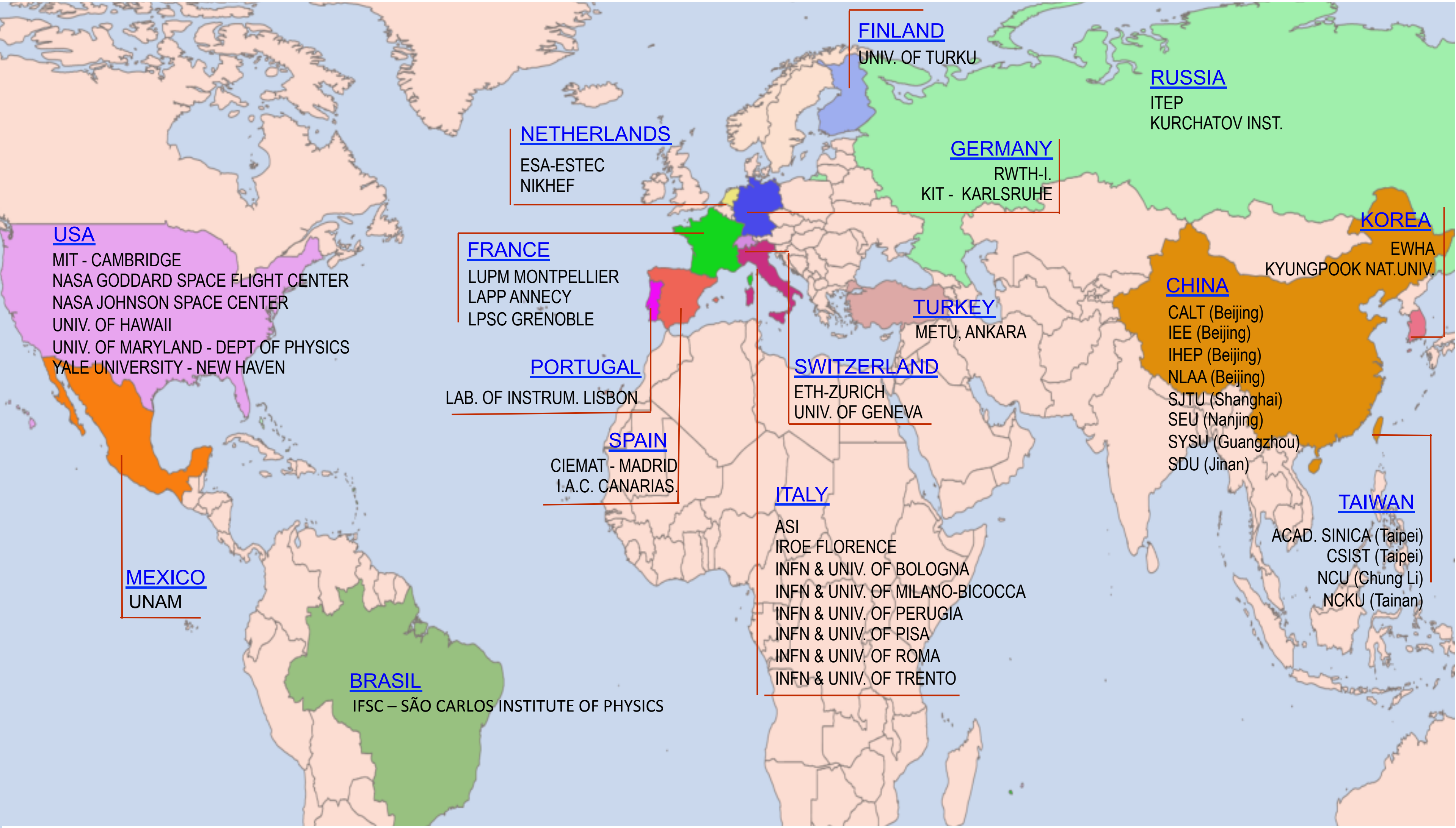
Dark Matter Searches at AMS:
Precision Measurement of Charged Elementary Particles in the Cosmos

W. Xu / MIT
on behalf of AMS Collaboration

LP2017, SYSU, GuangZhou, Aug. 7-12, 2017

AMS is an International Collaboration
46 Institutes from 15 Countries



AMS is sponsored by US DOE and NASA
and supported by many funding agencies around the world

Three independent methods to search for Dark Matter

Annihilation

HESS, HAWC, VERITAS, MAGIC, IceCube, …

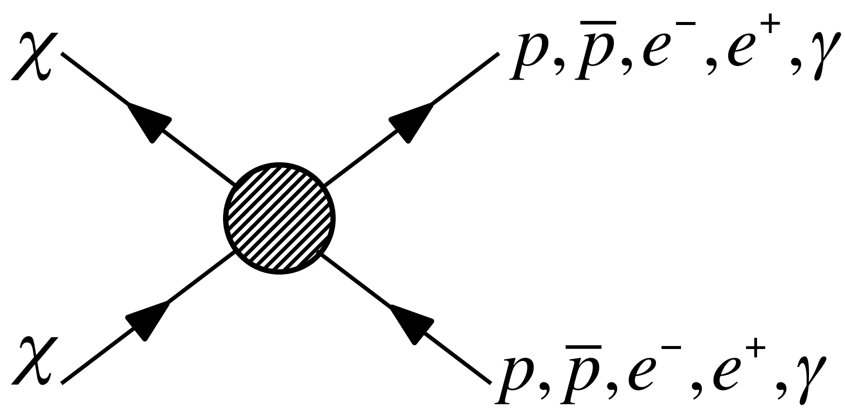
PAMELA, FERMI, CALET, DAMPE, AMS, …

$\chi + \chi \rightarrow e^{+}, \bar{p}, \gamma, \ldots$

Scattering

CDEX
CDMS
CRESST
DARKSIDE
DEAP
LUX
PandaX
PICO
XENON
…

$\chi + N \rightarrow \chi + N$



$\ldots + \chi + \chi \leftarrow p + p$

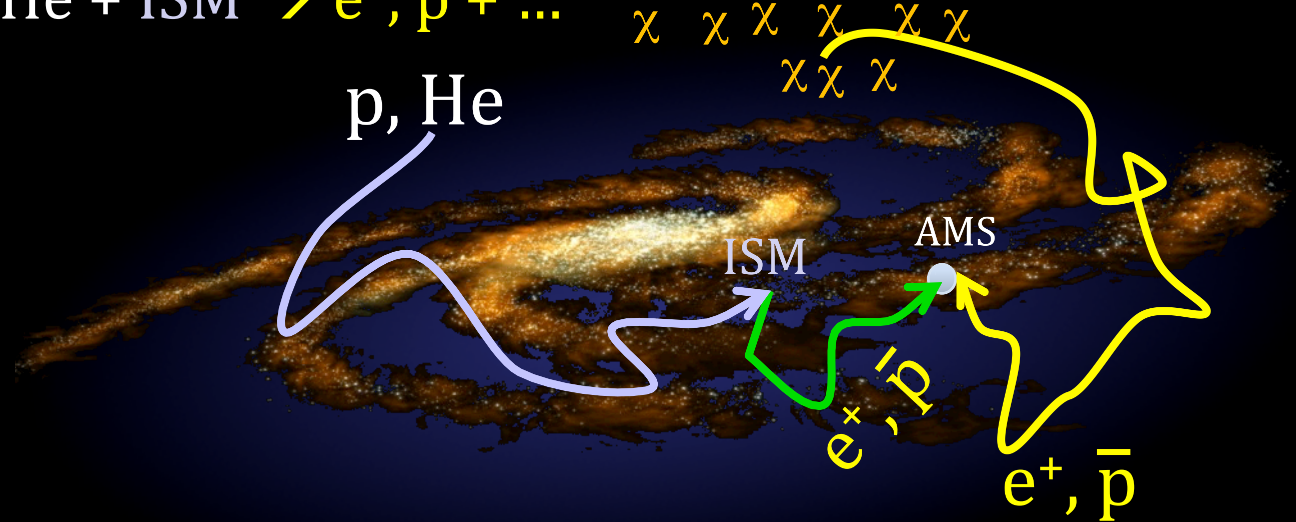
LHC

Production

Dark Matter Searches at AMS

e^+ and $\bar{p}$ are rare species in cosmic rays
The collision of cosmic rays with interstellar medium(ISM) will produce e^+ and $\bar{p}$

p, He + ISM → $e^+, \bar{p}$ + ...



M. Turner and F. Wilczek, Phys. Rev. D42 (1990) 1001; J. Ellis 26th ICRC (1999)

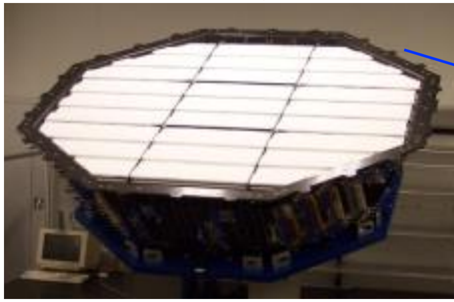
$\chi + \chi \rightarrow e^+, \bar{p} + \ldots$

The collision of dark matter particles will produce additional e^+ and $\bar{p}$

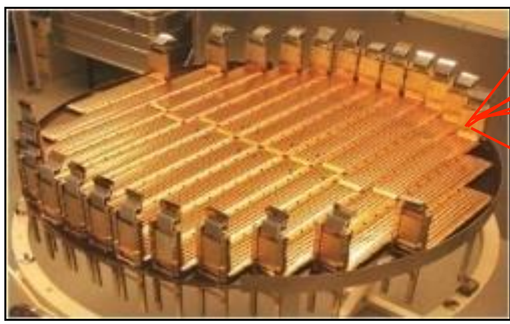
The excess of e^+ and $\bar{p}$ can be accurately measured by AMS

Alpha Magnetic Spectrometer

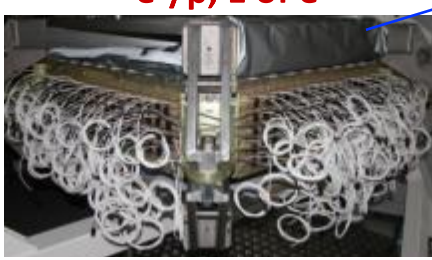
Transition Radiation Detector
$e^{\pm}/p$, Z

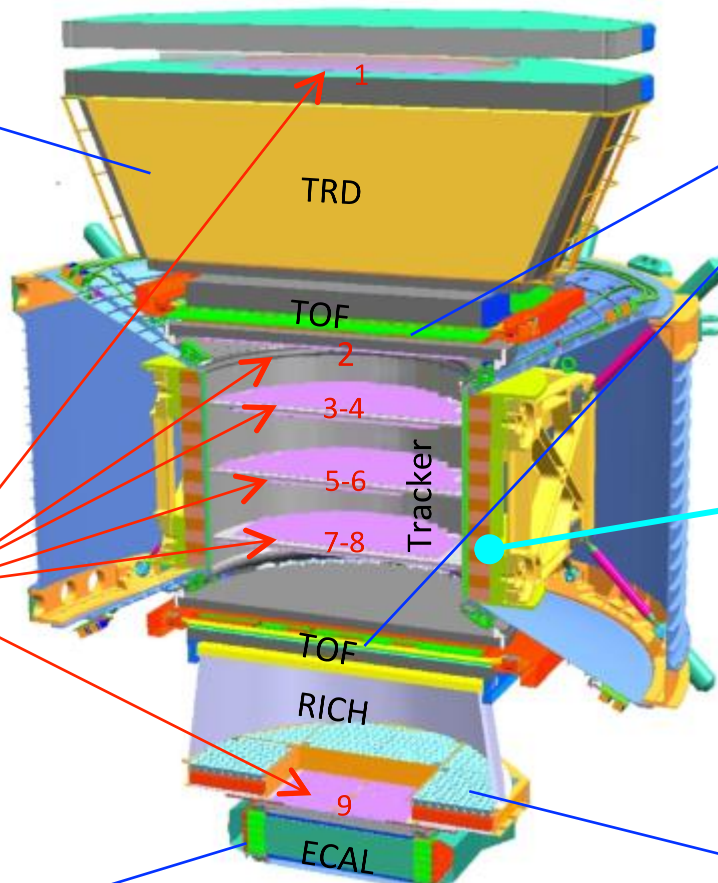


Silicon Tracker
Z, P, Rigidity(R=P/Z)



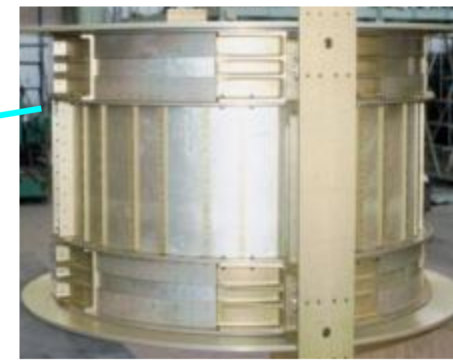
Electromagnetic Calorimeter
$e^{\pm}/p$, E of $e^{\pm}$





Time of Flight
Z, E

Magnet
±Z

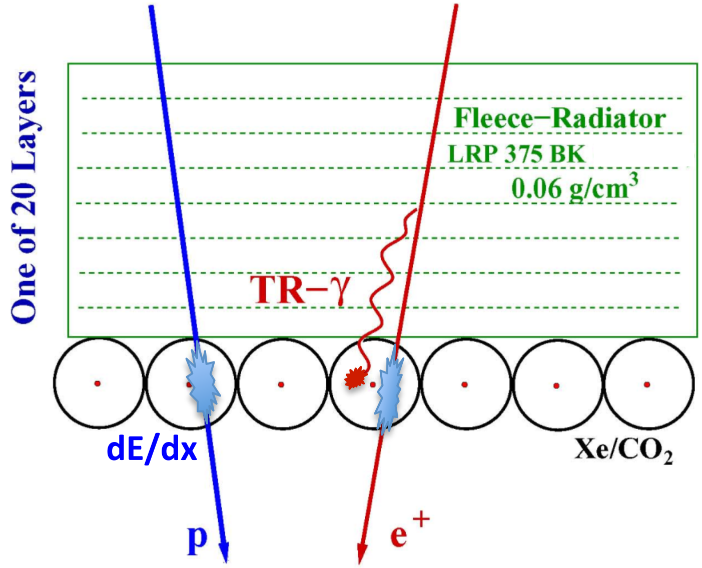


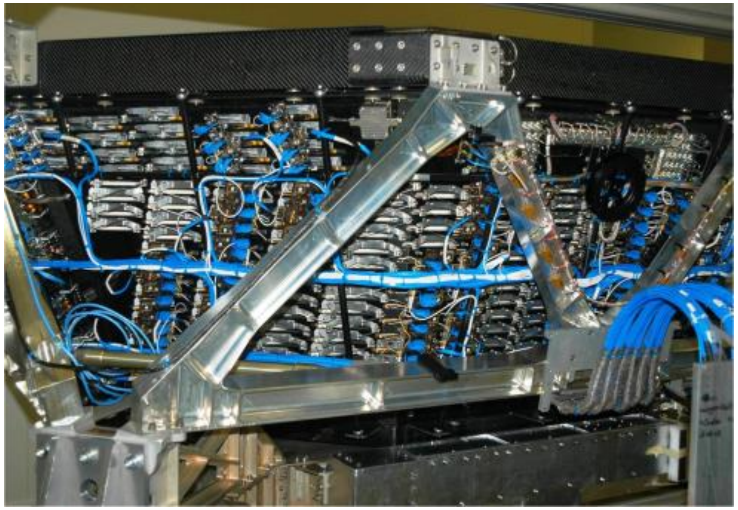
Ring Imaging Cherenkov
Z, E

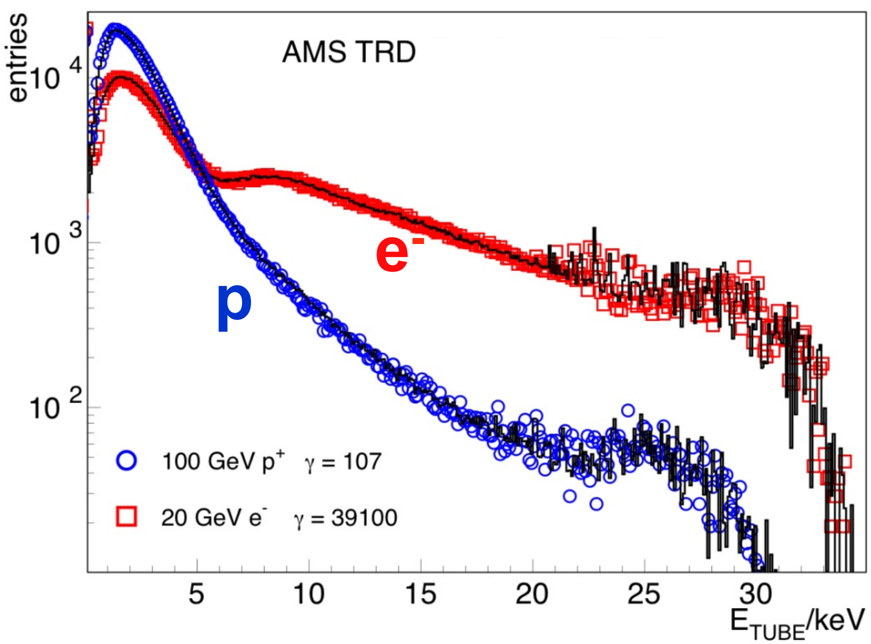
The Charge(Z) and Energy(E) are measured independently by several detectors

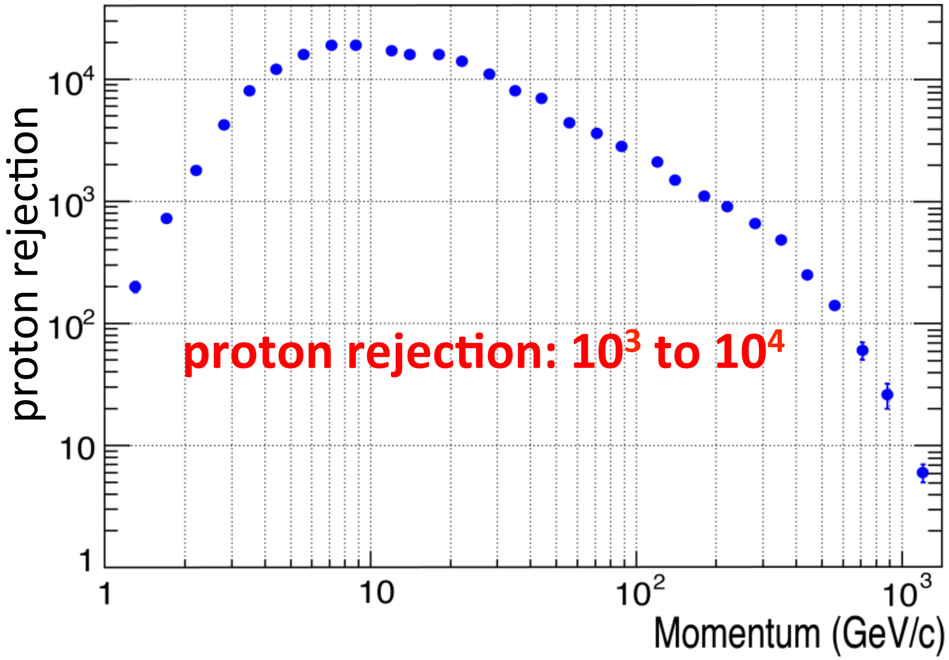
Precise identification of particle and nuclei species

Transition Radiation Detector (TRD)

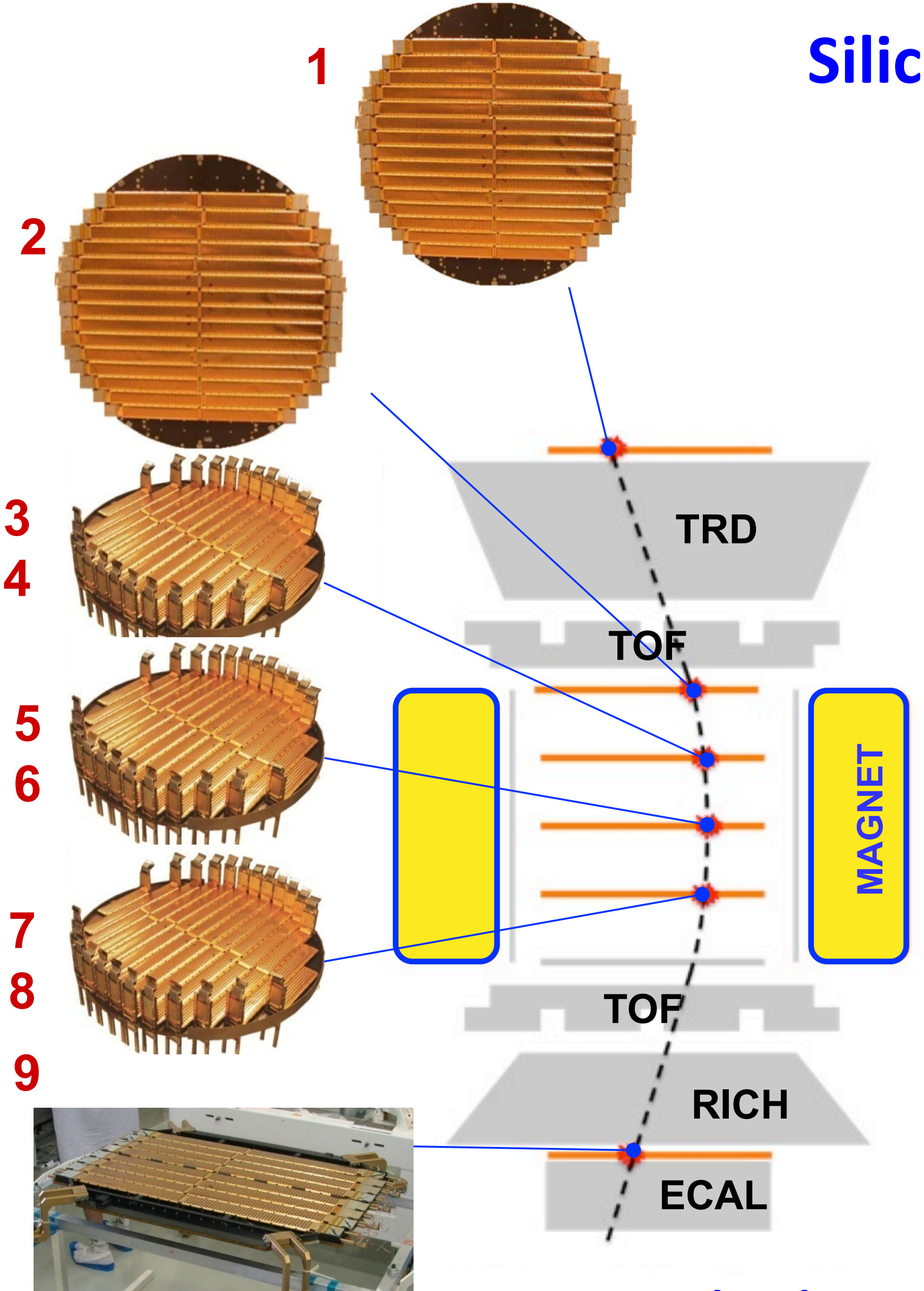




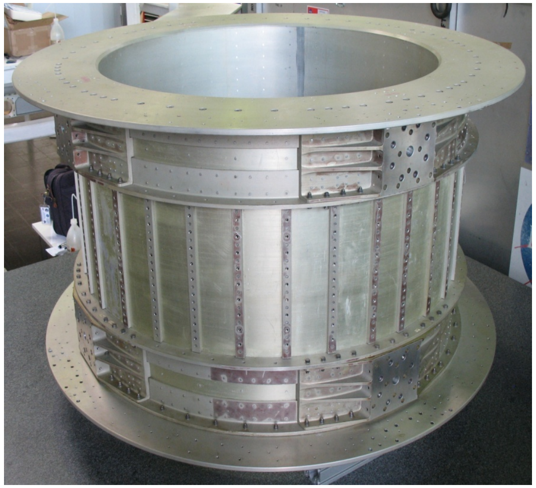




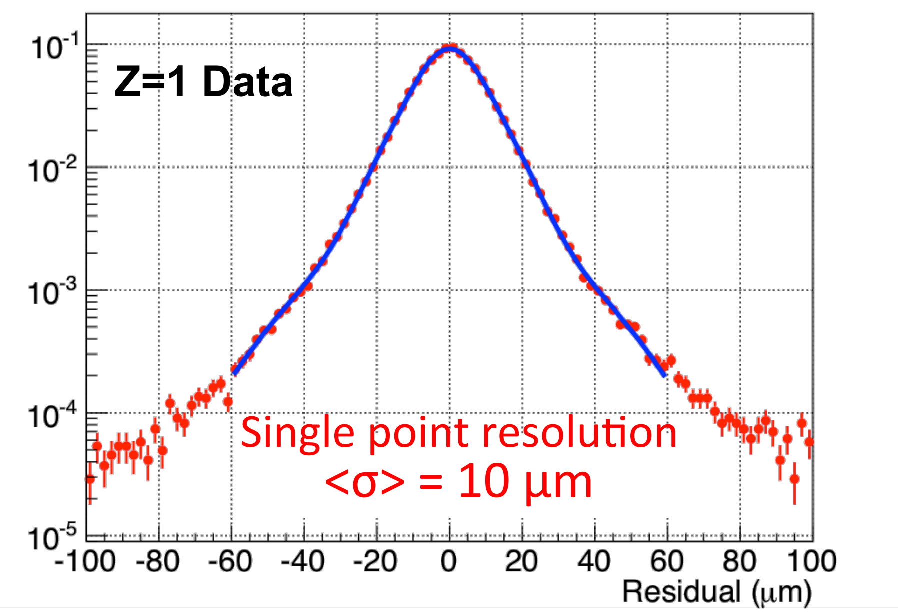
Silicon Tracker and Magnet



L1 to L9: 3 m level arm



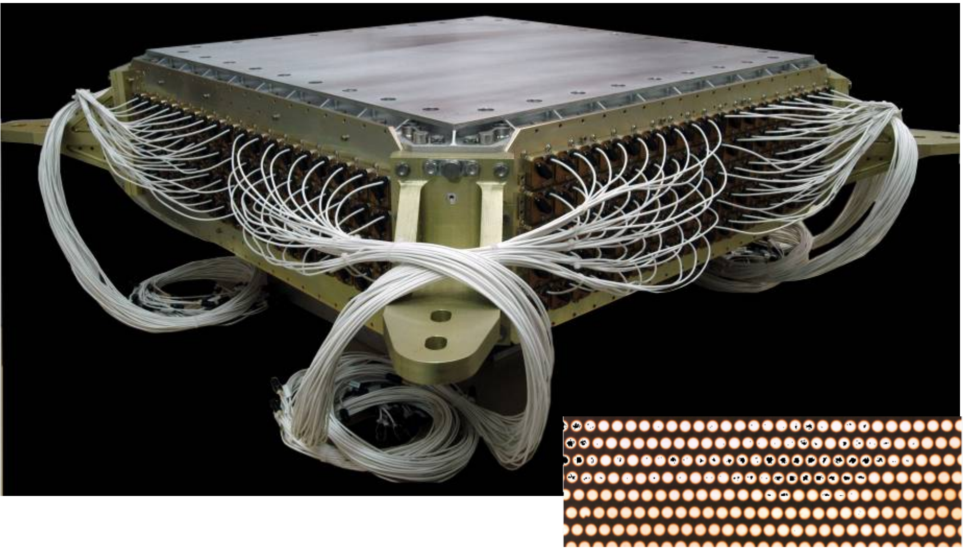
1.4 kG



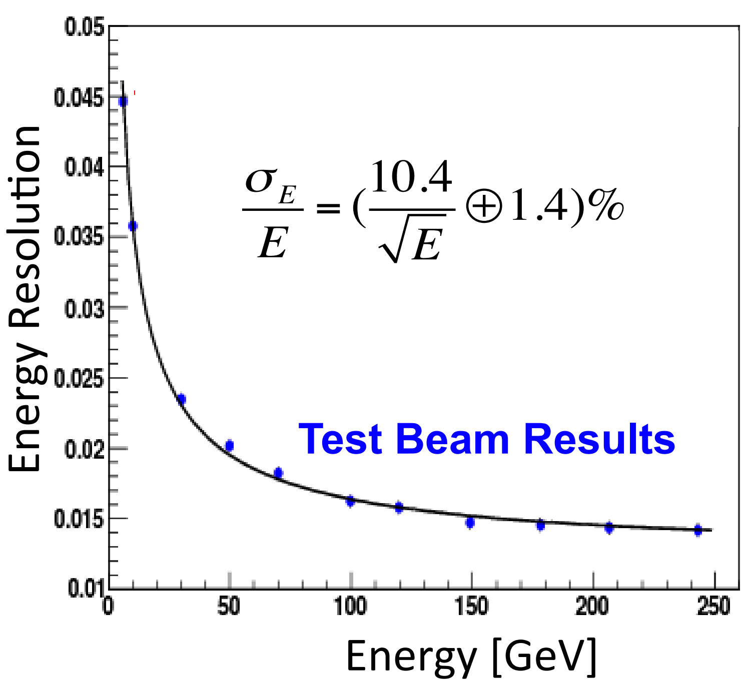
Maximum Detectable Rigidity(MDR)

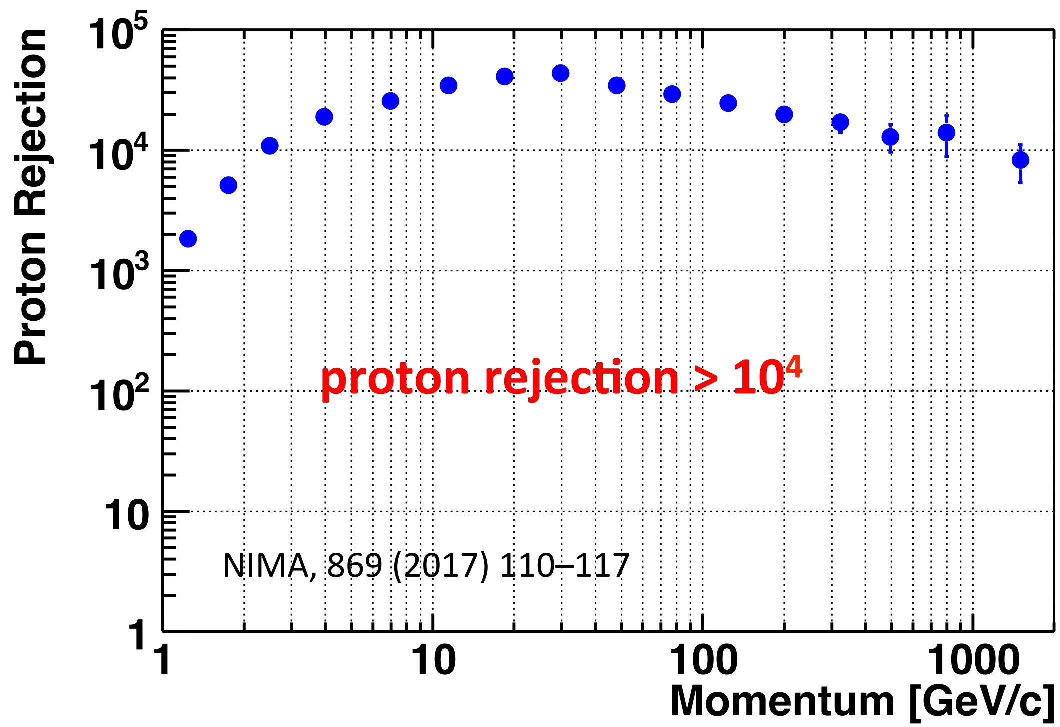
2.0 TV for Z=1 particles

Electromagnetic Calorimeter (ECAL)



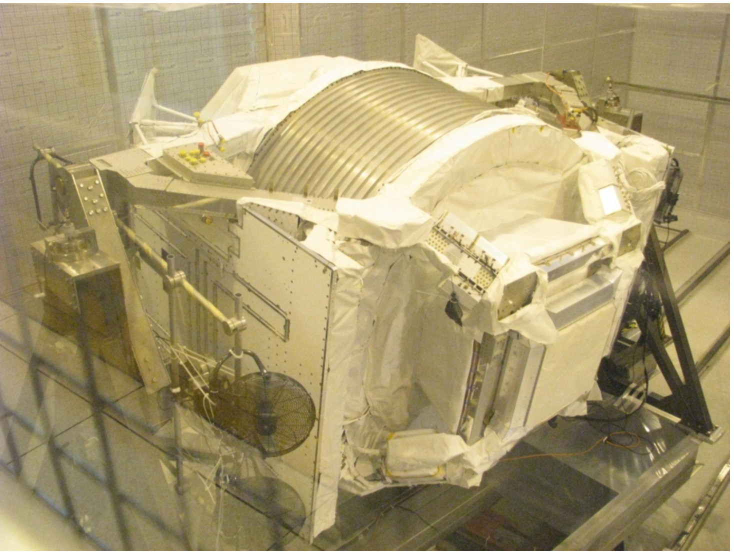
- 17 X_0, 3D measurement of the directions and energies of $e^{\pm}$ to TeV
- Energy scale and resolution measured with test beam
- Identify $e^{\pm}$ by 3D shower shape
- Proton rejection is above 10^4 with ECAL and Tracker



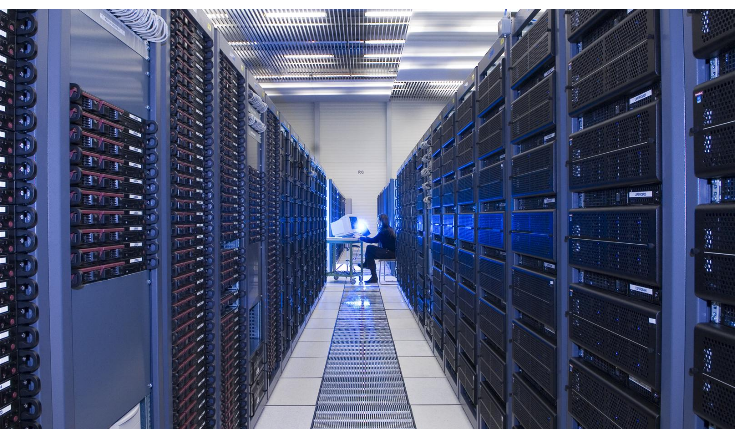


Detector Calibration and Monte Carlo simulation

Detector calibration



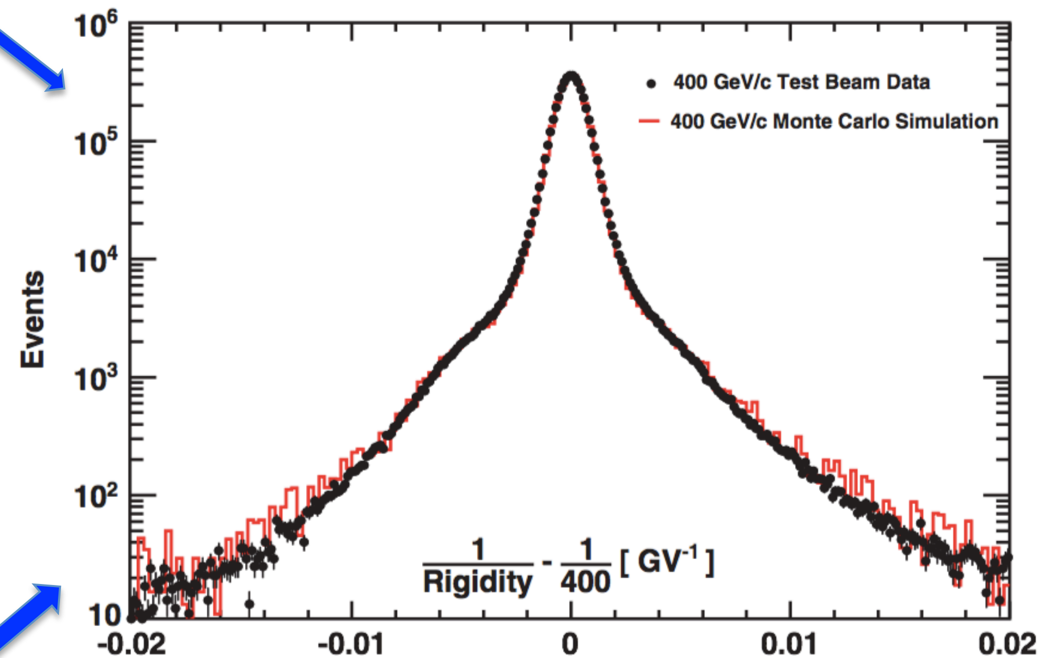
Monte Carlo simulation



10,000 CPU cores at CERN
+ regional centers

Intensive Test Beam @ CERN:

- Particle type: p, $e^{\pm}$, $\pi^{\pm}$
- Energy (10–400 GeV)
- Position (2000)

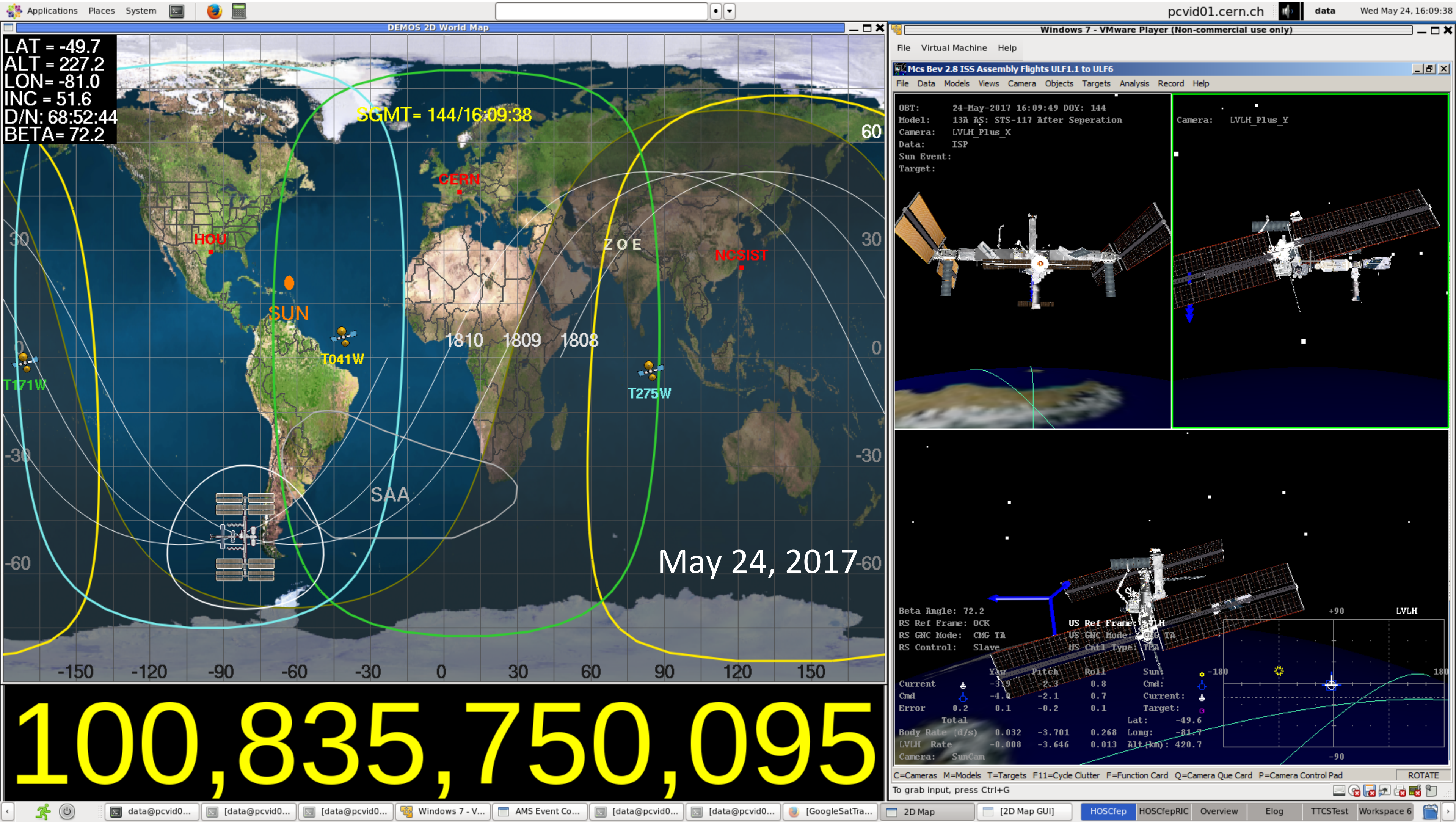


Monte Carlo simulation:

1. Interactions (physics and materials)
2. Digitization (electronics)

Results in data-like events

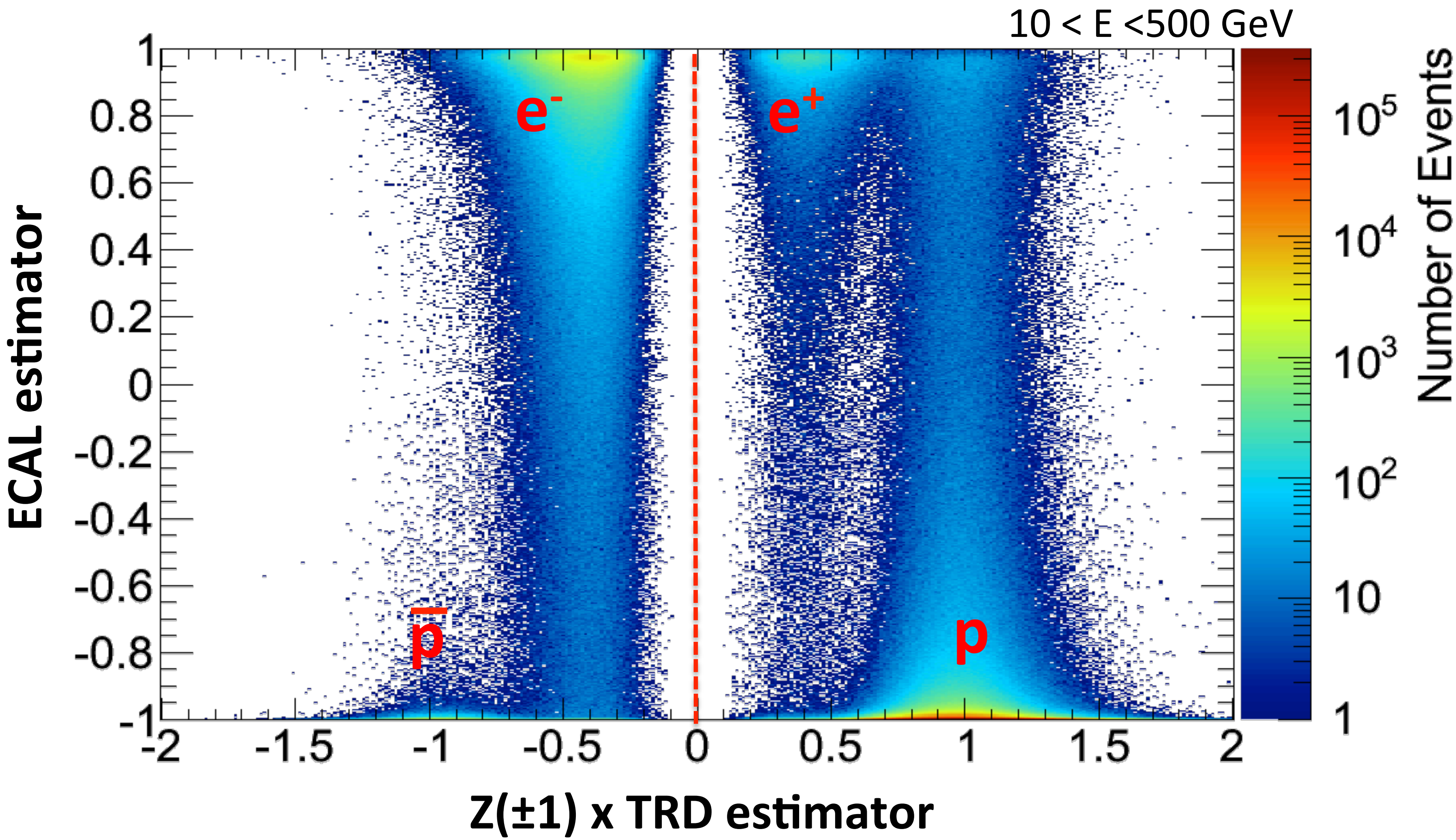
In 6 years AMS has collected over 100 billion events.



AMS will continue to collect data in the life time of ISS (2024)

Positron and electron selection in AMS

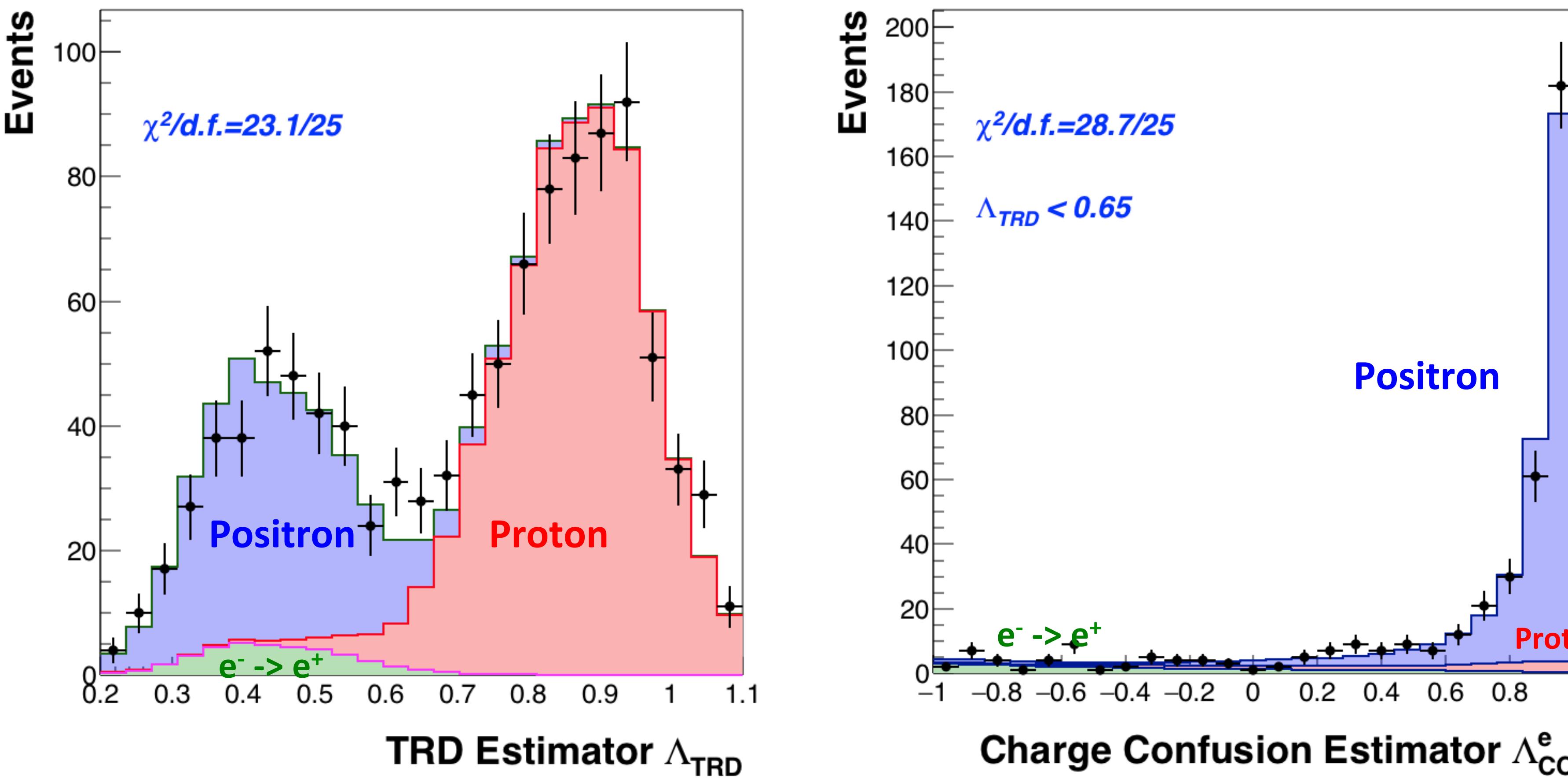
Redundant particle identification using TRD, ECAL and Tracker

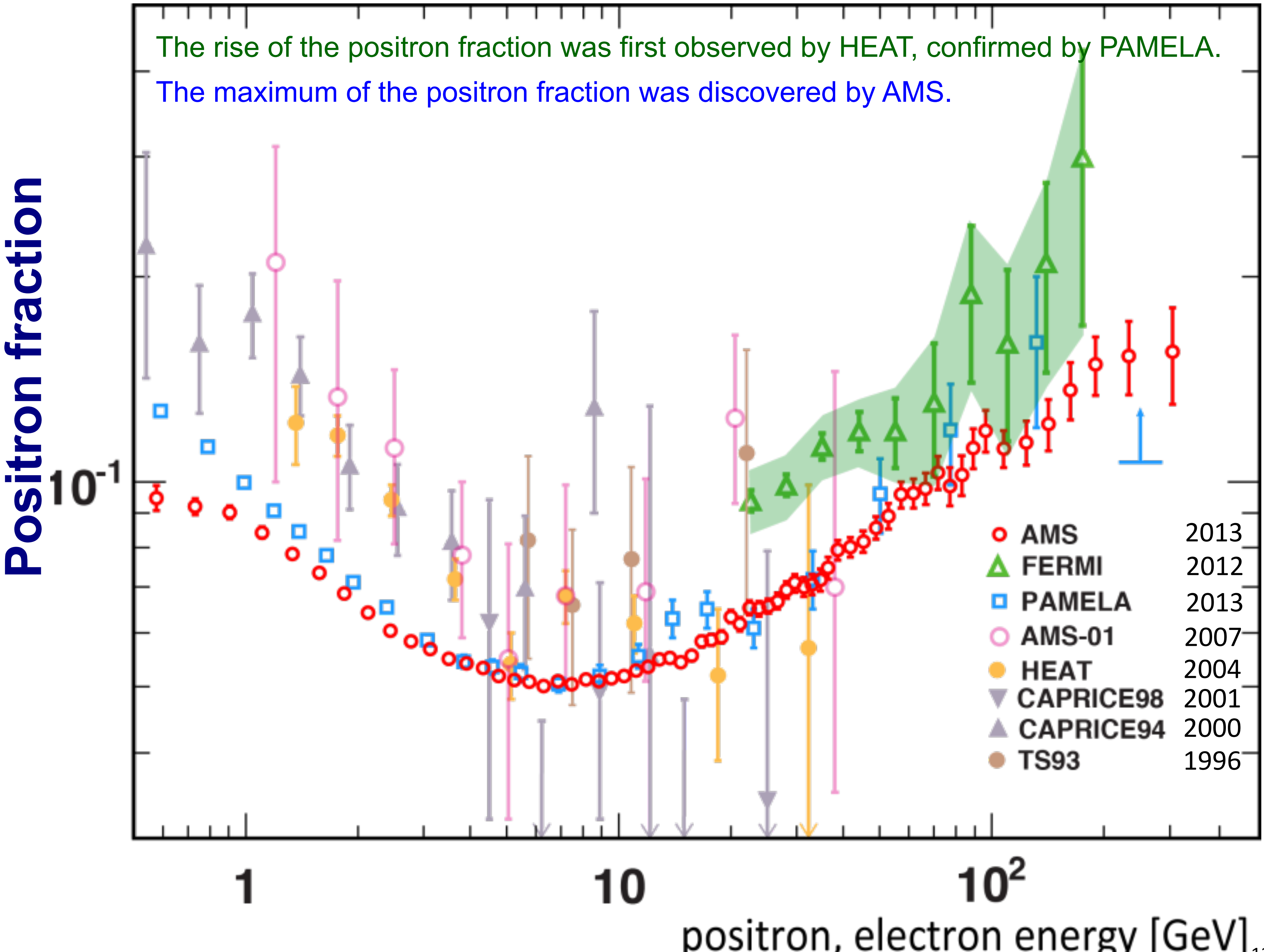


Positron and electron measurement in AMS

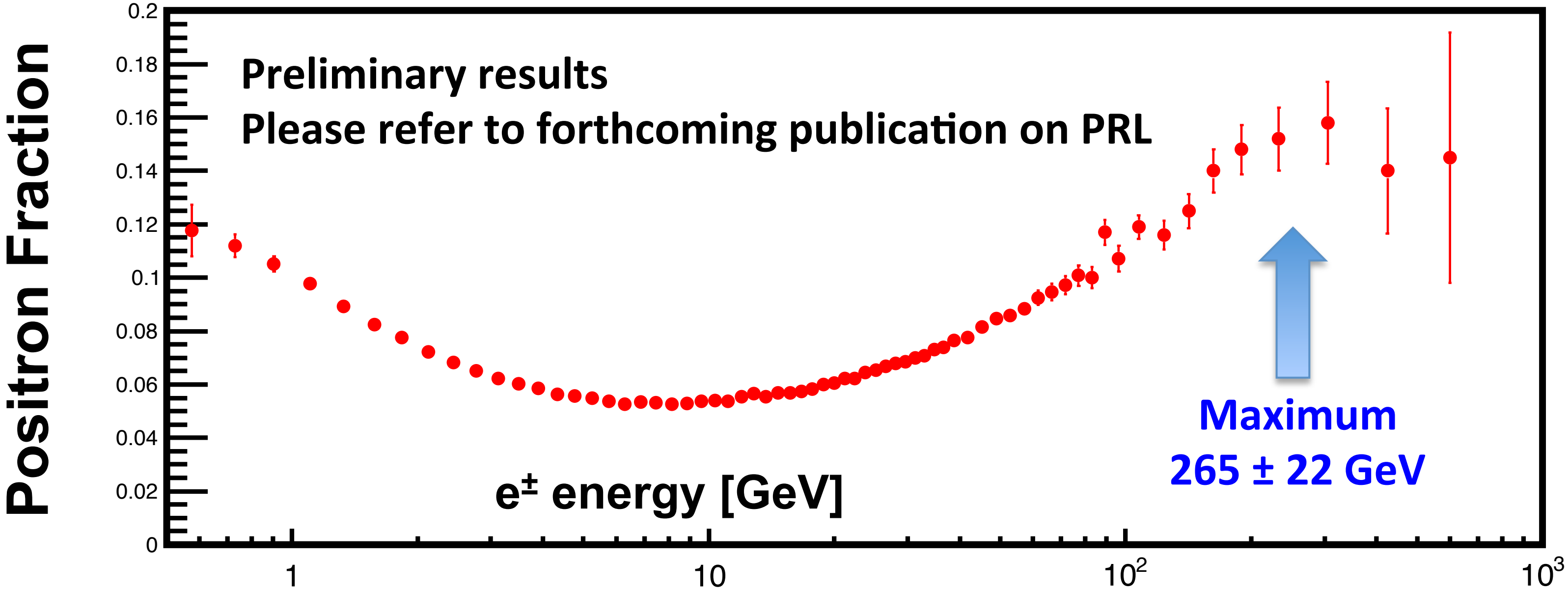
- The number of positrons and electrons are determined from a template fit in TRD - Charge Confusion Estimator 2D phase space
- The e^+ and proton template are obtained from high purity e^-, proton data
- Charge confusion studied using e^- test beam and MC

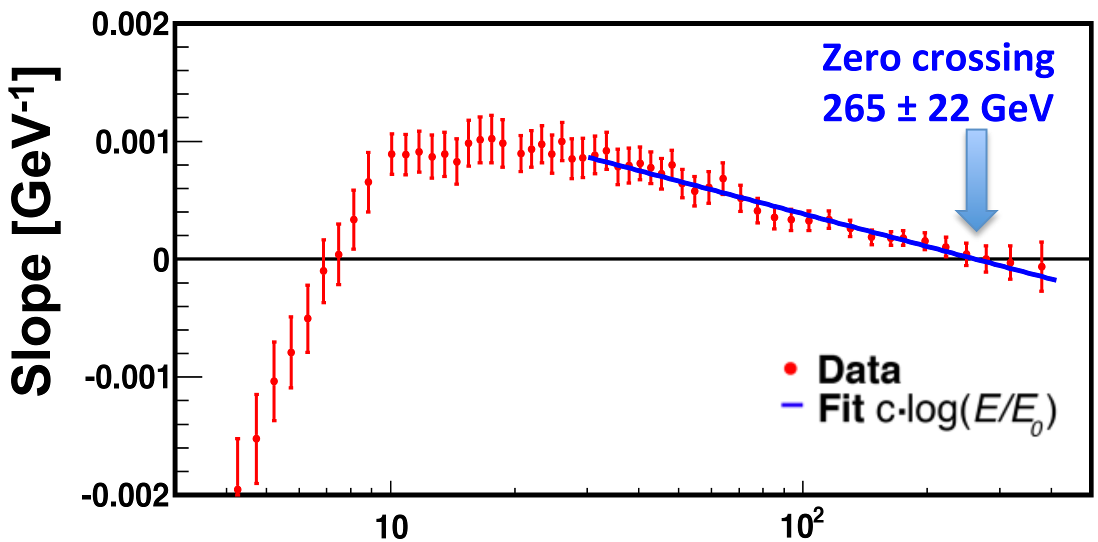
Fit to Data, Positive Rigidity, 151-173 GeV




The rise of the positron fraction was first observed by HEAT, confirmed by PAMELA.
The maximum of the positron fraction was discovered by AMS.
Positron fraction
10^{-1}
1
10
10^2
positron, electron energy [GeV]
AMS 2013
FERMI 2012
PAMELA 2013
AMS-01 2007
HEAT 2004
CAPRICE98 2001
CAPRICE94 2000
TS93 1996

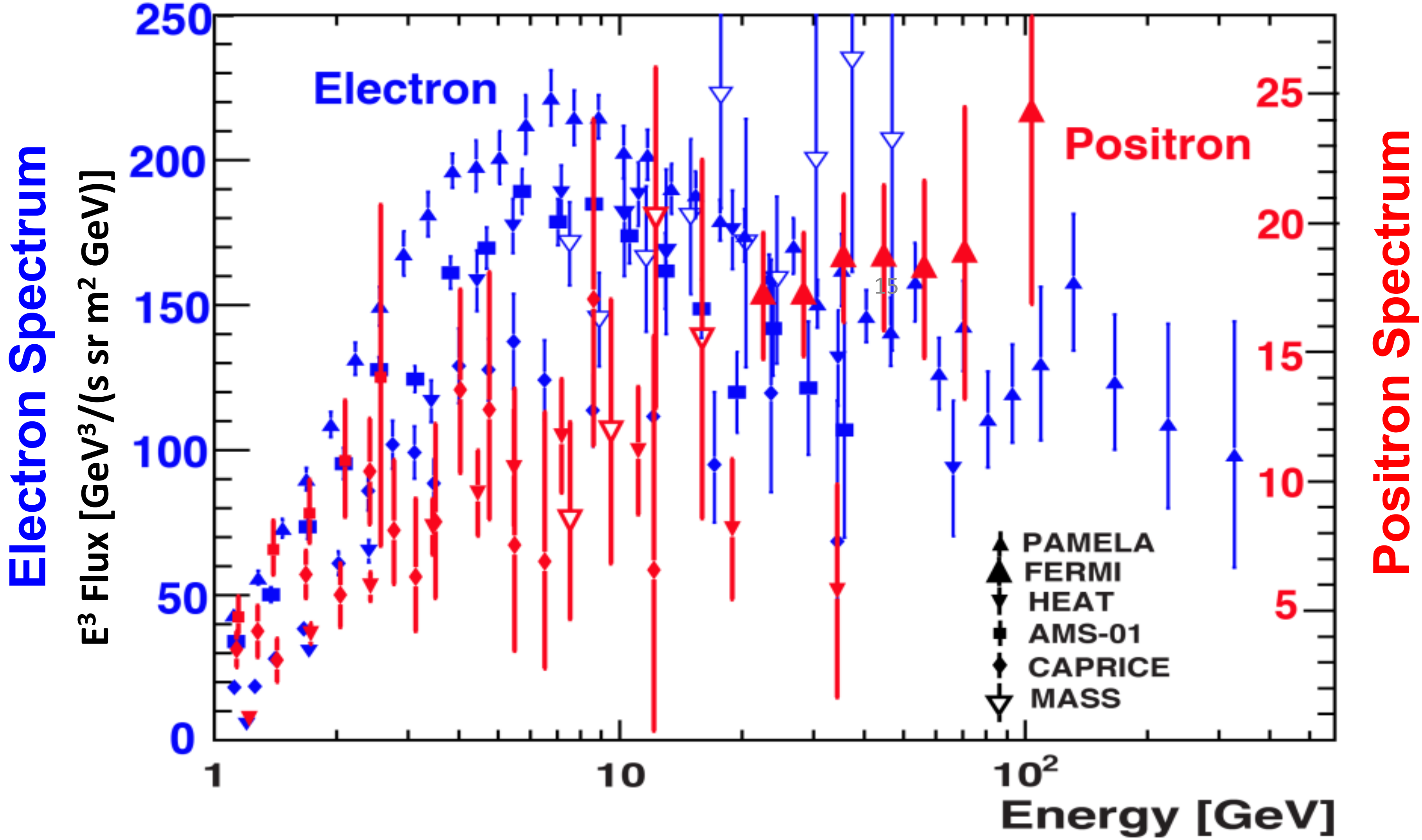
Positron Fraction: 5 years data



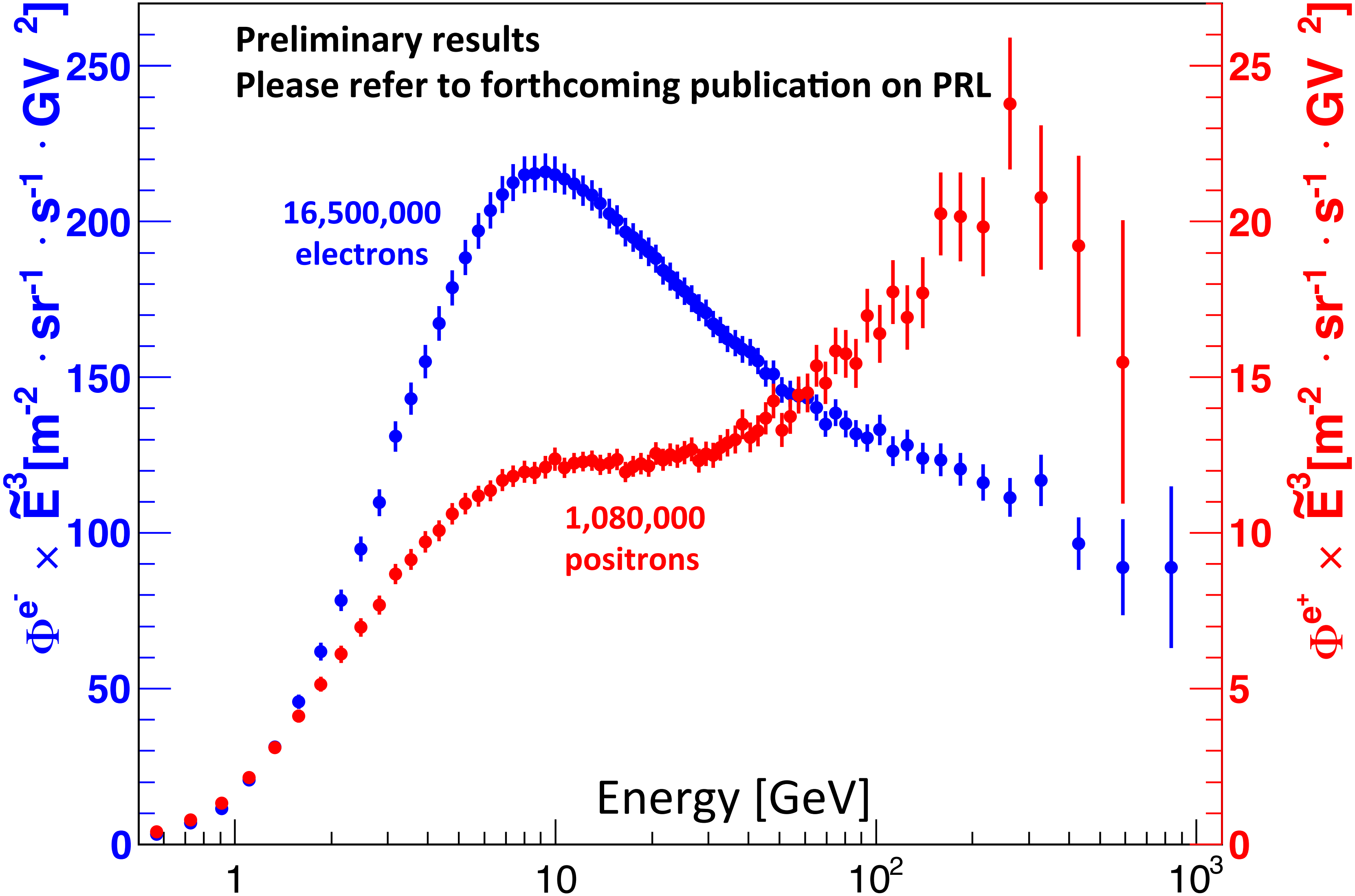


Electron and Positron spectra before AMS

1. These were the best data.
2. Nonetheless, the data have large errors and are inconsistent.
3. The data has created many theoretical speculations.



Electron and positron fluxes

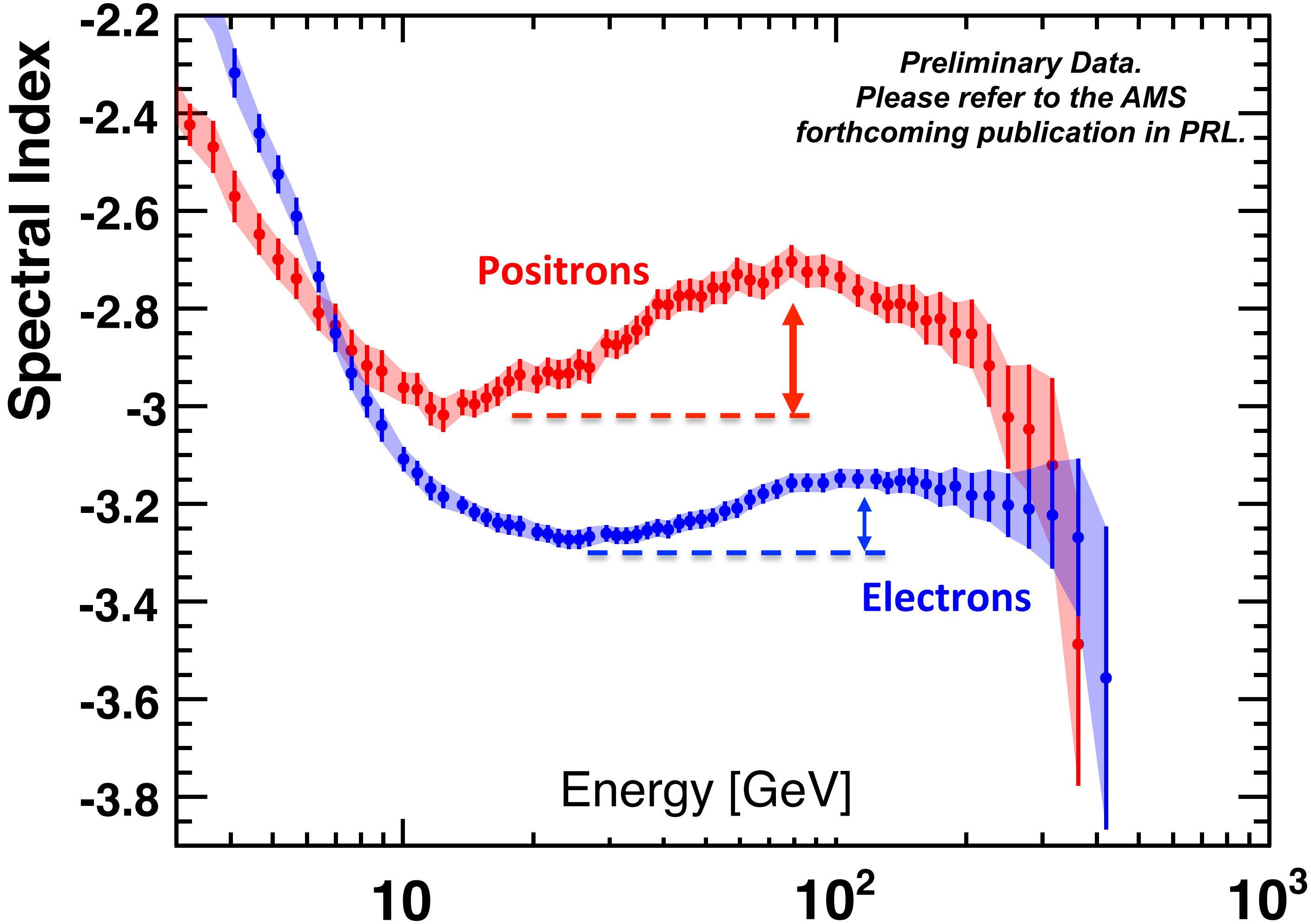


- The electron flux and positron flux are different in amplitude and energy behavior.
- Both spectra change behavior at ~30GeV
- Rise of positron fraction from ~10GeV is due to an excess of positron

The Electron and Positron spectral indices

Traditionally, the spectrum of cosmic rays is characterized by a single power law function $\Phi = CE^{\gamma}$ where γ is the spectral index and E is the energy.

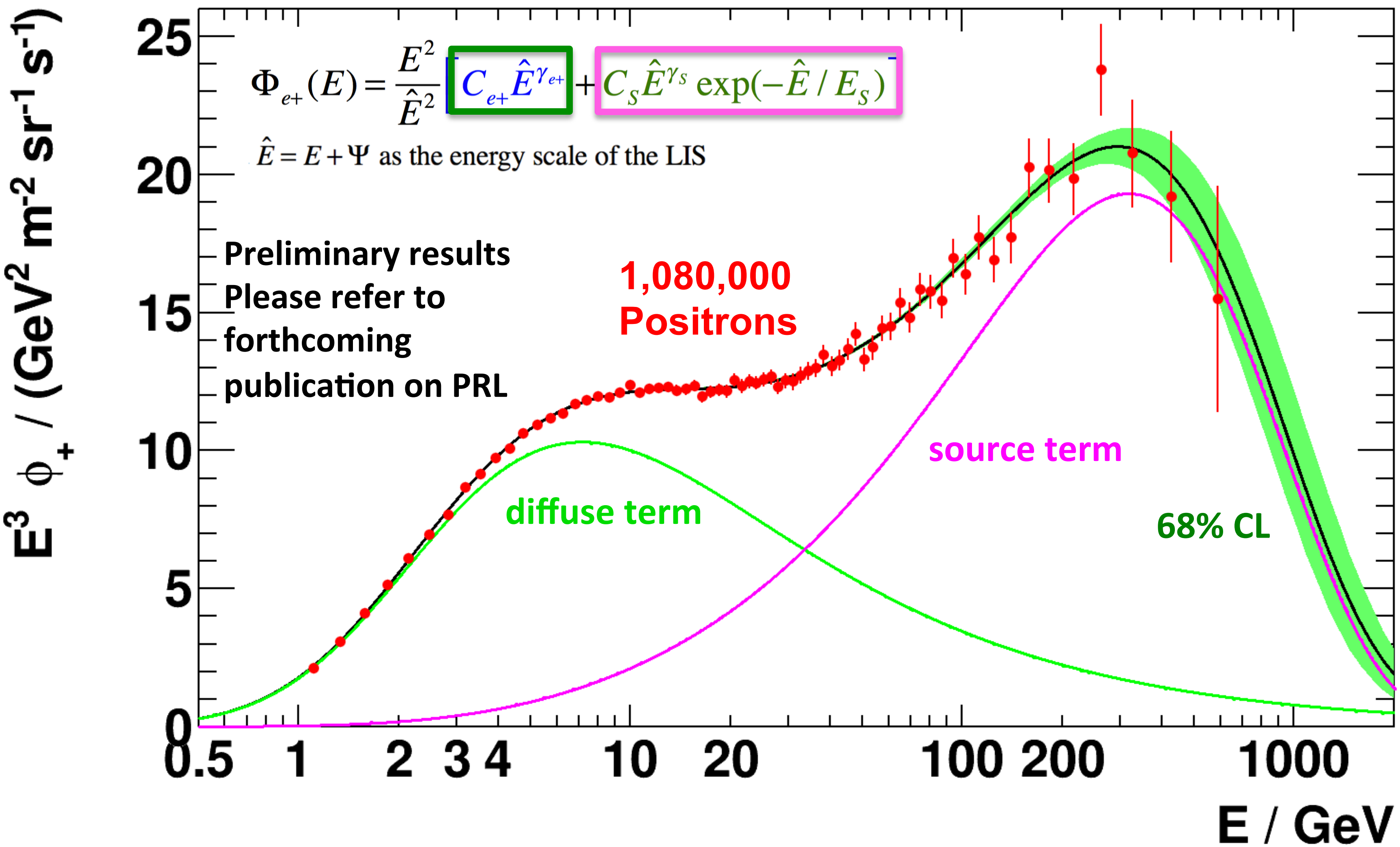
Before AMS, γ was assumed to be **constant** for the electron and positron spectra.



Electron and Positron Fluxes becomes harder at high energy

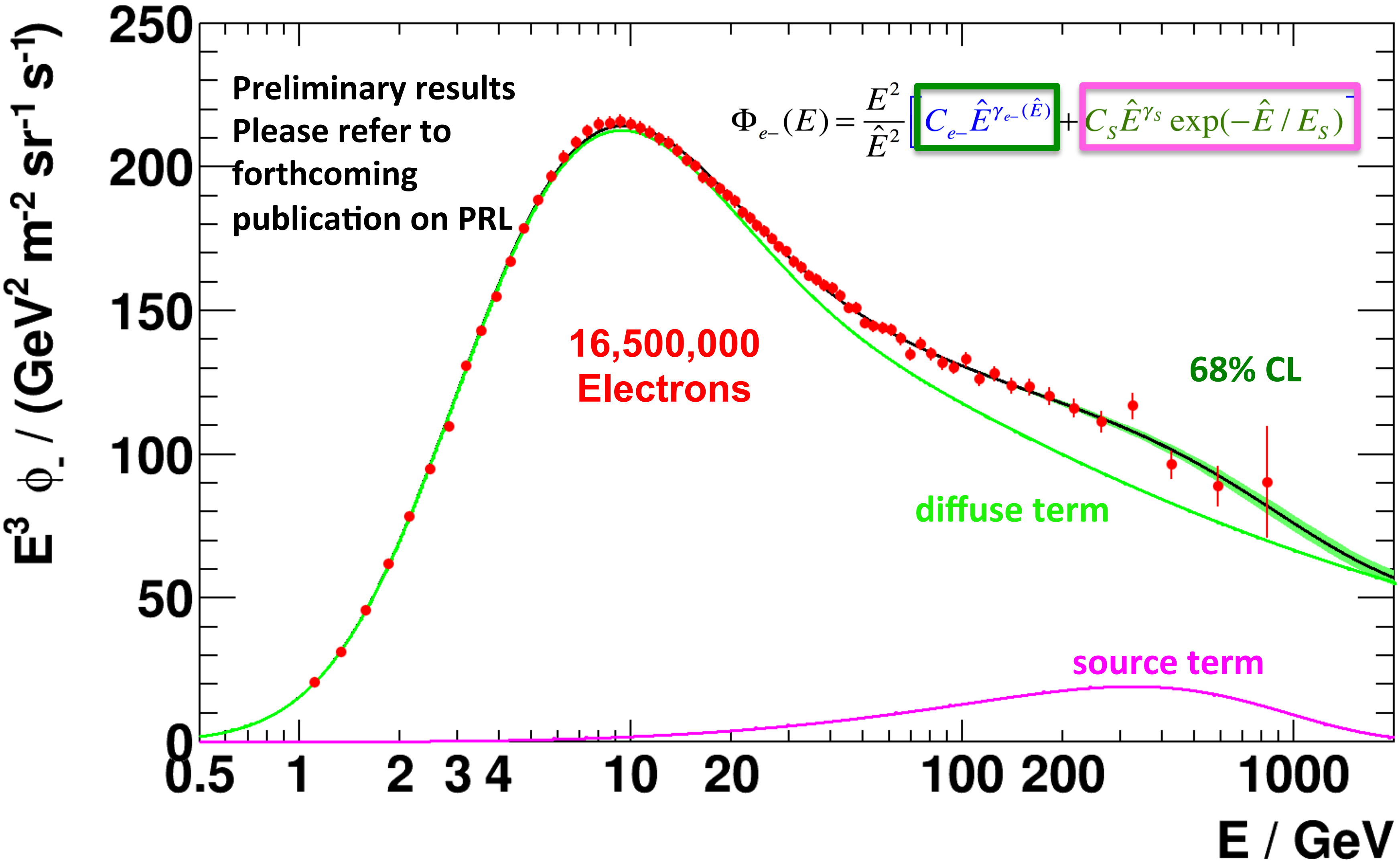
Additional source of cosmic ray positron and electron

Additional source of high energy electrons and positrons



Primary source of cosmic ray positron

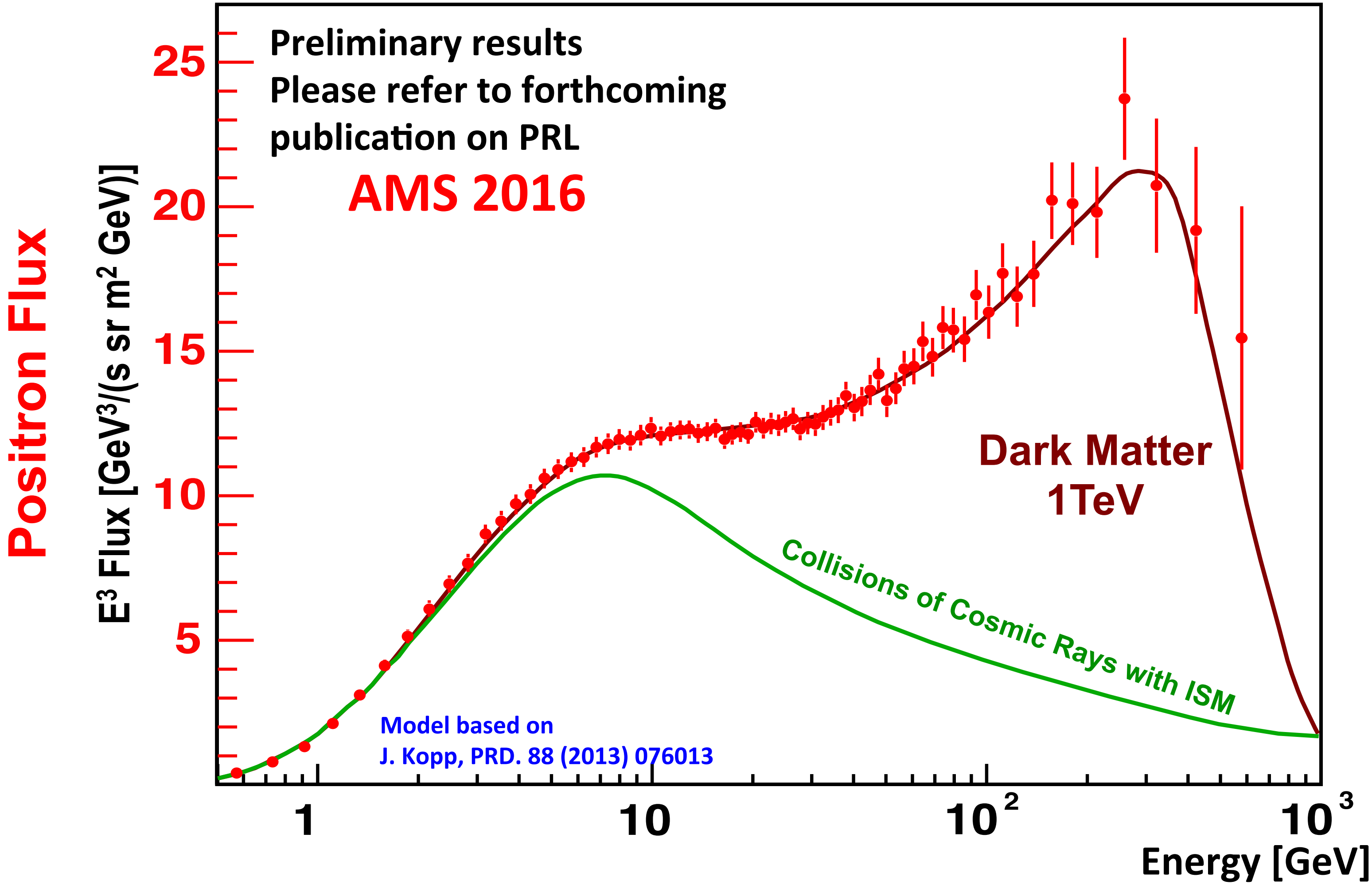
Additional source of high energy electrons and positrons



- The same source in the precision electron flux
- Common source of electrons and positrons by Charge Symmetry Process
- Require comprehensive modelling of cosmic rays to understand its origin

Models to explain the AMS Positron Fraction and Flux

1) Particle origin: Dark Matter
2) Modified Propagation of Cosmic Rays
3) Astrophysics origin: Pulsars, SNRs



The AMS results are in excellent agreement with some Dark Matter Model

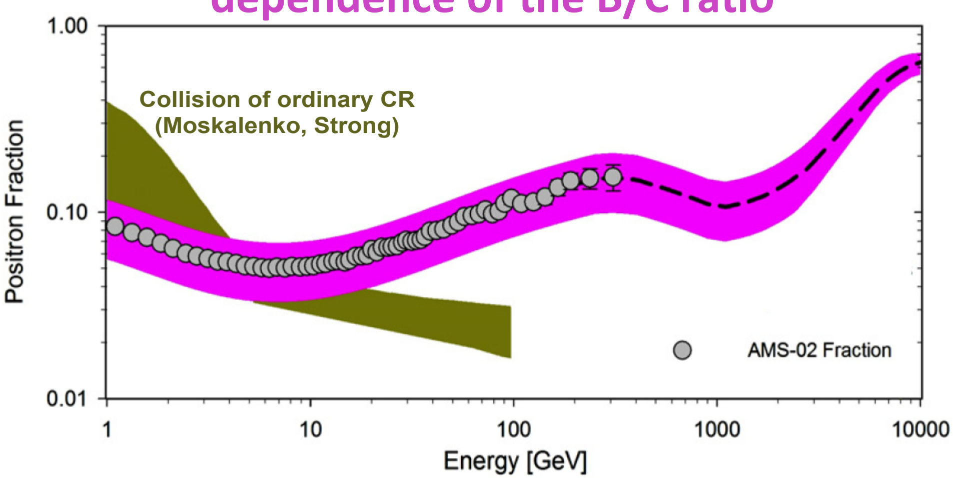
Alternative Models to explain the AMS Positron Flux and Positron Fraction Measurements

- Modified Propagation of Cosmic Rays
- Supernova Remnants
- Pulsars

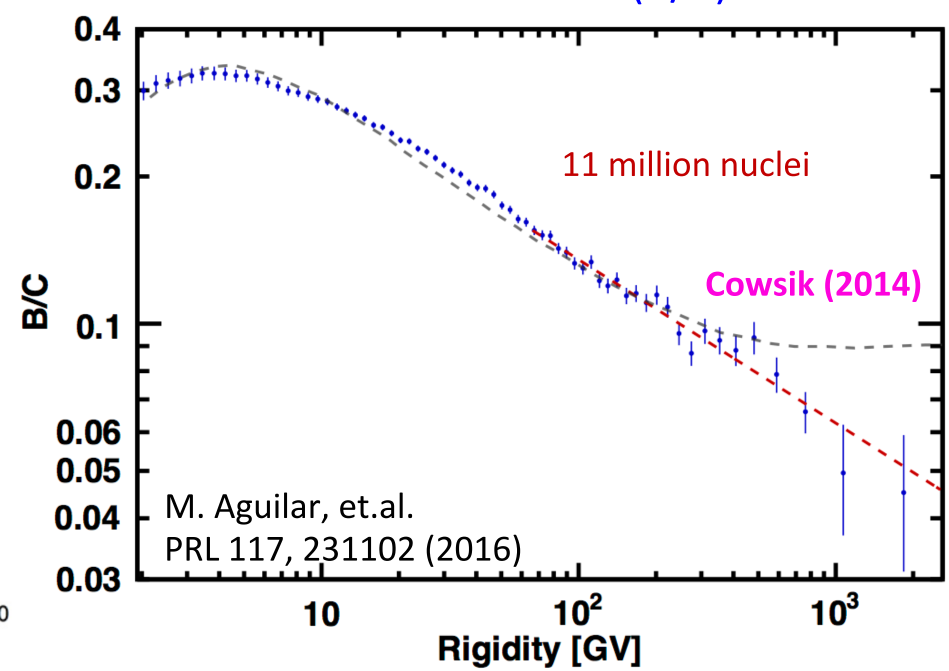
Examples:

R. Cowsik *et al.*, Ap. J. 786 (2014) 124, (pink band) explaining that the AMS positron fraction (gray circles) above 10 GeV is due to propagation effects.

However, this requires a specific energy dependence of the B/C ratio



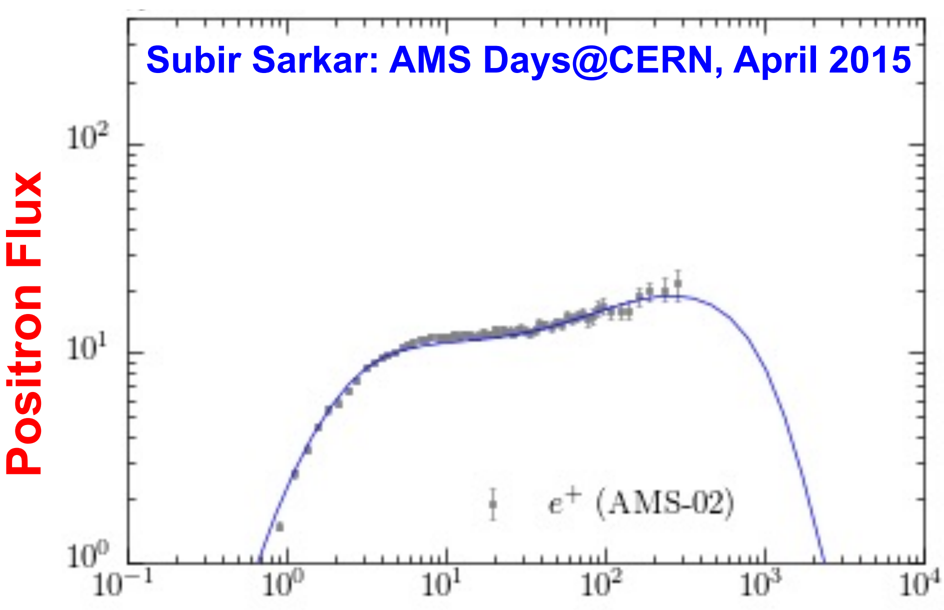
The AMS Boron-to-Carbon (B/C) flux ratio

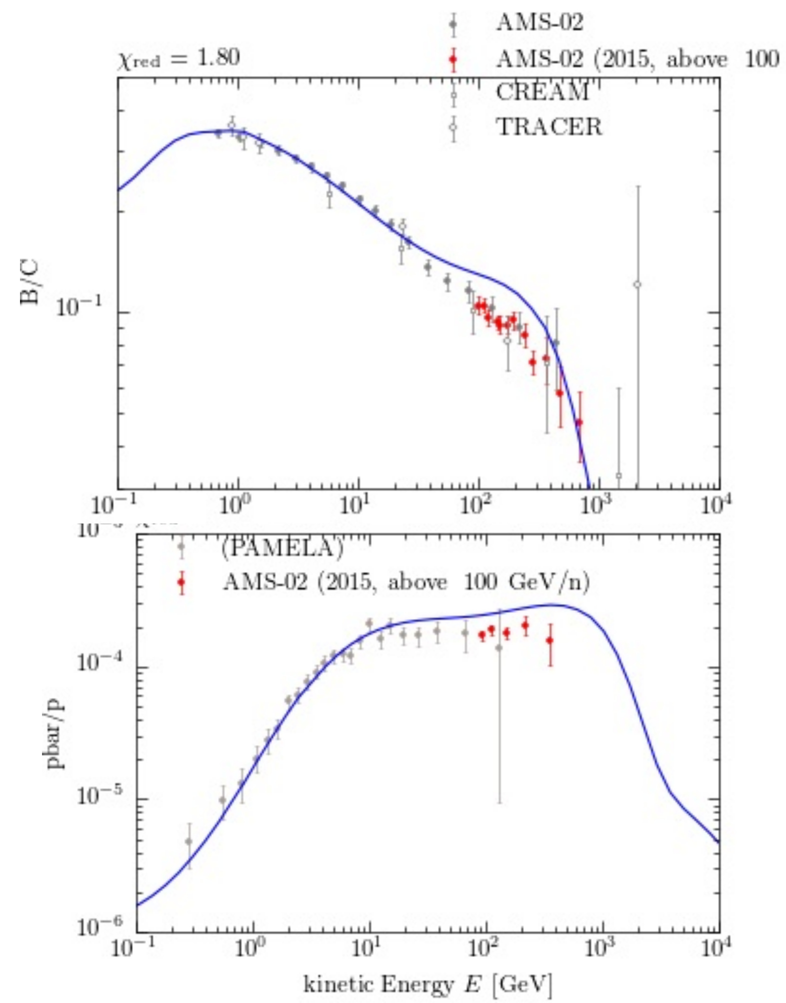


Alternative Models to explain the AMS Positron Flux and Positron Fraction Measurements

- **Modified Propagation of Cosmic Rays**
- **Supernova Remnants**
- **Pulsars**

Examples:





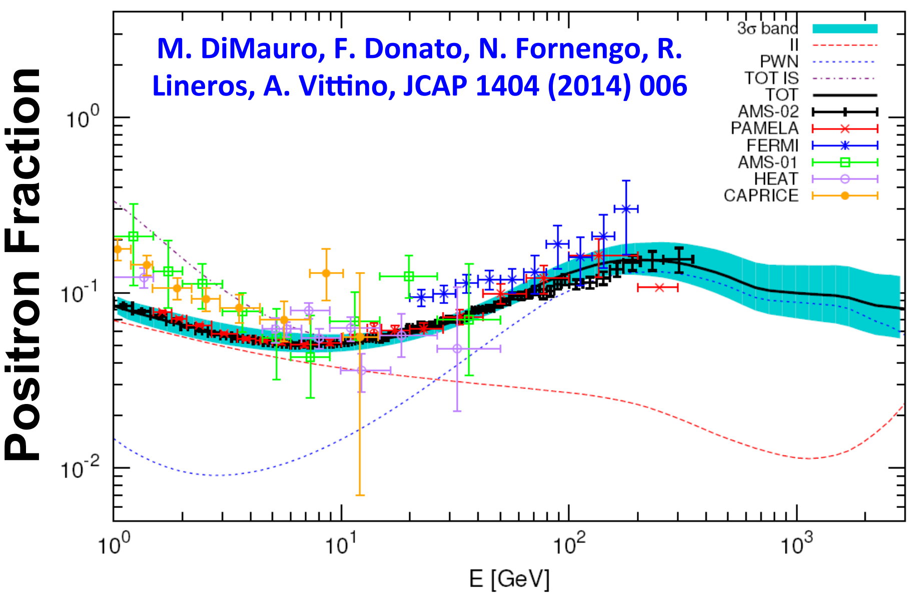
Challenged by AMS measurement of other CR particles: B/C, pbar/p

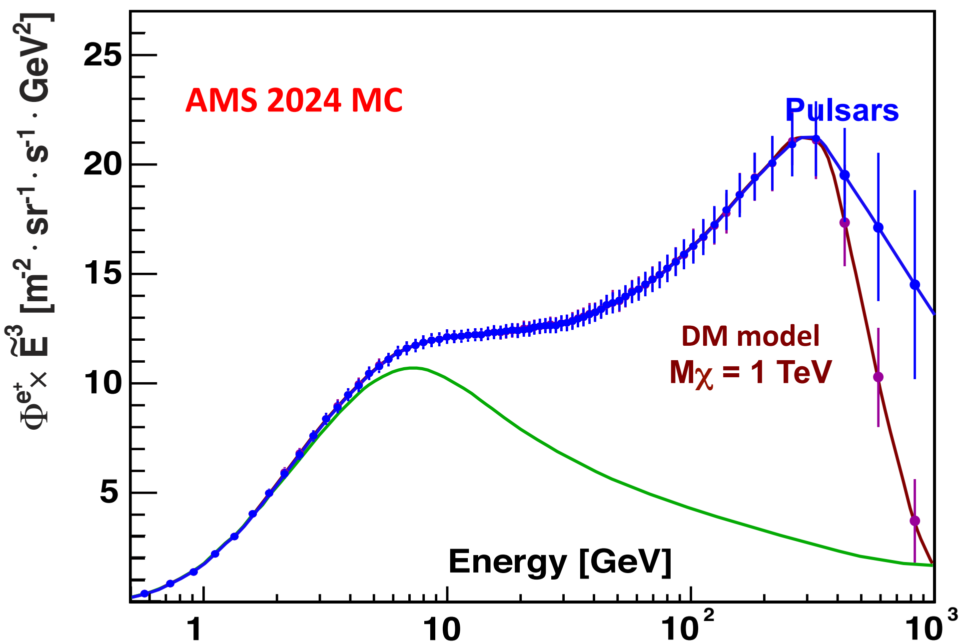
Alternative Models to explain the AMS Positron Flux and Positron Fraction Measurements

- Modified Propagation of Cosmic Rays
- Supernova Remnants
- Pulsars

Examples:

By 2024, AMS will distinguish Dark Matter from Pulsars



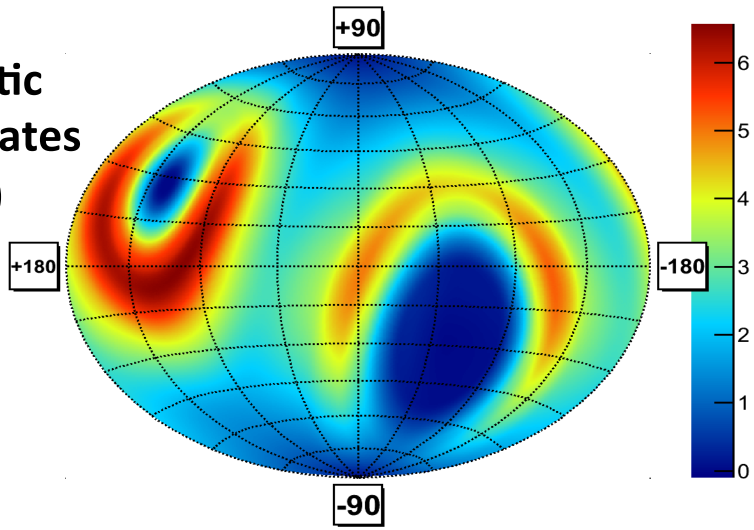


AMS Measurements on Positron, Electron anisotropy and on antiprotons will also help distinguish different models

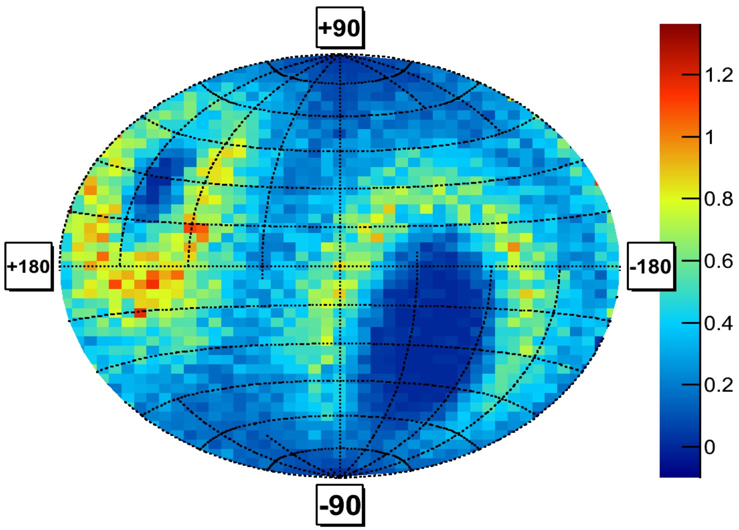
Positron and Electron Anisotropy

- Primary source of cosmic ray positrons and electrons may induce anisotropy on their arrival direction
- Astrophysical point sources like pulsars will imprint a higher level of anisotropy than a smooth dark matter halo.
- Method: Spherical harmonic expansion , dipole amplitude: $\delta = 3\sqrt{C_1 / 4\pi}$

Galactic coordinates (b,l)



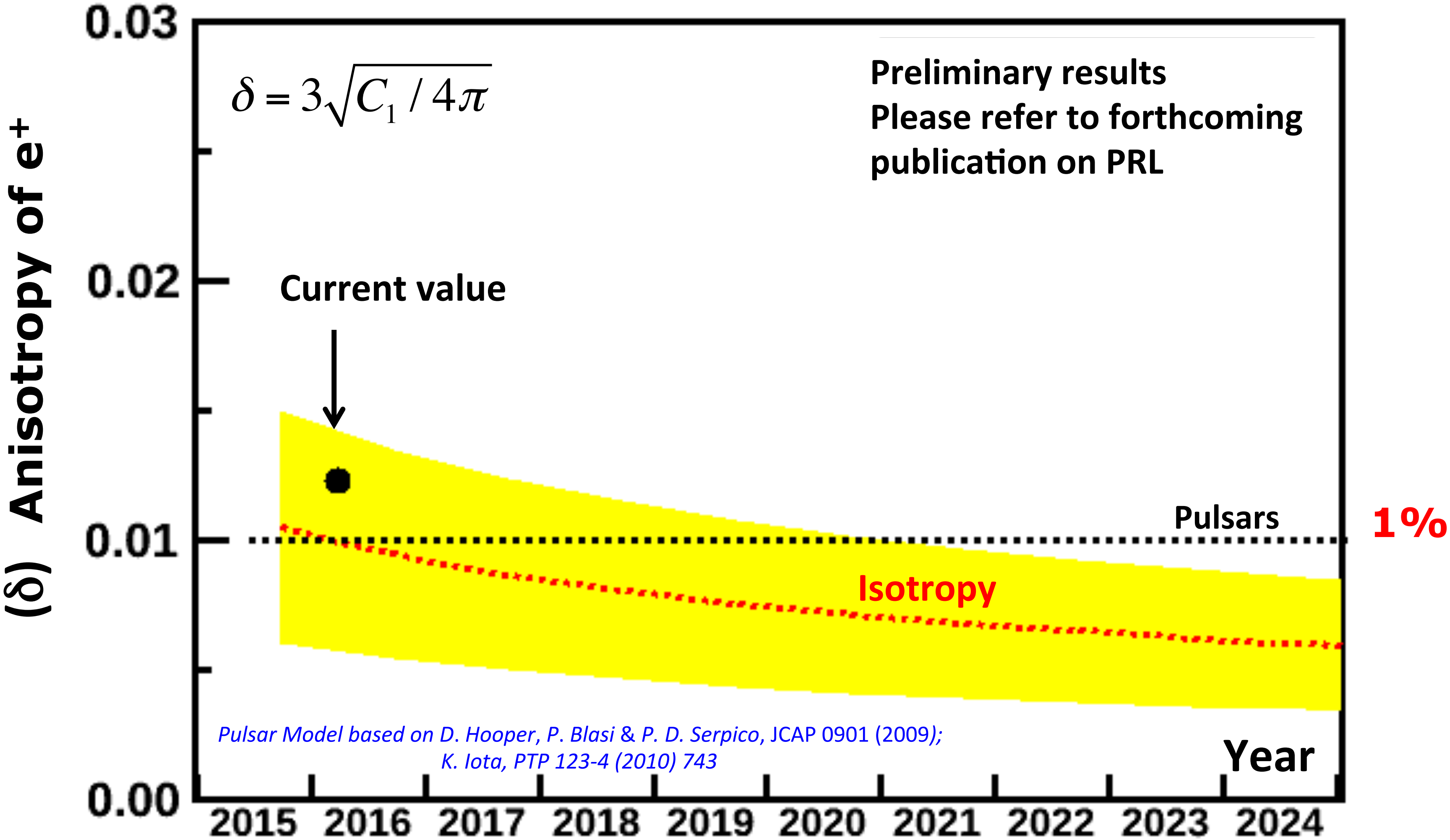
Expected exposure



Measured Positron

Positron and Electron Anisotropy

The fluctuations of the positron flux are isotropic in 16 < *E* [GeV] < 350.



Data taking to 2024 will allow to explore anisotropies of 1%

This will help distinguish dark matter models and astrophysical models

The Comprehensive Measurements by AMS

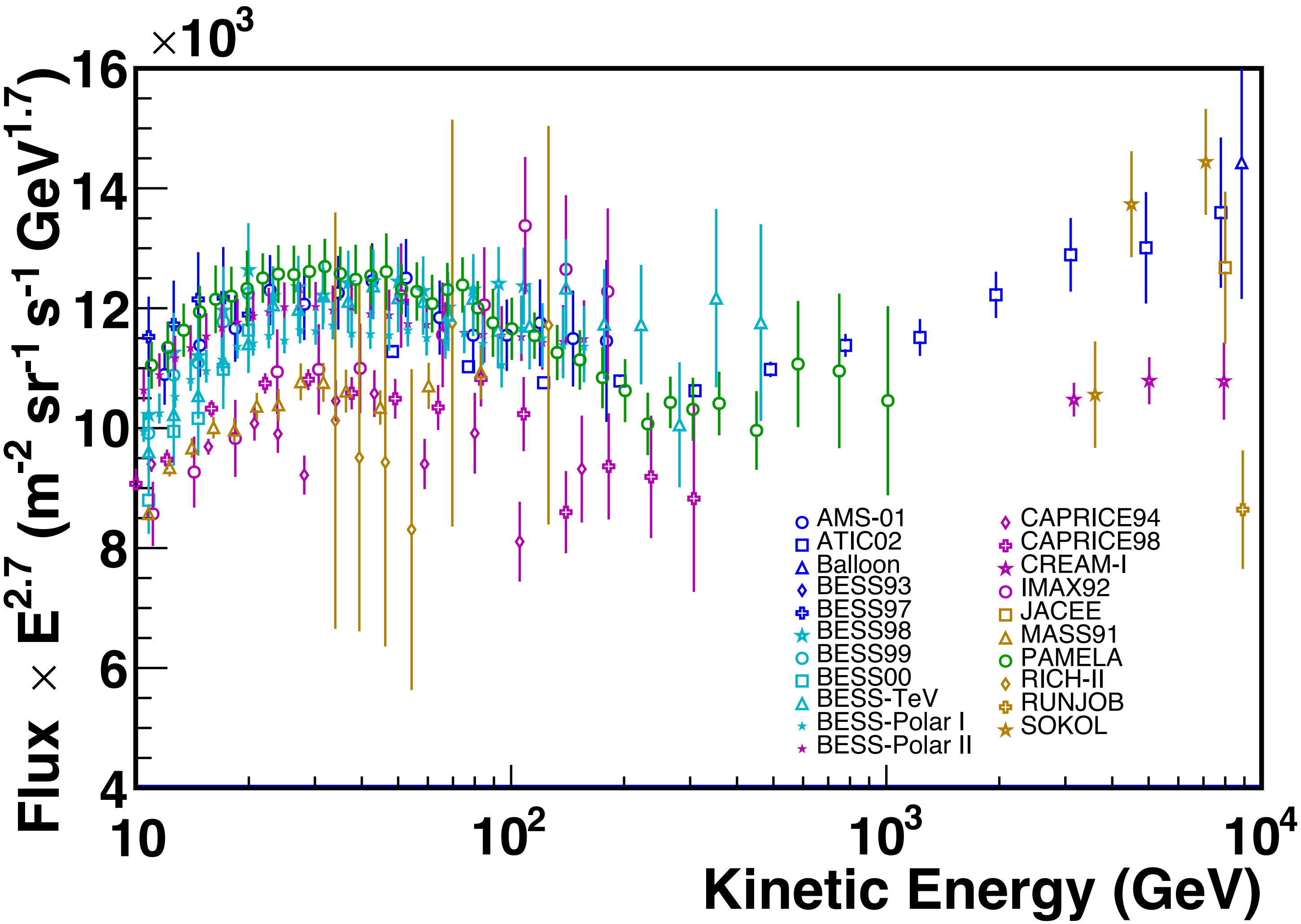
- **The precision data shows an common excess of high energy electrons and positrons**
- **The high energy electrons and positrons are isotropic**
- **The current data can be explained by Dark Matter or new astrophysical sources**

- **Antiproton is an independent channel to search for Dark Matter and can help to distinguish between Dark Matter and Pulsar models**
- **To measure antiprotons, we need to measure protons firstly.**

Cosmic ray protons

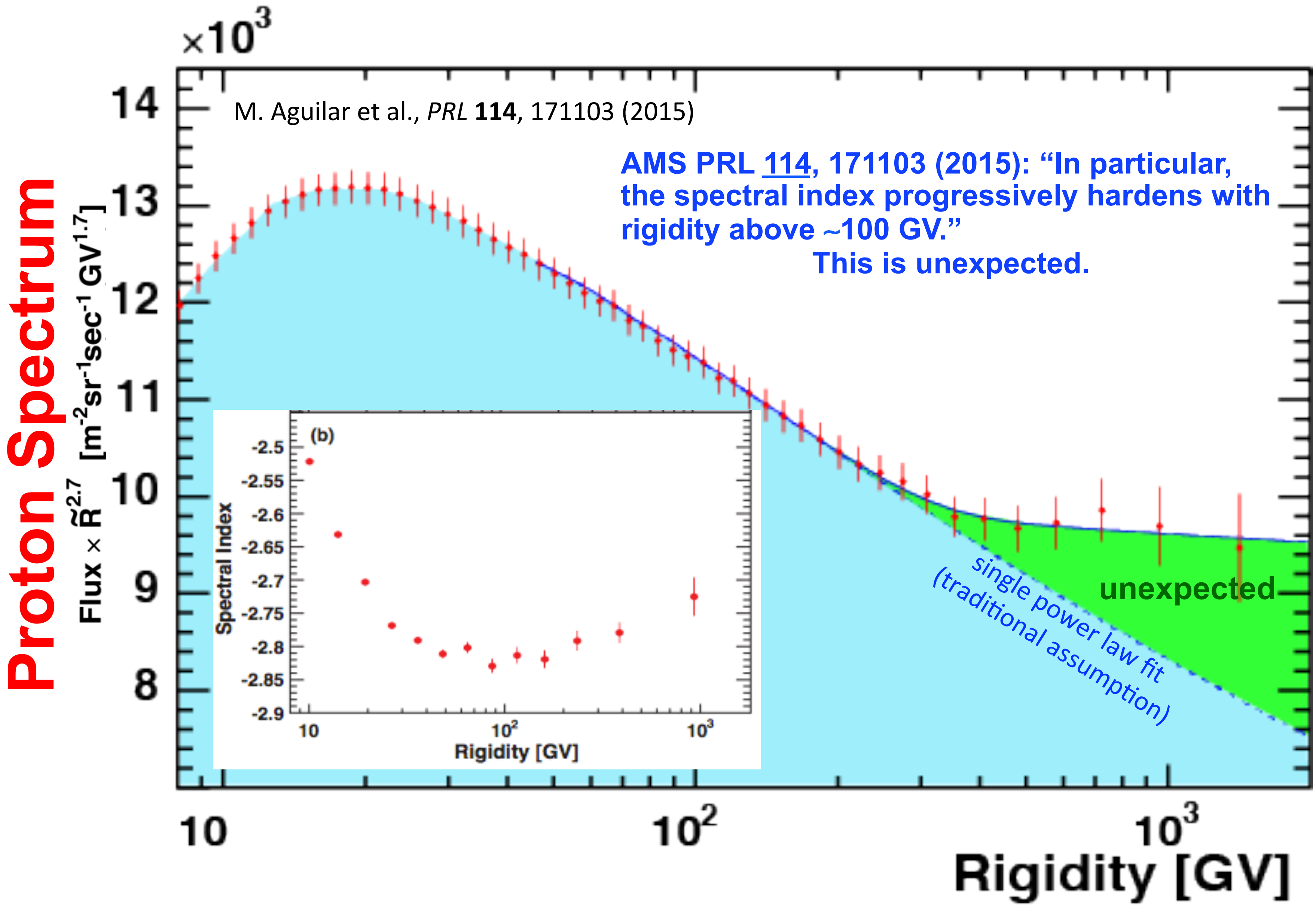
1. Protons are the most abundant cosmic rays.
2. Before AMS there have been many measurements of the proton spectrum.
3. Traditionally, the proton spectral function was assumed to be a single power law $\Phi = CE^{\gamma}$ with $\gamma = -2.7$

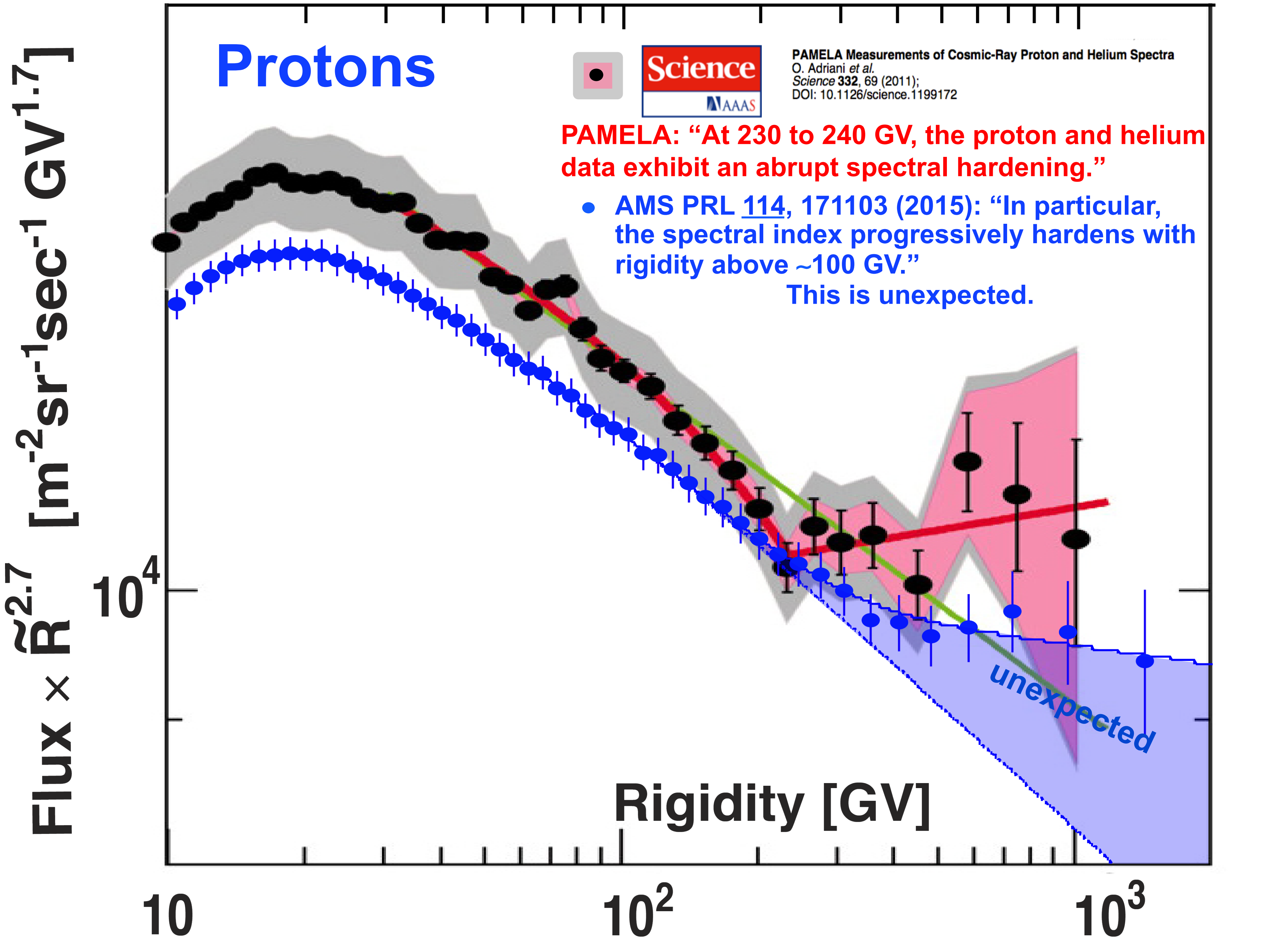
Proton Spectrum



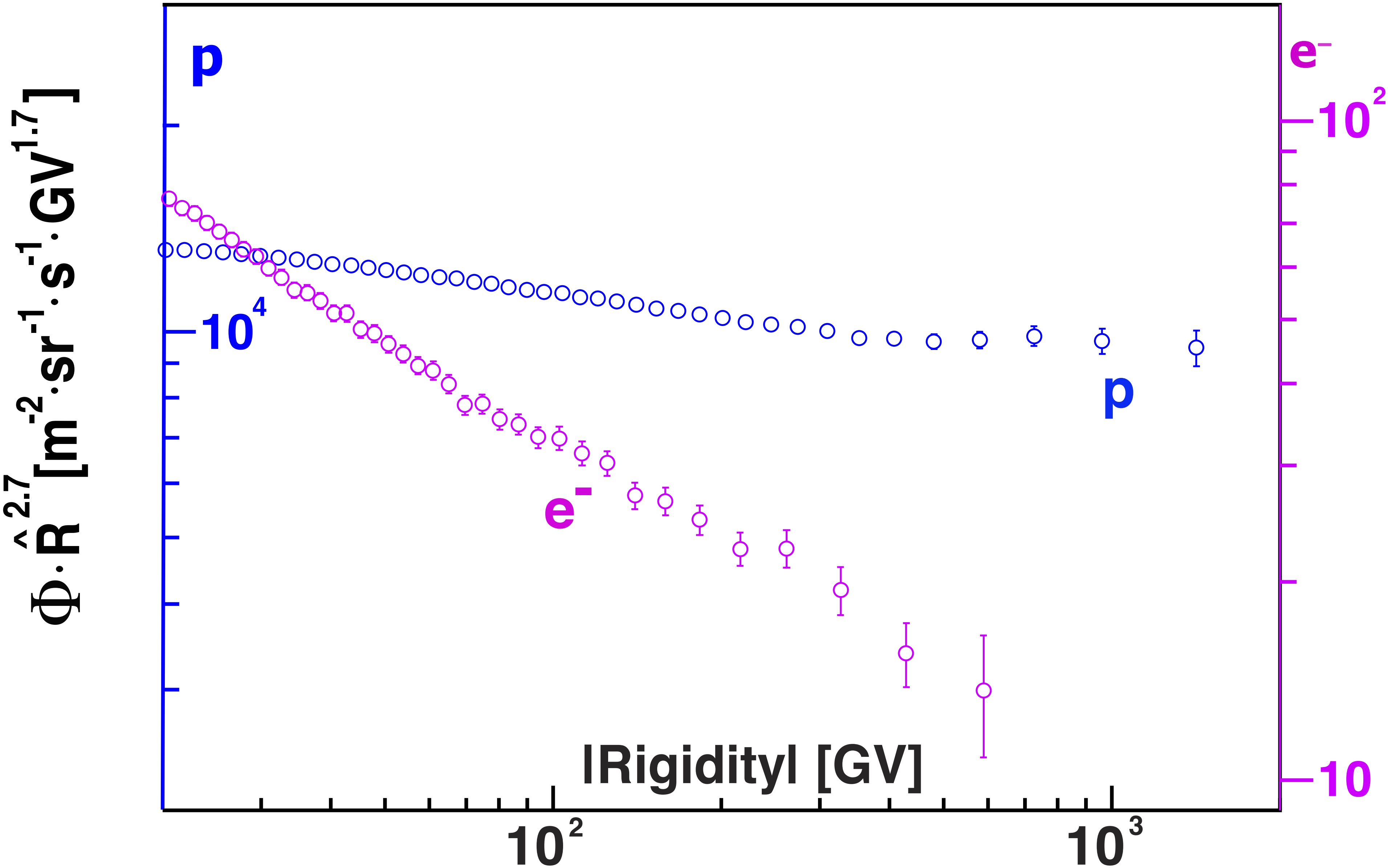
AMS proton flux

New information: The proton flux cannot be described by a single power law = CR^{γ}




Protons
PAMELA Measurements of Cosmic-Ray Proton and Helium Spectra
O. Adriani et al.
Science 332, 69 (2011);
DOI: 10.1126/science.1199172
PAMELA: "At 230 to 240 GV, the proton and helium data exhibit an abrupt spectral hardening."
AMS PRL 114, 171103 (2015): "In particular, the spectral index progressively hardens with rigidity above ~100 GV."
This is unexpected.
unexpected
Flux × R̃$^{2.7}$ [m^{-2}sr^{-1}sec^{-1} GV$^{1.7}$]
10^4
Rigidity [GV]
10
10^2
10^3

The rigidity dependence of e⁻ and p flux are different as expected.
e⁻ lose more energy in the interstellar magnetic field

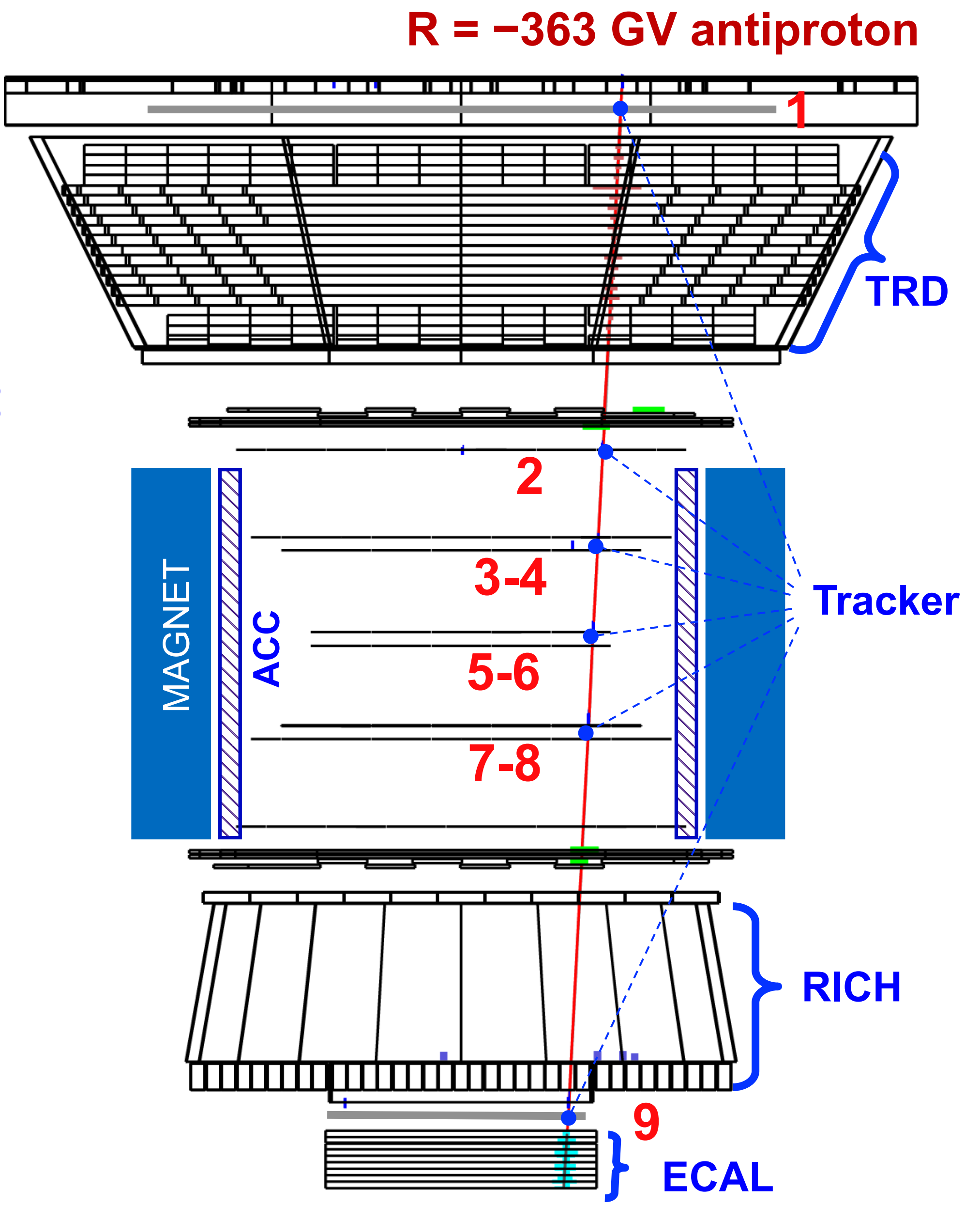


Antiproton Measurement with AMS

The antiproton flux is
~1/10000 of the proton flux.

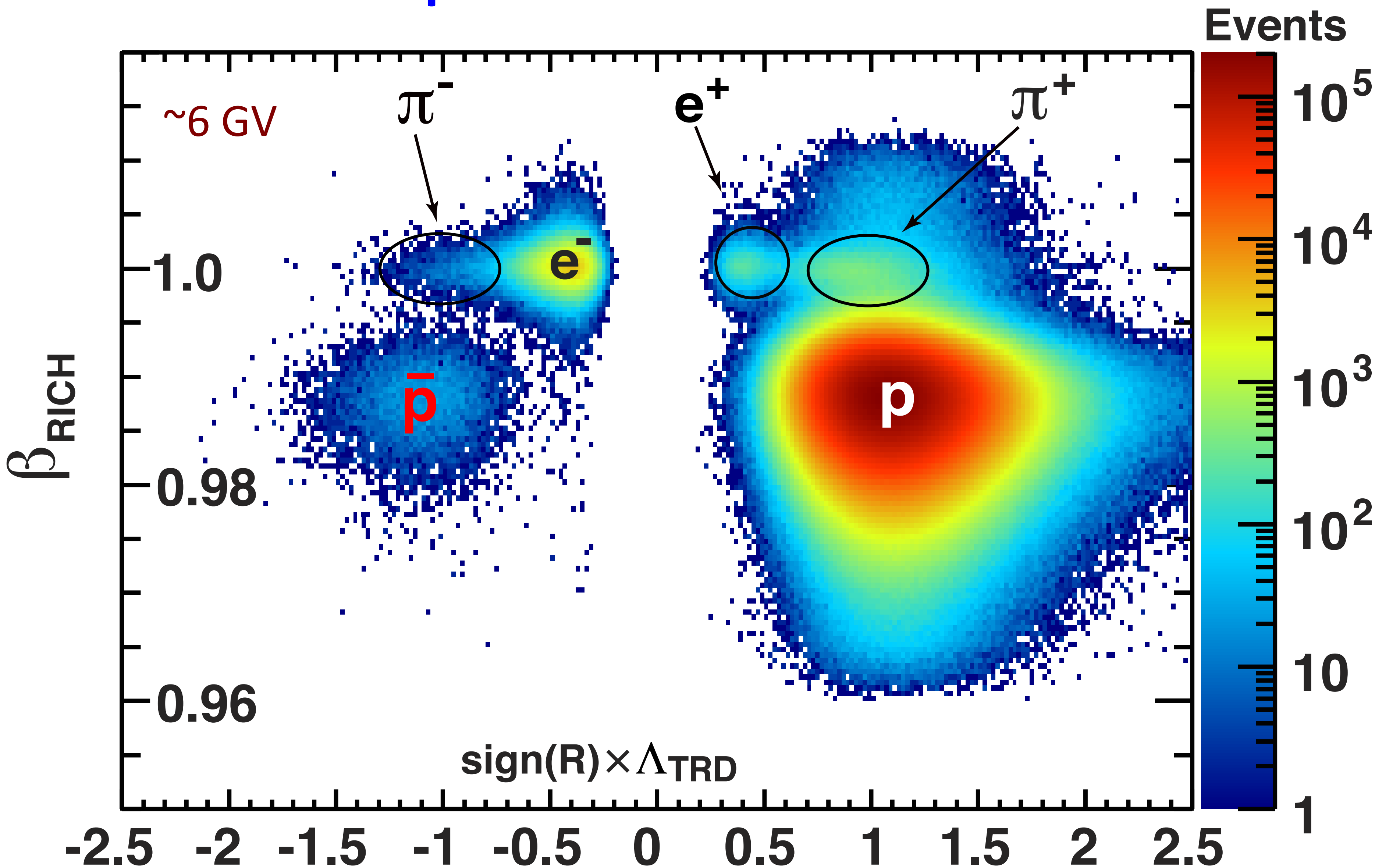
A percent precision experiment requires background rejection close to 1 in a million

Based on 65 billion cosmic rays collected in the first 4 years, 3.49×10^5 antiprotons are selected for $1<|R|<450$ GV



M. Aguilar et al., *PRL* **117**, 091103 (2016)

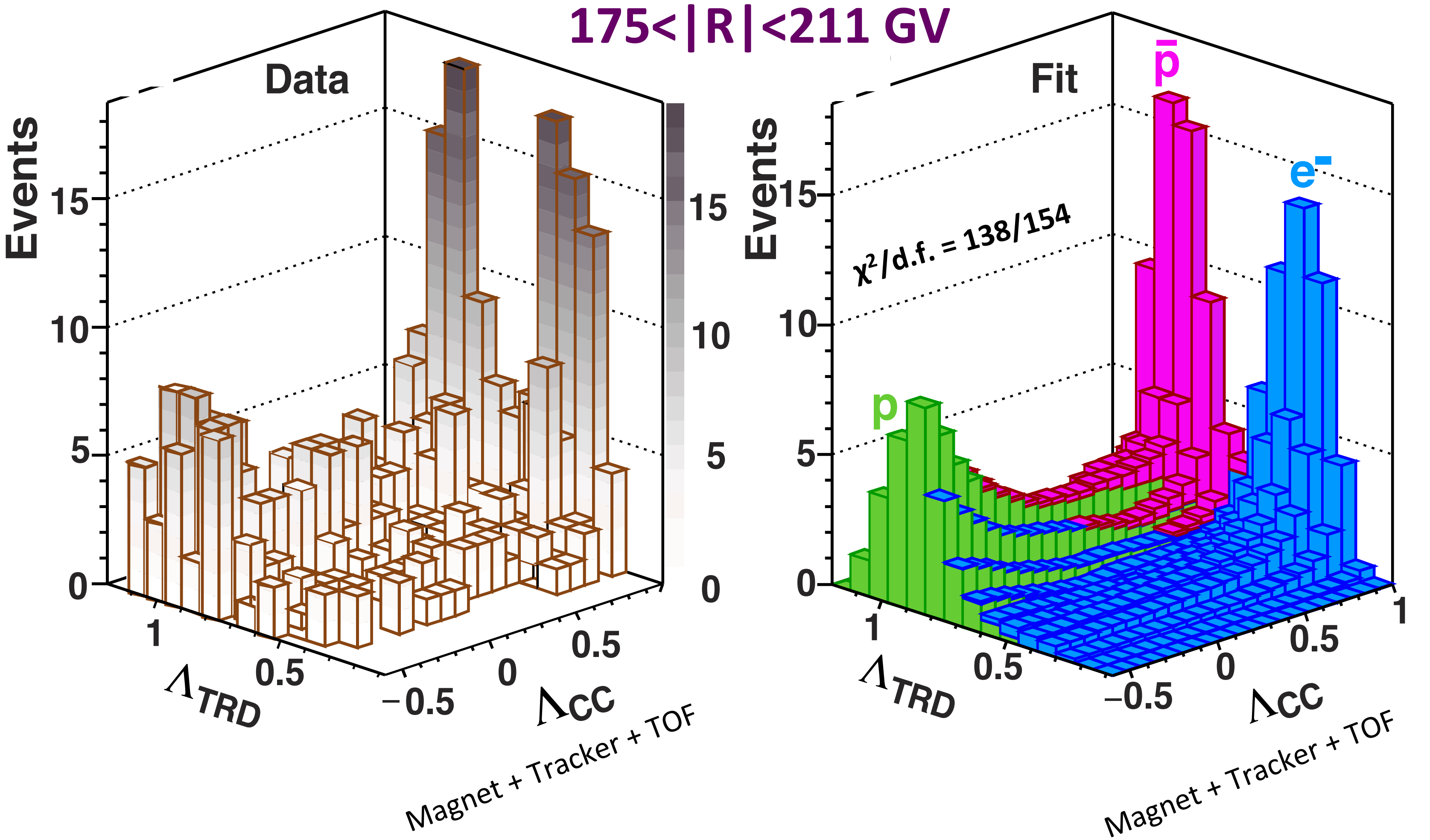
Antiproton selection in AMS



Antiproton signal is well separated from the backgrounds

Antiproton selection at high rigidities

The number of antiprotons is determined from template fit

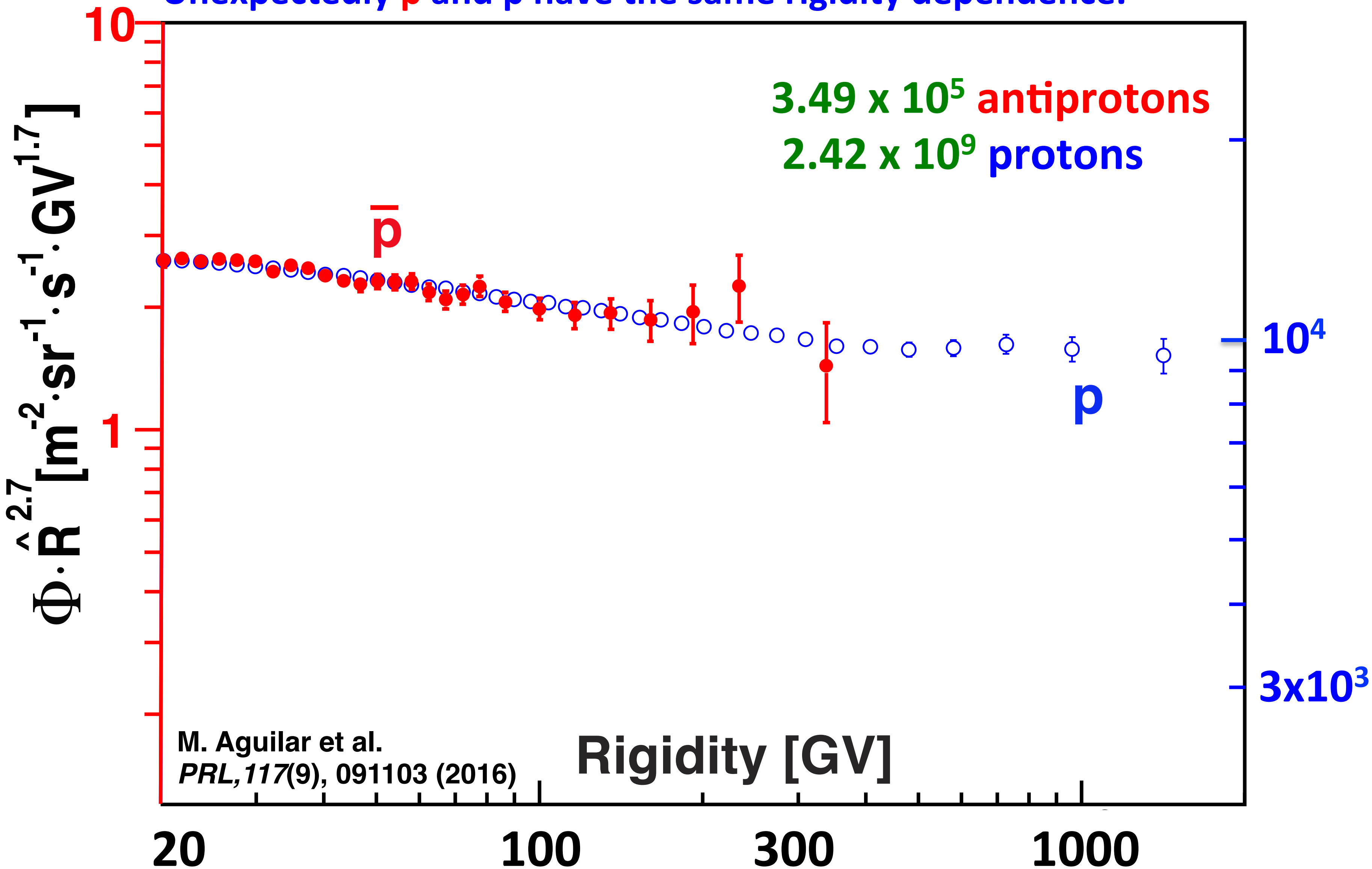


Unexpected: The Spectra of Protons and Antiprotons:

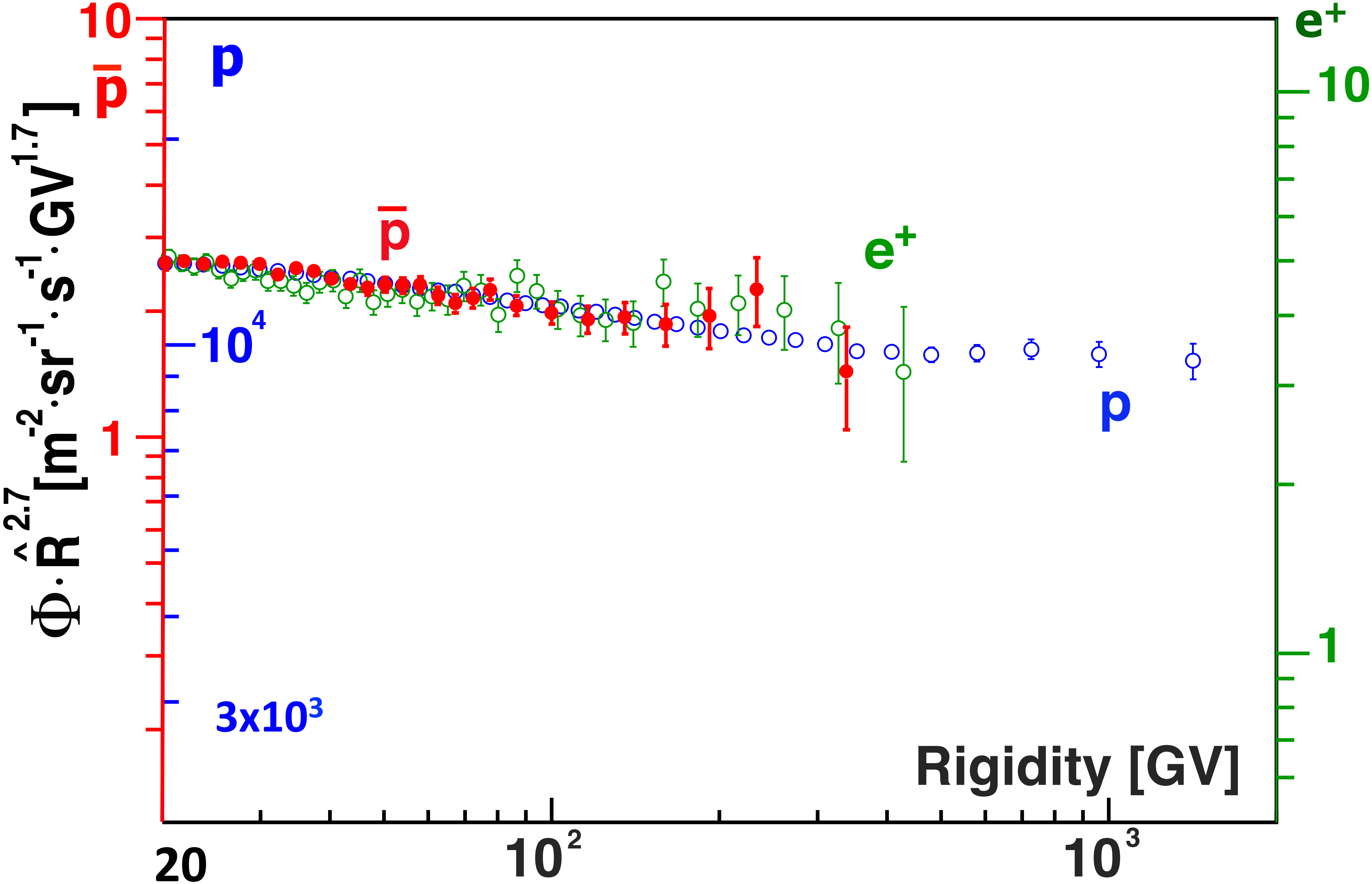
If $\bar{p}$ are secondaries, their rigidity dependence should be different than p:

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

Unexpectedly $\bar{p}$ and p have the same rigidity dependence.

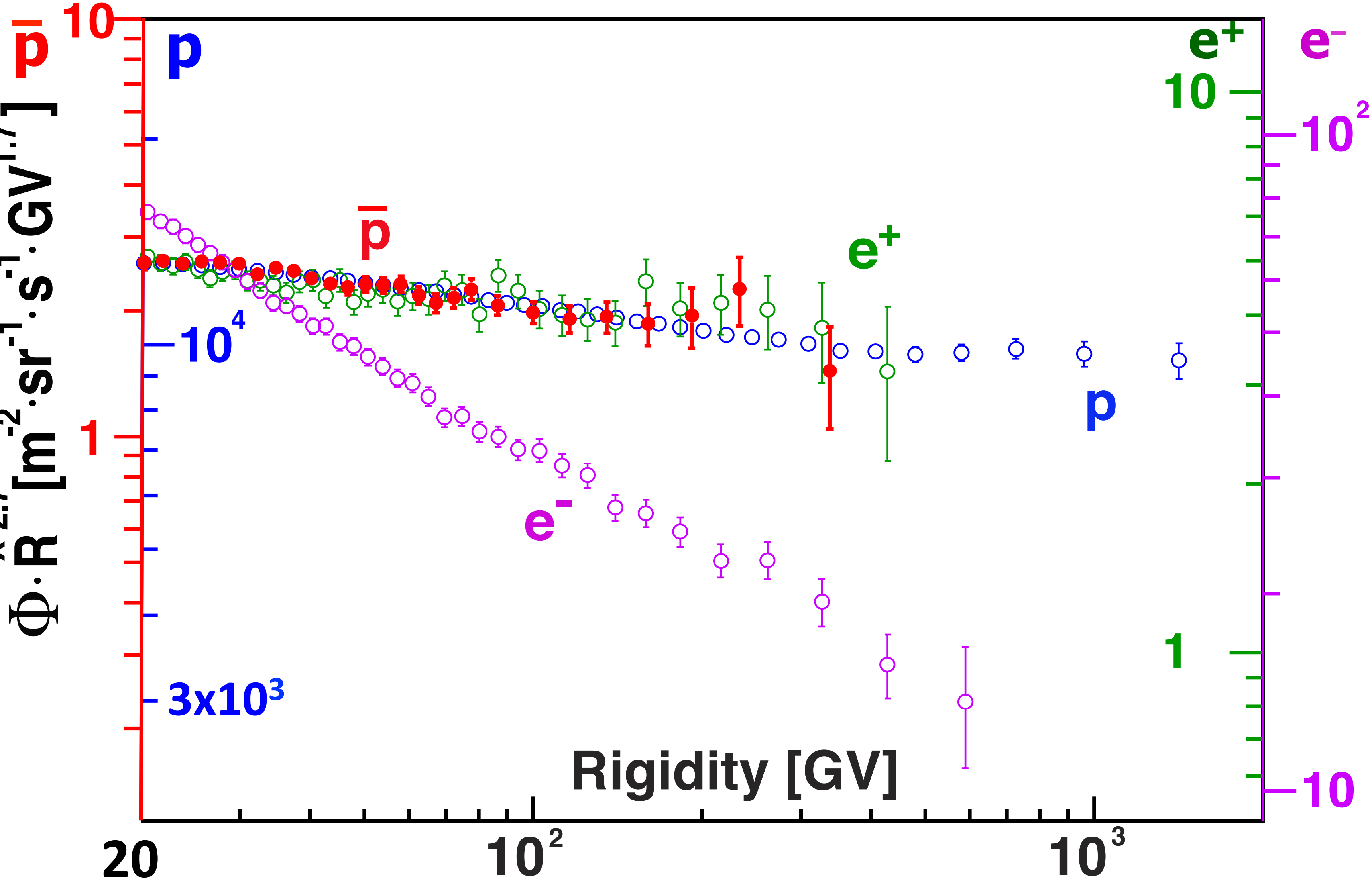


Unexpected results: the rigidity dependence of of e^+, $\bar{p}$, p are identical from ~60 to ~500 GV

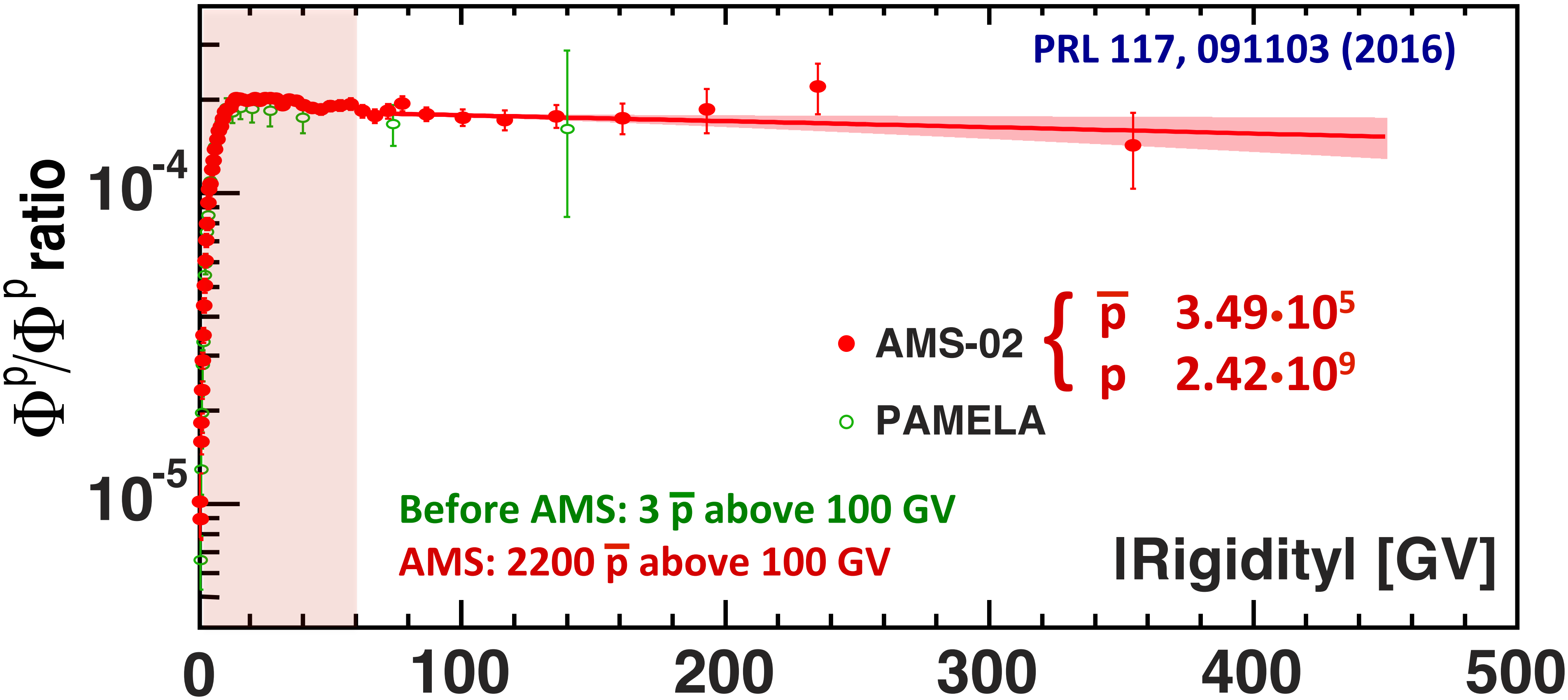


Unexpected results: the rigidity dependence of of e^+, $\bar{p}$, p are identical from ~60 to ~500 GV

e^- has a different rigidity dependence.



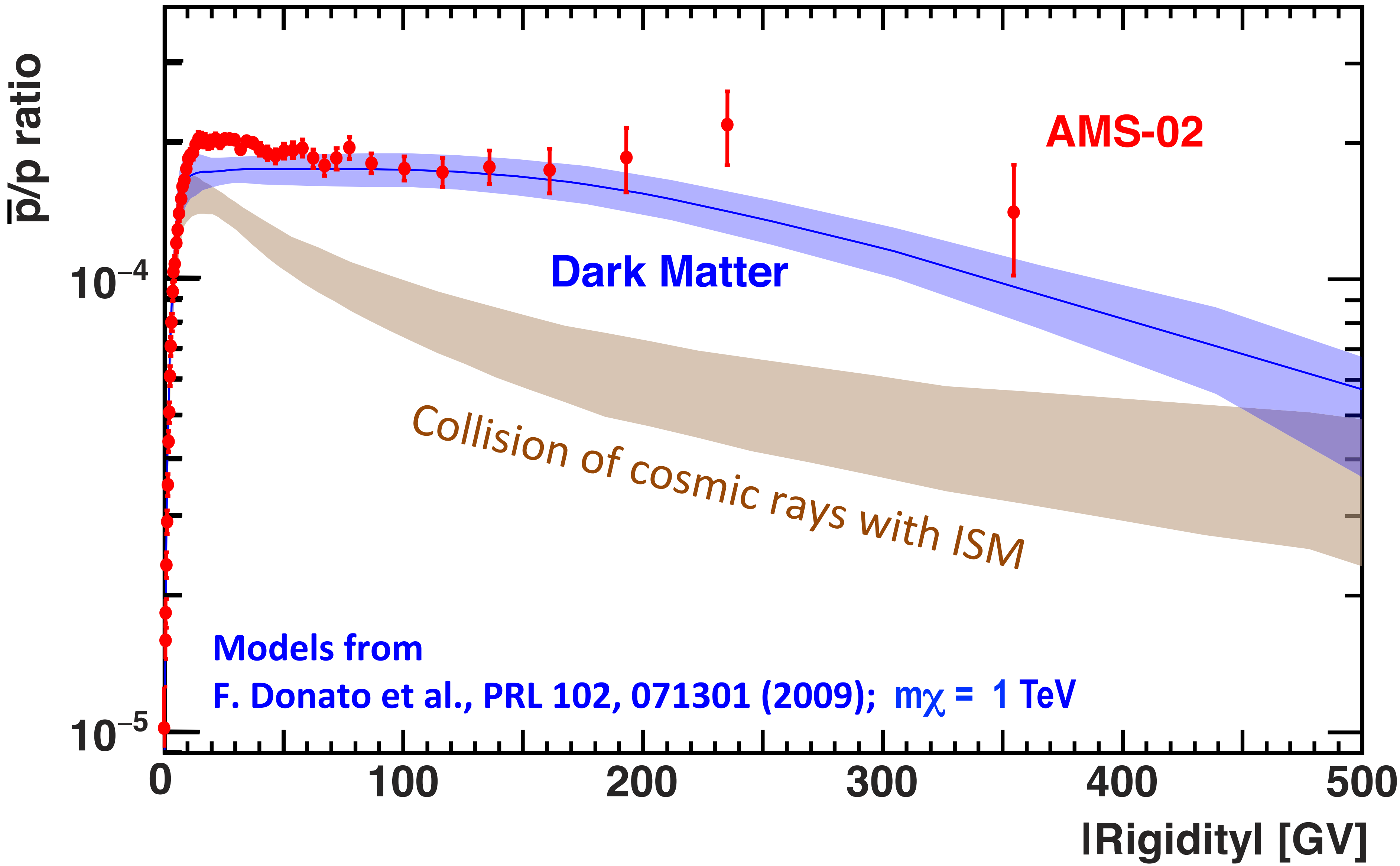
Flux Ratio of Elementary Particles $\bar{p}/p$ is energy independent above 60 GV



The measurement accuracy is not limited by the systematics!

M. Aguilar *et al*., Phys. Rev. Lett. **117,** 091103 (2016)

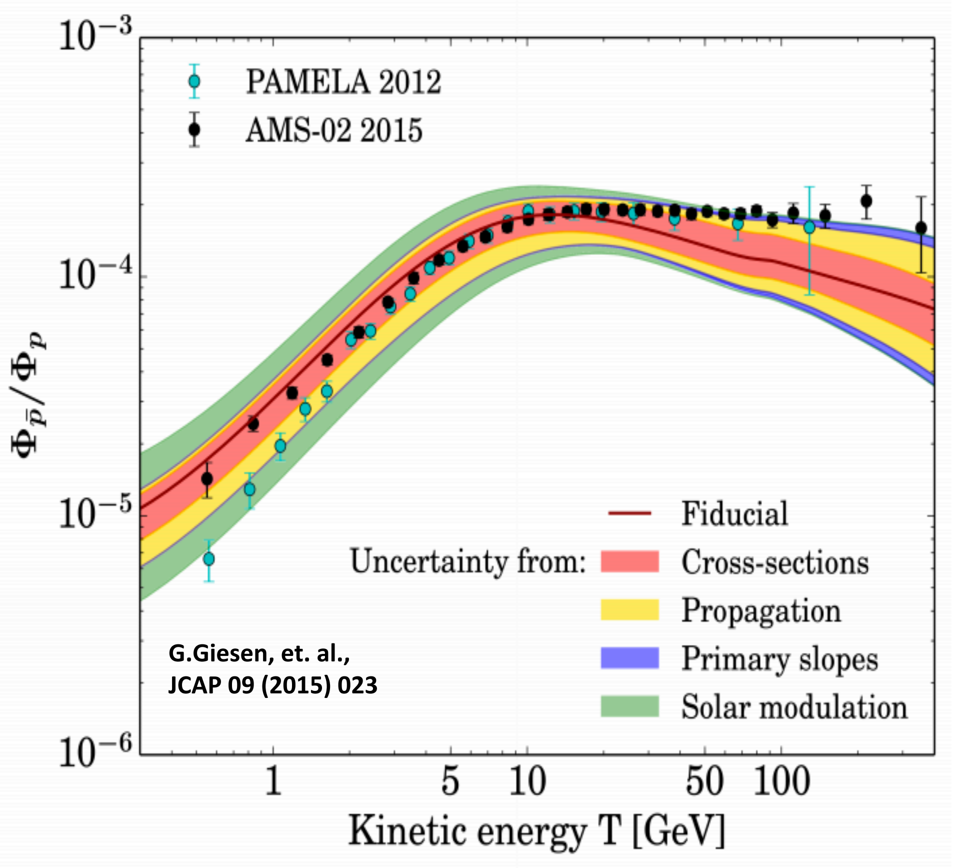
AMS $\bar{p}/p$ results and modeling



Recent models of antiproton production

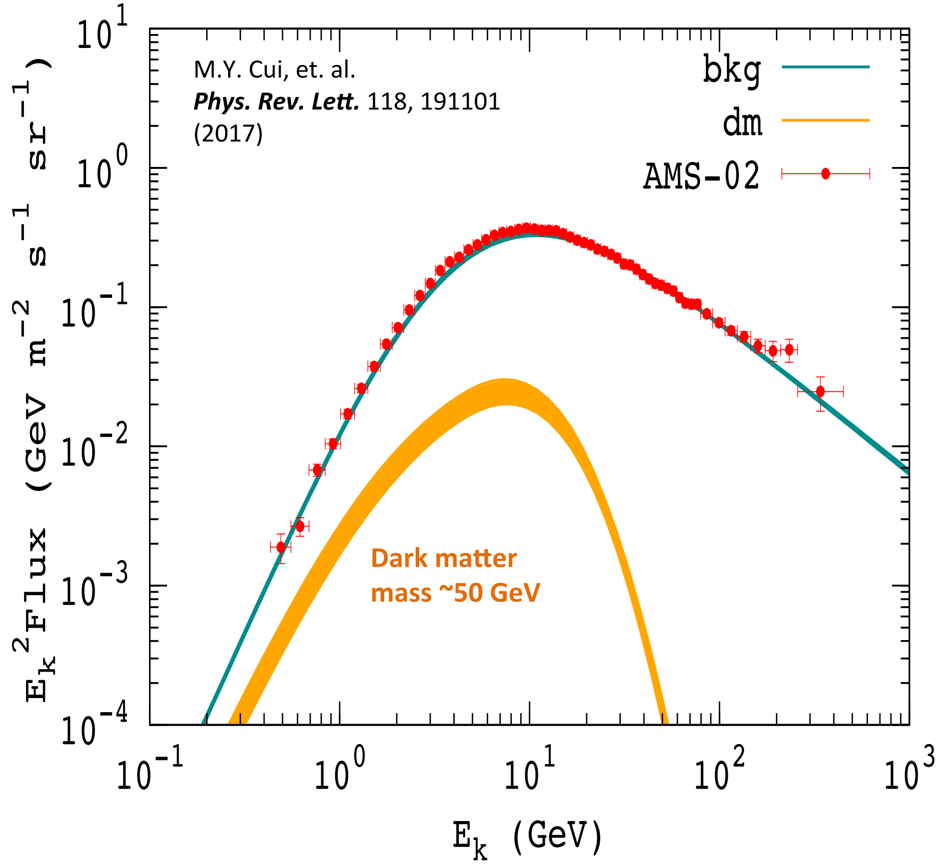
From collision of cosmic rays with interstellar medium:

G.Giesen, et. al., JCAP 09 (2015) 023
C.Evoli et. al., JCAP 12 (2015) 039
R.Kappl, et. al., JACP 10(2015) 034
…

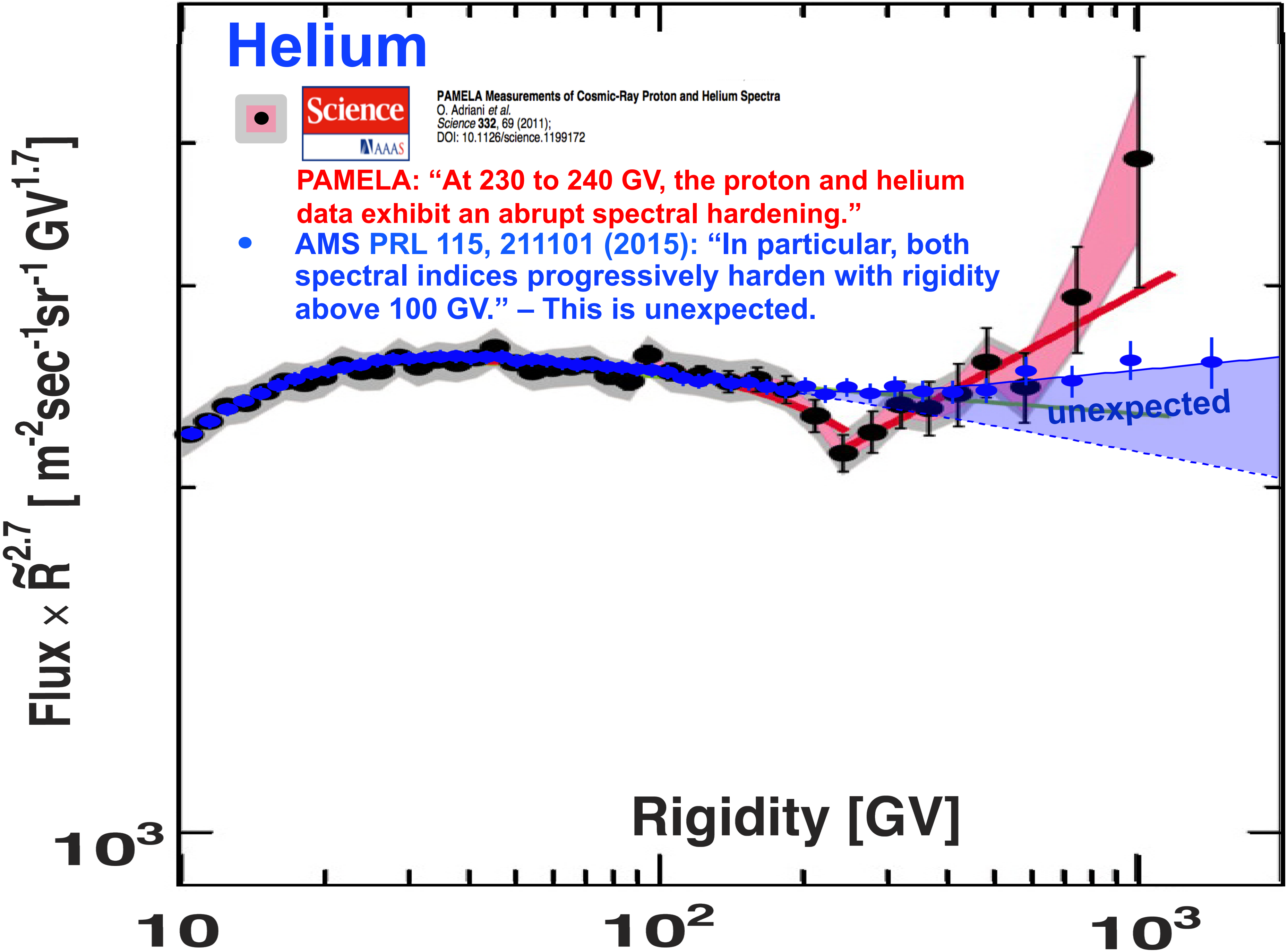


Dark matter contribution to explain the antiproton excess around 10 GV:

A. Cuoco, et. Al.*Phys. Rev. Lett.* 118, 191102
M.Y. Cui, et. al. *Phys. Rev. Lett.* 118, 191101 (2017)



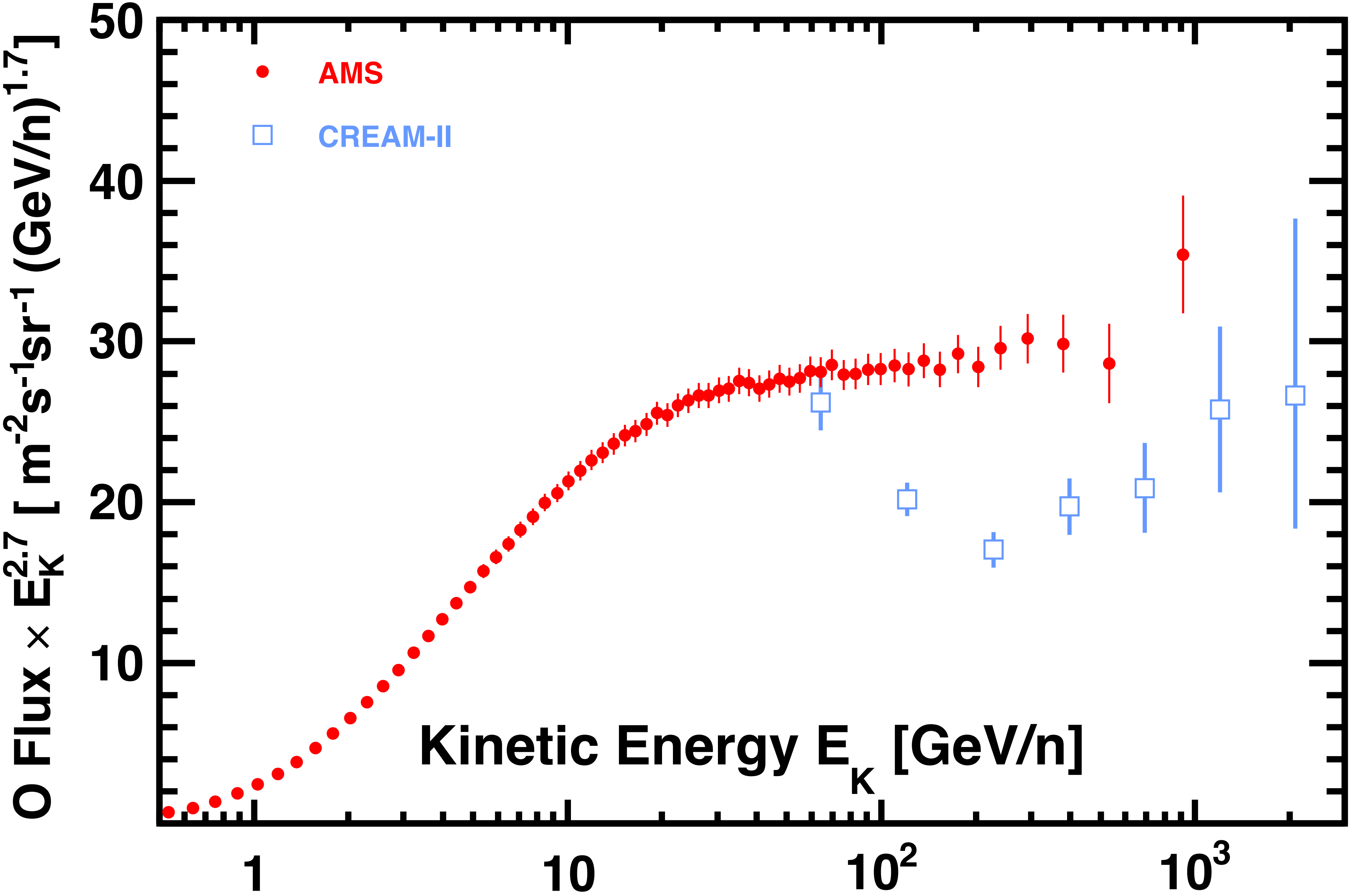
The precision and comprehensive data from AMS allows for the exploration of new phenomena



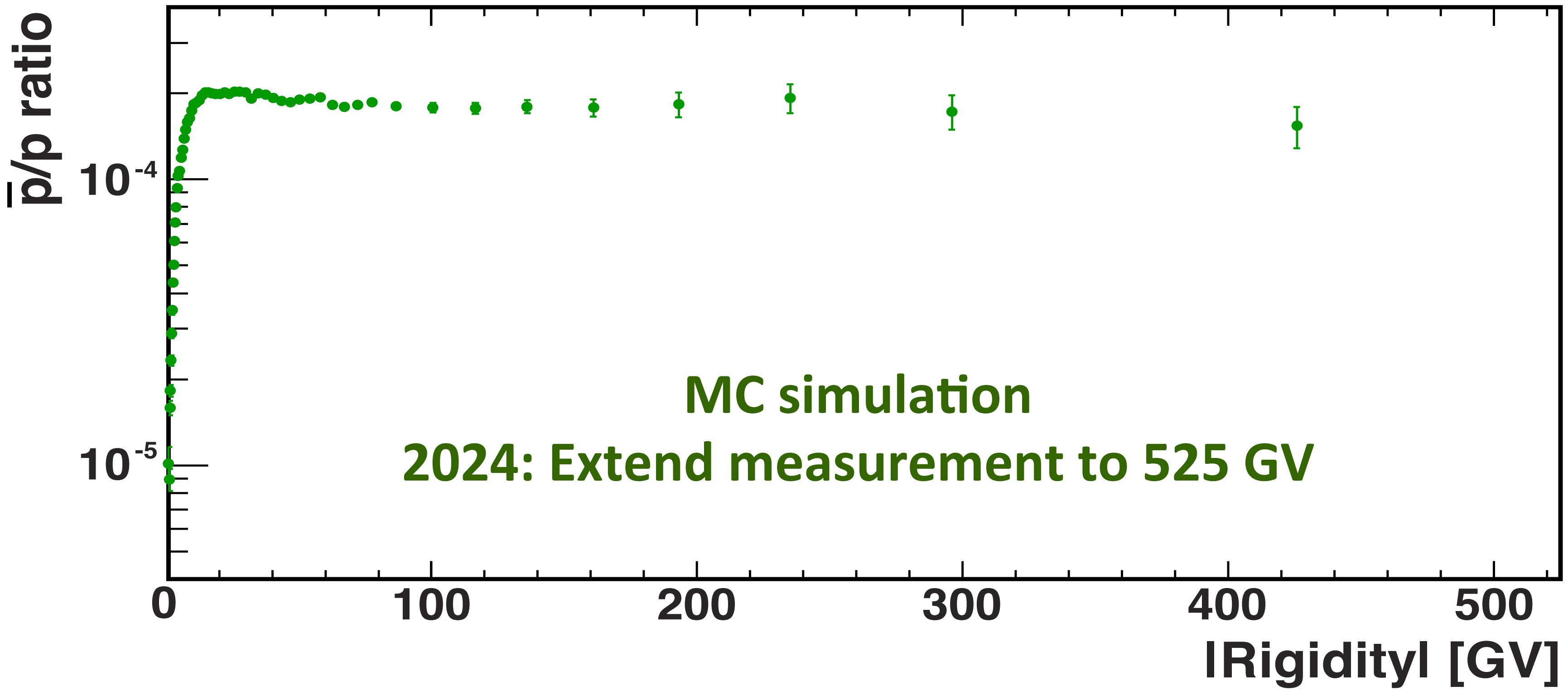
Helium
Science
AAAS
PAMELA Measurements of Cosmic-Ray Proton and Helium Spectra
O. Adriani et al.
Science 332, 69 (2011);
DOI: 10.1126/science.1199172
PAMELA: "At 230 to 240 GV, the proton and helium data exhibit an abrupt spectral hardening."
AMS PRL 115, 211101 (2015): "In particular, both spectral indices progressively harden with rigidity above 100 GV." – This is unexpected.
unexpected
Flux × R̃^2.7 [m^-2sec^-1sr^-1 GV^1.7]
10^3
Rigidity [GV]
10
10^2
10^3

The AMS Result on the Oxygen Flux

The precision AMS nuclei data provides new parameters for cosmic ray models.



Measuring antiproton through the life time of Space Station



By collecting more data,
AMS will explore to higher rigidity with better accuracy

Conclusion

- Dark Matter search is among the main physics objectives of AMS
- Positron fraction and fluxes of e^+ and e^- (20M events) require an additional source of high energy e^+ and e^- (e.g. DM)
- Antiproton-to-proton flux ratio (349k $\bar{p}$ events) is rigidity independent above 60 GV.
- Unexpected identical flux behavior for p, $\bar{p}$ and e^+ from 60 to 500 GV.
- By 2024 we will collect and analyze 3 times more data – will reach higher energies and greatly improve the accuracy

Physics of electrons and protons

SPEAR, DORIS, PEP, PETRA, LEP, … *Ψ, τ*

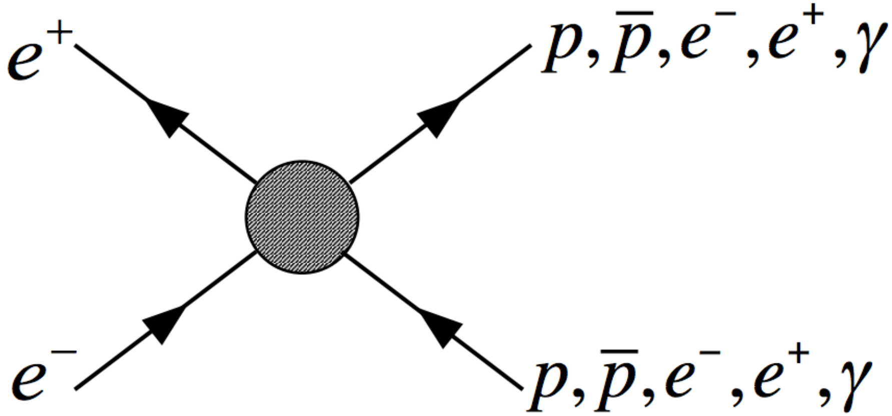
Annihilation

$e^+ + e^- \rightarrow p, \bar{p}, e^-, e^+, \gamma$

SLAC … *partons, electroweak*

Scattering

$e + p \rightarrow p, \bar{p}, e^-, e^+, \gamma$



$\ldots + e^+ + e^- \leftarrow p + p$

Production

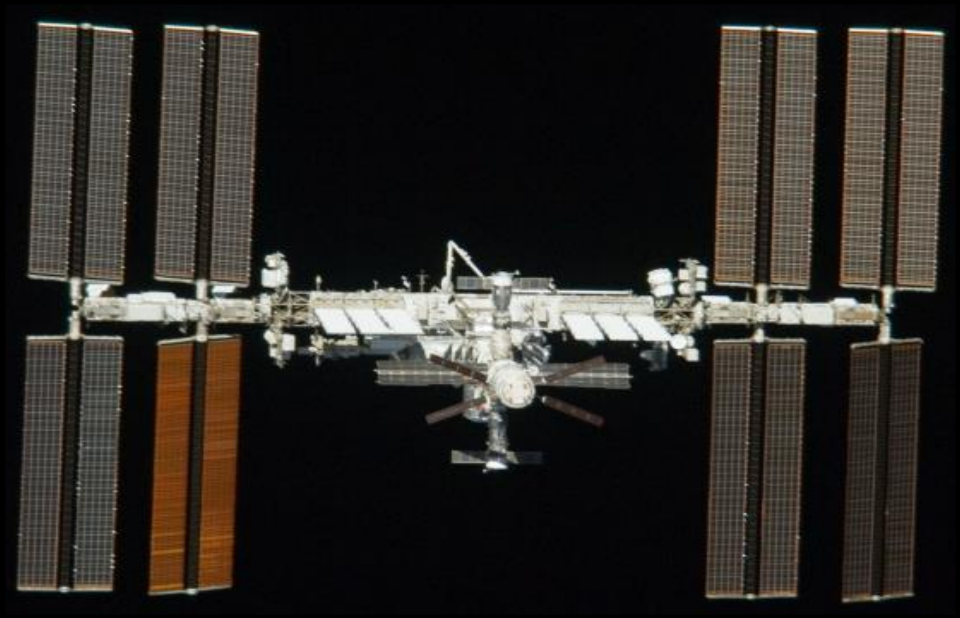
BNL, FNAL, LHC … *J, Y, t, Z, W, h^0*

To date, the results from AMS are unexpected and

need much improved accuracy of the theoretical predictions.

We work closely with theoretical community to develop

a comprehensive model to explain all our observations.



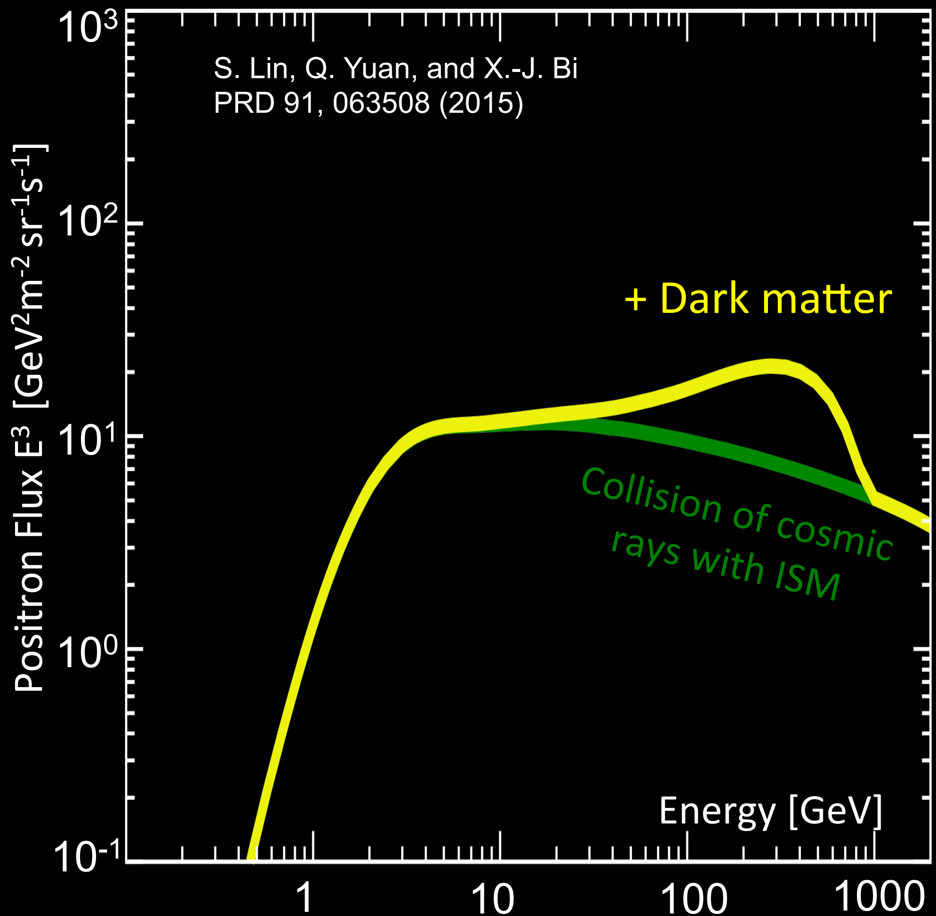
There is no other magnetic spectrometer in space in the foreseeable decades.

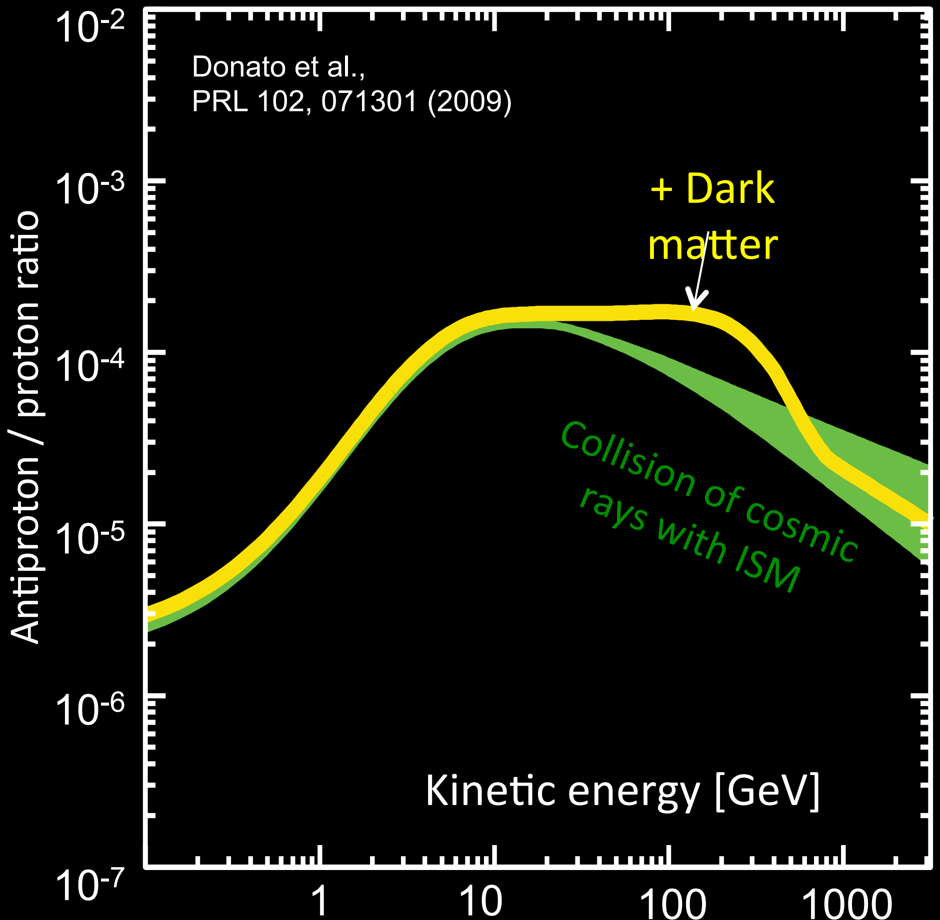
By collecting data through 2024,

we should be able to determine the origin of many unexpected observations.

Electron, Positron and Dark Matter

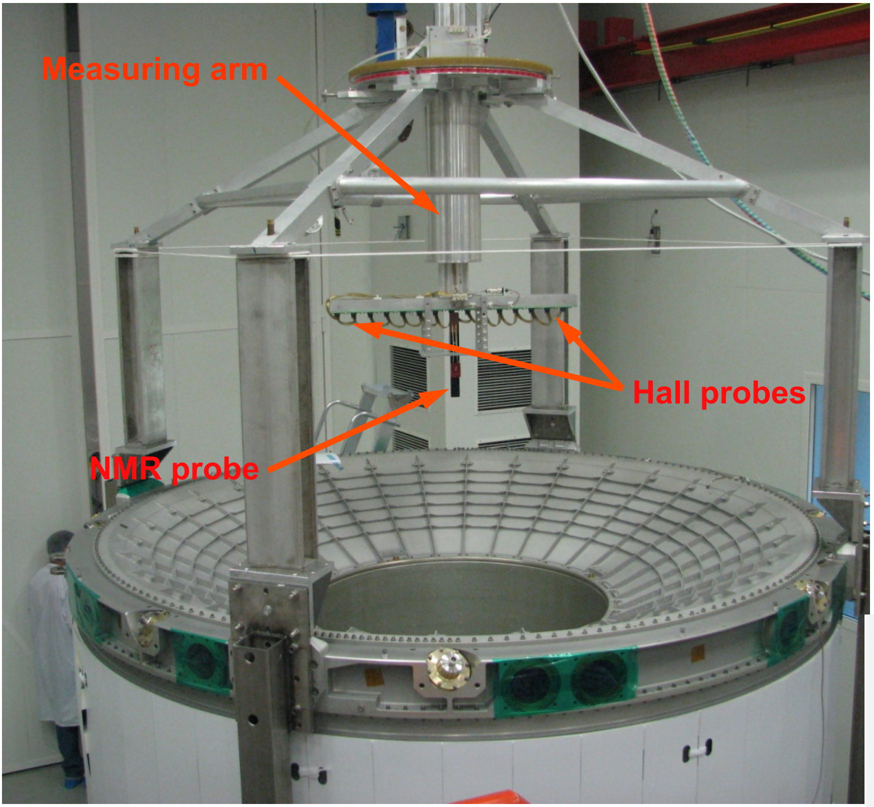
The collision of dark matter particles will produce additional e^+ and $\bar{p}$





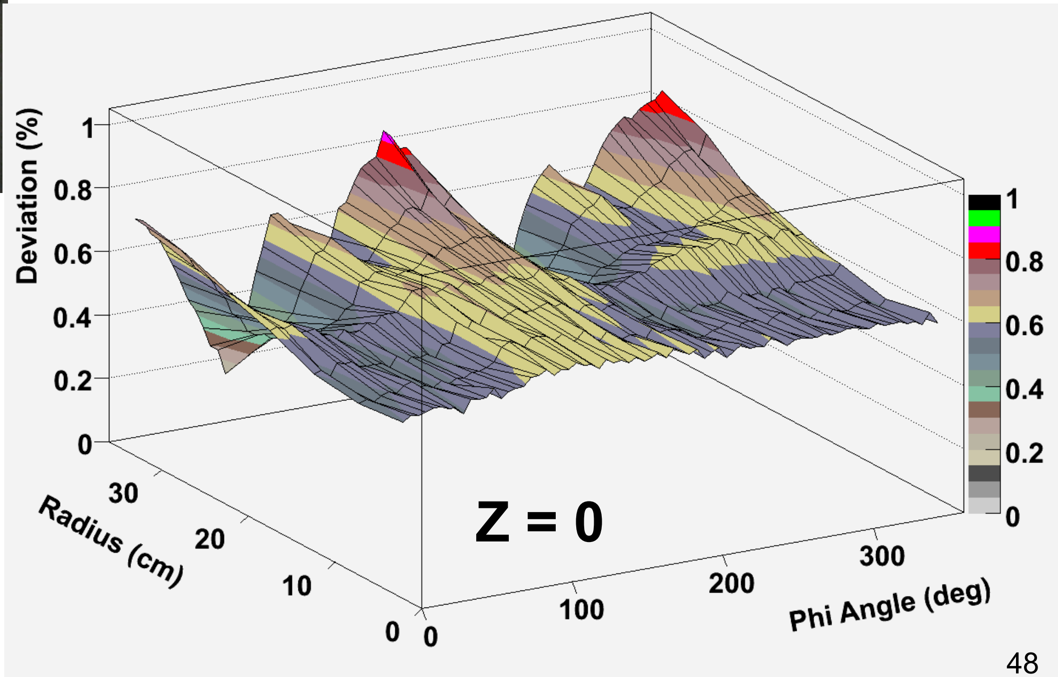
The excess of e^+ and $\bar{p}$ can be accurately measured by AMS

The permanent magnet



3D field map (120,000 locations)
Measured at CERN in May 2010

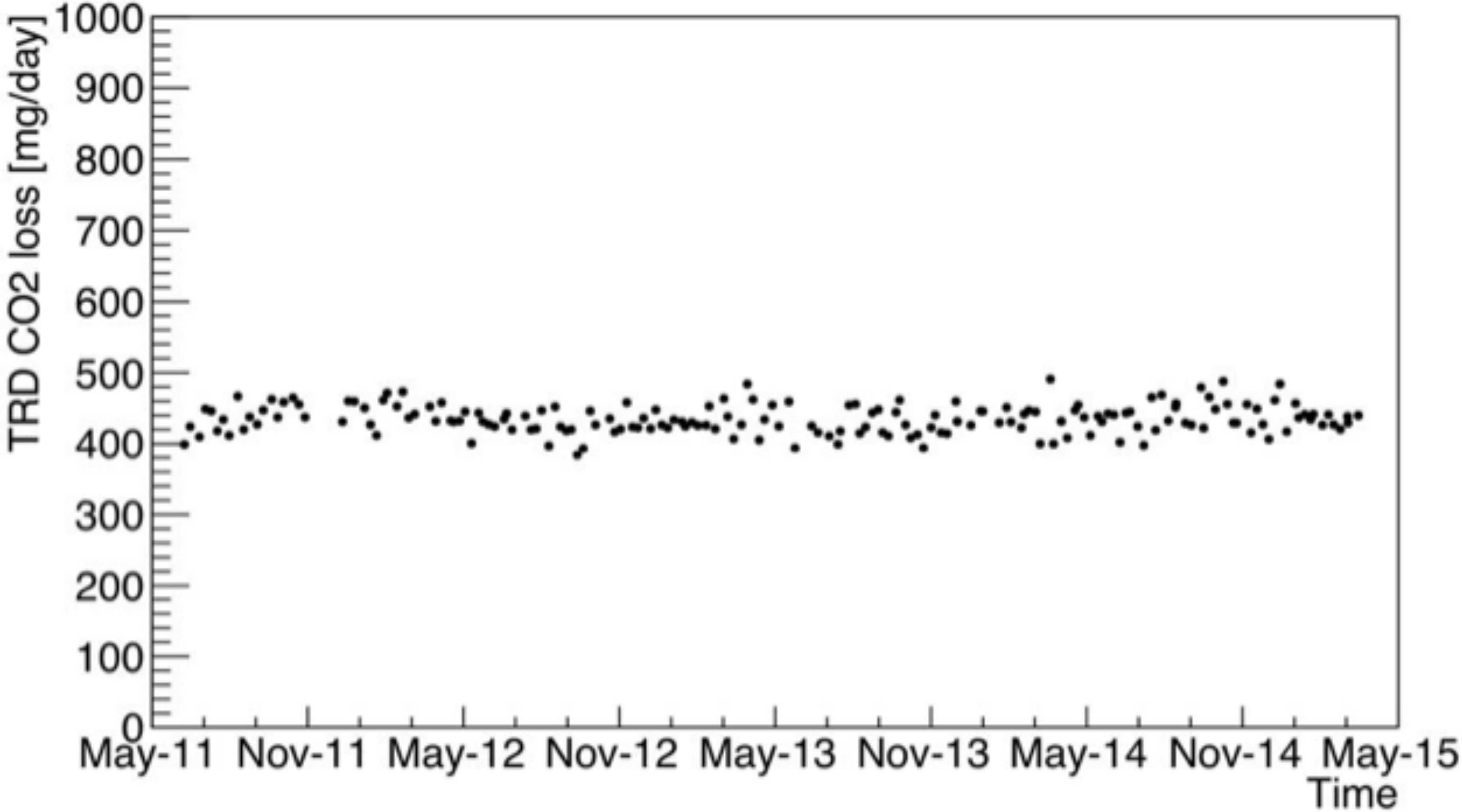
The difference between the 1997 and 2010 measurements is less than 1% (limited by the accuracy in 1997)



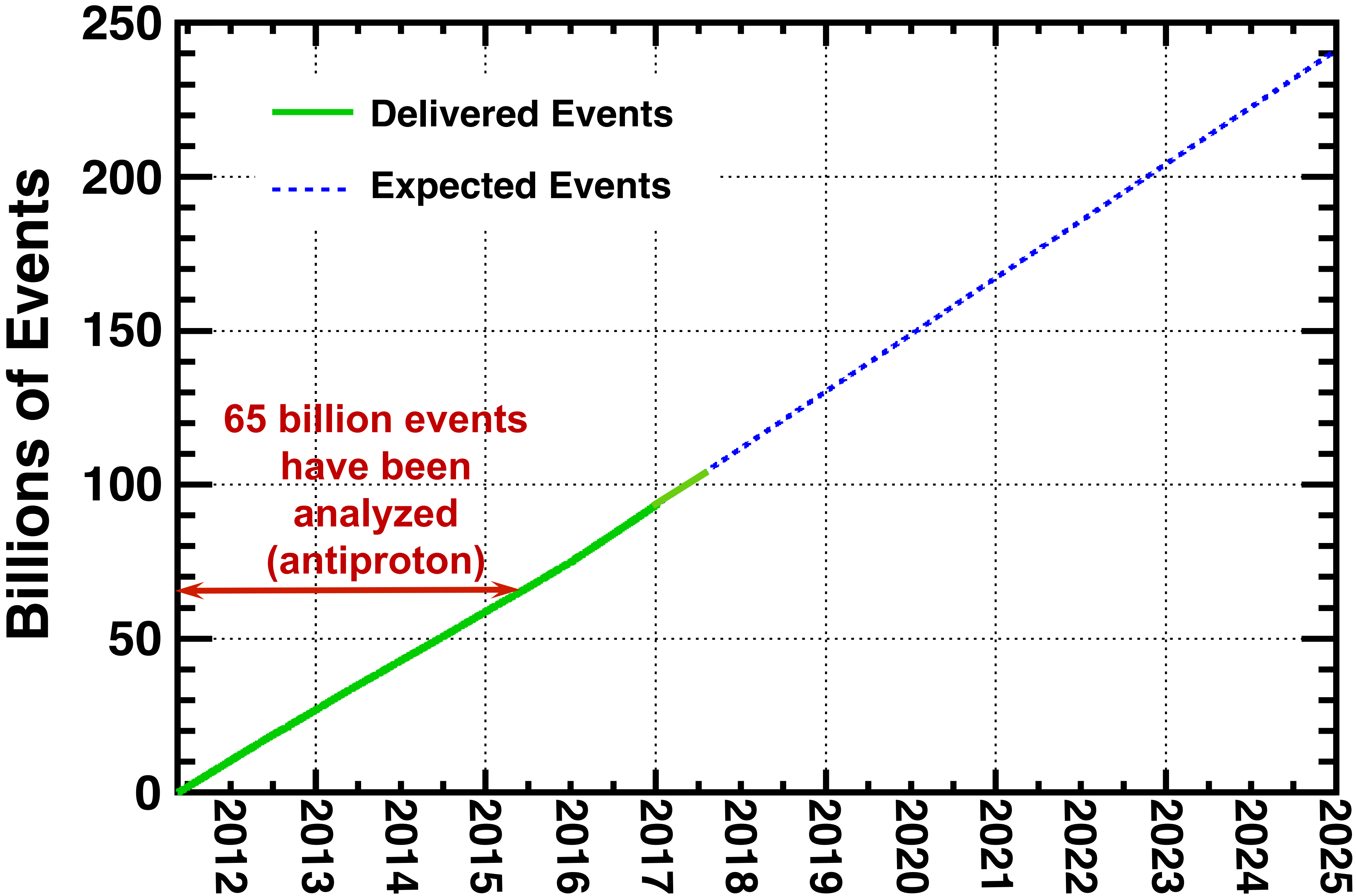
Magnetic field measurement (0.25%) and temperature corrections (0.1%) result in less than 0.5% systematic error on the flux.

TRD CO2 consumption

Lifetime: 5000g / 0.44g/d = 31 years



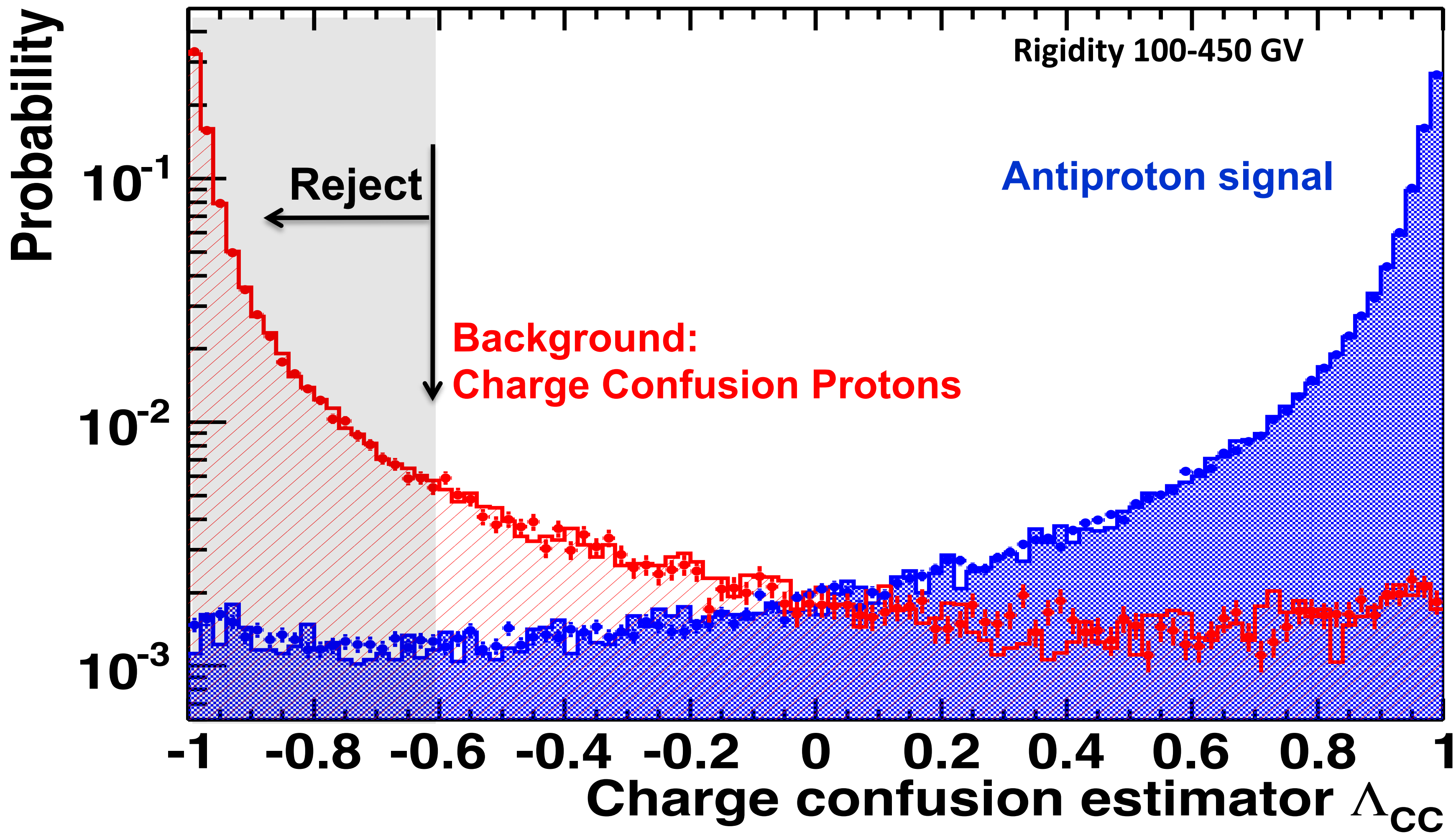
AMS on ISS to 2024: 240 Billion Events



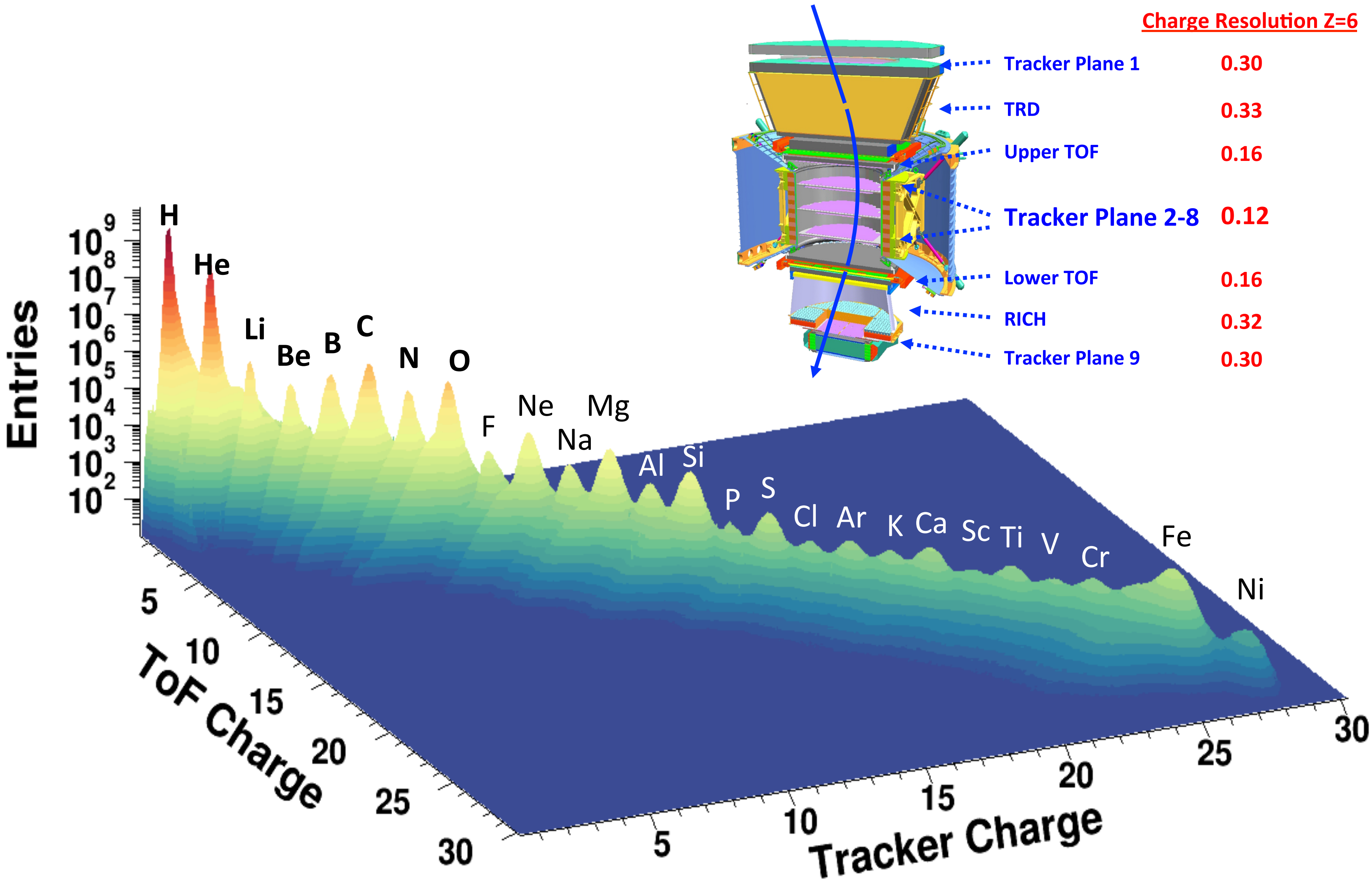
Separation of Positive and Negative Charges

Due to intrinsic position resolution and scattering in the Tracker, the charge sign has small probability to be measured incorrectly -> Charge confusion

At high rigidities it is particularly important to ensure that the charge sign of e+ and $\bar{p}$ is correctly identified in the tracker.



AMS has seven instruments which independently identify different elements

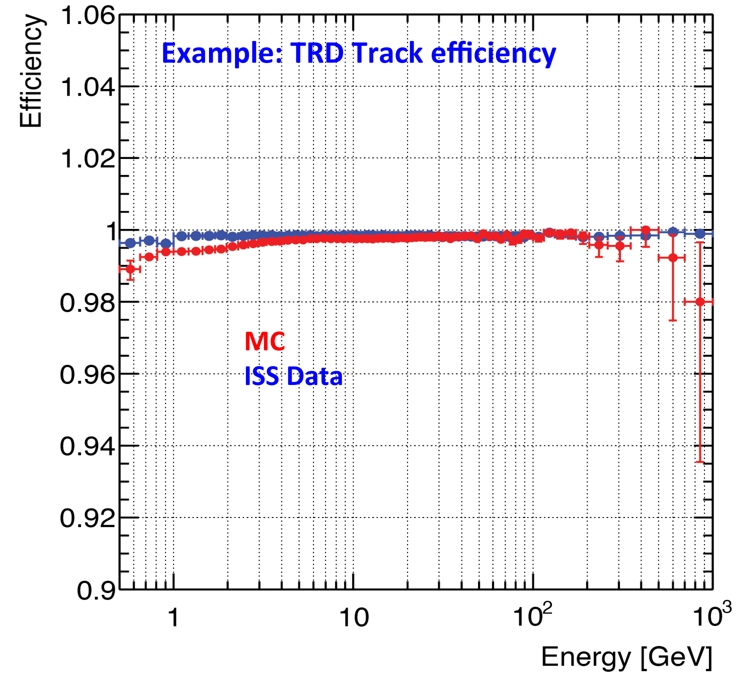


Electron/Positron Flux Measurement

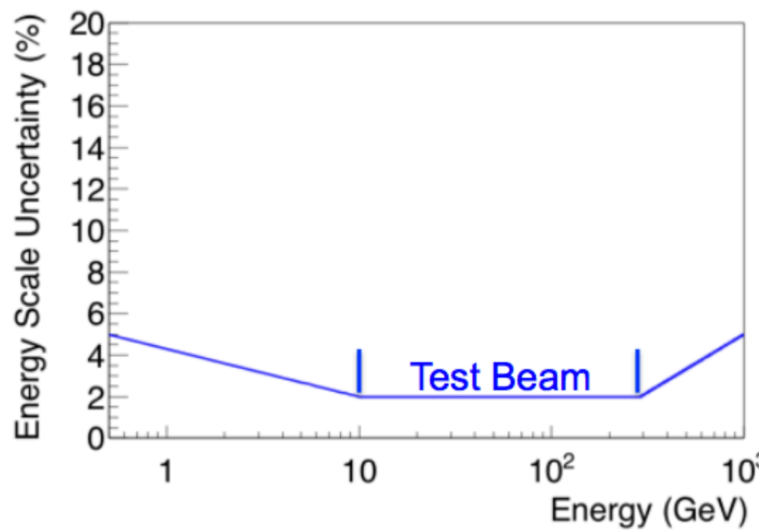
Isotropic flux:

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

- **Effective Acceptance:** $A_{eff} = A_{geom} \cdot \varepsilon_{sel} \cdot \varepsilon_{id} \cdot (1+\delta)$
  - Estimated from MC
  - Small correction applied based on efficiency measured from Data
  - Systematic uncertainties: 2% ~ 3%



- **Energy Measurement**
  - **Minimum effect from resolution**
  - **Uncertainty in the absolute energy scale:**
    ~2% at [10, 300] GeV
    ~5% at 1TeV

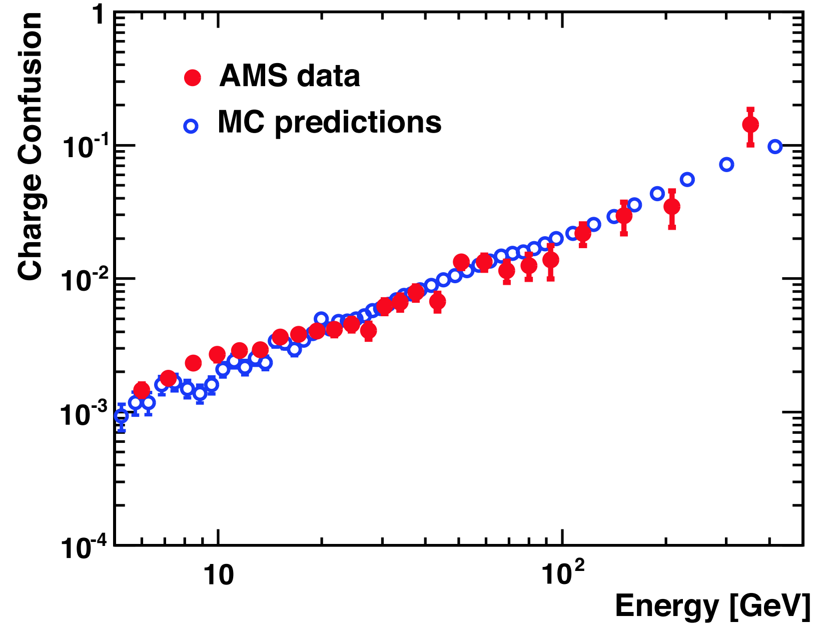


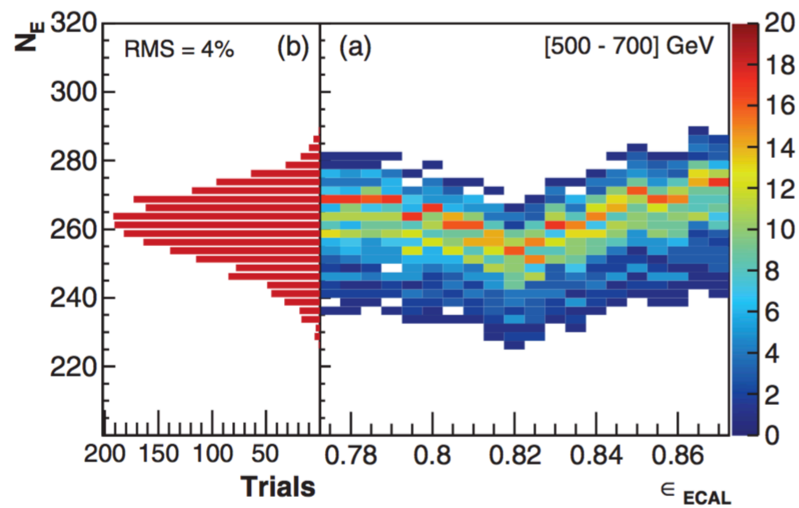
Electron, Positron Flux Measurement

Isotropic flux: $\Phi_{e^\pm}(E) = \dfrac{N_{e^\pm}(E)}{A_{eff}(E)\cdot \varepsilon_{trig}(E)\cdot T(E)\cdot \Delta E}$

Major Systematic Errors:

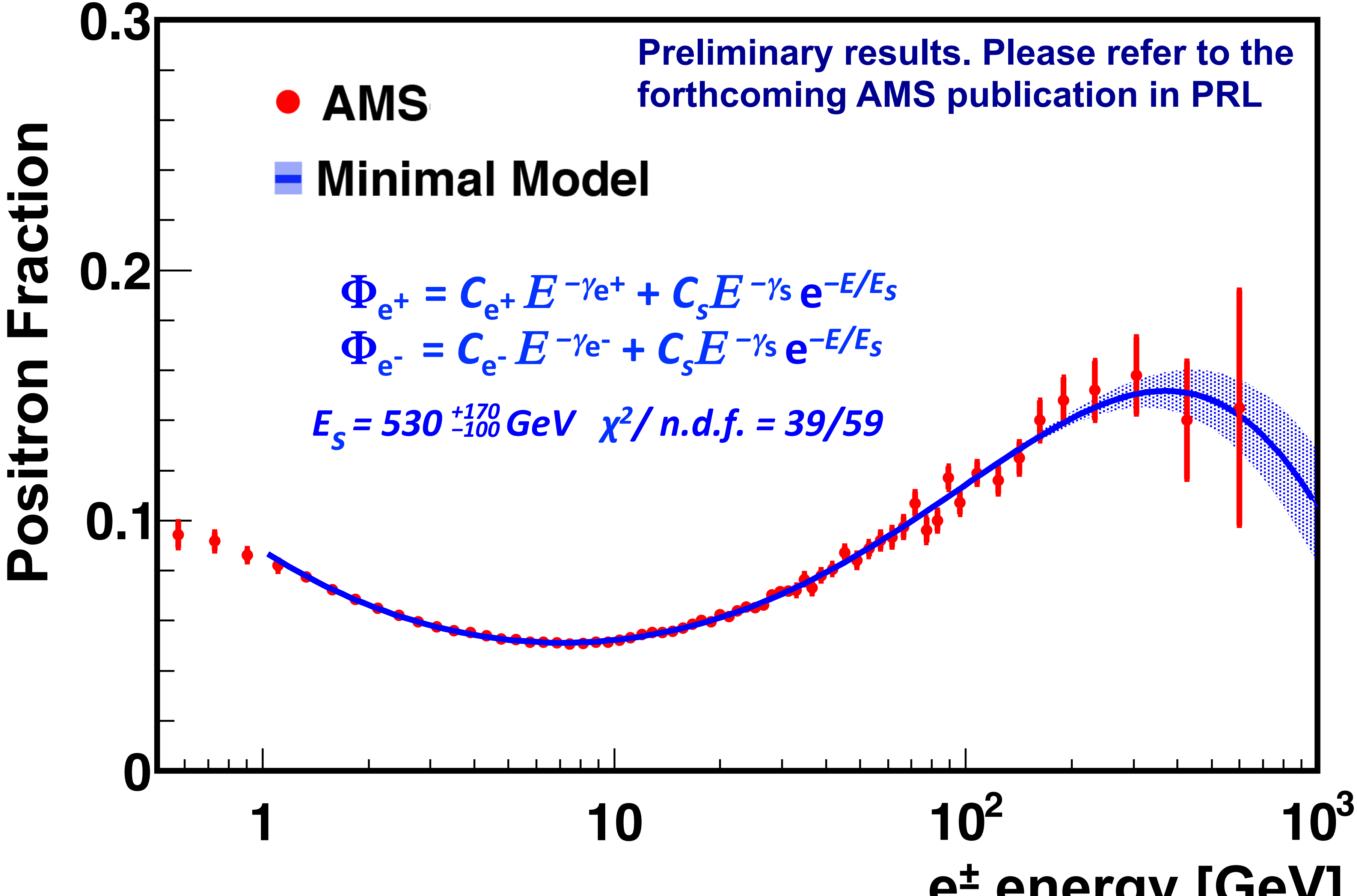
- **Charge confusion:**
  - Measured directly from data. Reproduced by the Monte Carlo. The difference is taken as a systematic error.
- **Selection, Template definition:**
  - For each energy bin, many sets of cuts (trials) were analyzed. The measurement is stable over wide ranges of the selections.
- **Effective Acceptance:**
  - Estimated from MC, Small correction applied based on efficiency measured from Data. Systematic uncertainties: 2% ~ 3%
- **Energy Measurement:**
  - Uncertainty in the absolute energy scale: ~2% at [10, 300] GeV, ~5% at 1TeV





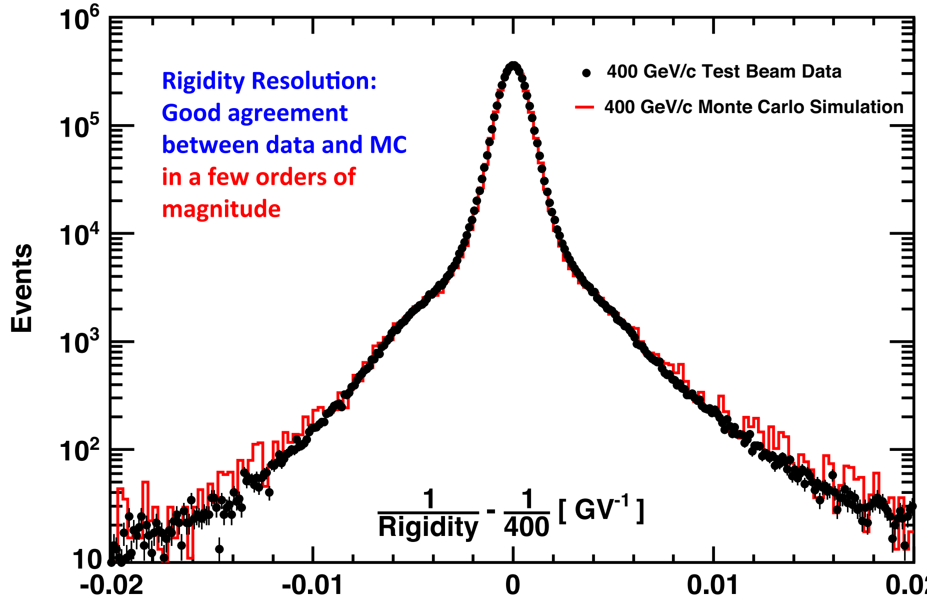
Systematic error are smaller than statistical error (> 30 GeV for e^+, >200GeV for e^-)

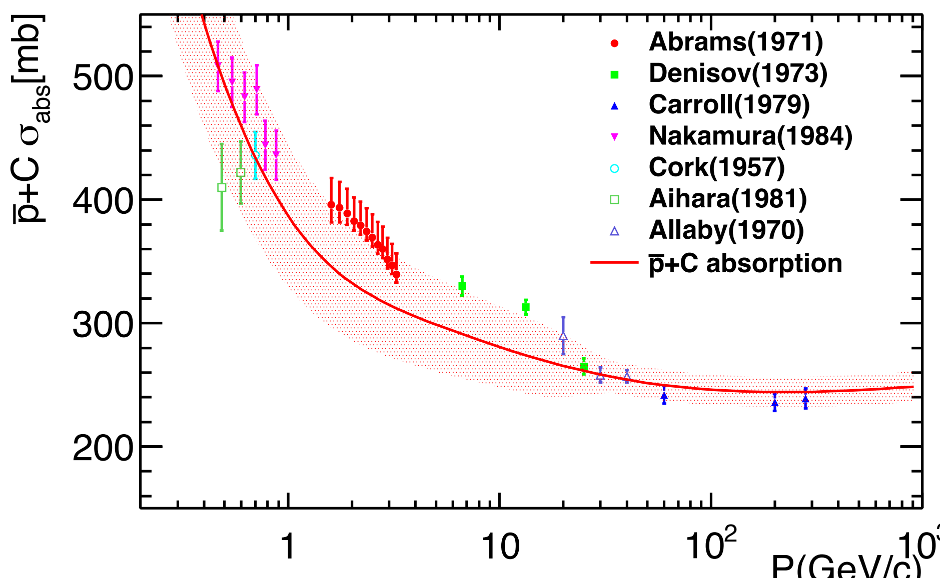
Additional source of high energy electrons and positrons



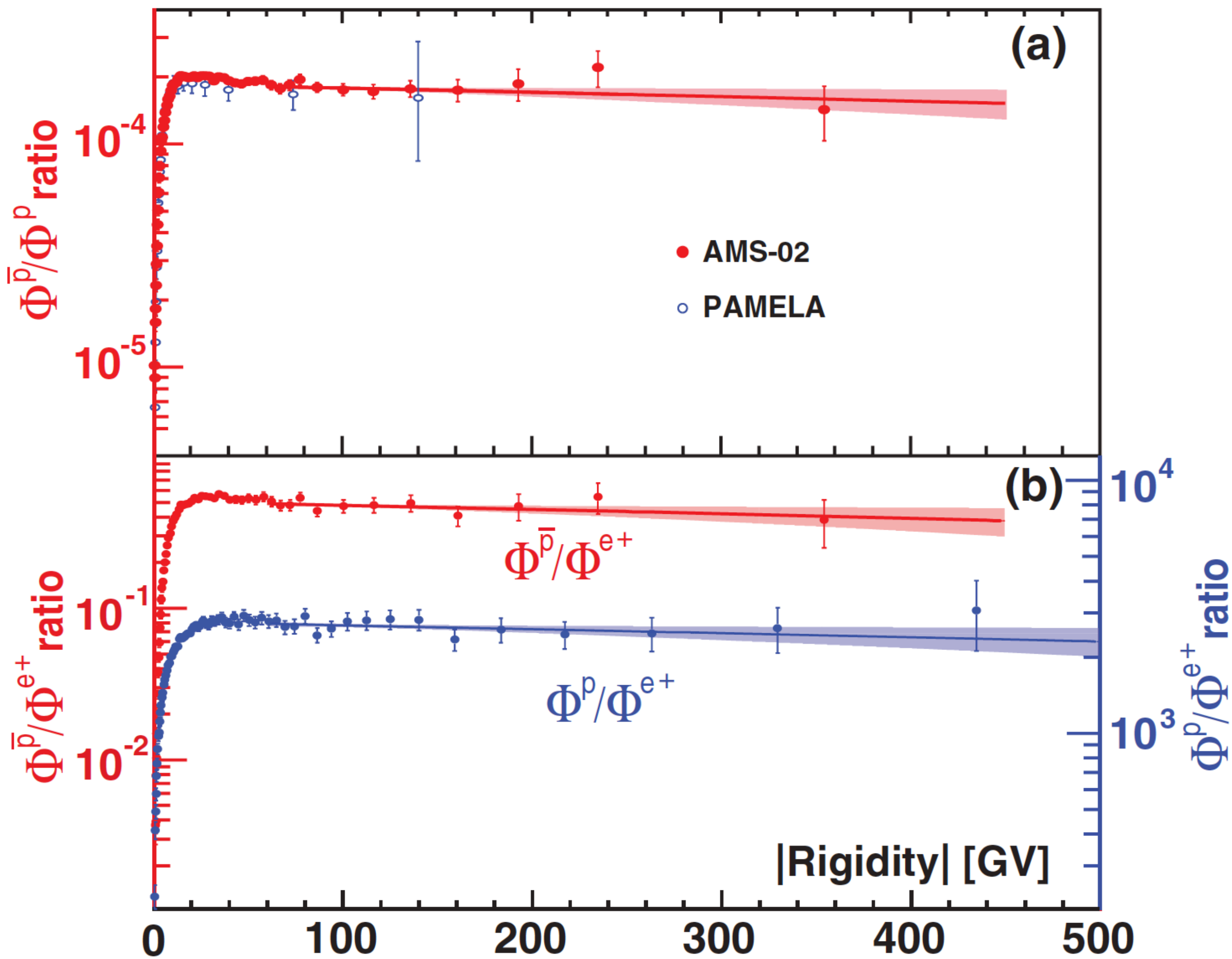
Systematic Errors on Antiproton Measurements

- **Antiproton counting σ_N**
  - Event selection
  - **Knowledge of charge confusion**
- **Acceptance, σ_A**
  - **Cross sections**
  - Migration matrix
  - Small correction in normalization
- **Rigidity scale, σ_R**
  - Affect positive and negative rigidity in opposite direction
- **The analysis is not limited by systematic errors**





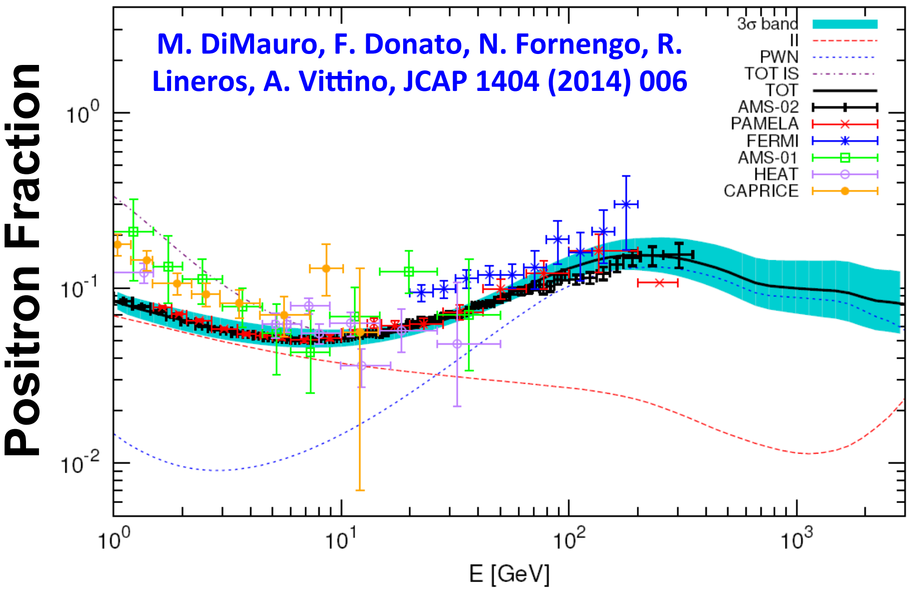
Flux ratio of $\bar{p}/p$, $\bar{p}/e^+$ and p/e^+ are energy independent in the energy range ~60 to ~500 GeV



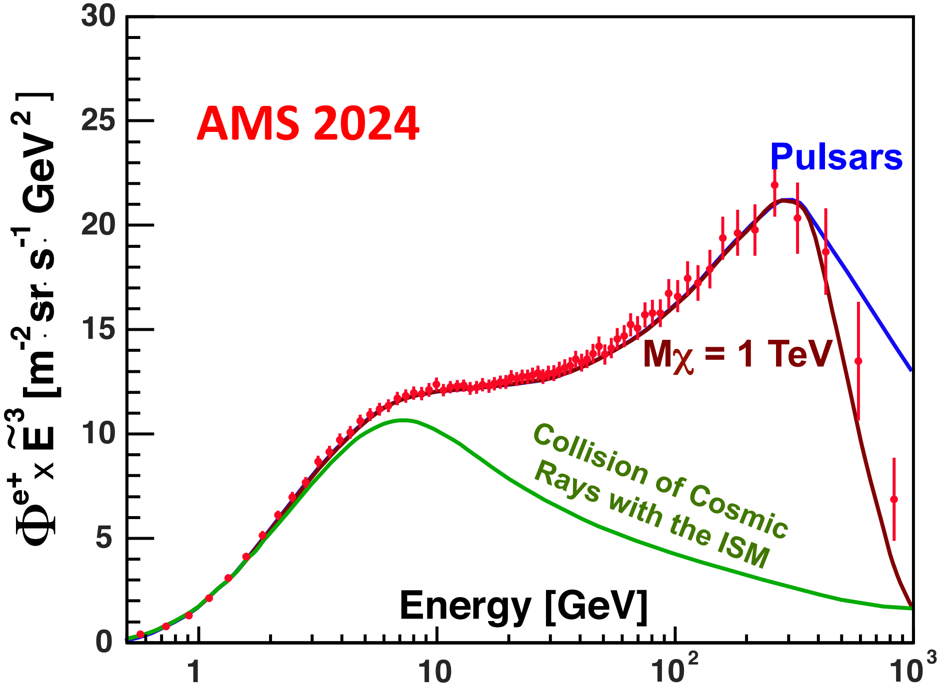
Alternative Models to explain the AMS Positron Flux and Positron Fraction Measurements

- Modified Propagation of Cosmic Rays
- Supernova Remnants
- Pulsars

Examples:



By 2024, AMS will distinguish Dark Matter from Pulsars



AMS Measurements on Positron, Electron anisotropy and on antiprotons will also help distinguish different models