CALETによる8.4 GeV/nから3.8 TeV/nの ホウ素/炭素比の観測結果

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Nuclei observations with CALET

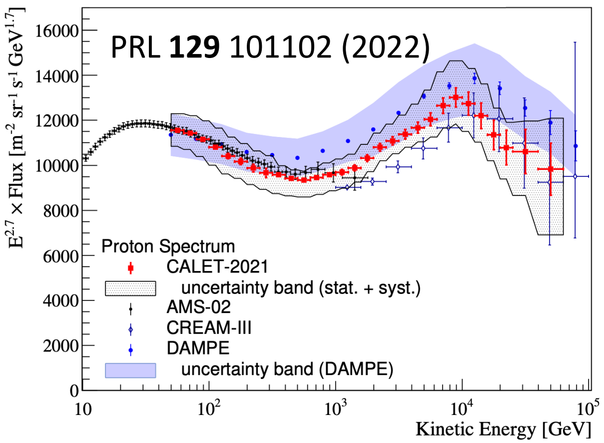
Results of primary CRs with CALET

- Energy spectra to 60 TeV for proton, to 2 TeV/n for C, O and Fe, to 240 GeV/n for Ni
- The spectra shows the hardening for light nuclei
- Fe and Ni spectra indicate a single power law function

Measurement of secondary CRs

- cosmic-ray propagation
- energy dependence of diffusion coefficient

➡ CALET measures the boron flux to TeV region with less background



P: $\Delta\gamma = 0.28^{+0.03}_{-0.02}$

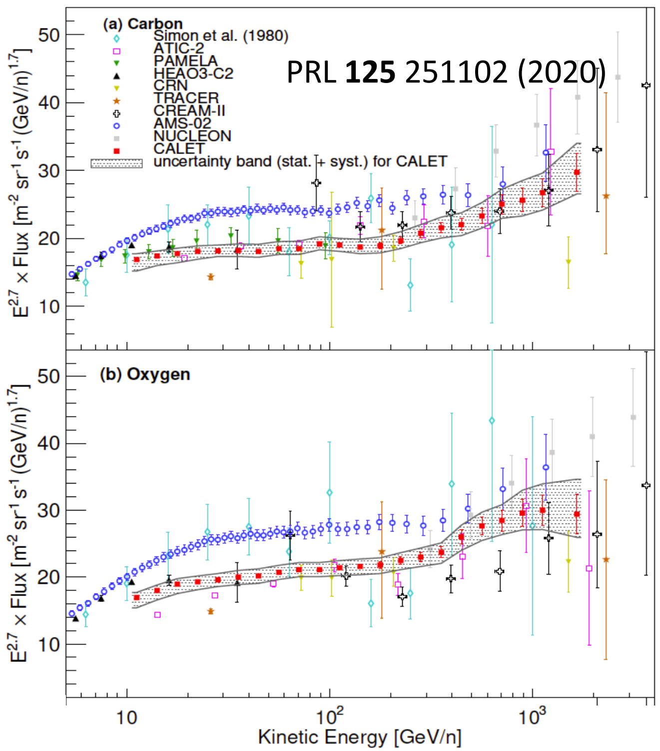
$E_0 = 584^{+60}_{-58}$ GeV

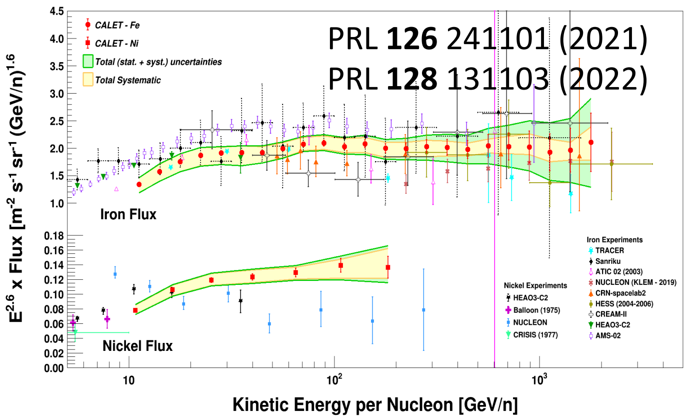
C: $\Delta\gamma = 0.166 \pm 0.042$

$E_0 = 215 \pm 54$ GeV/n

O: $\Delta\gamma = 0.158 \pm 0.053$

$E_0 = 264 \pm 53$ GeV/n





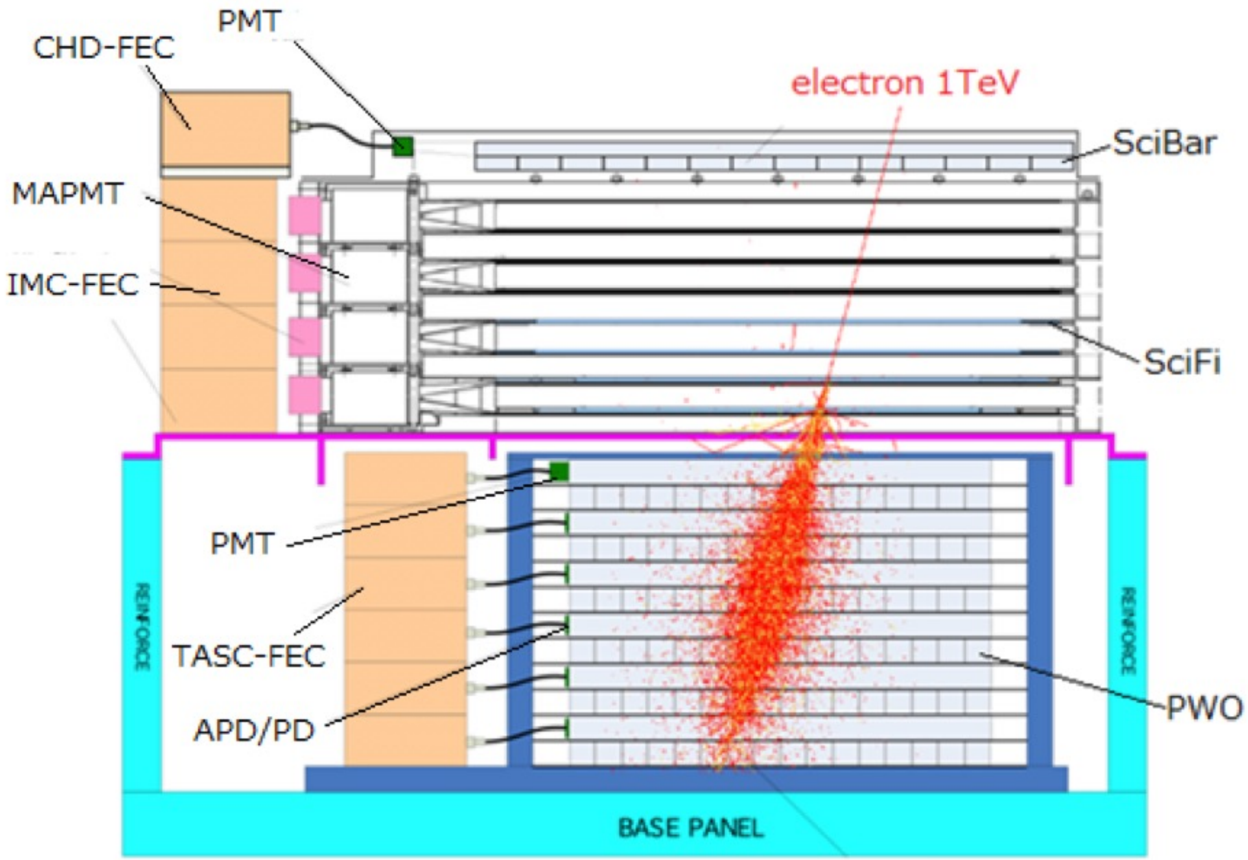
Fe: $\gamma = -2.60 \pm 0.03$, $E > 50$ GeV/n

Ni: $\gamma = -2.51 \pm 0.07$, $E > 20$ GeV/n

Detector for nuclei measurements

A 30-radiation length deep calorimeter designed to detect electrons and gammas to 20 TeV and cosmic rays up to 1 PeV

Since the start of operation on the ISS in October 2015,
CALET has been accumulating scientific data without any major interruption



CHD: Charge Detector

Charge measurements (Z=1-40)

- Plastic scintillator paddles 14 x (X, Y)
  Unit size: 32mm x 10 mm x 450 mm
  ΔZ/Z = 0.15 for C, 0.30 for Fe

IMC: Imaging Calorimeter

Arrival direction, Particle ID

- Scintillating fiber belts 448 x 16 layers
  Unit size: 1 mm^2 x 448 mm
- Tungsten plates 7 layers
  3 X_0 (=0.2 X_0 x 5 + 1.0 X_0x 2)
  ΔX at CHD = 200μm, ΔZ/Z = 0.20 for C

TASC: Total Absorption Calorimeter

Energy measurement, Particle ID

- PWO logs 16 x 12 layers
  Unit size: 19 mm x 20 mm x 326 mm
  27 X_0 for electrons
  1.2 interaction length for protons
  Dynamic range ; 1 – 10^6 MIP (1GeV – 1PeV)

Analysis procedure

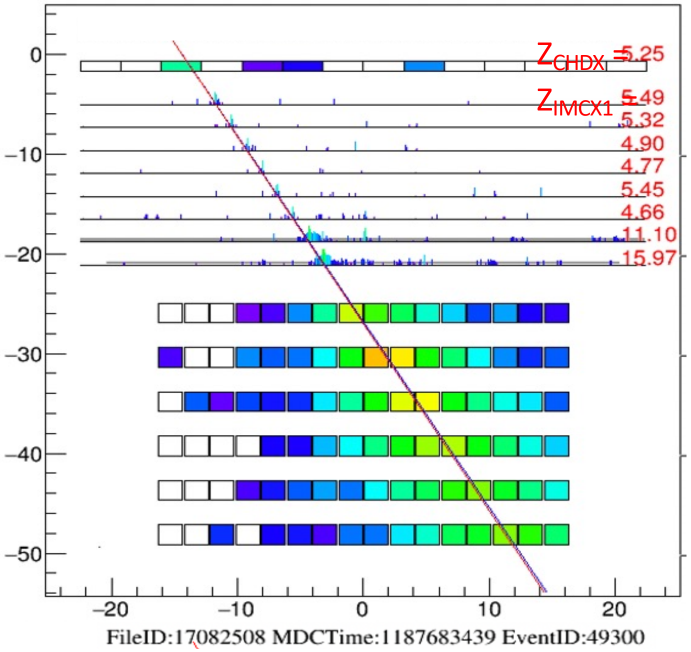
<u>Event selection;</u>

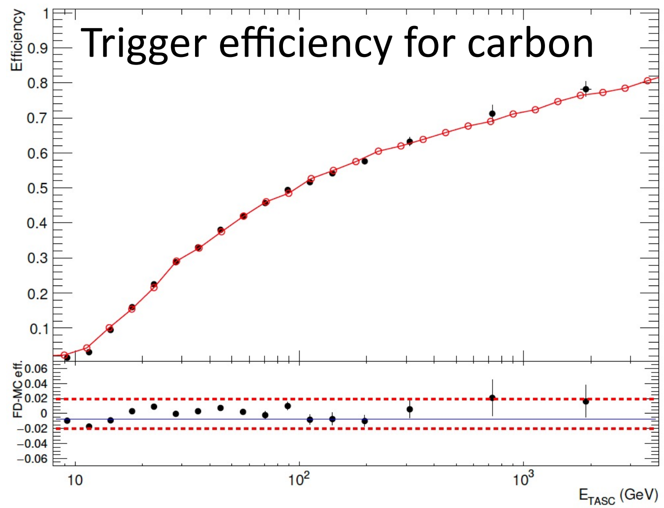
1. High energy shower trigger
   Oct.13 2015 – Feb.28 2022 (2331days)
2. Offline shower trigger
   50MIP in IMC-X/Y78, 100MIP in TASC-X1
3. Track reconstruction with IMC
4. Field of view cut
   Remove shielded region by ISS structure
5. Acceptance cut
   CHD, TASC top and bottom layers
6. Charge identification
   Charge consistency among CHD and IMC layers
   Track width selection
7. Estimate efficiency and background
8. Apply energy unfolding
9. Calculate flux and the ratio

<u>MC Simulations</u>

- EPICS with DPMJET-III
  Accuracy of the MC was tested by beam test at CERN-SPS

An example of Boron candidate (X-Z view)
E_{TASC} = 475.8 GeV





Event selection

Major possible background source is events interacting in CHD or upper surface materials

- **Charge consistency**

  with each CHD and upper 4 IMC layers

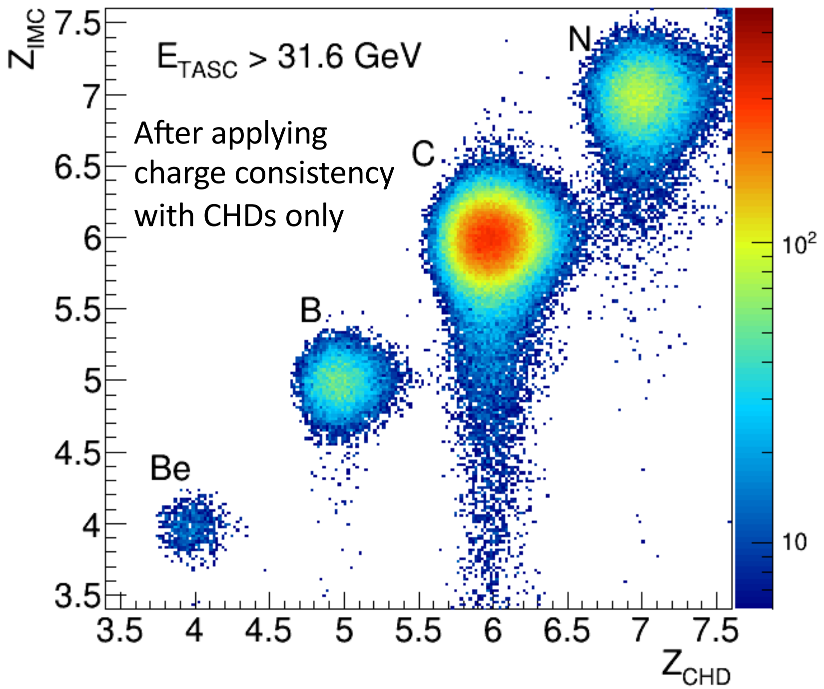
  - $1/1.10 < Z_{CHDY}/Z_{CHDX} < 1.10$
  - $1/1.15 < Z_{CHD}/Z_{IMC} < 1.15$
  - $|Z_{IMC12} - Z_{IMC34}| < 1$
  - $|(Z_{IMC12} + Z_{IMC34})/2 - Z_{CHD}| < 1$

- **Track width**

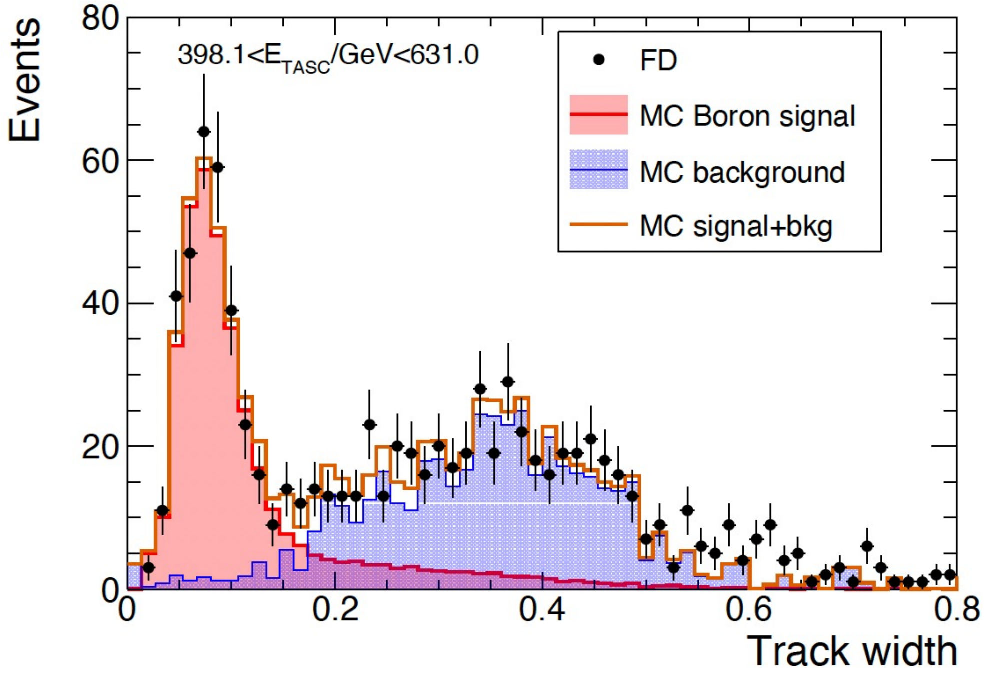
  Track width of the backgrounds spread wider

$$B_{\mathrm{IMCi}} = \Big(\underbrace{\sum_{j=-k}^{k} N_{\mathrm{IMCi,j}}}_{\text{Sum of 7 SciFis}} - \underbrace{\sum_{j=-1}^{1} N_{\mathrm{IMCi,j}}}_{\text{Sum of 3 SciFis}}\Big)\frac{1}{Z^2_{\mathrm{IMCi}}}$$

Z_{IMC} vs Z_{CHD} of flight data



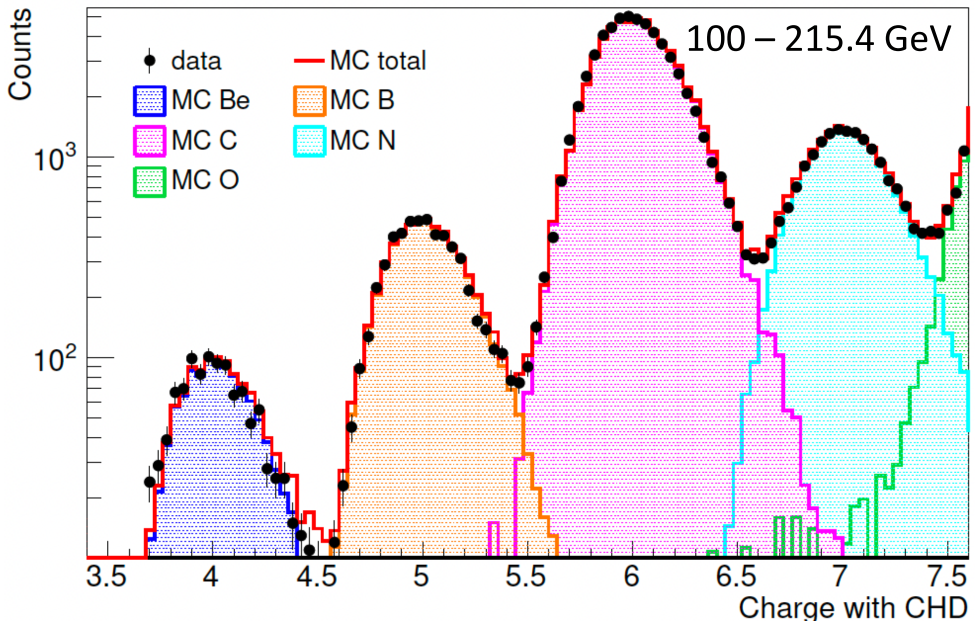
Track width distribution



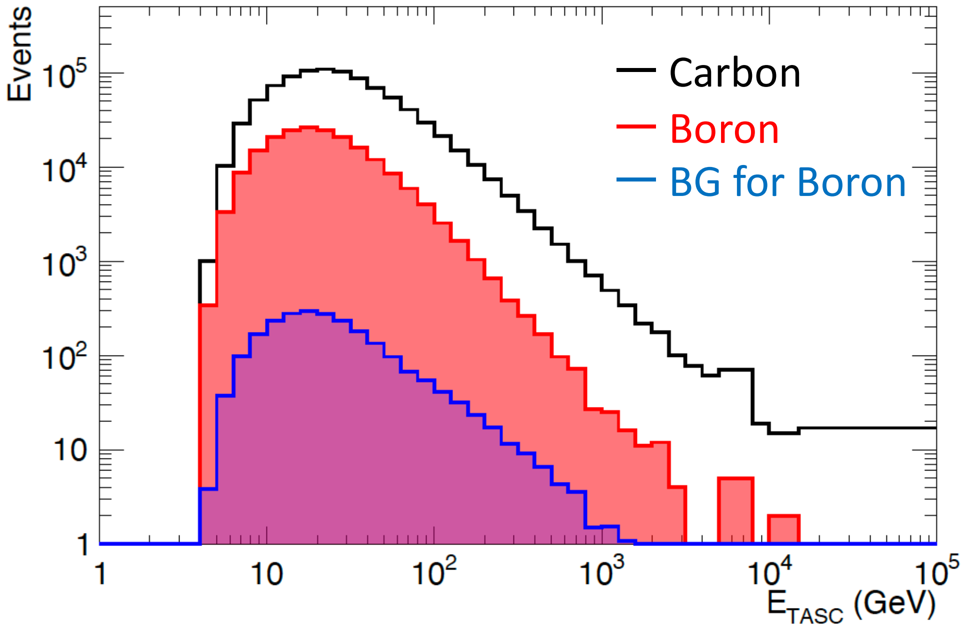
Number of selected events

- Events are selected by $Z < Z_{CHD} \pm 0.45e$
  - B: 1.99×10^5 events
  - C: 9.27×10^5 events
- Background contamination
  - B: 1% for E<100GeV, ~7% at 1.5 TeV
  - C: ~0.1%

Charge distribution of CHD



Energy distribution



Energy unfolding

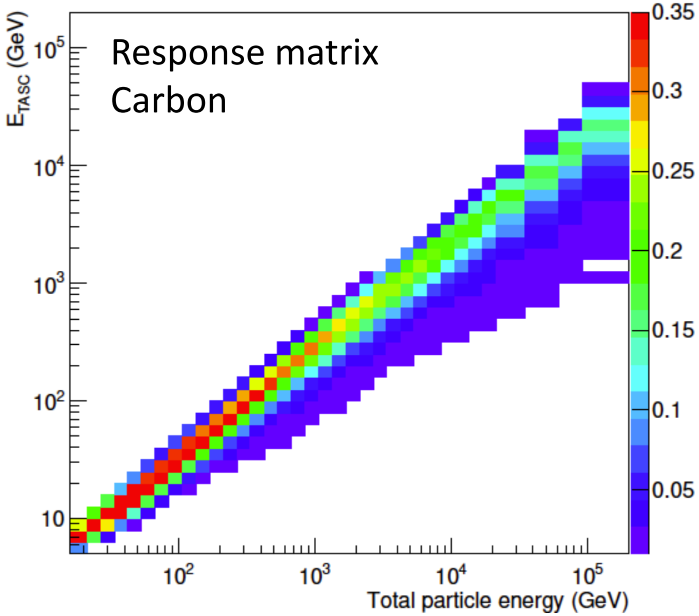
Characteristics of nuclei measurements with CALET calorimeter:

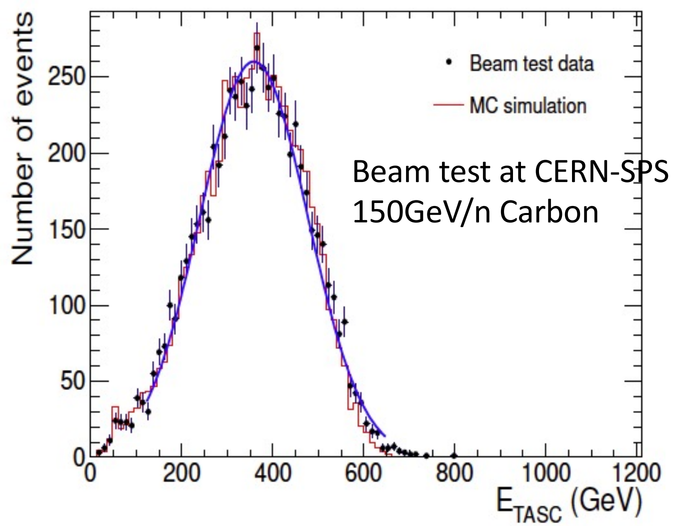
- thickness: 30 X_0 for electron, 1.3λ for proton
- σ(E)/E : 2% for electron, 30% for nuclei

➡ Need energy unfolding for nuclei to obtain primary energy spectrum

Iterative Bayesian unfolding

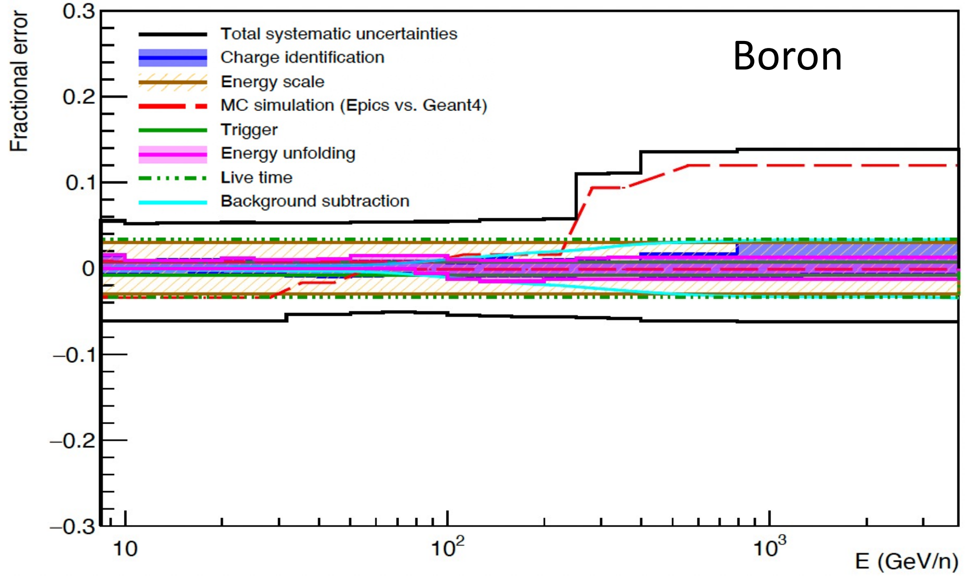
- Initial assuming spectra: f(E)=A x $E^{-2.60}$
  - A is normalized by charge distribution in CHD
- Response function:
  - E_{TASC} [GeV] (deposit energy in calorimeter) vs E_0 [GeV] (primary energy)

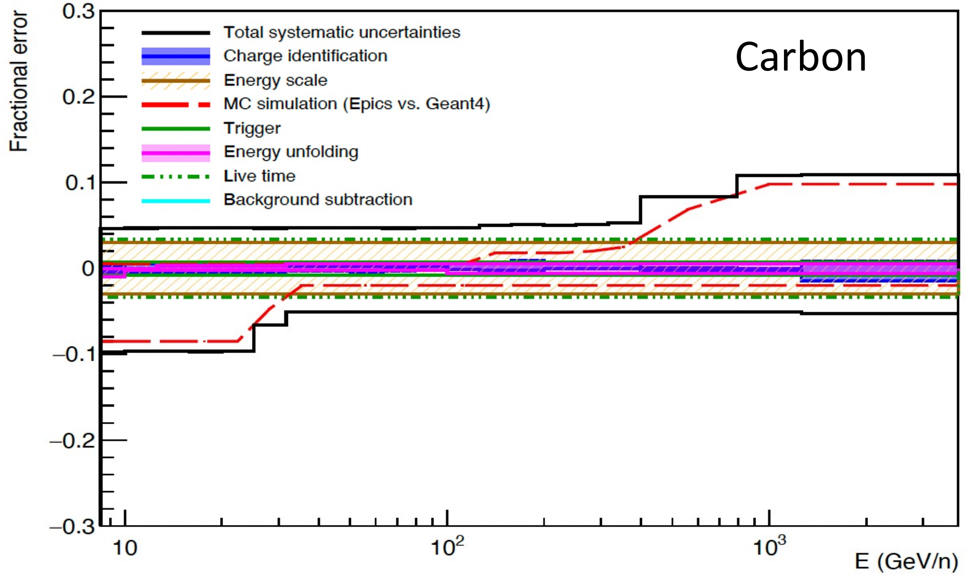




Correction factors of MC are 6.7% for E_{TASC}<45GeV and 3.5% for E_{TASC} >350GeV, respectively, while a simple linear interpolation Is used to determine the correction factor for intermediate energies

Systematic uncertainties





Sources of the systematic uncertainty

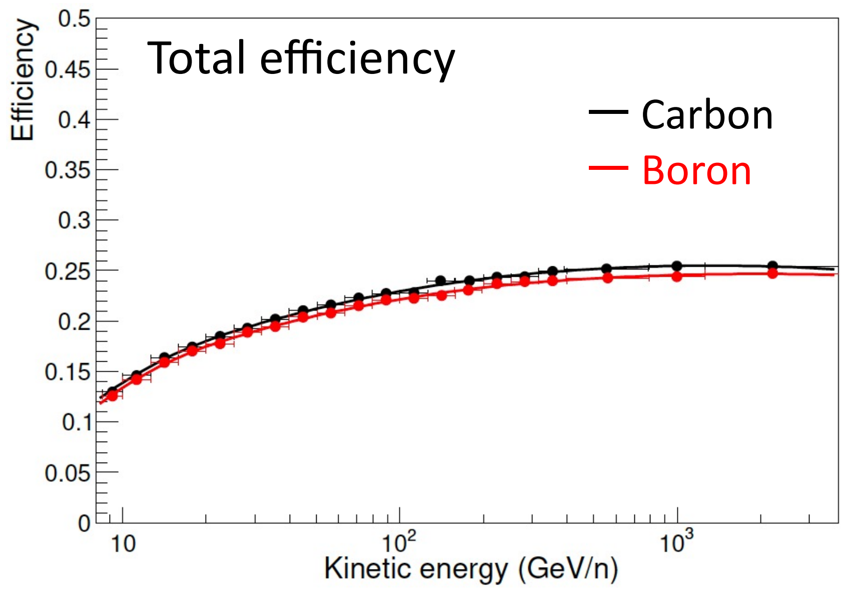
- Trigger efficiency
  subset of LE trigger events
- Charge identification
  0.43e – 0.47e for ZCHD
  0.9 – 1.1 for consistency cut
- Energy scale
  ±2% by beam test
- Energy unfolding
- MC simulations
  EPICS vs Geant4
- B isotopic composition
  30% B^{11} ± 10%
- Background subtraction
- Live time
- Long-term stability

Energy spectra of boron and carbon

$$\Phi(E) = \frac{N(E)}{\Delta E\ \varepsilon(E)\ S\Omega\ T}$$

$$N(E) = U\left[N_{obs}(E_{\mathrm{TASC}}) - N_{bg}(E_{\mathrm{TASC}})\right]$$

$N(E)$: Events in unfolded energy bin
ΔE : Energy bin width
$\varepsilon(E)$: Efficiency
$S\Omega$: Geometrical acceptance ($510 cm^2 sr$)
T : Live Time (4.72×10^9 hours)



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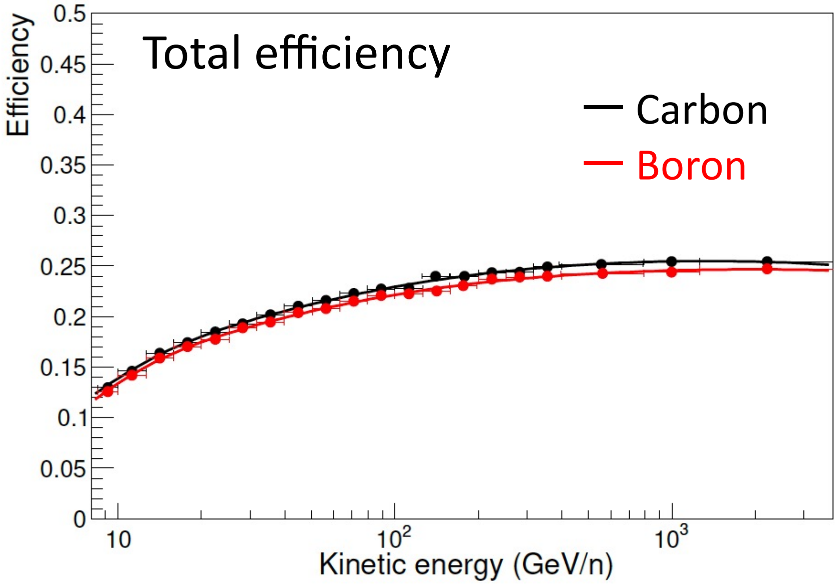
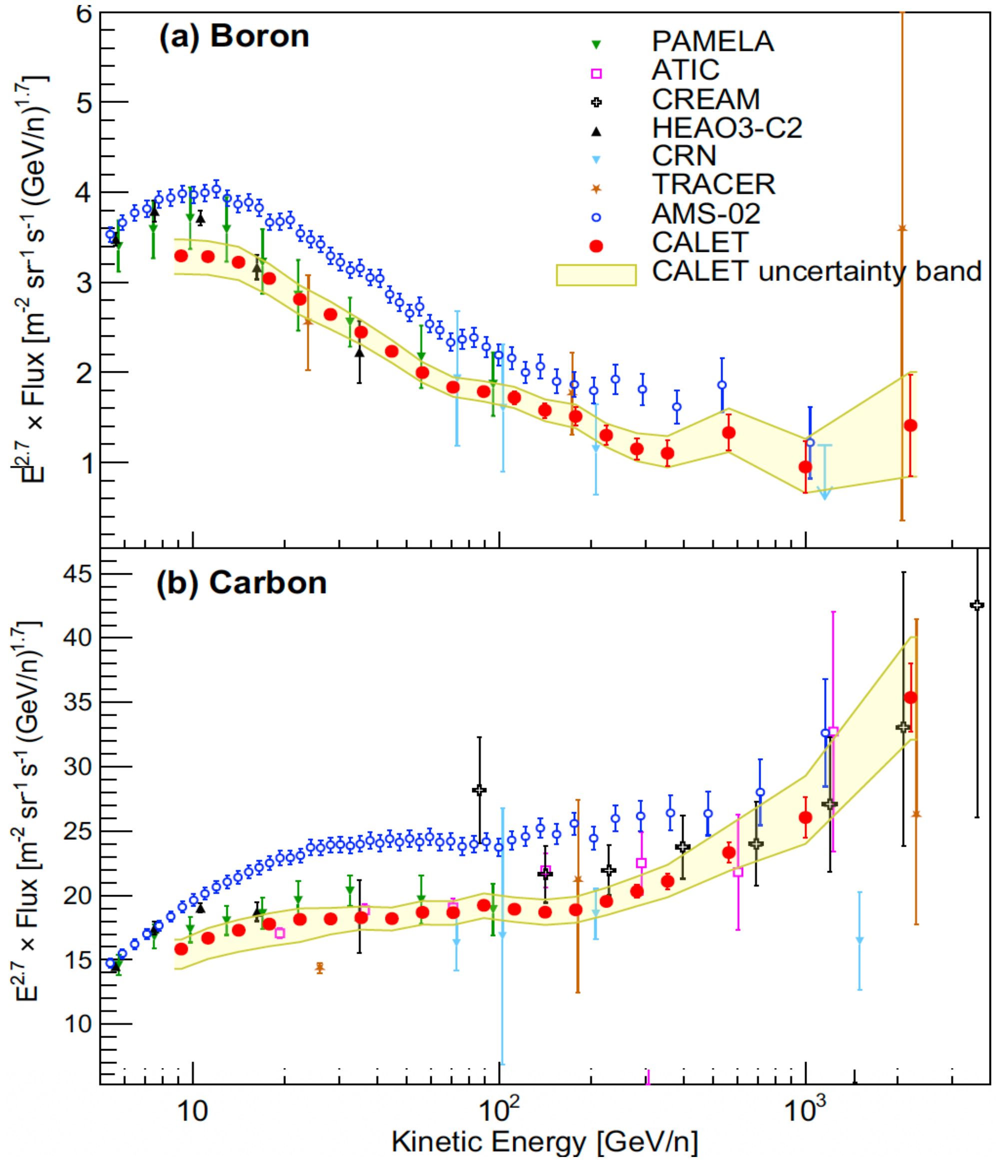
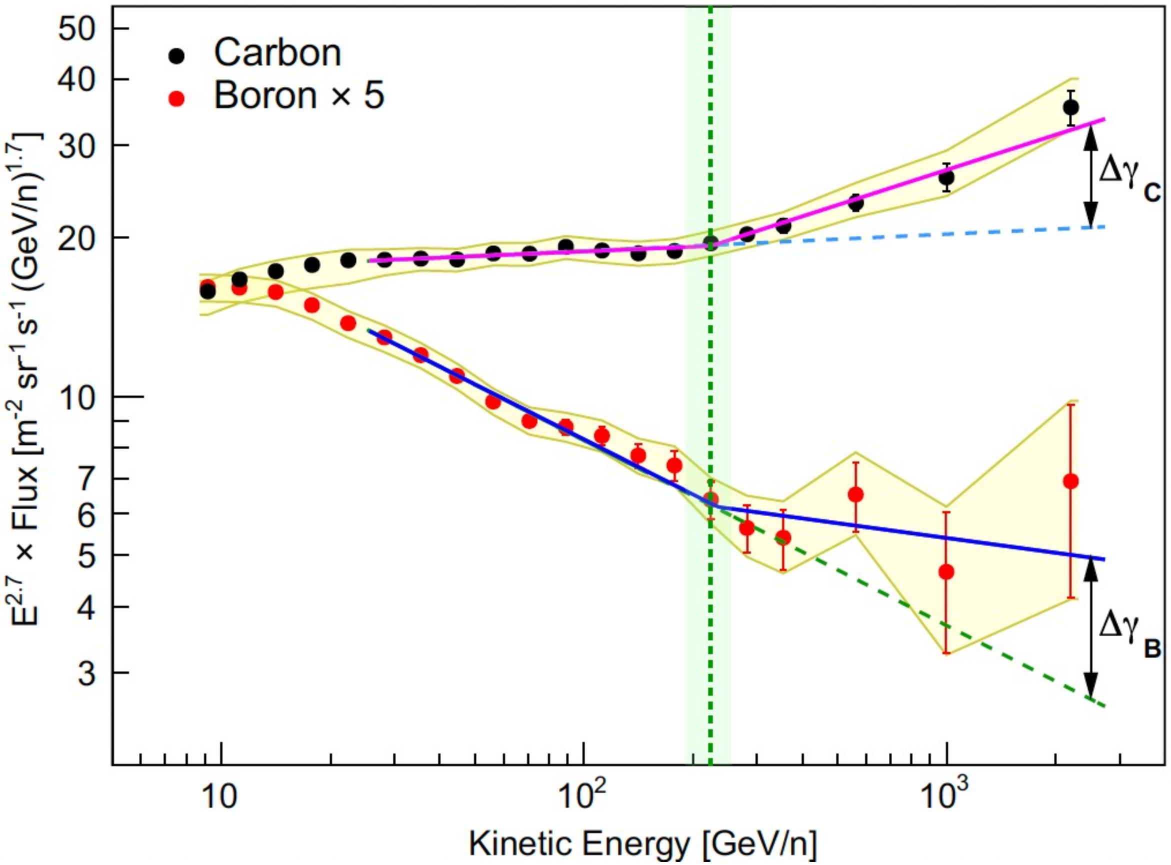




Boron and carbon spectra



Double power-law function

$$\Phi(E) = \begin{cases} c\left(\frac{E}{\mathrm{GeV}}\right)^{\gamma} & E \leq E_0 \\ c\left(\frac{E}{\mathrm{GeV}}\right)^{\gamma}\left(\frac{E}{E_0}\right)^{\Delta\gamma} & E > E_0 \end{cases}$$

Fit range: 25 – 3800 GeV

$\gamma_C = -2.670 \pm 0.005$

$\Delta\gamma_C = 0.19 \pm 0.03$

E_0^C = 220 ± 20 GeV

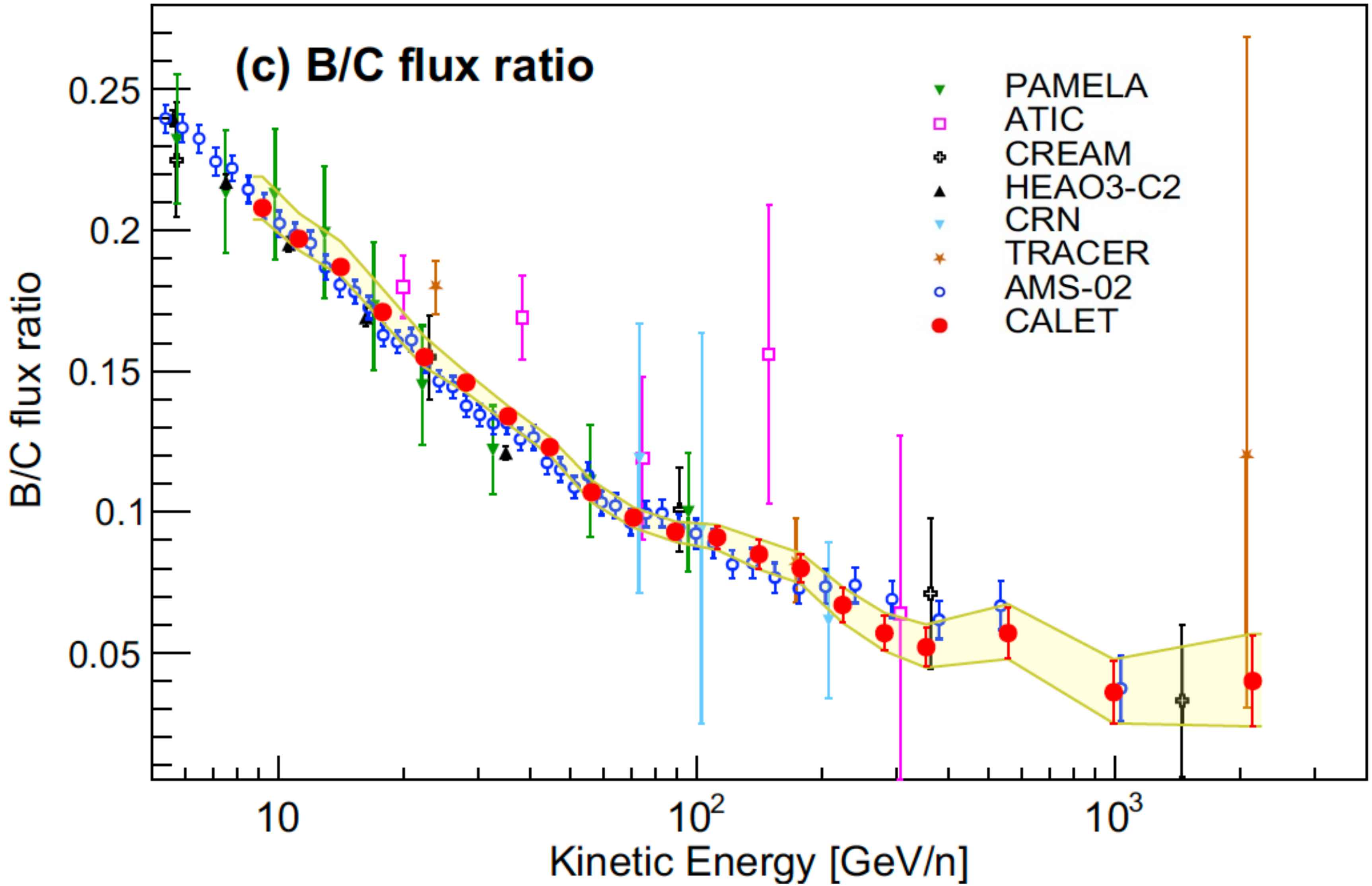
$\gamma_B = -3.047 \pm 0.024$

$\Delta\gamma_B = 0.25 \pm 0.12$

$\chi^2/\mathrm{d.o.f.} = 11.9/12$

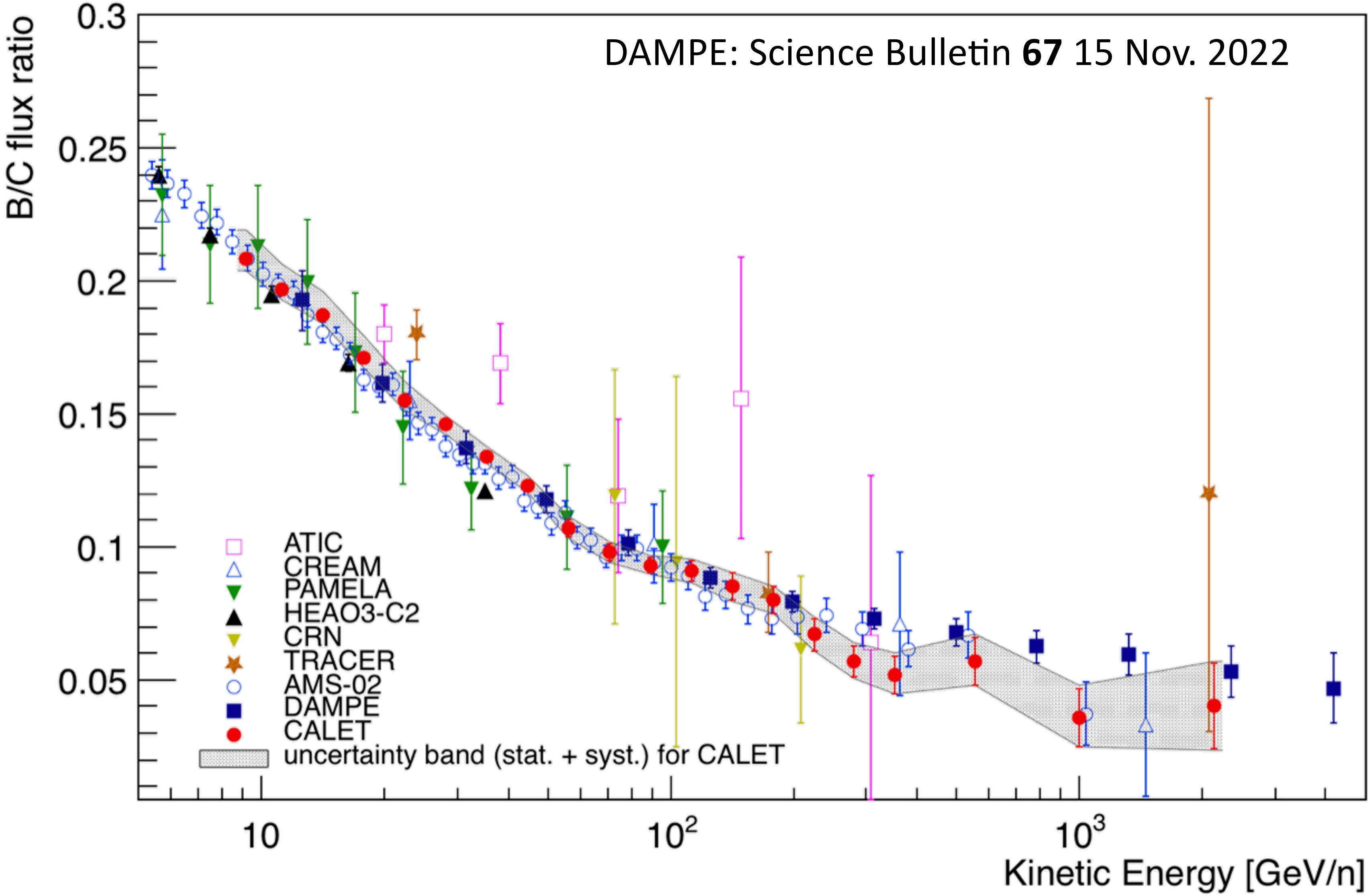
The energy spectra are clearly different as expected for primary and secondary CRs, and the fit results seem to indicate that the flux hardens more for B than for C above 200 GeV/n, albeit with low statistical significance.

B/C ratio



(c) B/C flux ratio
B/C flux ratio
0.25
0.2
0.15
0.1
0.05
10
10^2
10^3
Kinetic Energy [GeV/n]
PAMELA
ATIC
CREAM
HEAO3-C2
CRN
TRACER
AMS-02
CALET

B/C ratio



DAMPE: Science Bulletin **67** 15 Nov. 2022
B/C flux ratio
0.3
0.25
0.2
0.15
0.1
0.05
10
10^2
10^3
Kinetic Energy [GeV/n]
ATIC
CREAM
PAMELA
HEAO3-C2
CRN
TRACER
AMS-02
DAMPE
CALET
uncertainty band (stat. + syst.) for CALET

Fitting of B/C ratio

Single / Double power law fit:

$\Gamma = -0.366 \pm 0.018 \ (\chi^2/\mathrm{d.o.f.} = 9.4/13)$ in 25 – 3800 GeV/n

$\Delta\Gamma = 0.09 \pm 0.05 \ (\chi^2/\mathrm{d.o.f.} = 8.7/12)$ at 220 GeV/n

➡ consistent with that of AMS-02 and supports the hypothesis that secondary B exhibits a stronger hardening than primary C, although no definitive conclusion can be drawn due to the large uncertainty

Leaky-box model fit [ApJ **752** 69 (2012)]

$$\frac{\Phi_B(E)}{\Phi_C(E)} = \frac{\lambda(E)\lambda_B}{\lambda(E)+\lambda_B}\left[\frac{1}{\lambda_{C\to B}} + \frac{\Phi_O(E)}{\Phi_C(E)}\frac{1}{\lambda_{O\to B}}\right]$$

$\lambda(E)$: mean escape path length

$$\lambda(E) = kE^{-\delta} + \lambda_0$$

λ_0 : residual path length

δ : diffusion coefficient spectral index

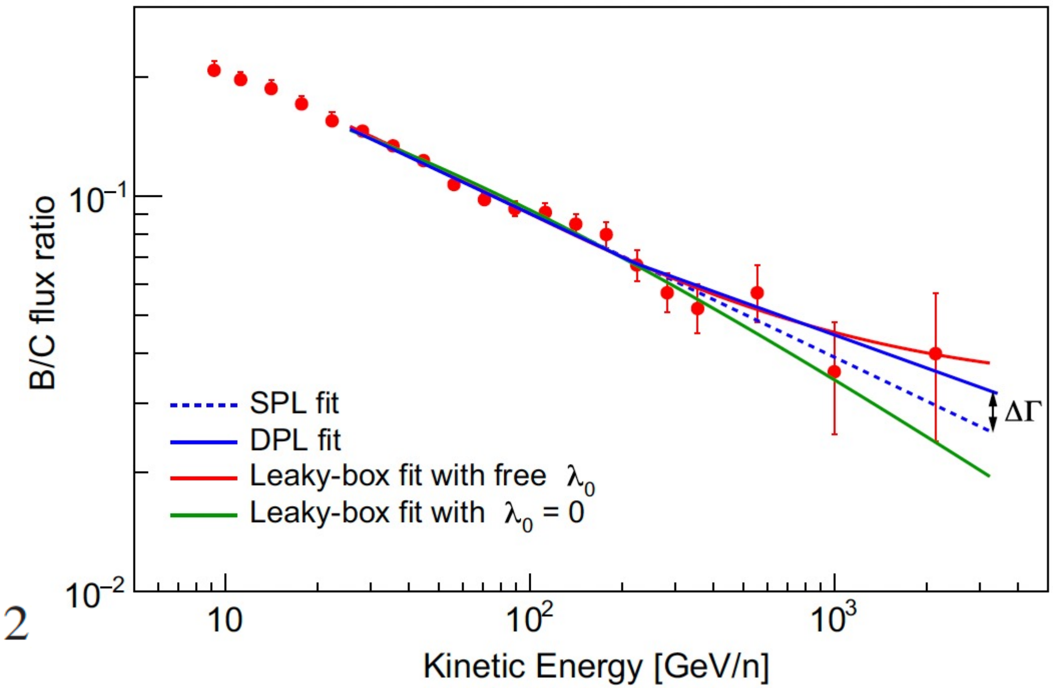
$\lambda_0 = 0$

$\delta = 0.52 \pm 0.02 \quad \chi^2/\mathrm{d.o.f.} = 13.6/13$

λ_0 : free

$\delta = 0.71 \pm 0.11 \quad \chi^2/\mathrm{d.o.f.} = 9.6/12$

$\lambda_0 = 0.95 \pm 0.35 \ \mathrm{g/cm^2}$



Summary

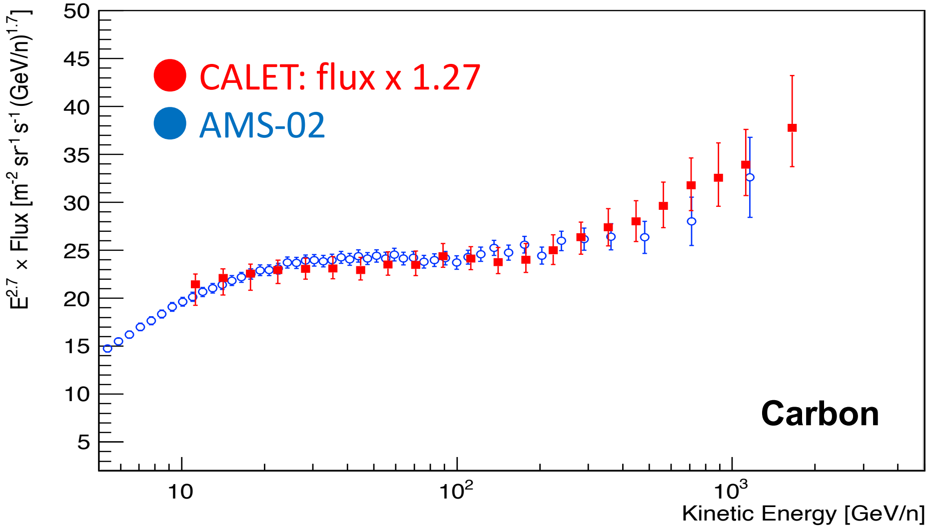
- CALET has measured the energy spectra of boron and carbon up to 3.8 TeV/n, and the results was published from PRL **129** 251102 (2022)
  - 1.99 x 10^5 events for boron and 9.27 x 10^5 events for carbon are selected in the data during 76.5 months of operation
  - Boron and carbon fluxes exhibit a spectral hardening occurring at about the same energy
  - The boron spectral index change is found to be slightly larger than that of carbon within the limitation of our data's present statistical significance

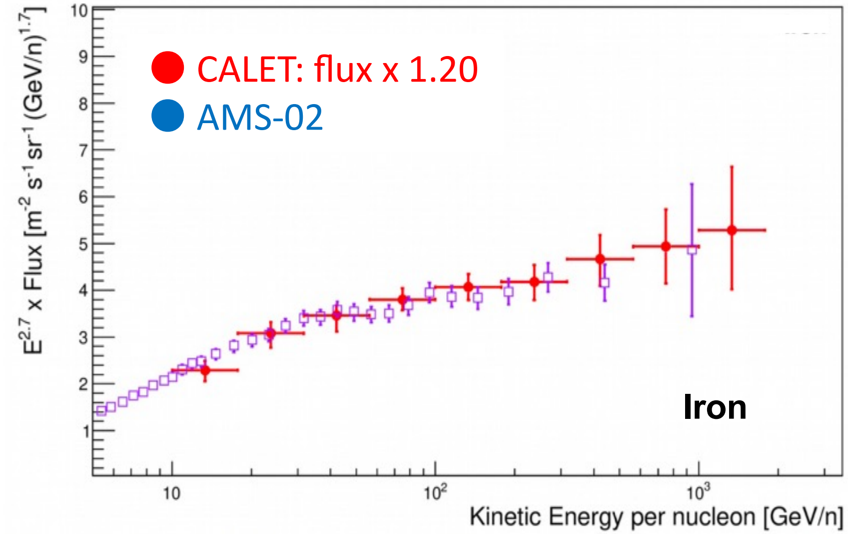
    $\gamma_C = -2.670 \pm 0.005 \quad \Delta\gamma_C = 0.19 \pm 0.03 \quad E_0^C = 220 \pm 20$ GeV

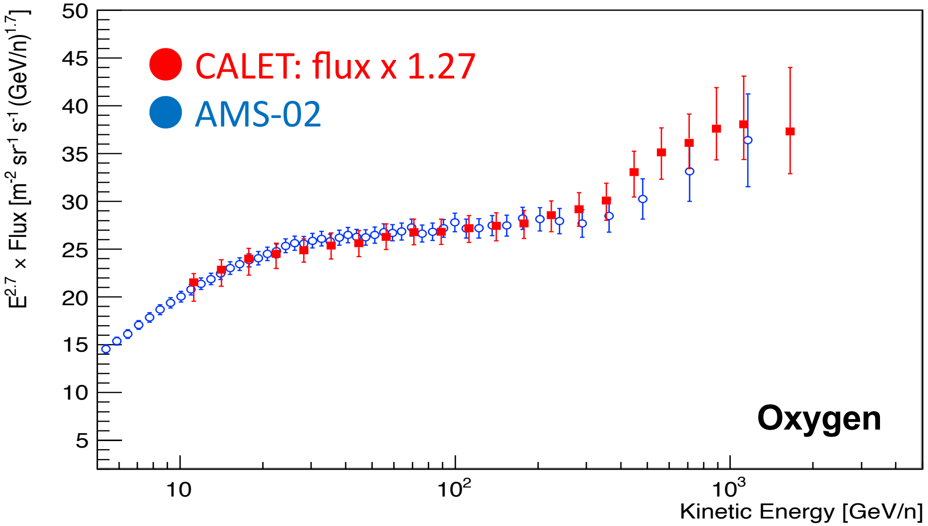
    $\gamma_B = -3.047 \pm 0.024 \quad \Delta\gamma_B = 0.25 \pm 0.12$
  - This trend seems to corroborate the hypothesis that secondary CRs harden more than the primaries, as recently reported by AMS-02

- Interpreting our data with LB model, we argue that the trend of the energy dependence of the B/C ratio in the TeV/n region could suggest a possible presence of a residual propagation path length, compatible with the hypothesis that a fraction of secondary B nuclei can be produced near the CR sources

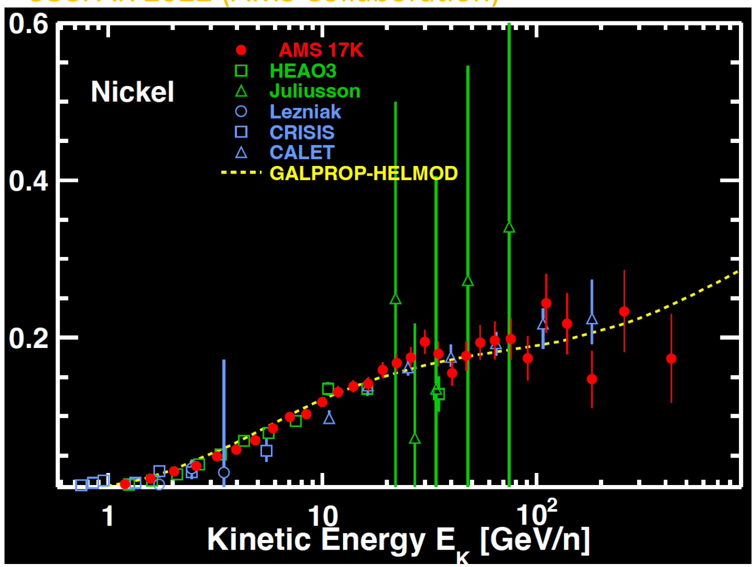
Fluxes normalized to AMS-02







COSPAR 2022 (AMS Collaboration)



The spectral shapes and their spectral indices are consistent with AMS-02,
but the absolute normalizations for B-Fe are lower than AMS-02.