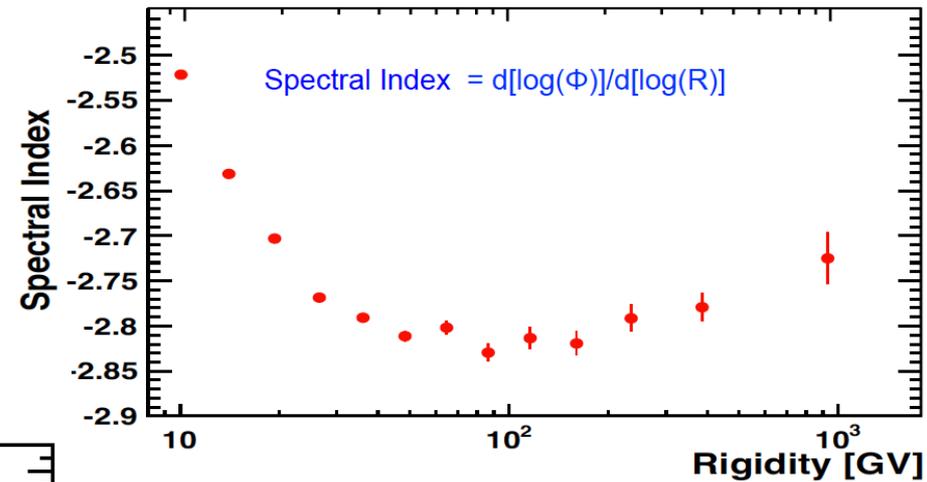
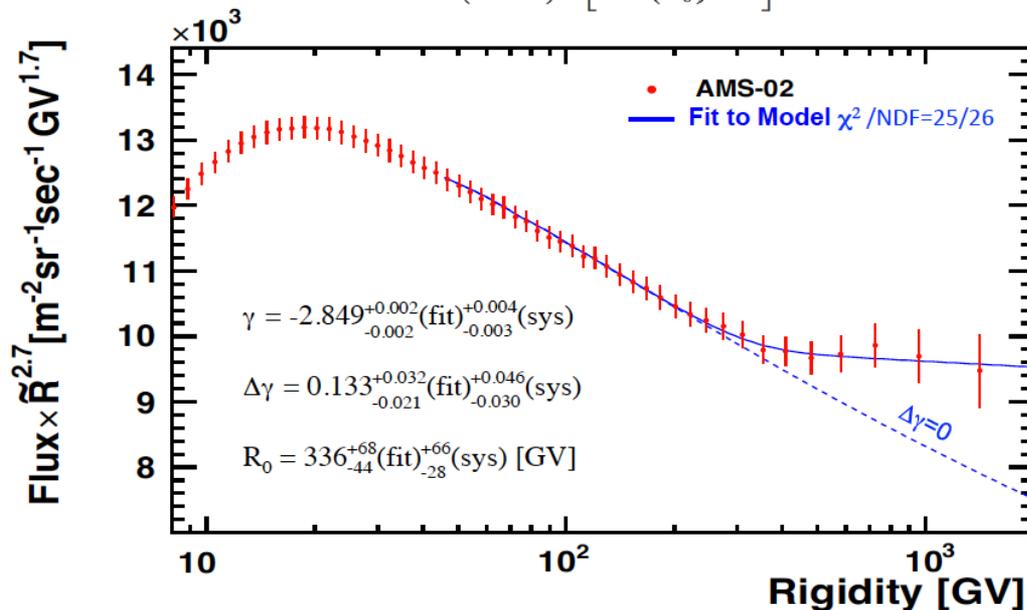


Proton Spectrum fitting

Not compatible with a single power law

We fit with two power laws with a smooth transition

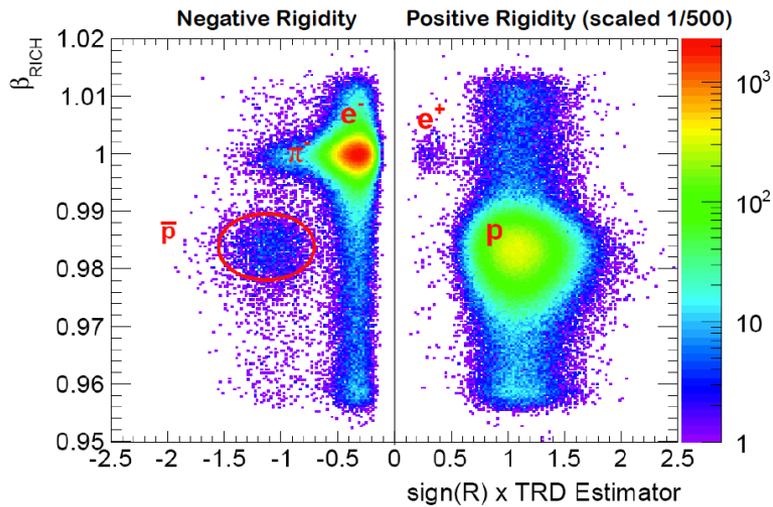
$$\Phi = C \left(\frac{R}{45 \text{ GV}} \right)^\gamma \left[1 + \left(\frac{R}{R_0} \right)^{\Delta\gamma/s} \right]^s$$



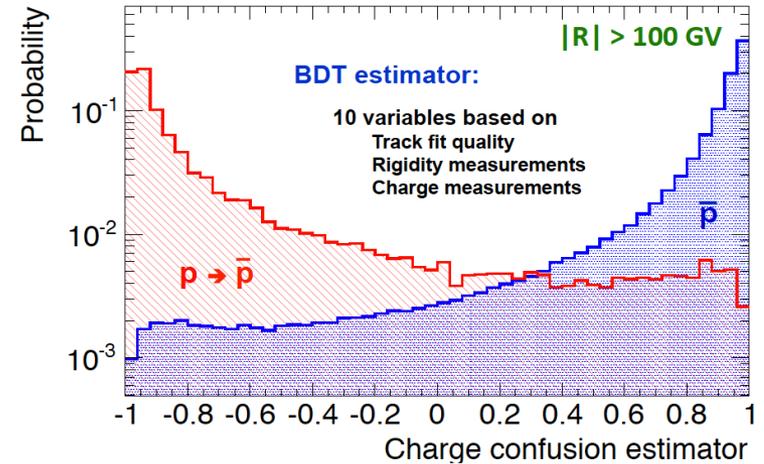
Evaluate the power index as function of rigidity

Selecting anti-protons

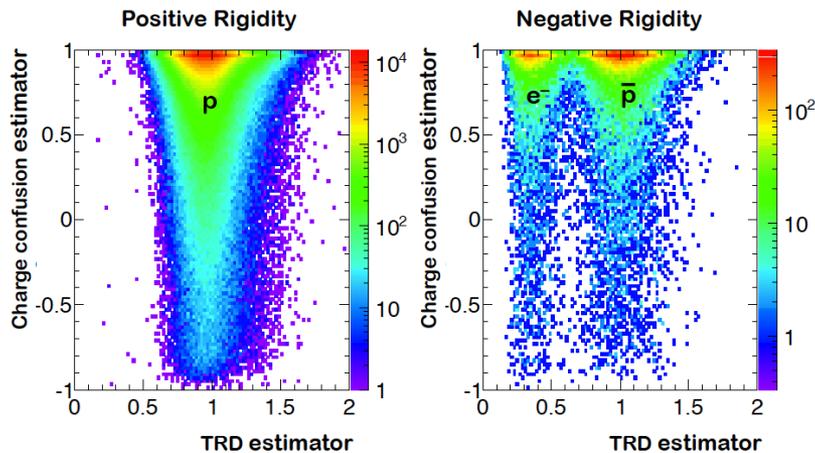
Low rigidity (<10GV) β measurement



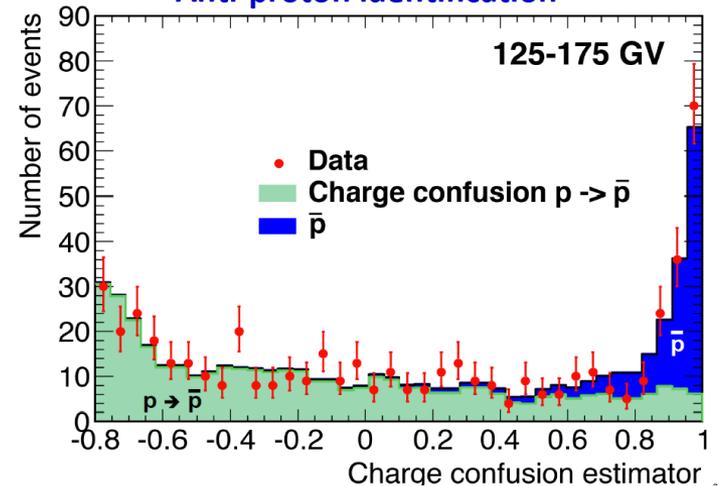
CC Templates



High rigidity Charge confusion BDT

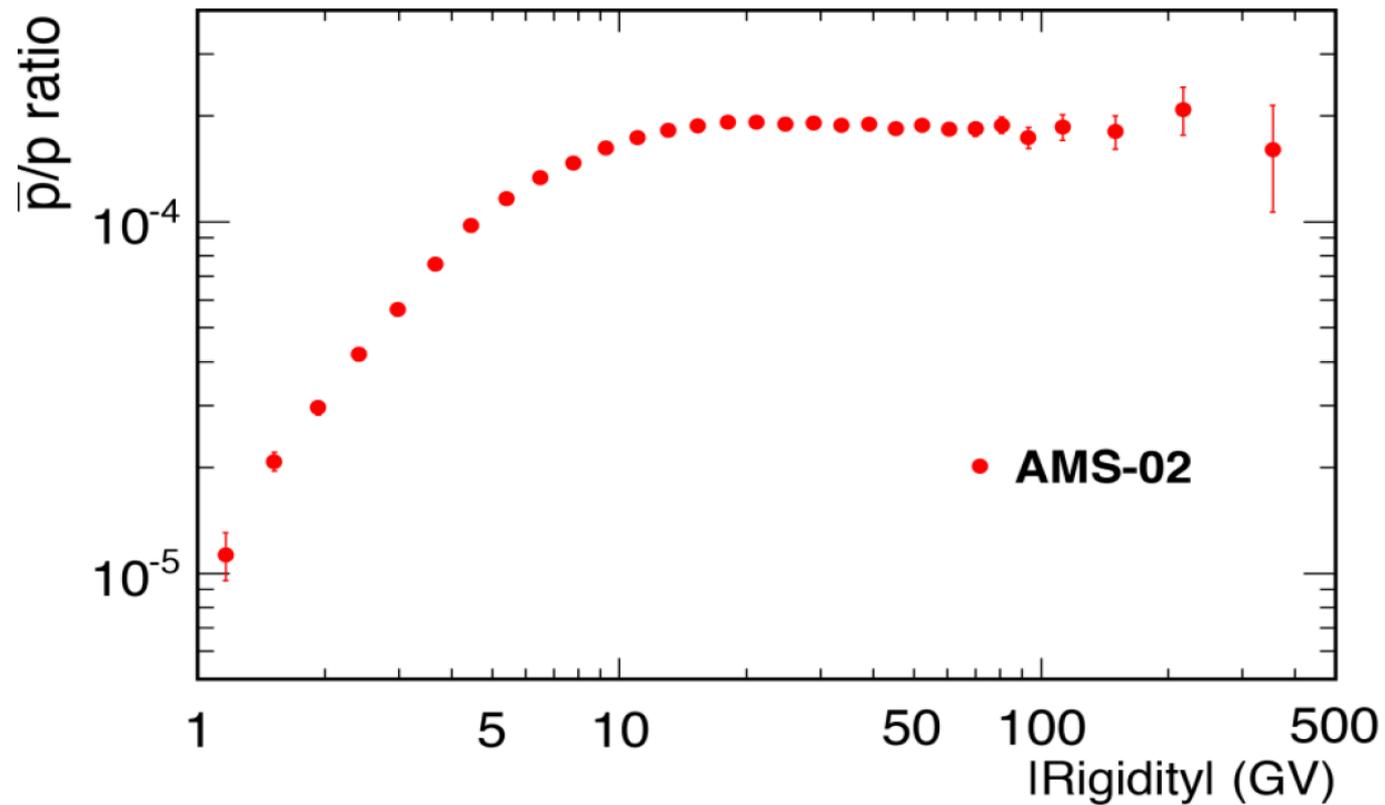


Anti-proton identification



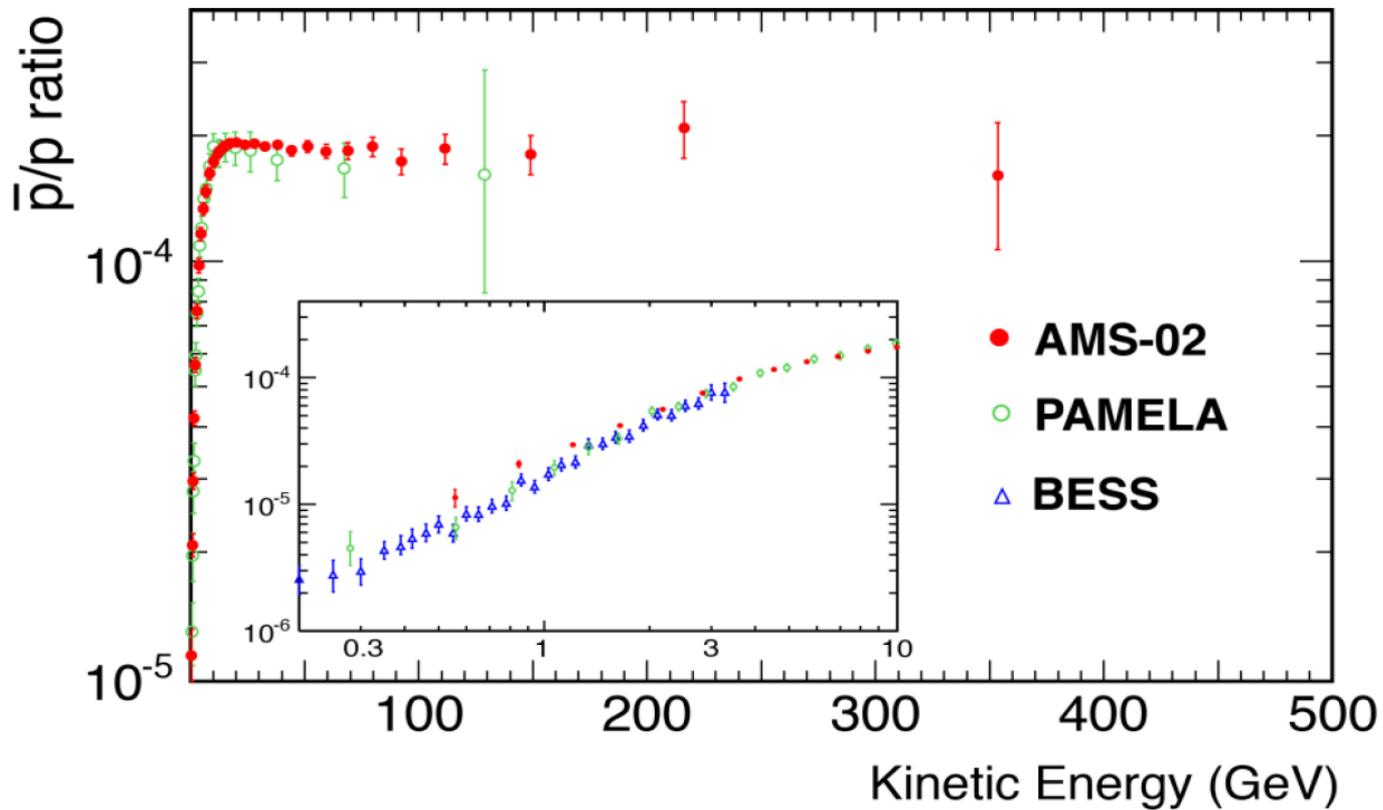
Anti-p/p Ratio

AMS \bar{p}/p results

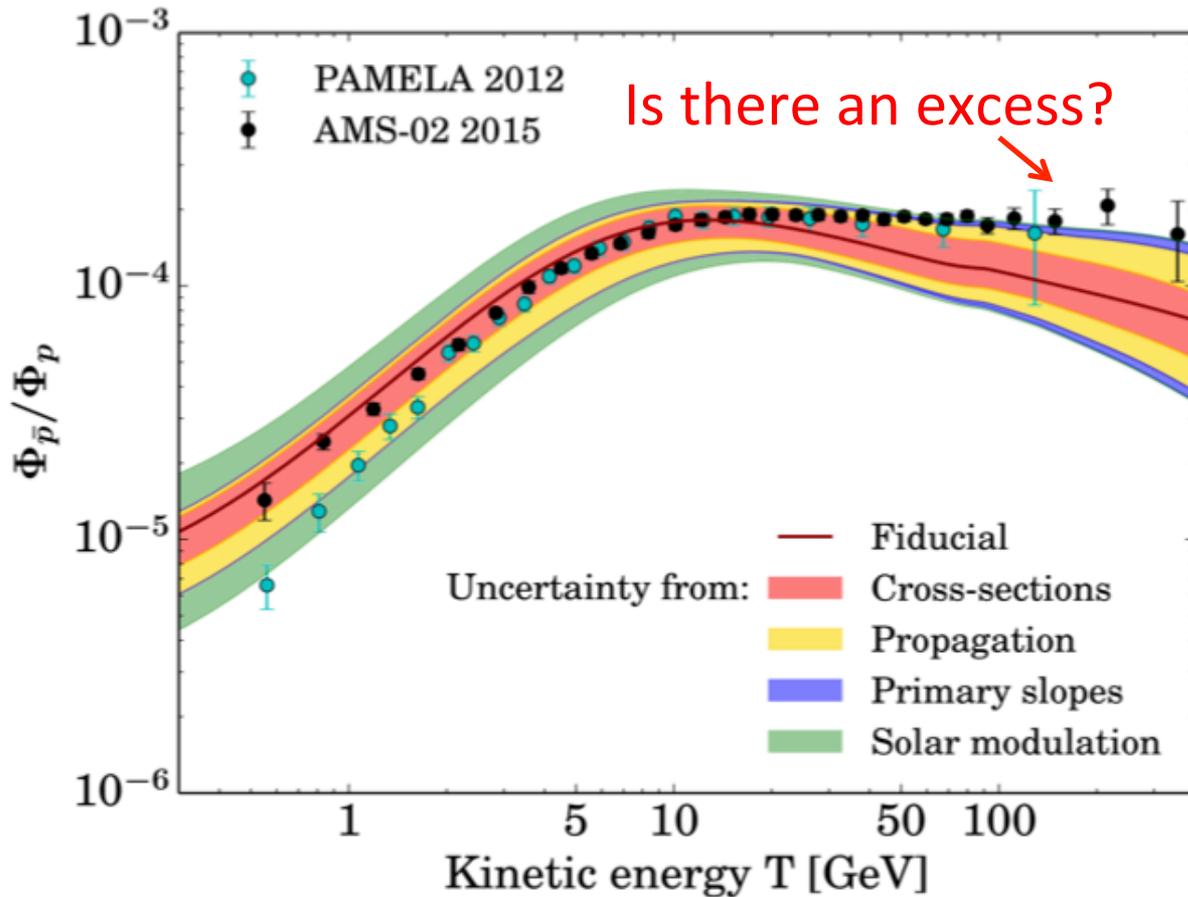


Anti-p/p Ratio

AMS \bar{p}/p results



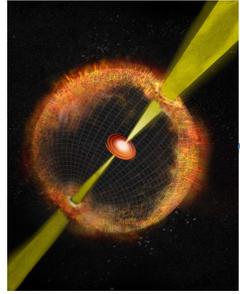
Compare antiproton fraction data to diffuse production scenario:



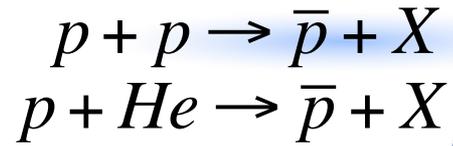
AMS data lies at the edge of the allowed band.

Propagation and primary slopes systematics can be improved through AMS measurements.

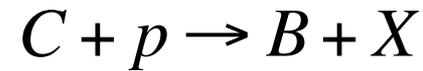
Precise B/C, isotope ratios, and others help to constrain these errors.



Primary CR (H, He, C, etc.)



Secondary CR (Li, Be, B, N, etc.)



Anti-proton
Production
Cross Section

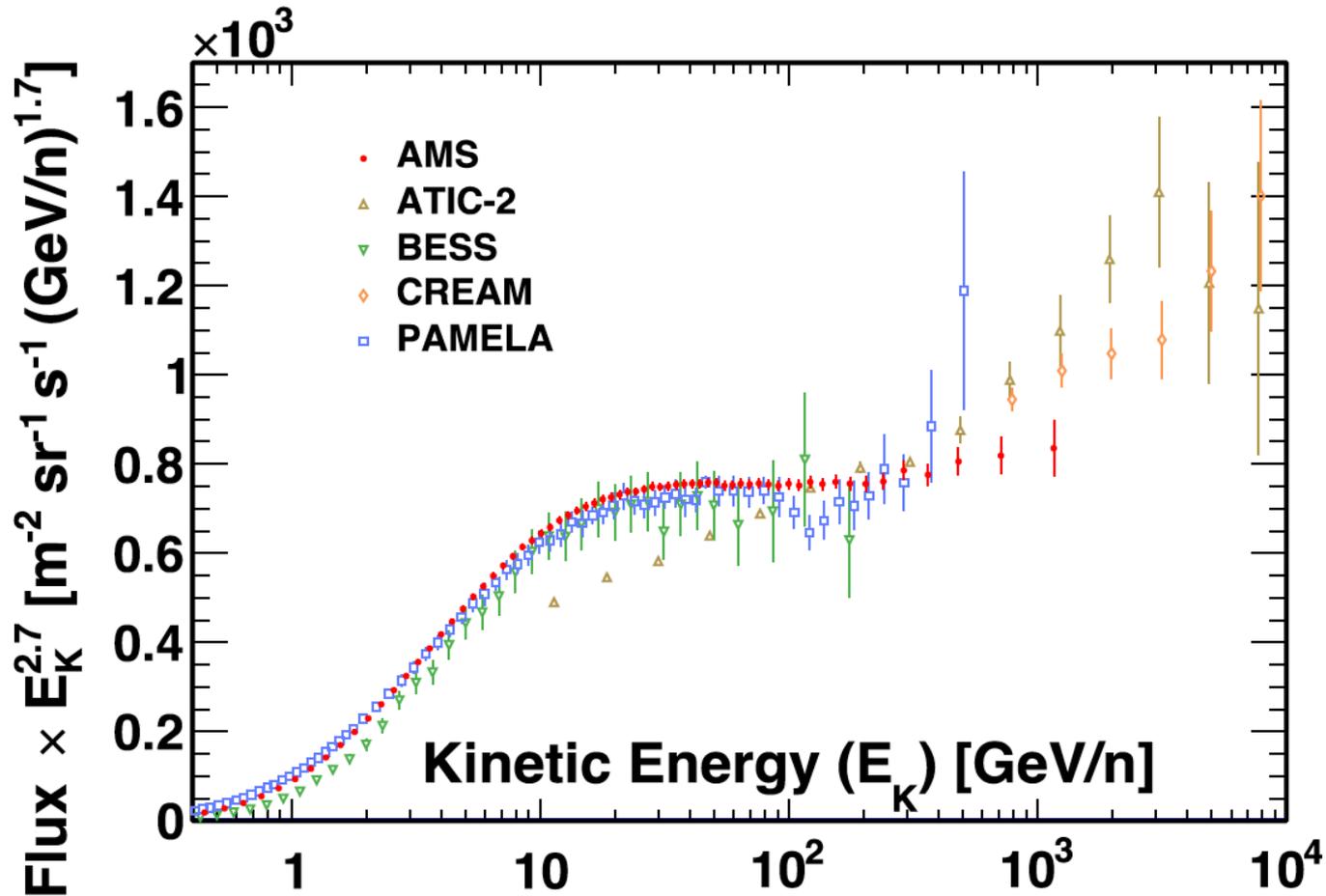


B/C

Spallation
Cross Section
(N-N)

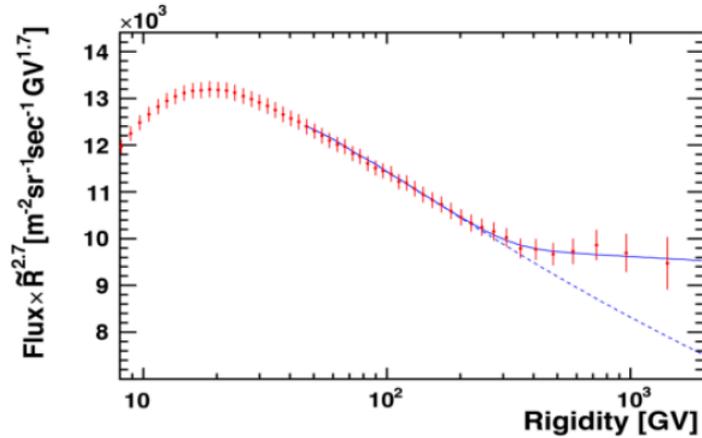


AMS Helium Flux

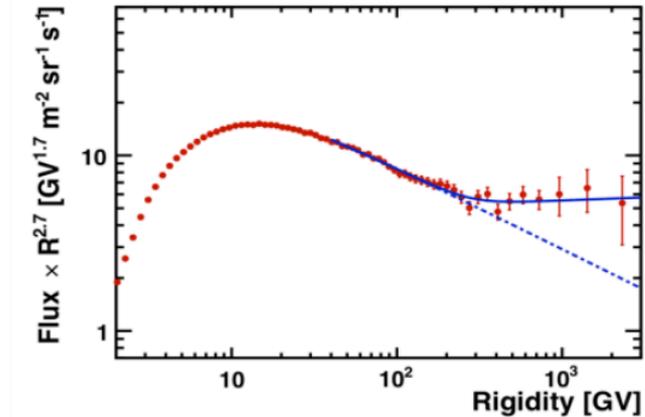


AMS Nuclei Measurements

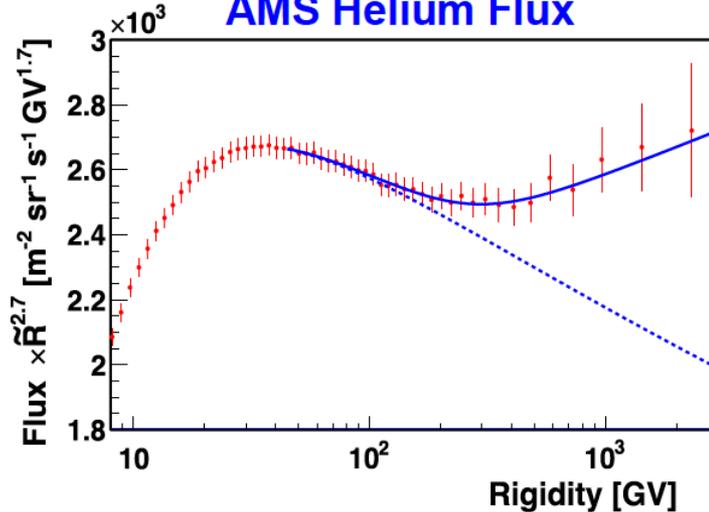
AMS proton flux



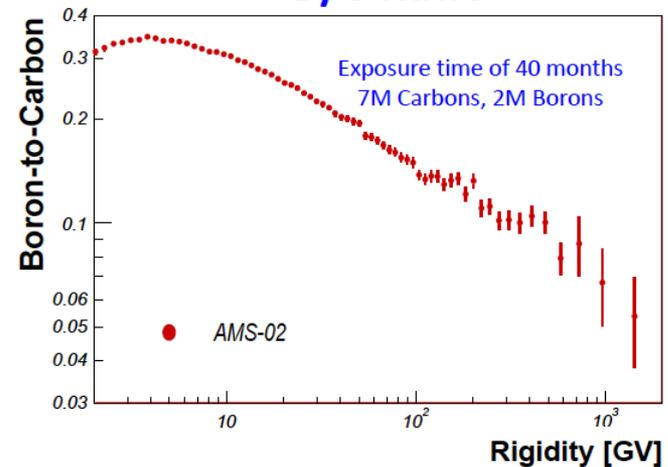
Lithium flux



AMS Helium Flux



B/C Ratio



Conclusions

- Discovering the identity of dark matter may be the biggest science accomplishment of our generation
- AMS-02 gives the opportunity to move forward in this direction.
- It will not be a quick or easy task and there may be surprises along this road.
- The full story of dark matter will be richer than we imagine, pointing us in new directions for particle physics and for cosmology
- We must pursue all the possible measurement opportunities that will help understanding the puzzle



STAY TUNED