Measurements of Nuclear Inelastic Cross Sections on Carbon Target with AMS

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XSCRC2019, CERN, Nov 14

AMS Nuclear Inelastic Interaction Simulation Software

- AMS Simulation Software:
  - ❑ Developed by the AMS collaboration based on the GEANT4-10 package
  - ❑ This program simulates electromagnetic and hadronic interactions of particles in the material of AMS and generates detector responses.
  - ❑ GEANT4-10 integrated multi-threading processing with parallelization at event level. Such technique allows to considerably reduce memory footprint per-thread, which makes possible for AMS for very high energy and high charged cosmic-ray nuclei simulation.

- Nuclear Inelastic Interaction Simulation Modelized into Two Stages
  - ❑ A fast collision that knock-out one or more nucleons with soft and hard interactions

    => Some existing models in GEANT4 below ~10 GeV/n:

    Binary Cascade, Quantum Molecular Dynamic , and Intra Nuclear Cascade

    => No elaborate model within GEANT4 for the simulation of high energy NN collisions

    External FORTRAN packages of DPMJET-II.5/DPMJET-III are therefore adapted and successfully interfaced to the GEANT4 by the AMS collaboration
  - ❑ De-excitation of the remnant pre-fragments

    => treated by GEANT4 de-excitation handler (Pre-Compond Model):

1: DPMJET+Geant4 for High Energy Nuclear Inelastic Interaction Simulation

ADPMjet_Model →

DPMJET Initialization

Pre-computed cross-section and impact parameters read from data files (ams36dpo.glb/ams07dpo.glb)
(complete matrix of projectile-target combination up to A=208 in the entire energy range from 4.4 GeV/n < E < 3×10^8 GeV/n)

↓

DPMJET Interaction

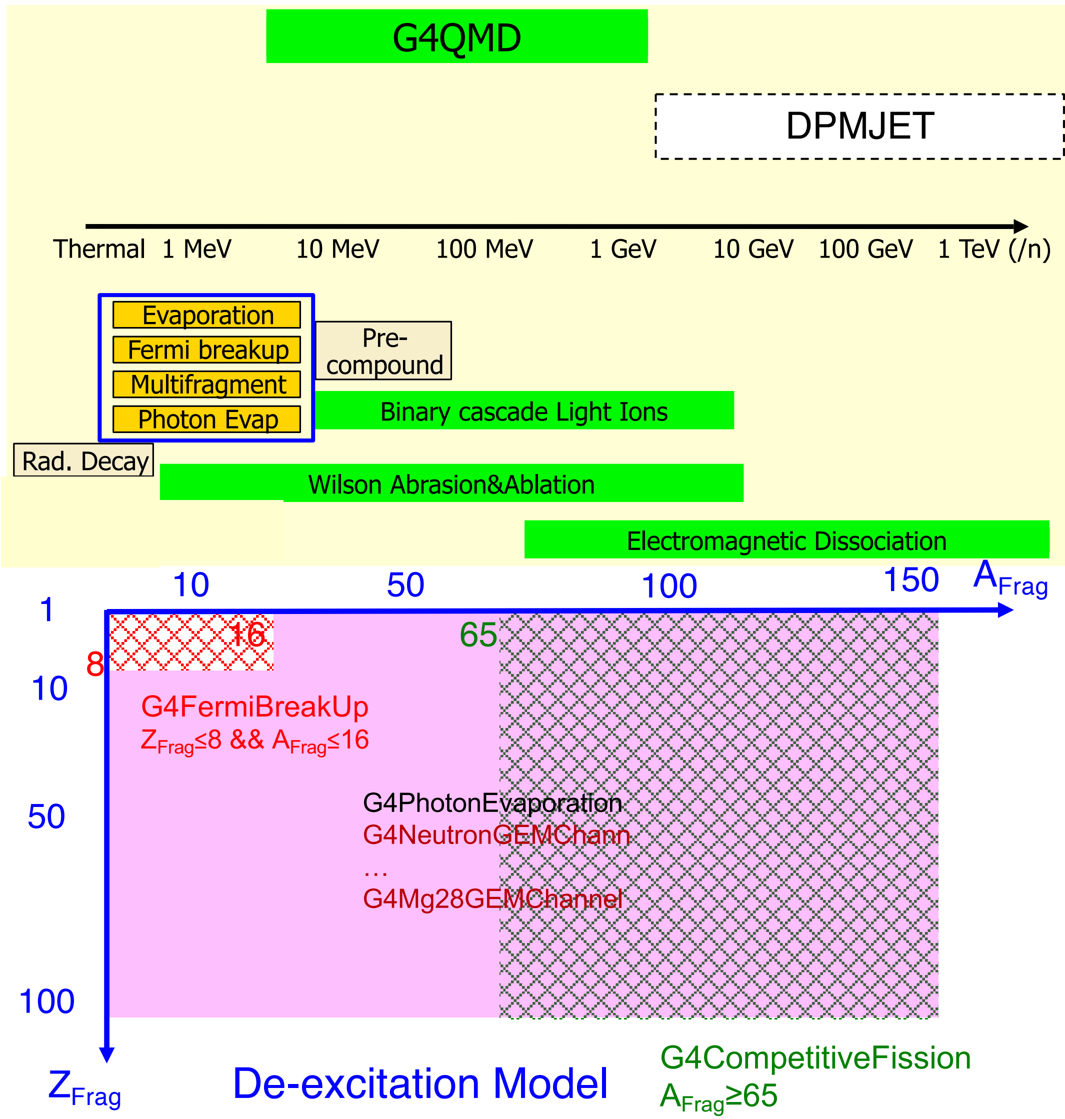
Call for nucleus-nucleus interaction, hadron-hadron and hadron-nucleus interactions (hadronization process):
A+A ➔p, n, π+, π-, ... , prefragments (hadrons, spectators)
low-energy intranuclear cascade is then treated

↓

Geant4 De-excitation

Fermi break-up, Evaporation, γ-deexcitation

2: De-excitation Model Used in AMS Simulation



The remnant pre-fragments produced from the first stage are then treated by the GEANT4 de-excitation handler:

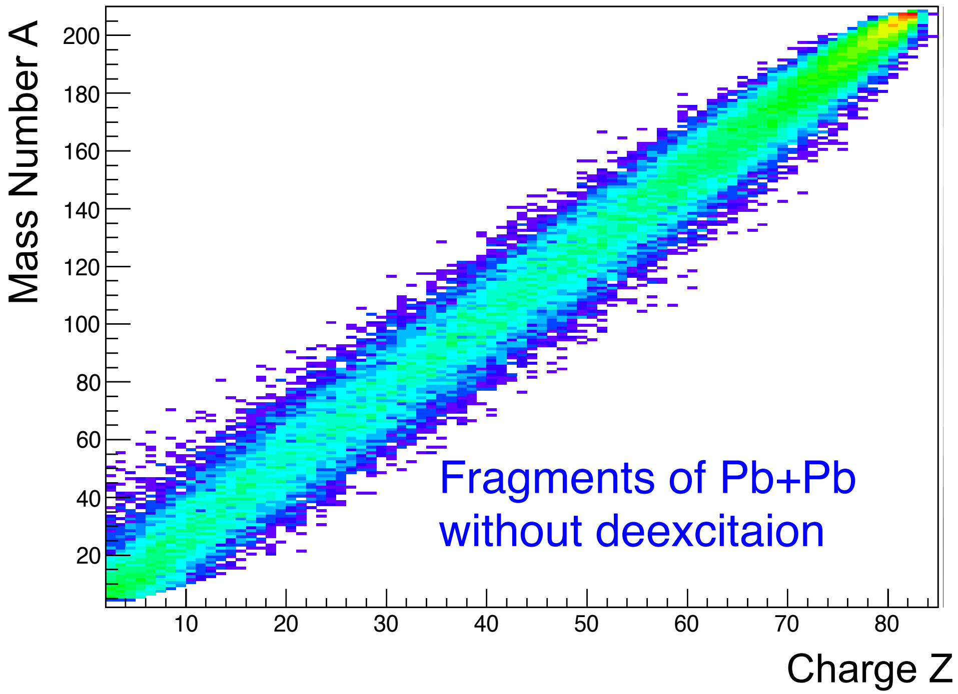
1: Lighter pre-fragments (A<17 && Z<9) are de-excited with Fermi break-up model

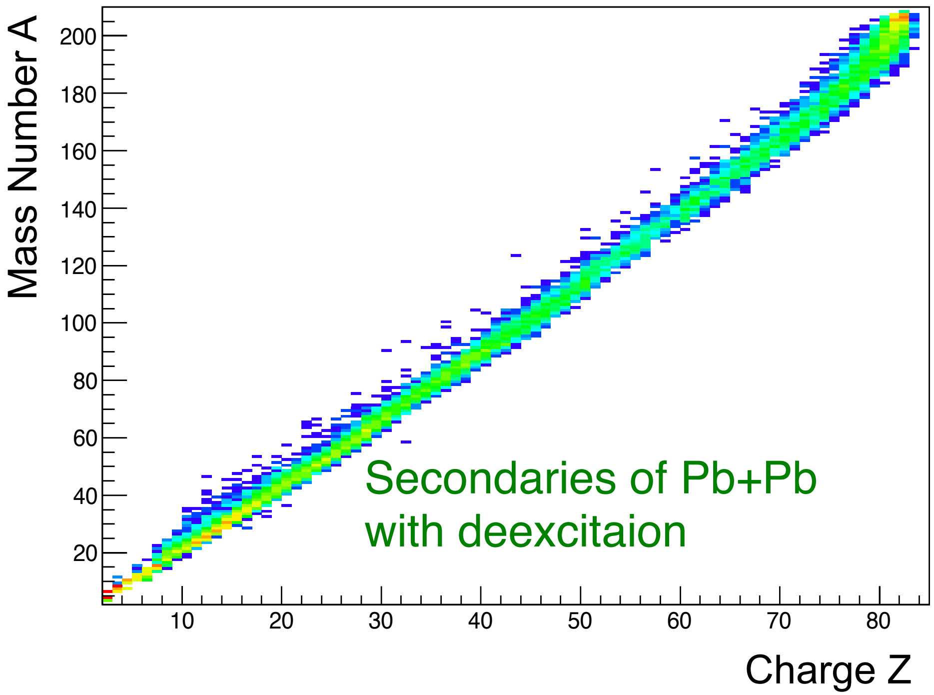
2: Heavier pre-fragments with Generalized Evaporation Model (GEM):
67 evaporation channels from photon to Mg28, and better agree with experimental data than Weisskopf-Ewing evaporation model in GEANT4

3: Very heavy ones A ≥ 65 chosen between GEM and Fission model by sampling

Fragments Without and With De-excitation

Charge-Z versus Mass-A band of particles generated from 100GeV/n Pb(Projectile)+Pb(Target) interaction

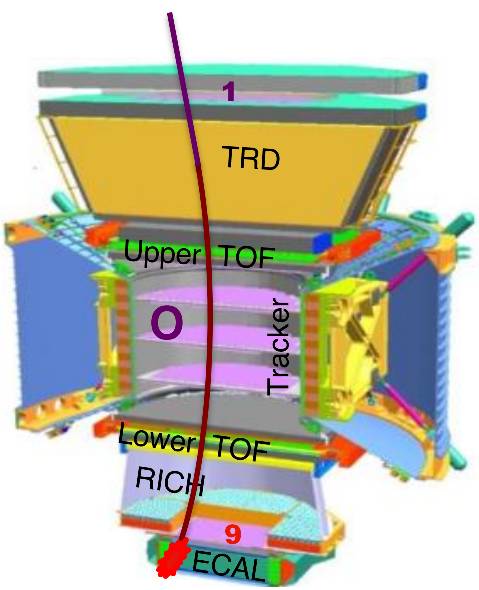


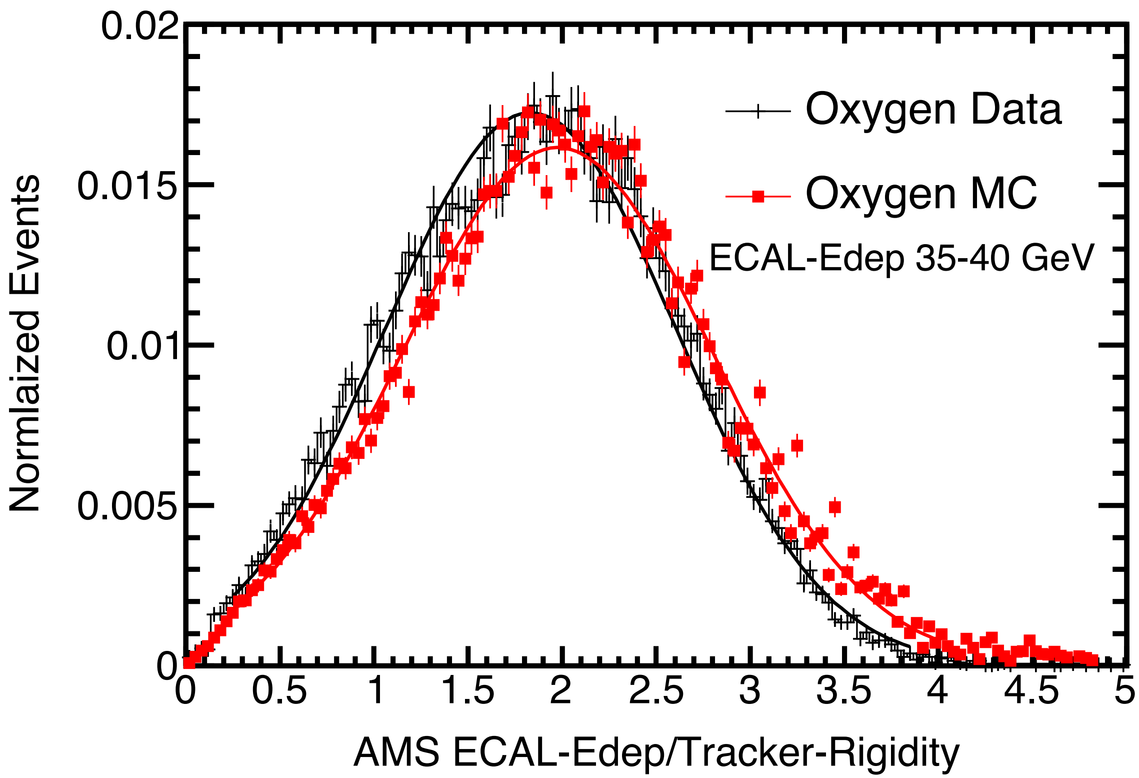


AMS Nuclear Inelastic Interaction Simulation

- To incorporate into the framework of the GEANT4 with multi-threading, a complete parallelization been performed to the AMS software using OPENMP platform. This includes the revision work on third party DPMJET-II.5/DPMJET-III written in FORTRAN.

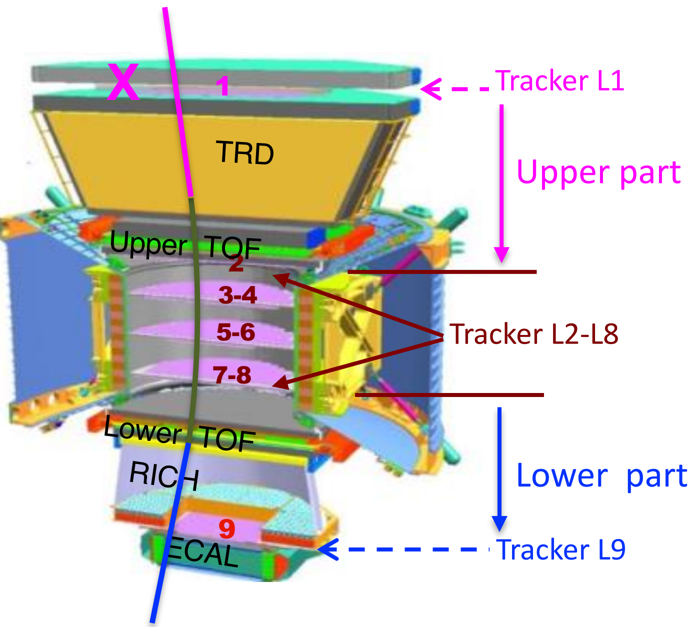
- AMS software is capable to accurate simulate all nucleus and hadron ($1 \leq A_p \leq 208$) inelastic-interaction, in all AMS materials including ECAL ($1 \leq A_t \leq 208$), and for all incoming nuclei with energy from MeV up to highest possible cosmic ray energies.





AMS Materials

The AMS detector components are mostly made of C and Al. The element compositions of the materials between Tracker L1 and L2 (Upper part: mostly the TRD and Upper TOF), and between Tracker L8 and L9 (Lower part: mostly the Lower TOF and RICH) are shown:



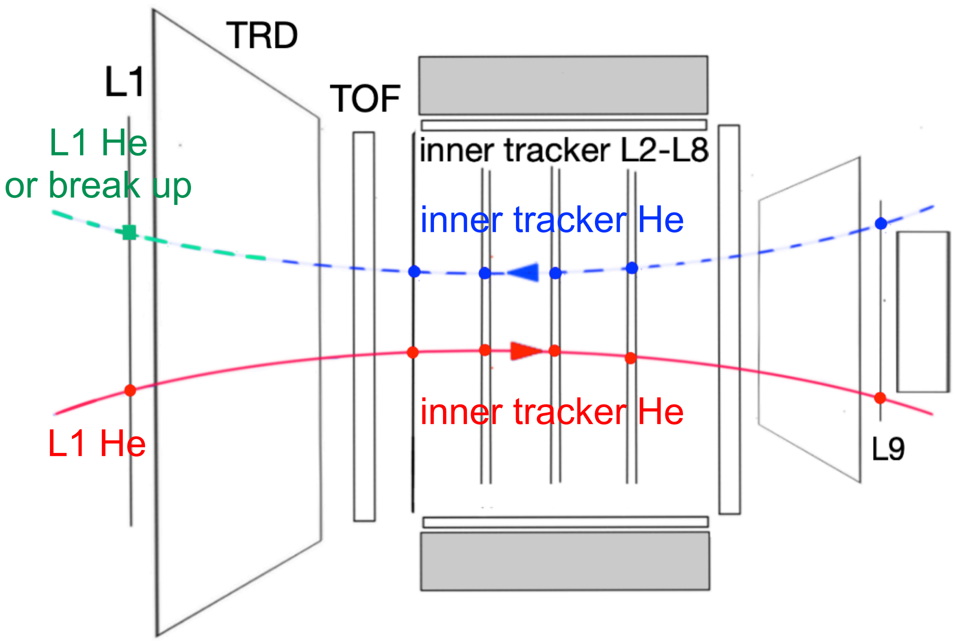
Materials	Element composition by weight (%)						
	H	C	O	F	Na	Al	Others
L1-L2	2	75	1	0	0	21	1
L8-L9	3	60	3	5	6	21	2

The averaged thickness (considering particle arriving in isotropic direction) of the Upper part is ~0.12 hadronic interaction length (λ_I) and of the Lower part is ~0.08 λ_I.

Considering Al composition, 10% relative uncertainty in inelastic cross section on Al target will propagate to our measured inelastic cross section on carbon target ~1%.

1: Measurements of Survival Probabilities with AMS Flying Horizontally

When AMS flies horizontally, cosmic rays can travel from two directions through AMS: from L9 to L1 (right-to-left) and from L1 to L9 (left-to-right).



1: Using right-to-left He identified by the inner tracker, the efficiency of He measured by Tracker L1 was given by:

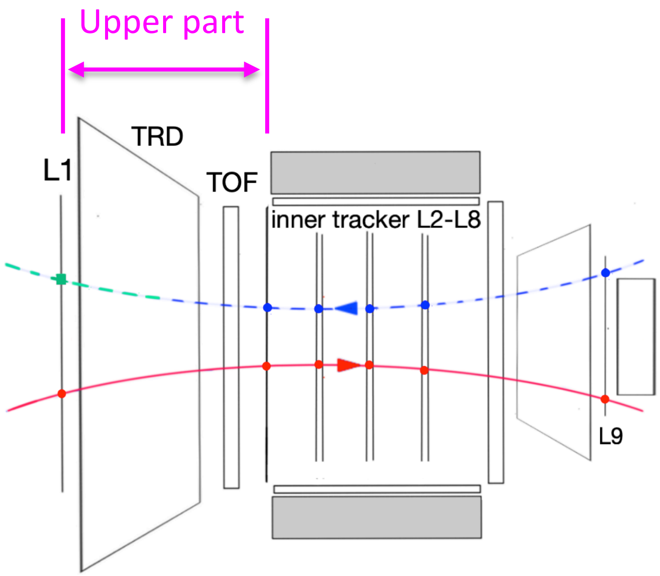
$$\varepsilon_{Z=2}^{L1} = \frac{N_{Z=2}^{L1}}{N_{Z=2}^{inner}} = \varepsilon_{Z=2}^{L12sur} \cdot \varepsilon_{Z=2}^{L1det}$$

2: For left-to-right He identified by the inner tracker, back tracing of these particles before the inner tracker should always be He. The L1 detector efficiency was simply obtained as:

$$\varepsilon_{Z=2}^{L1det} = \frac{N'^{L1}_{Z=2}}{N'^{inner}_{Z=2}}$$

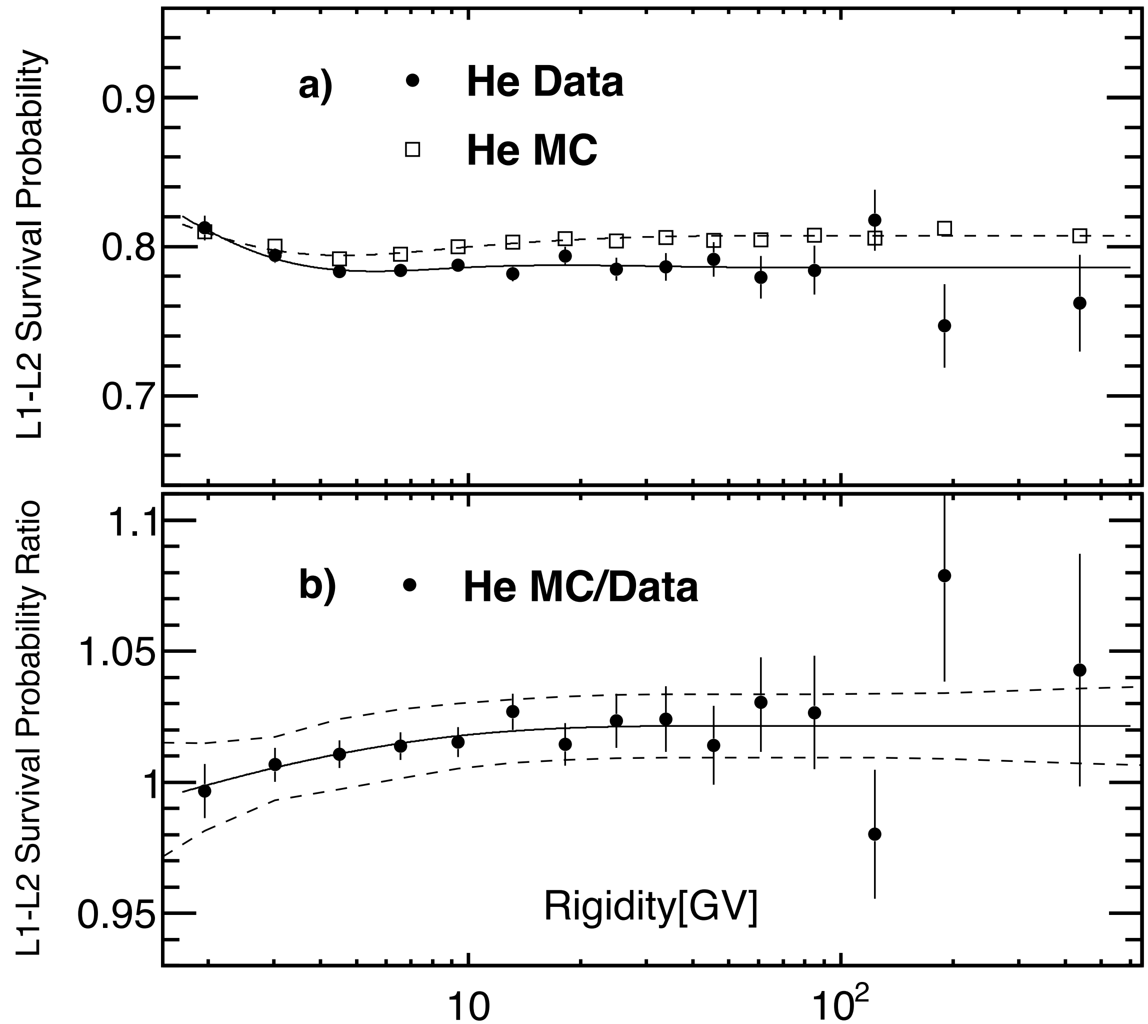
From the efficiencies of two direction beams, He survival probability between L2 and L1 can be derived ($\varepsilon_{Z=2}^{L12sur} = \varepsilon_{Z=2}^{L1} / \varepsilon_{Z=2}^{L1det}$).

He Survival Probabilities Measured with Horizontal AMS



$$\varepsilon^{sur} = \frac{N^{sur}_{out}}{N_{in}} = \exp(-\sum_i n_i \sigma_i)$$

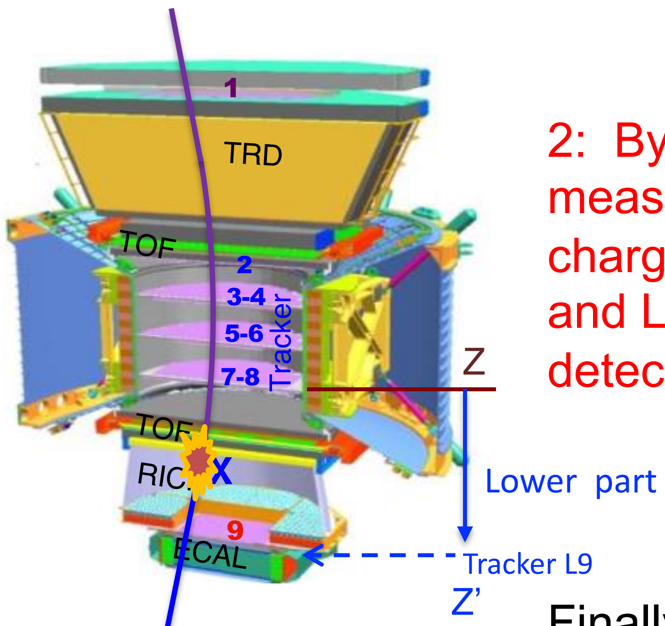
$$\sigma_C^{Data} = \frac{log(\varepsilon^{sur}_{Data})}{log(\varepsilon^{sur}_{MC})} \sigma_C^{MC}$$



To simulate He interactions with the AMS materials, the GEANT4 Glauber-Gribov model was adopted for the inelastic cross sections simulation; the INCL++ package was used to model inelastic interactions below 5 GeV/n while the DPMJET was used at higher energies; and the GEANT4 de-excitation handler was applied to de-excitate the resulting pre-fragments to the group state.

2: Measurements of L8-L9 Survival Probabilities with Normal AMS

AMS only flied a small portion of its time in horizontal position (0.13% of the total exposure time). When AMS was in normal operation condition, almost all cosmic rays entered AMS from top to bottom (from L1 to L9).



1: For the charge Z nuclei measured by the inner tracker, the efficiency of Tracker L9 measured charge to be Z was:

$$\varepsilon_Z^{L9} = \frac{N_Z^{L9}}{N_Z^{inner}} = \varepsilon_Z^{L89sur} \cdot \varepsilon_Z^{L9det}$$

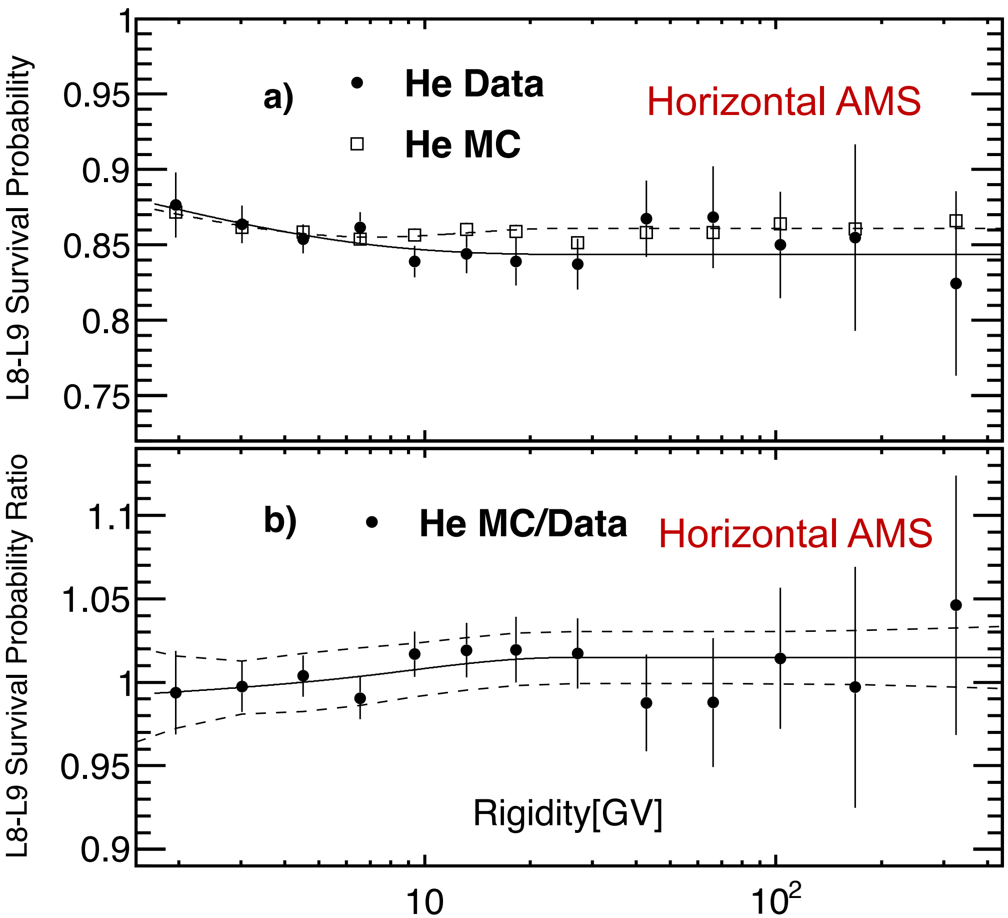
2: By selecting a sample with first few layers of ECAL measured charge (dE/dx) to be compatible with inner tracker charge Z, the probability of inelastic interaction between L8 and L9 was highly reduced as $\varepsilon_Z'^{L89sur} \sim 1 \gg \varepsilon_Z^{L89sur}$. The L9 detector efficiency can be estimated:

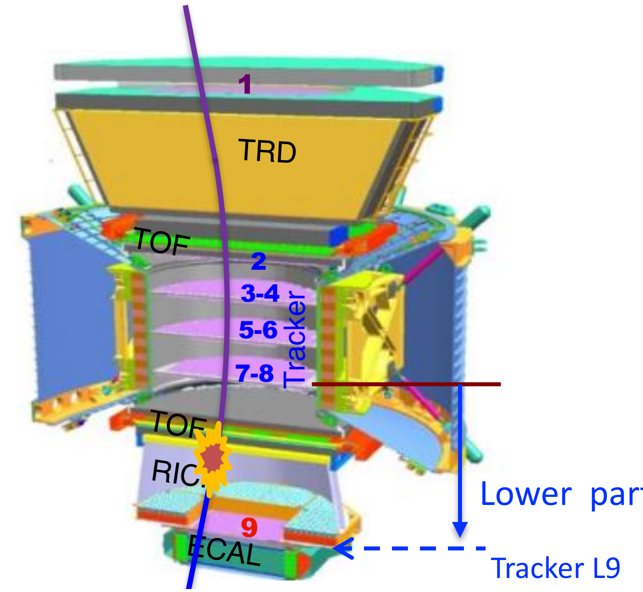
$$\varepsilon_Z^{L9det} = \frac{N_Z'^{L9}}{N_Z'^{inner} \varepsilon_Z'^{L89sur}}$$

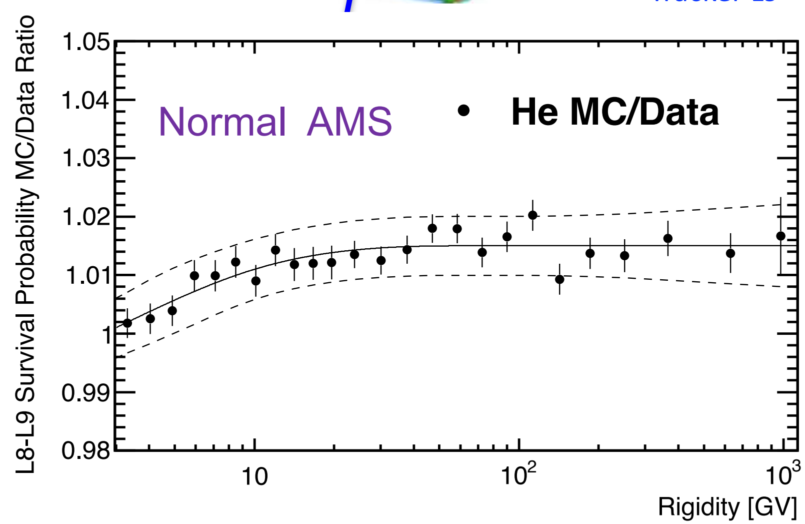
Finally, the measured L8-L9 survival probability was derived by:

$$\varepsilon_Z^{L89sur} = \varepsilon_Z^{L9} / \varepsilon_Z^{L9det}$$

He L8-L9 Survival Probabilities Horizontal VS Normal AMS

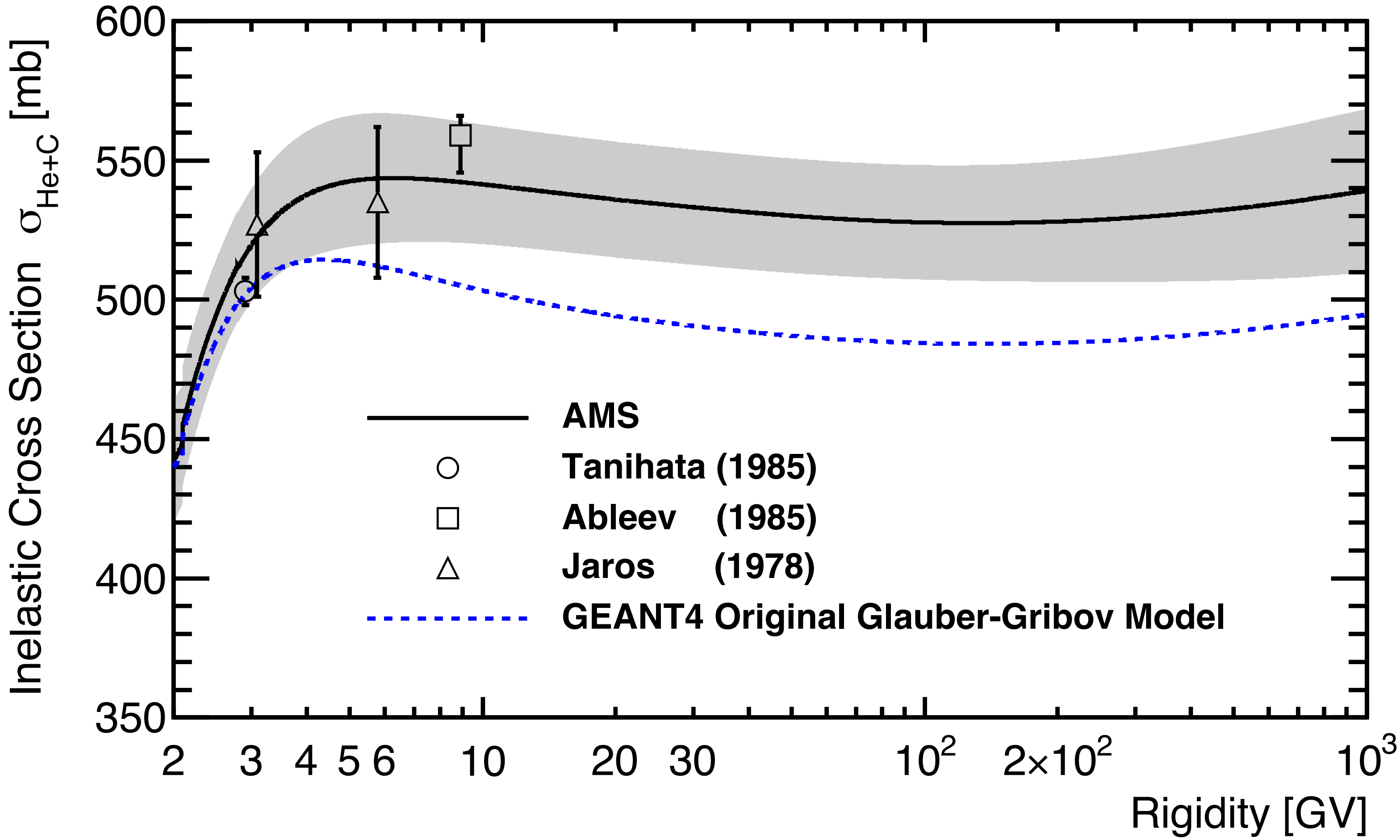






The result from Normal AMS is consistent with that from Horizontal AMS

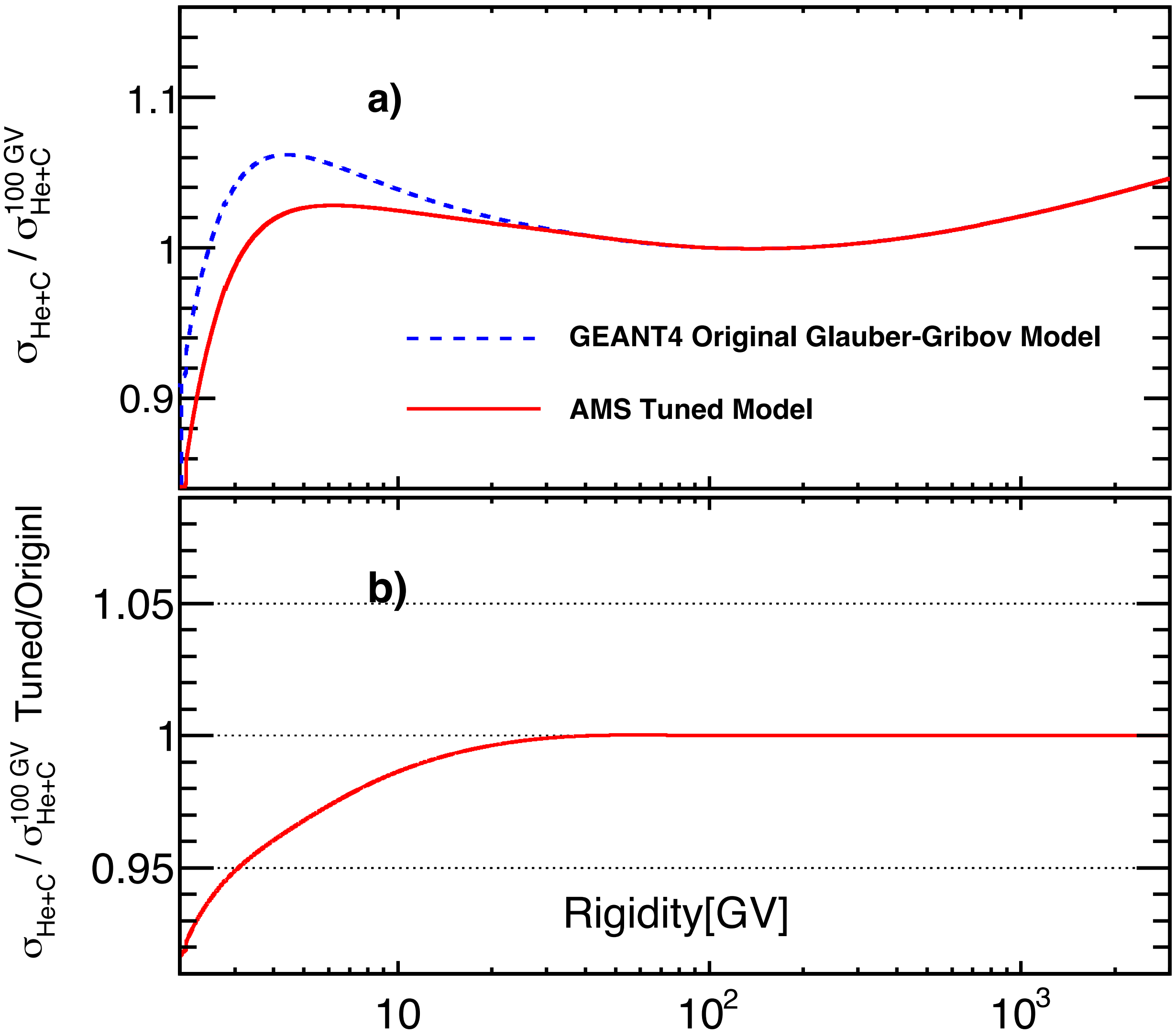
AMS measured He+C Inelastic Cross Section



The He inelastic cross sections on carbon target as functions of rigidity measured by AMS (solid curve) in the rigidity range from 2 GV to 1 TV, together with earlier measurements and GEANT4 Glauber-Gribov model (dashed curve). The grey band indicates the systematic error (68% CL) of AMS result.

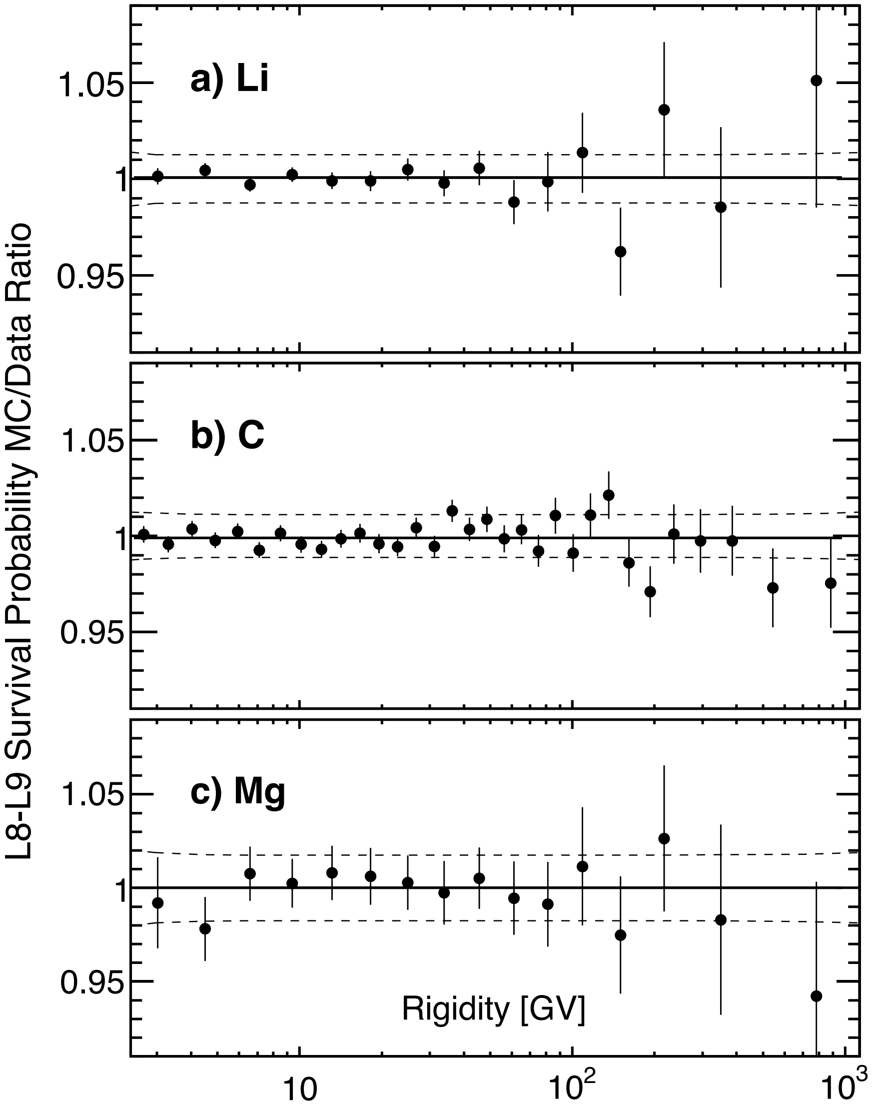
He+C Inelastic Cross Section Rigidity Dependence

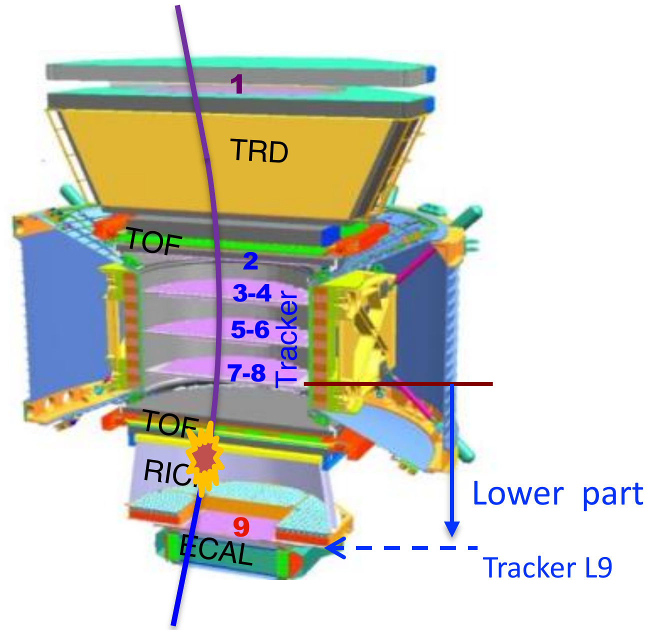
There are significant biases in the GEANT4 Glauber-Gribov model, not only the overall normalization but also the different rigidity function behavior below ~30 GV. Whereas above ~30 GV, the rigidity dependence of the MC to Data ratio becomes no longer visible.



Other Nuclei+C Inelastic Cross Section Rigidity Dependence

A developed model tuned from the AMS He data was scaled respectively for the description of each nuclear inelastic cross section in MC. The resulting survival probabilities in the simulation are in good agreement with the data.



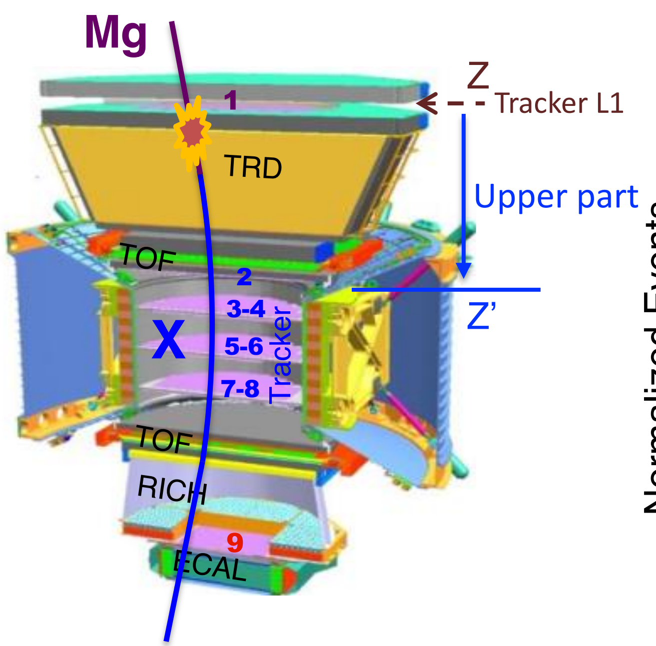


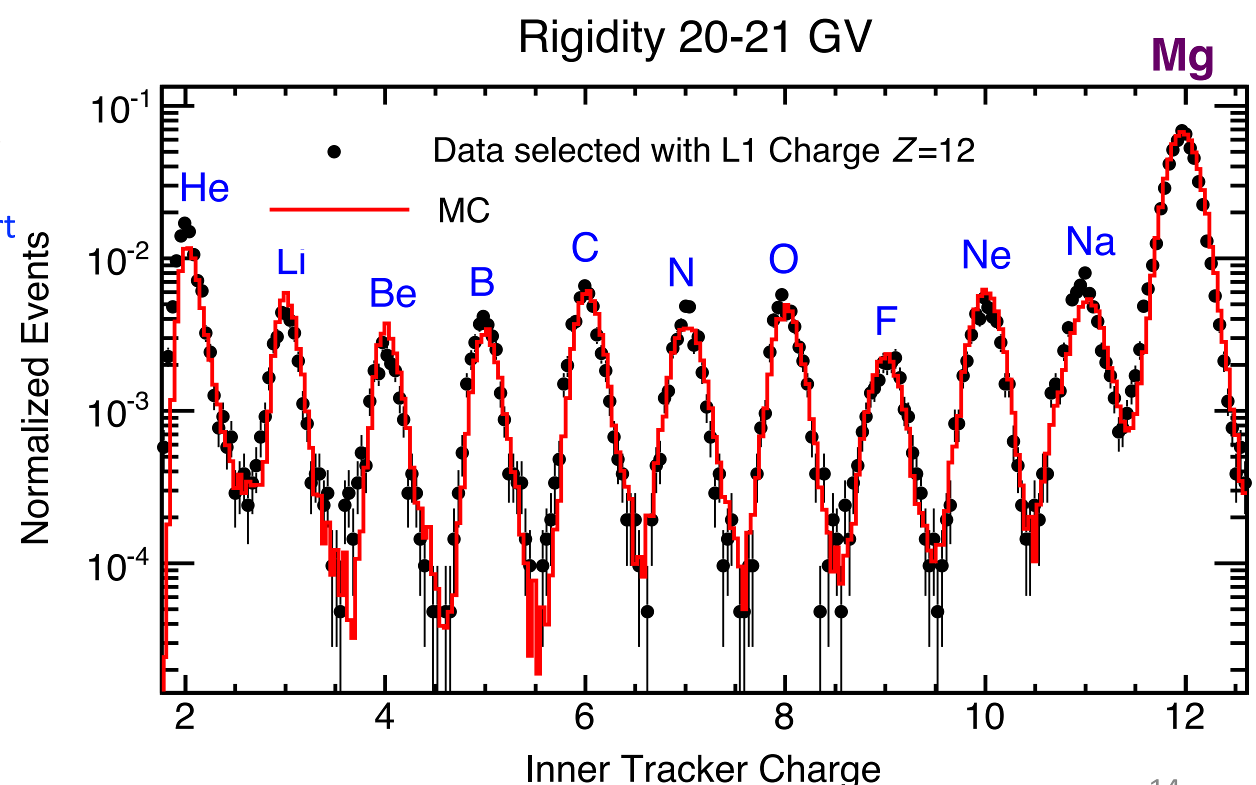
This further confirms that the bias in the inelastic cross section rigidity dependence of the GEANT4 Glauber-Gribov model is universal for all nuclei.

3: Measurements of L1-L2 Survival Probabilities with Normal AMS

Using particles when AMS in normal operation condition, the survival probabilities between L1 and L2 were also measured.

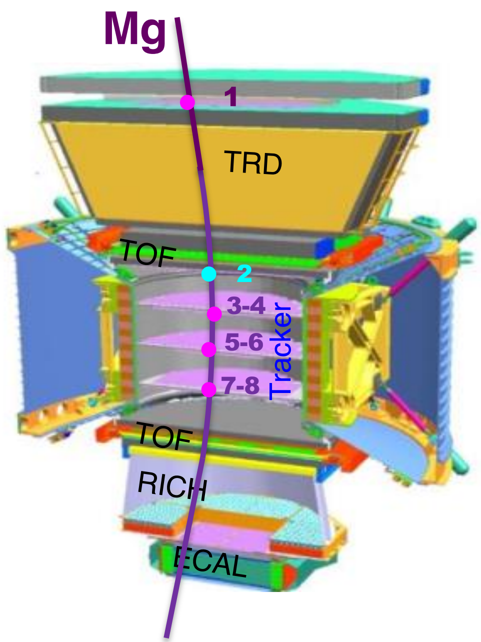
- Select primary nuclei by L1 charge (Z)
- Obtain survival probability by comparing charge measured with inner tracker (Z'): $\varepsilon_{Z}^{L12sur} = N_{Z'=Z}^{inner} / \sum_{Z''} N_{Z''}^{inner}$

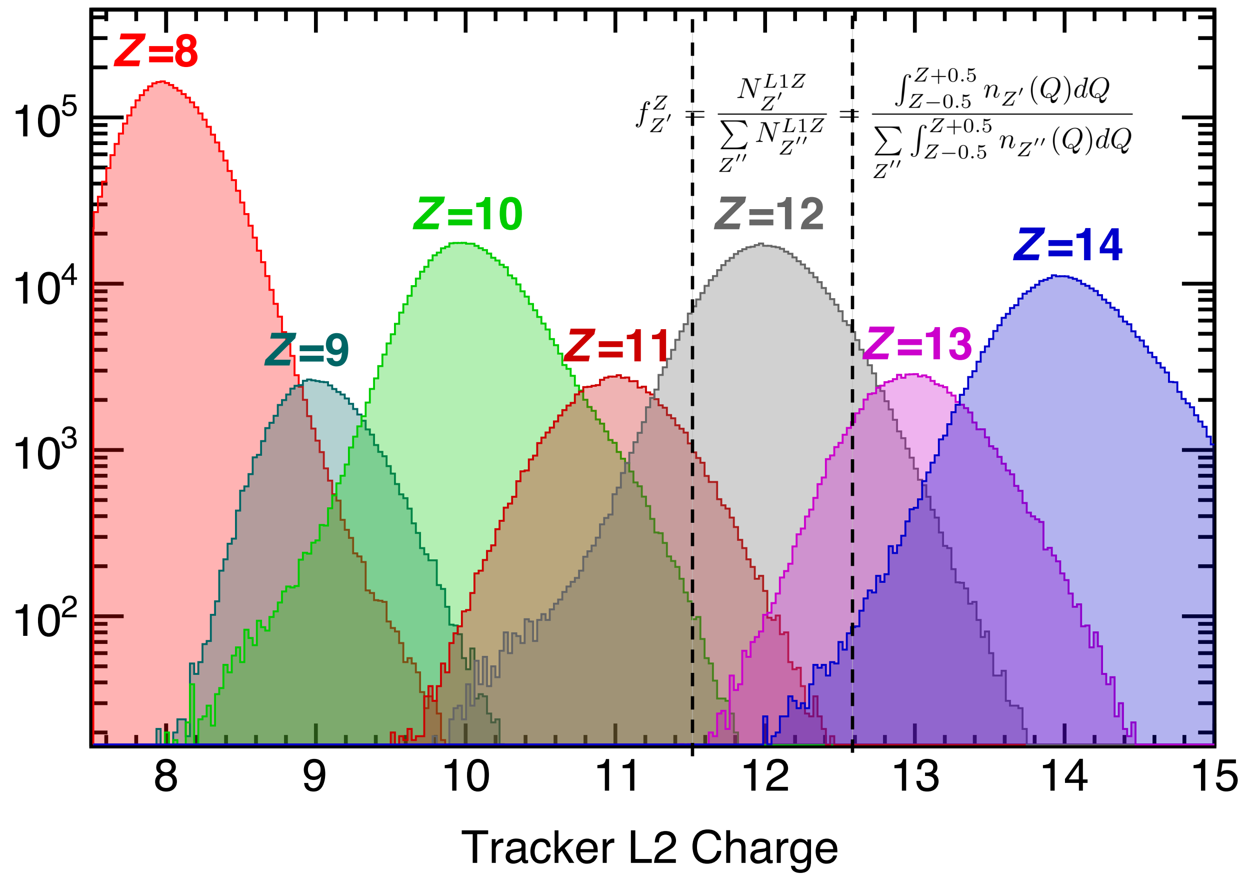




Background Evaluation of the L1 Selected Sample

However, Tracker L1 has finite charge resolution. The L1 selected charge Z sample would have contamination from other elements. The amount of the background depends both on the L1 charge resolution and the relative abundance of the different nuclear species in cosmic rays. Using the clean event distribution from L2 charge, the proportion of Z′ nuclei after the L1 charge selection (Z − 0.5, Z + 0.5) can be evaluated:

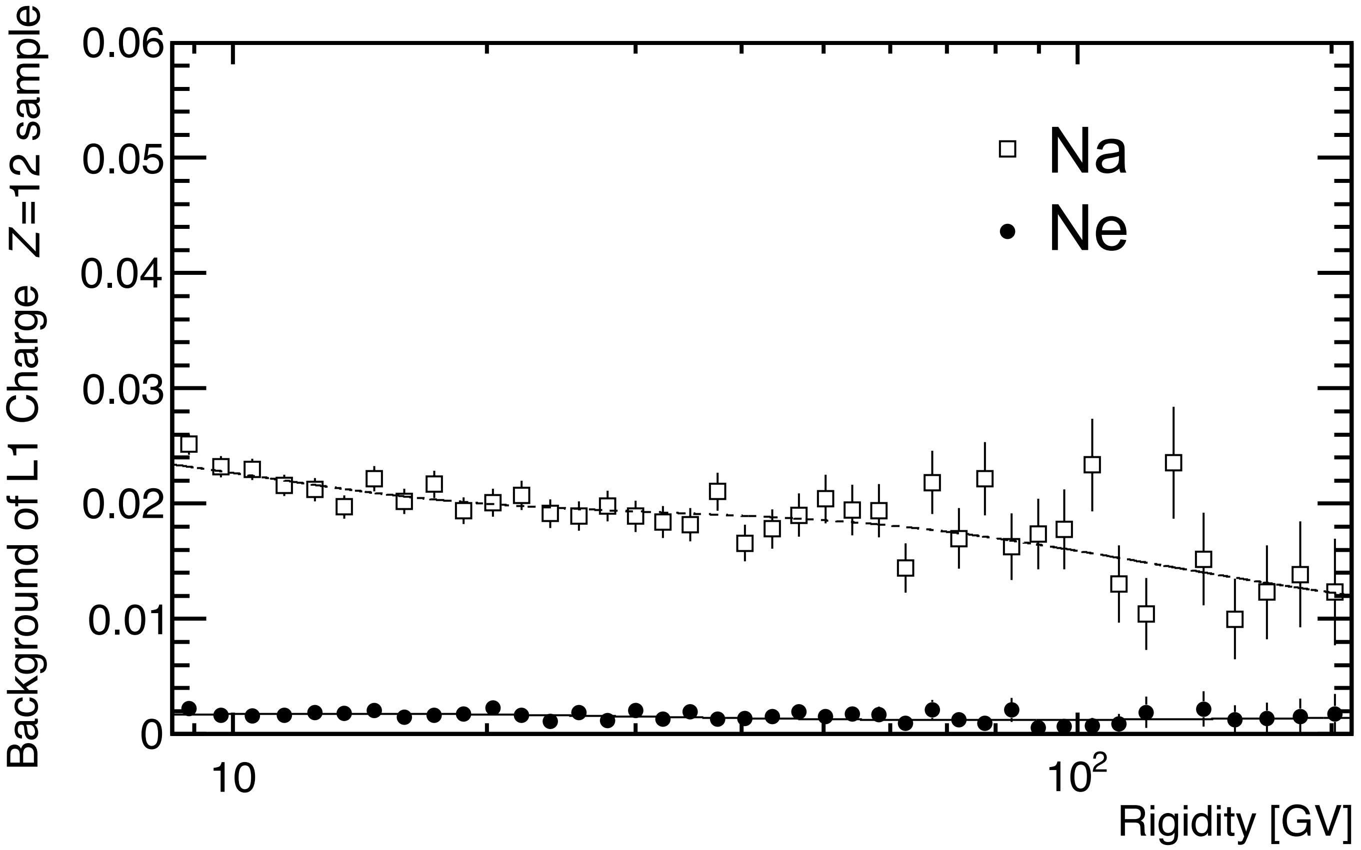




Event distribution of tracker L2 charge for 8≤Z≤14 nuclei samples selected with the charge measured on tracker L1, the Upper TOF, and tracker L3-L8.

Background of the L1 Selected Sample

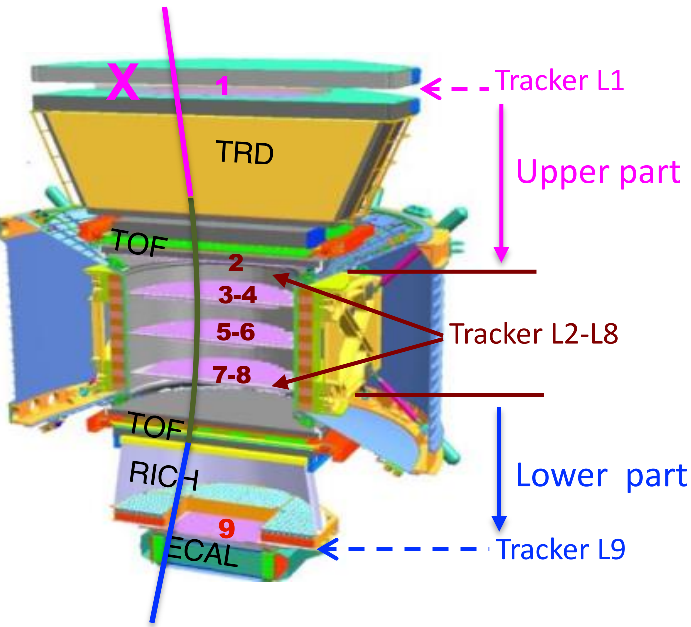
As an example, the background of Mg is 1-2.5% depending on rigidity.

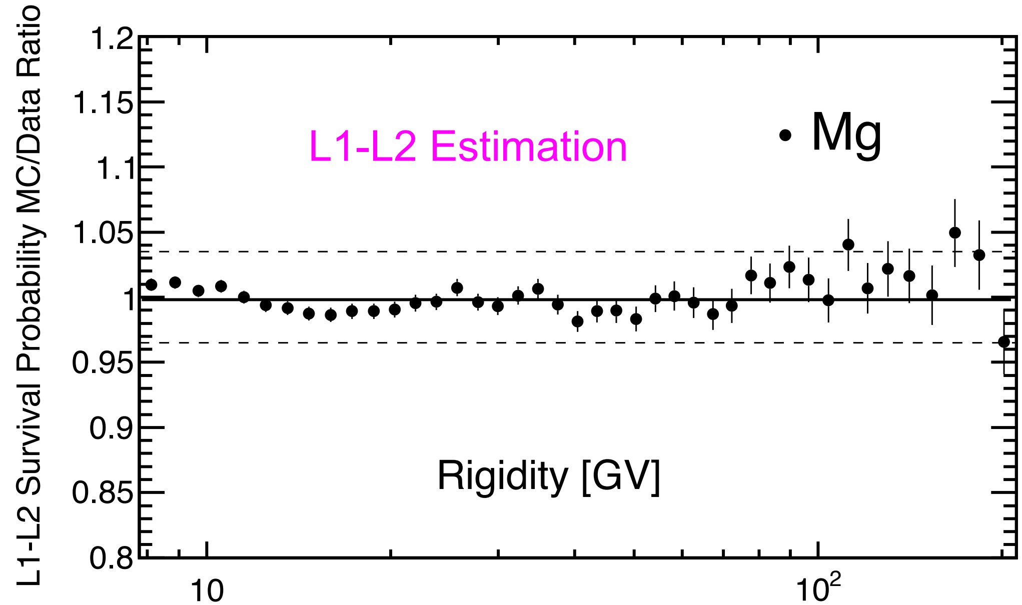


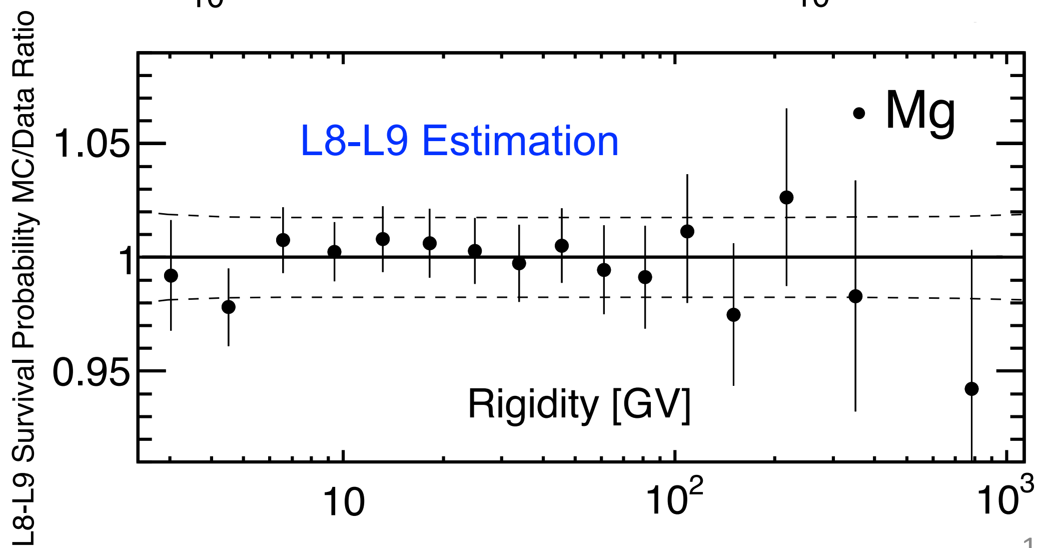
The estimated proportions of background from Na and Ne as functions of rigidity for a L1 selected Mg sample. The background from Z<10 is negligible.

Survival Probabilities with Normal AMS

Using the same produced MC, two different measurements of the survival probabilties during normal AMS - one from L1 to L2 and the other from L8 to L9 - give consistent results.

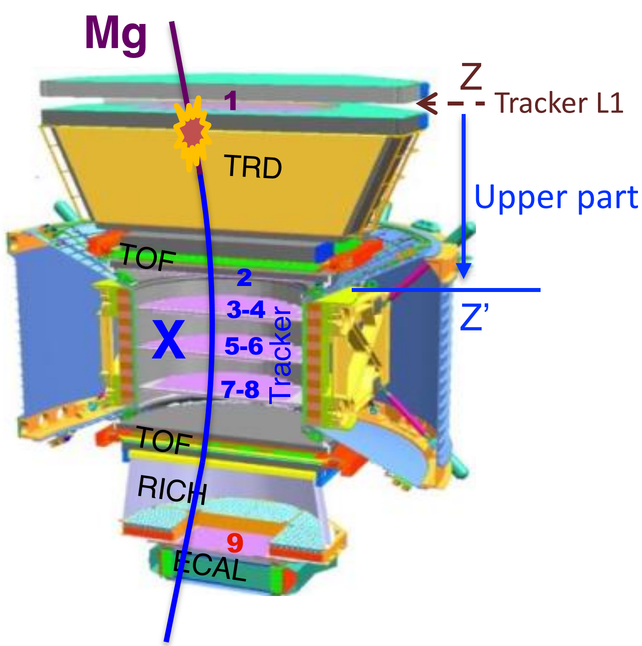


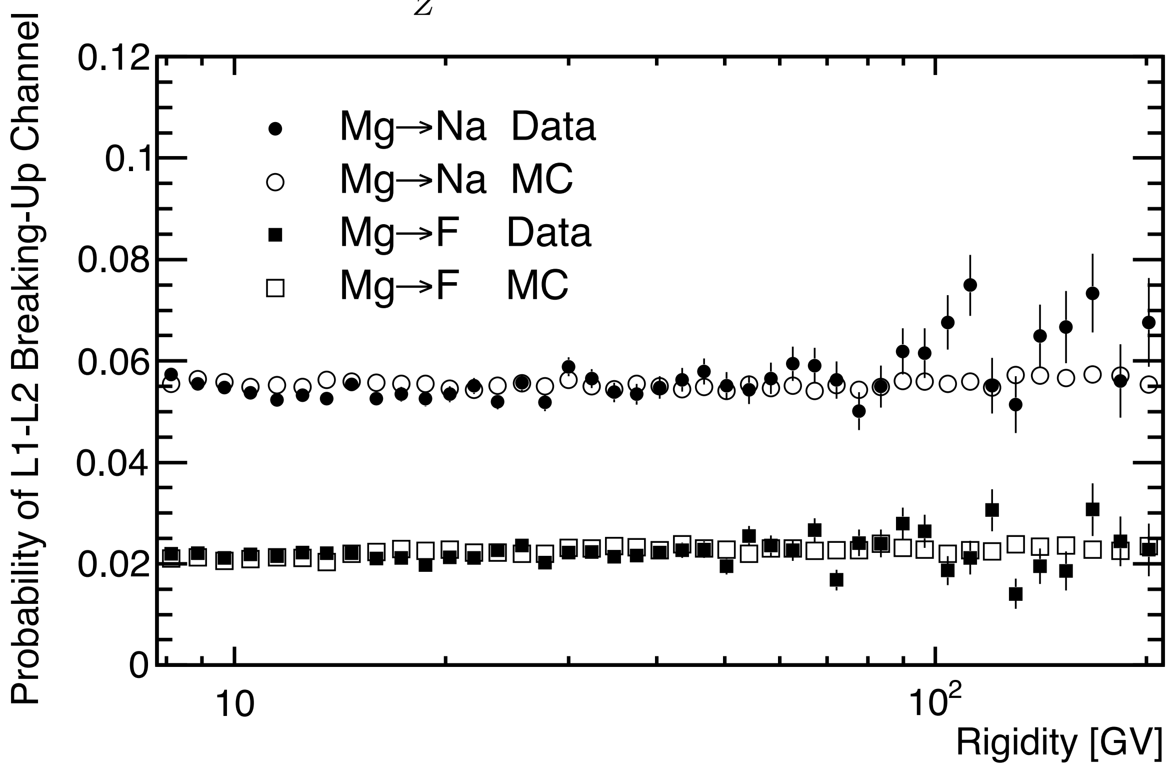




Probabilities of Nuclear Breaking-Up Channel between L1 and L2

There is also a good agreement between Data and MC for each individual nuclear breaking-up channel Z → Z' ($P^{Z}_{Z'} = \frac{N^{inner}_{Z'}}{\sum_{Z''} N^{inner}_{Z''}}$)





The nuclear breaking-up probabilities between tracker L1 and L2 of Mg→Na and Mg→F channels as functions of rigidity for Data and MC.

Nuclei+C Relative Partial Inelastic Cross Sections by AMS

- The total inelastic cross section has charge changing channels and isotope channels in which only neutrons are knocked out from projectile nucleus: $\sigma_C^{ZI} = \sigma_C^Z + \sigma_C^I = \sum_{Z''<Z} \sigma_C^{Z\to Z''} + \sum_{A''<A} \sigma_C^{ZA\to ZA''}$
- The relative partial inelastic cross section for charge-changing channel is $\sigma_C^{Z\to Z'}/\sigma_C^{ZI}$, and for isotope channel is σ_C^I/σ_C^{ZI} . The physics processes of knocking out neutrons and protons are similar, isotope cross section can be obtained from MC when it well reproduces the charge-changing channels nearby Z'≃Z − 1. This assumption has been verified by using the simulations with different NN collision and de-excitation models.

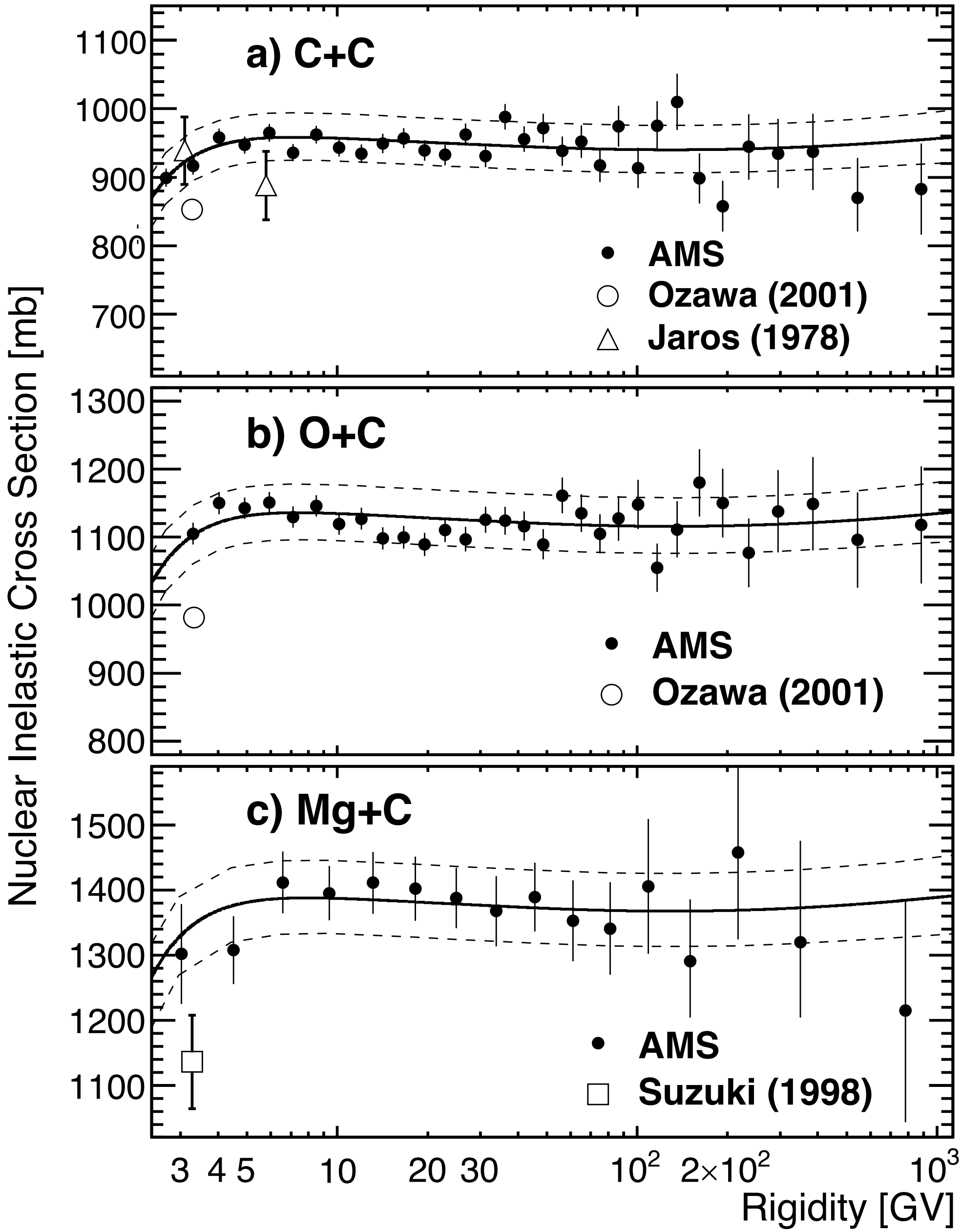
Relative partial inelastic cross sections on carbon target (%)

Fragment	Projectile				
	C	O	Ne	Mg	Si
He	45.4±1.9	38.2±1.7	30.8±3.0	25.9±2.9	20.2±3.1
Li	7.2±0.5	6.5±0.5	6.8±0.8	6.7±0.8	5.8±0.5
Be	5.4±0.5	4.2±0.4	4.3±0.3	4.0±0.6	3.7±0.5
B	13.3±0.9	6.1±0.4	5.4±0.8	5.1±0.3	4.3±0.6
C	10.3±0.9	14.6±1.0	11.0±0.9	10.5±0.6	9.5±0.5
N	—	13.9±0.9	8.8±0.8	7.2±0.8	6.2±0.5
O	—	7.9±0.5	12.5±1.4	8.1±0.6	6.8±0.5
F	—	—	9.3±0.7	3.7±0.5	3.1±0.3
Ne	—	—	8.3±0.9	8.8±1.0	6.1±0.8
Na	—	—	—	10.8±0.7	5.4±0.6
Mg	—	—	—	9.1±1.0	10.3±1.0
Al	—	—	—	—	10.2±0.7
Si	—	—	—	—	8.1±0.7

The measured nuclear relative partial inelastic cross sections on carbon target for projectile nuclei C, O, Ne, Mg and Si in the rigidity range from 8-200 GV. The produced fragment with the highest kinetic energy of all is used to define the break-up channel. The relative partial inelastic cross sections for isotope channels of $^{12}C \to ^{A<12}C$,..., $^{28}Si \to ^{A<28}Si$ derived from MC are also shown in this Table. There are no significant rigidity dependences in relative partial inelastic cross sections seen in our data.

$$\left(\frac{\sigma_C^{Z\to Z'}}{\sigma_C^Z}\right)^{Data} = \frac{\left(\frac{P_{Z'}^Z}{1-\varepsilon_Z^{L12sur}}\right)^{Data}}{\left(\frac{P_{Z'}^Z}{1-\varepsilon_Z^{L12sur}}\right)^{MC}} \left(\frac{\sigma_C^{Z\to Z'}}{\sigma_C^Z}\right)^{MC}$$

AMS measured Nuclei+C Inelastic Cross Sections

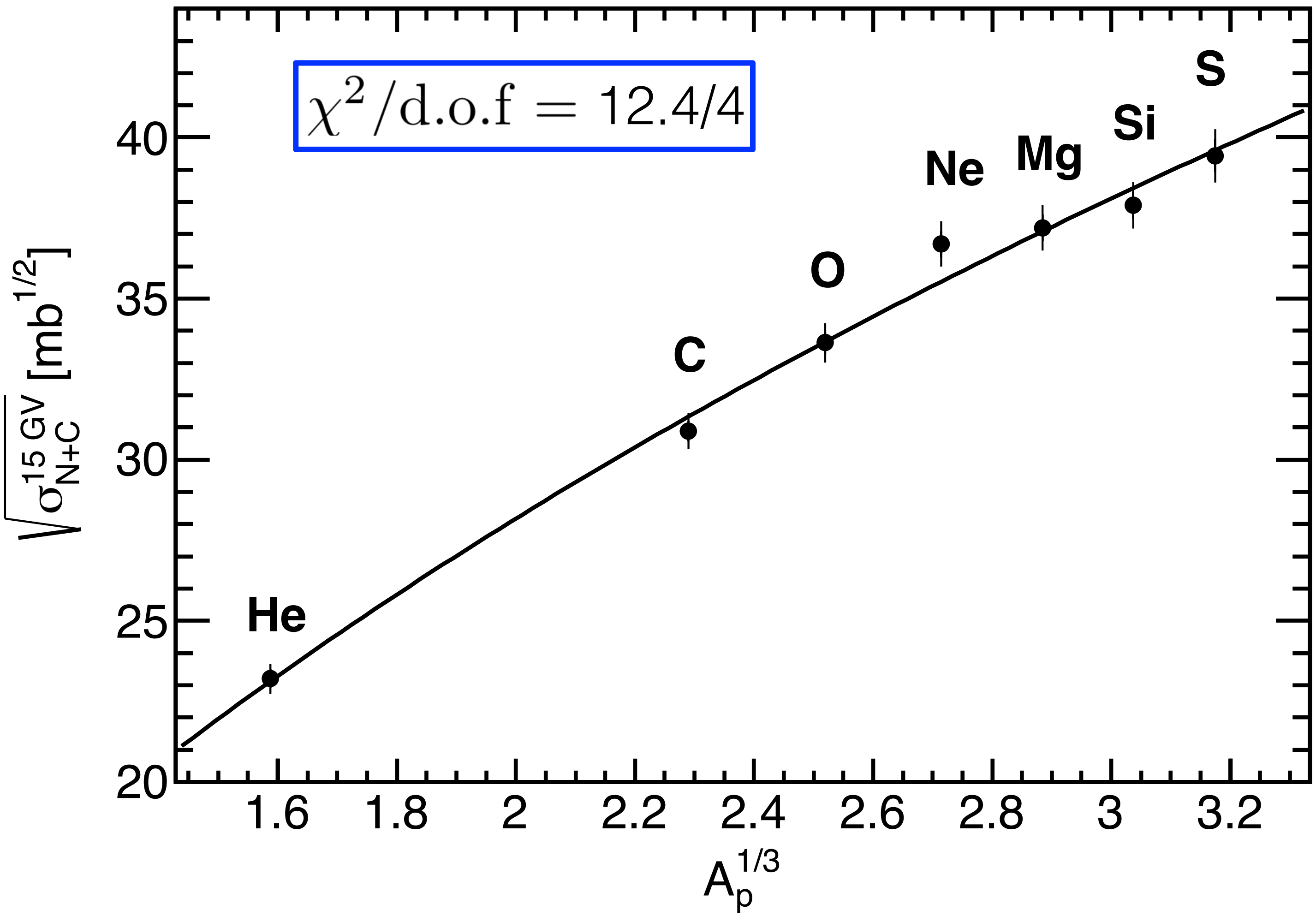


The nuclear inelastic cross sections as functions of rigidity measured by AMS, together with earlier measurements for a) C+C, b) O+C and c) Mg+C. The solid curves show the AMS model best scaled for the description of nuclear inelastic cross sections and the dashed curves indicate the systematic error range (68% CL).

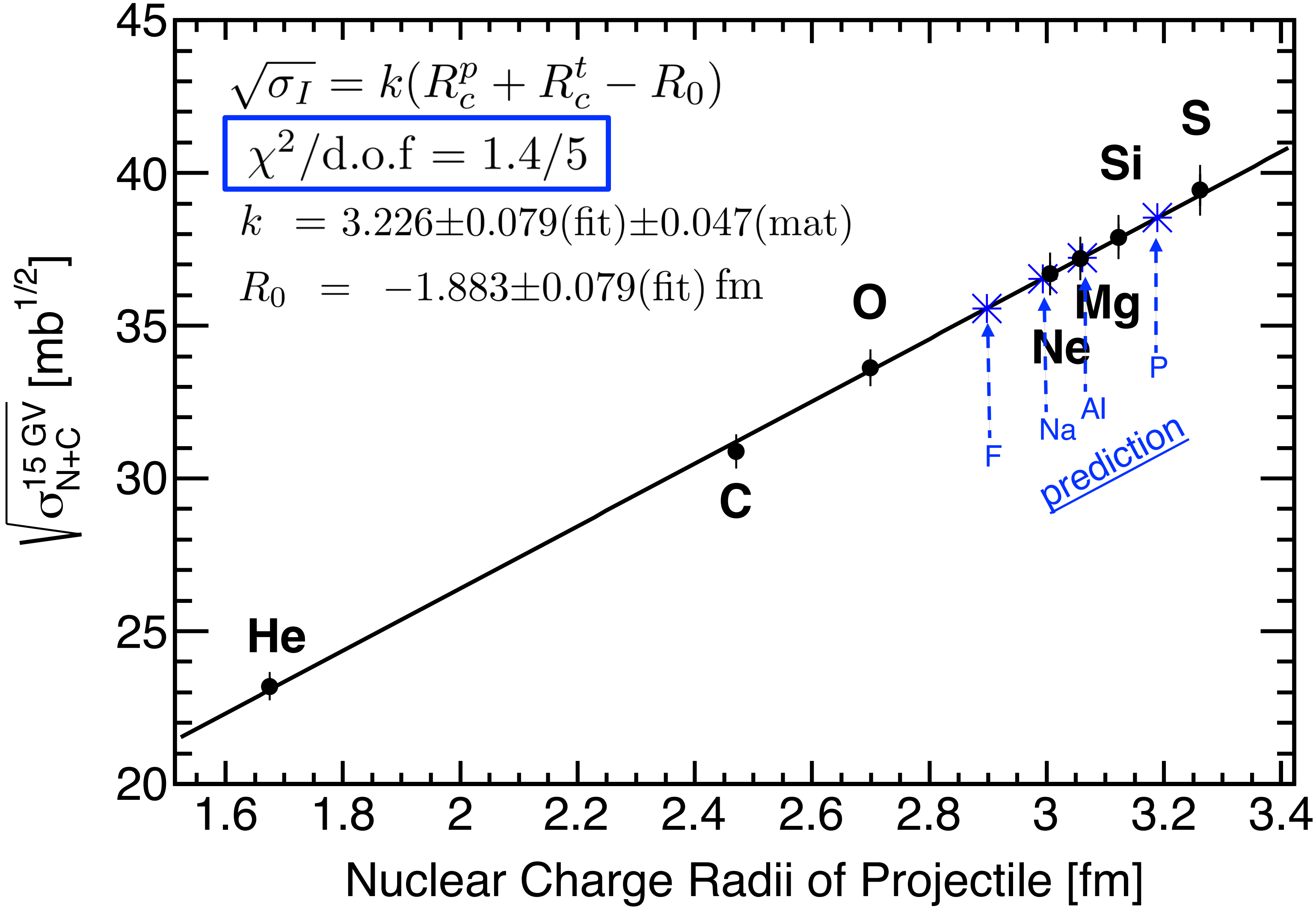
Nuclei+C Inelastic Cross Section by Phenomenological Formula

$$\sqrt{\sigma_I} = \sqrt{\pi} r_0 \cdot (A_p^{1/3} + A_t^{1/3} + a\frac{A_p^{1/3} A_t^{1/3}}{A_p^{1/3} + A_t^{1/3}} - A_0)$$

S. Kox, et al., Trends of total reaction cross sections for heavy ion collisions in the intermediate energy range, Physical Review C 35 (5) (1987) 1678.



Nuclei+C Inelastic Cross Section with New Parameterization



The square root of the inelastic cross section on carbon target at rigidity15 GV as function of nuclear charge radii (R_c^p) for the projectile nuclei He, C, O, Ne, Mg, Si and S. The nuclear charge radii measurements is cited from “I. Angeli and K. P. Marinova, Table of experimental nuclear ground state charge radii: An update, Atomic Data and Nuclear Data Tables 99 (2013) 69-95”.

Nuclei+C Inelastic Cross Sections Measurement Errors

- The nuclear measured survival probability depends on the amount of materials and the inelastic cross section as:

$$
\begin{aligned}
\varepsilon^{sur} &= \frac{N_{out}^{sur}}{N_{in}} = \exp(-\sum_i n_i \sigma_i) \\
&= \exp[-n_t \sigma_C (1 + \sum_i \frac{n_i}{n_t} \frac{\sigma_i - \sigma_C}{\sigma_C})] \\
&= \exp[-n_t \sigma_C (1 + \delta)] = \exp(-n_t \sigma_I)
\end{aligned}
$$

where n_i is the number of the target nuclei for i^{th} composition per area; n_t is the total number of the target nuclei per area; σ_i is the inelastic cross section on i^{th} target nuclei; and $\sigma_I = \sigma_C(1 + \delta)$ with $\delta = \sum_i n_i(\sigma_i - \sigma_C)/(n_t\sigma_C)$ is the averaged nuclear inelastic cross section.

- The measured nuclei+C inelastic cross sections therefore was derived to be:

$$
\frac{\Delta\sigma_C}{\sigma_C} = \sqrt{\left(\frac{\Delta\varepsilon^{sur}}{\varepsilon^{sur} log \varepsilon^{sur}}\right)^2 + \left(\frac{\Delta n_t}{n_t}\right)^2 + \left(\frac{\Delta\delta}{1+\delta}\right)^2}
$$

1) The first error from the survival probability measurement includes the uncertainties due to limited statistics, efficiencies determination, background subtraction, ect.
2) The second error associated with the overall materials was estimated to be ~3%.

- The measured nuclei+C inelastic cross sections was therefore derived to be:

$$\frac{\Delta\sigma_C}{\sigma_C} = \sqrt{\left(\frac{\Delta\varepsilon^{sur}}{\varepsilon^{sur} log \varepsilon^{sur}}\right)^2 + \left(\frac{\Delta n_t}{n_t}\right)^2 + \left(\frac{\Delta\delta}{1+\delta}\right)^2}$$

3) The last error from the material composition was estimated by:

$$\Delta\delta/(1+\delta) \approx n_{Al}(\Delta\sigma_{Al}/\sigma_{Al})/\sum n_i(\sigma_i/\sigma_{Al})$$

with $\Delta\sigma_{Al}/\sigma_{Al}$ obtained as following:

$$\frac{\Delta\sigma_{Al}}{\sigma_{Al}} = |1 - \left(\frac{\sigma_{\mathrm{Al+C}}}{\sigma_{\mathrm{C+C}}}\right)^{MC} / \left(\frac{\sigma_{\mathrm{Al+C}}}{\sigma_{\mathrm{C+C}}}\right)^{Data} |$$

where $(\sigma_{Al+C}/\sigma_{C+C})^{MC}$ and $(\sigma_{Al+C}/\sigma_{C+C})^{Data}$ are the inelastic cross section ratio between Al+C and C+C obtained from MC and Data respectively. The $\Delta\sigma_{Al}/\sigma_{Al}$ was found to be < 6% and the corresponding error on $\Delta\delta/(1 + \delta)$ was < 1%.

- Above all, these errors have already been included in the results shown before.

Conclusions

1. Precision measurements of the nuclear survival probabilities for cosmic-ray nuclei $2 \leq Z \leq 16$ by AMS are presented. With such measurements, the cosmic-ray nuclei fluxes are able to be determined within a few percent accuracy.

2. The derived total and partial inelastic interaction cross sections on carbon target for various nuclear species in the rigidity range from few GV to TV provide unique information for the development of nuclear collision model, from which other cosmic-ray nuclei detection technique would also profit.