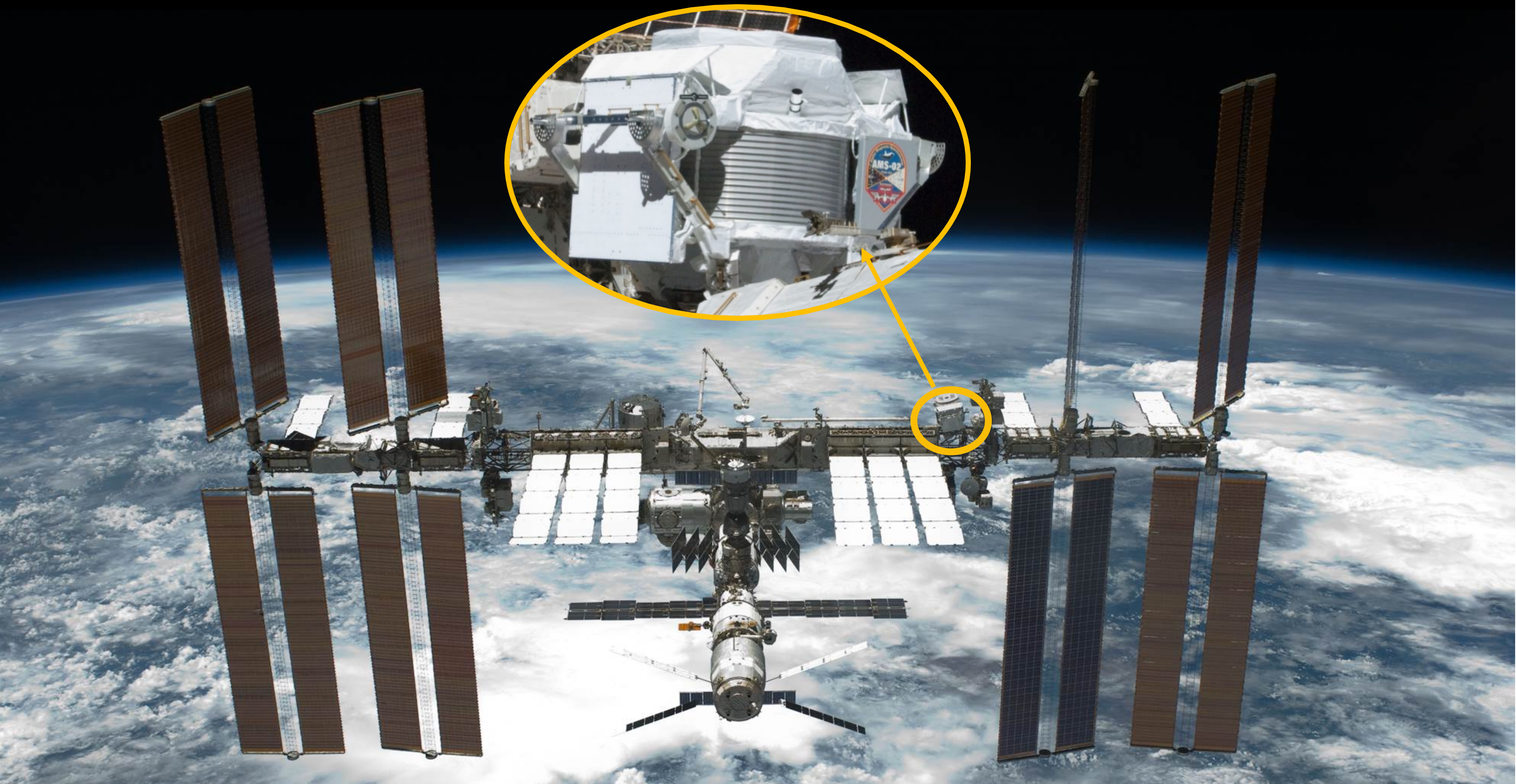
Properties of Elementary Particle Fluxes in Primary Cosmic Rays Measured with Alpha Magnetic Spectrometer (AMS) on the ISS

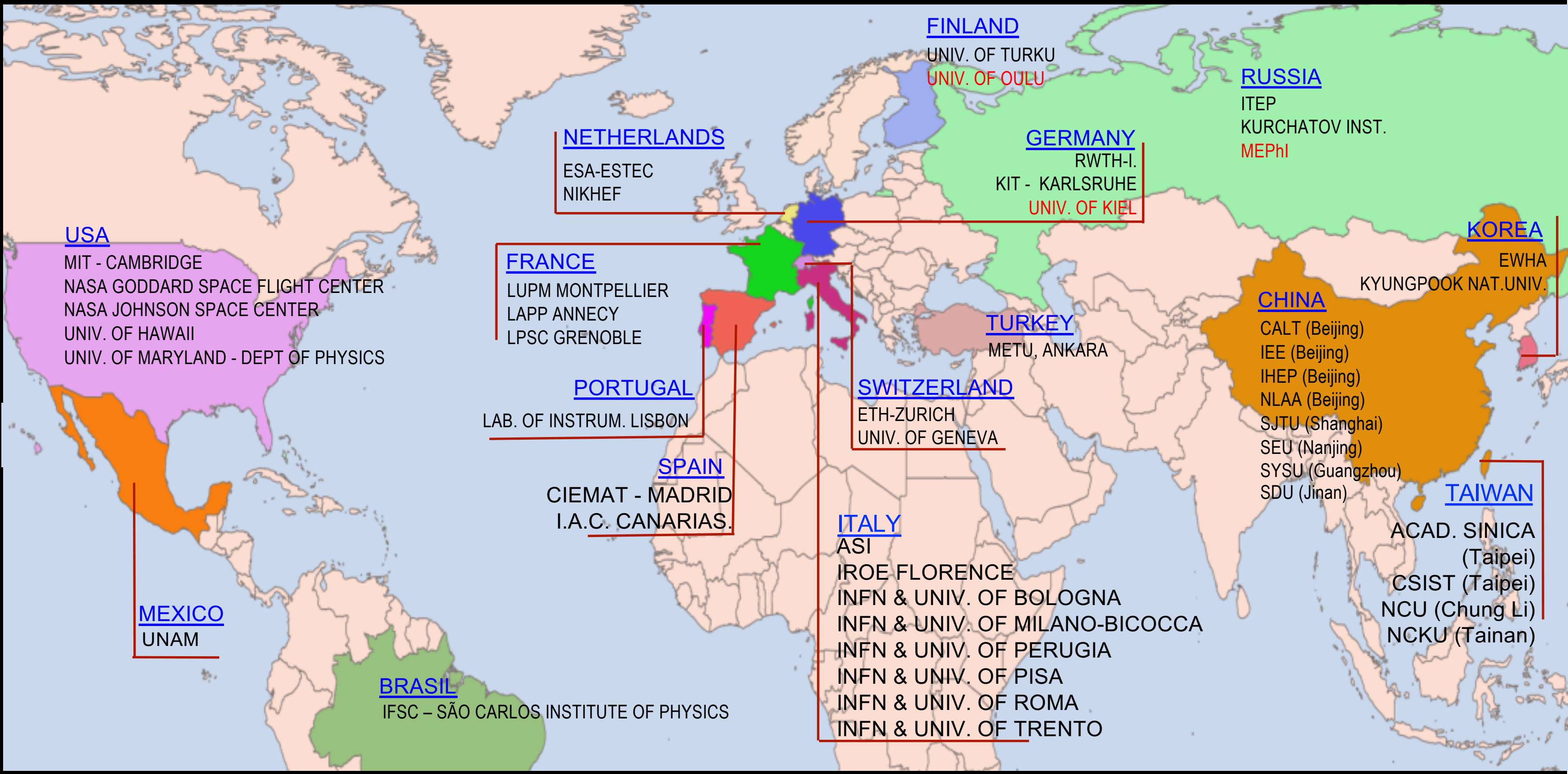


QuyNhon, Cosmology 2019
August 16th, 2019

Jie Feng/ M.I.T.
on behalf of the AMS Collaboration

AMS is an International Collaboration

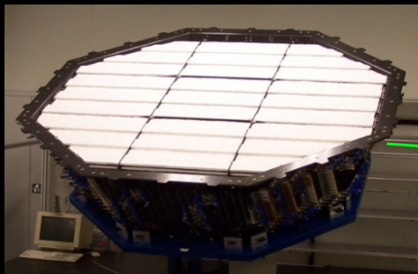
It took 650 physicists and engineers 17 years to build AMS



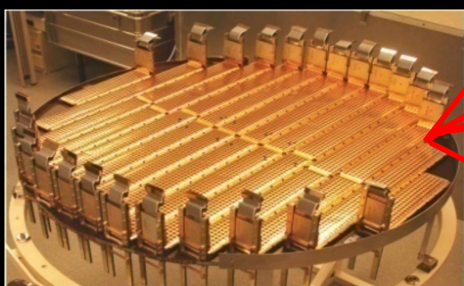
The detectors were constructed in Europe and Asia and assembled at CERN, Geneva

AMS is a space version of a precision detector used in accelerators

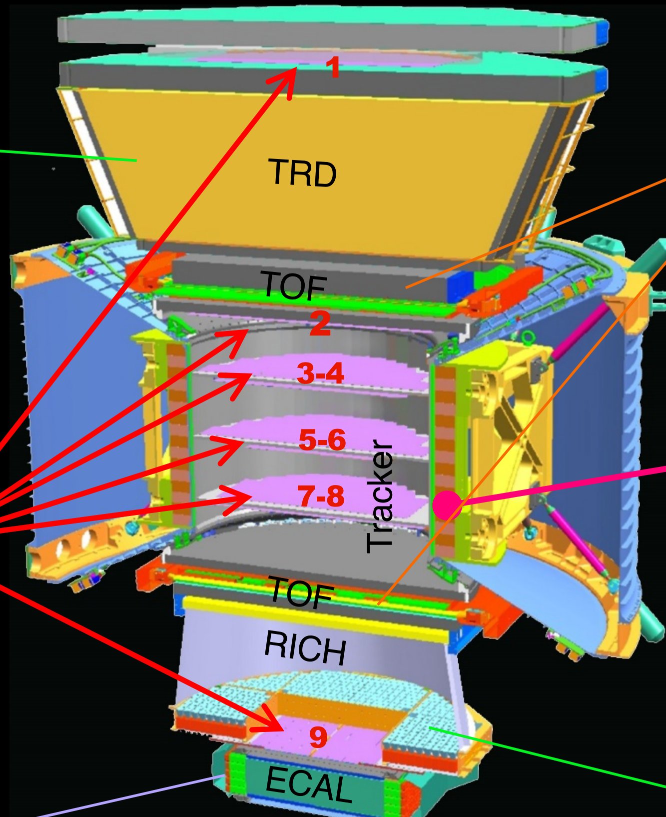
Transition Radiation Detector (TRD)



Silicon Tracker

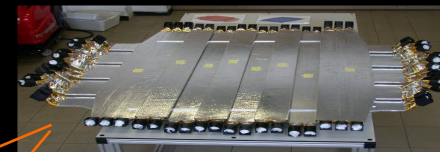


Electromagnetic Calorimeter (ECAL)

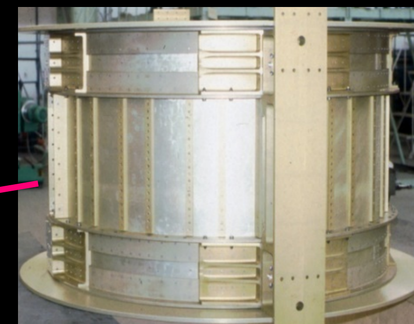


5m x 4m x 3m
7.5 tons

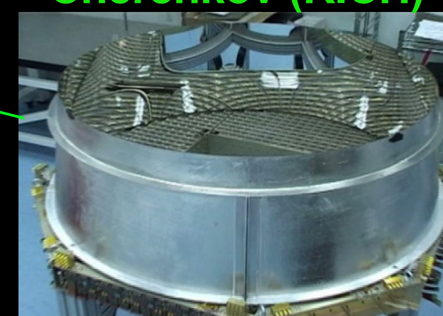
Time of Flight Counters (TOF)



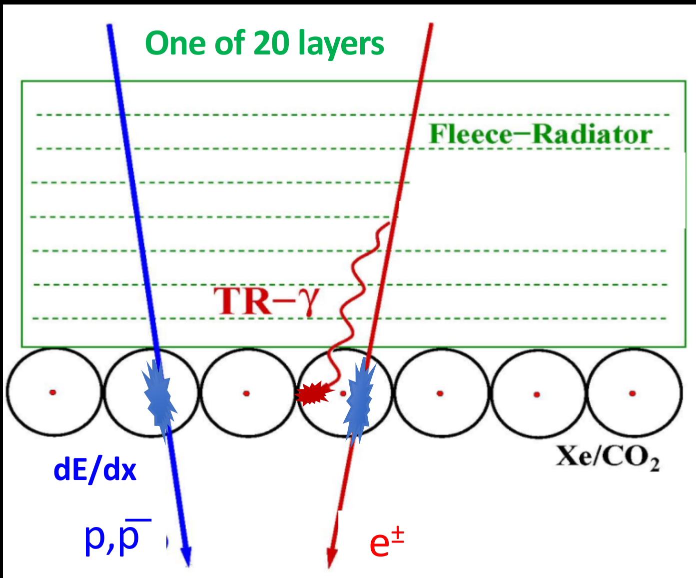
Magnet

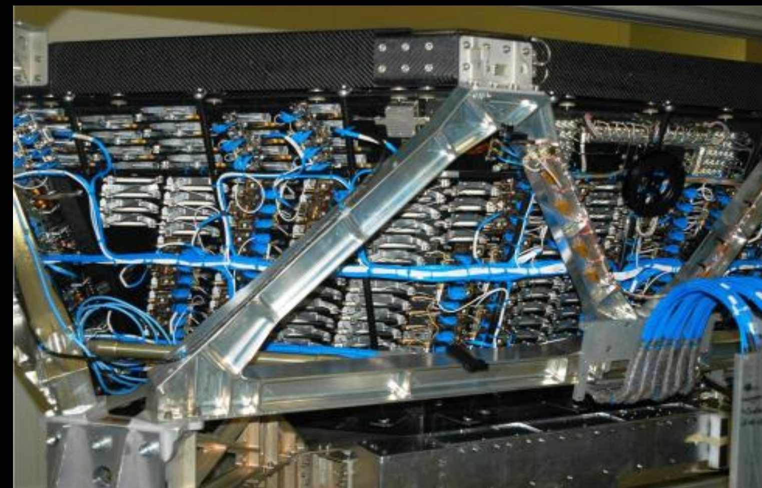


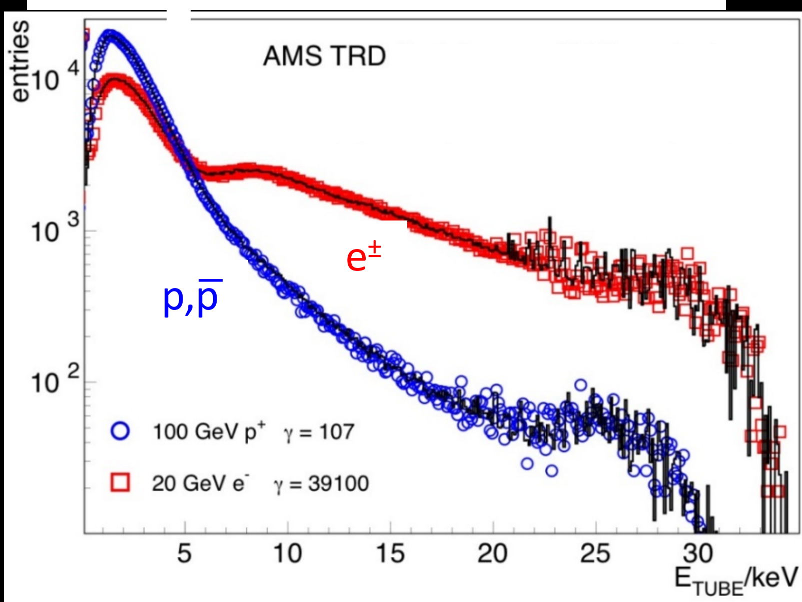
Ring Imaging Cherenkov (RICH)

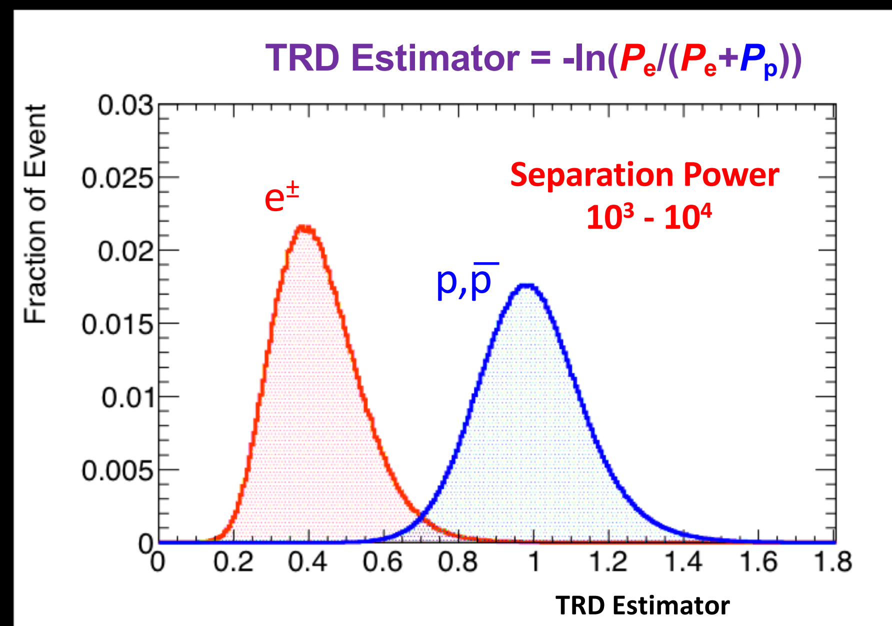


Transition Radiation Detector (TRD)







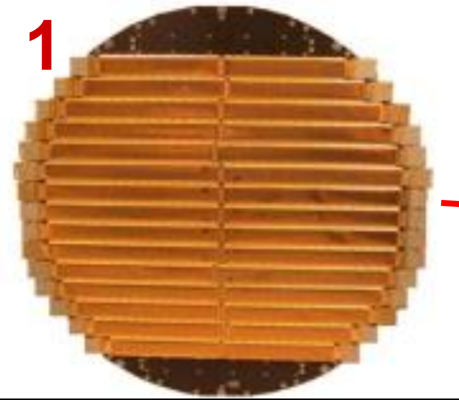


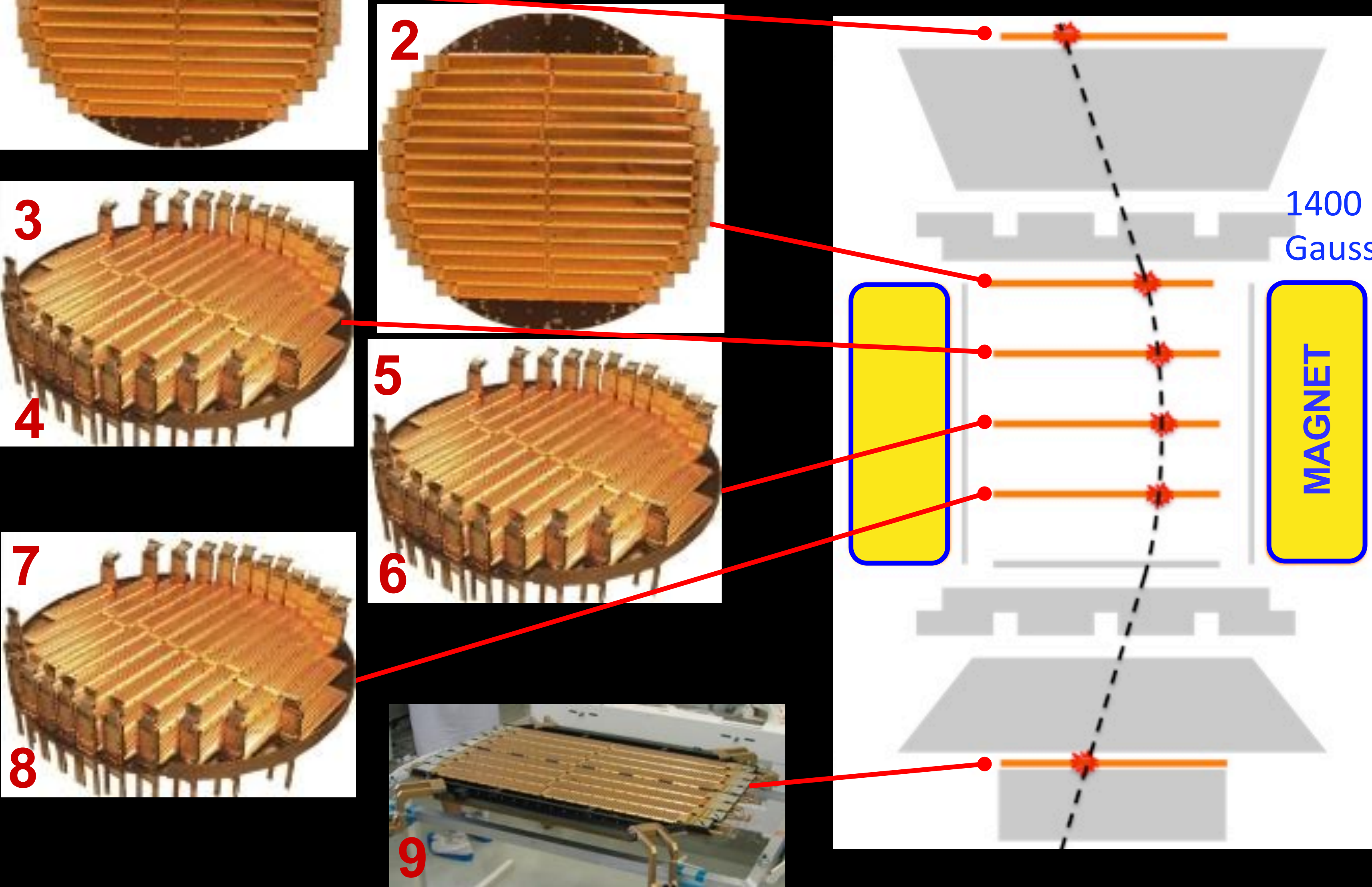
Silicon Tracker

Coordinate resolution 5-10 microns

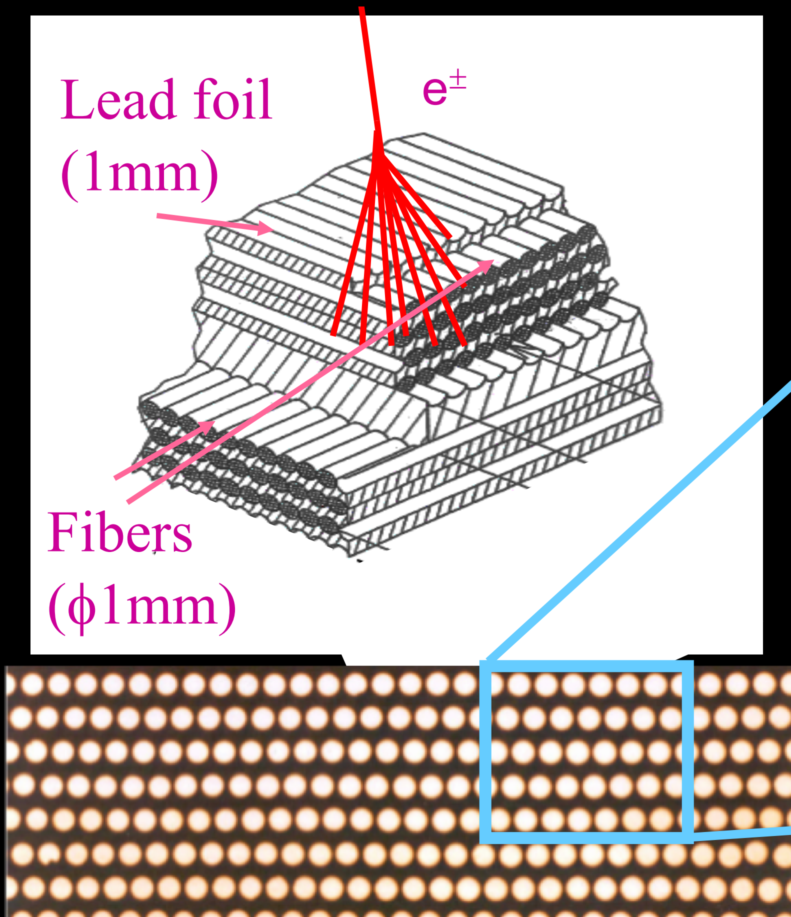
Measure momentum P and nuclear charge Z

Maximal Detectable Rigidity(P/Z) – 2TV for Z=1 particles

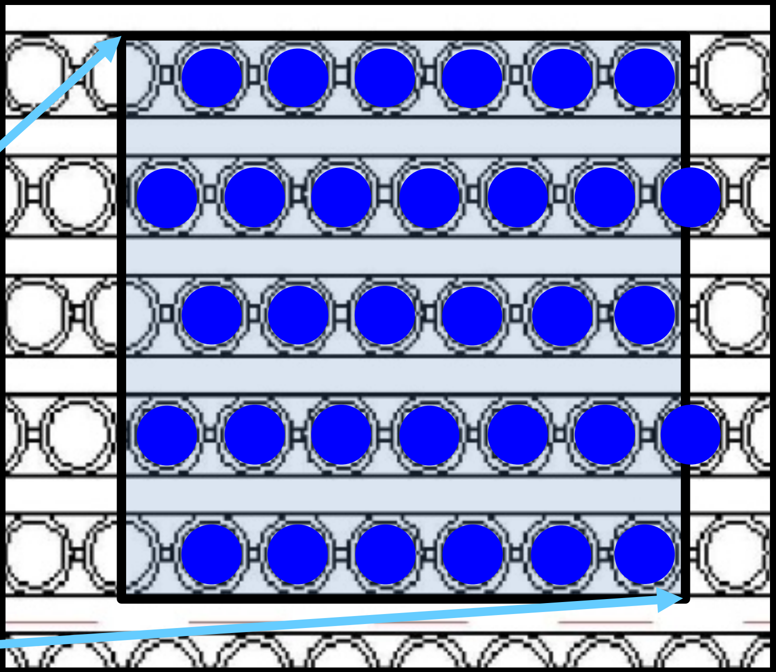




Electromagnetic Calorimeter (ECAL)



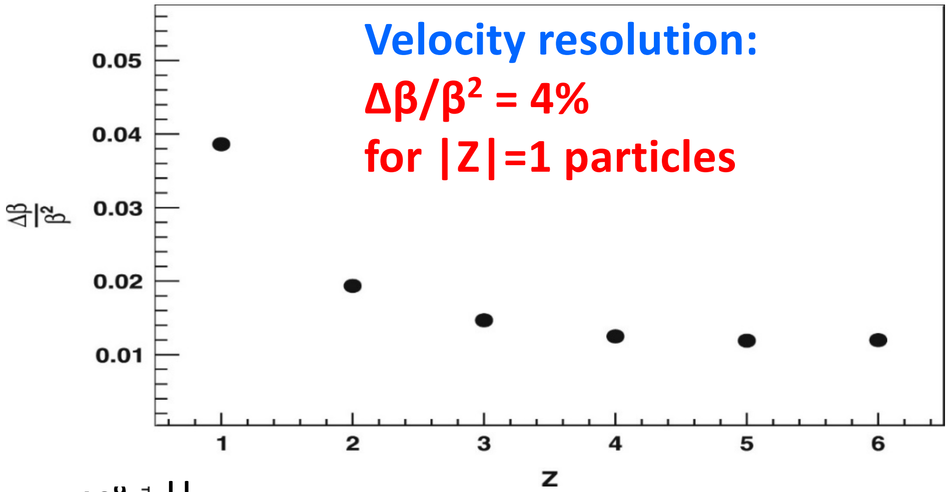
One of 1296 cells (9x9 mm^2)

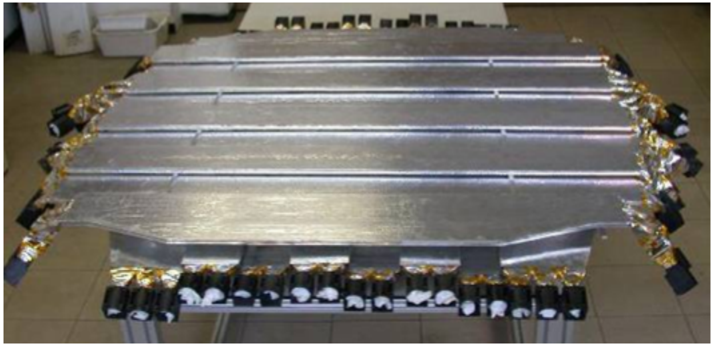


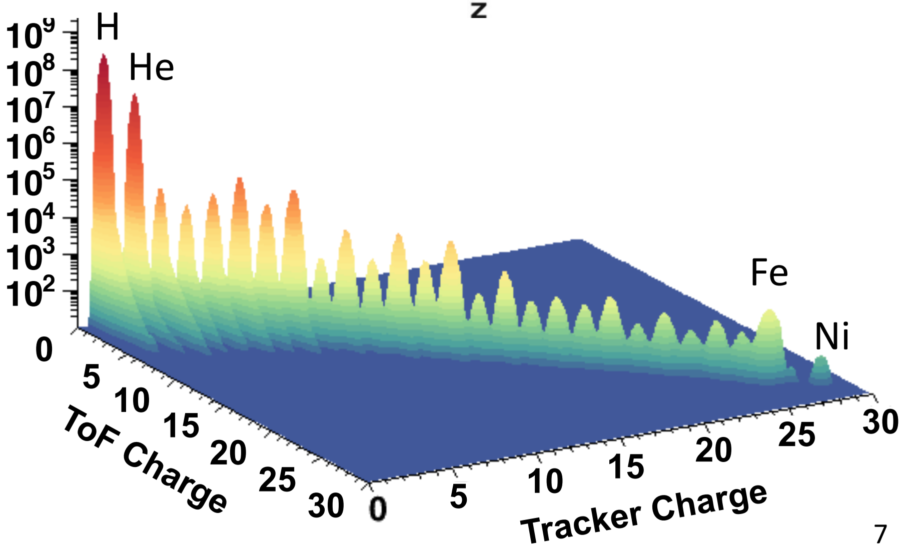
A precision, 17 X_0, TeV, 3-dimensional measurement of the directions and energies of e+/e-.

The energy resolution of e+/e- at the highest energy is ~2%

Time of Flight (TOF)

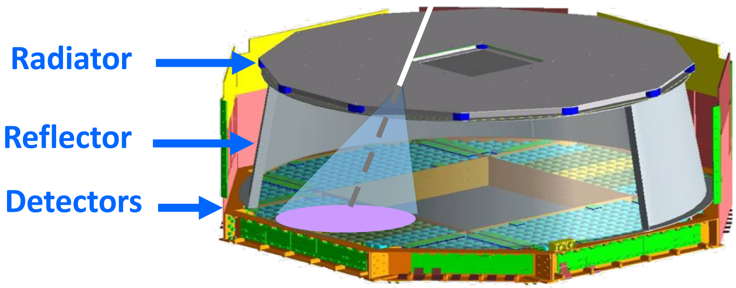




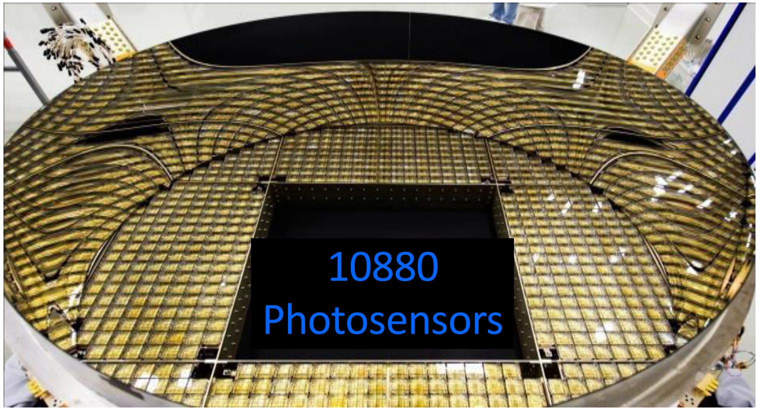


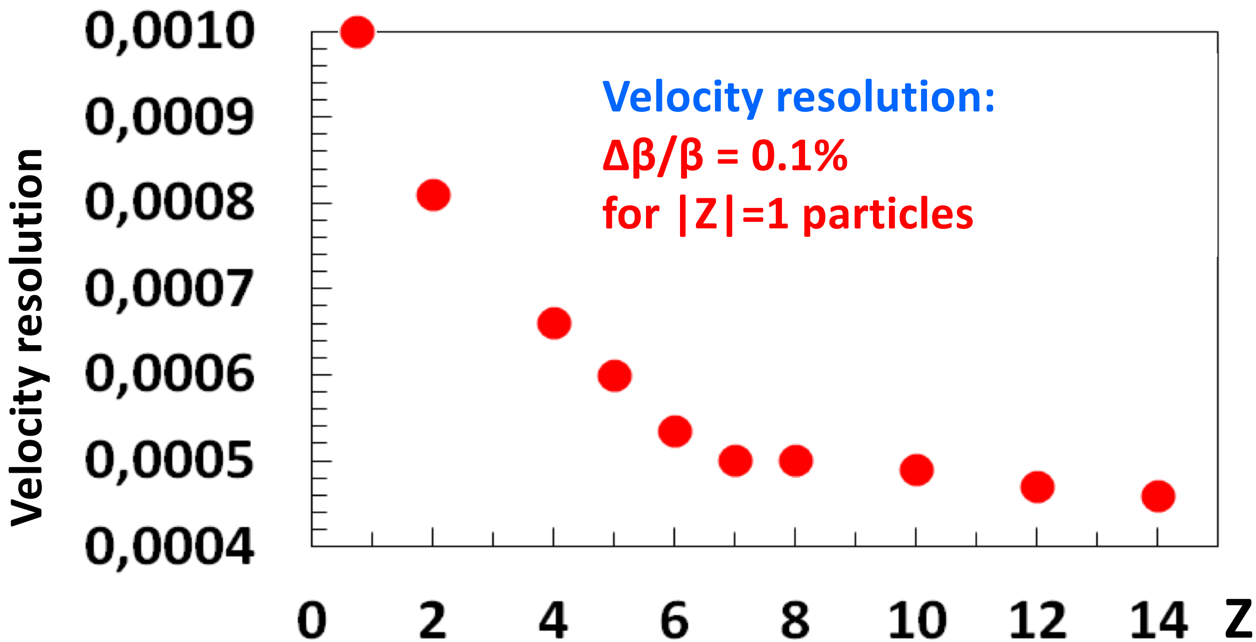
Particle mass is from the combination of TOF and Tracker measurements.

Ring Imaging Cherenkov detector (RICH)

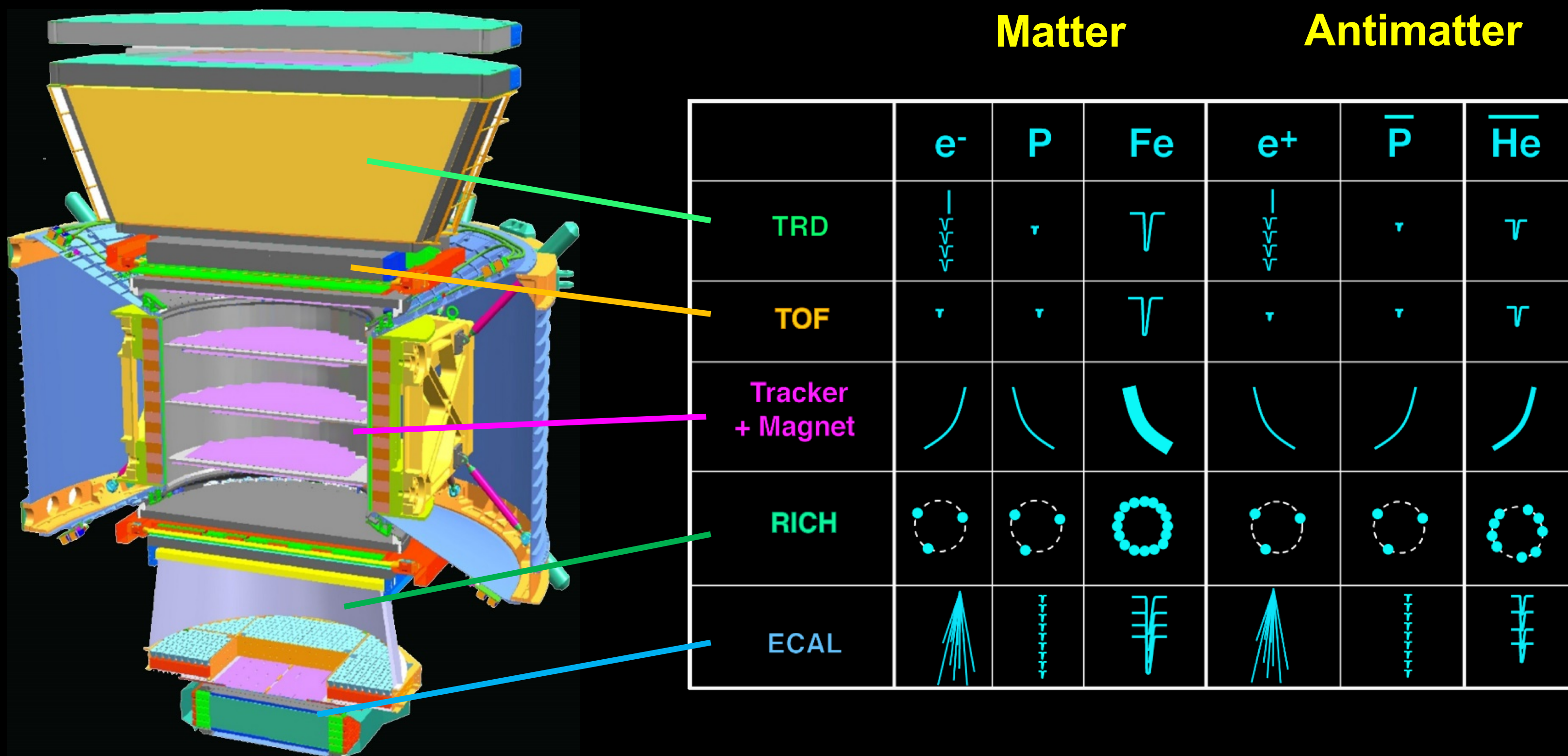


Intensity ∝ Z^2
$\Theta \propto V$





AMS is a unique magnetic spectrometer in space

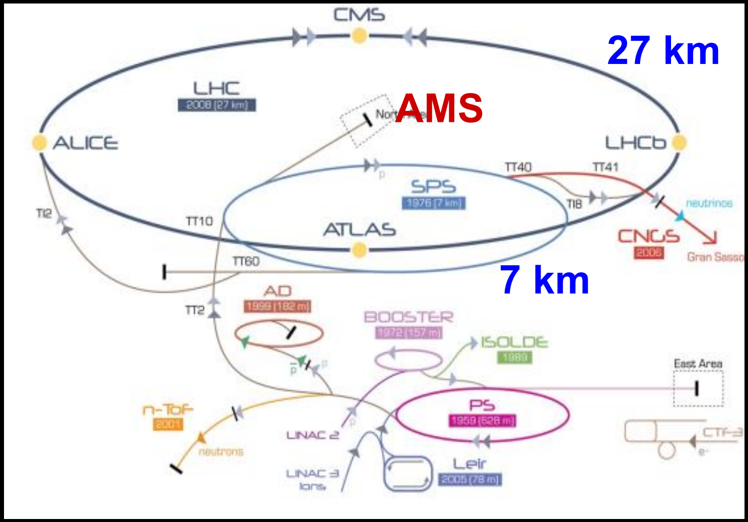


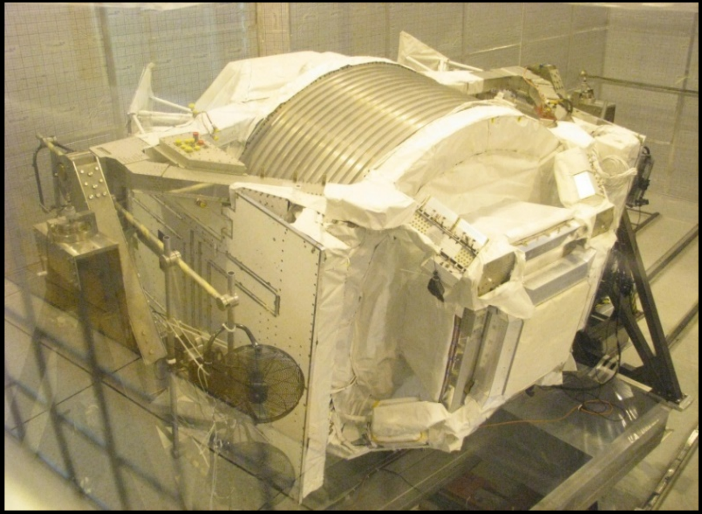
Cosmic rays are defined by:

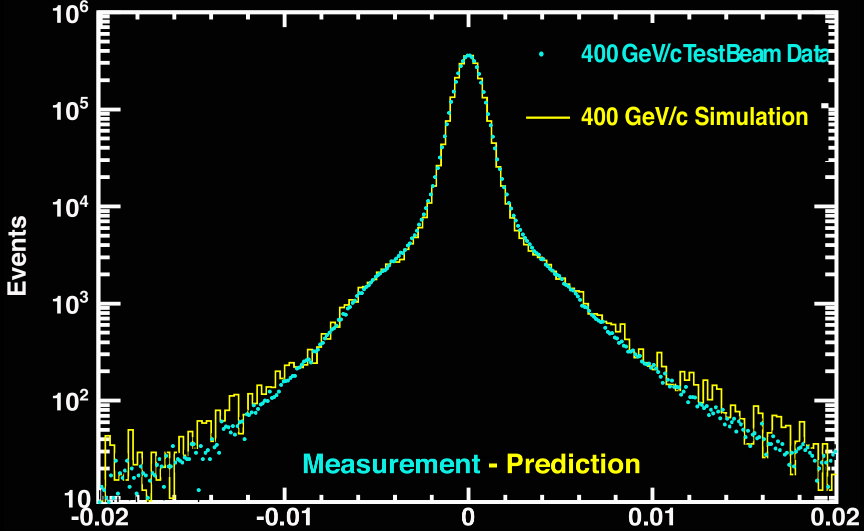
- Energy (E in units of GeV)
- Charge (Z - location on the periodic table: H Z=1, He Z=2, …)
- Rigidity (R=P/Z in units of GV)

Calibration at CERN

with different particles at different energies



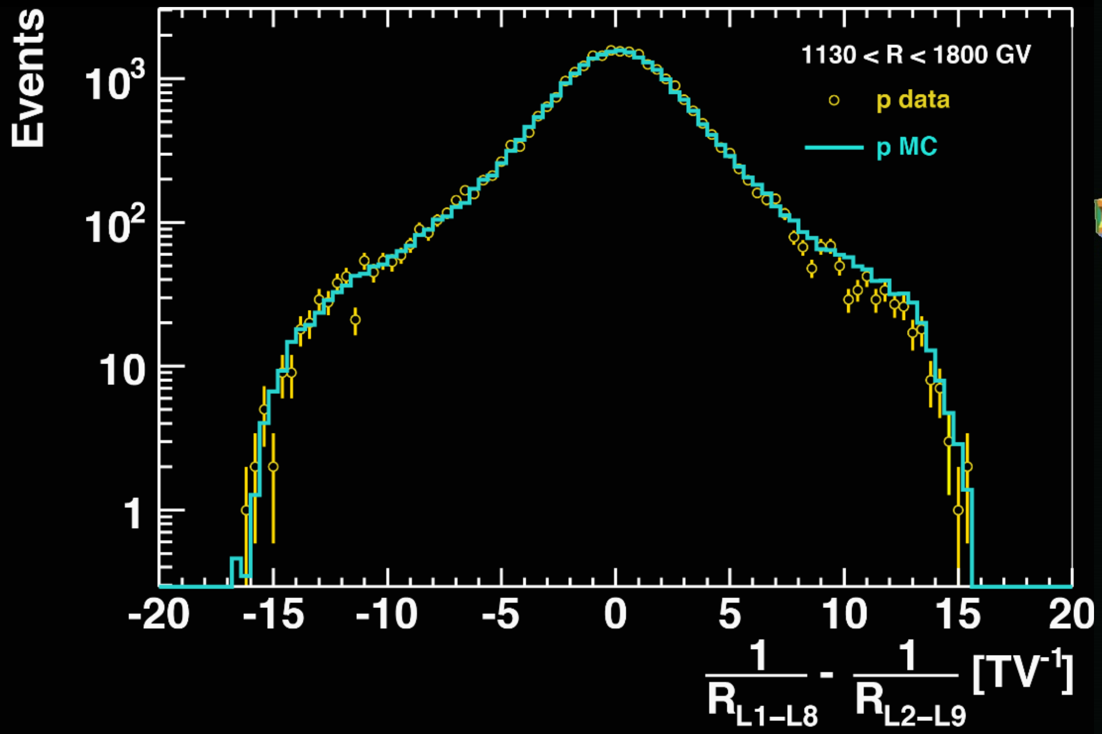


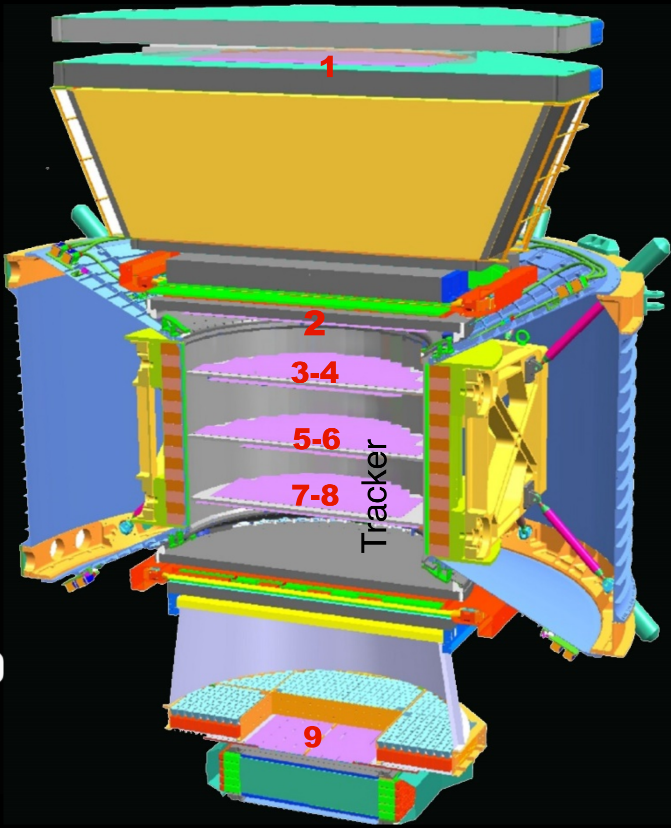


Unique properties of AMS:

Use the Space Station data to verify detector performance at TeV range

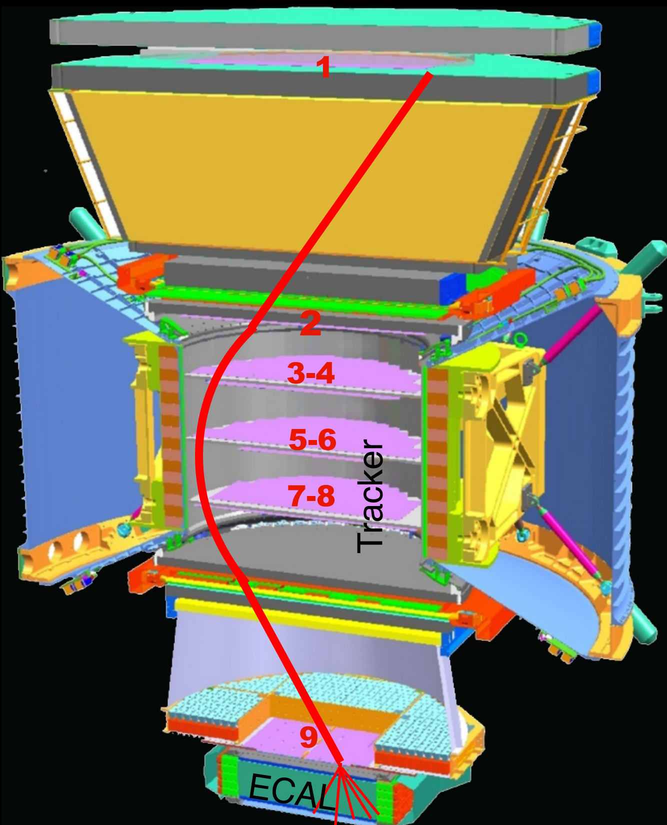
Calibrations above test beam rigidity



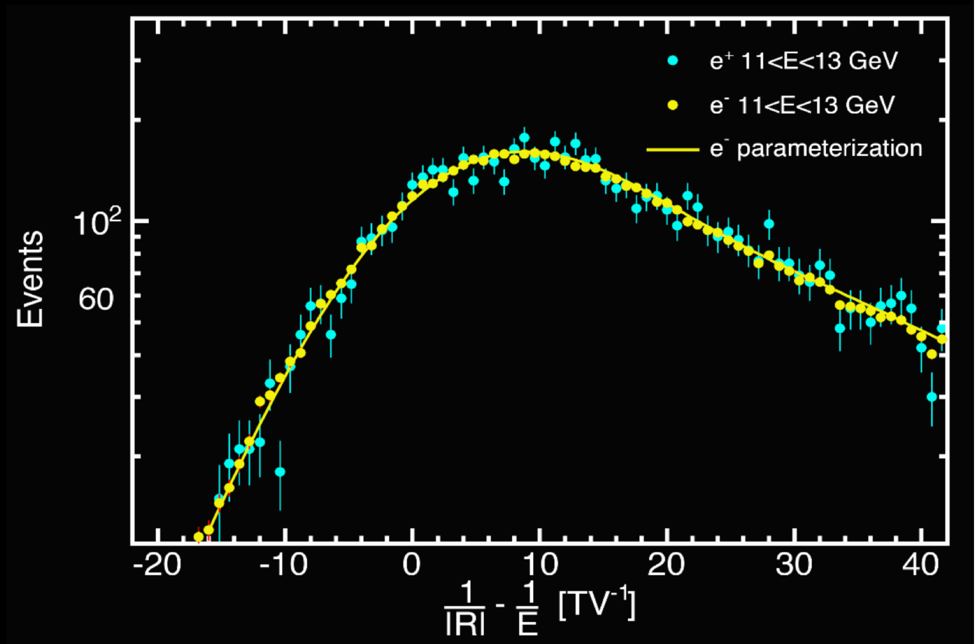


Verification of rigidity measurement with different part of the detectors

Unique properties of AMS:



Accuracy of the rigidity scale

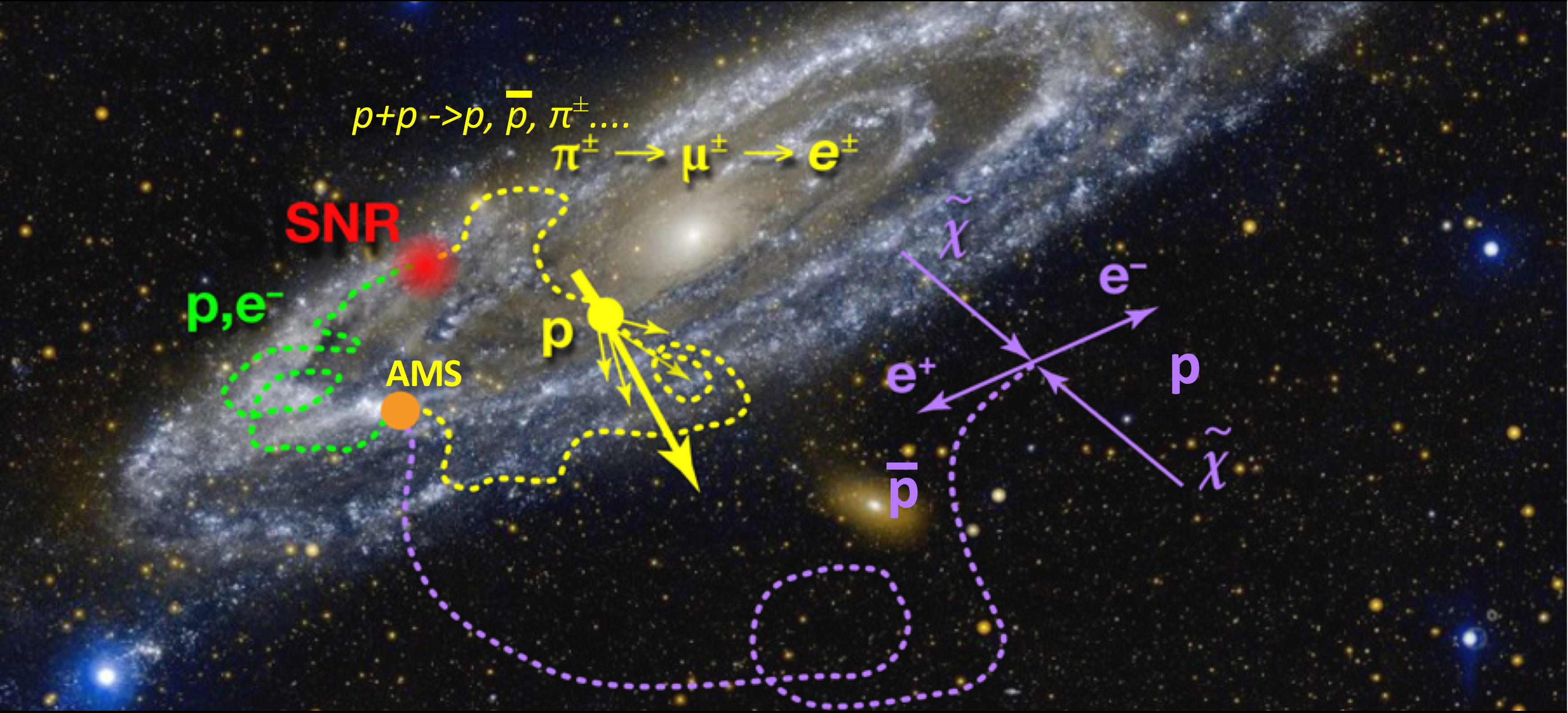


The accuracy of the rigidity scale is found to be 0.033 TV^{-1}, limited mostly by available positron statistics.

The scale is stable over time.


ELC2
ELC4
In 8 years,
over 140 billion
charged cosmic rays
have been measured by AMS

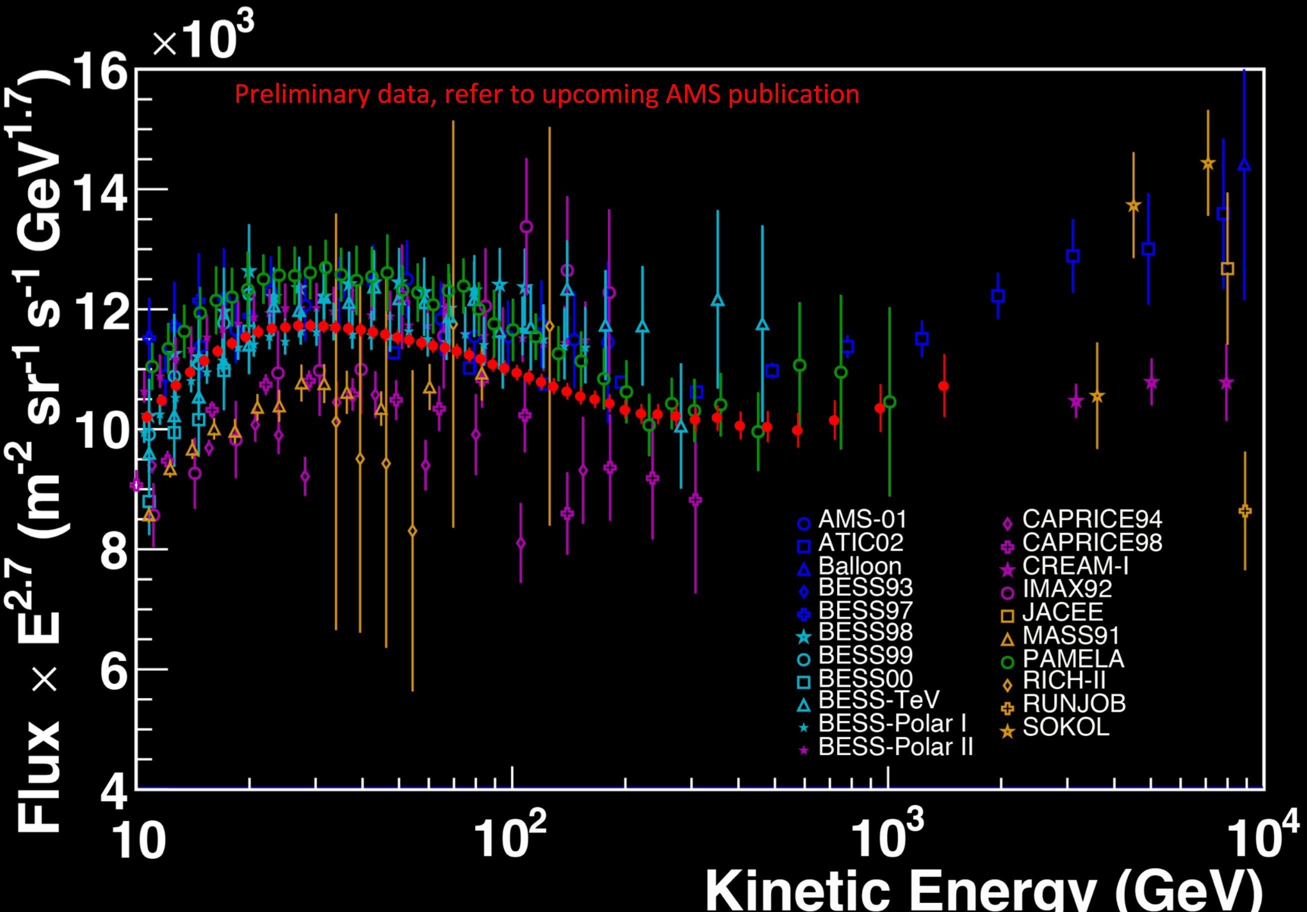
- **Elementary particles in the cosmos: electron, proton, positron, antiproton have infinite live time, they travel through space indefinitely.**
- Protons, Electrons are produced and accelerated in Supernovae Remnants (SNRs) together with other primary cosmic rays. These particles interact with the interstellar matter and produce secondary source of anti-particle: positrons, anti-protons
- New sources like Dark Matter produce particles and antiparticles in equal amount.



A major tool to look for new physics in space is to measure and compare the properties of the fluxes of these particle

Latest AMS Measurement of the proton spectrum

Latest results – 1 billion protons
The result shows progressively hardening above 200GeV and in agreement with previous publication (PRL 114, 171103 (2015)).

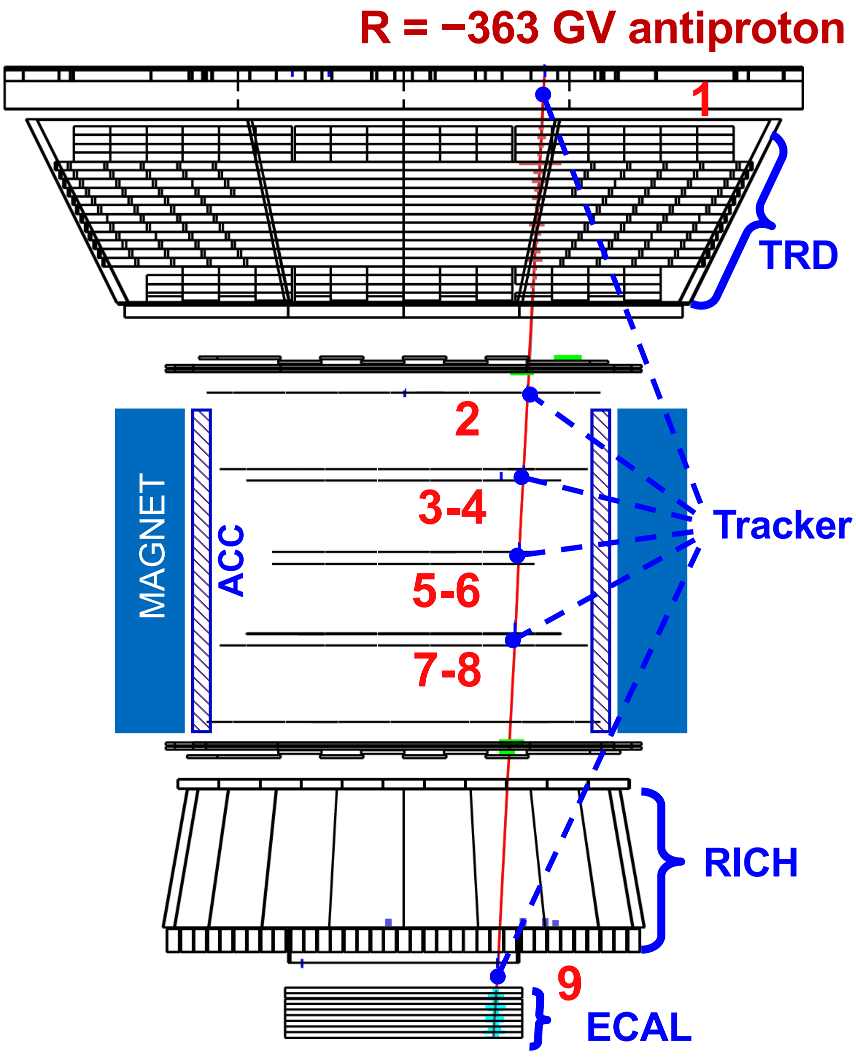


Antiproton Analysis

The Antiproton Flux is ~10^{-4} of the Proton Flux. A percent precision experiment requires background rejection close to 1 in a million

- **TOF & RICH:** select down going particles and measure velocity
- **TRD & ECAL:** reject electron background
- **Tracker:** Measure rigidity and reject misidentified protons

- **A charge confusion estimator was built with information from tracker and TOF, to reject protons measured as negative rigidity.**



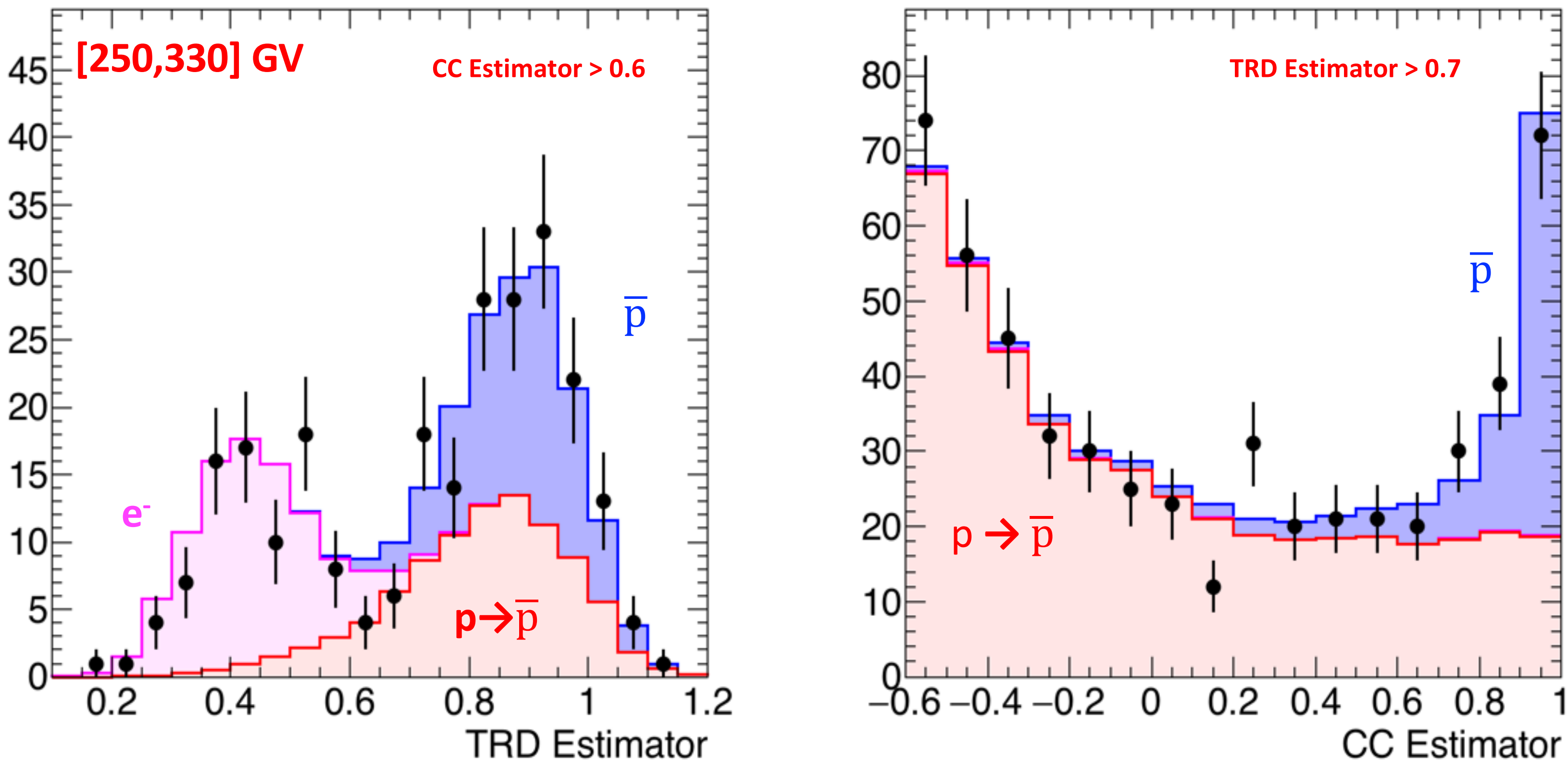
Antiproton identification at High Energy

- **Antiproton Signal are clearly identified in the signal region.**

total of 5.60 x 10^5 antiprotons in the rigidity range 1<|R|<525 GV.

- **Electron : are rejected using TRD estimator**
- **Proton Charge Confusion: identified by Charge Confusion estimator**

TRD Estimator Projection **Charge Confusion (CC) Estimator Projection**

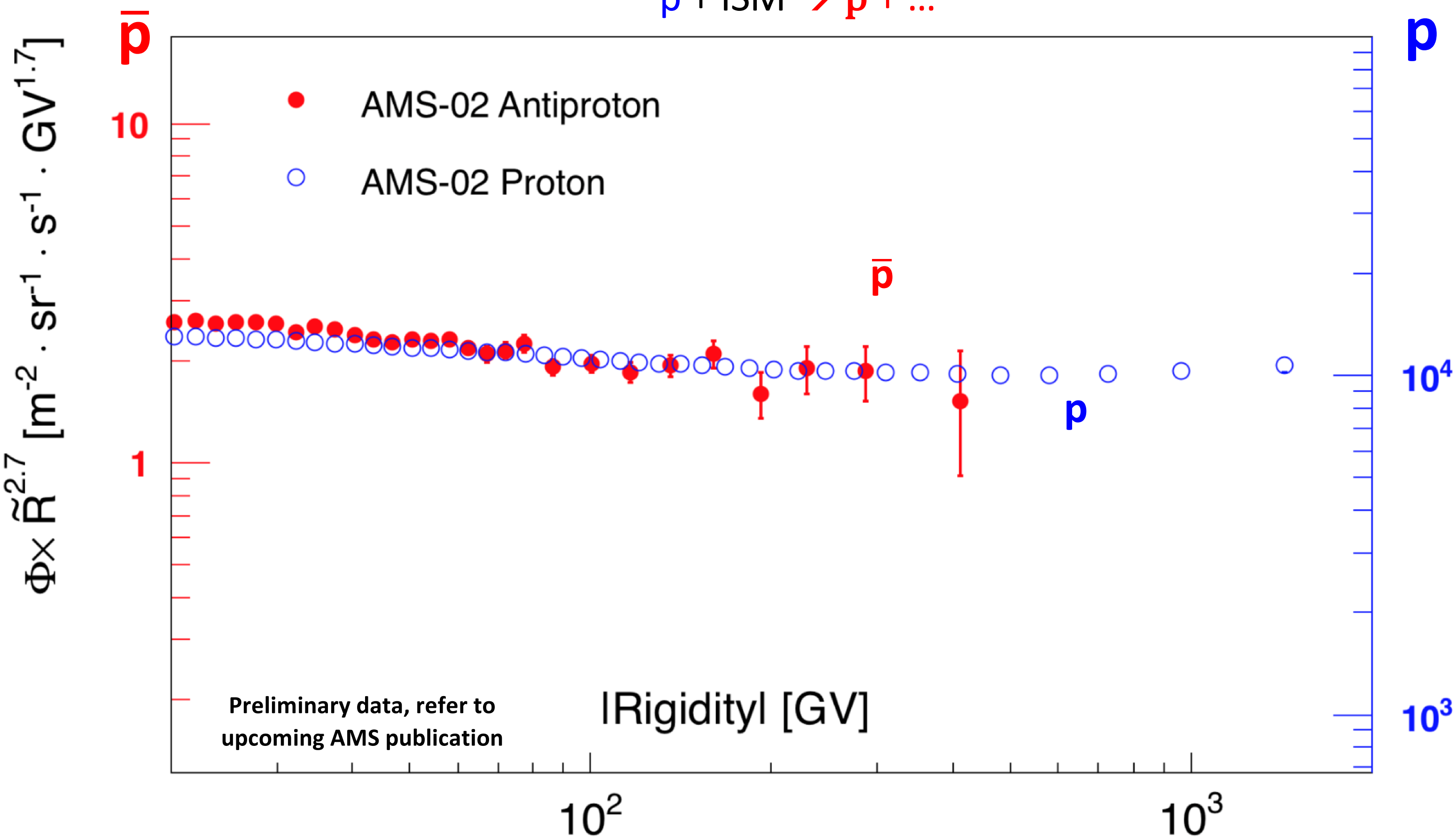


More than 3500 antiprotons above 100 GV be compared with 3 from all other experiments.

Precision study of the properties of antiproton flux

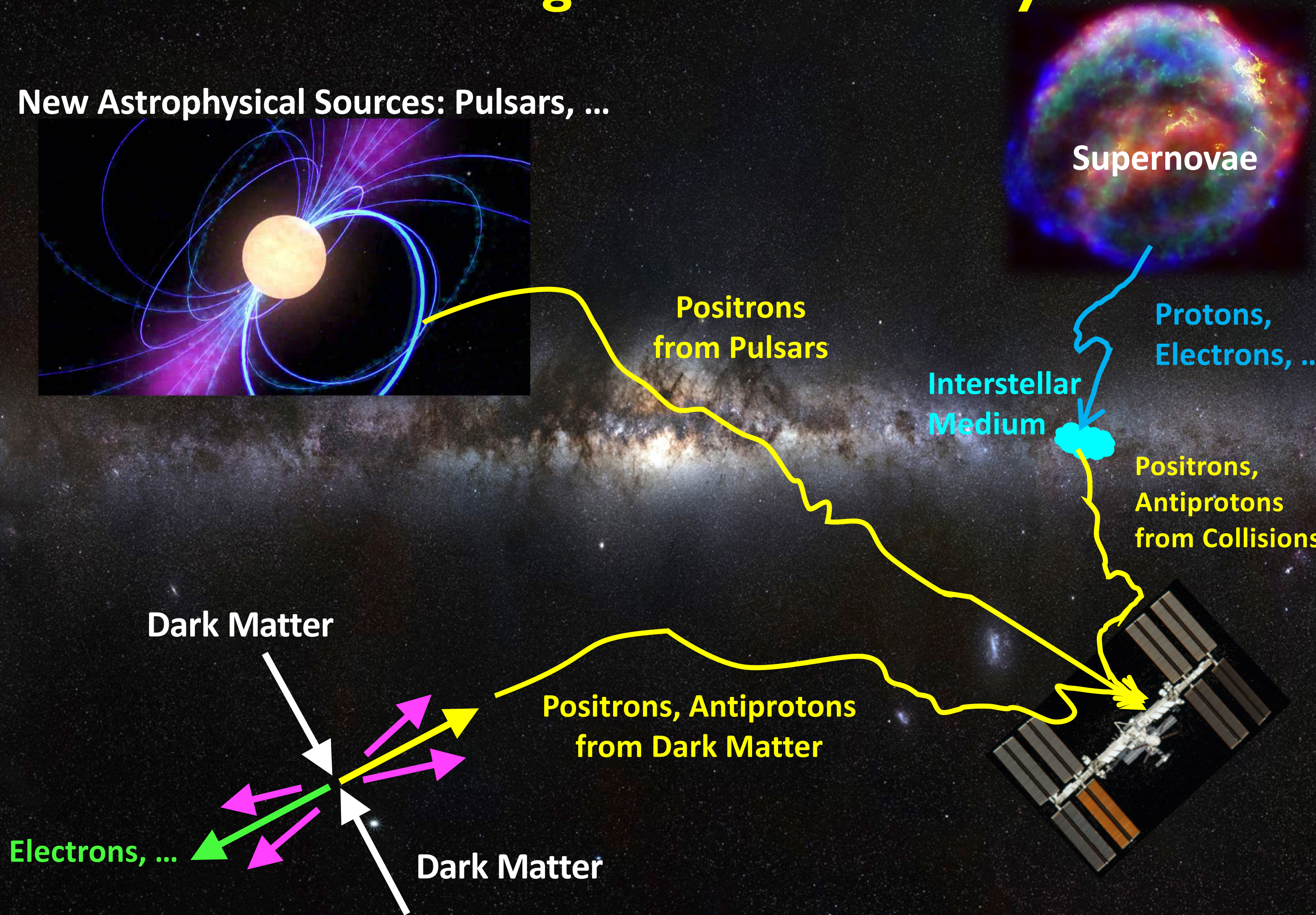
If $\bar{p}$ are secondaries produced in ISM, their rigidity dependence should be different than p:

p + ISM → $\bar{p}$ + ...



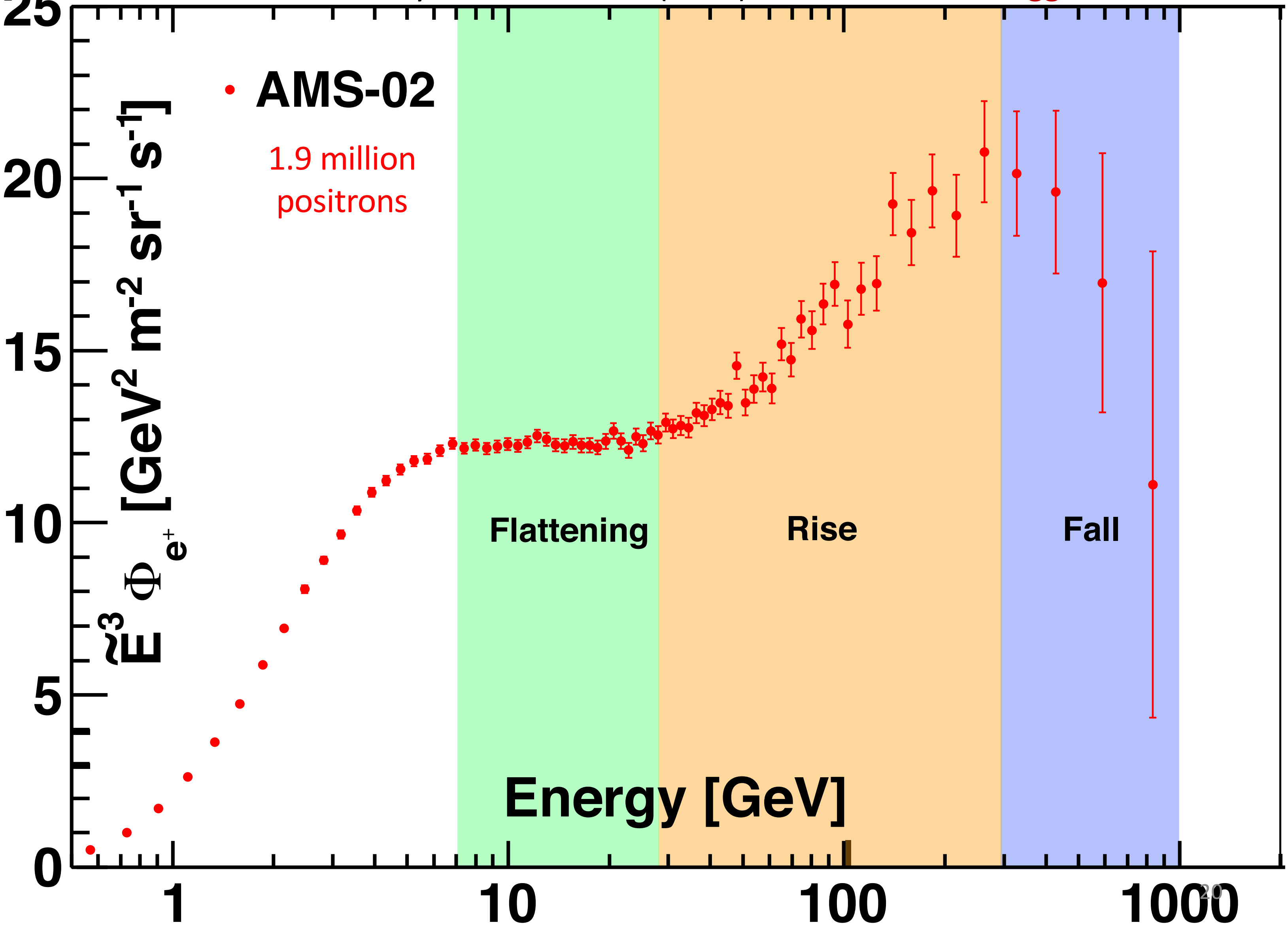
- AMS observed for the first time that above 60 GV, p and $\bar{p}$ have identical Rigidity dependence: Not consistent with only secondary antiproton produced from proton interaction with ISM.

On the Origins of Cosmic Rays

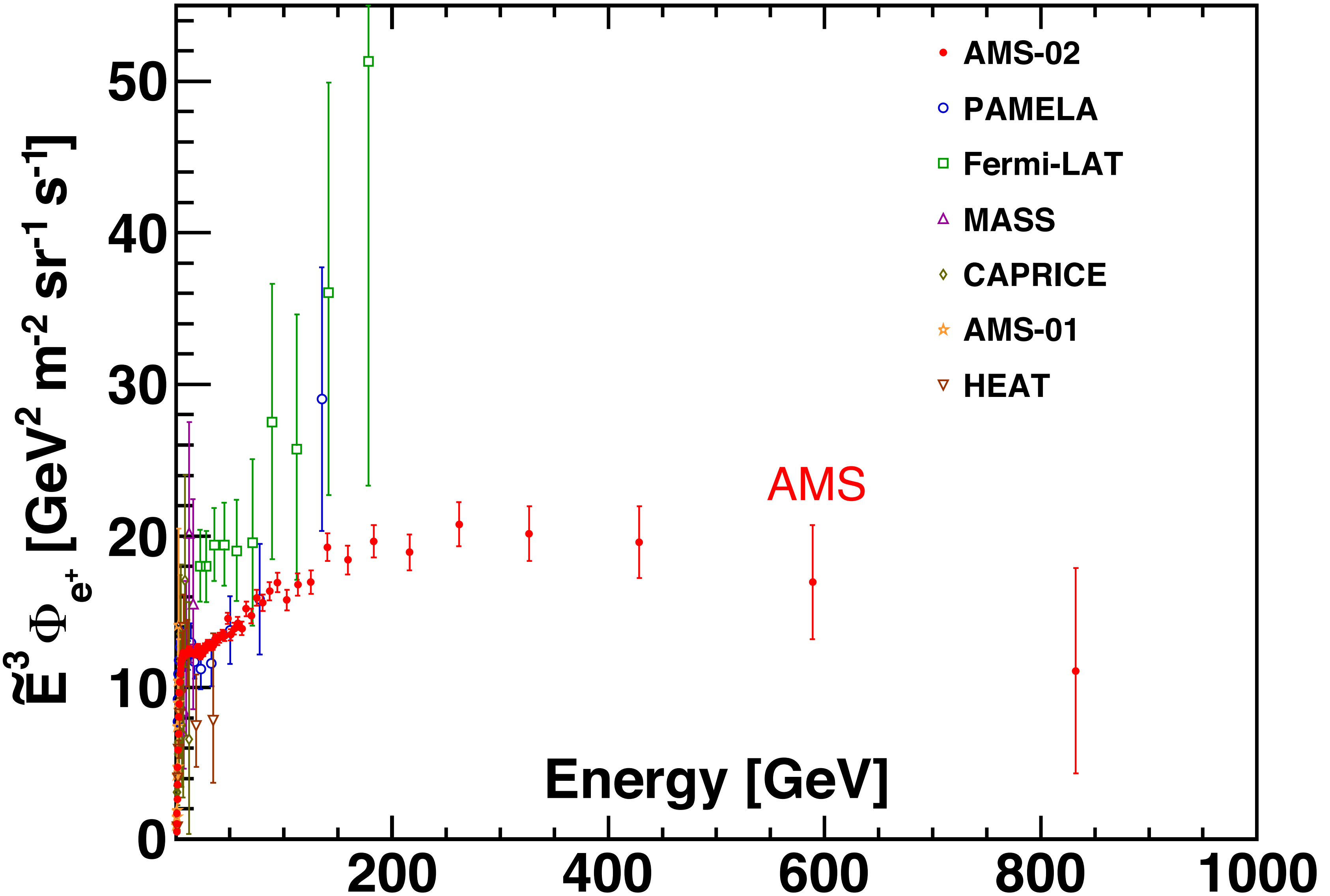


Towards understanding the origin of cosmic ray positrons

Phys. Rev. Lett. 122 (2019) 041102. Editor's Suggestion



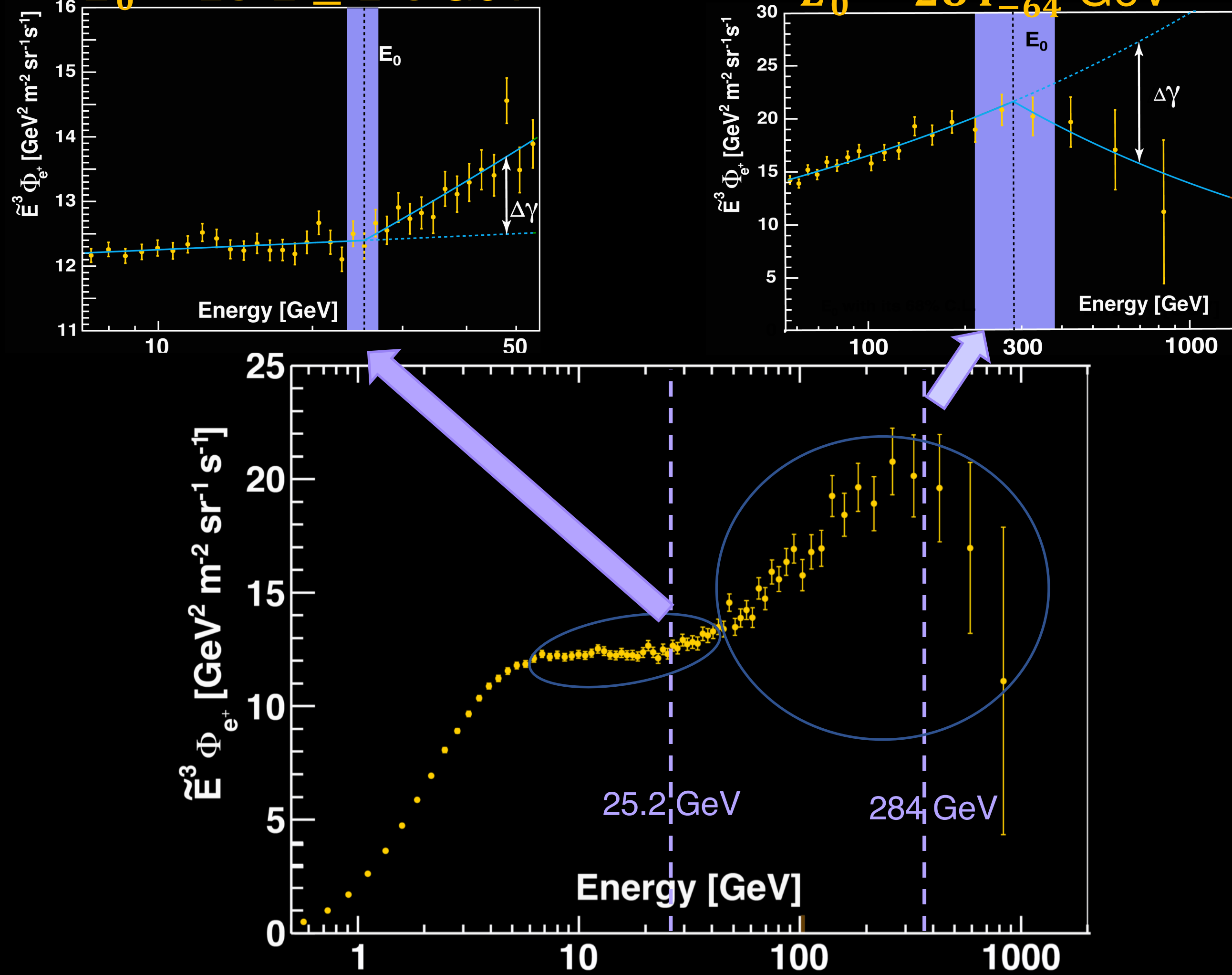
Comparison with other recent measurements



Fits of the data to $$\Phi_{e^+}(E) = \begin{cases} C\boldsymbol{E}^{\gamma}, & E \le E_0; \\ C\boldsymbol{E}^{\gamma}(E/E_0)^{\Delta\gamma}, & E > E_0. \end{cases}$$

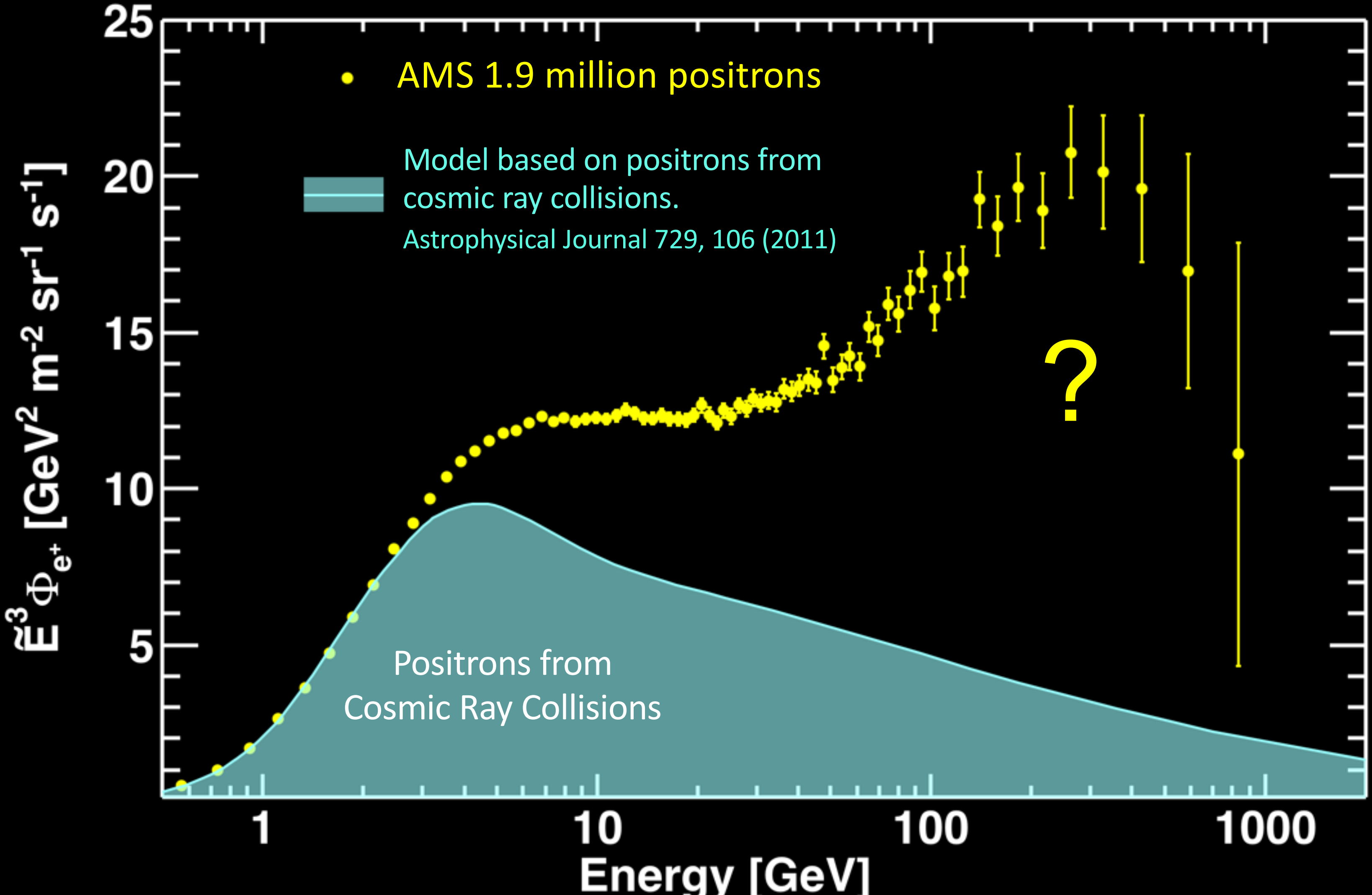
(a) An excess **above** $E_0 = 25.2 \pm 1.8$ GeV

(b) A sharp drop-off at $E_0 = 284^{+91}_{-64}$ GeV



The Origin of Positrons

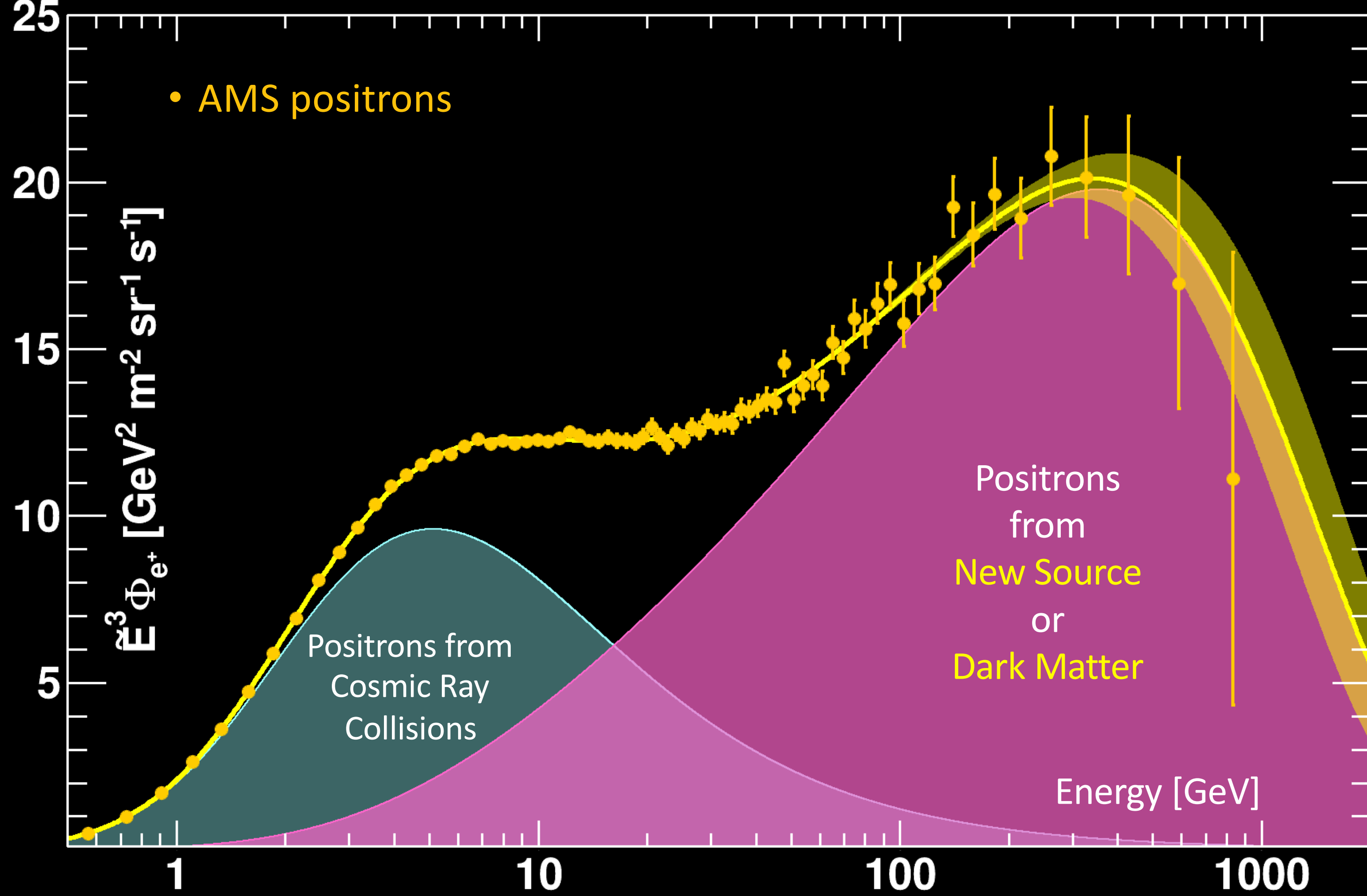
Low energy positrons mostly come from cosmic ray collisions



The positron flux is the sum of low-energy part from cosmic ray collisions plus a high-energy part from a new source or dark matter both with a cutoff energy E_S.

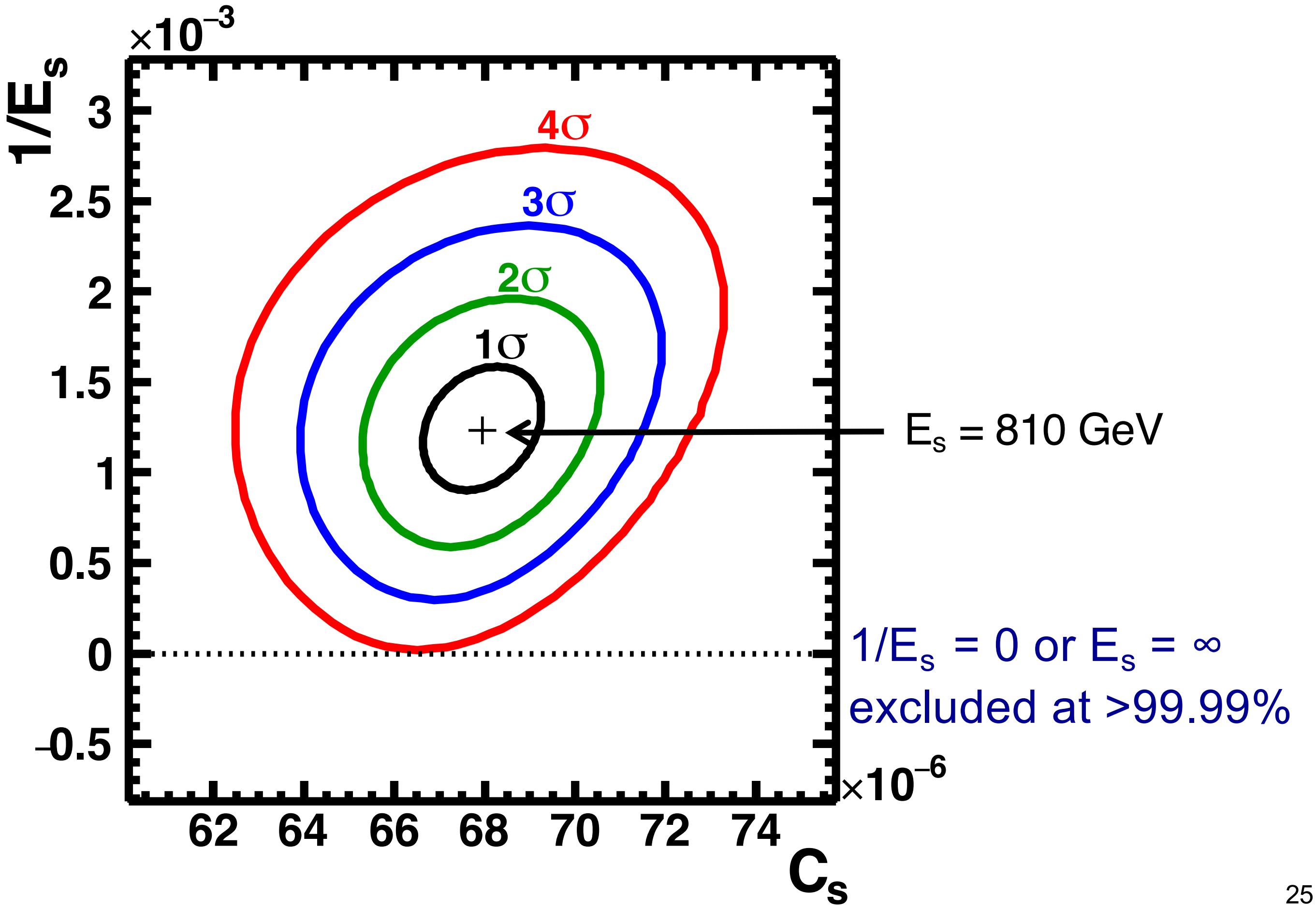
Collisions | New Source or Dark Matter

$$\Phi_{e^+}(E) = \frac{E^2}{\hat{E}^2}\left[C_d(\hat{E}/E_1)^{\gamma_d} + C_s(\hat{E}/E_2)^{\gamma_s}\exp(-\hat{E}/E_s)\right]$$



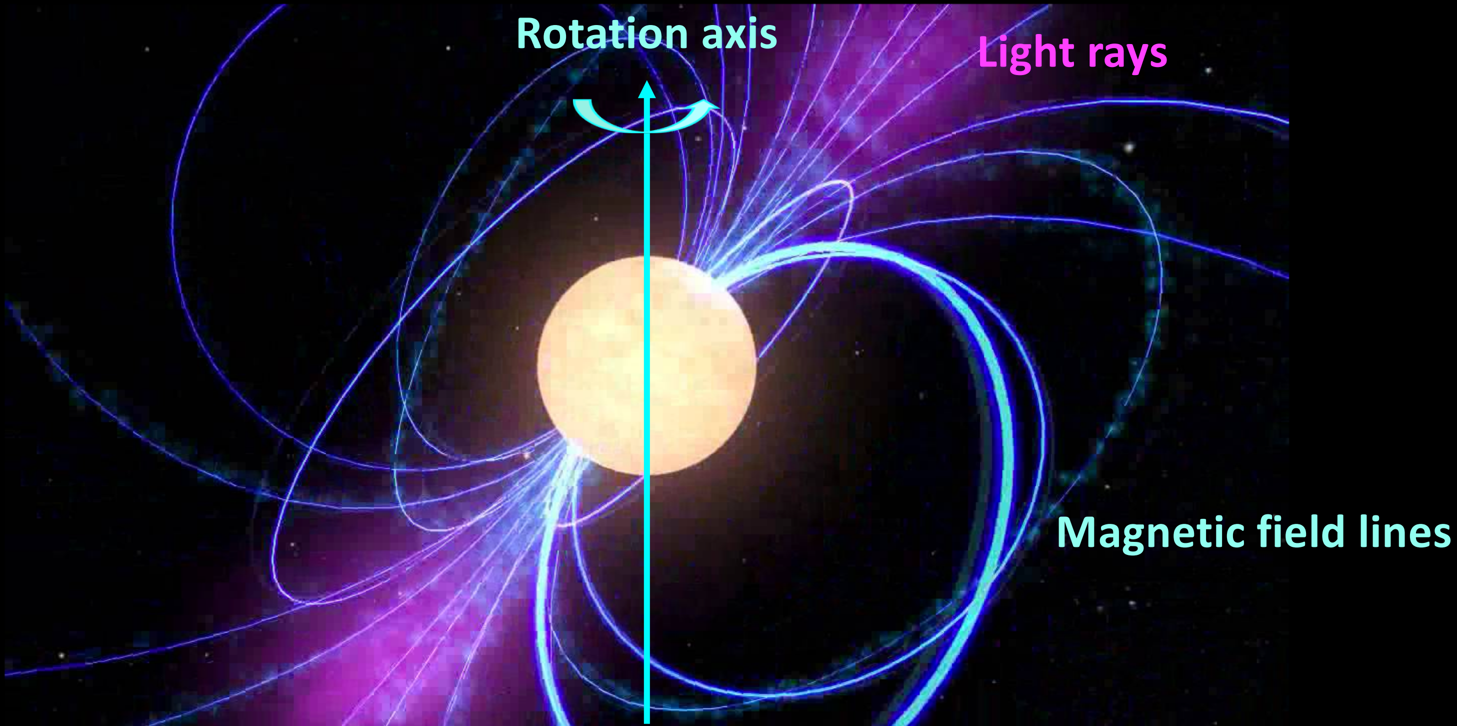
A finite energy cutoff of the source term $E_s = 810^{+310}_{-180}$ GeV, is established with a significance more than 99.99%.

$$\Phi_{e^+}(E) = \frac{E^2}{\hat{E}^2}\Big[\underbrace{C_d(\hat{E}/E_1)^{\gamma_d}}_{\text{Collisions}} + \underbrace{C_s(\hat{E}/E_2)^{\gamma_s}\exp(-\hat{E}/E_s)}_{\text{Source}}\Big]$$

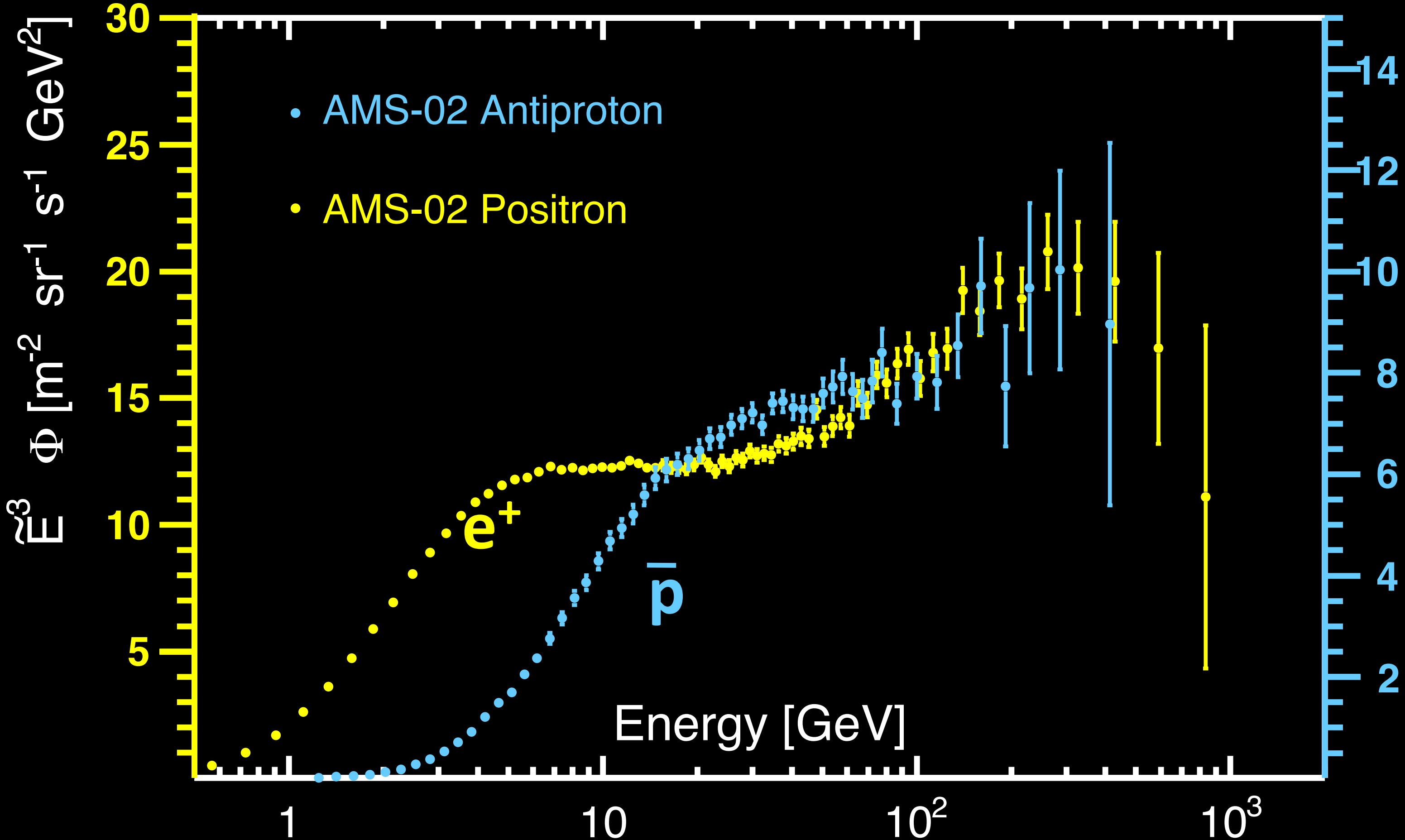


Positrons from Pulsars

1. Pulsars produce and accelerate positrons to high energies.
2. Pulsars do not produce antiprotons.
3. Pulsars cause higher anisotropy on the arrival directions of energetic positrons.



AMS Physics Results:
Antiproton data show a similar trend as positrons.



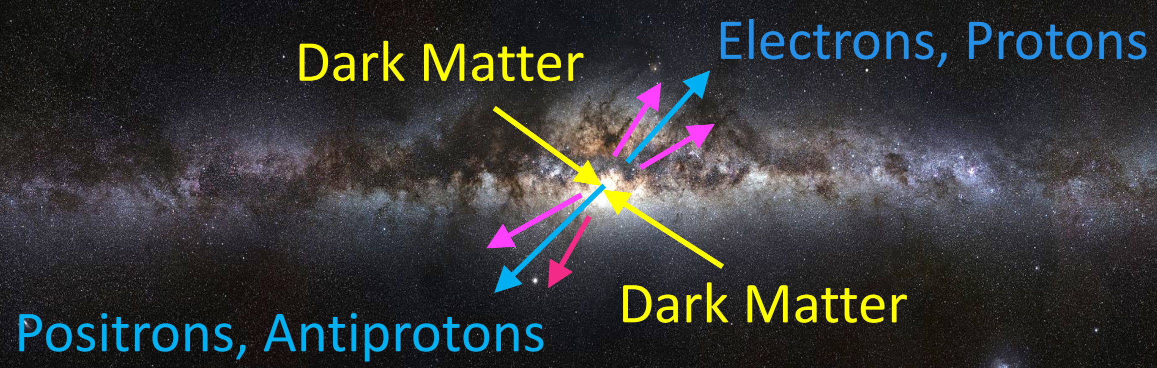
•The similarity between antiproton and positron indicate a primary source of positron and antiprotons.

•Their behavior is inconsistent with pulsar origin of positrons

Dark Matter

Collision of Dark Matter produces positrons and antiprotons.

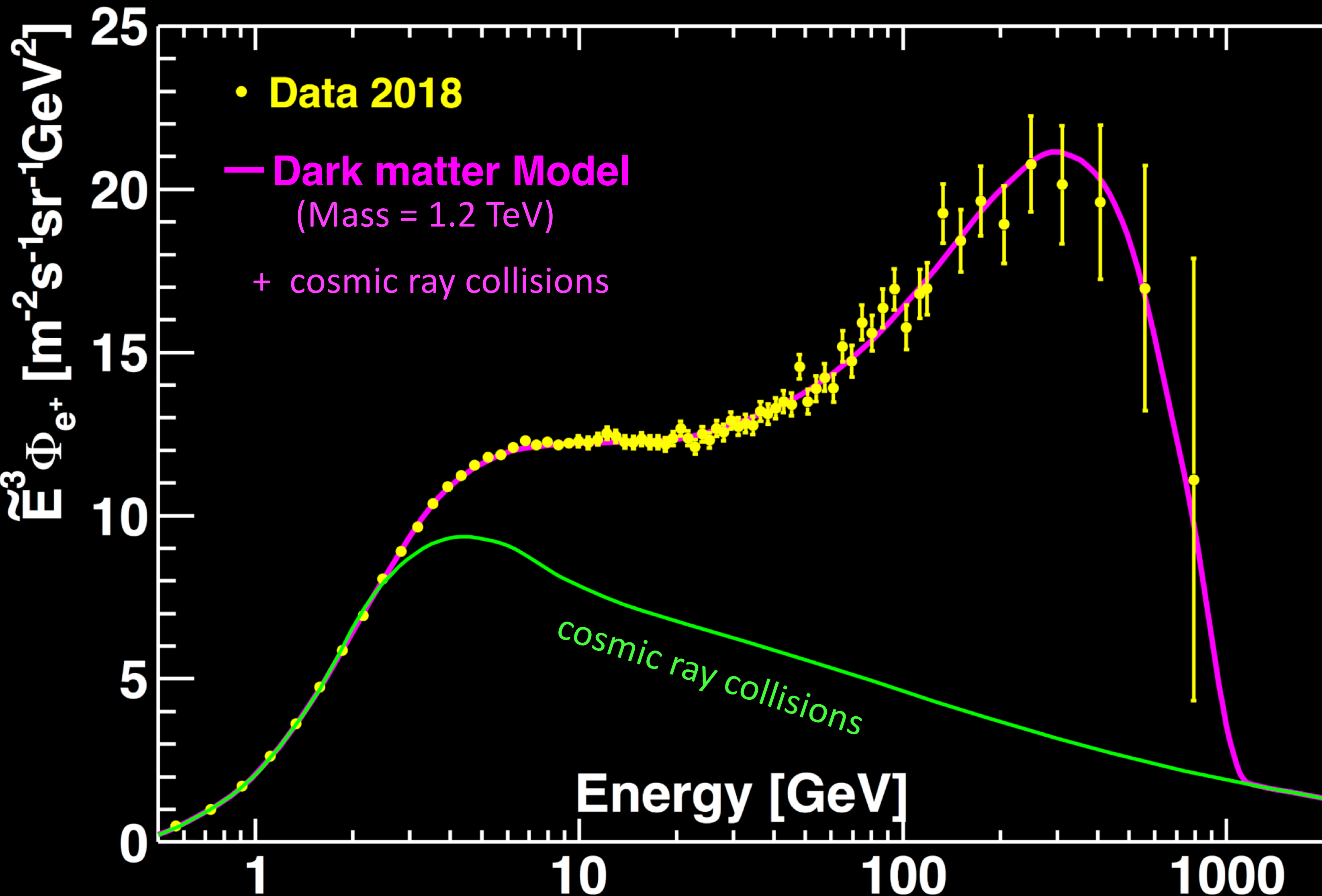
Dark Matter particles have mass M and they move slowly.
Before collision the total energy ≈ $2M$.



The conservation of energy and momentum requires that the positron or antiproton energy must be smaller than M.

So, there is a sharp cutoff in the spectra at M.

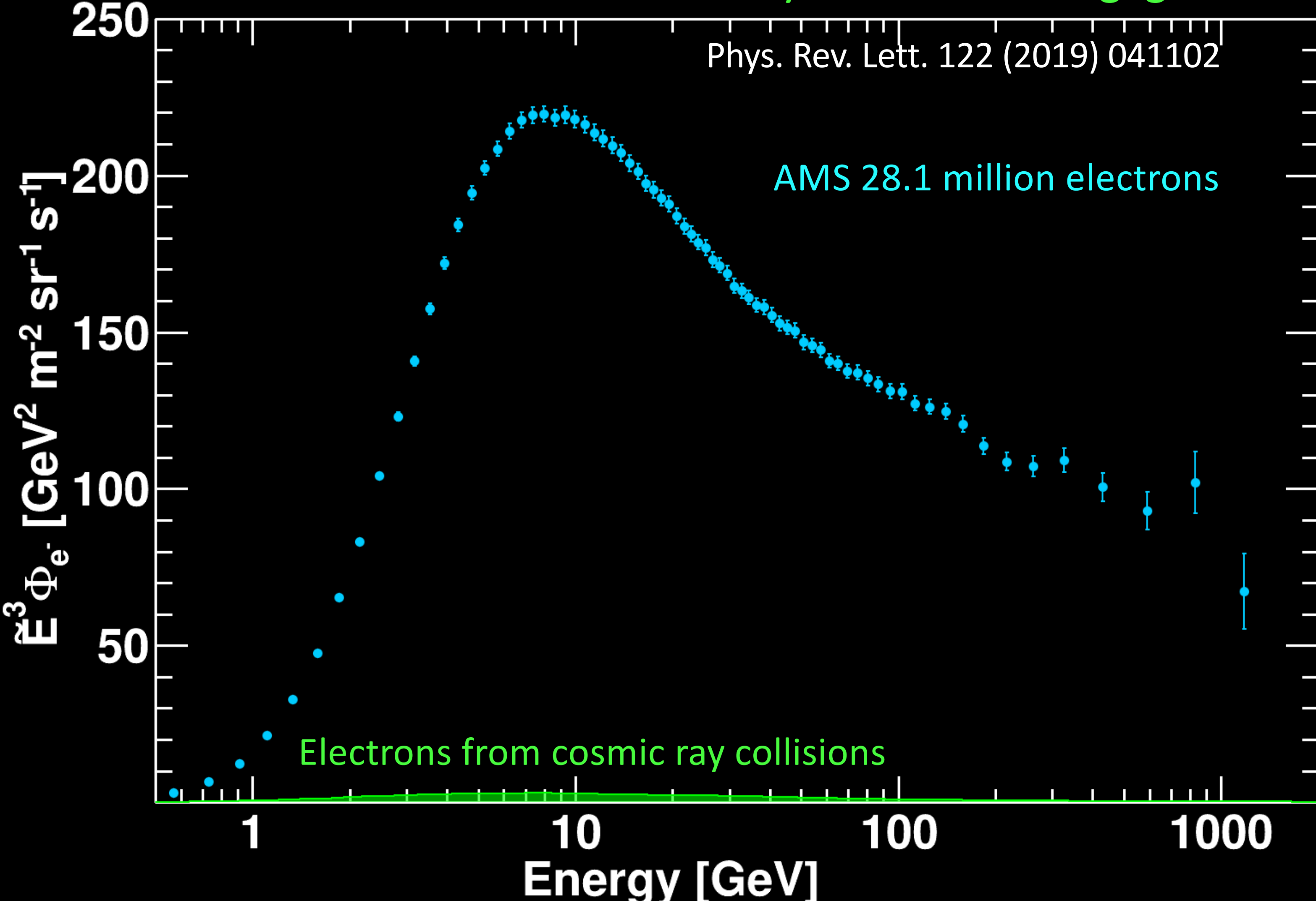
Positrons and Dark Matter 2018



AMS Physics Results:

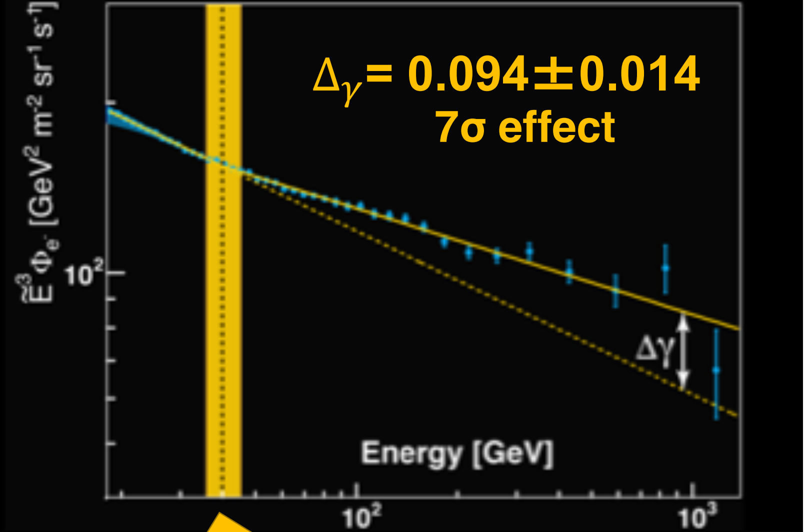
The Origins of Cosmic Electrons

The contribution from cosmic ray collisions is negligible



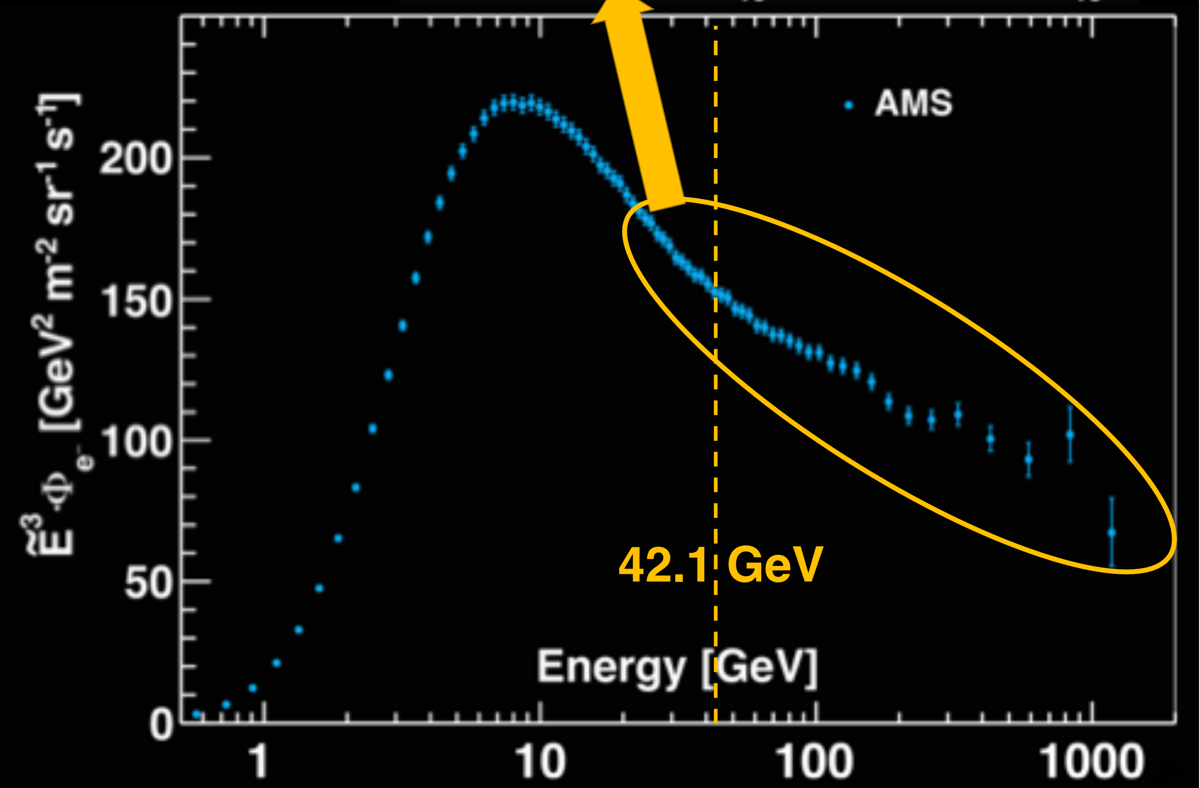
Fit to the data

$$\Phi_{e^+}(E) = \begin{cases} CE^{\gamma}, & E \leq E_0; \\ CE^{\gamma}(E/E_0)^{\Delta\gamma}, & E > E_0. \end{cases}$$



A significant excess at

$E_0 = 42.1^{+5.4}_{-5.2}$ **GeV**

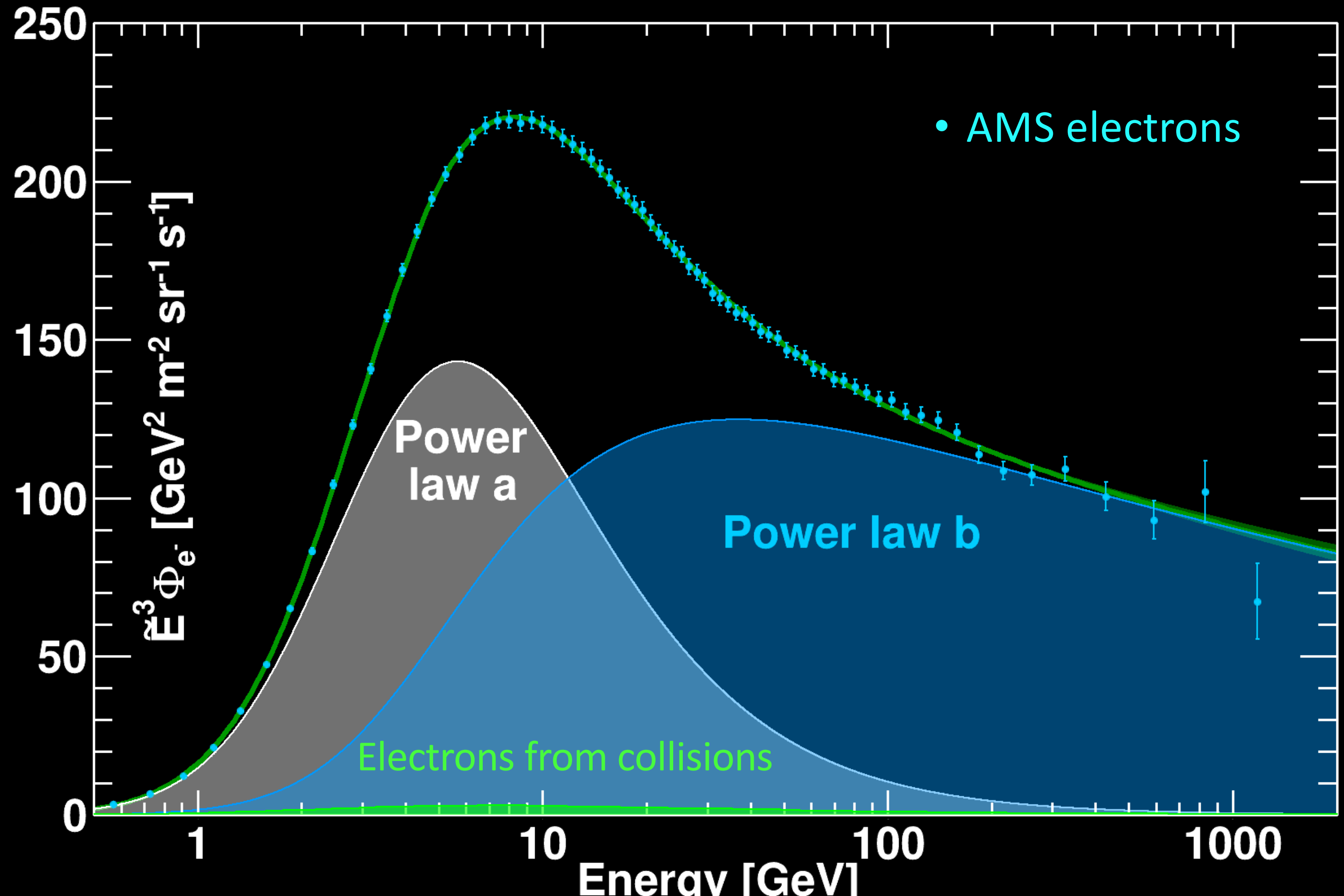


The electron flux can be described by two power law functions:

$$\Phi_{e^-}(E) = S(E)\left[C_a\left(\hat{E}/E_a\right)^{\gamma_a} + C_b\left(\hat{E}/E_b\right)^{\gamma_b}\right]$$

Solar & low-energy — Power law *a* — Power law *b*

What is the origin of power law a and power law b?

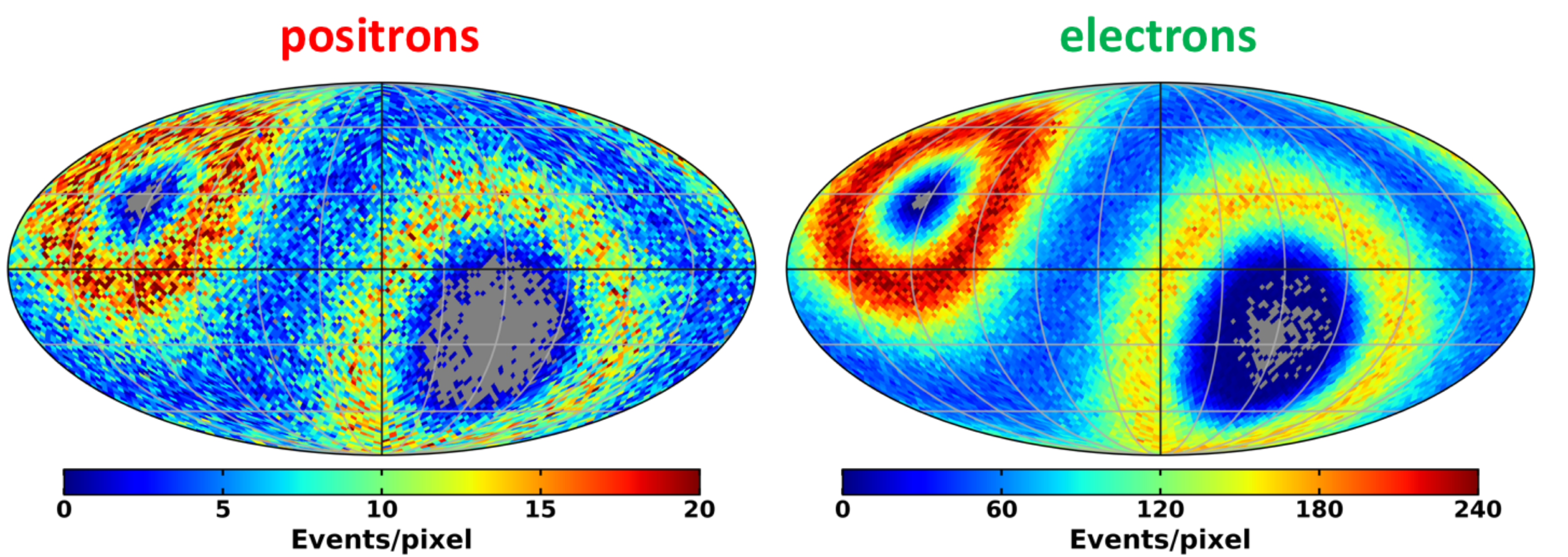


Positron Anisotropy and Dark Matter

Astrophysical point sources like pulsars will imprint a higher anisotropy on the arrival directions of energetic positrons than a smooth dark matter halo.

The anisotropy in galactic coordinates

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



Currently at 95% C.L.: for 16<E<350

positrons: $\delta < 0.019$

electrons: $\delta < 0.005$

AMS Publications in PRL

In yellow: editors' suggestion

1. *First Result from the AMS on the ISS: Precision Measurement of the Positron Fraction in Primary Cosmic Rays of 0.5–350 GeV (2013)*
2. *Electron and Positron Fluxes in Primary Cosmic Rays Measured with the AMS on the ISS (2014)*
3. *High Statistics Measurement of the Positron Fraction in Primary Cosmic Rays of 0.5–500 GeV with the AMS on the ISS (2014)*
4. *Precision Measurement of the $e^+ + e^-$ Flux in Primary Cosmic Rays from 0.5 GeV to 1 TeV with the AMS on the ISS (2014)*
5. *Precision Measurement of the Proton Flux in Primary Cosmic Rays from Rigidity 1 GV to 1.8 TV with the AMS on the ISS (2015)*
6. *Precision Measurement of the He Flux in Primary Cosmic Rays of Rigidities 1.9 GVto 3 TV with the AMS on the ISS (2015)*
7. *Antiproton Flux, Antiproton-to-Proton Flux Ratio, and Properties of Elementary Particle Fluxes in Primary Cosmic Rays Measured with the AMS on the ISS (2016)*
8. *Precision Measurement of the B to C Flux Ratio in Cosmic Rays from 1.9 GV to 2.6 TV with the AMS on the ISS (2016)*
9. *Observation of the Identical Rigidity Dependence of He, C, and O Cosmic Rays at High Rigidities by the AMS on the ISS (2017)*
10. *Observation of New Properties of Secondary Cosmic Rays Lithium, Beryllium, and Boron by the AMS on the ISS (2018)*
11. *Observation of Fine Time Structures in the Cosmic Proton and Helium Fluxes with AMS on the ISS (2018)*
12. *Observation of complex time structures in the cosmic-ray electron and positron fluxes with the AMS on the ISS (2018)*
13. *Precision measurement of cosmic-ray nitrogen and its primary and secondary components with AMS on the ISS (2018)*
14. *Towards Understanding the Origin of Cosmic-Ray Positrons (2019)*
15. *Towards Understanding the Origin of Cosmic-Ray Electrons (2019)*

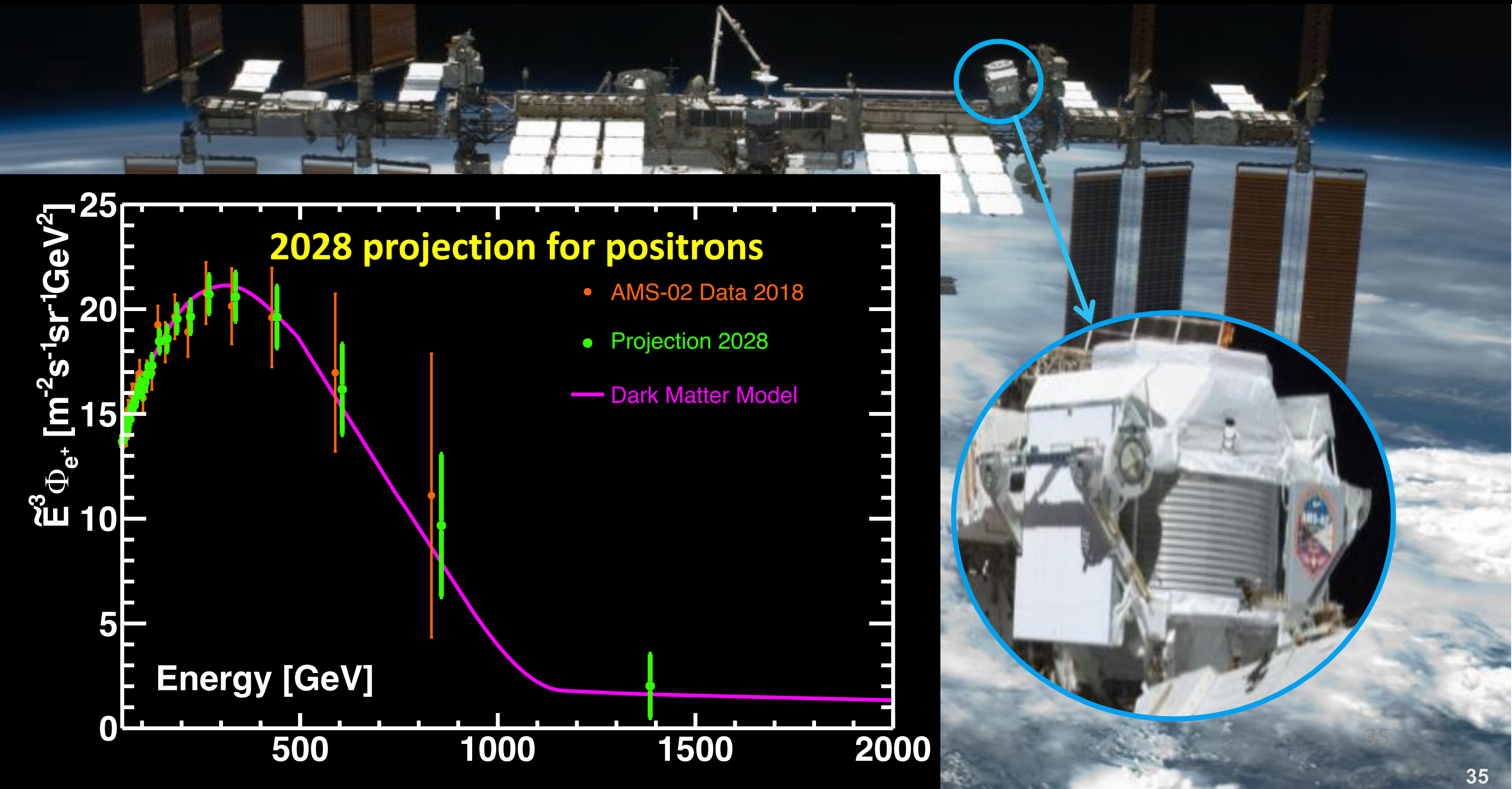
… "Helium Isotopes in the Cosmos "

… "Rigidity Dependence of Ne, Mg, and Si Cosmic Rays"

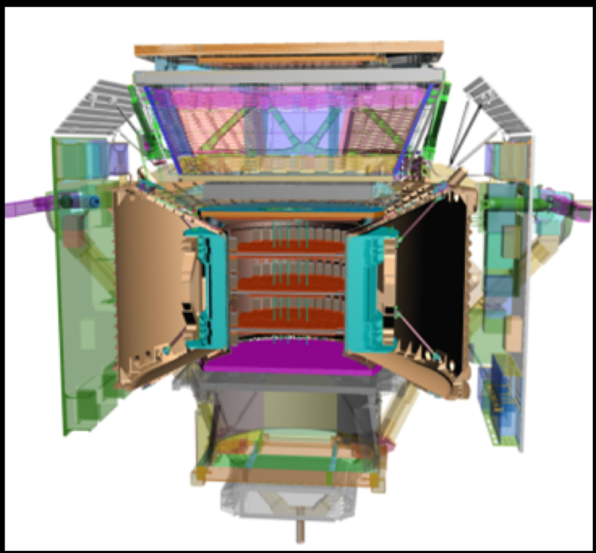
…

AMS is exploring fundamental physics in space with many different types of cosmic rays. Our new and exciting phenomena are observed.

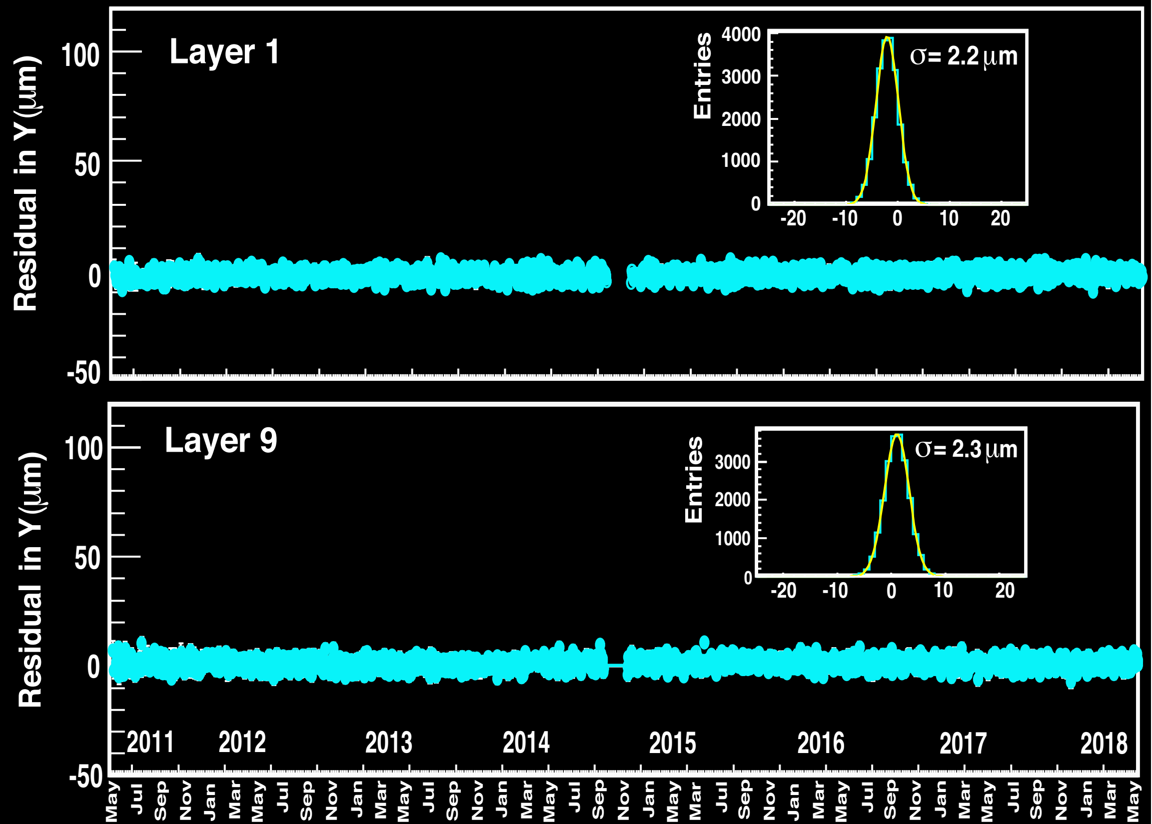
AMS will continue to collect and analyze data for the lifetime of the Space Station because whenever a precision instrument such as AMS is used to explore the unknown, new and exciting discoveries can be expected



Tracker stable to 2 microns over eight years



Inner tracker (Layer 2-Layer 8) alignment (< 1 micron) monitored with infrared lasers



Outer tracker stable to 2 microns over 8 years

Maximal Detectable Rigidity – 2TV for Z=1 particles

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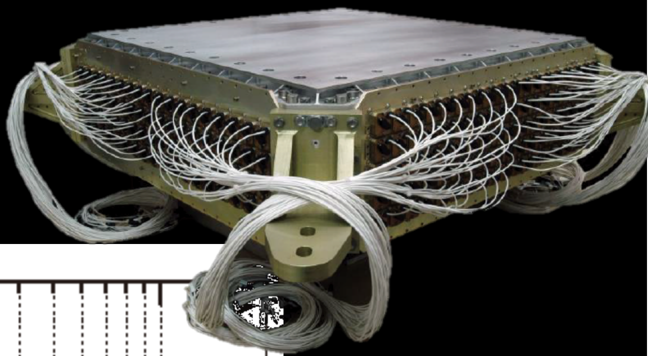
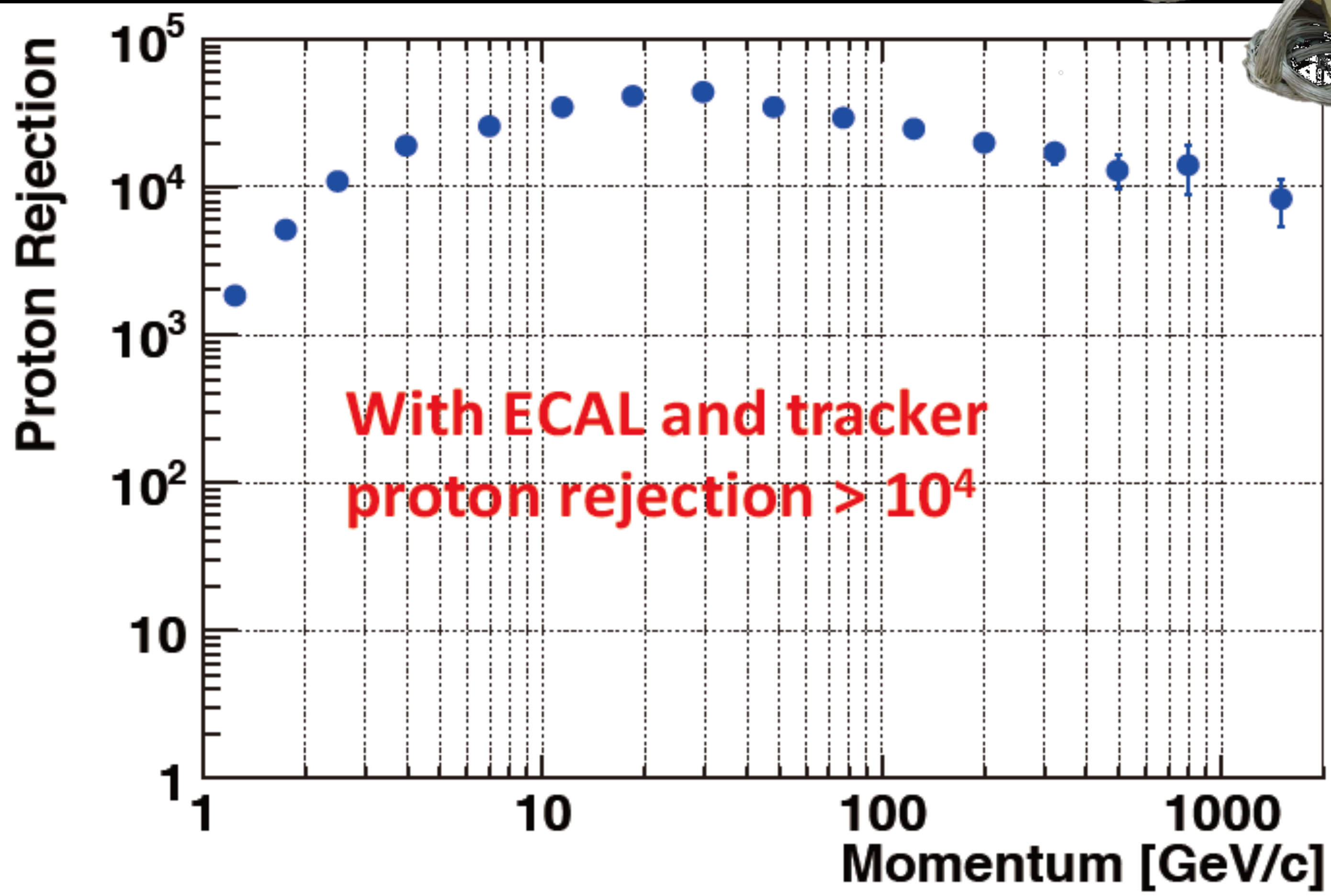
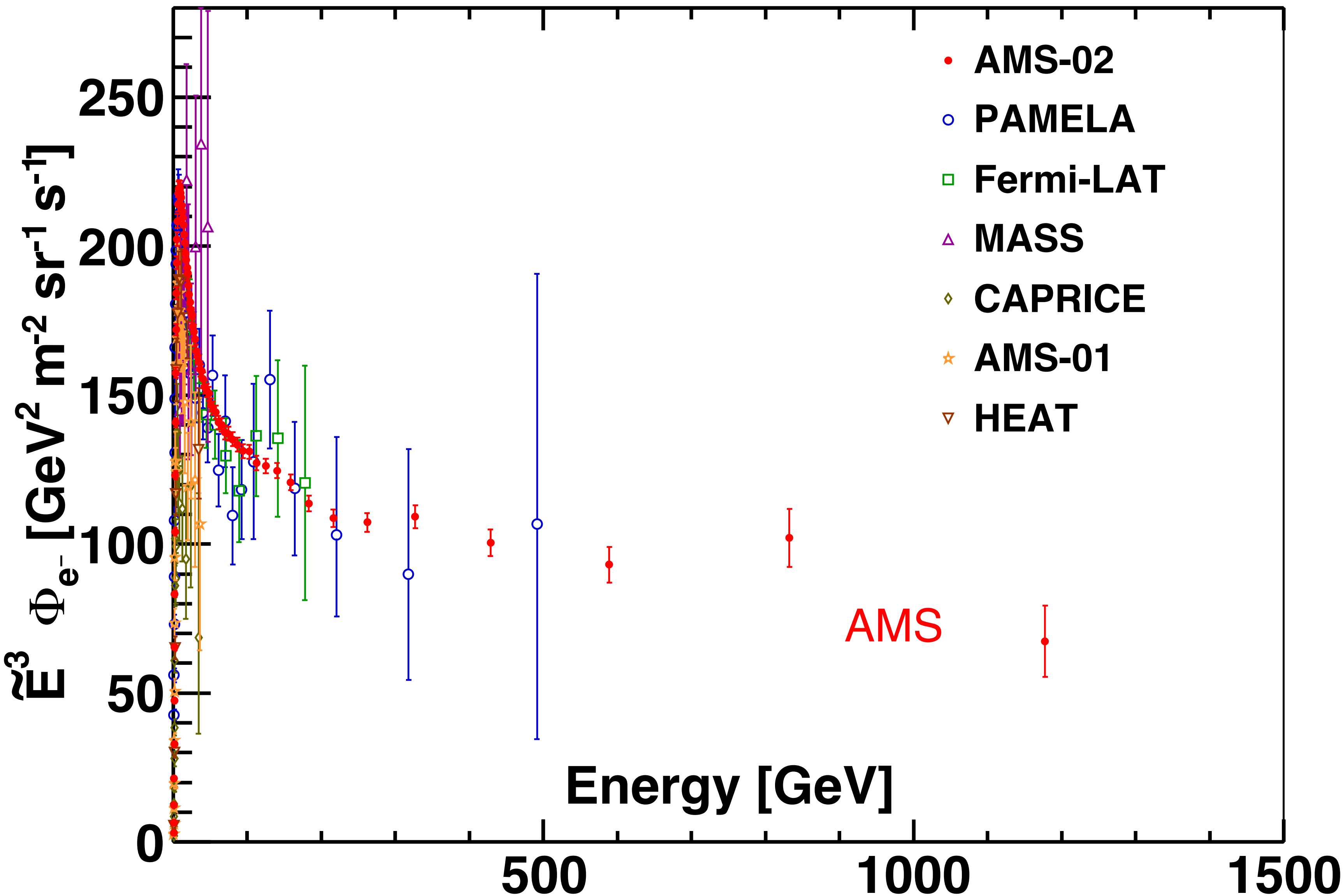
Electromagnetic Calorimeter (ECAL)



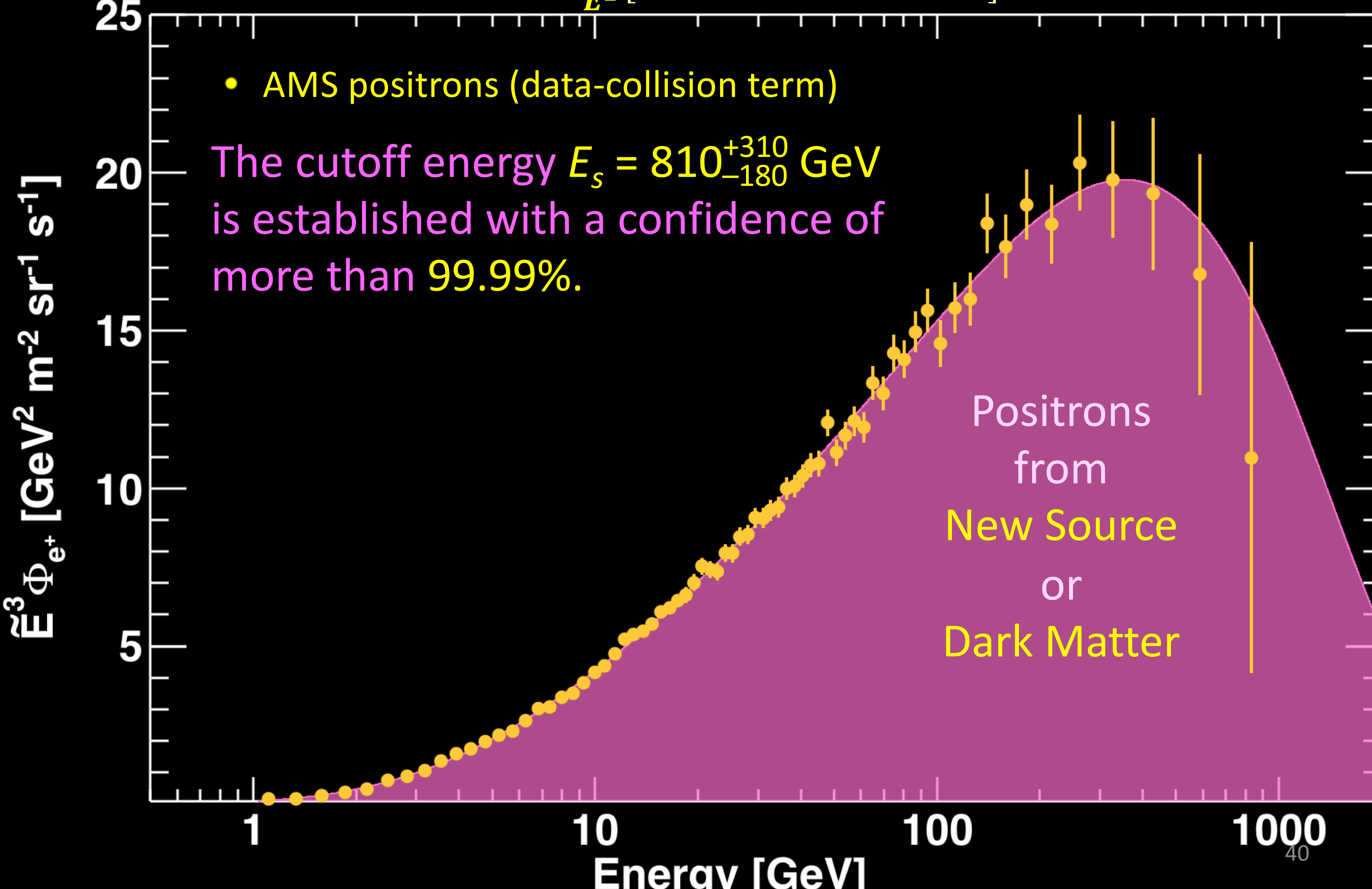


Comparison with other recent measurements



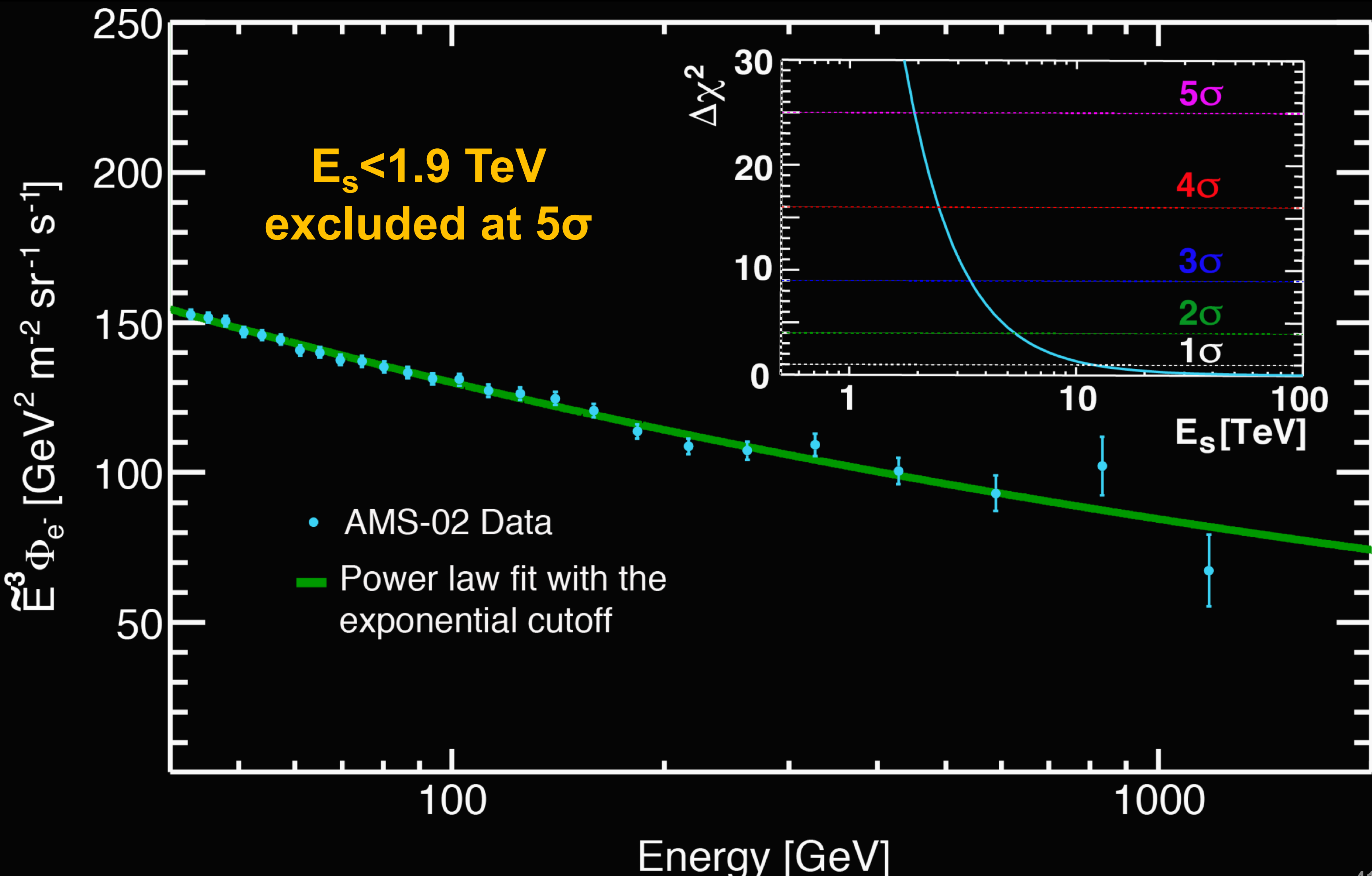
At high energies positrons come from dark matter or new astrophysical sources with a cutoff energy E_s.

$$\Phi_{e^+}(E) = \frac{E^2}{\hat{E}^2}\left[C_s(\hat{E}/E_2)^{\gamma_s}\exp(-\hat{E}/E_s)\right]$$



No source term in the electron spectrum

$$\Phi_{e^-}(E) = C_S\,(E/41.61\ \text{GeV})^{\gamma_S}\,\exp(-E/E_S)$$



Positrons:

(a) a significant excess starting from 25.2 ± 1.8 GeV;

(b) a sharp drop-off above 284^{+91}_{-64} GeV;

(c) positron flux is well described by the sum of a term associated with the positrons produced in the collision of cosmic rays, which dominates at low energies, and a new source term of positrons, which dominates at high energies;

(d) a finite energy cutoff of the source term of $E_s = 810^{+310}_{-180}$ GeV is established with a significance of more than 99.99%.

⇒ at high energies, positrons predominantly originate from a new source – most likely from dark matter annihilation.

Electrons:

(a) a significant excess starting from $42.1^{+5.4}_{-5.2}$ GeV, but the nature of this excess is different from the positron flux excess above 25.2 ± 1.8 GeV.

(b) Contrary to the positron flux, which has an exponential energy cutoff of 810^{+310}_{-180} GeV, at the 5σ level the electron flux does not have an energy cutoff below 1.9 TeV.

(c) In the entire energy range the electron flux is well described by the sum of two power law components.

⇒ clear evidence that most high energy electrons originate from different sources than high energy positrons .

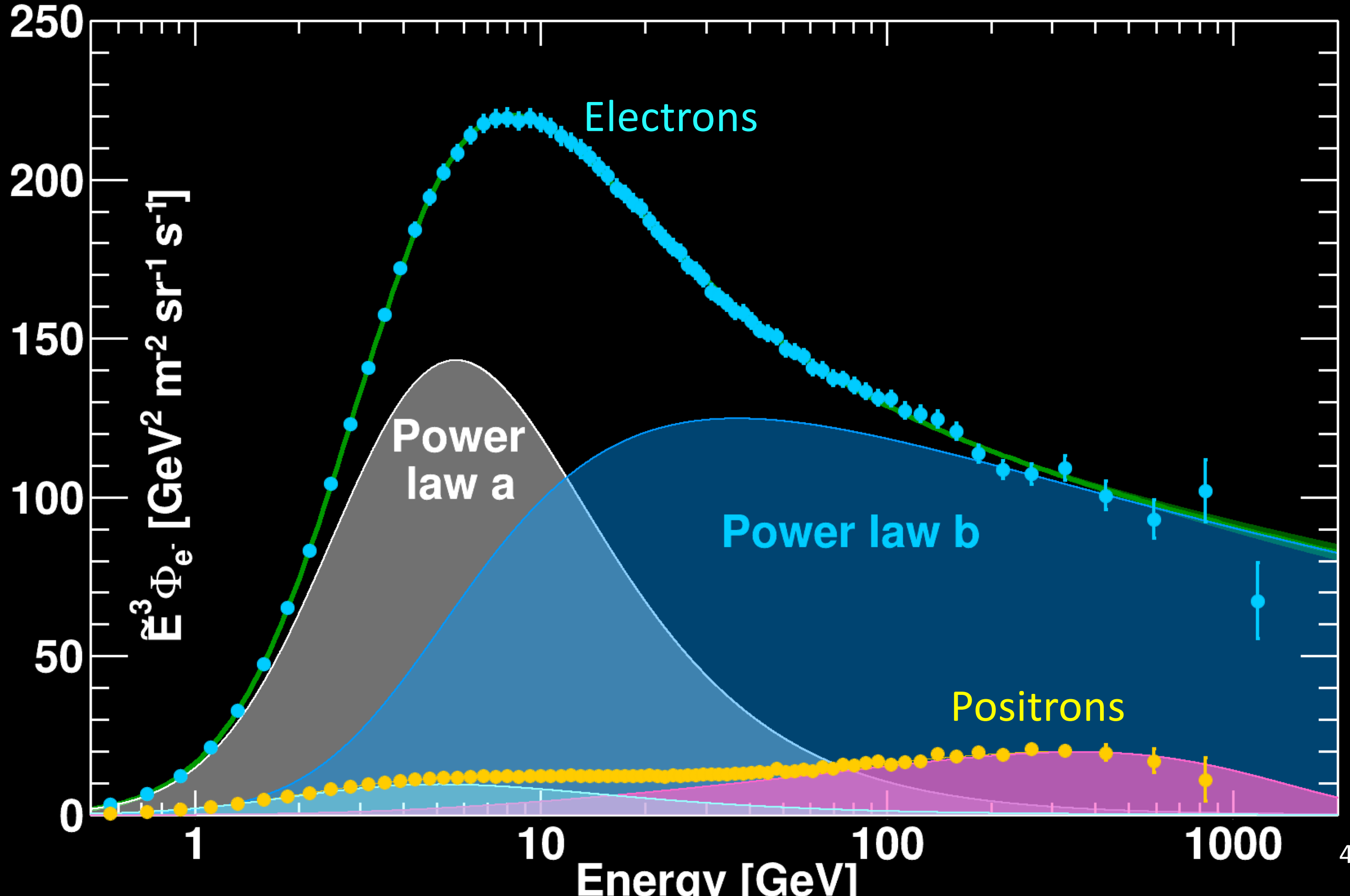
AMS Physics Results:

Electrons originate from different sources than positrons;

the electron spectrum comes from two power law contributions.

The positron flux is the sum of low-energy part from cosmic ray collisions plus

a high-energy part from a new source or dark matter both with a cutoff energy E_S.



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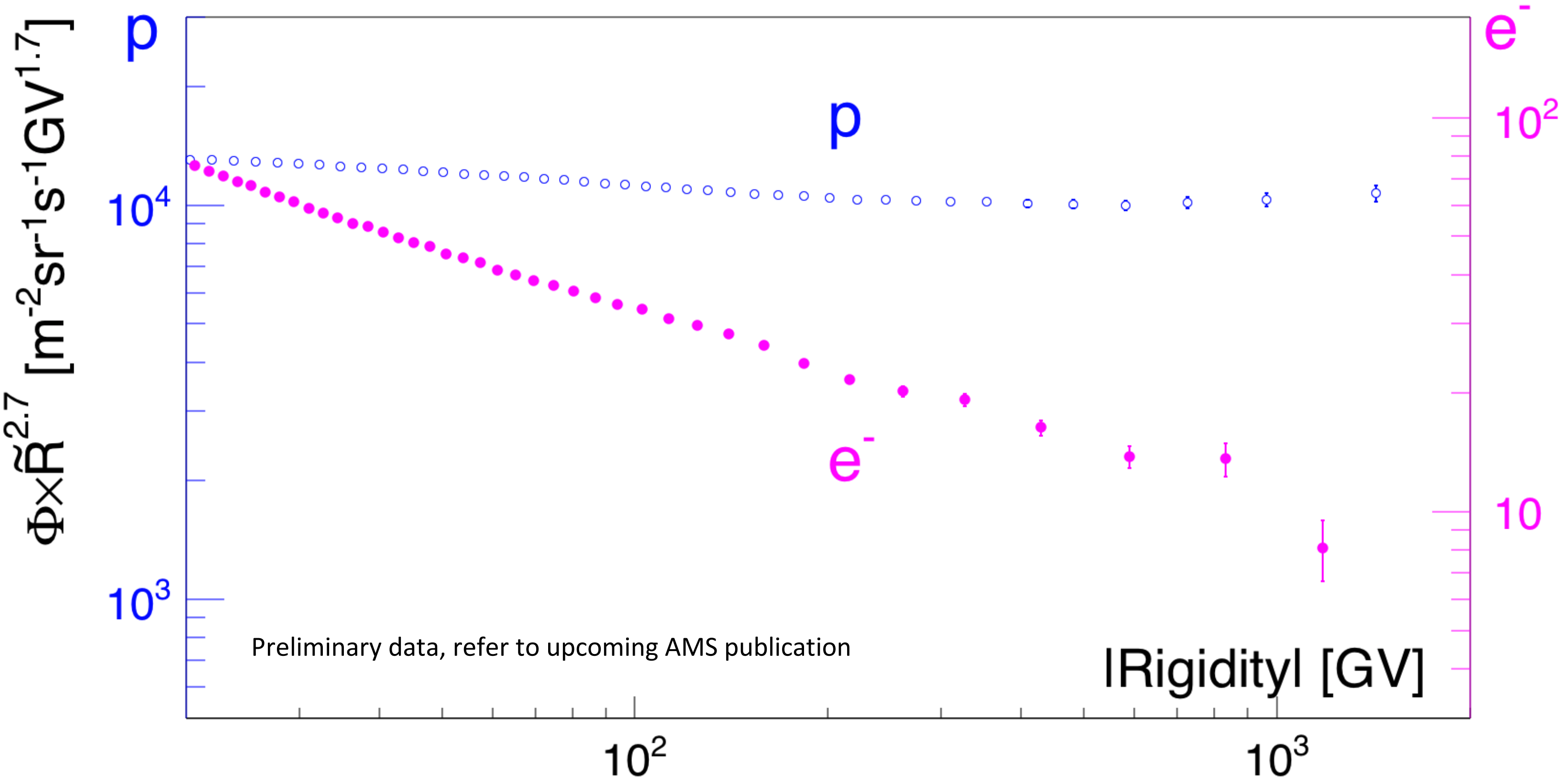
The Spectra of Protons and Electrons

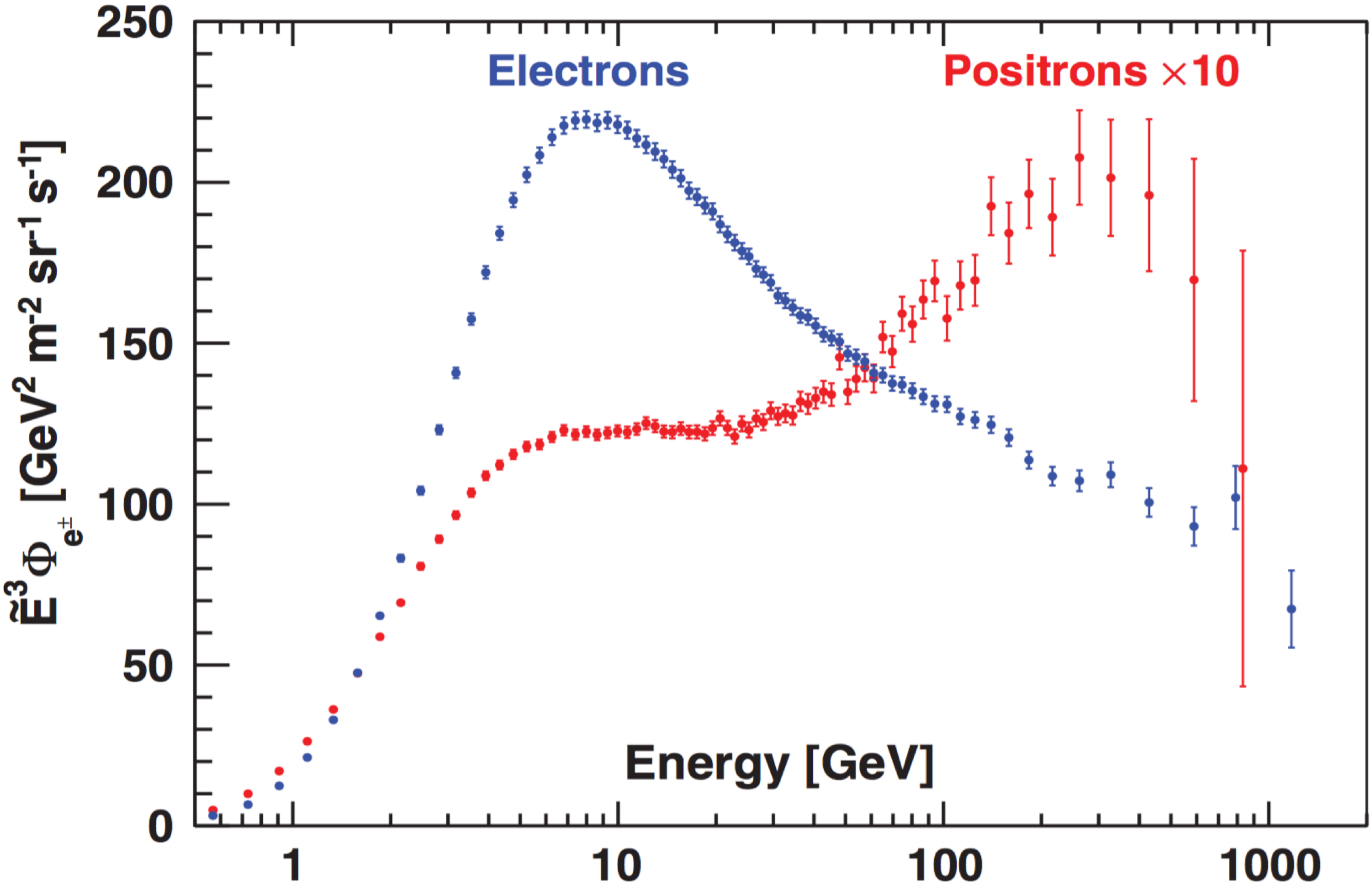
Electron flux decreases with energy much faster than proton



AMS Measurement of Electron and Positron Flux

Latest results – 28M electrons and 1.9 M positrons

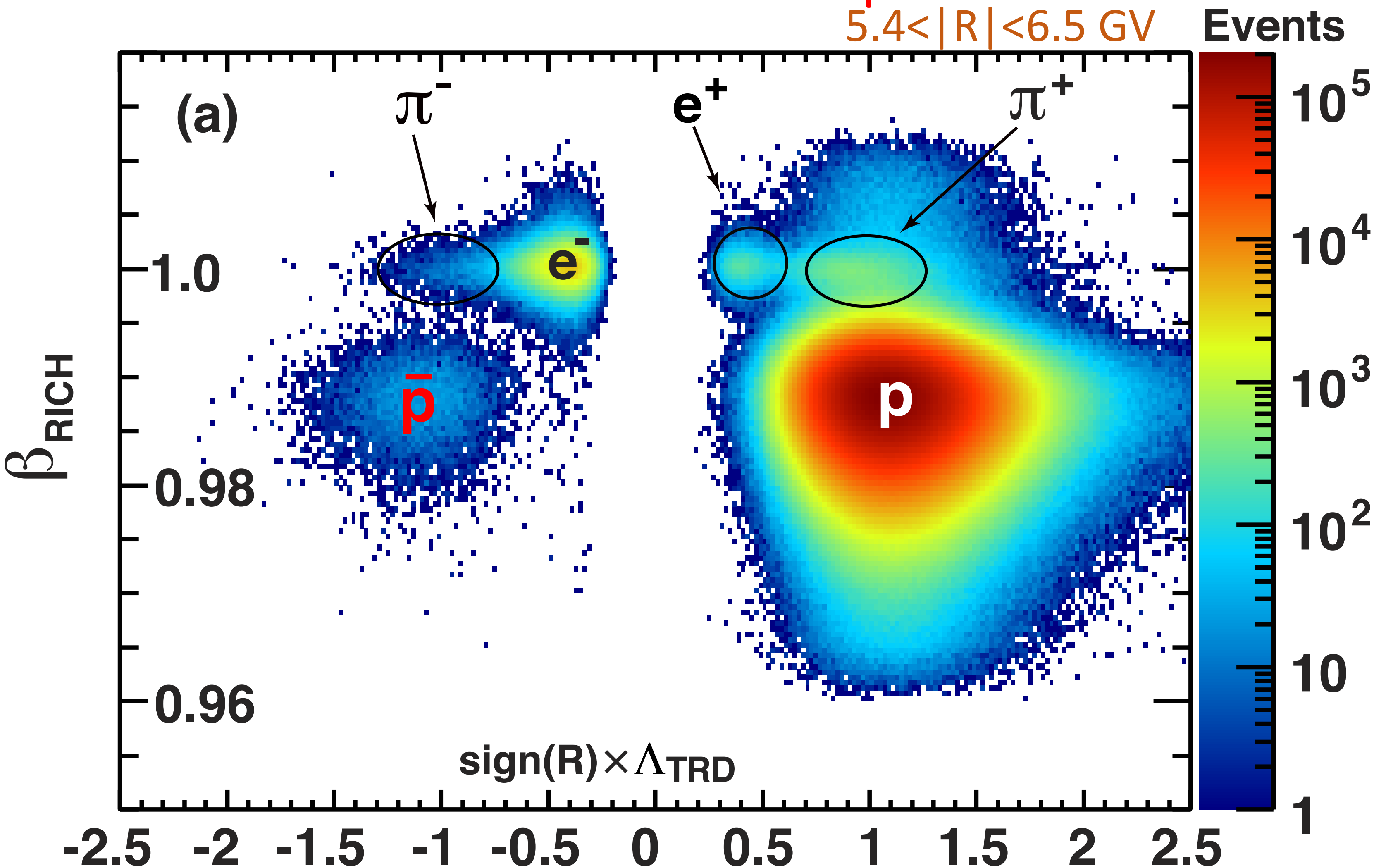
PRL 122, 041102(2019) and PRL 122, 101101 (2019)



Positron spectrum is not consistent with pure secondary origin of positron in cosmic ray: Primary source of cosmic positron with energy cut-off.

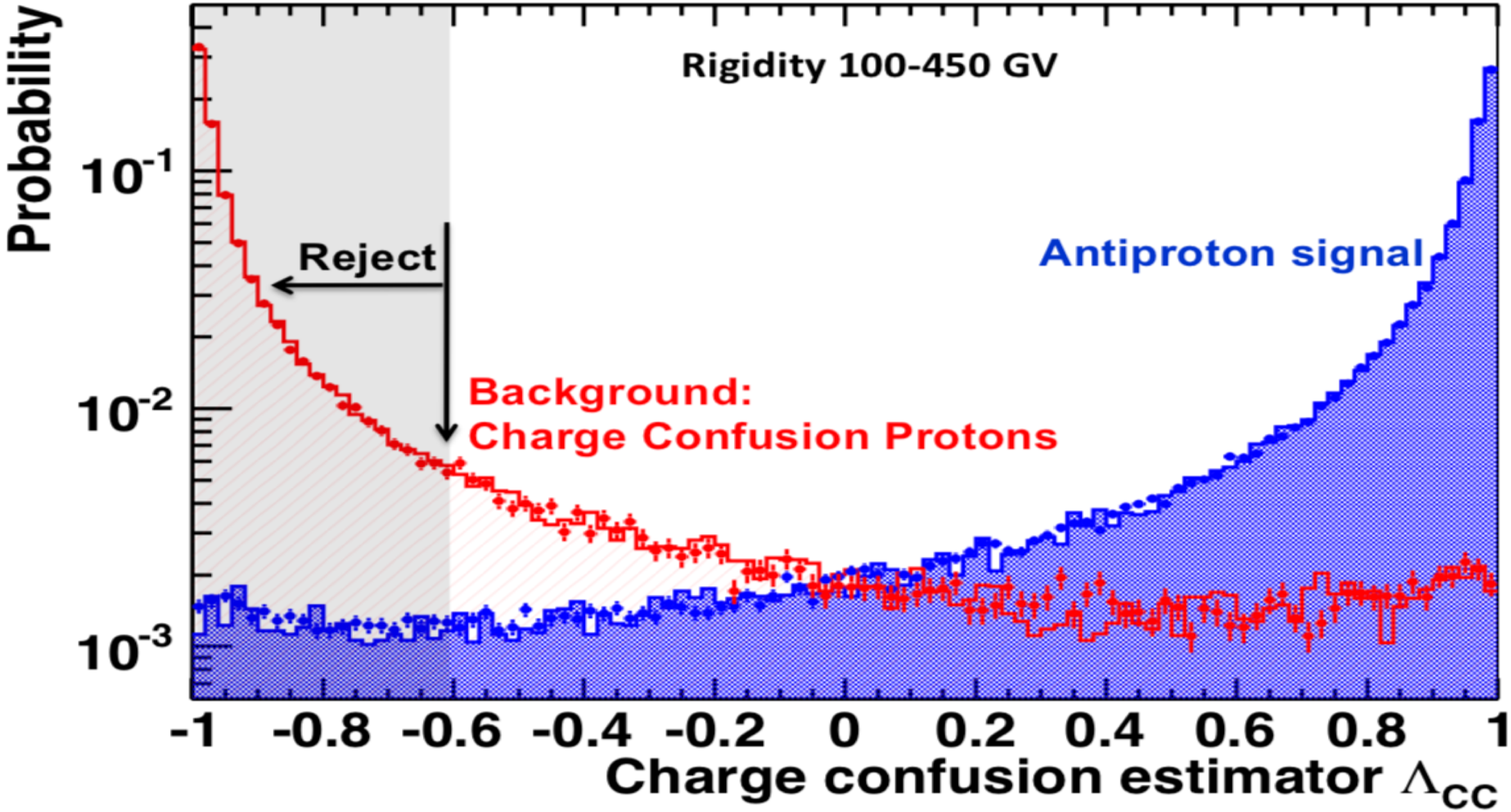
Antiproton identification with AMS

Particle identification with multiple subdetectors



Separation of Positive and Negative Charges

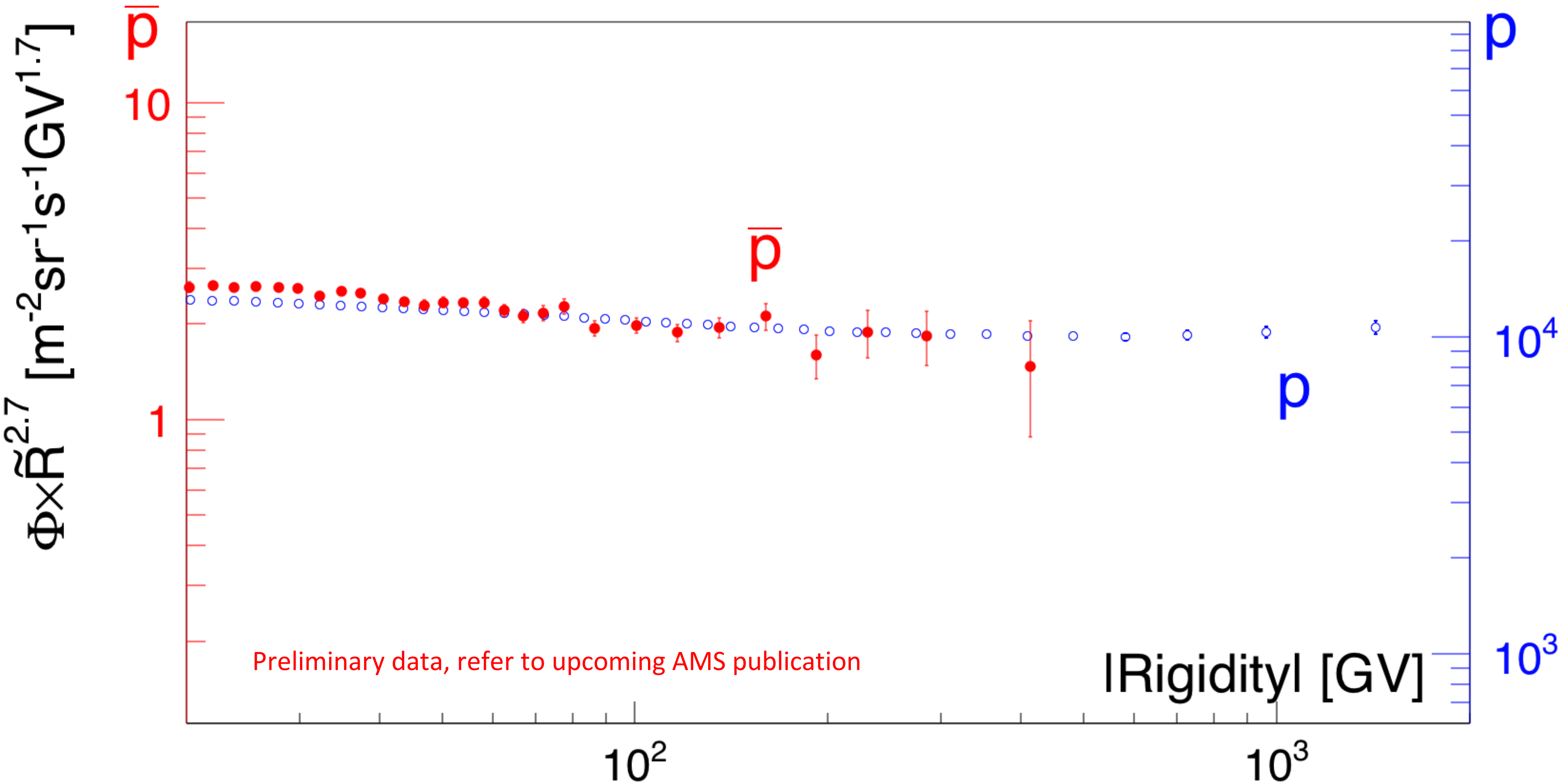
At high rigidities it is particularly important to ensure that the charge sign of antiproton is correctly identified in the tracker.
A charge confusion estimator was build with information from tracker and TOF, to reject misidentified protons



Precision study of the properties of antiproton flux

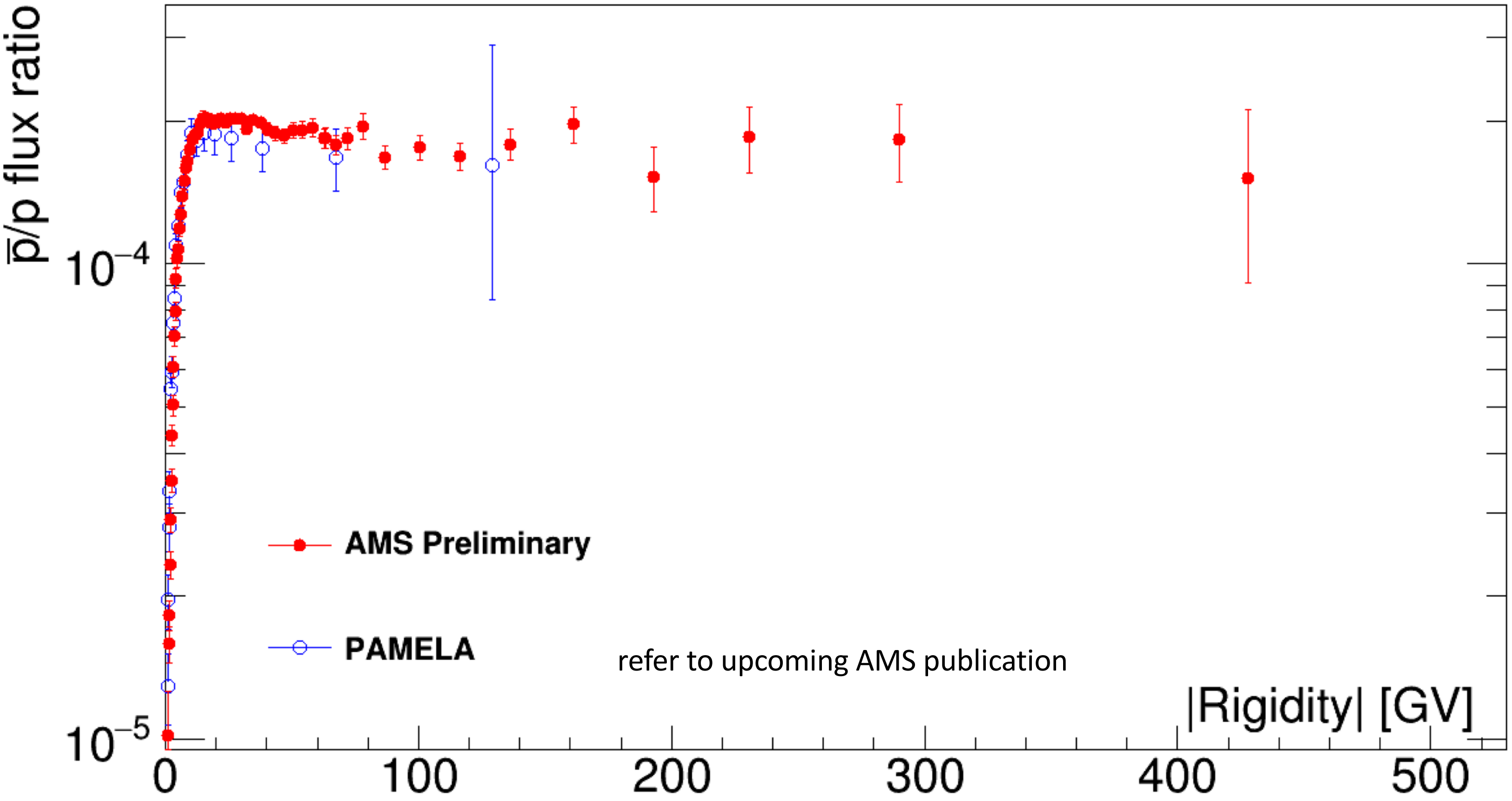
If $\bar{p}$ are secondaries produced in ISM, their rigidity dependence should be different from p:

p + ISM -> $\bar{p}$ + ...



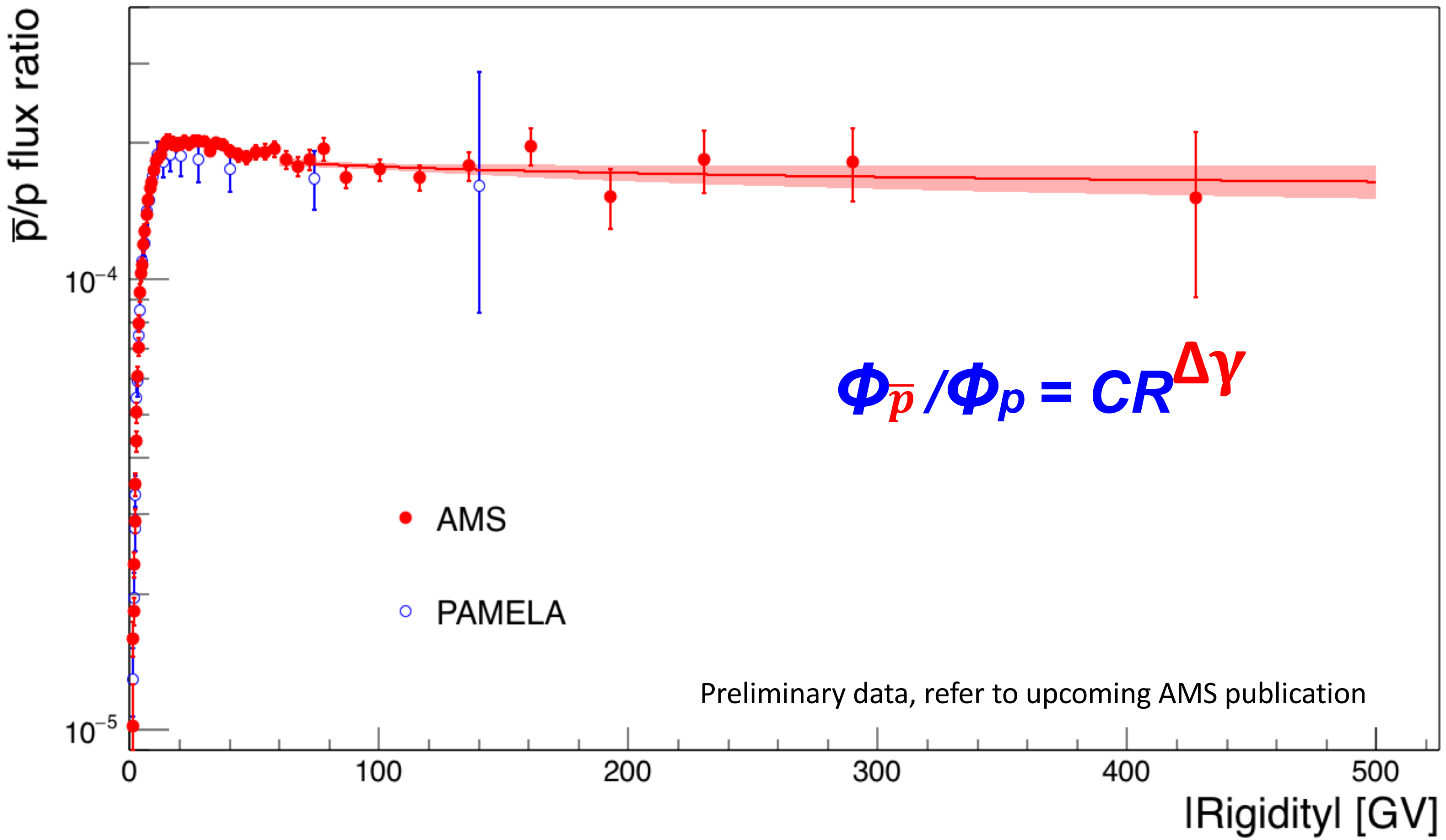
AMS observed for the first time that above 60 GeV, p and $\bar{p}$ have identical rigidity dependence: Not consistent with secondary antiproton produced from proton, helium interaction with ISM.

Antiproton-to-Proton flux ratio



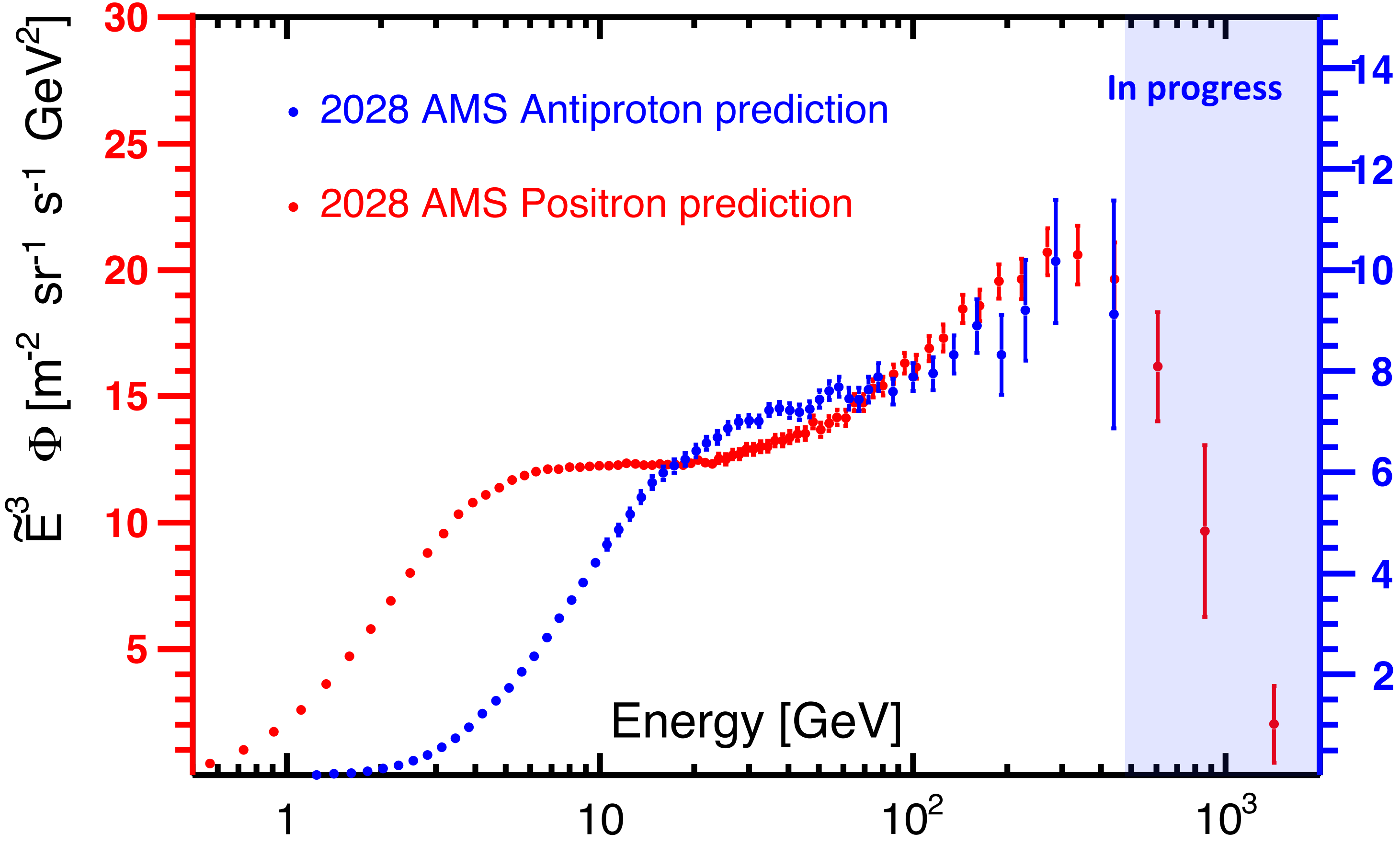
- More than 3500 antiprotons above 100 GV in 6.5 years, while all the other experiments have only 3.
- Extensive systematic study been done, similar to method in PRL 117.091103

Antiproton-to-Proton flux ratio



- Starting from 60GeV, the flux ratio is surprisingly flat up to 525 GV.
- Fit to a power law in the range [60,525] GV: $\Delta\gamma$=-0.05±0.06, consistent with 0.
- Distinctly different from the flux ratio of secondary/primary nuclei and traditional CR models, which predict a decreasing $\bar{p}/p$ with a power law index -0.2 to -0.3

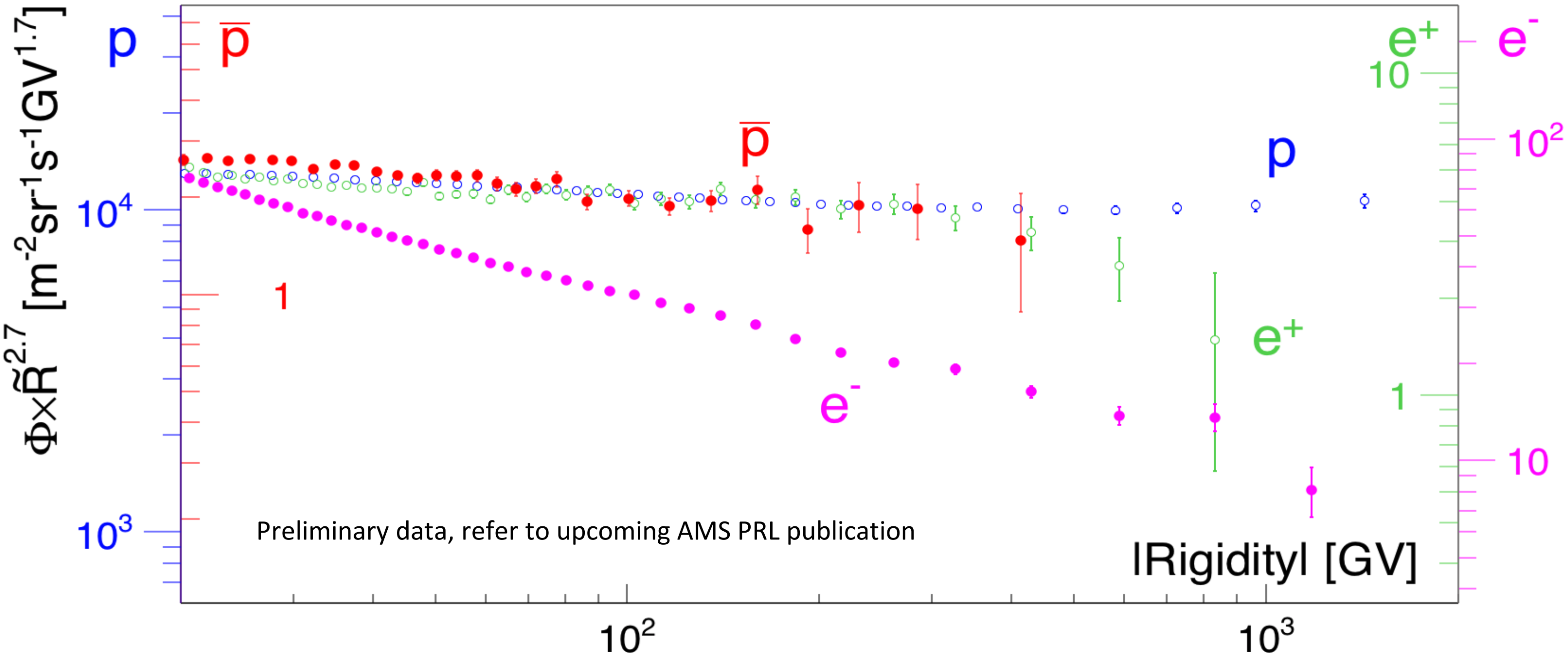
Antiproton and Positrons to 2028



By continue taking data, AMS will improve the accuracy of these measurements and extend to higher energies.

Conclusion

Properties of elementary particle fluxes



1. The spectra of positrons, antiprotons, and protons are identical in a large energy range [60, 500] GV
2. Positron spectrum shows a cut-off at ~280 GeV.
3. New source of high energy positron and antiprotons in cosmic rays.