The Alpha Magnetic Spectrometer on the International Space Station

on behalf of the AMS-02 collaboration

S.Rosier-Lees

LAPP-CNRS-IN2P3-Université de Savoie

CEA Seminar – 6th November 2013

Outline

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

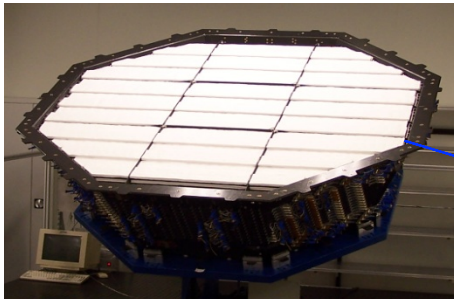
References: S.Ting Cern Seminar, April 2013, ICRC2013 July 2013, Phys.Rev.Lett. 110 (2013) 14, ICRC2013_ 1257,1261,1266,1265, 1264,1267,1263 **ICRC2013 talks and proceedings**

AMS: A TeV precision, multipurpose spectrometer in space

Particles and nuclei are identified by their charge (Z) and energy (E ~ P)

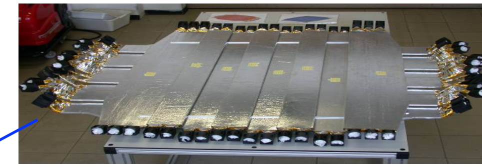
TRD

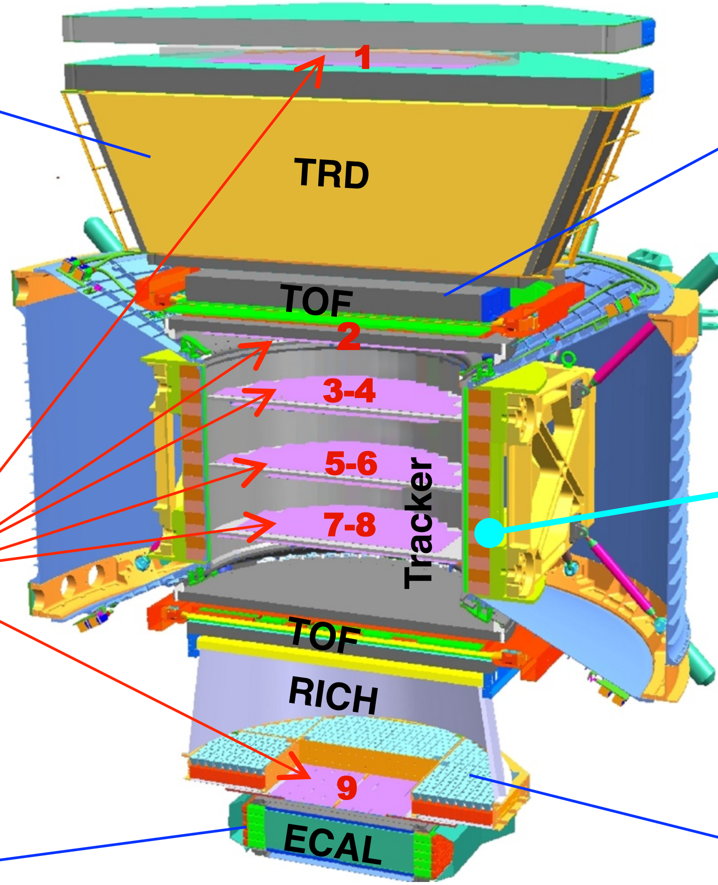
Identify e+, e-



TOF

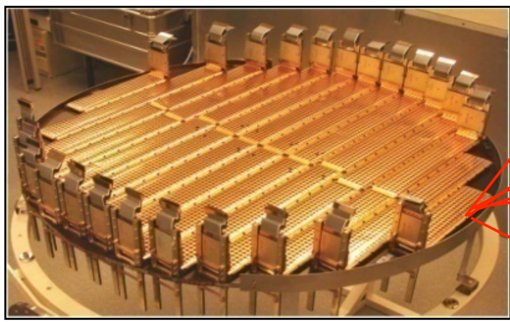
Z, E





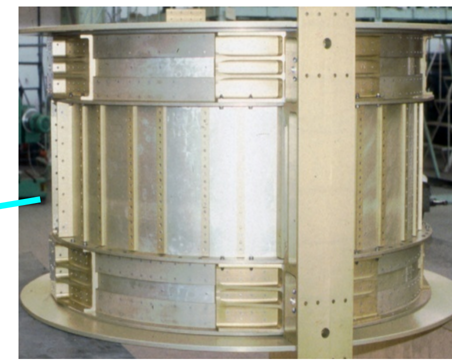
Silicon Tracker

Z, P



Magnet

±Z



3D imaging ECAL

E of e+, e-, γ

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

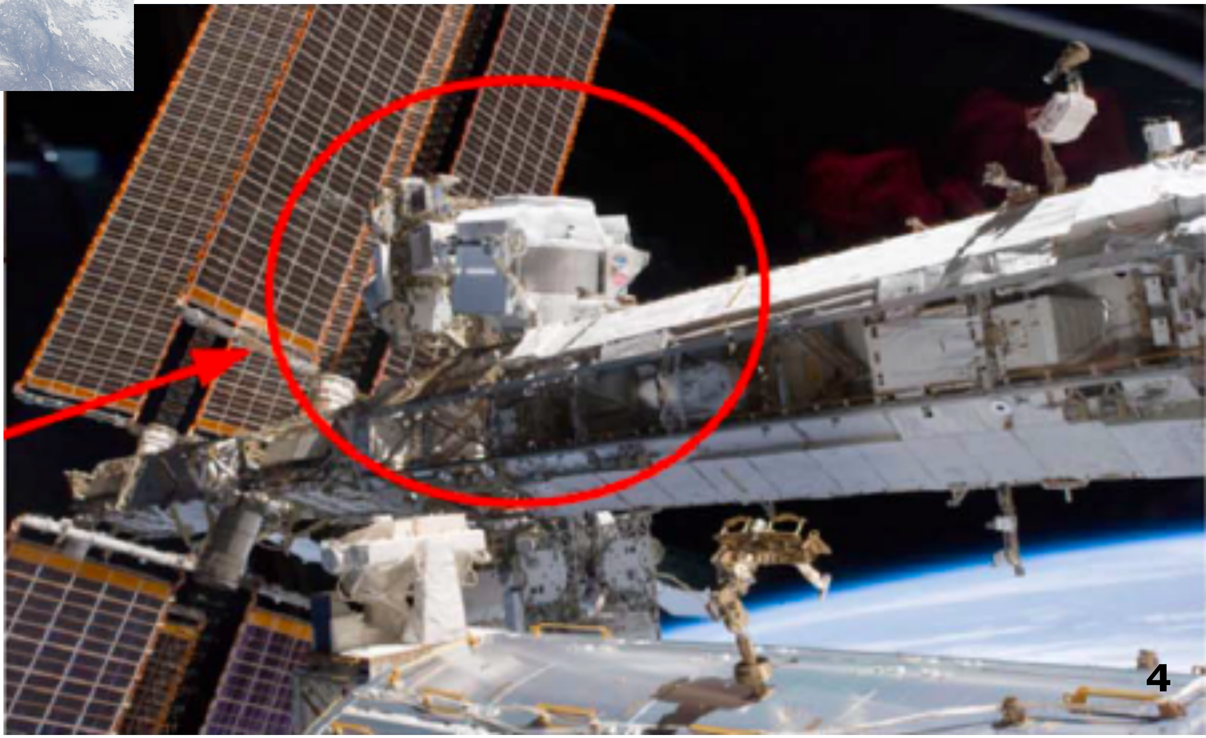
Cape Canaveral, May 16 2011.
STS 134 Mission, Launch of Endeavour Shuttle

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:

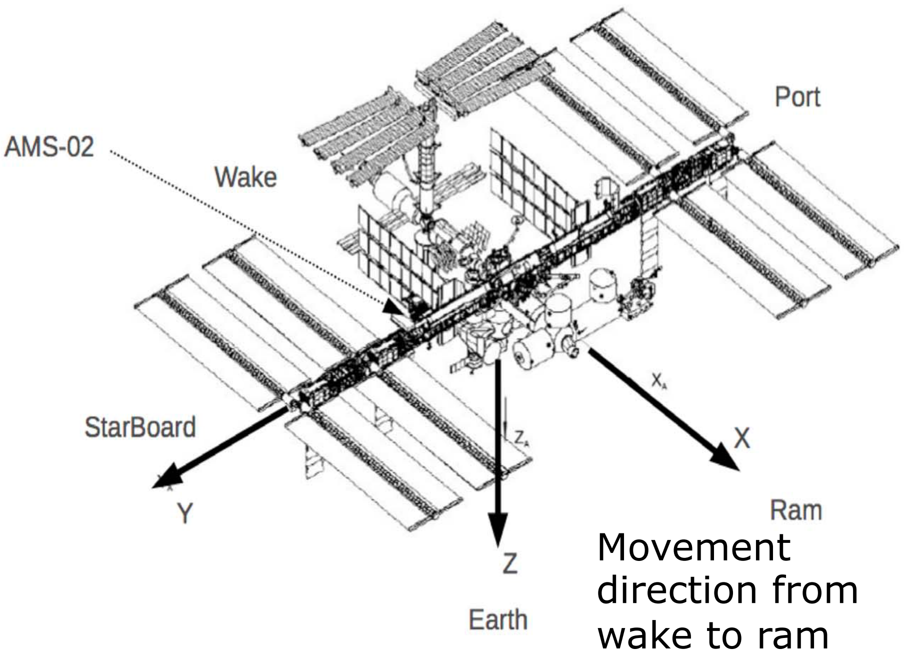
AMS installation completed on ISS at 5:15 CDT,

start taking data 9:35 CDT

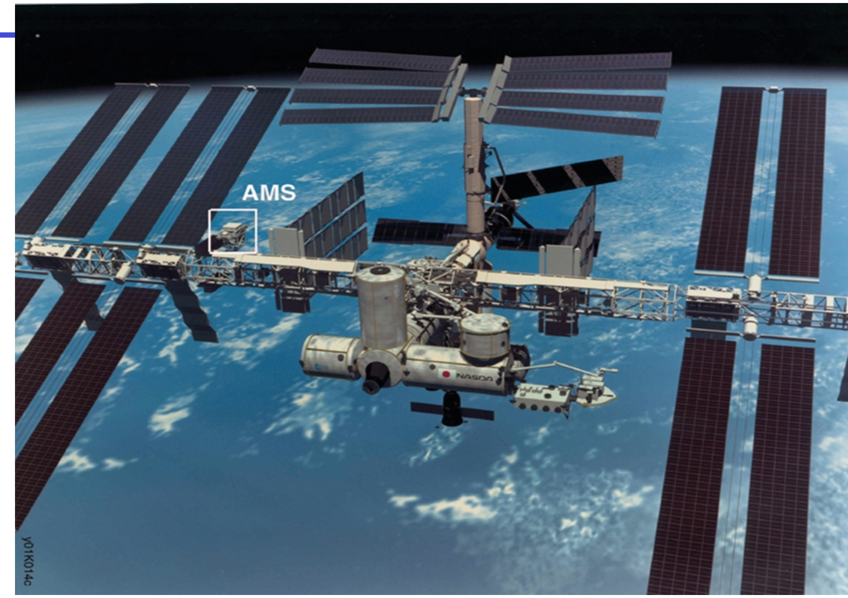
Until 2020

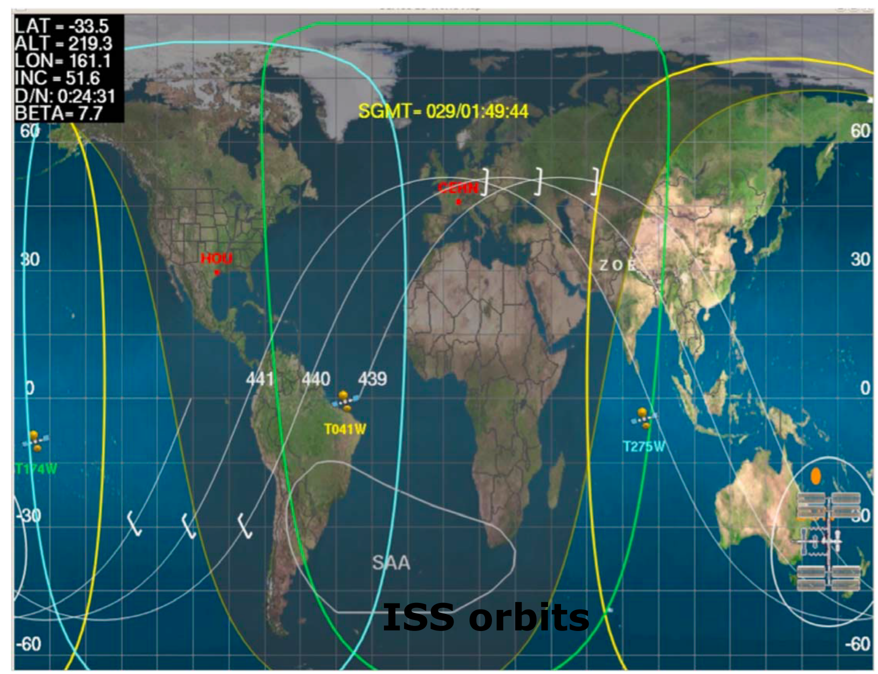
(CDT Central Daylight Time)

ISS orbit



Movement direction from wake to ram



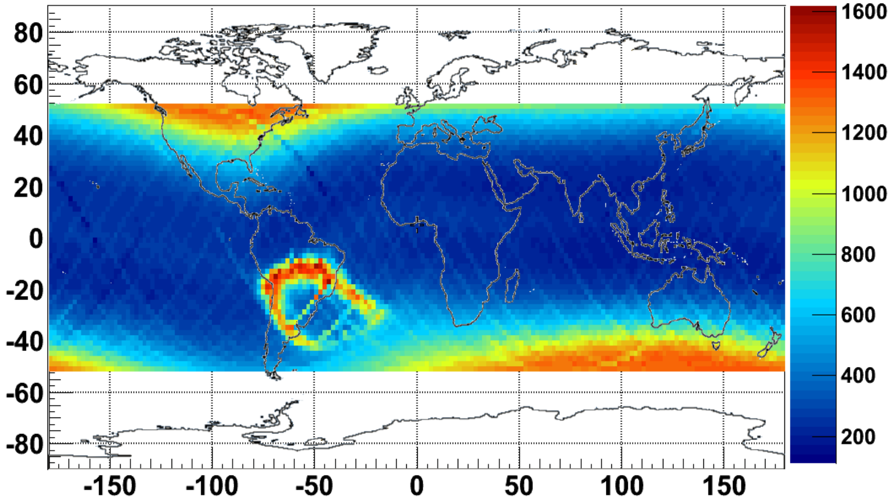


ISS velocity: 8km/s, one orbit every 90 mn

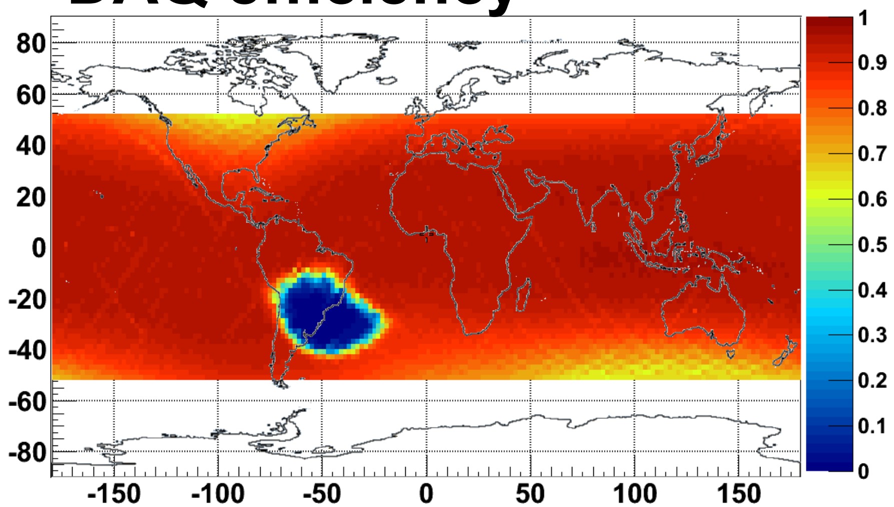
Altitude 340-400 km

Orbital DAQ parameters

Acquisition rate [Hz]



DAQ efficiency



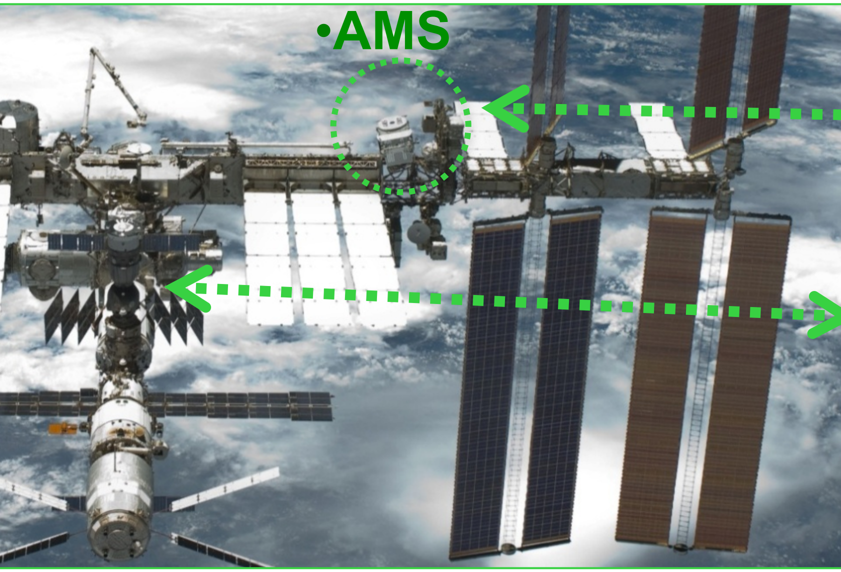
Particle rates vary from 200 to 2000 Hz per orbit

On average:

DAQ efficiency 85%

DAQ rate ~700Hz

AMS Data Flow



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

Astronaut at ISS AMS Laptop

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

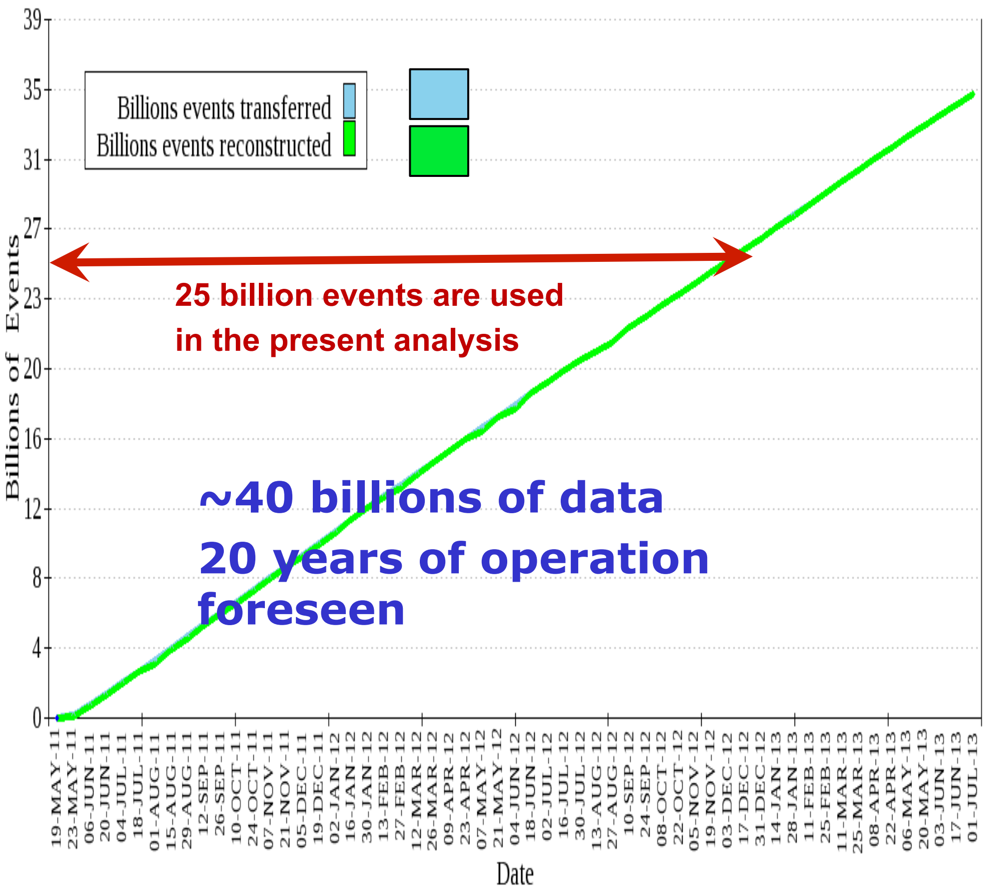
AMS Physics Potential

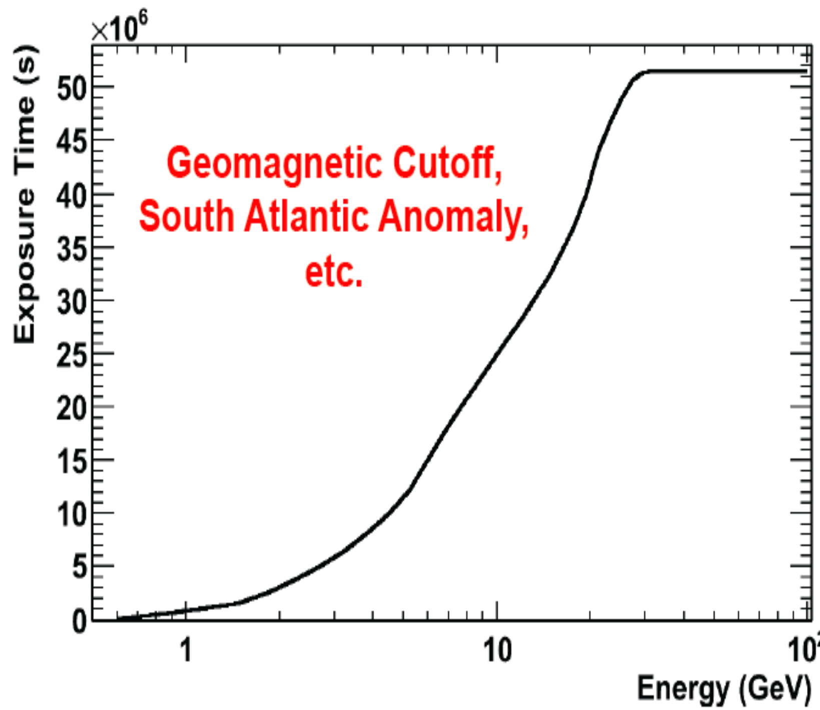
- Searches for primordial antimatter:
  - Anti-nuclei: anti He, …
- **Dark Matter searches:**
  - **e^+ , $e^\pm$,** anti p , γ…
  - simultaneous observation of several signal channels.
- Searches for new forms of matter:
  - strangelets, …
- **Measuring CR spectra – refining propagation models;**
- 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 : $T_{exp.}$ (*Rigidity* > 25 GV) = 51.2 $\times$ 10^6 s



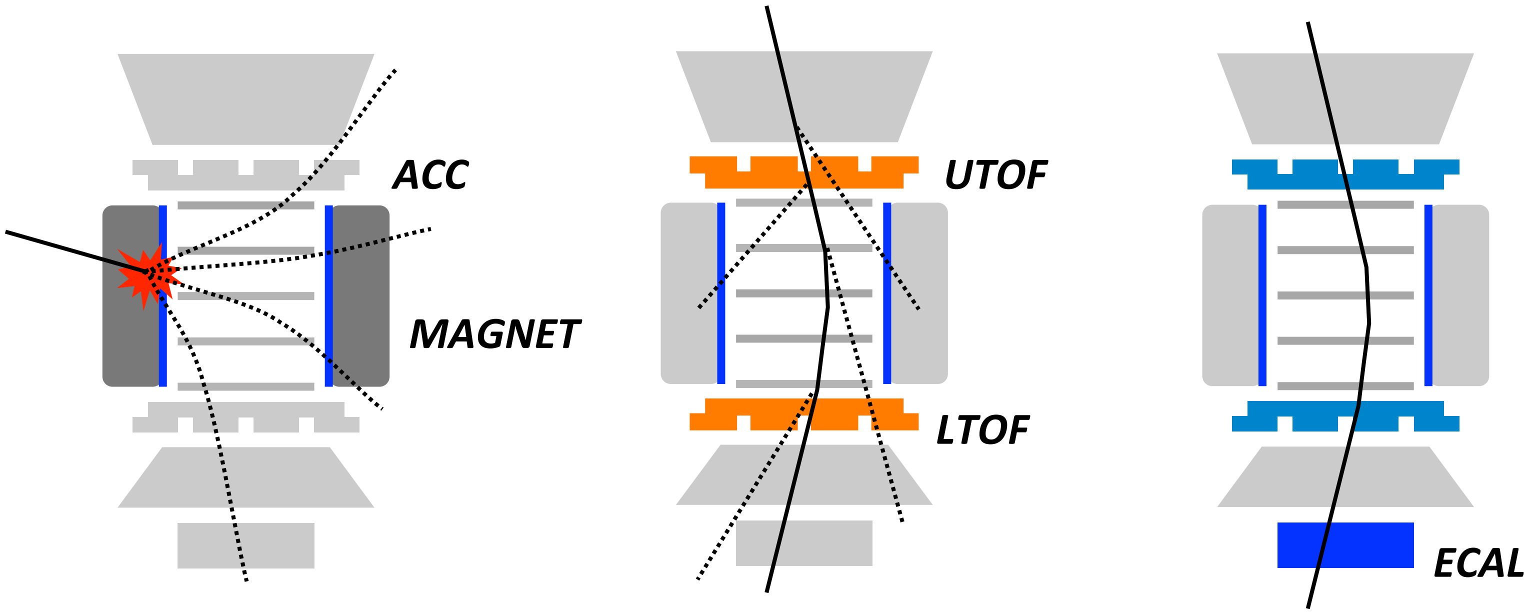


Average live time = 82 %

AMS-02 Trigger

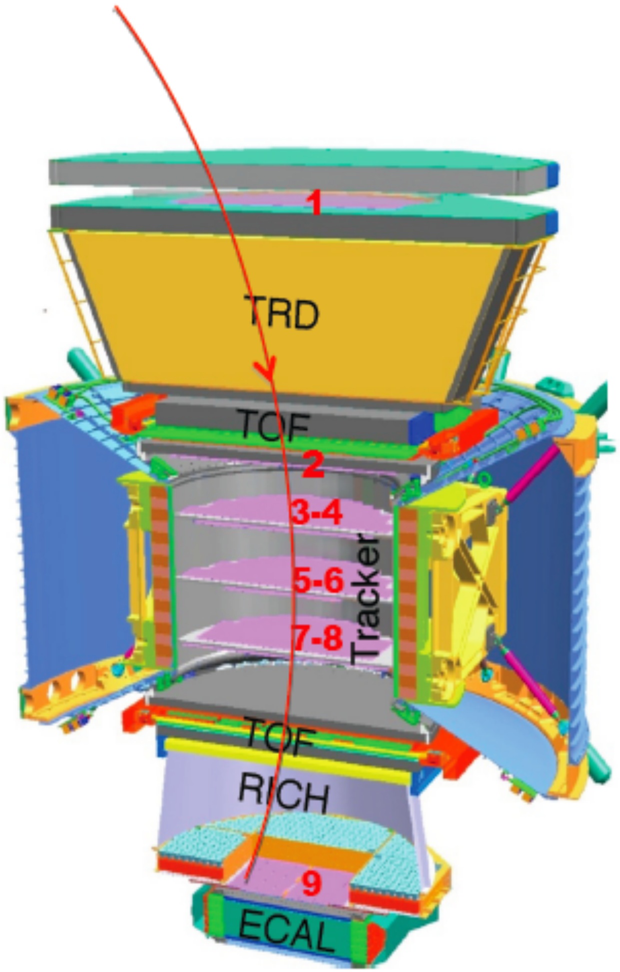
Trigger efficiency is estimated with an unbiased trigger sample.

.



Horizontal Particle	***High-Z particle***	***TOF + ECAL Trigger***
Rejected	***Accepted***	***Accepted***

AMS-02 Nuclei Properties Measurement



Rigidity, Direction and Charge Sign

Tracker

Bending Coordinate Resolution 6 to 7 μm

MDR (Z=2) ≈ 3.2 TV

Velocity and Direction

TOF

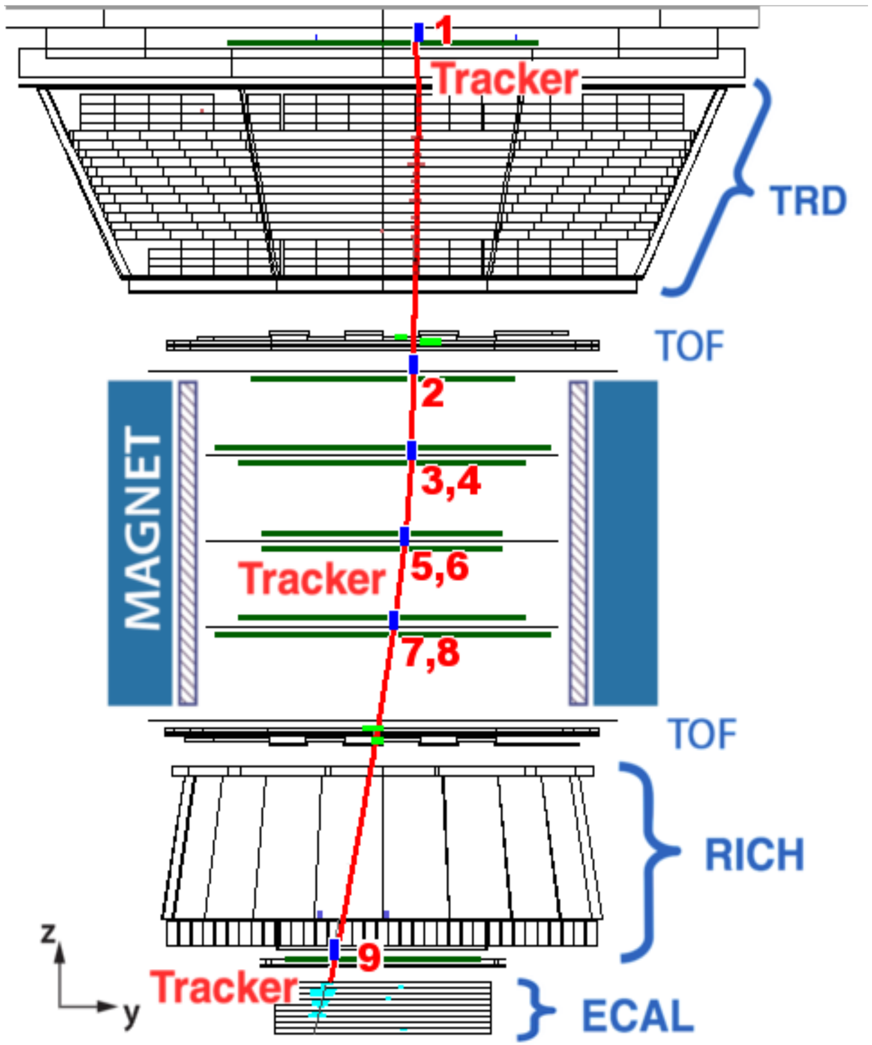
$\Delta\beta/\beta^2(Z=2) \approx 2\%$

Charge Magnitude Along He Trajectory

TRD, Tracker, RICH ,TOF, ECAL

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

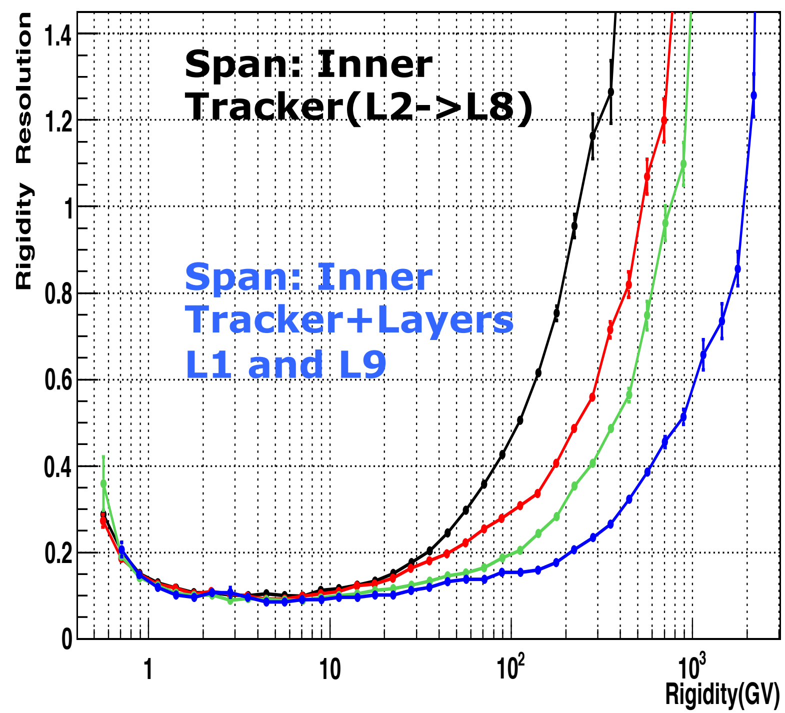
Rigidity measurement



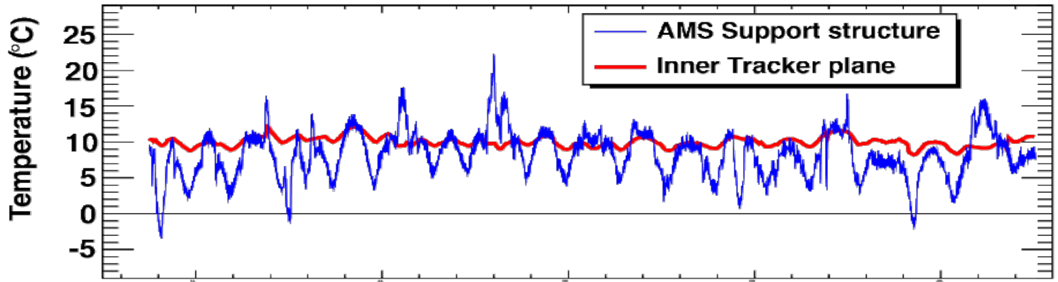
Challenges:

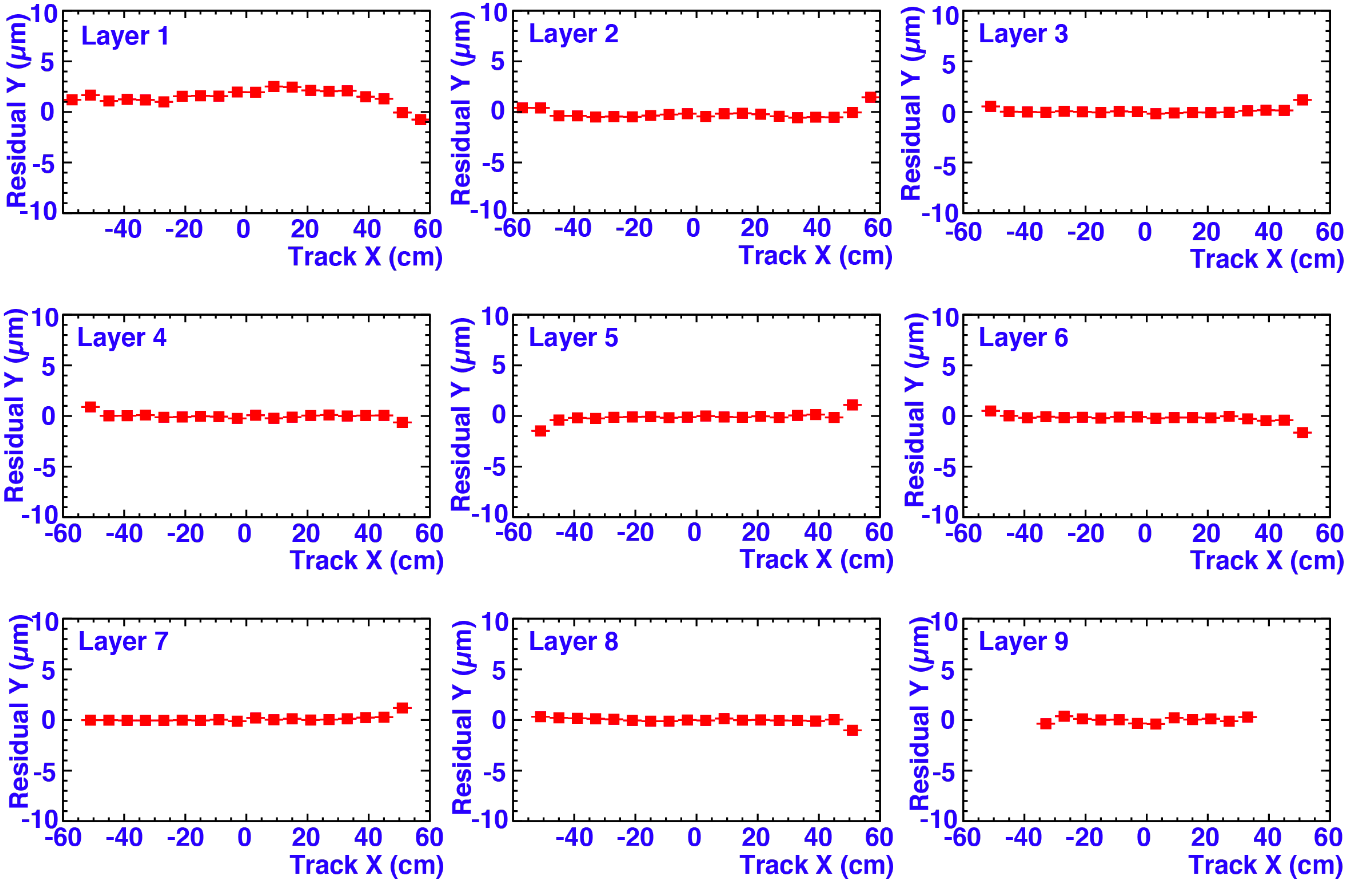
Alignment feature: Inner and external layers (due to the temperature variations on the ISS)

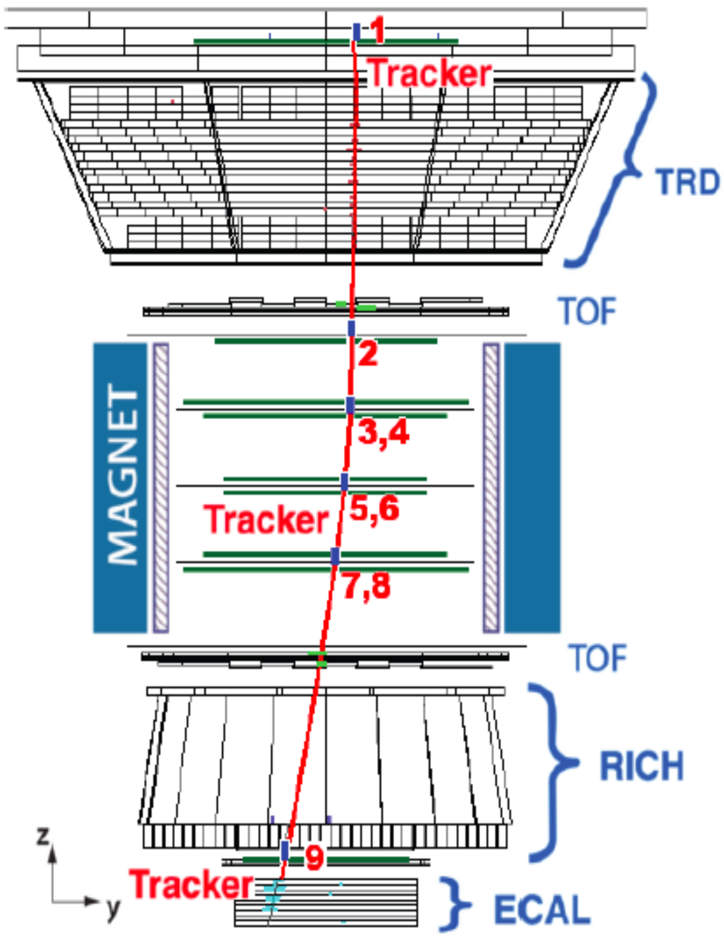
Track resolution depends on the number of layers included in the reconstruction



Tracker Alignement Occuracy

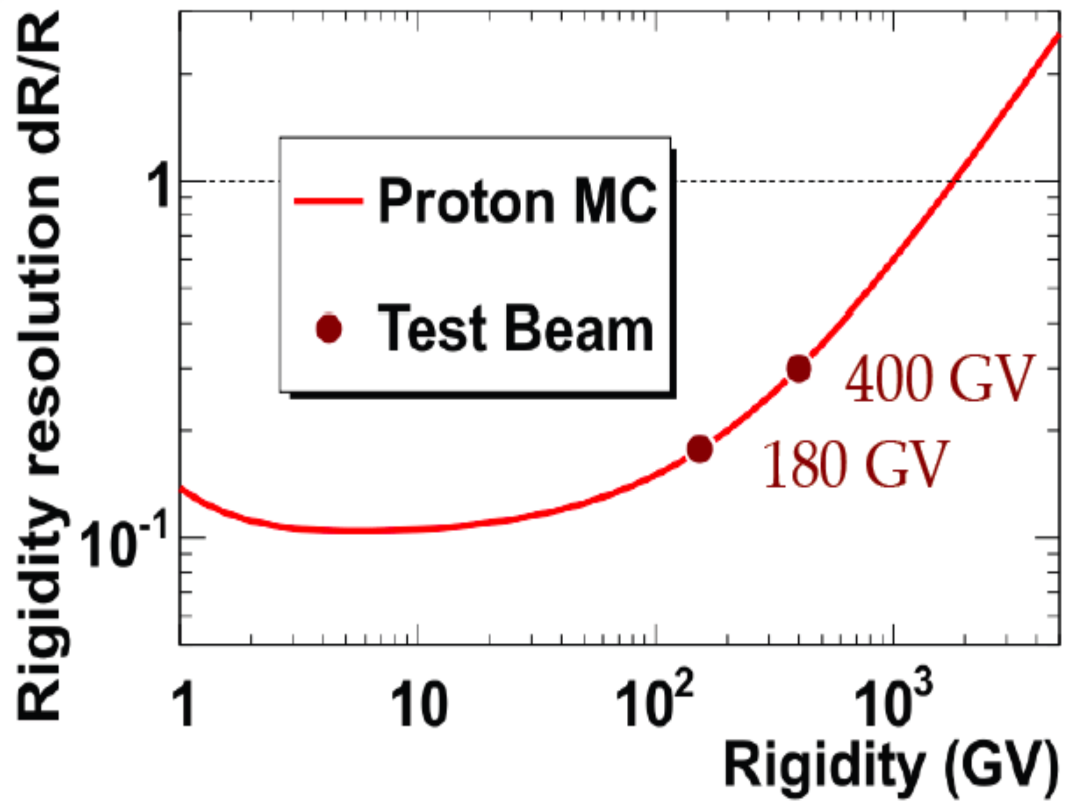






$B_x = \sim 0.14\ \mathrm{T}$ $L = \sim 3\mathrm{m}$

$\sigma_y = \sim 10\mu\mathrm{m}$ MDR : ~2TV

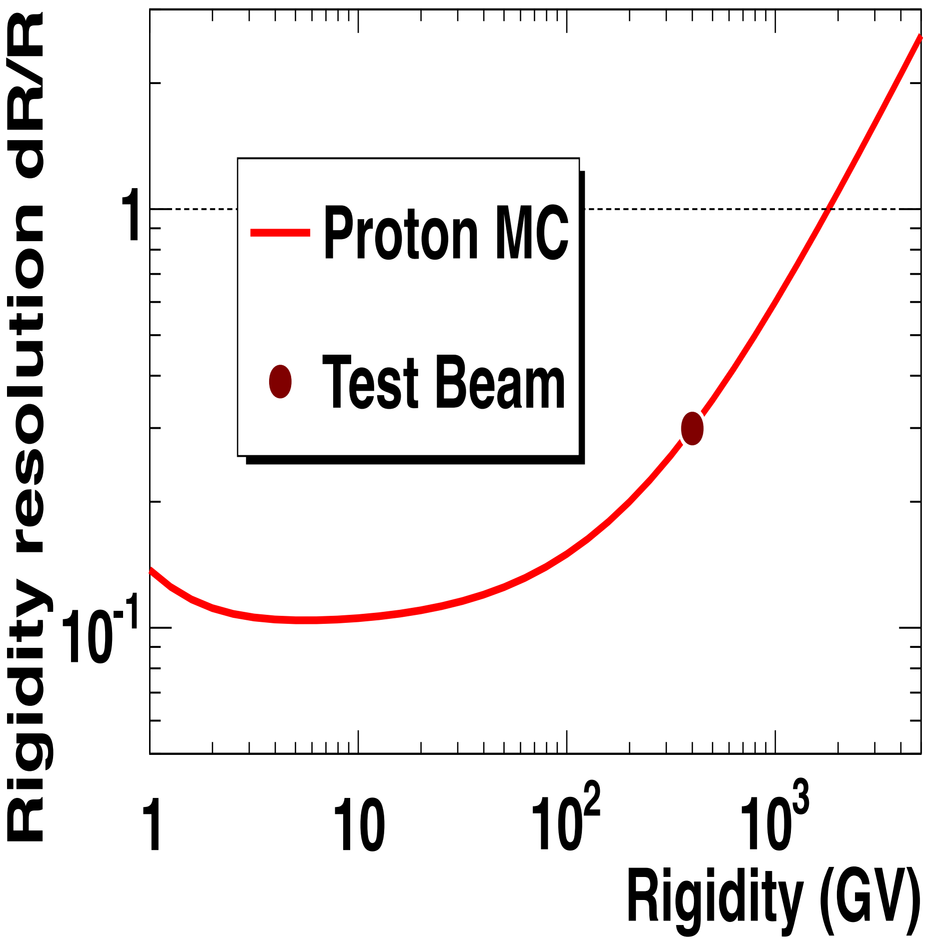


Rigidity measurement

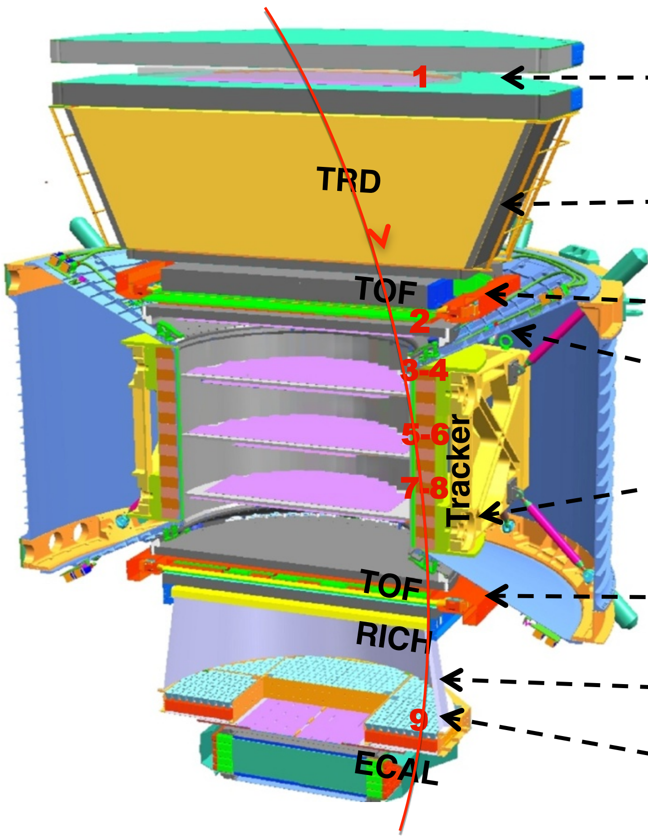
	Inner	L1	L9	L19
p	240 GV	540 GV	750 GV	2000 GV
He	400 GV	1100 GV	1600 GV	3200 GV

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

Protons

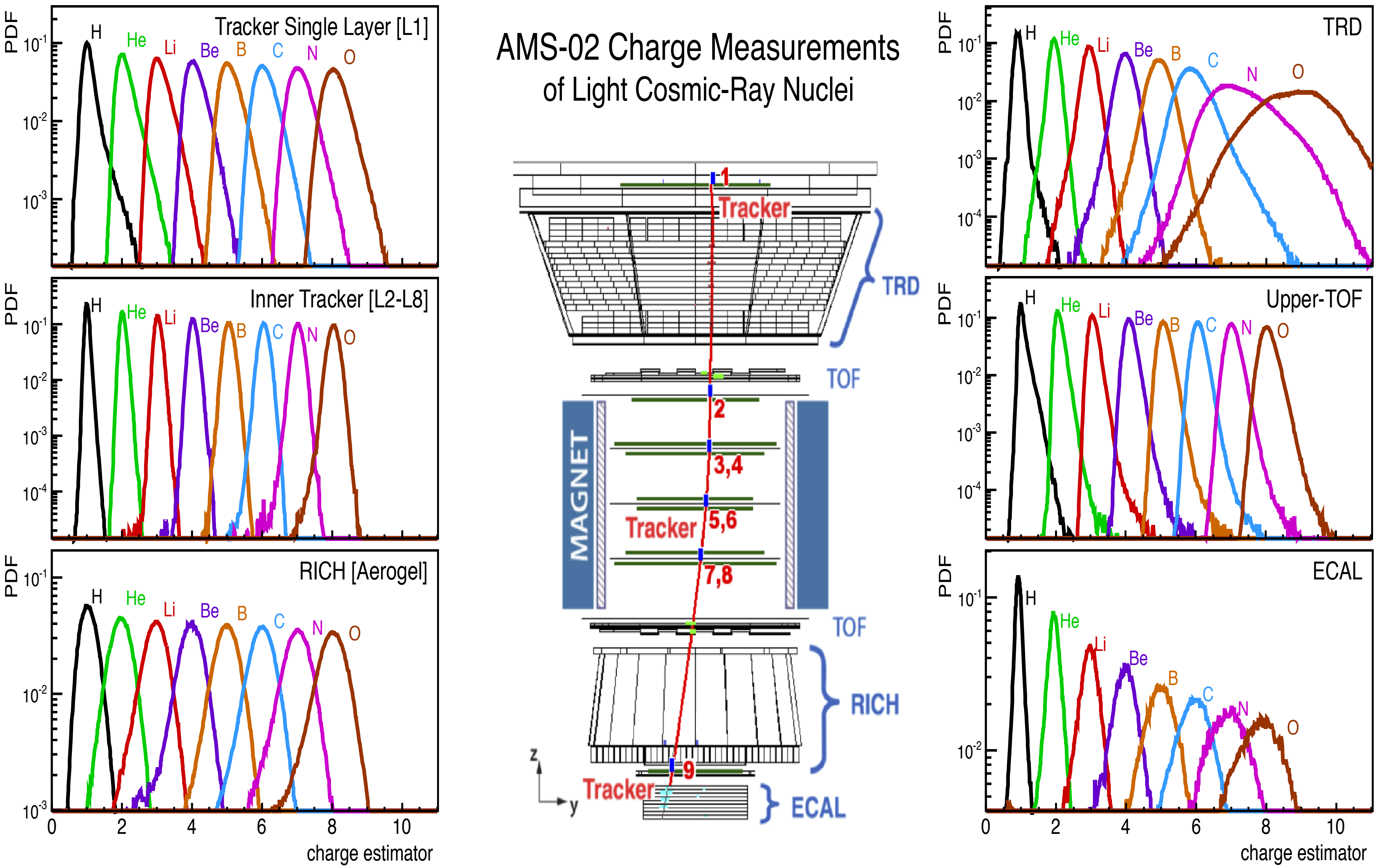


Charge measurement (|Z|)

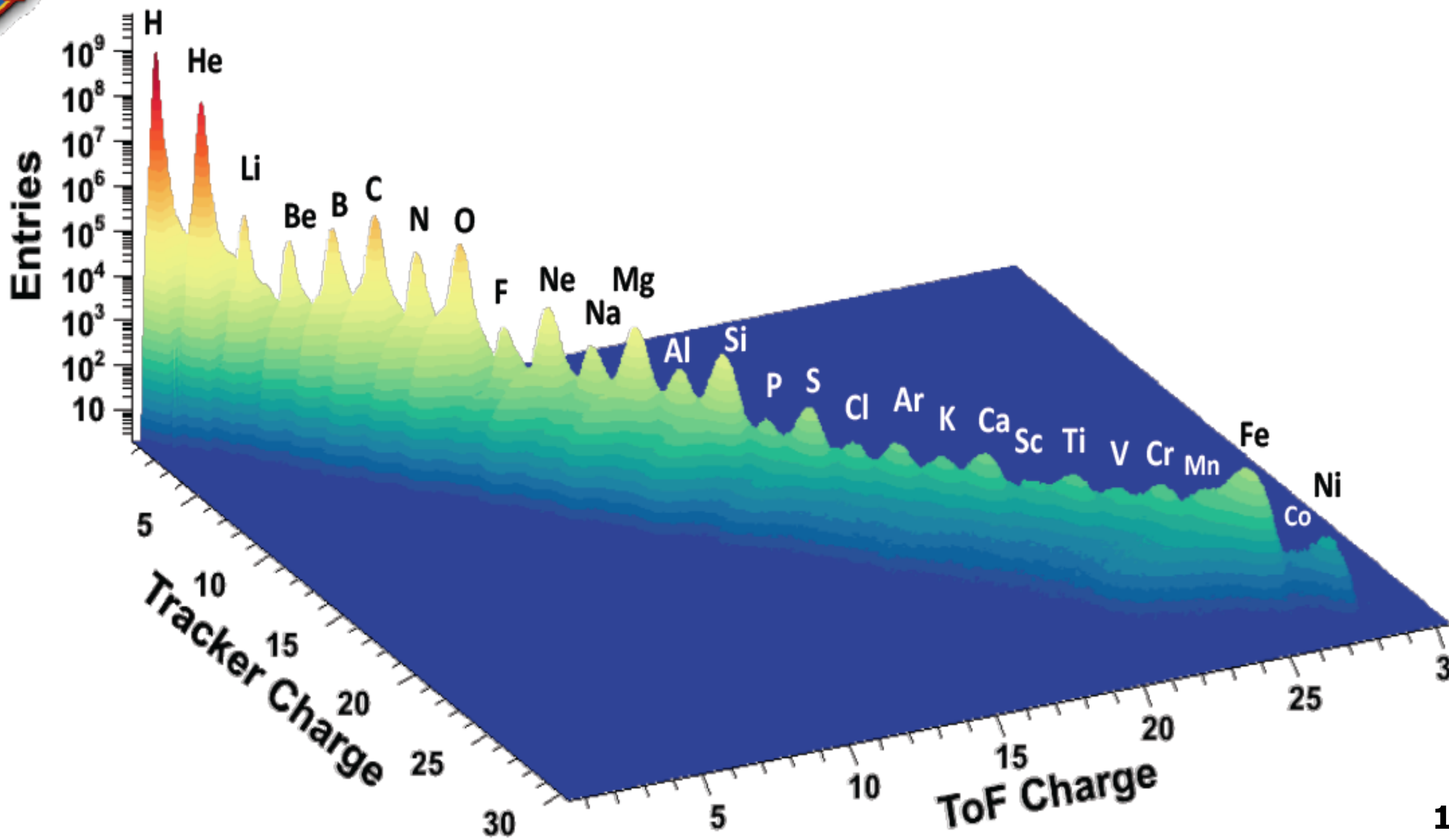


	Carbon (Z=6) ΔZ (cu)
Tracker Plane 1 (L1)	*0.30*
TRD	*0.33*
Upper TOF (1 counter)	*0.16*
Inner Tracker (L2-L8)	*0.12*
Lower TOF (1 counter)	*0.16*
RICH	*0.32*
Tracker Plane 9 (L9)	*0.30*

Charge Measurement

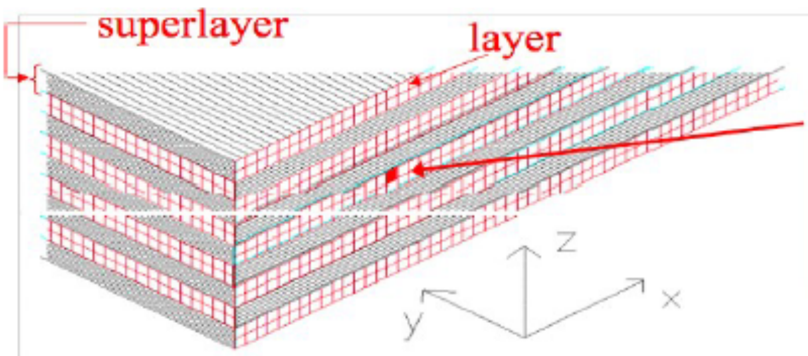


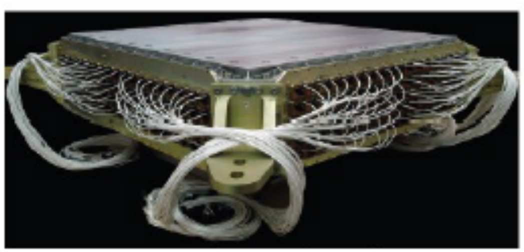
Nuclei Identification in AMS: ToF and Tracker



Energy Measurement

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



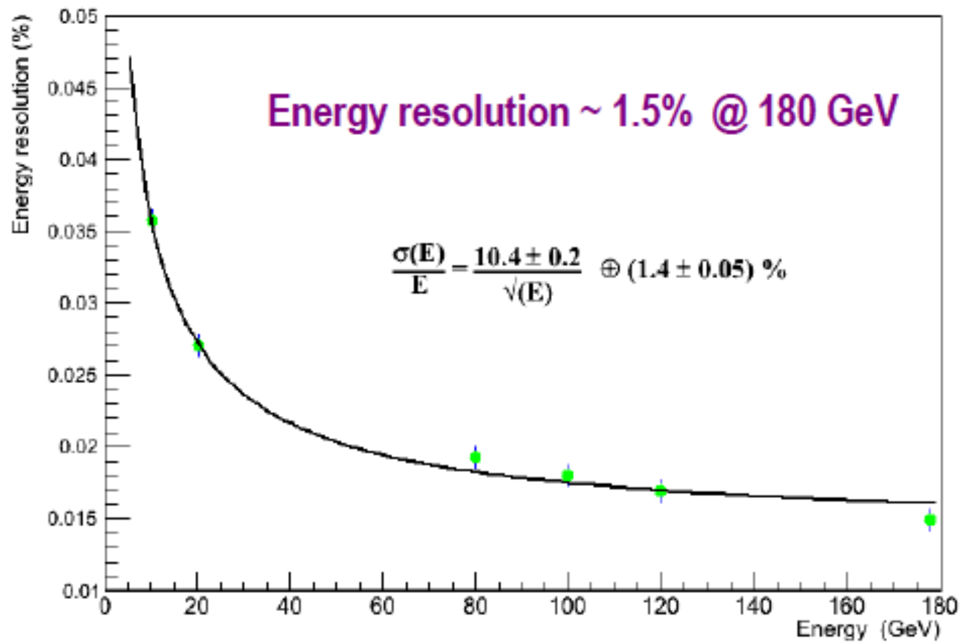


High granularity: ~ 0.9 x 0.9 cm

18 Longitudinal samplings

72 Lateral samplings

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



Flux and Ratio Determination

Flux is given by:

Number of counts

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

Acceptance
(m^2 sr)

Efficiency
(trigger,
selection)

Exposure Time

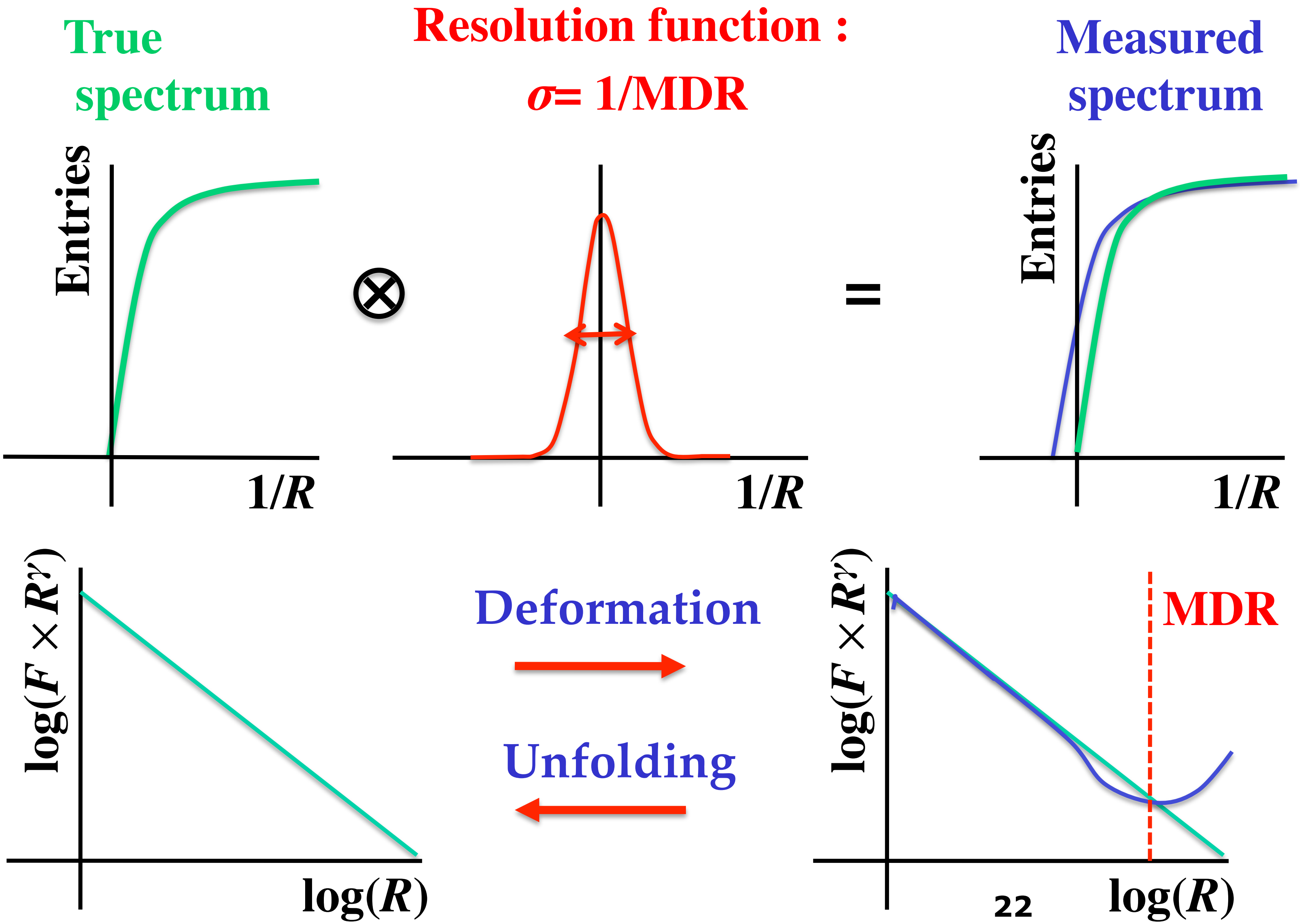
Bin Width

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



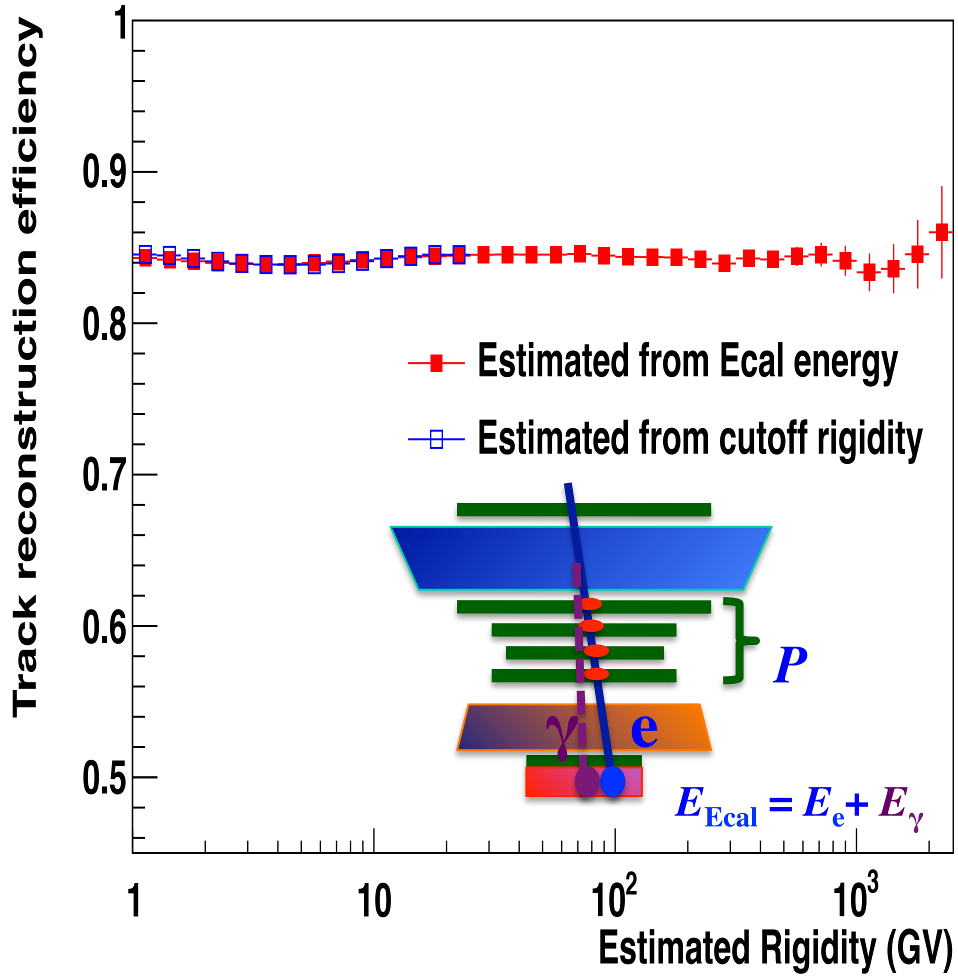
protons - Systematic errors

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

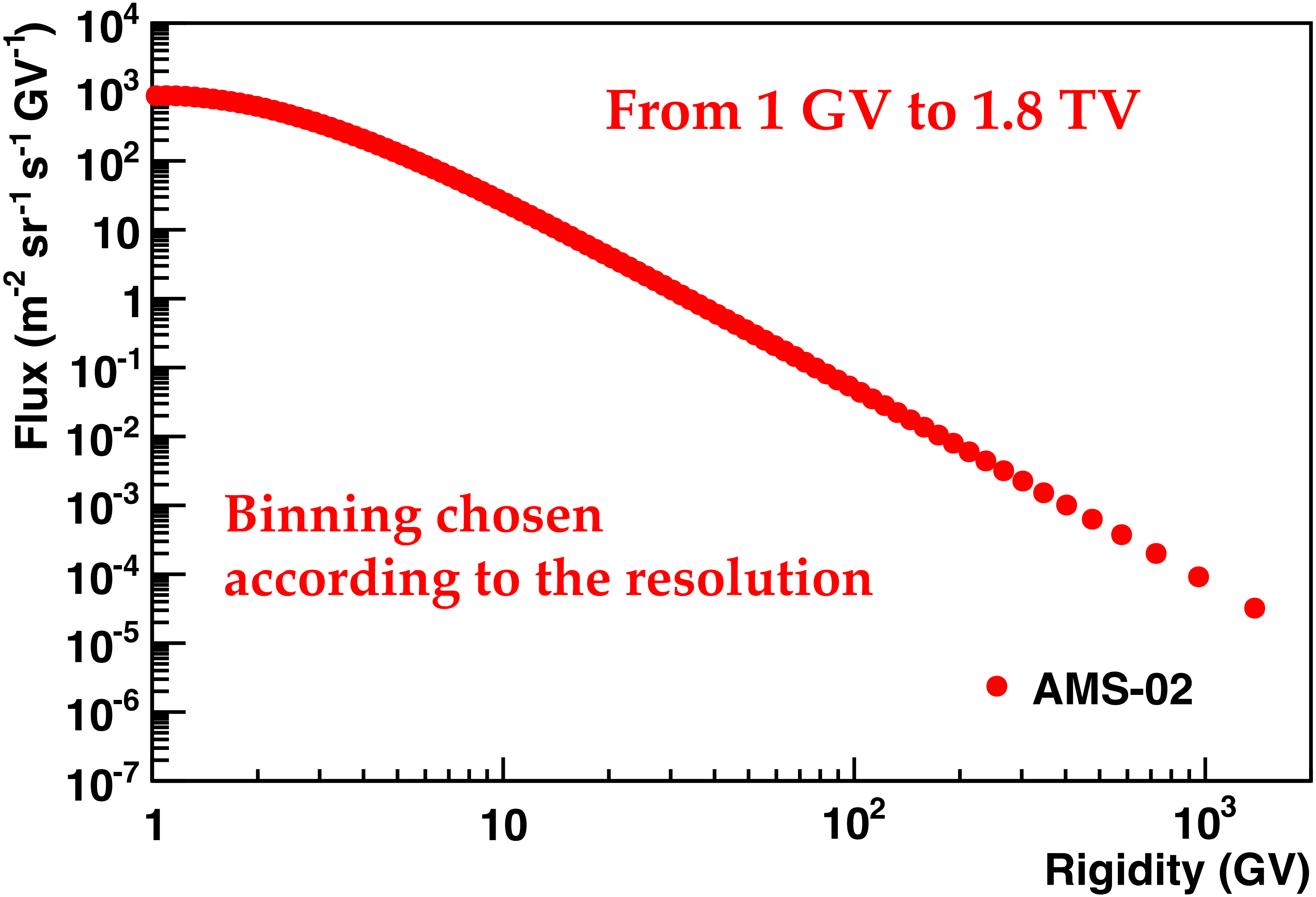
$\varepsilon_{norm.} = (\varepsilon_{acc}^2 + \varepsilon_{trg}^2 + \varepsilon_{trk}^2)^{½}$ = 3.1 %

- Systematic error of unfolding
  $\varepsilon_{unfold} <$ 1 % at $R <$ 200 GV
  ε_{unfold} = 5.4 % at R = 1 TV

Systematic errors will be reduced with more data

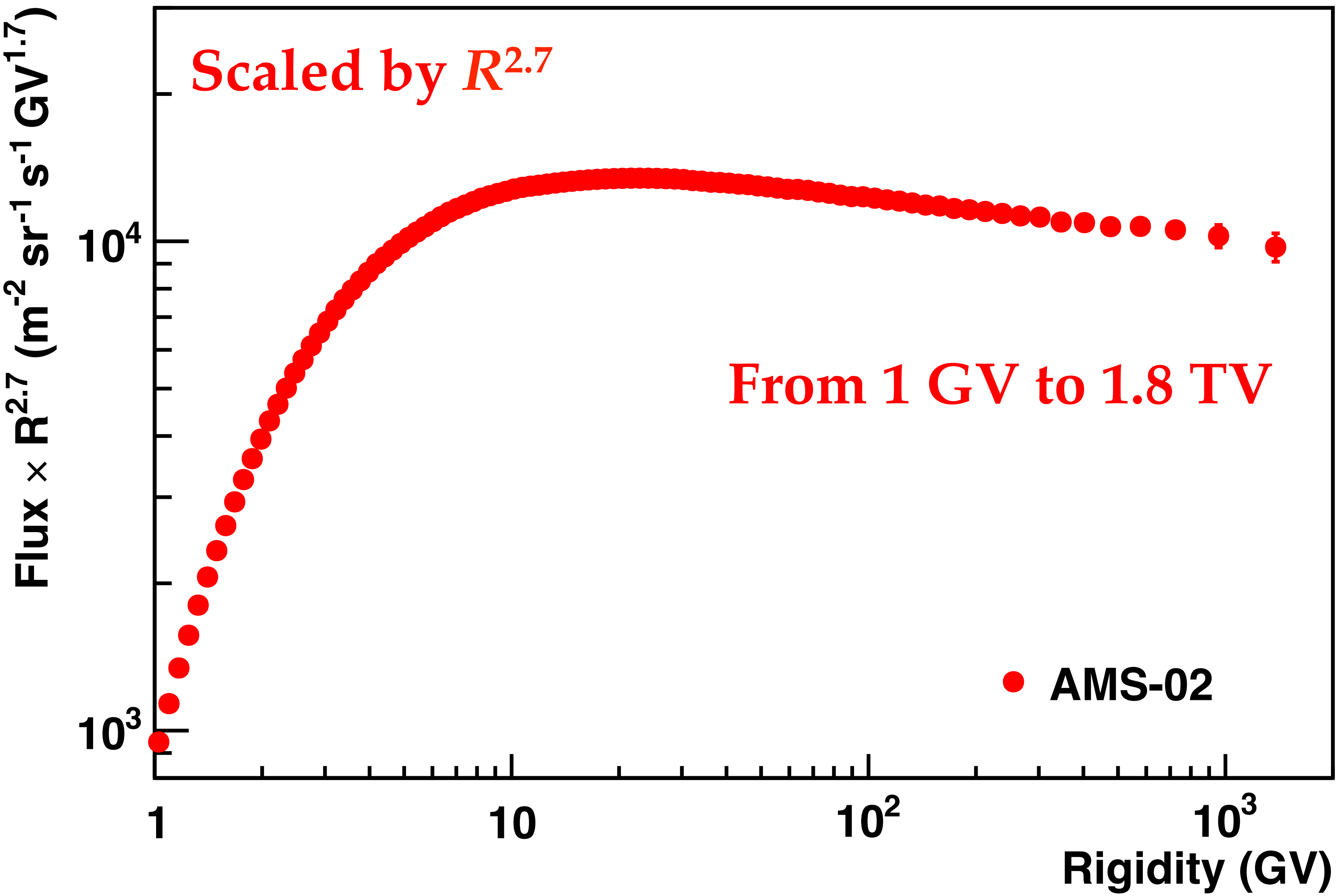


Proton Fluxes



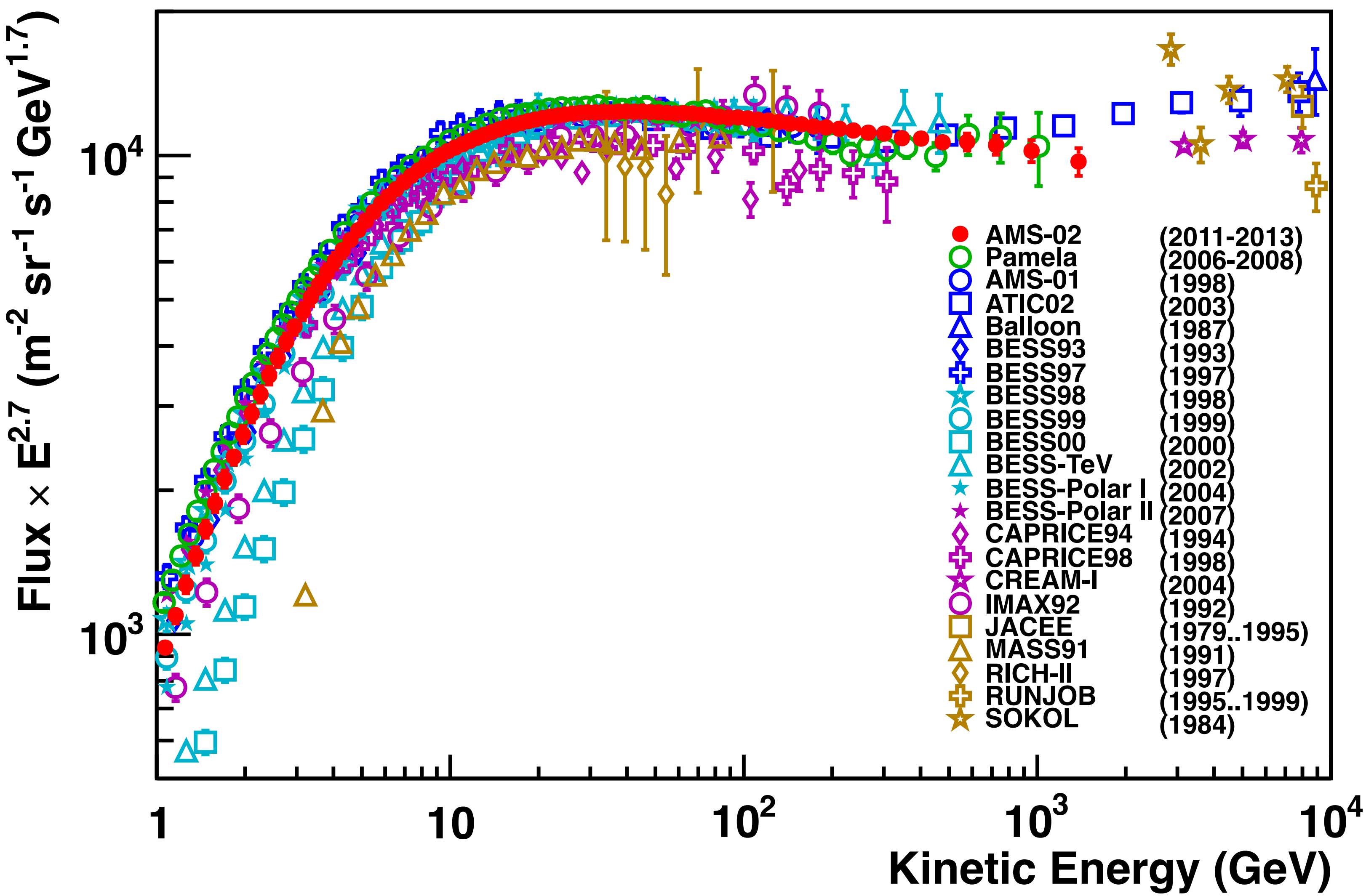
Power law behaviour, index > 2.7, > 1000 protons above 1 TV

Proton Flux



Scaled by $R^{2.7}$
From 1 GV to 1.8 TV
AMS-02
Flux × R^2.7 (m^-2 sr^-1 s^-1 GV^1.7)
Rigidity (GV)
10^4
10^3
1
10
10^2
10^3

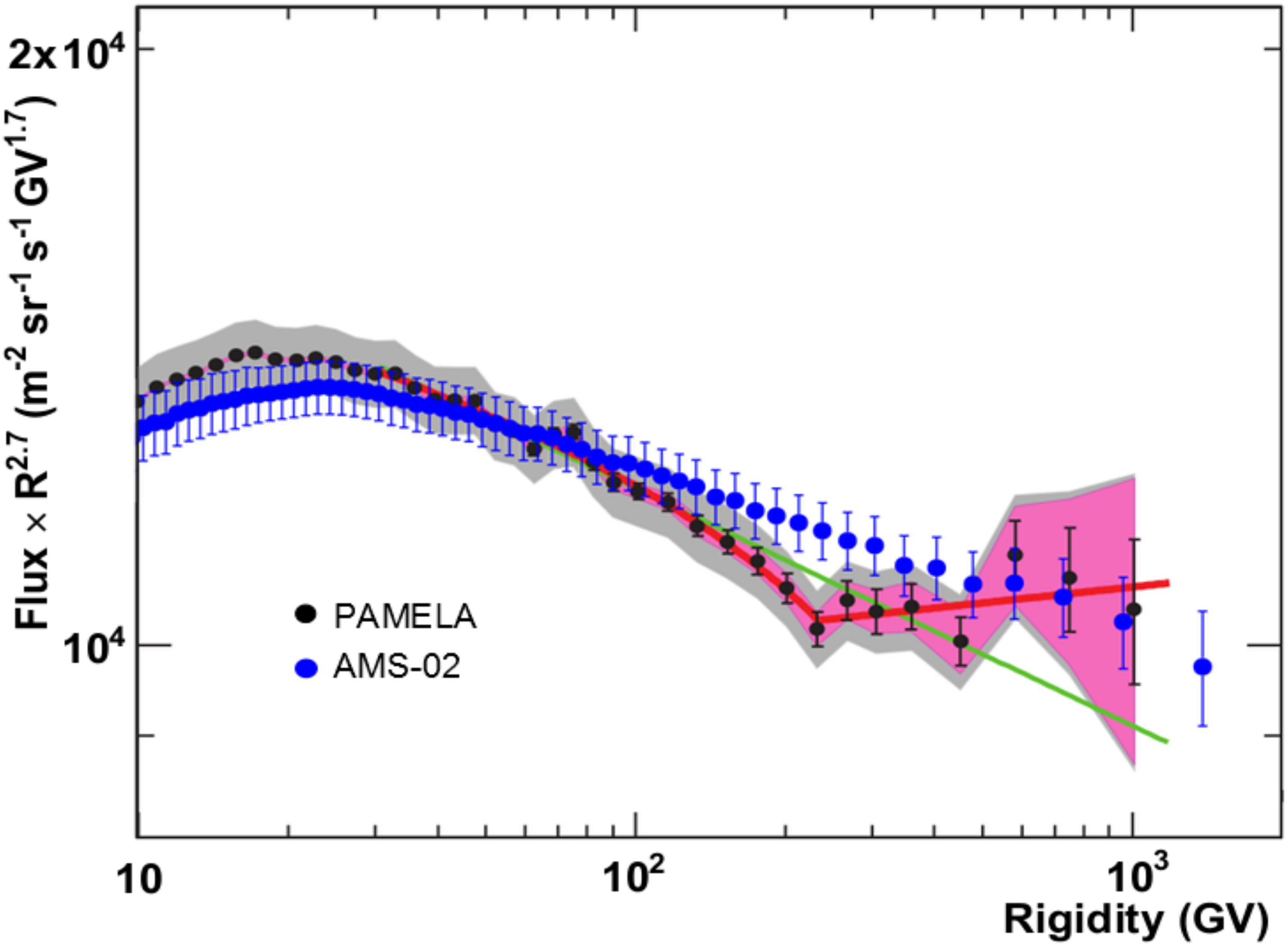
Protons- Comparison with previous measurements



AMS-02 Protons- Comparison with Pamela measurements

Science AAAS

PAMELA Measurements of Cosmic-Ray Proton and Helium Spectra
O. Adriani *et al.*
Science **332**, 69 (2011);
DOI: 10.1126/science.1199172

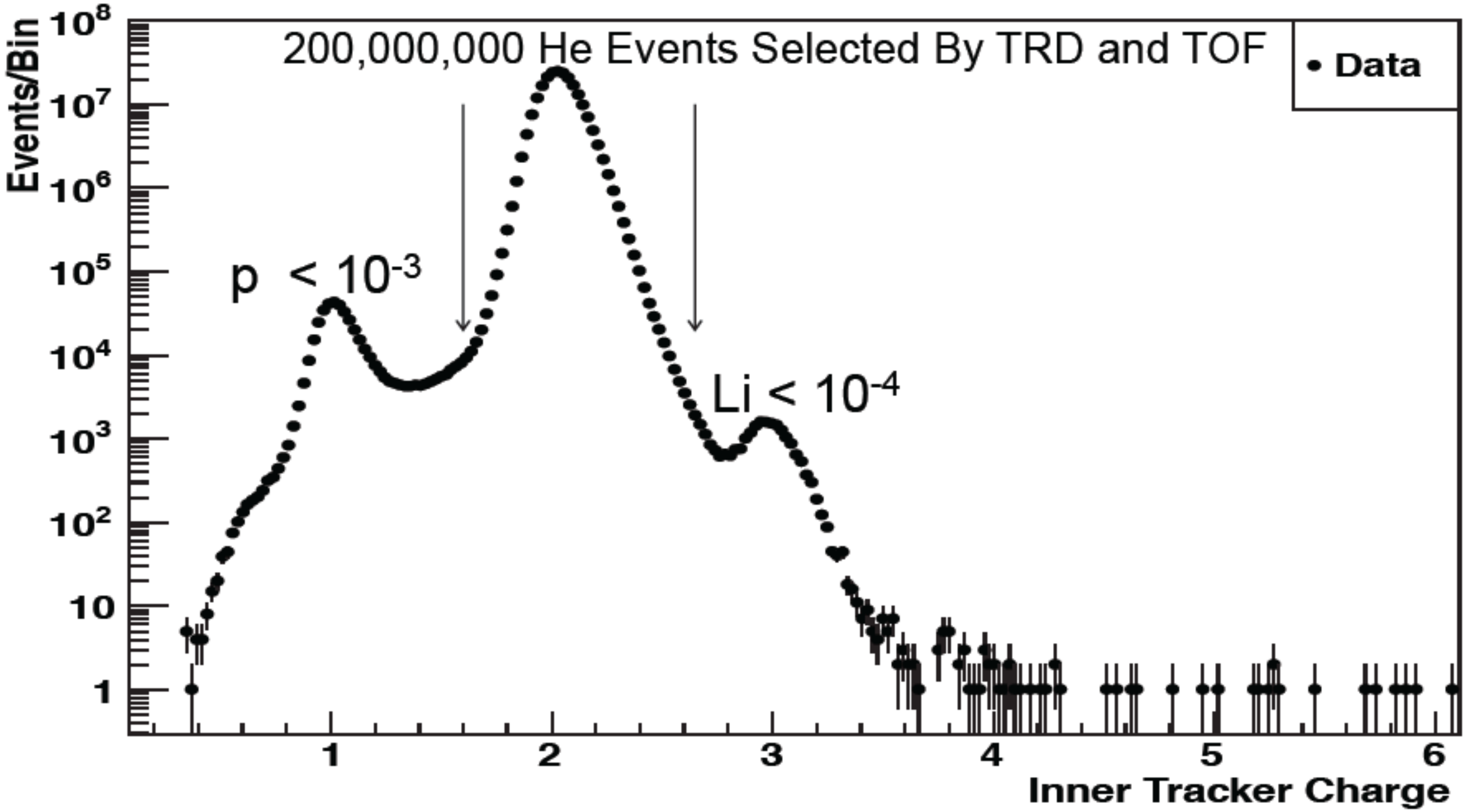


Helium Nuclei Selection

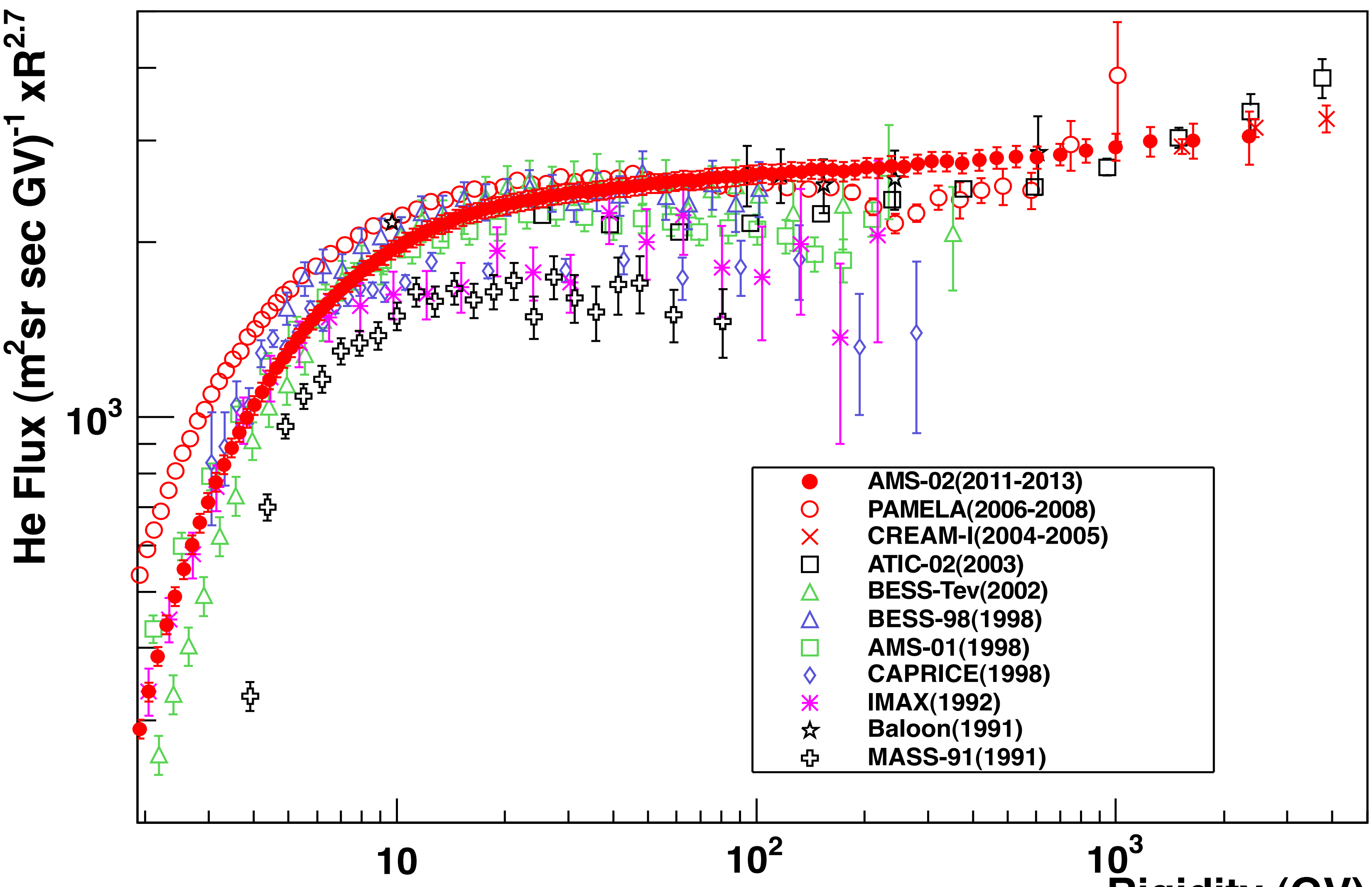
Helium Selection

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

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



Ams-02 Helium flux Comparison with previous measurements



Power law behaviour, index < 2.7

Helium - Comparison with Pamela measurements

PAMELA Measurements of Cosmic-Ray Proton and Helium Spectra
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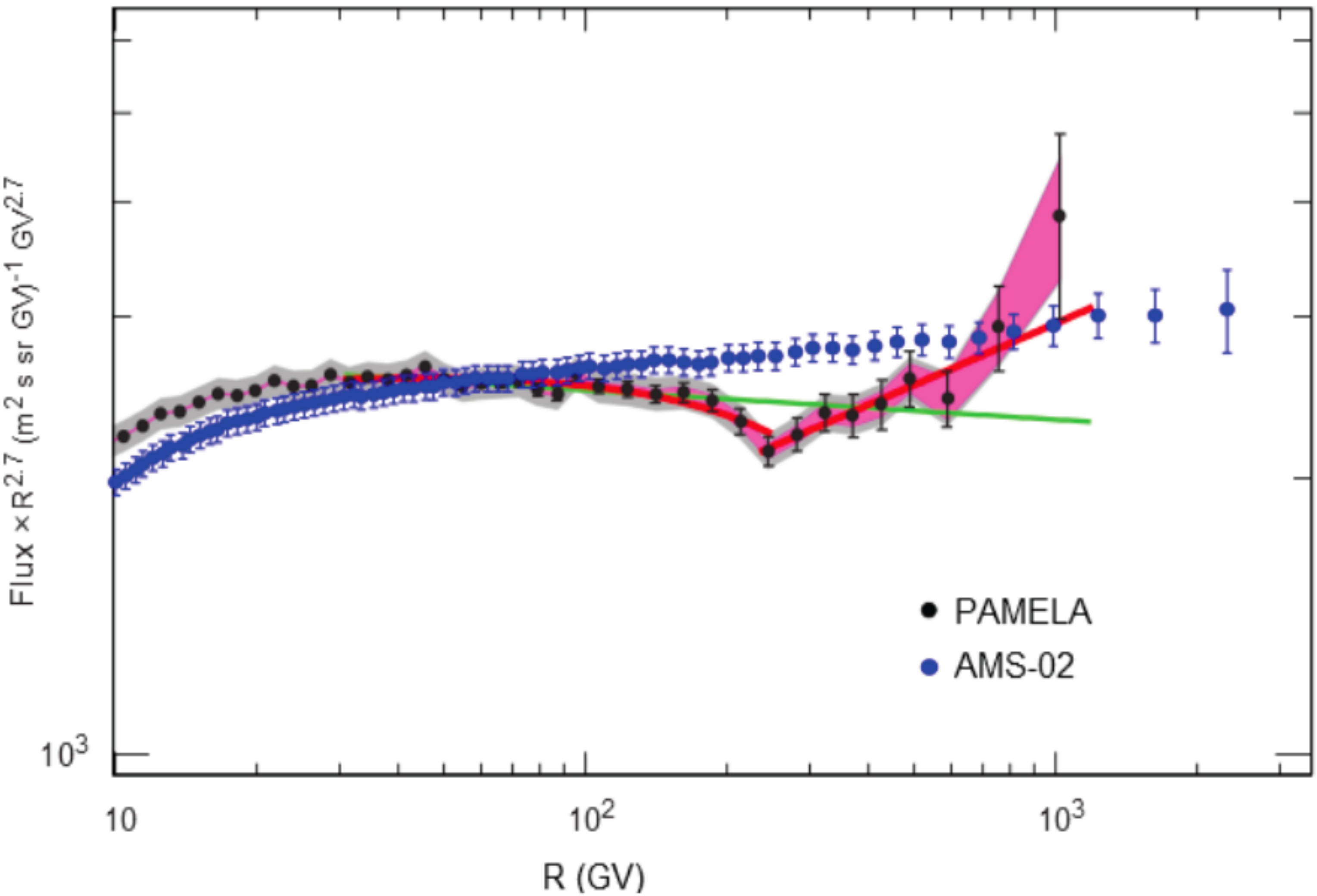
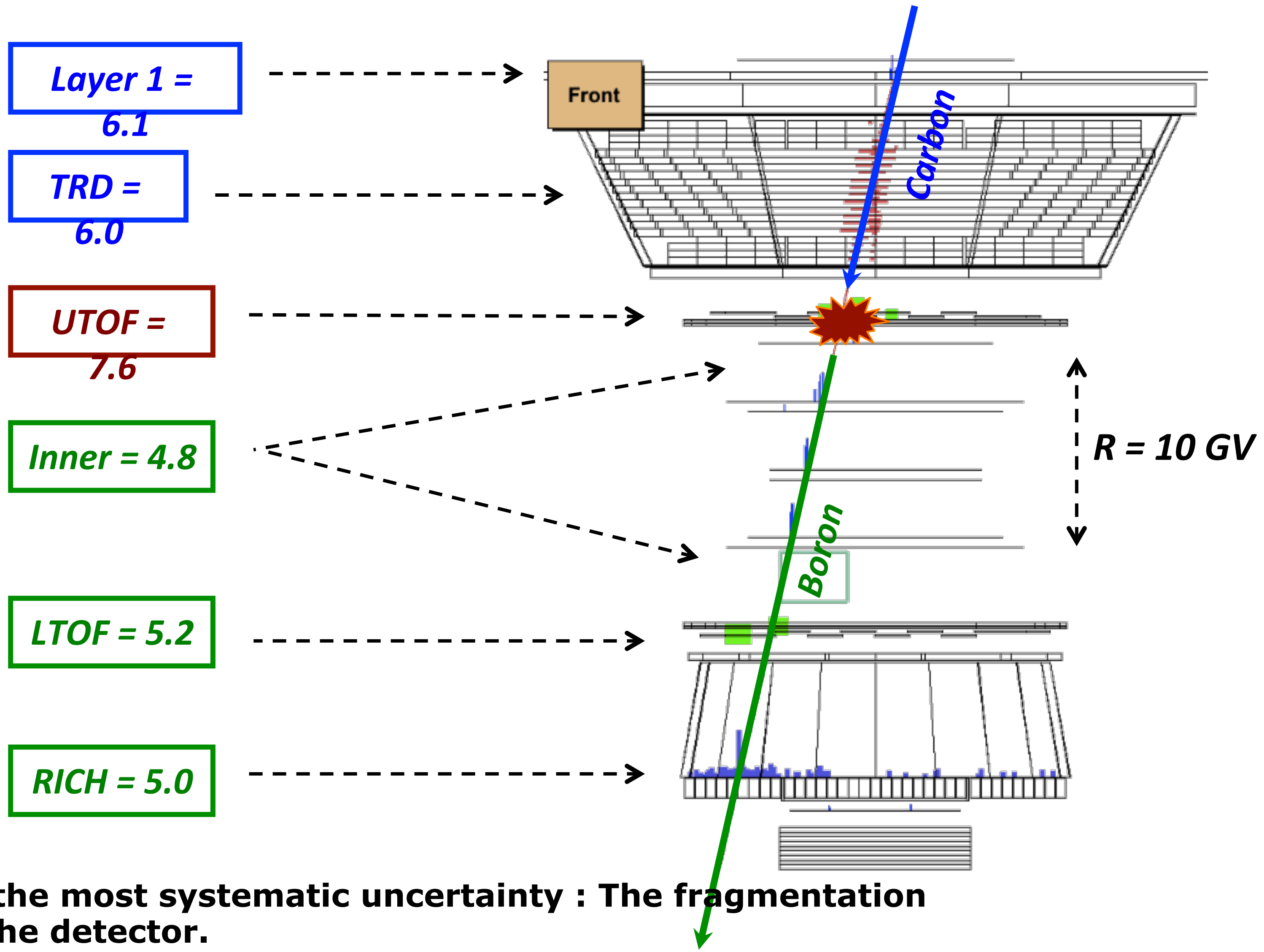


Power law behaviour, index < 2.7

B/C :Identification of Fragmentation Events

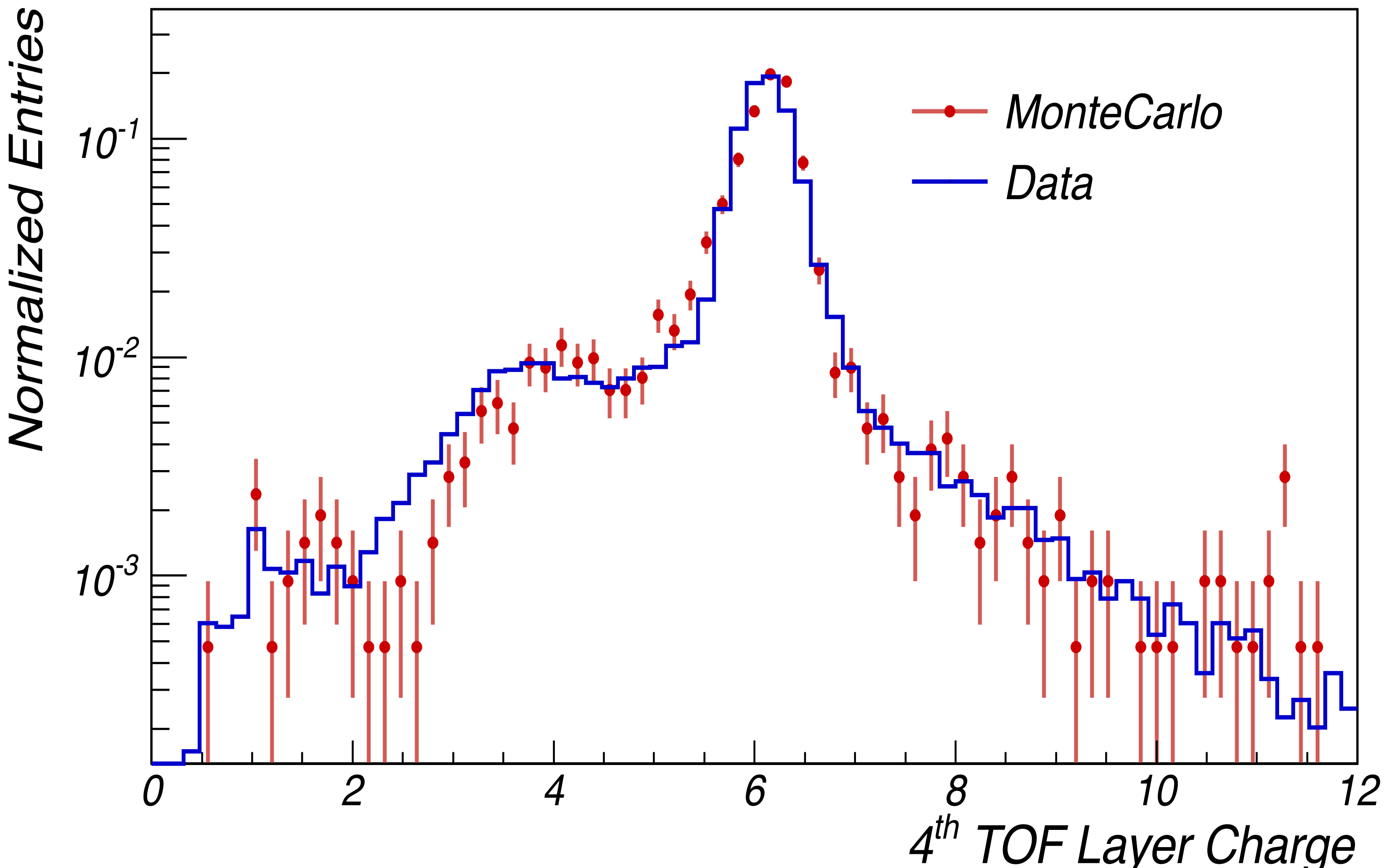


One of the most systematic uncertainty : The fragmentation inside the detector.

The first layer do play a key role in the selection

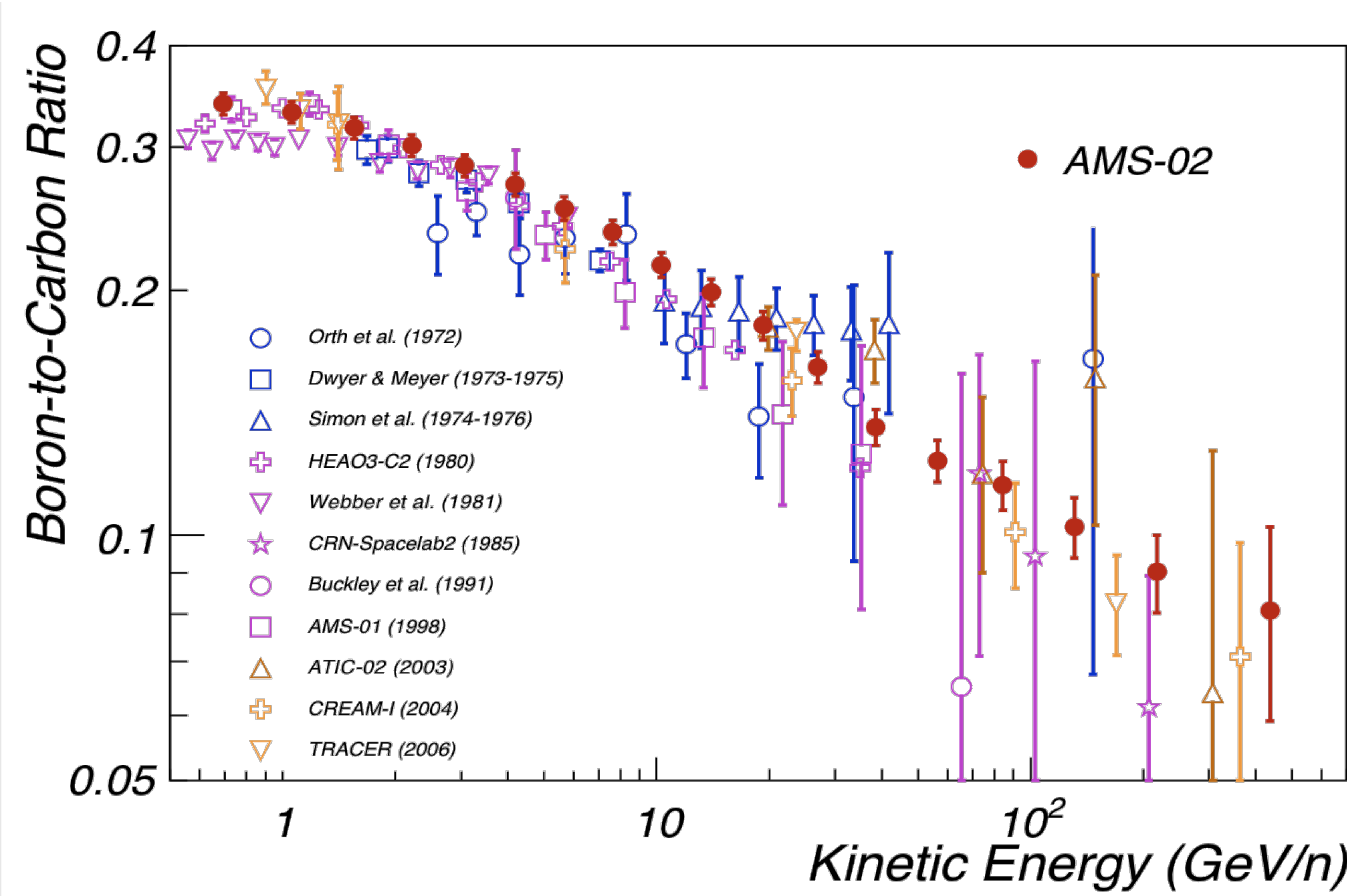
Estimation of the fragmentation B/C

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

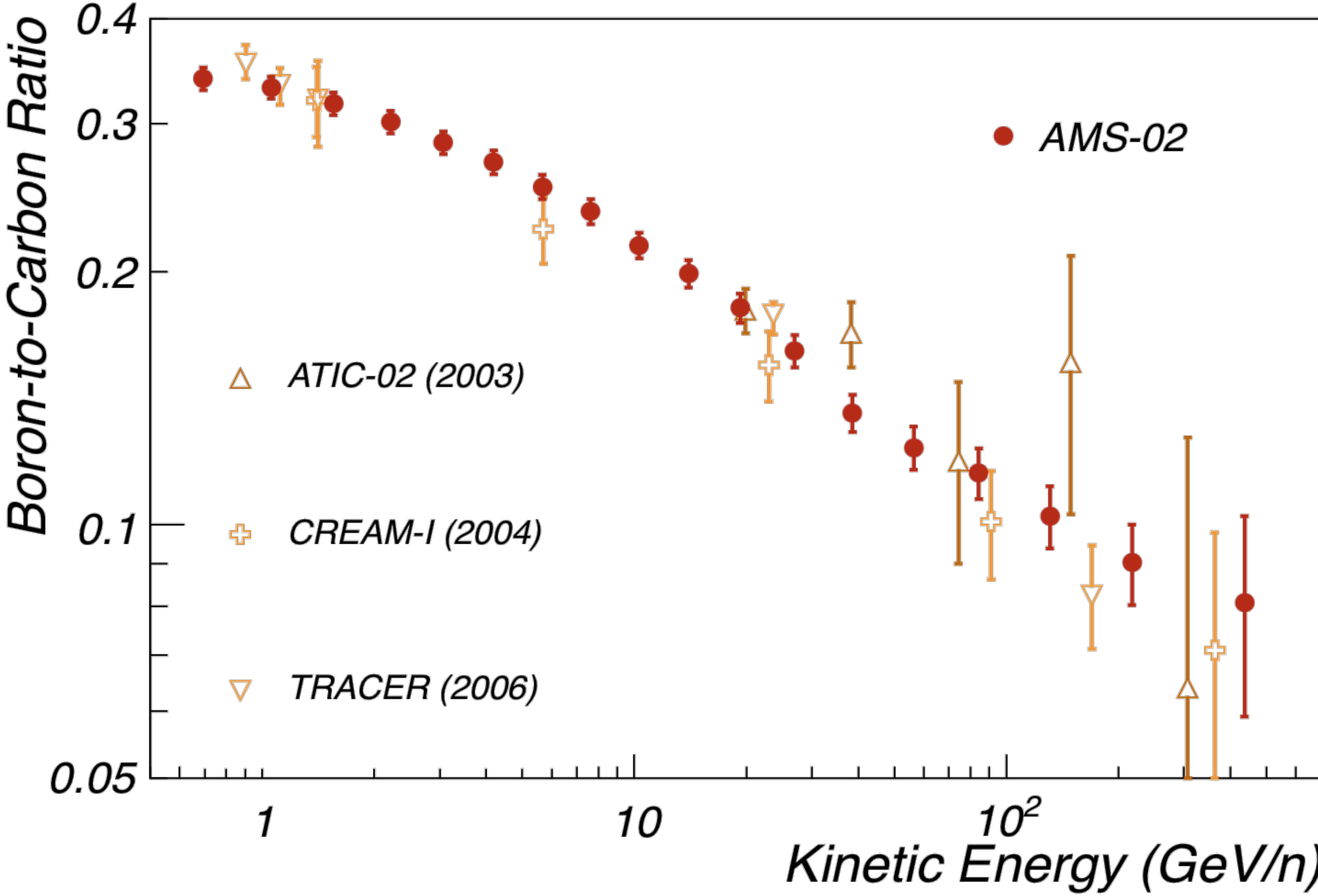


Data and MC agreement evaluated being at 2% level.

AMS-02 Boron/Carbon Ratio

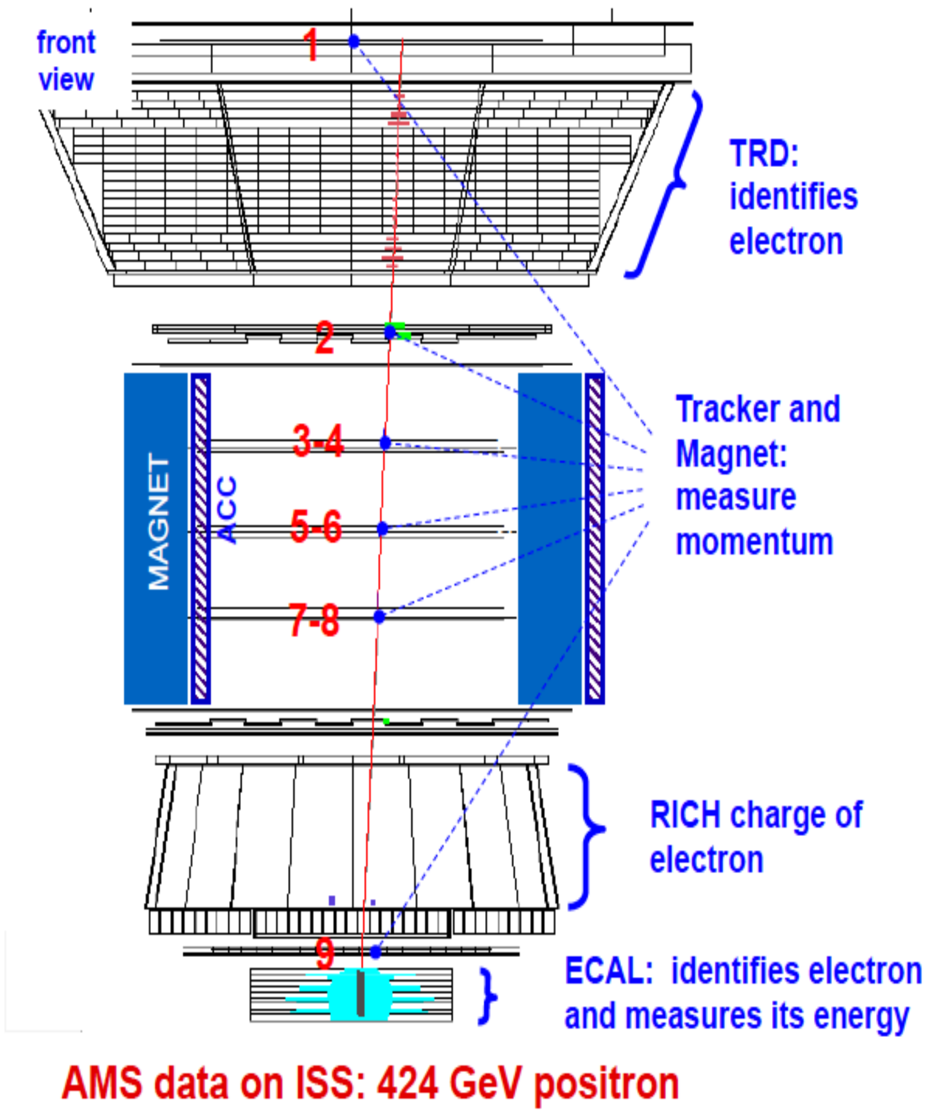


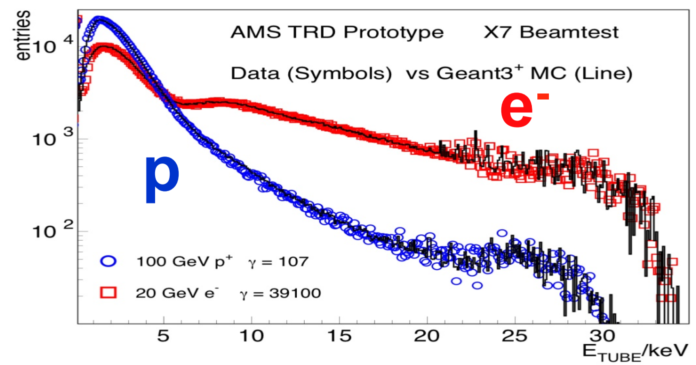
AMS-02 Boron/Carbon Ratio band recent measurements (>2000)

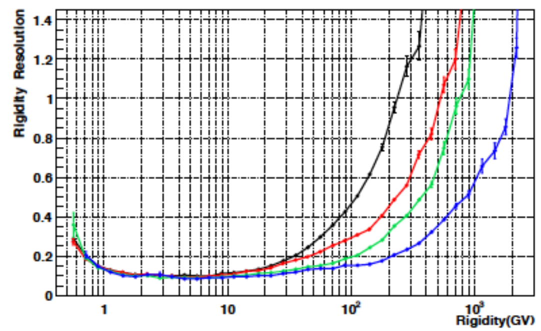


e+,e- Identification in AMS

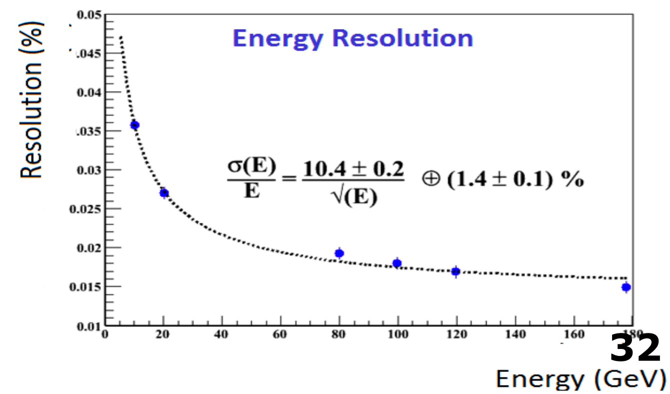
Proton rejection goal > 1/100000 => 3 independent detectors are used





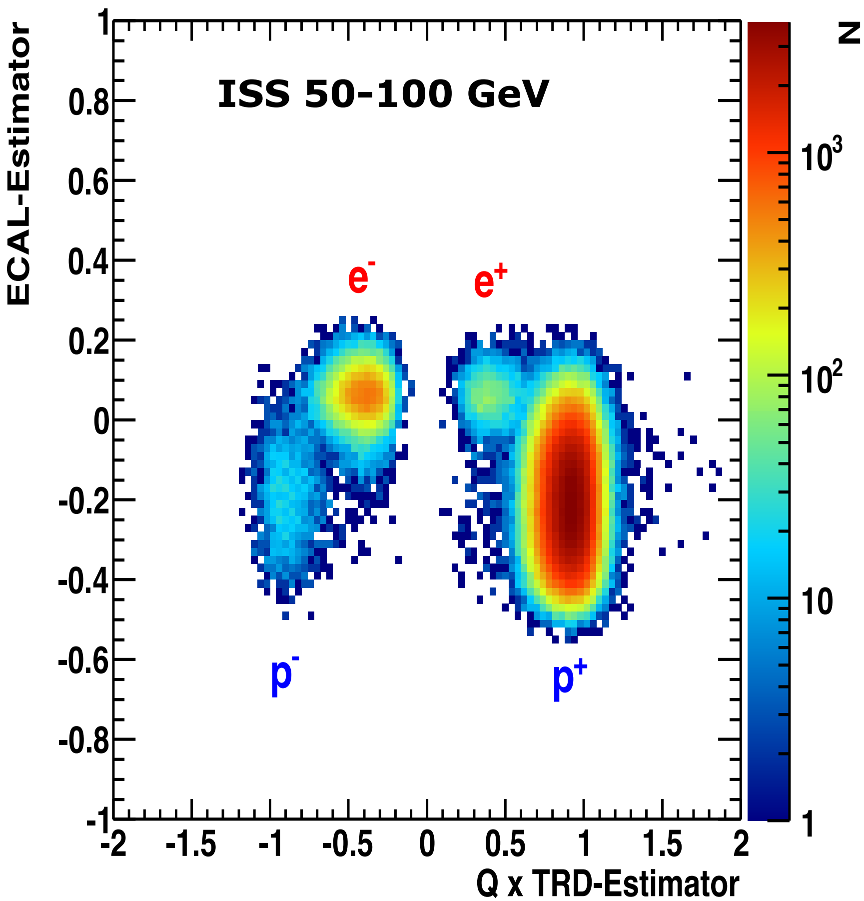


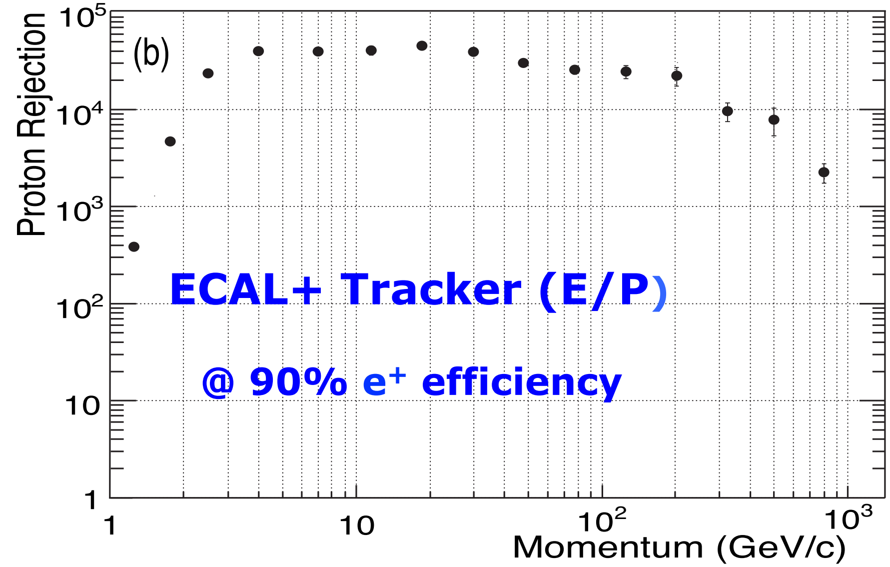
MDR=2 TV

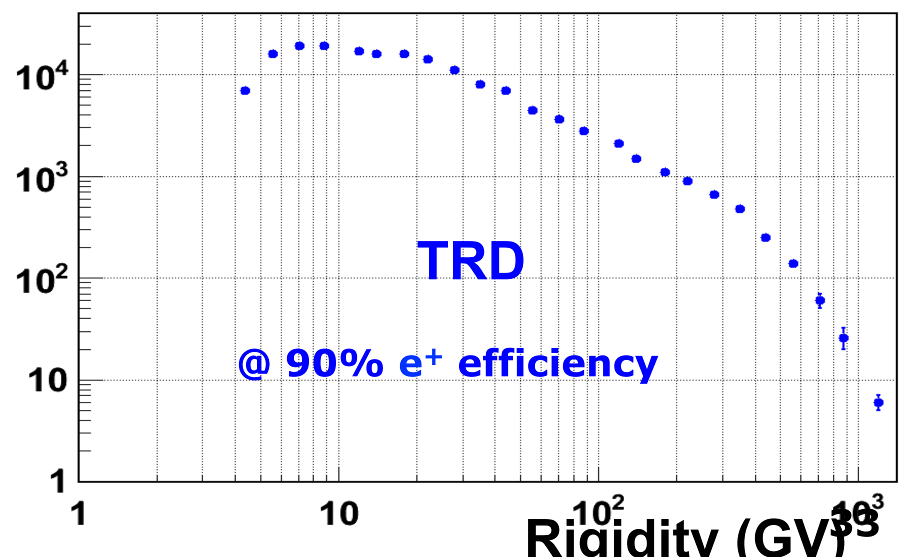


Proton rejection

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



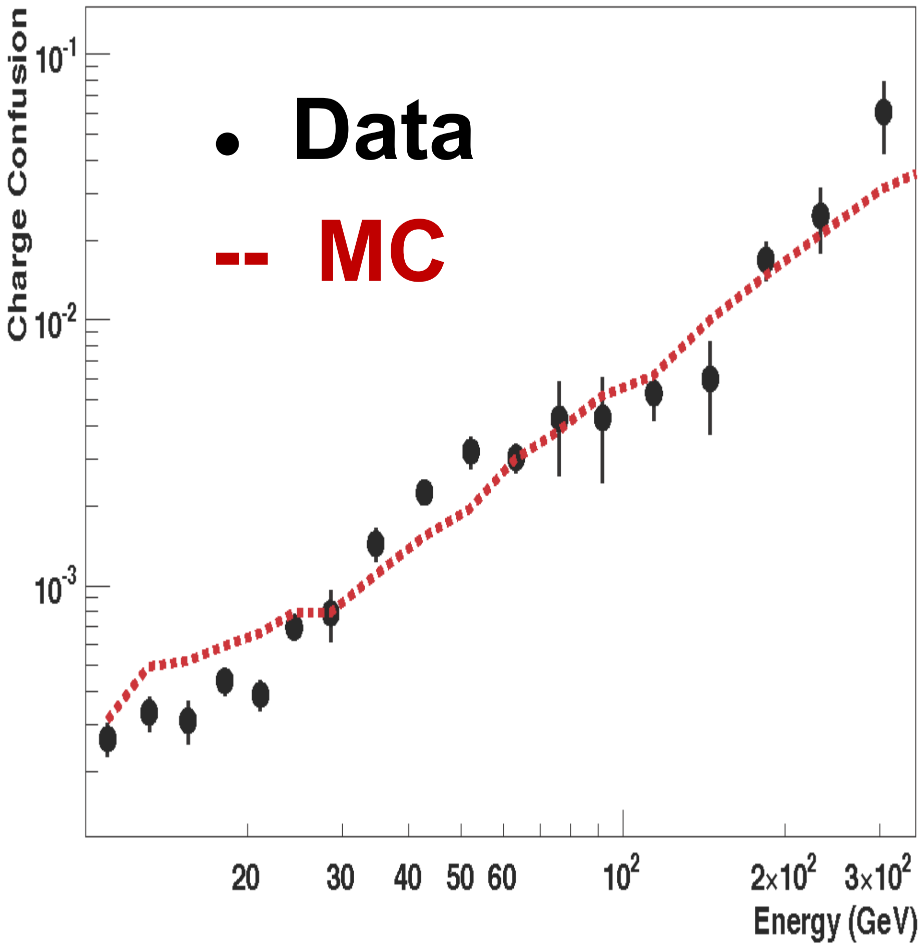




TRD estimator :likelihood based on
the signal amplitude in each layer (20 in total)

Electron rejection

Charge confusion average Tracker patterns



2 sources

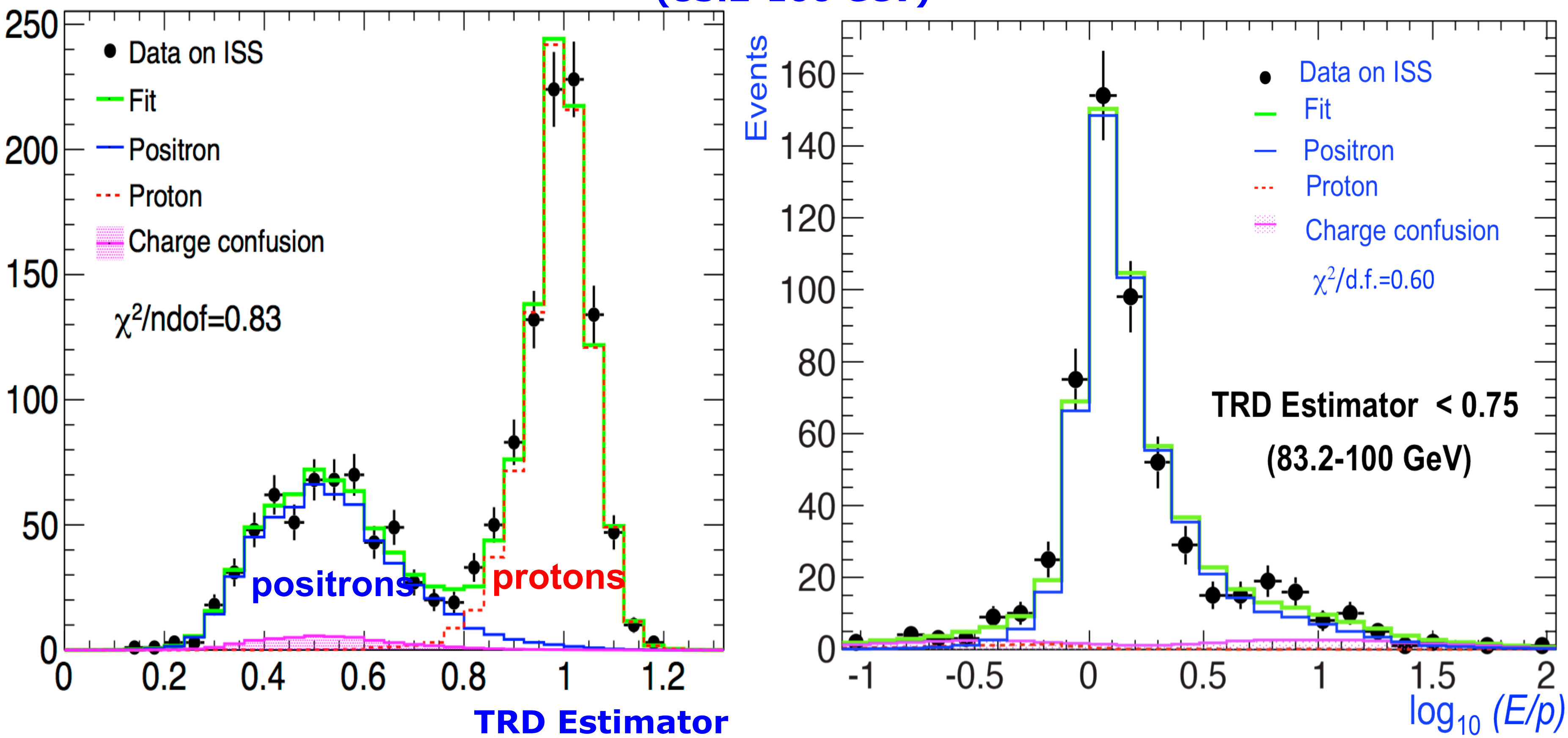
- Multiple scattering and finite resolution of the tracker
- Secondary tracks produced along the the path of primary e^{+-} (tagged and controlled with the lower TOF)

Good agreement Data/MC

Analysis: 2D fit to measure **N$e^{\pm}$** and 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

(83.2-100 GeV)

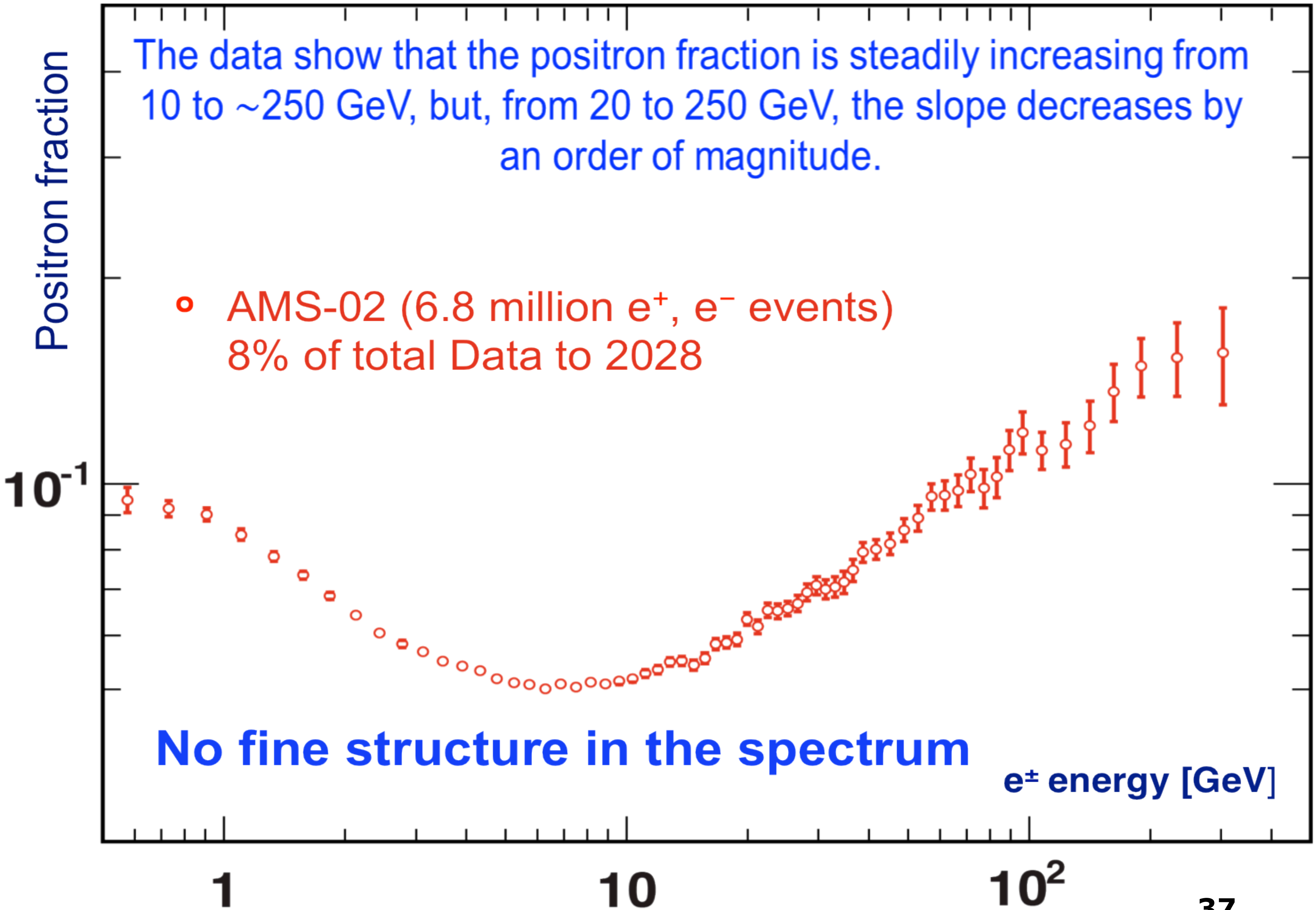


The large redundancy allows to control precisely the systematics uncertainties

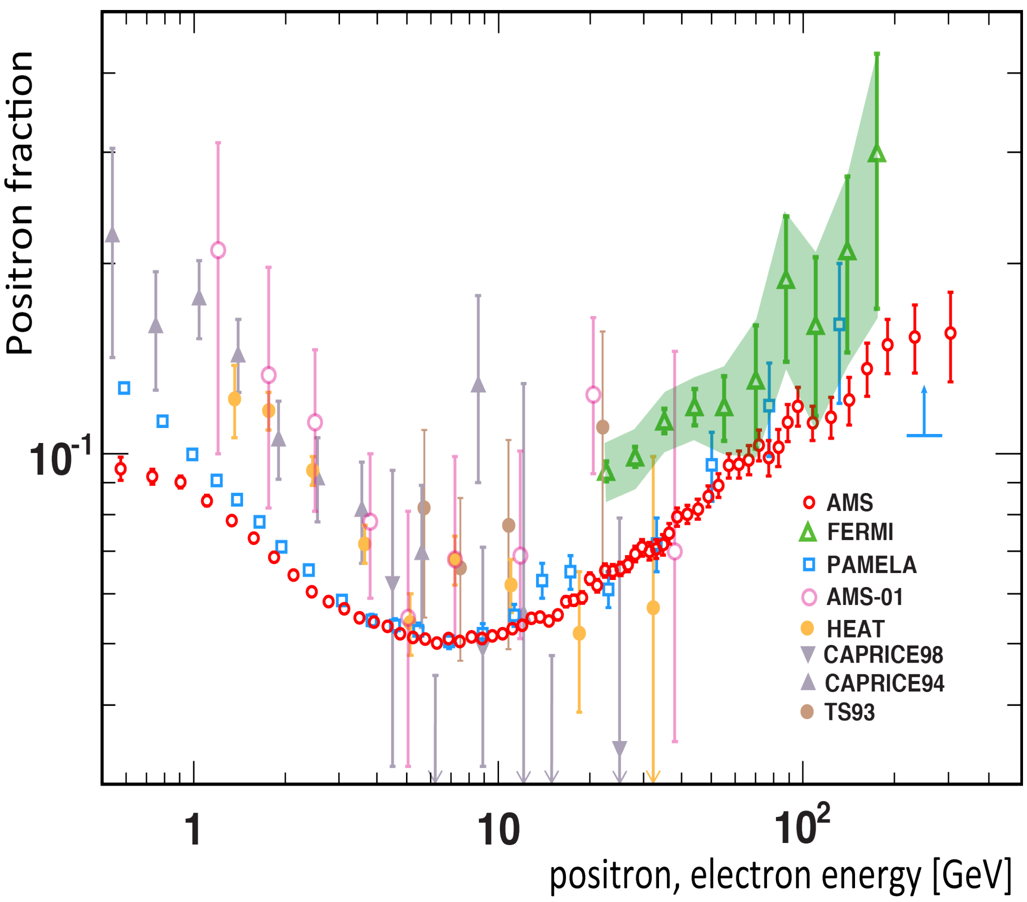
Representative bins of the positron fraction

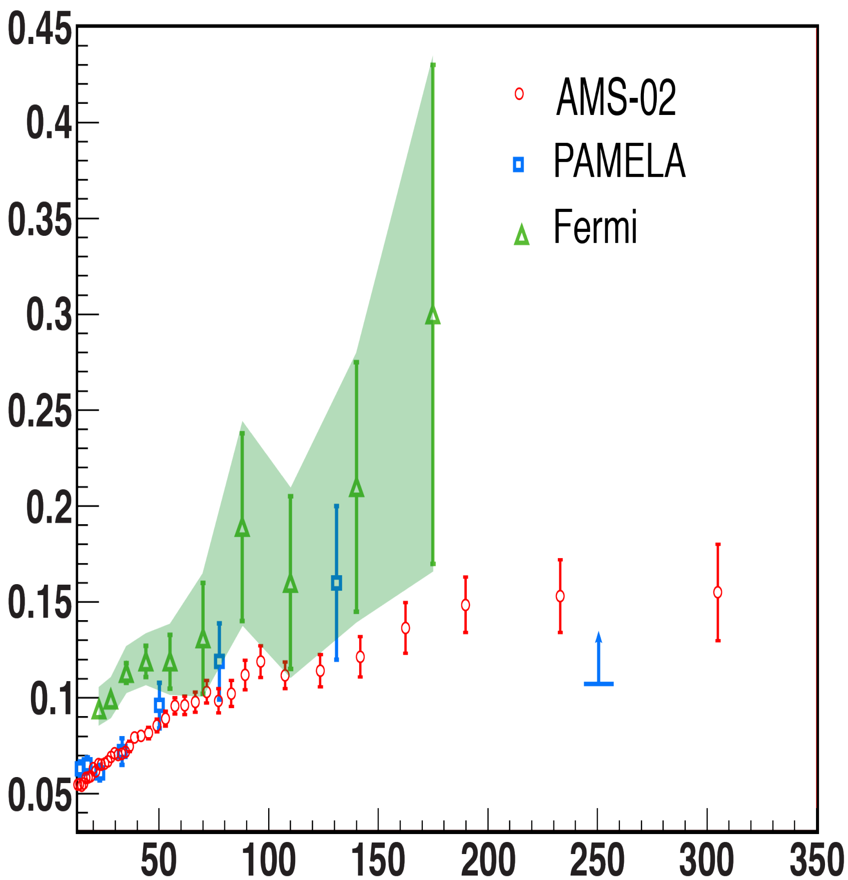
positron fraction				Systematic Errors					
Energy [GeV]	N_{e+}	Fraction	statistical error	acceptance asymmetry	event selection	bin-to-bin migration	reference spectra	charge confusion	total systematic uncertainty
Energy[GeV]	N_{e+}	Fraction	$\sigma_{stat.}$	$\sigma_{acc.}$	$\sigma_{sel.}$	$\sigma_{mig.}$	$\sigma_{ref.}$	$\sigma_{c.c.}$	$\sigma_{syst.}$
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
09.95 -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

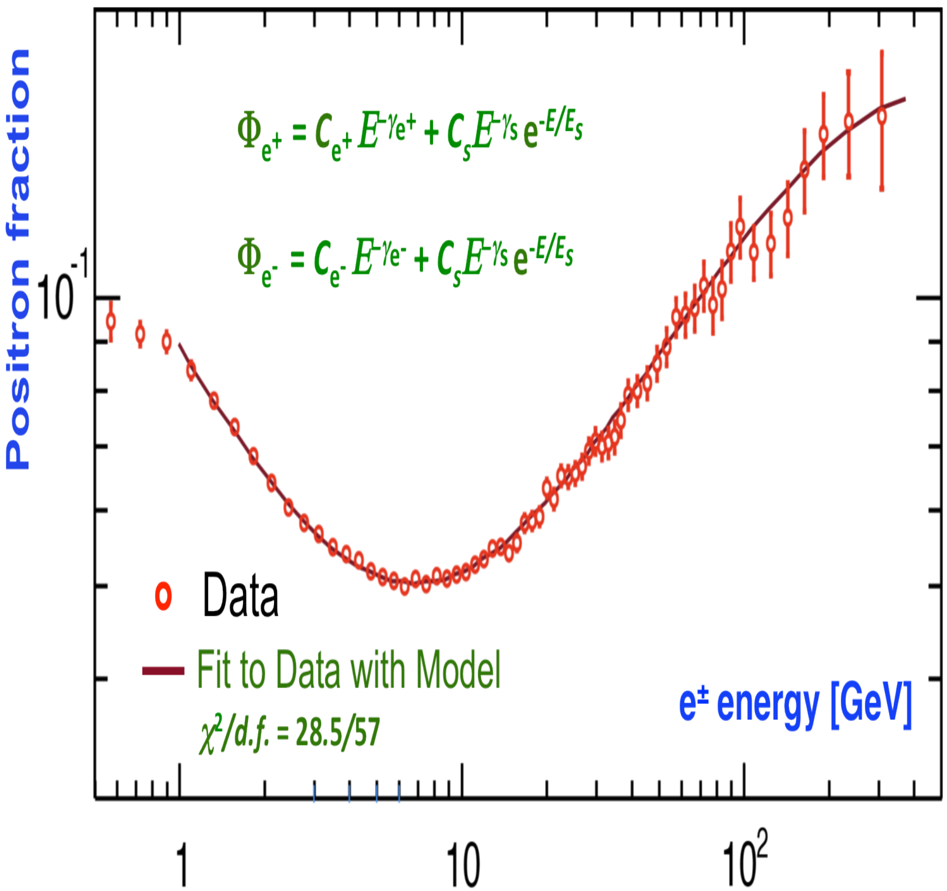




->e± Energy [GeV]

Positron fraction AMS

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

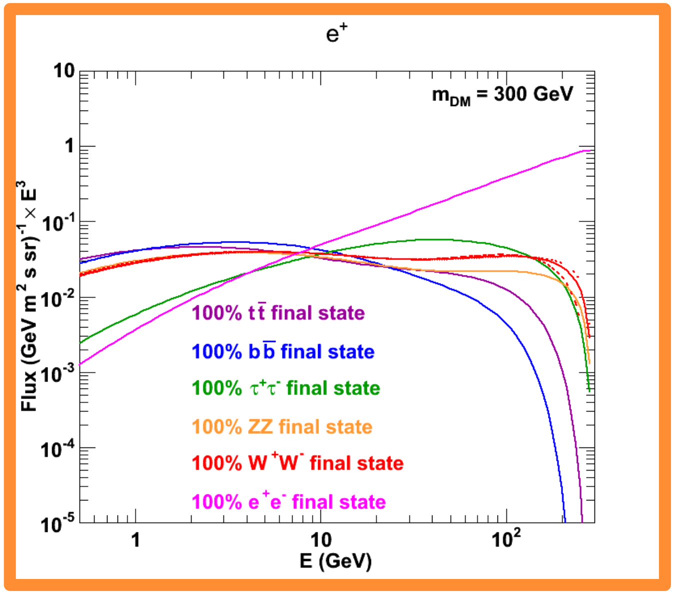
Positron source components: pulsars, Dark matter , …

Positron mode : features and strategy

Particle Physics

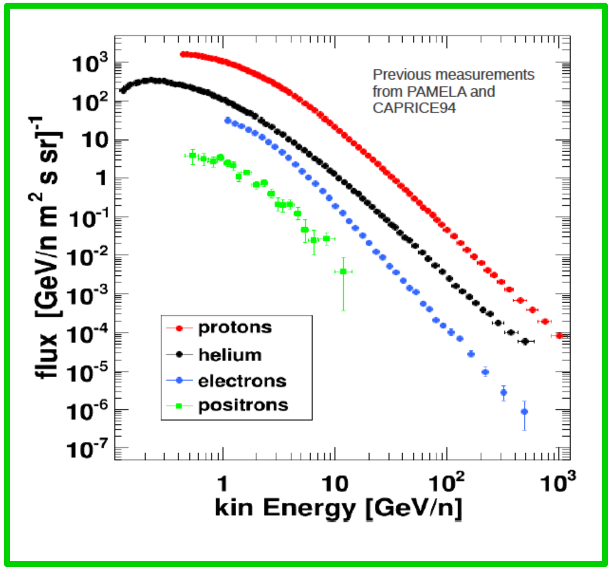
(annihilation modes)

$$\frac{d\Phi_{e^+}}{dE_{e^+}}(E_{e^+}) = \frac{<\sigma_{ann}v>}{2m^2_{WIMP}} \sum_f \frac{dN^f_{e^+}}{dE_{e^+}} B_f \times B \times \rho^2_\chi$$



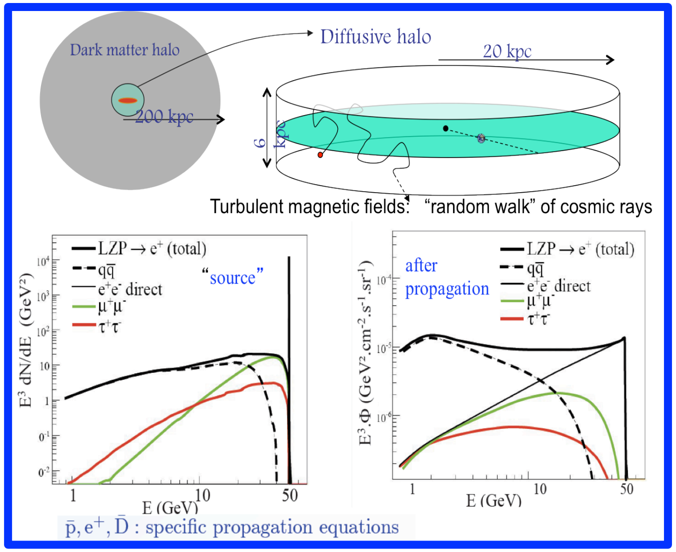
Positron flux

(Signal in data)



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

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



Background

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

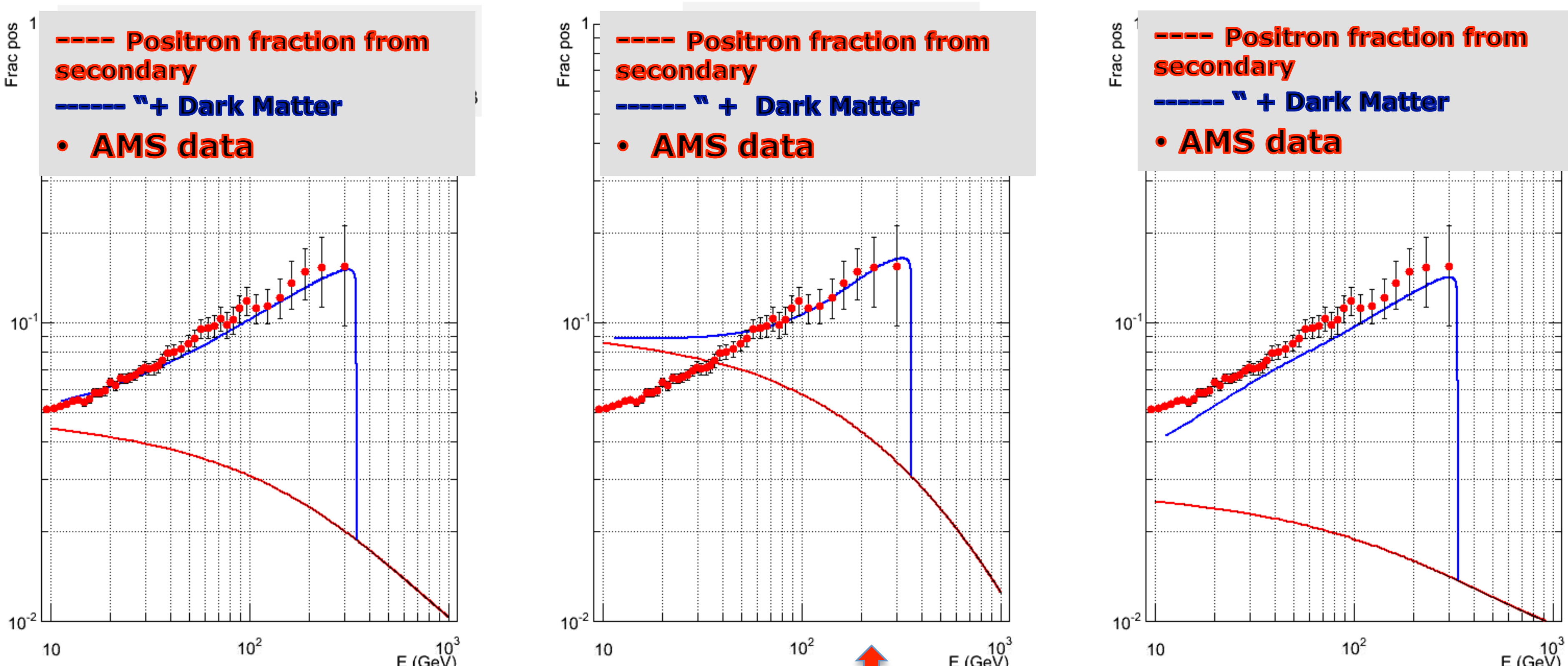
electrons : $\Phi_{e-} \sim 10 * \Phi_{e+}$

Propagation Model tests

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

Independently of the origin of the Source

Medium Model **Minimal Model** **Maximal Model**



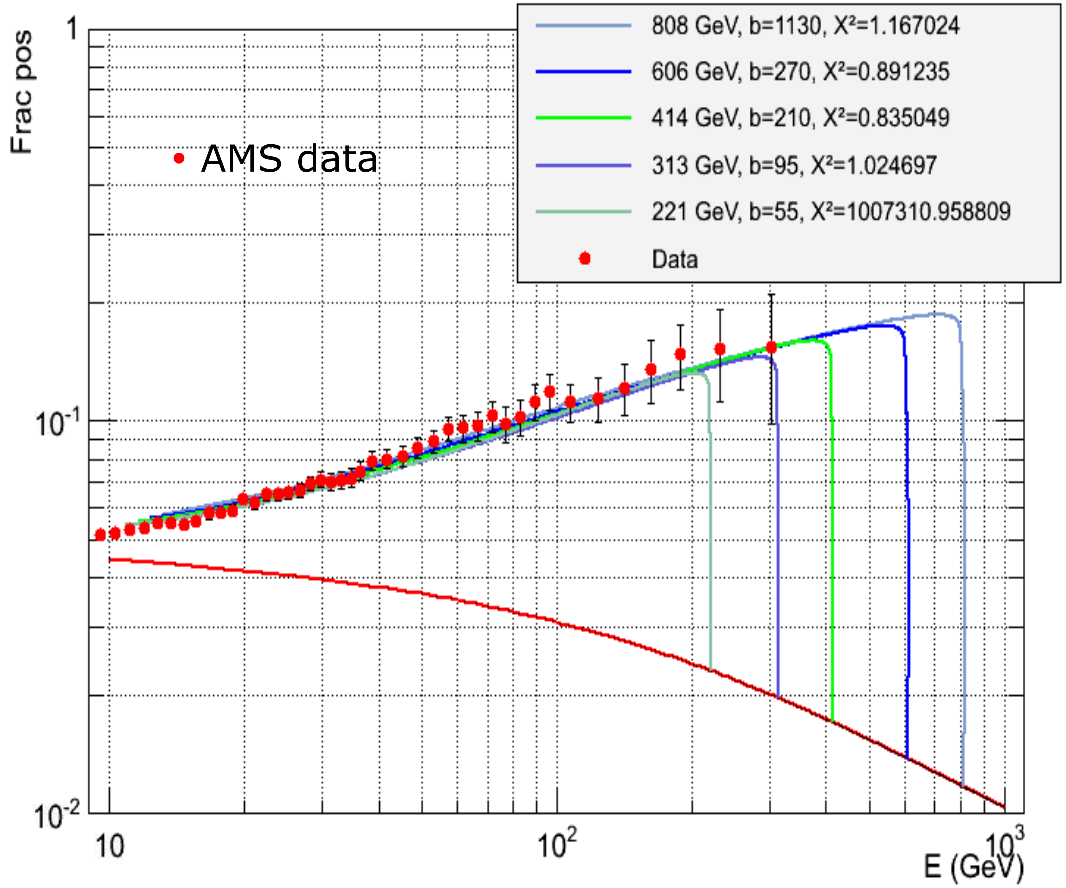
Excluded

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

⇒ 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

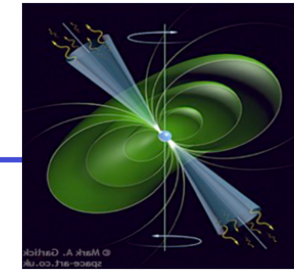


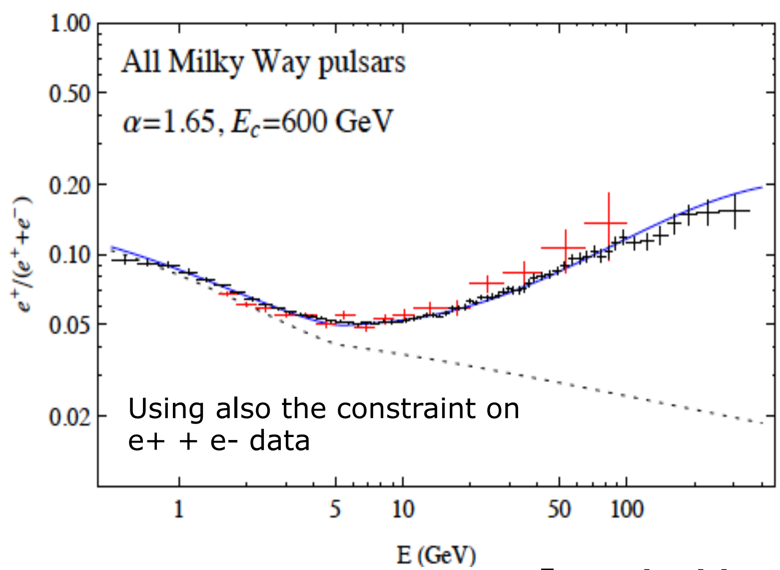
TABLE I

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: $\Phi_{e\pm} = E^{-\alpha} exp(-\frac{E}{E_c})$ $alpha \sim 2$ $E_c = few\ TeV$

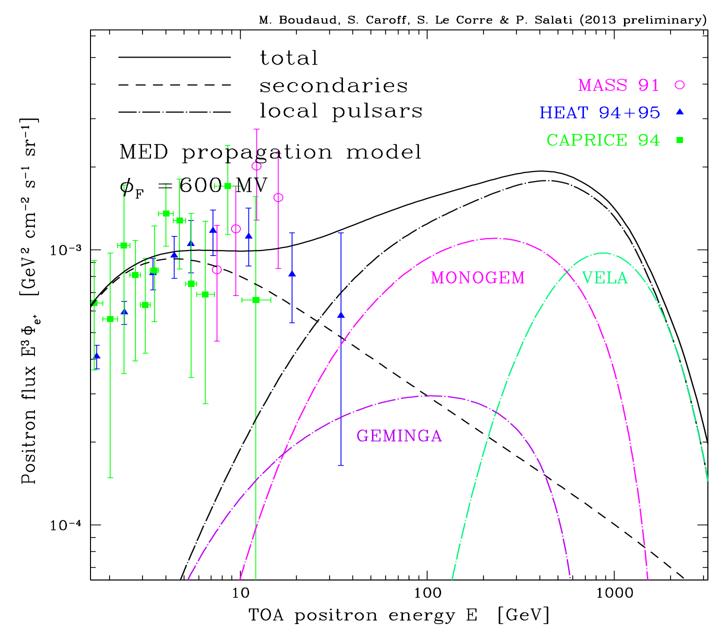
16% of the pulsar energy goes into e+e- pairs **for all the pulsars**



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

Or

Positron Spectrum

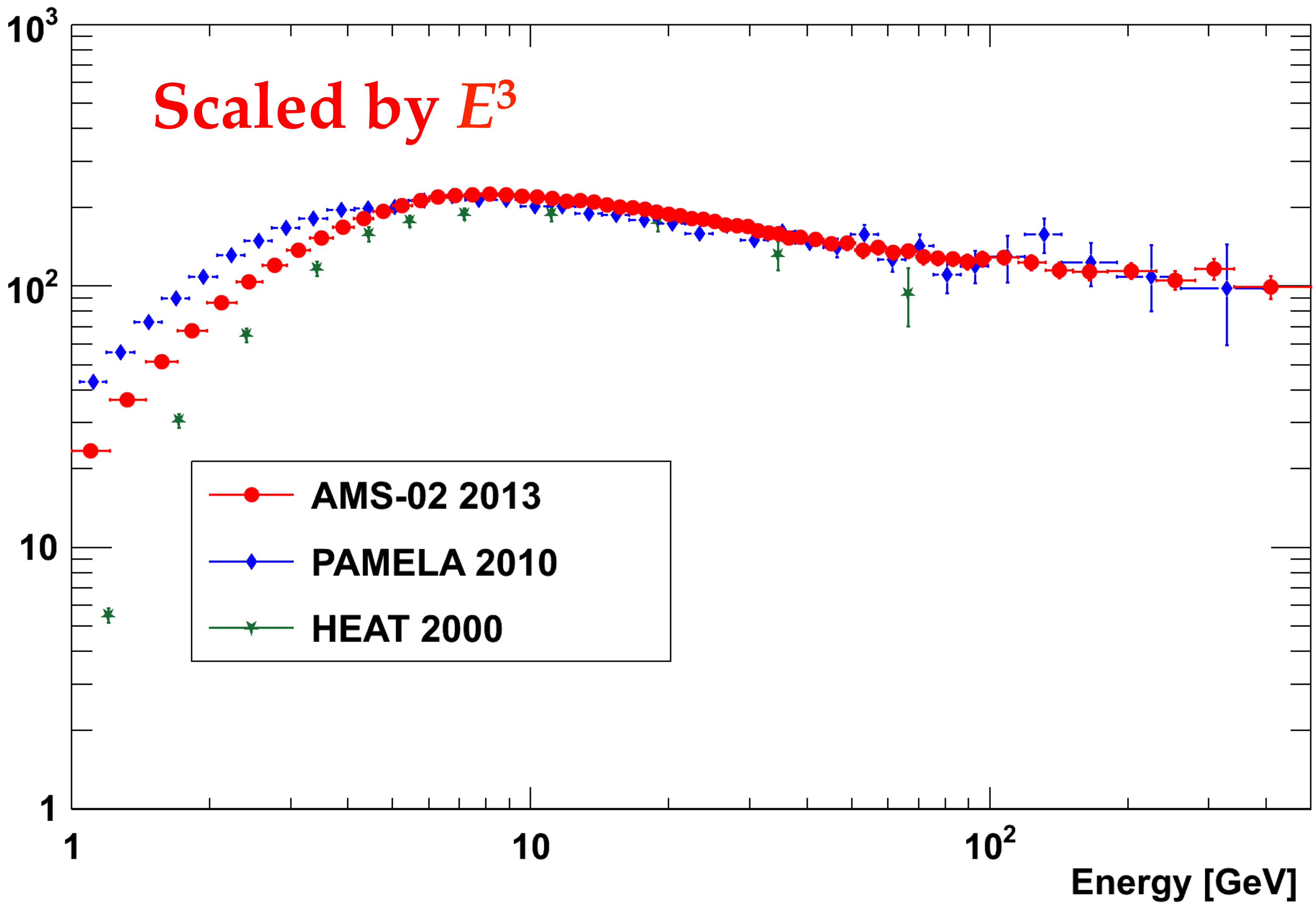


⇒ **Important to measure the positron and electron spectrum separately**

⇒ **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

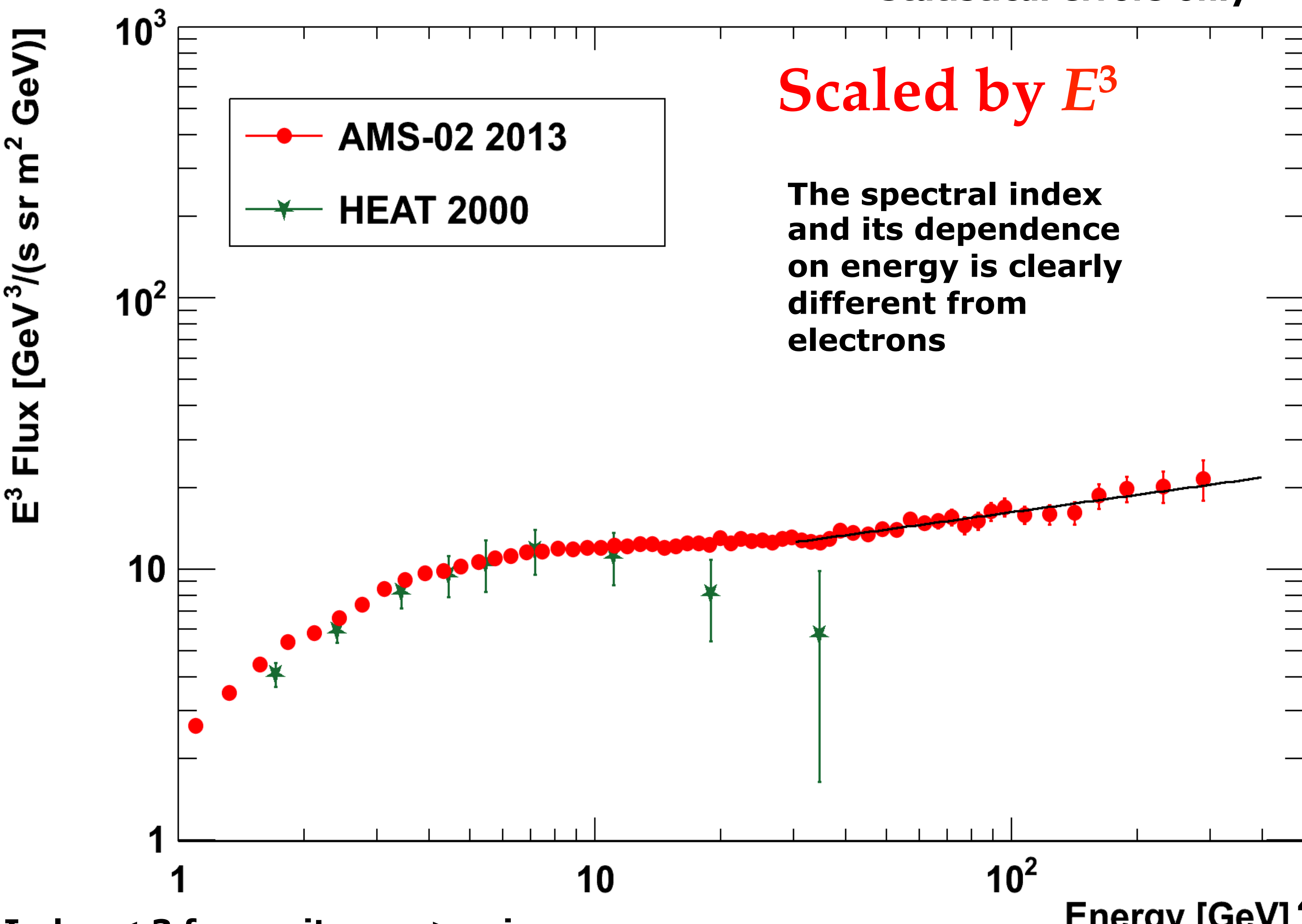
Statistical errors only



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

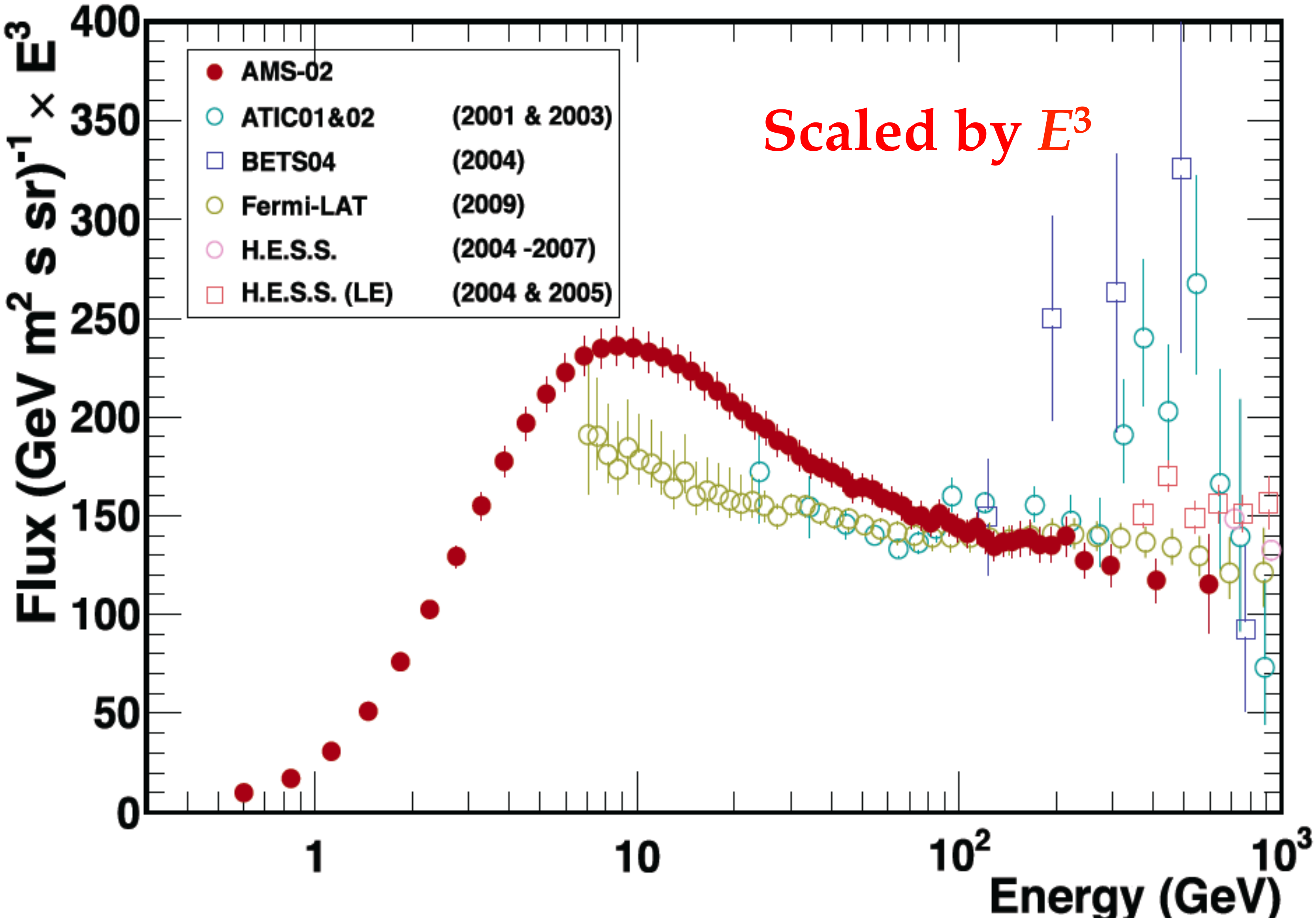
AMS-02 Positron Flux up to 350 GeV

Statistical errors only



Index < 3 for positrons=> primary source

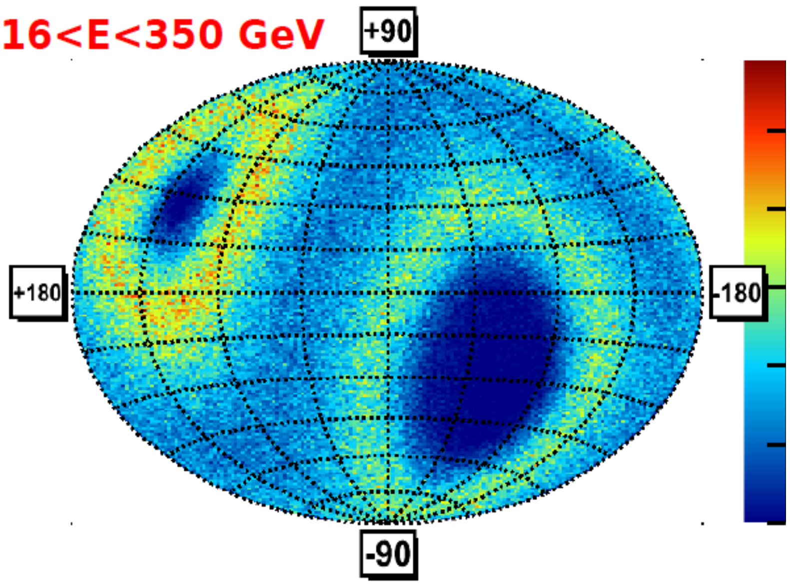
AMS-02 lepton Flux up to 350 GeV



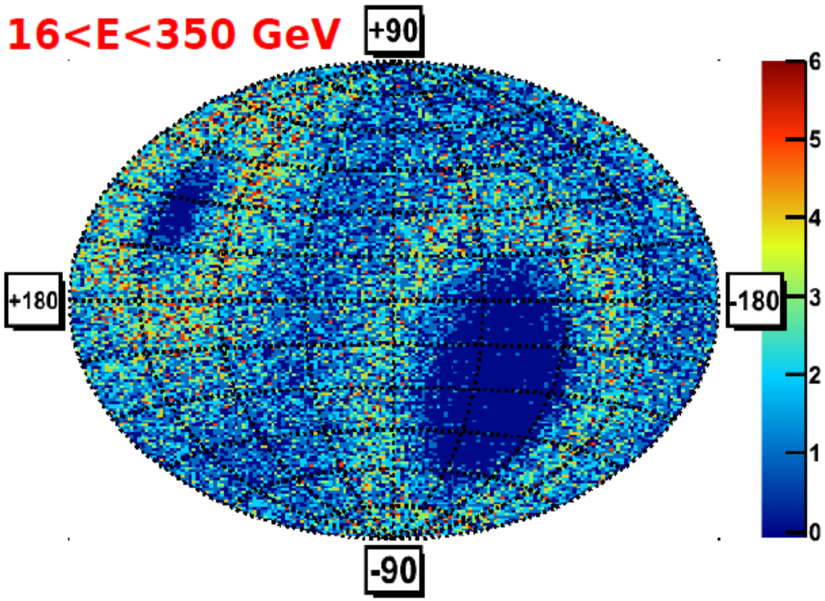
Anisotropy Measurements

- 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)

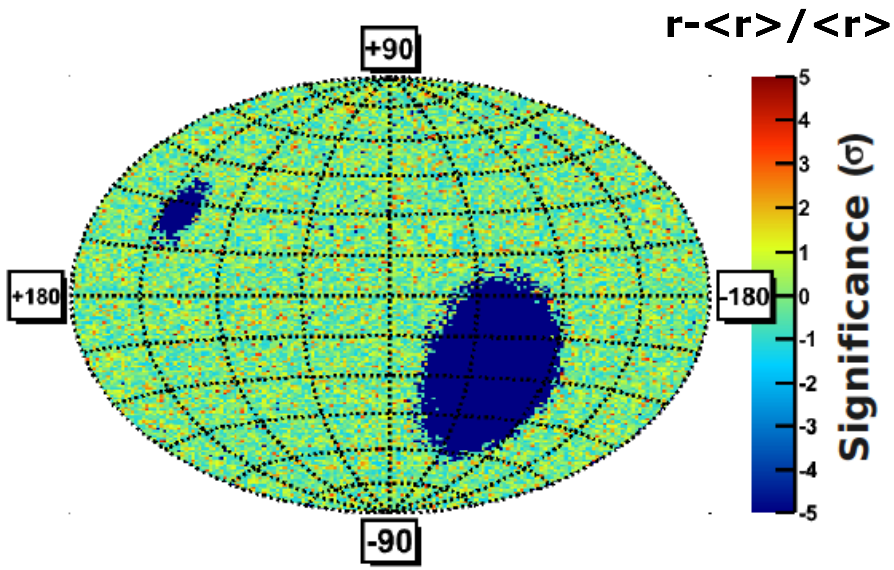
e^- - 16<E<350 GeV



e^+ - 16<E<350 GeV

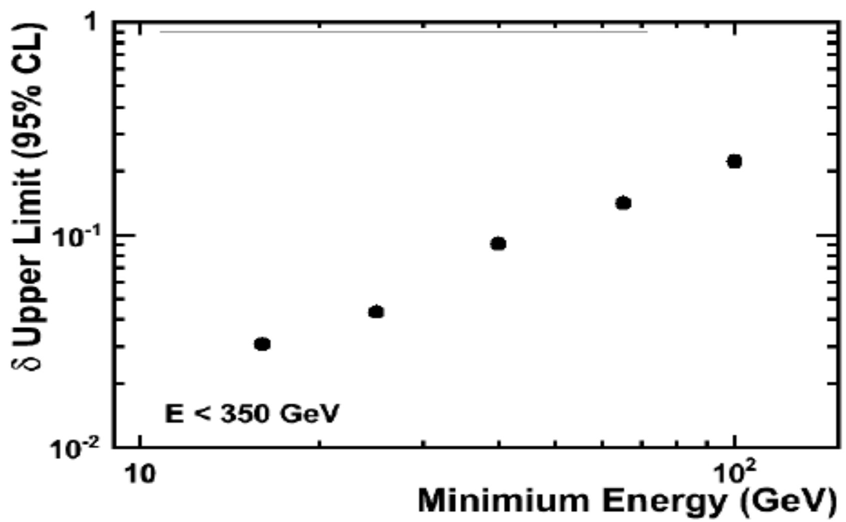


Anisotropy Measurements



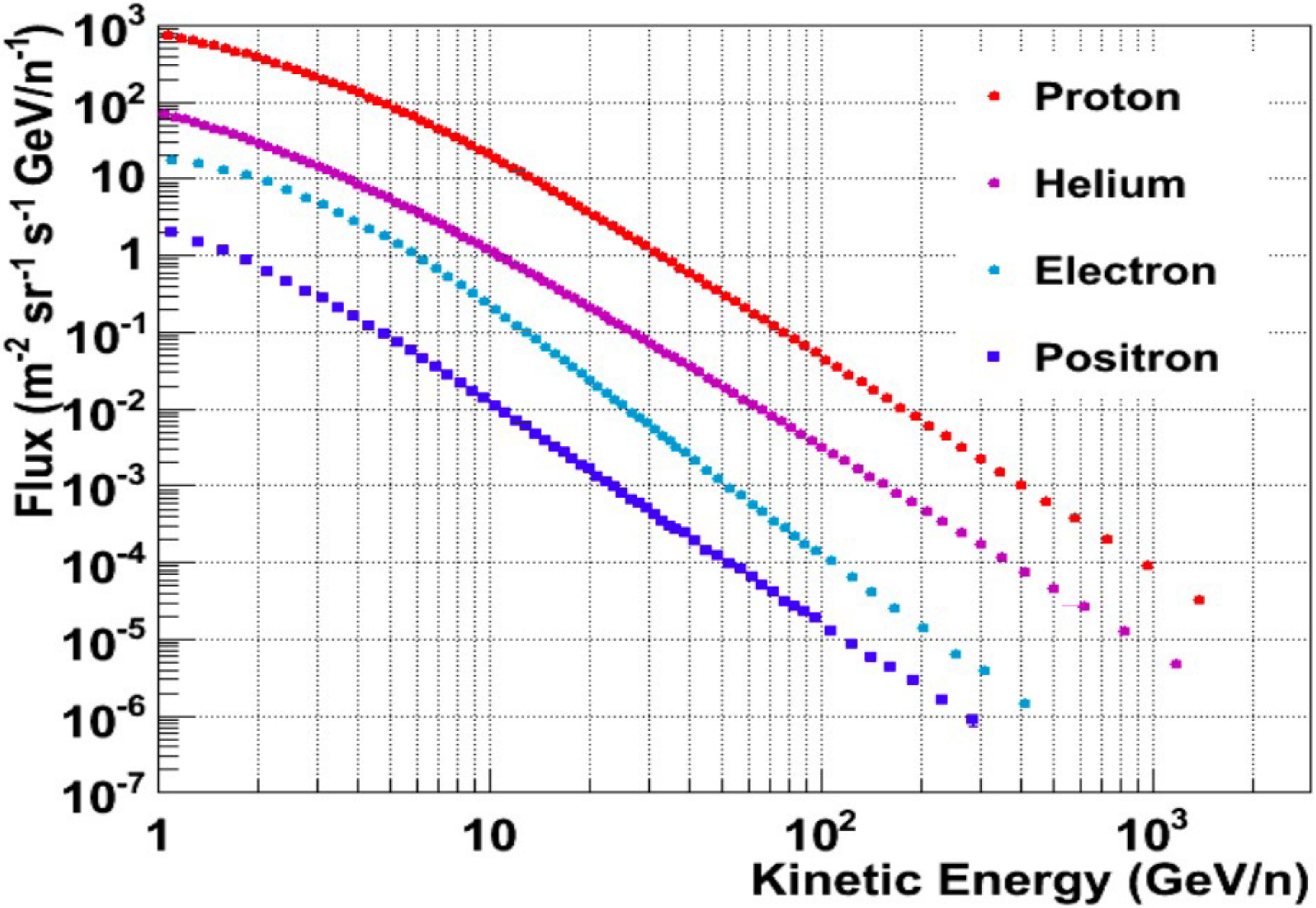
The relative fluctuations of the ratio across the observed sky map show no evident pattern

- 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 ⇔ could it constraint the pulsar component ?



$\delta < 0.030$ for $16 < E < 350$GeV

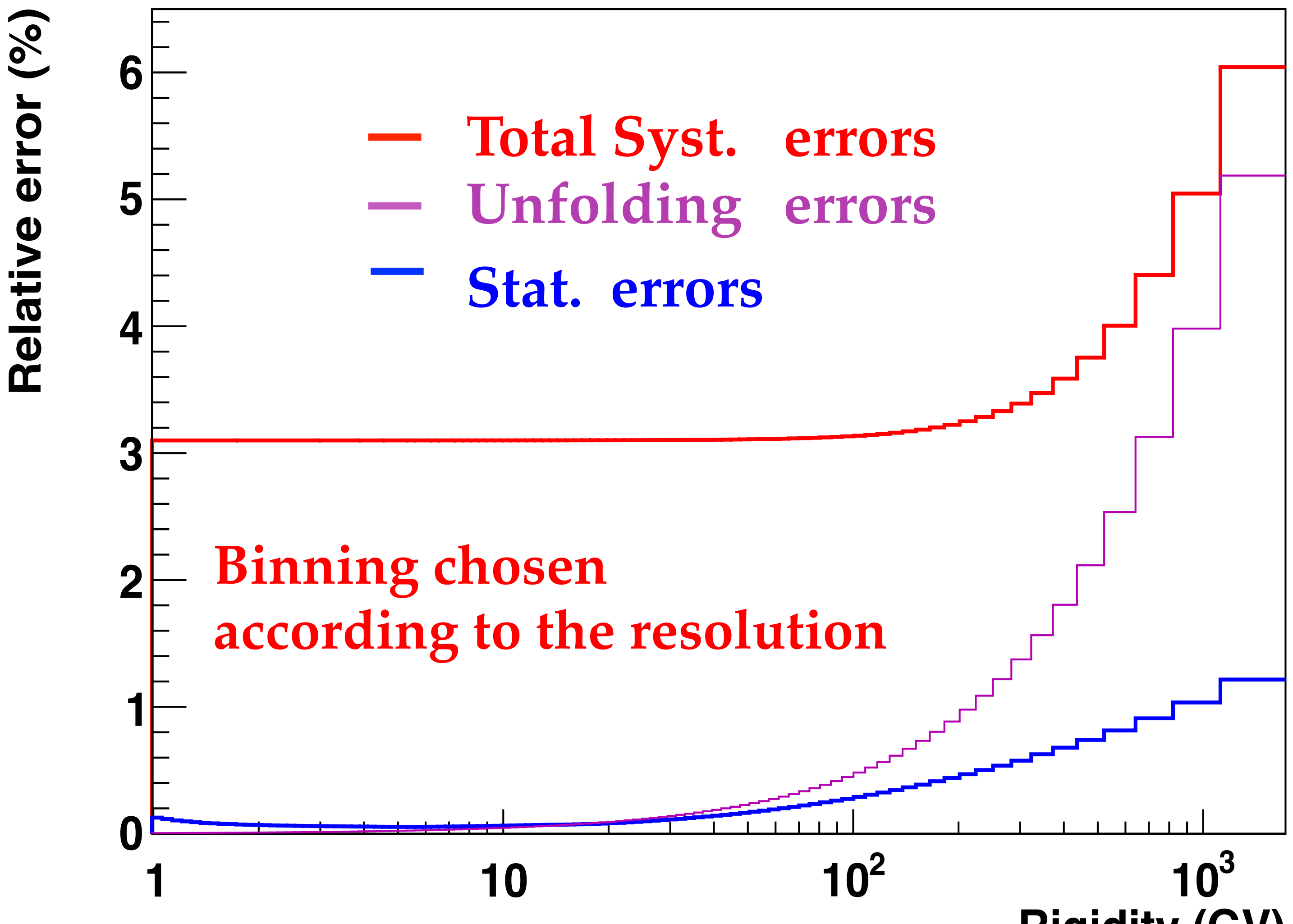
First flux measurements by AMS



Summary

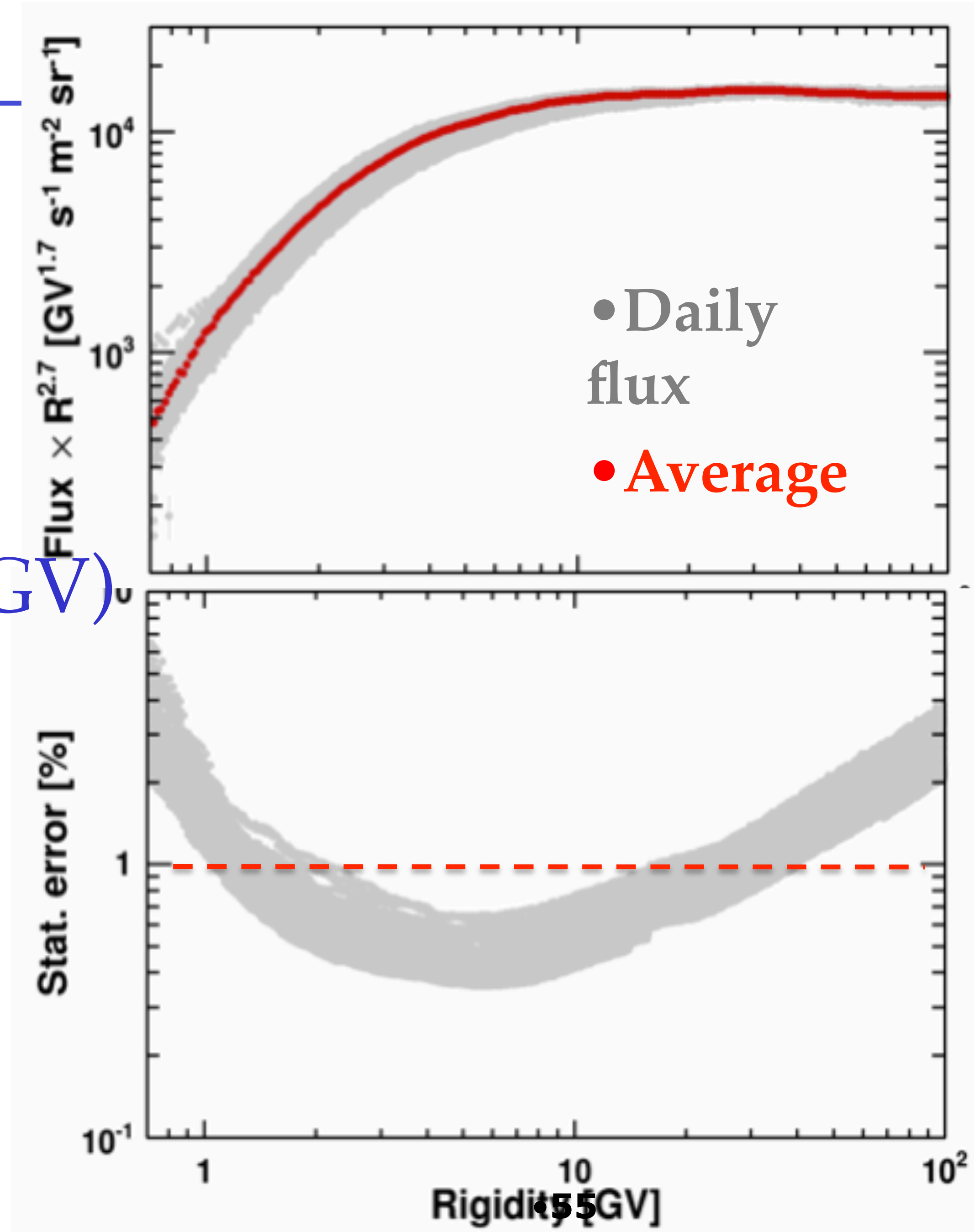
- AMS02 is operating on the ISS since the 19th May 2011 and has collected more than 35 billions of events: All AMS subsystems are fully operational and behaves as expected.
- Variations of ambient conditions (temperature in first place) are accounted for, with proper calibrations and alignments
- For 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



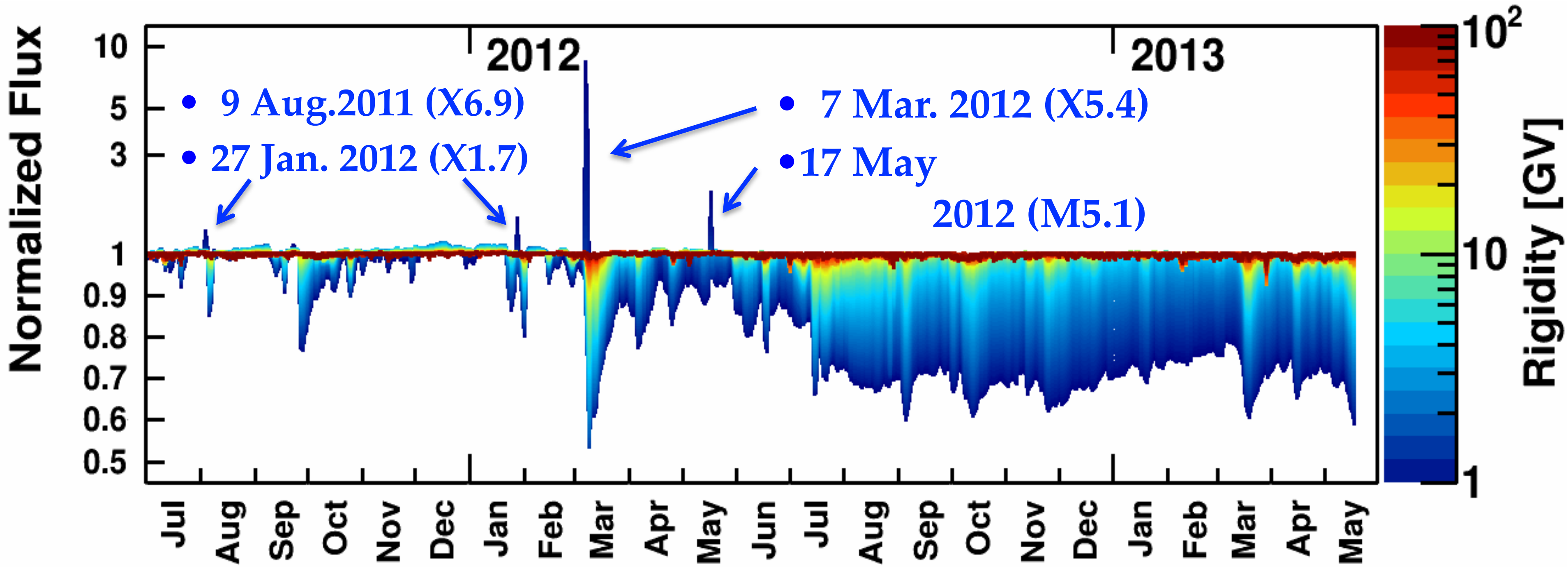
Daily flux

Stat. Error < ~1%
(1 < R < ~20 GV)



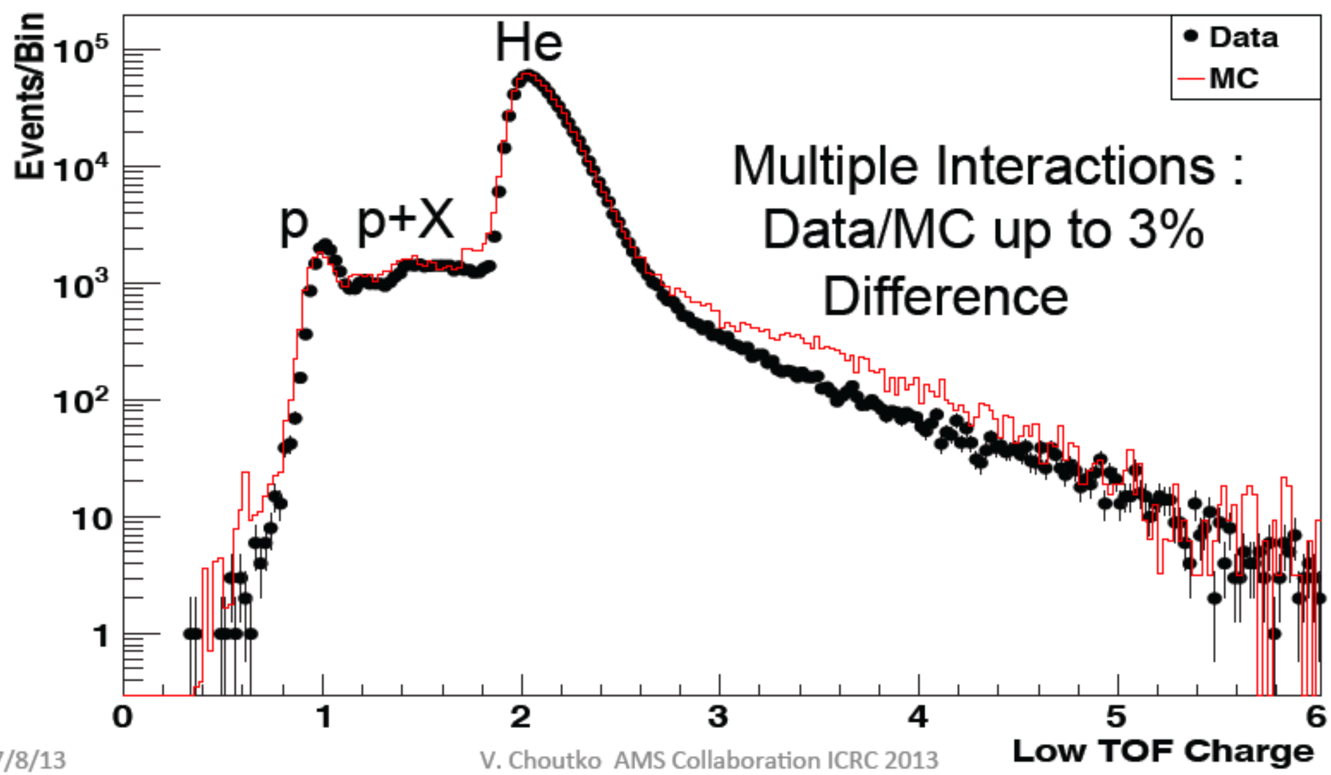
Daily normalized flux

R < ~30 GV : Variation due to the solar modulation and solar events



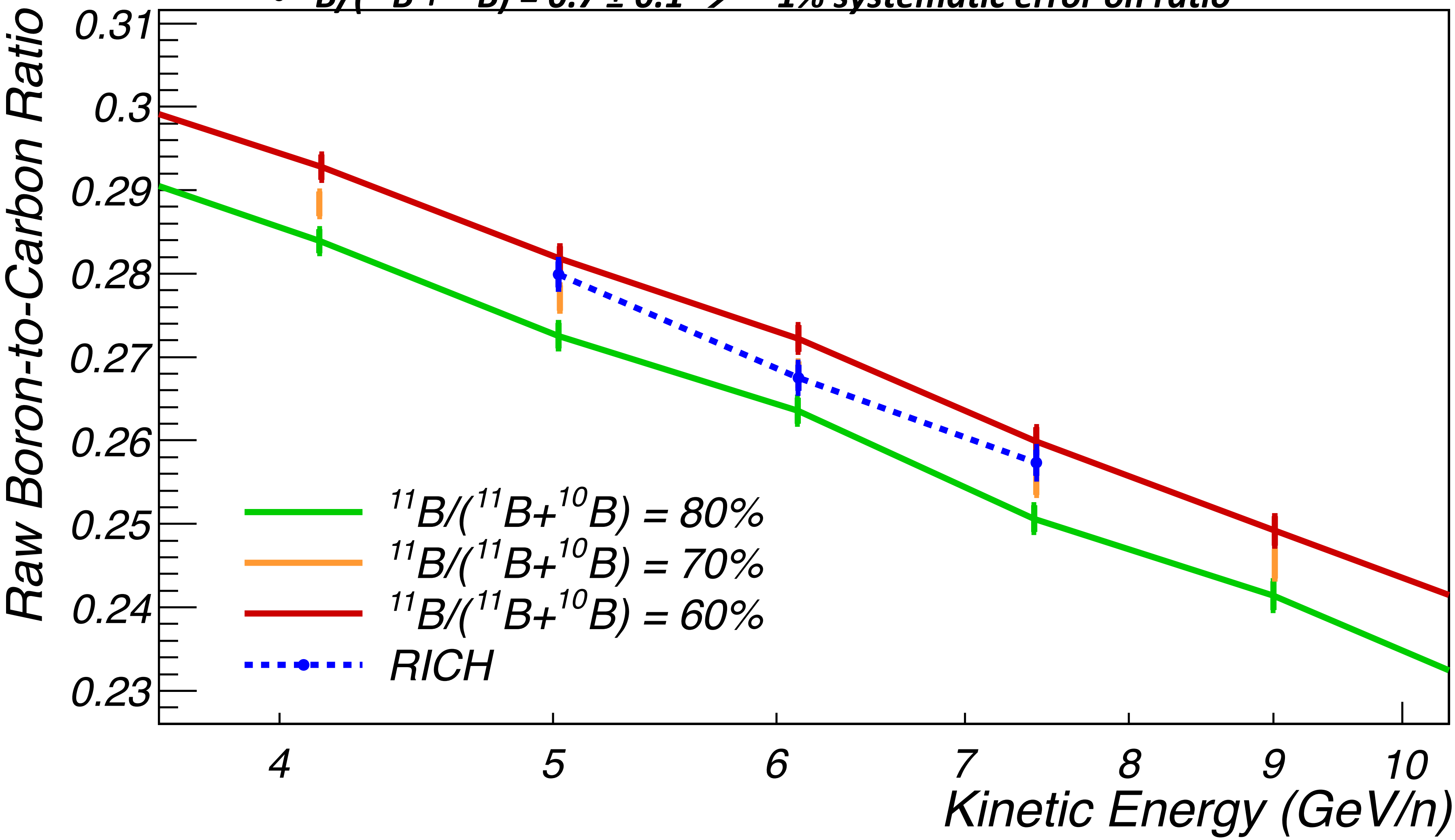
Helium Nuclei Selection

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



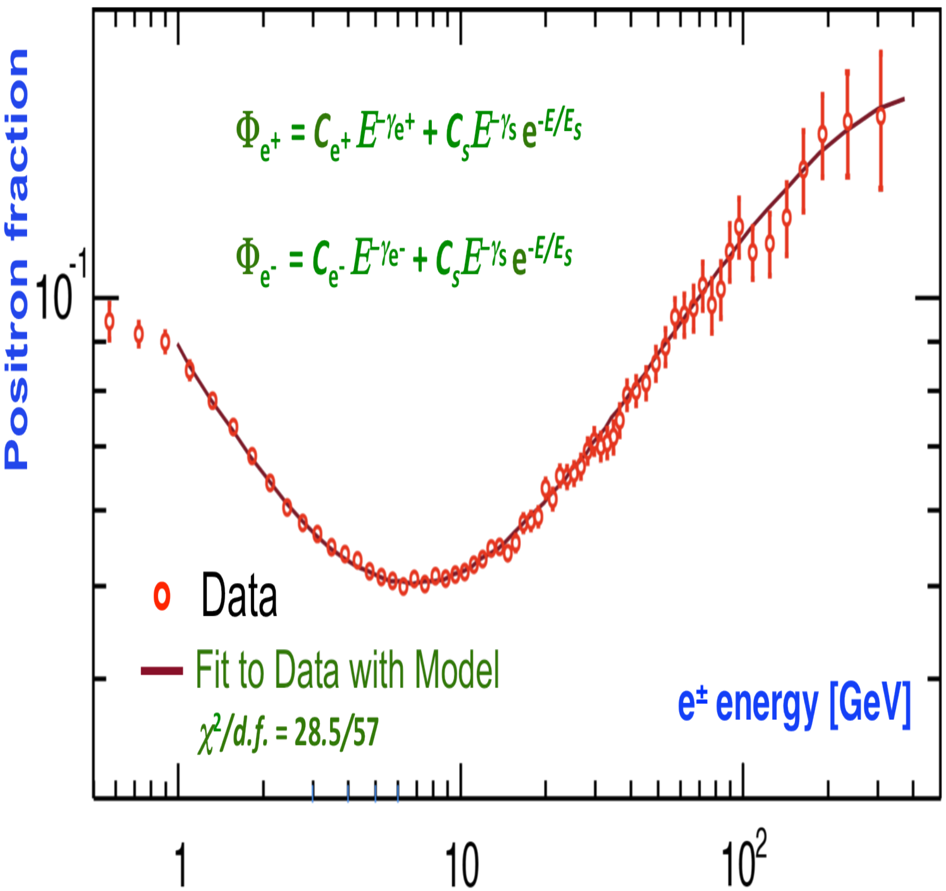
Isotopic Fraction Evaluation

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



Positron fraction AMS

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;

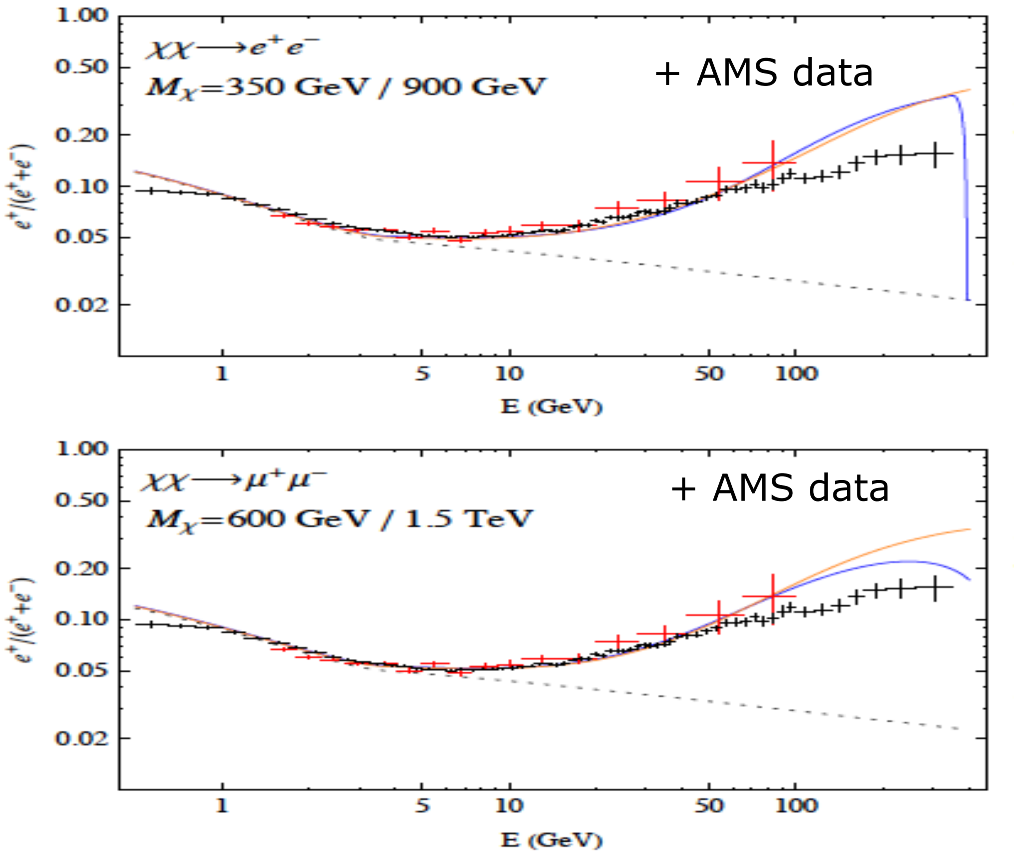
- $1/E_s = 0.0013 \pm 0.0007\ \mathrm{GeV}^{-1}$, corresponding to a cutoff energy of 760^{+1000} GeV.

=> 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"