

Alpha Magnetic Spectrometer



The Alpha Magnetic Spectrometer on the International Space Station on behalf of the AMS-02 collaboration

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Outline

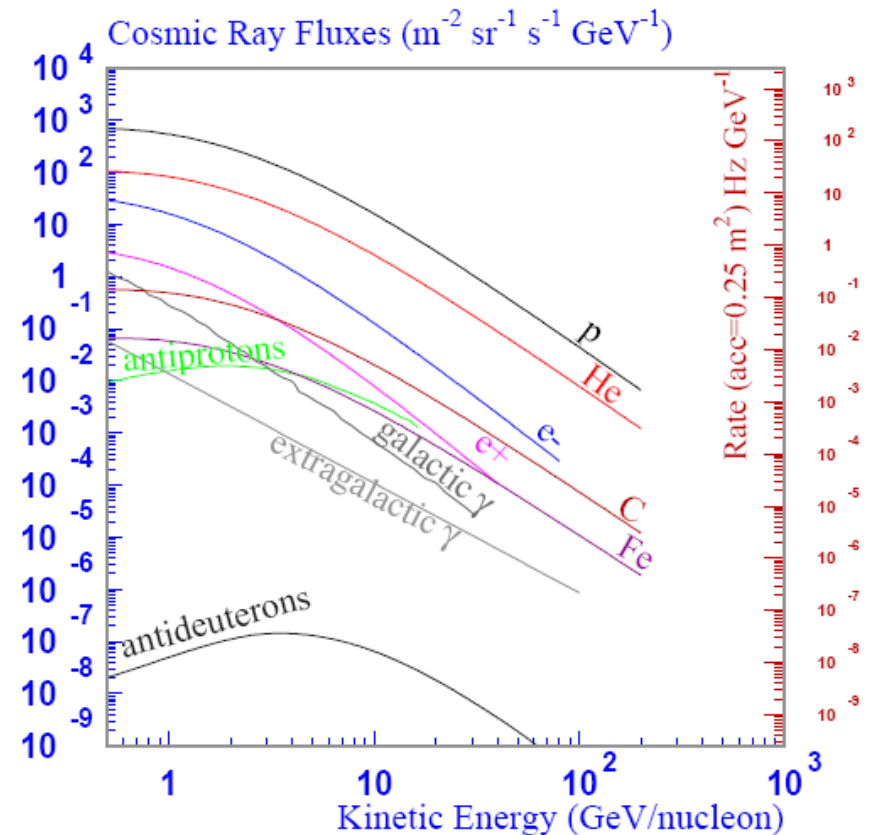
- Introduction
- Nuclei flux measurements
 - Hydrogen, helium nuclei
 - Boron/carbon
- Positron fraction, positron and electron fluxes
- Summary

References: S.Ting Cern Seminar, April 2013, ICRC2013 July 2013, Phys.Rev.Lett. 110 (2013) 14, ICRC2013_ 1257,1261,1266,1265, 1264,1267,1263 **ICRC2013 talks and proceedings**

Cosmic Ray Flavors (balloons, PAMELA,..)

- Power Law $E^{-\gamma}$ $\gamma[2-3]$
- Protons : 88 %
- Electrons: 1%

<i>protons</i>	~ 1
<i>heliums</i>	$\sim 10^{-1}$
<i>electrons</i>	$\sim 10^{-2}$
<i>positrons</i>	$\sim 10^{-3}$
<i>carbon</i>	$\sim 10^{-4}$
<i>iron</i>	$\sim 10^{-5}$



Cosmic Ray Issues

$$\gamma = \alpha + \delta \approx 2.7 \text{ (Nuclei)}$$

$$\frac{N_{\text{cr}}(E)}{\tau(E)} = Q_{\text{cr}}(E)$$

$E^{-\gamma}$ Measured CR density
 $E^{-\alpha}$ Source spectrum Injection rate
 $E^{-\delta}$ Diffusion/confinement time
 $\alpha = 2.0 \dots 2.4$
 $\delta = 0.3 \dots 0.7$

- ▷ Measured spectrum index (γ) results from :
 - ▷ Production/acceleration mechanism (α)
 - ▷ Diffusion term (δ)

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Cosmic Ray Issues

- **Production = Primaries (protons, Nuclei, e-, ...)** from the sources (SNR, Pulsars)

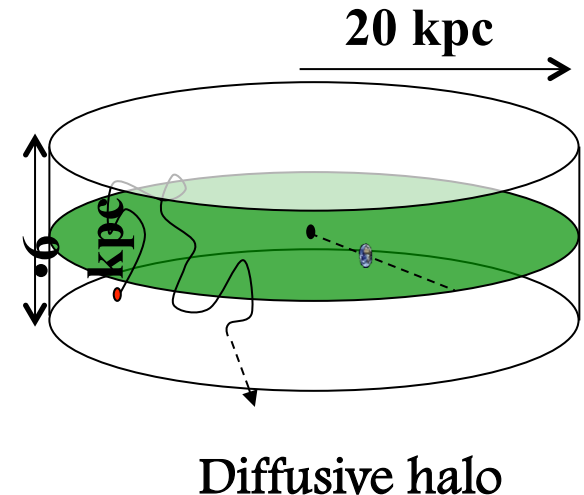
- $E^{-\alpha} \propto \sim 2$

- **Propagation and diffusion**

$\Rightarrow$ **Power Law** $E^{-\gamma} \gamma : [2-3]$

- **Secondaries**

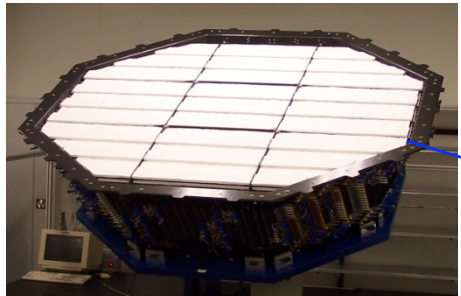
- **C, O spallation within the Interstellar Medium**
 - Boron, Be, Li,
 - **He and H nuclei interacting with the Interstellar Model**
 - Positrons, Anti protons ,



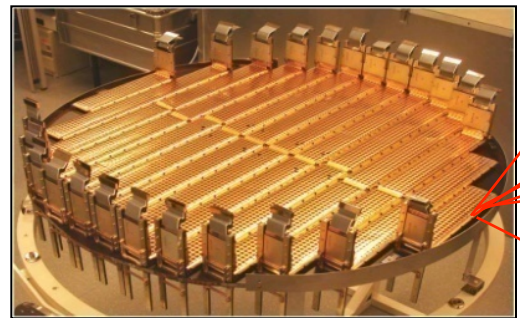
AMS: A TeV precision, multipurpose spectrometer in space

TRD

Identify e^+ , e^-



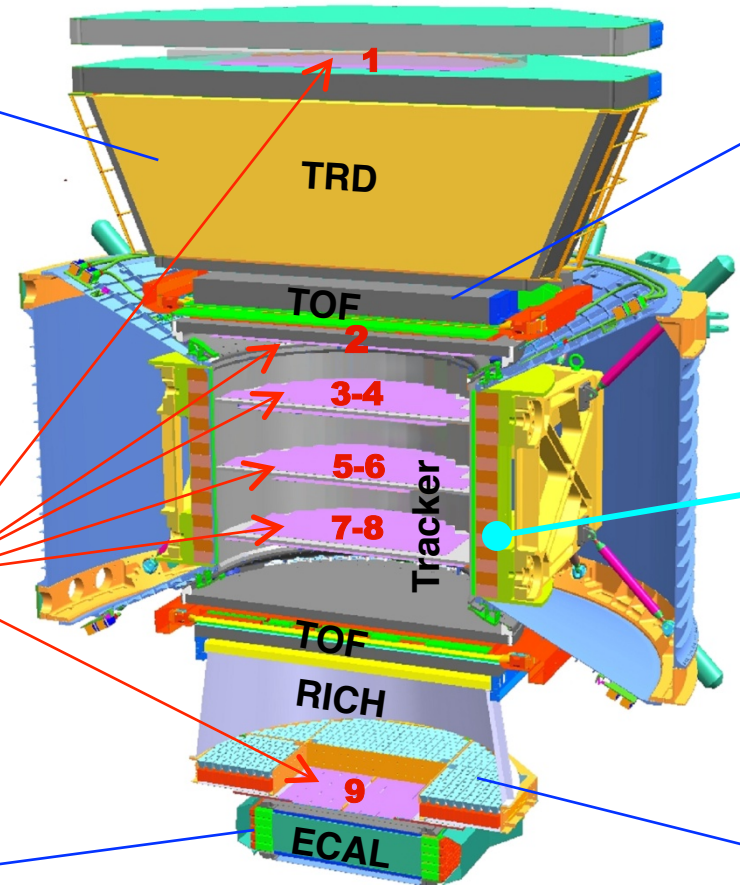
Silicon Tracker
 Z, P



3D imaging ECAL
 E of e^+ , e^- , γ

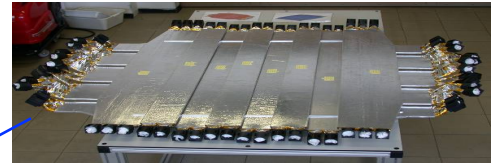


Particles and nuclei are identified by their charge (Z) and energy ($E \sim P$)



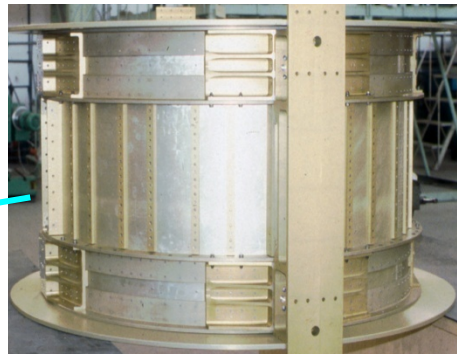
TOF

Z, E



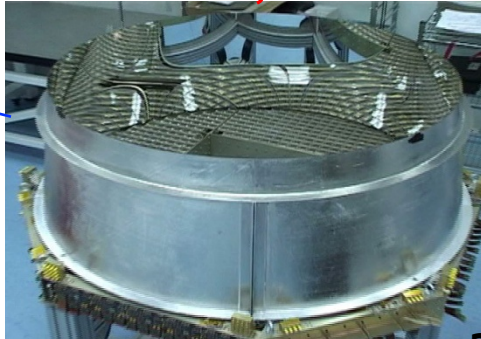
Magnet

$\pm Z$



RICH

Z, E



5m x 4m x 3m 7.5 tons

Z, P are measured independently from Tracker, RICH, TOF and ECAL

AMS02 – May 2011

**Cape Canaveral, May 16 2011.
STS 134 Mission, Launch of
Endeavour Shuttle**



**Endeavour approaches the
International Space Station (ISS ~300 km)**

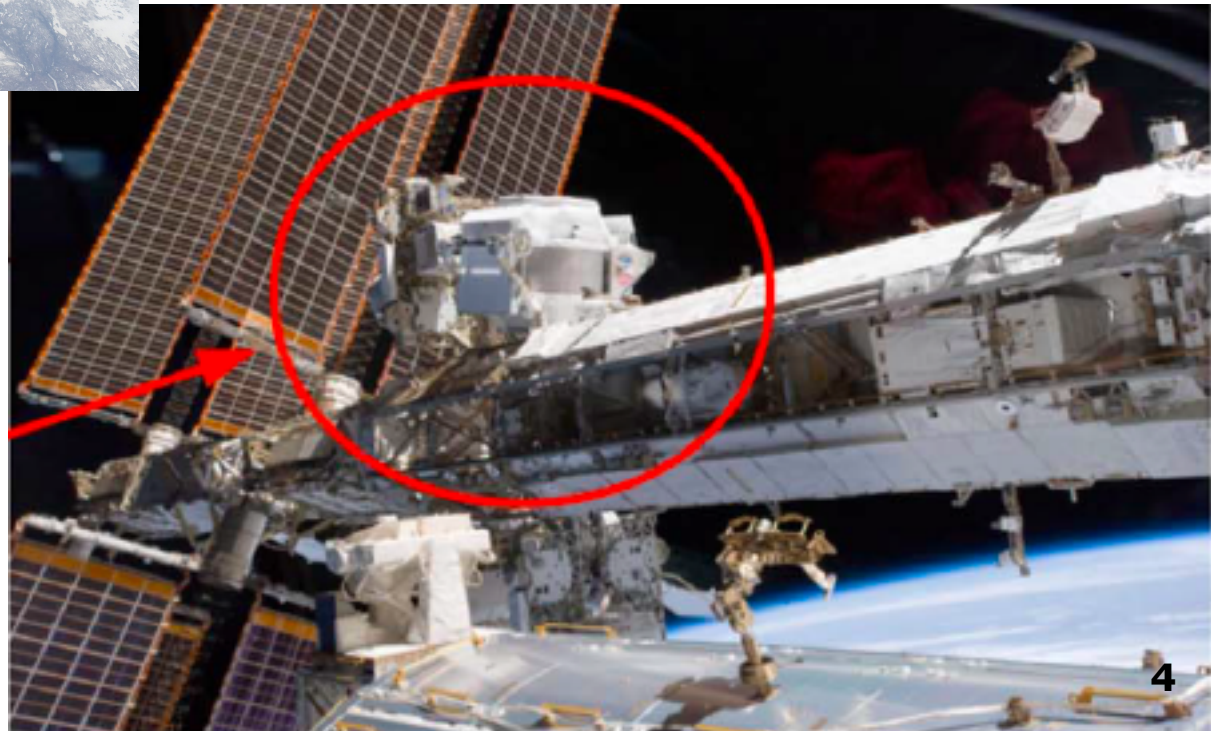
AMS02 on board of the ISS



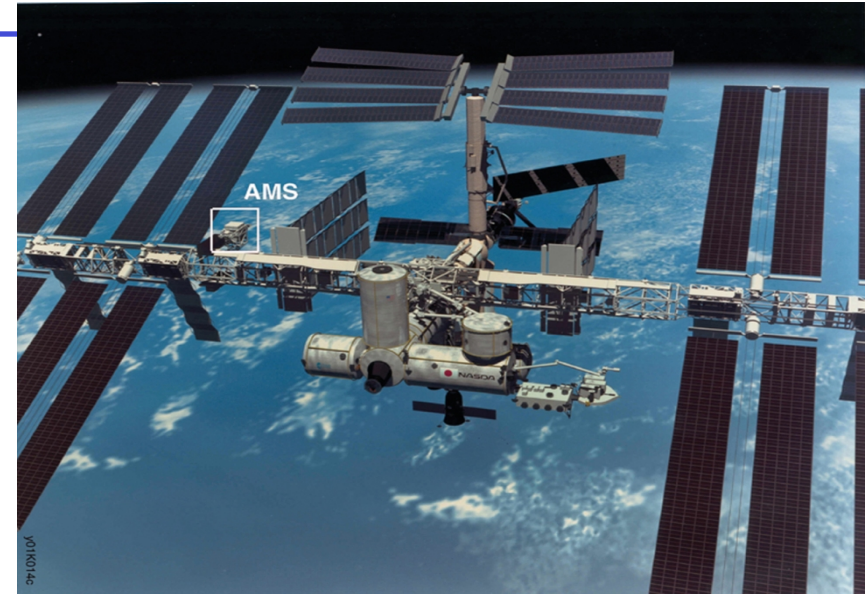
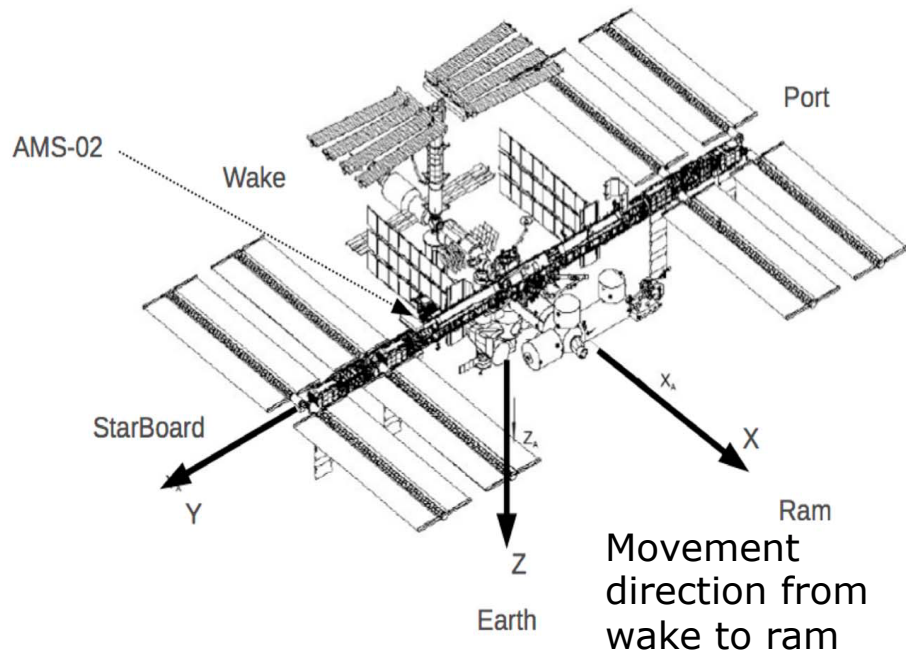
**AMS02 is grappled by the Shuttle Remote Manipulator System (SRMS)
May 19, 2011**

**May 19 2011:
AMS installation
completed on ISS
at 5:15 CDT,
start taking data
9:35 CDT
Until 2020**

(CDT Central Daylight Time)

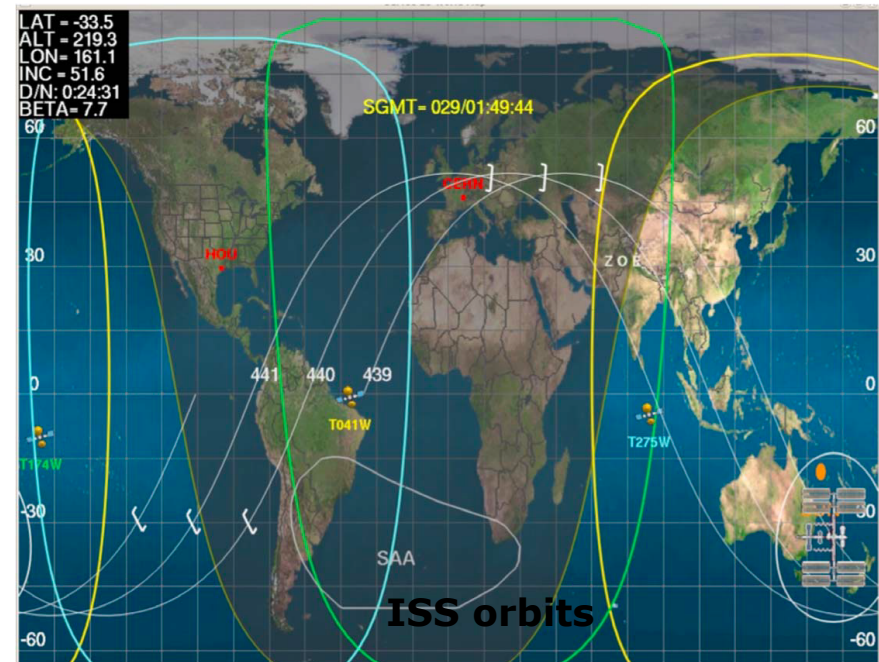


ISS orbit



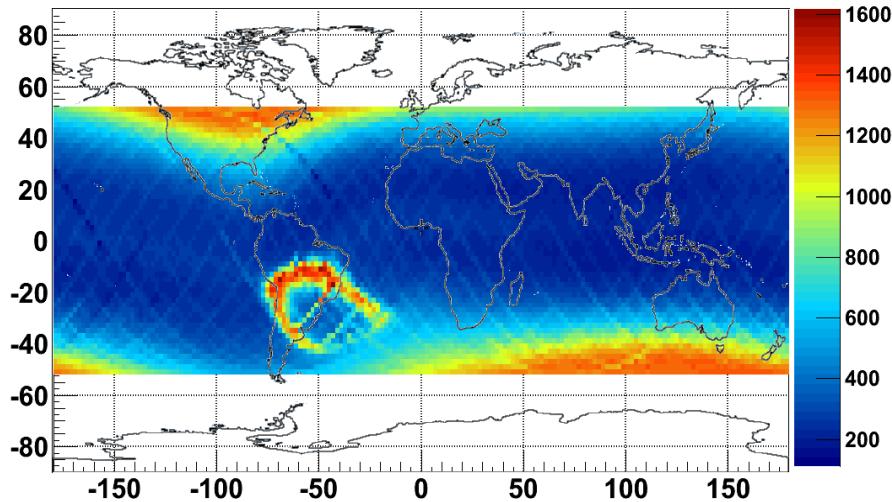
ISS velocity: 8km/s, one orbit every 90 mn

Altitude 340-400 km



Orbital DAQ parameters

Acquisition rate [Hz]



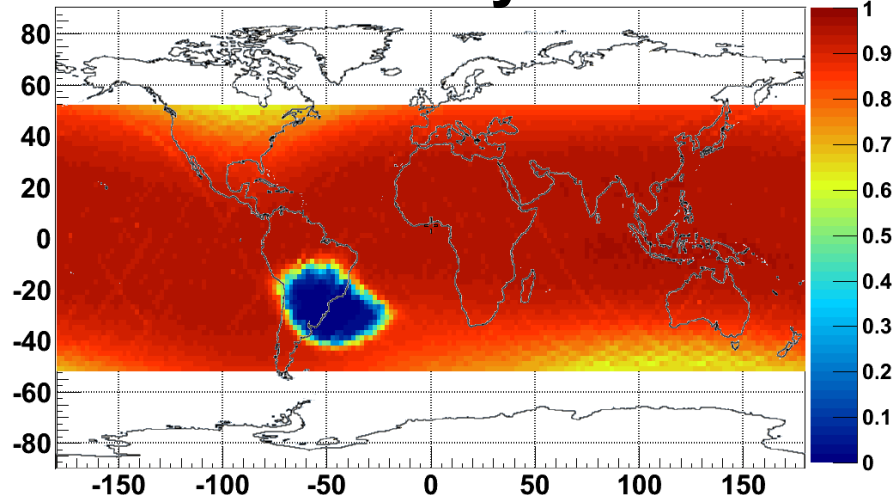
**Particle rates vary from
200 to 2000 Hz per orbit**

On average:

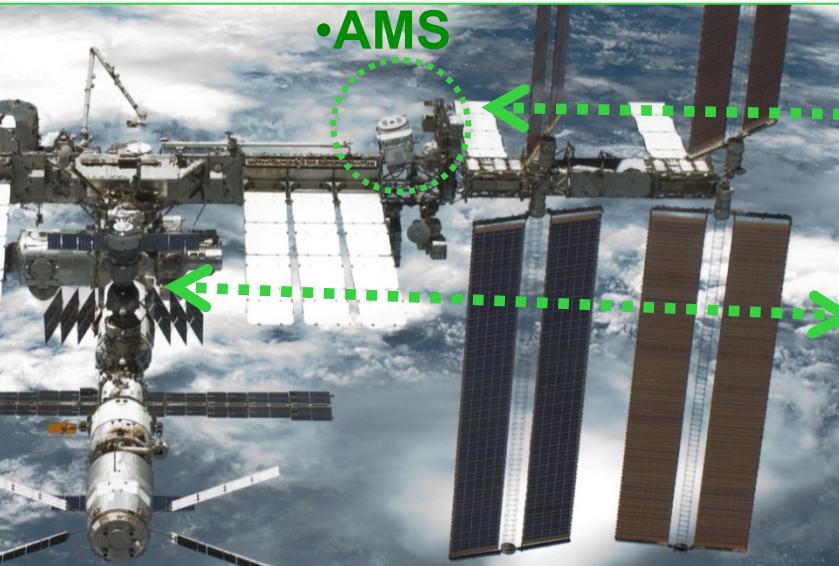
DAQ efficiency 85%

DAQ rate ~700Hz

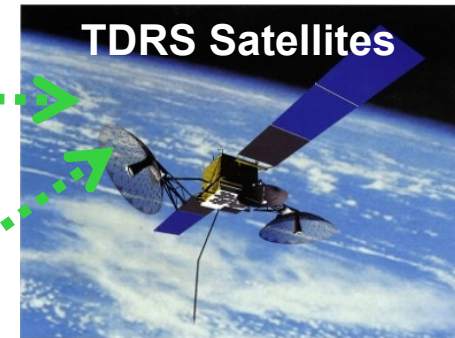
DAQ efficiency



AMS Data Flow



Astronaut at ISS AMS Laptop



TDRS Satellites

Ku-Band
High Rate (down):
Events <10Mbit/s

S-Band
Low Rate (up & down):
Commanding: 1 Kbit/s
Monitoring: 30 Kbit/s



**AMS Payload Operations Control and
Science Operations Centers
(POCC, SOC) at CERN since June 2011**



**AMS Computers
at MSFC, AL**



**White Sands Ground
Terminal, NM**

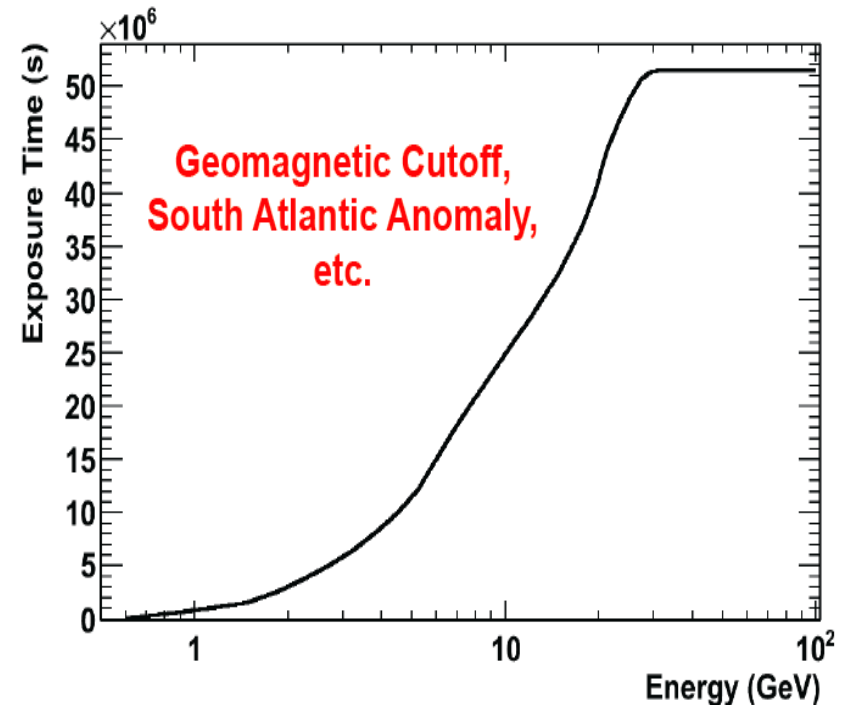
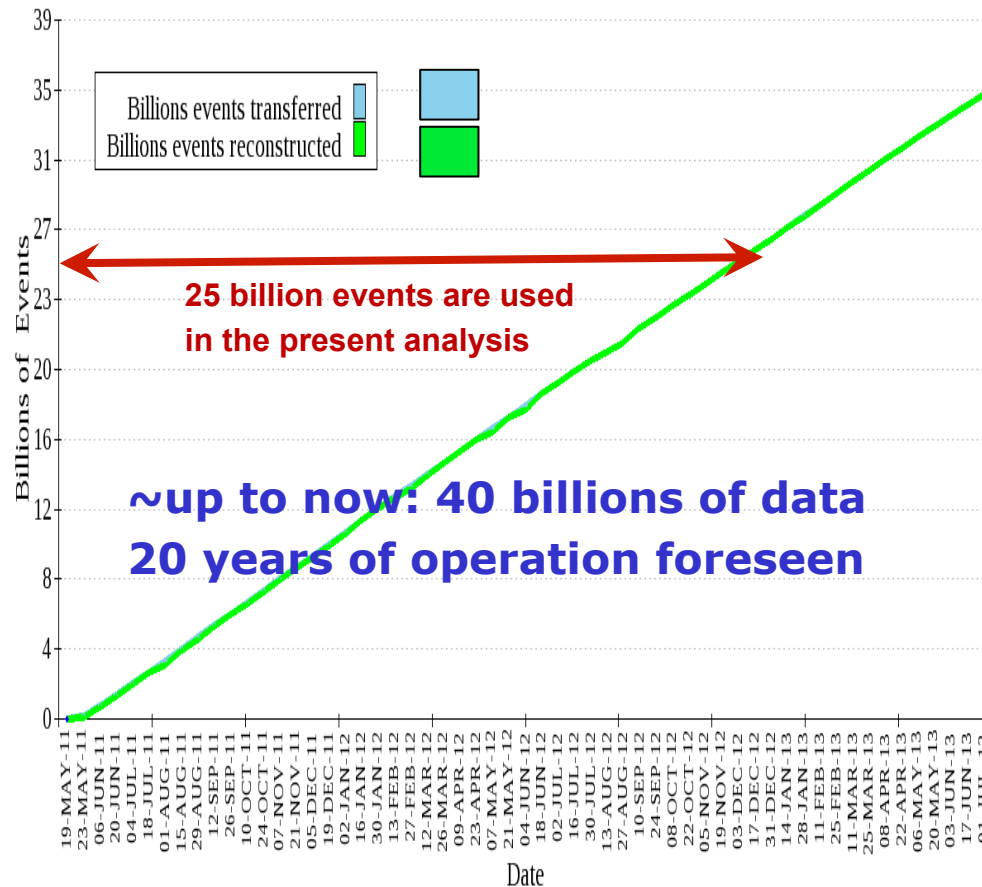
AMS Physics Potential

- Searches for primordial antimatter:
 - Anti-nuclei: anti He, ...
- **Dark Matter searches:**
 - e^+ , $e^\pm$, anti p, γ ...
 - simultaneous observation of several signal channels.
- Searches for new forms of matter:
 - strangelets, ...
- **Measuring CR spectra – refining propagation models;**
- Study effects of solar modulation on CR spectra over 11 year solar cycle
- ...

Data sample and data taking time

Data take from : 19 May 2011 to : 19 May 2013 (1.5 or 2 years)

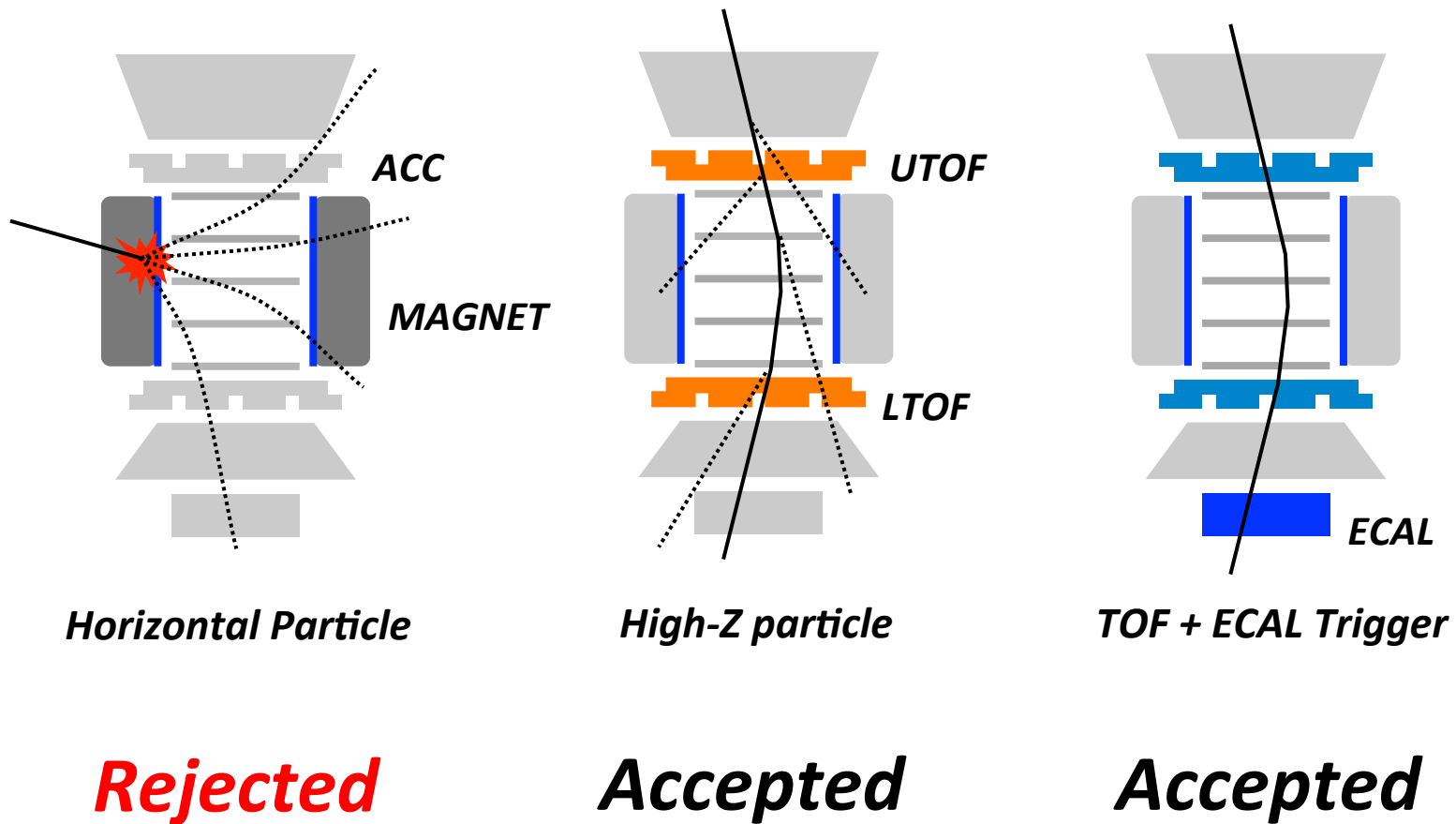
Total exposure time : $T_{\text{exp.}}$ (*Rigidity* > 25 GV) = 51.2×10^6 s



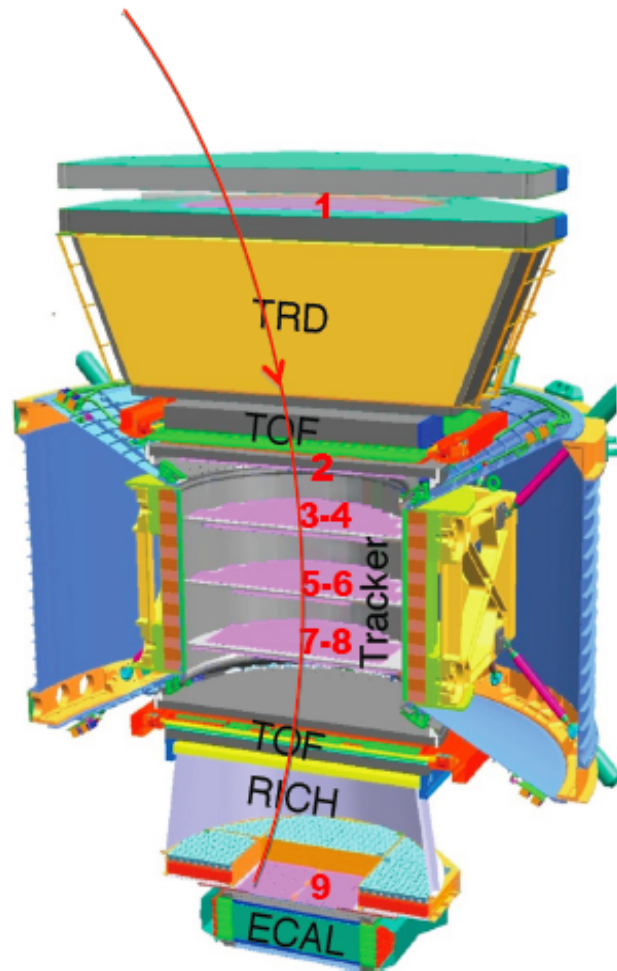
Average live time = 82 %

AMS-02 Trigger

Trigger efficiency is estimated with an unbiased trigger sample.



AMS-02 Nuclei Properties Measurement



Rigidity, Direction and Charge Sign

Tracker

Bending Coordinate Resolution 6 to 7 μm

MDR ($Z=2$) $\approx 3.2 \text{ TV}$

Velocity and Direction

TOF

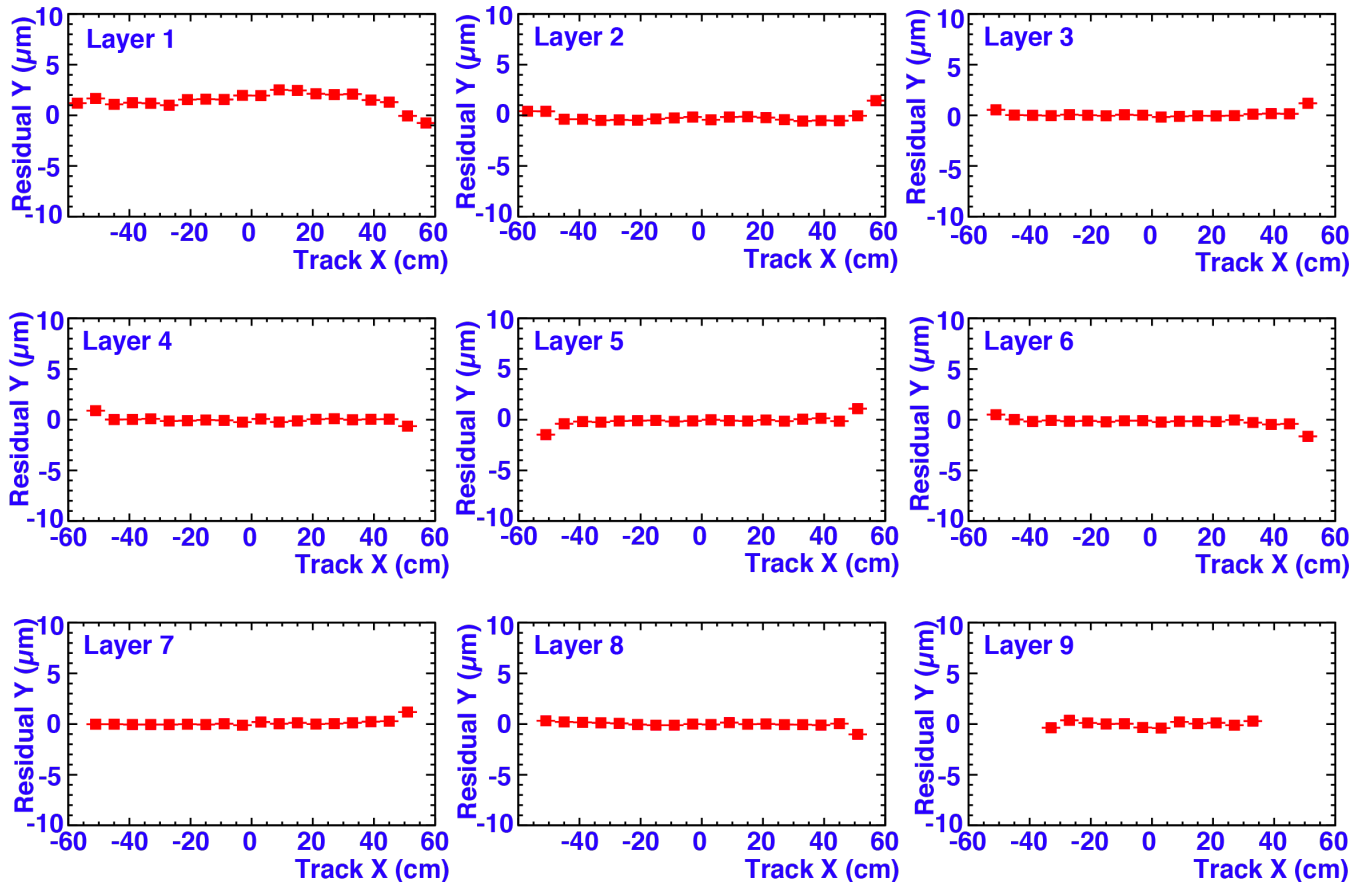
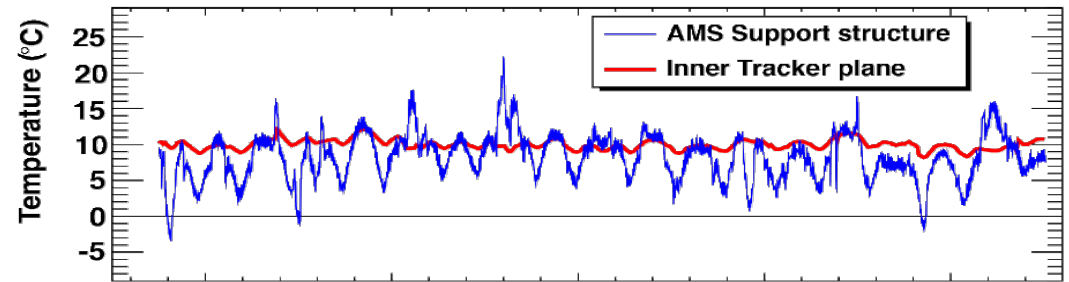
$\Delta\beta/\beta^2(Z=2) \approx 2\%$

Charge Magnitude Along He Trajectory

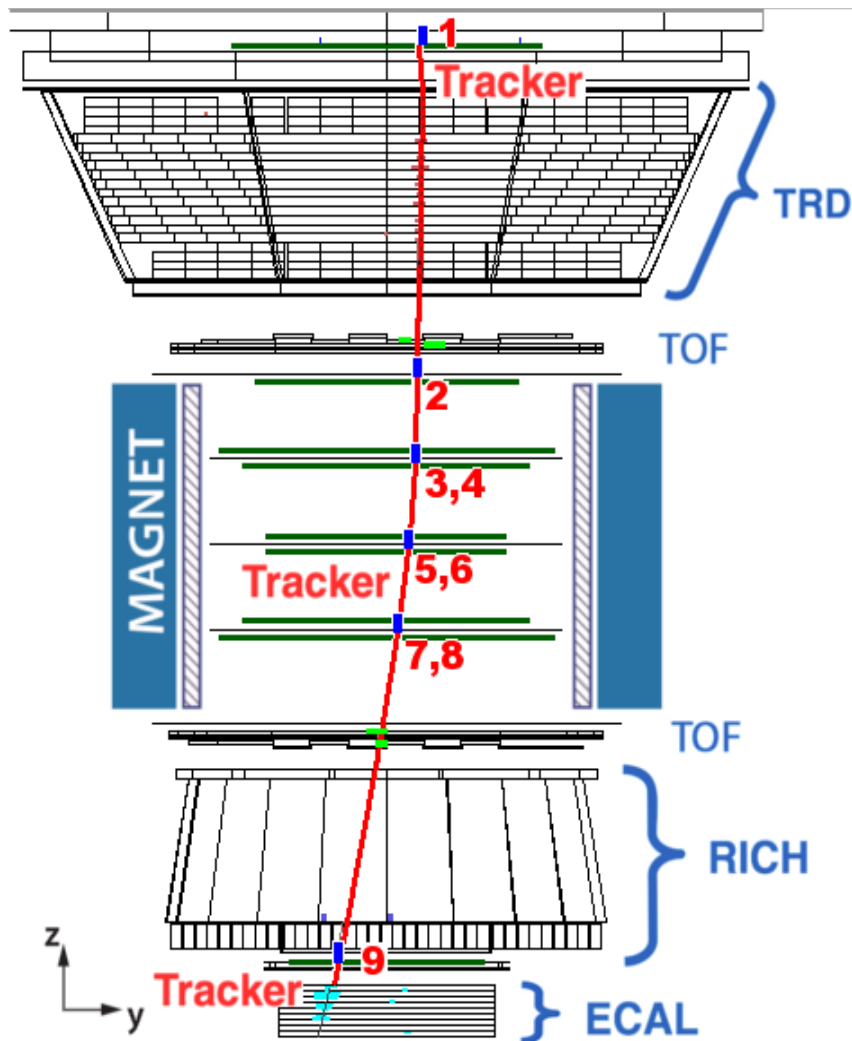
TRD, Tracker, RICH, TOF, ECAL

$\Delta Z (Z=2) \approx 0.08-0.2$

Tracker Alignment Occuracy



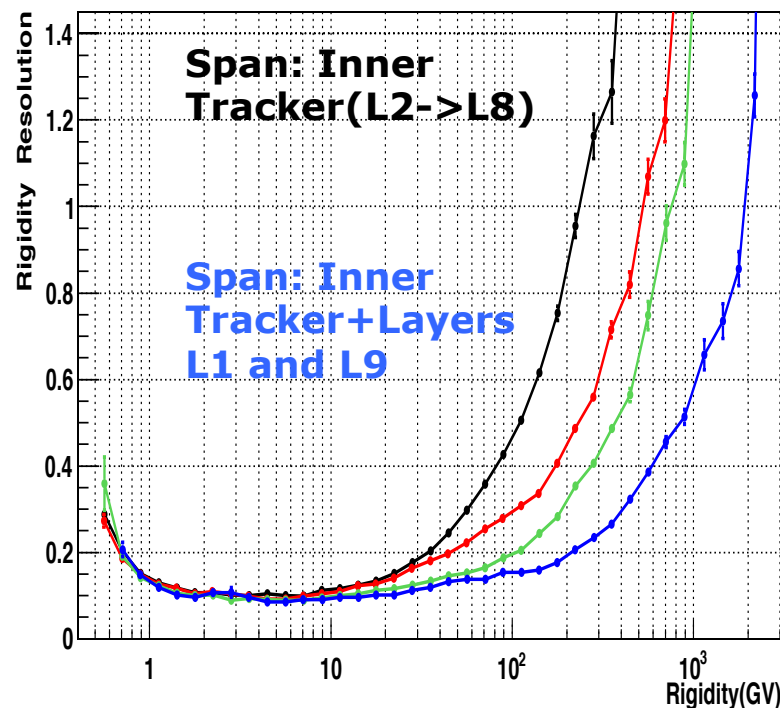
Rigidity measurement

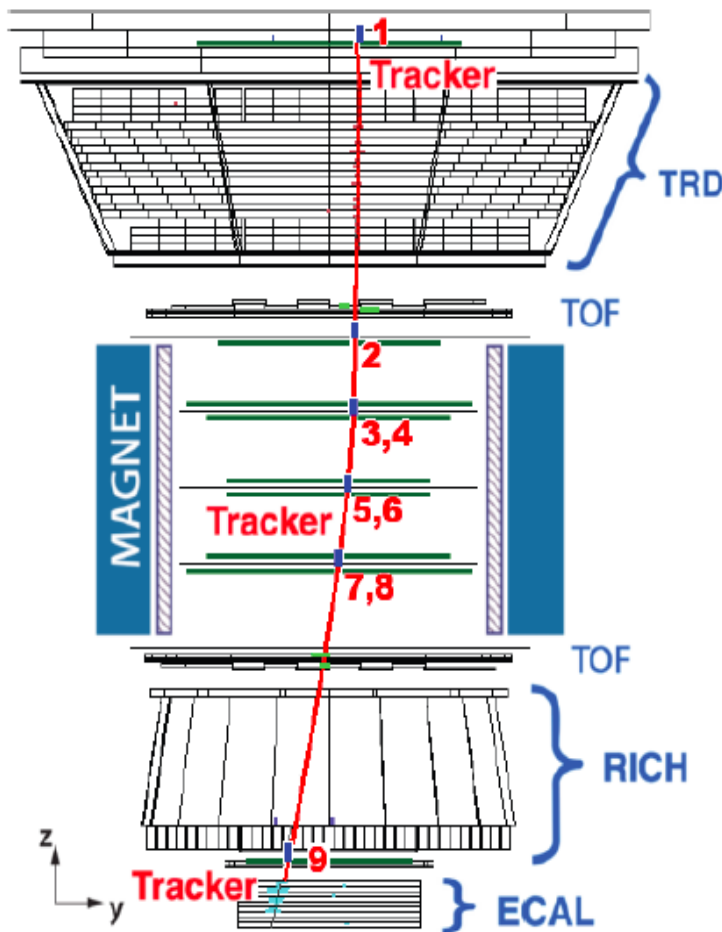


Challenges:

Alignment feature: Inner and external layers (due to the temperature variations on the ISS)

Track resolution depends on the number of layers included in the reconstruction

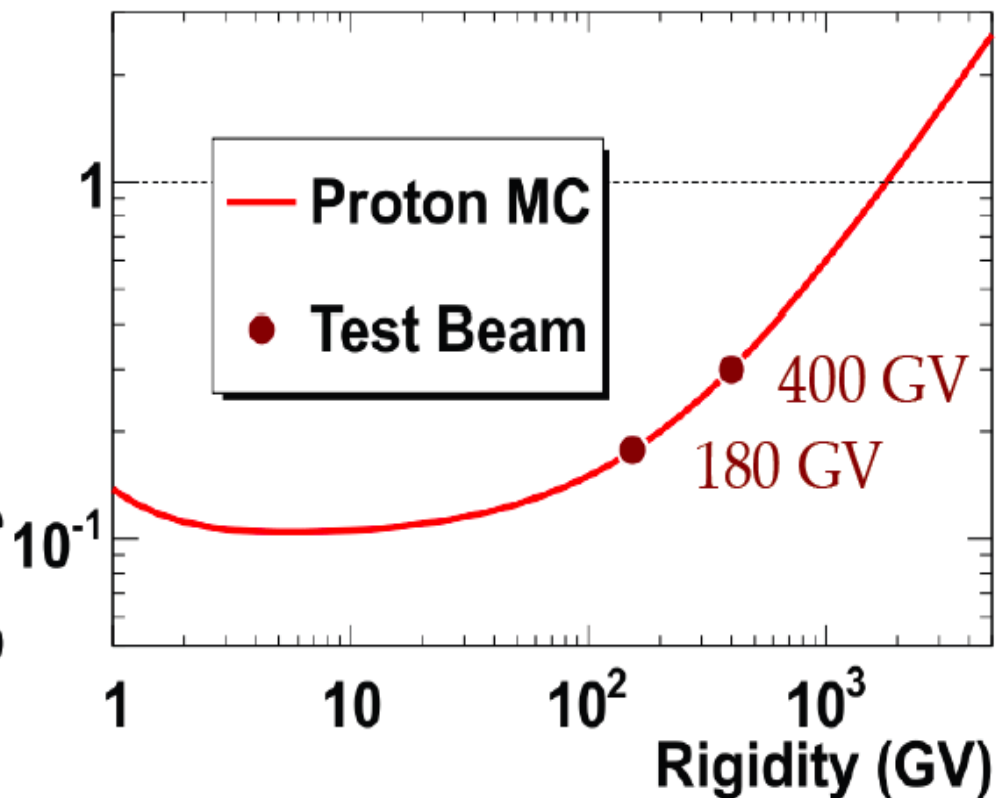




$$B_x = \sim 0.14 \text{ T} \quad L = \sim 3 \text{ m}$$

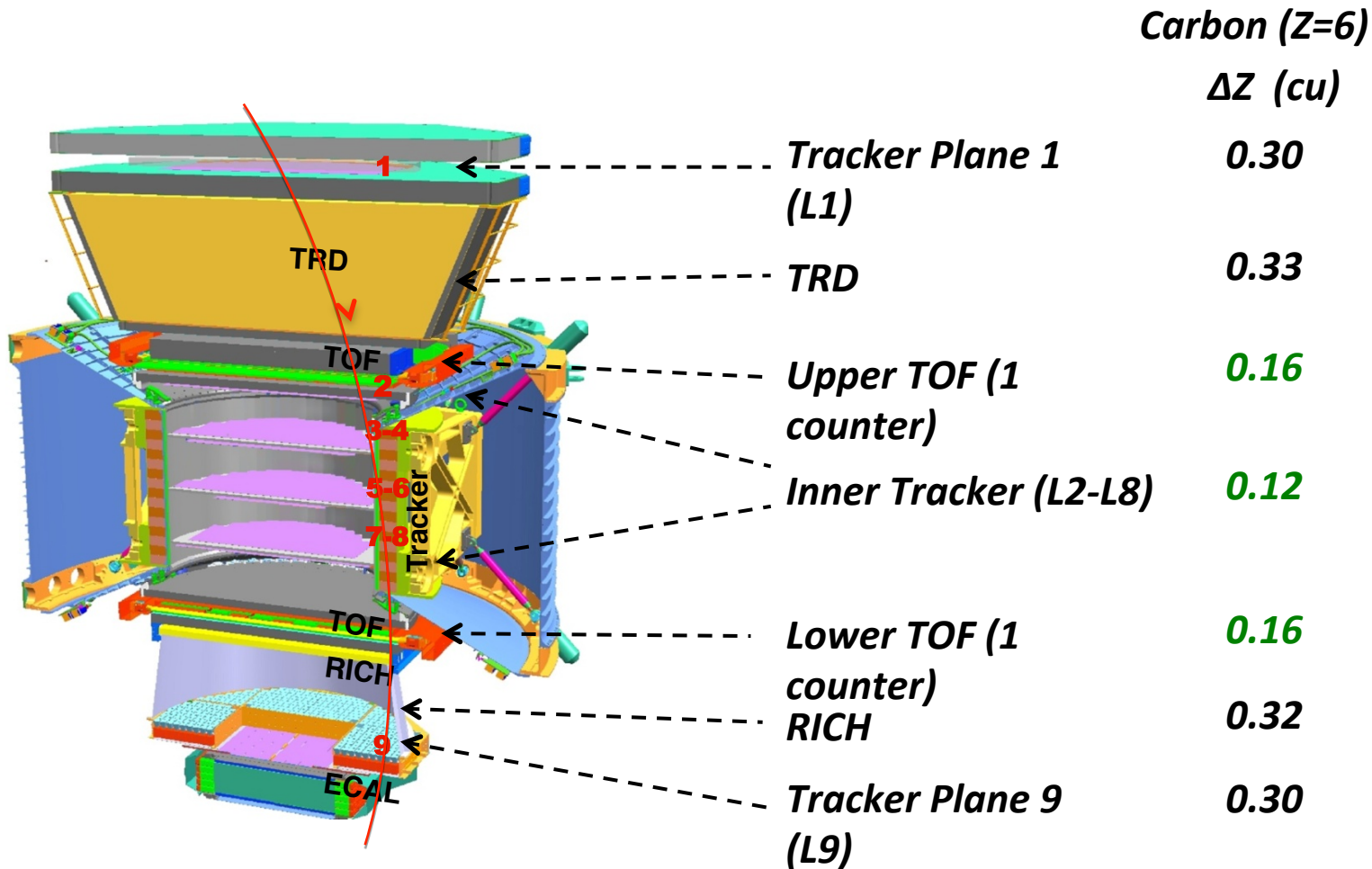
$$\sigma_y = \sim 10 \mu\text{m} \quad \text{MDR} : \sim 2 \text{ TV}$$

Rigidity resolution dR/R

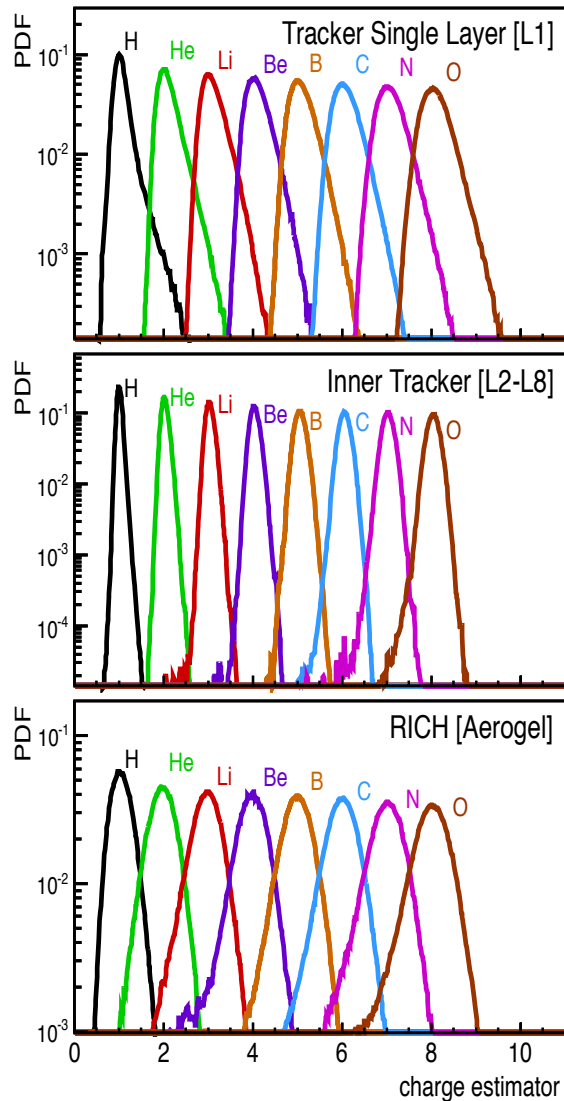


100% relative error for the rigidity
So called Maximum Detectable Rigidity
(MDR)

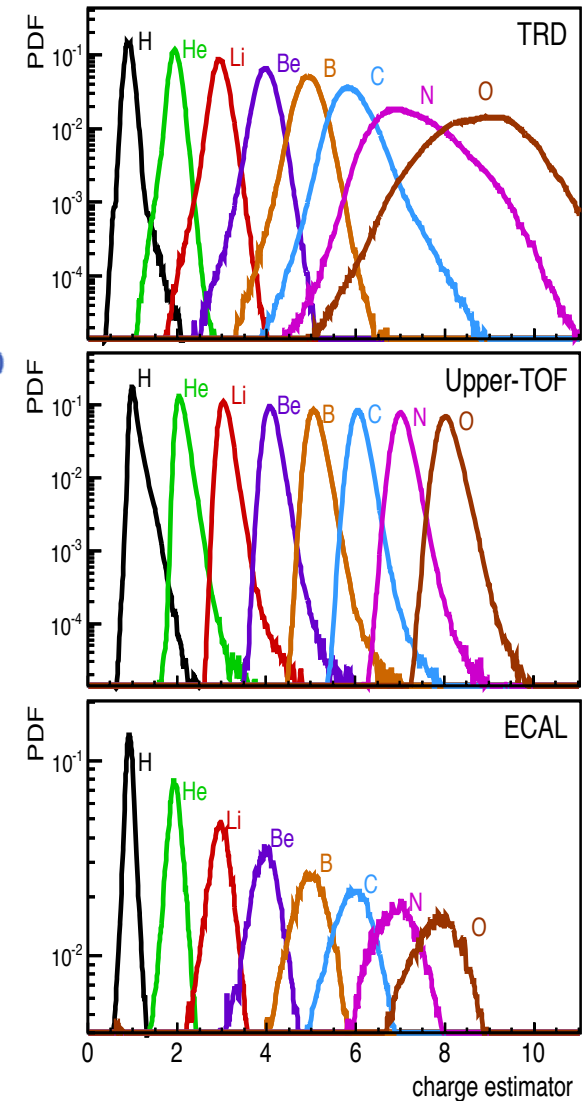
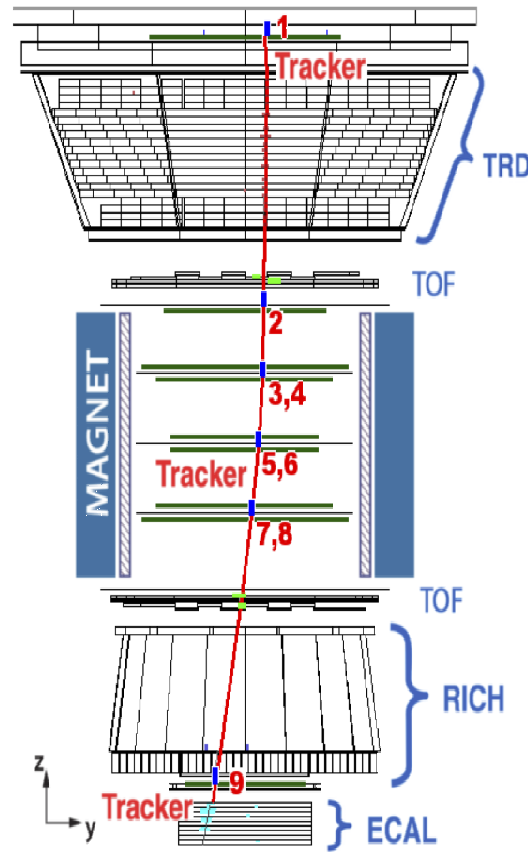
Charge measurement ($|Z|$)



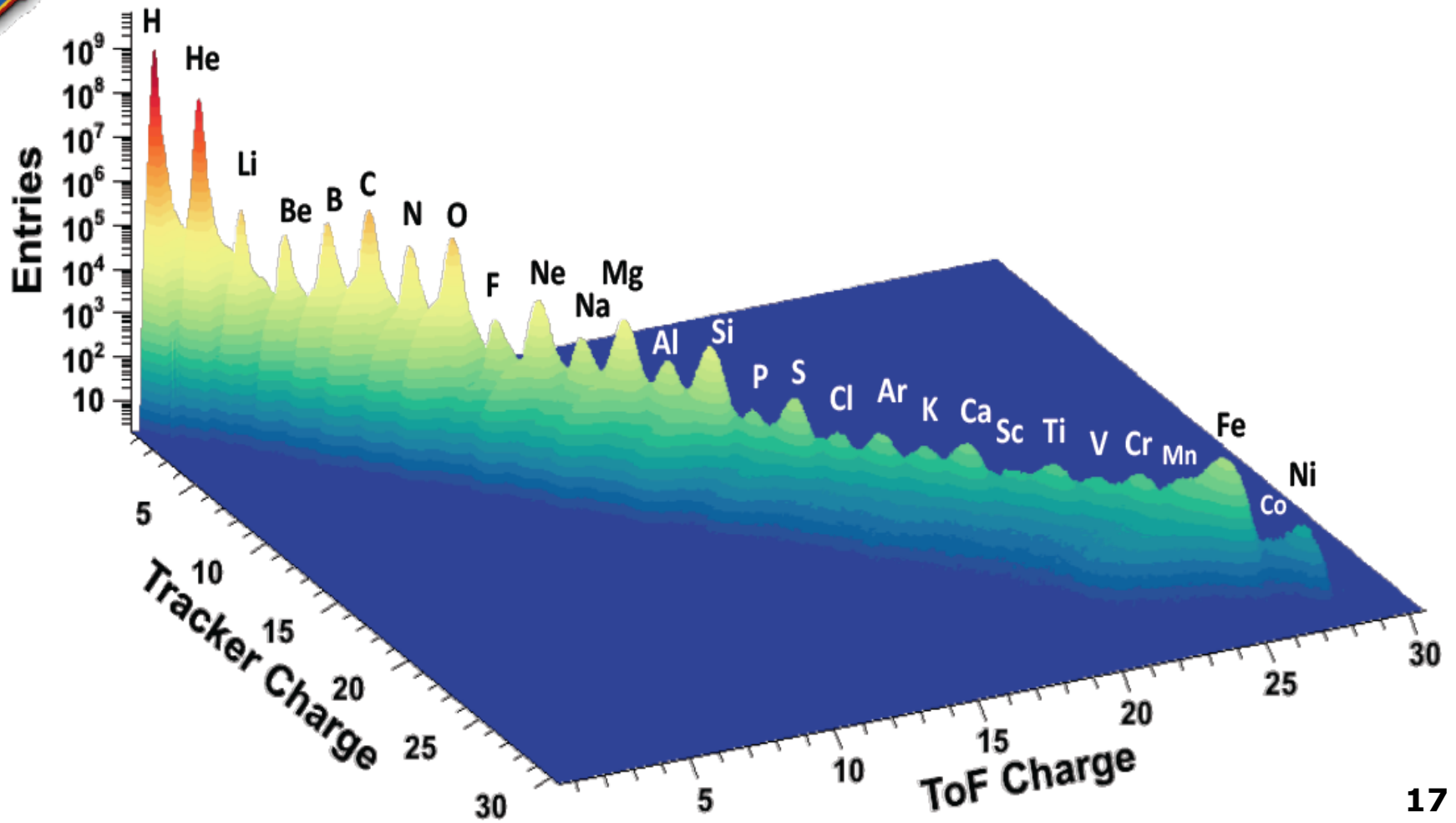
Charge Measurement



AMS-02 Charge Measurements of Light Cosmic-Ray Nuclei

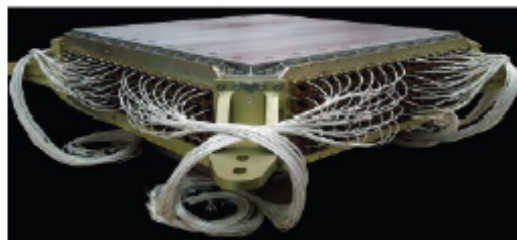
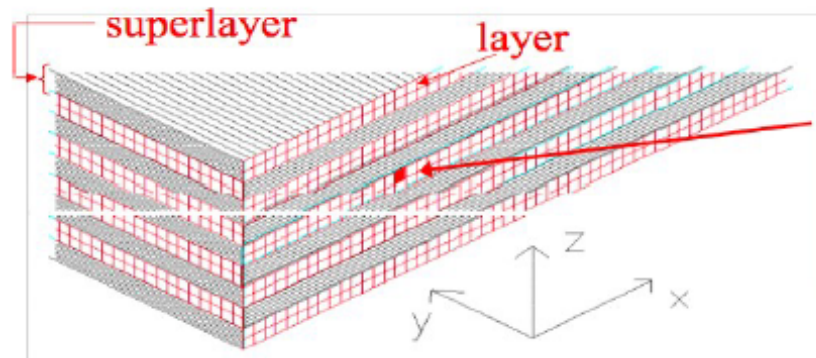


Nuclei Identification in AMS: ToF and Tracker



Energy Measurement

The AMS-02 electromagnetic calorimeter: a 3-D sampling calorimeter made out of **lead** and **scintillating fibers**

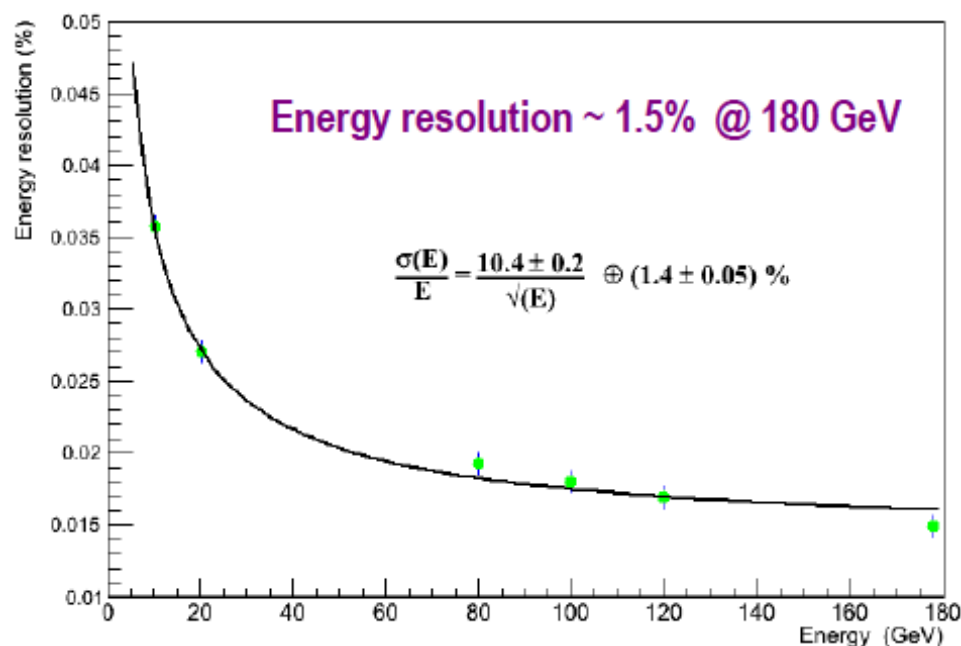


High granularity: $\sim 0.9 \times 0.9$ cm

18 Longitudinal samplings

72 Lateral samplings

17 X_0 , $\lambda_1 / X_0 \sim 22$



Flux and Ratio Determination

Flux is given by:

$$\Phi(\overline{K_n}) = \frac{N(K_n, K_n + \Delta K_n)}{A \epsilon \Delta T \Delta K_n}$$

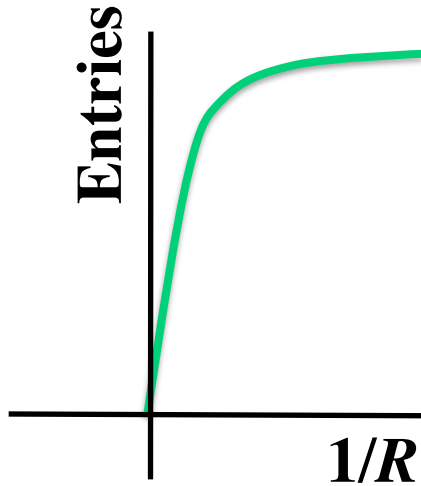
Diagram illustrating the components of the flux equation:

- Number of counts** points to $N(K_n, K_n + \Delta K_n)$.
- Acceptance ($m^2 sr$)** points to A .
- Efficiency (trigger, selection)** points to ϵ .
- Exposure Time** points to ΔT .
- Bin Width** points to ΔK_n .

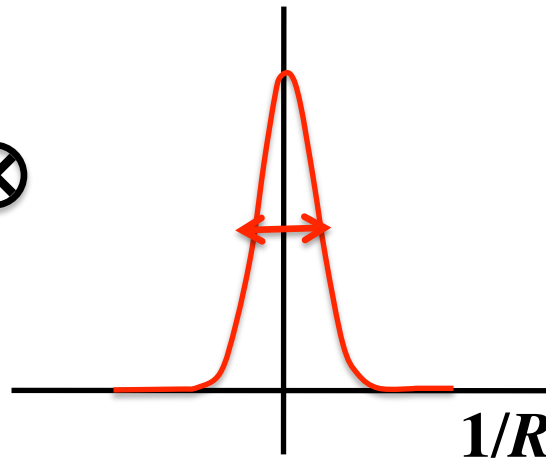
K_n is the kinetic energy per nucleon, or the momentum for electron, positron is measured from TOF and RICH (beta)
or from Tracker (rigidity) or ECAL(leptons)

Spectrum unfolding

**True
spectrum**

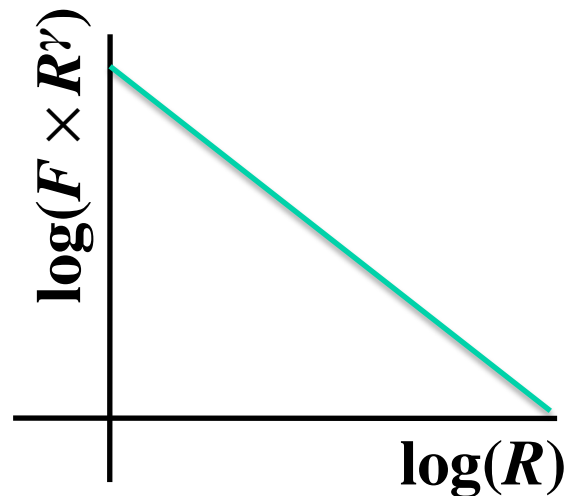
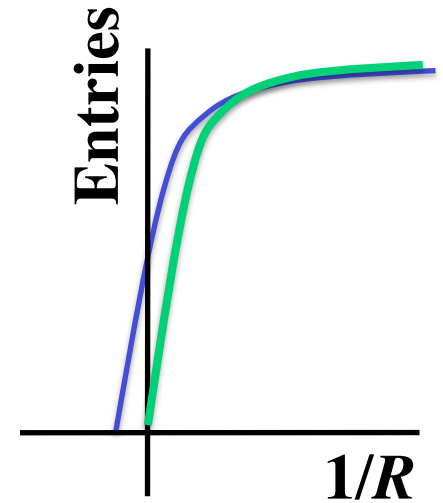


Resolution function :
 $\sigma = 1/\text{MDR}$



=

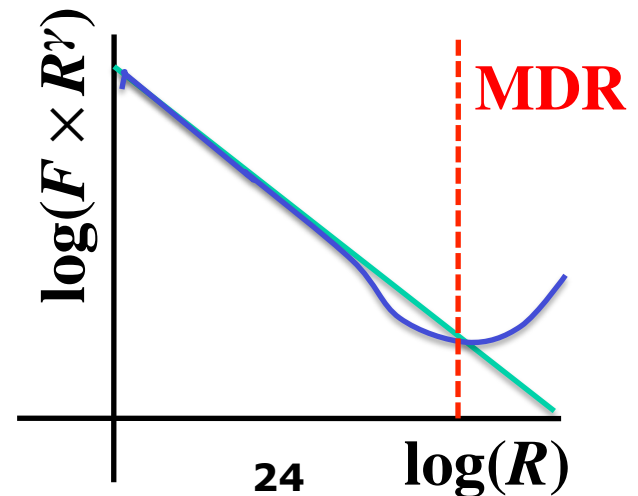
**Measured
spectrum**



Deformation



Unfolding



protons - Systematic errors

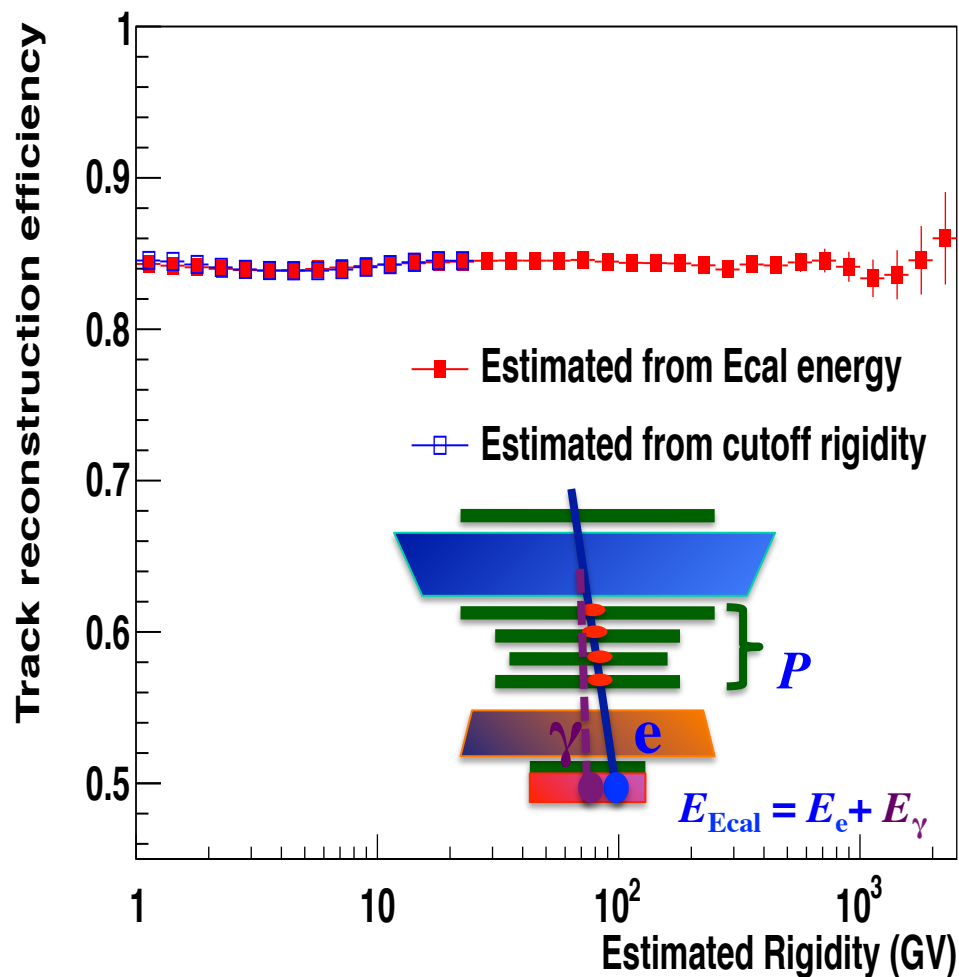
- Acceptance $\epsilon_{ac} = 2.8 \%$
- Trigger efficiency $\epsilon_{trg.} = 1.0 \%$
- Track reconstruction efficiency $\epsilon_{trk.} = 1.0 \%$
- Total systematic errors of normalization :

$$\epsilon_{norm.} = (\epsilon_{acc}^2 + \epsilon_{trg.}^2 + \epsilon_{trk.}^2)^{1/2} = 3.1 \%$$
- Systematic error of unfolding

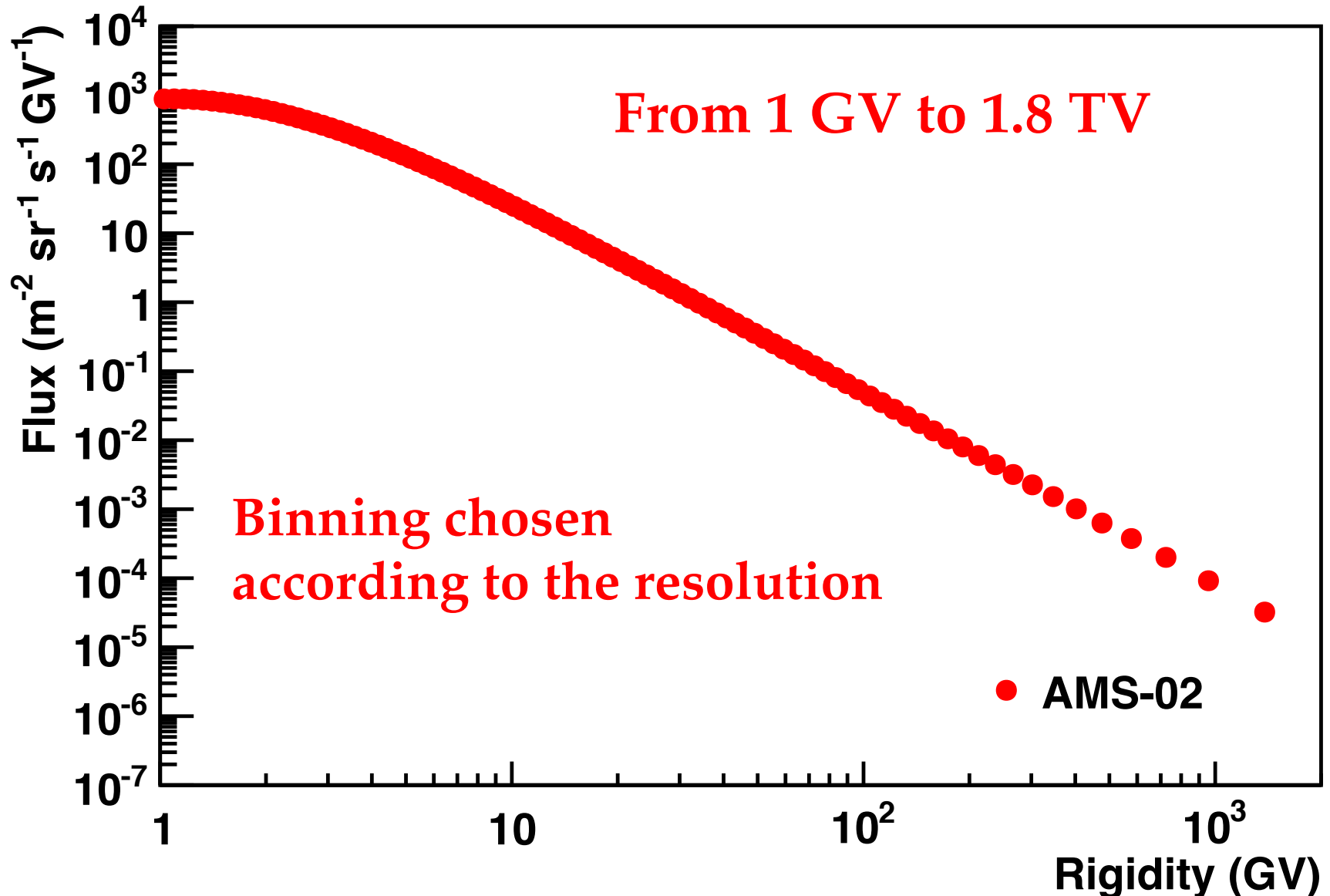
$$\epsilon_{unfold} < 1 \%$$
 at $R < 200$ GV

$$\epsilon_{unfold} = 5.4 \%$$
 at $R = 1$ TV

Systematic errors will be reduced with more data

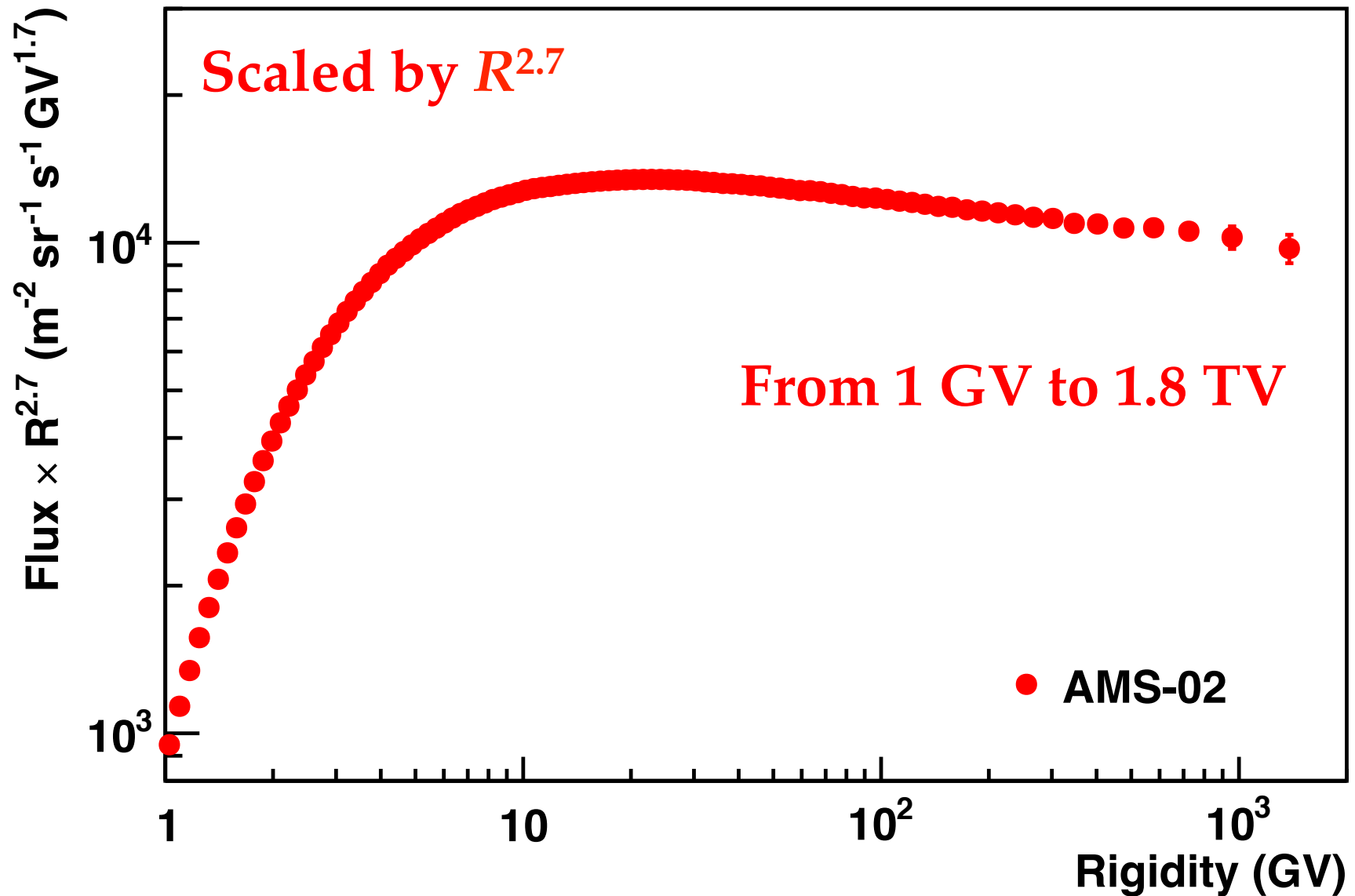


Proton Fluxes

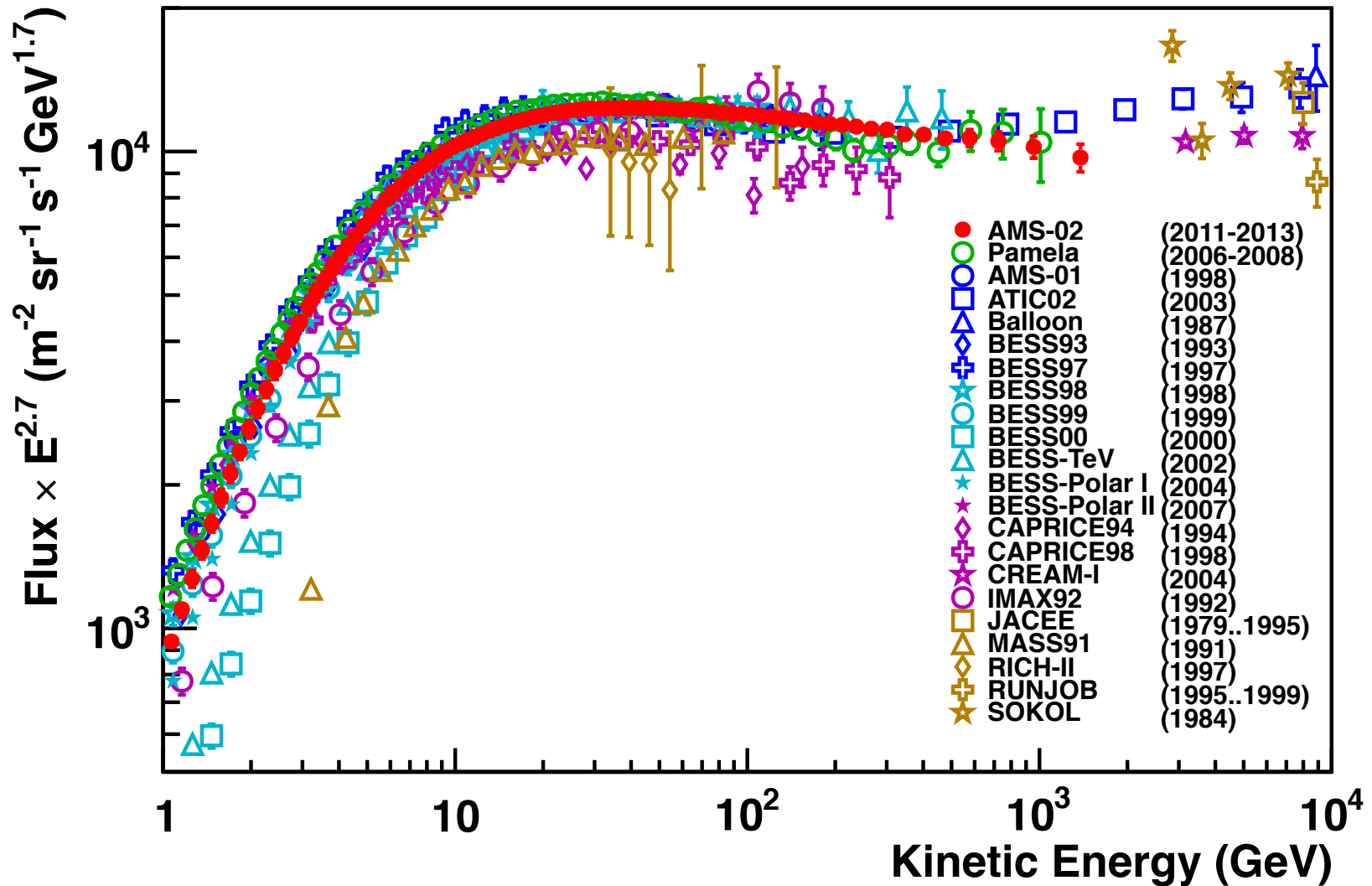


Power law behaviour, index > 2.7 , > 1000 protons above 1 TV

Proton Flux



Protons- Comparison with previous measurements



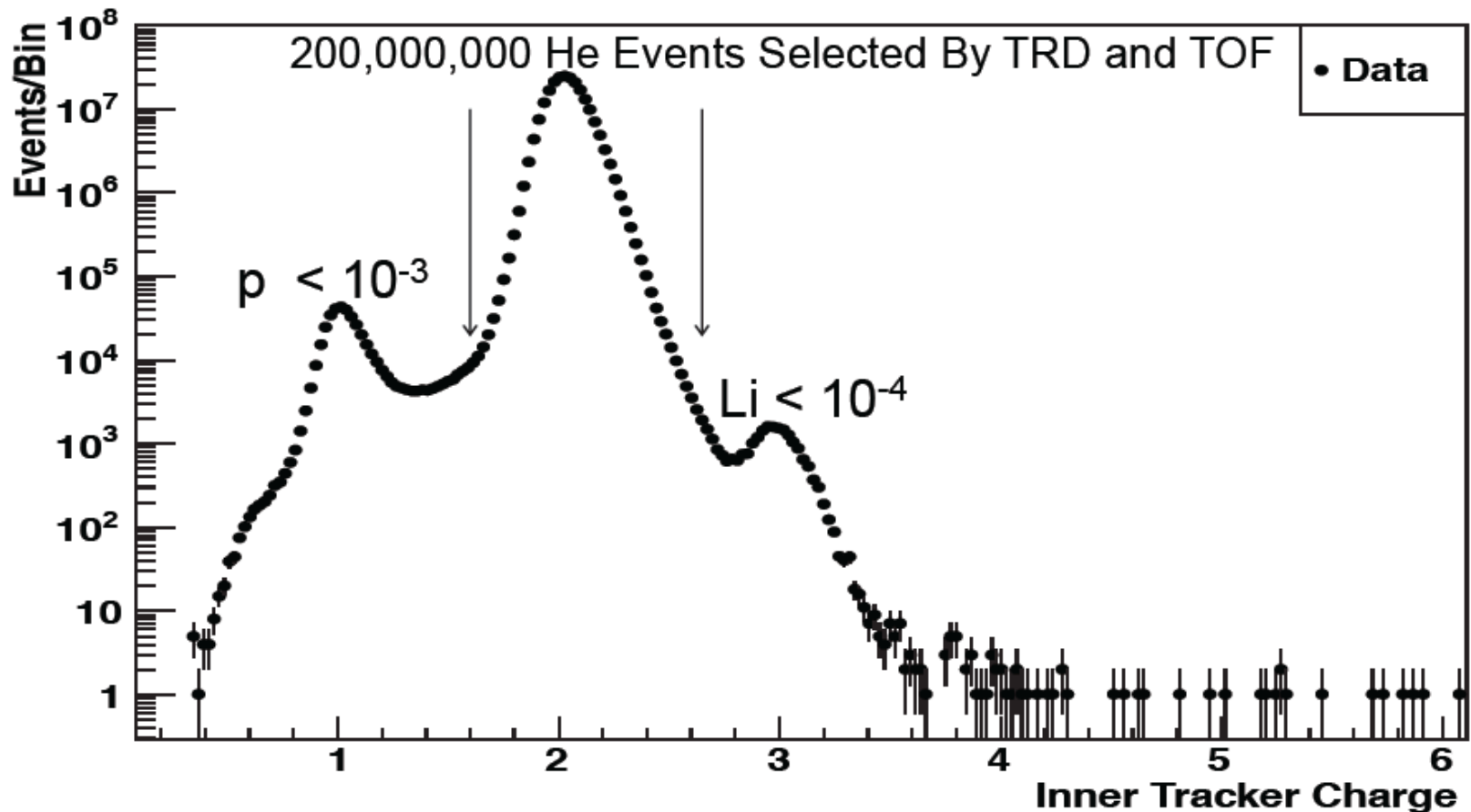
Helium Nuclei Selection



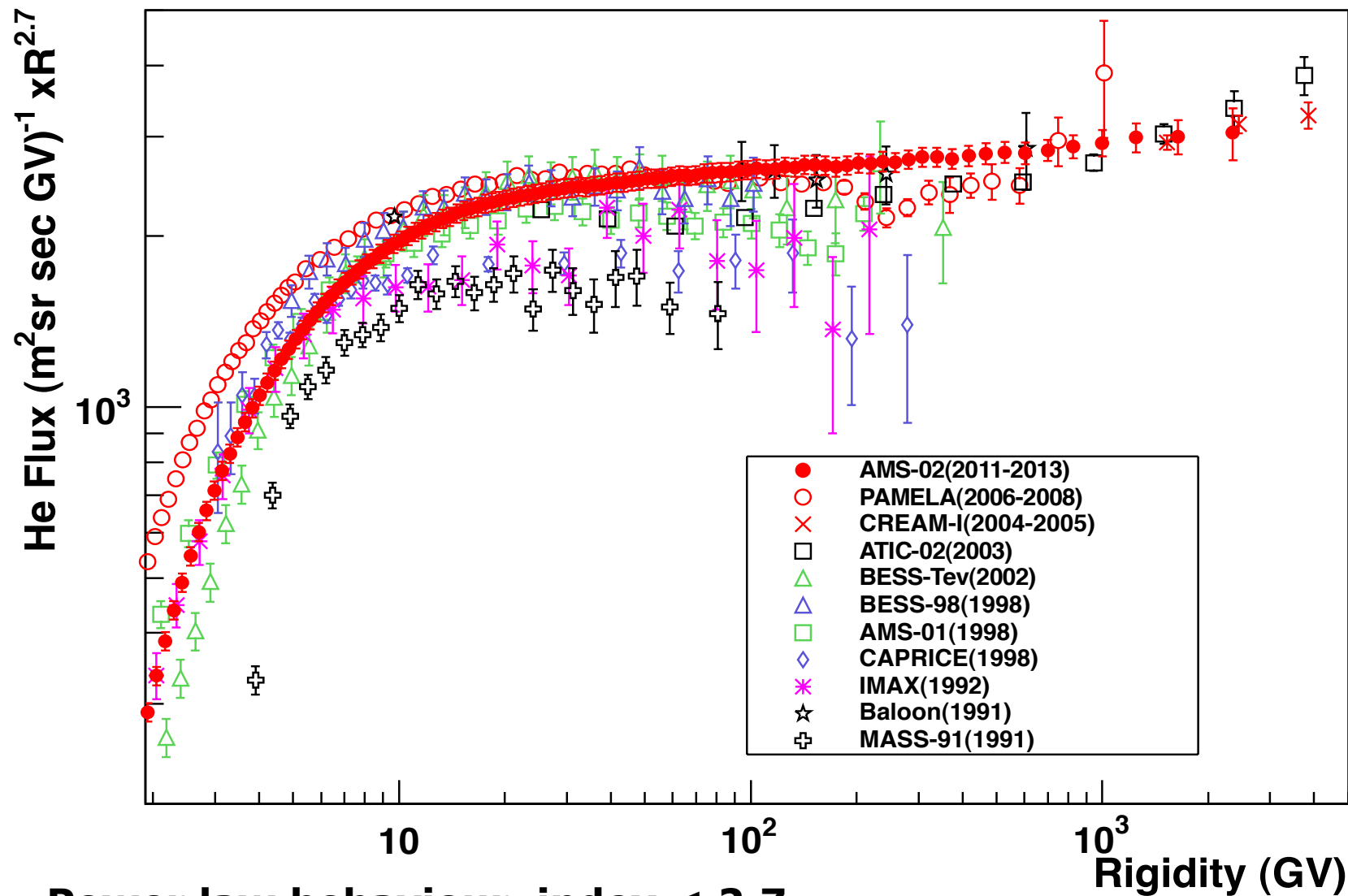
Helium Selection

Proton background: $<10^{-5}$

Main Remaining Background: Ions Interacted on Top of AMS $<10^{-3}$

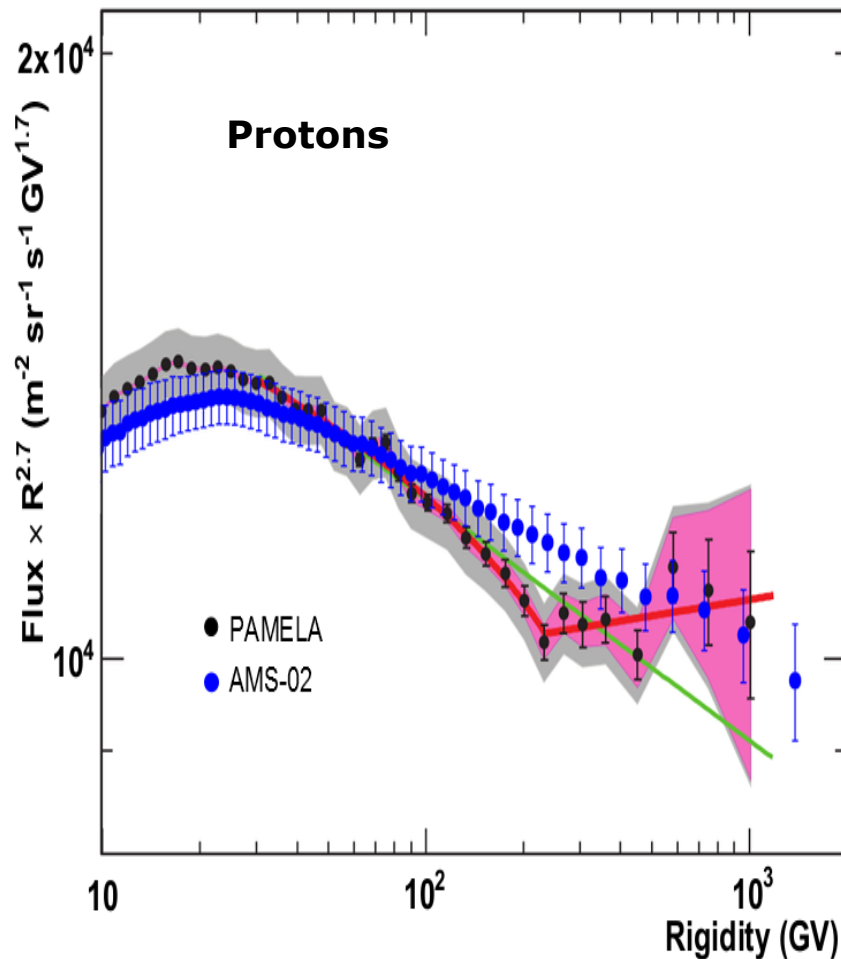


Ams-02 Helium flux Comparison with previous measurements

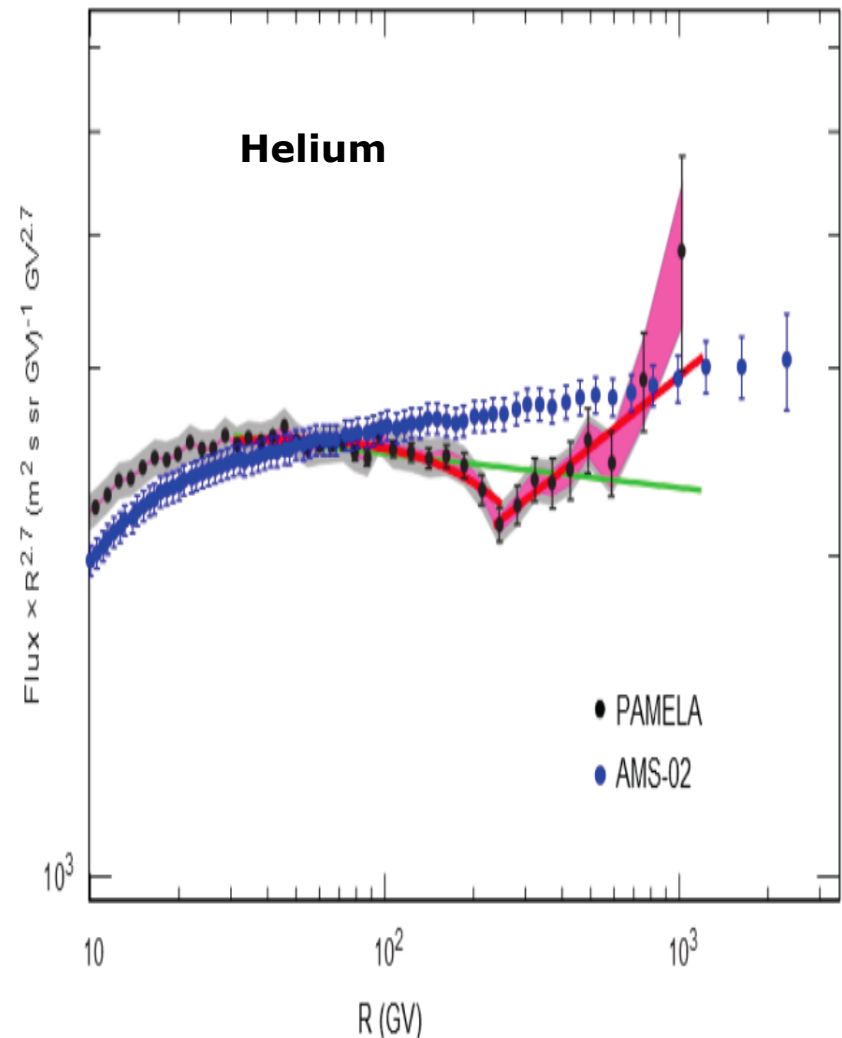


Helium - Comparison with Pamela measurements

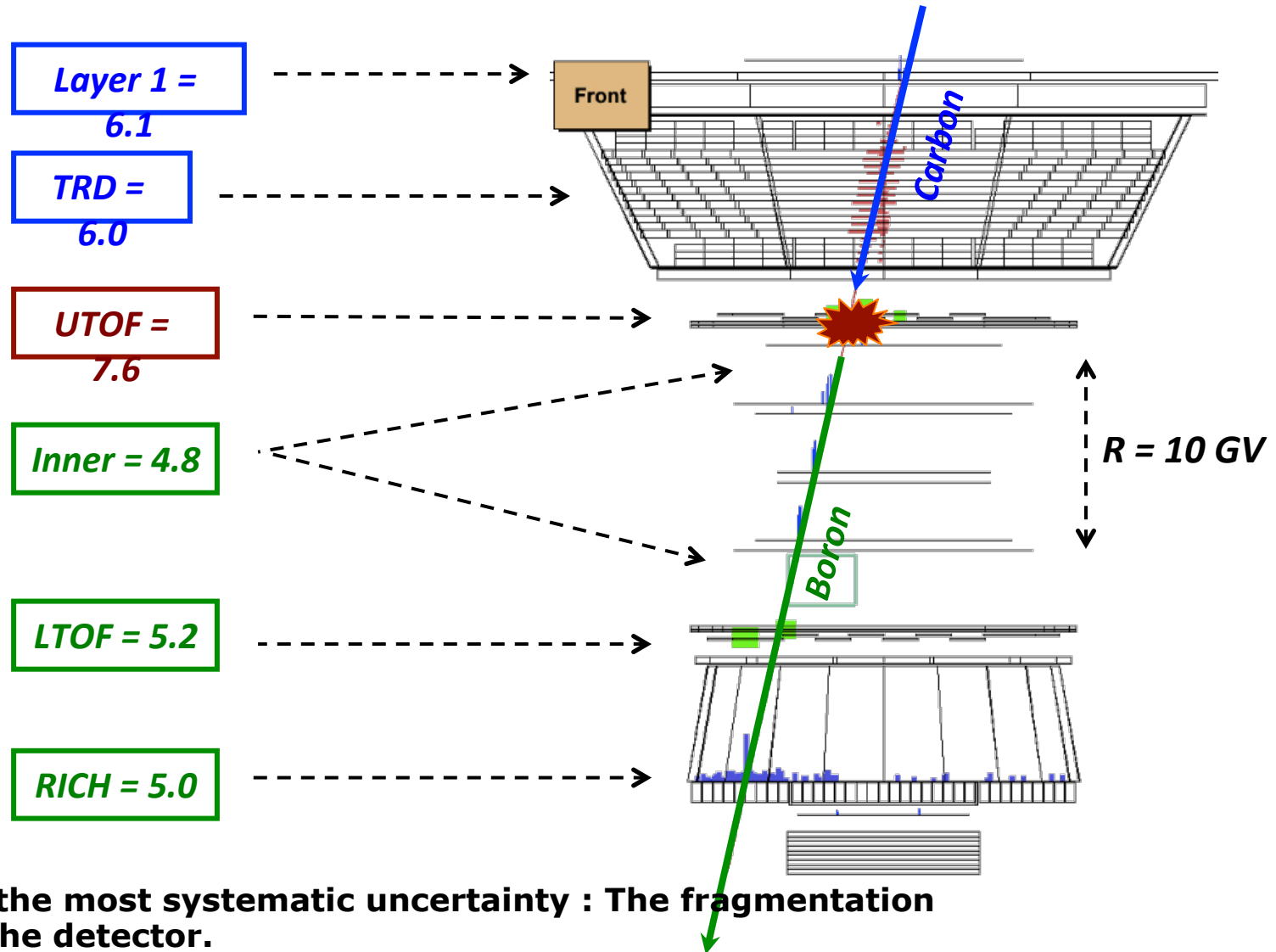
**H Power law behaviour,
index > 2.7**



**He Power law behaviour,
index < 2.7**



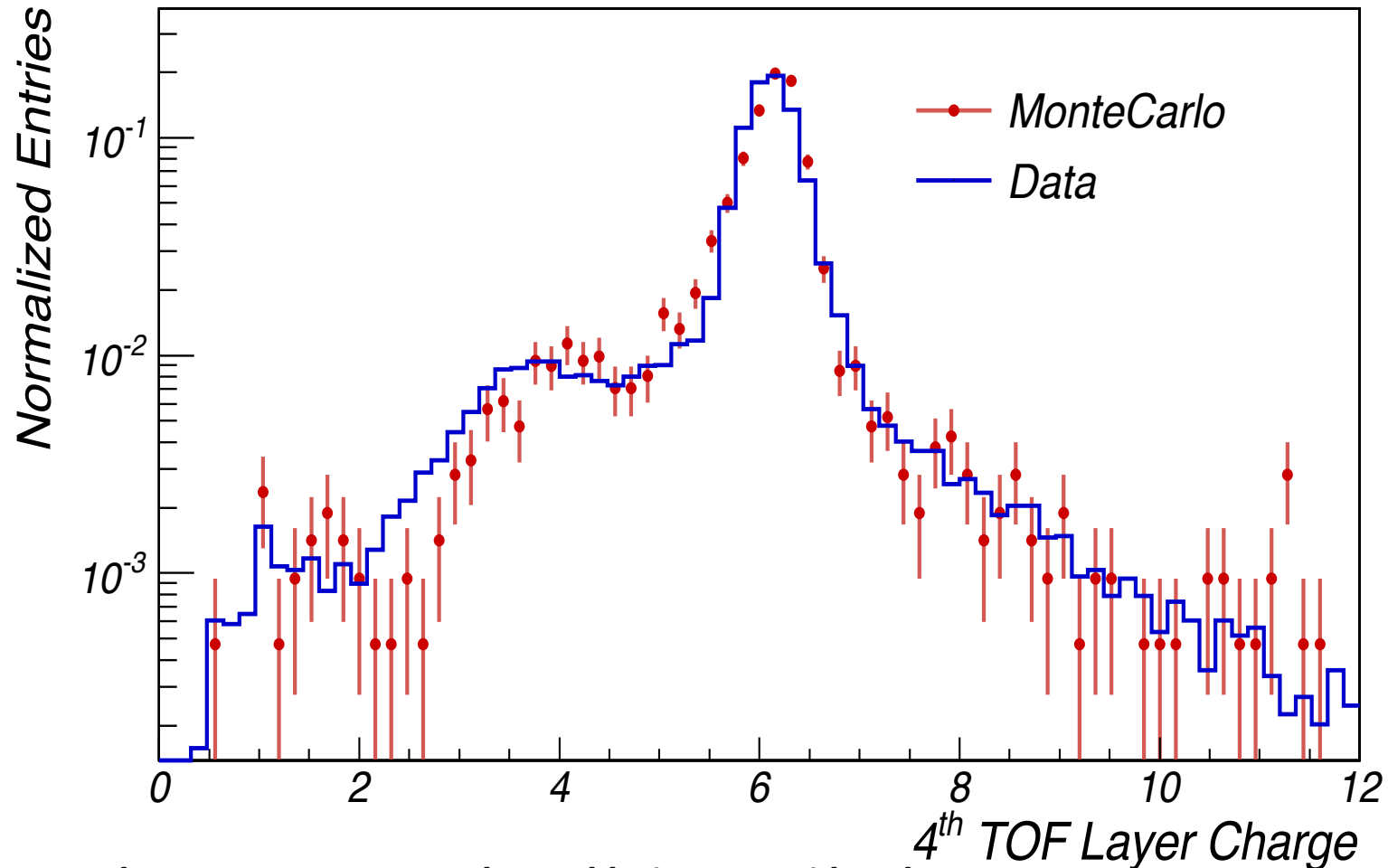
B/C : Identification of Fragmentation Events



One of the most systematic uncertainty : The fragmentation inside the detector.

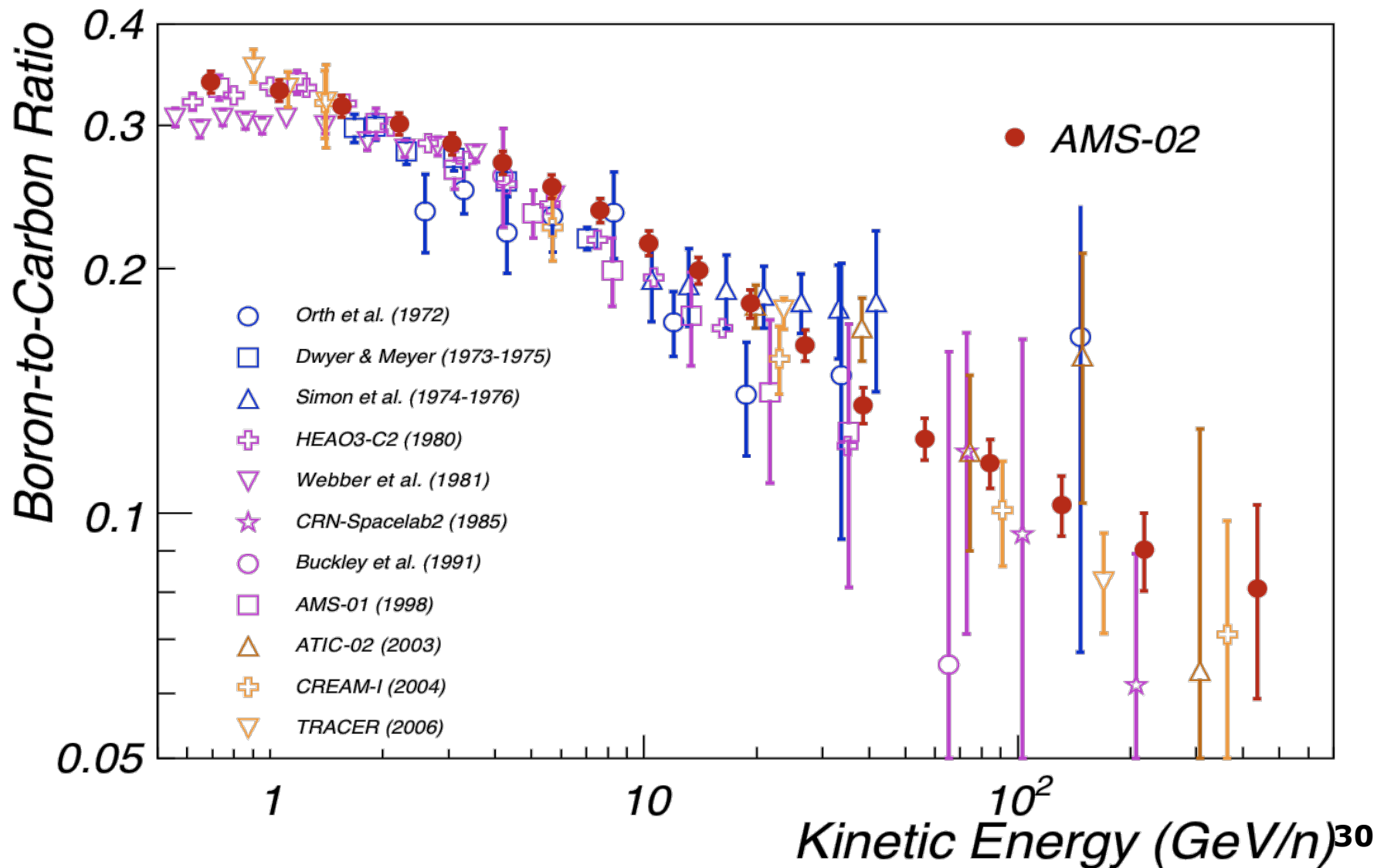
The first layer do play a key role in the selection

- *Acceptance is convolution of geometry and fragmentation effects.*
- *Carbon selected with L1 and UTOF. Fragmentation distribution evaluated with LTOF.*



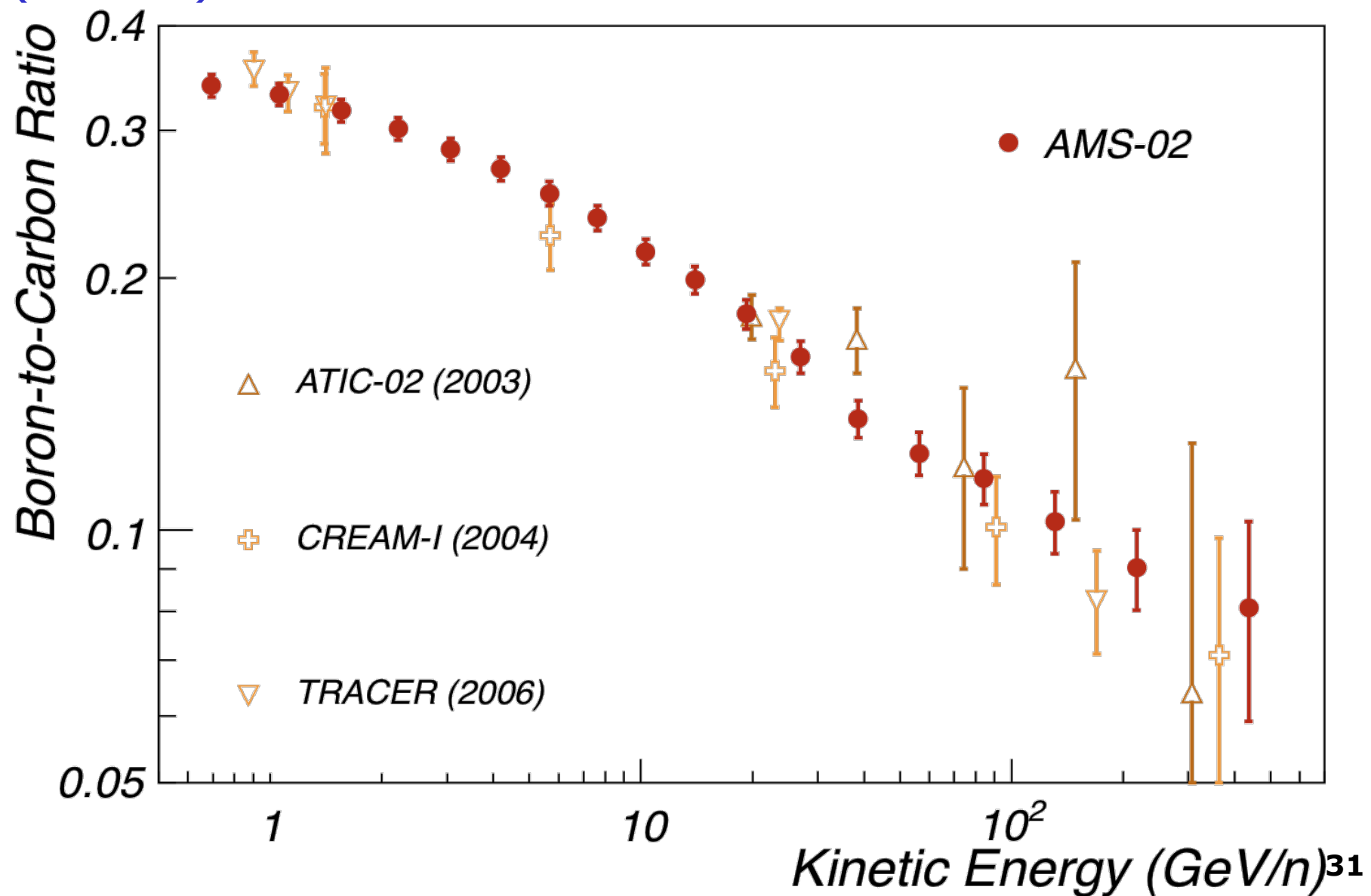
Data and MC agreement evaluated being at 2% level.

AMS-02 Boron/Carbon Ratio



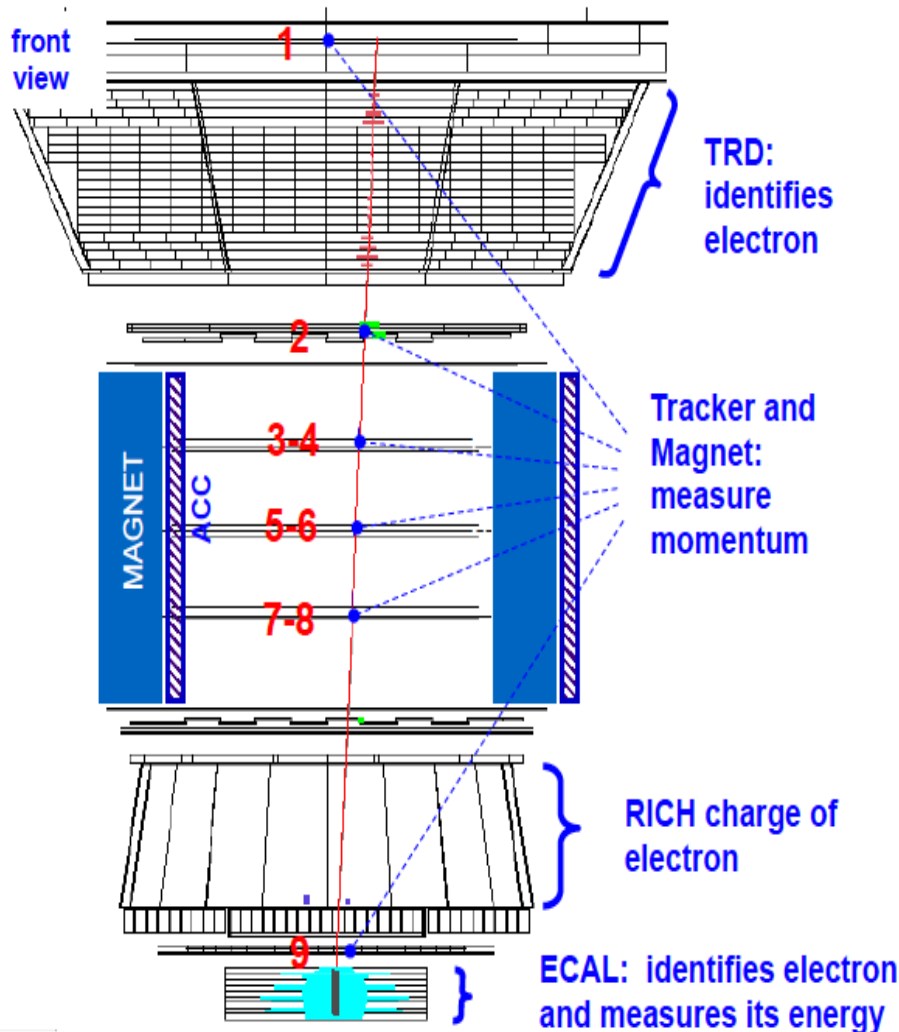
AMS-02 Boron/Carbon Ratio band recent measurements

(>2000)

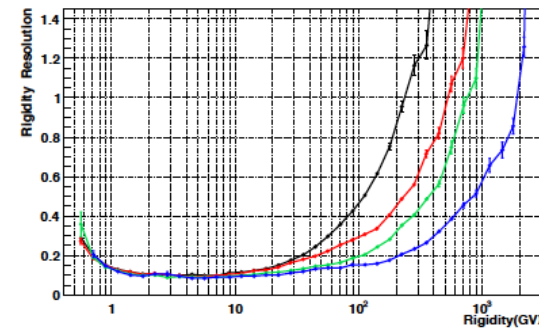
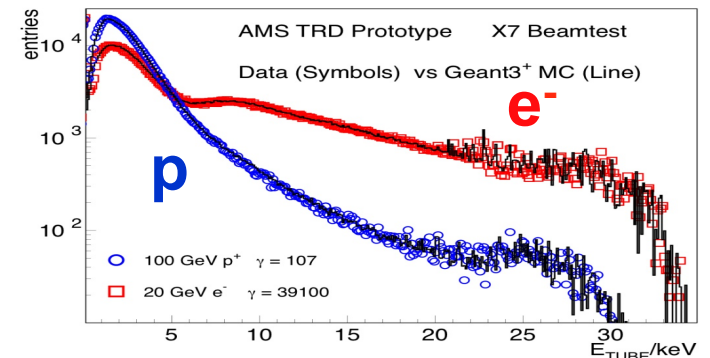


e+,e- Identification in AMS

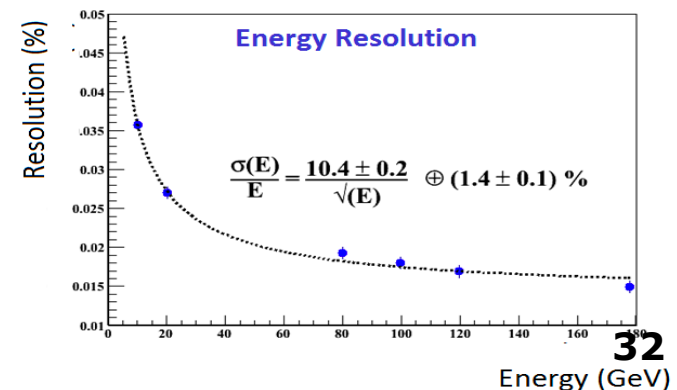
Proton rejection goal $> 1/100000 \Rightarrow$ 3 independent detectors are used



AMS data on ISS: 424 GeV positron

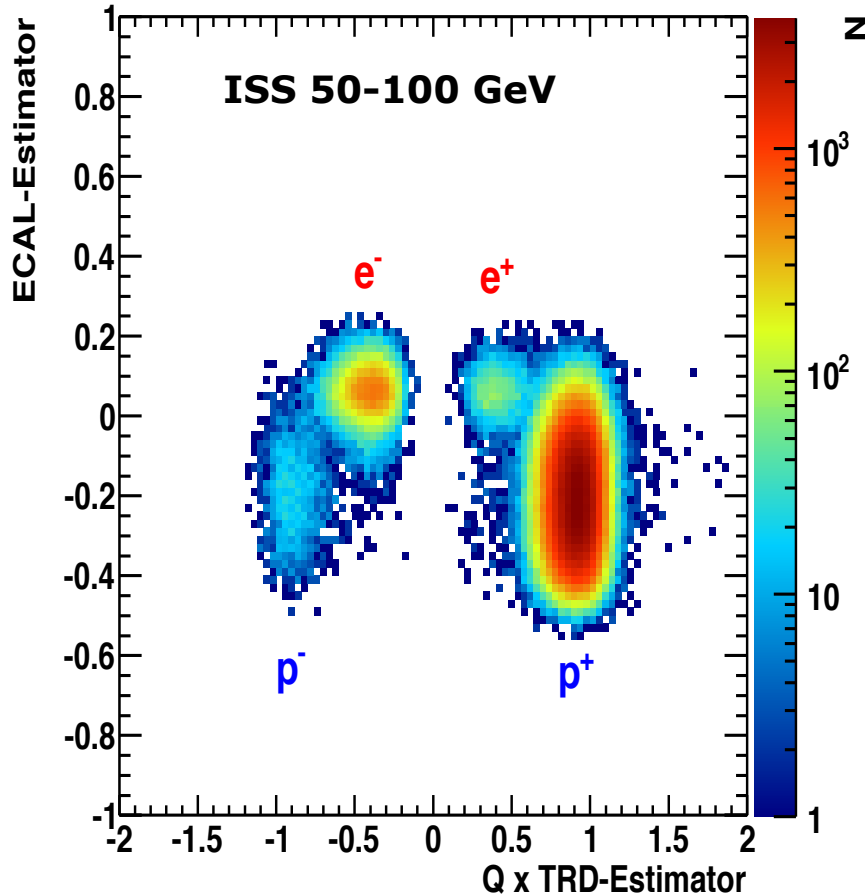


MDR=2 TV

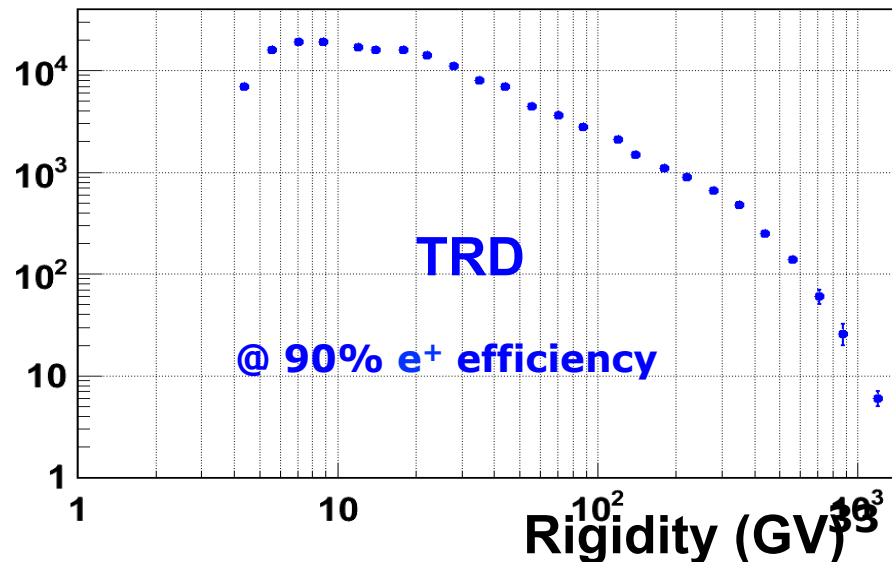
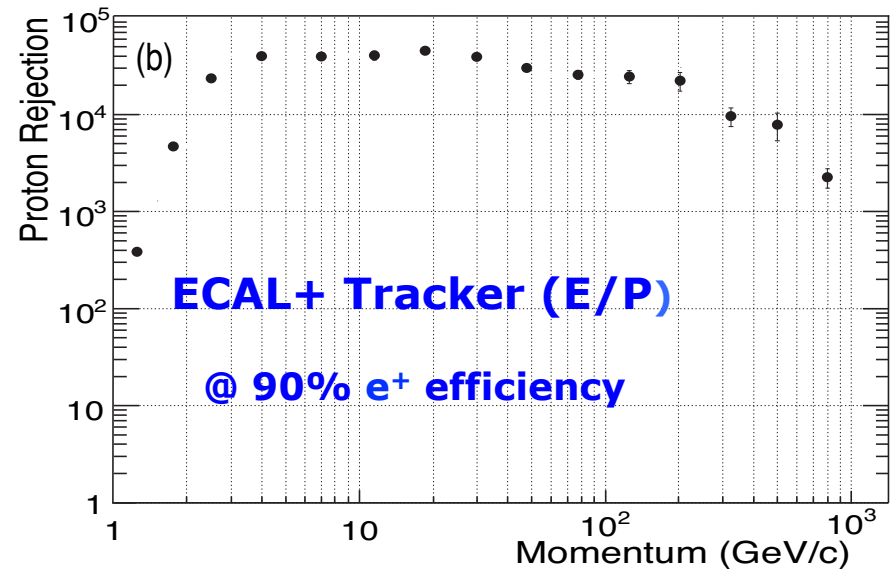


Proton rejection

ECAL estimator : Boost Decision Tree
based on the 3D shower shape features

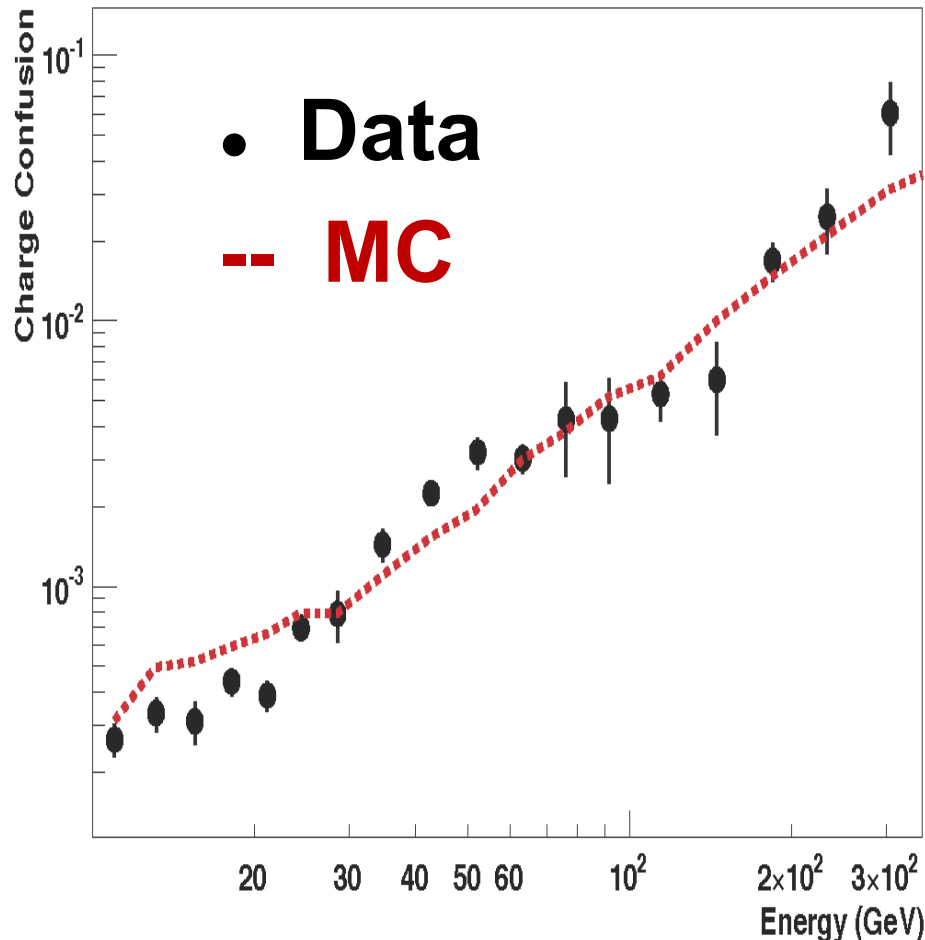


TRD estimator : likelihood based on
the signal amplitude in each layer (20 in total)



Electron rejection

Charge confusion average Tracker patterns



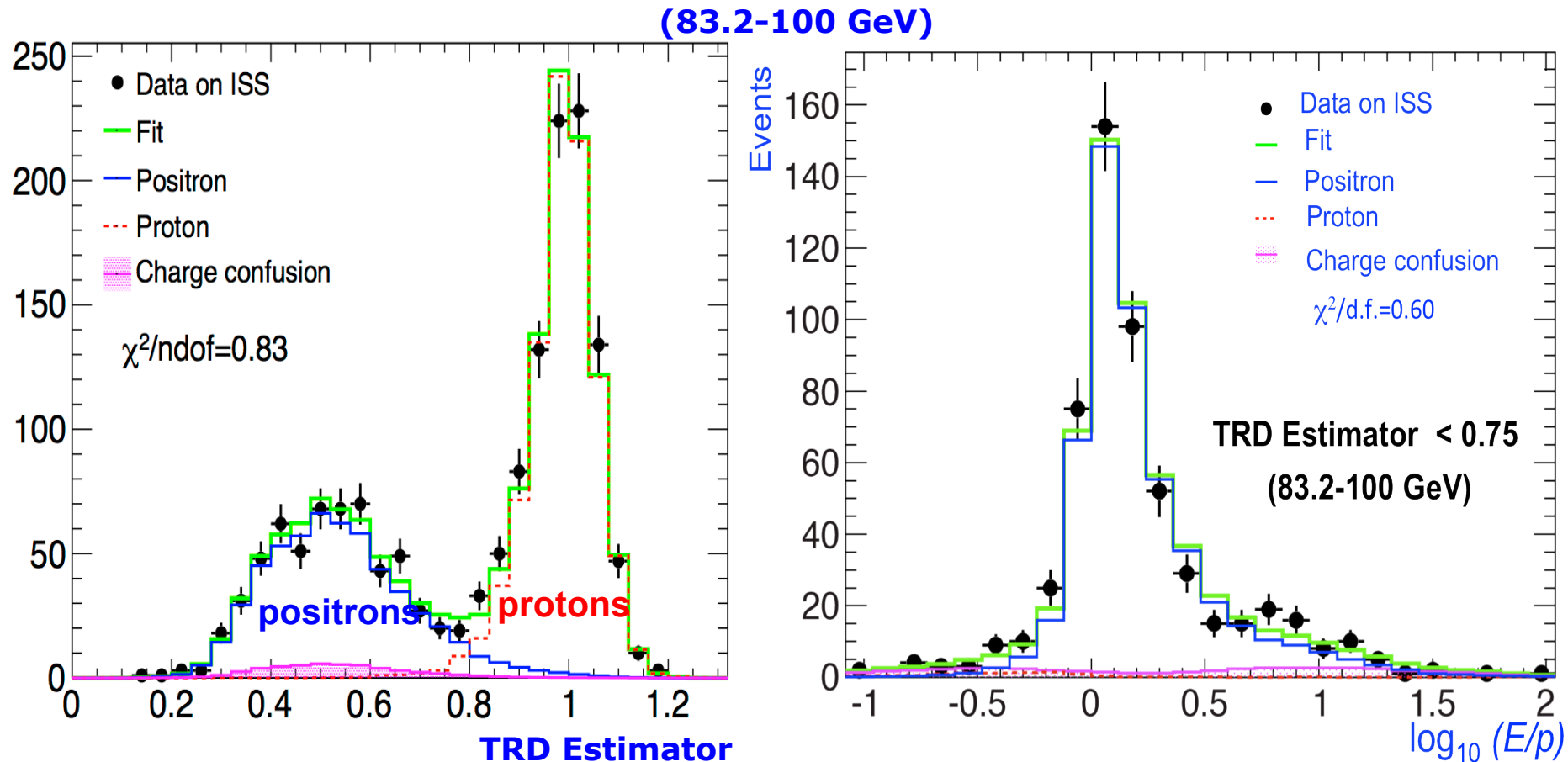
2 sources

- Multiple scattering and finite resolution of the tracker
- Secondary tracks produced along the the path of primary e^+ (tagged and controlled with the lower TOF)

Good agreement Data/MC

Analysis: 2D fit to measure $\mathbf{Ne^\pm}$ and $\mathbf{Np}$

Large statistics: 2-D reference spectra for the signal and **background** are fitted in the (E/P –TRD estimator) plane for each energy bin, after a pre-selection on the ECAL

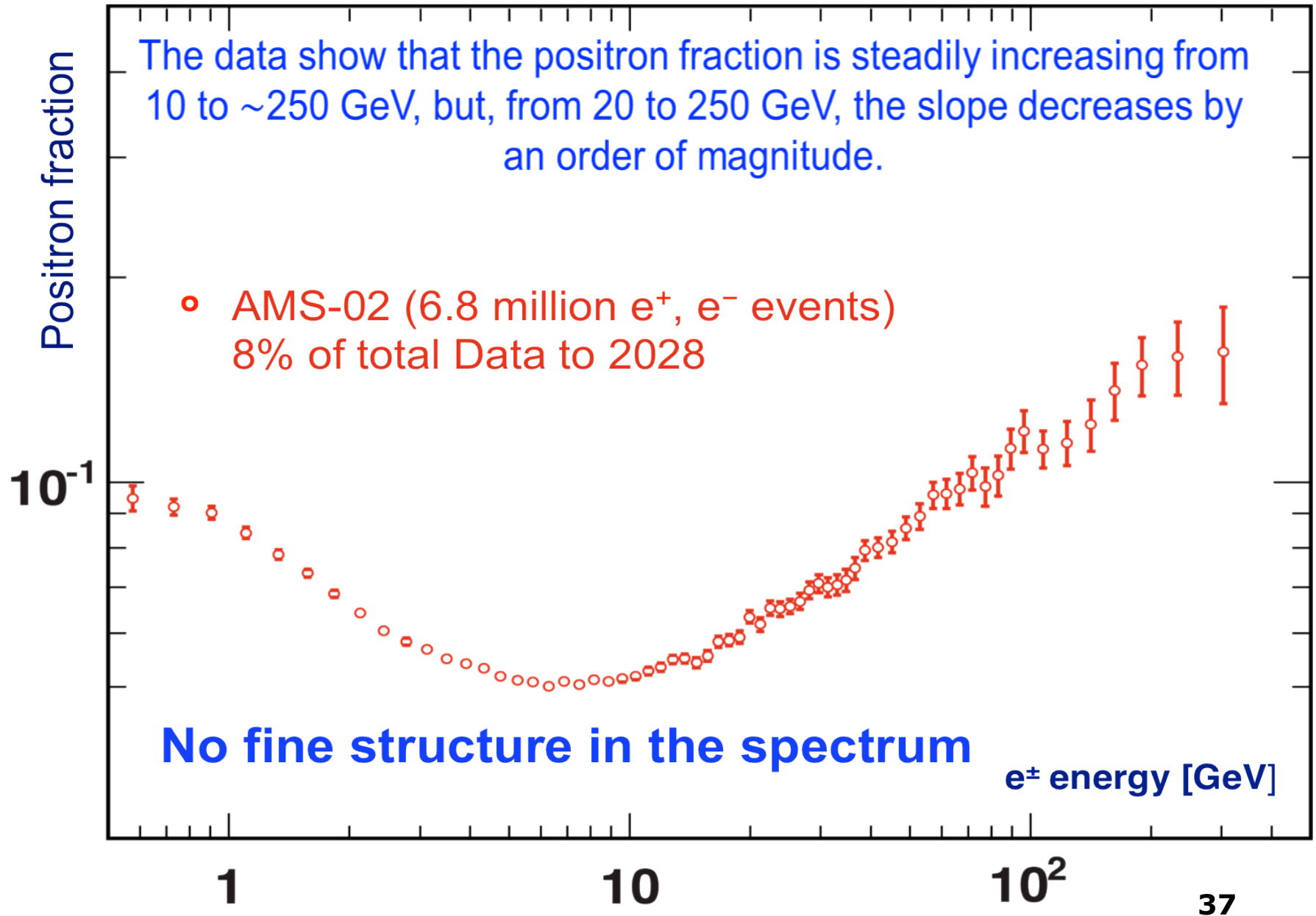


The large redundancy allows to control precisely the systematics uncertainties

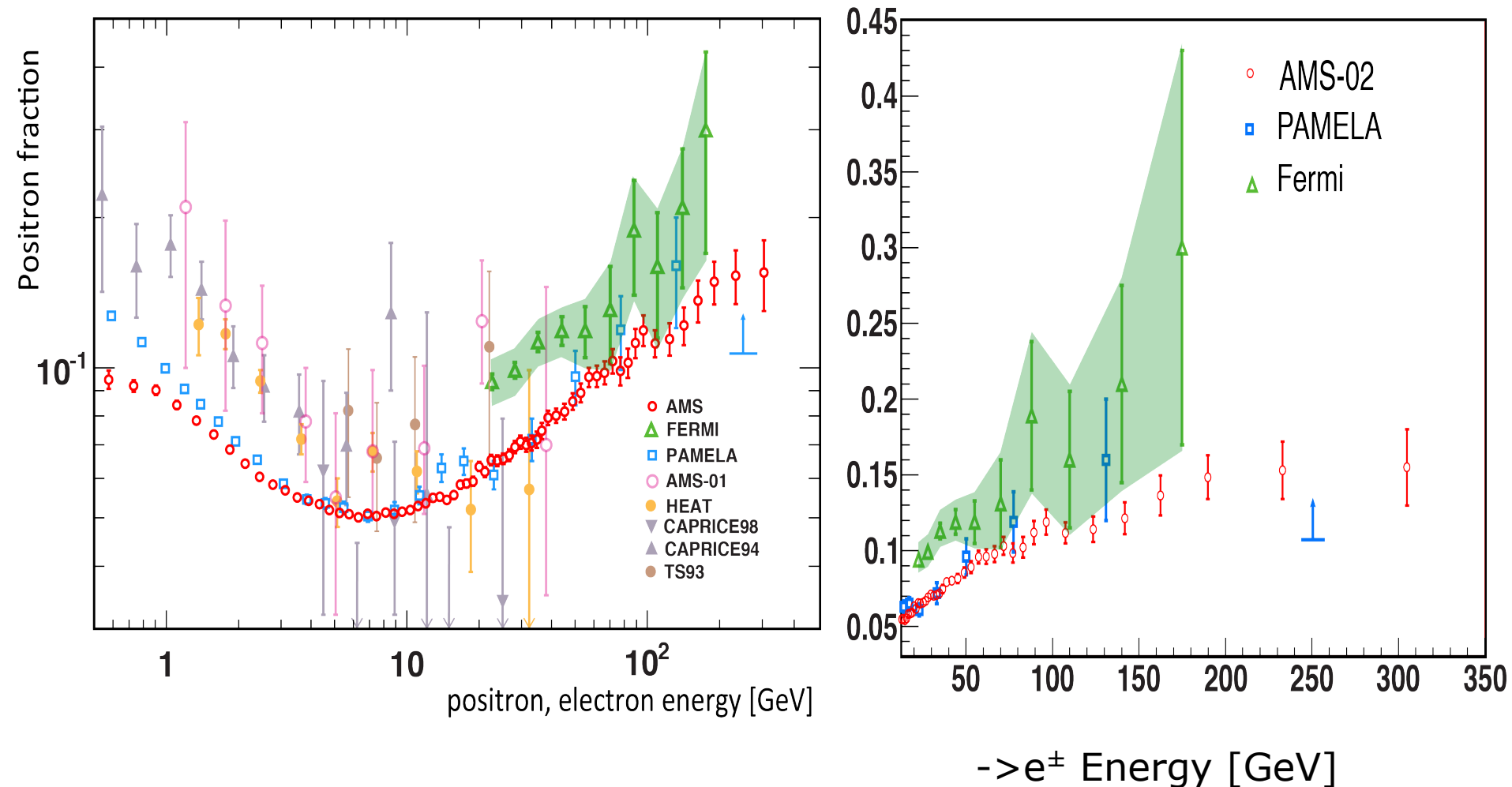
Representative bins of the positron fraction

positron fraction				Systematic Errors					
Energy [GeV]	N_{e^+}	Fraction	statistical error	acceptance asymmetry	event selection	bin-to-bin migration	reference spectra	charge confusion	total systematic uncertainty
Energy[GeV]	N_{e^+}	Fraction	$\sigma_{\text{stat.}}$	$\sigma_{\text{acc.}}$	$\sigma_{\text{sel.}}$	$\sigma_{\text{mig.}}$	$\sigma_{\text{ref.}}$	$\sigma_{\text{c.c.}}$	$\sigma_{\text{syst.}}$
1.00 -1.21	9 335	0.0842	0.0008	0.0005	0.0009	0.0008	0.0001	0.0005	0.0014
1.97 -2.28	23 893	0.0642	0.0004	0.0002	0.0005	0.0002	0.0001	0.0002	0.0006
3.30 -3.70	20 707	0.0550	0.0004	0.0001	0.0003	0.0000	0.0001	0.0002	0.0004
6.56 -7.16	13 153	0.0510	0.0004	0.0001	0.0000	0.0000	0.0001	0.0002	0.0002
9.95 -10.73	7 161	0.0519	0.0006	0.0001	0.0000	0.0000	0.0001	0.0002	0.0002
19.37 -20.54	2 322	0.0634	0.0013	0.0001	0.0001	0.0000	0.0001	0.0002	0.0003
30.45 -32.10	1094	0.0701	0.0022	0.0001	0.0002	0.0000	0.0001	0.0003	0.0004
40.00 -43.39	976	0.0802	0.0026	0.0002	0.0005	0.0000	0.0001	0.0004	0.0007
50.87 -54.98	605	0.0891	0.0038	0.0002	0.0006	0.0000	0.0001	0.0004	0.0008
64.03 -69.00	392	0.0978	0.0050	0.0002	0.0010	0.0000	0.0002	0.0007	0.0013
74.30 -80.00	276	0.0985	0.0062	0.0002	0.0010	0.0000	0.0002	0.0010	0.0014
86.00 -92.50	240	0.1120	0.0075	0.0002	0.0010	0.0000	0.0003	0.0011	0.0015
100.0 -115.1	304	0.1118	0.0066	0.0002	0.0015	0.0000	0.0003	0.0015	0.0022
115.1 -132.1	223	0.1142	0.0080	0.0002	0.0019	0.0000	0.0004	0.0019	0.0027
132.1 -151.5	156	0.1215	0.0100	0.0002	0.0021	0.0000	0.0005	0.0024	0.0032
151.5 -173.5	144	0.1364	0.0121	0.0002	0.0026	0.0000	0.0006	0.0045	0.0052
173.5 -206.0	134	0.1485	0.0133	0.0002	0.0031	0.0000	0.0009	0.0050	0.0060
206.0 -260.0	101	0.1530	0.0160	0.0003	0.0031	0.0000	0.0013	0.0095	0.0101
260.0 -350.0	72	0.1550	0.0200	0.0003	0.0056	0.0000	0.0018	0.0140	0.0152

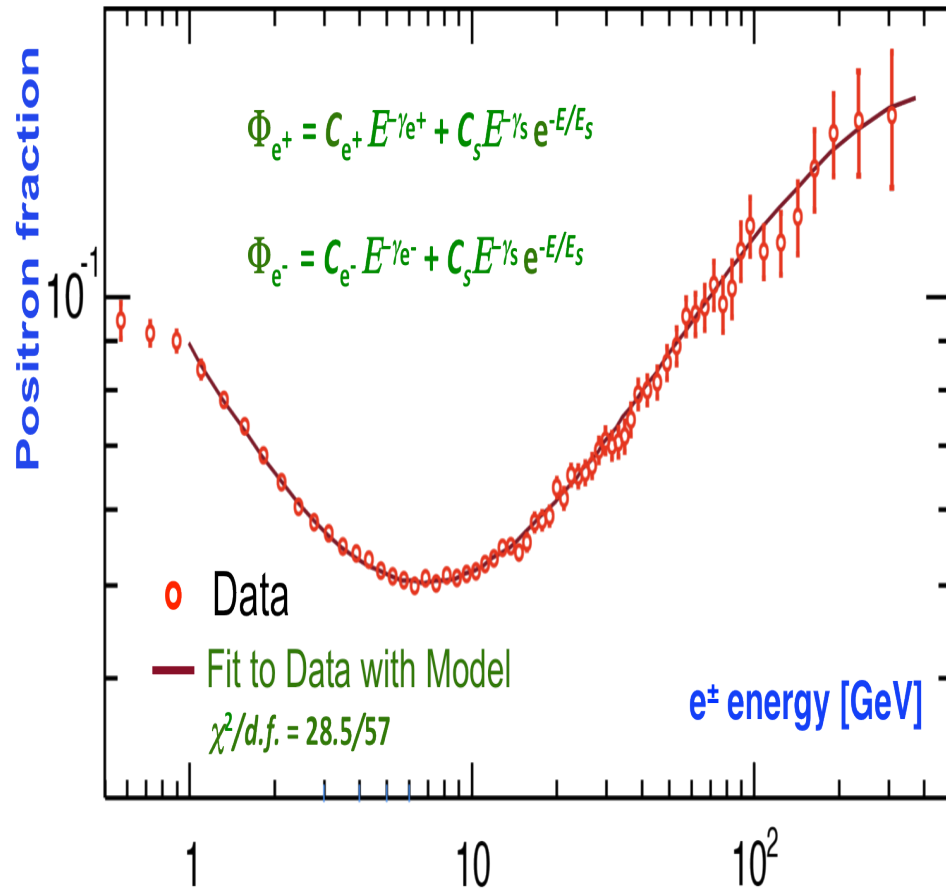
Positron fraction



Positron fraction : measurement comparison



Physics Example: Comparing data with a minimal model.



Positrons:

$$\Phi_{e^+} = C_{e^+} E^{-\gamma_{e^+}} + C_s E^{-\gamma_s} e^{-E/E_s}$$

Secondaries **plus source component**

Electrons :

$$\Phi_{e^-} = C_{e^-} E^{-\gamma_{e^-}} + C_s E^{-\gamma_s} e^{-E/E_s}$$

Secondaries+ Astrophysics primaries (SNR+..) **plus the same source component**

Positron source components: pulsars, Dark matter , ...

Positron mode : features and strategy

Particle Physics (annihilation modes)

$$\frac{d\Phi_{e^+}}{dE_{e^+}}(E_{e^+})$$

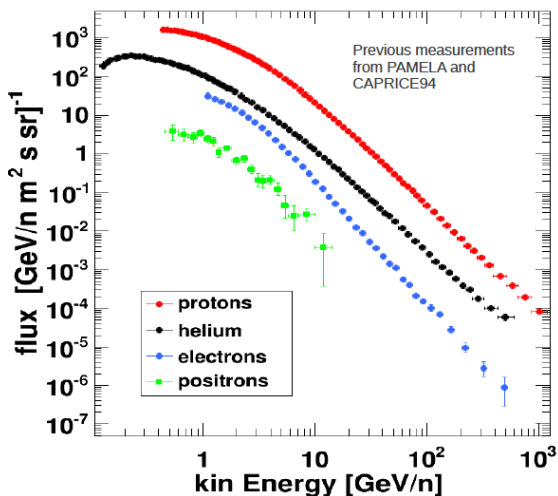
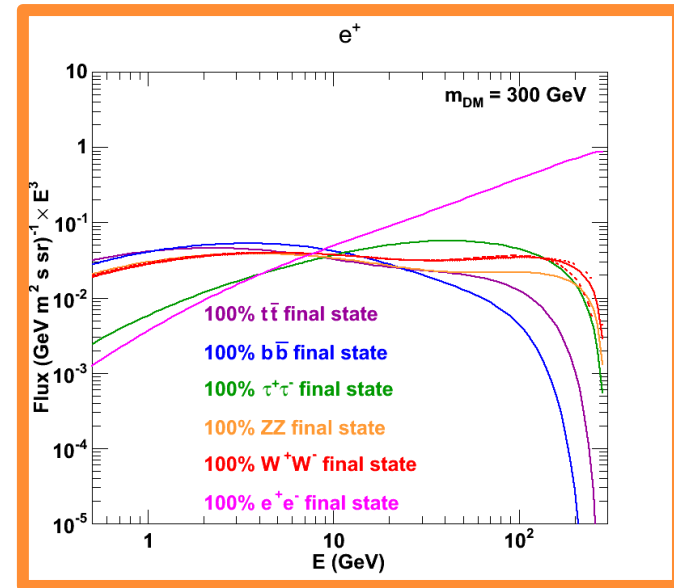
=

$$\frac{\langle \sigma_{ann} v \rangle}{2m_{WIMP}^2} \sum_f \frac{dN_{e^+}^f}{dE_{e^+}} B_f$$

×

$$B \times \rho_\chi^2$$

Positron flux
(Signal in data)



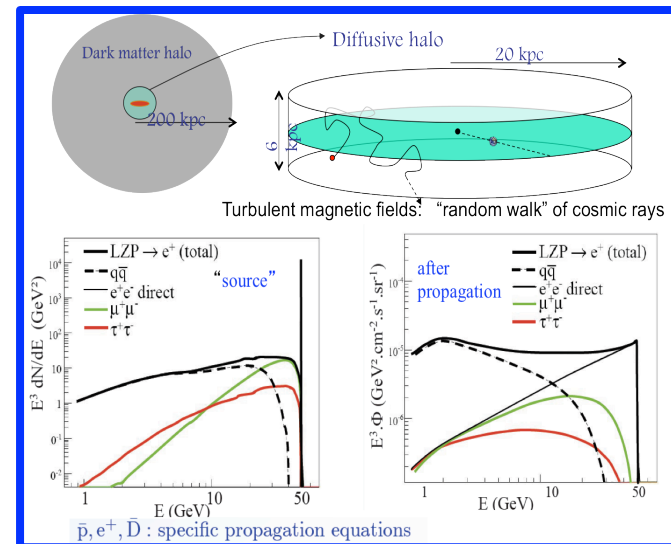
- **Propagation effect:** probed zones for e^+, e^- within 1-4 kpc
- **Boost factor:** over densities (clumps)

Background

protons : $\Phi_p \sim 10^{3-4} * \Phi_{e^+}$

electrons : $\Phi_e \sim 10 * \Phi_{e^+}$

$$B \propto \frac{\langle \rho^2 \rangle}{\langle \rho \rangle^2}$$

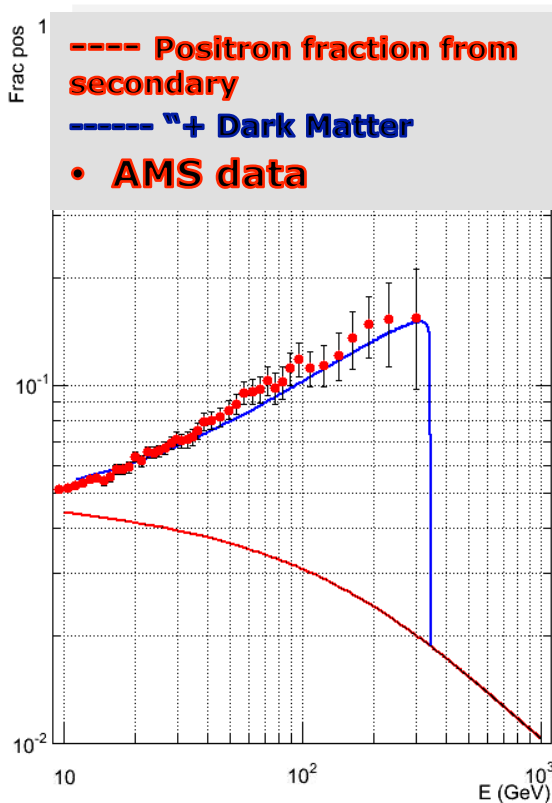


Propagation Model tests

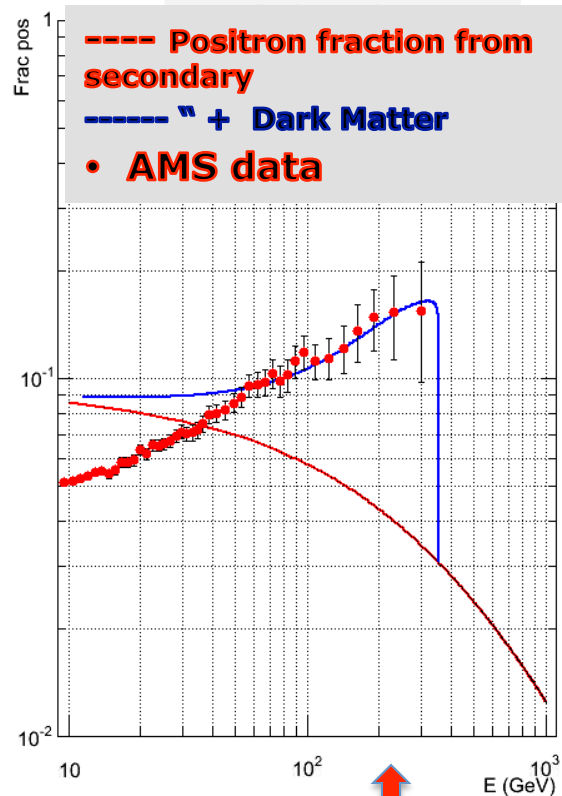
Independently of the origin of the Source

Modèle	δ	K_0 [kpc ² /Myr]	L [kpc]
min	0.85	0.0016	1
med	0.70	0.0112	4
max	0.46	0.0765	15

Medium Model



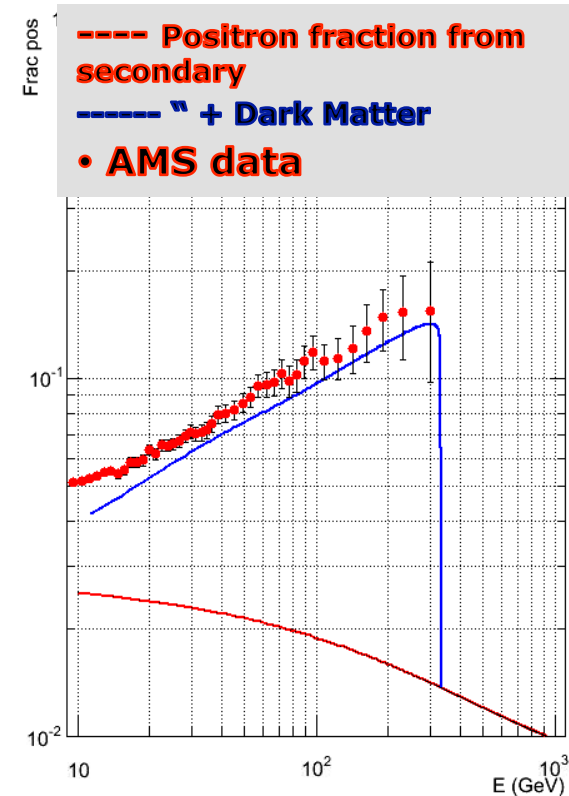
Minimal Model



Excluded



Maximal Model



⇒ Important to constraint the propagation model parameters to draw any interpretations (B/C and δ)

40

⇒ Important also to look at the positron and electron fluxes separately

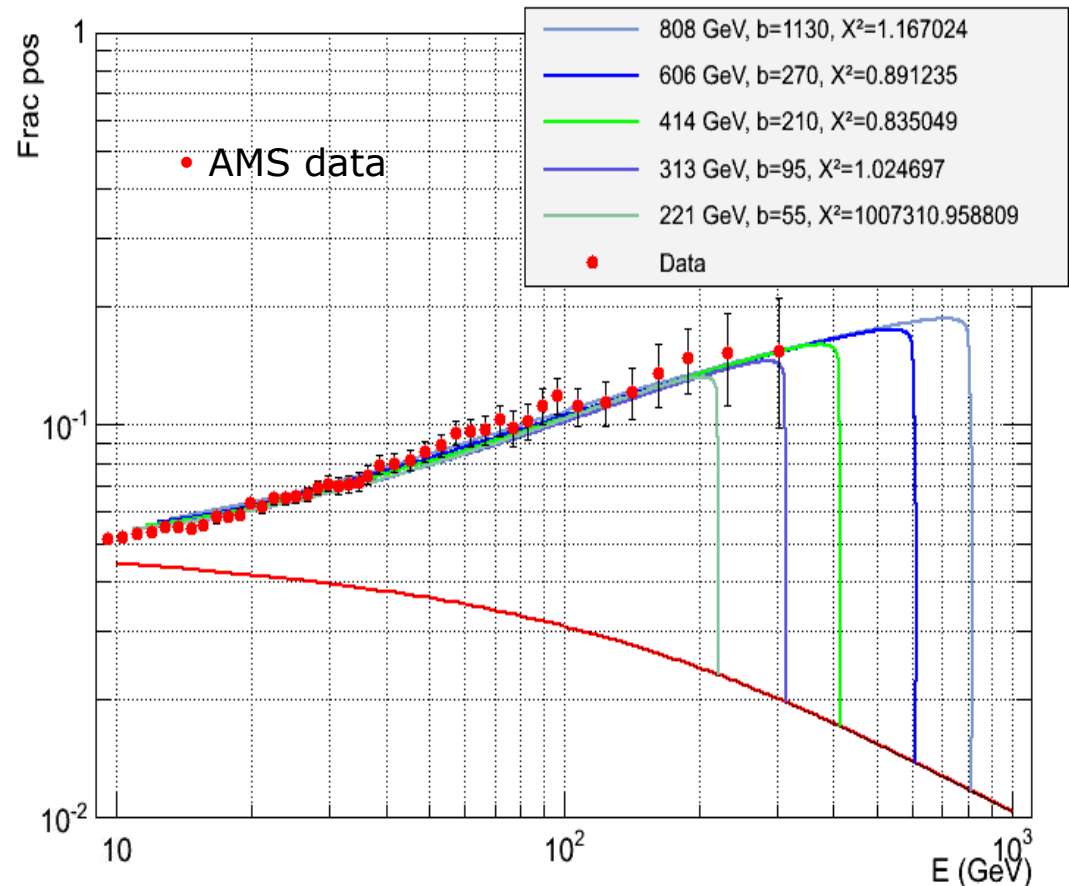
Impact of the precision of the measurement: shape

If 100% WIMP DM origin: different masses are tested

MicrOmegas

50% branching ration
into tau tau

- 25% branching ratio into $W+W^-$ pairs
- 25% into $e=e^-$ and $\mu+\mu^-$ pairs
- Low masses are disfavored (Energy cut off)
- Large masses are disfavored (very high boost factor)



Extended analysis (low mass exclusion <90 GeV) see: L.Bergstrom et al.arXiv: 1306.398 [astro-ph.HE]

Pulsars: Possible sources of primary positrons

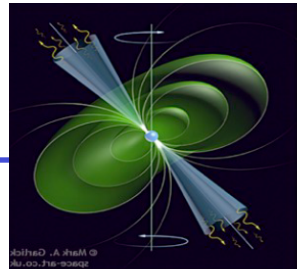
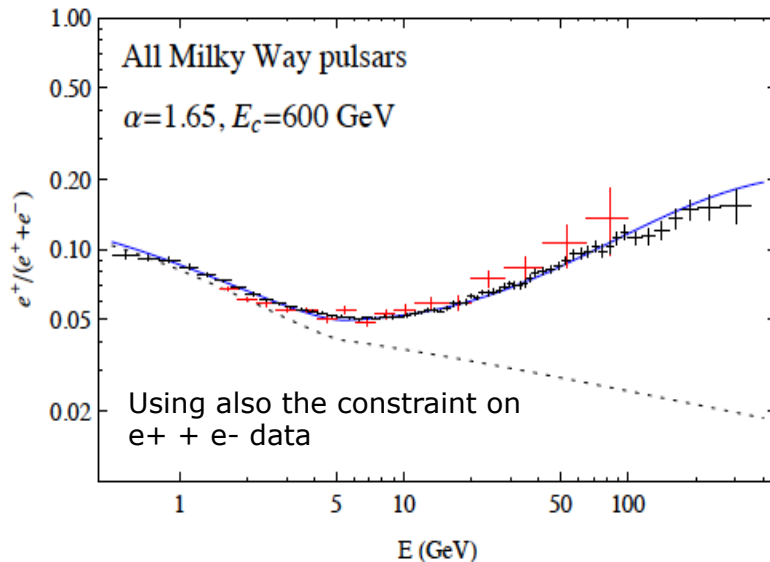


TABLE 1
LIST OF NEARBY SNRs

SNR	Distance (kpc)	Age (yr)	$E_{\max}^a$ (TeV)
SN 185	0.95	1.8×10^3	1.7×10^2
S147	0.80	4.6×10^3	63
HB 21	0.80	1.9×10^4	14
G65.3+5.7	0.80	2.0×10^4	13
Cygnus Loop.....	0.44	2.0×10^4	13
Vela	0.30	1.1×10^4	25
Monogem	0.30	8.6×10^4	2.8
Loop1	0.17	2.0×10^5	1.2
Geminga	0.4	3.4×10^5	0.67

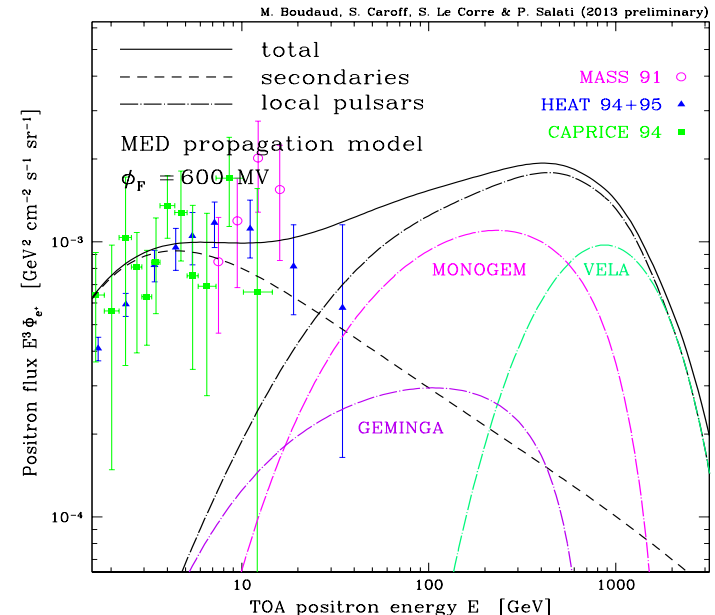
- Mechanism : the spinning B of the pulsar strips electrons that emit gamma => production of e+e- pair that are trapped in the cloud, further accelerated and later released
- The pulsar must be young ($< 10^5$ years) and nearby (< 1 kpc)
- Predicted Flux: $\Phi_{e\pm} = E^{-\alpha} \exp(-\frac{E}{E_c})$ $\alpha \sim 2$ $E_c = \text{few TeV}$

16% of the pulsar energy goes into e+e- pairs **for all the pulsars**



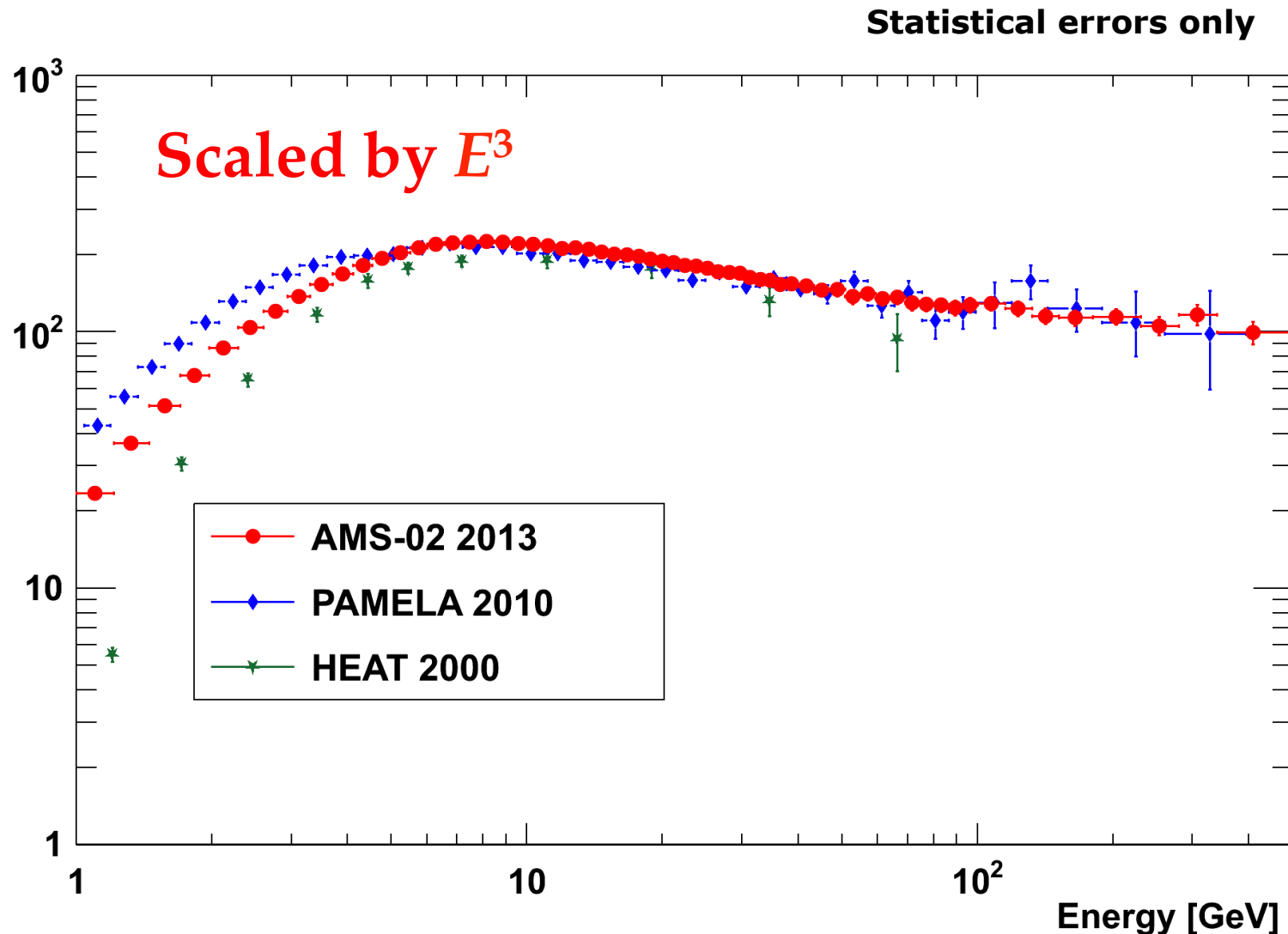
I. Colls et al arXiv:1304.1840 [astro-ph.HE]

Or
Positron Spectrum



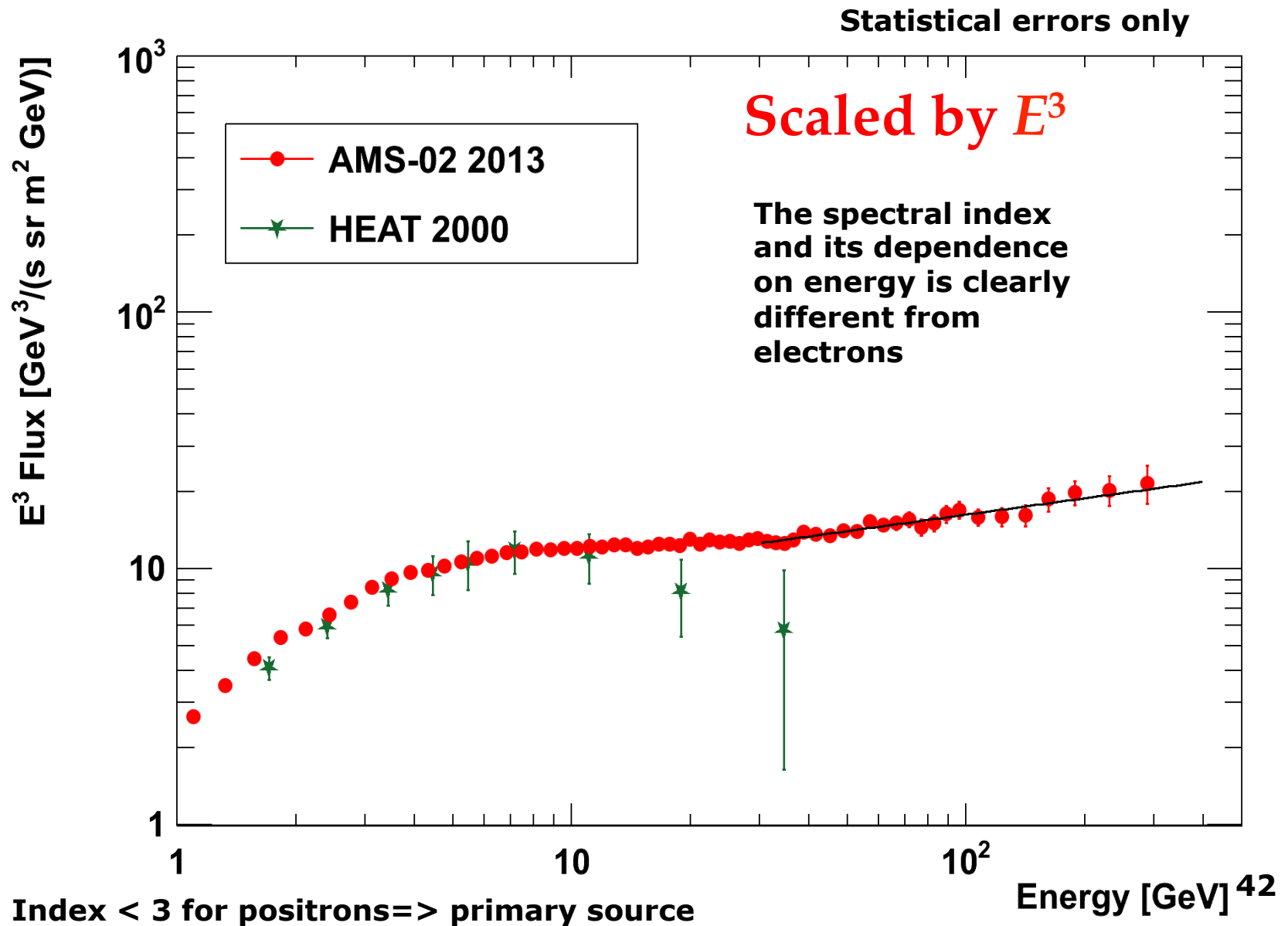
- ⇒ Important to measure the positron and electron spectrum separately
- ⇒ Anisotropy for both electrons and positrons (r :distance, t =age $\delta_{\max} = \frac{3}{2c} \frac{r}{t}$)

AMS-02 Electron Flux up to 500 GeV

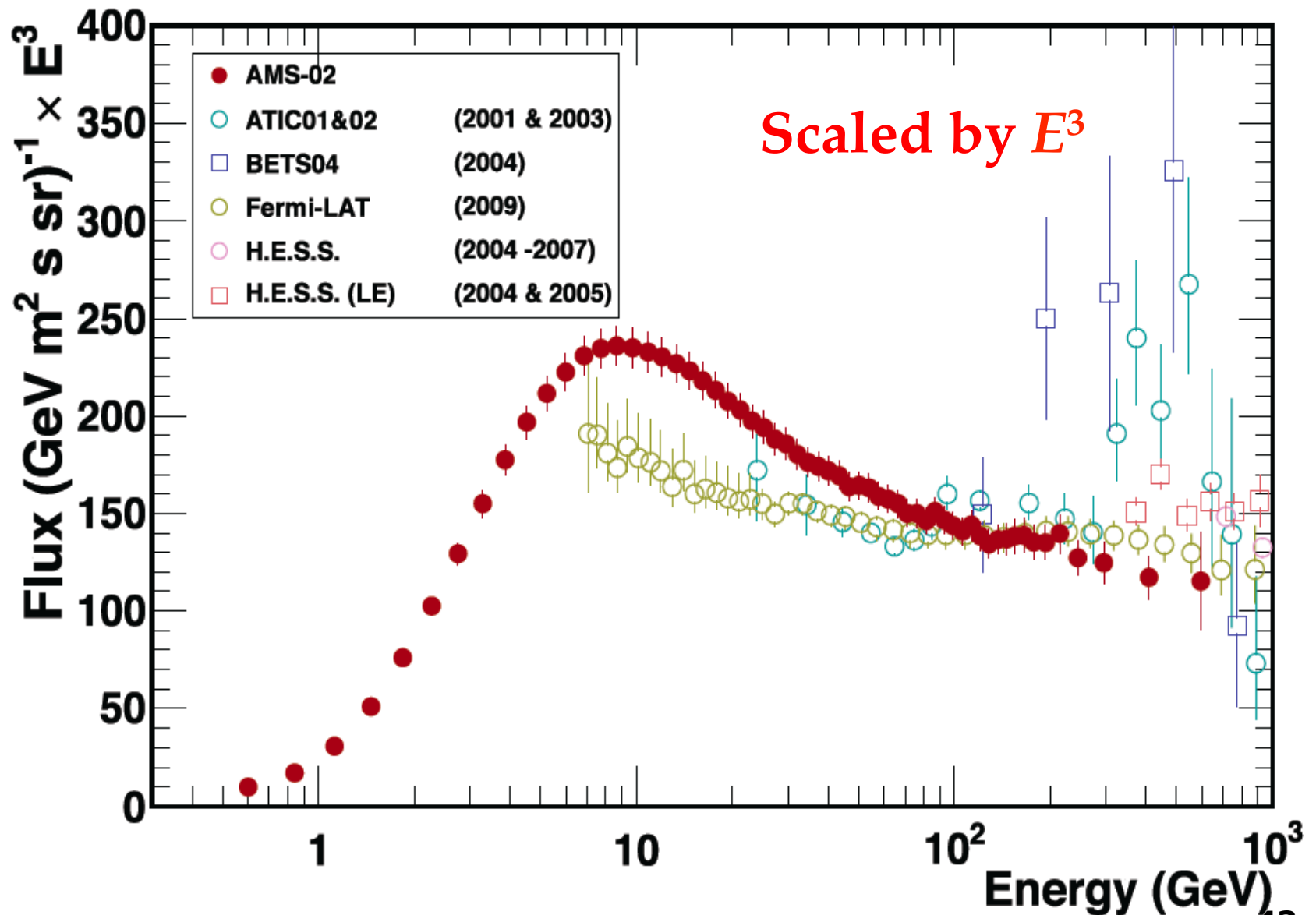


Index > 3 for electrons, 500 electrons expected in 4 years above 500 GeV

AMS-02 Positron Flux up to 350 GeV

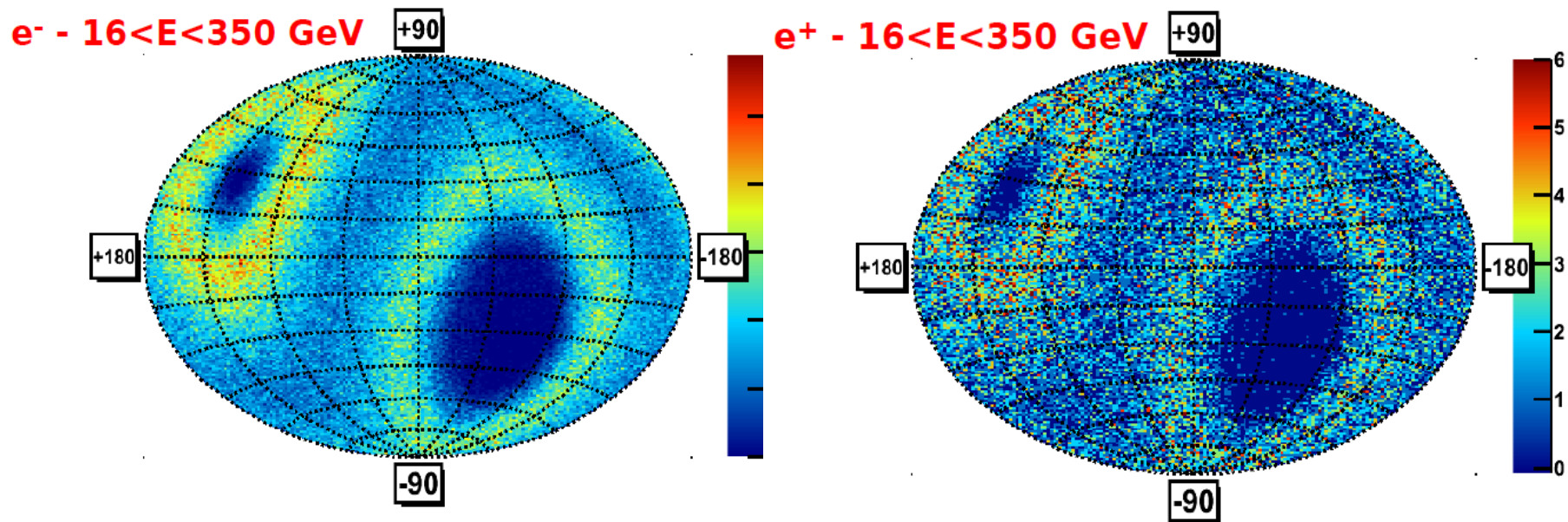


AMS-02 lepton Flux up to 350 GeV

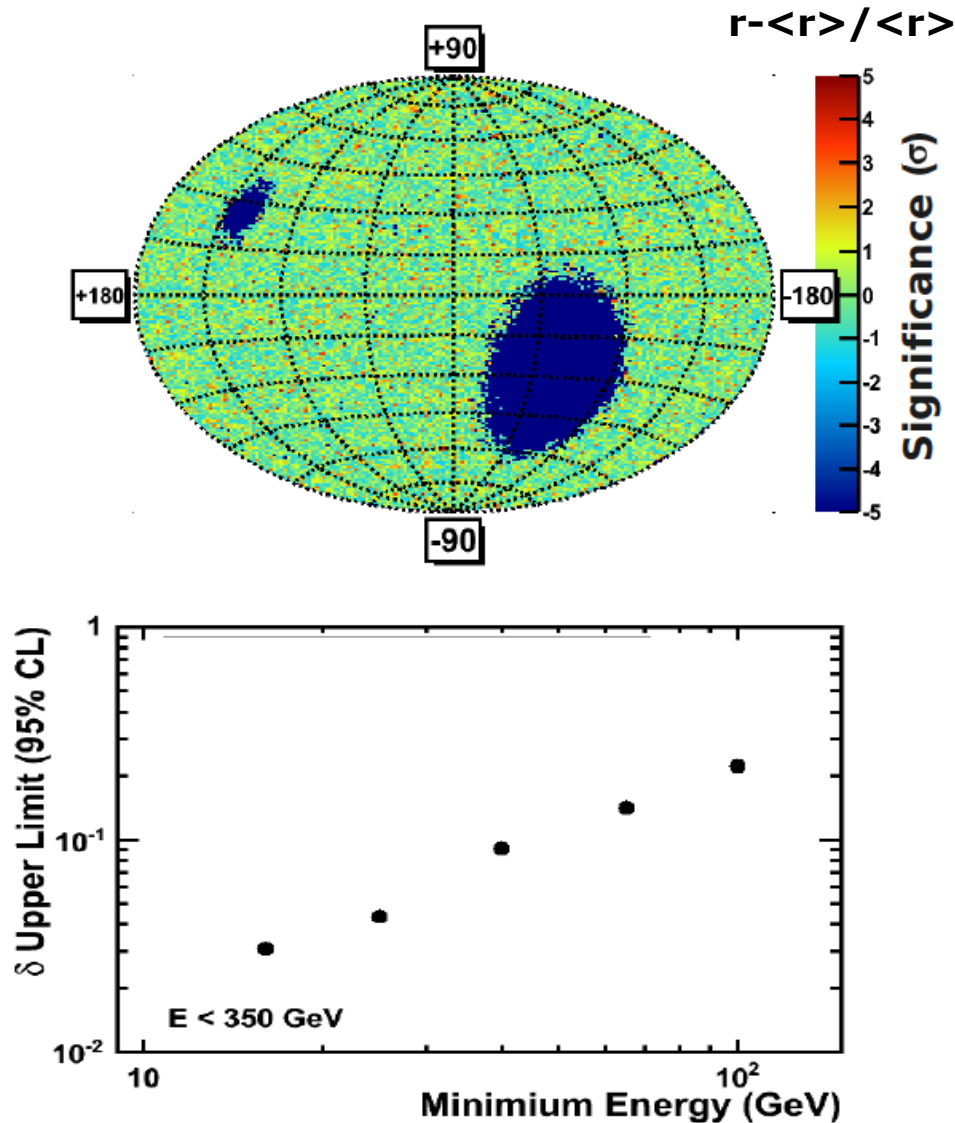


Anisotropy Measurements

- Selected events are grouped in 5 cumulative energy bins:
16-350, 25-350, 40-350, 65-350 and 100-350 GeV
- Their arrival directions are used to build sky maps in the galactic coordinate(b, l)



Anisotropy Measurements

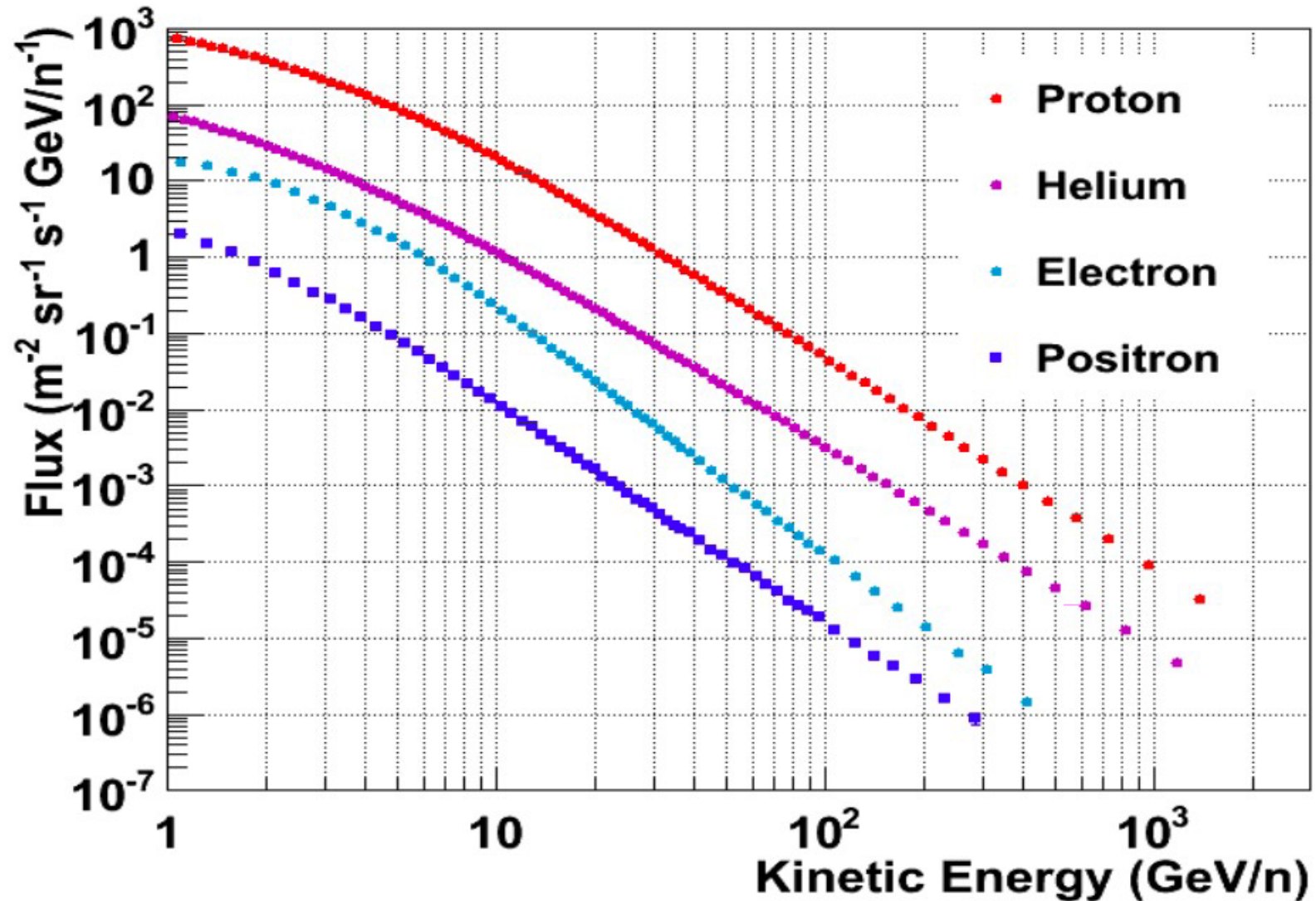


The relative fluctuations of the ratio across the observed sky map show no evident pattern

- The coefficients of the multiple expansion are found to be consistent with the expectations from isotropy.
- Upper limits on the dipole parameter δ are set.
- - After 20 years a sensitivity of the order of **0.014** is expected
 $\Leftrightarrow$ could it constraint the pulsar component ?

$\delta < 0.030$ for $16 < E < 350 \text{ GeV}$

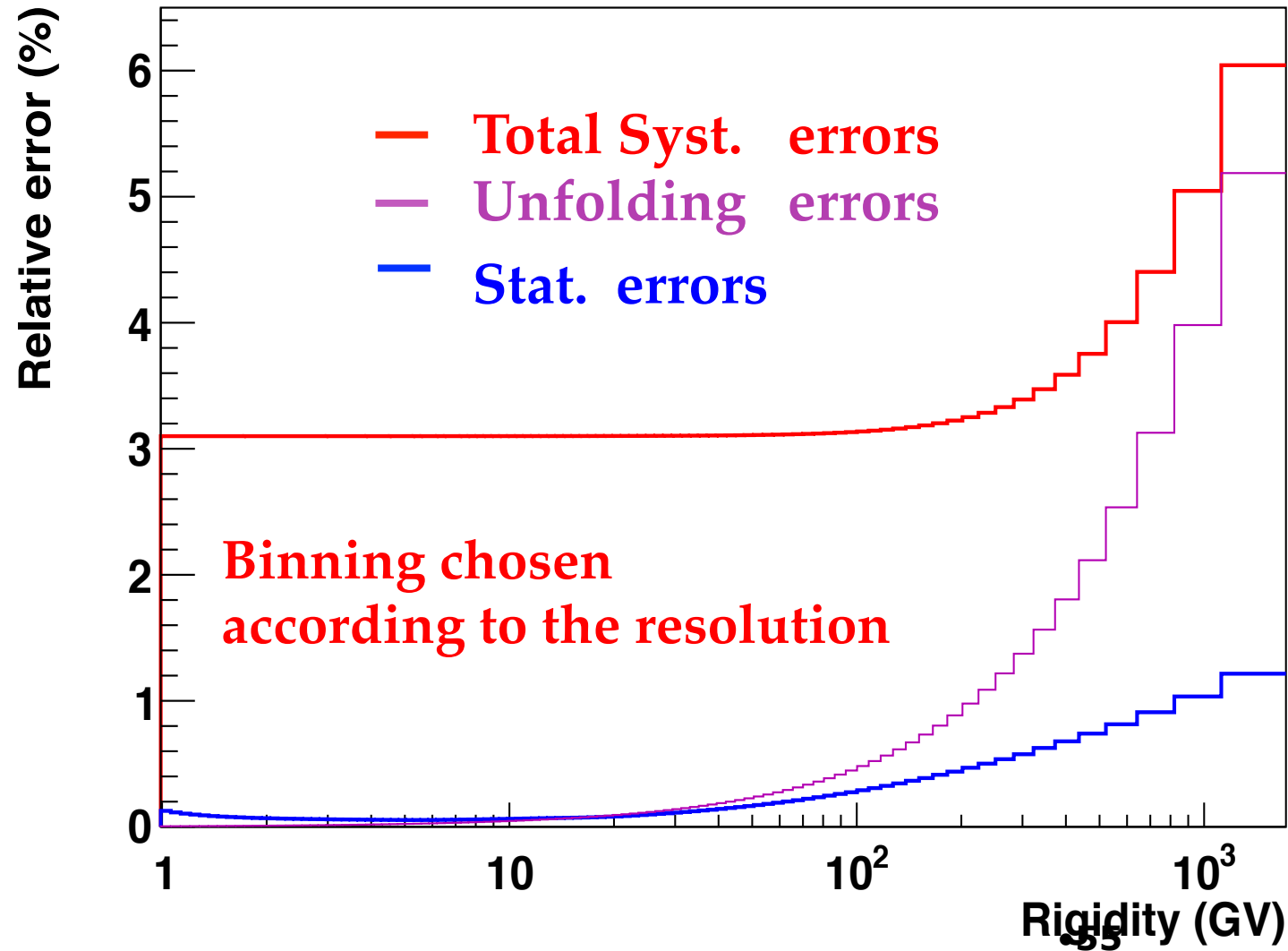
First flux measurements by AMS



Summary

- AMS02 is operating on the ISS since the 19th May 2011 and has collected more than 40 billions of events: All AMS subsystems are fully operational and behaves as expected.
- Variations of ambient conditions (temperature in first place) are accounted for, with proper calibrations and alignments
- For most of the measurements, systematics uncertainties are estimated from the data thanks to the redundancy of AMS-02
- **Proton flux** from 1 GV to 1.8 TV and **Helium flux** from 2GV to 3.2GV for have been measured by AMS during the first two years of operation on ISS
 - In high rigidity region ($R > 100$ GV) : The spectra are consistent with a single power law and shows no structure nor break
- **B/C ratio** has been measured between 05 to 670 GeV/n. the behaviour at high energy will become more clear with more statistics
- Positron fraction has been measured from 0.5 to 350 GeV using the first 6.8 million positron and electrons. **Nearby Primary positron sources are needed to explain the measurement.**
- An electron spectrum in the energy 1-500 GeV and and a positron spectrum in the energy range 1-300 GeV were shown with different spectral indices of electrons and positrons. Systematic errors being under study. **The behaviour at high energy will become more clear with more statistics.**

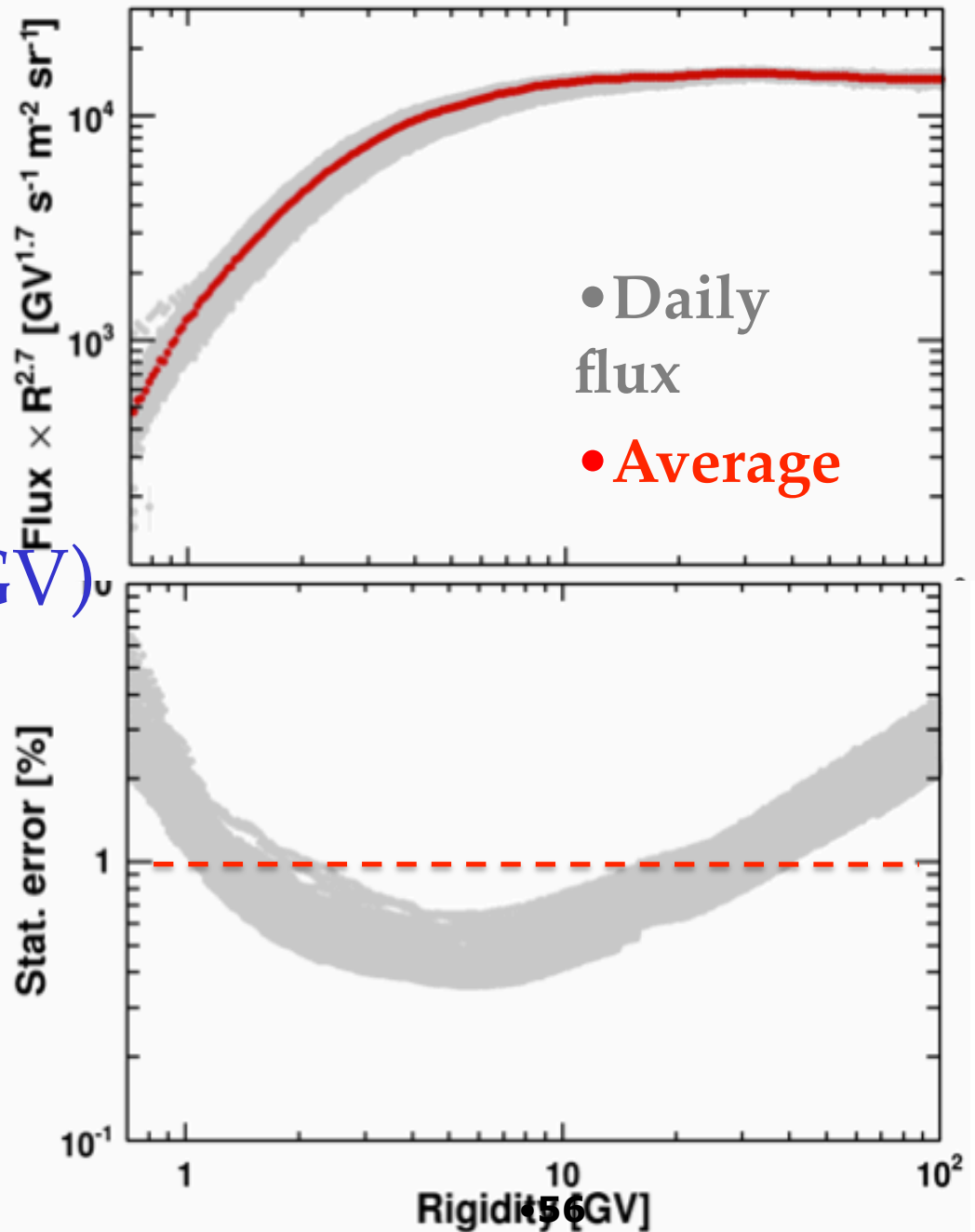
Errors and binning





Daily flux

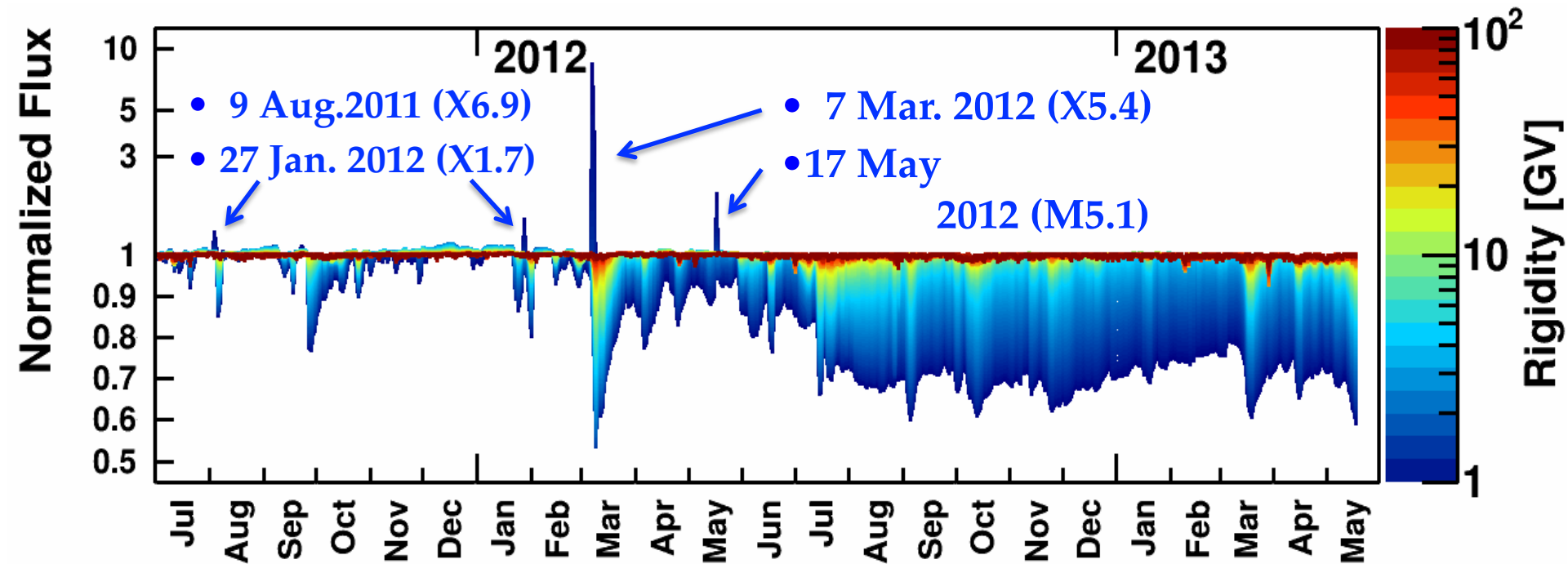
Stat. Error $< \sim 1\%$
 $(1 < R < \sim 20 \text{ GV})$





Daily normalized flux

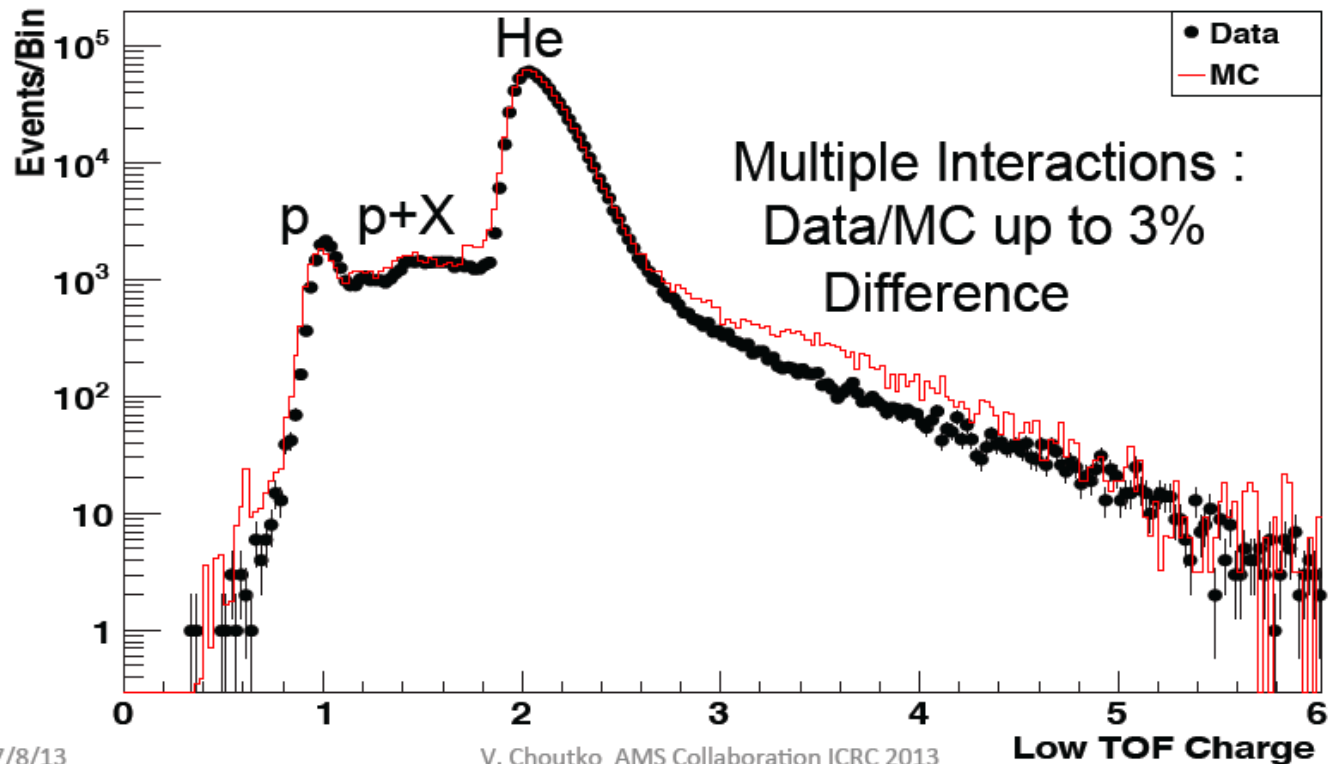
$R < \sim 30$ GV : Variation due to the solar modulation and solar events



Helium Nuclei Selection

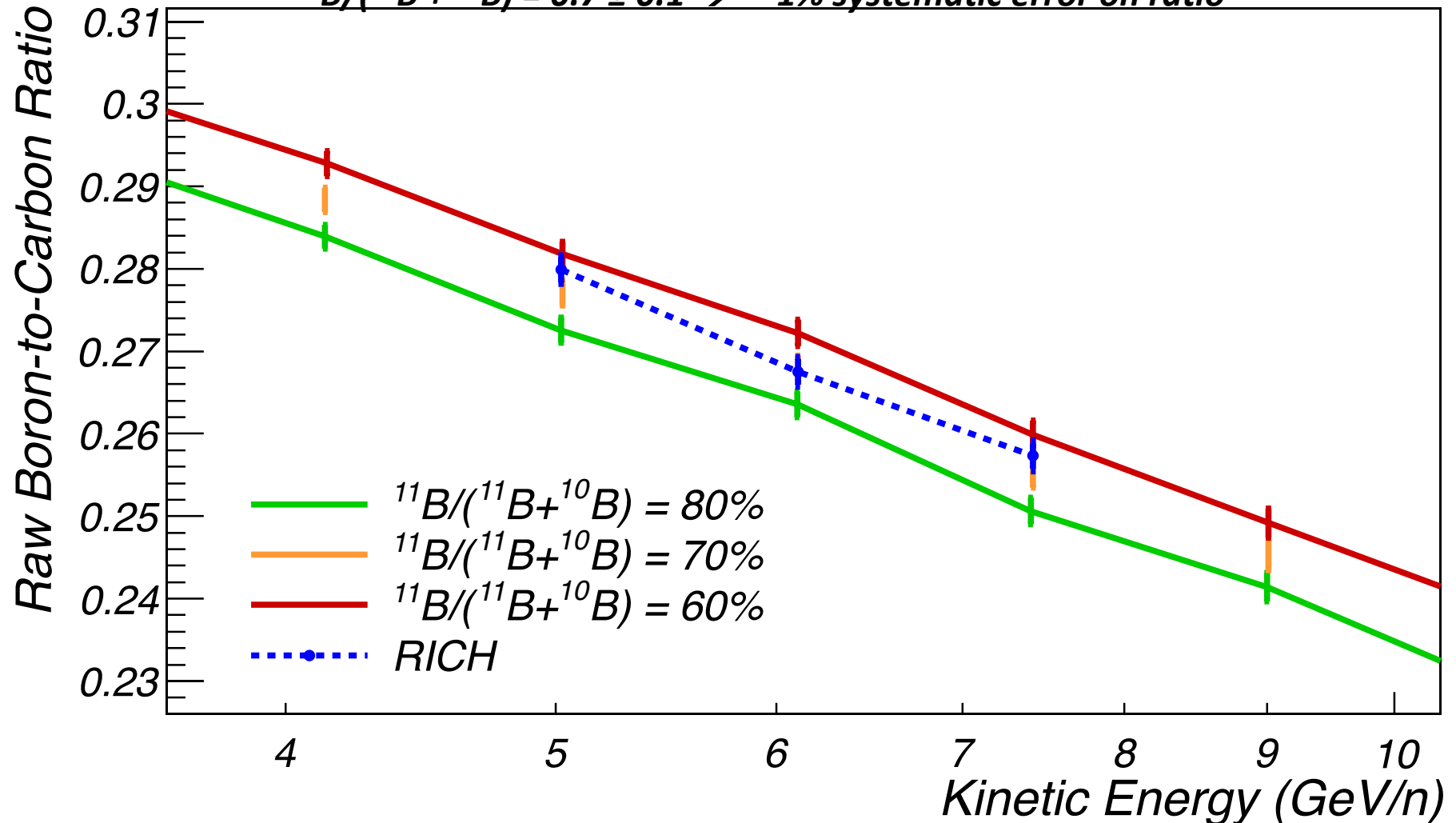


Rigidity > 20 GV He Events Selected by
Tight Cut on Tracker Layer1 Charge

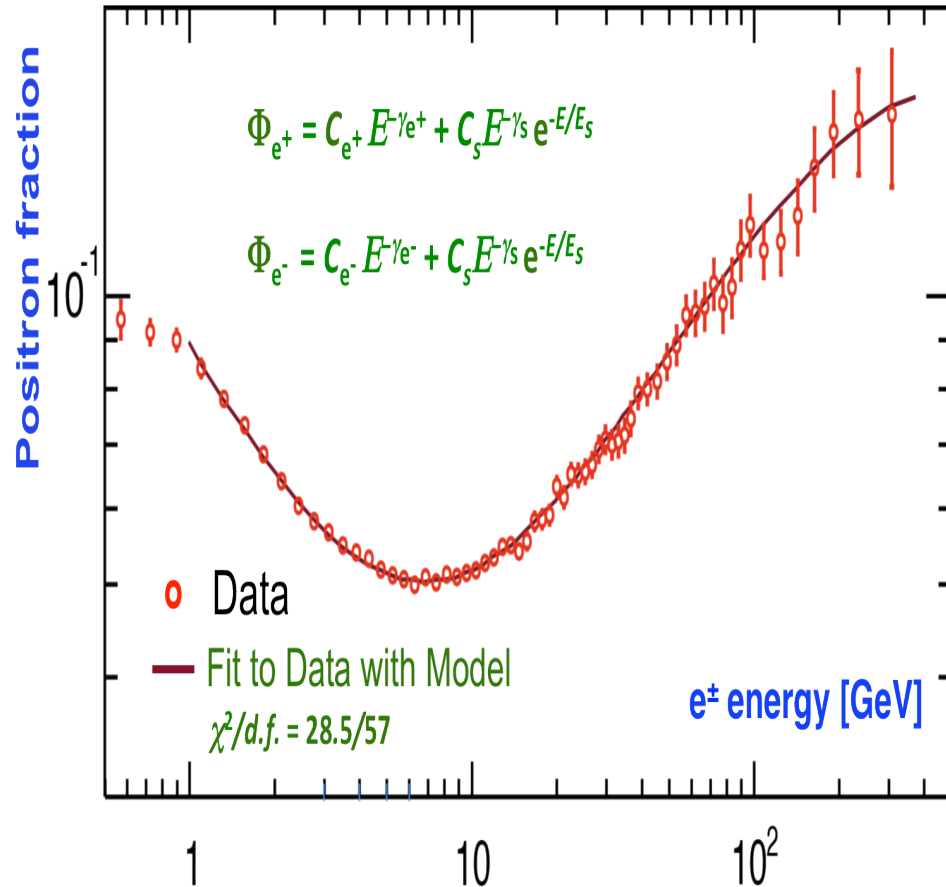


Isotopic Fraction Evaluation

- RICH evaluates the isotopic composition of Boron.
- This fraction is used for the Tracker rigidity $\rightarrow$ kinetic energy conversion.
- $^{11}\text{B}/(^{11}\text{B} + ^{10}\text{B}) = 0.7 \pm 0.1 \rightarrow \sim 1\%$ systematic error on ratio



Physics Example: Comparing data with a minimal model.



Results of the fit to the data in the energy range 1 to 350 GeV yields:

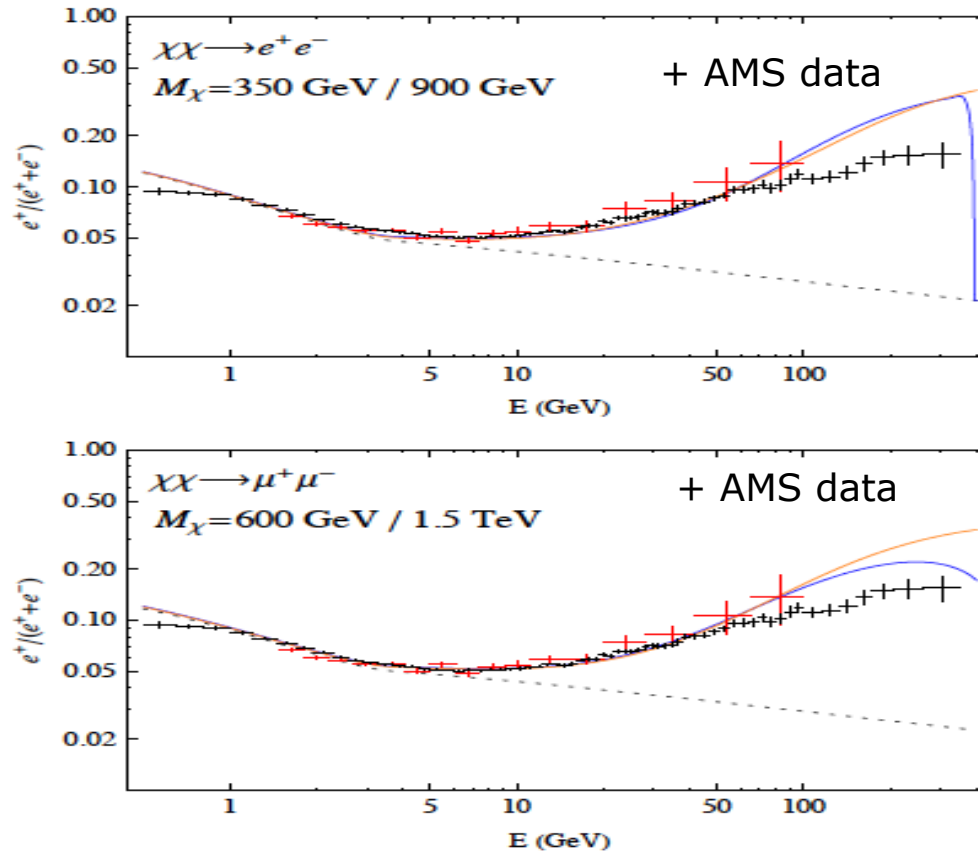
- $\gamma_{e^-} - \gamma_{e^+} = -0.63 \pm 0.03$, *i.e.*, the diffuse positron spectrum is less energetic than the diffuse electron spectrum;
- $\gamma_{e^-} - \gamma_s = 0.66 \pm 0.05$, *i.e.*, the source spectrum is more energetic than the diffuse electron spectrum;
- $C_{e^+}/C_{e^-} = 0.091 \pm 0.001$, *i.e.*, the weight of the diffuse positron flux amounts to ~10% of that of the diffuse electron flux;
- $C_s/C_{e^-} = 0.0078 \pm 0.0012$, *i.e.*, the weight of the common source constitutes only ~1% of that of the diffuse electron flux;
- $1/E_s = 0.0013 \pm 0.0007 \text{ GeV}^{-1}$, corresponding to a cutoff energy of 760^{+1000} GeV .

=> Primary positrons are needed

Impact of the precision of the measurement: shape

If 100% WIMP DM origin: different branching ratio scenarios can be tested

I. Colis et al arXiv:1304.1840 [astro-ph.HE]



“Dark Matter models in which the WIMP annihilates 100% into e^+e^- are no longer of producing positron rise in the positron fraction”