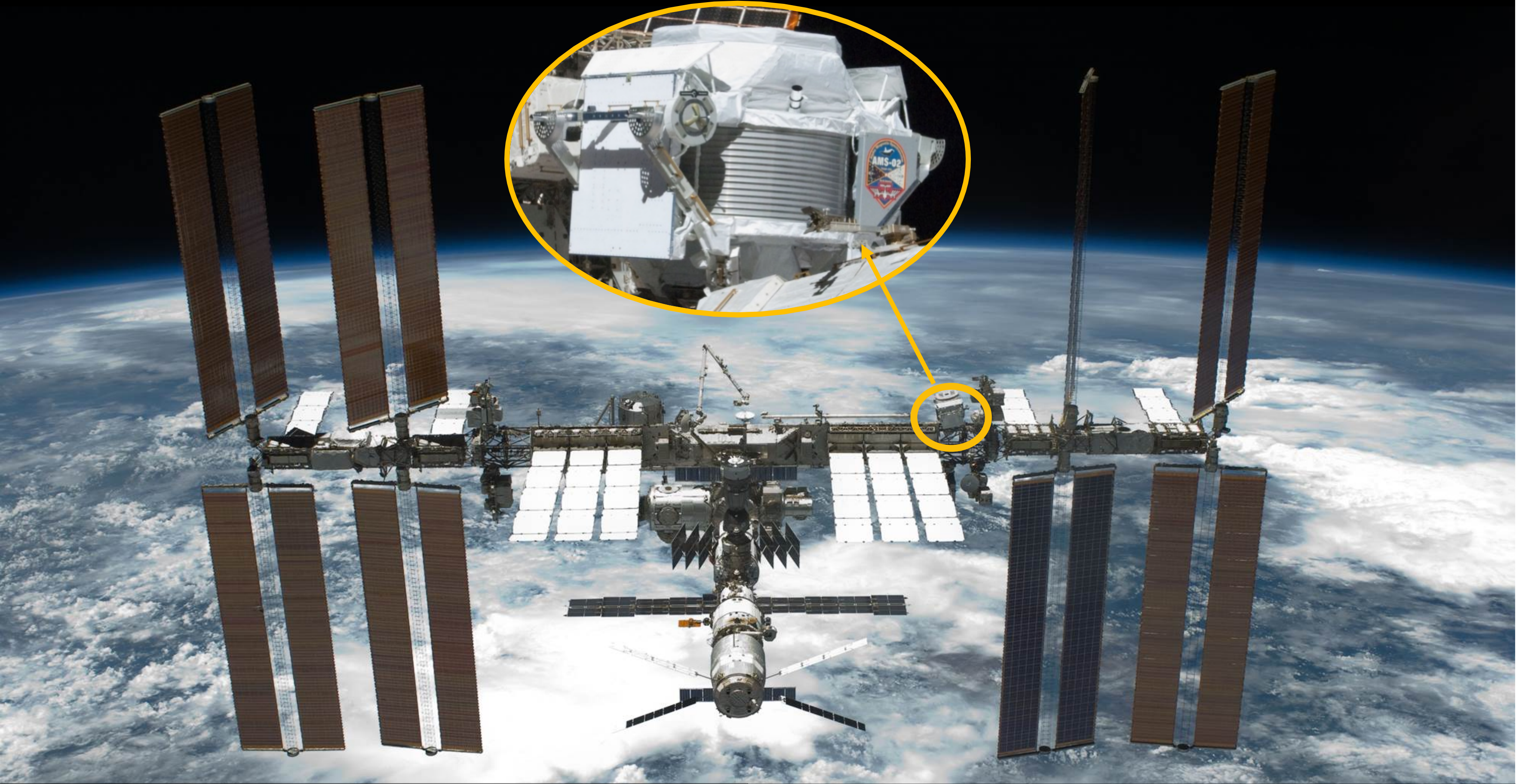
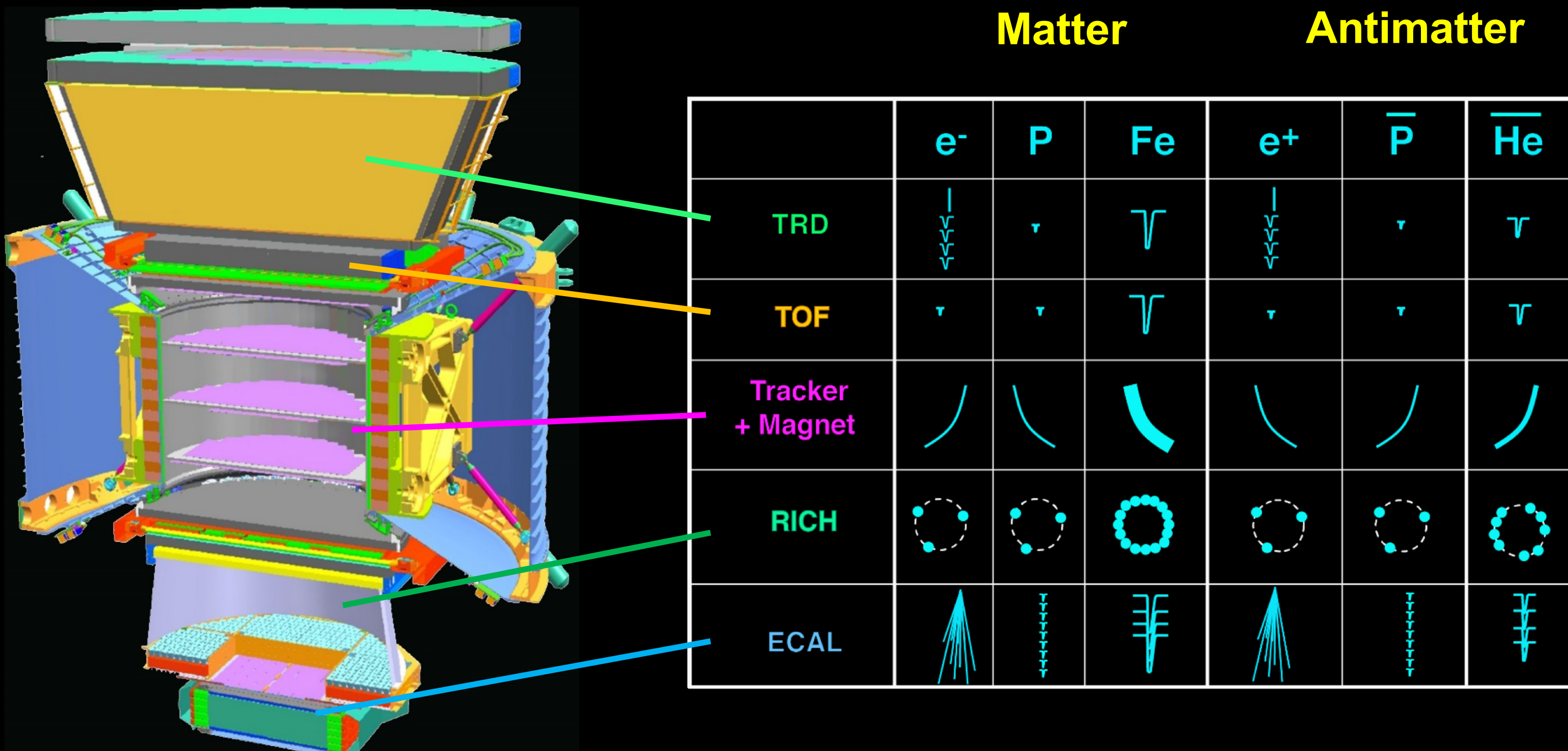
Properties of Elementary Particle Fluxes in Primary Cosmic Rays Measured with Alpha Magnetic Spectrometer (AMS) on the ISS



Sydney, TeVPA 2019
December 5th, 2019

Senquan Lu / Academia Sinica
on behalf of the AMS Collaboration

AMS is a unique magnetic spectrometer in space

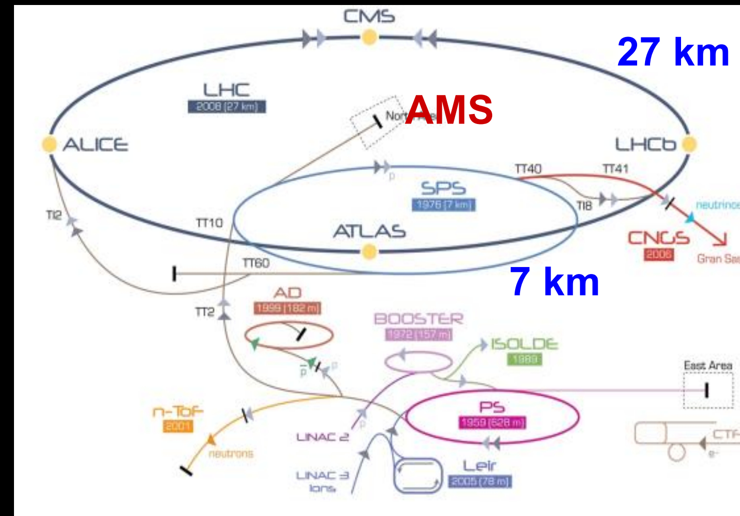


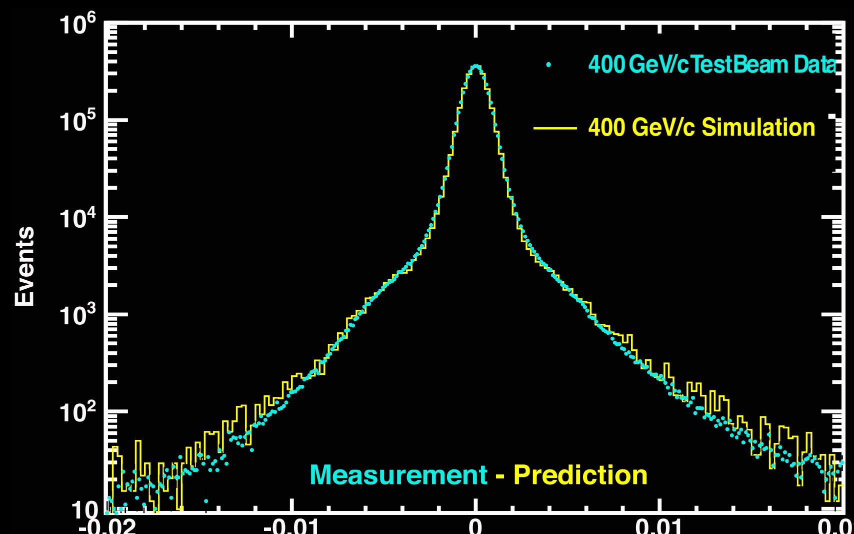
Cosmic rays are defined by:

- 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

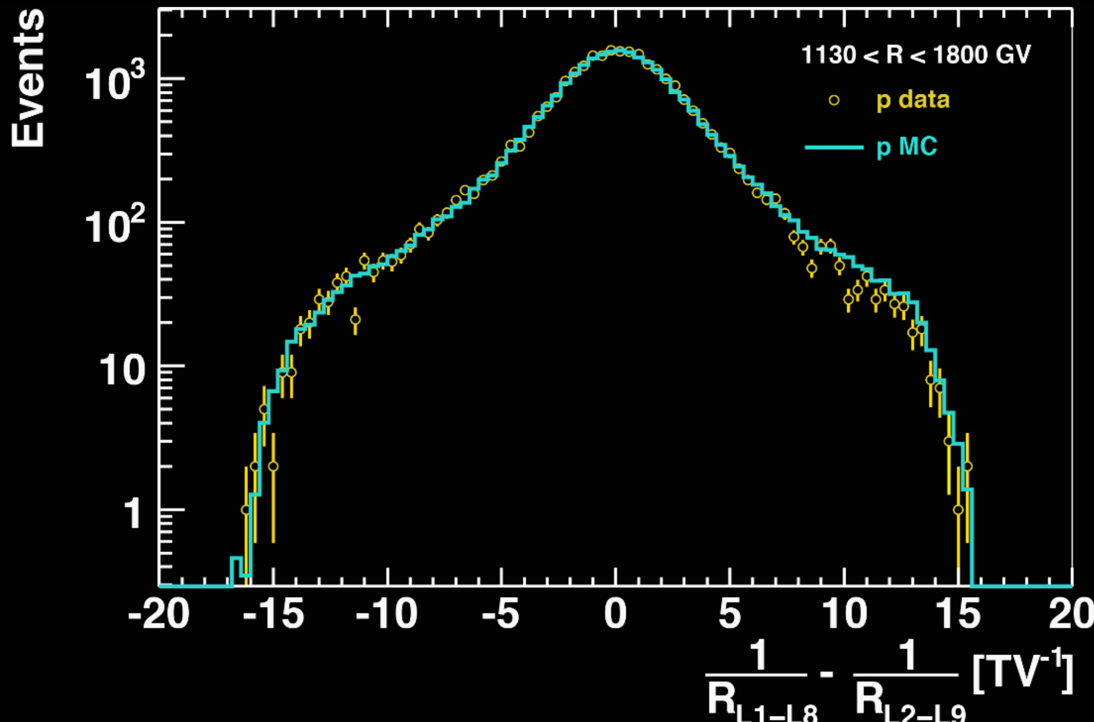


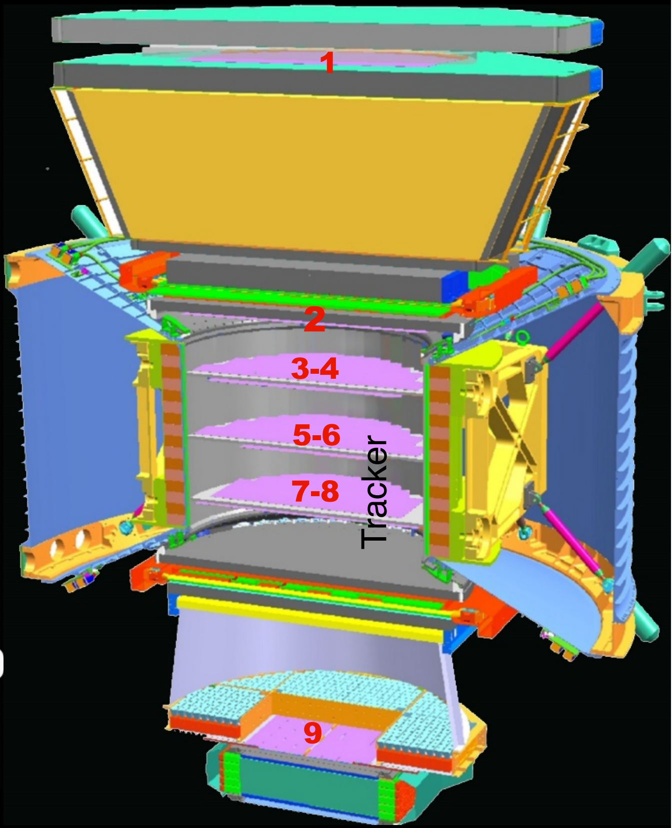


Unique properties of AMS:

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

Calibrations above test beam rigidity

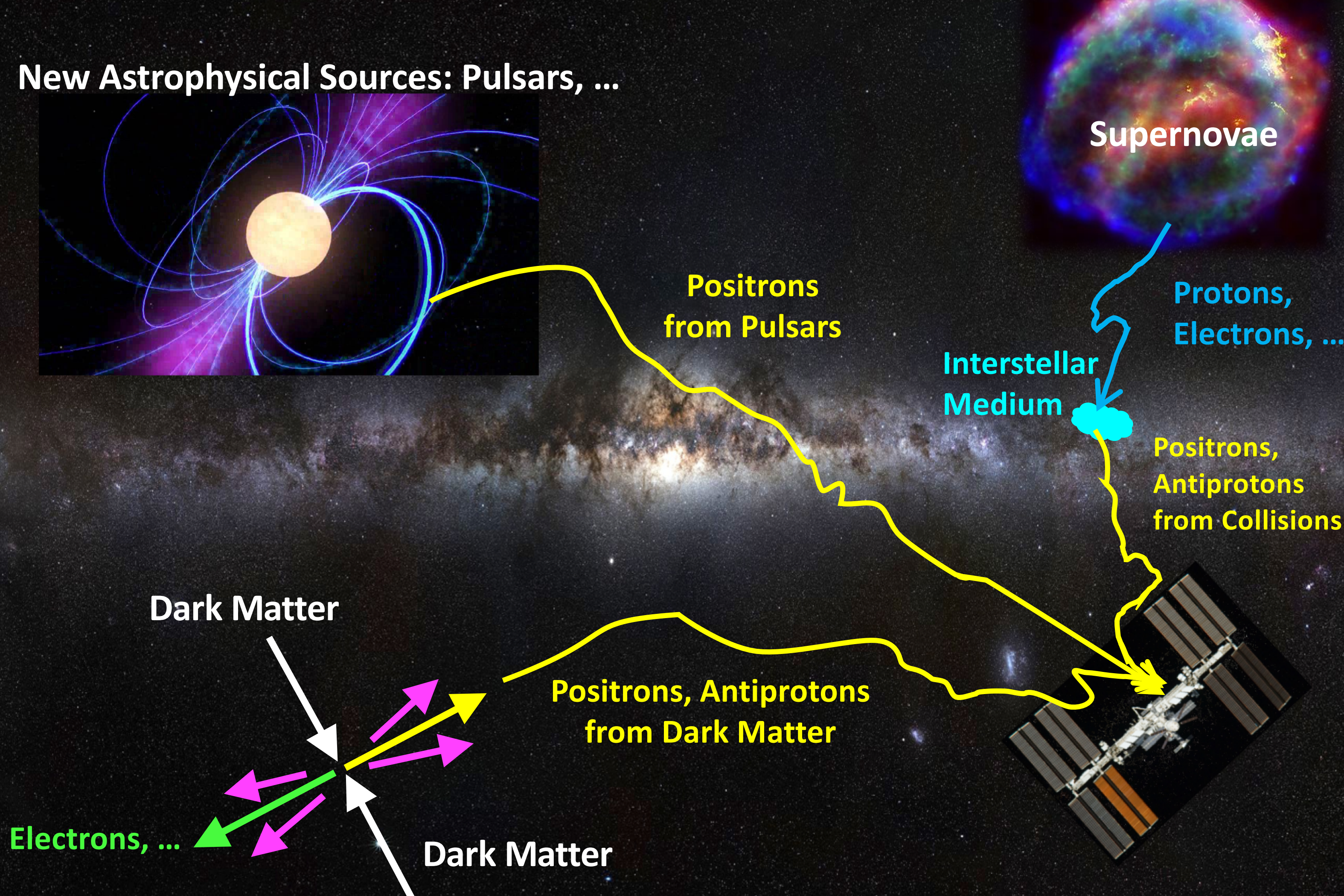




Verification of rigidity measurement with different part of the detectors


ELC2
ELC4
AMS-02
In 8 years,
over 140 billion
charged cosmic rays
have been measured by AMS

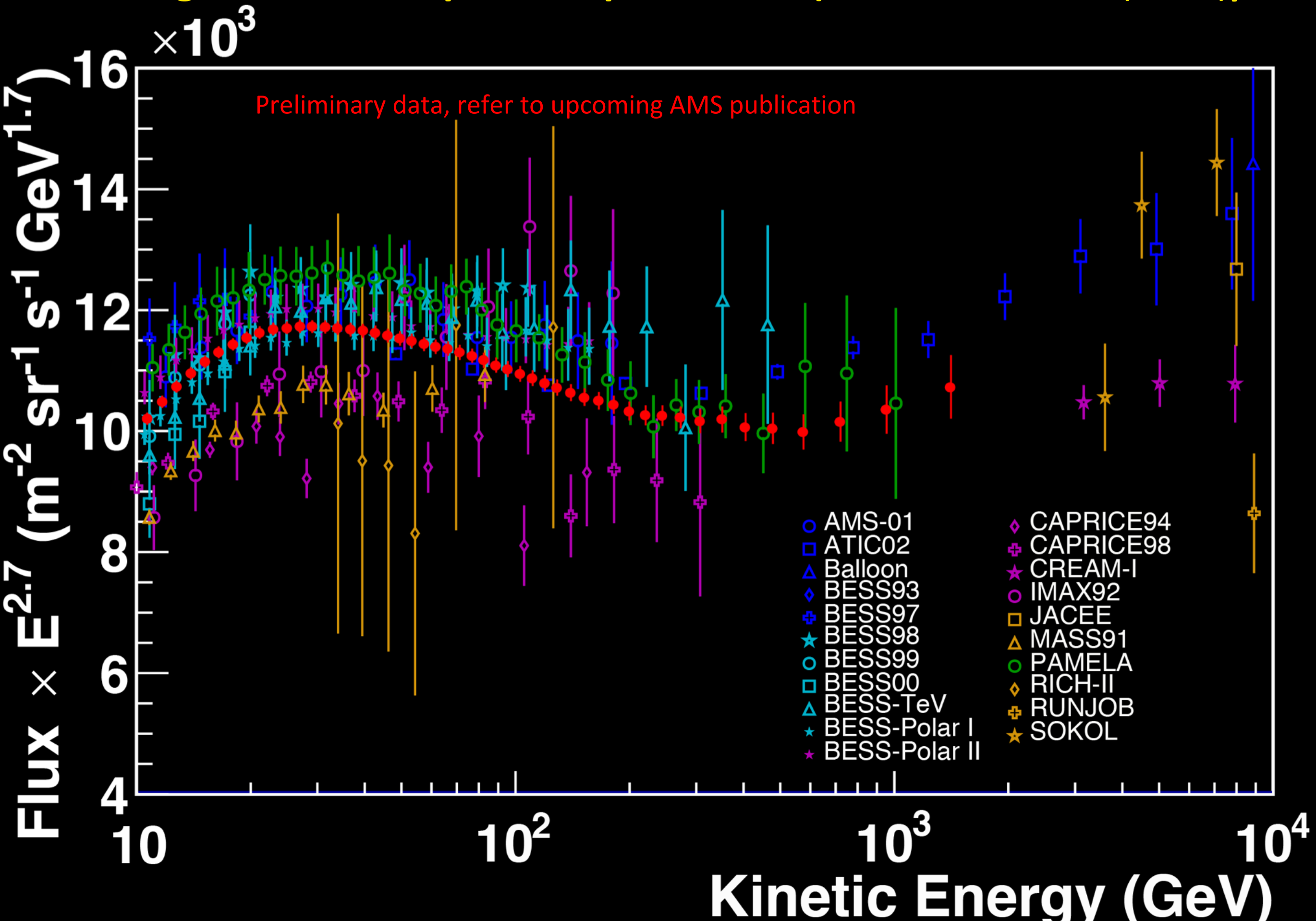
On the Origins of Cosmic Rays



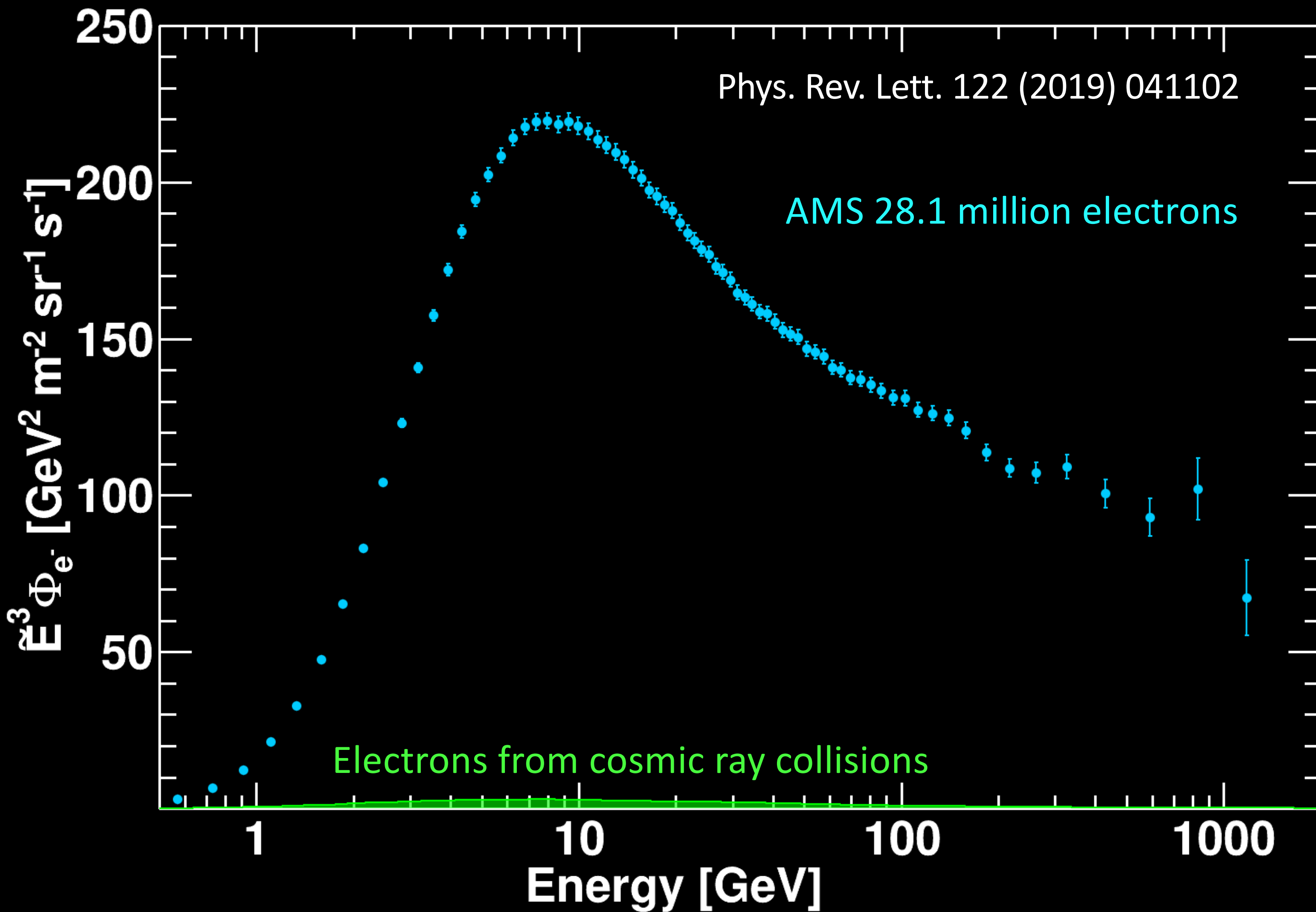
Measurement of these elementary particles ($p, \bar{p}, e^{-}, e^{+}$) is a major tool to search for new physics in space

Latest AMS Measurement of the proton spectrum

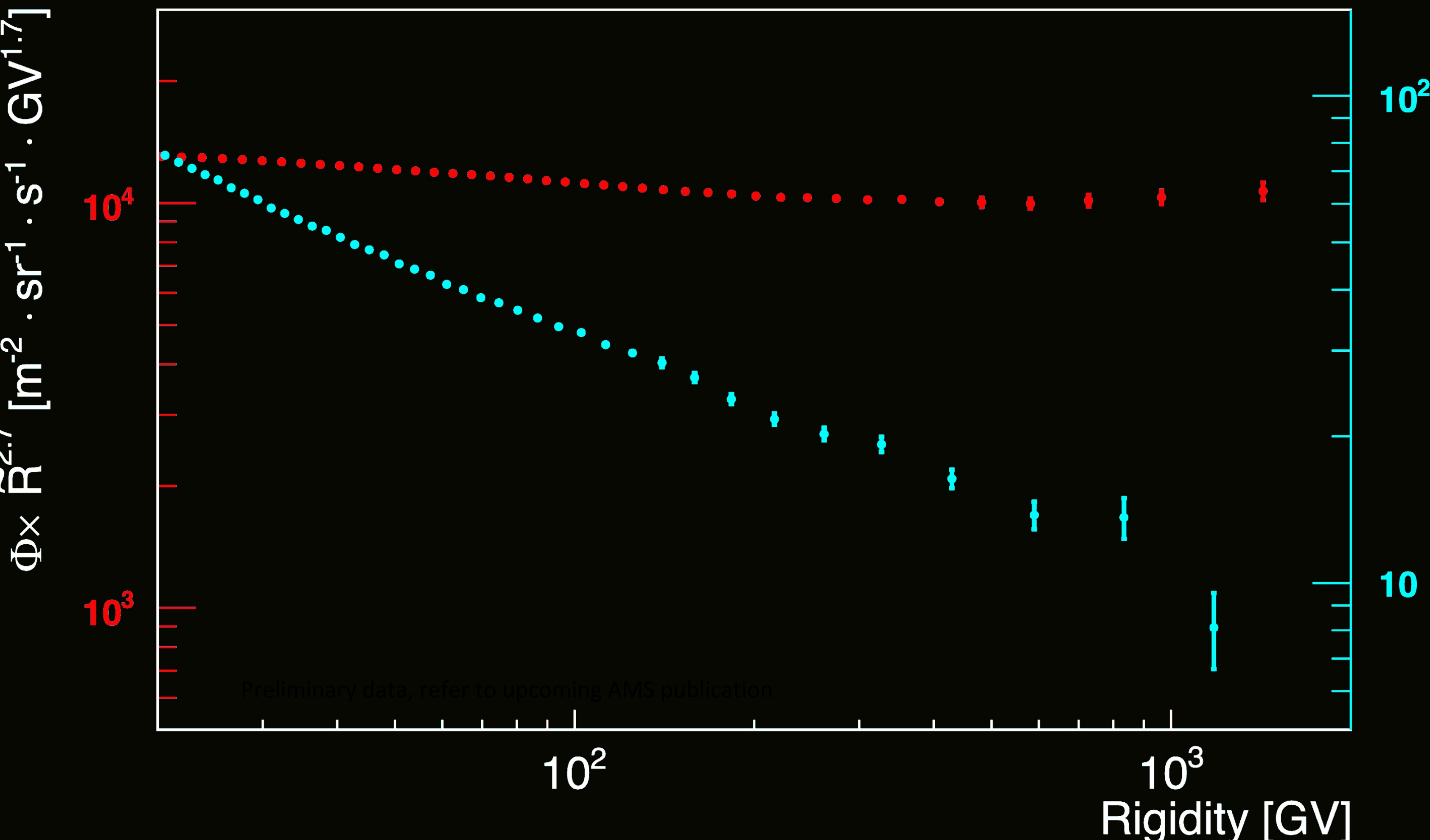
Latest results – 1 billion protons
The result shows progressively hardening above 200GeV and in agreement with previous publication (PRL 114, 171103 (2015)).



AMS Measurement of The Electron Spectrum



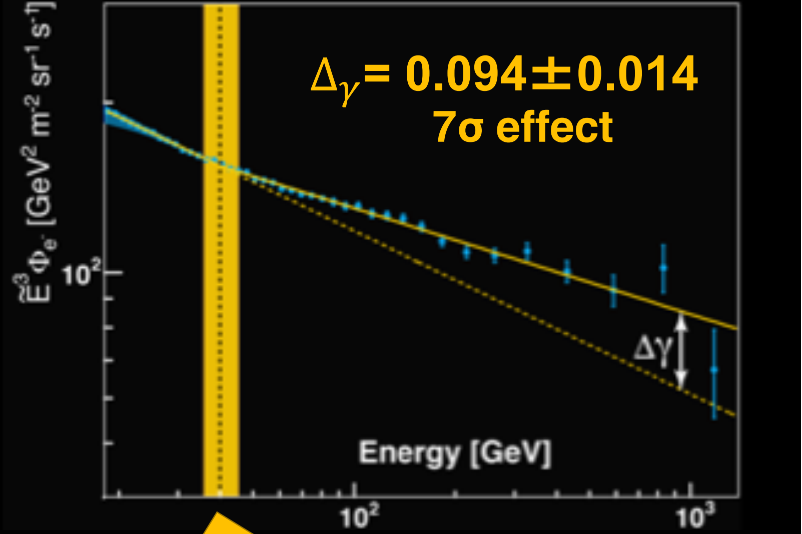
The Spectra of Protons and Electrons



- Protons and Electrons are accelerated in SNR in a similar way
- Electrons lose energy much faster than proton during propagation

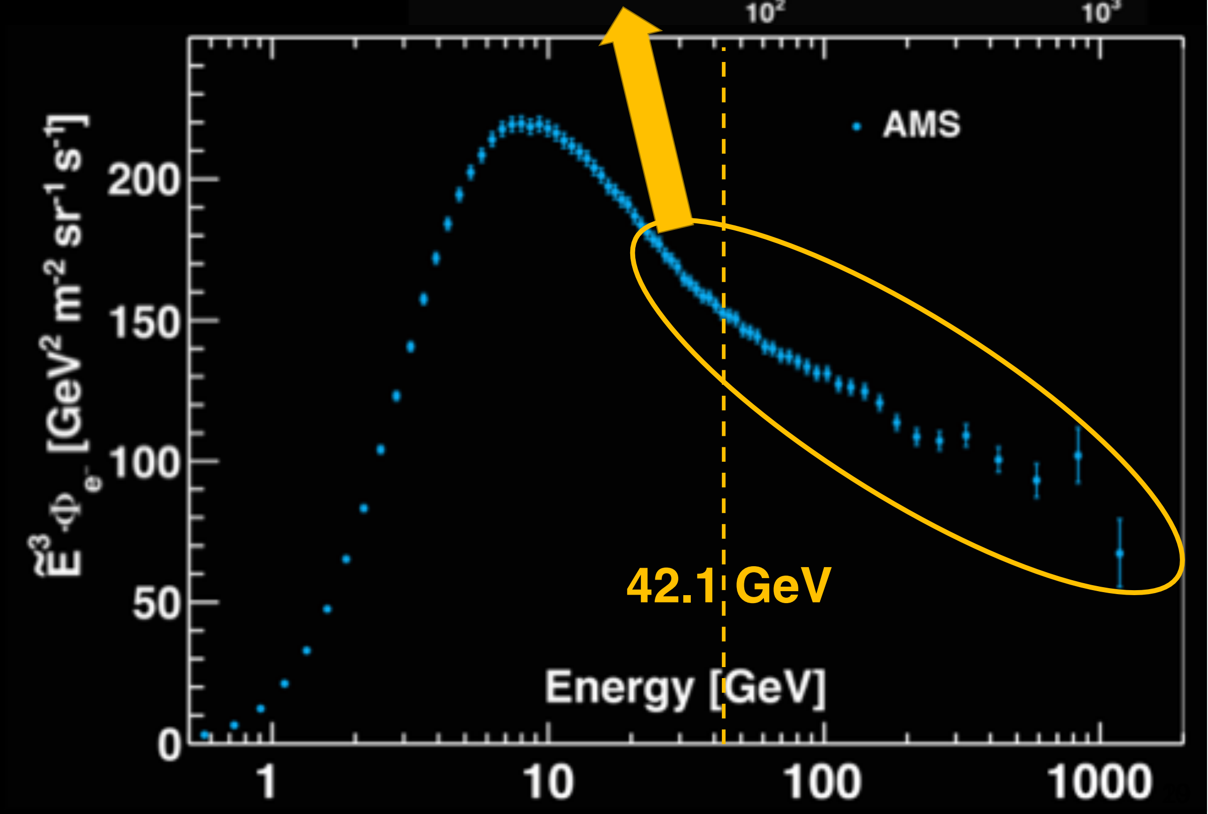
Fit to the data

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



A significant excess at

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



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

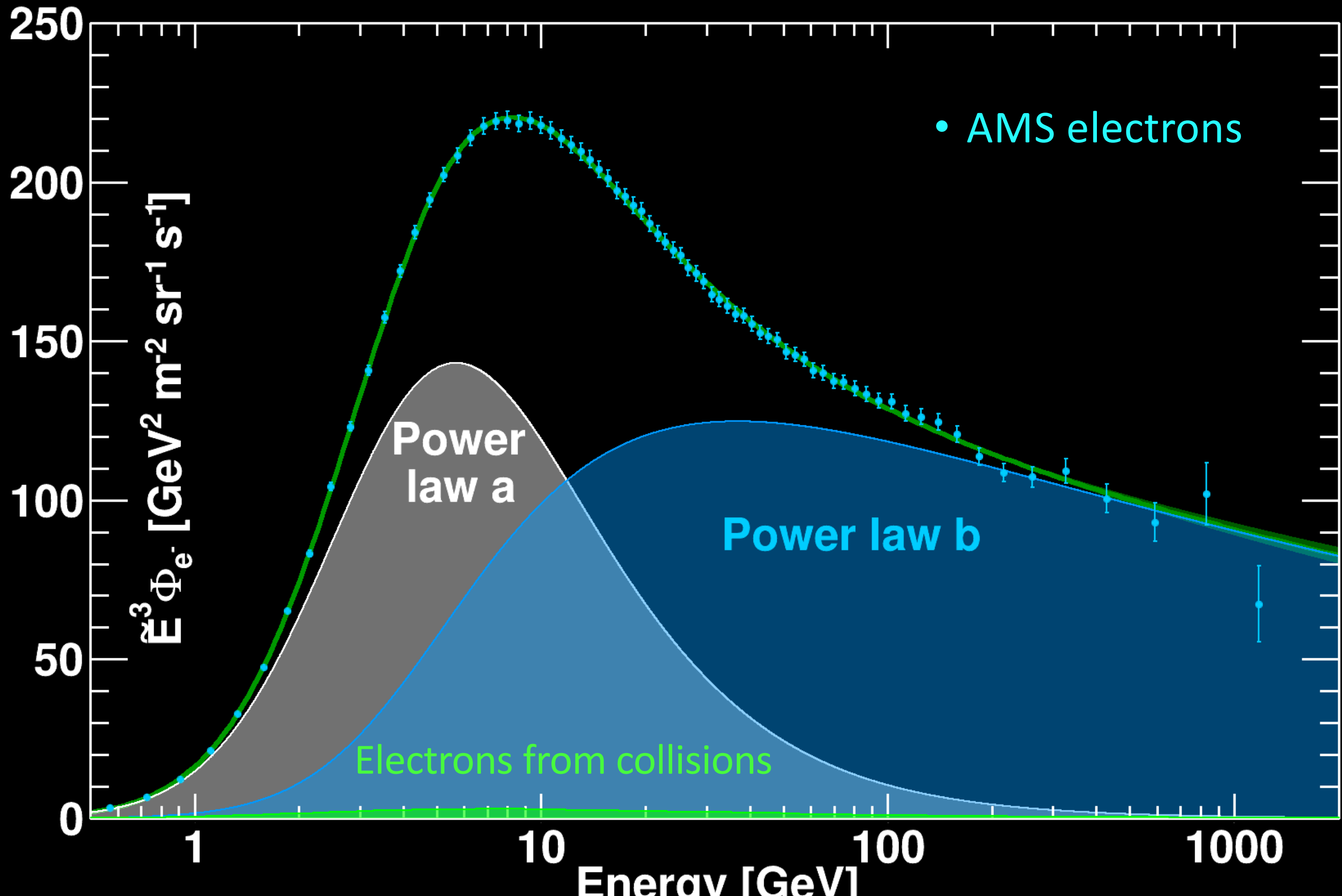
$$\Phi_{e^-}(E) = S(E)\left[C_a\left(\hat{E}/E_a\right)^{\gamma_a} + C_b\left(\hat{E}/E_b\right)^{\gamma_b}\right]$$

Solar & low-energy

Power law *a*

Power law *b*

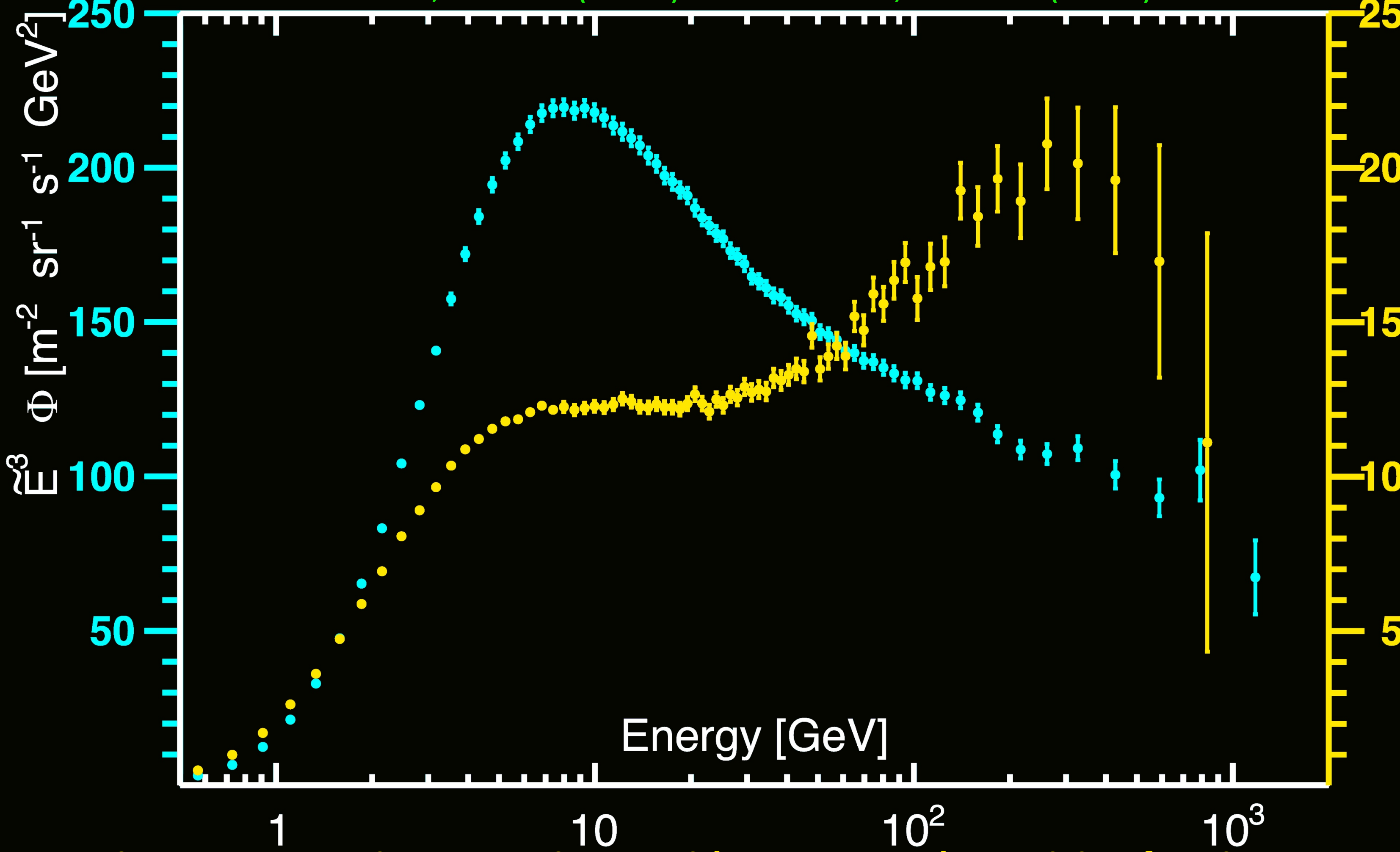
What is the origin of power law a and power law b?



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)

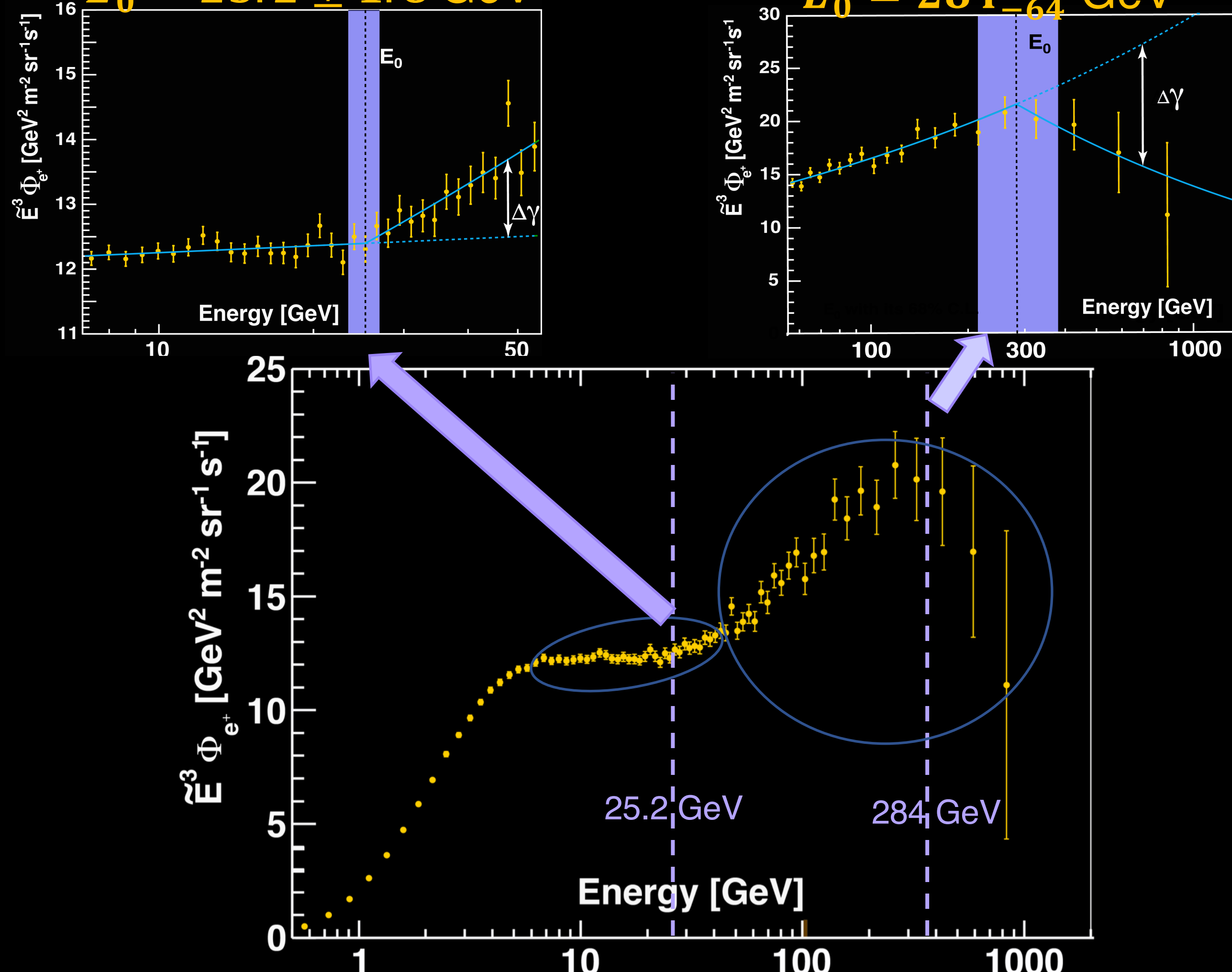


Positron spectrum is not consistent with pure secondary origin of positron in cosmic ray.

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** $\boldsymbol{E_0 = 25.2 \pm 1.8}$ GeV

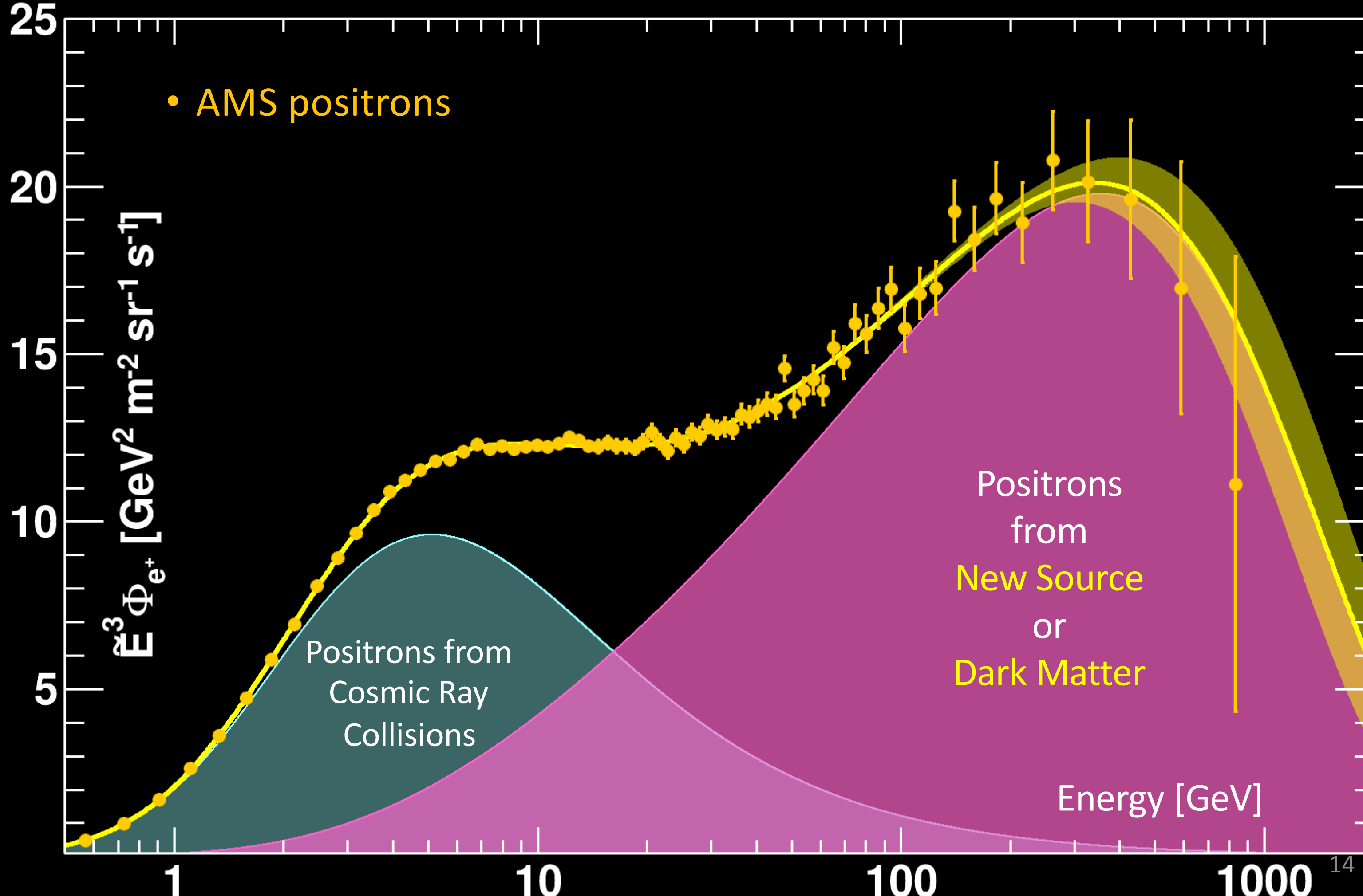
(b) A sharp drop-off at $\boldsymbol{E_0 = 284^{+91}_{-64}}$ GeV



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.

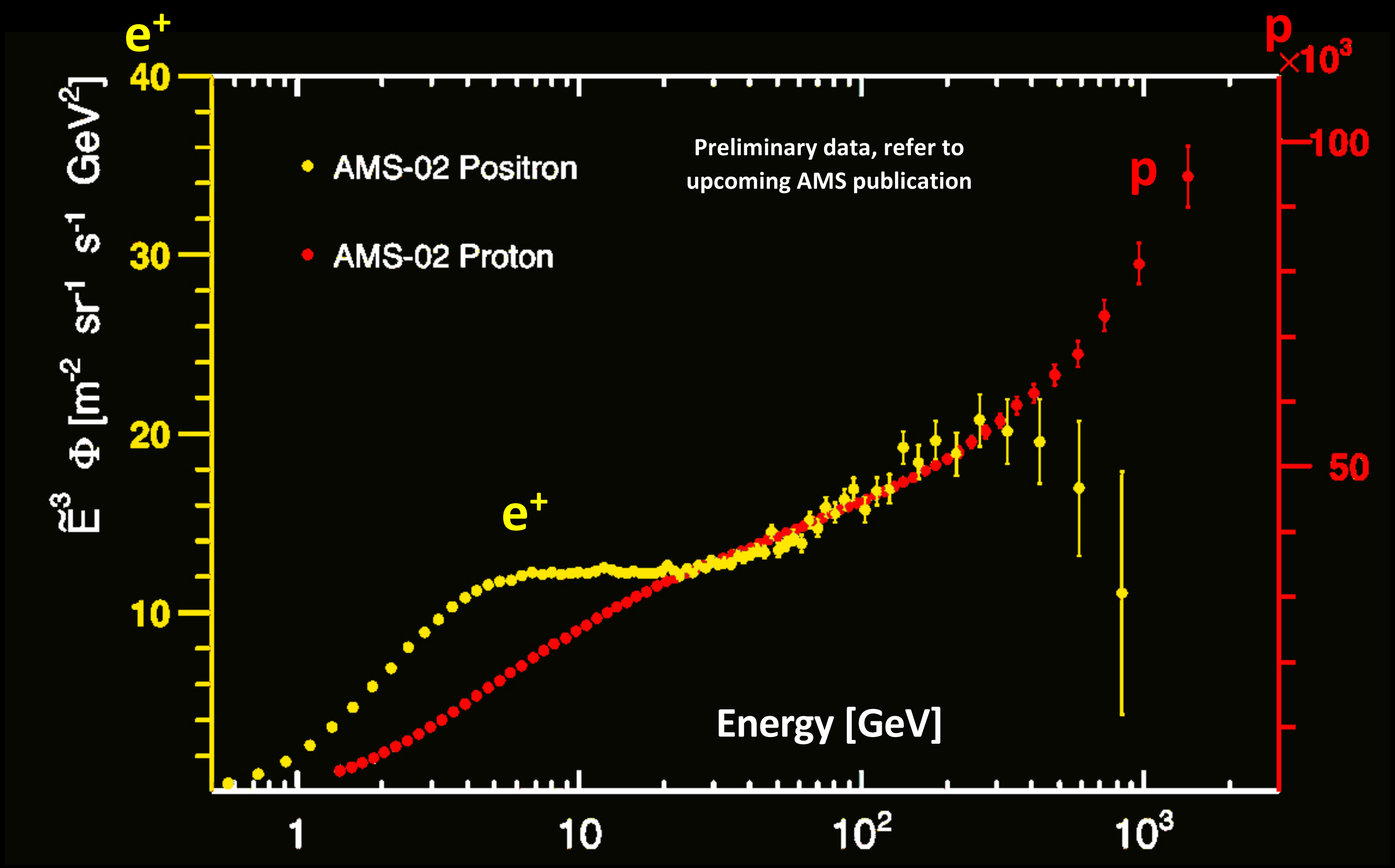
Collisions New Source or Dark Matter

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



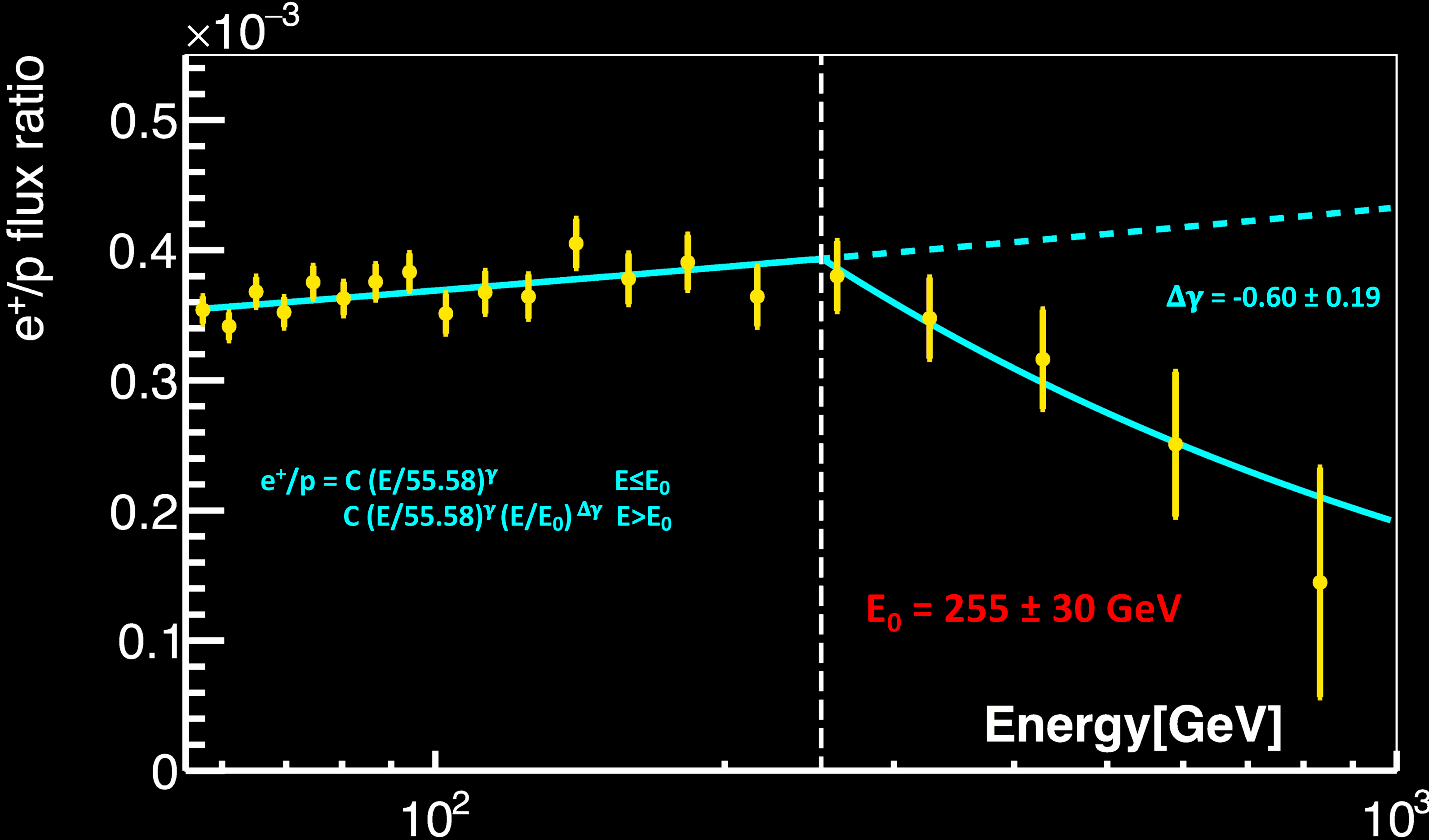
The Spectra of Protons and Positrons

- **Protons and positron have very different origin and propagation history:**
  - Secondary positrons: softer than proton due to diffusion and energy loss



- **From ~60 GV , Positron and Proton have very similar rigidity dependence**
- **Starting from ~280 GeV, two flux start to show significant deviation: Positron flux shows drop-off**

Positron-to-Proton Flux Ratio



- From ~60 GeV , Positron and Proton have very similar rigidity dependence
- Starting from ~250 GeV, positron to proton flux ratio shows drop-off
- These behavior are not explained by current CR models: Primary source of High energy positron with finite energy cutoff.

Antiproton Measurements with AMS

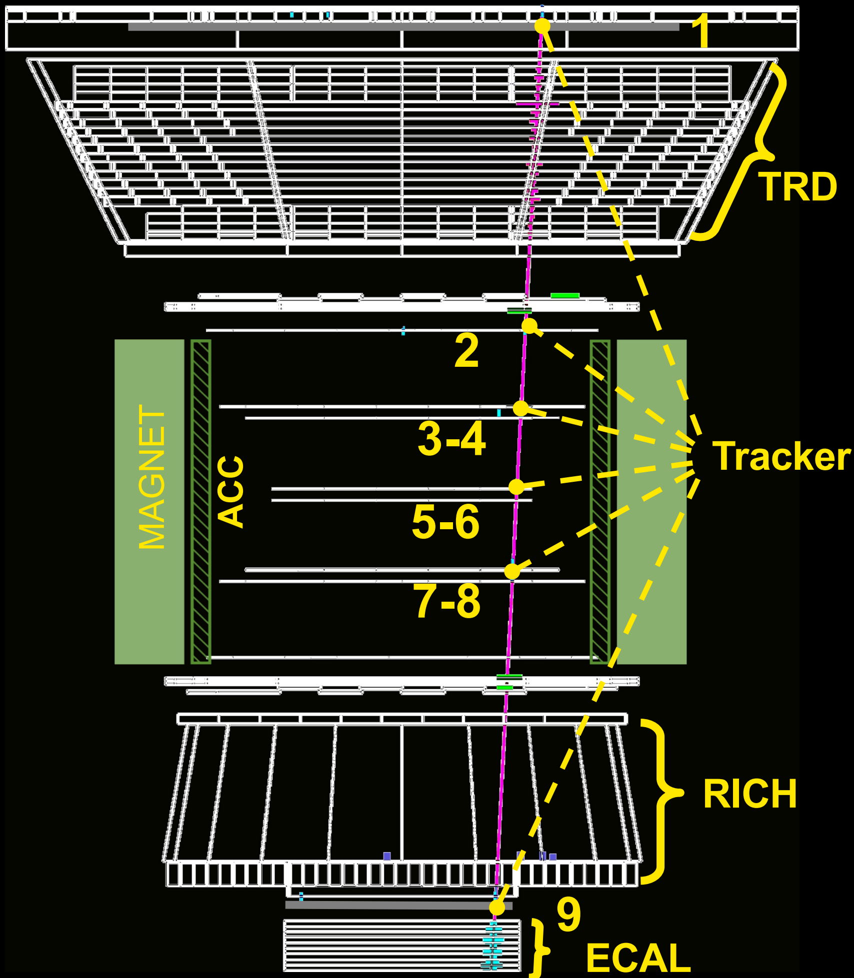
The Antiproton Flux is ~10^{-4} of the Proton Flux.

A percent precision experiment requires background rejection close to 1 in a million

- **Tracker:** Measure rigidity, separate antiprotons from protons
- **TRD & ECAL:** reject electron background
- **TOF & RICH:** select down going particle and measure velocity

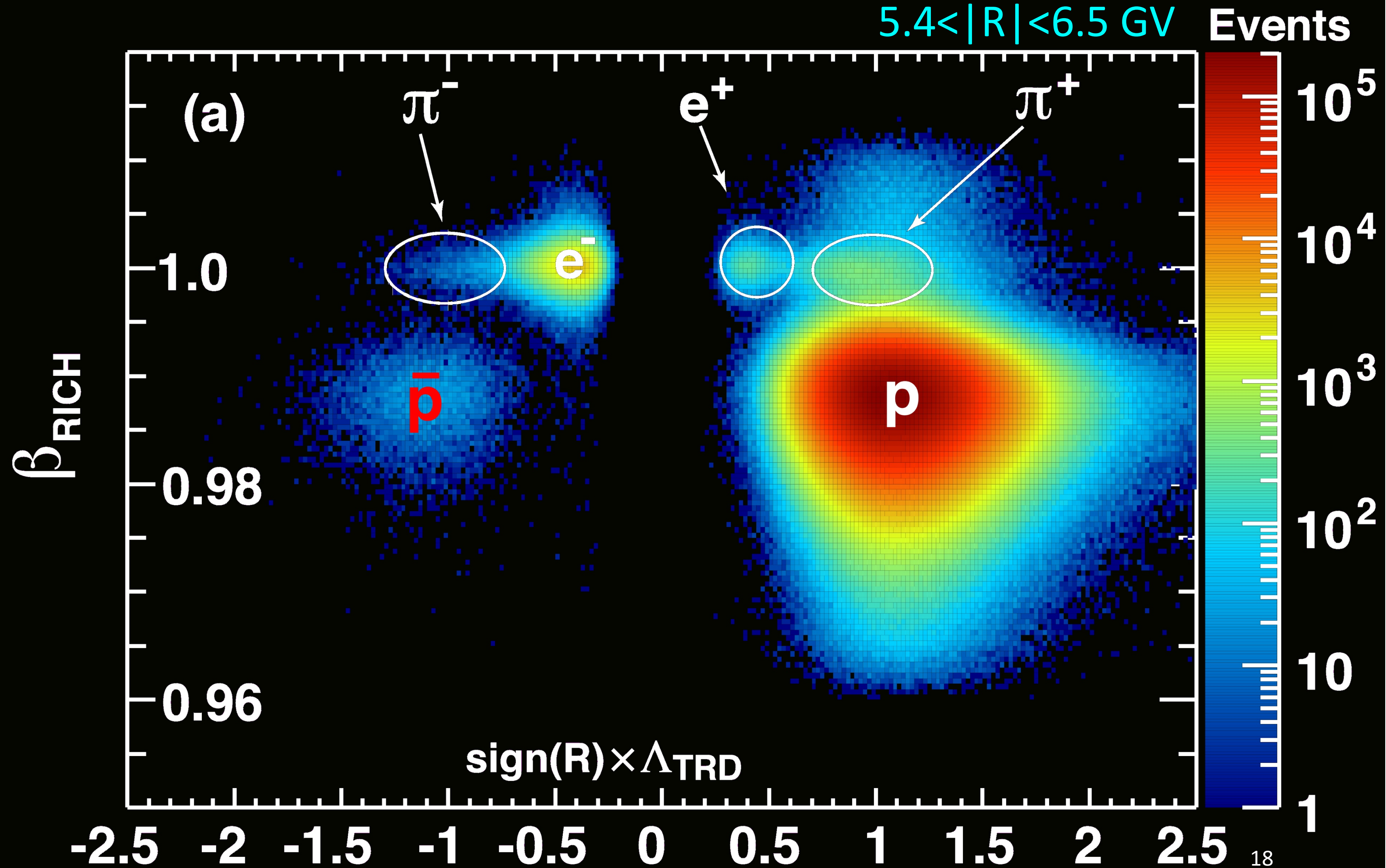
- A charge confusion estimator Λ_{CC} was built with information from tracker and TOF, to reject protons measured as negative rigidity.

R = −363 GV antiproton



Antiproton Identification

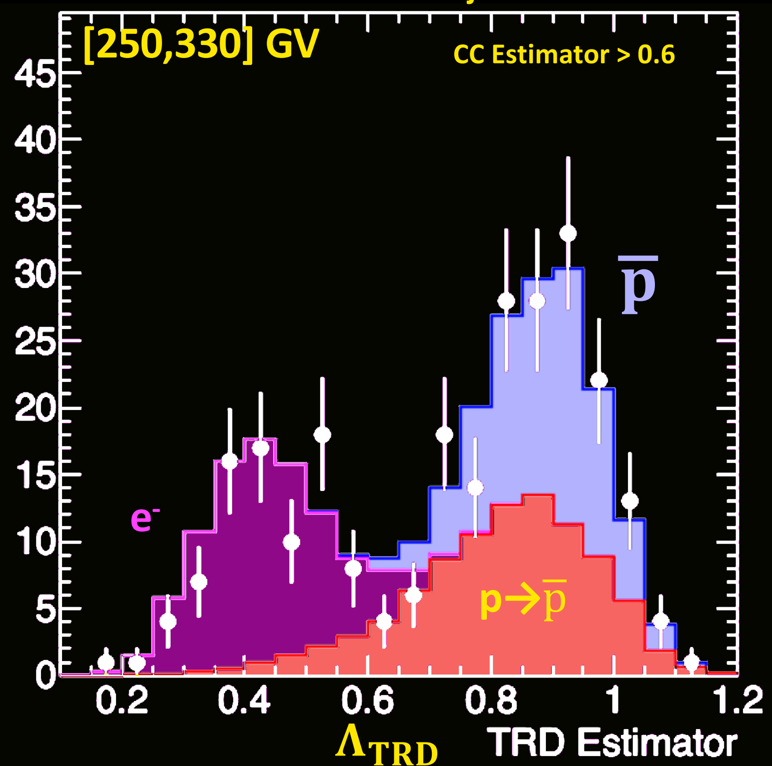
Particle identification with multiple subdetectors



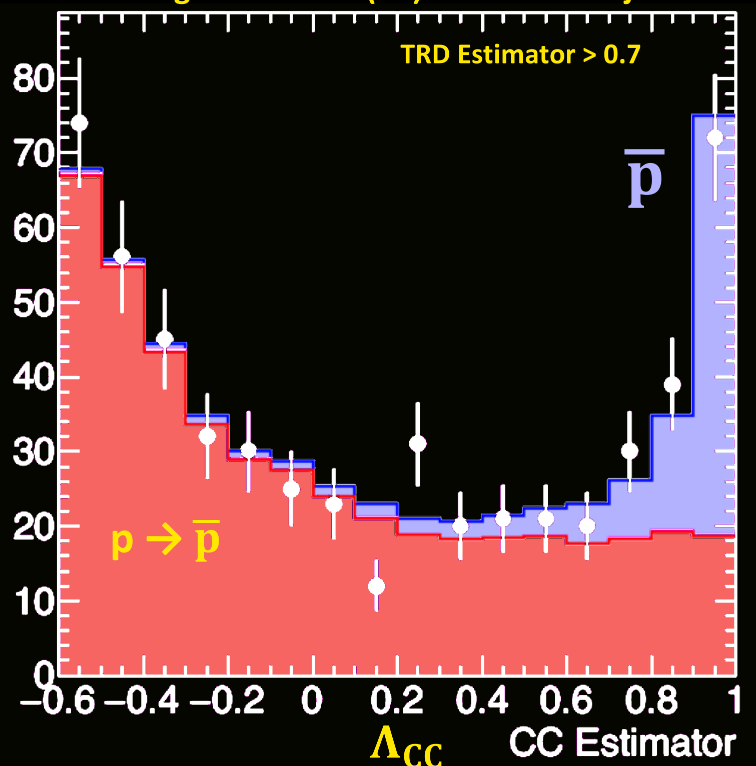
Antiproton identification at High Energy

- At high rigidities, number of antiprotons are obtained by a fit to data sample in ($\Lambda_{TRD} - \Lambda_{CC}$) plane
- Precision determination of Signal and Background events:
  - Antiproton Signal are clearly identified in the signal region
  - Electron : identified by TRD estimator Λ_{TRD}
  - Proton Charge Confusion: identified by Charge Confusion estimator

TRD Estimator Projection



Charge Confusion (CC) Estimator Projection

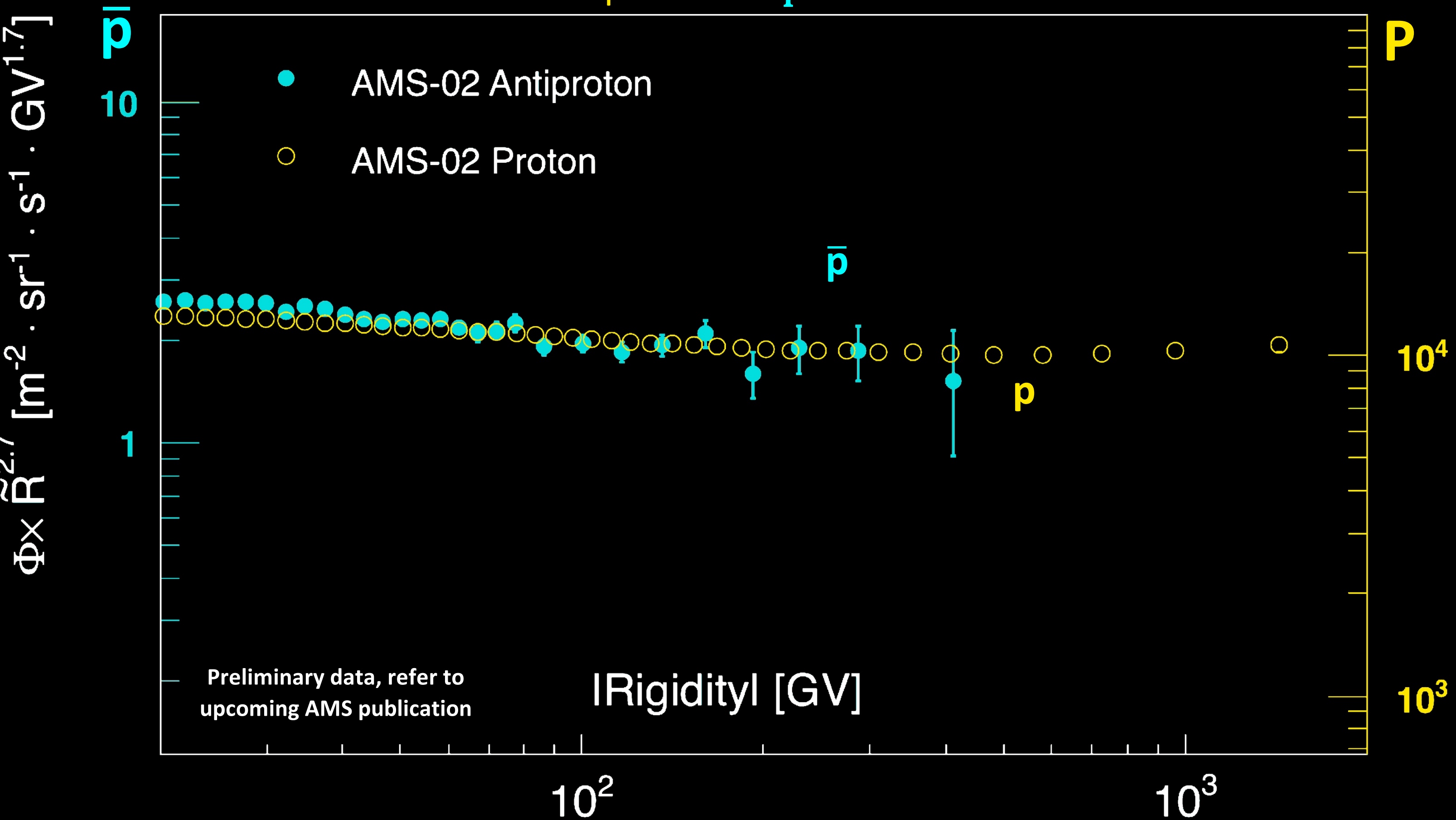


More than 3500 antiprotons above 100 GV
be compared with 3 from all other experiments.

Precision study of the properties of antiproton flux

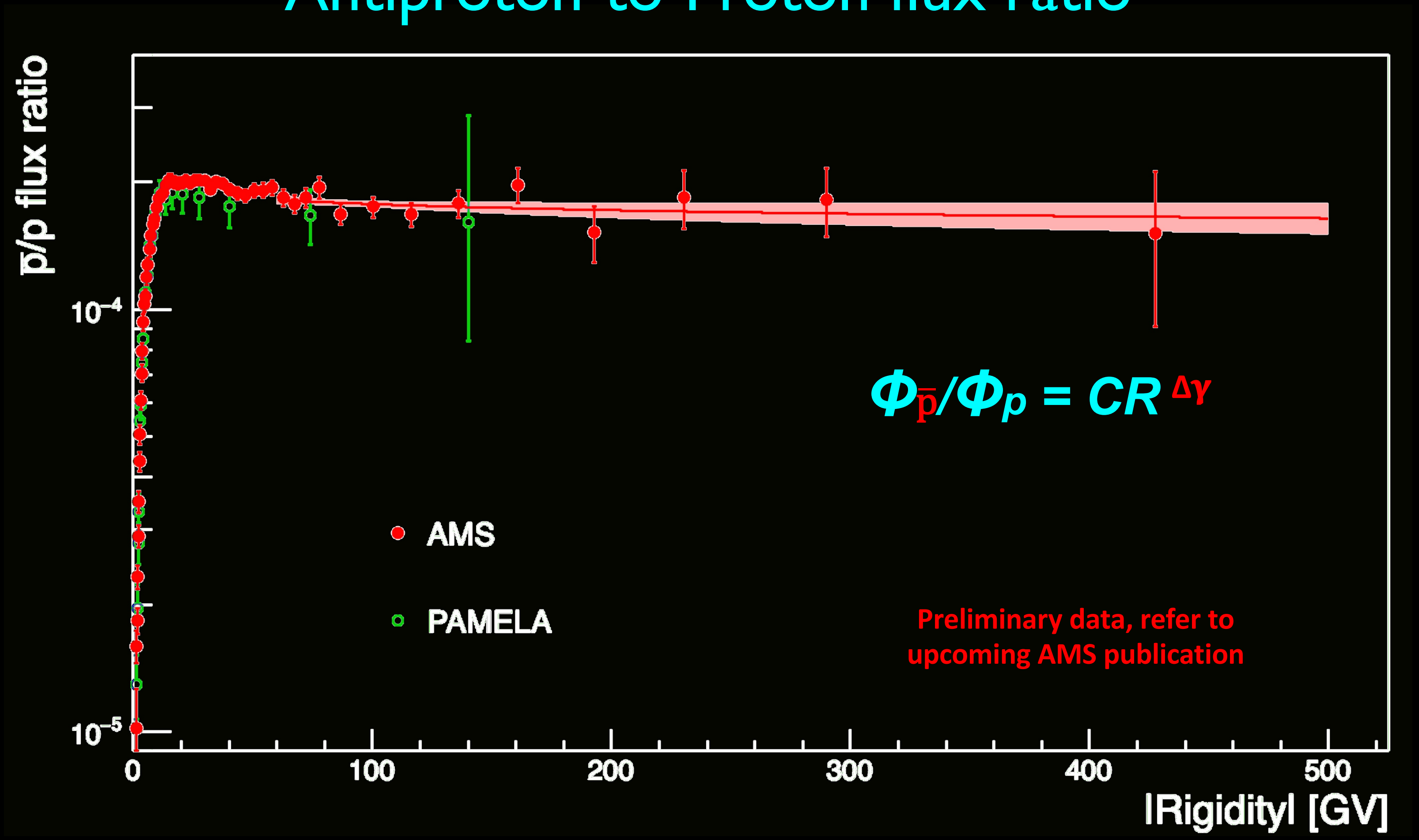
If $\bar{p}$ are secondaries produced in ISM, their rigidity dependence should be different than p:

$p + ISM \rightarrow \bar{p} + \ldots$



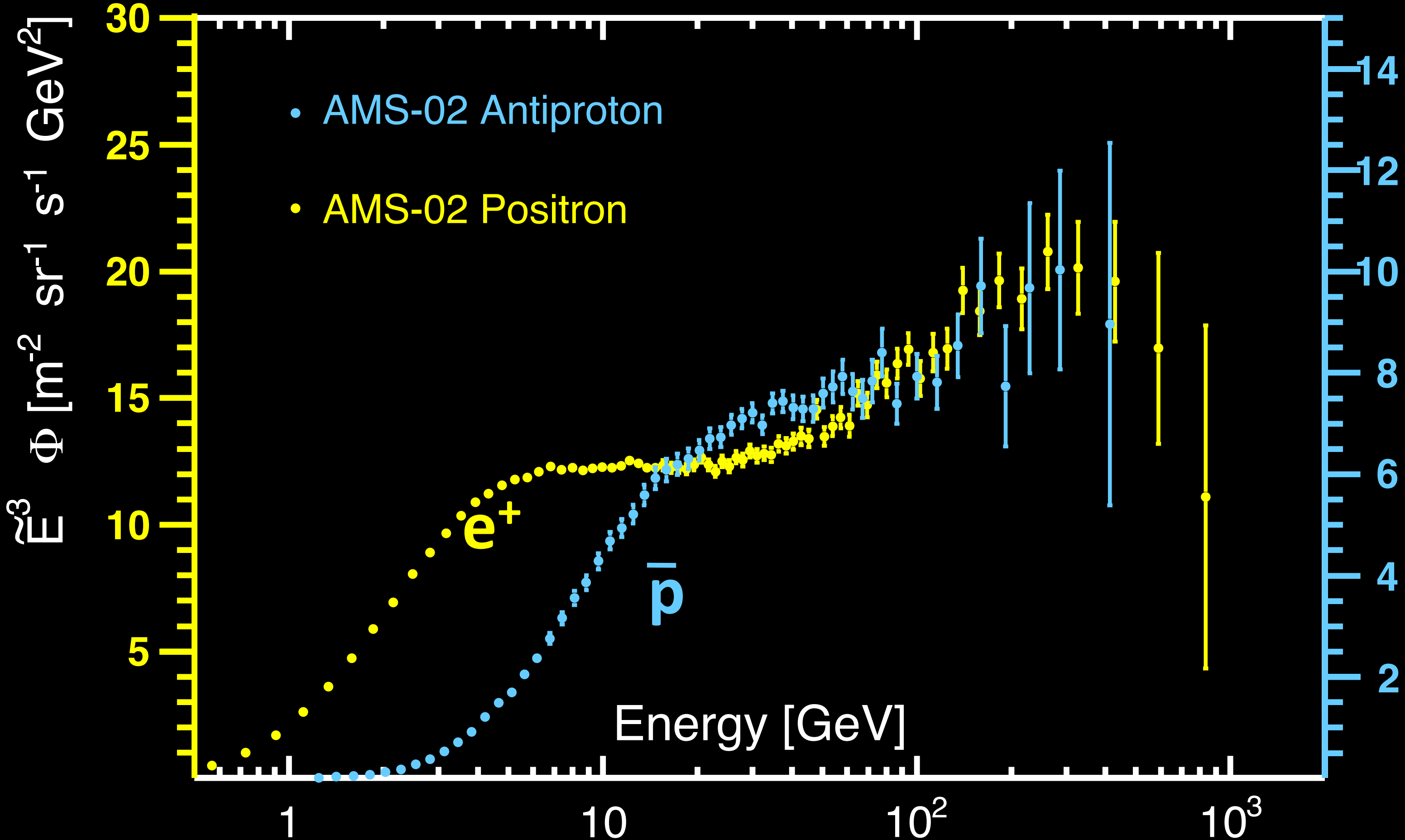
- **AMS observed for the first time that above 60 GV, *p* and $\bar{p}$ have identical Rigidity dependence: Not consistent with only secondary antiproton produced from proton interaction with ISM.**

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 power law index -0.2 to -0.3**

The Antiprotons and Positrons Spectra



- The similarity between antiproton and positron indicate a primary source of positron and antiprotons.
- Their behavior is inconsistent with pulsar origin of positrons

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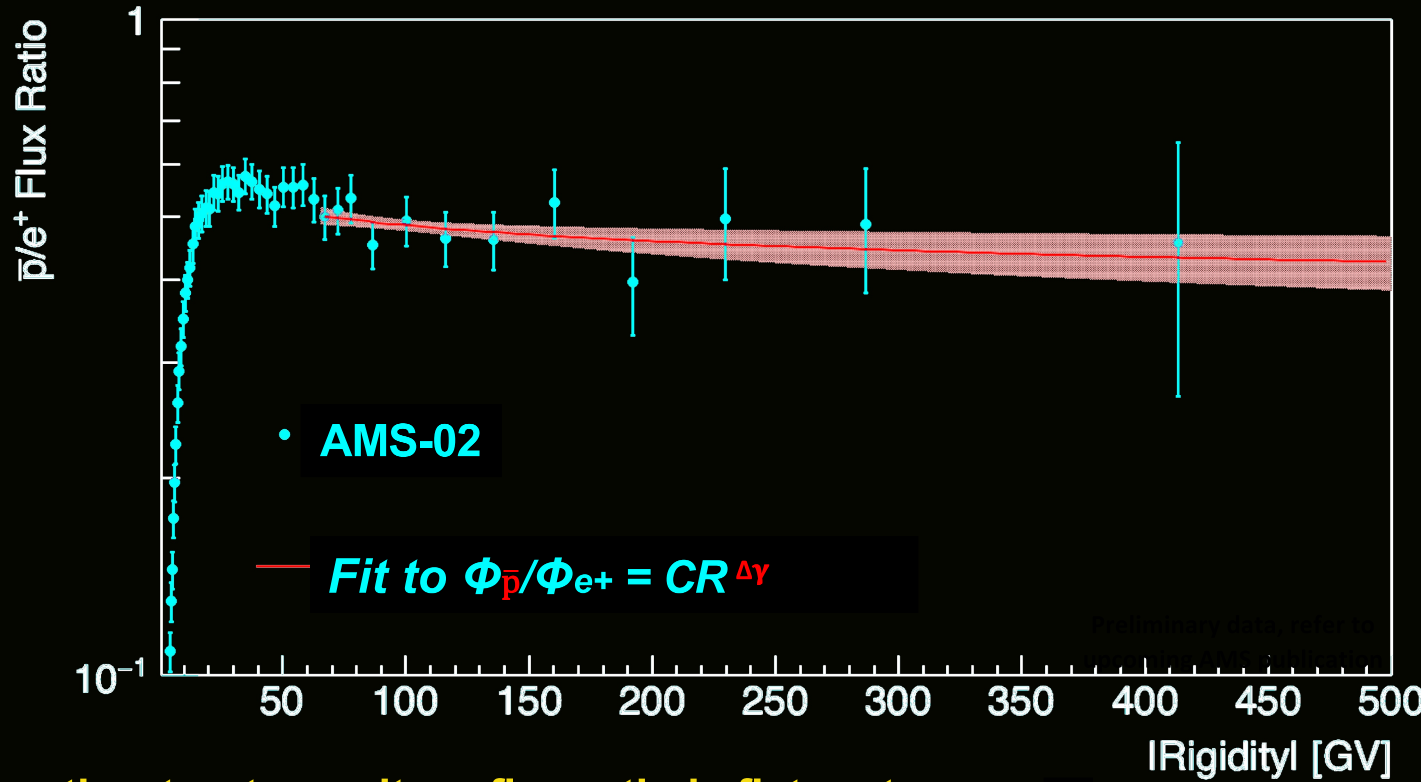
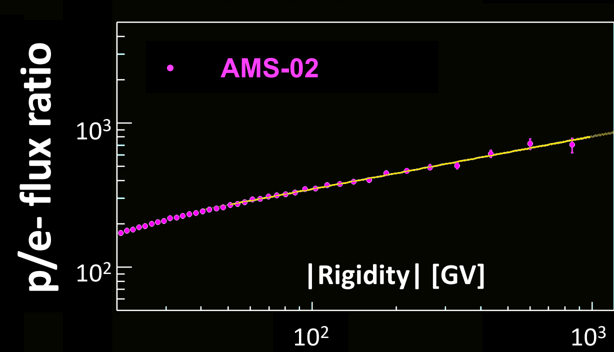
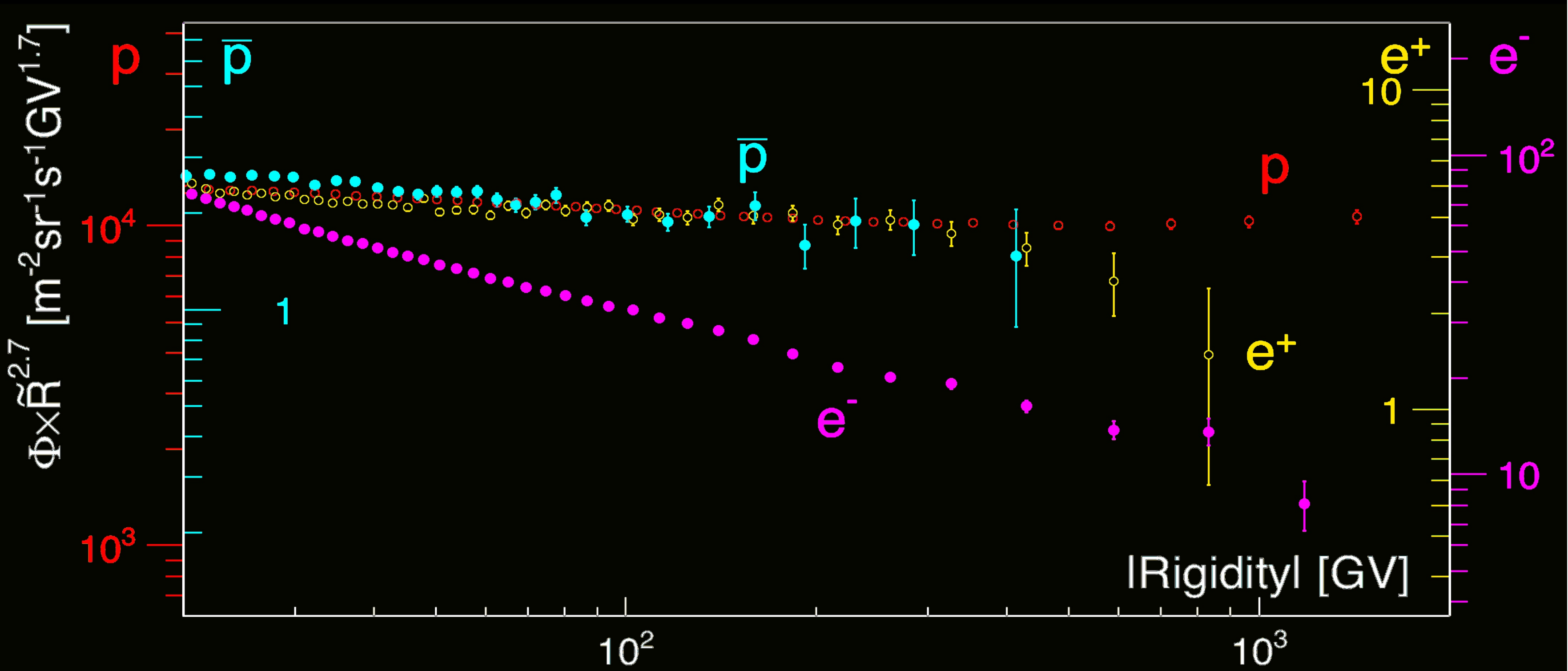
Antiproton-to-positron ratio



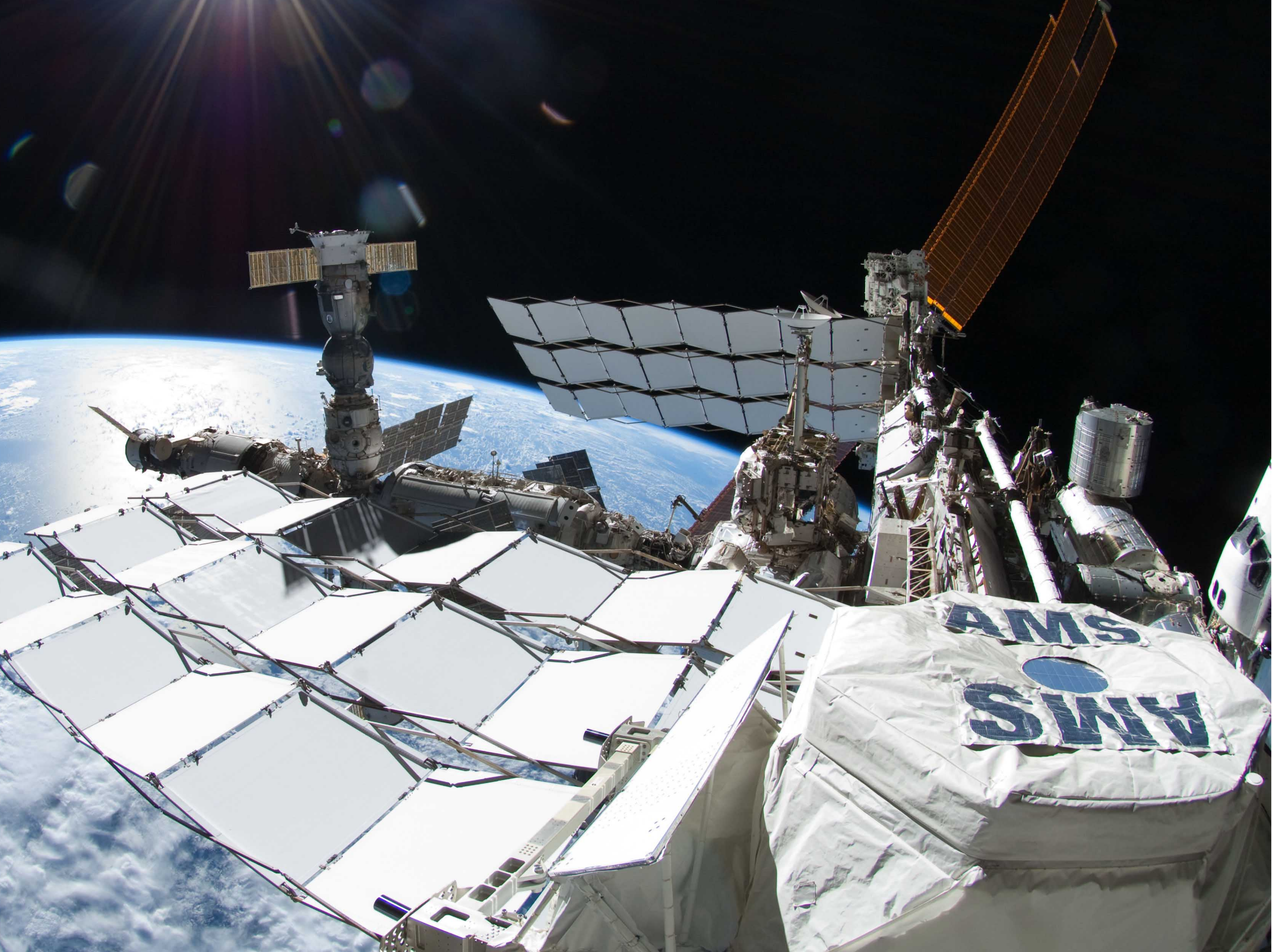
- **The antiproton-to-positron flux ratio is flat up to 525 GV. Fit to a power law in the range [65,525] GV: Δγ=-0.07±0.07, consistent with 0.**
- **In contrast: electron have much softer spectrum and the p/e- flux ratio is continuously rising.**
- **Not compatible with common understandings of secondary origin of positron and antiprotons**



Properties of elementary particle fluxes



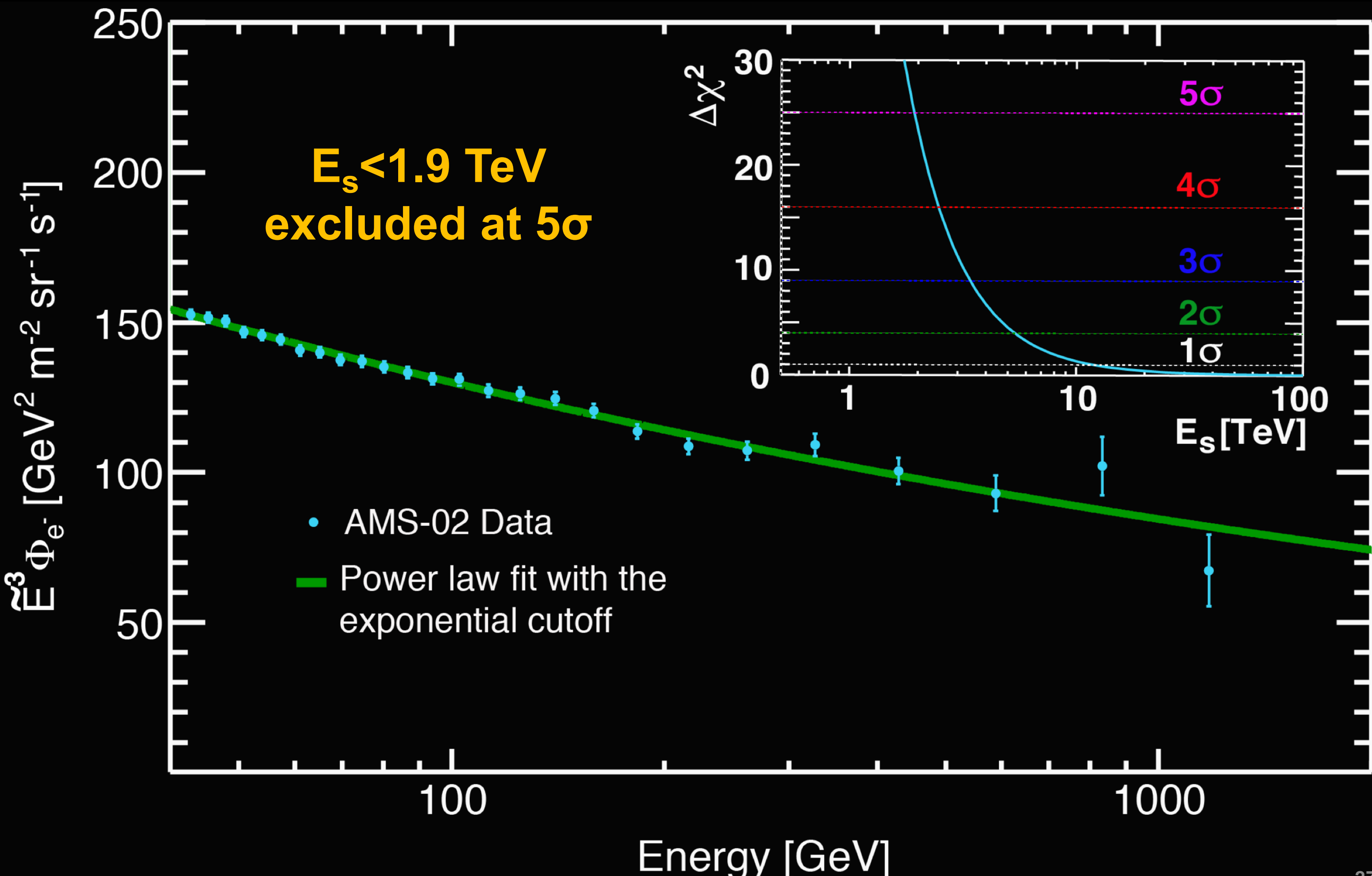
1. The spectra of positrons, antiprotons, and protons are nearly identical in a large energy range [60, 500] GV
2. Positron spectrum shows a sharp drop-off above ~280 GeV.
3. Electron spectrum exhibits different rigidity dependence.


AMS

Backup

No source term in the electron spectrum

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



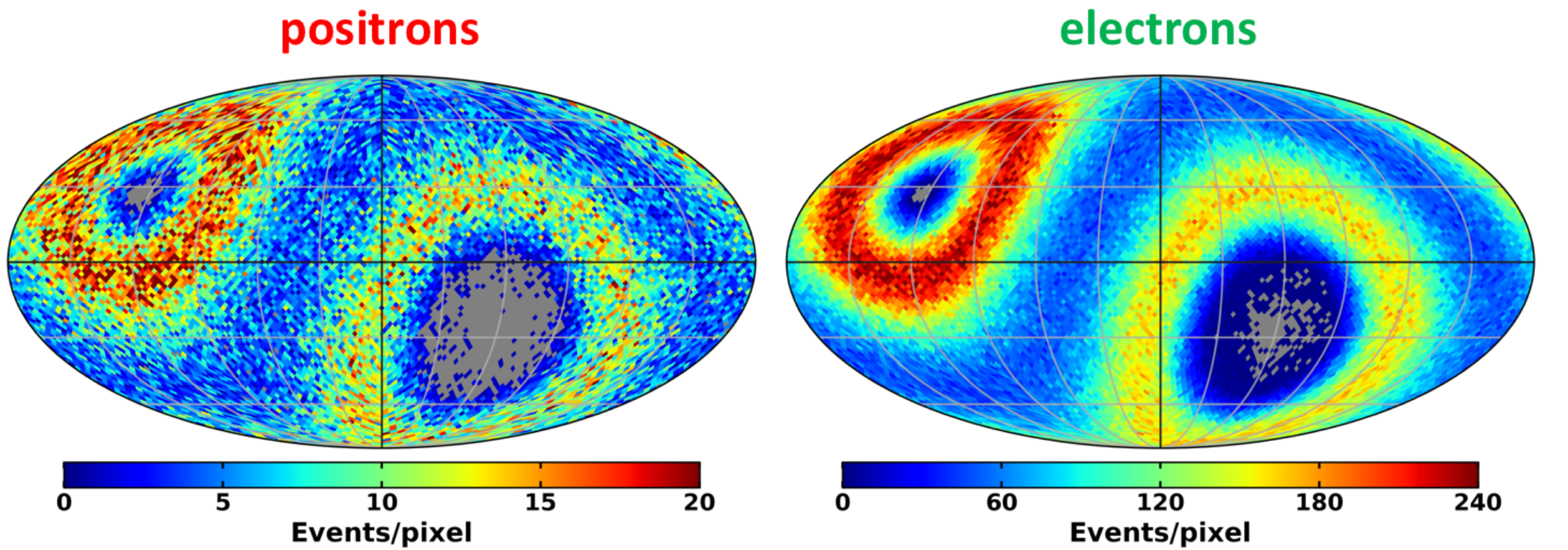
Positron Anisotropy and Dark Matter

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

$$\delta = 3\sqrt{C_1/4\pi}$$

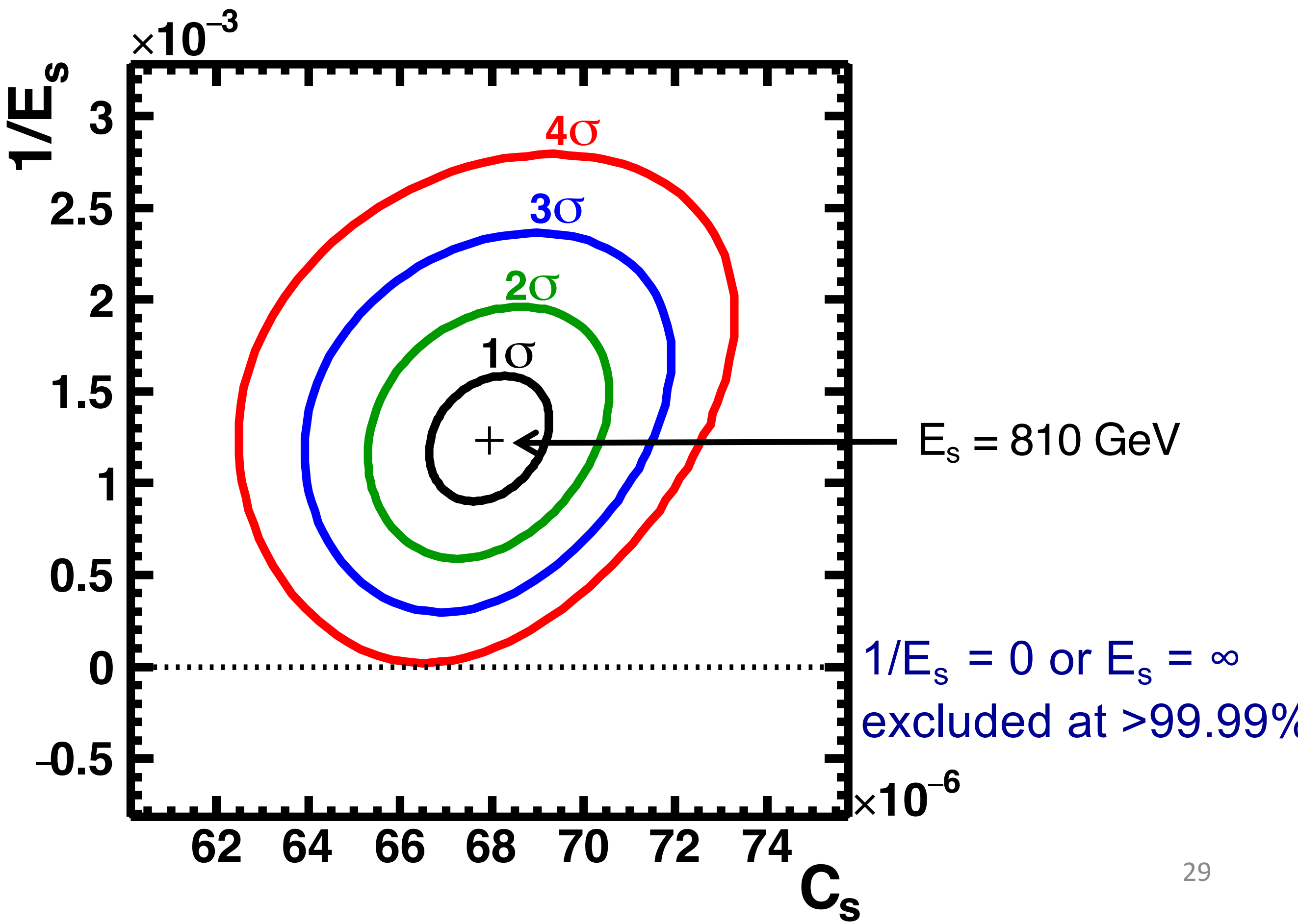
C_1 is the dipole moment



Currently at 95% C.L.: **positrons: δ < 0.019**
for 16<E<350 **electrons: δ < 0.005**

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

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



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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