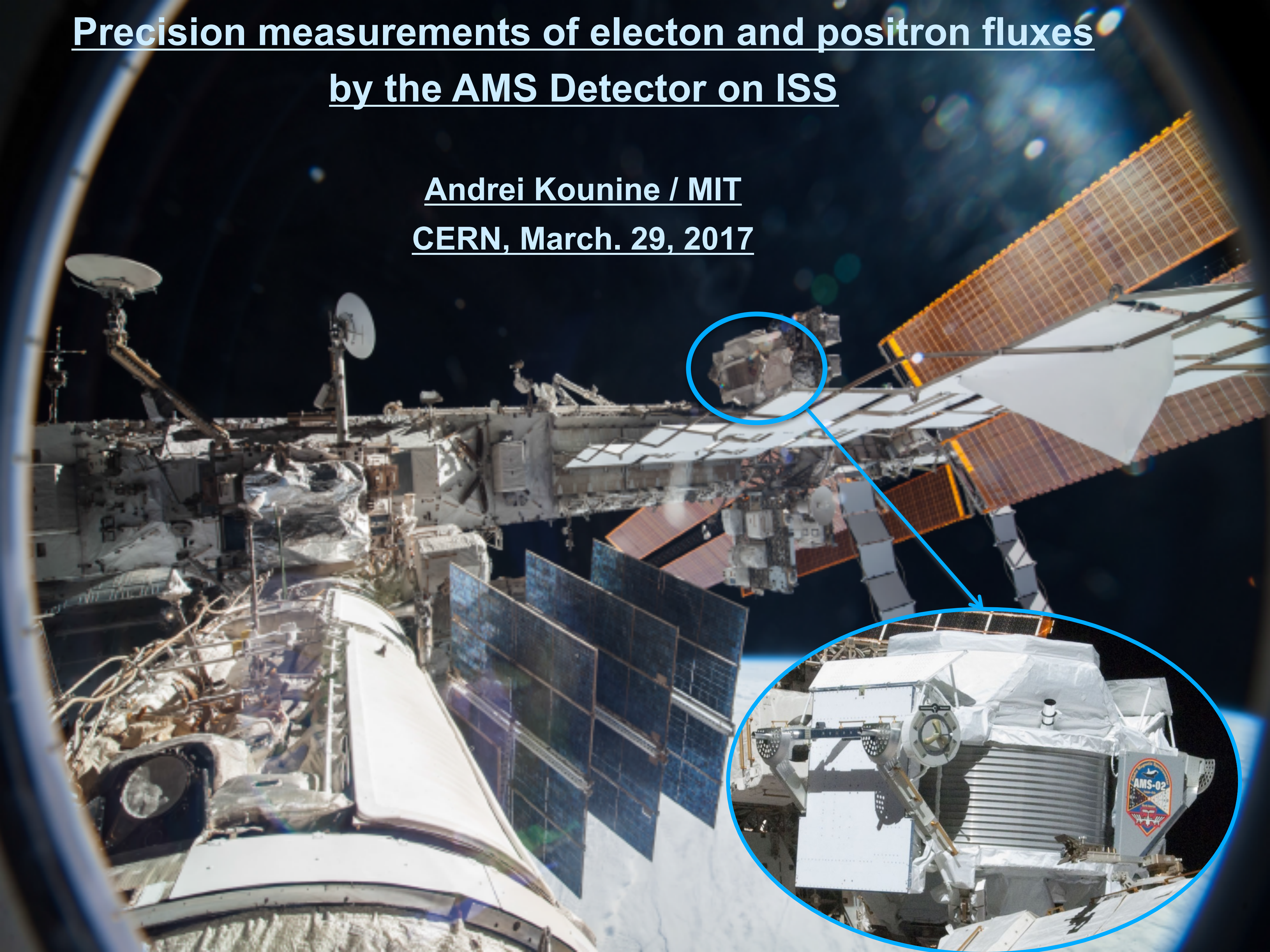
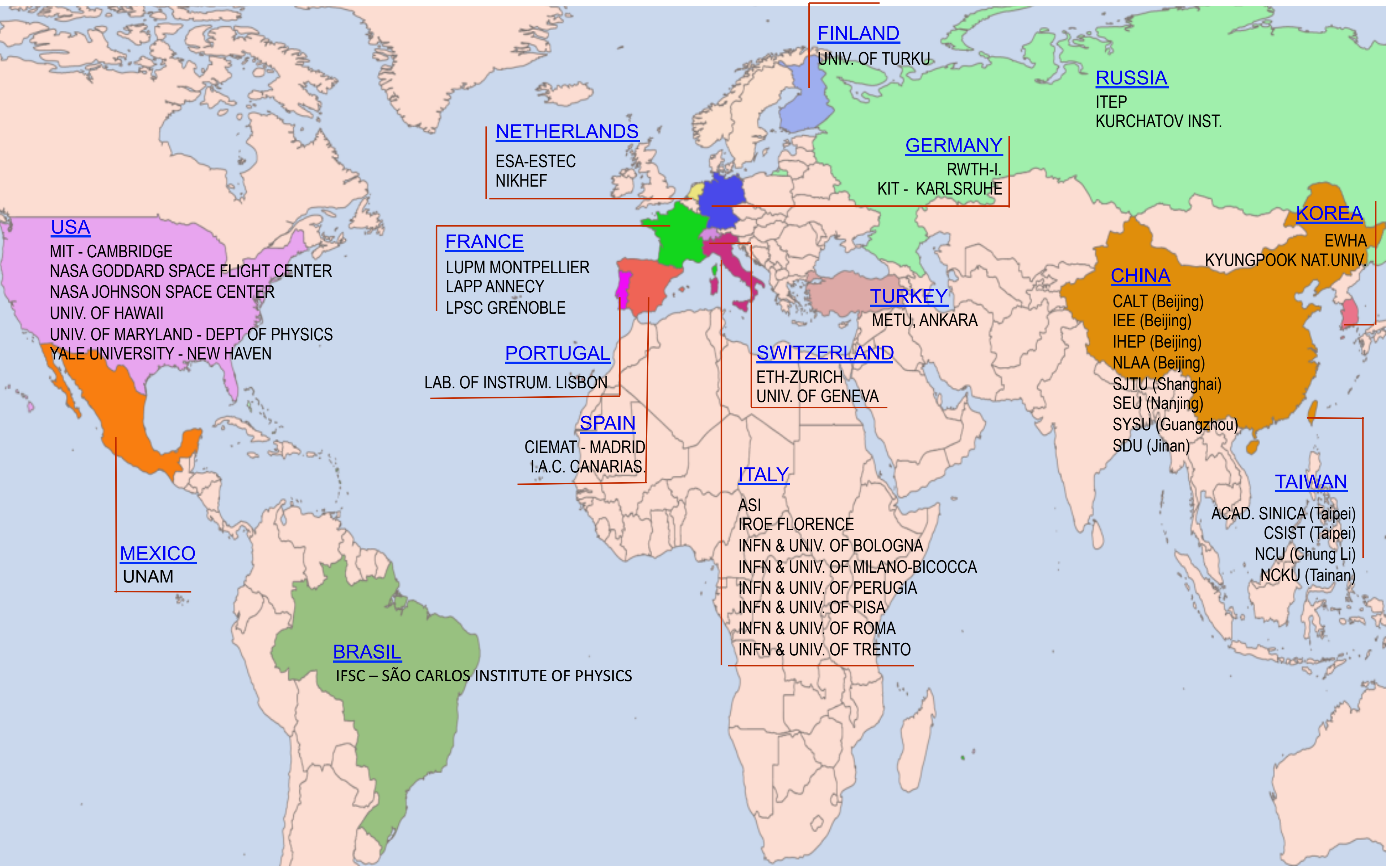
Precision measurements of electon and positron fluxes by the AMS Detector on ISS

Andrei Kounine / MIT

CERN, March. 29, 2017



AMS is an International Collaboration
15 Countries, 46 Institutes



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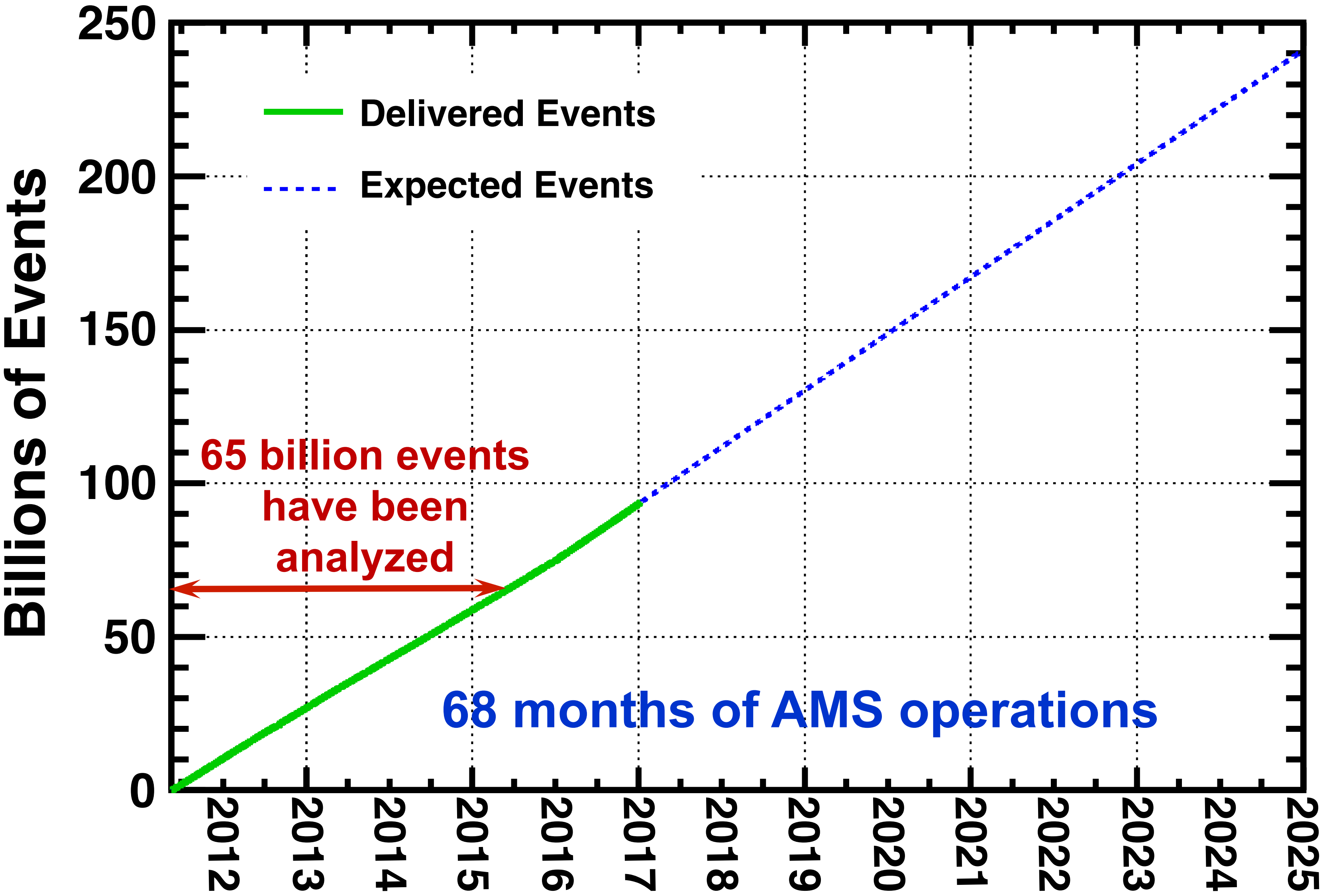
AMS is strongly supported by DOE and NASA

AMS POCC at JSC, May 19, 2011

AMS installed on the ISS at
5:15 CDT May 19, 2011

AMS taking data since
9:35 CDT May 19, 2011

AMS on ISS to date: 95 Billion Events
AMS on ISS to 2024: 240 Billion Events

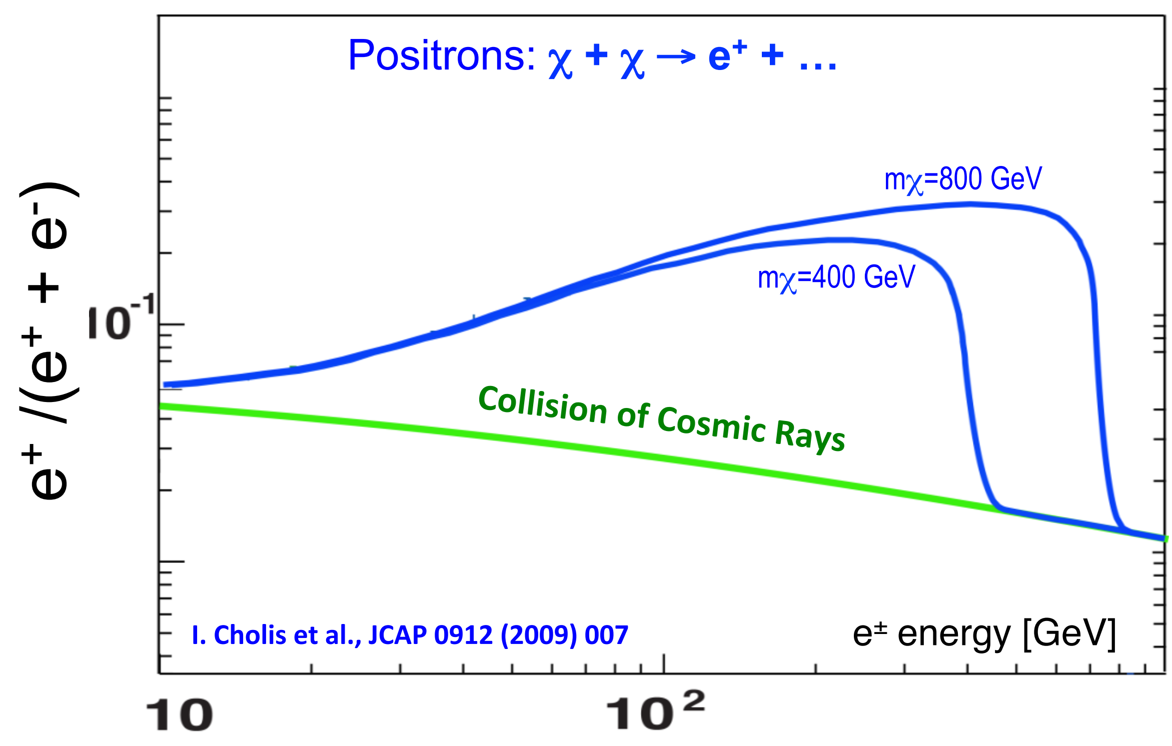


Dark Matter

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

Annihilation of Dark Matter (neutralinos, χ) will produce additional e^+, $\bar{p}$

M. Turner and F. Wilczek, Phys. Rev. D42 (1990) 1001



Positrons: $\chi + \chi \rightarrow e^+ + \ldots$

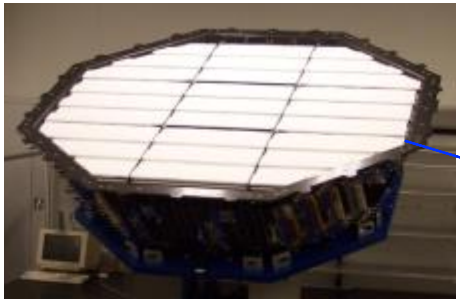
I. Cholis et al., JCAP 0912 (2009) 007

First Result from the AMS on the ISS: Precision Measurement of the Positron Fraction in Primary Cosmic Rays of 0.5-350 GeV, PRL 110 (2013) 141102

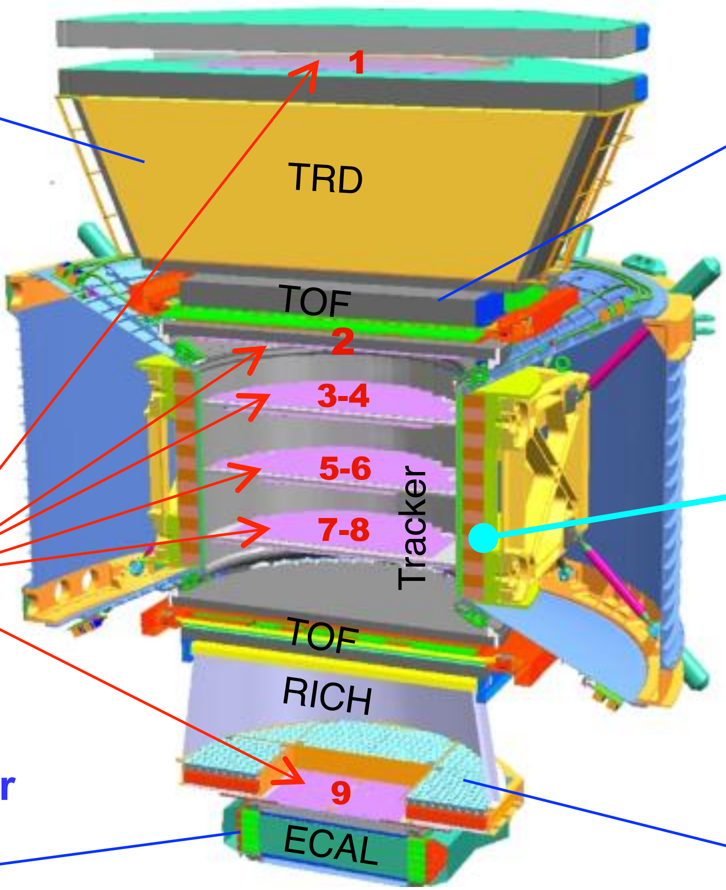
Selected by APS as a Highlight of the Year 2013

AMS: A TeV precision, multipurpose spectrometer

Transition Radiation Detector
Identify e^+, e^-

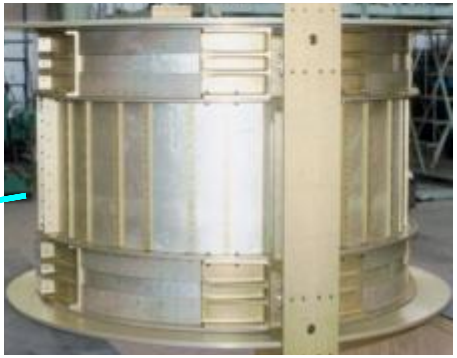


Redundant particle identification

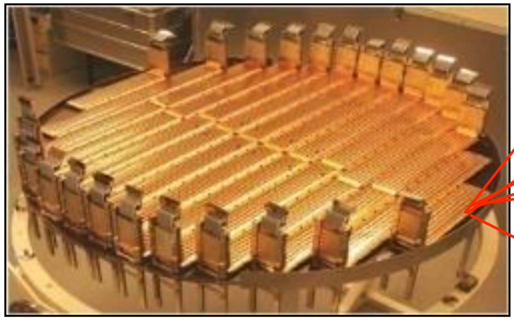


Time of Flight
Z, E

Magnet
±Z



Silicon Tracker
Z, P



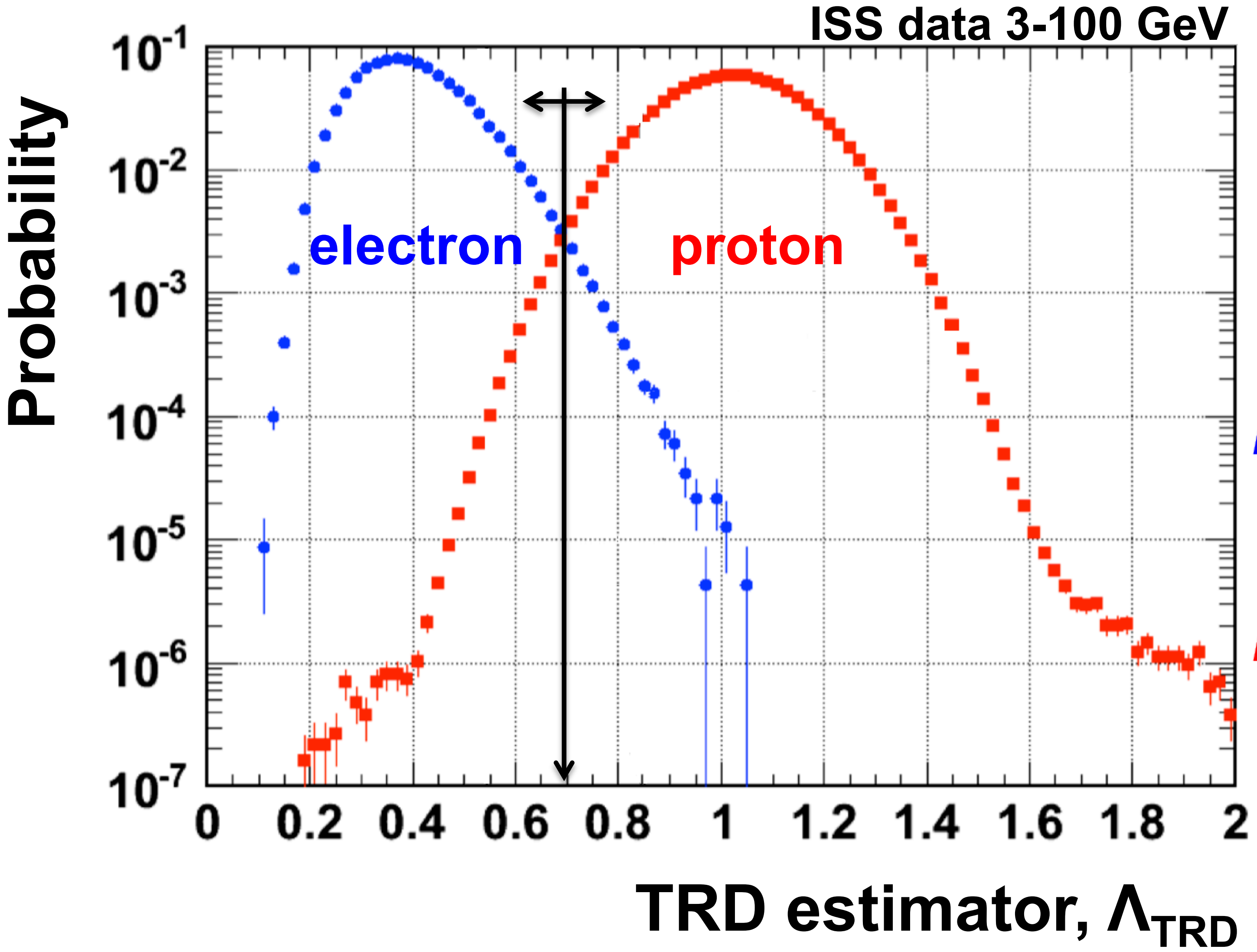
Ring Imaging Cherenkov
Z, E

Electromagnetic Calorimeter
E of e^+, e^-

Maximal Detectable Rigidity
MDR (Z=1) = 2 TV

Separation of protons and electrons with TRD

TRD estimator, $\Lambda_{TRD} = -\ln(P_e/(P_e+P_p))$

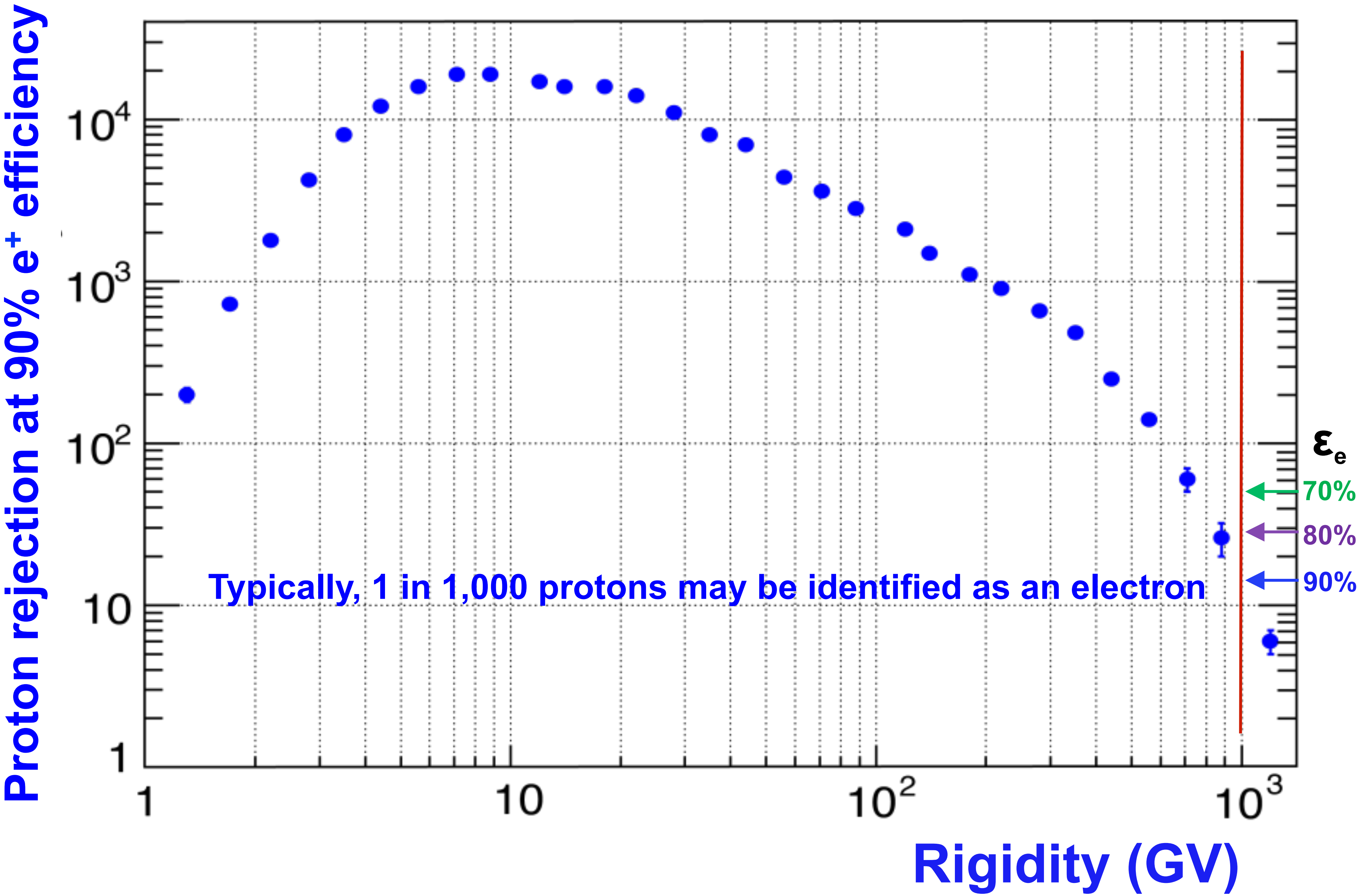


Normalized probabilities P_e and P_p

$$P_e = \sqrt[n]{\prod_{i}^{n} P_e^{(i)}(A)}$$

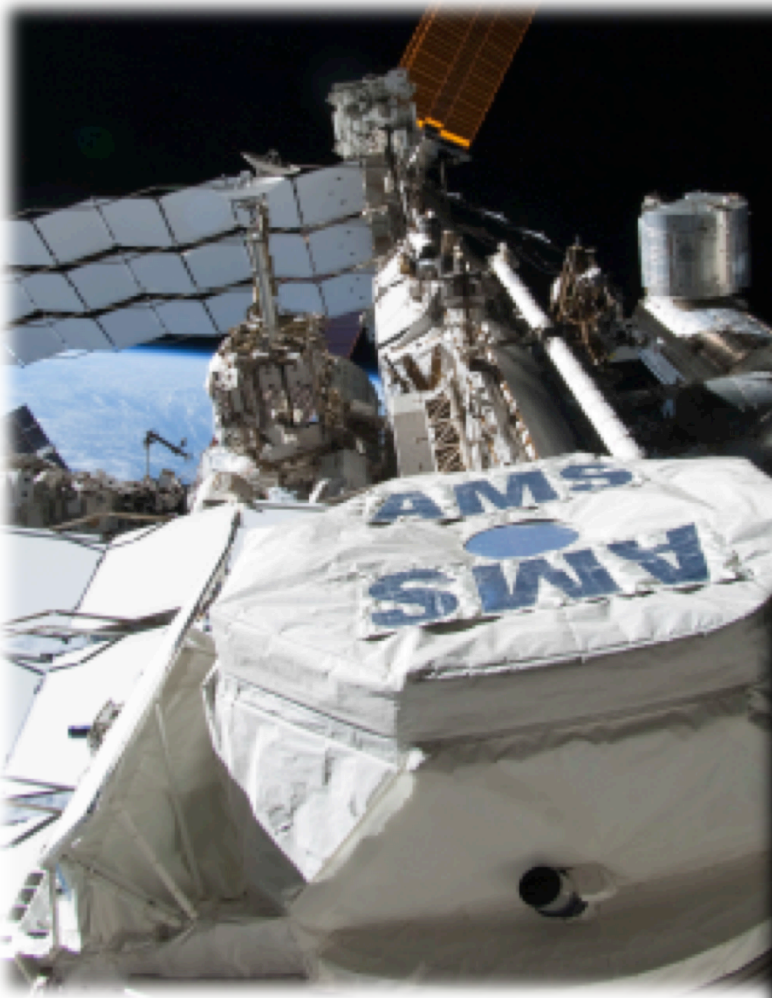
$$P_p = \sqrt[n]{\prod_{i}^{n} P_p^{(i)}(A)}$$

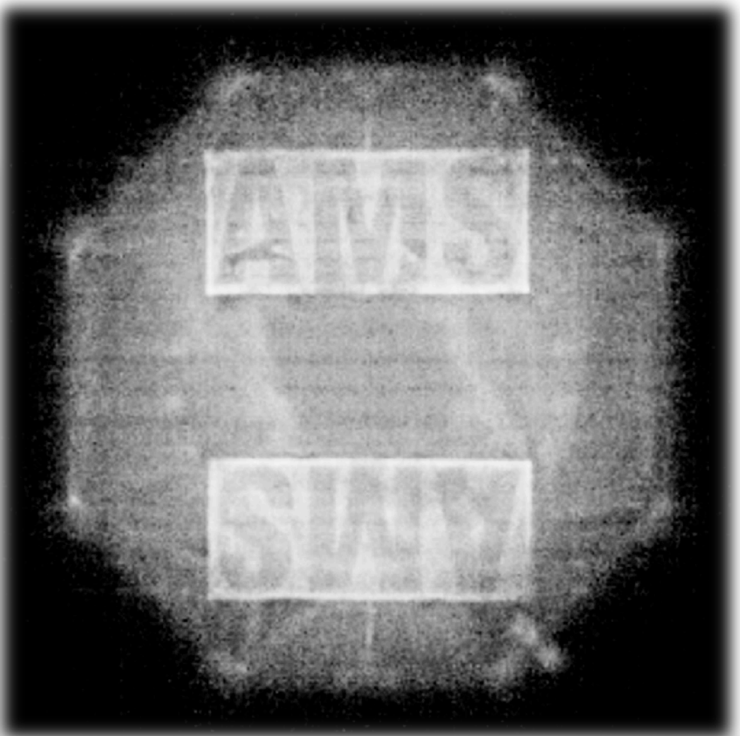
Separation of protons and electrons with TRD

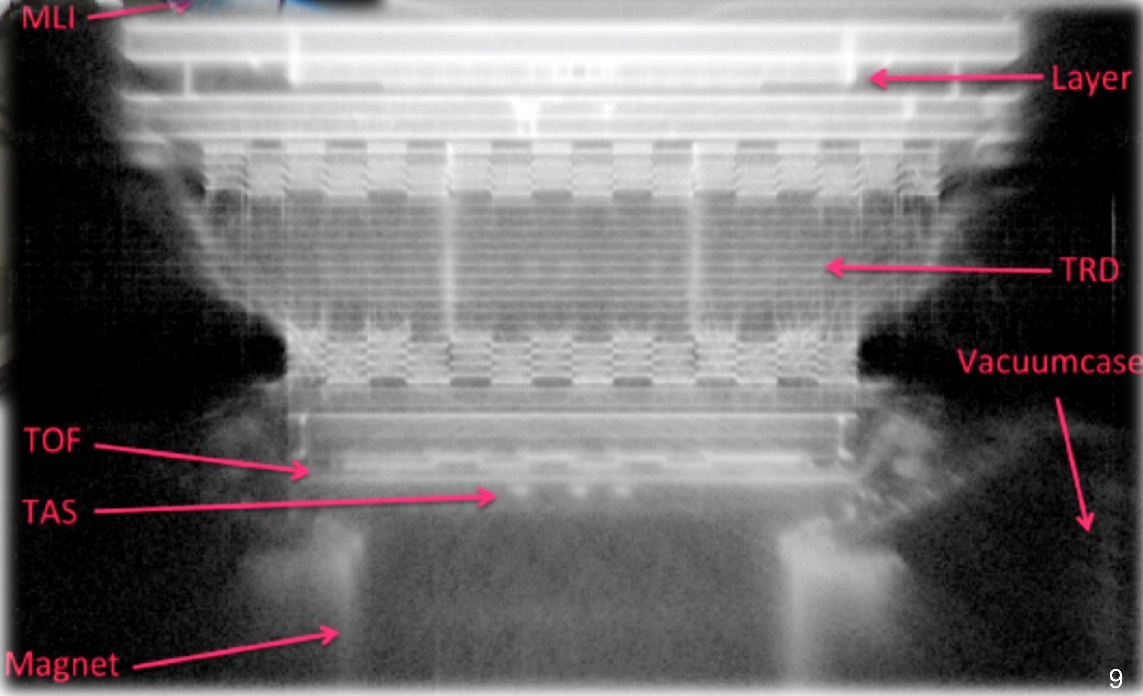


Typically, 1 in 1,000 protons may be identified as an electron

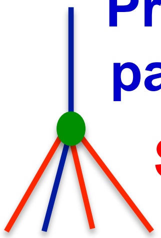
Precision – CAT scan using vertices







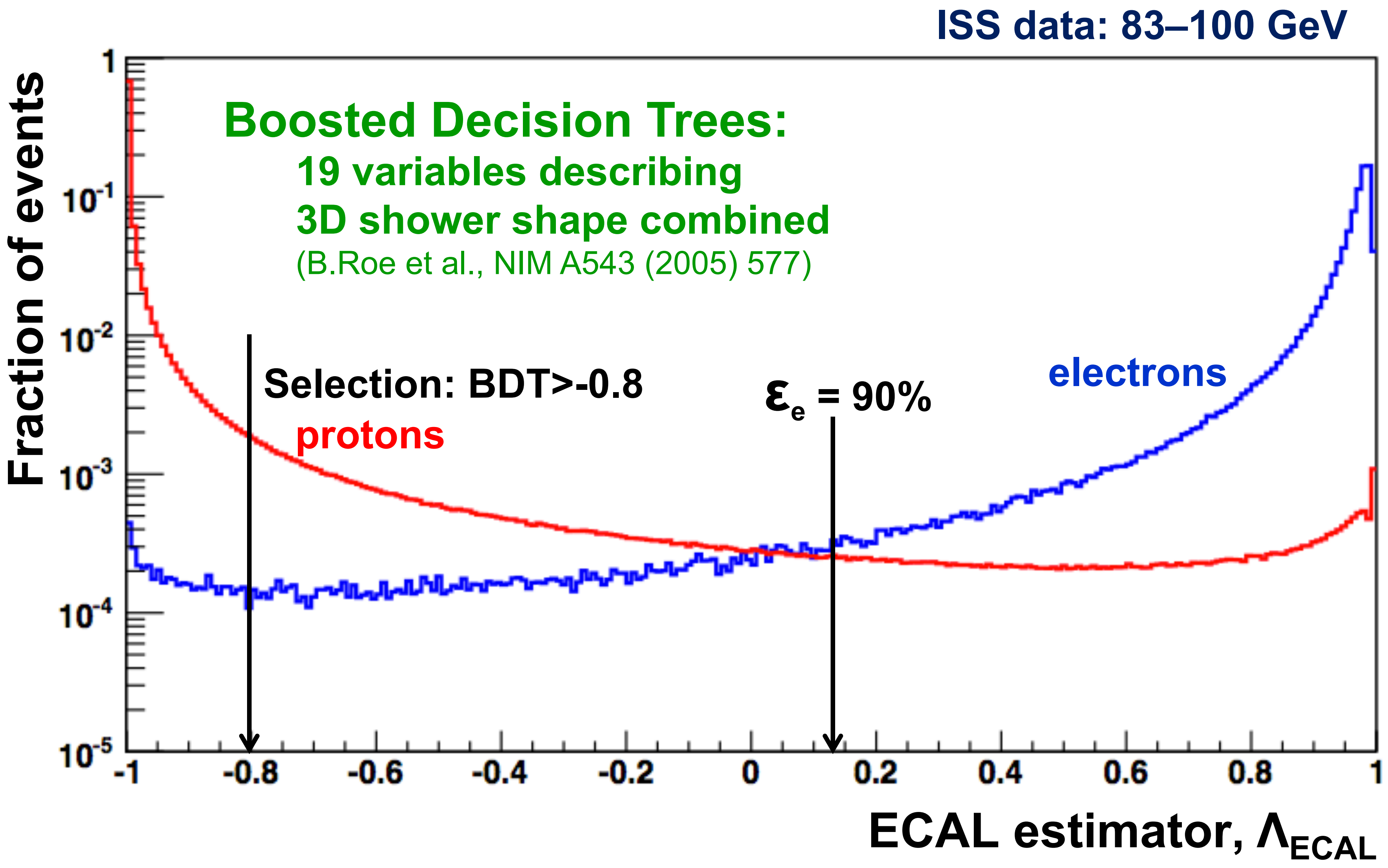
Vertex:



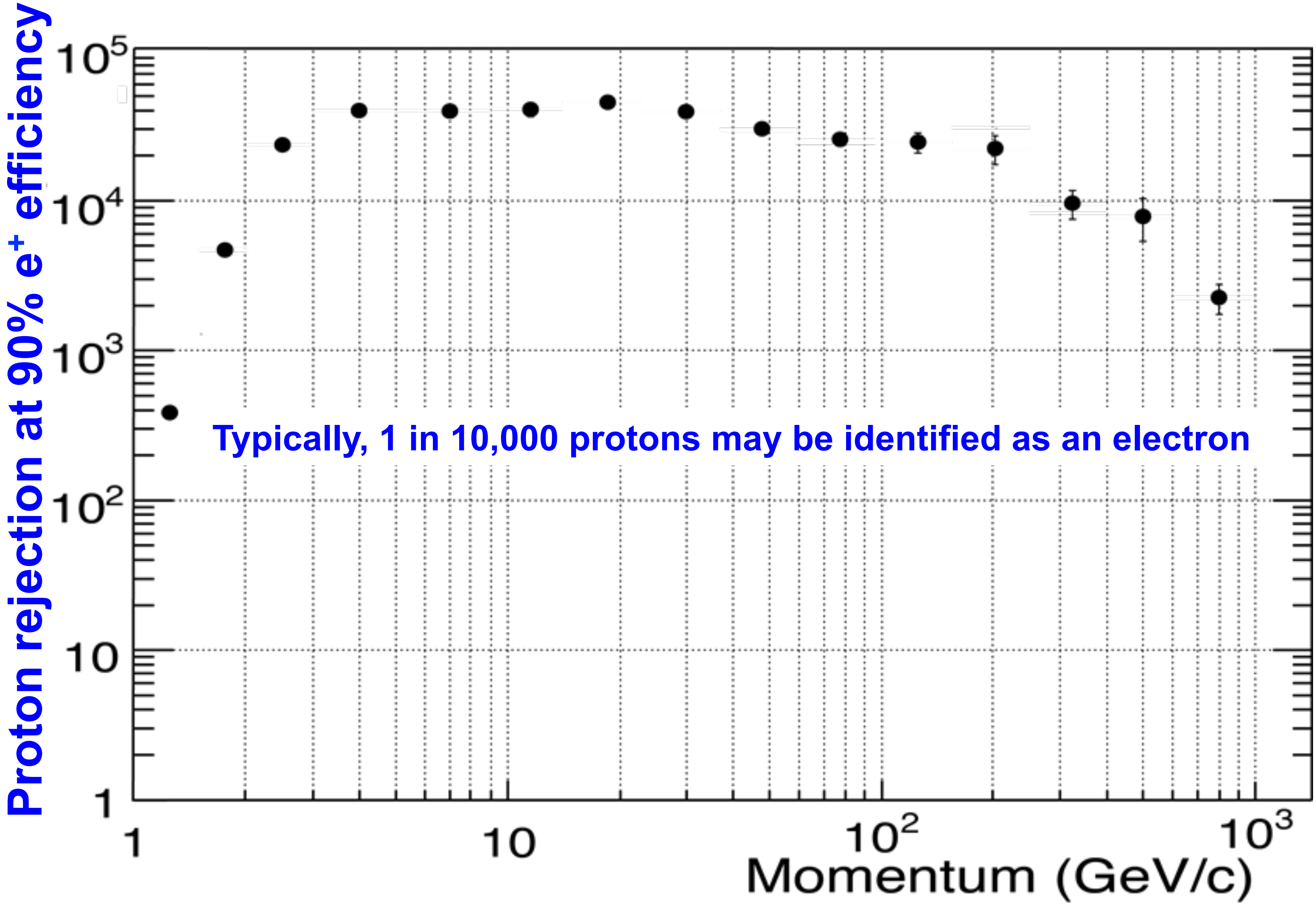
Primary particle

Secondary

Separation of protons and electrons with ECAL



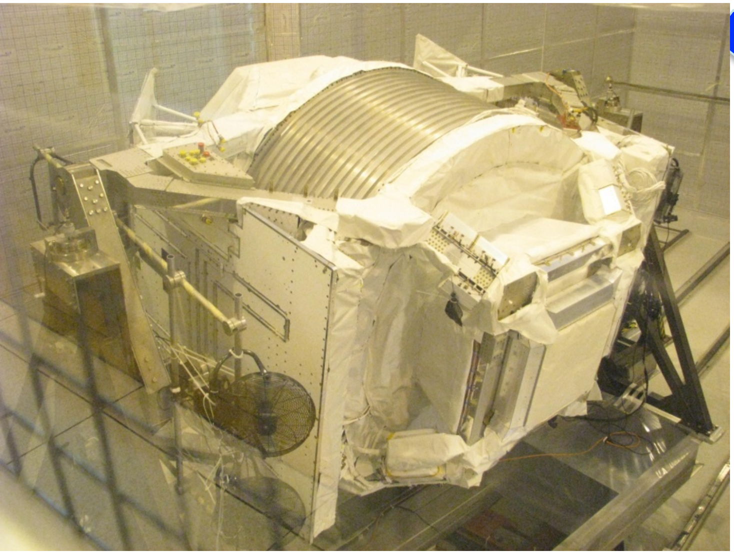
Separation of protons and electrons with ECAL



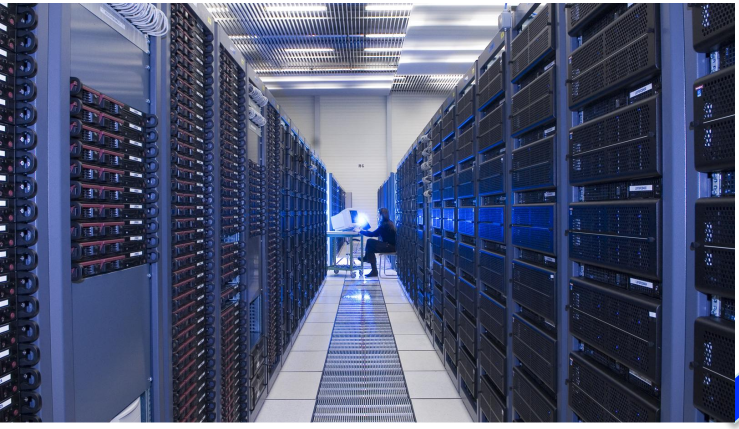
Typically, 1 in 10,000 protons may be identified as an electron

Monte Carlo simulation

Detector calibration



Monte Carlo simulation

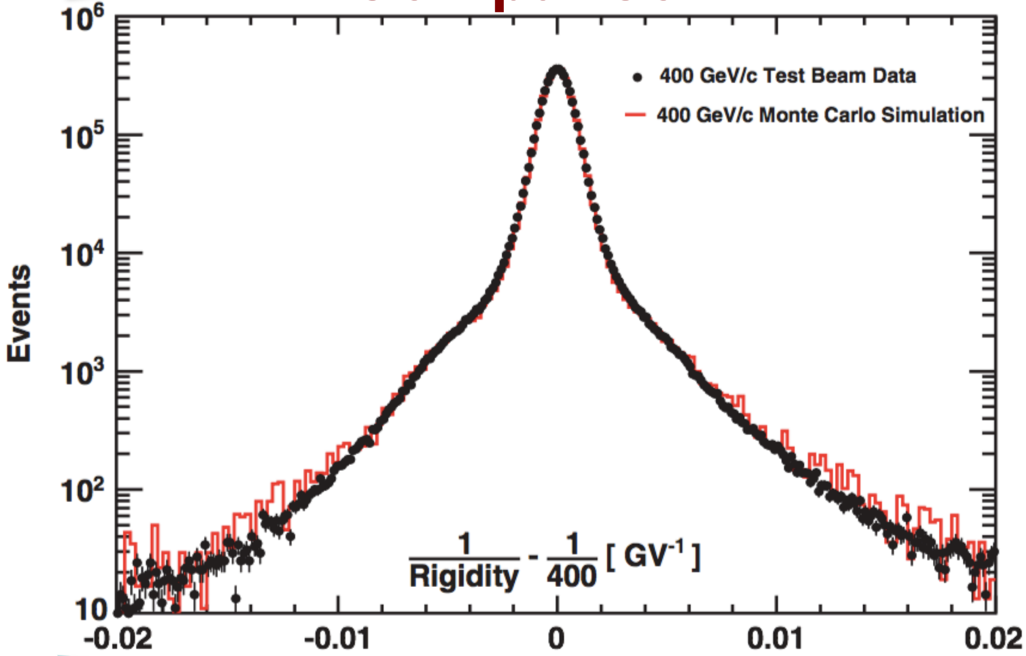


6,000 CPU cores at CERN
+ regional centers

Detector response:

1. Particle type (p, e±, π±)
2. Energy (10−400 GeV)
3. Position (1600)

Comparison

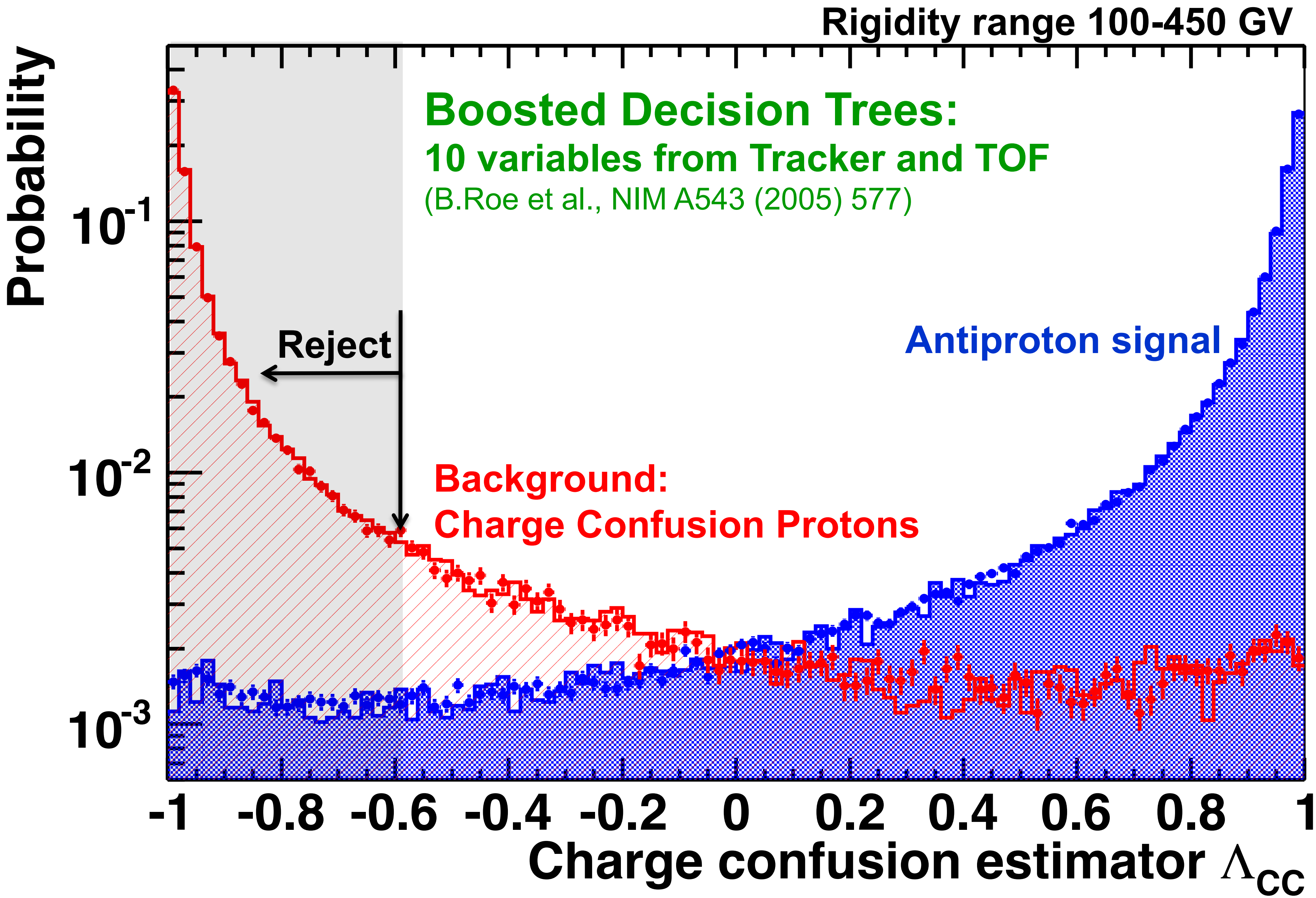


Computer simulation program:

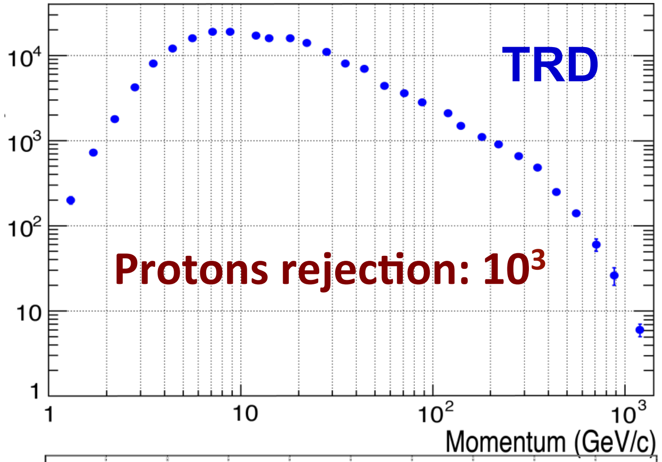
1. Interactions (physics and materials)
2. Digitization (electronics)

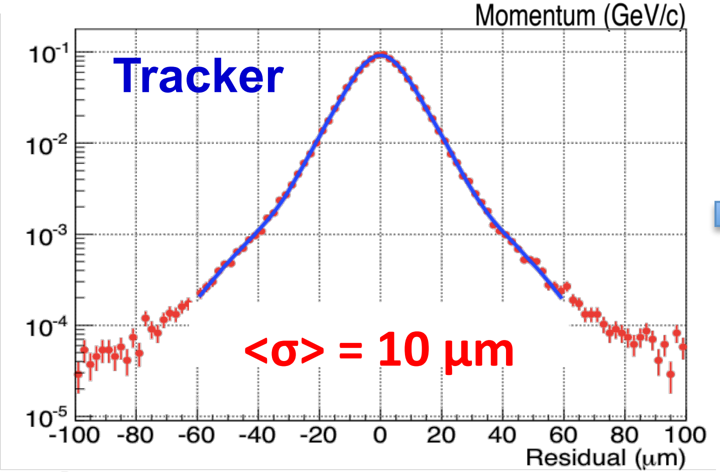
Results in data-like events

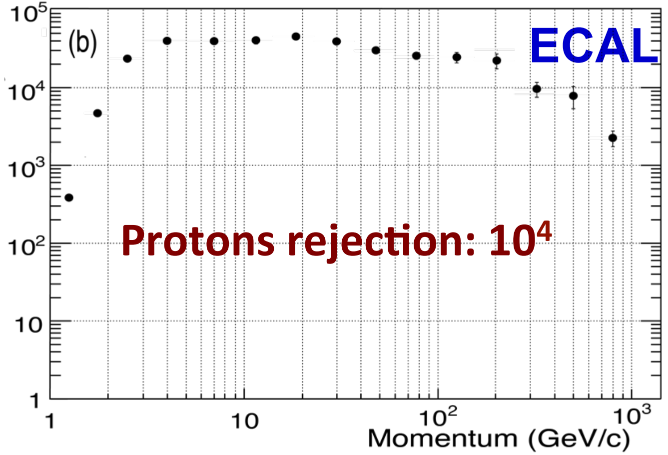
Separation of positive and negative charges

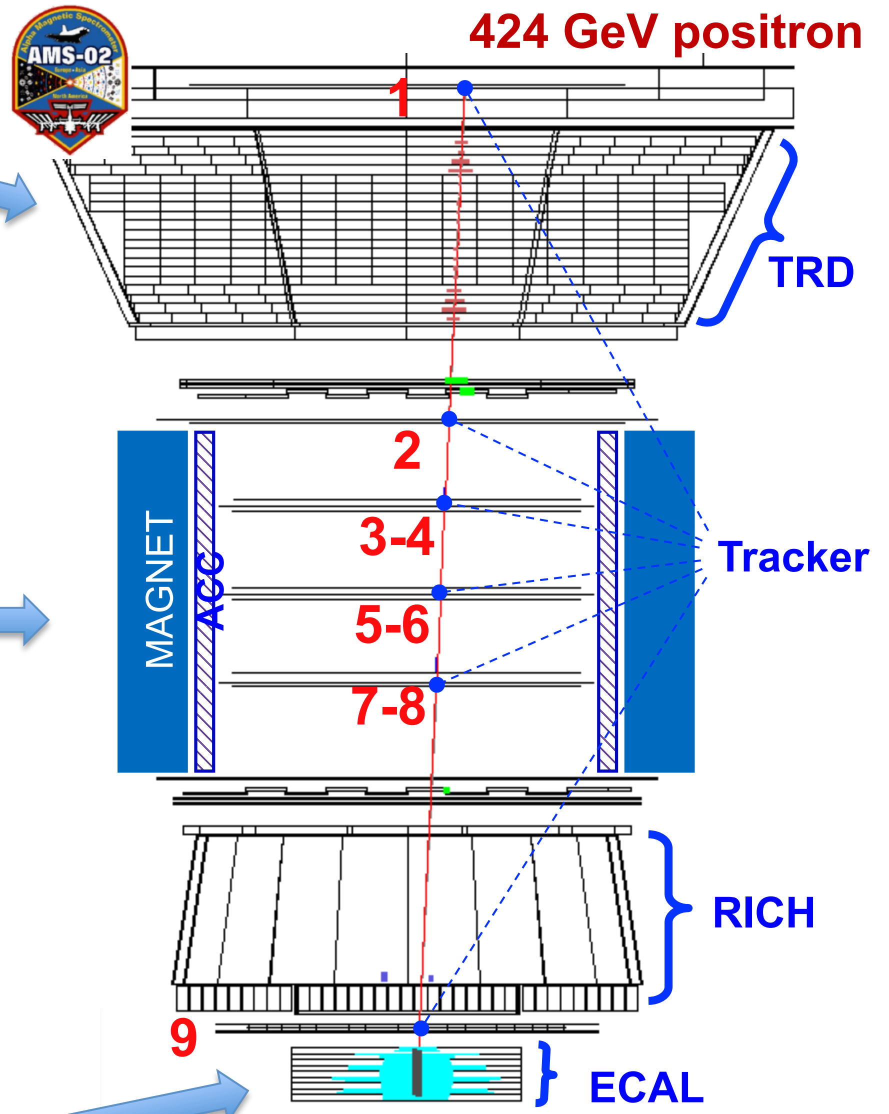


Positron fraction analysis





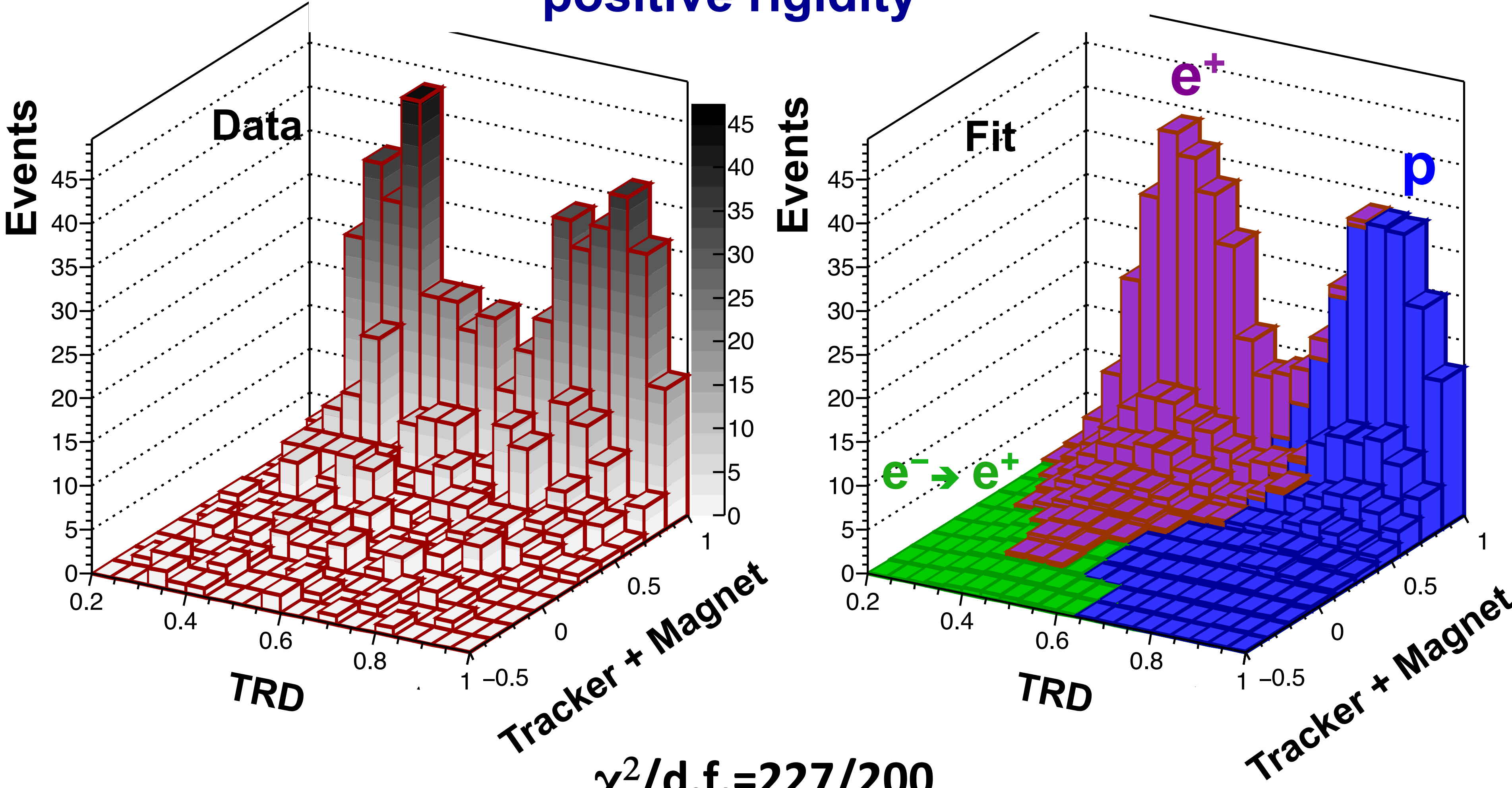




20 million of e± events are selected in the energy range 0.5–700 GeV

TRD Estimator shows clear separation between positrons and protons with a small charge confusion background

Energy range 206−260 GeV, positive rigidity



χ^2/d.f.=227/200

Systematic errors on the positron fraction, $N_{e^+} / (N_{e^+} + N_{e^-})$:

1. **Acceptance asymmetry**
2. **Selection dependence**
3. **Absolute energy scale and bin-to-bin migration**
4. **Reference spectra uncertainties**
5. **Charge confusion**

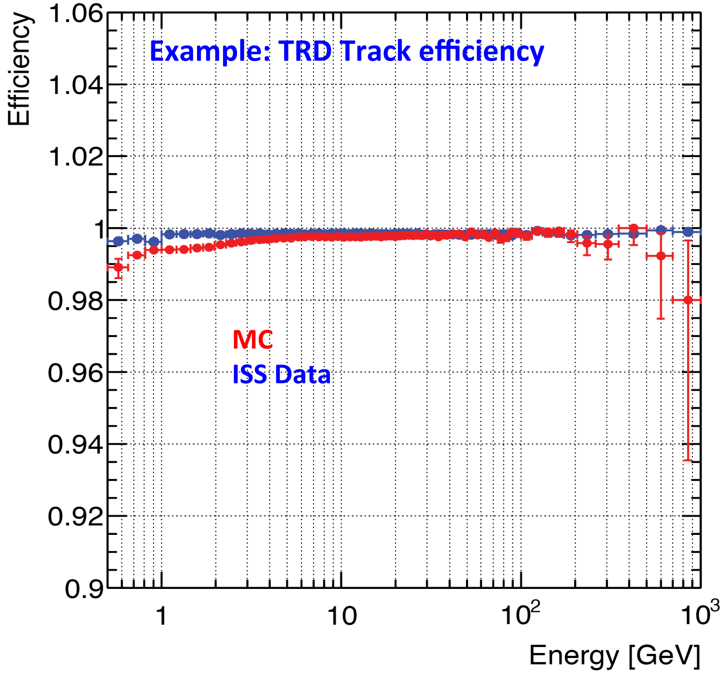
			Stat.						**Syst.**
Energy[GeV]	$\mathbf{N_{e^+}}$	**Fraction**	$\boldsymbol{\sigma_{stat.}}$	$\sigma_{acc.}$	$\sigma_{sel.}$	$\sigma_{mig.}$	$\sigma_{ref.}$	$\sigma_{c.c.}$	$\boldsymbol{\sigma_{syst.}}$
80.00–86.00	651	0.0998	0.0038	0.0002	0.0010	0.0007	0.0002	0.0006	0.0014
86.00–92.50	648	0.1170	0.0044	0.0002	0.0010	0.0007	0.0002	0.0008	0.0015
92.50–100.0	551	0.1071	0.0045	0.0002	0.0010	0.0007	0.0002	0.0009	0.0015
100.0–115.1	897	0.1190 **3.4%**	0.0041	0.0002	0.0010	0.0007	0.0002	0.0010	0.0016 **1.3%**
115.1–132.1	580	0.1160	0.0047	0.0002	0.0020	0.0007	0.0005	0.0015	0.0027
132.1–151.5	494	0.1250	0.0058	0.0002	0.0020	0.0007	0.0005	0.0018	0.0028
151.5–173.5	398	0.1400	0.0071	0.0002	0.0020	0.0007	0.0007	0.0030	0.0037
173.5–206.0	363	0.1480	0.0079	0.0002	0.0025	0.0007	0.0010	0.0040	0.0049
206.0–260.0	309	0.1520	0.0090	0.0003	0.0028	0.0007	0.0012	0.0070	0.0077
260.0–350.0	234	0.1580	0.0110	0.0003	0.0030	0.0007	0.0015	0.0100	0.0106
350.0–500.0	126	0.1400	0.0170	0.0003	0.0060	0.0007	0.0020	0.0150	0.0163
500.0–700.0	41	0.1450 **27%**	0.0400	0.0003	0.0100	0.0007	0.0100	0.0200	0.0245 **17%**

Analysis of the systematic uncertainties

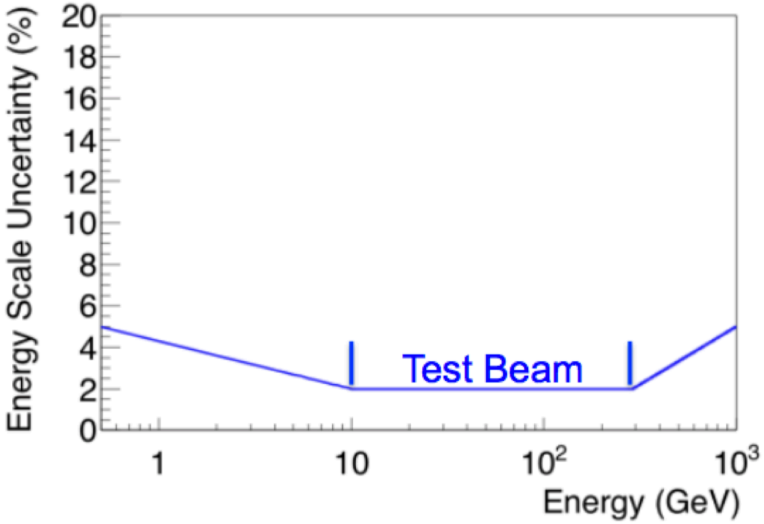
Isotropic flux:

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

- **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

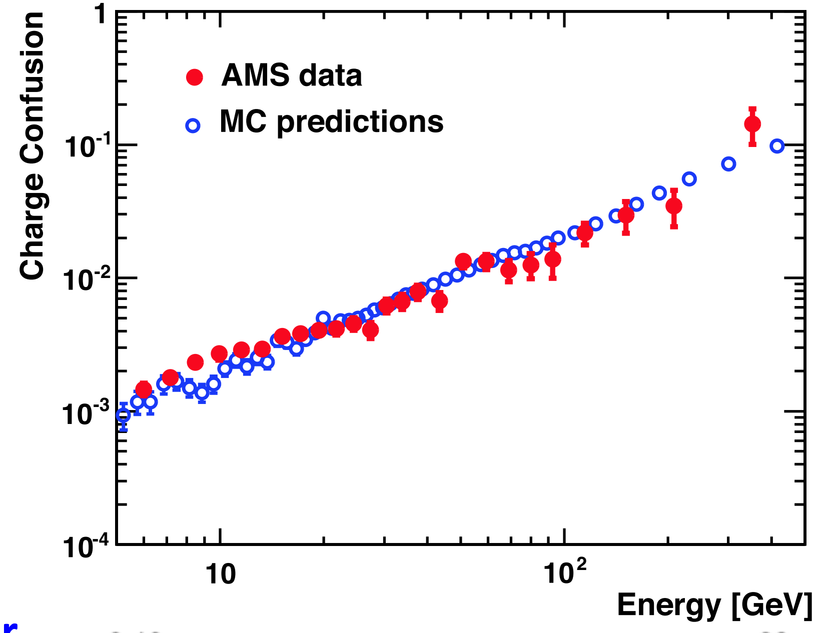


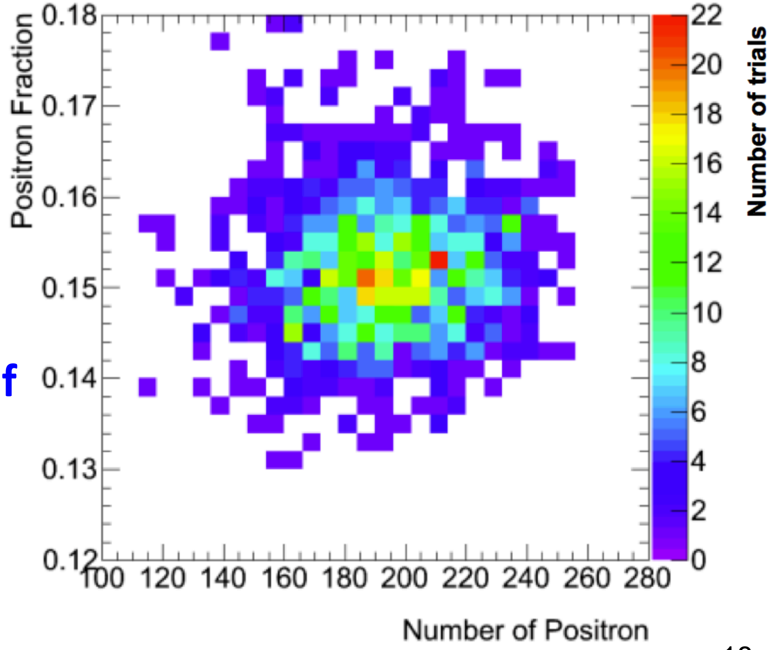
Analysis of the systematic uncertainties

Major Systematic Errors:

- **Charge confusion**
  1. Large angle scattering,
  2. Production of secondaries.
  - Well reproduced by the Monte Carlo.
  - Measured directly from data.
  - The difference is taken as a systematic error.

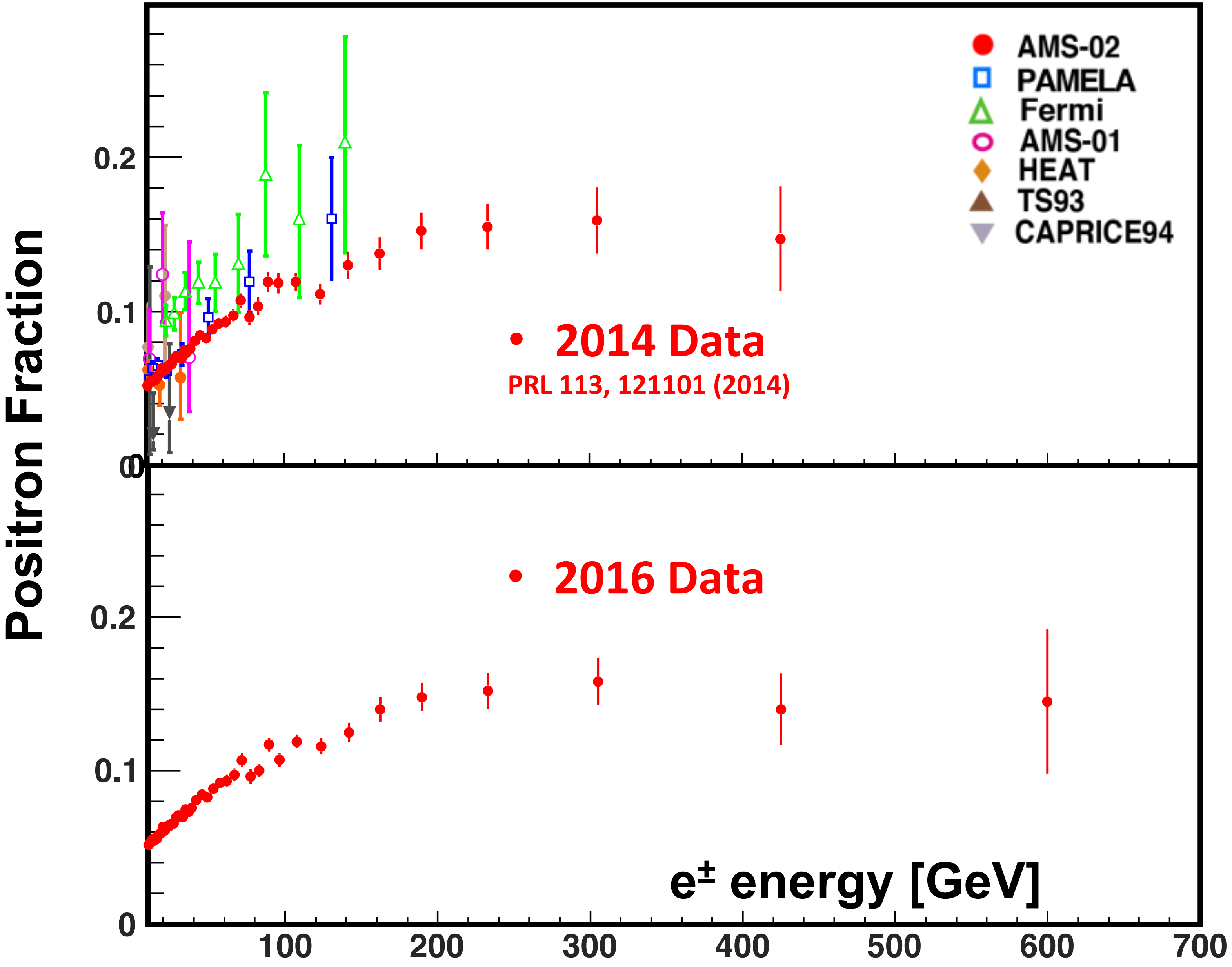
- **Selection, Template definition;**
  - For each energy bin, over 1,000 sets of cuts (trials) were analyzed.
  - The measurement is stable over wide ranges of the selections.





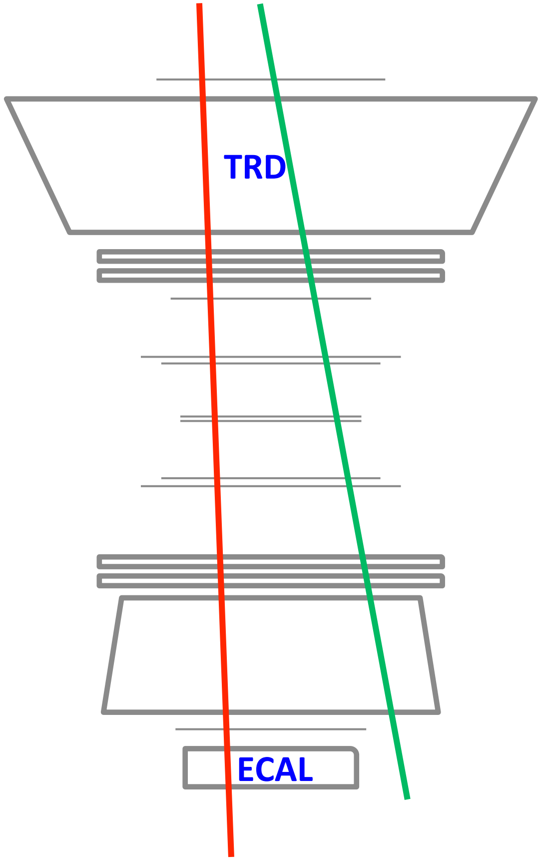
Systematic error are smaller than statistical ones

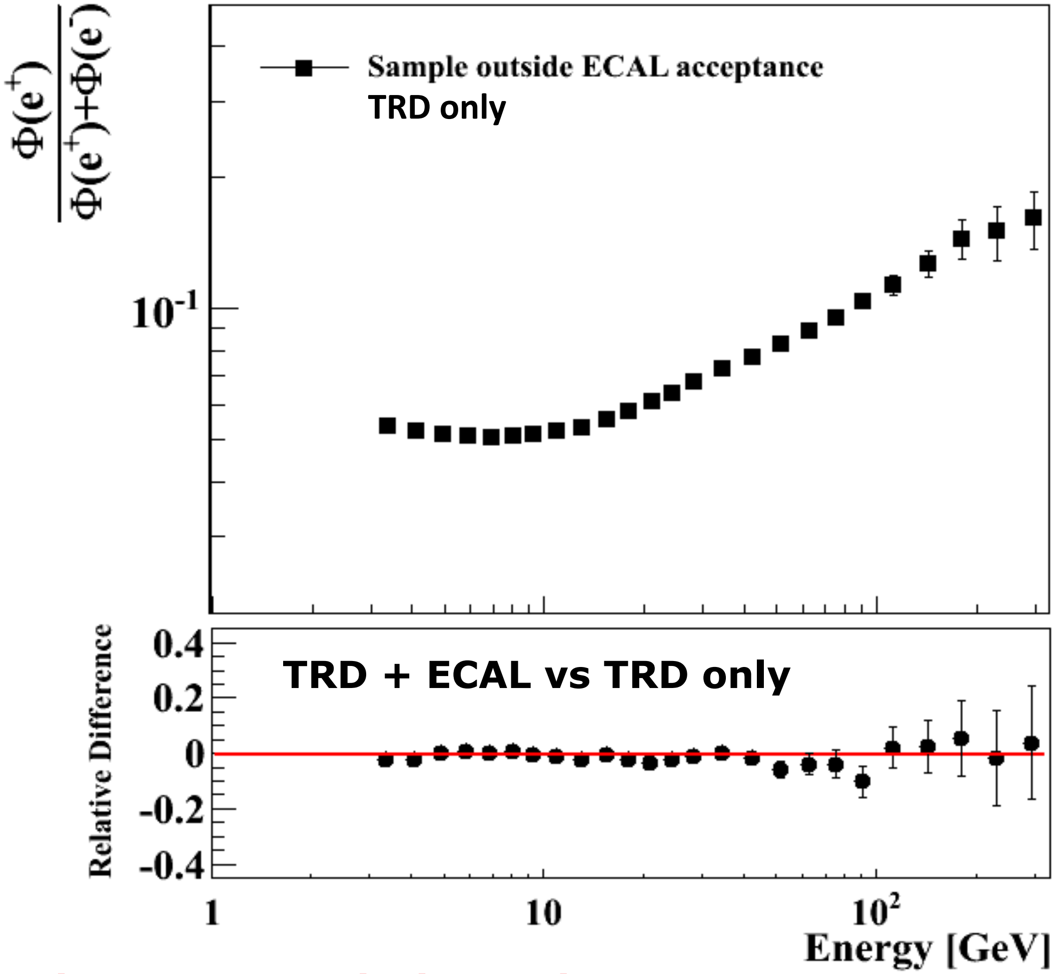
New analysis includes 5 years of data – 20 million e± events



Independent verification of the positron fraction analysis

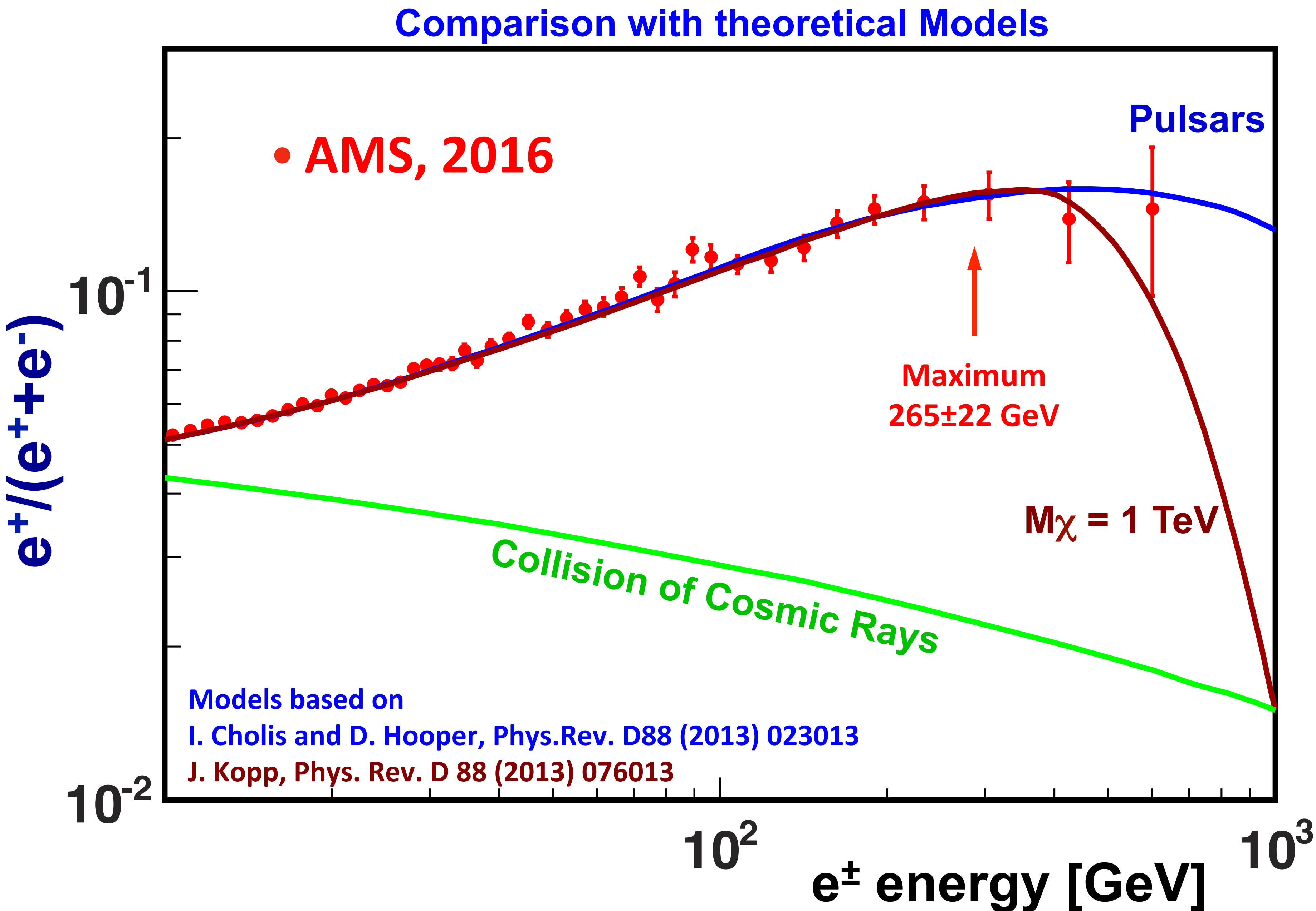
Positron fraction analysis with TRD+ECAL compared with TRD Only





Good agreement between two independent samples

Behavior of the positron fraction at high energies

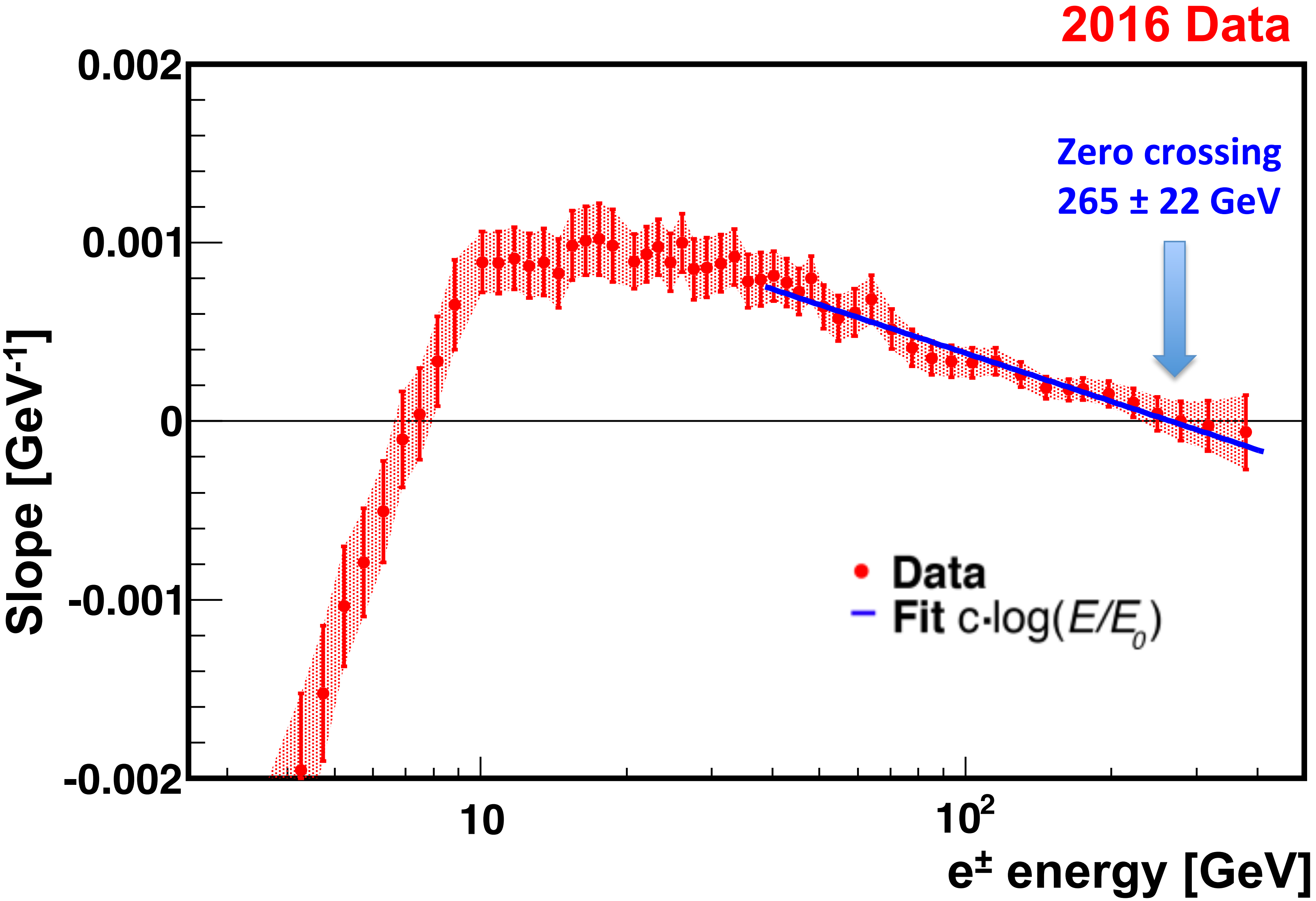


Comparison with theoretical Models

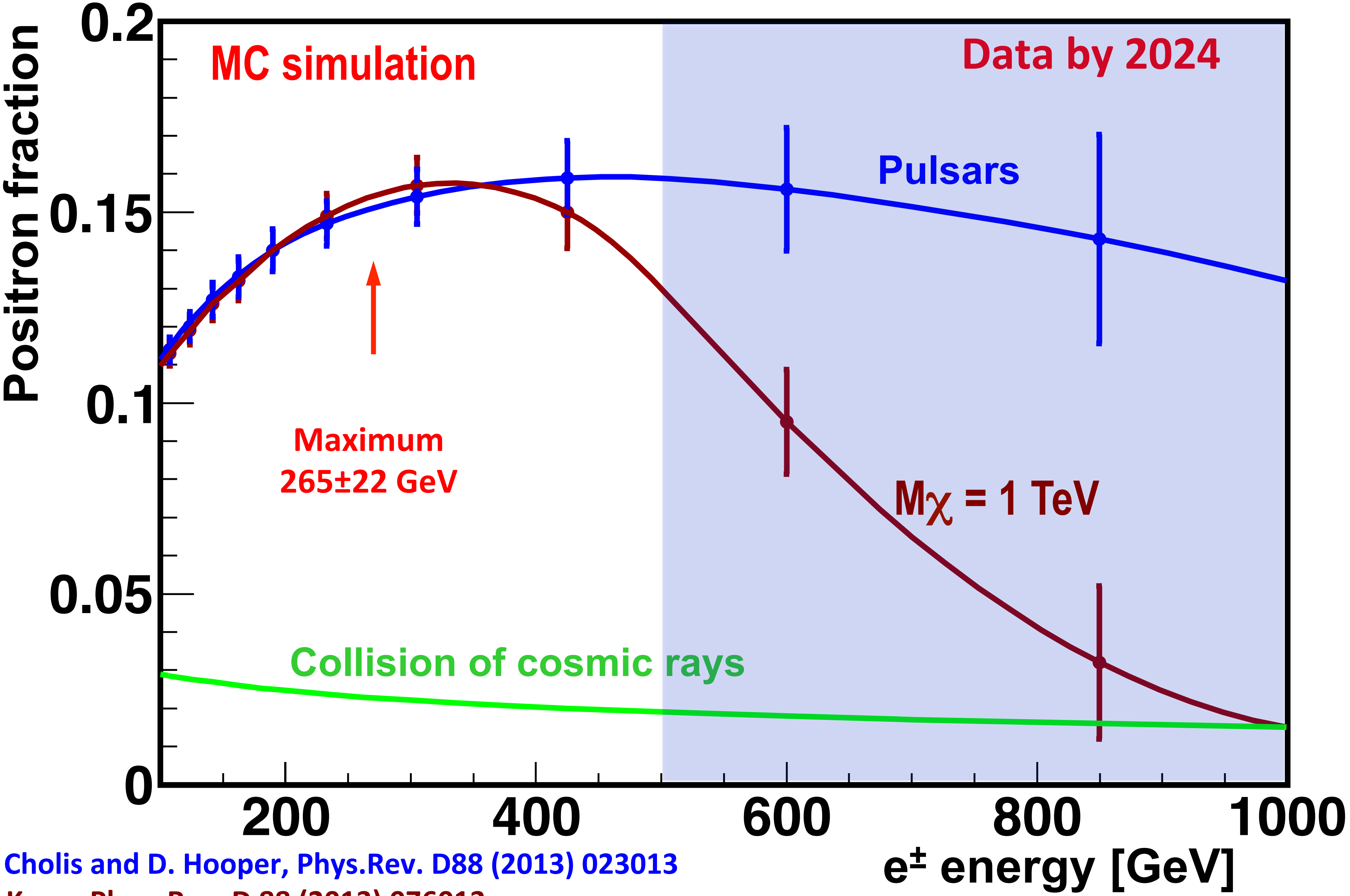
Maximum
265±22 GeV

Models based on
I. Cholis and D. Hooper, Phys.Rev. D88 (2013) 023013
J. Kopp, Phys. Rev. D 88 (2013) 076013

The energy beyond which it ceases to increase.



The expected rate at which it falls beyond the turning point.

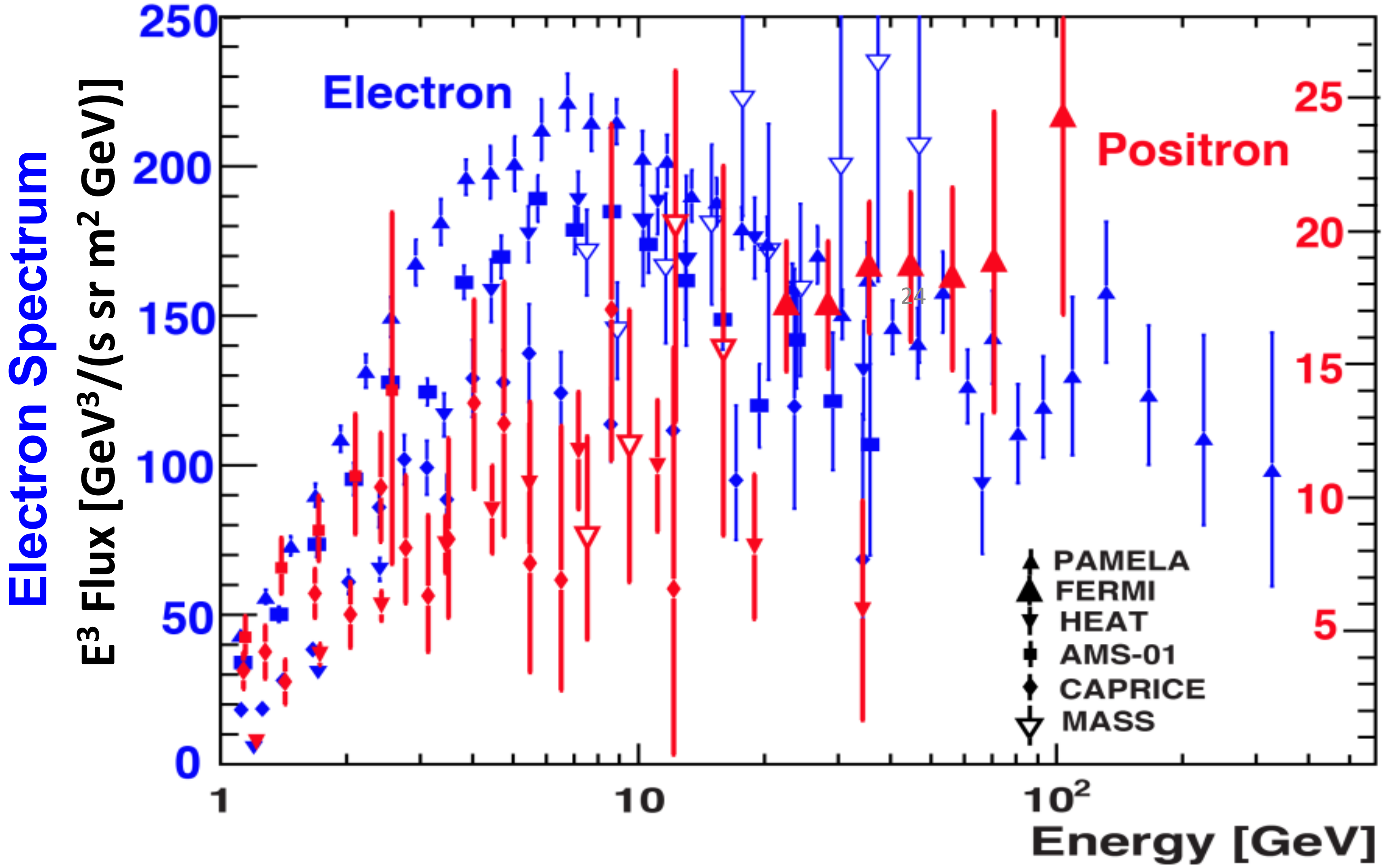


I. Cholis and D. Hooper, Phys.Rev. D88 (2013) 023013

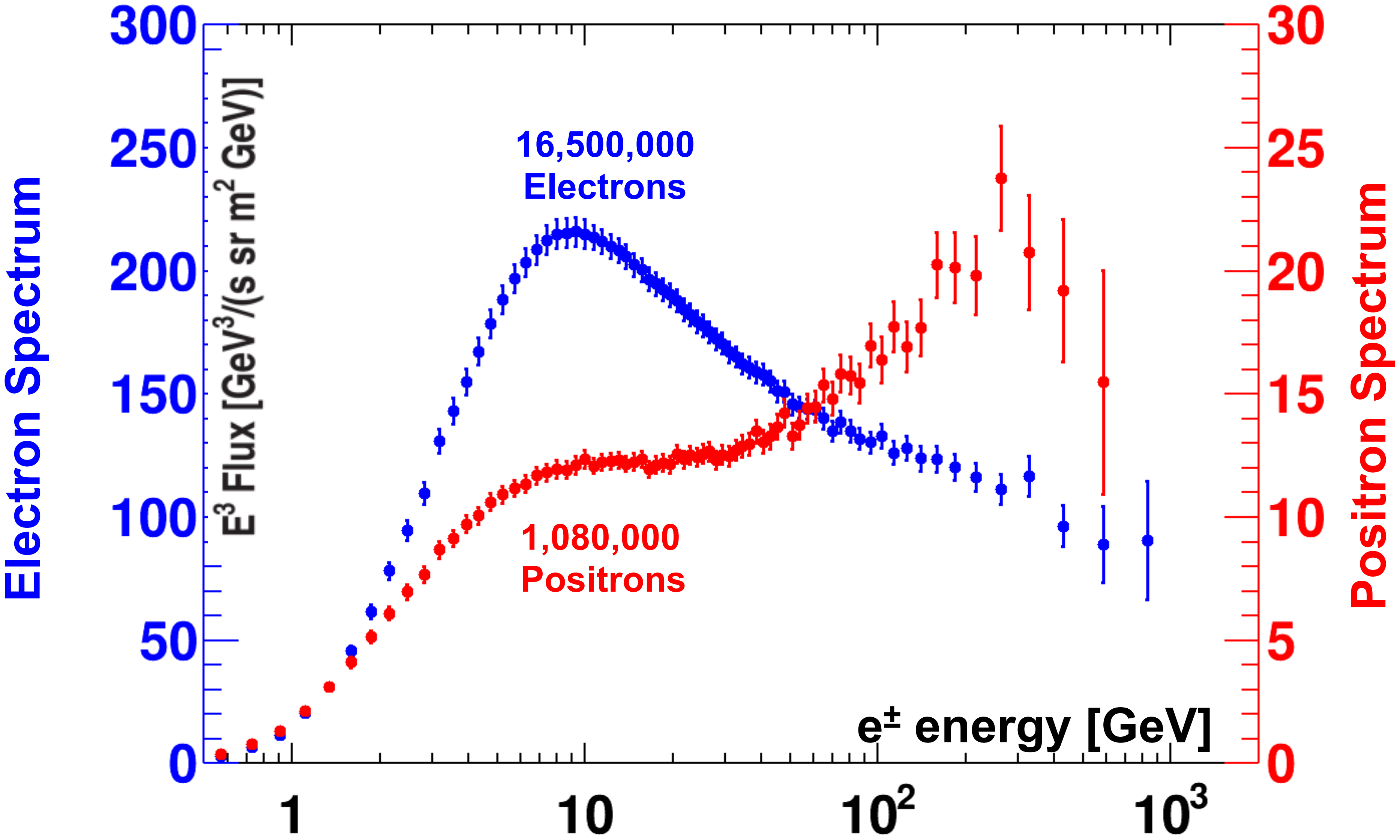
J. Kopp, Phys. Rev. D 88 (2013) 076013

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.

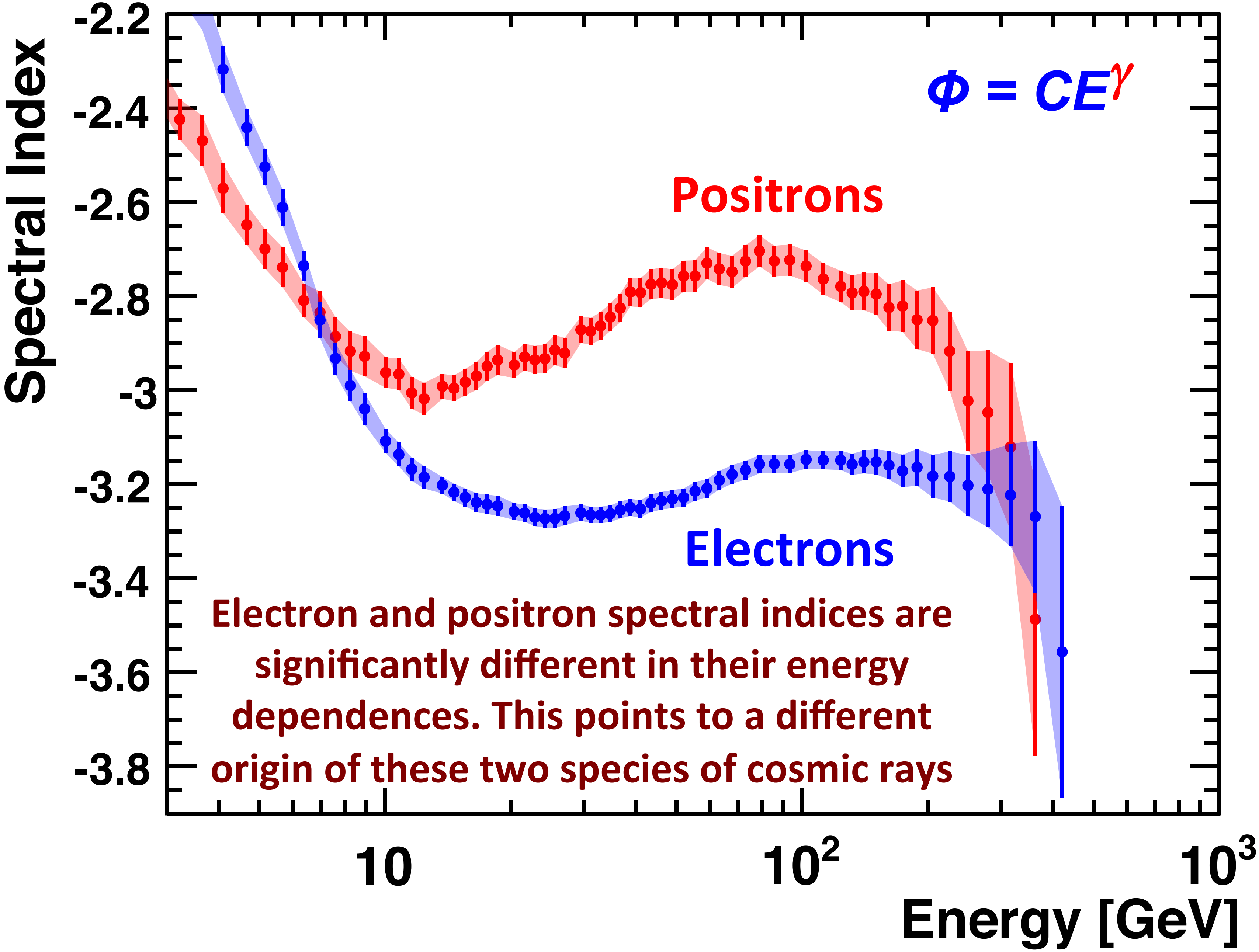


AMS measurements of the Electron and Positron spectra



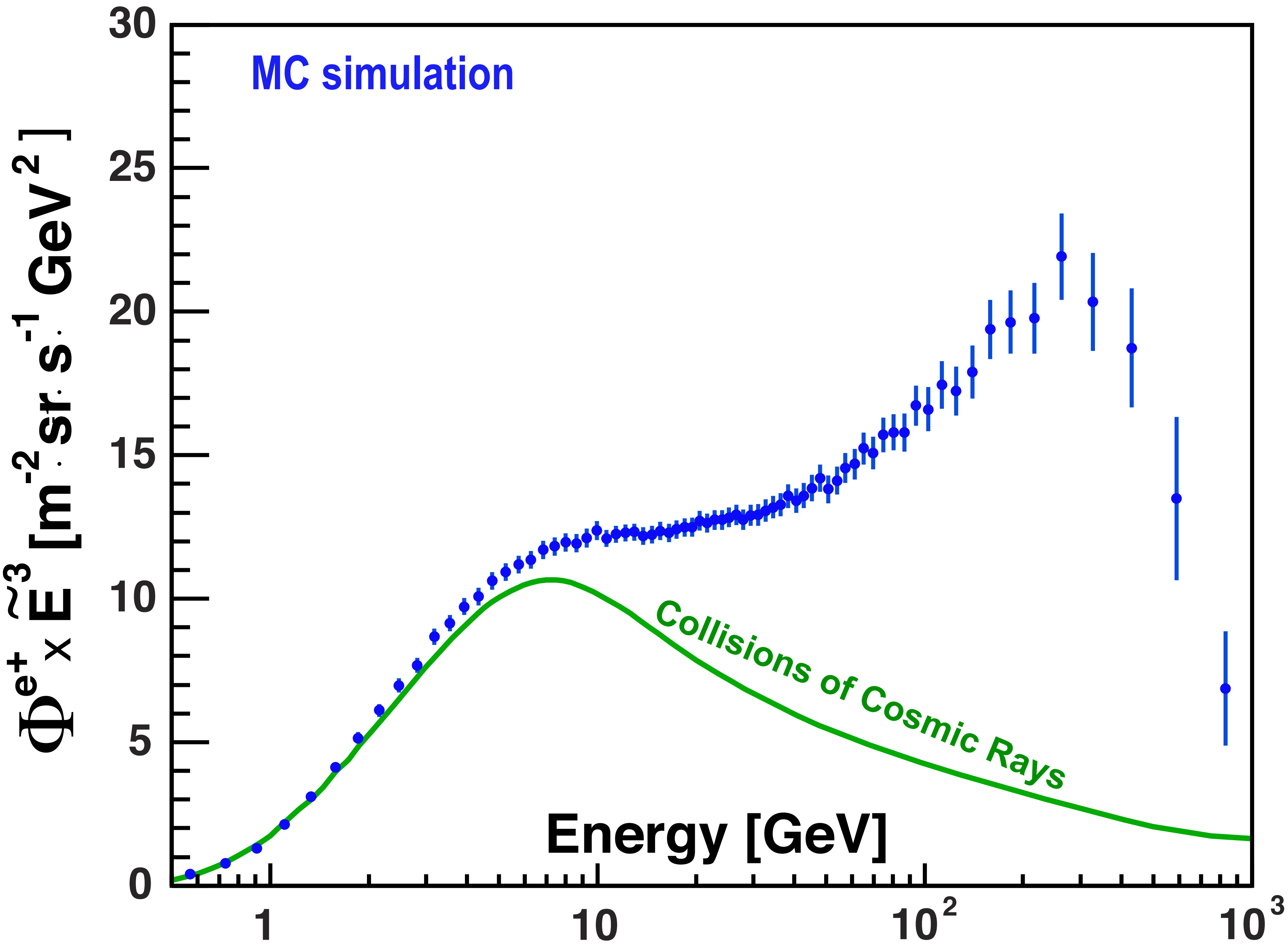
Electron and positron spectra are significantly different in their magnitudes and energy dependences. This is a clear indication of a different origins of these two species of cosmic rays

Electron and Positron spectral indices

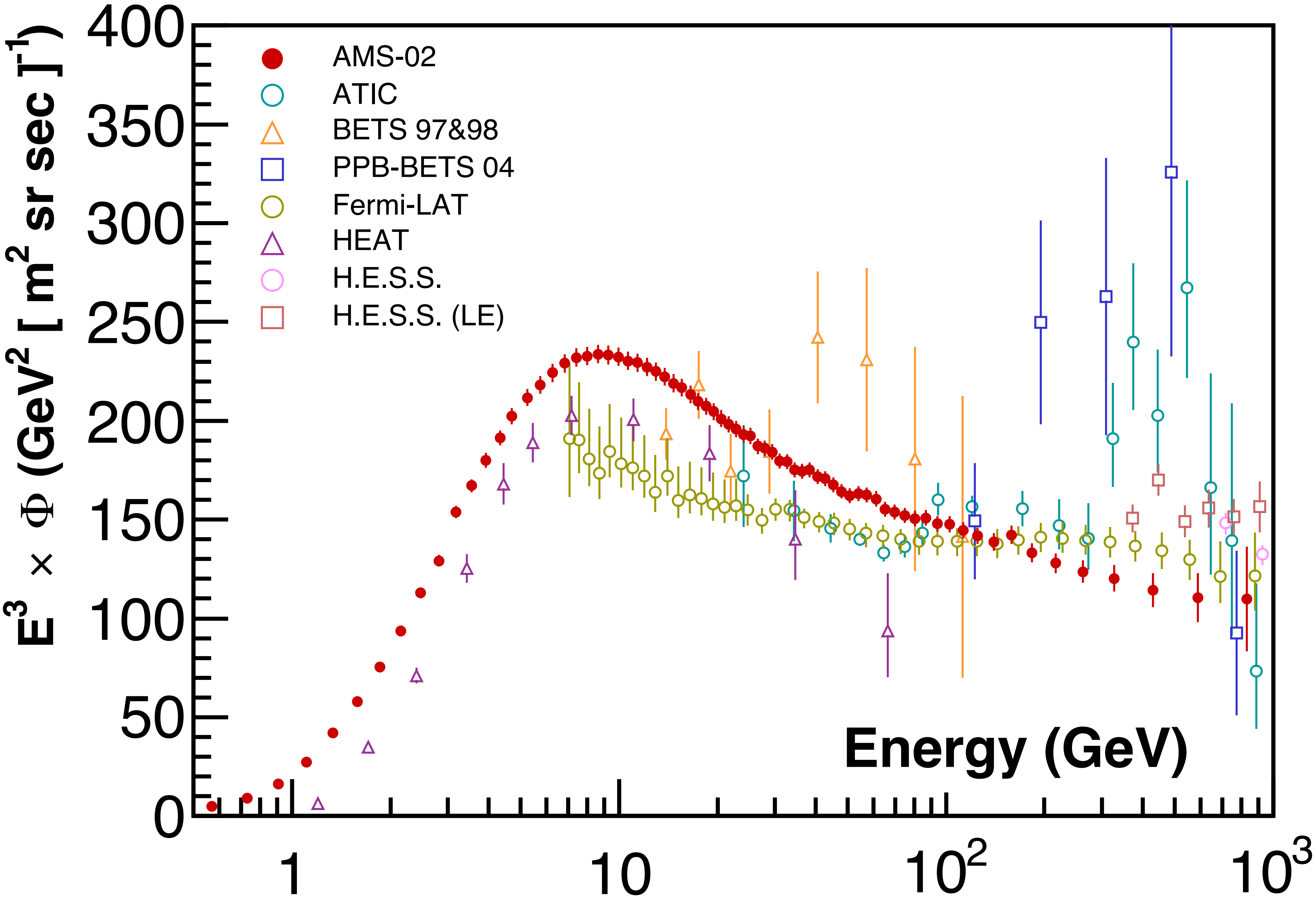


Electron and positron spectral indices are significantly different in their energy dependences. This points to a different origin of these two species of cosmic rays

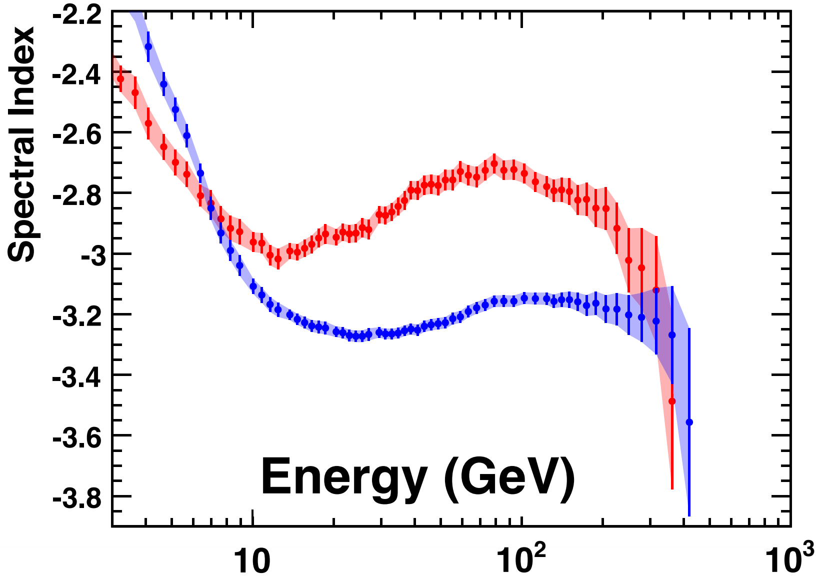
2024: Extend measurement to 1 TeV



Measurement of the $(e^+ + e^-)$ flux

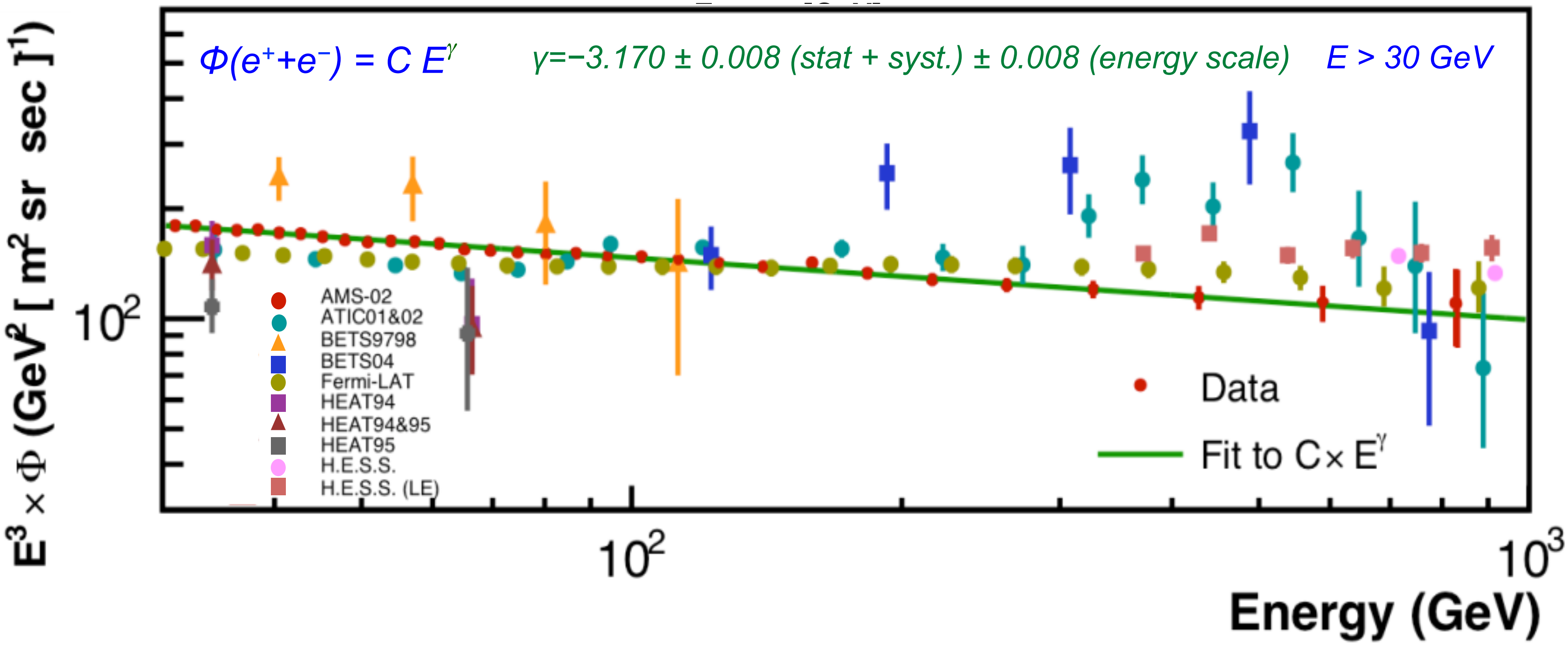


Spectral Indices of electrons, positrons, and (electrons + positrons)



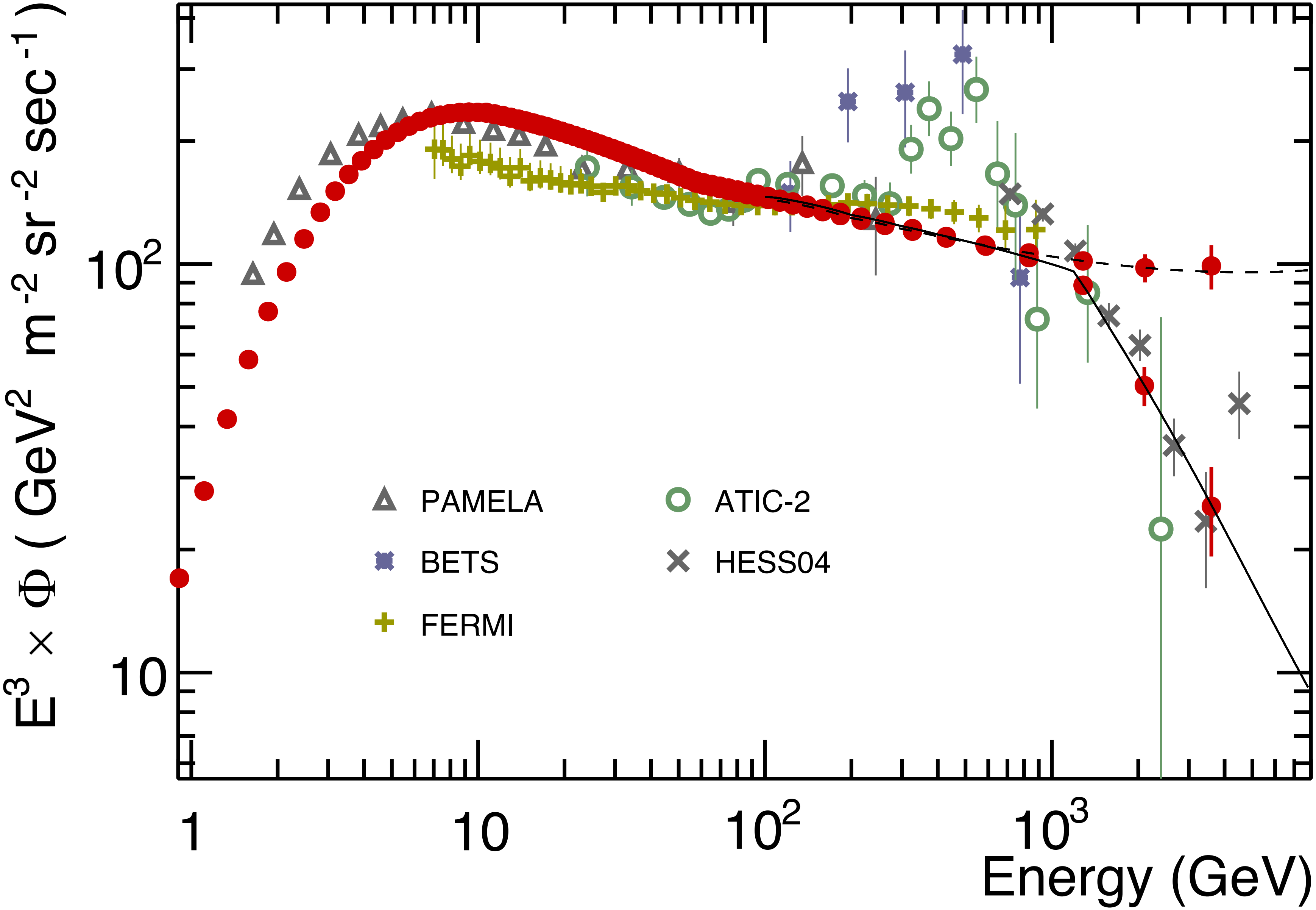
The spectral indices of electrons and positrons are not constant (γ=-3), but change with energy

The spectral index of $(e^+ + e^-)$ is energy independent



$\Phi(e^+ + e^-) = C\,E^{\gamma}$ $\gamma = -3.170 \pm 0.008$ (stat + syst.) $\pm\ 0.008$ (energy scale) E > 30 GeV

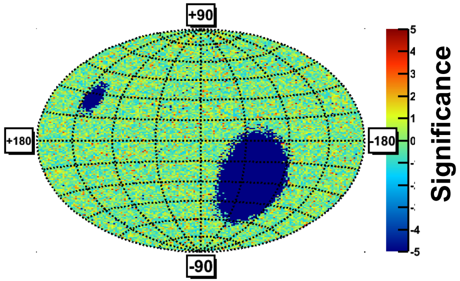
The AMS ($e^+ + e^-$) flux in 2024



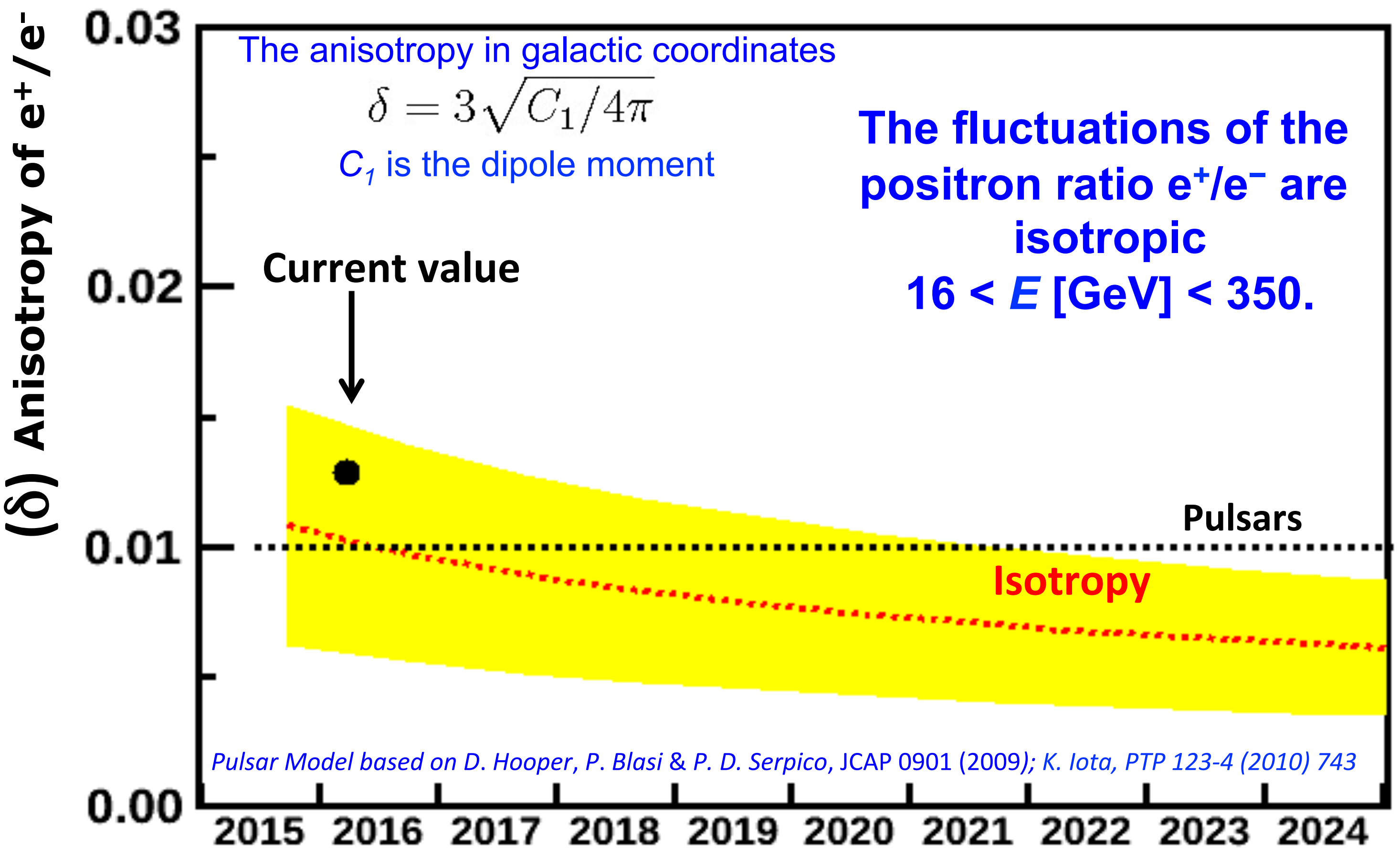
AMS will be able to distinguish the ($e^+ + e^-$) flux behavior above 1 TeV

The anisotropy of the e^+/e^- ratio

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



Galactic coordinates (b,l)



The anisotropy in galactic coordinates

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

C_1 is the dipole moment

The fluctuations of the positron ratio e^+/e^- are isotropic
$16 < E$ [GeV] < 350.

Pulsar Model based on D. Hooper, P. Blasi & P. D. Serpico, JCAP 0901 (2009)*; K. Iota, PTP 123-4 (2010) 743*

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

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

1) Particle origin: Dark Matter
2) Astrophysics origin: Pulsars, SNRs
3) Secondaries: peculiarities of 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

Examples of Theoretical Models for positrons and antiprotons

From Dark Matter

1) J. Kopp, Phys. Rev. D 88, 076013 (2013);
2) L. Feng, R.Z. Yang, H.N. He, T.K. Dong, Y.Z. Fan and J. Chang Phys.Lett. B728 (2014) 250
3) M. Cirelli, M. Kadastik, M. Raidal and A. Strumia ,Nucl.Phys. B873 (2013) 530
4) M. Ibe, S. Iwamoto, T. Moroi and N. Yokozaki, JHEP 1308 (2013) 029
5) Y. Kajiyama and H. Okada, Eur.Phys.J. C74 (2014) 2722
6) K.R. Dienes and J. Kumar, Phys.Rev. D88 (2013) 10, 103509
7) L. Bergstrom, T. Bringmann, I. Cholis, D. Hooper and C. Weniger, PRL 111 (2013) 171101
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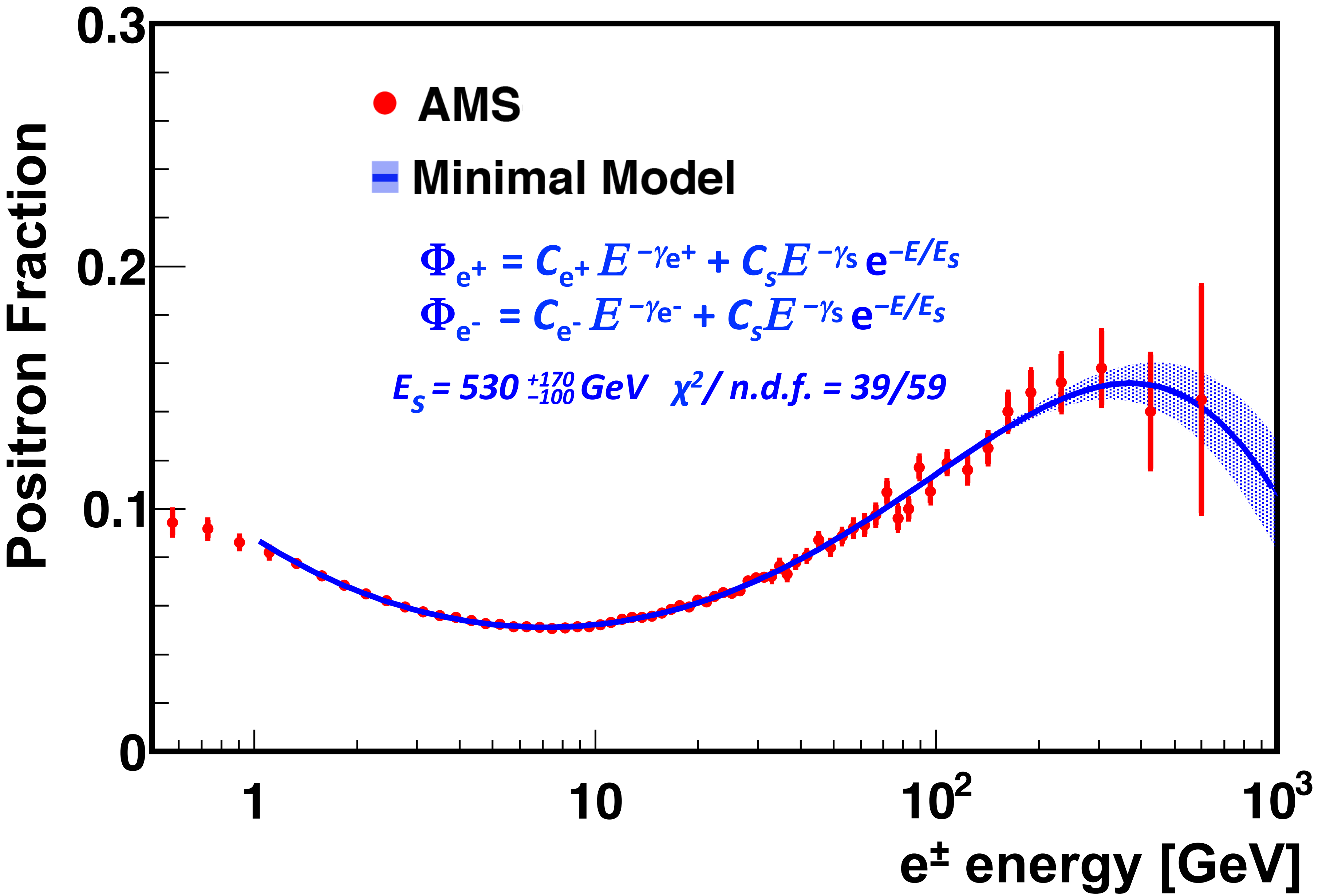
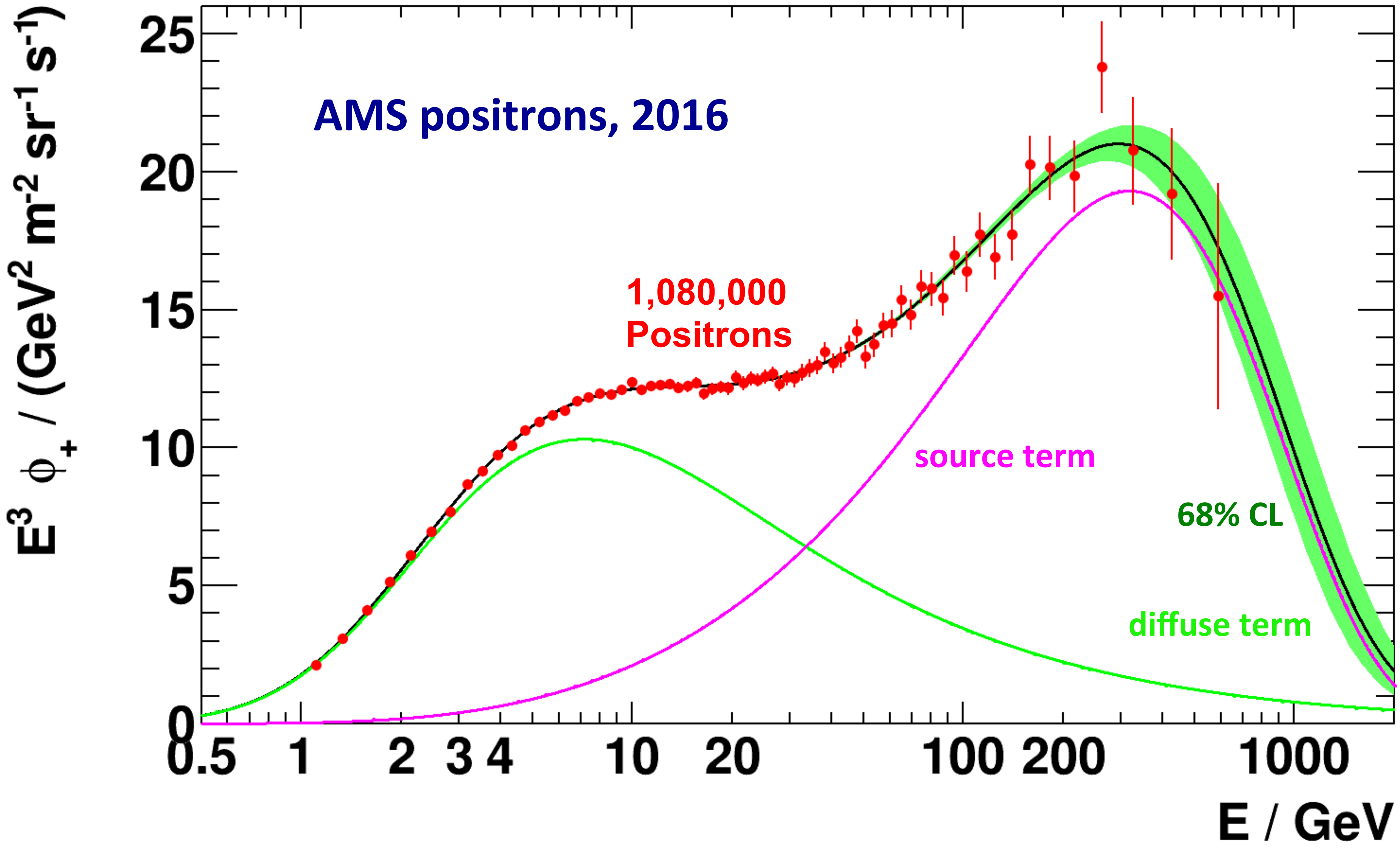
Additional source of high energy electrons and positrons

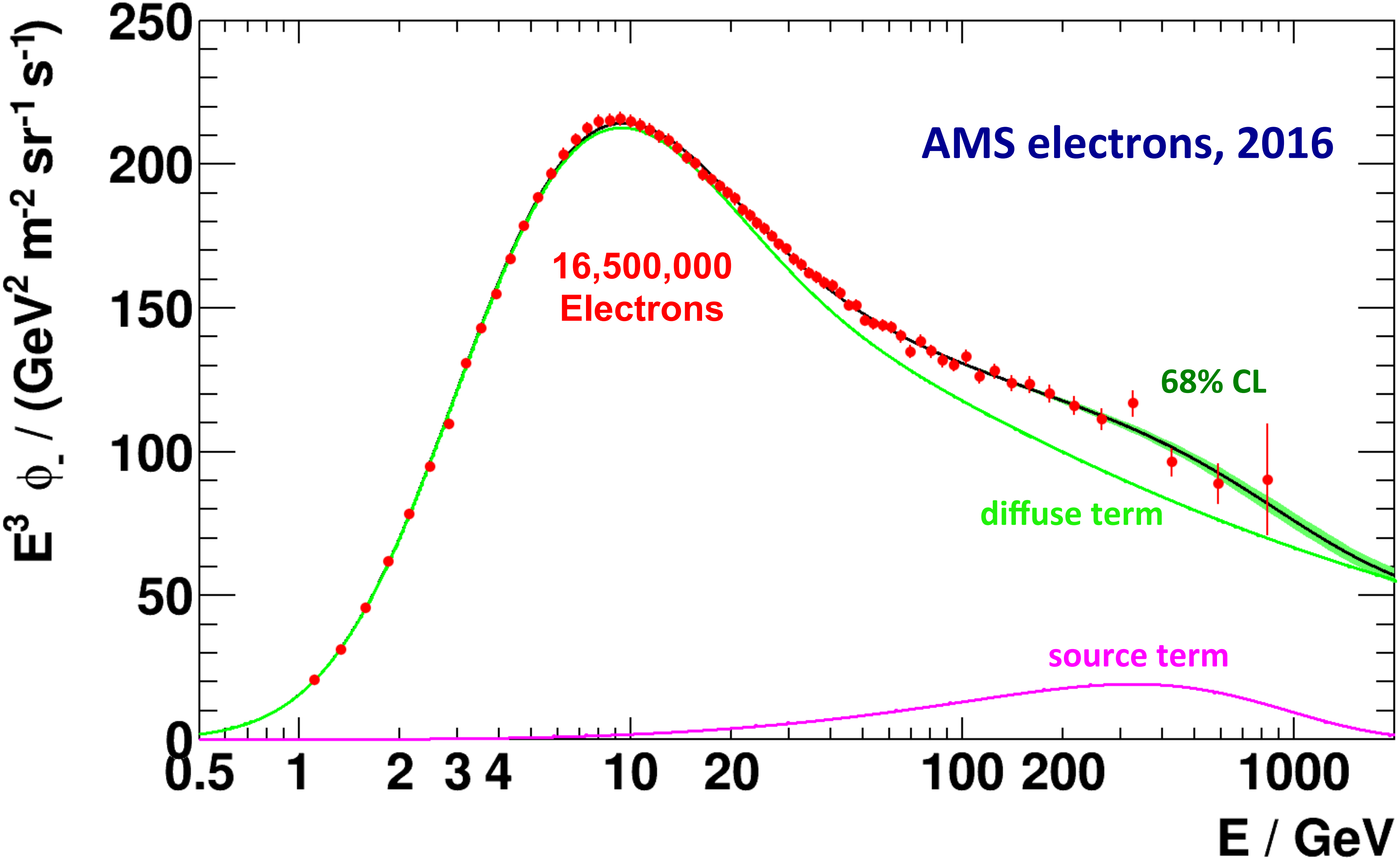


Additional source of high energy electrons and positrons



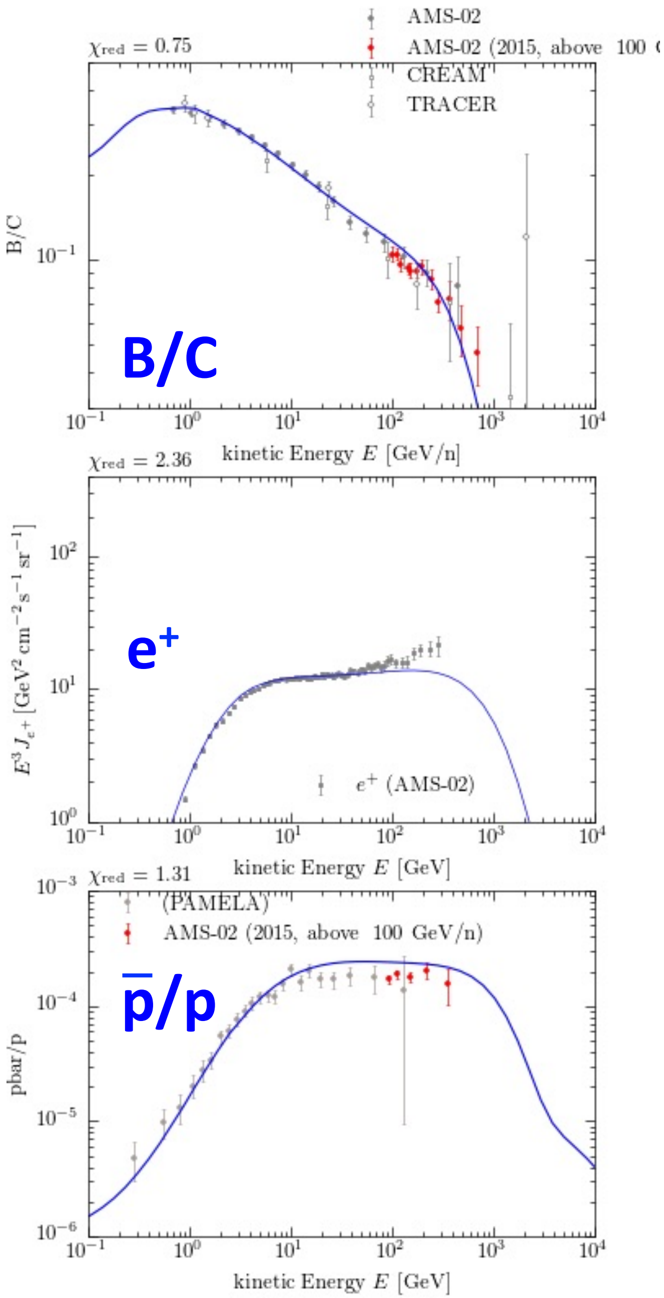
- The significance of the energy cutoff of the source term is ~3σ.

Additional source of high energy electrons and positrons



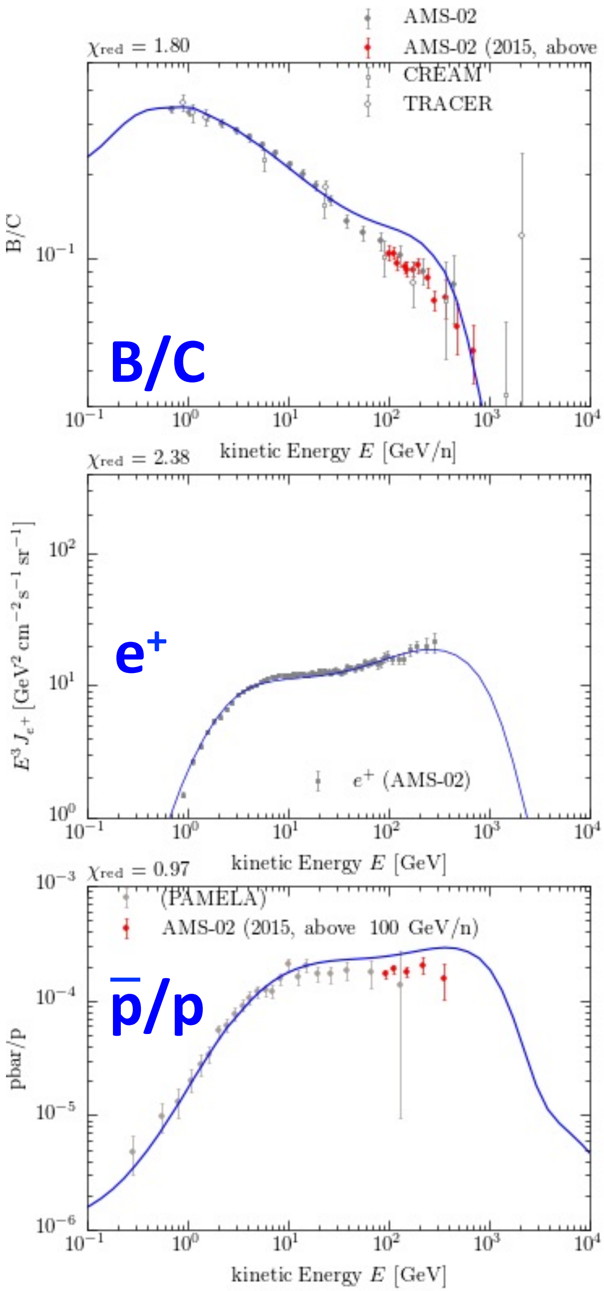
- ➢ **Contribution of the source term becomes clearly visible**

Astrophysical sources: S. Sarkar, April 2015



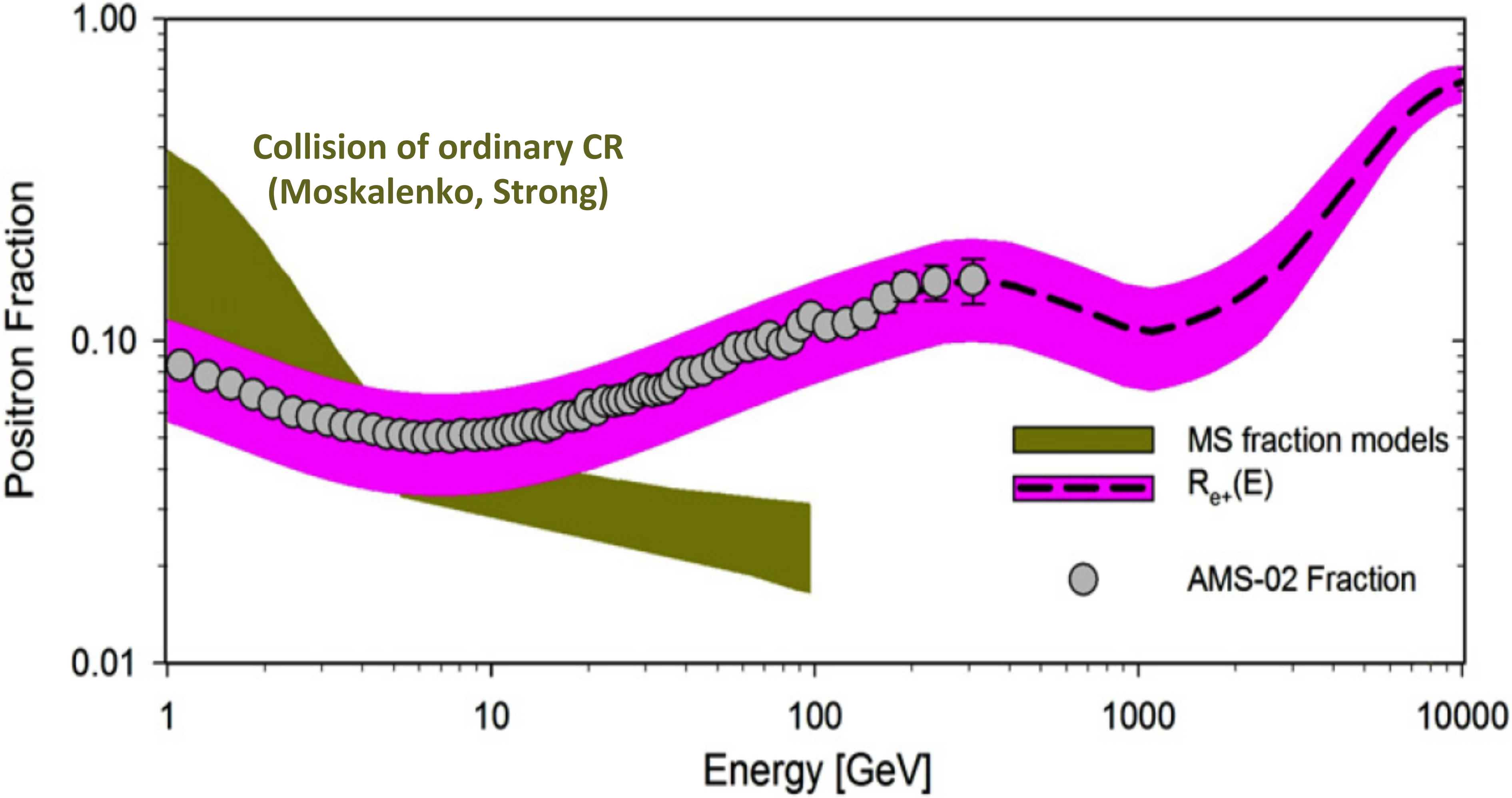
We have been trying (late last night!) to get better fits to the new data but it is not easy ... perhaps our model is *too* simple and some further refinements are necessary.

This is justified now that we have *precision* data from AMS!



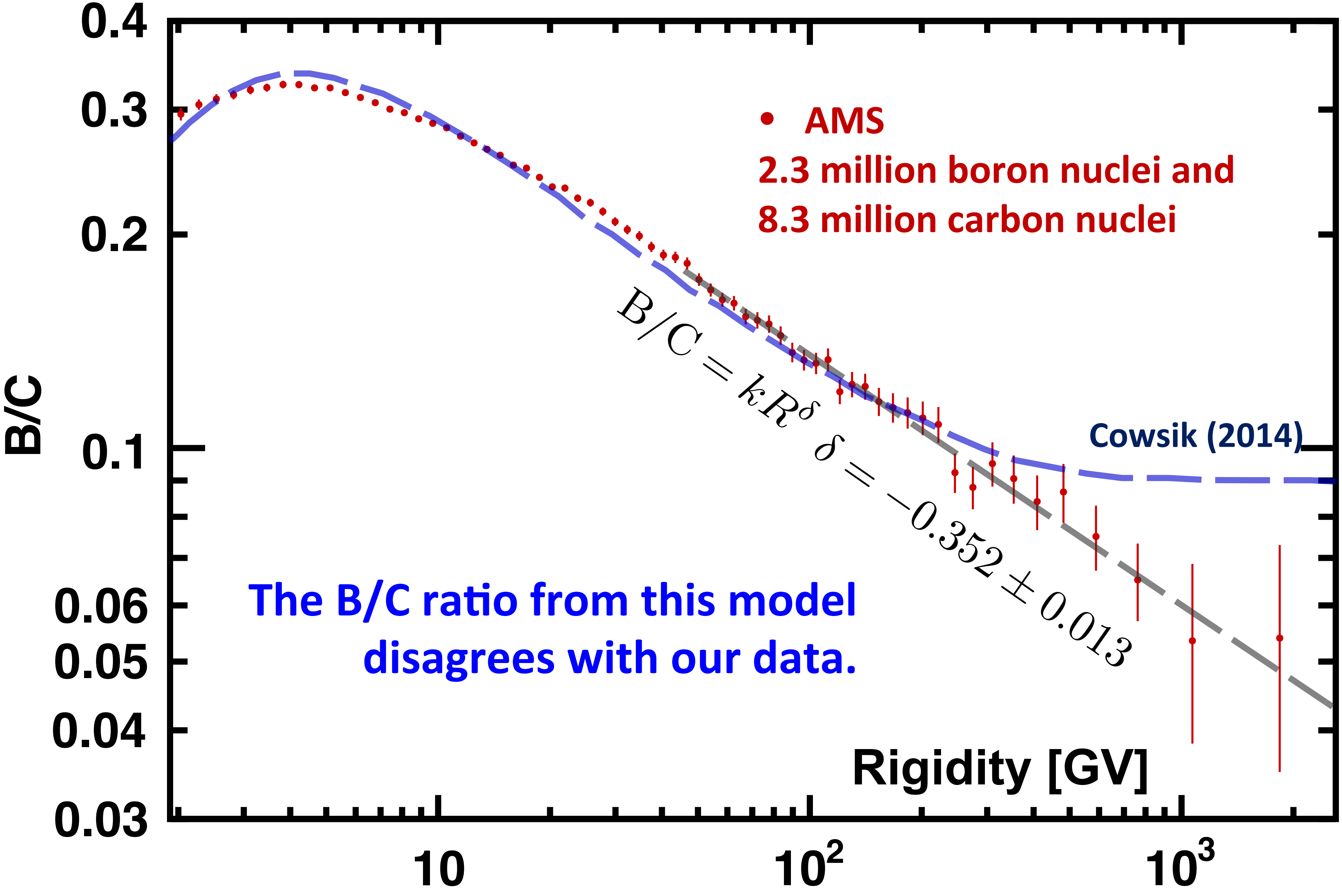
Propagation of secondaries (example of many)

R. Cowsik, B. Burch, and T. Madziwa-Nussinov, Ap. J. 786 (2014) 124



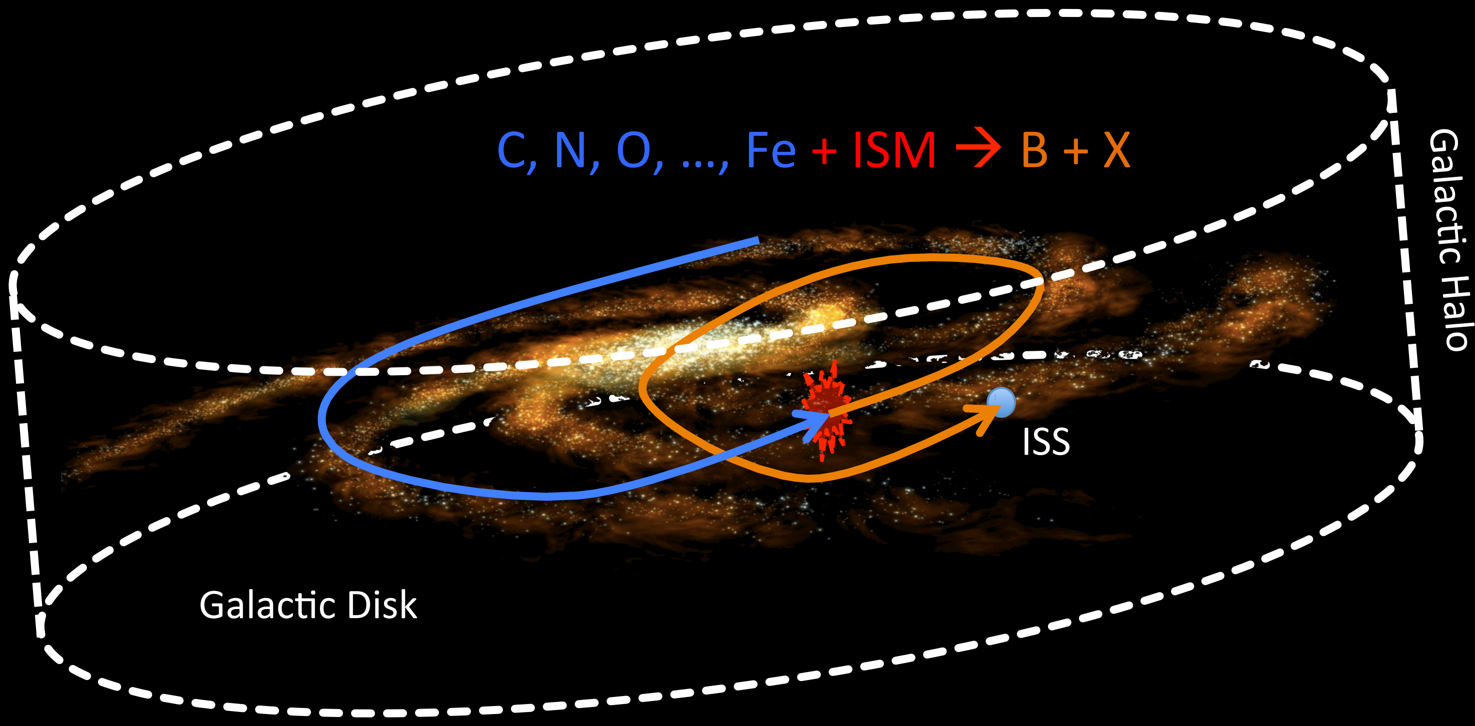
Propagation of secondaries

R. Cowsik, B. Burch, and T. Madziwa-Nussinov, Ap. J. 786 (2014) 124



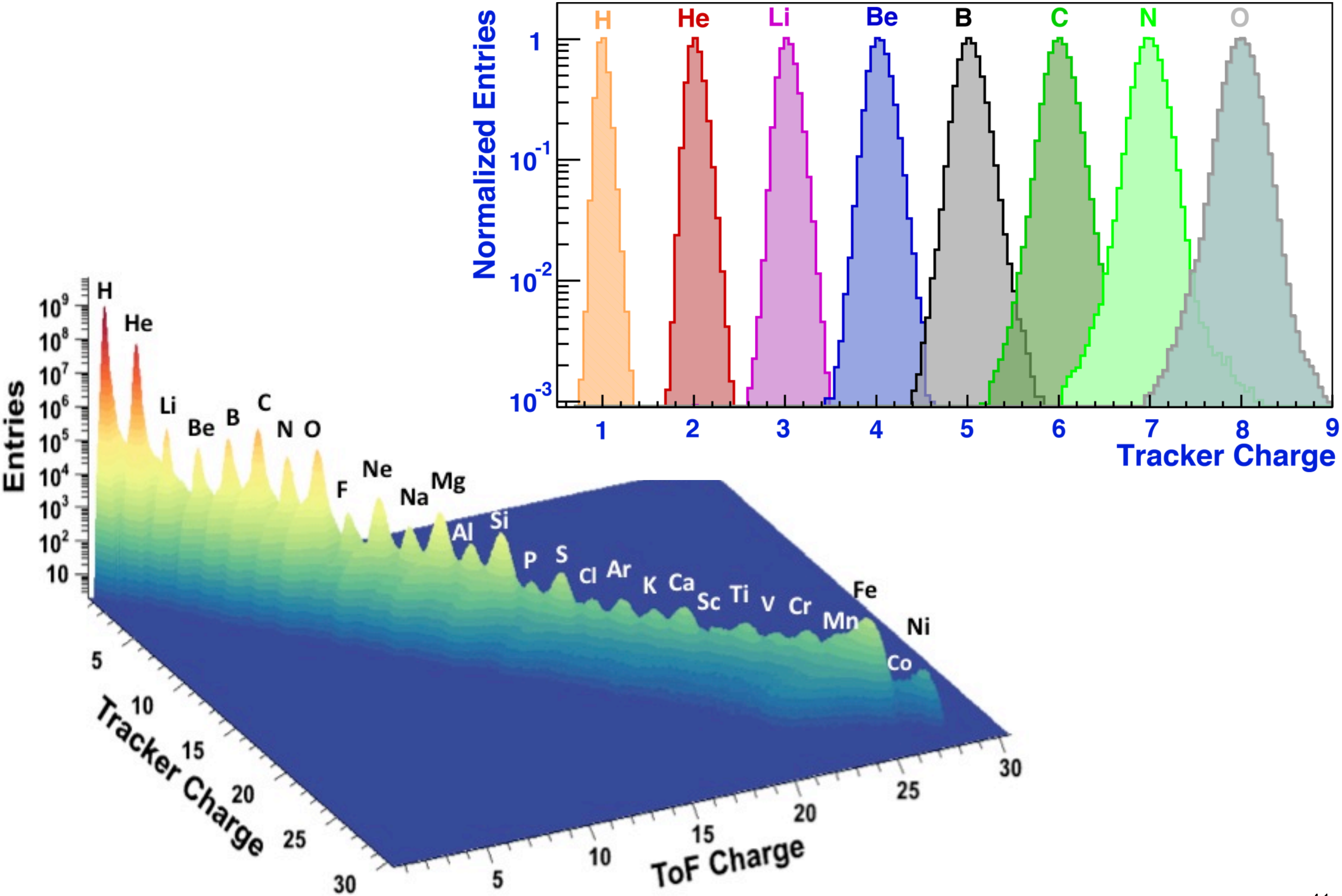
The B/C ratio from this model disagrees with our data.

Boron-to-Carbon Flux Ratio



The Boron-to-Carbon ratio (B/C) in cosmic rays is a powerful tool to **determine cosmic ray propagation (the amount of matter)** as Boron is assumed to be produced purely from collision of primary cosmic rays, such as Carbon and Oxygen, with the interstellar medium (ISM).

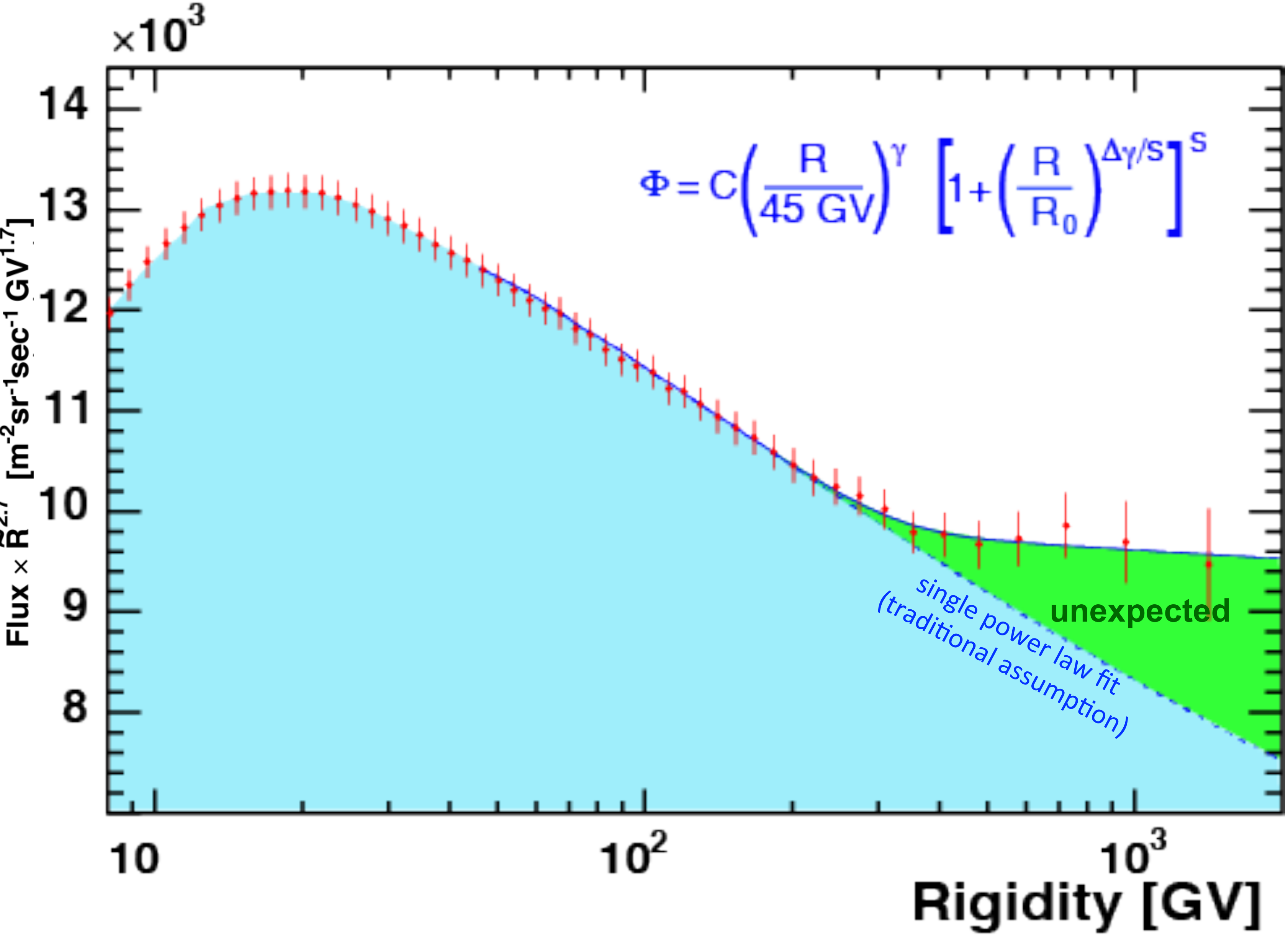
AMS Measurements of Nuclei



AMS proton flux

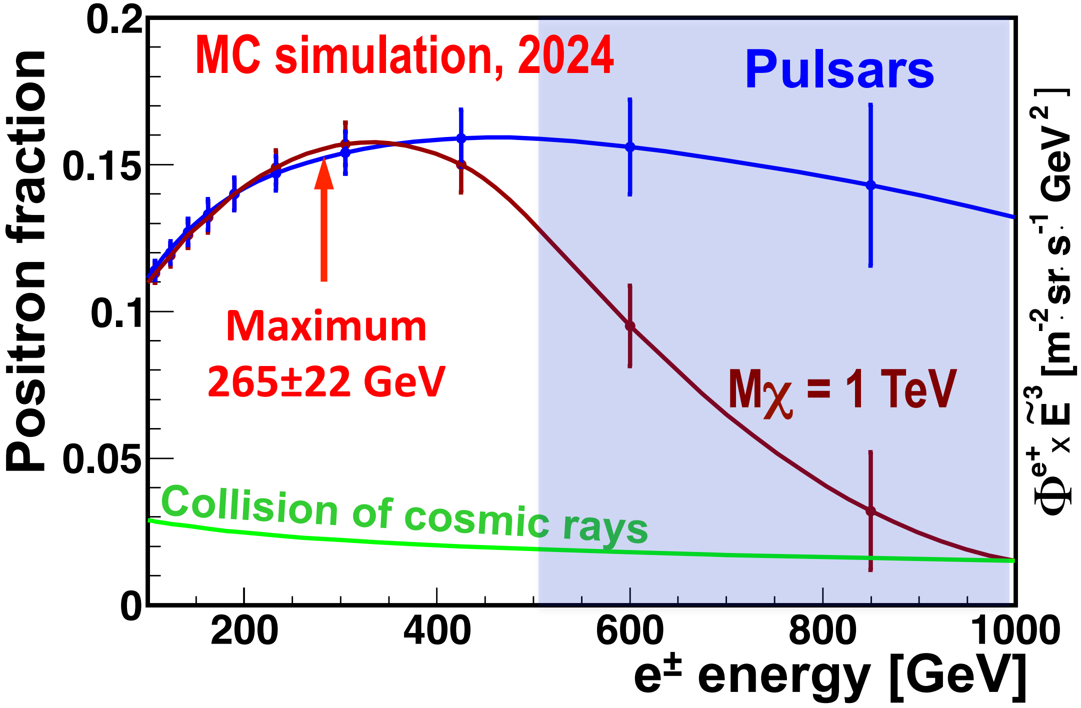
New information: The proton flux cannot be described by a single power law = CR^{γ}

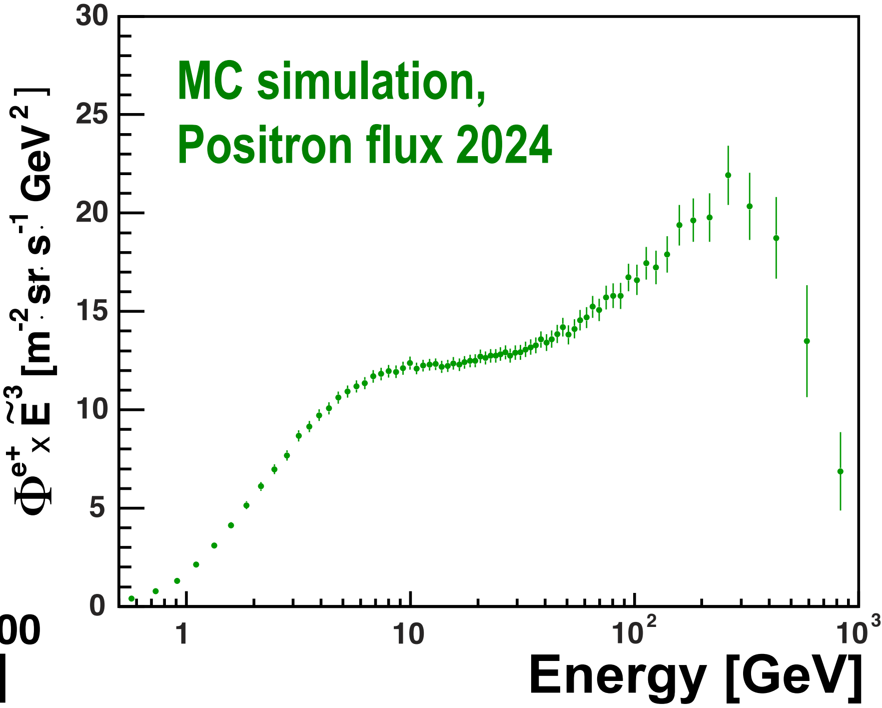
Proton Spectrum



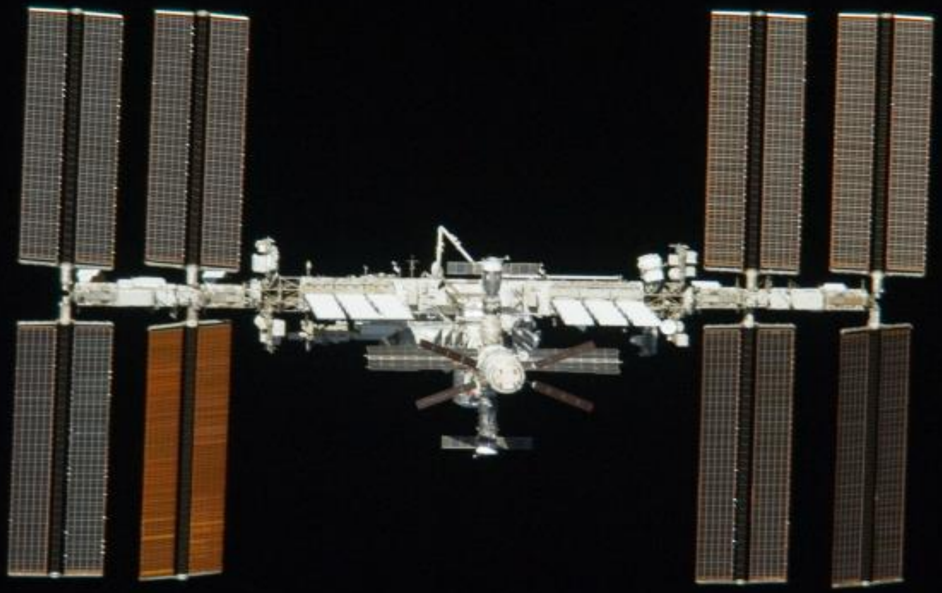
Conclusions

1. **Positron fraction (2×10^7 e^+ and e^- events) requires an additional source of high energy e^+ and e^- (e.g. DM models):**
   - **can't be explained by the ordinary CR collisions**
   - **at 265±22 GeV the fraction reaches its maximum;**
   - **measurement to 2024 enable us to determine the origin of the behavior of CR positrons at high energies**





The latest AMS measurements of the positron fraction, the antiproton/proton ratio, the behavior of the fluxes of electrons, positrons, protons, helium, and other nuclei provide precise and unexpected information. The accuracy and characteristics of the data, simultaneously from many different types of cosmic rays, require a comprehensive model to ascertain if their origin is from dark matter, astrophysical sources, acceleration mechanisms or a combination.



Physics in the next ten years:

Accurate measurement (~1%) of Cosmic Rays to higher energies including:

a. Continue the study of Dark Matter

b. Search for the Existence of Antimatter

c. Search for New Phenomena, Strangelets …