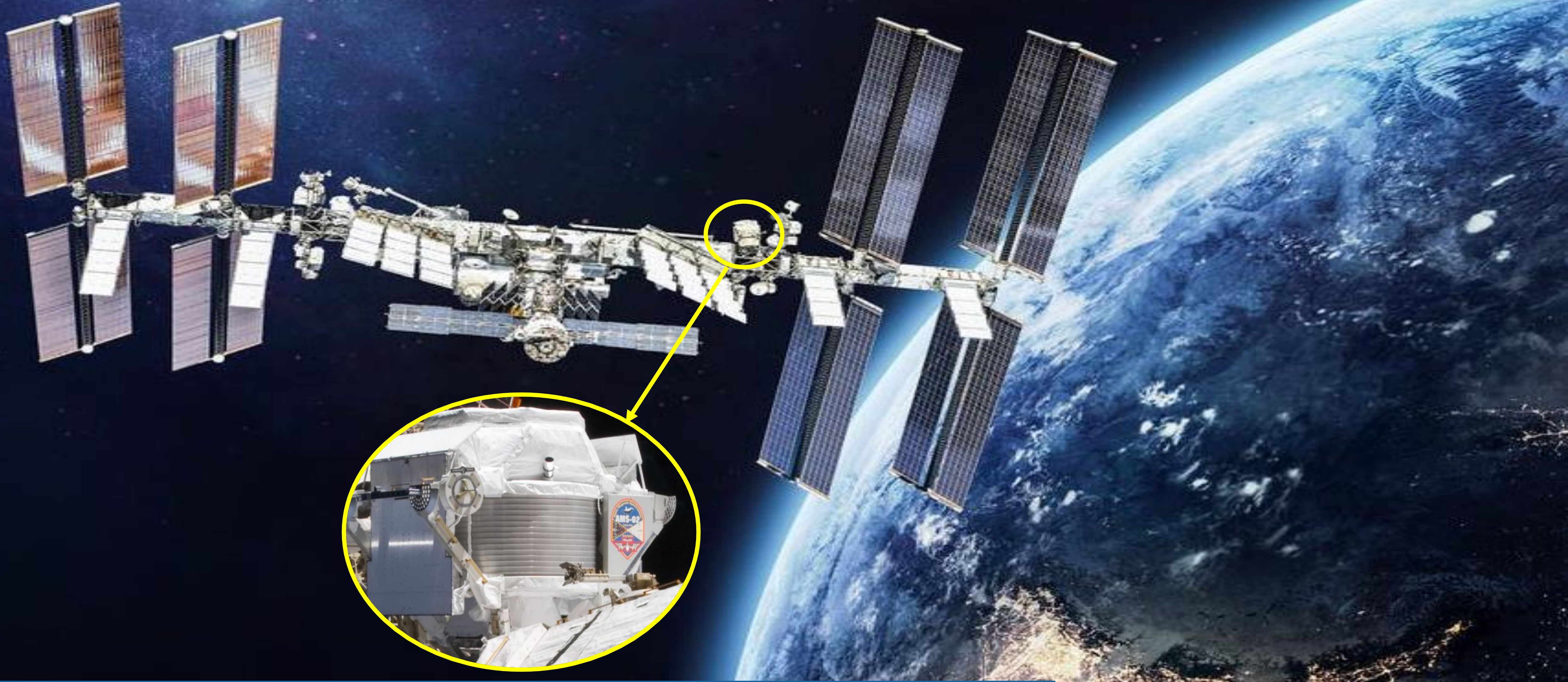
Properties of Cosmic Positron, Electron and Anti-Proton Measured by the Alpha Magnetic Spectrometer



中国物理学会高能物理分会第十四届全国粒子物理学术会议（2024）

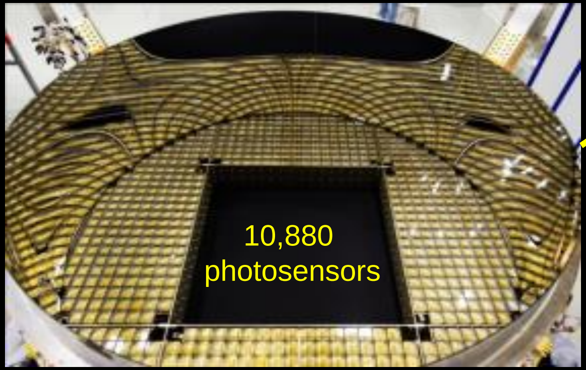
Cheng ZHANG / IHEP,CAS

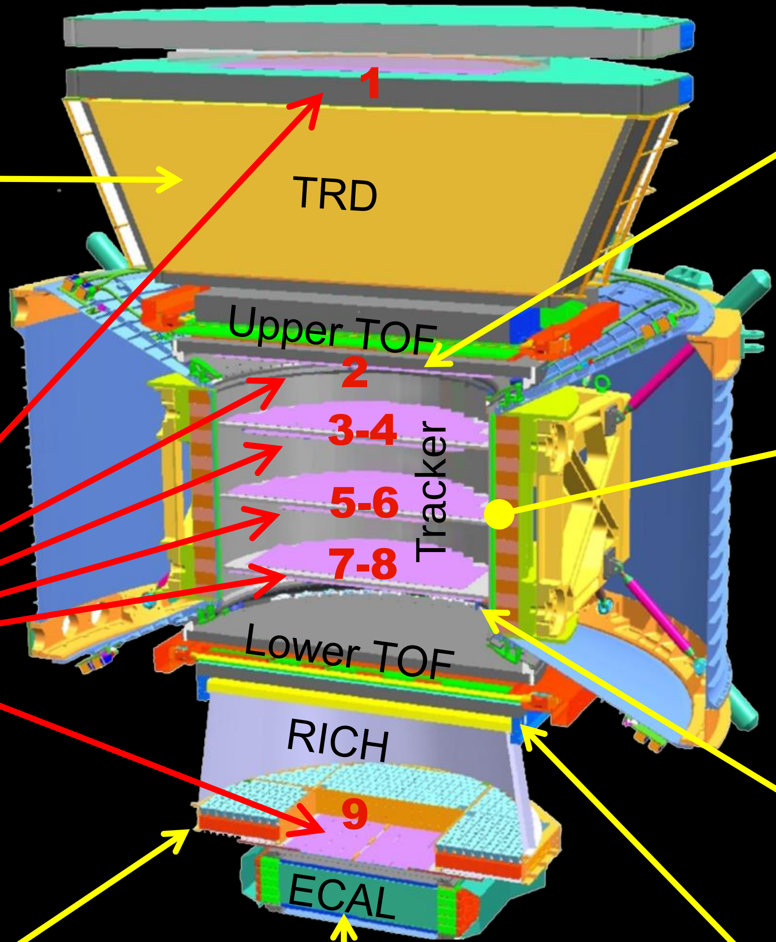
AMS is a space version of a precision magnetic spectrometer

Transition Radiation Detector (TRD)
identify e^+, e^-

Silicon Tracker
measure Z, P

Ring Imaging Cerenkov (RICH)
measure Z, E





Electromagnetic Calorimeter (ECAL)
measure E of e^+, e^-

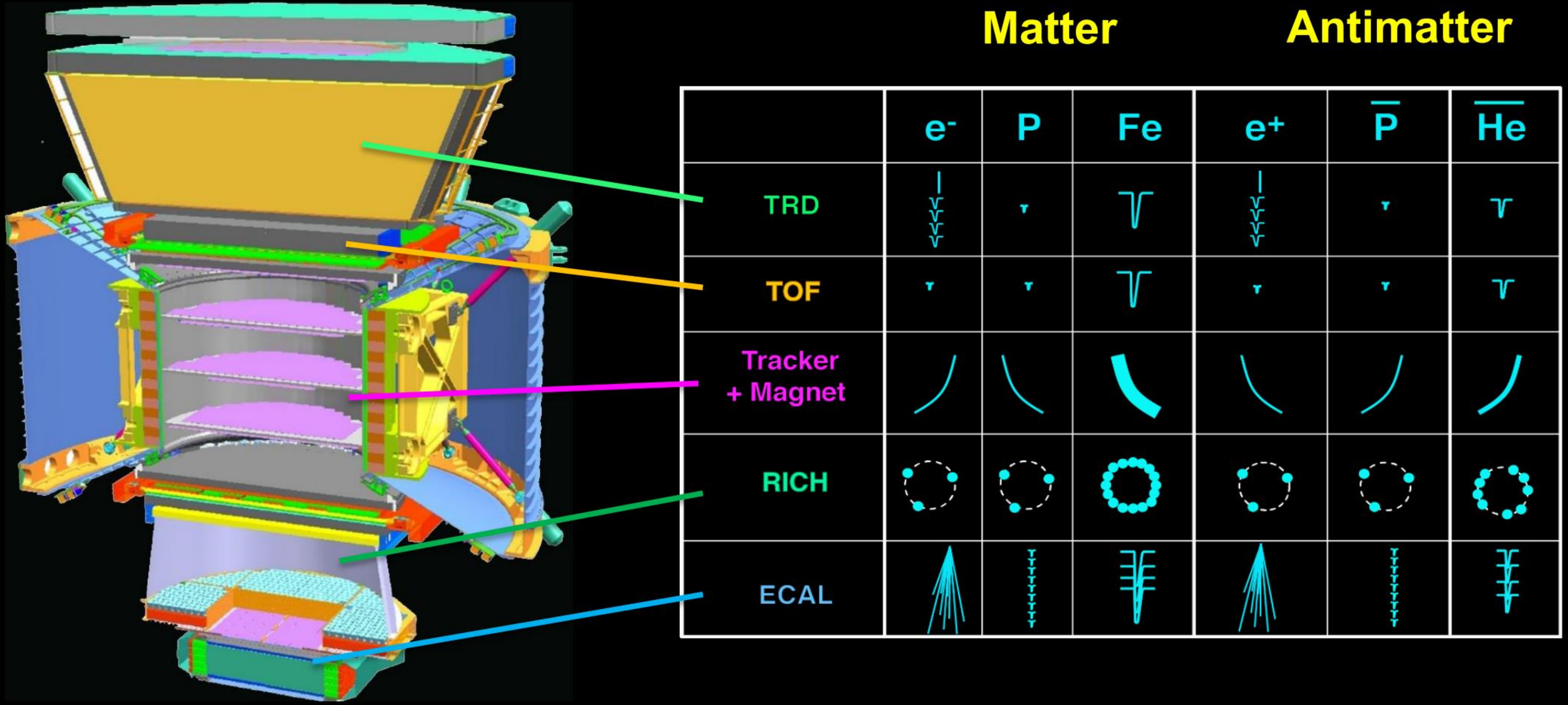
Upper TOF measure Z, E

Magnet identify ±Z, P

Anticoincidence Counters (ACC)
reject particles from the side

Lower TOF measure Z, E

AMS is a unique magnetic spectrometer in space

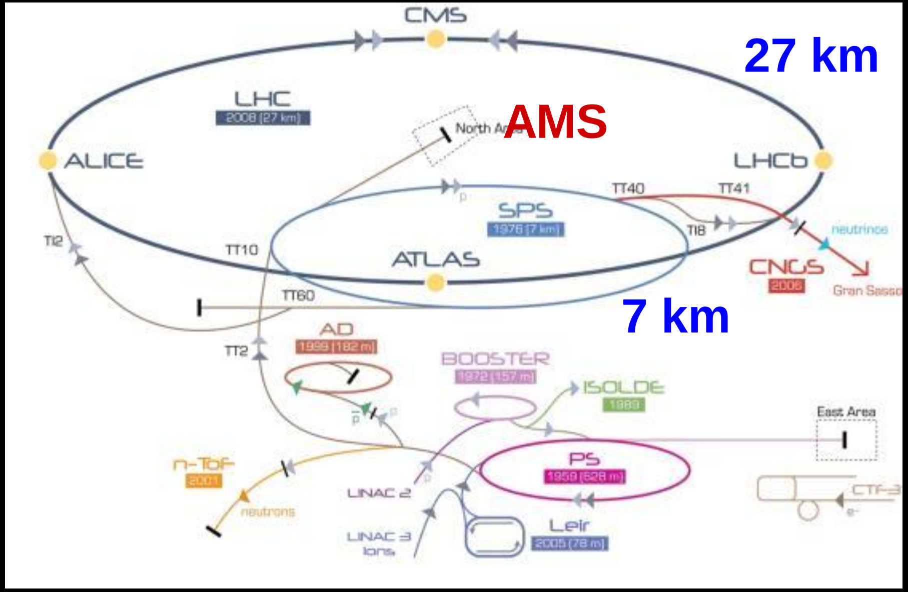


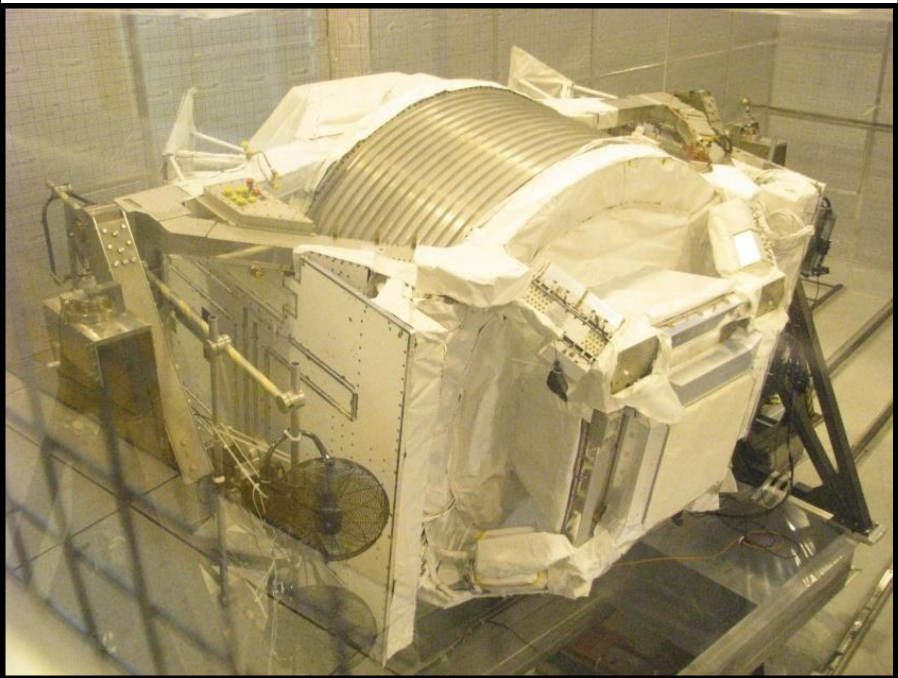
AMS is able to pick out 1 positron from 1,000,000 protons; unambiguously separate positrons from electrons up to a trillion eV; and accurately measure all cosmic rays to trillions of eV.

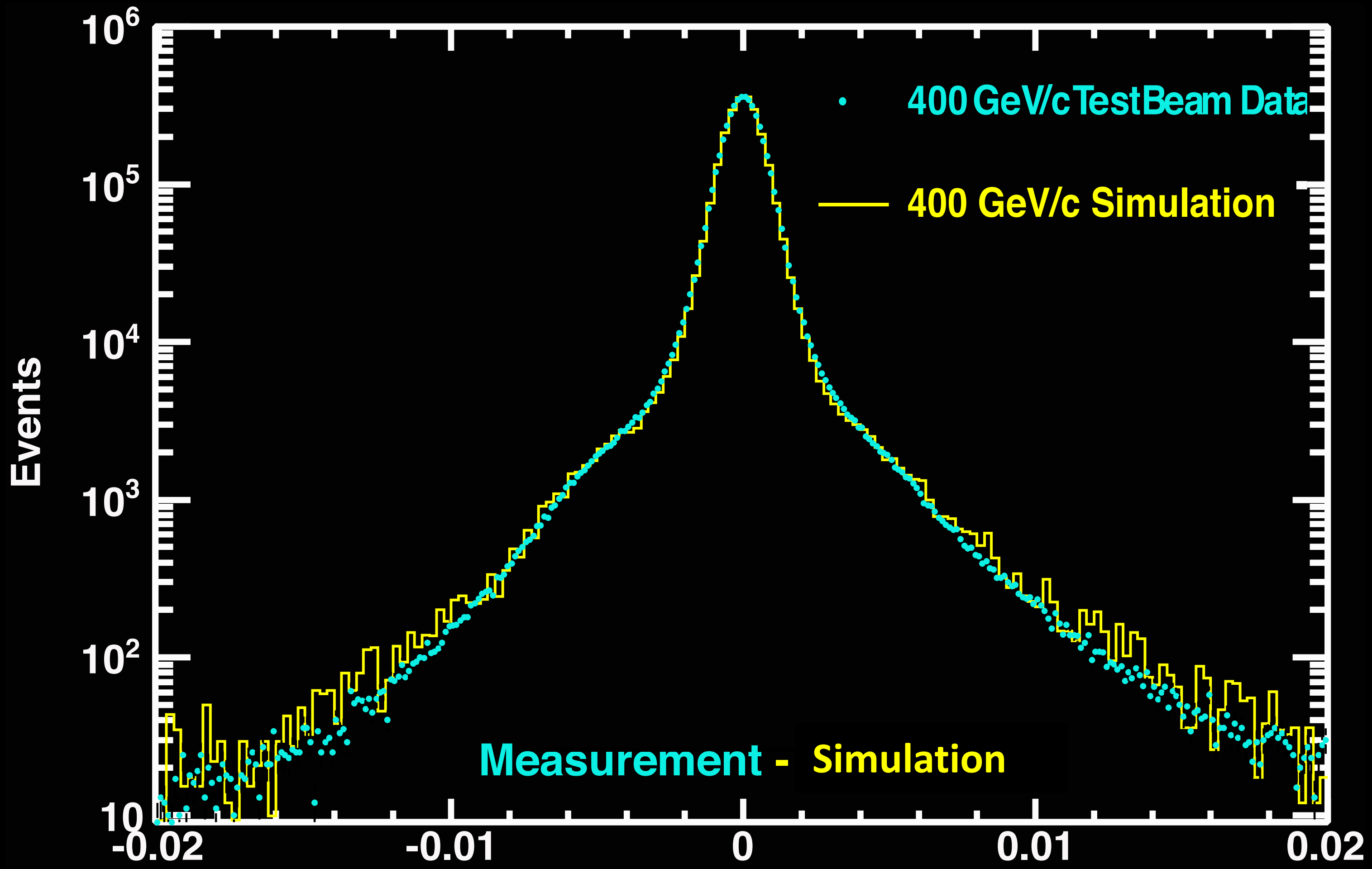
In 13 years, the detectors have performed flawlessly, collected more than 230 billion cosmic rays.

Calibration at CERN

with different particles at different energies







AMS on ISS

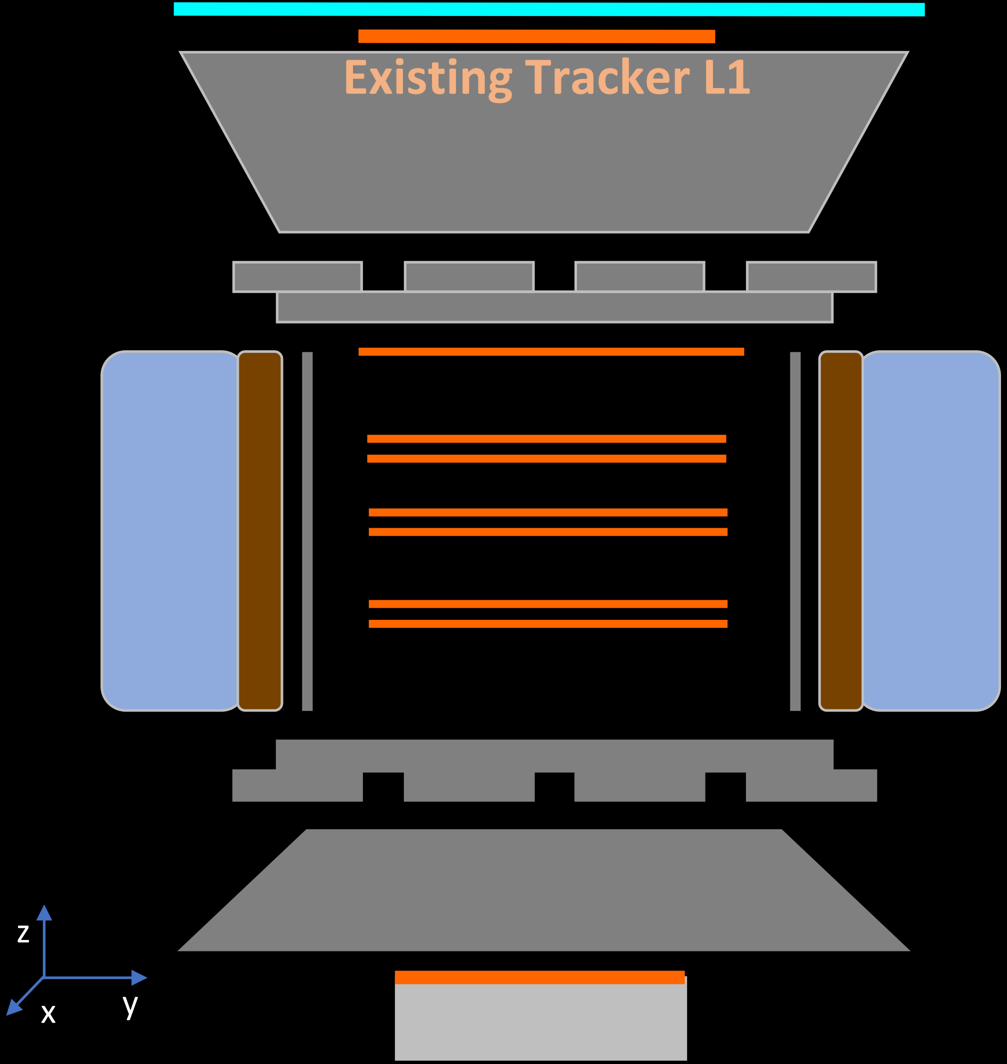
AMS 2011-2025

Continuous data-taking

Latest Results: 2011-2024

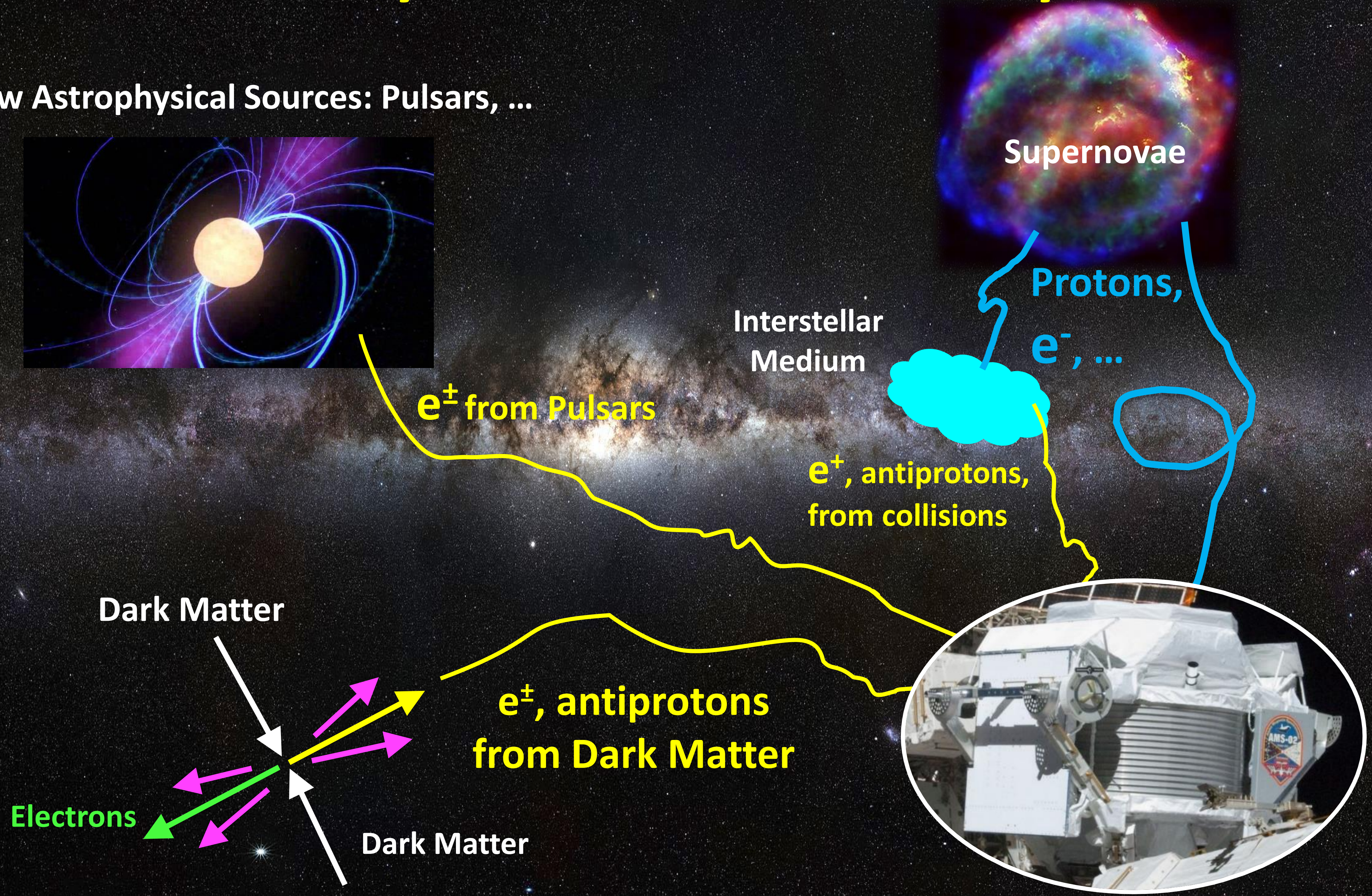
AMS 2025-2030

New 8m^2 Silicon Tracker Layer
Acceptance increased to 300%



and Projections to 2030

Elementary Particles in Cosmic Rays



New Astrophysical Sources: Pulsars, …

Supernovae

Protons, e^-, …

Interstellar Medium

$e^{\pm}$ from Pulsars

e^+, antiprotons, from collisions

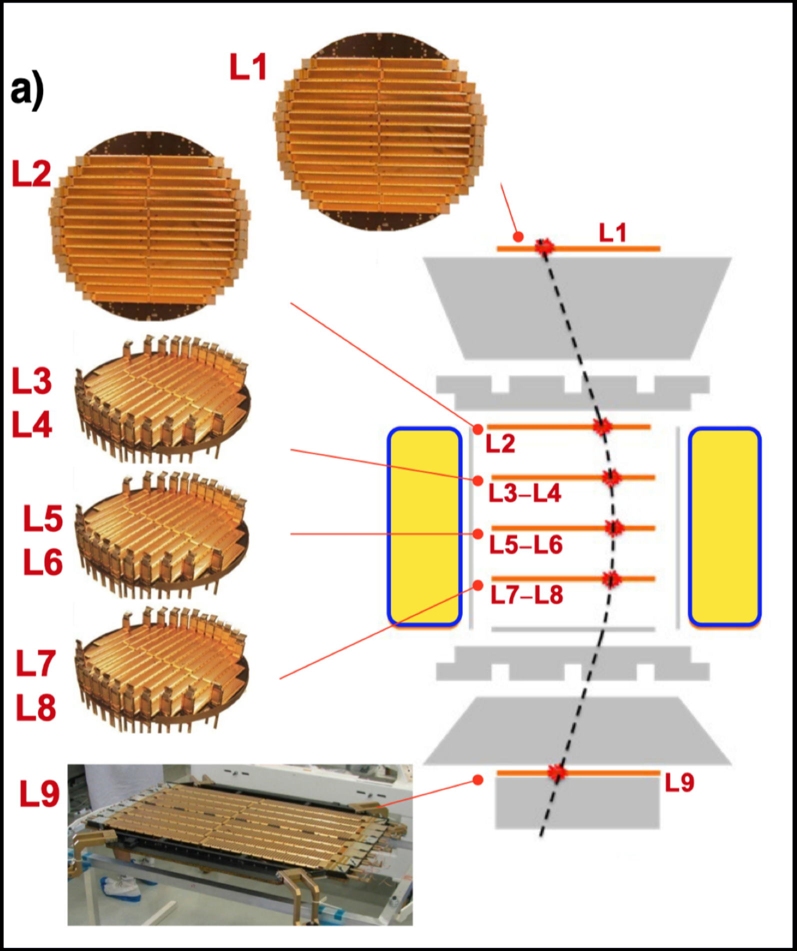
Dark Matter

$e^{\pm}$, antiprotons from Dark Matter

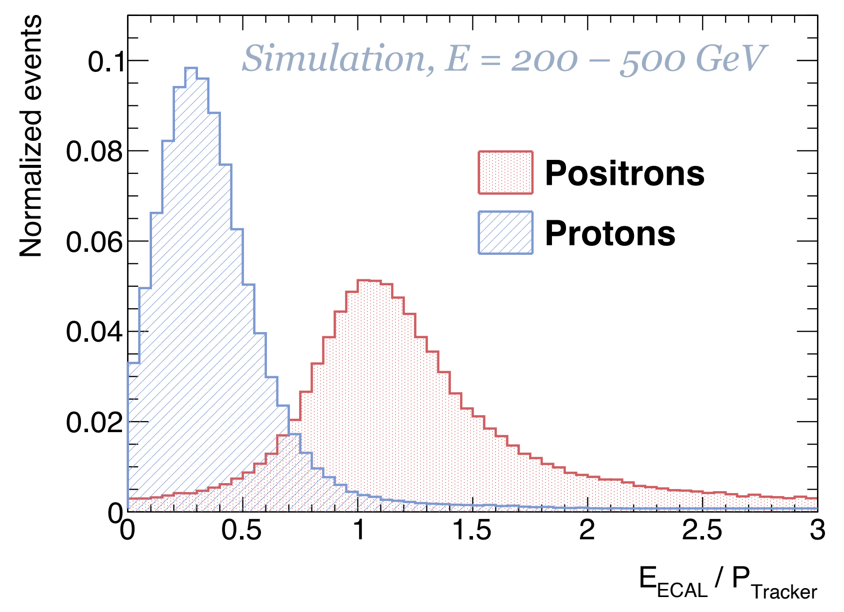
Electrons

Dark Matter

Energy and momentum measurements



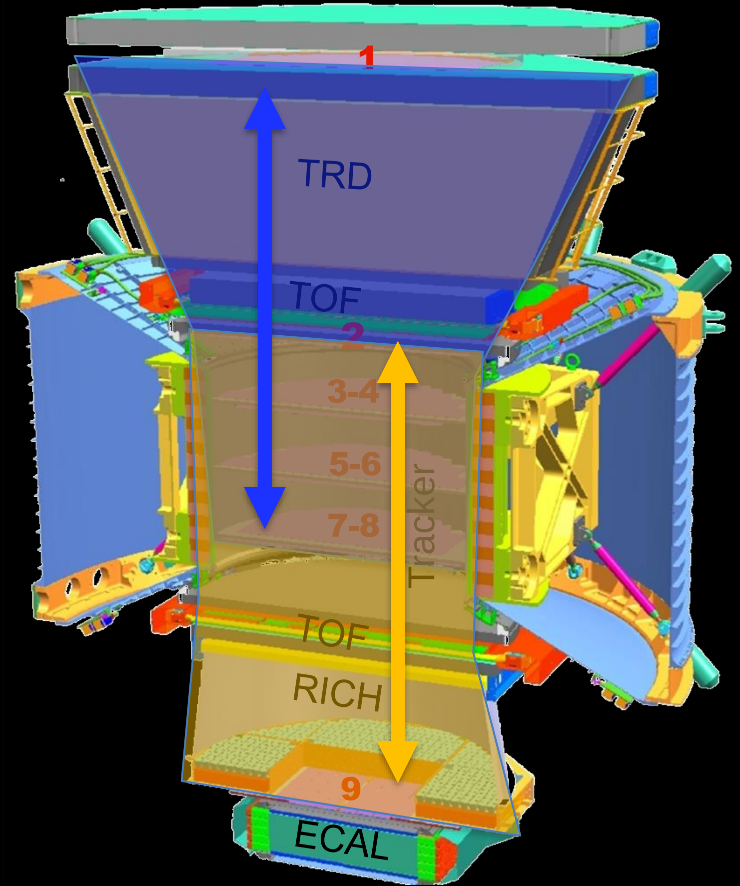
- Nine layers in AMS tracker forms 3 m lever arm
- For particle with Z=1:
  - Single point resolution is **10 µm**
  - The maximum detectable rigidity is **2 TeV**

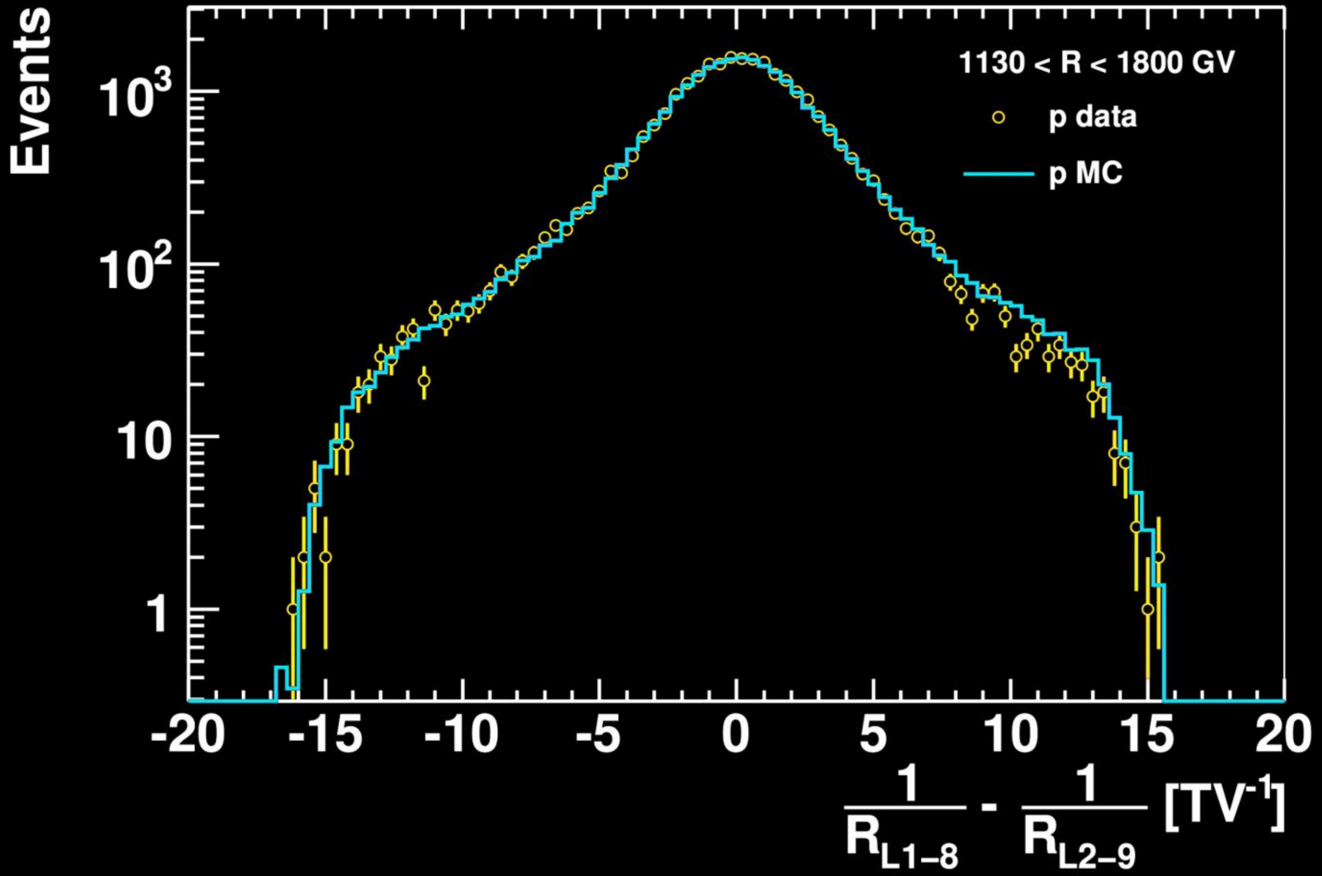


Independent momentum (by tracker) and energy (by calorimeter) measurements allows to distinguish $e^{\pm}$ from protons

Charge Identification

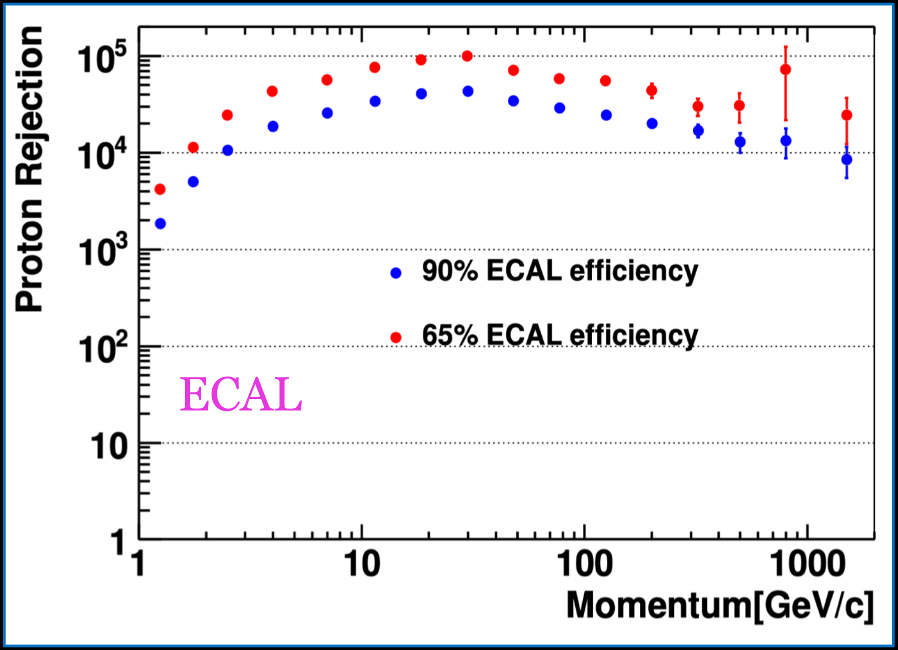
- **Charge identification is based on Tracker and Magnet.**
- **Unique Feature of AMS: Use cosmic ray to verify detector performance beyond test beam energies.**

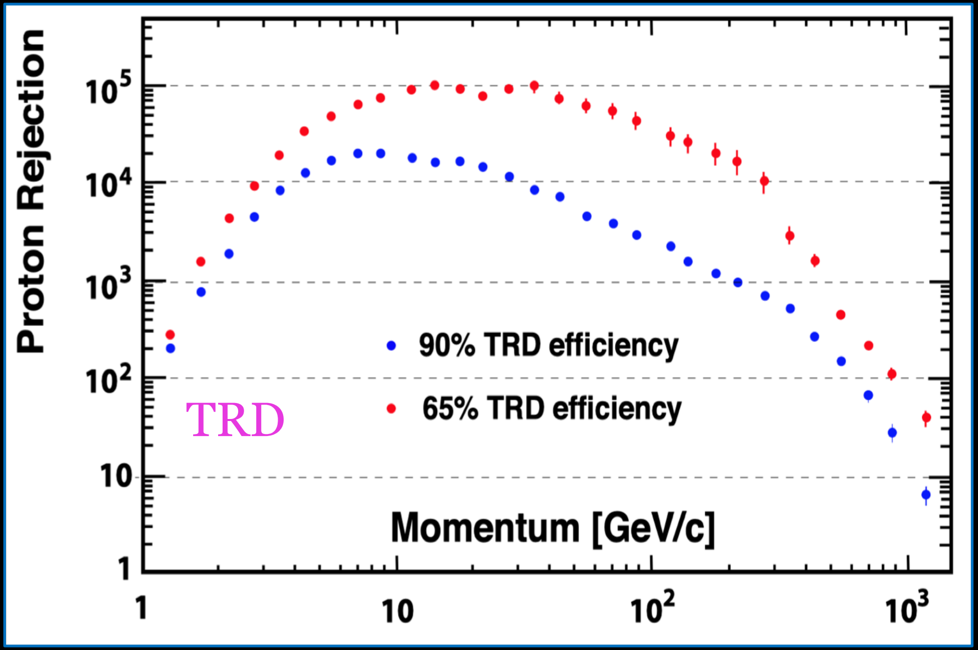




Proton rejection

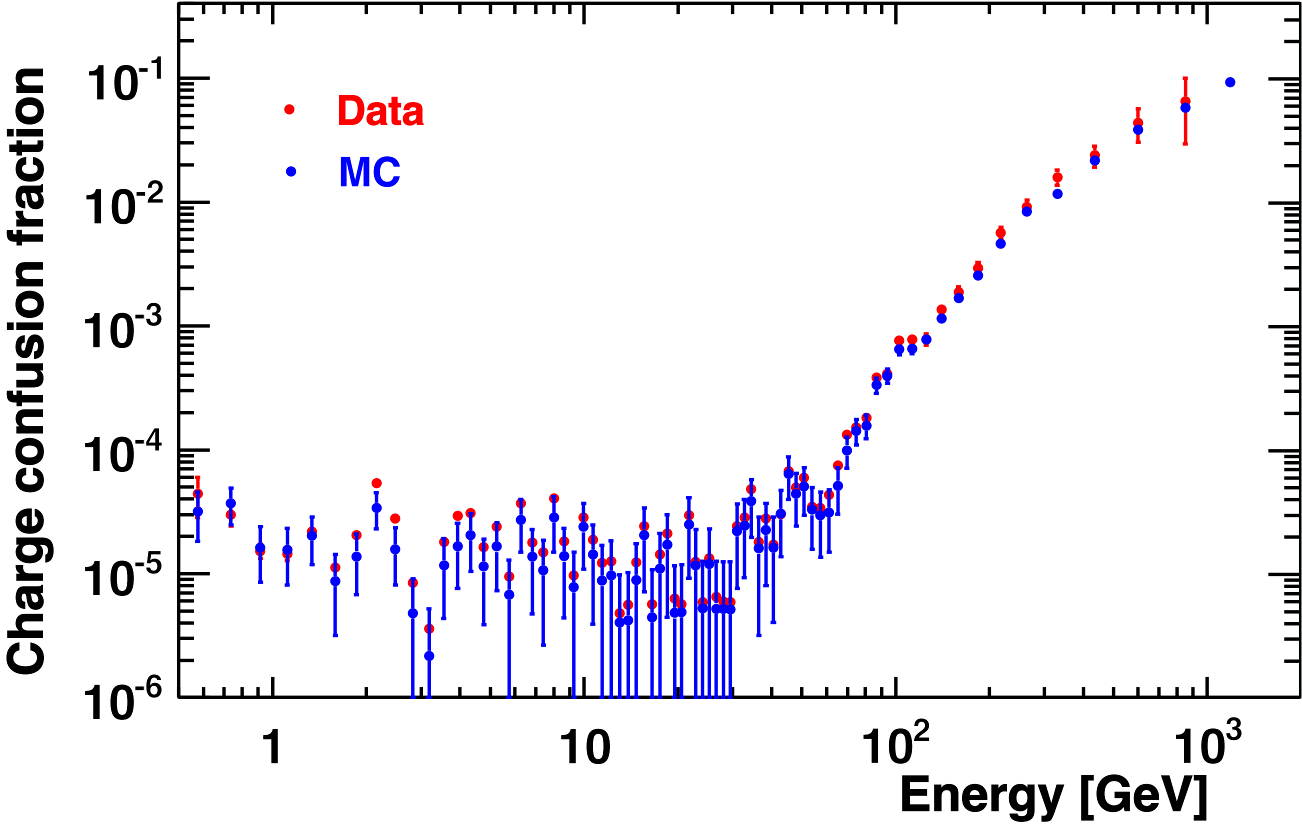
- ECAL and TRD provides independent proton rejection
- Combined proton rejection power at 90% signal efficiency is ~ **1 in 10^6**





Charge sign confusion

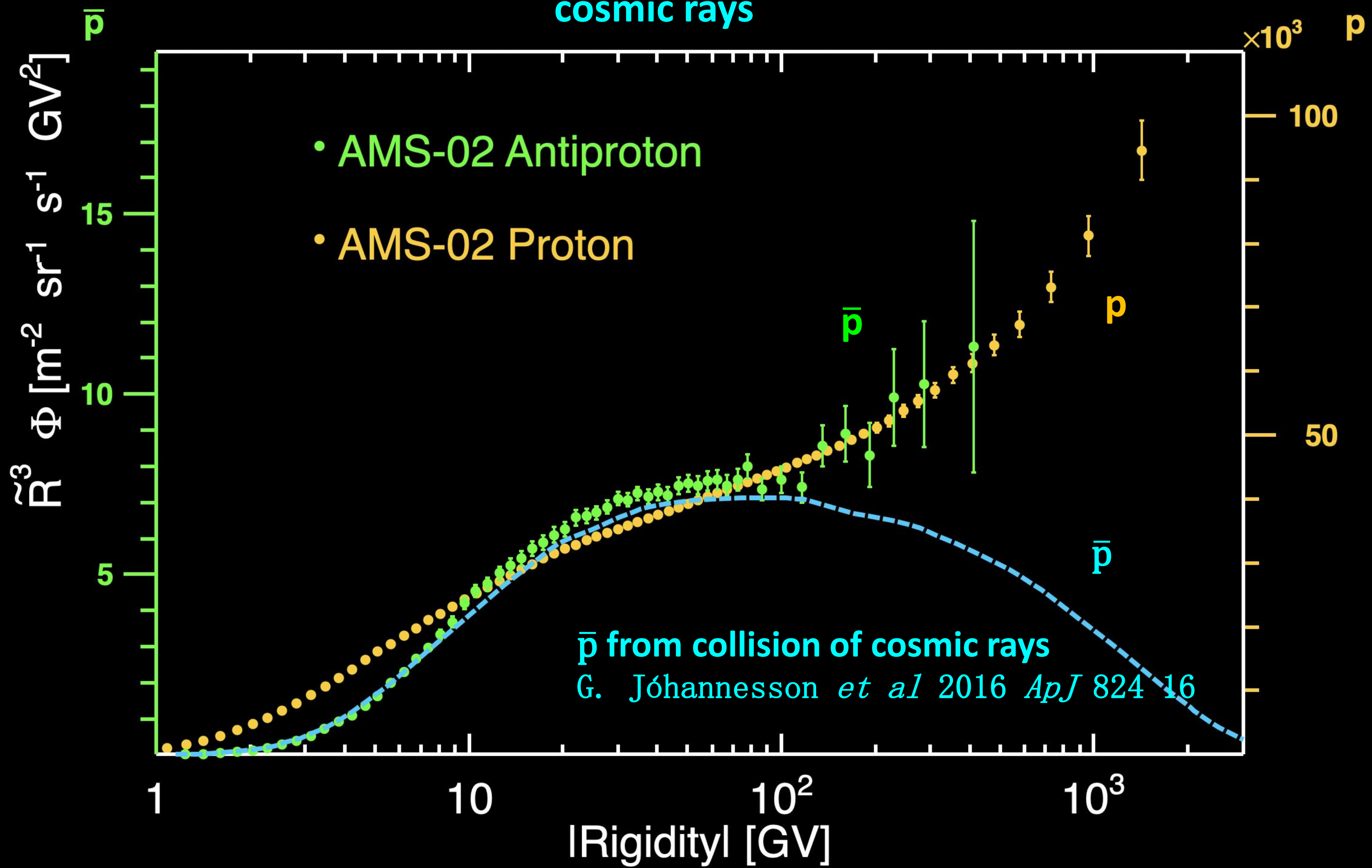
Charge sign confusion events are identified using BDT based **Charge confusion estimator**. This estimator uses information from various detectors (tracker, TOF, ECAL) and is efficient up to with the highest measured energy.



Precision study of the properties of antiproton flux

AMS measurements show that p and $\bar{p}$ have identical rigidity dependence

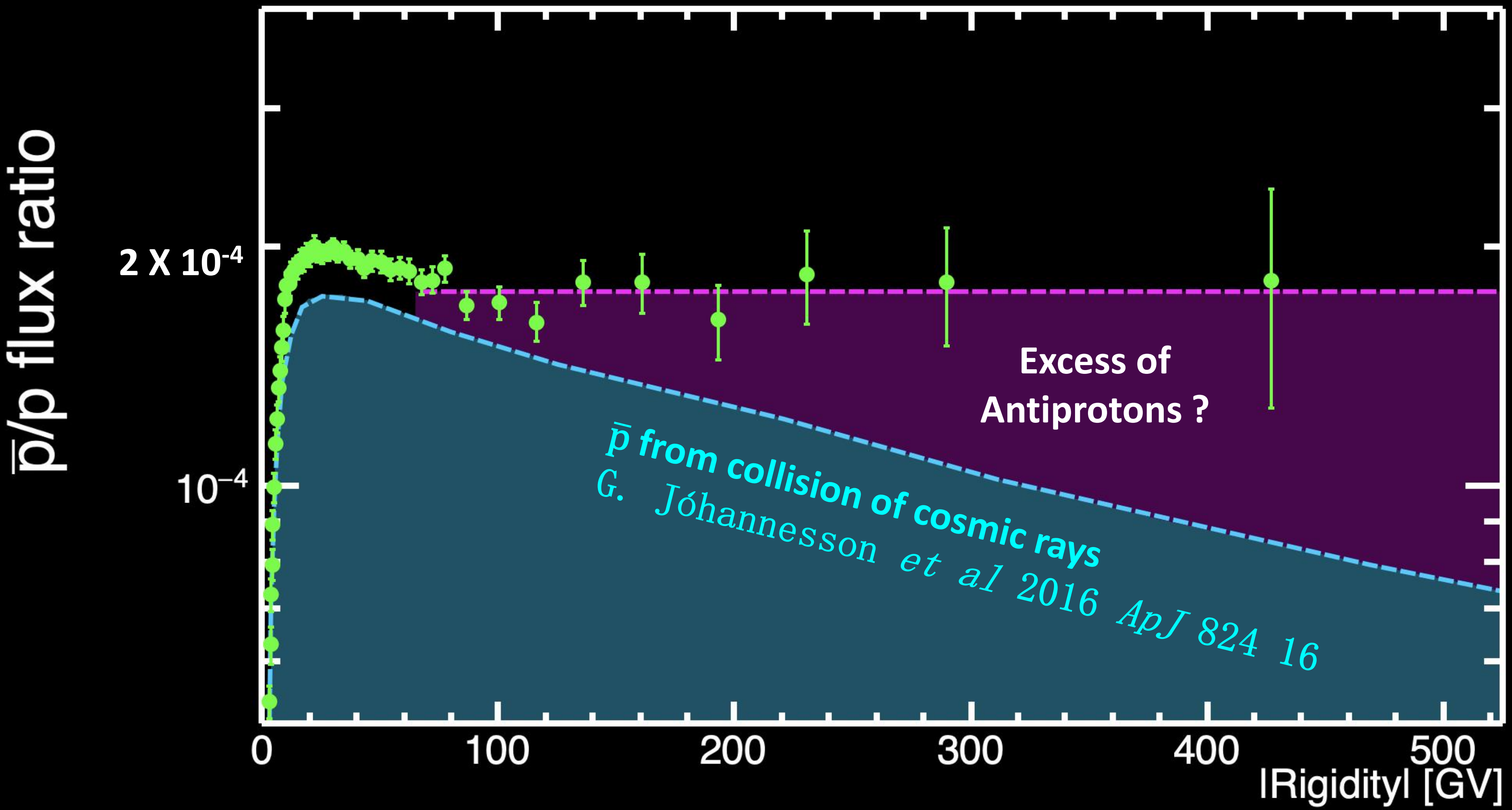
Contradict with traditional cosmic ray model with only secondary $\bar{p}$ produced from collision of cosmic rays



Antiproton-to-Proton flux ratio

The antiproton-to-proton flux ratio shows unexpected energy dependence

Distinctly different from antiprotons from collision of cosmic rays



A sample of recent papers on AMS antiproton data

P. Mertsch *et al.*, **Phys. Rev. D 104 (2021) 103029**

M. Boudaud et al., **Phys. Rev. Research 2, 023022 (2020)**

V. Bresci *et al.,* **Mon. Not. R. Astron. Soc., 488 (2019), p. 2068**

M. Korsmeier *et al.,* **Phys. Rev. D 97 (2018), 103019**

P. Lipari, **Phys. Rev. D, 95 (2017), 063009**

I. Cholis *et al.,* **Phys. Rev. D 95(2017), 123007**

M. Winkler, **JCAP, 2017(02), 048**

……

Antiproton production and propagation

J. Heisig, **Modern Physics Letters A, (2021), 36, 05**

Y. Genolini *et al.,* **arXiv:2103.04108 (2021)**

I. Cholis *et al.,* **Phys. Rev. D, 99 (2019), 103026**

A. Cuoco *et al.,* **Phys. Rev. D, 99 (2019), 103014**

M. Carena *et al.,* **Phys. Rev. D, 100 (2019), 055002**

A. Reinert *et al.,* **JCAP, 01 (2018), p. 055**

A. Cuoco *et al.,* **Phys. Rev. Lett., 118 (2017), 191102**

M. Cui *et al.,* **Phys. Rev. Lett., 118 (2017), 191101**

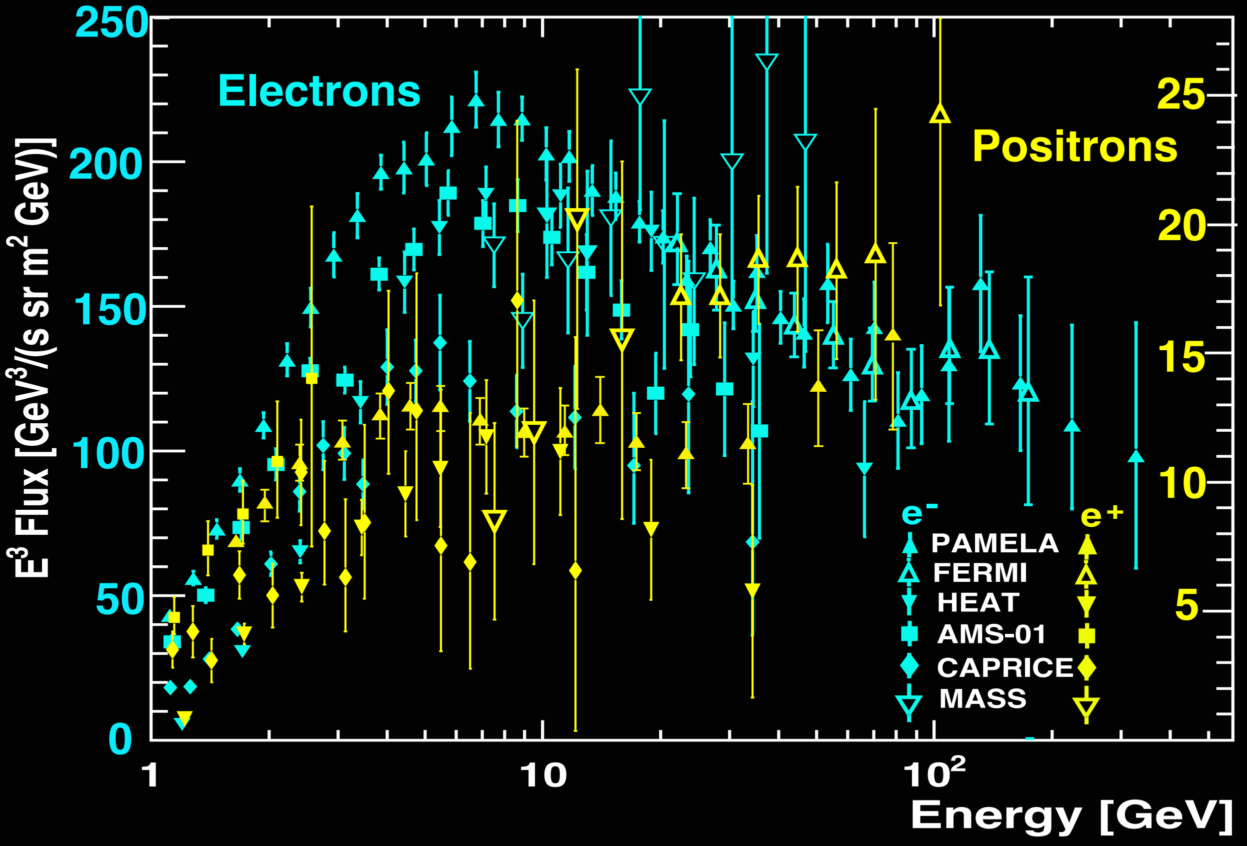
Y. Chen *et al.,* **Phys. Rev. D, 93 (2016), p. 015015**

……

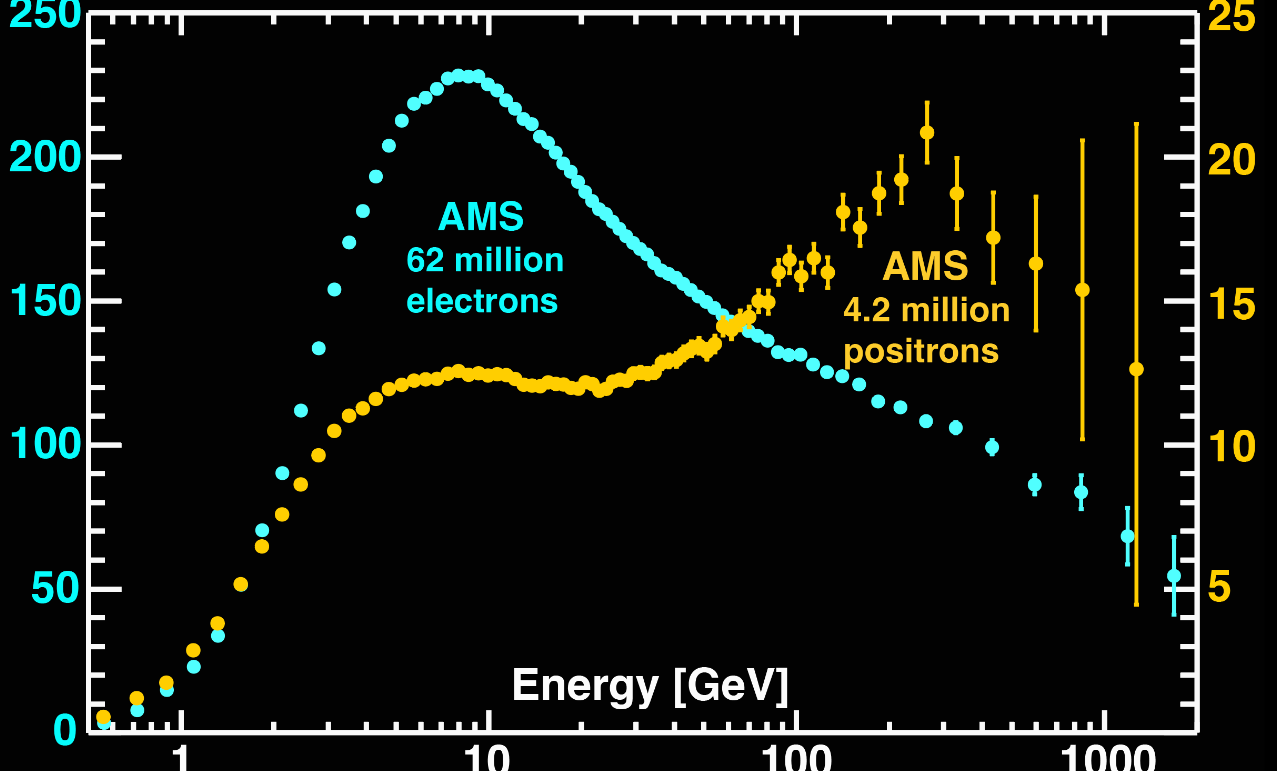
Antiprotons from Dark Matter

Study of Positrons & Electrons

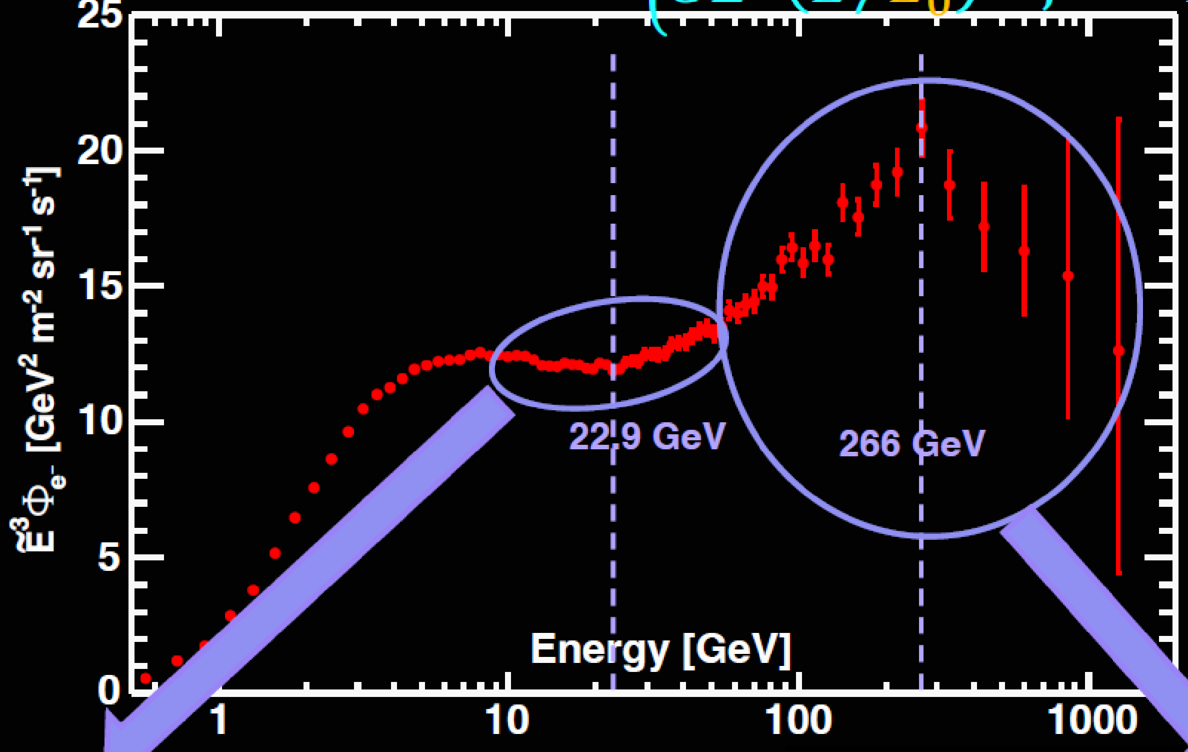
Measurements before AMS



AMS measurements

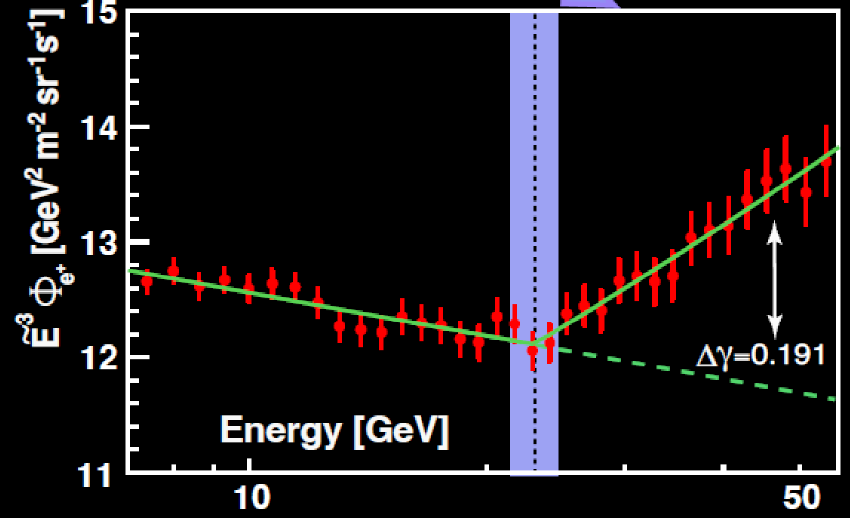


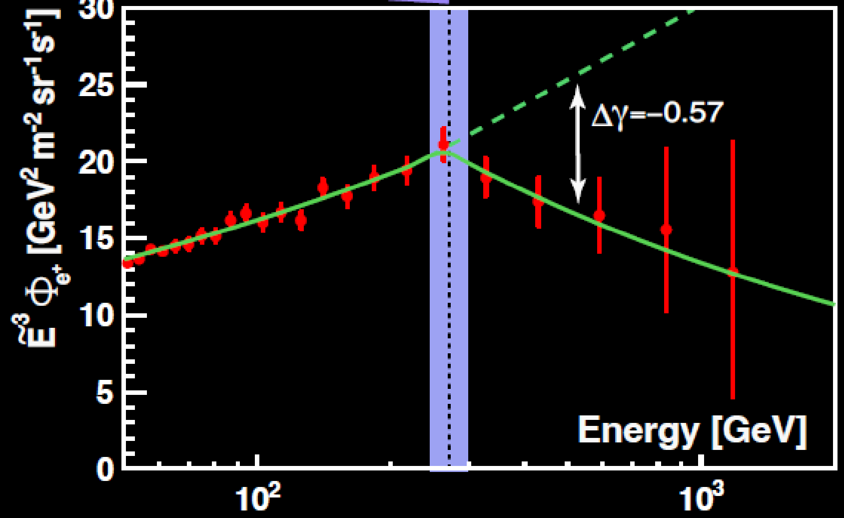
Fits of the data to $\Phi_{e^+}(E) = \begin{cases} CE^{\gamma}, & E \le E_0; \\ CE^{\gamma}(E/E_0)^{\Delta\gamma}, & E > E_0. \end{cases}$



10σ excess above $E_0 = 22.9 \pm 1.0$ GeV

5.0σ sharp drop-off at $E_0 = 266^{+29}_{-27}$ GeV

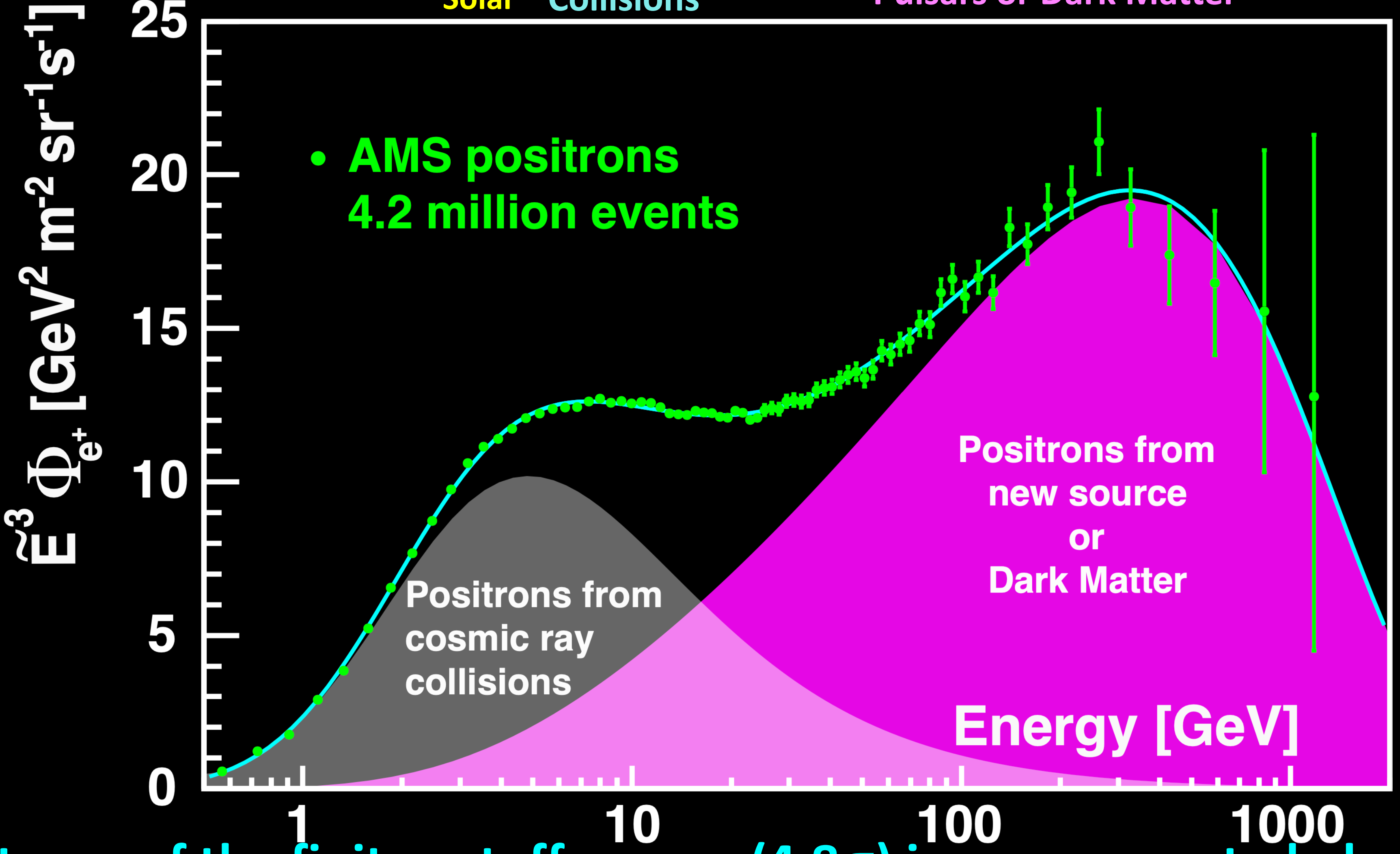




The positron flux is the sum of low-energy part from cosmic ray collisions plus a high-energy part from pulsars or dark matter both with a cutoff energy E_S.

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

Solar Collisions Pulsars or Dark Matter

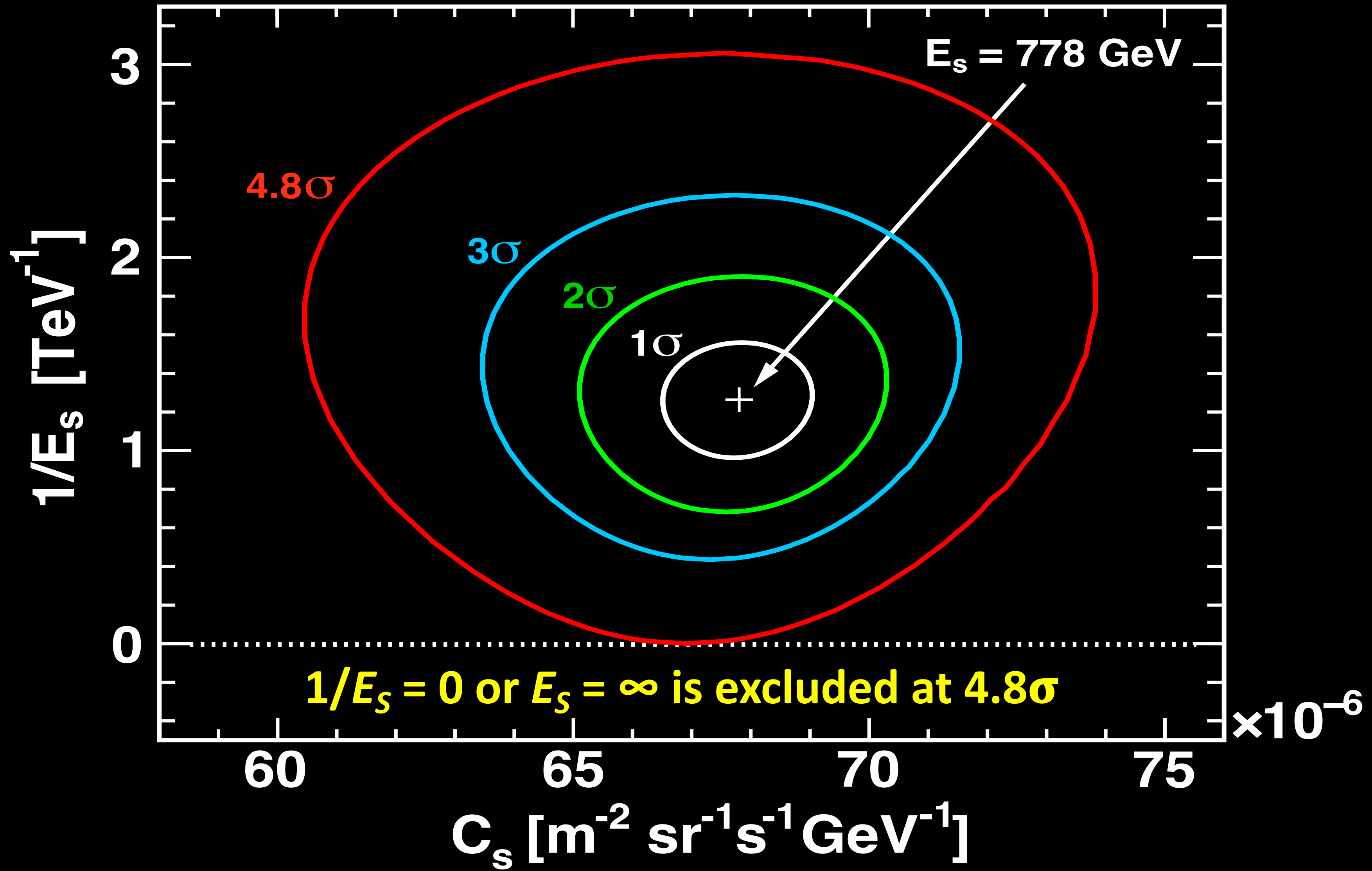


The existence of the finite cutoff energy (4.8σ) is an unexpected observation

Determination of the cutoff energy E_S

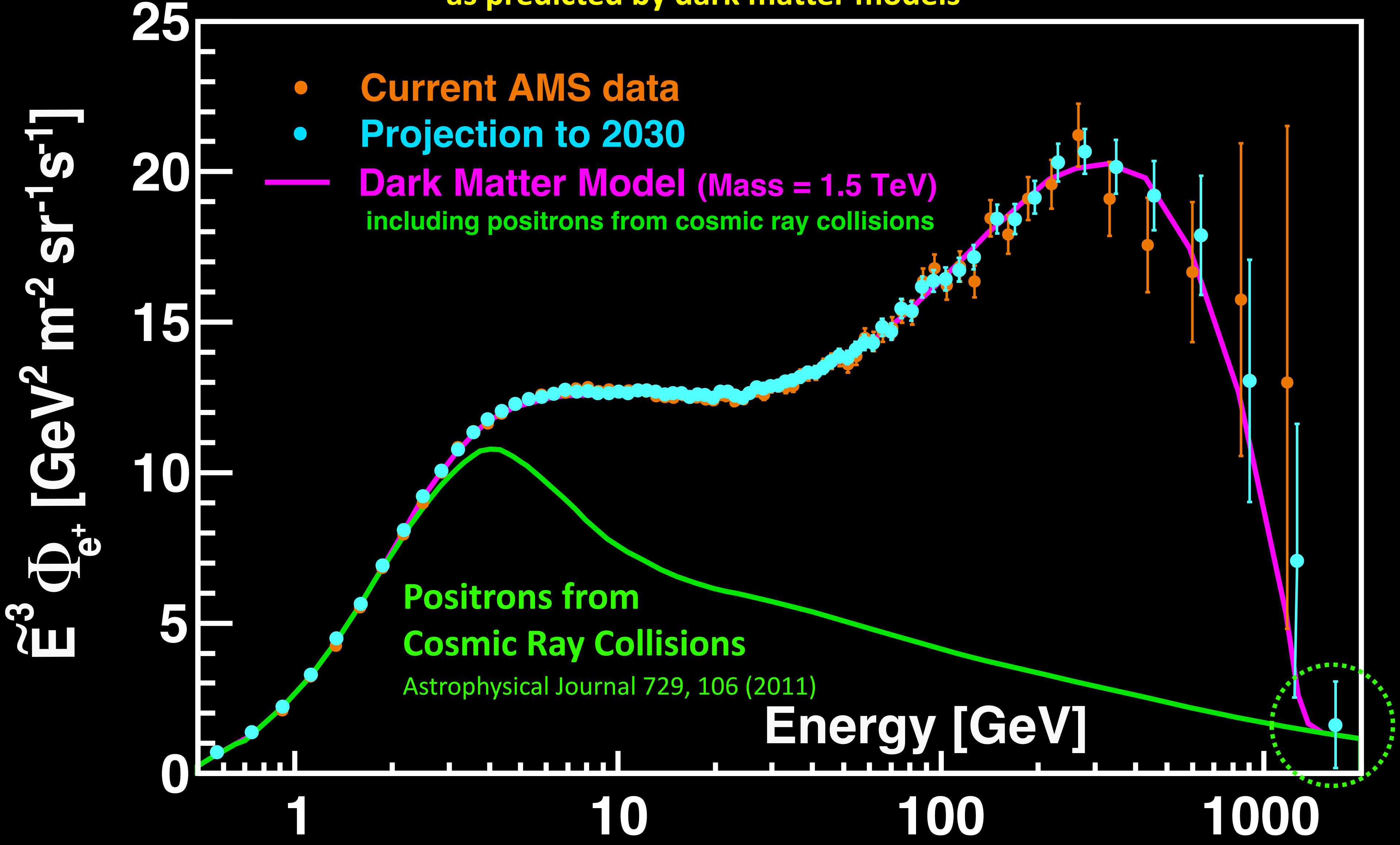
Collisions New Source or Dark Matter

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



Determination of the Origin of Cosmic Positrons by 2030

AMS will ensure that the measured high energy positron spectrum indeed drops off quickly and, at the highest energies, the positrons only come from cosmic ray collisions as predicted by dark matter models



A sample of recent theoretical models explaining AMS positron and electron data (overall >3000 citations)

Dark Matter

1) I. Krommydas, I. Cholis, Phys. Rev. D 107 (2023) 2, 023003
2) I. John, T. Linden, JCAP 12 (2021) 007
3) H. Motz, H. Okada, Y. Asaoka, and K. Kohri, Phys.Rev. D102 (2020) 8, 083019
4) Z.Q. Huang, R.Y. Liu, J.C. Joshi, X.Y. Wang, Astrophys.J. 895 (2020) 1, 53
5) R. Diesing and D. Caprioli, Phys.Rev. D101 (2020) 10
6) A. Das, B. Dasgupta, and A. Ray, Phys.Rev. D101 (2020) 6
7) F. S. Queiroz and C. Siqueira, Phys.Rev. D101 (2020) 7, 075007
8) Z.L. Han, R. Ding, S.J. Lin, and B. Zhu, Eur.Phys.J. C79 (2019) 12, 1007
9) C.Q. Geng, D. Huang, and L. Yin, Nucl.Phys. B959 (2020) 115153
10) S. Profumo, F. Queiroz, C. Siqueira, J.Phys.G 48 (2020) 1, 015006

and many other excellent papers …

Astrophysical sources

1) O. M. Bitter, D. Hooper, JCAP 10 (2022) 081
2) T.P. Tang, Z.Q. Xia, Z.Q. Shen, et al., Phys. Lett. B 825 (2022) 136884
3) P. Mertsch, A. Vittino, and S. Sarkar, Phys.Rev. D 104 (2021) 103029
4) P. Zhang et al., JCAP 05 (2021) 012
5) C. Evoli, E. Amato, P. Blasi, and R. Aloisio, Phys.Rev. D103 (2021) 8, 083010
6) K. Fang, X.J. Bi, S.J. Lin, and Q. Yuan, Chin.Phys.Lett. 38 (2021) 3, 039801
7) C. Evoli, P. Blasi, E. Amato, and R. Aloisio, Phys.Rev.Lett. 125 (2020) 5, 051101
8) O. Fornieri, D. Gaggero, and D. Grasso, JCAP 02 (2020) 009
9) P. Cristofari and P. Blasi, Mon.Not.Roy.Astron.Soc. 489 (2019) 1, 108
10) S. Recchia, S. Gabici, F.A. Aharonian, and J. Vink, Phys.Rev. D99 (2019) 10, 103022

and many other excellent papers …

Propagation

1) E. Silver, E. Orlando, Astrophys. J. 963 (2024) 2, 111
2) M. Di Mauro, F. Donato, M. Korsmeier, et al., Phys. Rev. D 108 (2023) 6, 063024
3) E. Amato and S. Casanova, J.Plasma Phys. 87 (2021) 1, 845870101
4) Z. Tian et al., Chin.Phys. C44 (2020) 8, 085102
5) W. Zhu, P. Liu, J. Ruan, and F. Wang, Astrophys.J. 889 (2020) 127
6) P. Liu and J. Ruan, Int.J.Mod.Phys. E28 (2019) 09, 1950073
7) R. Diesing and D. Caprioli, Phys.Rev.Lett. 123 (2019) 7, 071101
8) W. Zhu, J. S. Lan and J. H. Ruan, Int. J. Mod. Phys. E27 (2018) 1850073

and many other excellent papers …

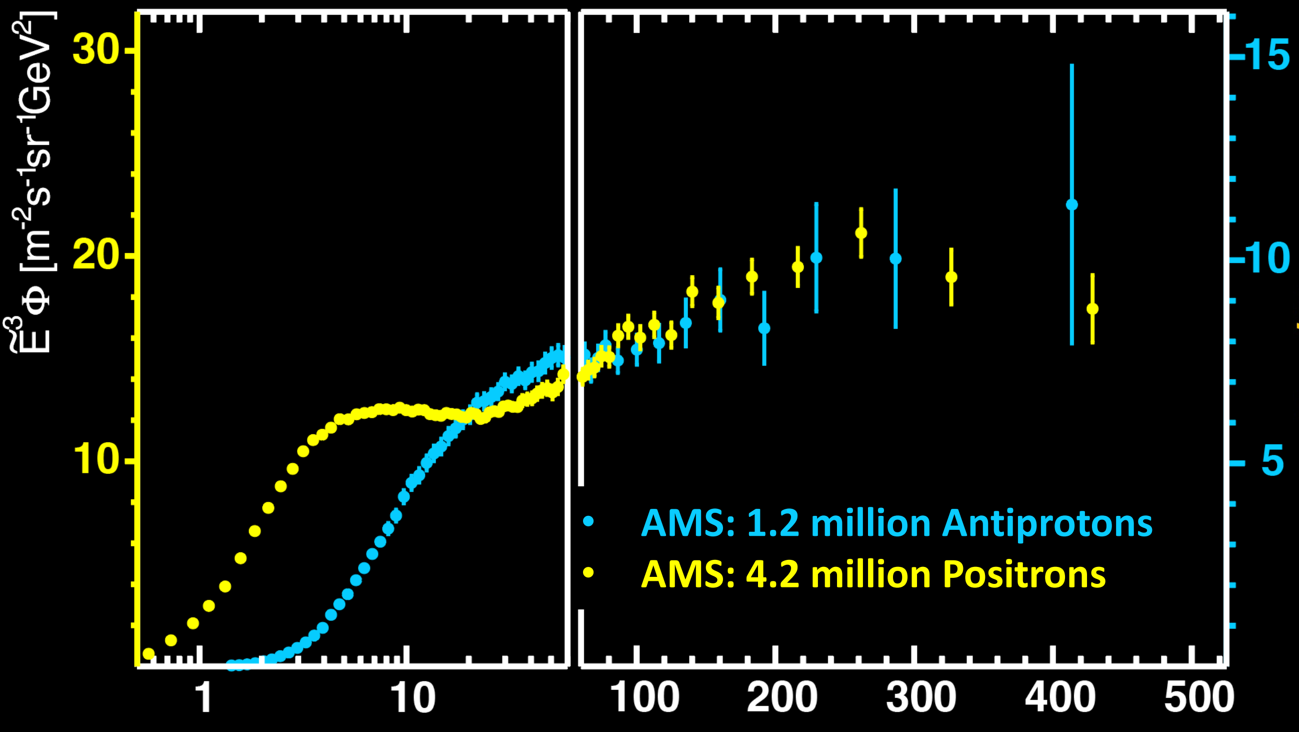
AMS Publications on electrons and positrons

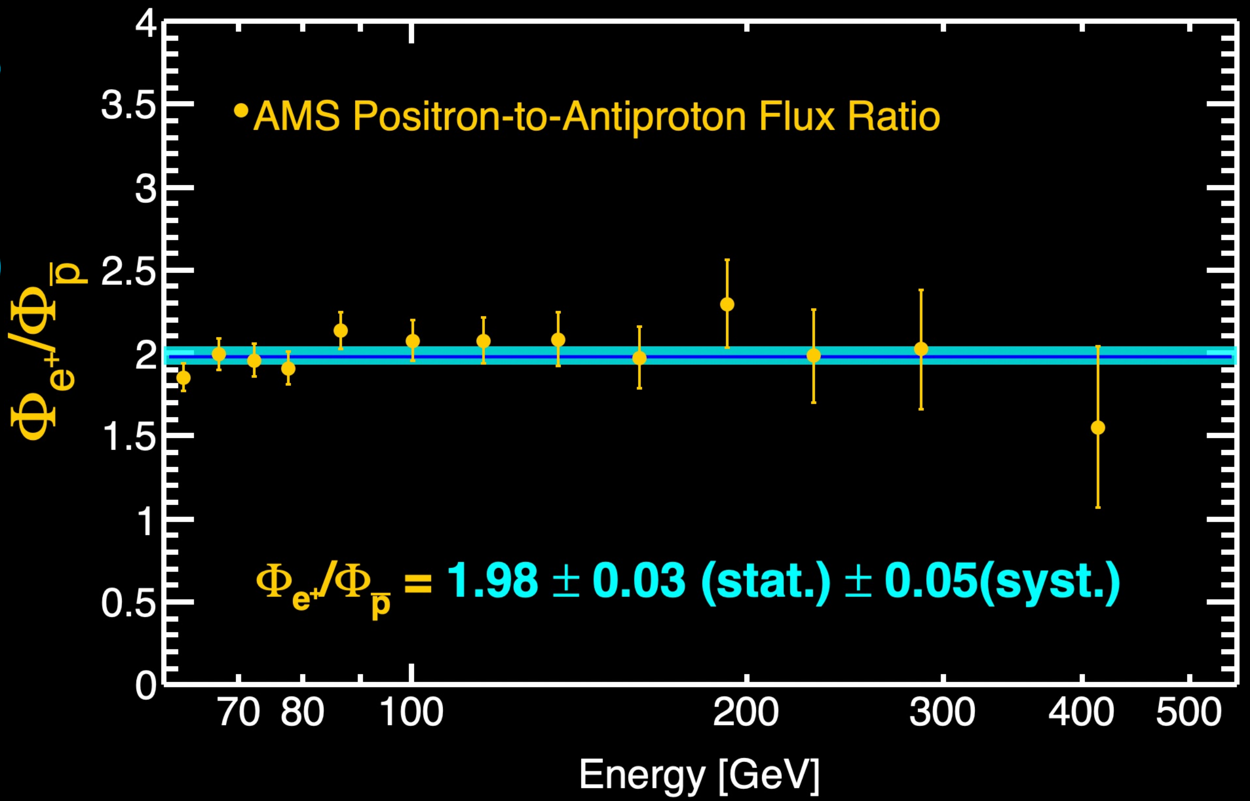
1) M. Aguilar *et. al.*, Phys. Rev. Lett. 110 (2013) 141102.
   APS Highlight of the Year 2013
   10-year Retrospective of Editors' Suggestions
2) L. Accardo *et al.*, Phys. Rev. Lett. 113 (2014) 121101.
   Editor's Suggestion
3) M. Aguilar *et. al.*, Phys. Rev. Lett. 113 (2014) 121102.
   Editor's Suggestion
4) M. Aguilar *et. al.*, Phys. Rev. Lett. 113 (2014) 221102.
5) M. Aguilar *et. al.*, Phys. Rev. Lett. 122 (2019) 041102.
   Editor's Suggestion
6) M. Aguilar *et. al.*, Phys. Rev. Lett, 122 (2019) 101101.
7) M. Aguilar et. al., Physics Reports, 894 (2021) 1.

Unique Observation from AMS:

Positron and Antiproton have nearly identical energy dependence

The positron-to-antiproton flux ratio is independent of energy.

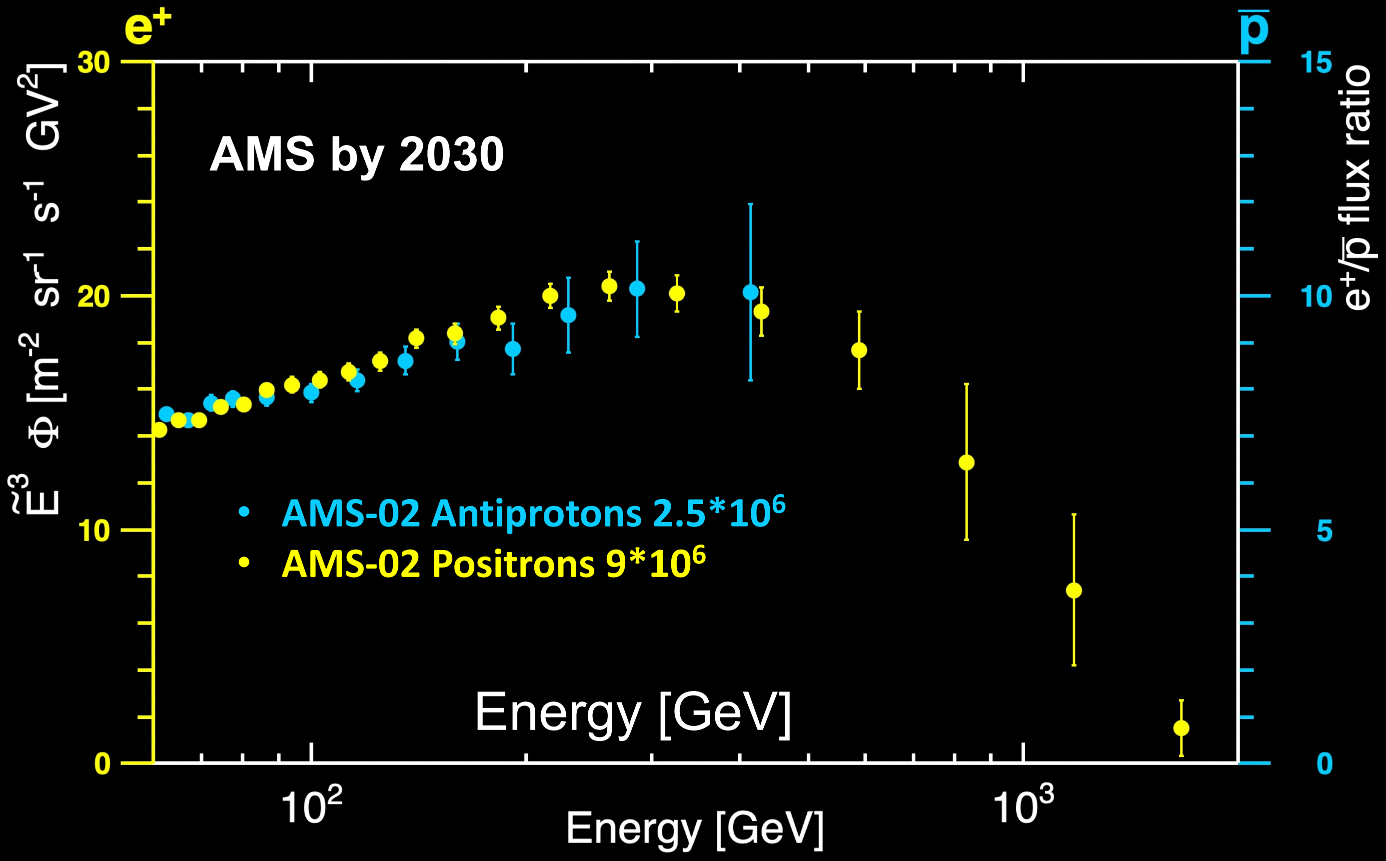




Antiprotons cannot come from pulsars.

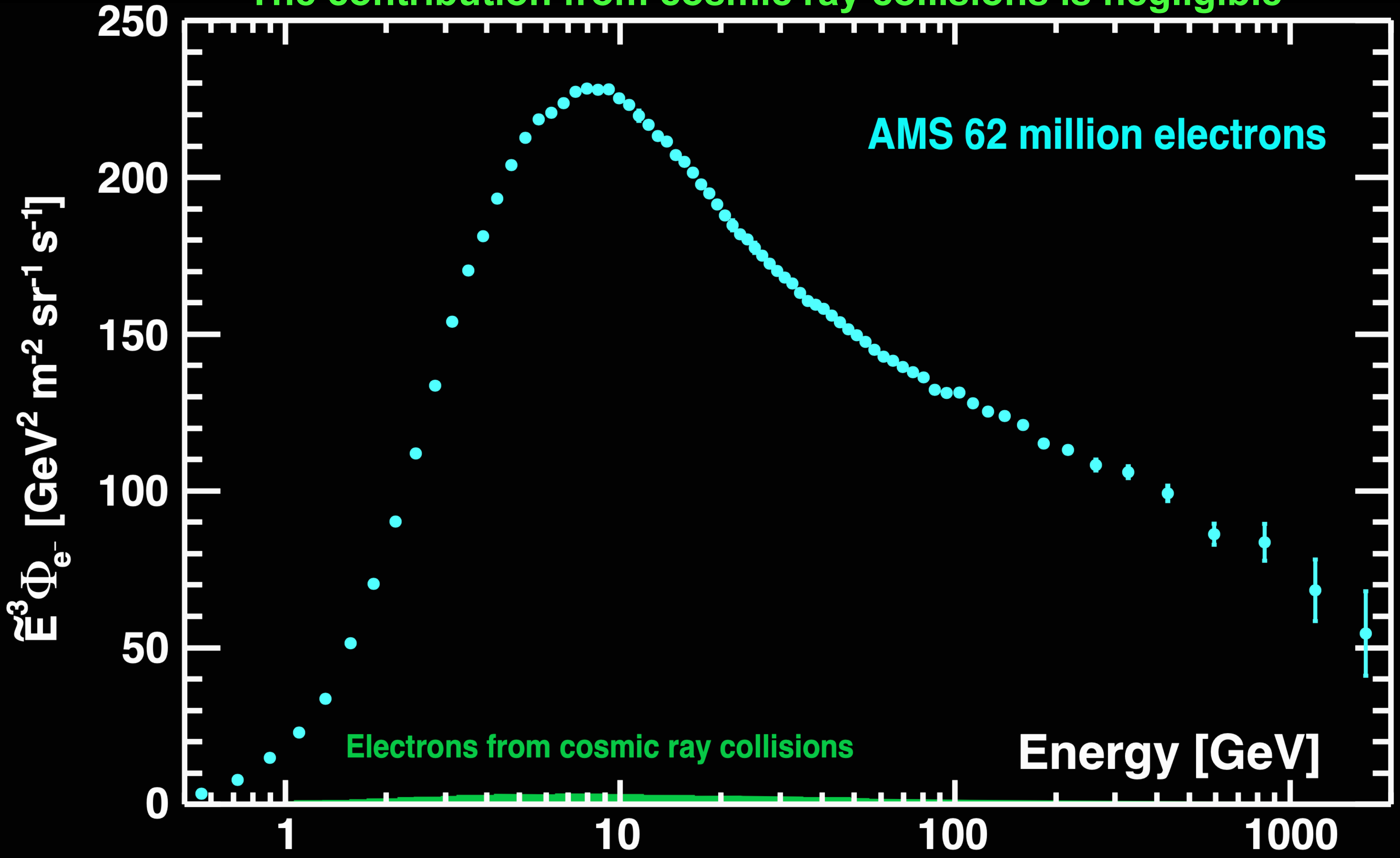
By 2030, AMS will greatly improve the accuracy of the antiproton spectra

The identical behaviour of positrons and antiprotons excludes the pulsar origin of positrons



Origins of Cosmic Electrons

The contribution from cosmic ray collisions is negligible



Origins of Cosmic Electrons

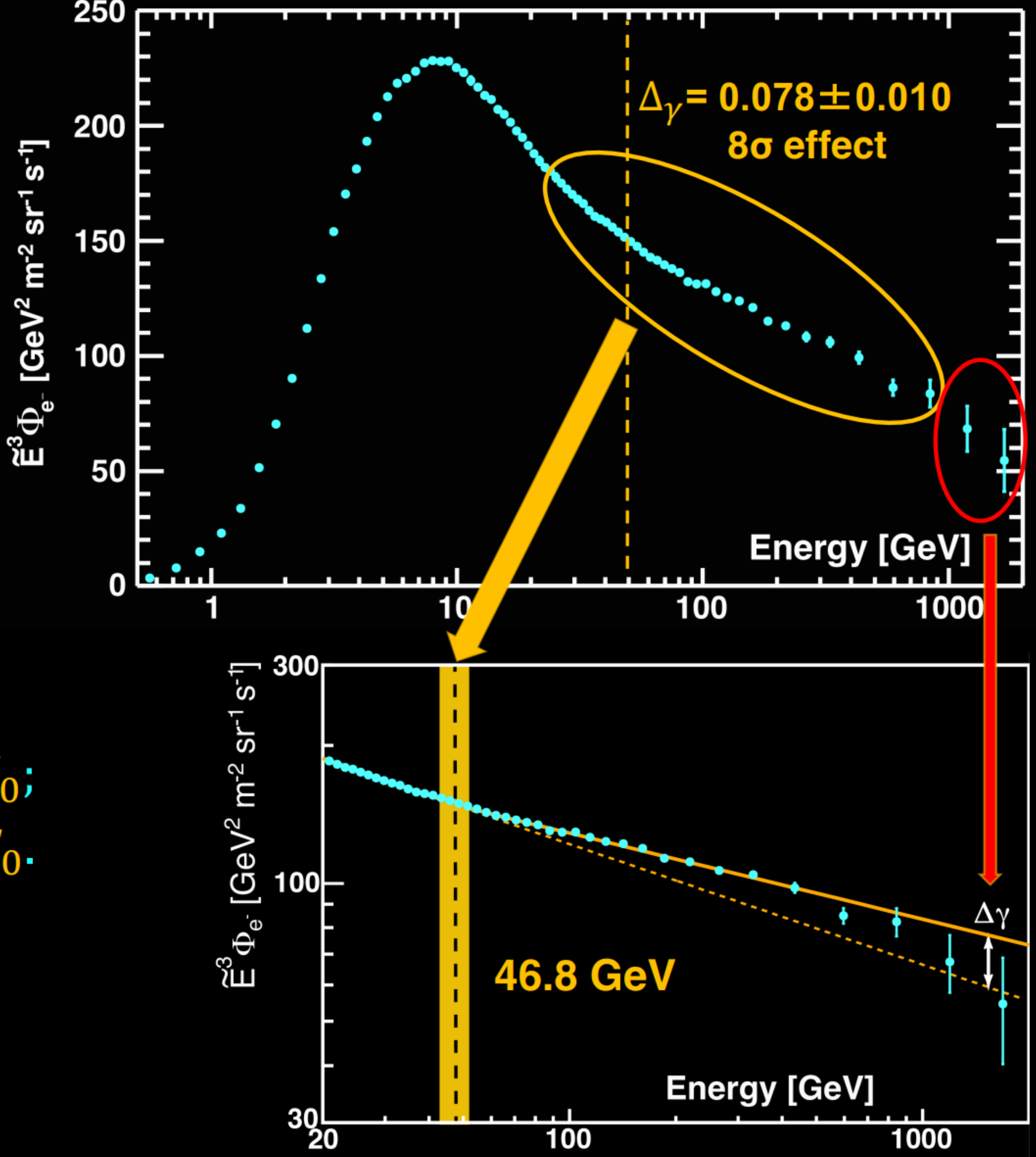
Traditionally, Cosmic Ray spectrum is described by a power law function

Change of the behavior at 46.8 GeV and at ~1 TeV

Fit to data

$$\Phi_{e^-}(E) = \begin{cases} CE^{\gamma}, & E \le E_0; \\ CE^{\gamma}(E/E_0)^{\Delta_\gamma}, & E > E_0. \end{cases}$$

8 sigma excess at E_0 = 46.8±3.1 GeV



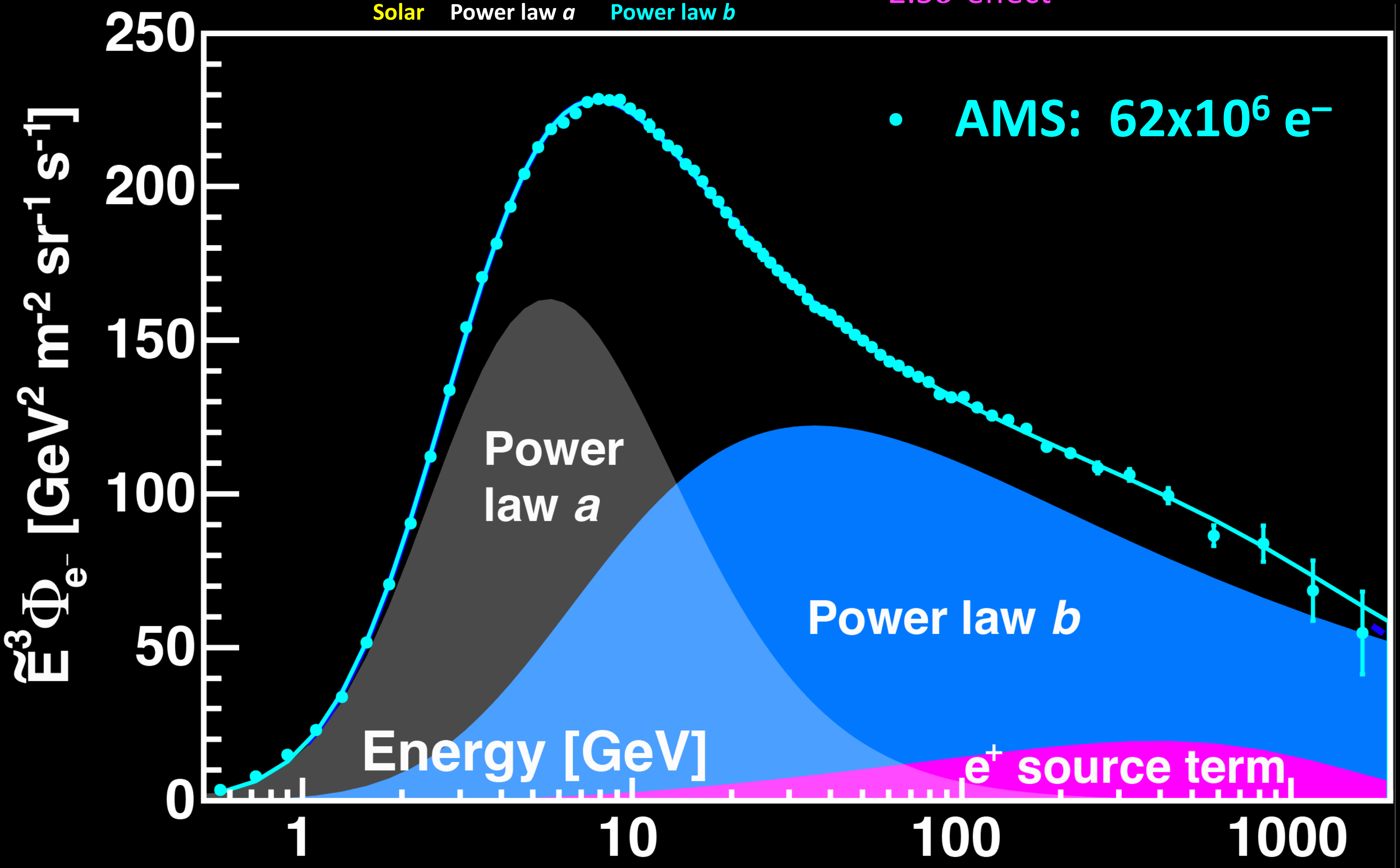
AMS Result on the electron spectrum

The spectrum fits well with two power laws (*a*, *b*) and **a source term like positrons**

$$\Phi_{e^-}(E) = \frac{E^2}{\widehat{E}^2}\left(C_a \widehat{E}^{\gamma_a} + C_b \widehat{E}^{\gamma_b} + \text{Positron Source Term}\right)$$

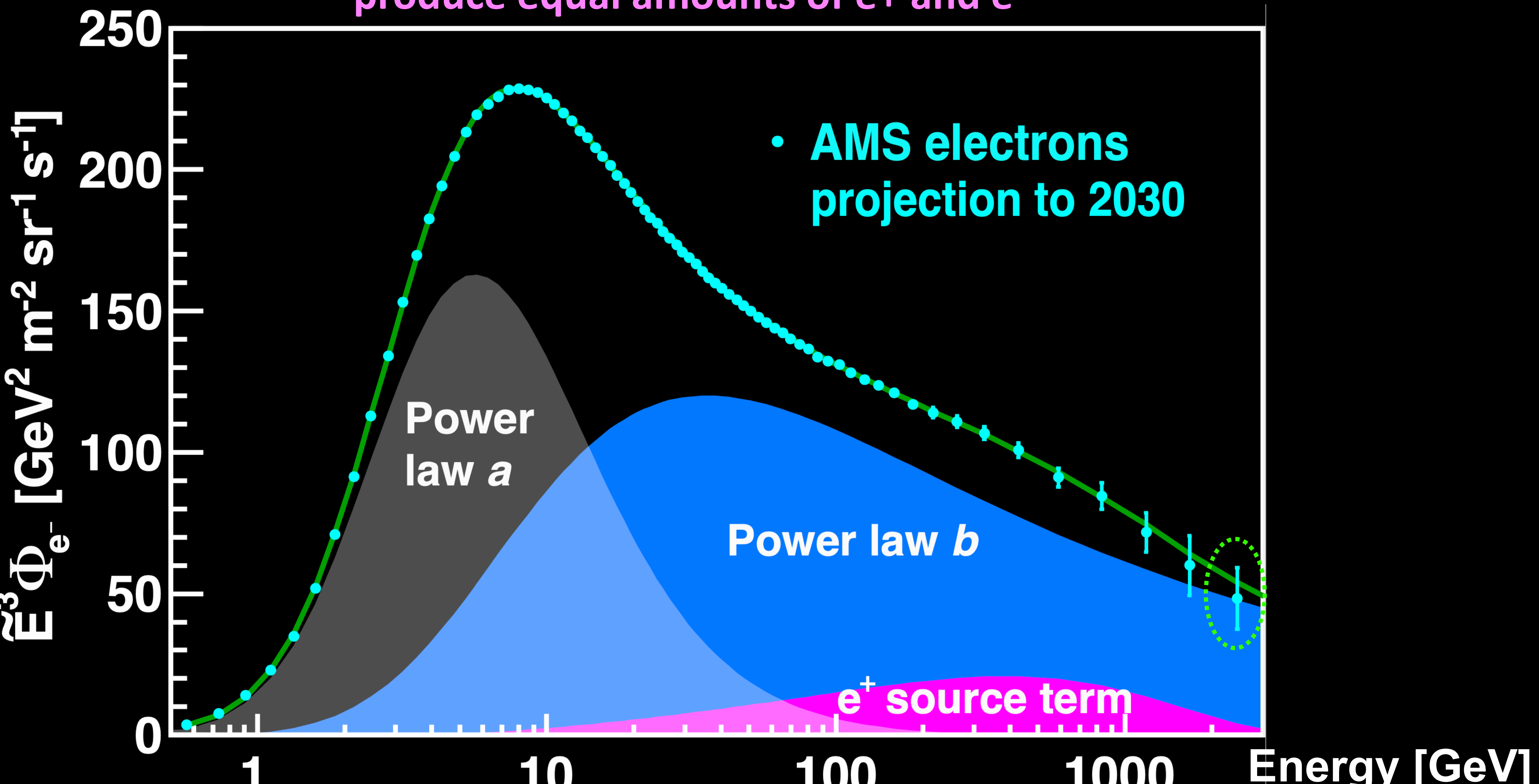
2.5σ effect

Solar Power law *a* Power law *b*



By 2030, the charge-symmetric nature of the high energy source will be established at the 4σ level

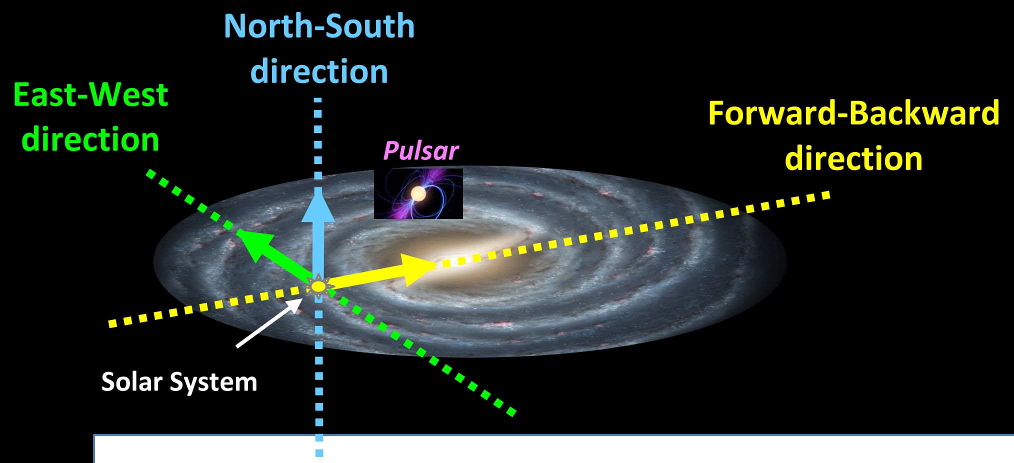
New sources, like Dark Matter or Pulsars, produce equal amounts of e+ and e–



By simultaneous measurement of cosmic protons, electrons, antiprotons, and positrons through the lifetime of the space station,

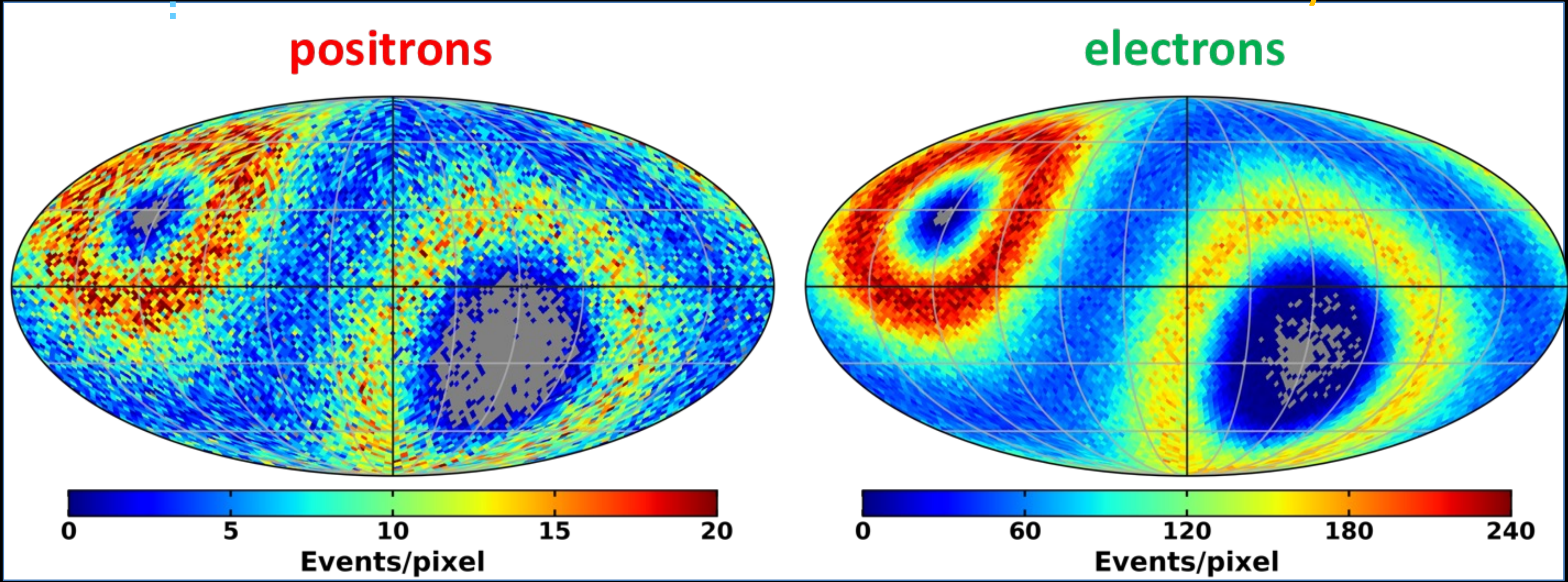
AMS will provide the definitive dataset to resolve the mystery of the origin of elementary particles in cosmic rays.

Positron Anisotropy and Dark Matter



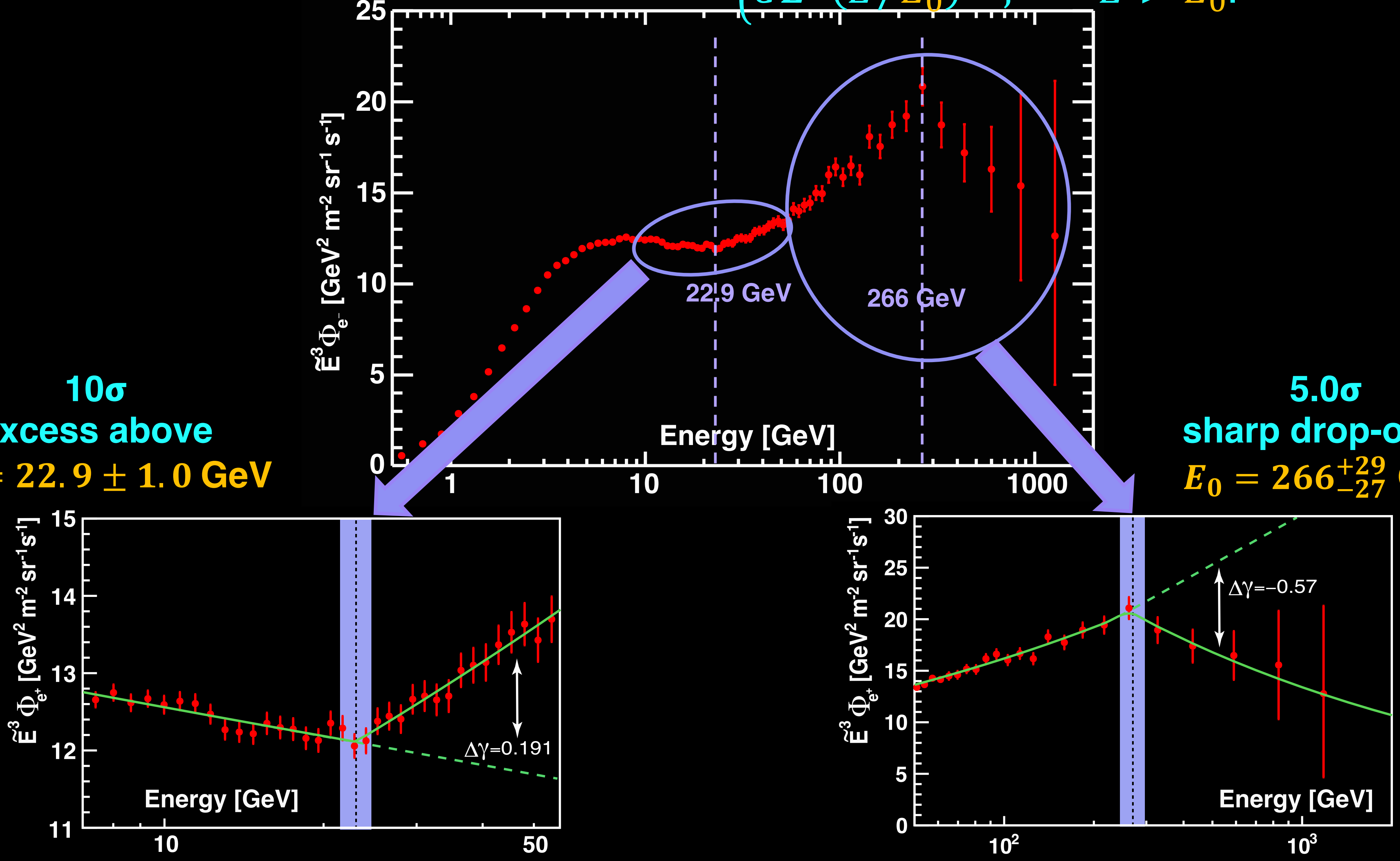
Astrophysical point sources will imprint a higher anisotropy on the arrival directions of energetic positrons than a smooth dark matter halo.

Presented by M. Molero



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

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



10σ
excess above
$E_0 = 22.9 \pm 1.0$ GeV

5.0σ
sharp drop-off at
$E_0 = 266^{+29}_{-27}$ GeV