Latest Results of the Alpha Magnetic Spectrometer on the International Space Station

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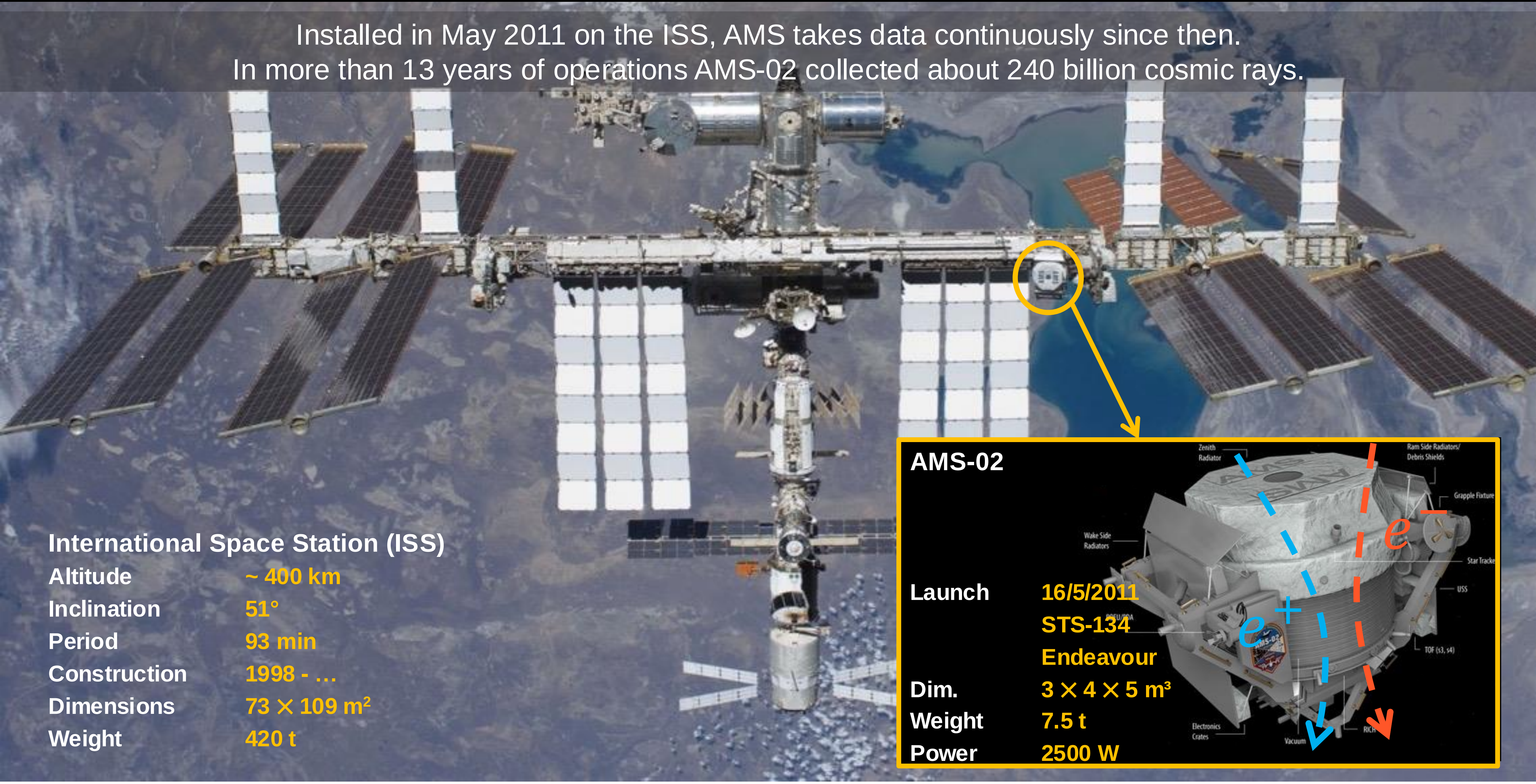
JENAA Workshop @ CERN, 20/08/2024

AMS-02: The Alpha Magnetic Spectrometer

Installed in May 2011 on the ISS, AMS takes data continuously since then.
In more than 13 years of operations AMS-02 collected about 240 billion cosmic rays.



International Space Station (ISS)

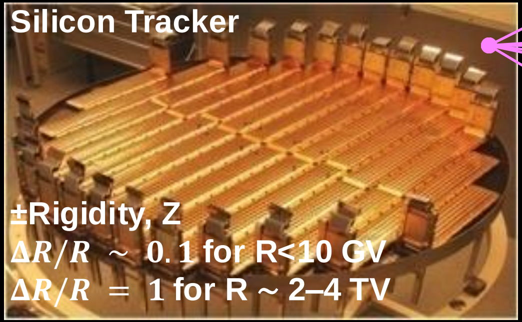
Altitude	~ 400 km
Inclination	51°
Period	93 min
Construction	1998 - …
Dimensions	73 × 109 m^2
Weight	420 t

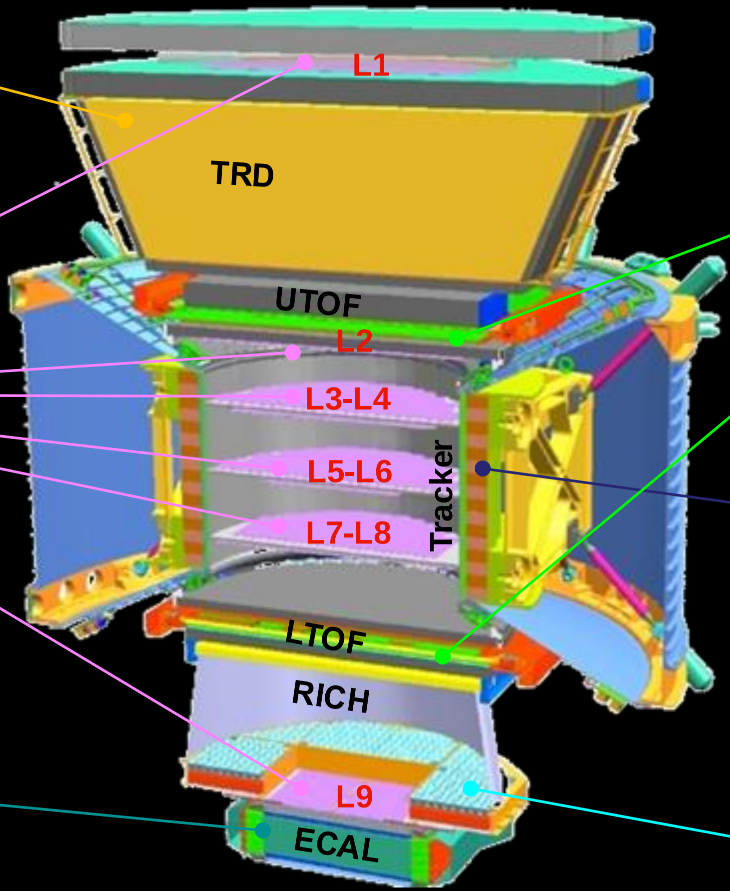
AMS-02

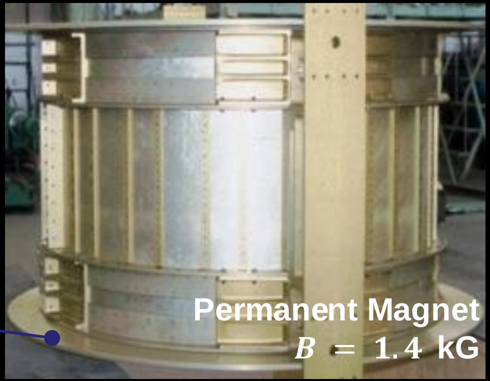
Launch	16/5/2011
	STS-134
	Endeavour
Dim.	3 × 4 × 5 m^3
Weight	7.5 t
Power	2500 W

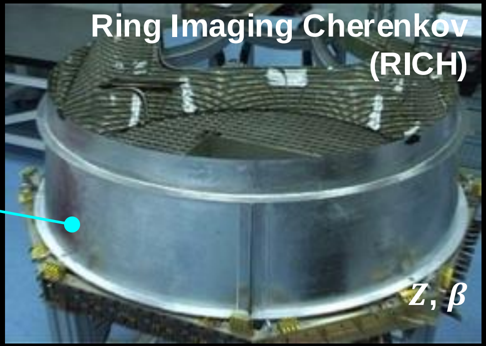
A TeV Multi-Purpose Spectrometer

AMS-02 separates **hadrons** from **leptons**, **matter** from **antimatter**, **chemical** and **isotopic** composition from fraction of GeV to multi-TeV.





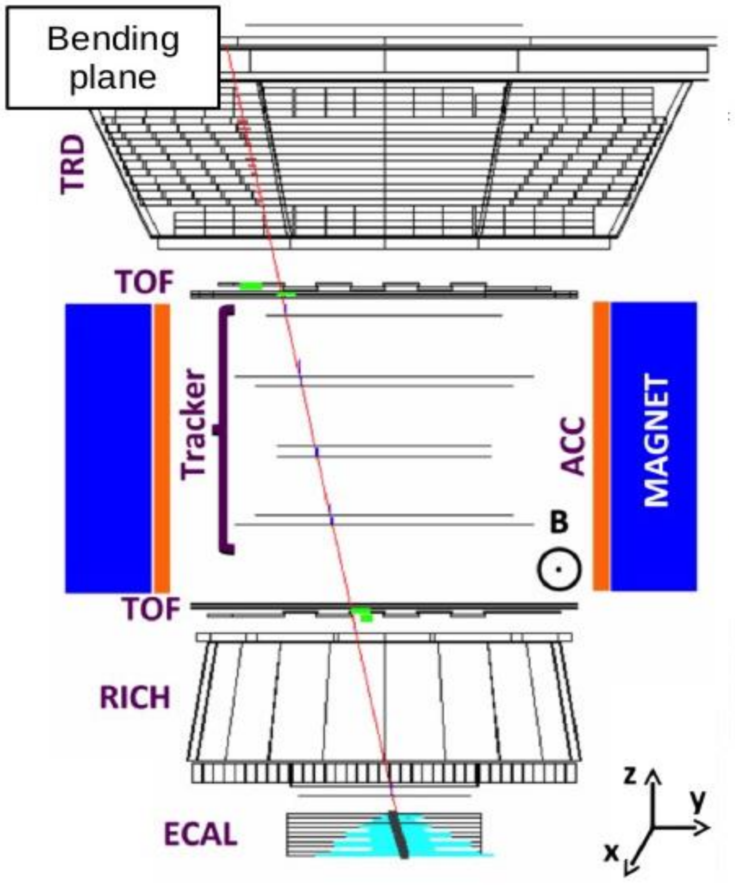




Multiple measurements of charge (Z), energy (β, p, E) and charge sign (±).

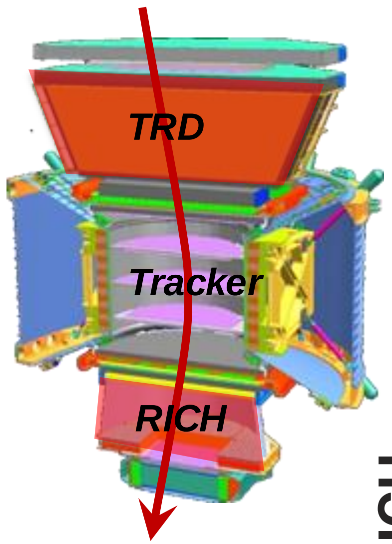
A TeV Multi-Purpose Spectrometer

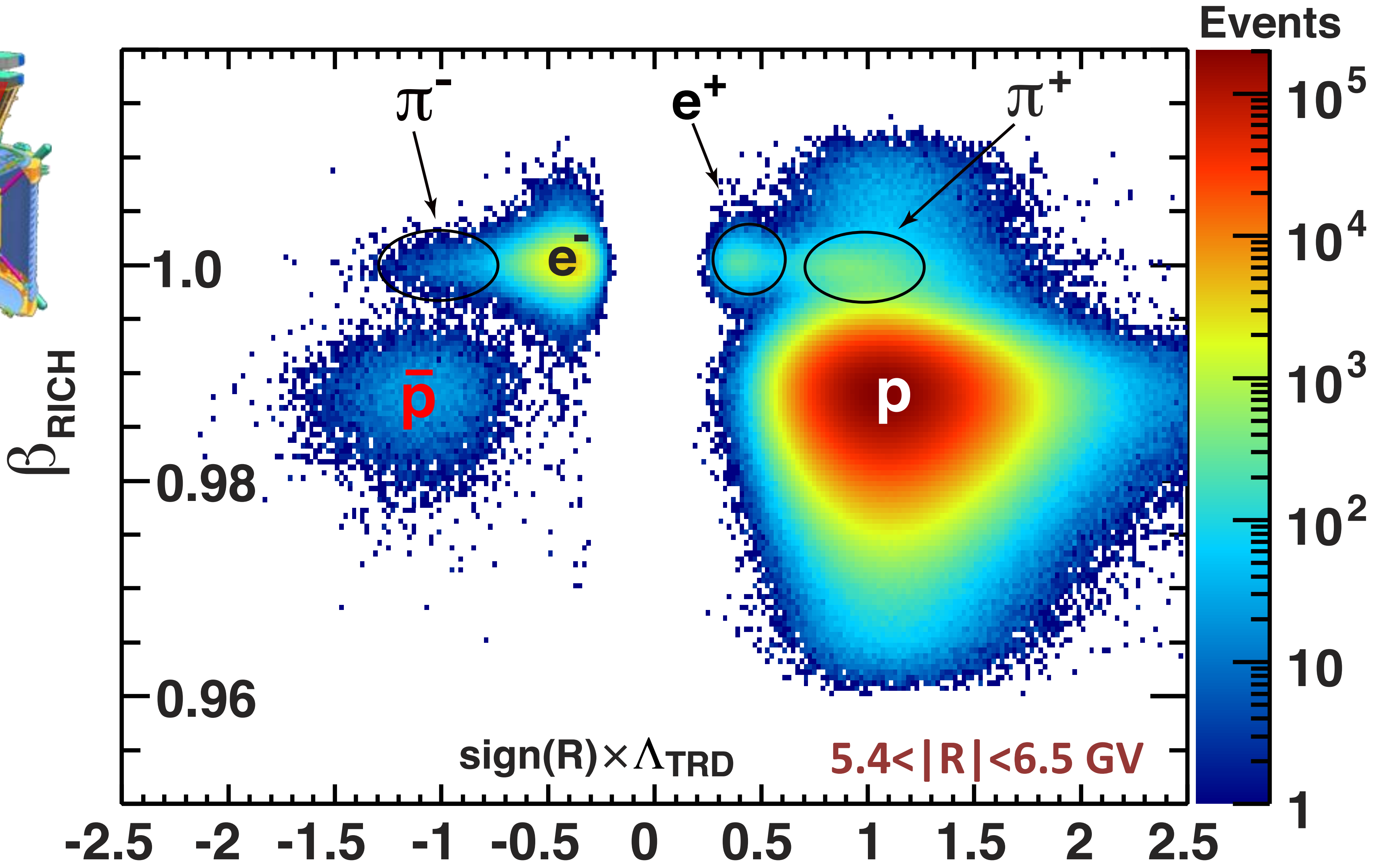
600 GeV electron



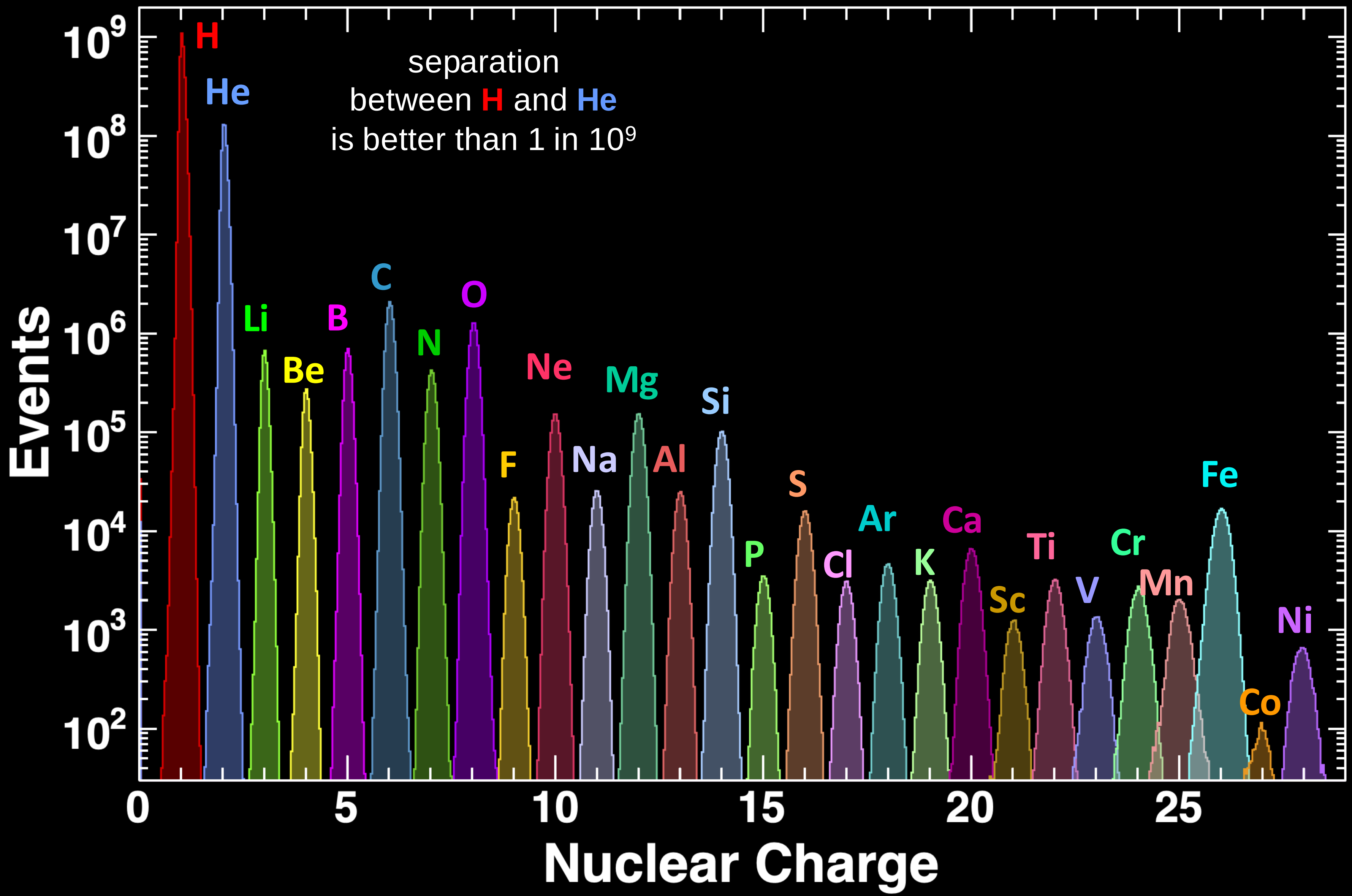
	e^+	e^-	p	$\bar{p}$	He	$\overline{He}$	
TRD 20 layers							*e/p* separation charge, *Z*
TOF 4 layers							trigger velocity, β charge, *Z*
TRK 9 layers							rigidity, p/Z sign, $\pm$ charge, *Z*
RICH							velocity, β charge, *Z*
ECAL 18 layers							$e^{\pm}$,γ energy *e/p* separation EM-trigger

AMS-02 Anti-Proton Identification





Chemical Composition with AMS



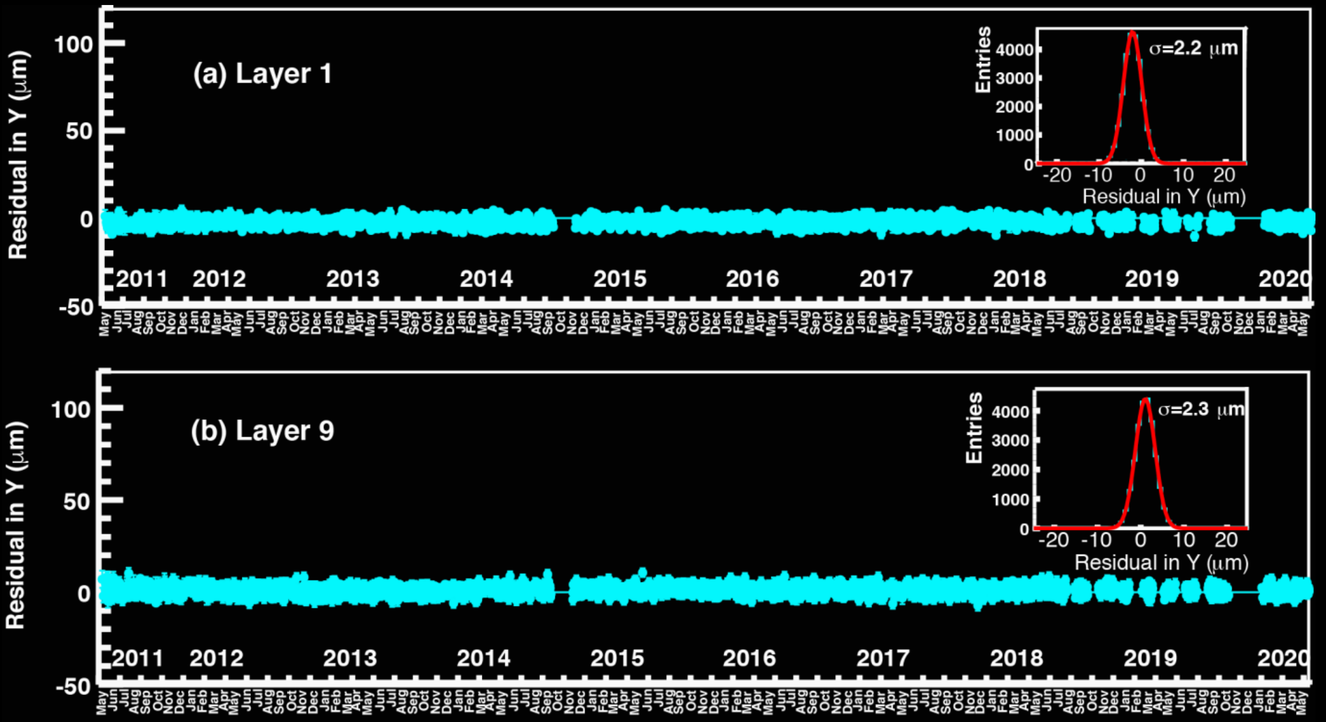
separation
between Fe and Co
is better than 1 in 10^2

With the unprecedented statistics of ~240 billion events we have precise spectroscopy of all cosmic ray nuclei.

Momentum Scale and Sign Determination

Alignment

Position of inner layers L2-L8 monitored with lasers to an accuracy below 1 μm.

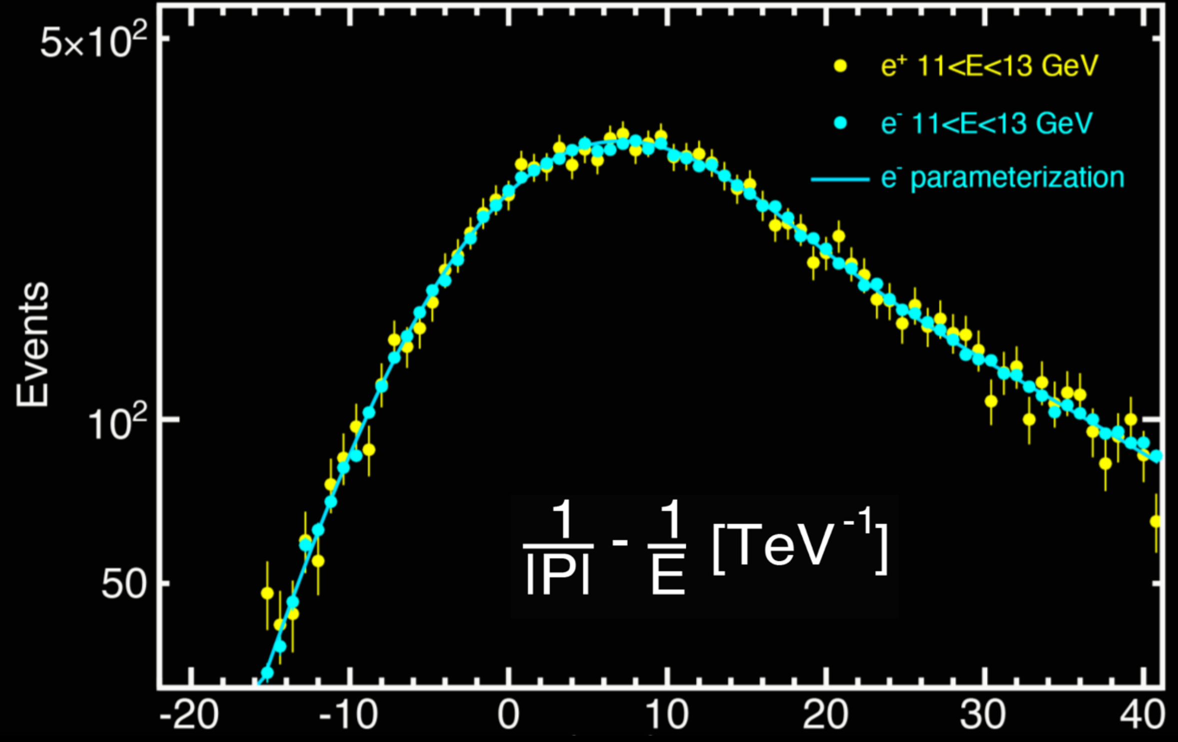


Position of outer layers L1 and L9 monitored every 2 minutes by cosmic rays with an accuracy up to 2 μm over 13 years.

Momentum Scale

Comparison of momentum from Tracker (P) and Energy (E) from ECAL for samples of positrons and electrons.

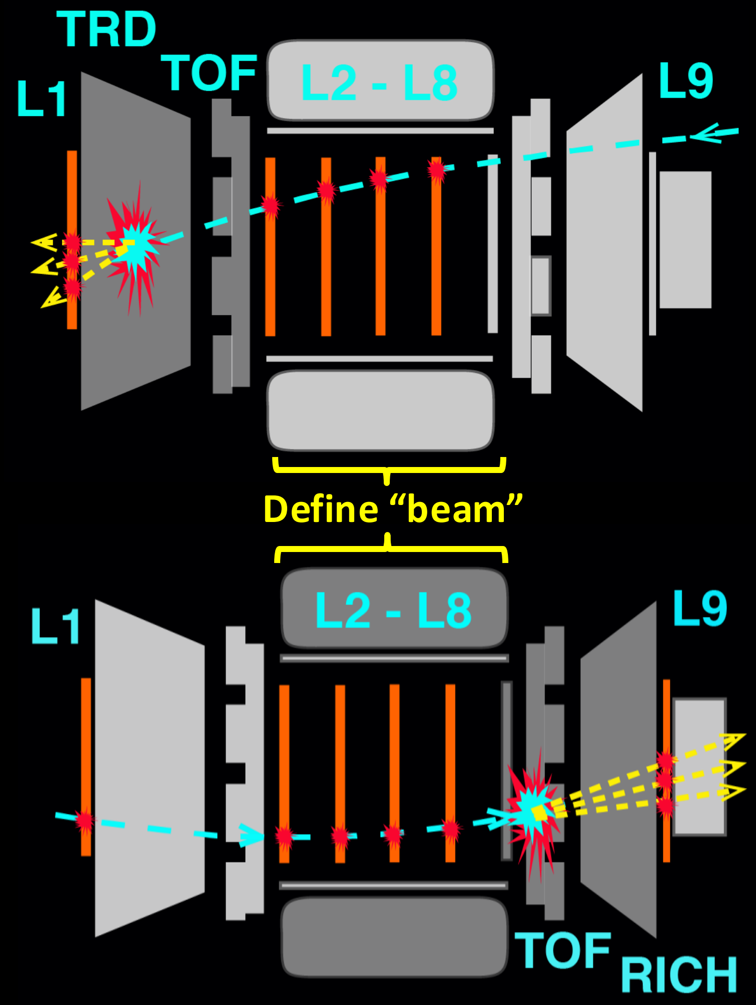
M. Aguilar *et al.*, Phys. Rep. **894** (2021) 1-116.



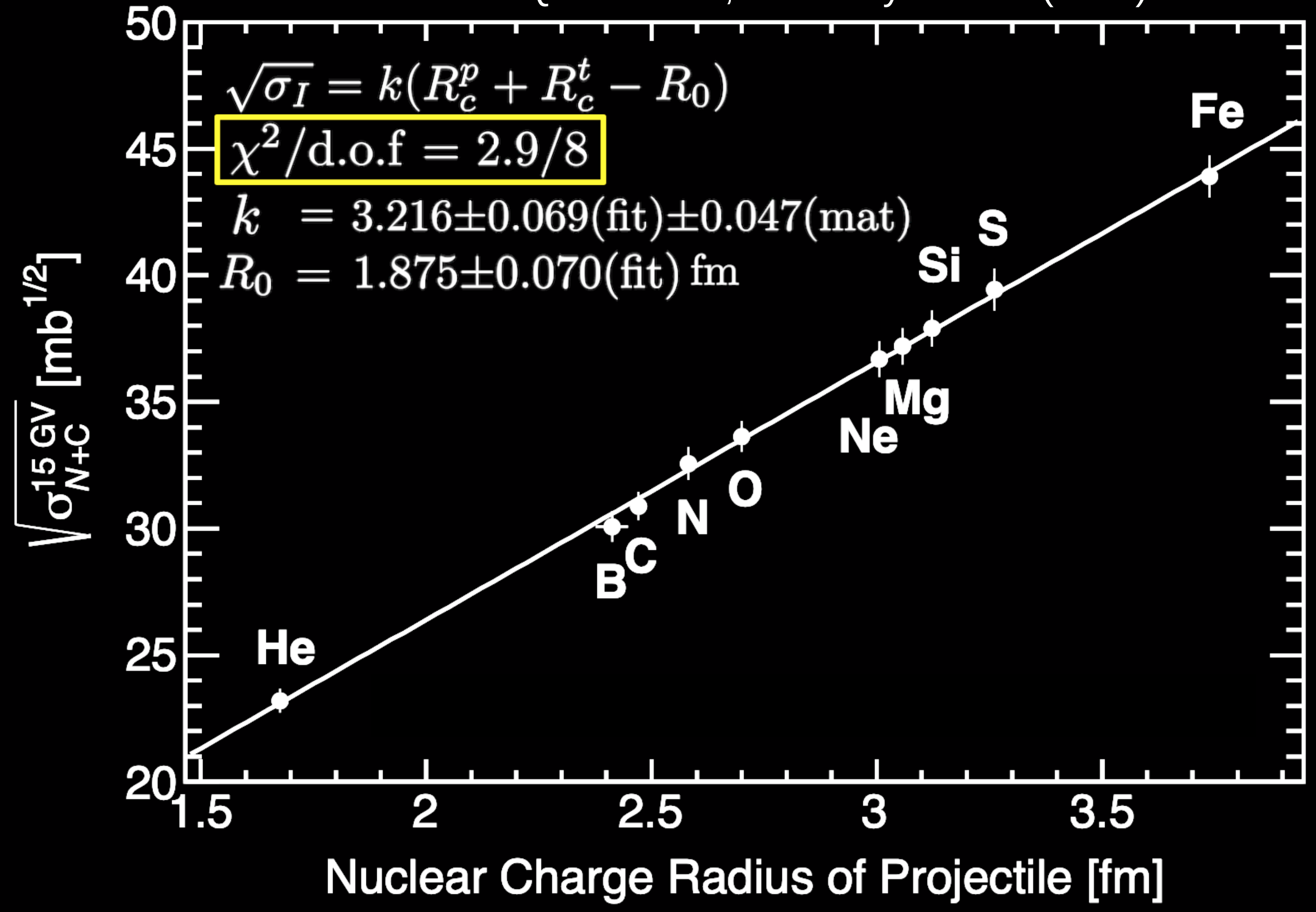
The accuracy of the momentum scale is determined to be 1/(34 TeV) i.e., at 1 TeV the uncertainty is less than 3%.

Nuclear Cross Section Measurement with AMS

The absolute value of the cosmic ray fluxes is controlled by the direct measurement of nuclear inelastic cross-section with cosmic rays with AMS material (mainly C, Al).

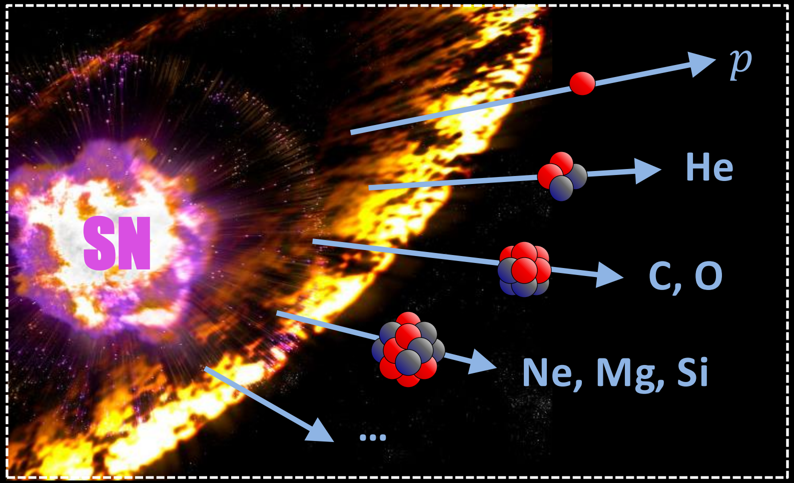


Q. Yan *et al.*, Nucl. Phys. A **996** (2020) 121712.

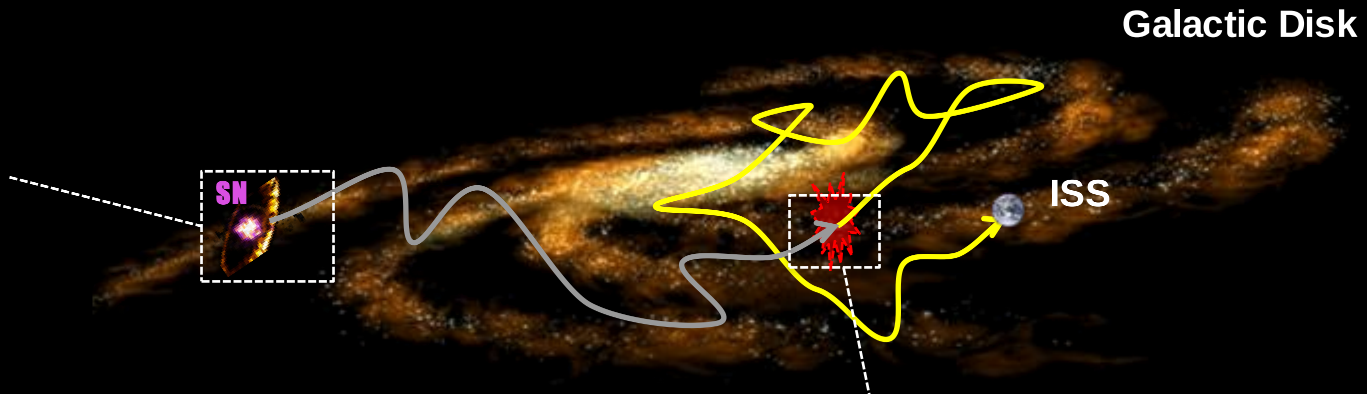


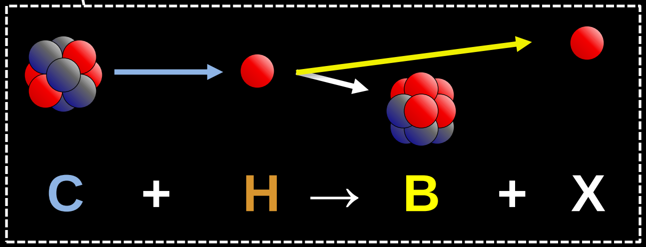
AMS has made nuclei Interaction cross-section measurements (N+C) in a wide rigidity range from a few GV to TV allowing for the precise control of the flux normalization.

Primary and Secondary CRs



Primary GCRs (e^-, p, He, C, O, Ne, Mg, Si, ..., Fe) are thought to be mostly produced during the lifetime of stars and accelerated by astrophysical processes (as supernovae shocks) in our Galaxy.

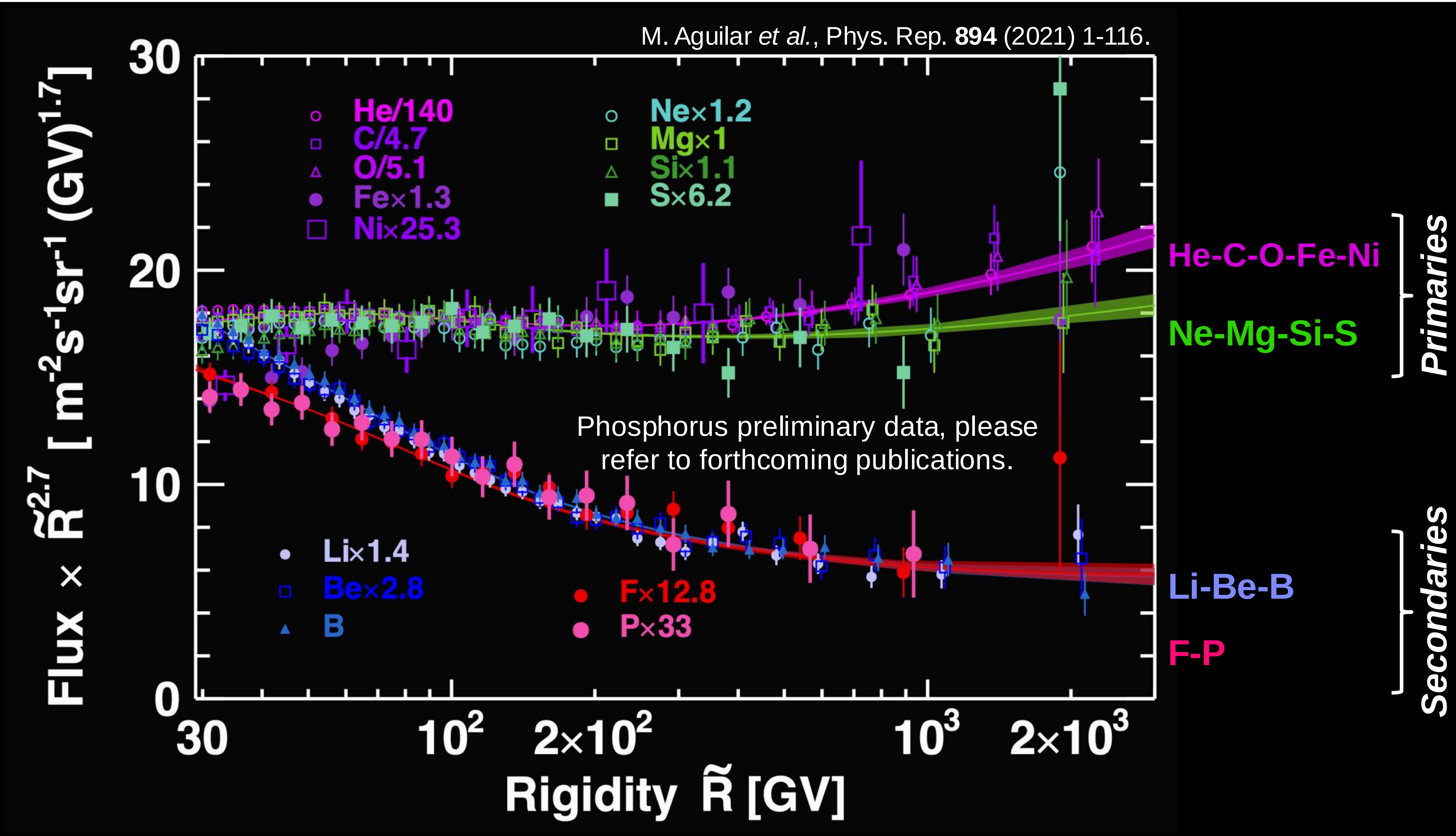




Secondary GCRs (e^+, $\bar{p}$, Li, Be, B, F, sub-Fe, …) are mostly produced from collision of primaries with the interstellar medium.

Measurements of primary and secondary cosmic ray fluxes allow the understanding the origin and propagation of cosmic rays in the Galaxy. In turn this allows to calculate the **antimatter astrophysical background** and, therefore, to inspect with precision the presence of relic antimatter or dark matter annihilation products in CRs.

Precision Measurement of Primary and Secondary Species with AMS

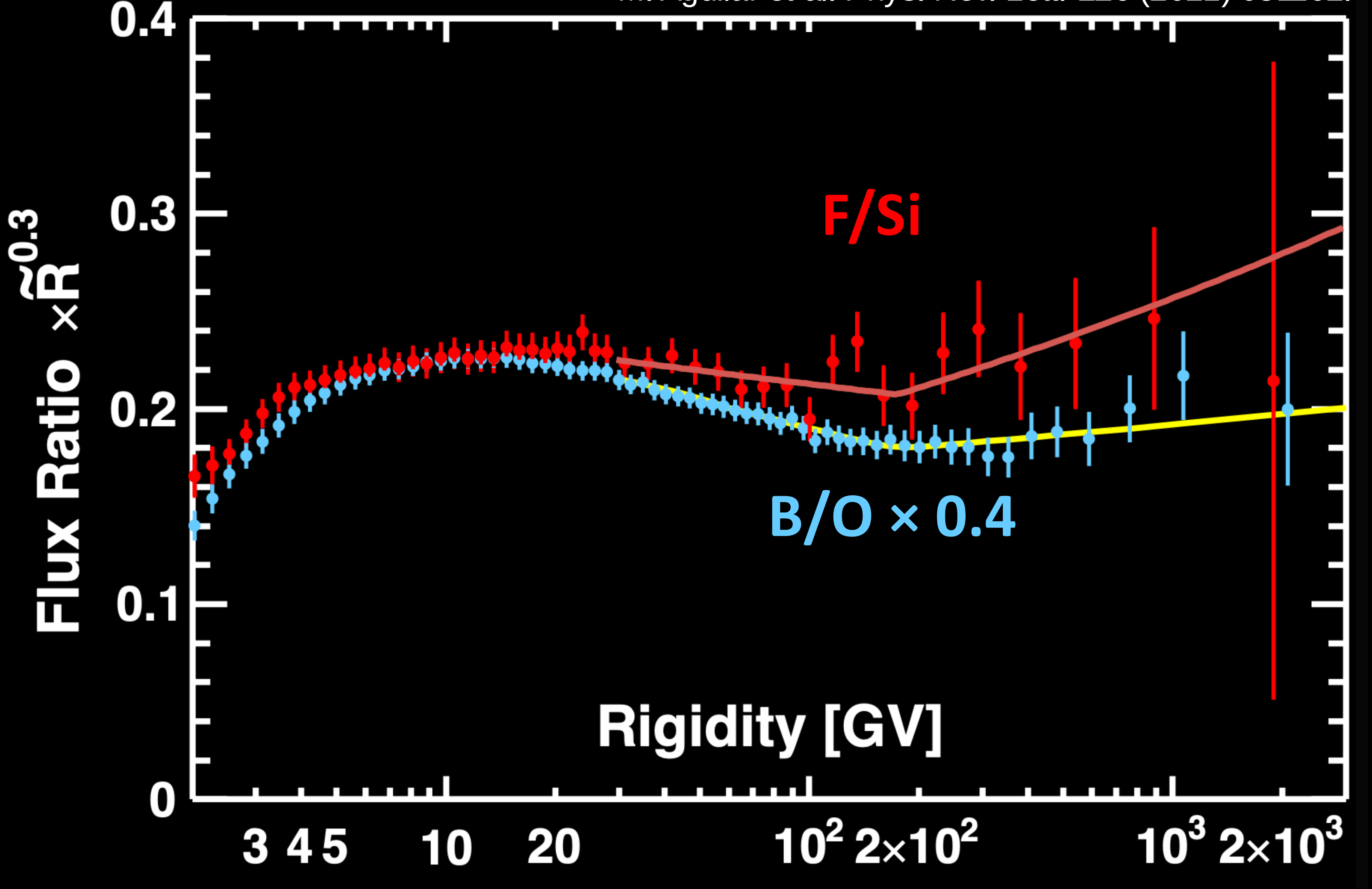


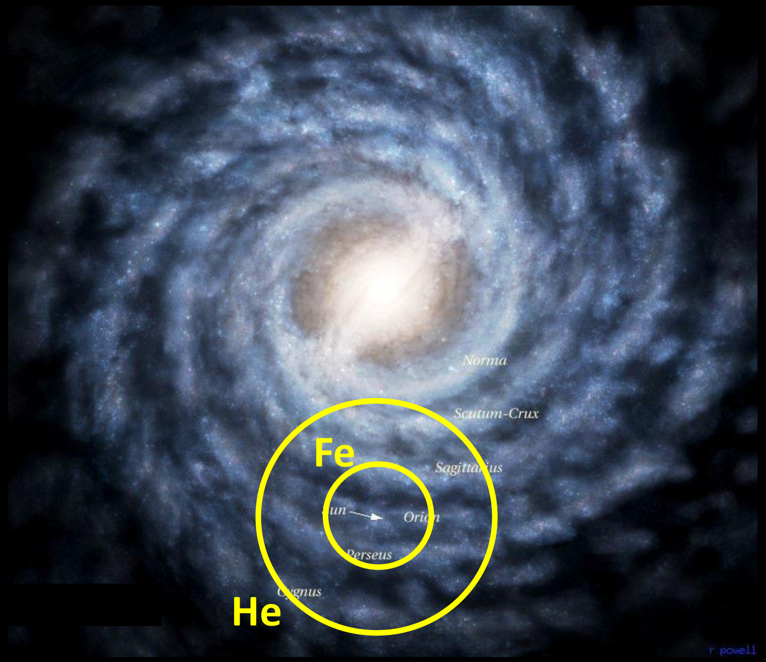
AMS found spectral structures in all CR spectra at about 200 GV that revealed new properties of the CR propagation.

Secondary/Primary Ratios

Secondary/primary is directly connected with cosmic ray diffusion.
The study of ratios at different Z tests diffusion in different galactic volumes.

M. Aguilar et al. Phys. Rev. Lett. **126** (2021) 081102.

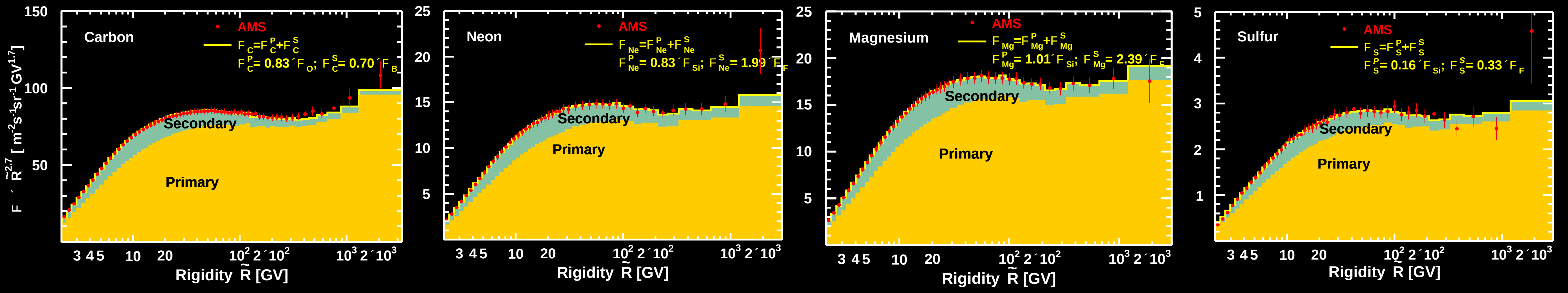




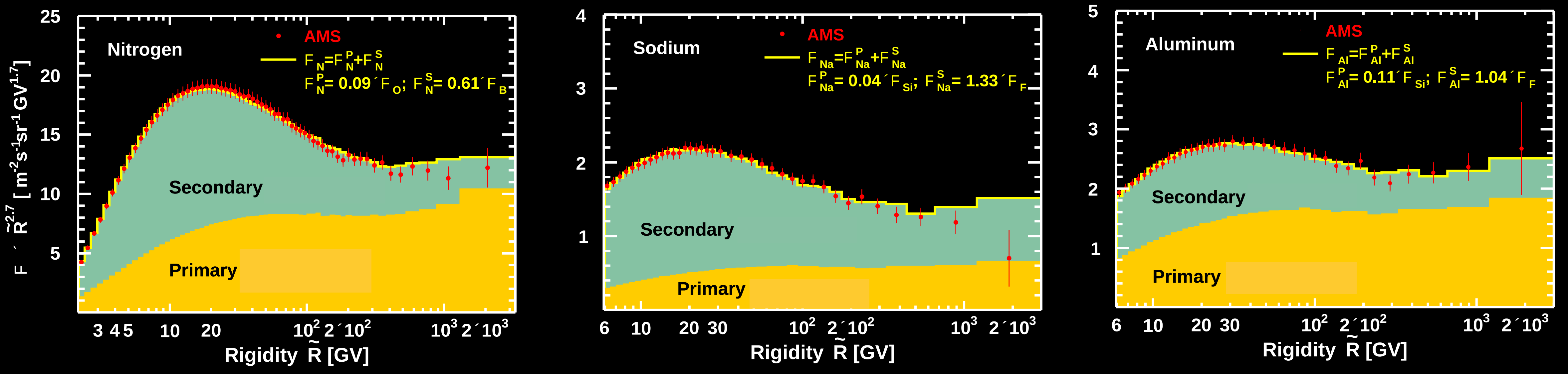
Above 175 GV, the F/Si ratio exhibits a hardening compatible with B/O ratio.

Model Independent Primary/Secondary Composition with AMS

The composition fits are based on assumed pure primary (O, Si) and secondary (B, F) fluxes.

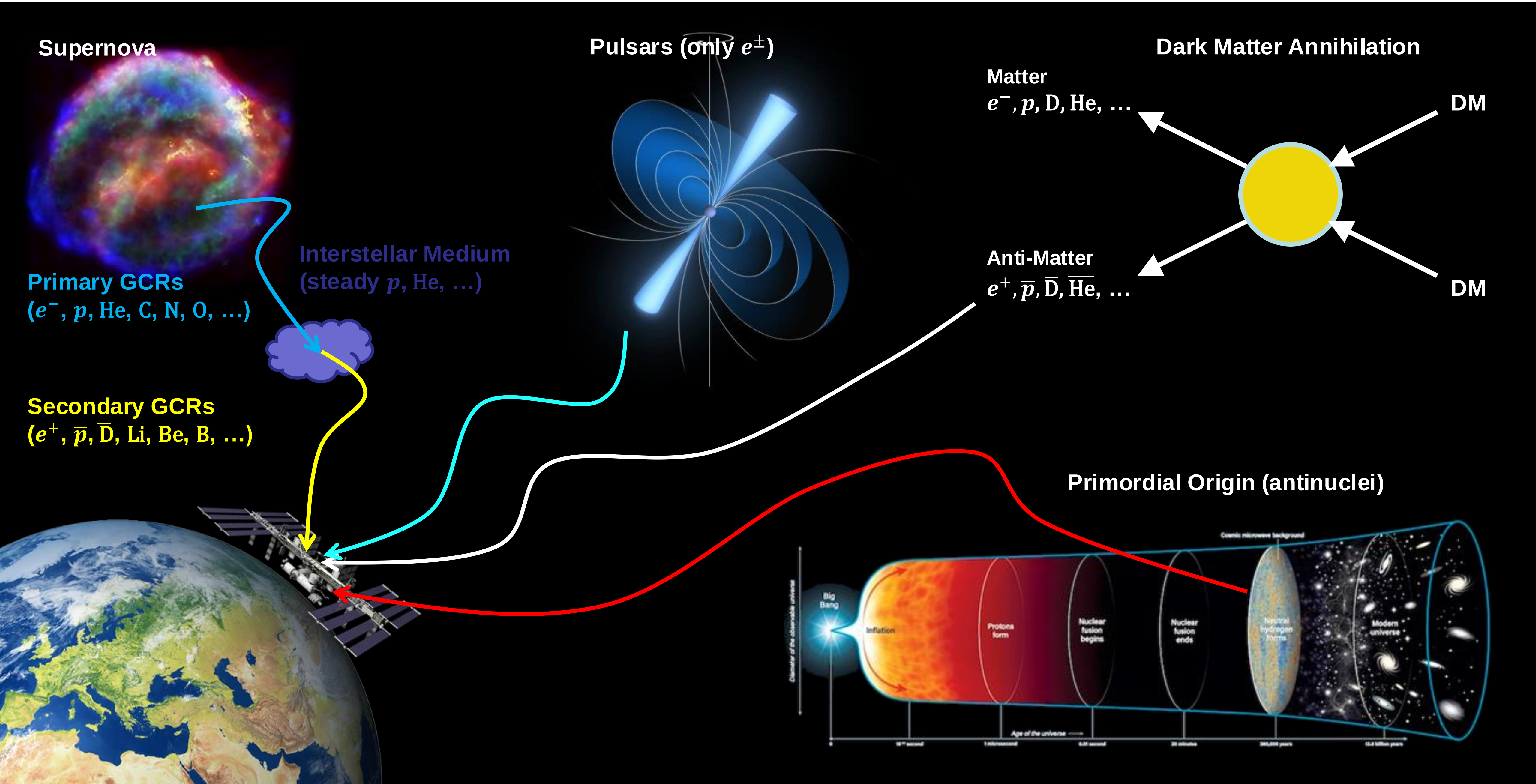


Even-Z nuclei are dominated by primaries



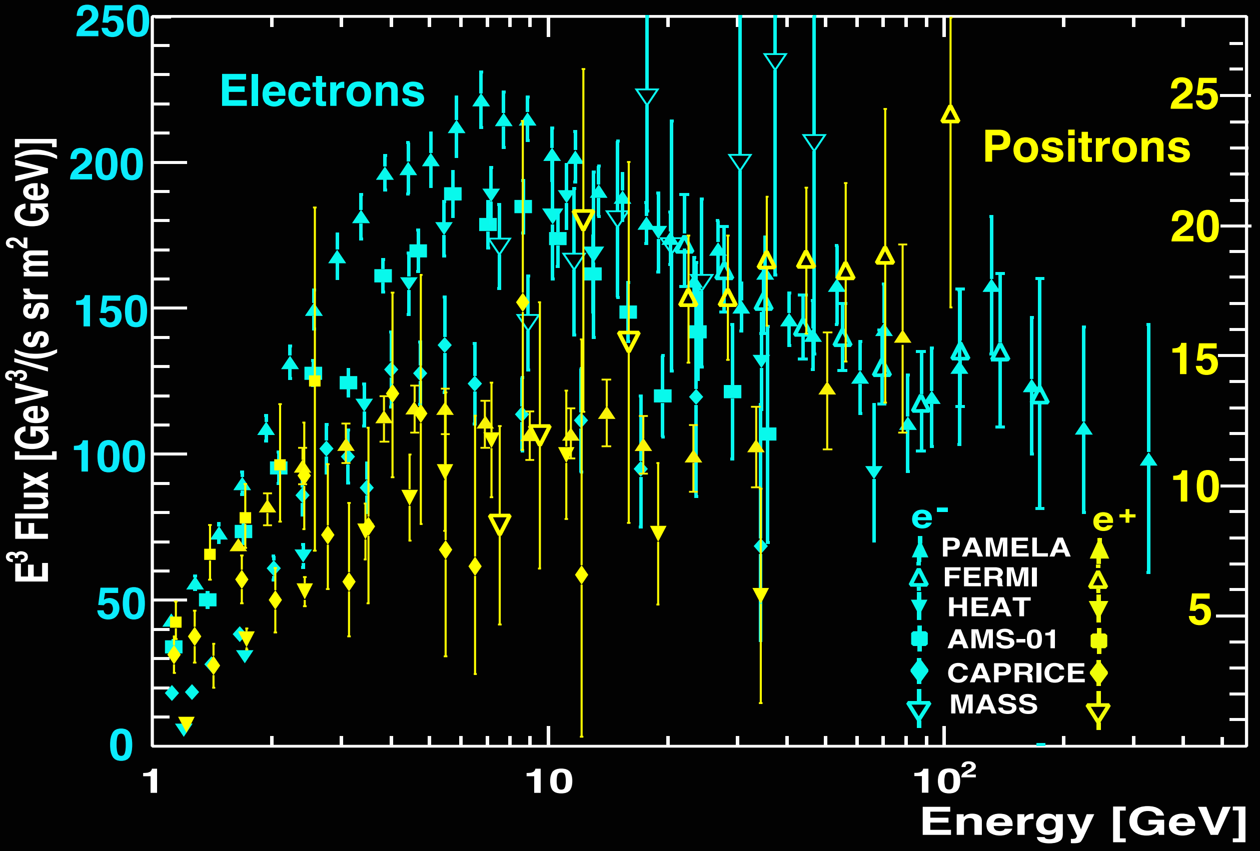
Odd-Z nuclei have more secondaries than even-Z

CRs Antimatter as a Probe for New Physics



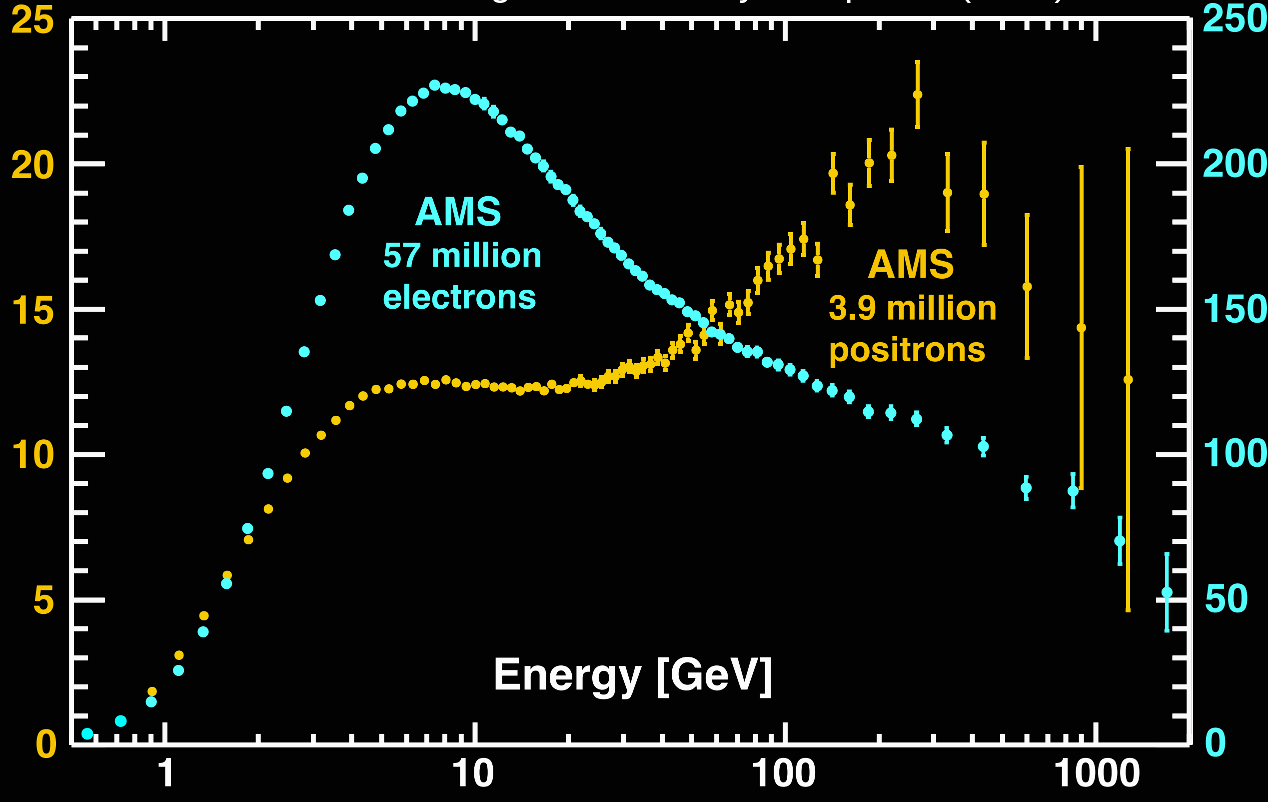
AMS Electron and Positron Fluxes

Measurements before AMS



AMS measurements

M. Aguilar *et al.*, Phys. Rep. **894** (2021) 1-116.



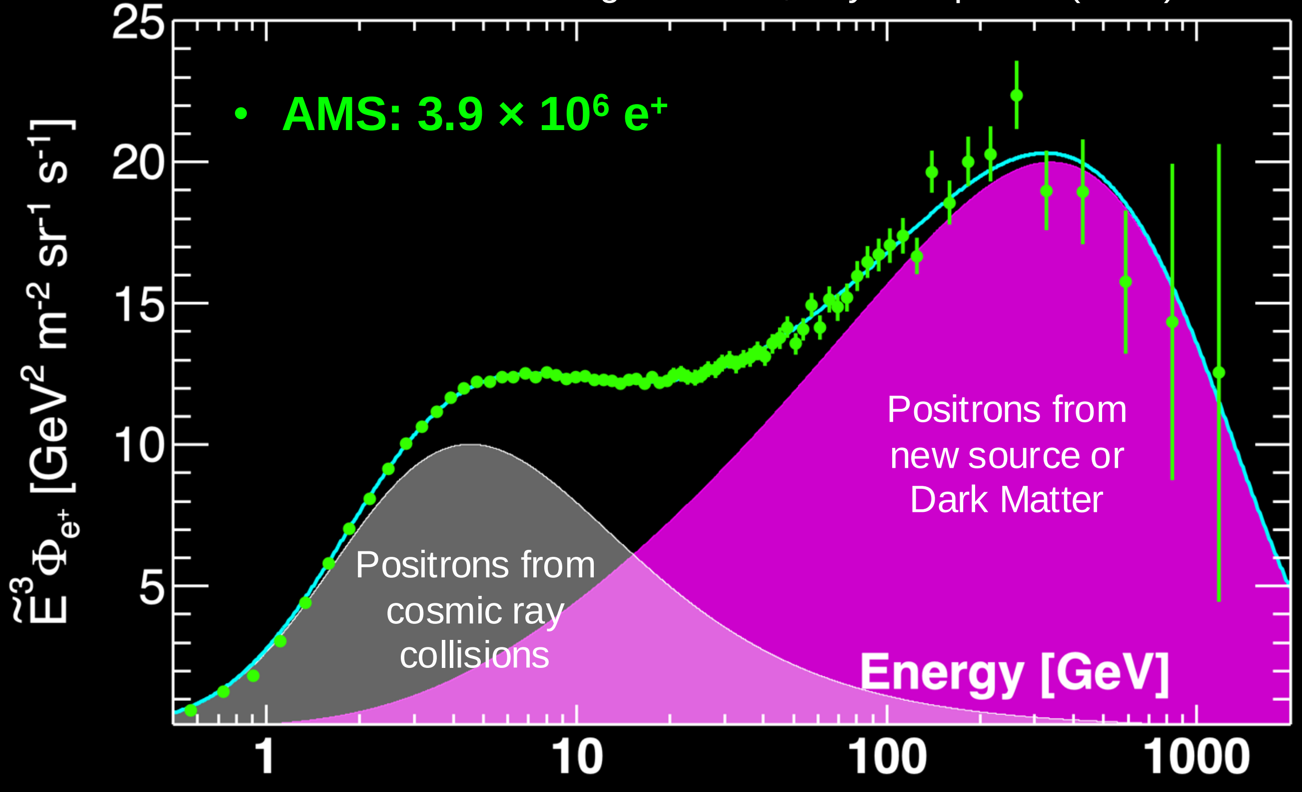
AMS Positron Flux

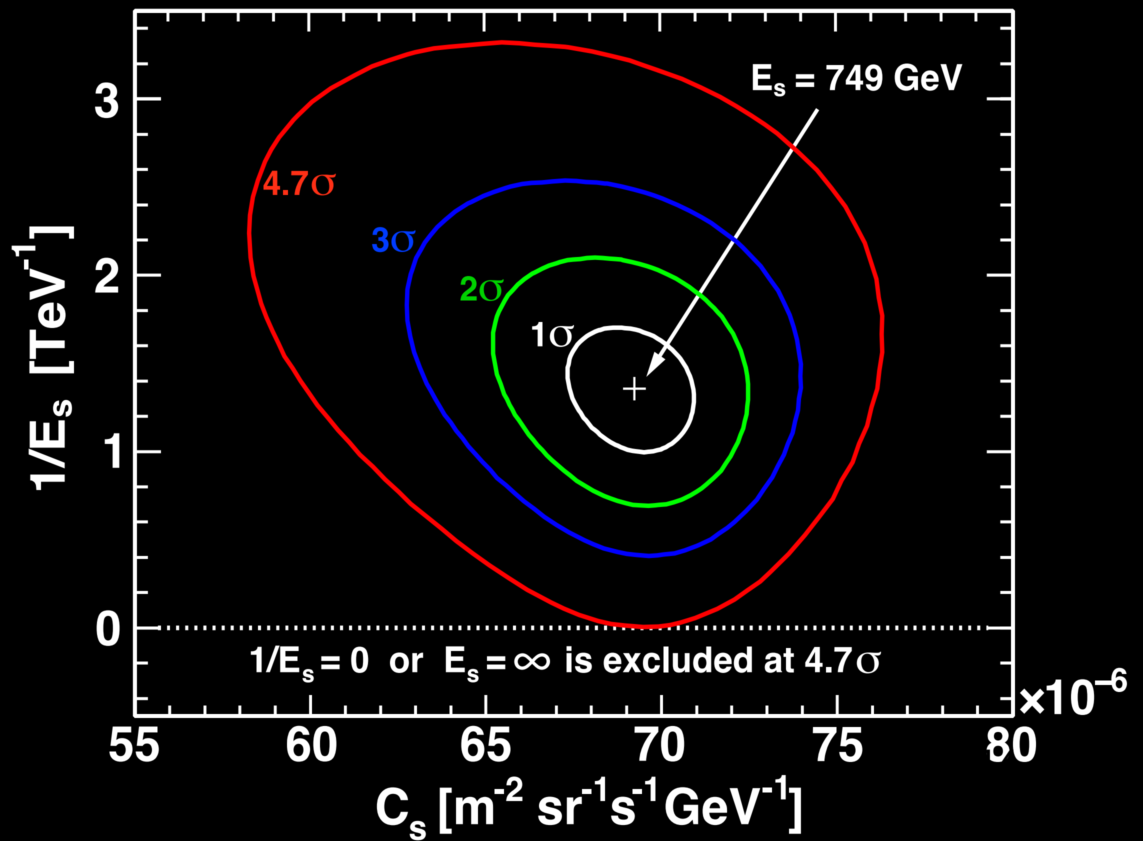
The positron flux is modeled with the sum of low-energy part from cosmic ray collisions plus a high-energy part from pulsars or dark matter both with a cutoff energy E_S.

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

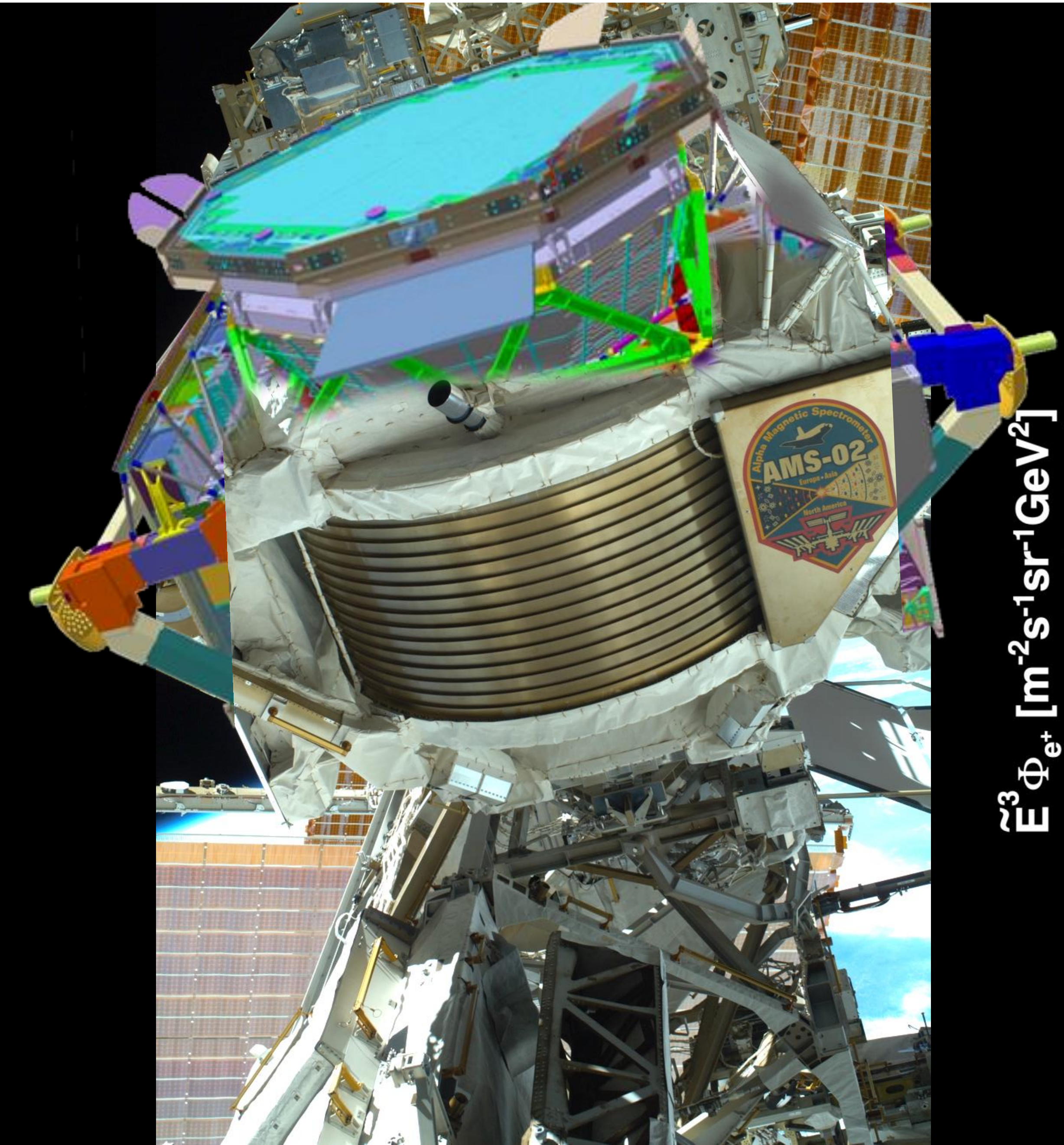
Solar Collisions Pulsars or Dark Matter

M. Aguilar *et al.*, Phys. Rep. **894** (2021) 1-116.

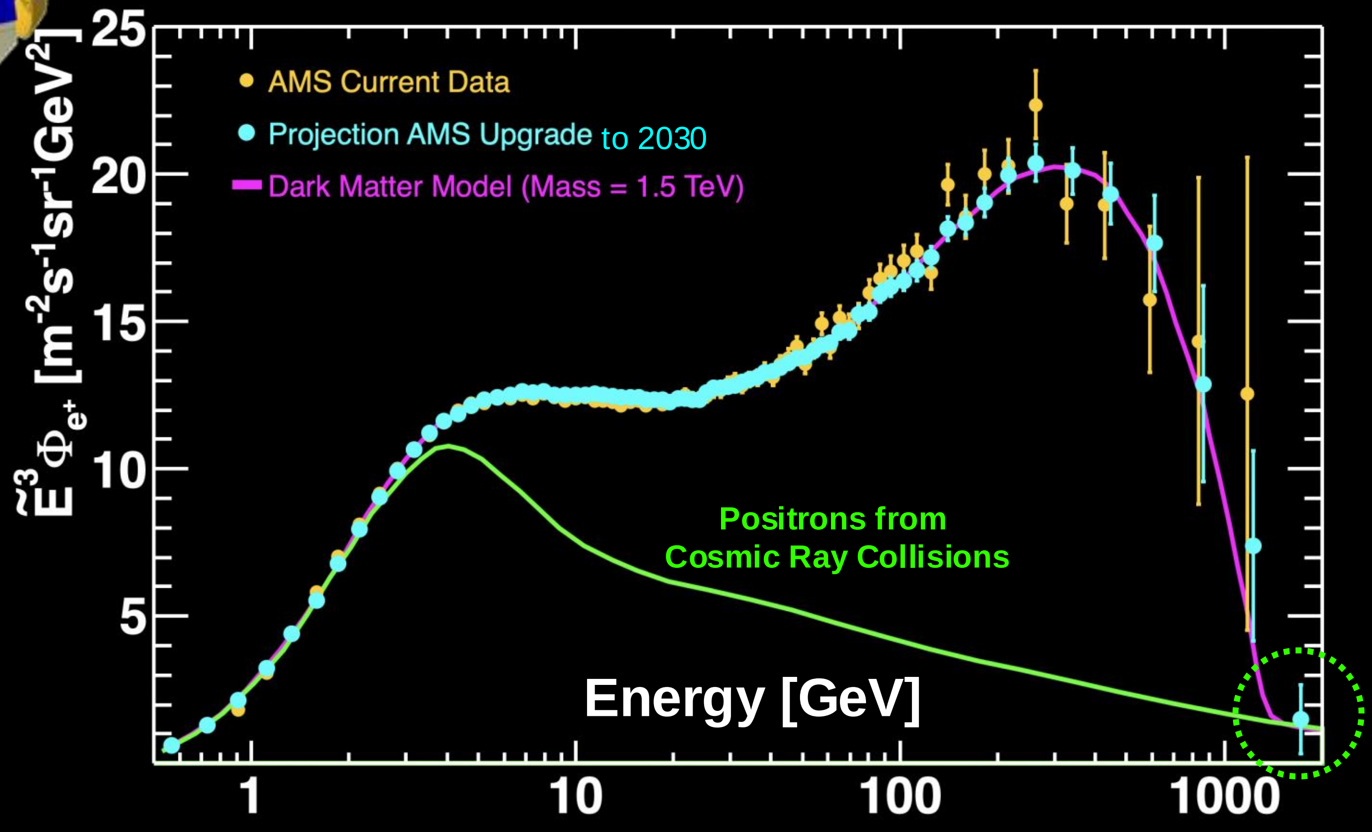




The AMS-02 Upgrade and Projection of AMS Positron Flux



- A large (2.6m diagonal) layer with silicon sensors on both sides to be added on top of AMS.
- Set to be installed on AMS in **2026**.
- The upgrade will allow to collect high energy positrons (and many other particles) with a **3-fold rate**.
- This will allow to study the difference between sources and secondary production models for positrons.



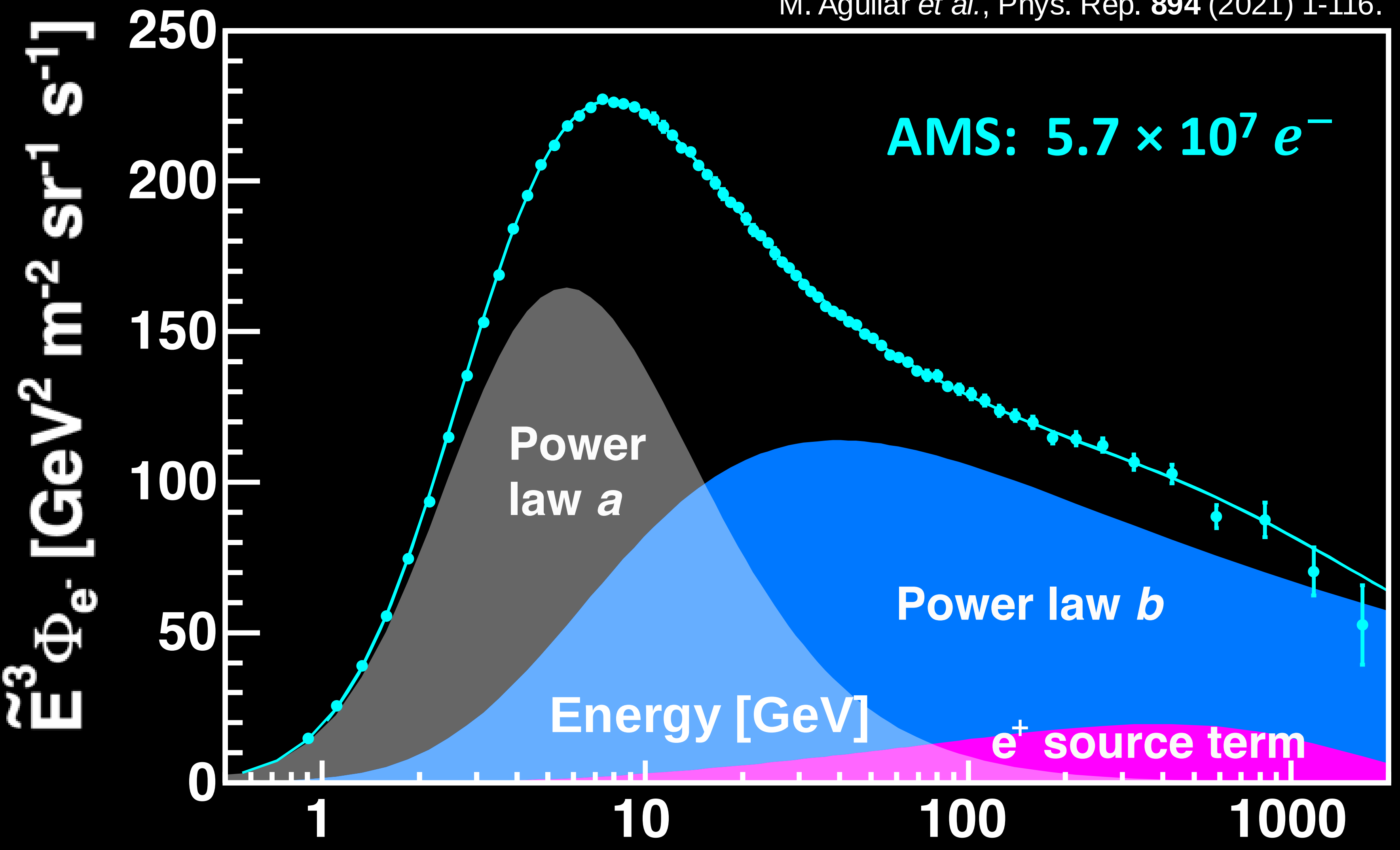
AMS Electron Flux

The spectrum fits well with two power laws (*a*, *b*) and a **source term like positrons (2.6σ).**

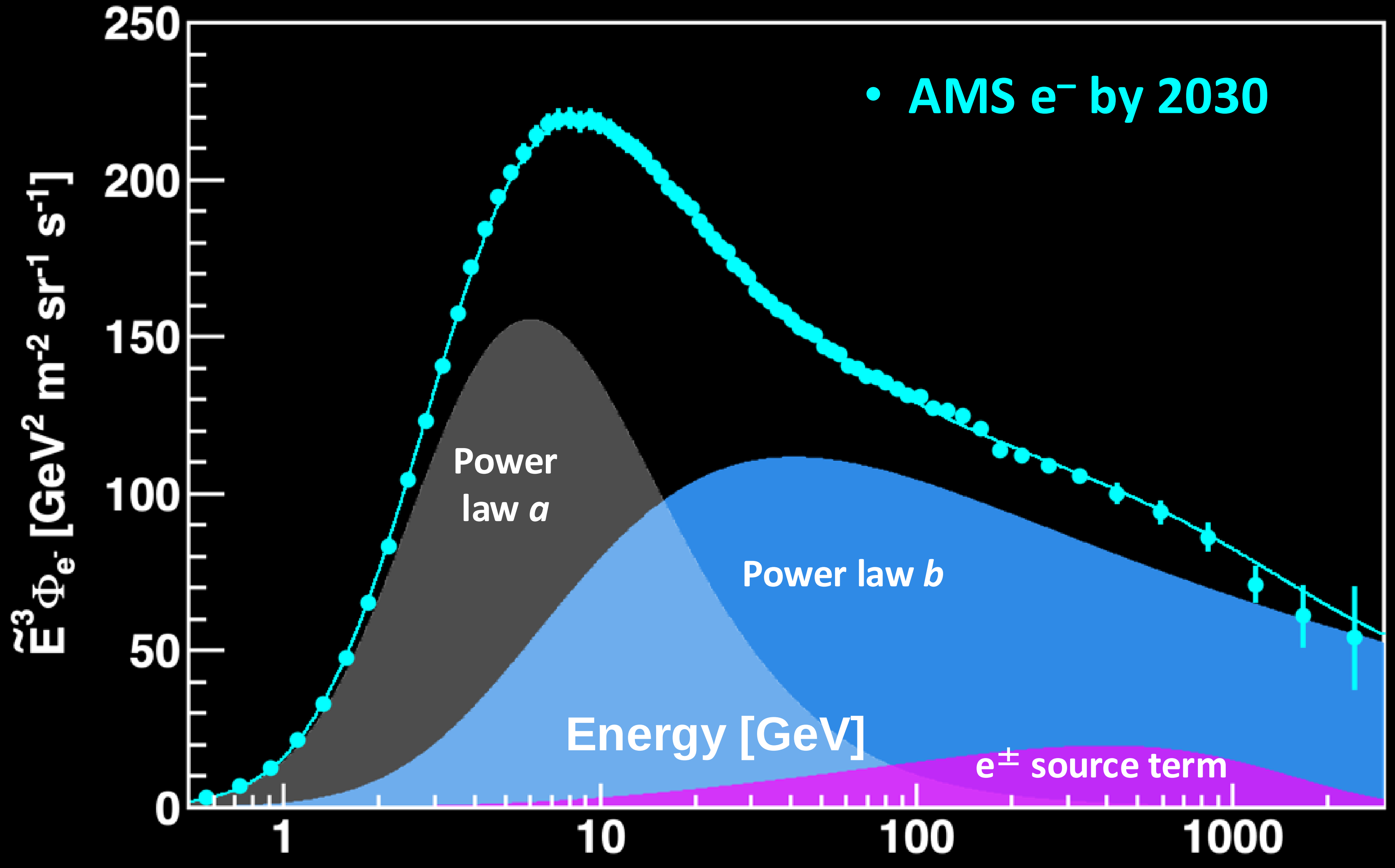
$$\Phi_{e^-}(E) = \frac{E^2}{\hat{E}^2}\left(C_a \hat{E}^{\gamma_a} + C_b \hat{E}^{\gamma_b} + \text{Positron Source Term}\right)$$

Solar **Power law *a*** **Power law *b***

M. Aguilar *et al.*, Phys. Rep. **894** (2021) 1-116.

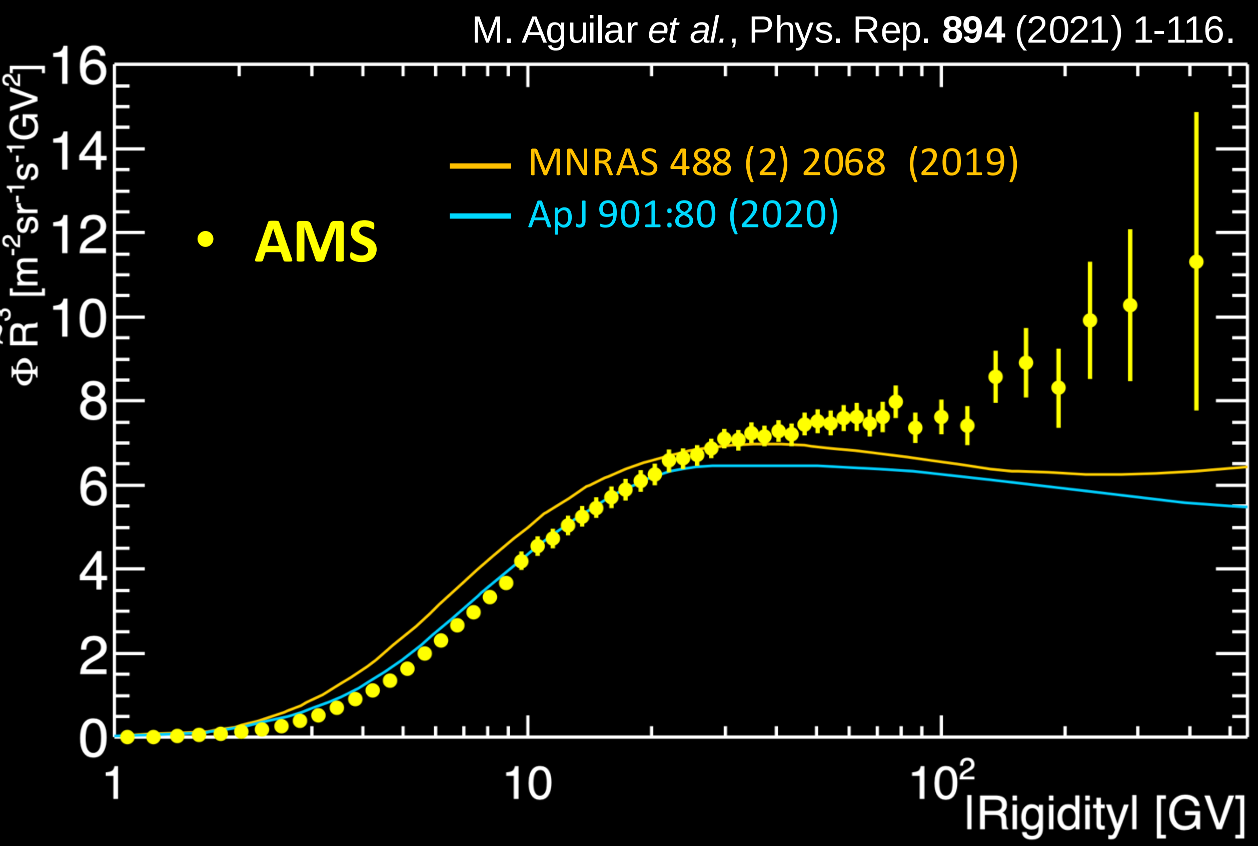


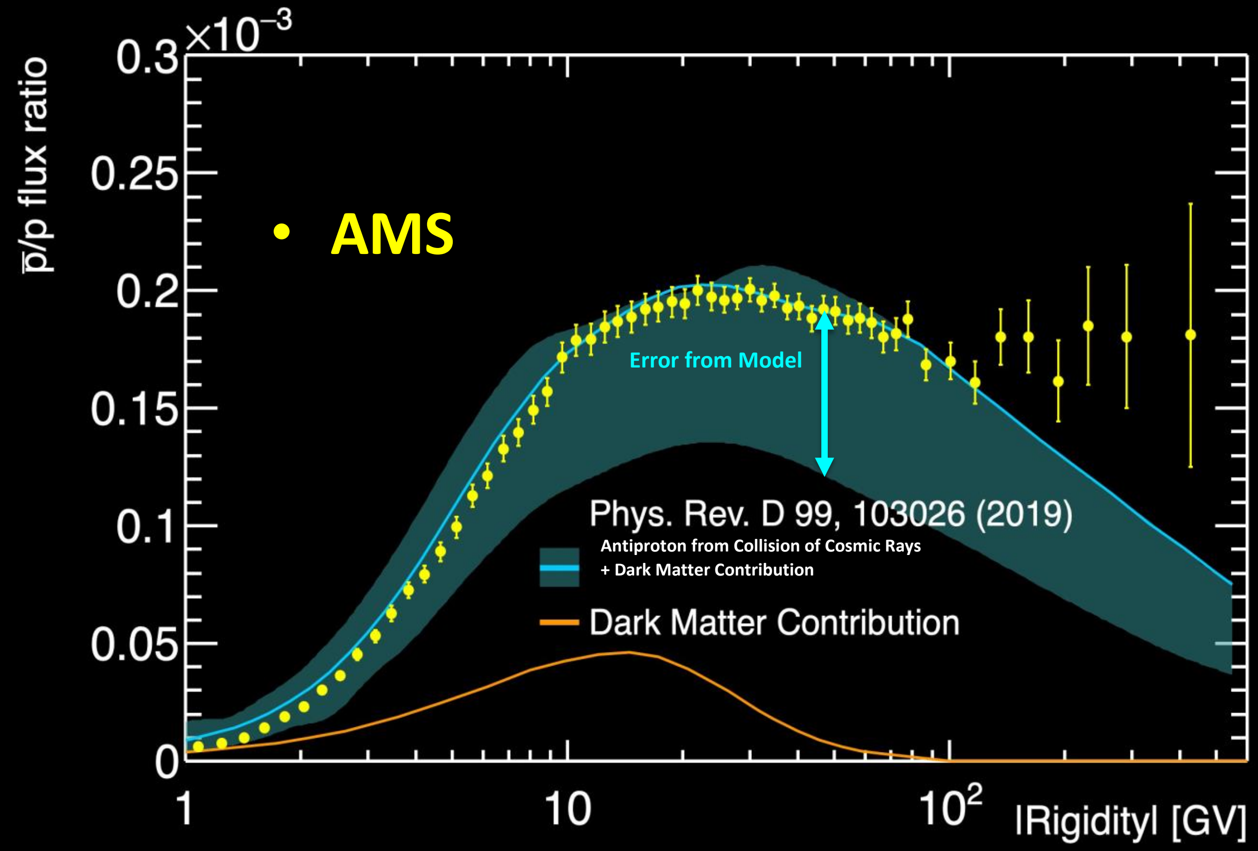
Projection of AMS Electron Flux



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

AMS-02 Antiproton Flux and the $\overline{p}/p$ Flux Ratio

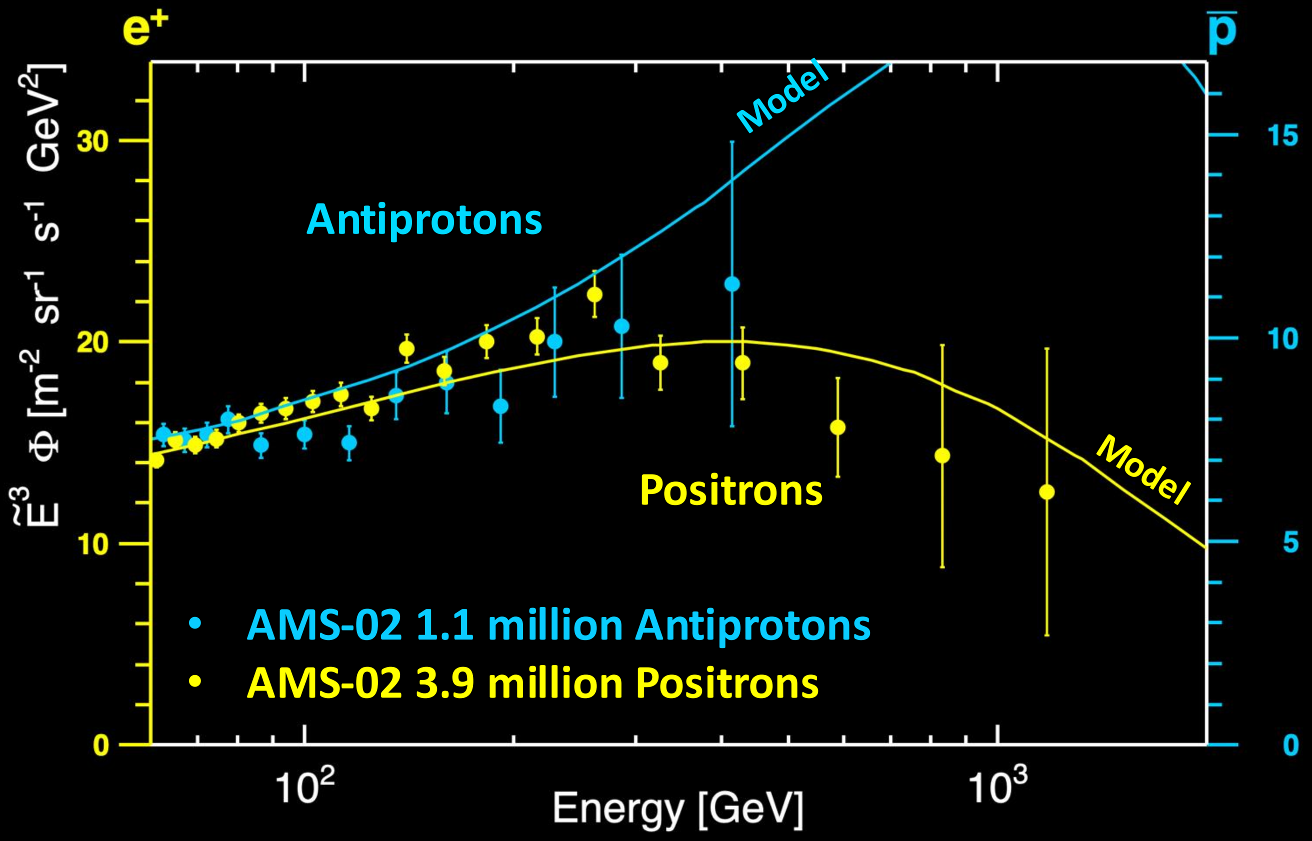


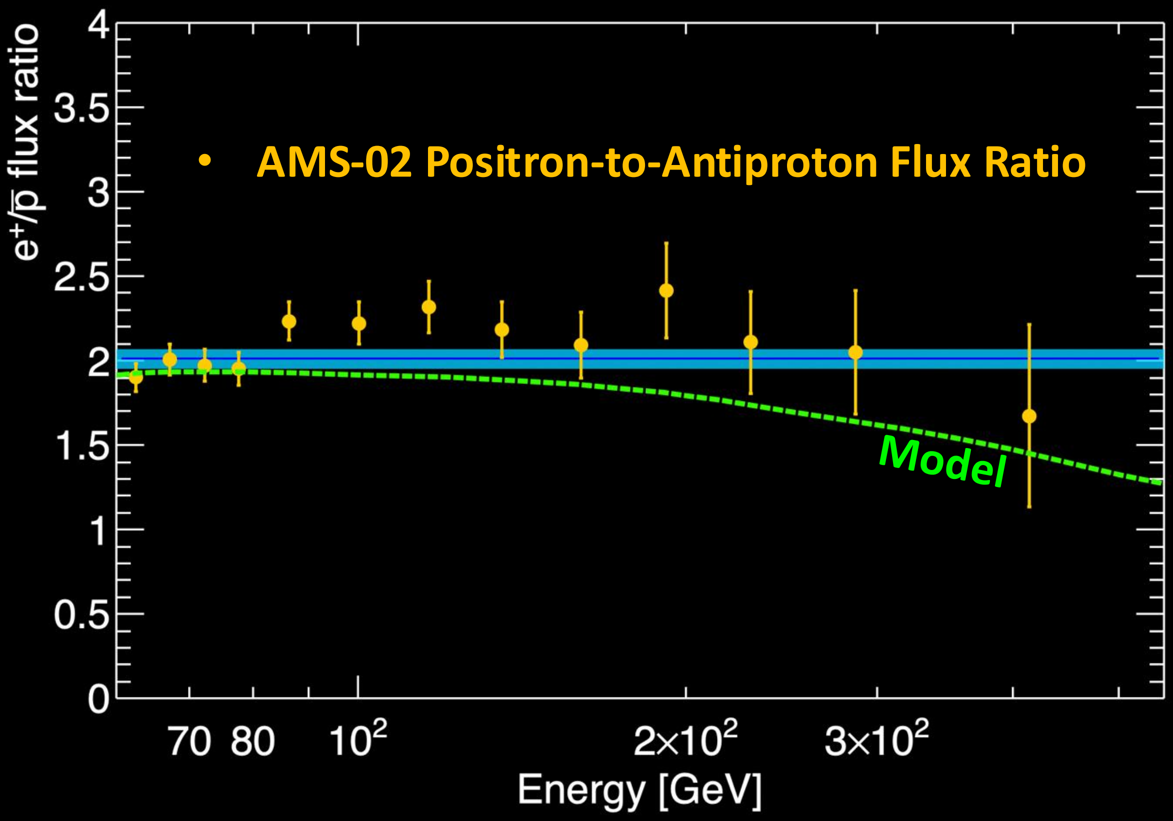


The interpretation of AMS data requires knowledge of the astrophysical background.
Uncertainties in the modelling include **production cross section**, **propagation**, and **solar modulation**.

AMS Positron and Antiproton Fluxes

Model from P. Mertsch, A. Vittino, S. Sarkar, *Explaining cosmic ray antimatter with secondaries from old supernova remnants*, Phys. Rev. D **104** (2021) 103029.

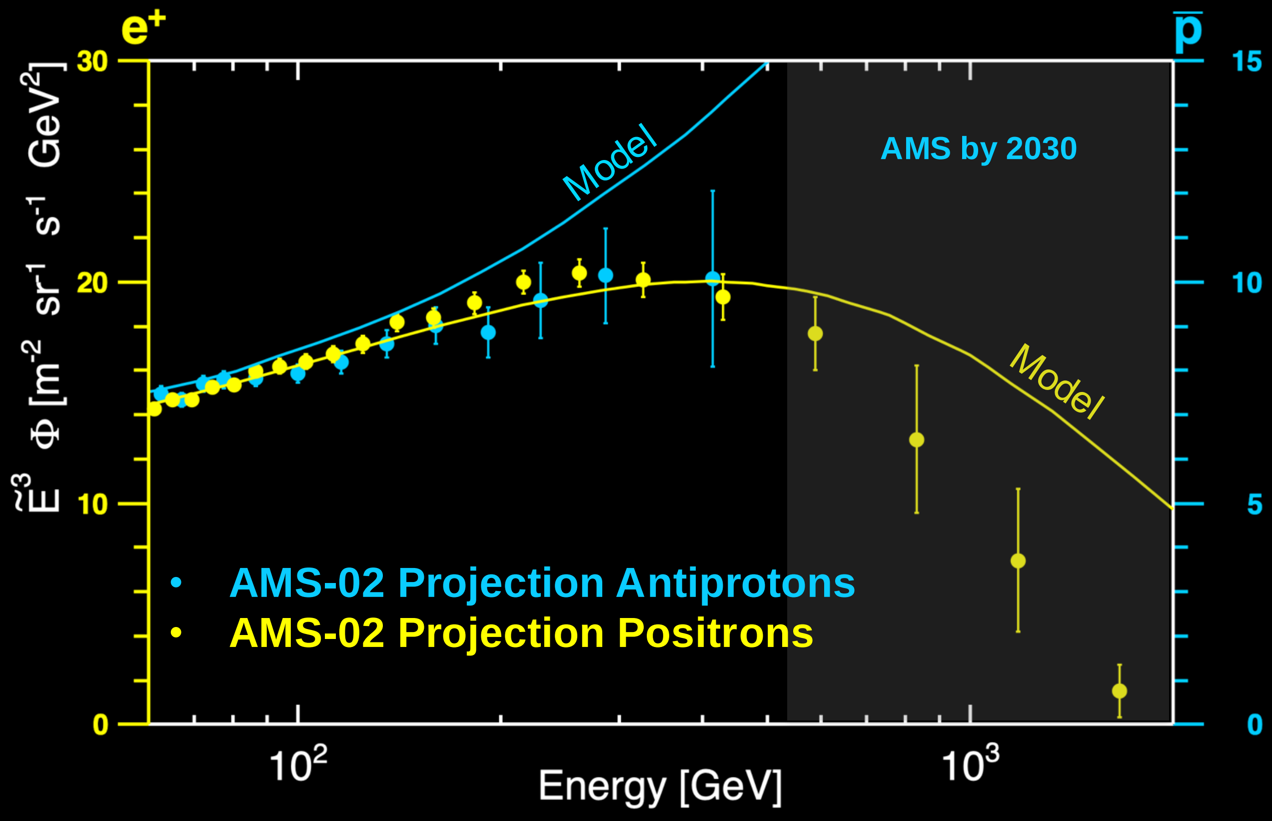


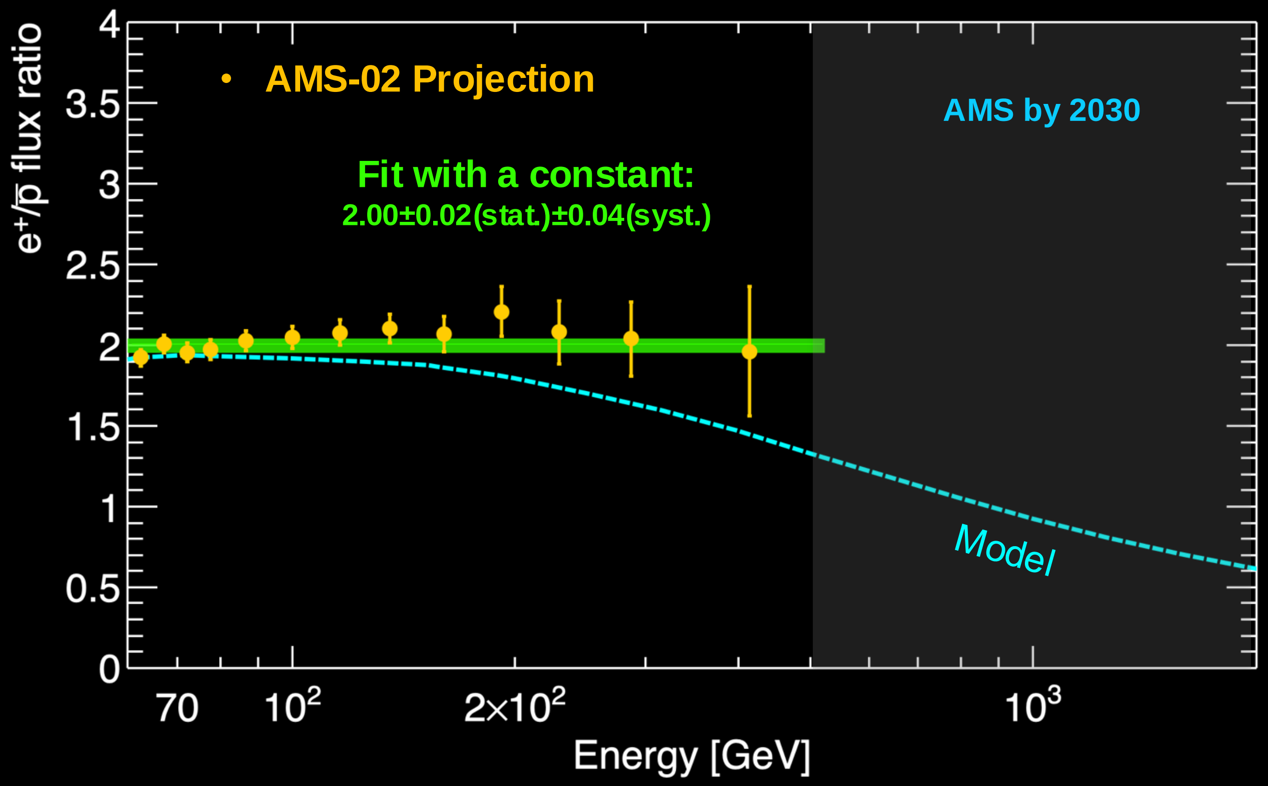


Positrons and **antiprotons** have nearly identical energy dependence.

Projection of AMS Positron and Antiproton Fluxes

Model from P. Mertsch, A. Vittino, S. Sarkar, *Explaining cosmic ray antimatter with secondaries from old supernova remnants*, Phys. Rev. D **104** (2021) 103029.



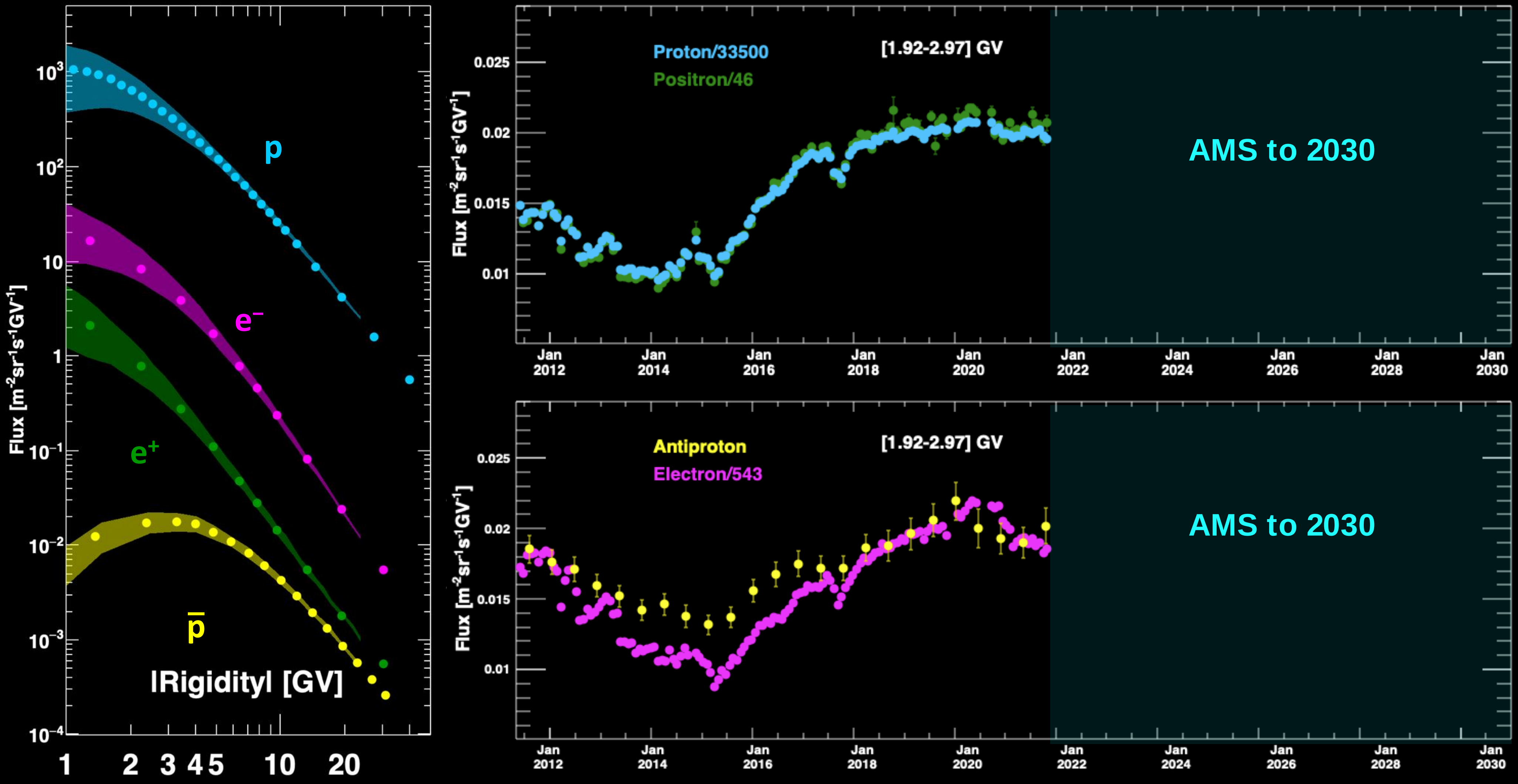


AMS will significantly improve the measurement of the **positrons** and **antiprotons**.
The identical behaviour of positrons and antiprotons disfavours the pulsar origin of positrons.

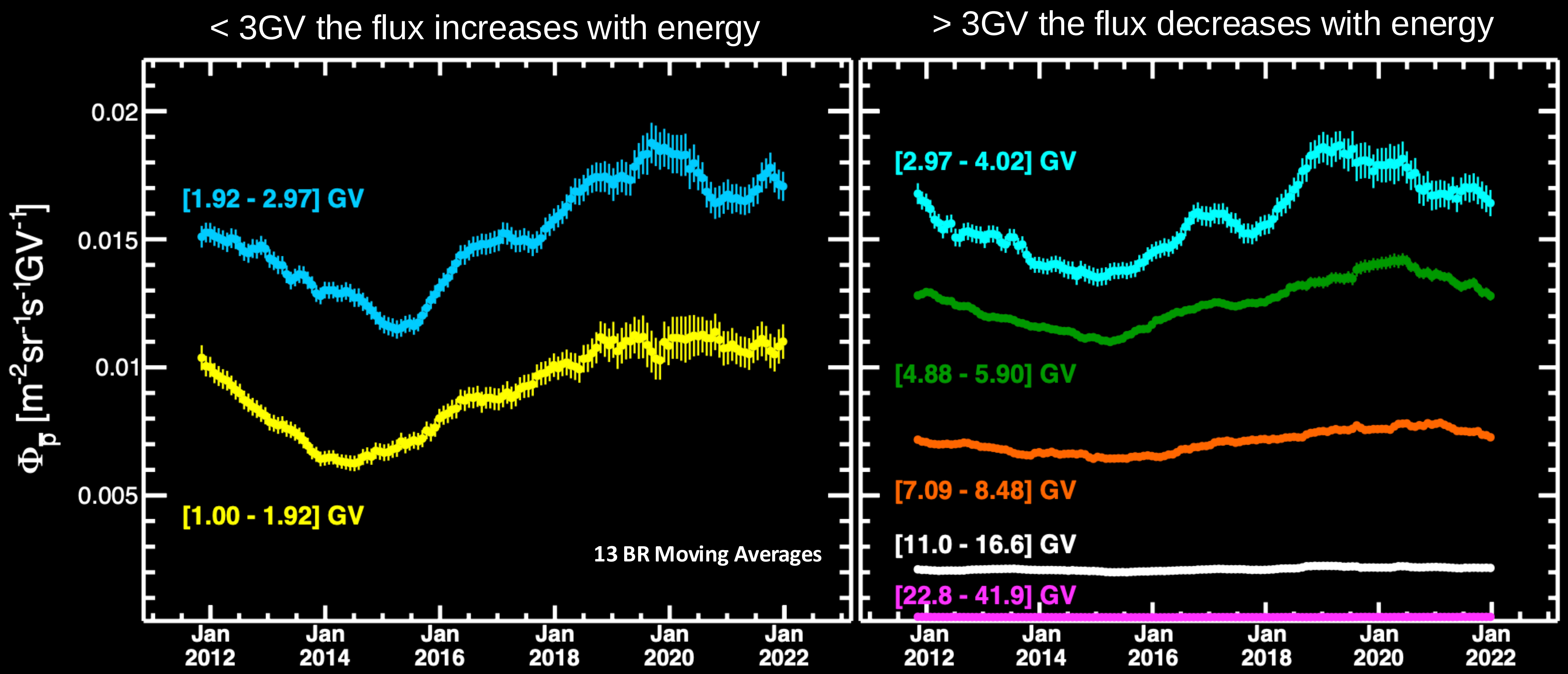
Understanding the Antiproton Solar Modulation

For the first time, the time dependence of p, e^-, e^+, and $\bar{p}$ are studied in detailed with the same experiment in an entire 11 years solar cycle. By 2030 AMS will cover 22 years.

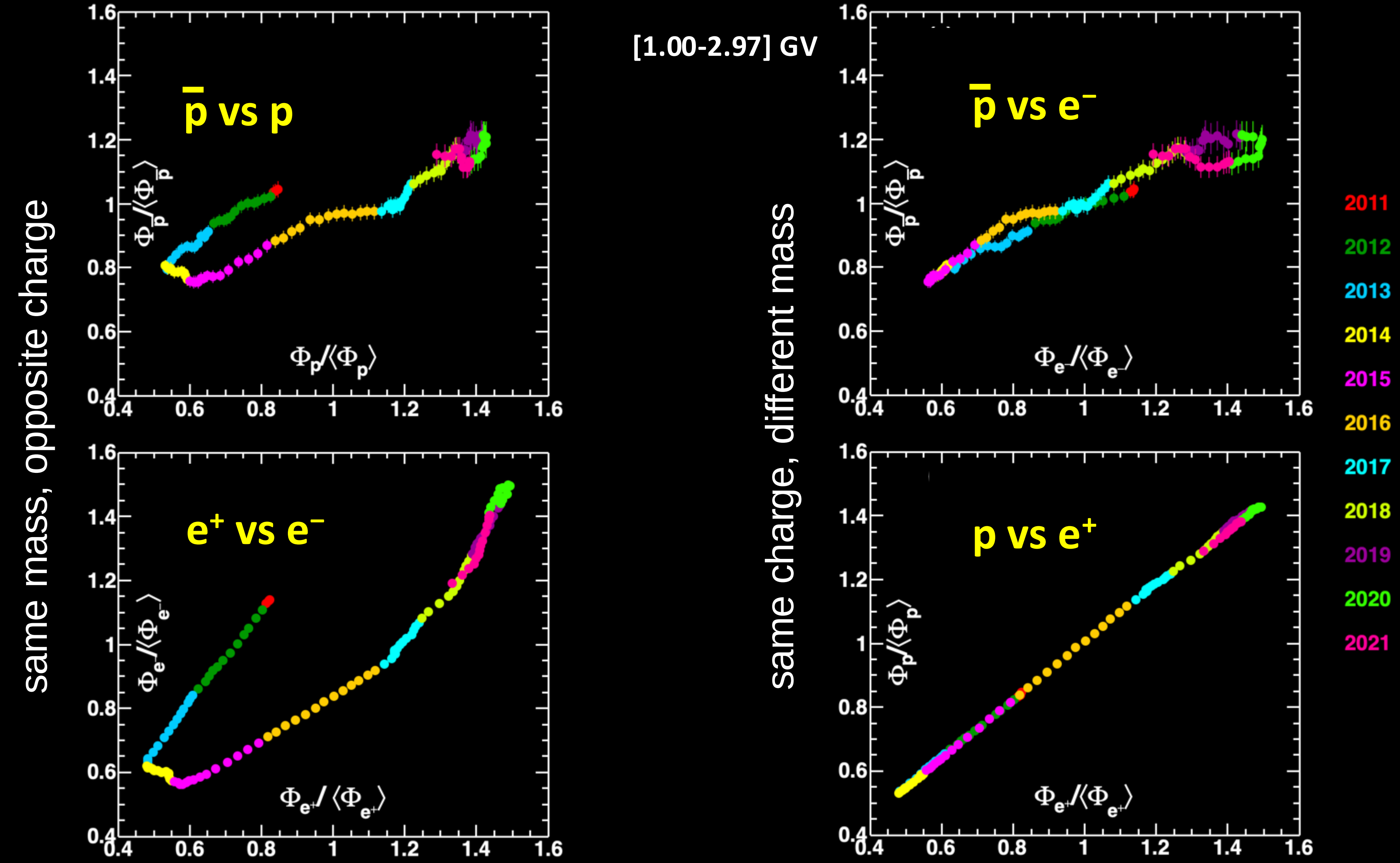
Submitted to Phys. Rev. Lett.



Understanding the Antiproton Solar Modulation



Differences in Solar Modulation between p, e^-, e^+, and $\bar{p}$



This information will help constraining solar modulation, and to understand the origin of CRs antiprotons.

Antideuteron Search

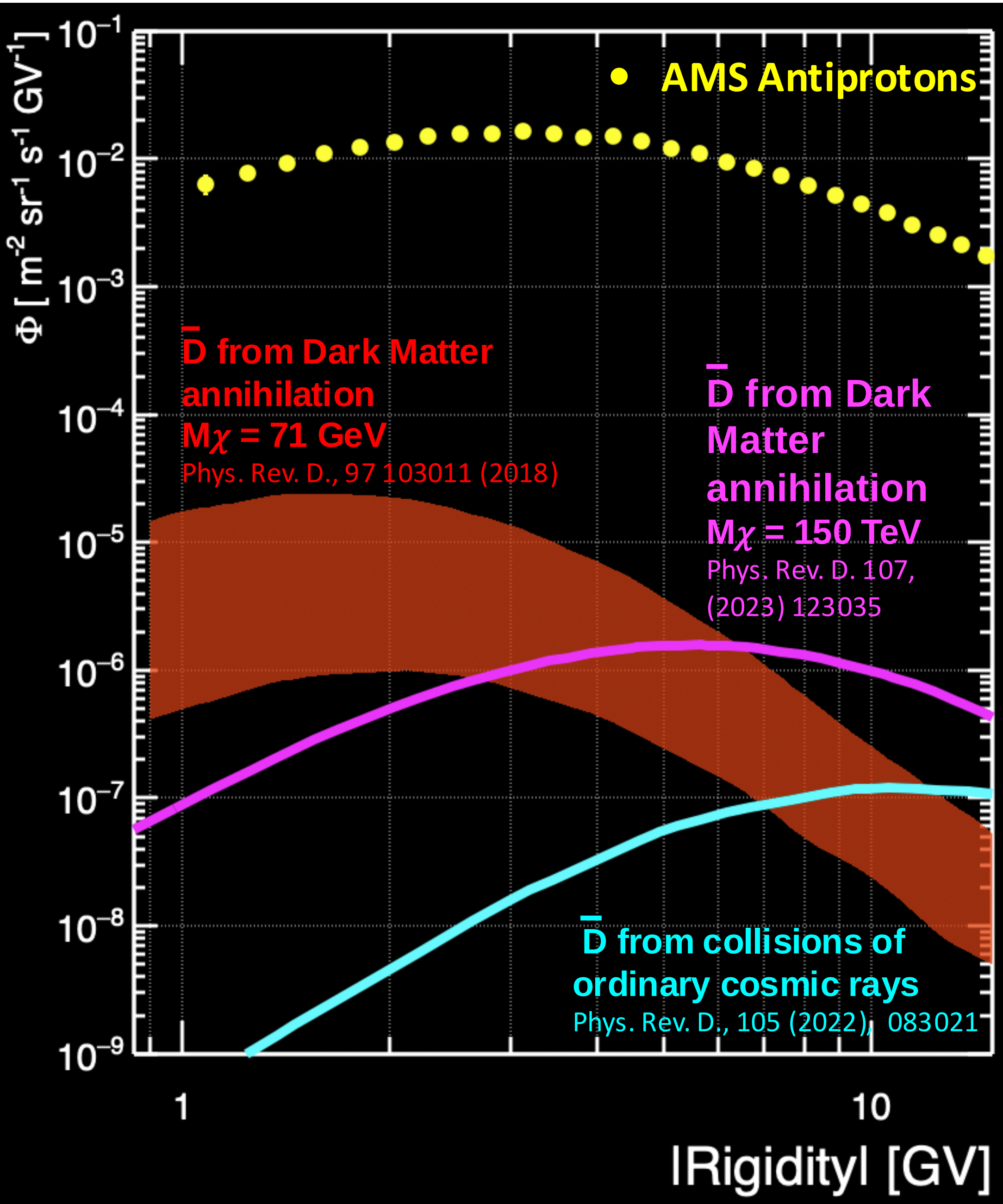
Anti-deuterons have never been observed in space

Very low background at low energy for indirect search of Dark Matter.

Expected very low flux. High rejection to other species is needed: $\bar{D}/\bar{p} < 10^{-4}, \bar{D}/p < 10^{-9}, \bar{D}/e^{-} < 10^{-6}$.

AMS has collected ~10 billion protons, ~100 million deuterons, and ~1 million antiprotons.

Simultaneous measurement from AMS of $\bar{p}$ and $\bar{D}$ will provide precise and consistent information on their origin.



AMS-02 Identification of |Z|=1 Particles

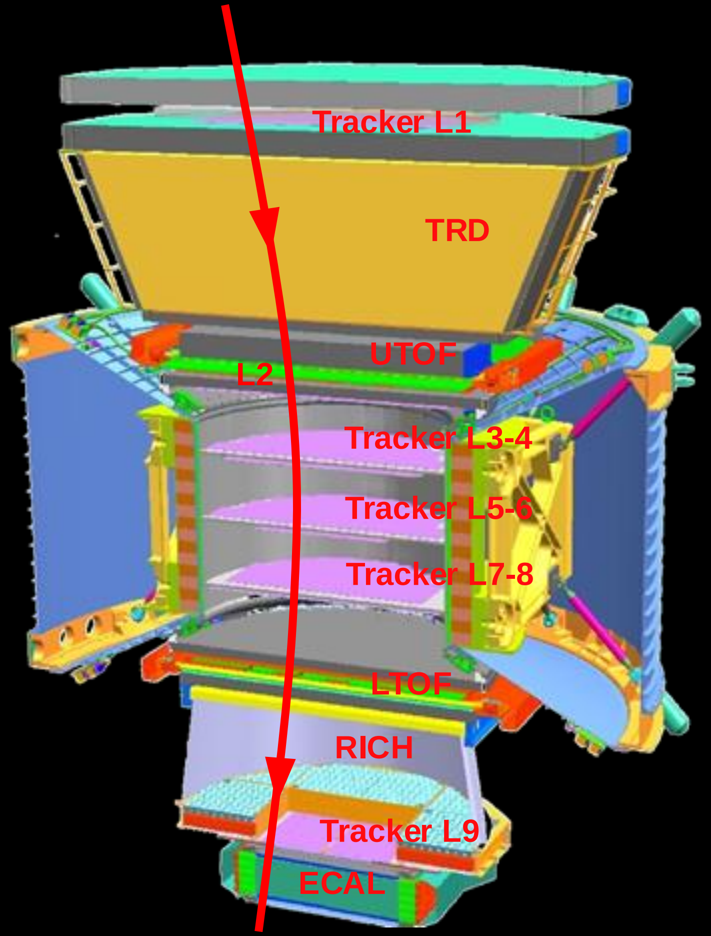
Charge and Sign

TRD, elimination of electron background,
select $|Z| = 1, \Delta Z/Z \approx 0.1$ **c.u.**

Tracker, particle sign (+/–),
select $|Z| = 1, \Delta Z/Z \approx 0.5$ **c.u.**

ToF, separate upgoing/downgoing
select $|Z| = 1, \Delta Z/Z \approx 0.6$ **c.u.**

RICH, select $|Z| = 1, \Delta Z/Z \approx 0.3$ **c.u.**

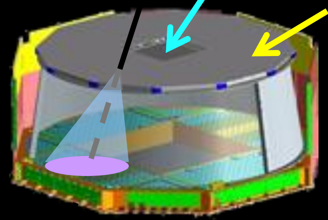


Mass Separation

Tracker, momentum p**,**
$\Delta p/p \approx 10\%$ **up to 20 GV**

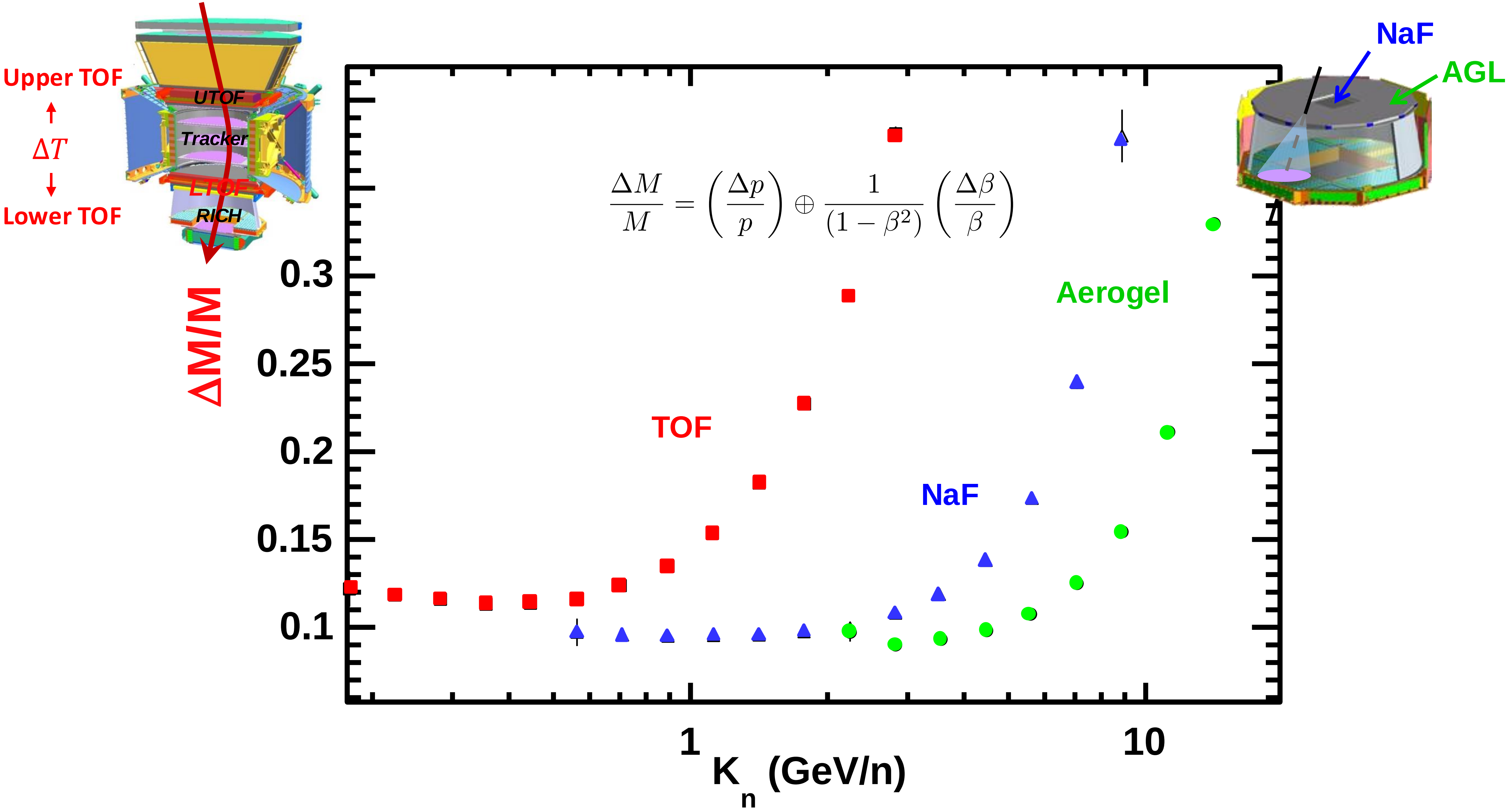
$$M = p\frac{\sqrt{1-\beta^2}}{\beta}$$

ToF, velocity $\beta, \Delta\beta/\beta^2 \approx 4\%$



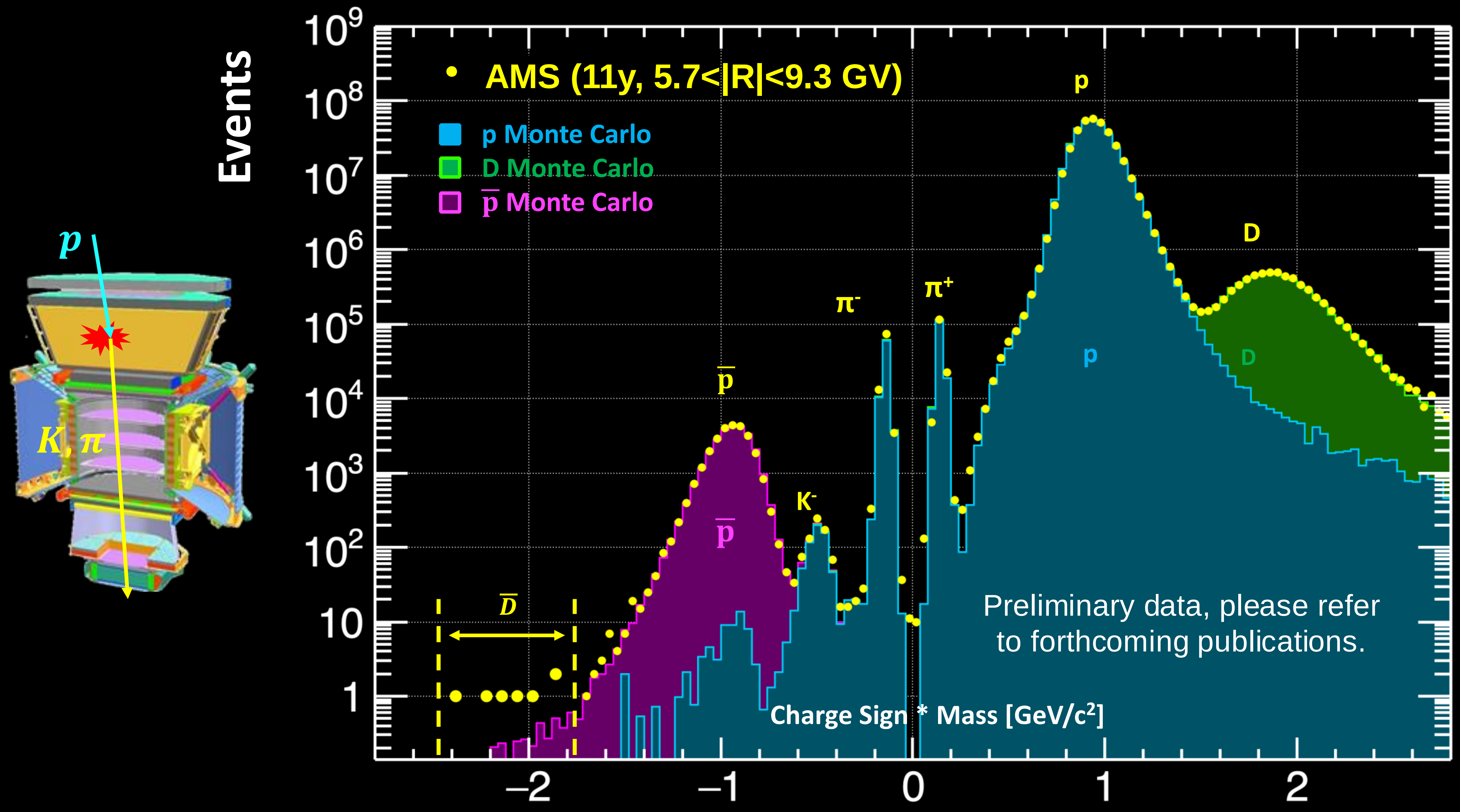
RICH, velocity β**, in two radiators:**
NaF: $\Delta\beta/\beta \approx 0.4\%, \beta > 0.75$
Aerogel: $\Delta\beta/\beta \approx 0.1\%, \beta > 0.96$

AMS-02 Mass Measurement of |Z|=1 Particles



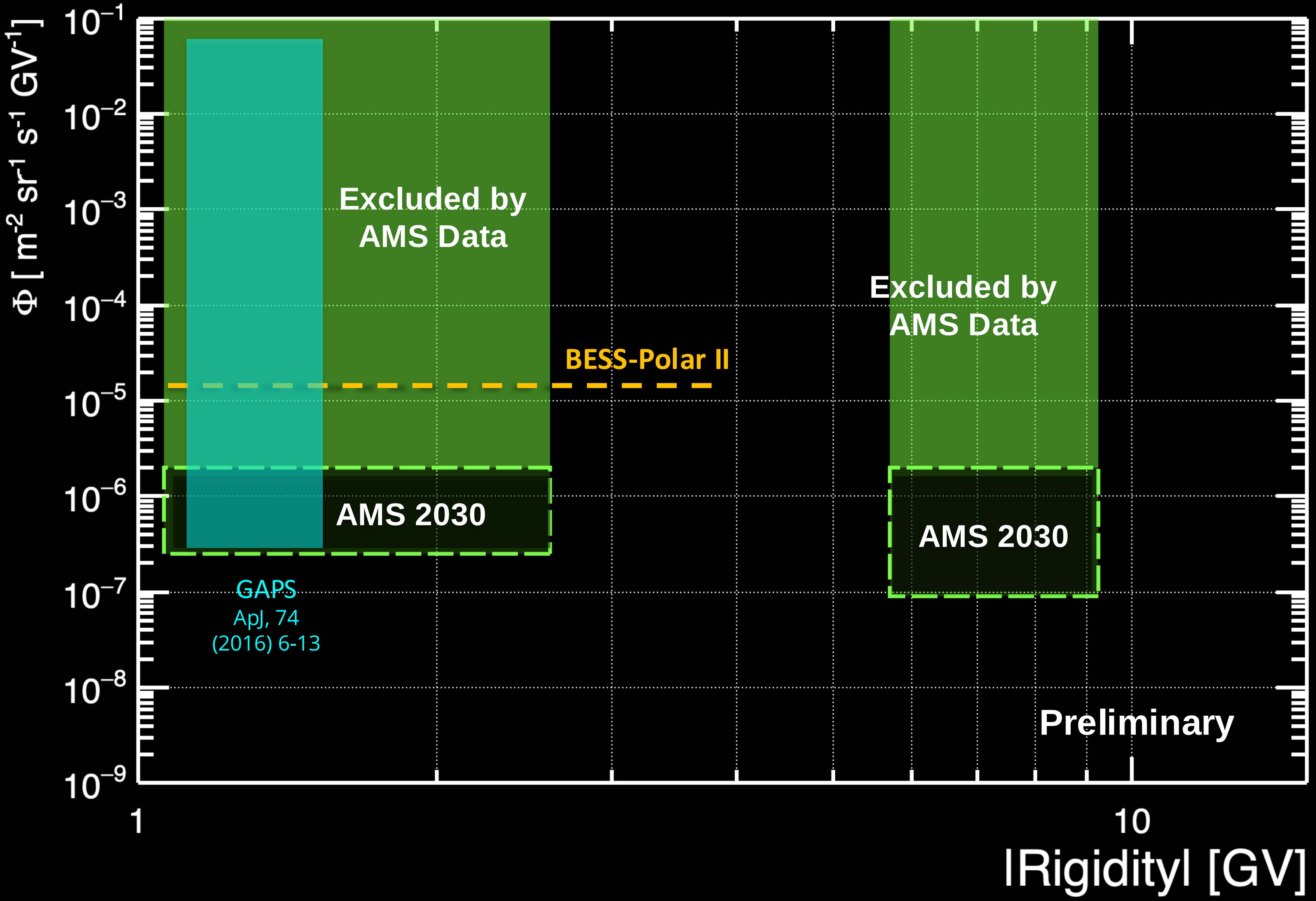
$$\frac{\Delta M}{M} = \left(\frac{\Delta p}{p}\right) \oplus \frac{1}{(1-\beta^2)}\left(\frac{\Delta \beta}{\beta}\right)$$

Current Status of Antideuteron Search



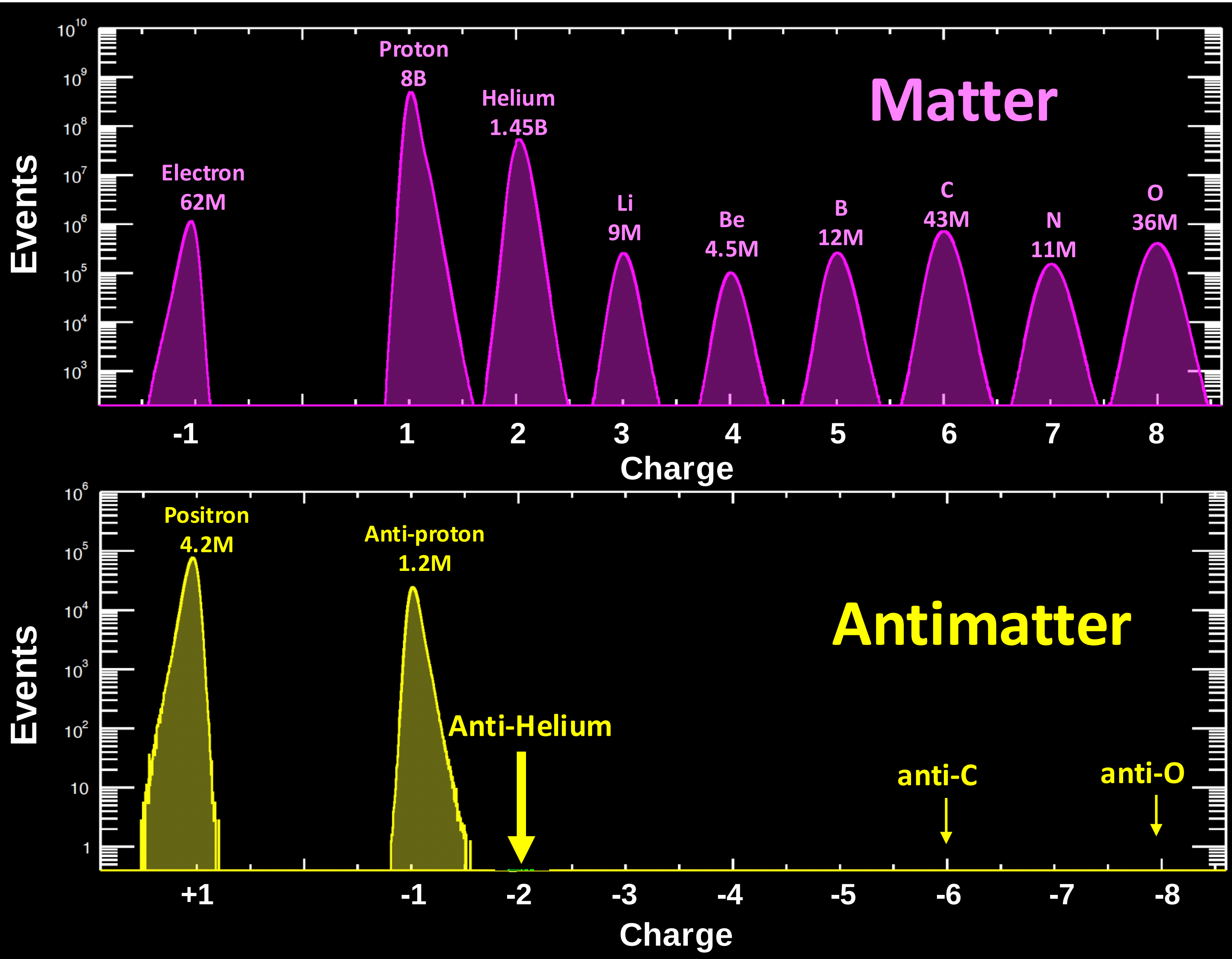
Developments of analysis techniques ongoing. Further MC study are needed to better understand the backgrounds. Future AMS upgrade will provide additional measurement point to antideuterons.

Projection of AMS Antideuteron Search



AMS has a unique opportunity to look for antideuterons in the cosmos.

Current Statistics for Matter/Antimatter



By 2030, AMS will have additional improvement in statistics add understanding of systematic error on antimatter.

Conclusions

- AMS has been operating in the Space Station since May 2011 performing precision measurements of cosmic rays and revealing new details about origin and propagation of all CRs species.
- With its unprecedented statistics and accuracy, AMS has a unique capability to detect antimatter in cosmic rays and study their properties.
- AMS is the only operating spectrometer in space and will continue to collect and analyze data for the lifetime of the Space Station (now projected to 2030).
- An upgrade of AMS is in production to make the best use of the remaining time on the space station.