Properties of Elementary Particle Fluxes in Primary Cosmic Rays Measured with the Alpha Magnetic Spectrometer on the International Space Station

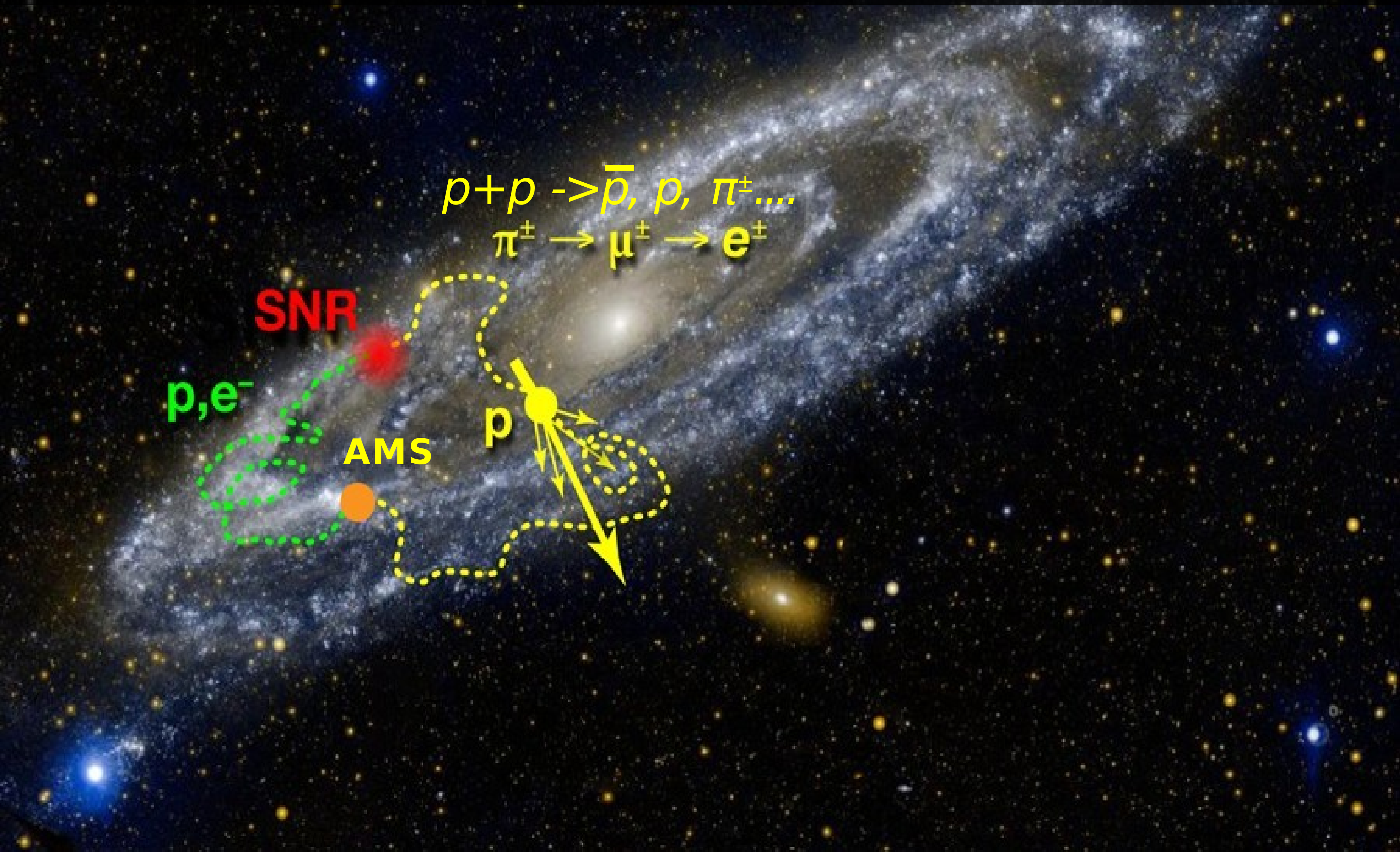
7th Roma International Conference on Astroparticle Physics
05/09/2018 - Roma

Francesco Nozzoli
INFN-TIFPA

Elementary Particles in Cosmic Rays

e^- and p are produced and accelerated from SNR

Collision of "ordinary" Cosmic Rays produce secondary e^+, e^-, $\bar{p}$



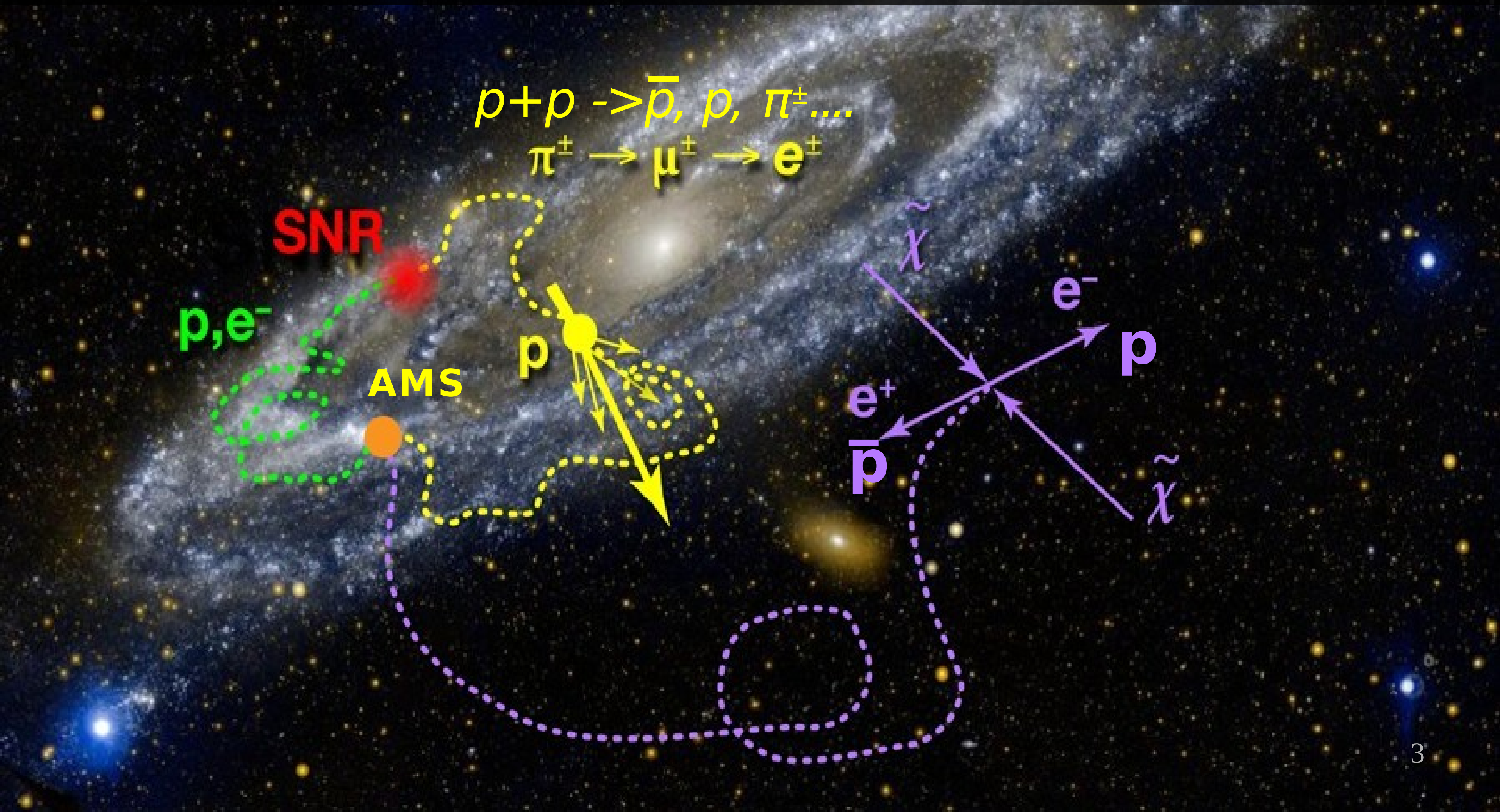
Elementary Particles in Cosmic Rays

e^- and p are produced and accelerated from SNR

Collision of “ordinary” Cosmic Rays produce secondary e^+, e^-, $\bar{p}$

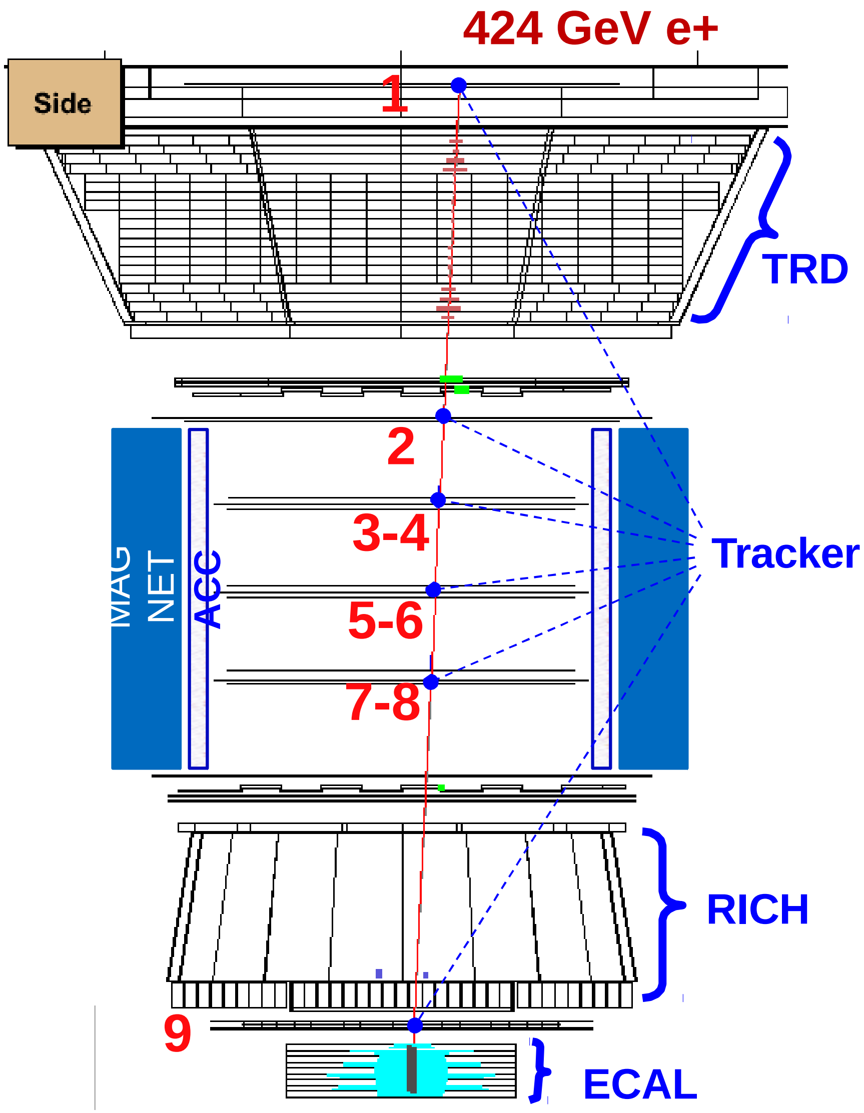
Among many possible mechanisms:

Collisions of Dark Matter will produce additional e^+, e^- , $\bar{p}$



Precision measurement of elementary particle fluxes

- **AMS: General purpose detector with multiple redundant particle identification**
- **The TRD and the ECAL provide independent rejection power**
- **Tracker and Magnet measures rigidity and charge sign, and compare rigidity measurement with energy measured in ECAL**
- **Four species are measured up to TeV Range simultaneously in the same detector**



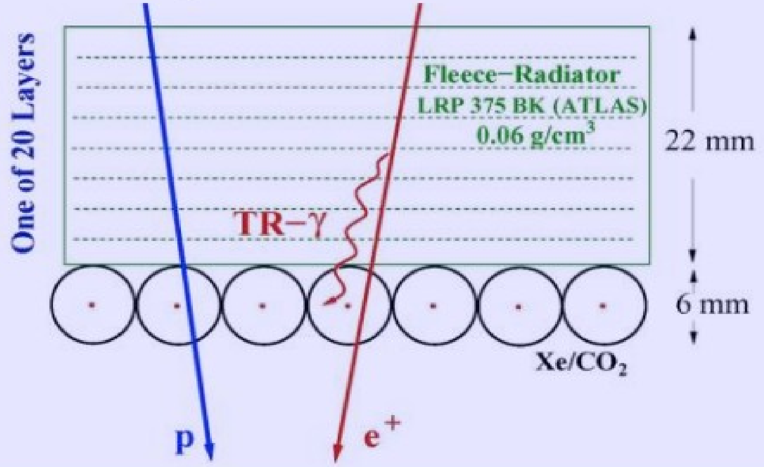
We have analyzed：

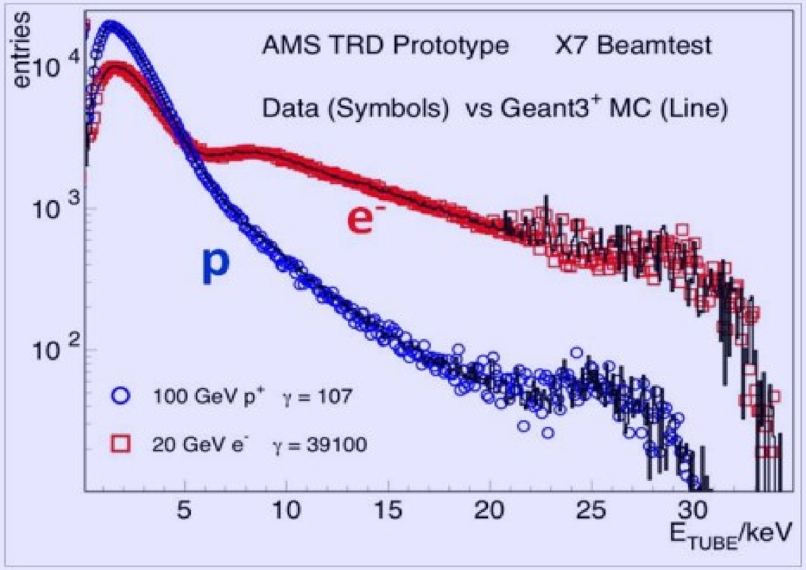
25 million of $e^{\pm}$ events
2.4 billion proton, 350 thousand p-bar

Unprecedented data sample to study the properties of these particle fluxes.

TRD Transition Radiation Detector

Identifies nuclei by dE/dX and e± by transition radiation

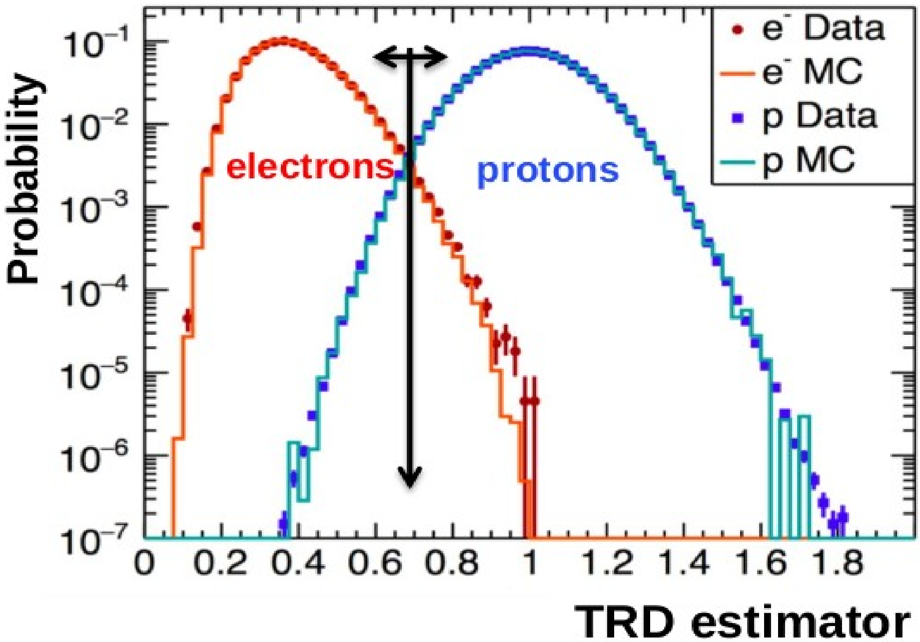




N = 20 layers

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

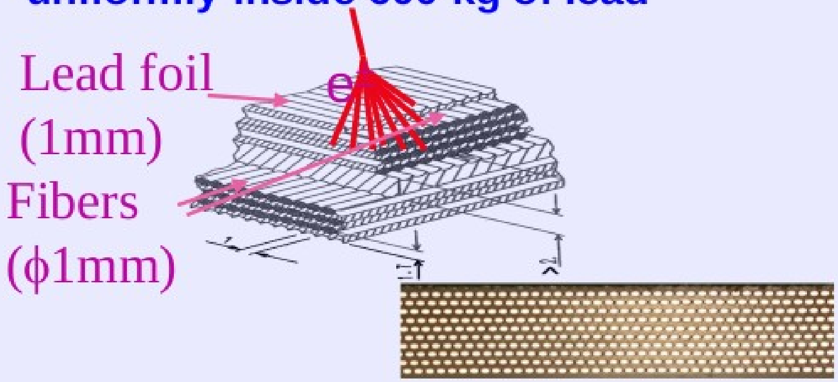
TRD estimator = -ln(P_e/(P_e+P_p))

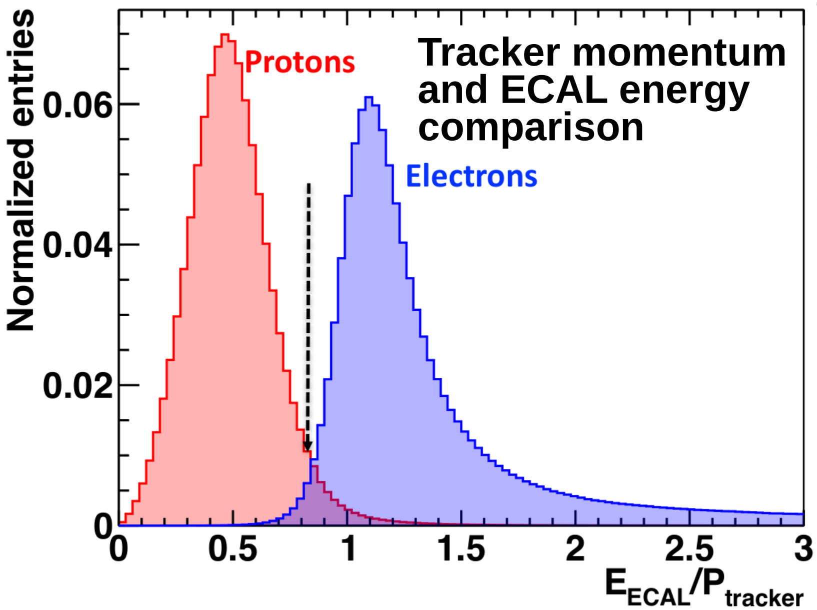


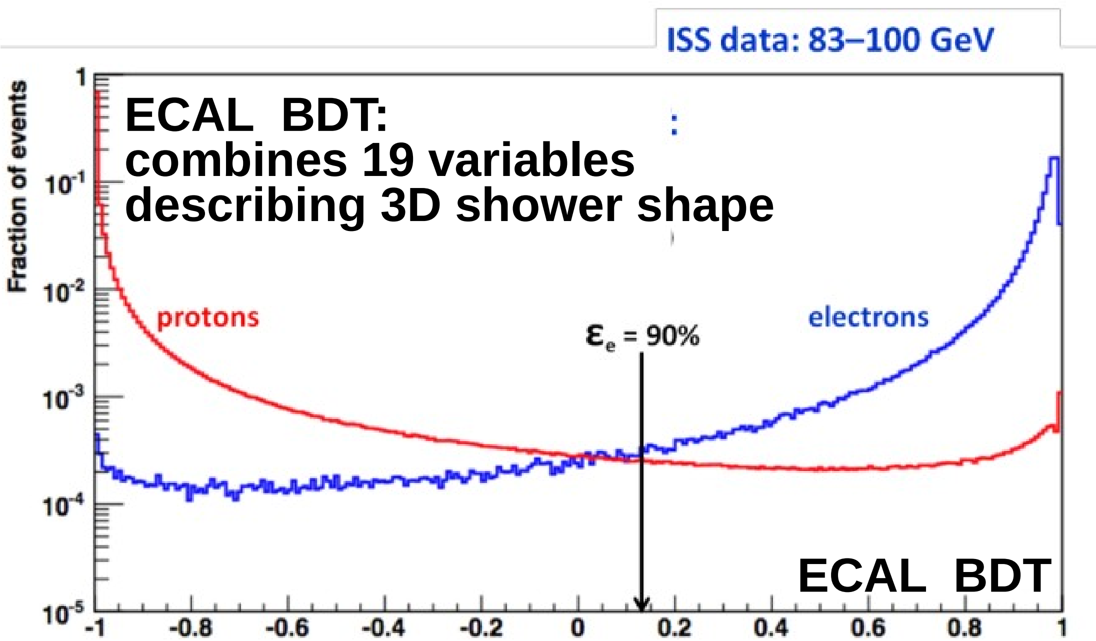
ECAL Electromagnetic Calorimeter

3-dimensional measurement of the shower

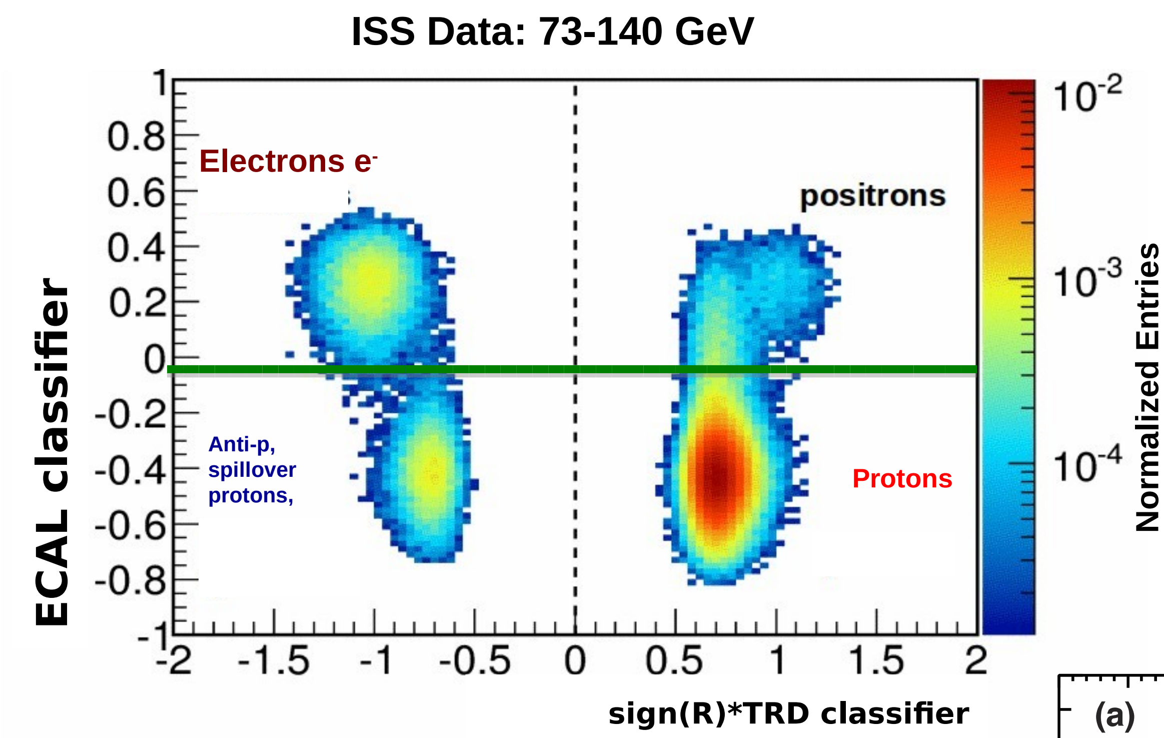
50 000 fibers, $\phi = 1$ mm distributed uniformly Inside 600 kg of lead







AMS: Z=1 Particle Identification



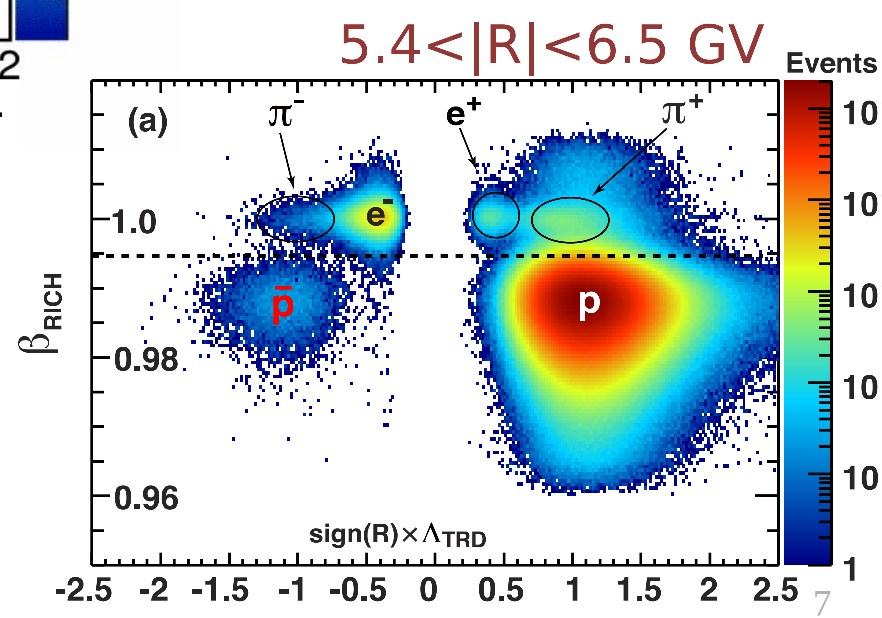
p/e⁺ separation

@ high Energy:

- **ECAL** (3D shower shape)
- **TRD** (transition radiation)
- **Tracker** (P vs ECAL energy)

@ low Energy

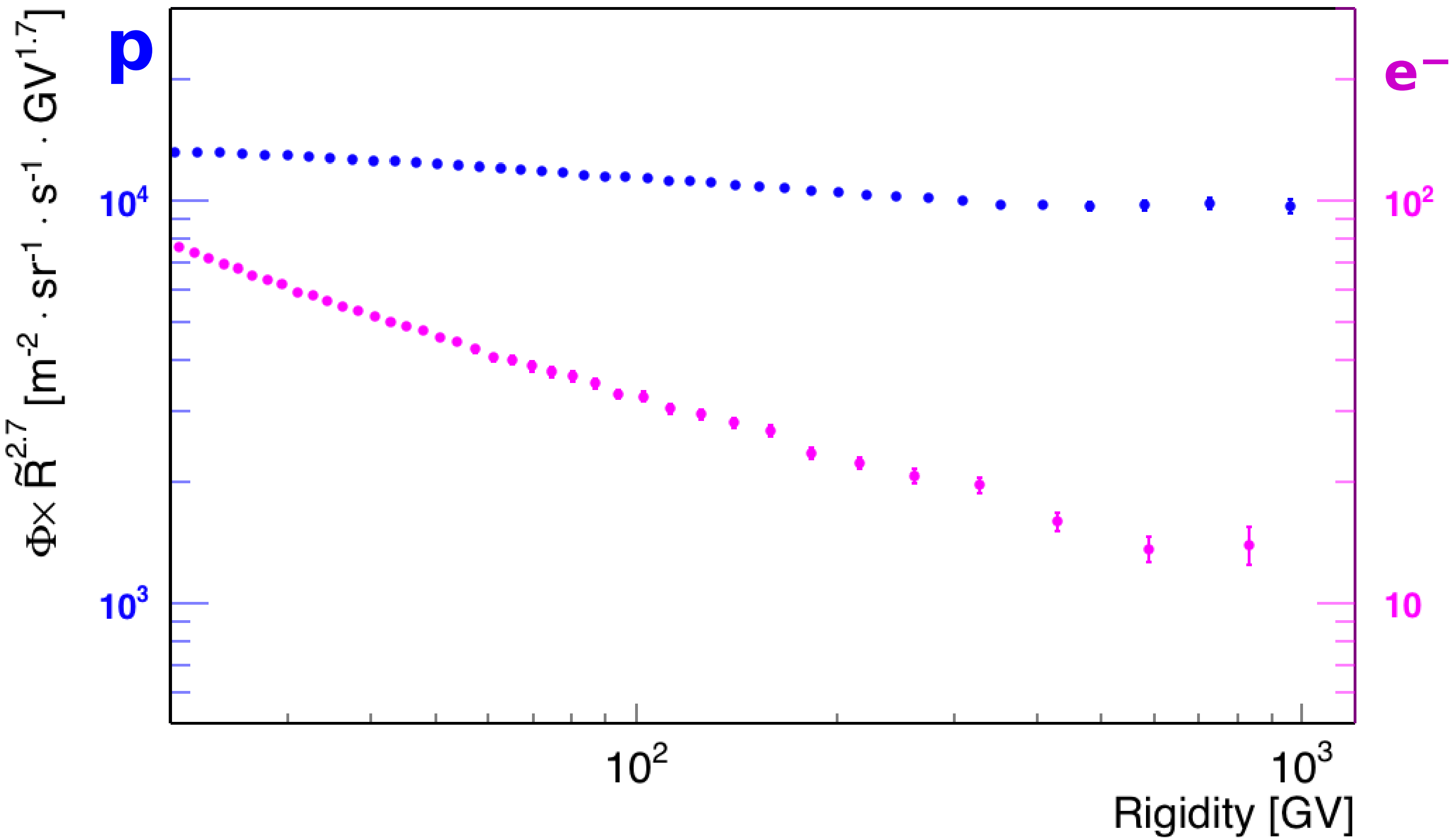
- **Velocity** (RICH or ToF)



AMS redundancy allows elementary particle identification and flux measurements in cosmic rays with unprecedented precision and small systematic errors.

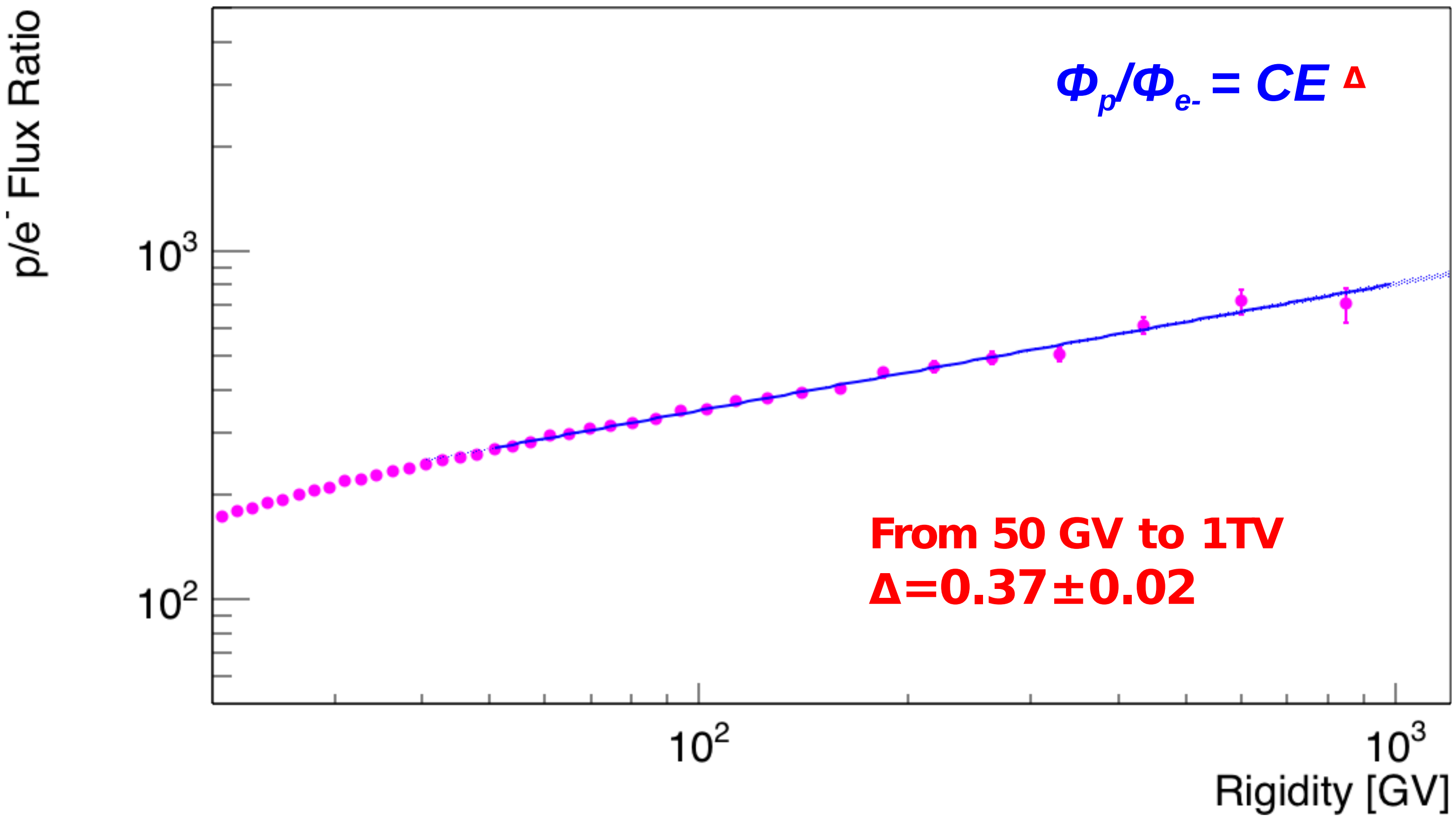
The Spectra of Electrons and Protons

- Protons and electrons are primary cosmic ray produced and accelerated in SNR in similar ways.



- **Electron loss energy much faster than proton during propagation**

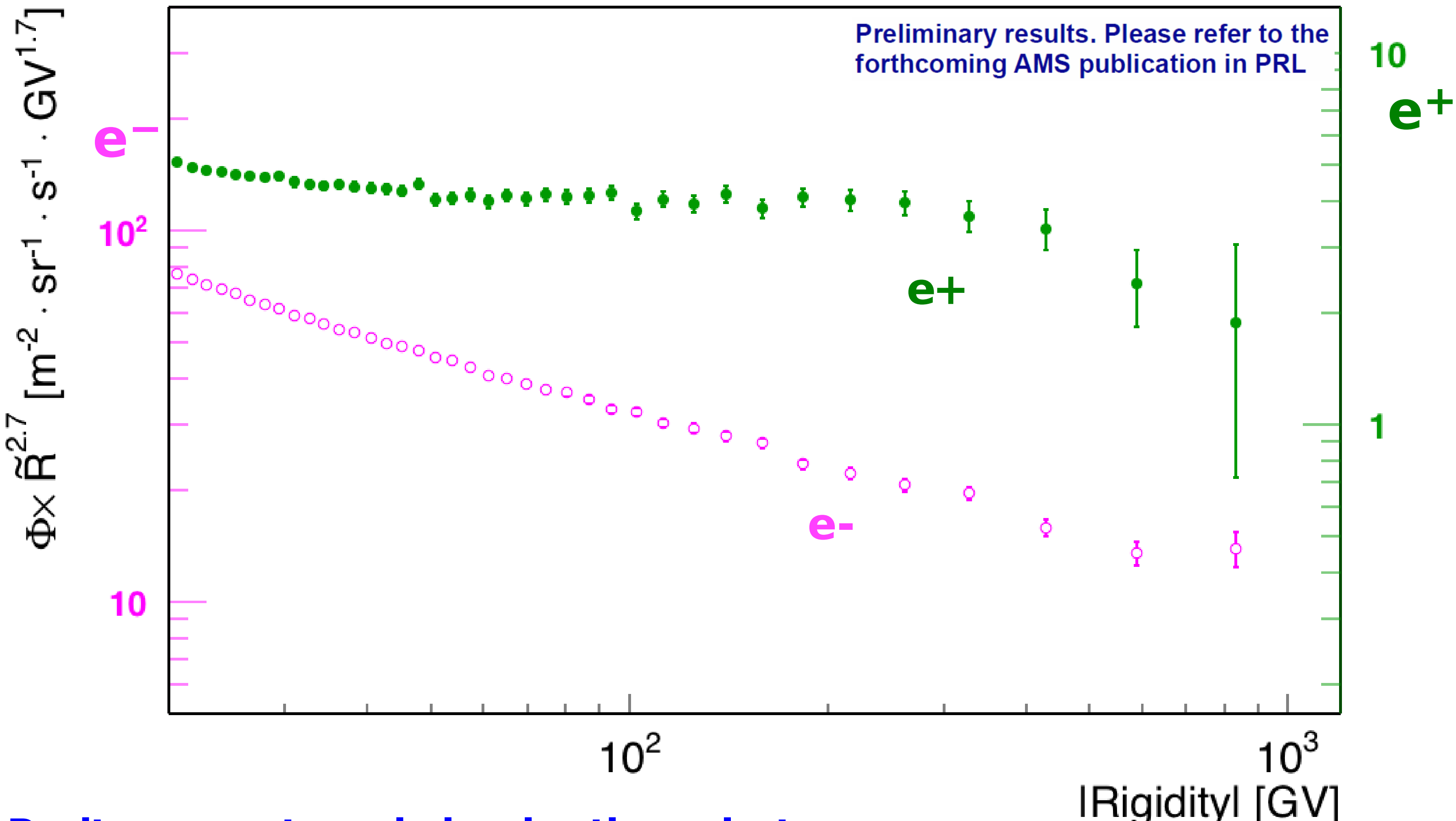
The Spectra of Electrons and Protons



- **The Proton/Electron flux ratio is measured to be a single power law**
- The difference between electron and proton is commonly attributed to the propagation effect in the galaxy

The Spectra of Electrons and Positrons

If e+ are secondaries, their energy dependence should be softer than e-

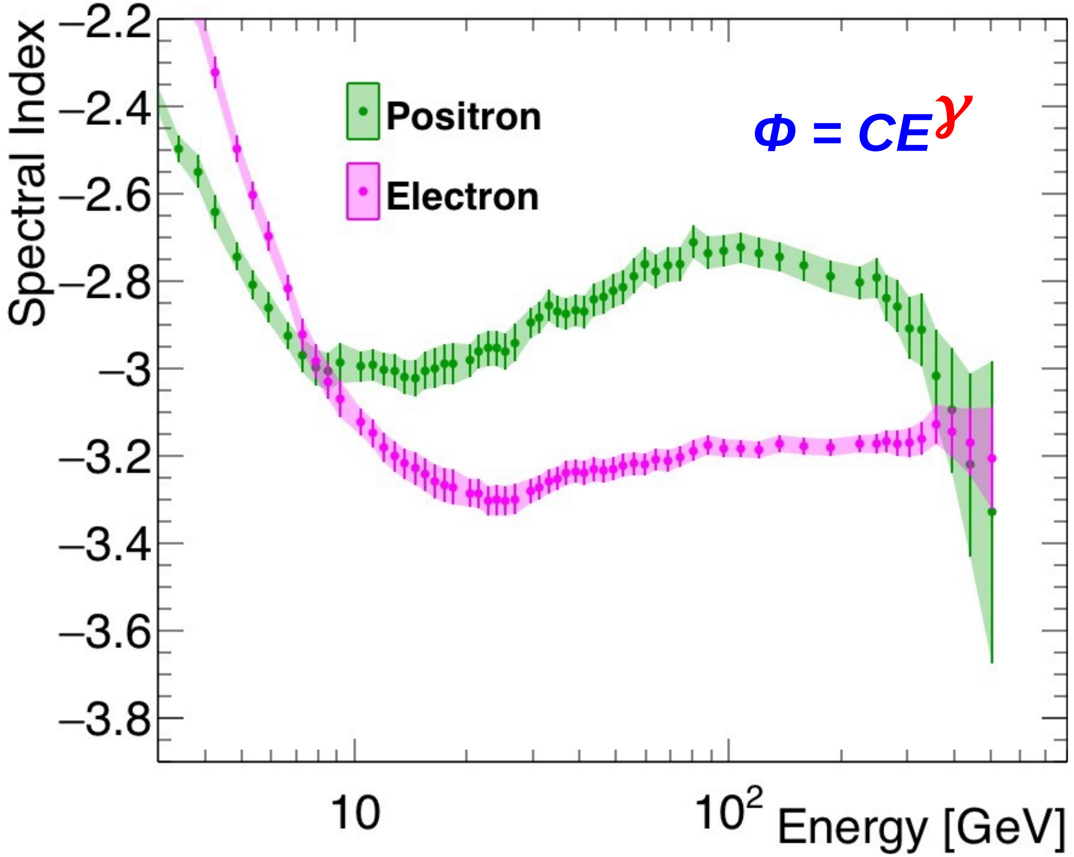


- **Positron spectrum is harder than electron:** Not consistent with pure secondary origin of positron in cosmic ray.
- Both positron and electron can not be described by a single power law behavior.

The Electron and Positron spectral indices

AMS measures the spectral indices as a function of energy:

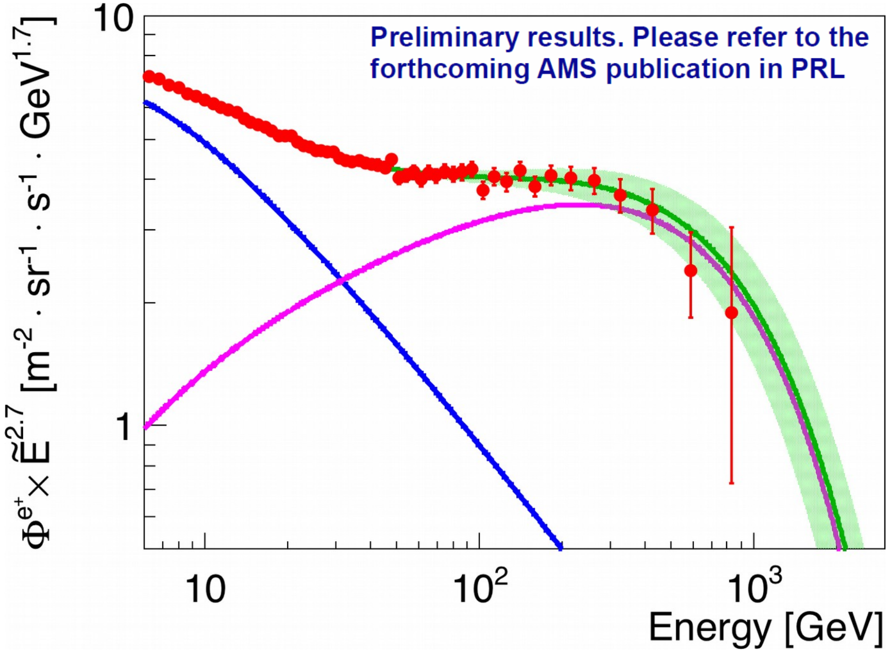
Electron and Positron Fluxes can not be described by a single power law



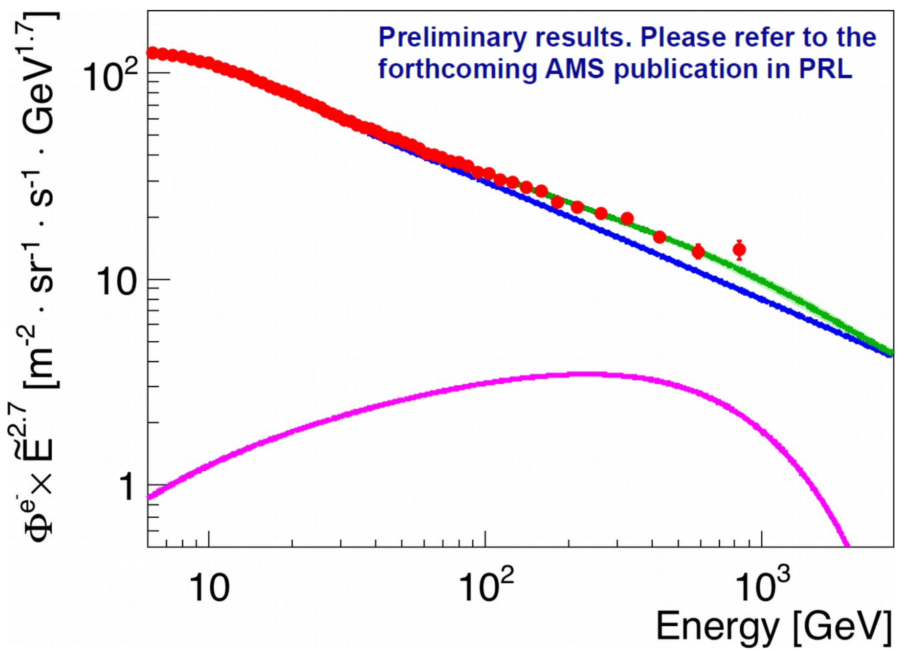
- Positron and Electron both show hardening from low energy
- Positron shows softening/cut-off effect at 300GeV
- **Softening of positron does not correspond to the same softening in electron: Not a propagation effect.**

Primary source of high energy electrons and positrons

$$\Phi_{e+}(E) = \frac{E^2}{\hat{E}^2}\left[C_{e+}\hat{E}^{\gamma_{e+}} + C_S\hat{E}^{\gamma_S}\exp(-\hat{E}/E_S)\right]$$



$$\Phi_{e-}(E) = \frac{E^2}{\hat{E}^2}\left[C_{e-}\hat{E}^{\gamma_{e-}(\hat{E})} + C_S\hat{E}^{\gamma_S}\exp(-\hat{E}/E_S)\right]$$



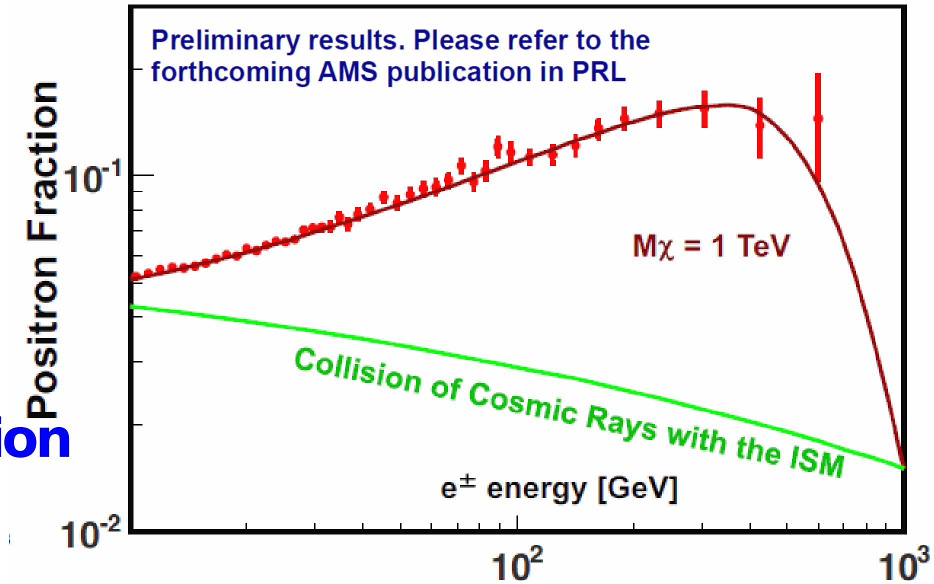
- **Additional source of cosmic ray positron and electron**
- **Energy cut off ~3 sigma significance from infinity**
- **Hardening of positron spectra is more visible due to lower background from secondary positrons.**

Many models proposed to explain the physics origin of the observed behavior

1) Particle origin: Dark Matter

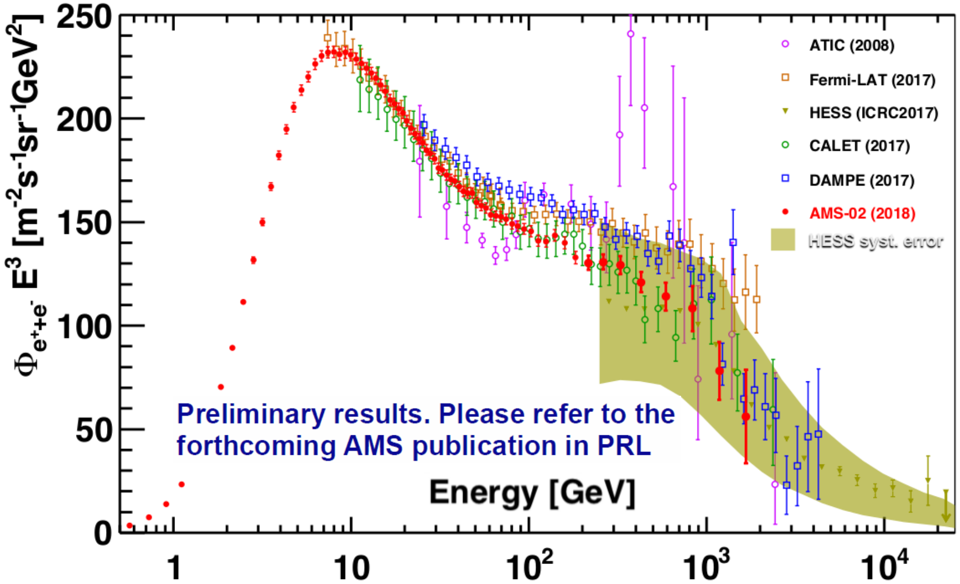
2) Astrophysics origin:
Pulsars, SNRs

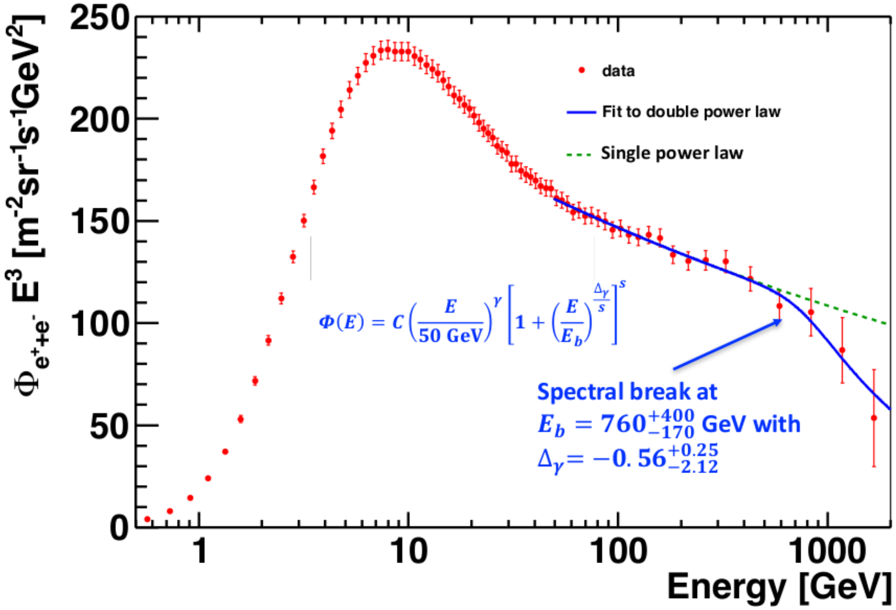
3) Secondary production, propagation



- Models based on very different assumptions describe observed trends in the data.
- New precision AMS measurements require accurate models to uncover the underlying physics :
  Not only need to explain specific sets of observation, but should be able to describe all the properties of the flux of different particles.

Electron and Positron sum spectrum





There are many interesting recent measurements of the combined (electron + positron) flux from space and on the ground

AMS is a magnetic spectrometer providing accurate measurement of the (electron + positron) flux

The AMS results do not rely on MC simulation of the energy measurement and proton background estimation.

Antiproton-to-Proton flux ratio

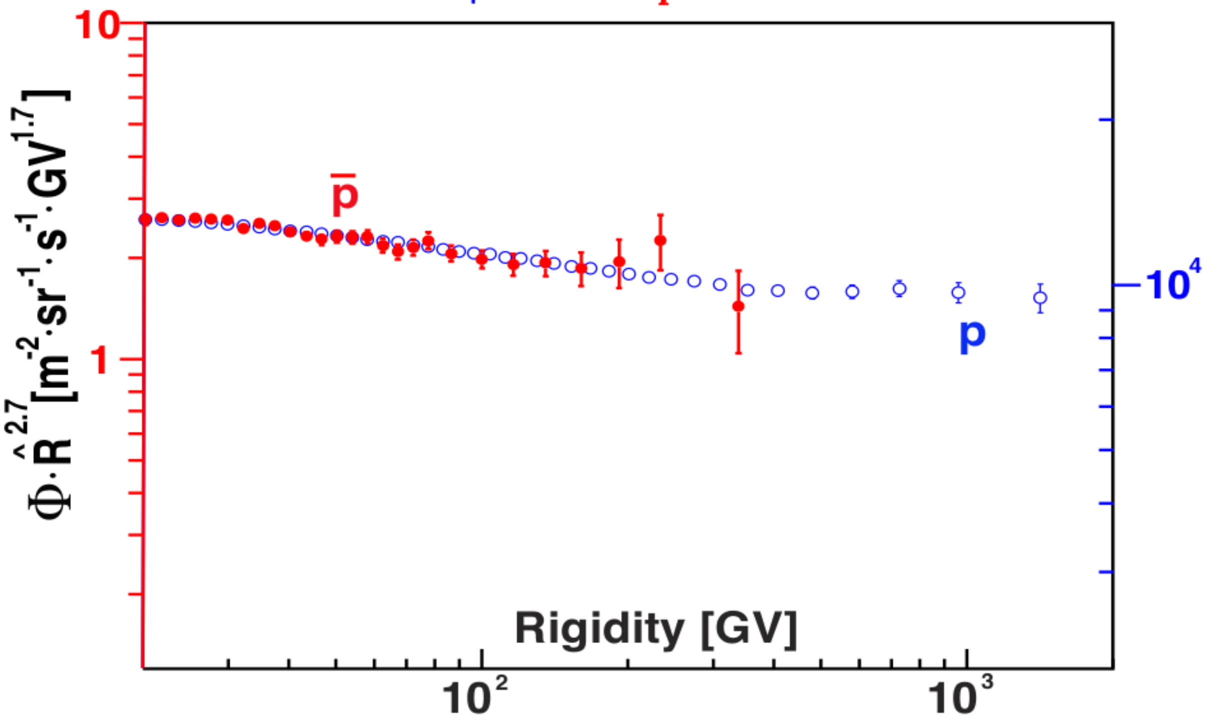
Using the data from the first 4 years, AMS has collected over 350 thousand antiproton,

>2200 antiprotons above 100 GV

This allows precision study of the properties of antiproton flux

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

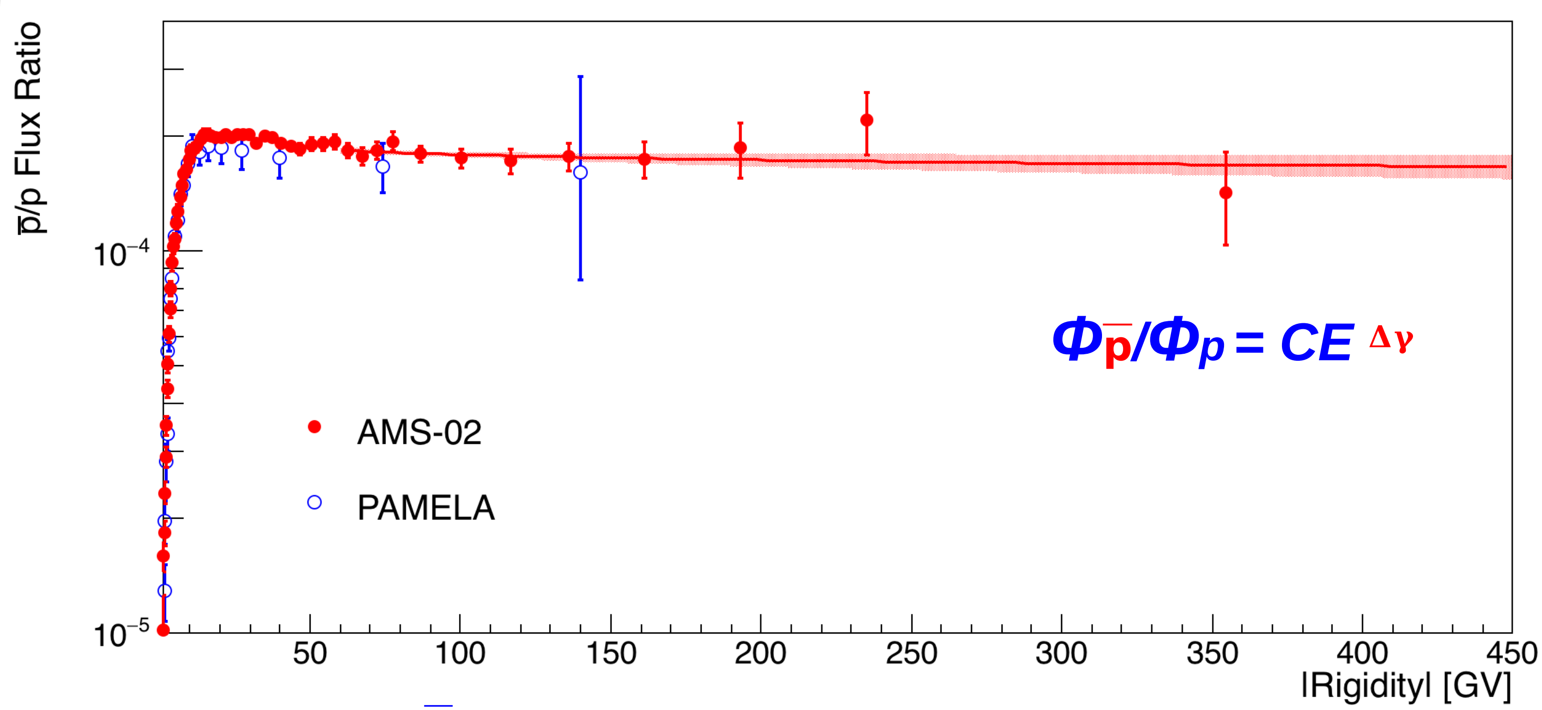
p + ISM → $\bar{p}$ + ...



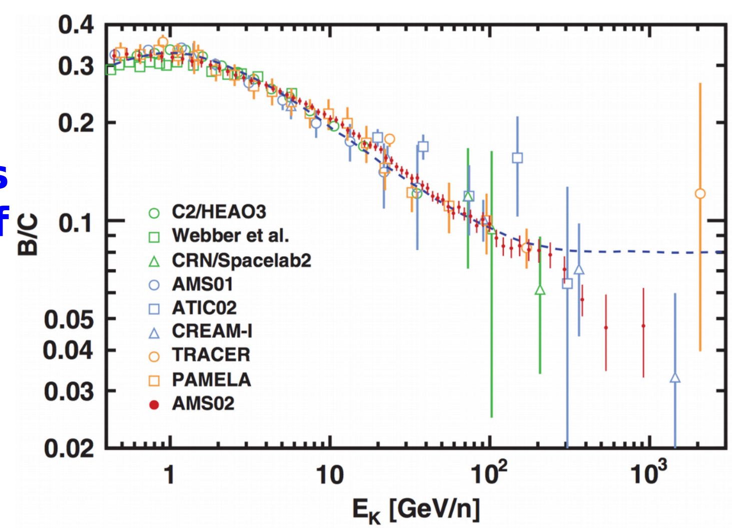
AMS observed for the first time that above 60 GeV, p and $\bar{p}$ have identical behavior

the antiproton spectral index is consistent with the proton spectral index.

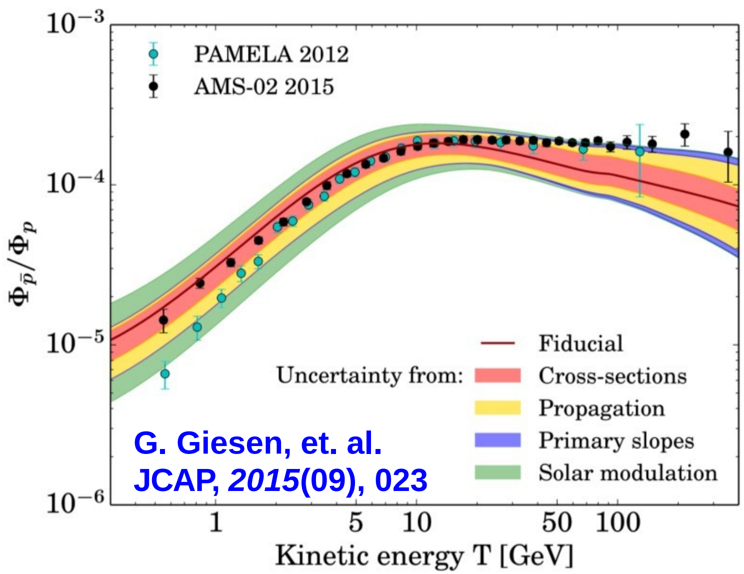
Antiproton-to-Proton flux ratio



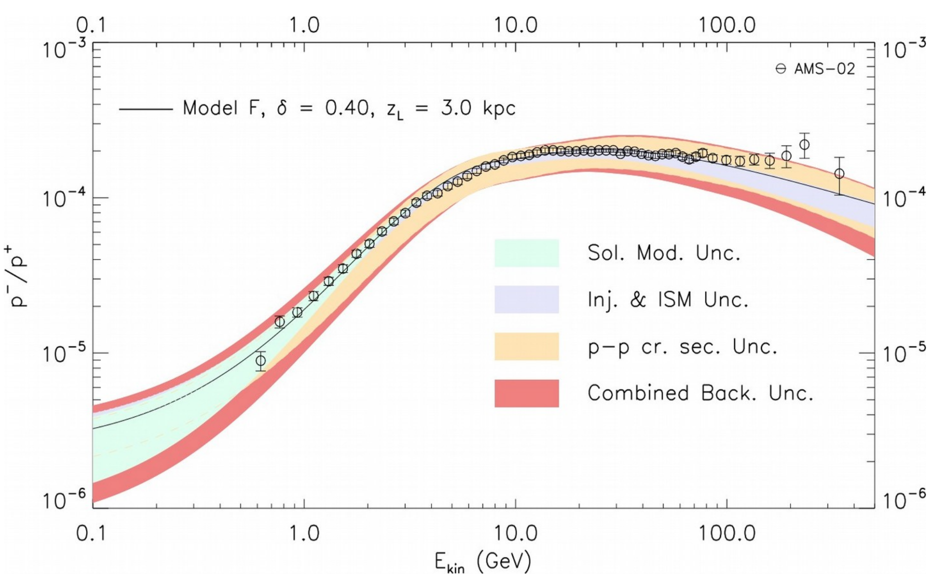
- The AMS measurement of $\bar{p}/p$ flux ratios shows that starting from 60GeV, the flux ratio is surprisingly flat up to 450GV.
- Fit to a power law in the range [60,450] GV shows that the difference between the power law index of proton and antiproton is 0.05±0.06 consistent with 0.
- This is distinctly different than the flux ratio of secondary/primary nuclei. Traditional models predict a falling $\bar{p}/p$ with power law index 0.2 - 0.3



Antiproton-to-Proton flux ratio



G. Giesen, et. al.
JCAP, *2015*(09), 023



Cholis, et. al. PRD 95, 123007

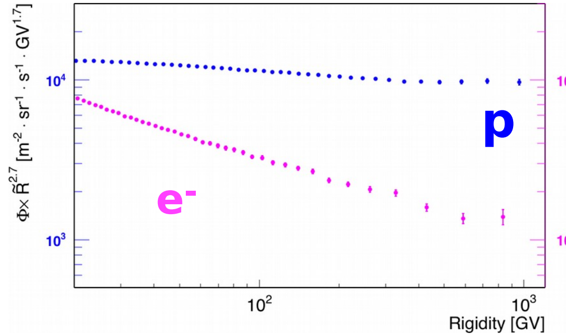
- **Large uncertainties on the background prediction:**
  - **Primary fluxes**
  - **Secondary fluxes**
  - **Solar modulation**
- **Latest AMS data will resolve the large uncertainties**
- **Nuclear Cross-sections**
  - **Equally important to improve accuracy of the background prediction**

M. Kachelriess et.al, ApJ, 803:54 (13pp), 2015 April 20
M. Winkler, JCAP, vol. 2017(02) pp. 048
…
However, despite that fact that model prediction have large systematic uncertainties, Current models predict a falling pbar/p with power law index 0.1 – 0.2 → **room for Dark Matter**

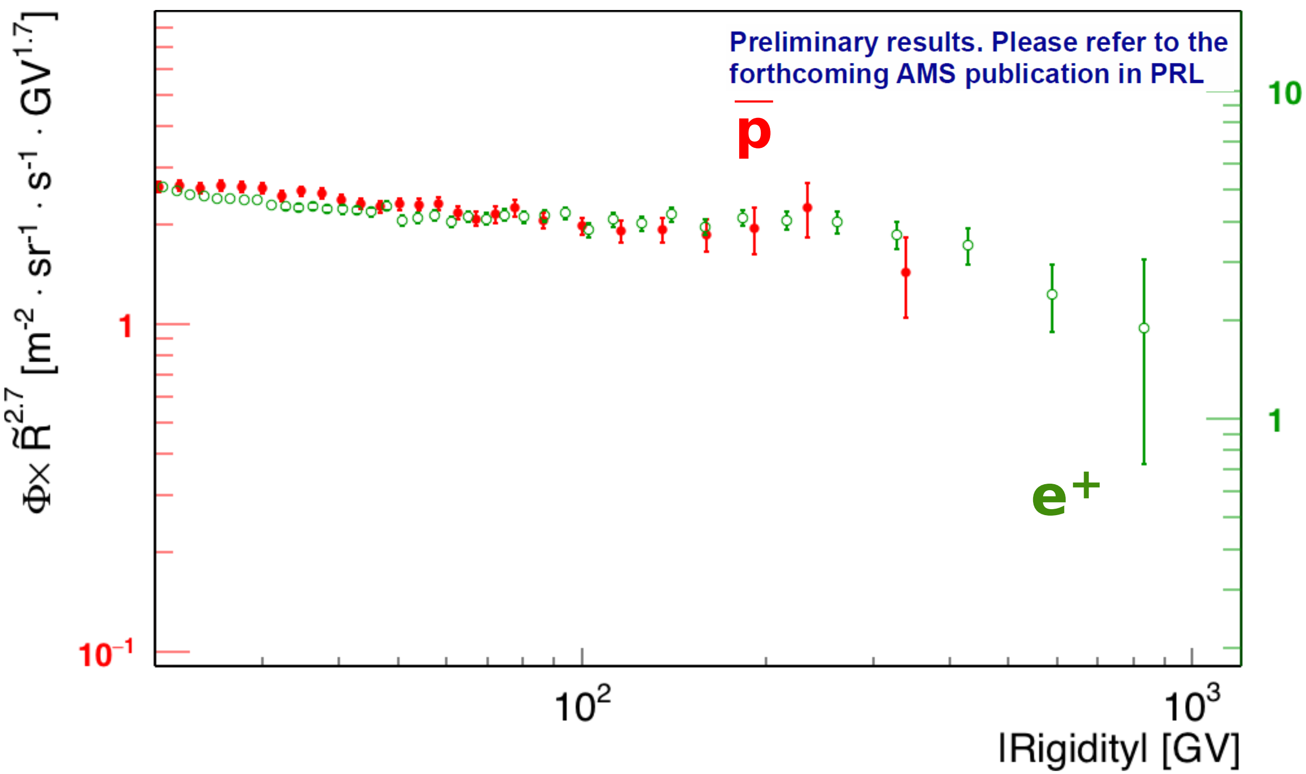
AMS measurement accuracy is not limited by the systematics

The Spectra of Antiprotons and Positrons

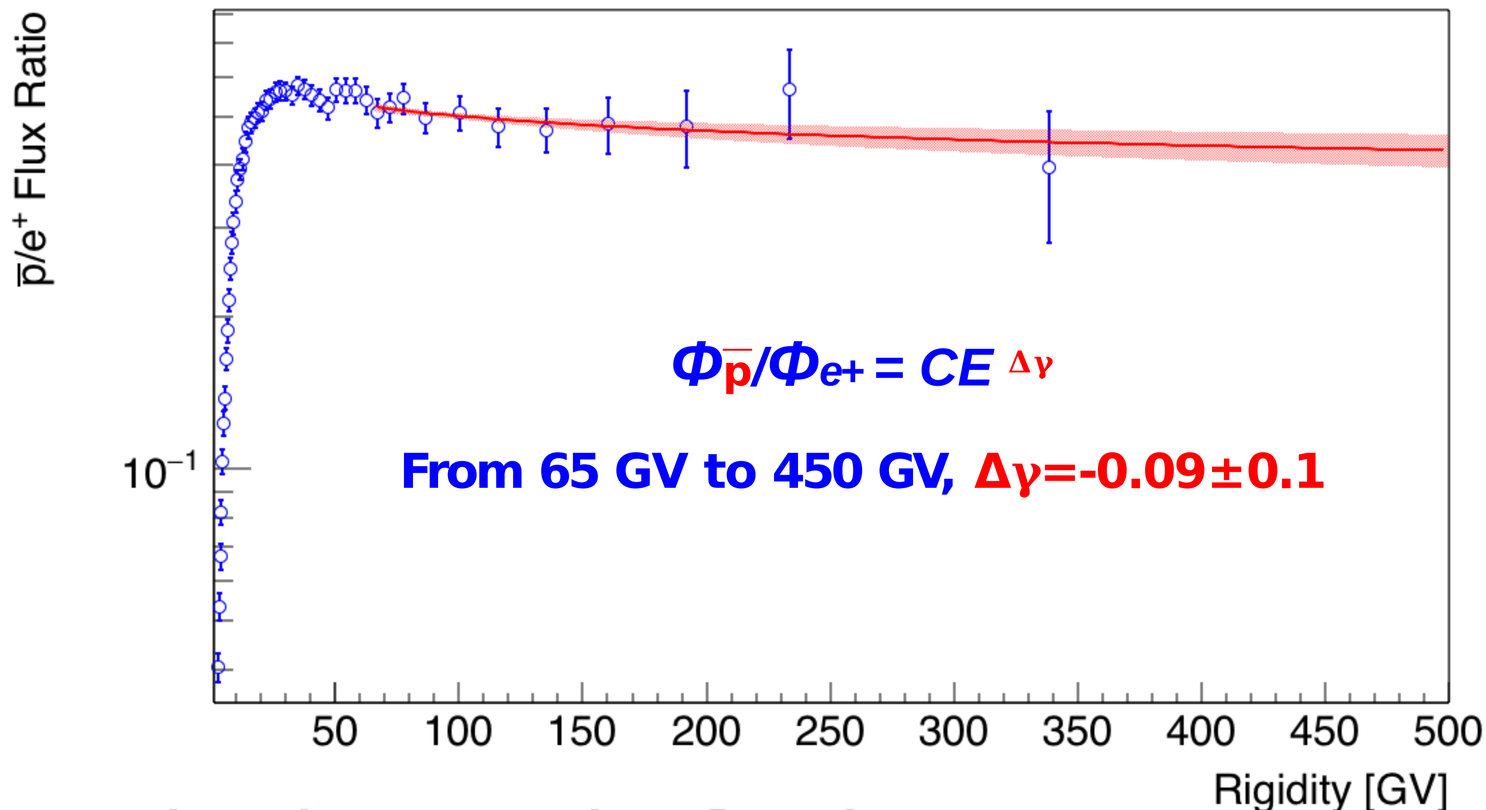
- **Difference between electron and proton is commonly attributed to different propagation effect between electrons and protons.**
- **For secondary positron and antiproton, we expect similar difference.**



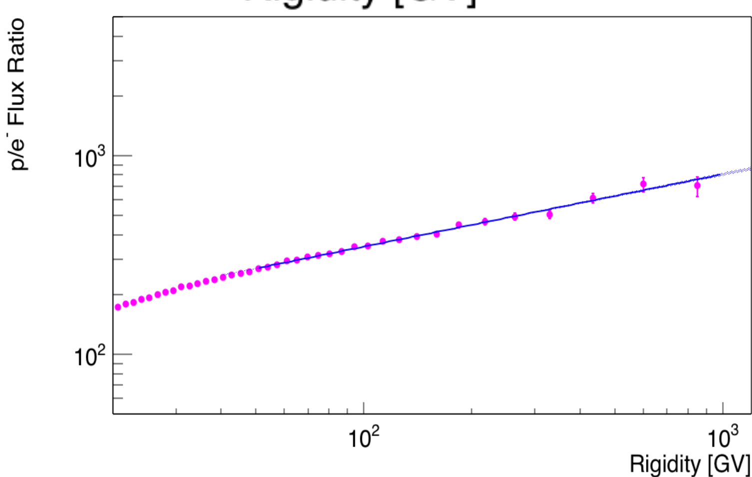
- **Surprising observation: Positron and Antiproton have identical rigidity dependence**



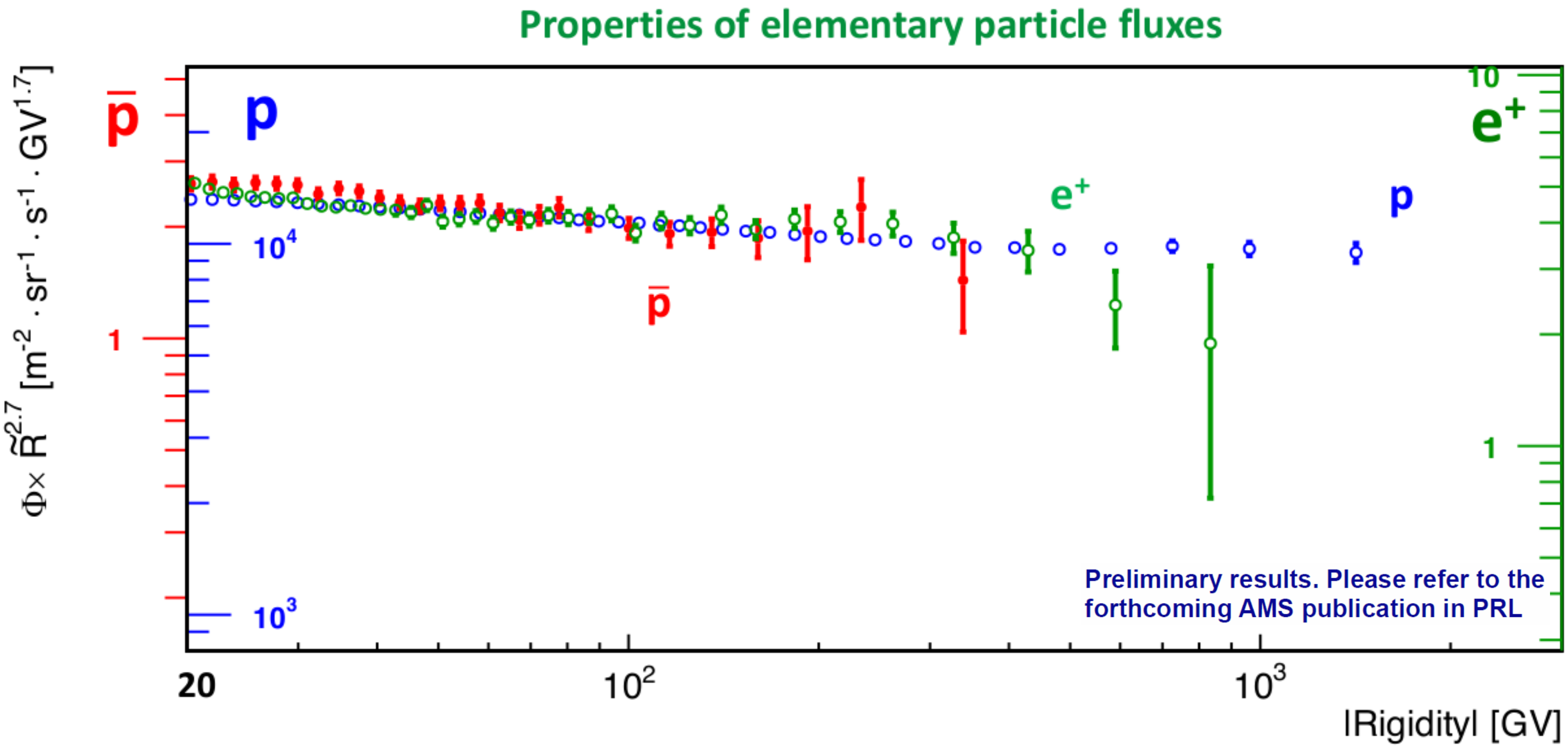
Antiproton-to-Positron flux ratio



- **From 65 GV , the antiproton to positron flux ratio is consistent with a constant**
- **Not compatible with common understandings of secondary origin of positron and $\bar{p}$**
- **With the newly released AMS data, as well as improved understanding from propagation and production, we hope to eventually understand this exact behavior.**



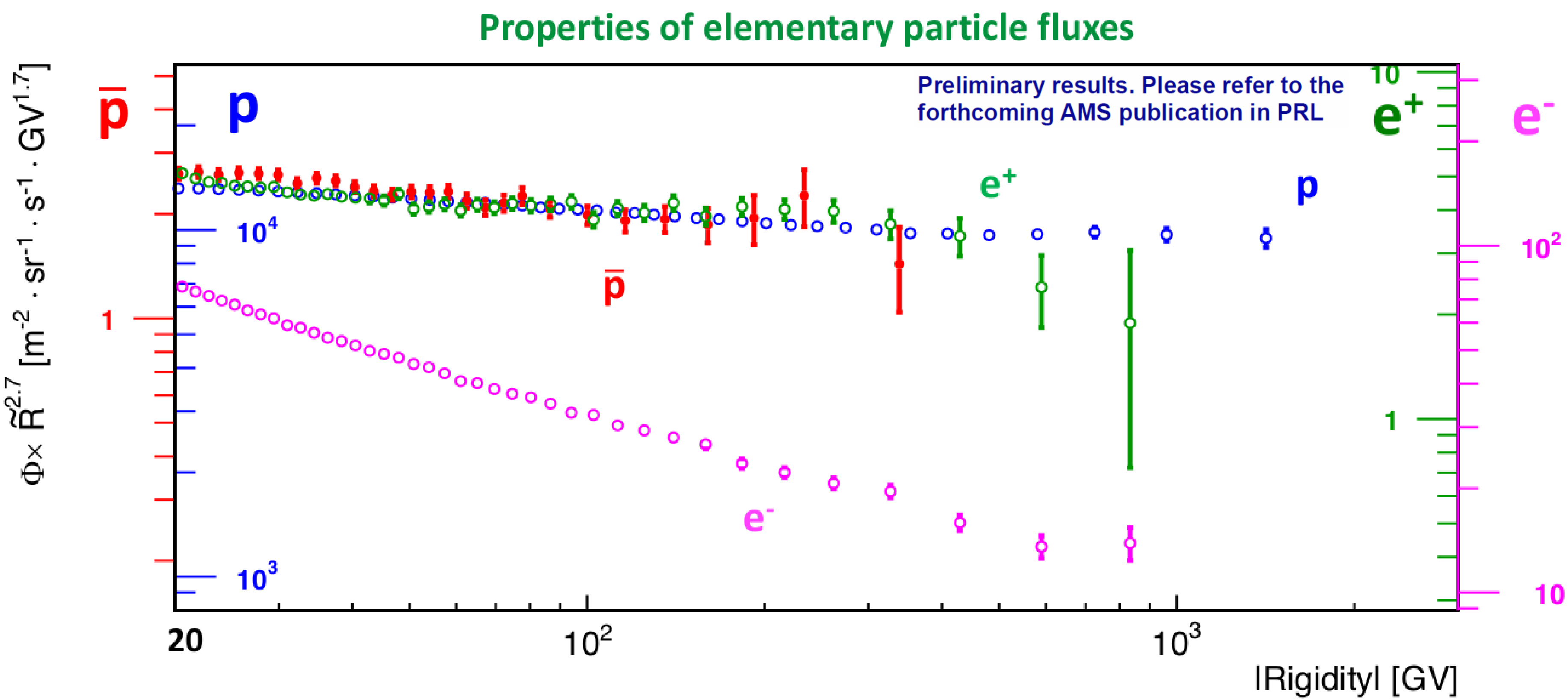
Conclusion



1. The spectra of positrons, antiprotons, and protons are identical in a large energy range [60, 500] GV

2. Not consistent with pure secondary origin of positron and antiprotons.

Conclusion



3. Electron have much softer spectrum, compatible with a single power law behaviour from 30 GV up to 1TV.
4. By collecting data through 2024, AMS will greatly improve the accuracy of these measurements and reaches to higher energy.
5. We work closely with the theoretical community to understand and determine the origin of many observed unexpected phenomena.