A review of AMS-02 and its results after nearly 5 years of operation.

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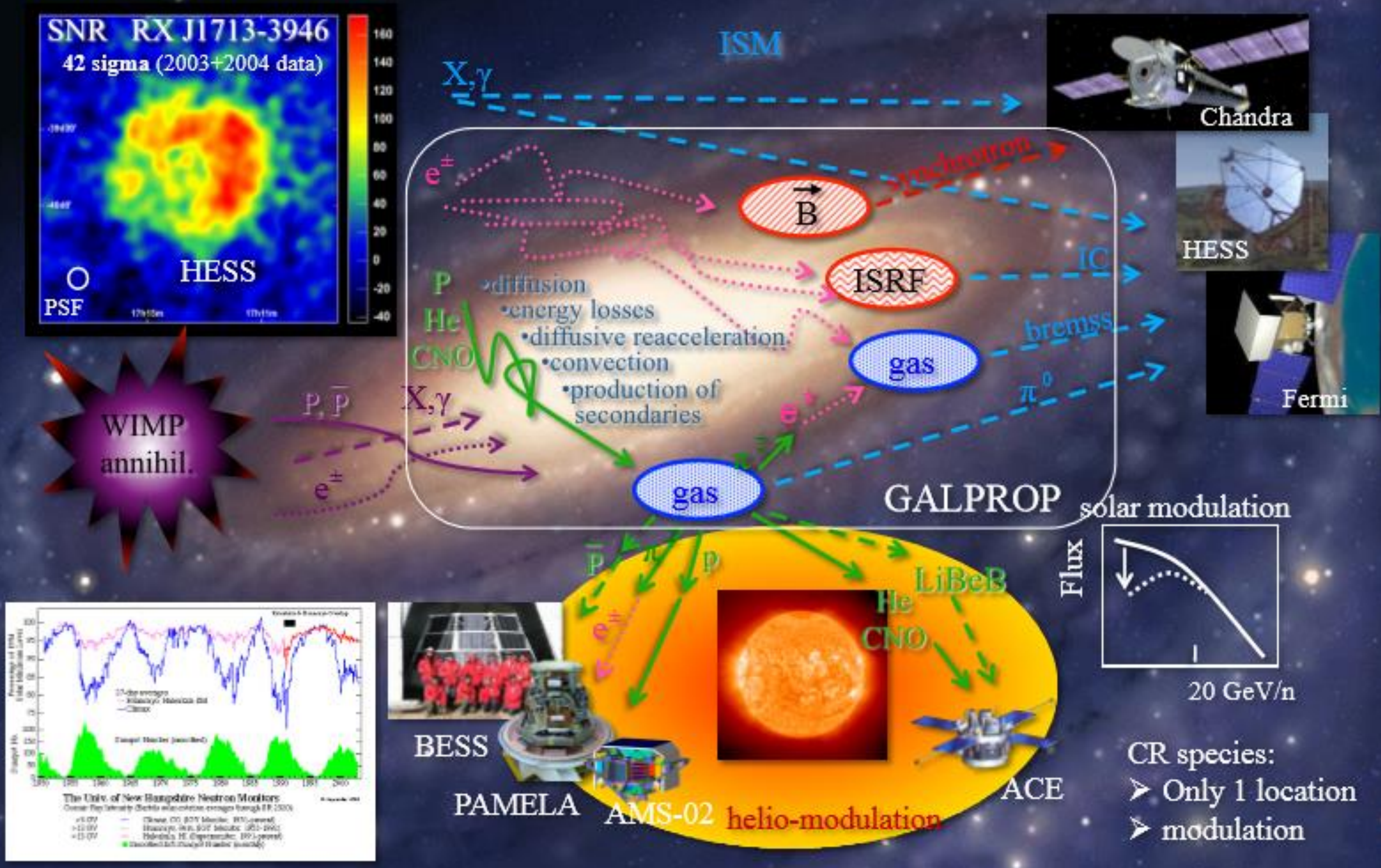
ICRR, CIEMAT

Outline

- Intuition about charged cosmic rays propagation
- The AMS-02 experiment
- An analysis example
- Results
- Conclusions

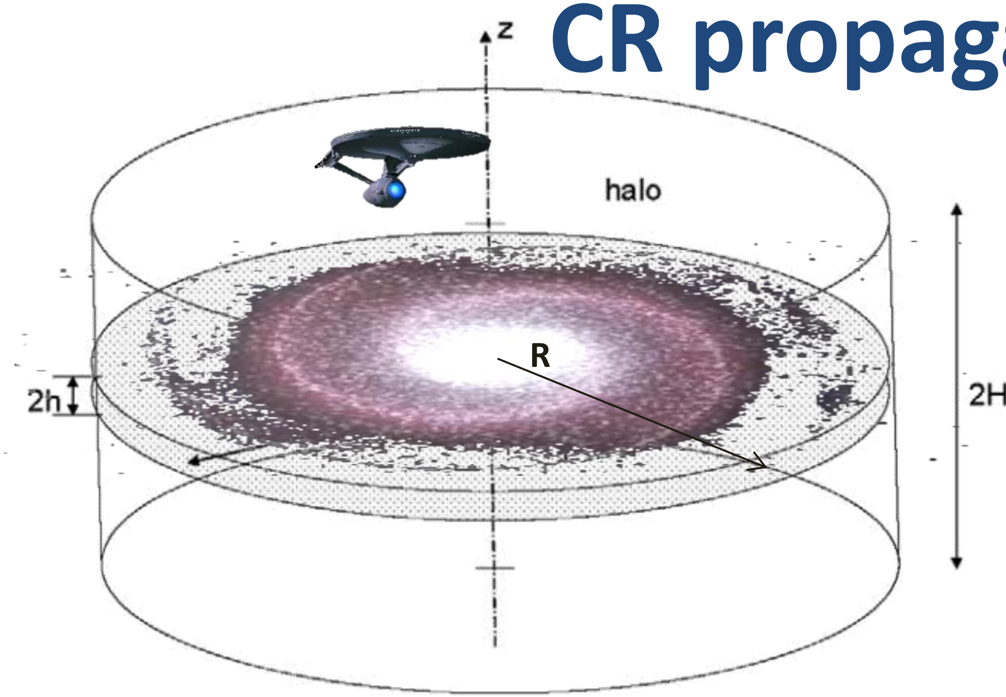
BUILDING SOME INTUITION ABOUT COSMIC RAYS PROPAGATION

CRs in the interstellar medium



I. Moskalenko

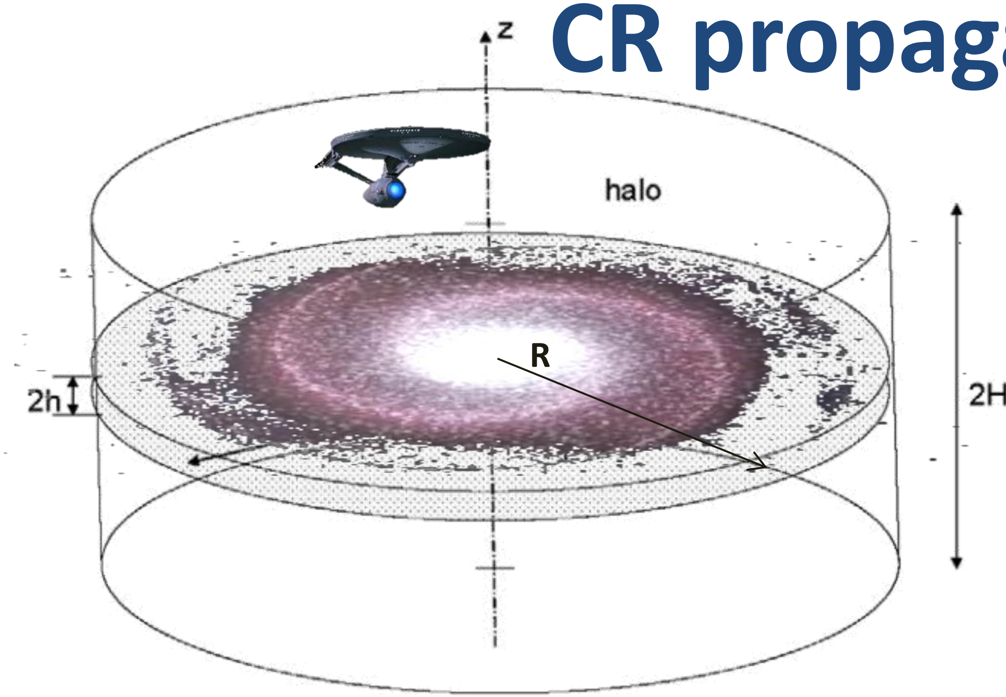
Building the intution about charged CR propagation



R about 30 kpc
H about 2 kpc
h about 0.15 kpc
Average density **n** about 5 protons/cm^3
Primary sources located in the disk
Diffusion due to magnetic field with diffusion coeff. **D**

$$\frac{\partial F(\mathbf{r},p,t)}{\partial t} - \nabla(\mathbf{D}_{xx}\nabla F) + \nabla(\mathbf{u}F) - \frac{\partial}{\partial p}\left(p^2 D_{pp}\frac{\partial}{\partial p}\frac{F}{p^2}\right)$$
$$+\frac{\partial}{\partial p}\left[\dot{p}F - \frac{p}{3}(\nabla\mathbf{u})F\right] + \frac{F}{\tau_f} + \frac{F}{\tau_d} = q(\mathbf{r},p,t),$$

Building the intution about charged CR propagation



R about 30 kpc
H about 2 kpc
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Average density **n** about 5 protons/cm^3
Primary sources located in the disk
Diffusion due to magnetic field with diffusion coeff. **D**

$$\frac{F}{\tau_{esc}}$$

$$\frac{\partial F(\mathbf{r},p,t)}{\partial t} - \nabla(\mathbf{D}_{xx}\nabla F) + \nabla(\mathbf{u}F) - \frac{\partial}{\partial p}\left(p^2 D_{pp}\frac{\partial}{\partial p}\frac{F}{p^2}\right) + \frac{\partial}{\partial p}\left[\dot{p}F - \frac{p}{3}(\nabla\mathbf{u})F\right] + \frac{F}{\tau_f} + \frac{F}{\tau_d} = q(\mathbf{r},p,t),$$

Except for electrons

Building the intution about charged CR propagation

- Time scale to reach reach Halo limit and escape:

$$\tau_{esc}(H) \approx \frac{H^2}{D} = \frac{H^2}{D_0\left(\frac{R}{3GV}\right)^{0.6}\beta^{-2}} \approx 5\ 10^7\ years$$

- Time spent in the disk given a diffusion length L

$$t(L) = \frac{1}{\sqrt{2\pi}}\frac{hL}{D}$$

$$t\ (H) \approx 10^6\ years$$

- Energy loss time scale (synchrotron & IC)

$$\tau_{loss} \approx 2\ 10^5 \left(\frac{1TV}{R}\right)\left(\frac{M}{Z\ m_e}\right)^2\ years$$

Building the intution about charged CR propagation

Diffusion parameters from
Astroparticle Physics 39–40 (2012) 44–51

- Effective diffusion length due to fragmentation:

$$L \approx \frac{\sqrt{2\pi}}{n\, c\beta\, \sigma} \frac{D}{h} = 1.5\beta^{-3} \left(\frac{R}{3GV}\right)^{0.6} \left(\frac{A}{12}\right)^{-\frac{2}{3}} kpc$$

$$for\ p \approx 15 \left(\frac{R}{GV}\right)^{0.6} kpc$$

$$for\ He \approx 6\left(\frac{R}{GV}\right)^{0.6} kpc$$

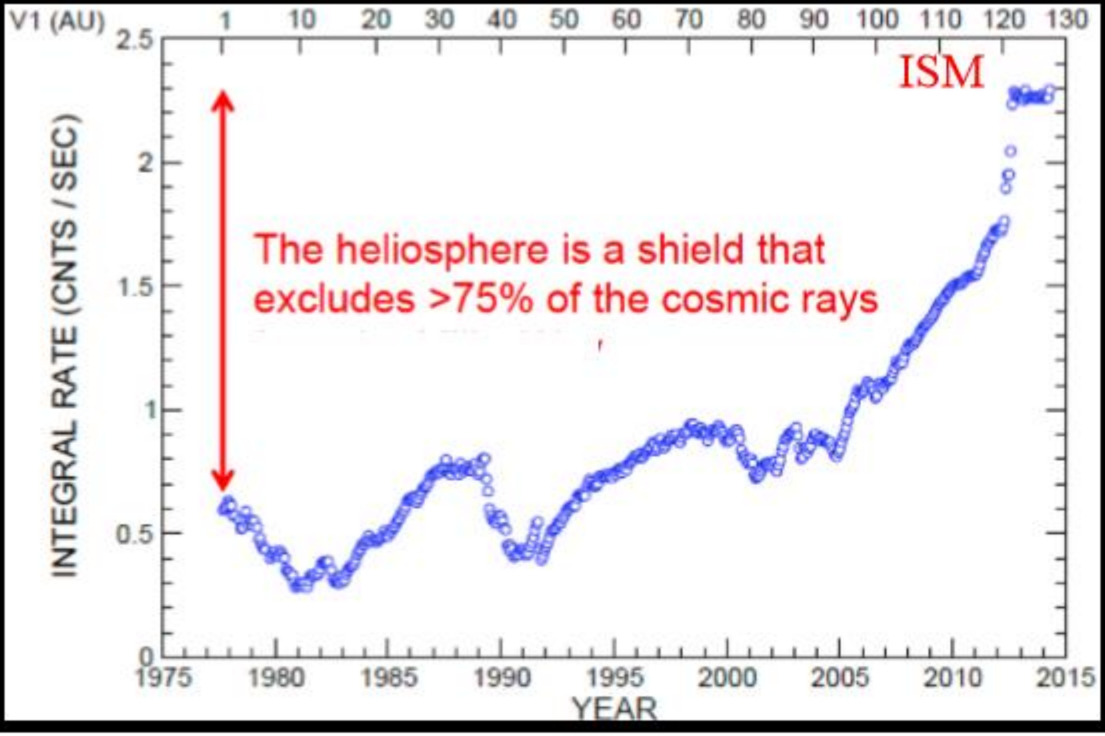
$$for\ C \approx 3\left(\frac{R}{GV}\right)^{0.6} kpc$$

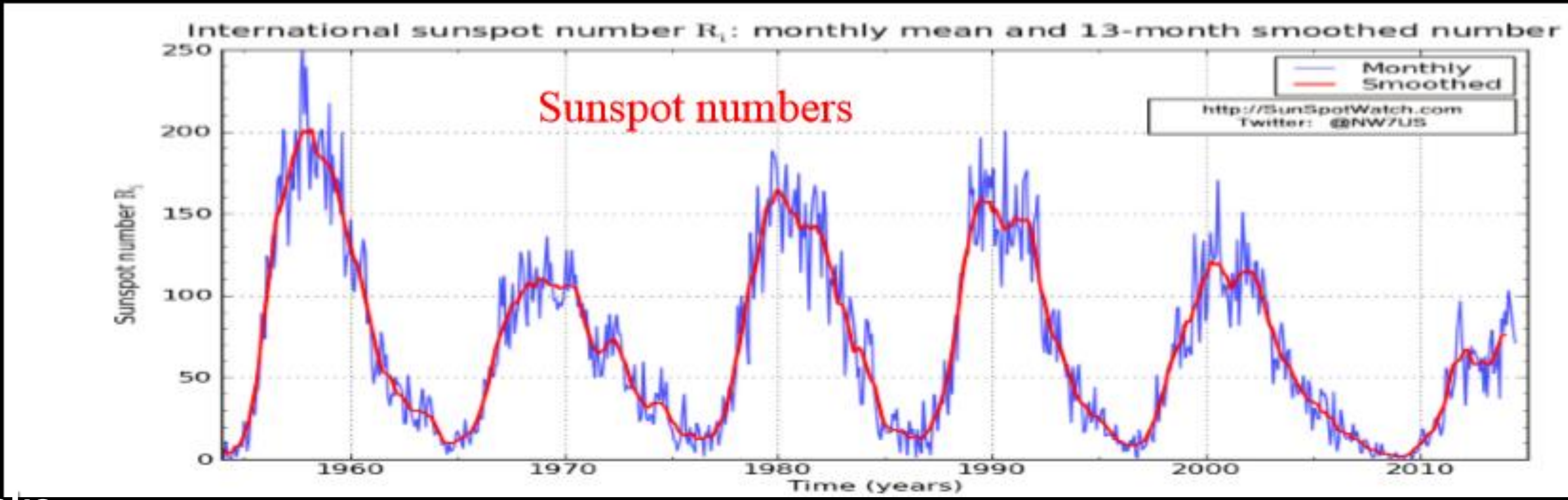
- Secondary to primary ratio
  - Kinetic energy per nucleon conserved in fragmentation

$$\frac{N_{sec}(E_{kin}/A)}{N_{prim}(E_{kin}/A)} \sim \frac{hH}{D} n\, c\beta\, \sigma \sim \frac{nhH}{D_0} \beta^3 \left(\frac{R}{3GV}\right)^{-0.6} \left(\frac{A}{12}\right)^{\frac{2}{3}}$$

Cosmic ray fluxes in the heliosphere

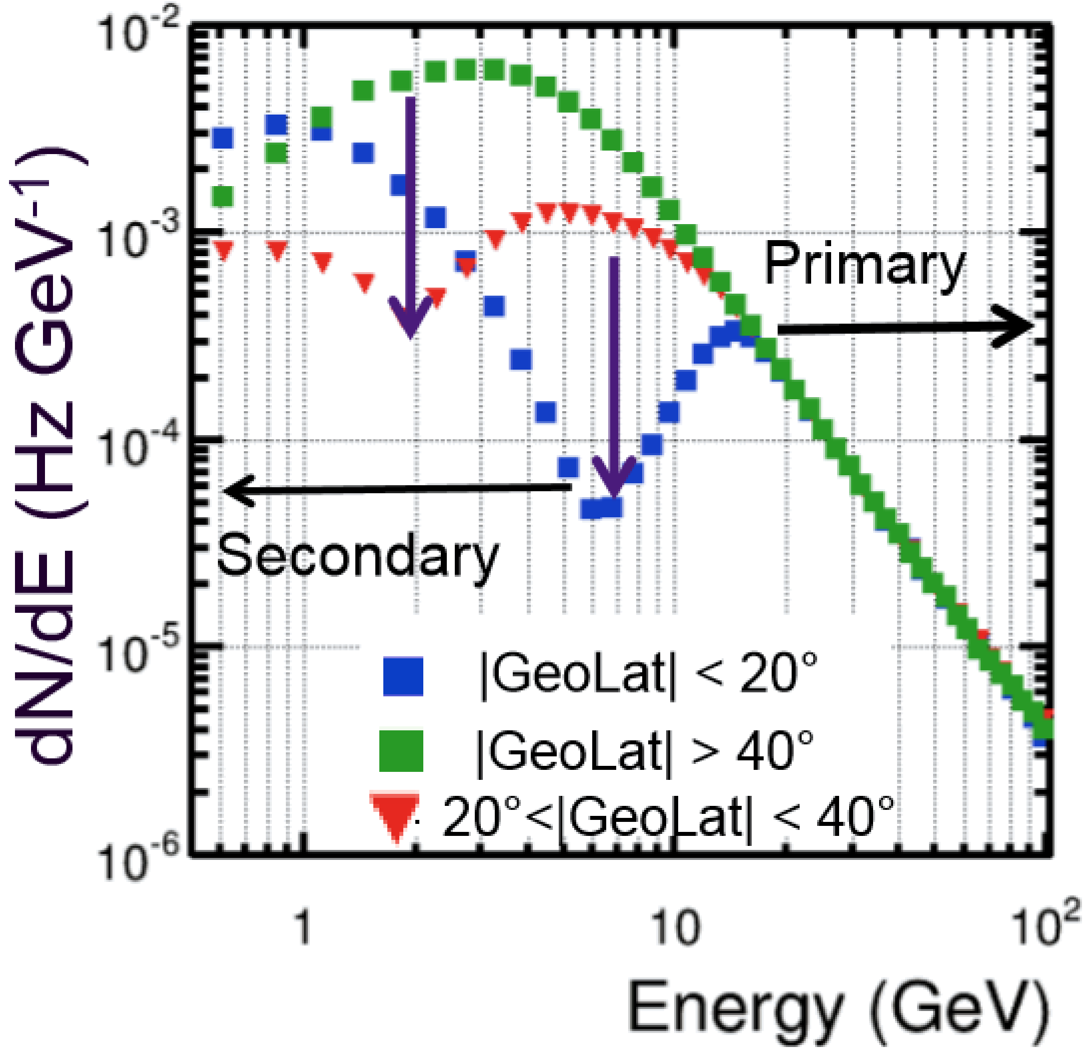
- CR flux along the Voyager 1 path
- Note some delay relative to the sunspot maxima
- Weak last solar max helps – smaller size of the heliosphere



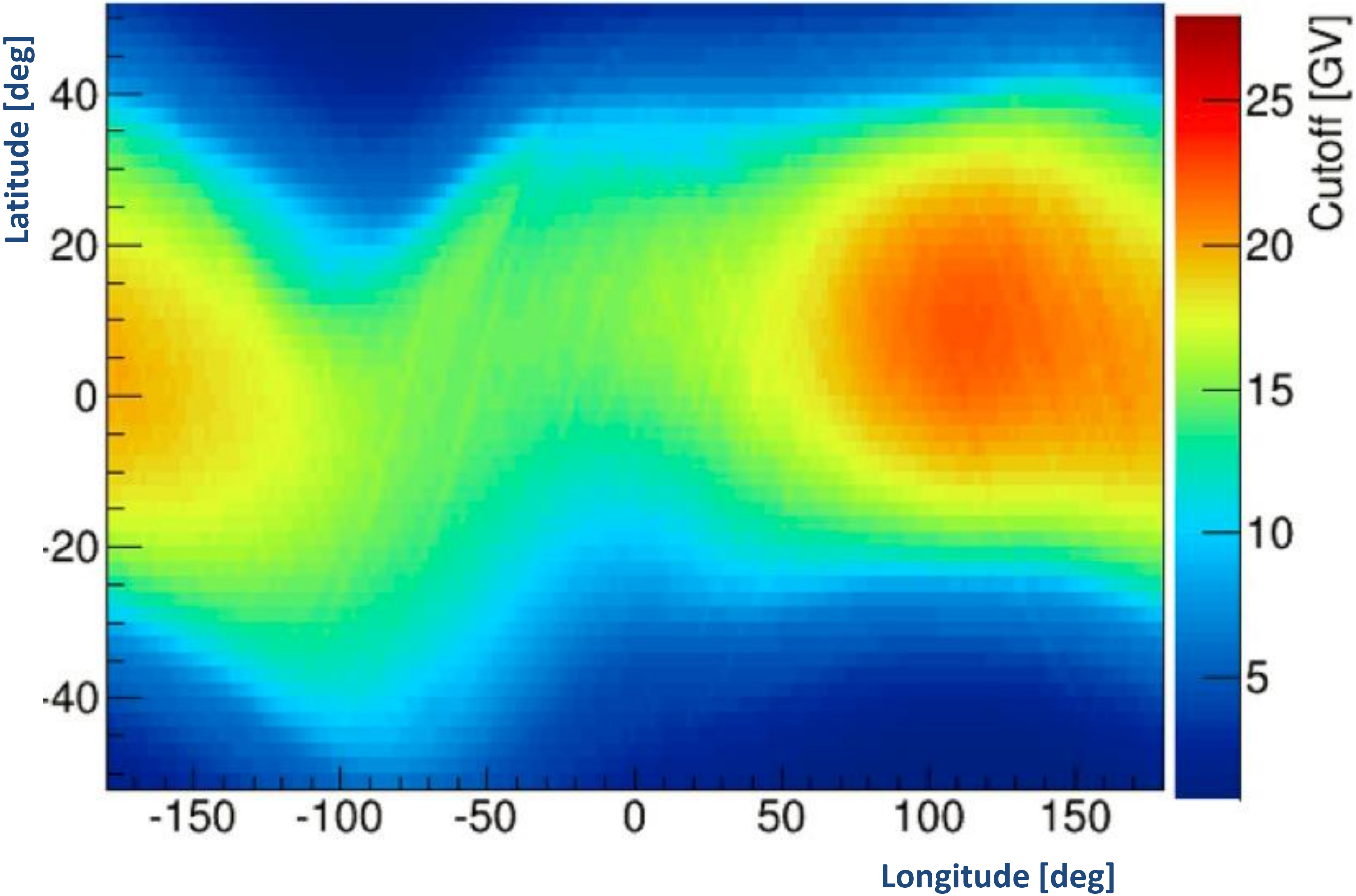


I. Moskalenko

Geomagnetic shielding



Geomagnetic shielding vs position of the orbit

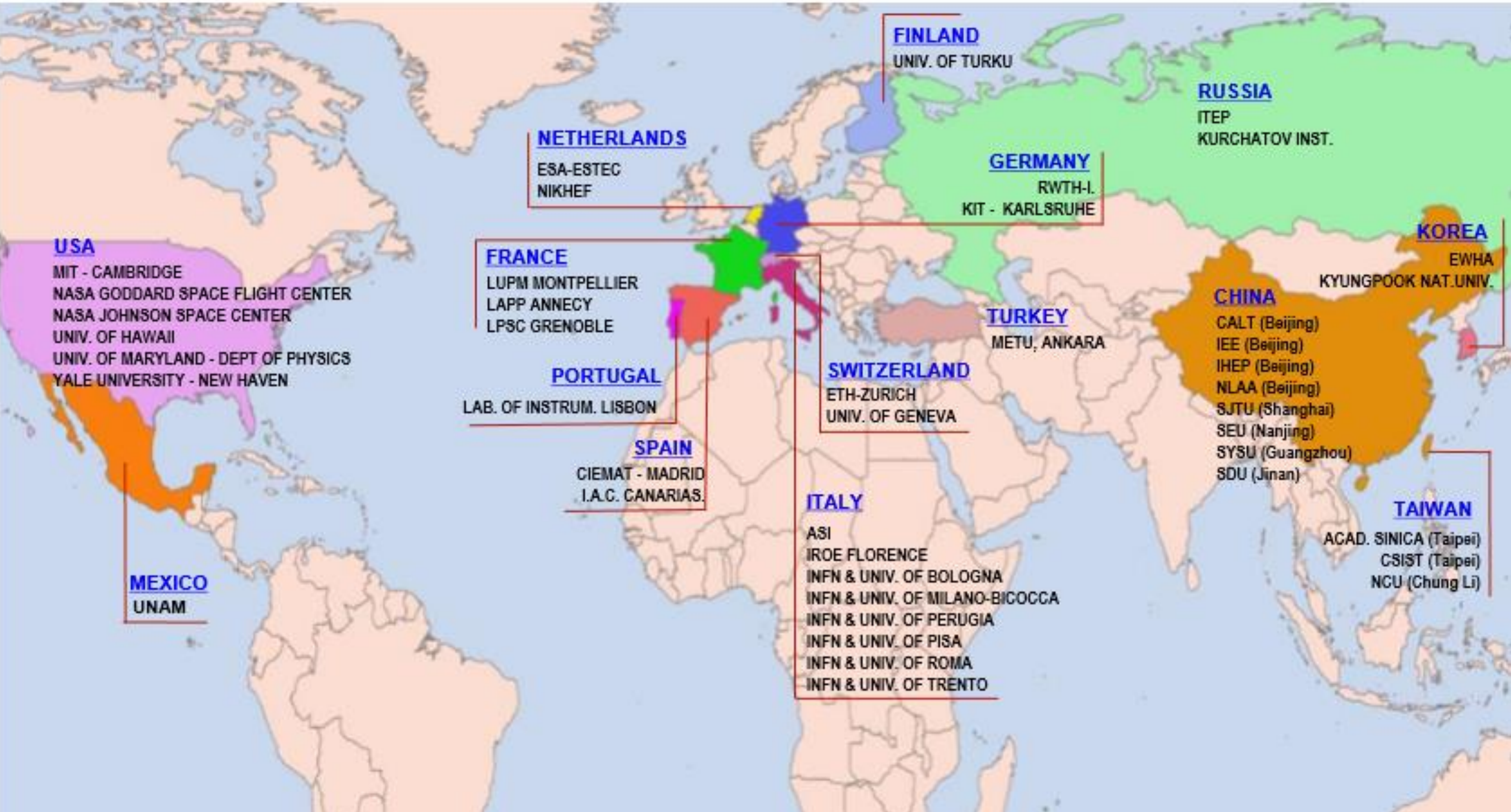


THE AMS-02 EXPERIMENT

AMS is a U.S. DOE sponsored international collaboration

CERN provided assembly, testing and the Control Center

Strong support from R. Heuer, S. Lettow, S. Bertolucci, S. Myers, A. Siemko, ...




United States

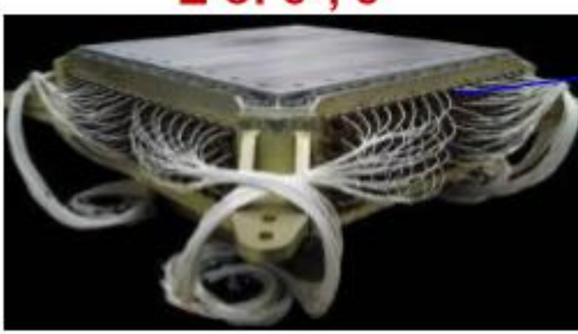
AMS: A TeV precision, multipurpose spectrometer

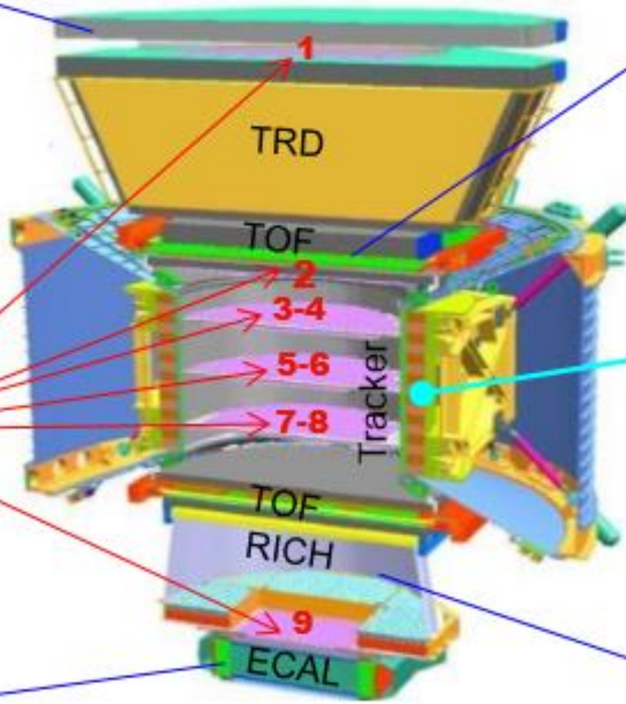
Particles and nuclei are defined by their charge (Z) and energy (E ~ P)

TRD
Identify e^+, e^-

Silicon Tracker
Z, P

ECAL
E of e^+, e^-

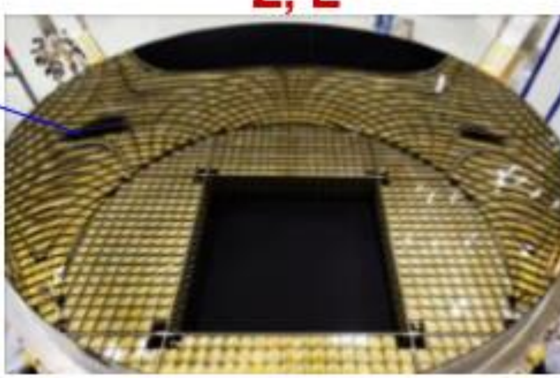




TOF
Z, E

Magnet
±Z

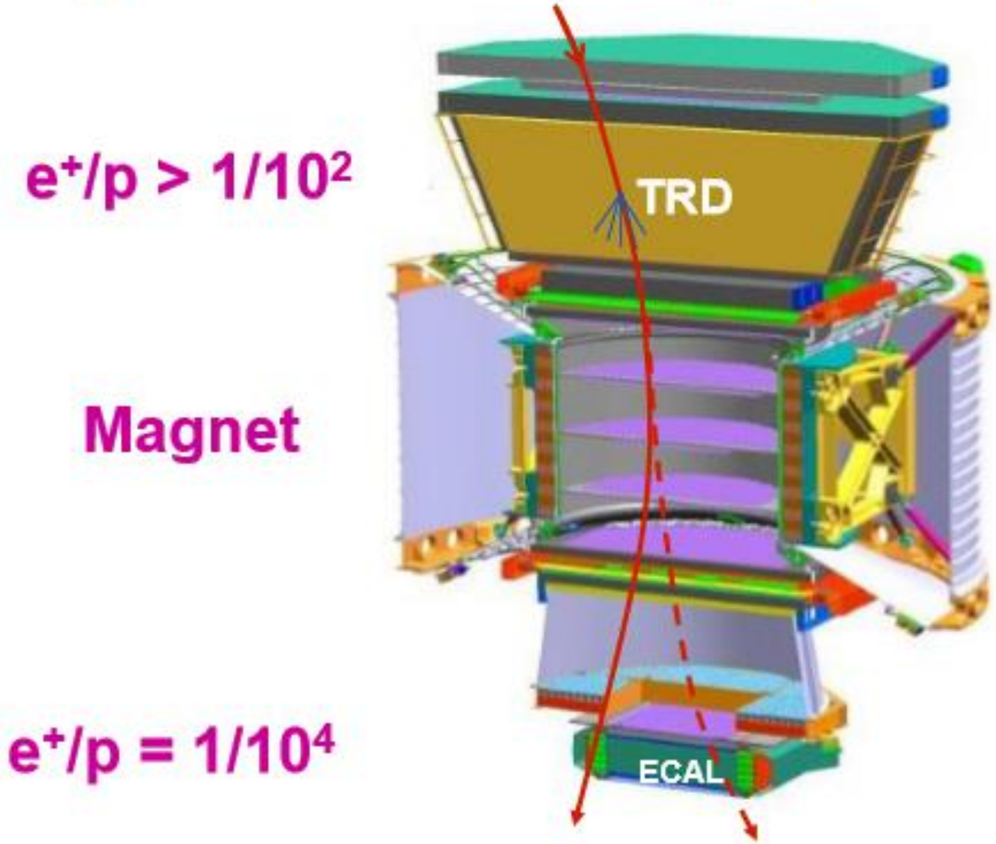
RICH
Z, E



Z and P

are measured independently by the Tracker, RICH, TOF and ECAL

AMS goals: $\overline{He}/He = 1/10^{10}$, $e^+/p > 1/10^6$ & Spectra to 1%



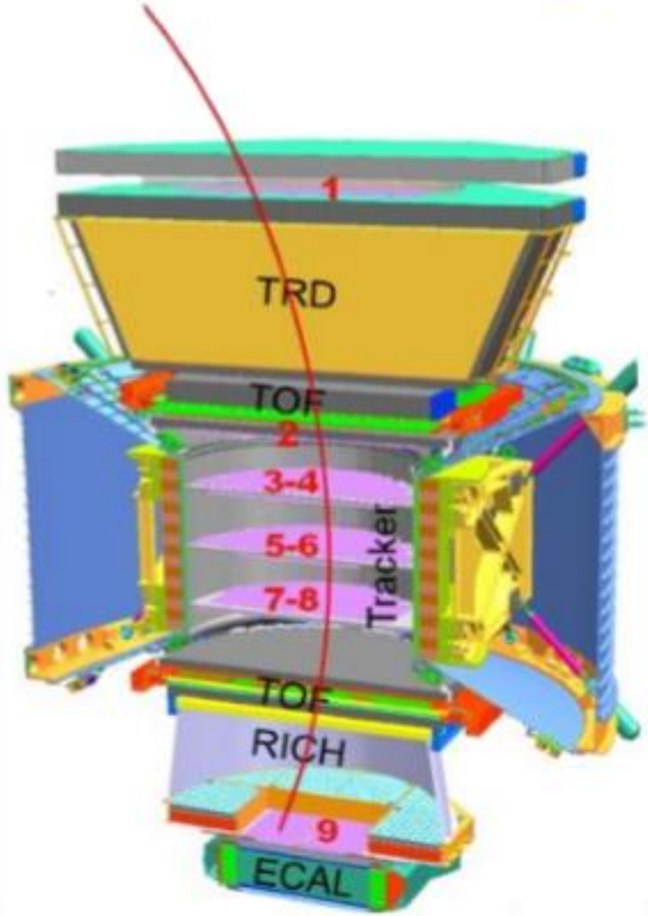
a) Minimal material in the TRD and Tracker, so that the detector itself does not become a source of background nor of large angle scattering

b) Repetitive measurements of momentum, to ensure that particles which had large angle scattering are not confused with the signal.

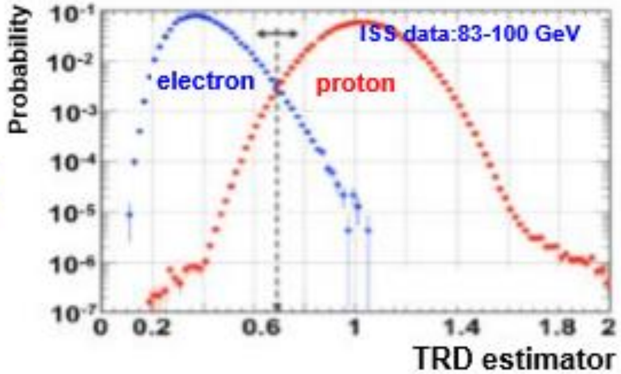
c) $e^\pm$ detectors are separated by magnetic field, so that secondary particles from TRD do not enter into ECAL.

Physics of 11 million e^+, e^- events

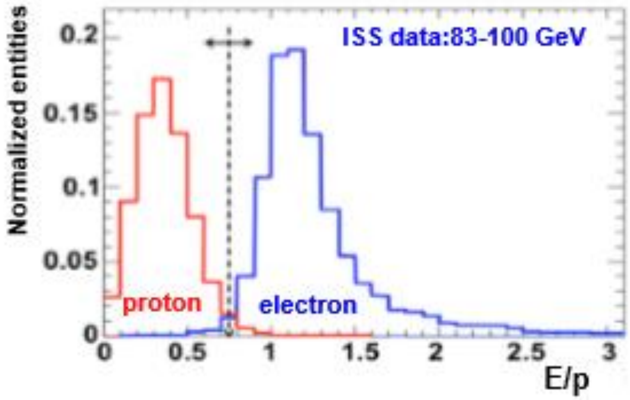
Measuring electrons and positrons



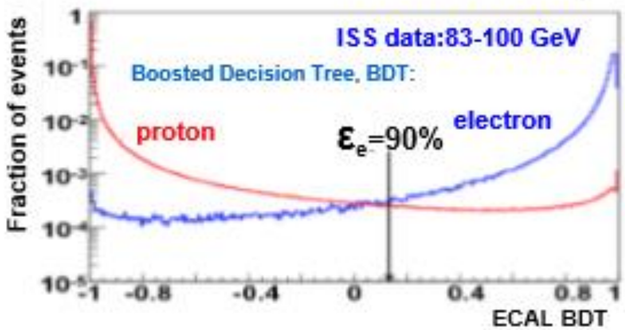
TRD
(transition radiation)
to identify $e^\pm$

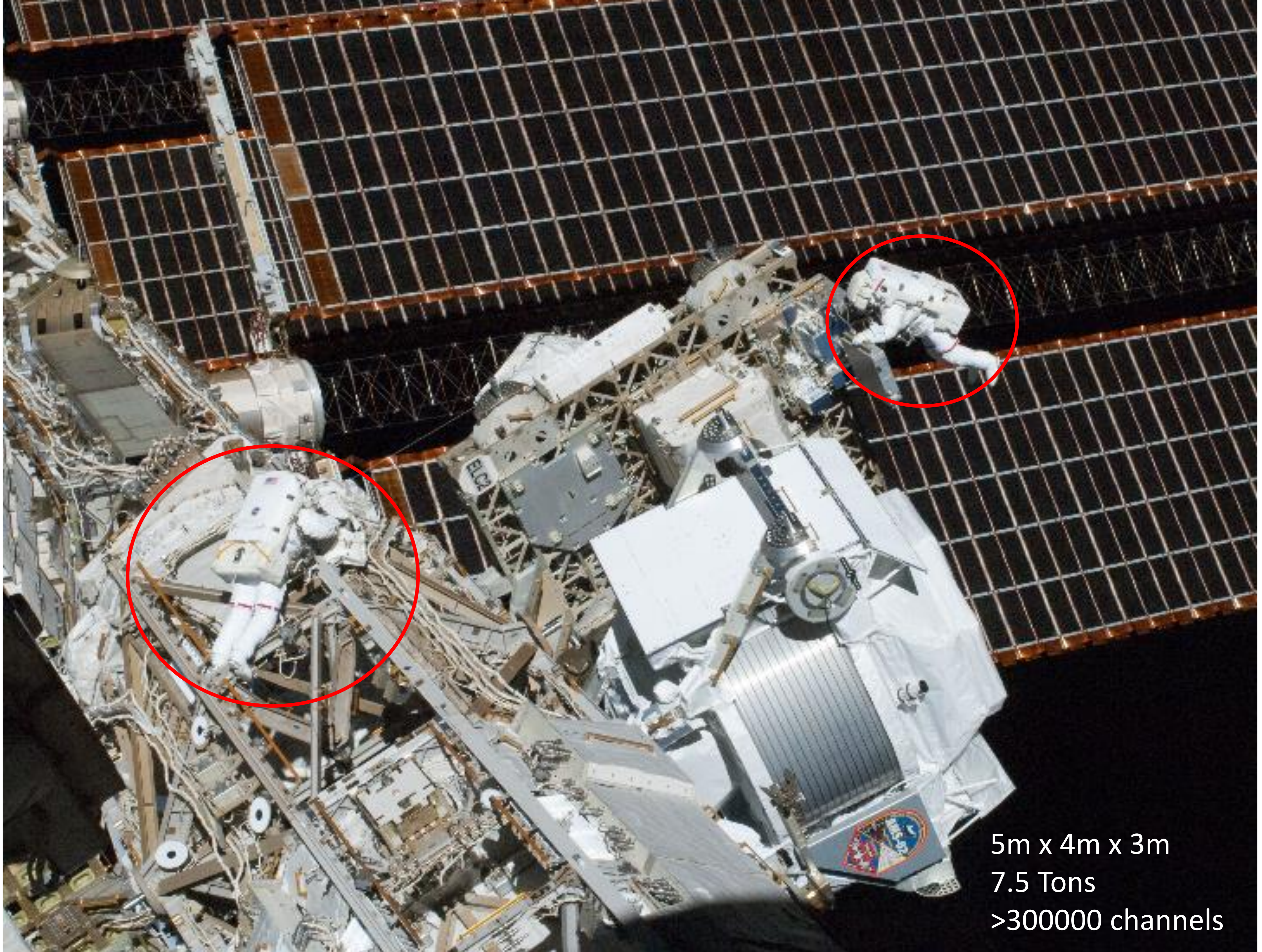


ECAL measures E
Tracker measures p
$e^\pm$: E=p
proton: E<p



ECAL
(shower shape)
to separate $e^\pm$
from protons




5m x 4m x 3m
7.5 Tons
>300000 channels

In 4 years on ISS,

AMS has collected >60 billion cosmic rays.

To match the statistics,

systematic errors studies have become important.

AMS ANALYSIS EXAMPLE: HELIUM

Precision Measurement of the Helium Flux in Primary Cosmic Rays of Rigidities 1.9 GV to 3 TV with the Alpha Magnetic Spectrometer on the International Space Station

M. Aguilar,[26] D. Aisa,[32,33] B. Alpat,[32] A. Alvino,[32] G. Ambrosi,[32] K. Andeen,[22] L. Arruda,[24] N. Attig,[21] P. Azzarello,[16] A. Bachlechner,[1] F. Barao,[24] A. Barrau,[17] L. Barrin,[15] A. Bartoloni,[38] L. Basara,[36] M. Battarbee,[47] R. Battiston,[36,37,a] J. Bazo,[32,b] U. Becker,[9] M. Behlmann,[9] B. Beischer,[1] J. Berdugo,[26] B. Bertucci,[32,33] V. Bindi,[19] S. Bizzaglia,[32] M. Bizzarri,[32,33] G. Boella,[28,29] W. de Boer,[22] K. Bollweg,[20] V. Bonnivard,[17] B. Borgia,[38,39] S. Borsini,[32] M. J. Boschini,[28] M. Bourquin,[16] J. Burger,[9] F. Cadoux,[16] X. D. Cai,[9] M. Capell,[9] S. Caroff,[3] J. Casaus,[26] G. Castellini,[14] I. Cernuda,[26] D. Cerreta,[32,33] F. Cervelli,[34] M. J. Chae,[41] Y. H. Chang,[10] A. I. Chen,[9] G. M. Chen,[6] H. Chen,[9] H. S. Chen,[6] L. Cheng,[42] H. Y. Chou,[10] E. Choumilov,[9] V. Choutko,[9] C. H. Chung,[1] C. Clark,[20] R. Clavero,[23] G. Coignet,[3] C. Consolandi,[19] A. Contin,[7,8] C. Corti,[19] E. Cortina Gil,[16,c] B. Coste,[36,15] W. Creus,[10] M. Crispoltoni,[32,33] Z. Cui,[42] Y. M. Dai,[5] C. Delgado,[26] S. Della Torre,[28] M. B. Demirköz,[2] L. Derome,[17] S. Di Falco,[34] L. Di Masso,[32,33] F. Dimiccoli,[36,37] C. Díaz,[26] P. von Doetinchem,[19] F. Donnini,[32,33] M. Duranti,[32,33] D. D'Urso,[32,d] A. Egorov,[9] A. Eline,[9] F. J. Eppling,[9,*] T. Eronen,[47] Y. Y. Fan,[46,e] L. Farnesini,[32] J. Feng,[3,46,f] E. Fiandrini,[32,33] A. Fiasson,[3] E. Finch,[31] P. Fisher,[9] V. Formato,[32,15] Y. Galaktionov,[9] G. Gallucci,[34] B. García,[26] R. García-López,[23] C. Gargiulo,[15] H. Gast,[1] I. Gebauer,[22] M. Gervasi,[28,29] A. Ghelfi,[17] F. Giovacchini,[26] P. Goglov,[9] J. Gong,[30] C. Goy,[3] V. Grabski,[27] D. Grandi,[28] M. Graziani,[32,33] C. Guandalini,[7] I. Guerri,[34,35] K. H. Guo,[18] D. Haas,[16,g] M. Habiby,[16] S. Haino,[46] K. C. Han,[25] Z. H. He,[18] M. Heil,[9] J. Hoffman,[10,19] T. H. Hsieh,[9] Z. C. Huang,[18] C. Huh,[13] M. Incagli,[34] M. Ionica,[32] W. Y. Jang,[13] H. Jinchi,[25] K. Kanishev,[36,37,15] G. N. Kim,[13] K. S. Kim,[13] Th. Kirn,[1] M. A. Korkmaz,[2] R. Kossakowski,[3] O. Kounina,[9] A. Kounine,[9] V. Koutsenko,[9] M. S. Krafczyk,[9]

He event selection

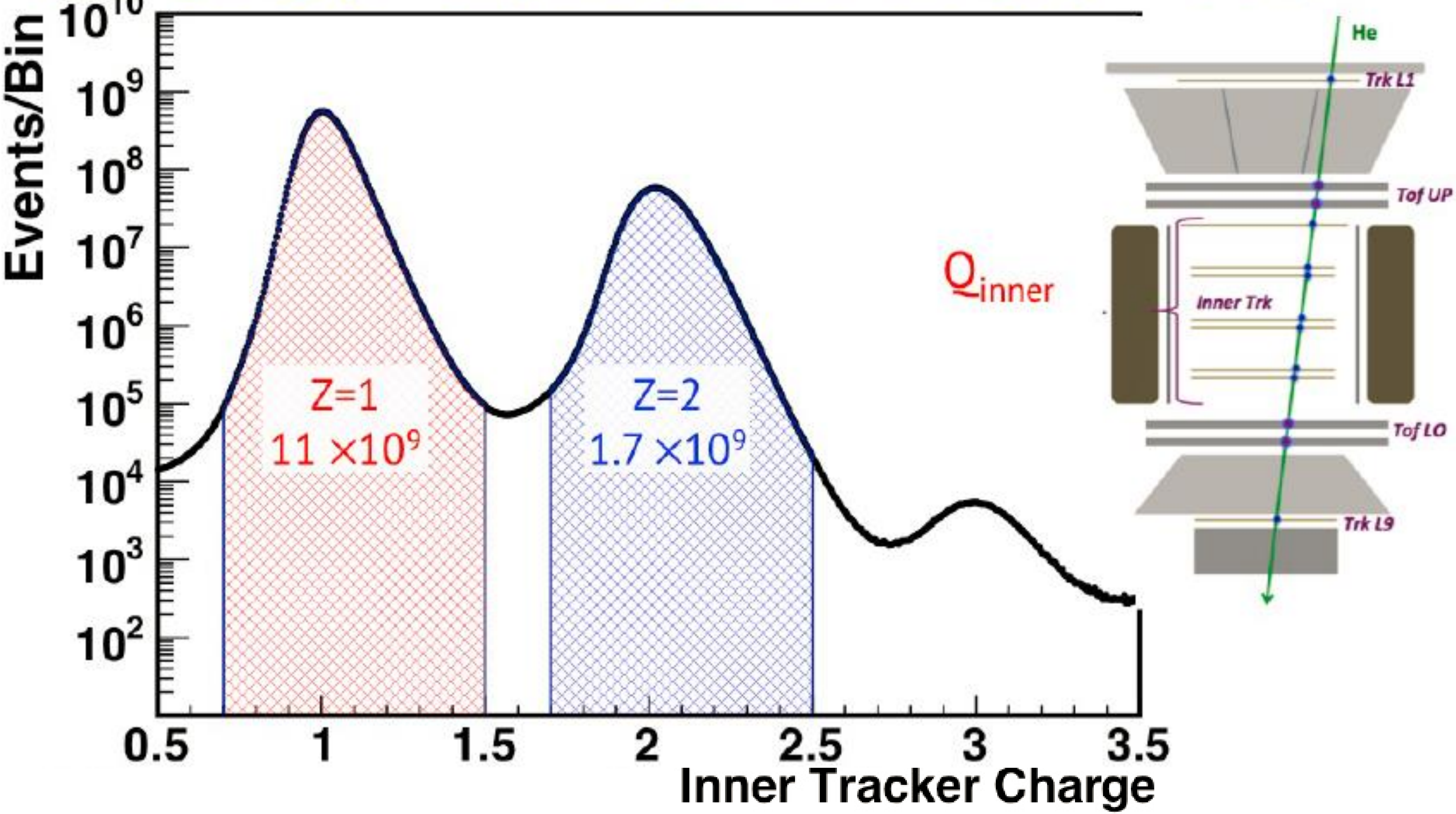
1. Downgoing particle ($\beta > 0.3$)
2. Rigidity (R) above Geomagnetic cutoff :

   $R > 1.2\ R_{\text{IGRF-cutoff}}$
3. Track has top (L1) and bottom (L9) layers to ensure the best resolution ($\text{MDR}_{\text{L19}} \approx 3.2$ TV)
4. Charge compatible with Z=2 along the trajectory

   e.g. Inner Tracker : $1.7 < Q_{\text{inner}} < 2.5$
5. Quality of the track fitting : $\chi^2/\text{d.f.} < 10$

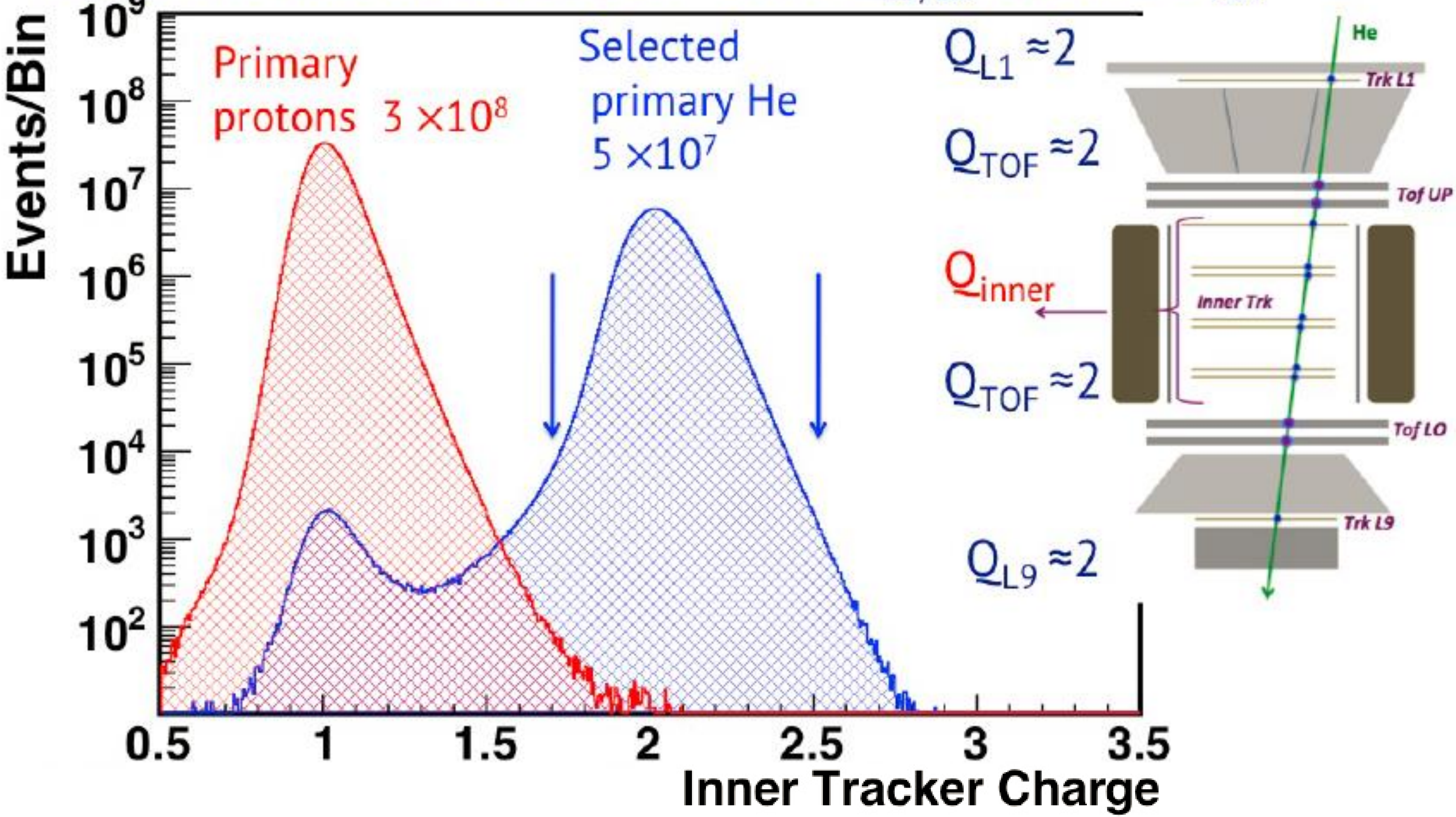
He selection (1)

Downgoing (β > 0.3) and positive charge (R > 1 GV)



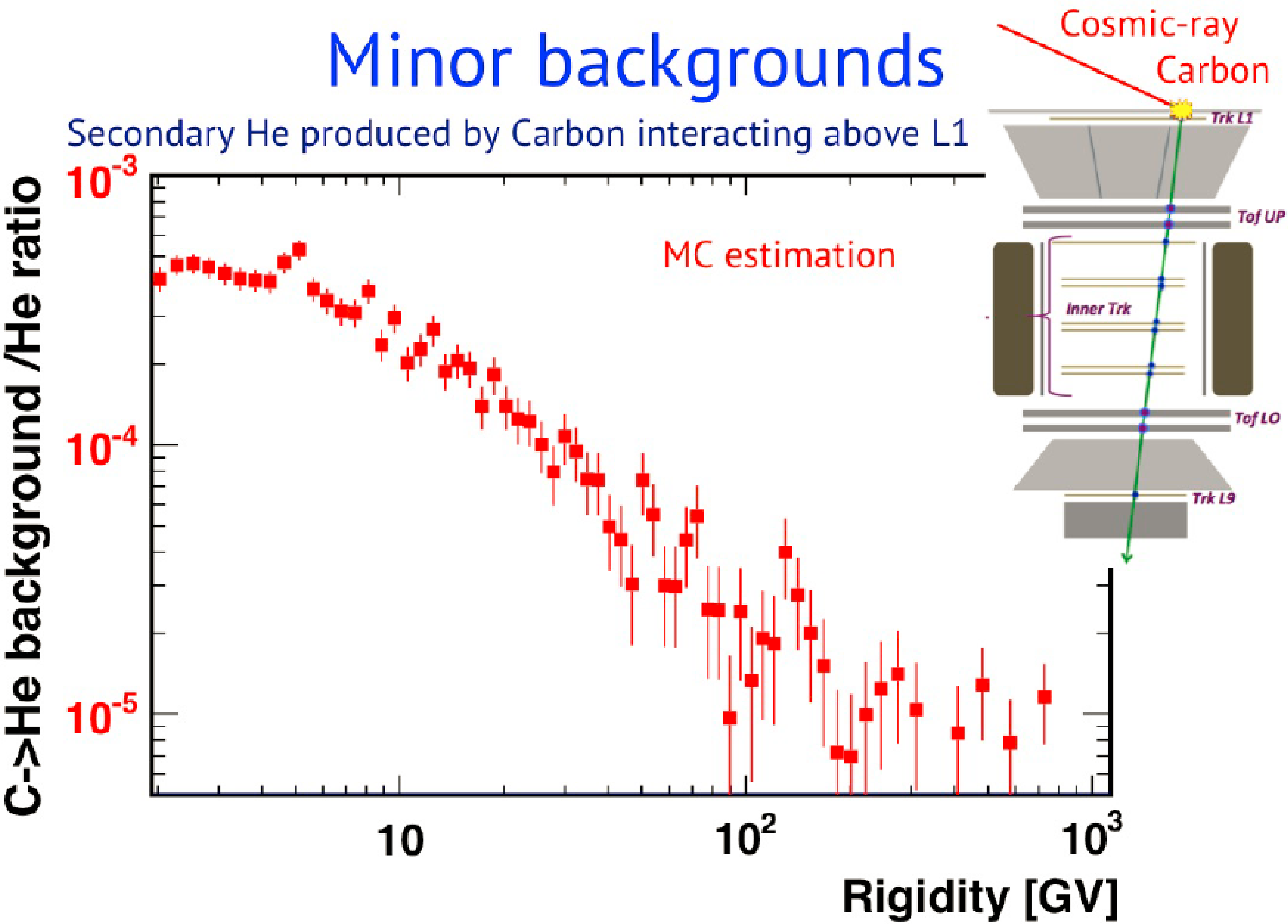
He selection (2)

Track has hits in L1 and L9 with $Z_{L1/L9} \approx 2$, and $Z_{TOF} \approx 2$



Minor backgrounds

Secondary He produced by Carbon interacting above L1



Flux measurement

Assuming flux over geomagnetic cutoff is isotropic
The differential flux is defined as :

$$\Phi_i(R_i) = \frac{N_i}{T_i \, \varepsilon_i \, A_i \, \Delta R_i}$$

Events Corrected for Bin to Bin Migration due to Tracker Rigidity Resolution

Rigidity
2-3000 GV

Time
6.3×10^7 sec

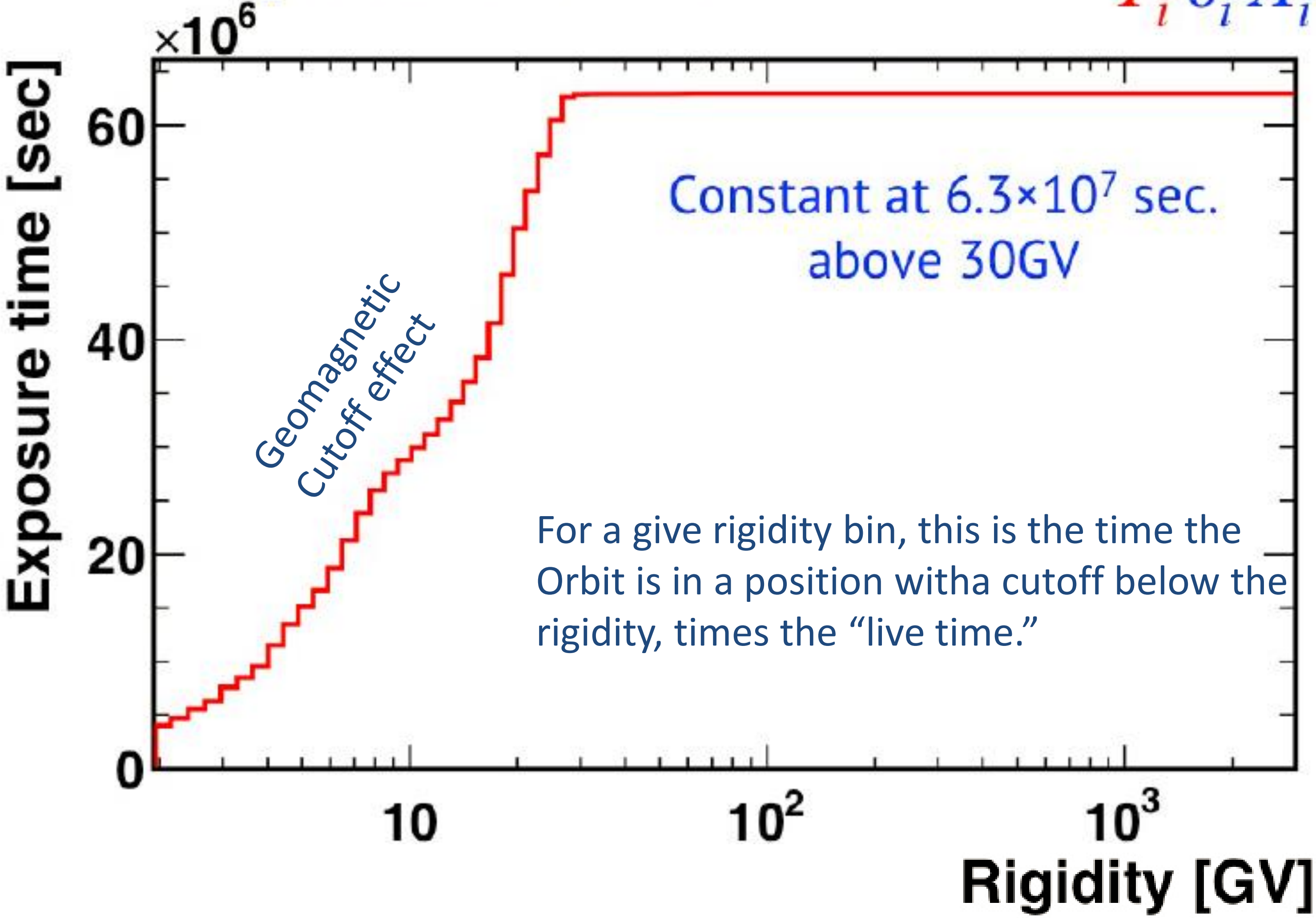
Trigger
Efficiency

Effective
Acceptance

Bin width

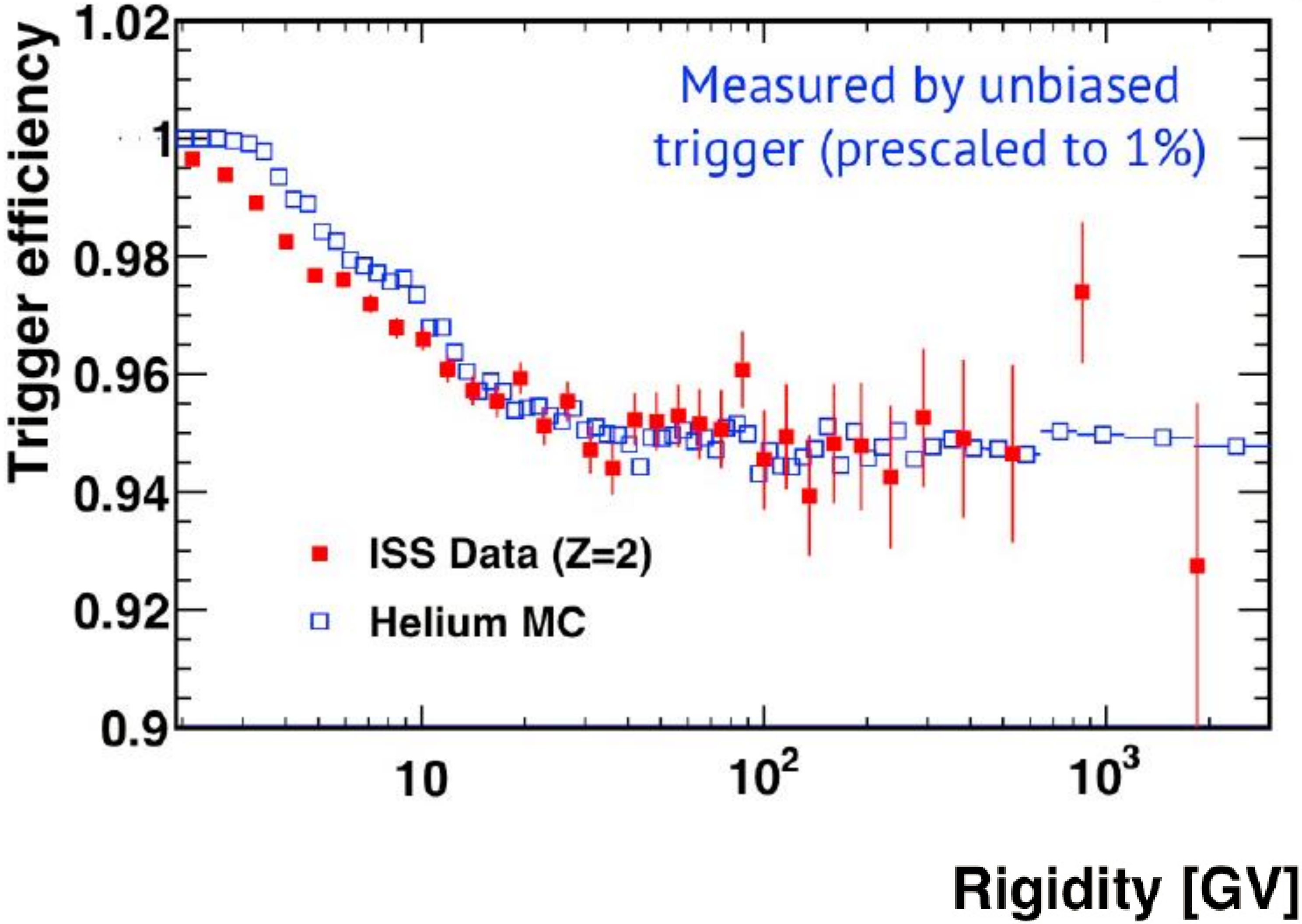
Exposure time

$$\Phi_i(R_i) = \frac{N_i}{T_i\, \varepsilon_i\, A_i\, \Delta R_i}$$



For a give rigidity bin, this is the time the Orbit is in a position witha cutoff below the rigidity, times the “live time.”

Trigger efficiency $\Phi_i(R_i) = \frac{N_i}{T_i\, \varepsilon_i\, A_i\, \Delta R_i}$



Acceptance – MC validation

$$\Phi_i(R_i) = \frac{N_i}{T_i\,\varepsilon_i\,A_i\,\Delta R_i}$$

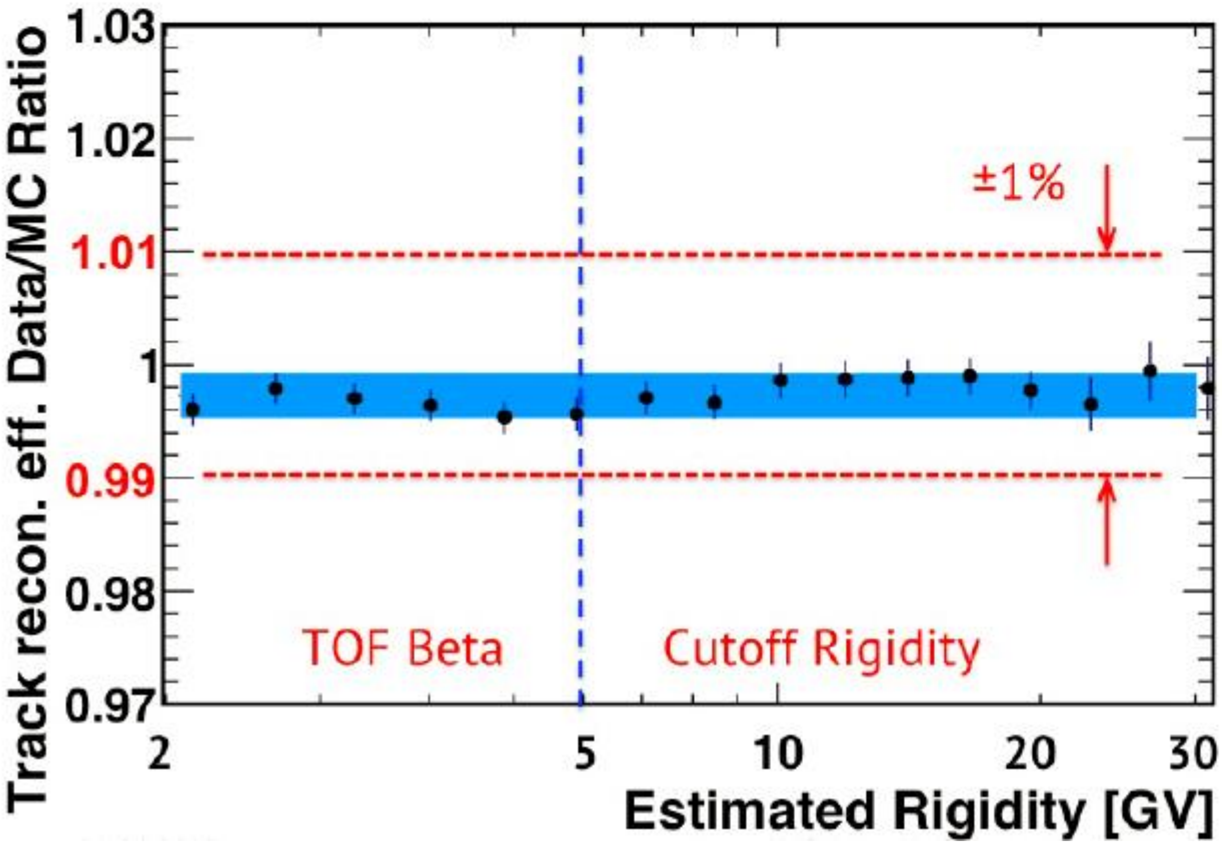
1. Track reconstruction efficiency
   - Validation of the description of the detector performance in MC simulation

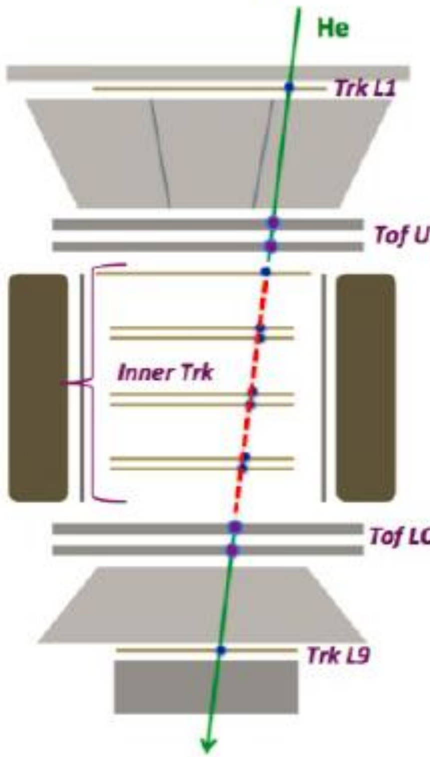
2. L1 hit association efficiency
   - Validation of the He elastic scattering

3. Survival probability between L8 and L9
   - Validation of the He inelastic cross section

Data/MC comparison (1)

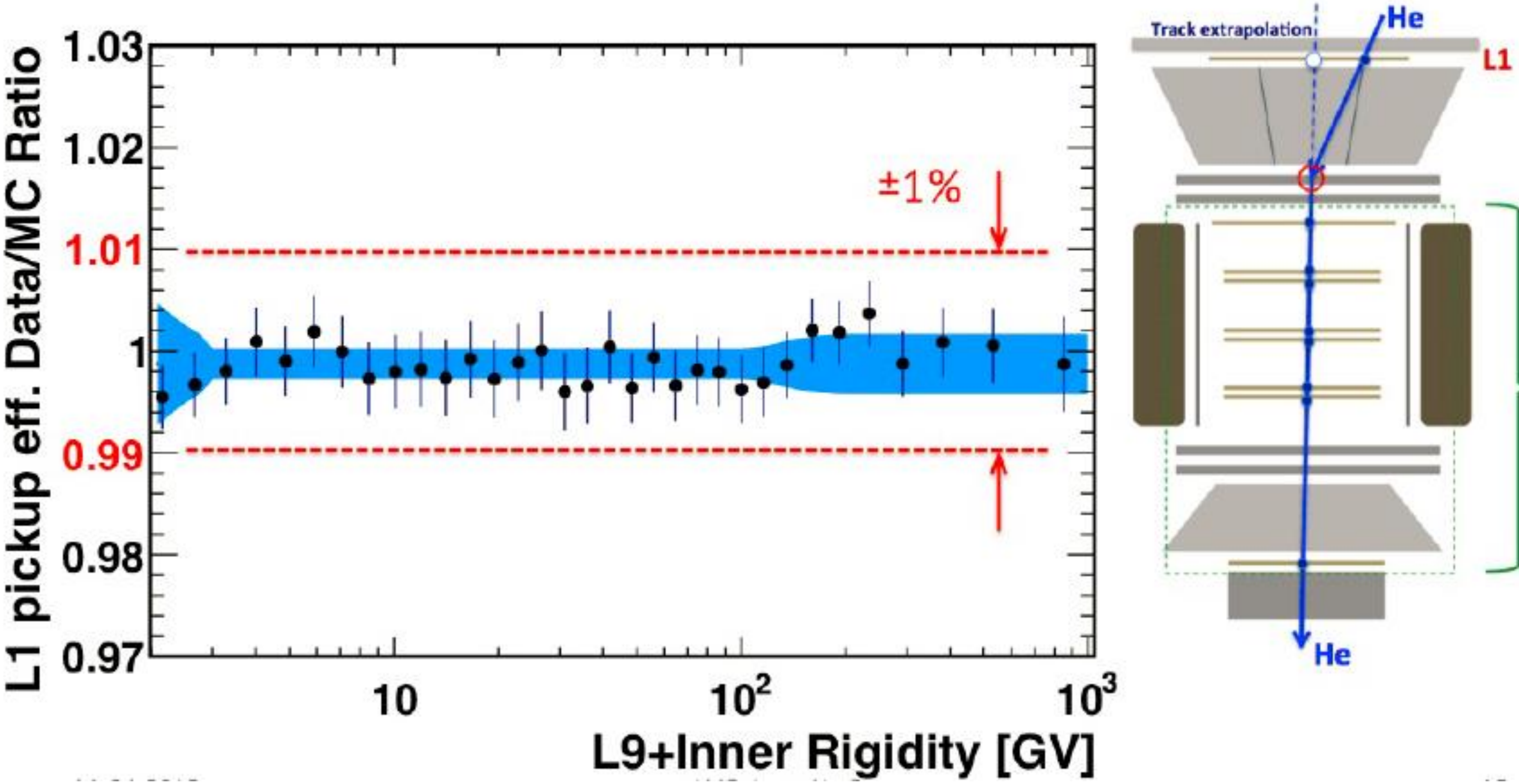
Comparison of Track reconstruction efficiency





Data/MC comparison (2)

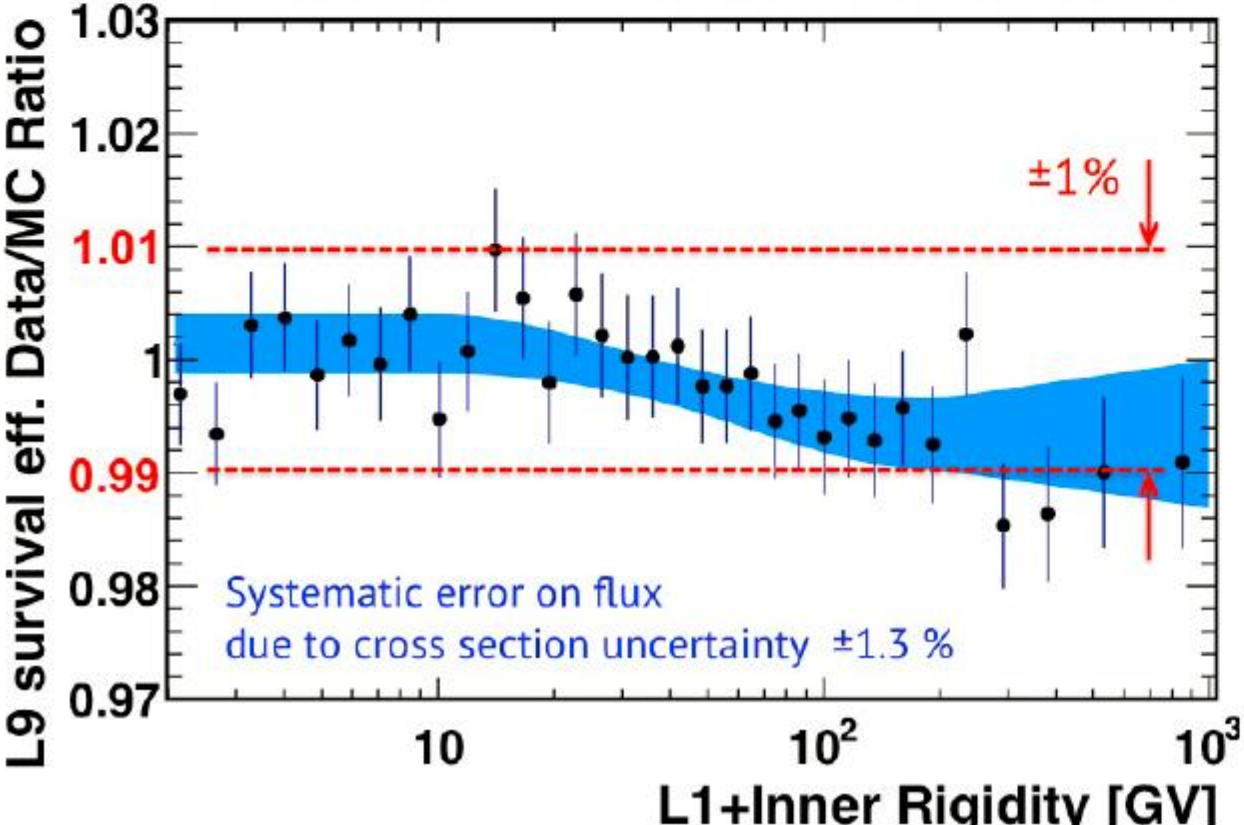
L1 hit association : Validation of elastic scattering

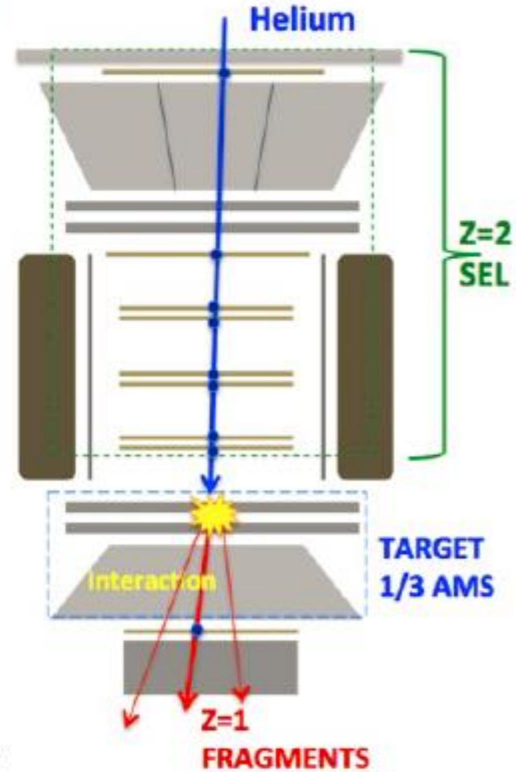


Data/MC comparison (3)

Survival probability between L8 and L9 :

Validation of He inelastic cross section





Verifications of systematic errors

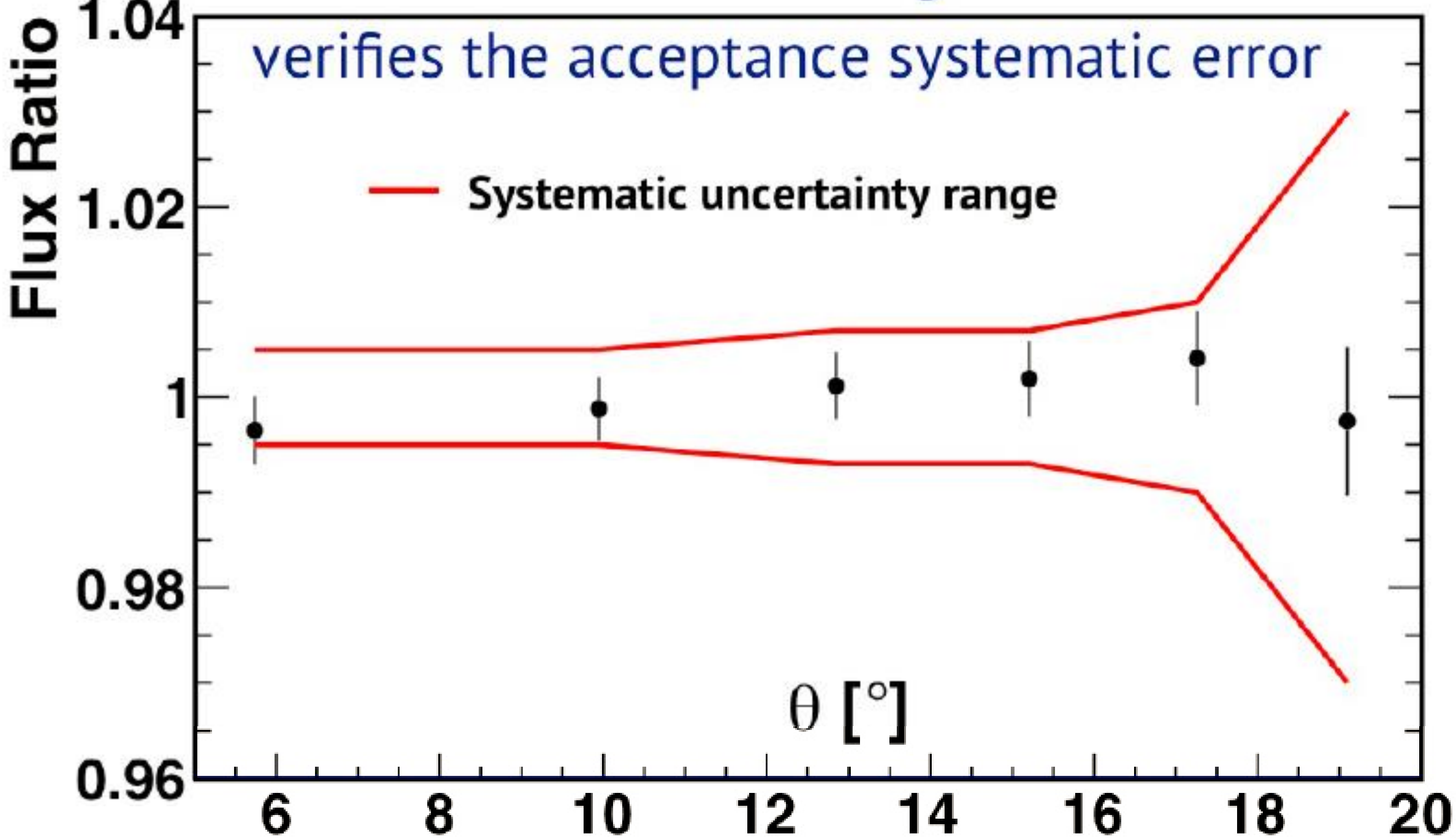
1. Flux ratio above 30 GV versus angle to AMS z-axis
   - Verification of systematic error on acceptance

2. Flux ratio above 45 GV versus time
   - Stability of detector performance over time

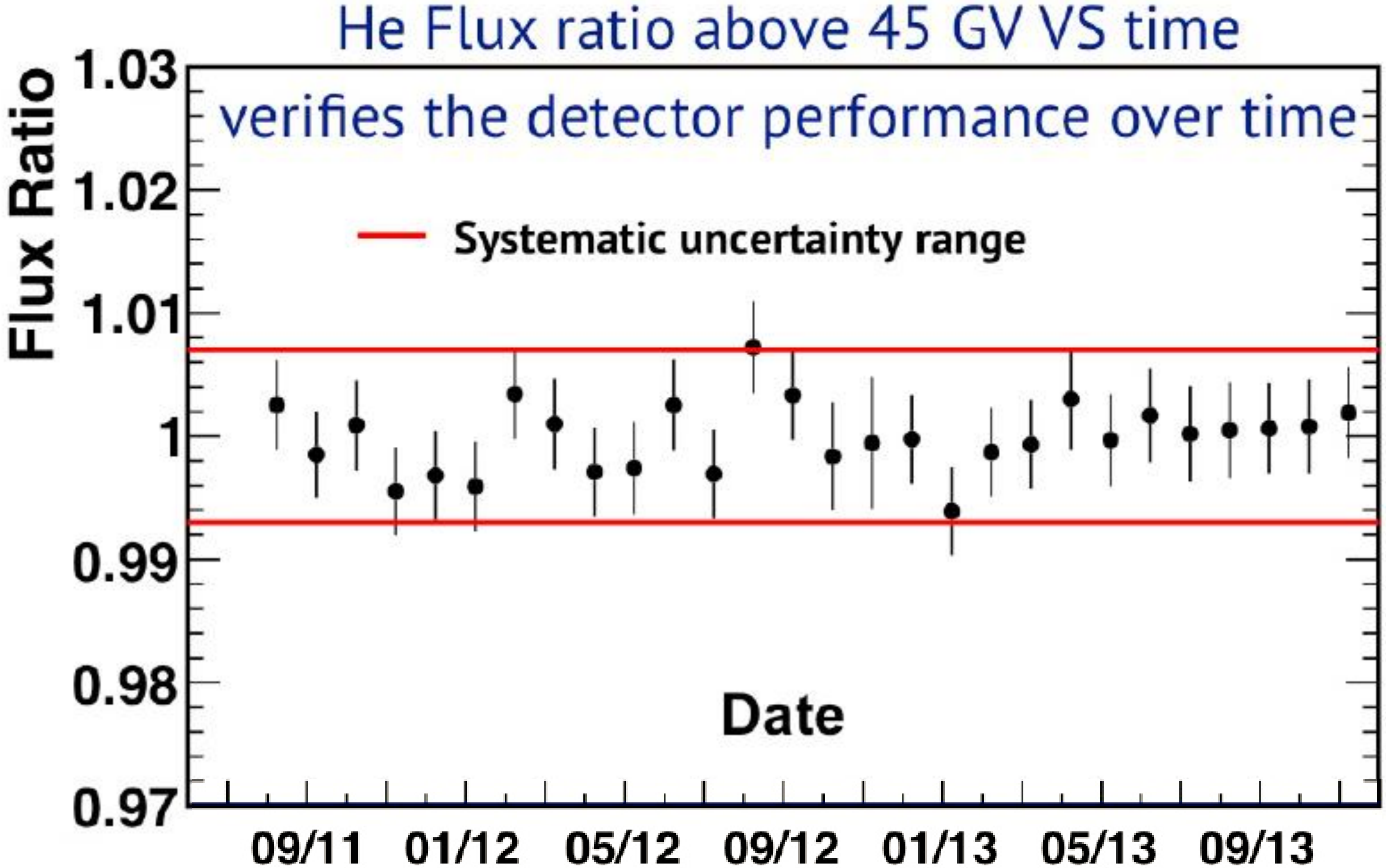
3. Flux ratio between Inner and Full Tracker
   - Verification of systematic errors on unfolding and rigidity resolution function

Verifications of Systematic errors (1)

He Flux ratio above 30 GV VS angle θ to the AMS z-axi

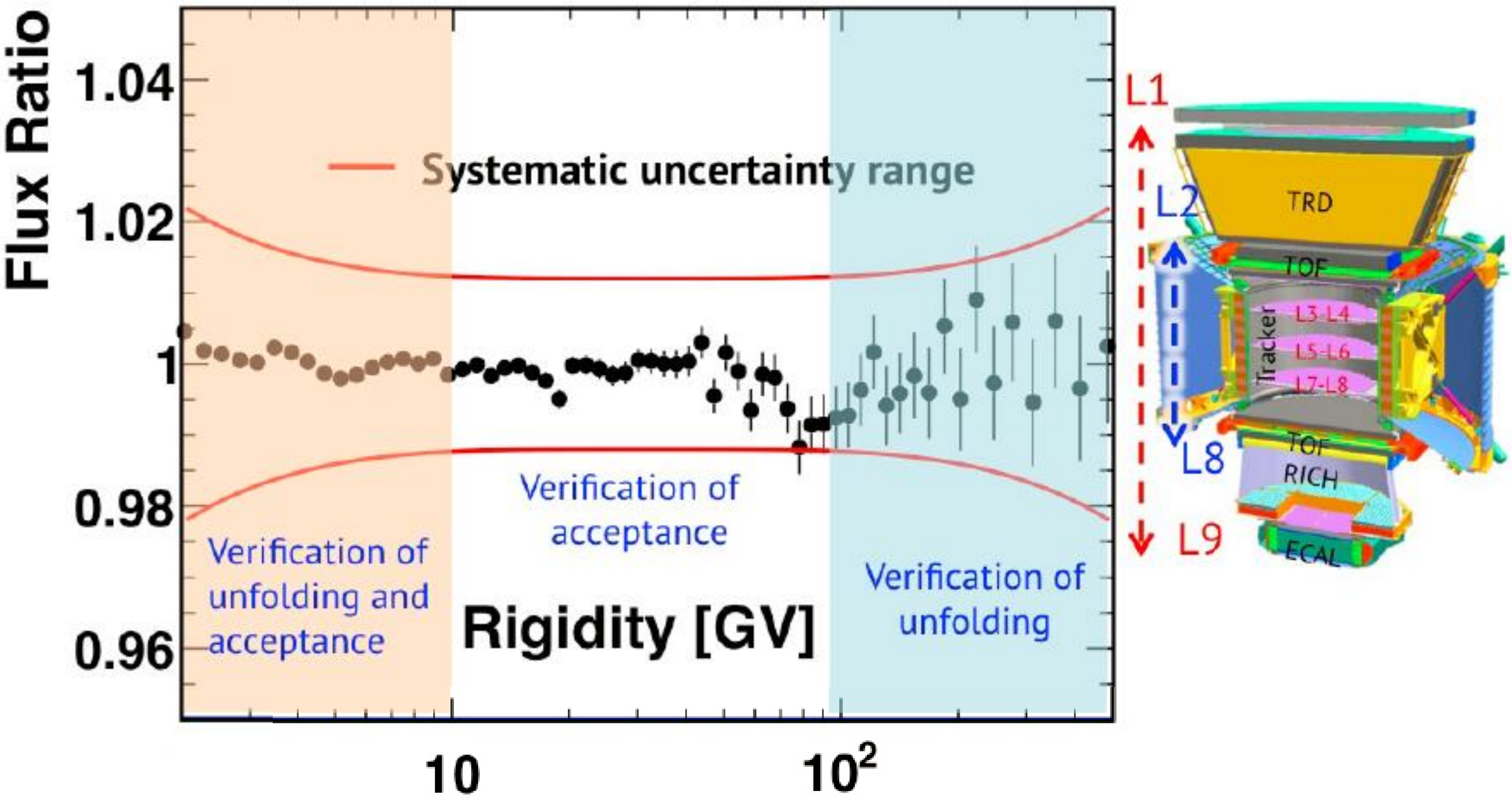


Verifications of Systematic errors (2)



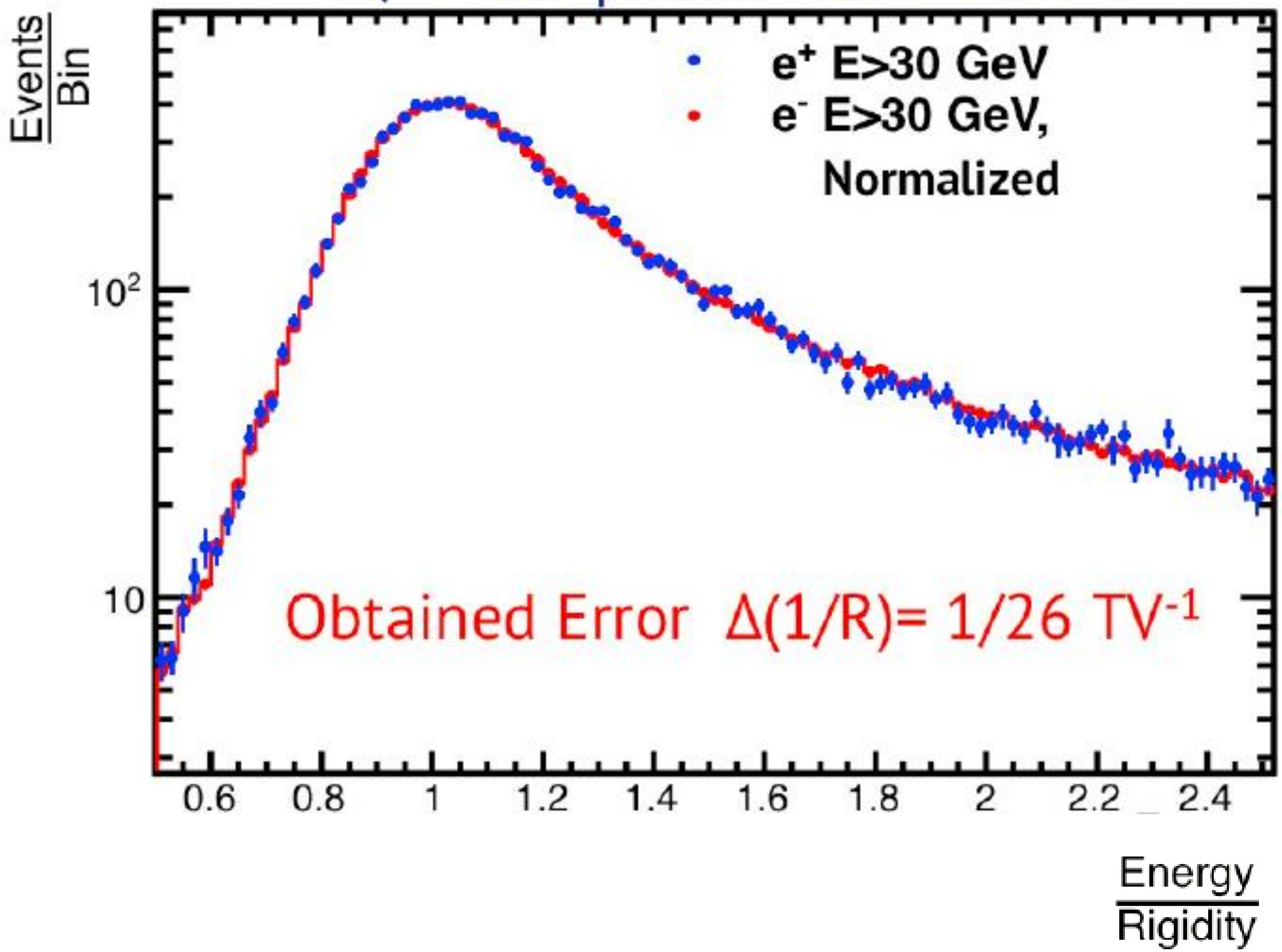
Verifications of Systematic errors (3)

He Flux ratio between Inner and Full Tracker

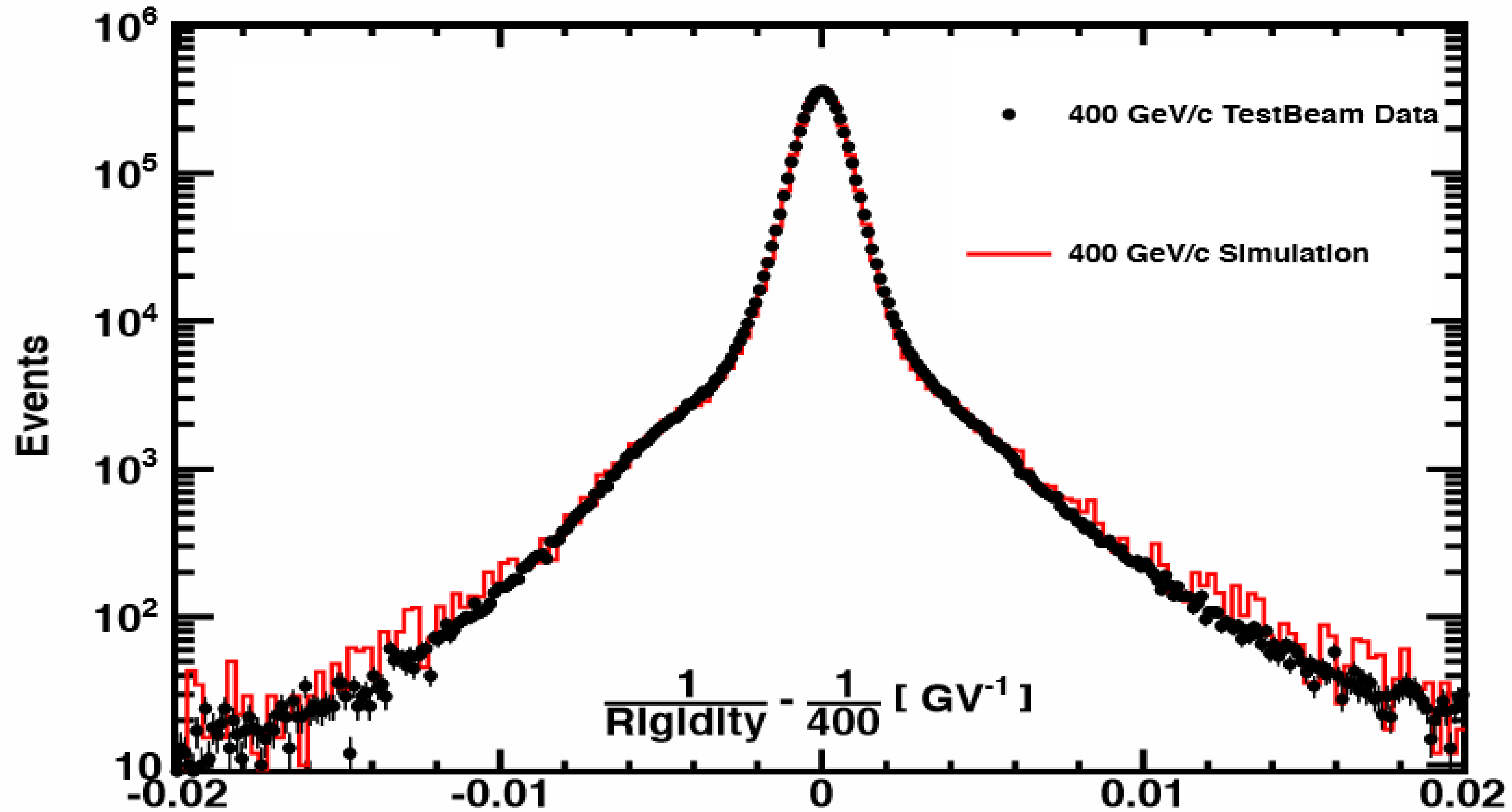


Verification of Rigidity scale

E / P comparison for e+ and e-



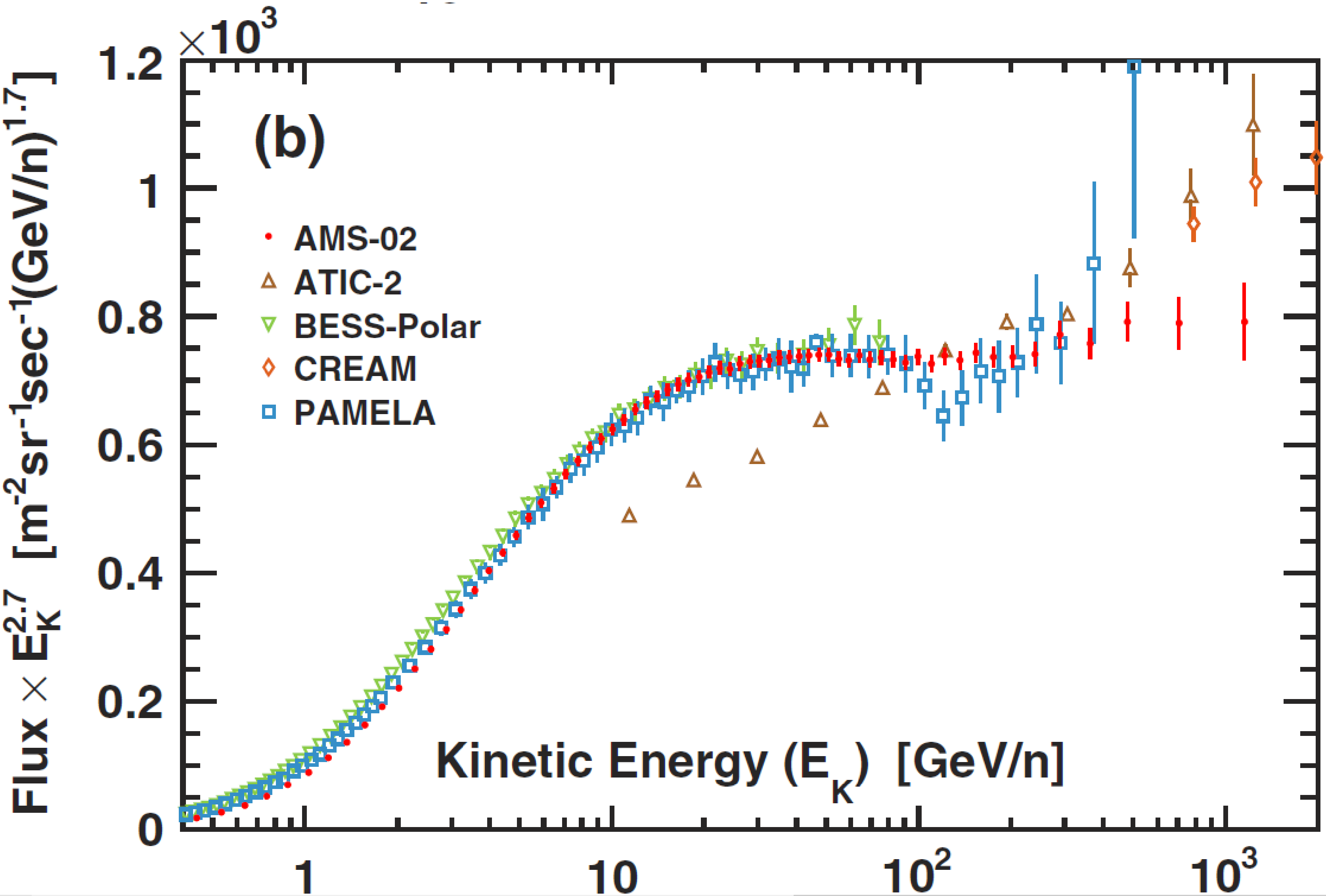
Explicit verification of the tracker on ground



The resolution function for 400 GeV/*c* protons measured in the test beam compared with Monte Carlo simulated events.

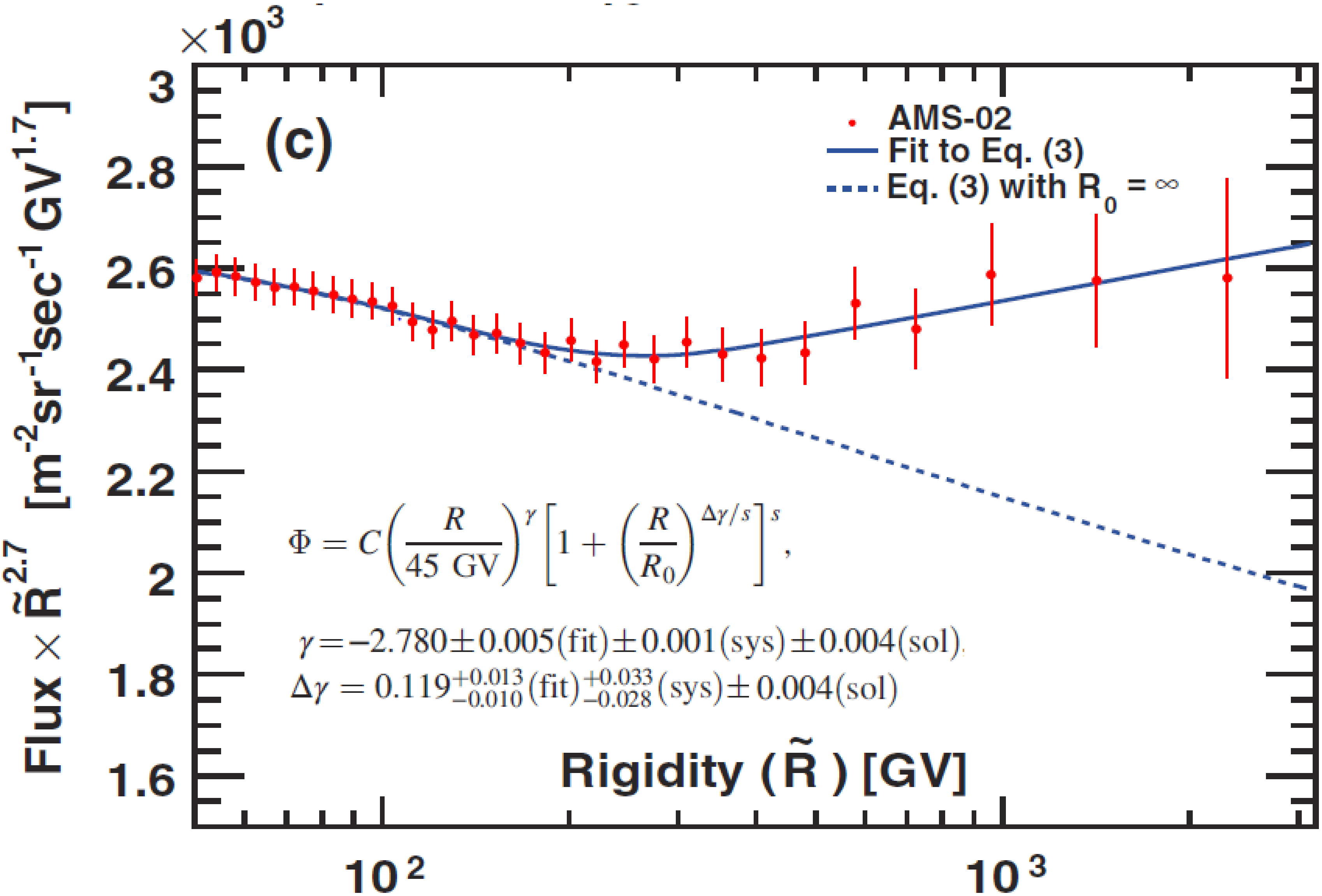
SOME AMS-02 RESULTS: NUCLEI

He flux



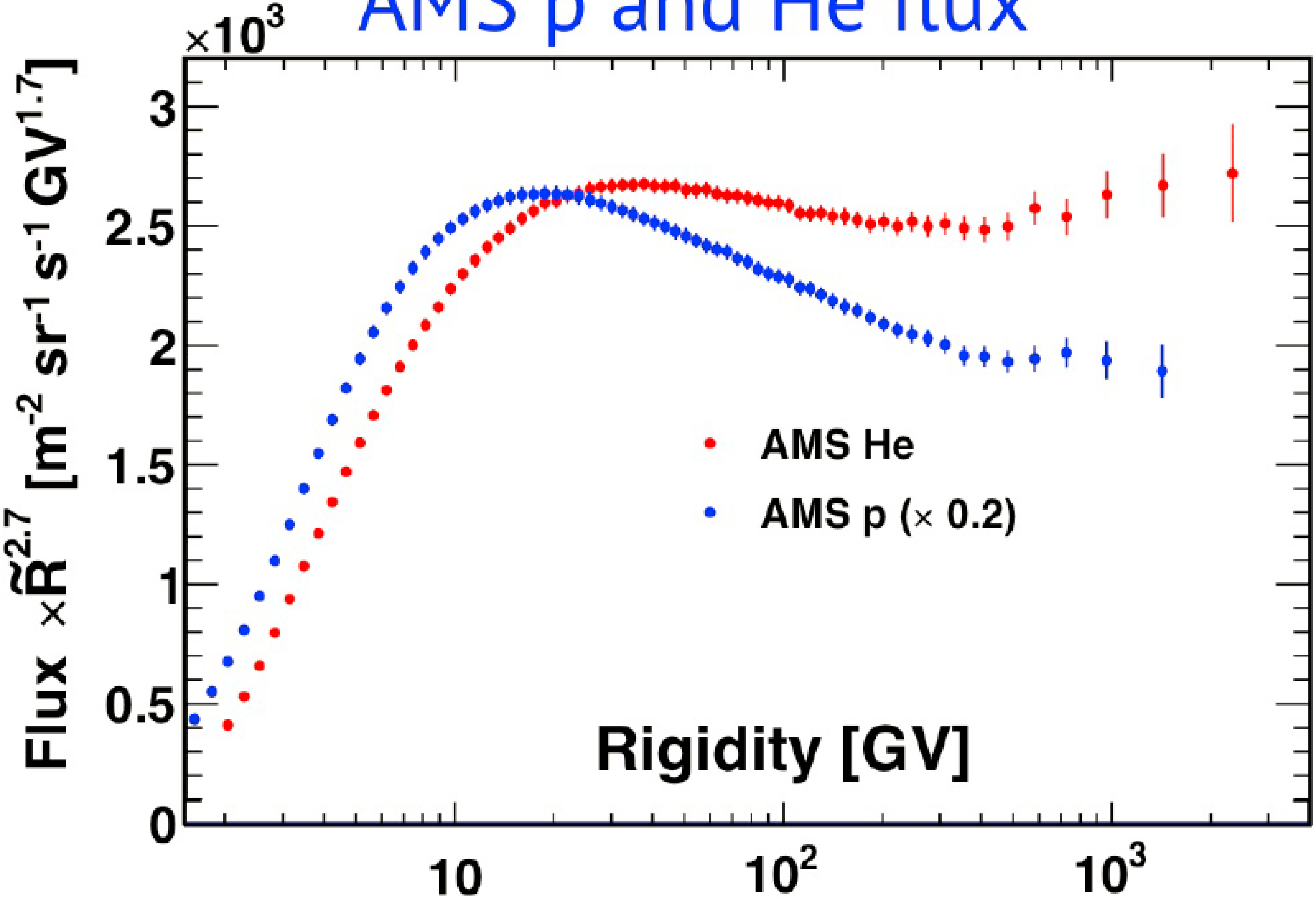
×10³
1.2
1
0.8
0.6
0.4
0.2
0
(b)
AMS-02
ATIC-2
BESS-Polar
CREAM
PAMELA
Flux × E_K^2.7 [m^-2sr^-1sec^-1(GeV/n)^1.7]
Kinetic Energy (E_K) [GeV/n]
1
10
10²
10³

He flux

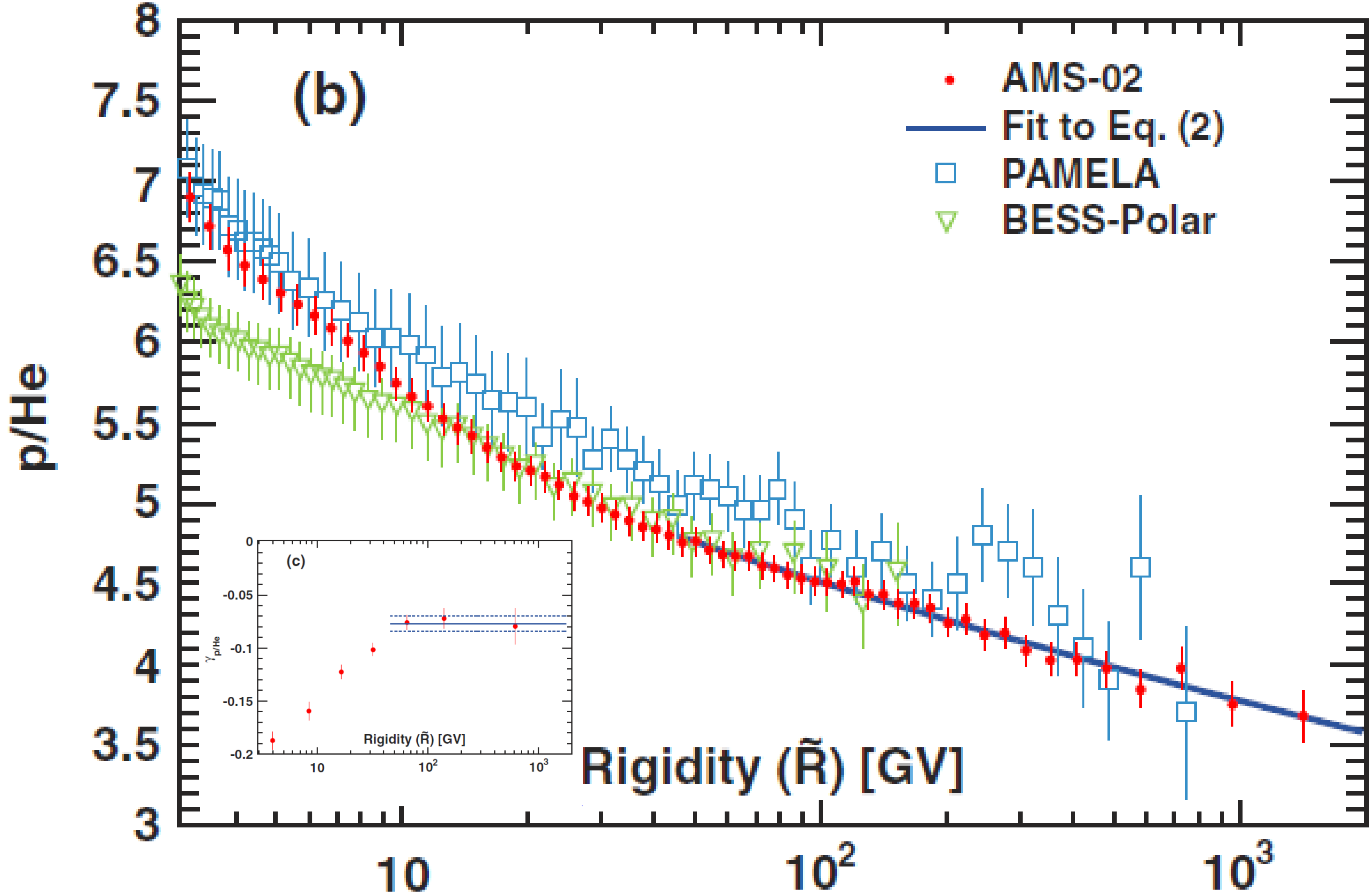


$\times 10^3$
3
2.8
2.6
2.4
2.2
2
1.8
1.6
(c)
AMS-02
Fit to Eq. (3)
Eq. (3) with $R_0 = \infty$
$$\Phi = C\left(\frac{R}{45\ \mathrm{GV}}\right)^{\gamma}\left[1 + \left(\frac{R}{R_0}\right)^{\Delta\gamma/s}\right]^{s},$$
$\gamma = -2.780 \pm 0.005(\mathrm{fit}) \pm 0.001(\mathrm{sys}) \pm 0.004(\mathrm{sol})$.
$\Delta\gamma = 0.119^{+0.013}_{-0.010}(\mathrm{fit})^{+0.033}_{-0.028}(\mathrm{sys}) \pm 0.004(\mathrm{sol})$
Flux $\times \tilde{R}^{2.7}$ [$m^{-2}sr^{-1}sec^{-1}GV^{1.7}$]
Rigidity ($\tilde{R}$) [GV]
10^2
10^3

AMS p and He flux

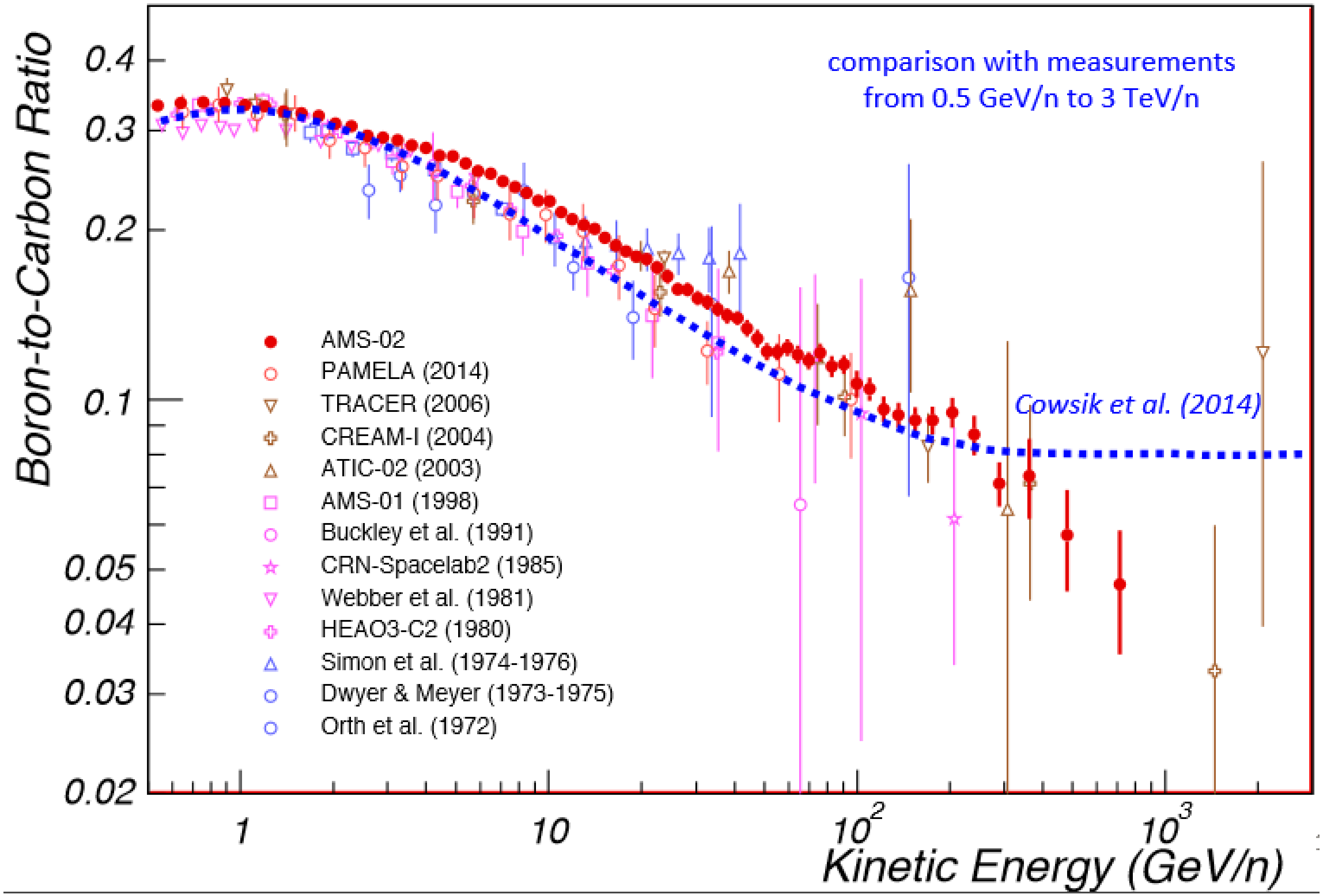


He vs p fluxes



SOME AMS-02 RESULTS: SECONDARY TO PRIMARY

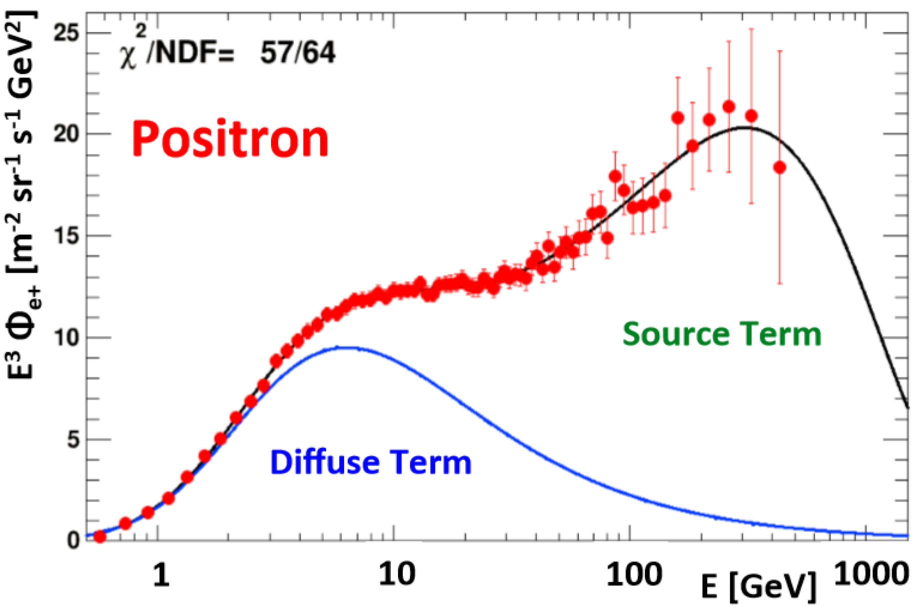
B/C ratio

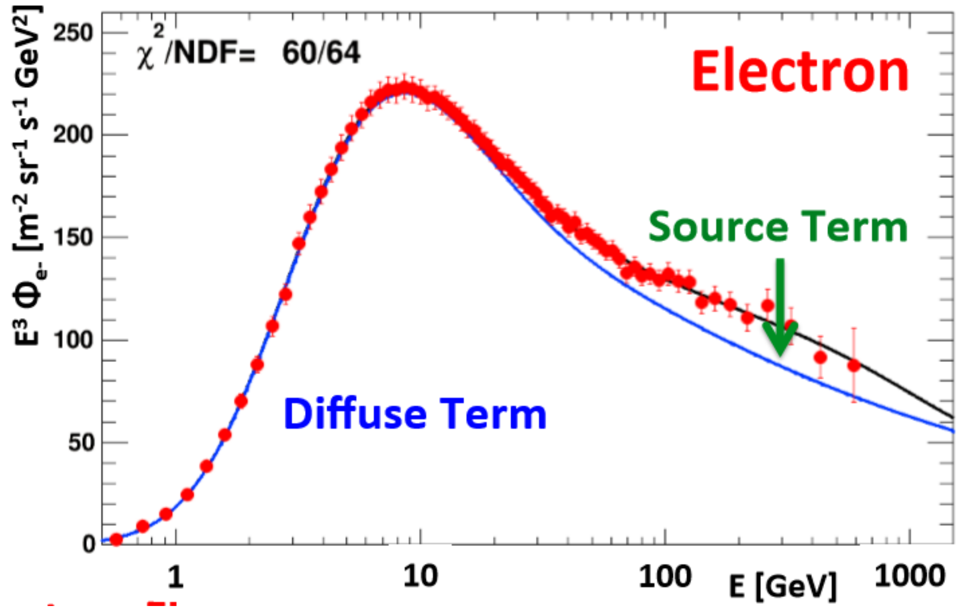


comparison with measurements
from 0.5 GeV/n to 3 TeV/n
Cowsik et al. (2014)
Boron-to-Carbon Ratio
0.4
0.3
0.2
0.1
0.05
0.04
0.03
0.02
1
10
10^2
10^3
Kinetic Energy (GeV/n)
AMS-02
PAMELA (2014)
TRACER (2006)
CREAM-I (2004)
ATIC-02 (2003)
AMS-01 (1998)
Buckley et al. (1991)
CRN-Spacelab2 (1985)
Webber et al. (1981)
HEAO3-C2 (1980)
Simon et al. (1974-1976)
Dwyer & Meyer (1973-1975)
Orth et al. (1972)

SOME AMS-02 RESULTS:
ELECTRONS & POSITRONS

Result

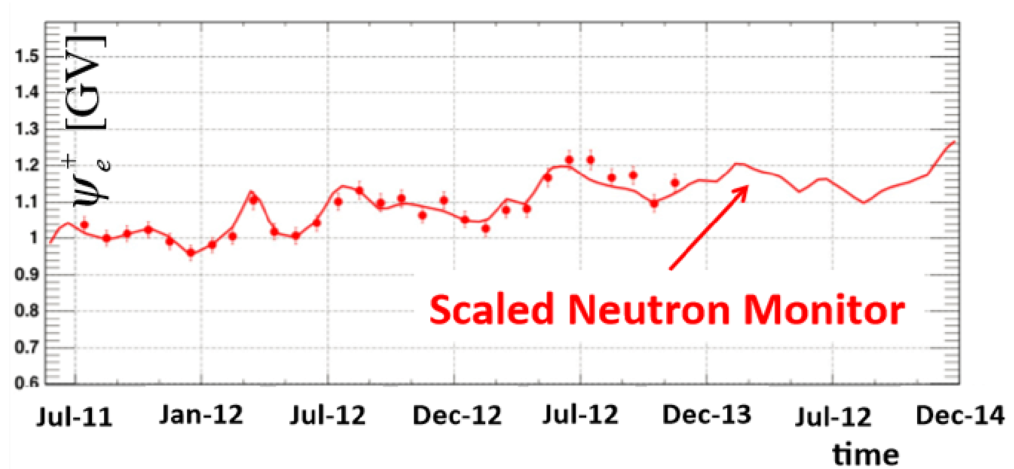




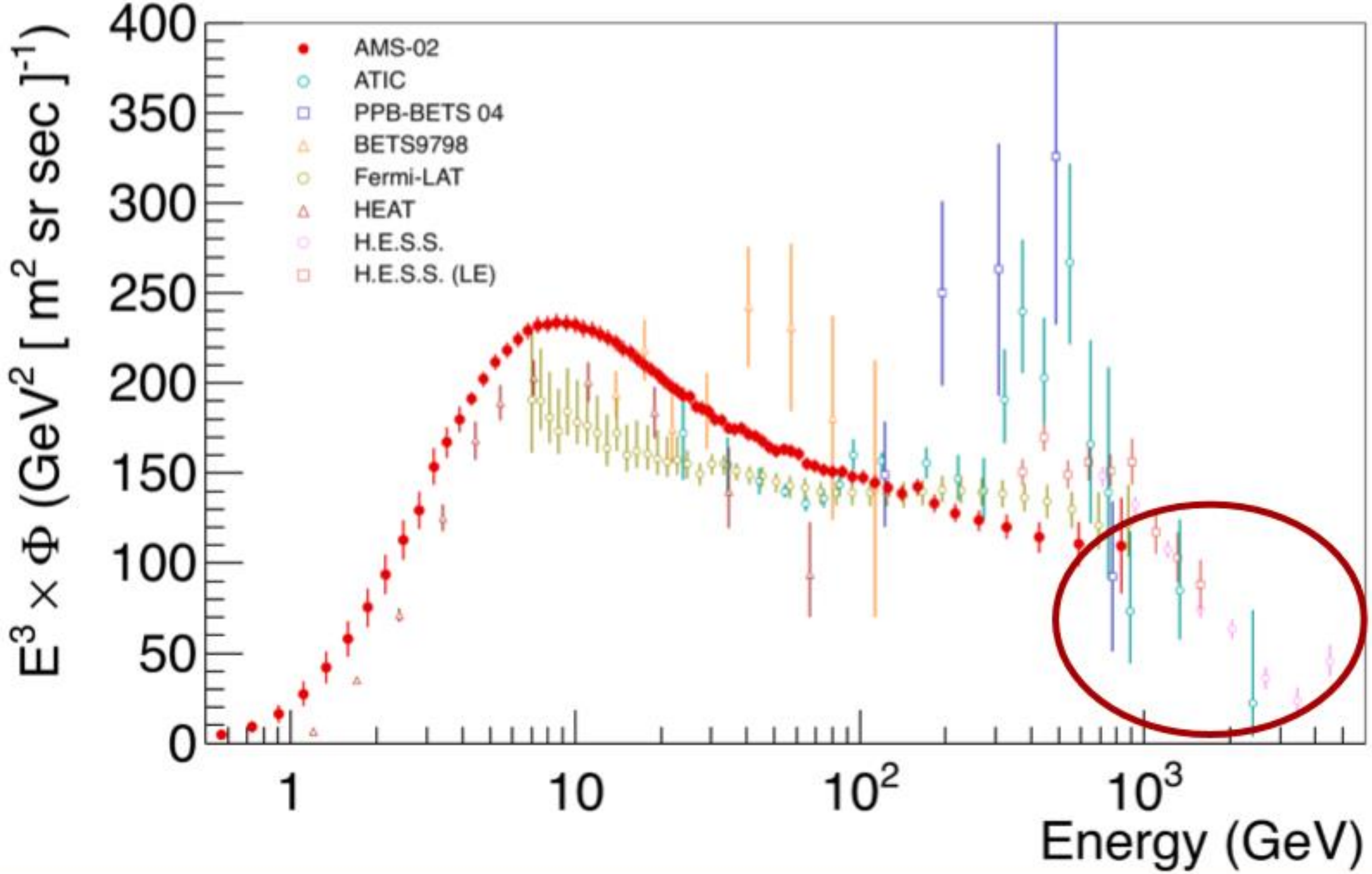
$$\Phi_{e+}(E) = \frac{E^2}{\hat{E}^2}\left[C_{e+}\hat{E}^{\gamma_{e+}} + C_S\hat{E}^{\gamma_S}\exp(-\hat{E}/E_S)\right]$$

$$\hat{E} = E + \psi_e^+(t)$$

$$E_S = 540\,^{+250}_{-130}\ \mathrm{GeV}$$



e- + e+ flux



AMS-02
ATIC
PPB-BETS 04
BETS9798
Fermi-LAT
HEAT
H.E.S.S.
H.E.S.S. (LE)
$E^3 \times \Phi$ (GeV^2 [m^2 sr sec]$^{-1}$)
400
350
300
250
200
150
100
50
0
1
10
10^2
10^3
Energy (GeV)

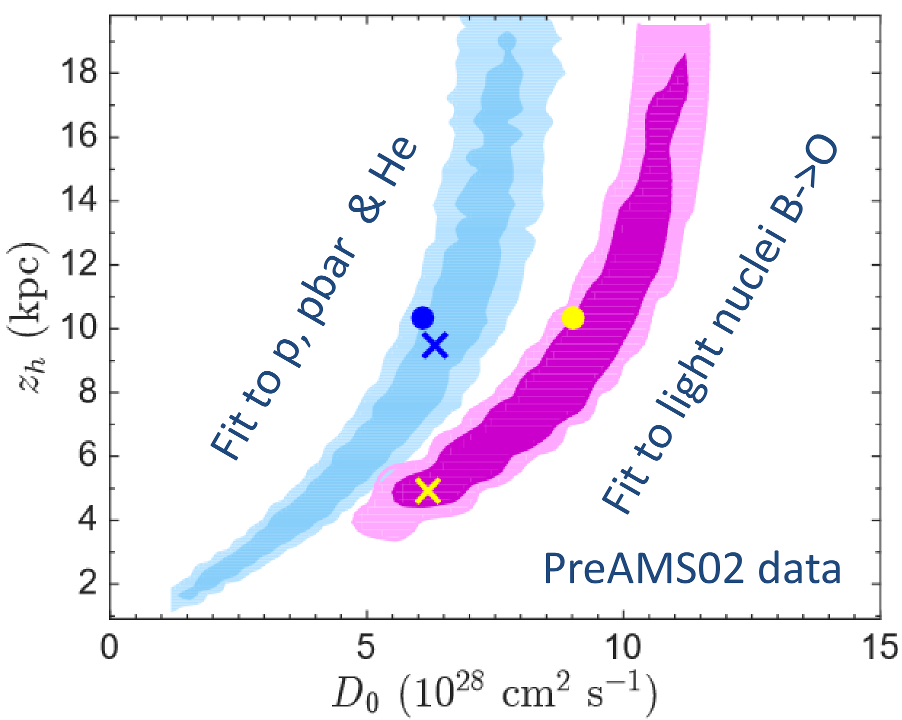
CONCLUSIONS

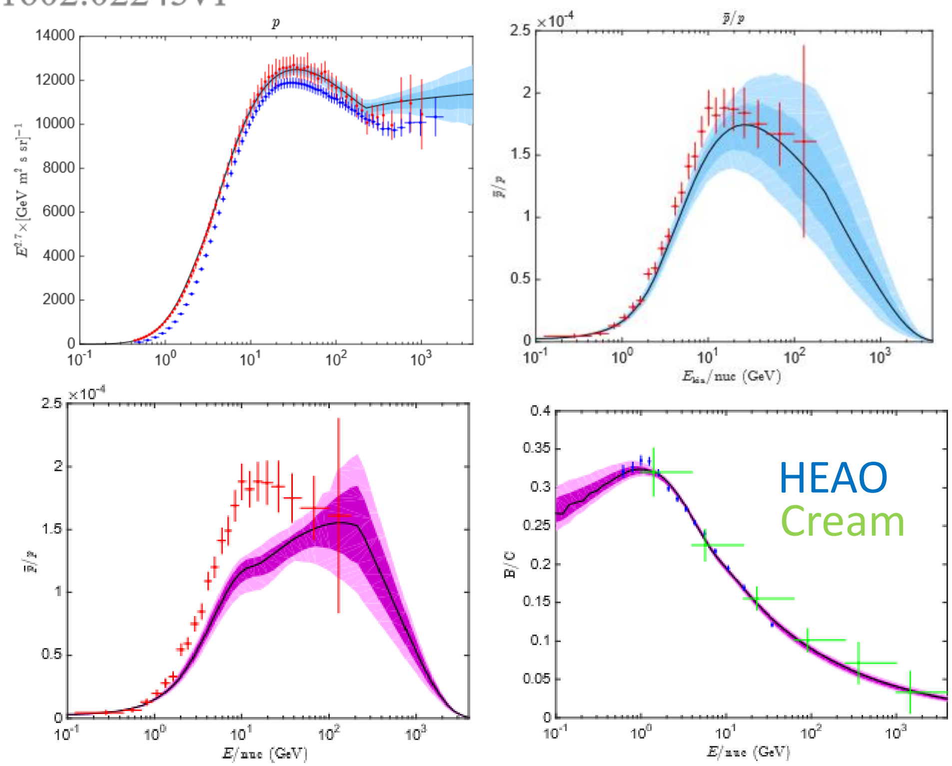
Conclusions

BAYESIAN ANALYSIS OF COSMIC-RAY PROPAGATION: EVIDENCE AGAINST HOMOGENEOUS DIFFUSION

G. Jóhannesson[1], R. Ruiz de Austri[2], A.C. Vincent[3], I. V. Moskalenko[4,5], E. Orlando[4], T. A. Porter[4], A. W. Strong[6], R. Trotta[7], F. Feroz, P. Graff[9], and M.P. Hobson[10]

arXiv:1602.02243v1





Non uniform diffusion is clearly the case, even more after AMS-02 data.
Problems with anti protons: there are too many (maybe a problem with x-section)
Positrons /electrons additional source to be found: getting closer to the cutoff.
High precission data beyond models precision now.

Thank you