CALETによる宇宙線原子核成分観測の最新成果

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Nuclei measurement with CALET

”Standard” model of galactic cosmic rays

- Diffusive shock acceleration via supernovae remnant
- Diffusion propagation in our Galaxy
  - Same power law spectra for all primary cosmic rays ($dN/dE \propto E^{-\gamma-\delta}$)
  - Acceleration limit proportional to the charge (Ec ∼ 100*Z*TeV), etc.

Unexpected observation results

- Helium spectrum is harder than proton
- Spectra of proton and light nuclei break at R~200GV

Direct measurements with CALET

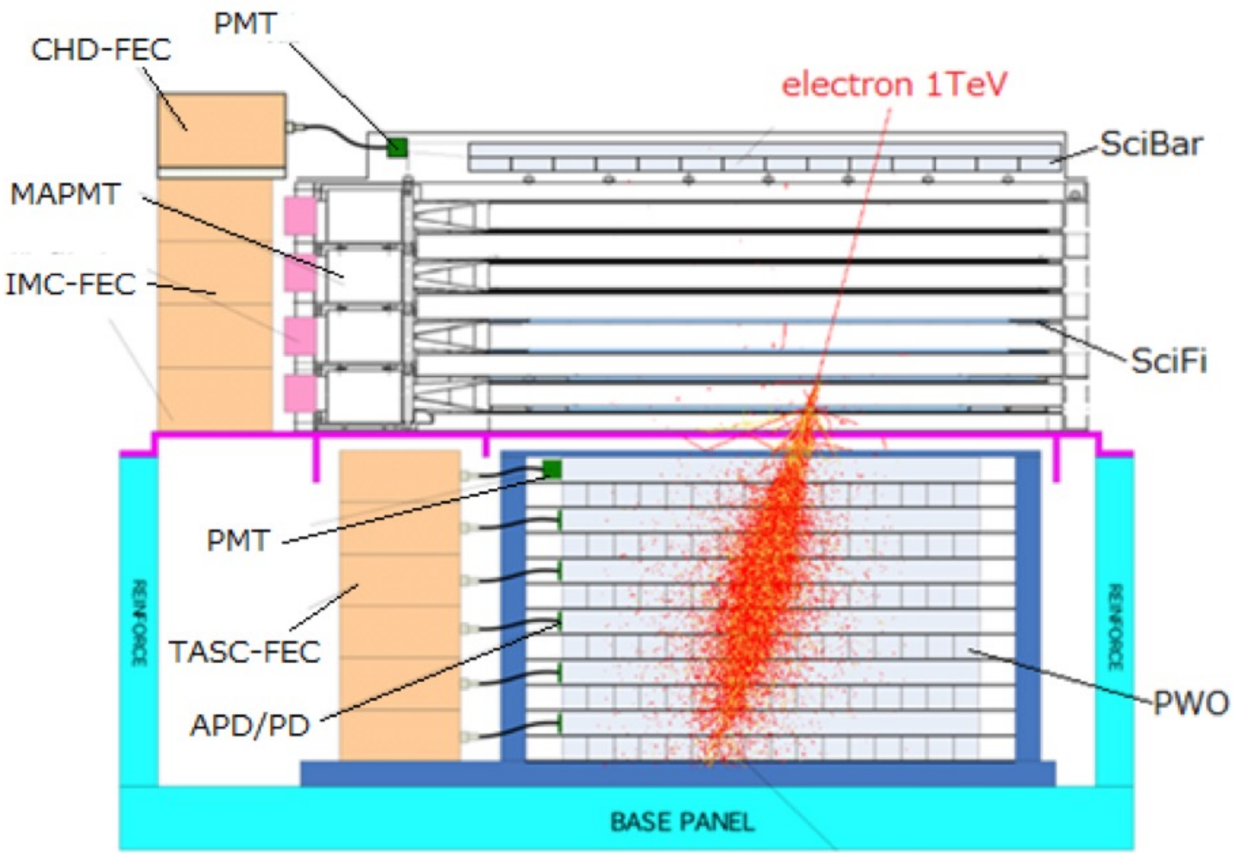
Precisely measure the energy spectra from proton through iron and nickel

- Energy measurement in 10 GeV – 1PeV: wide dynamic range 1 – 10^6 MIP
- Charge measurement in Z = 1 – 40: excellent charge resolution 0.18*e*(C) - 0.3*e* (Fe)

➡ CALET can cover the whole energy range previously investigated in separate subranges by magnetic spectrometers and calorimeters

Instrument of CALET

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



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

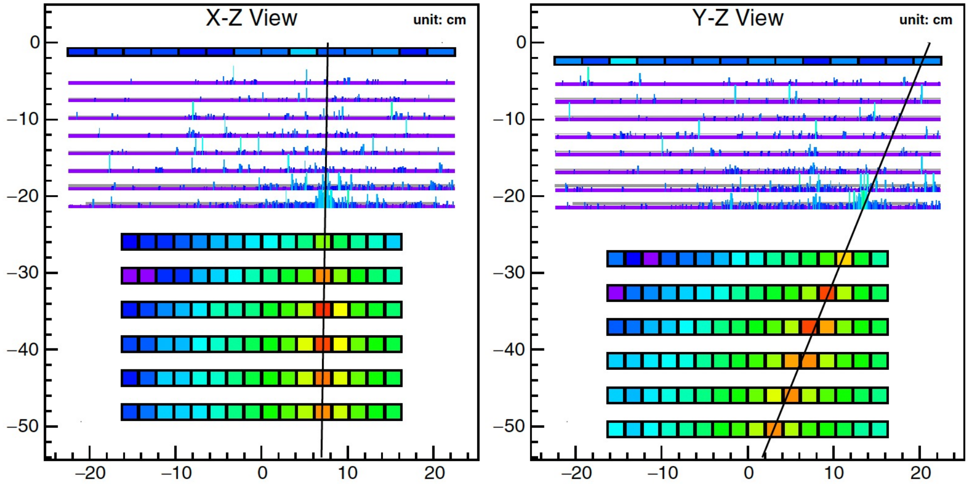
TASC: Total Absorption Calorimeter

Energy measurement, Particle ID

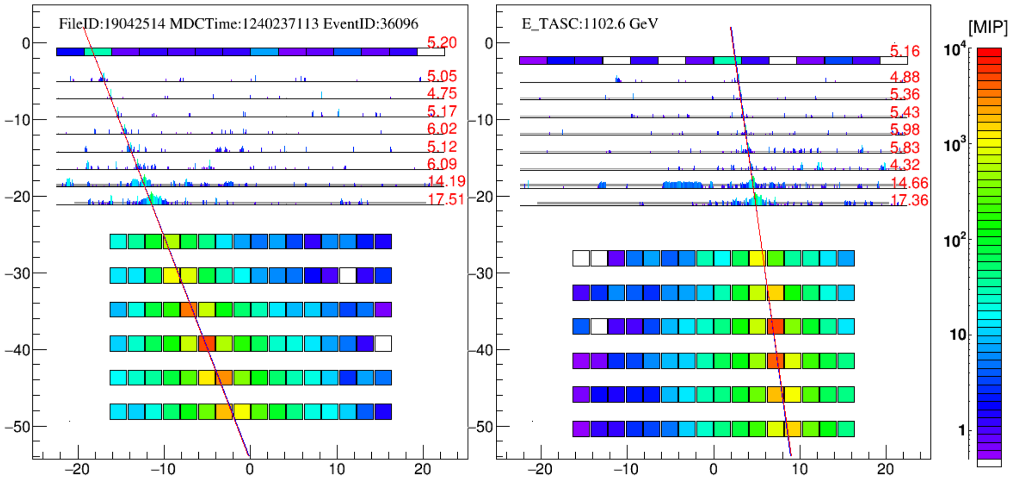
- PWO logs 16 x 12 layers
  Unit size: 19 mm x 20 mm x 326 mm
  27 X_0 for electrons
  1.2 interaction length for protons
  Dynamic range ; 1 – 10^6 MIP (1GeV – 1PeV)

Observed Events

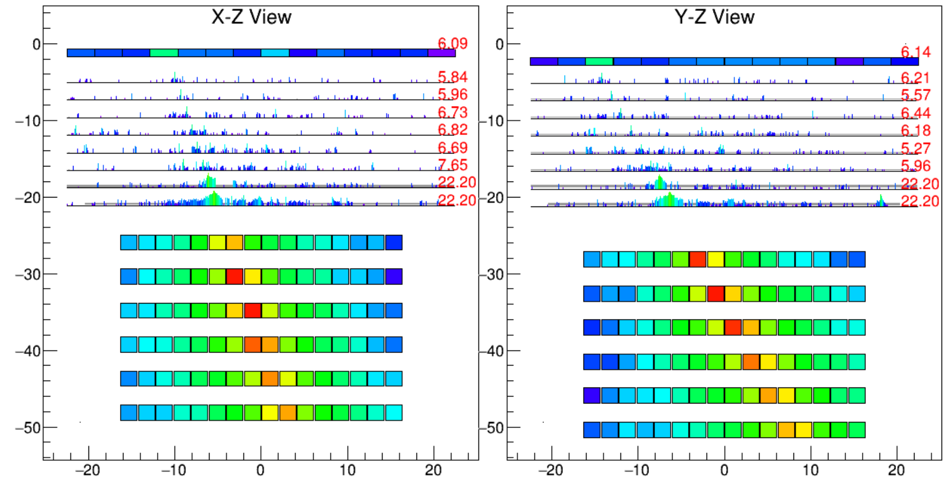
Proton ΔE_{TASC} = 10 TeV



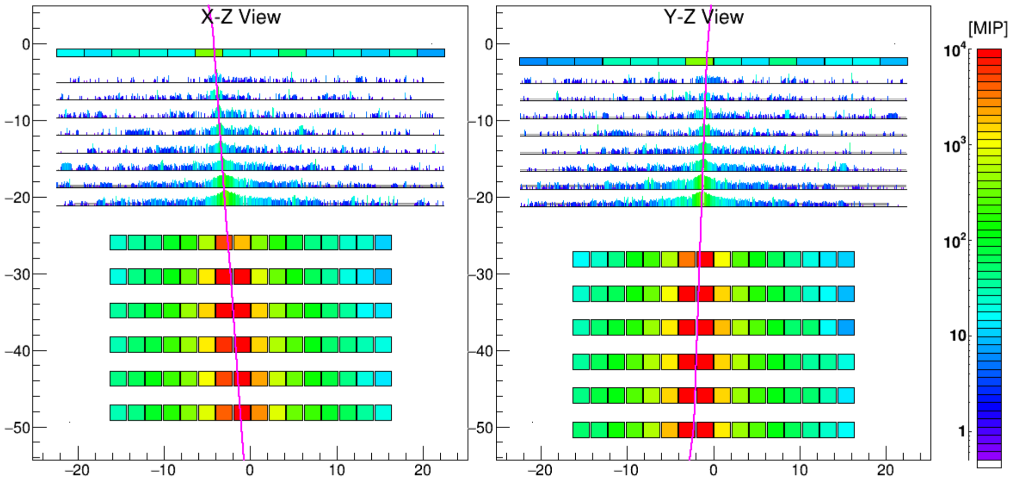
Boron ΔE_{TASC} = 1.1 TeV



Carbon ΔE_{TASC} = 2.1 TeV



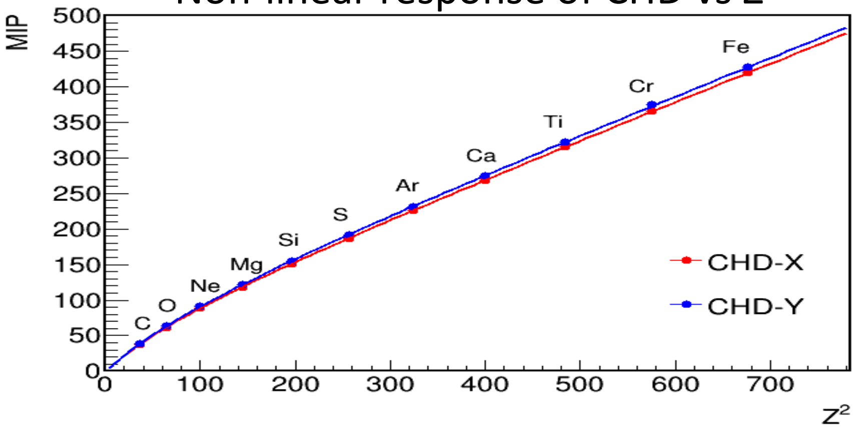
Fe, ΔE_{TASC} = 9.2 TeV



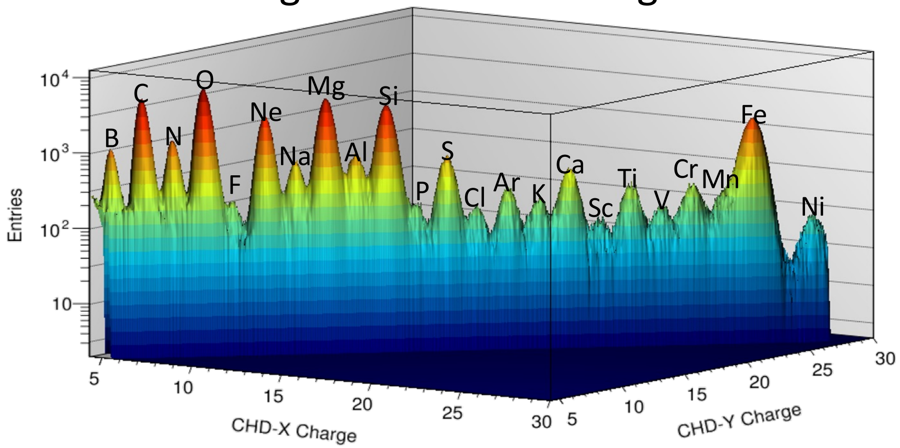
Charge measurement with CALET

- Charge range: Z=1 – 40
- Charge resolution:
  - CHD: 0.15*e* for C, 0.30*e* for Fe
  - IMC : 0.20*e* for C

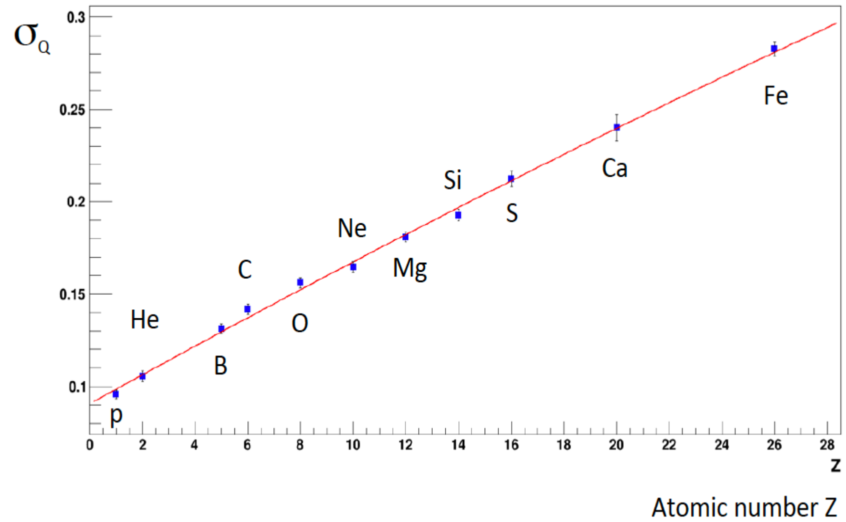
Non-linear response of CHD vs Z^2



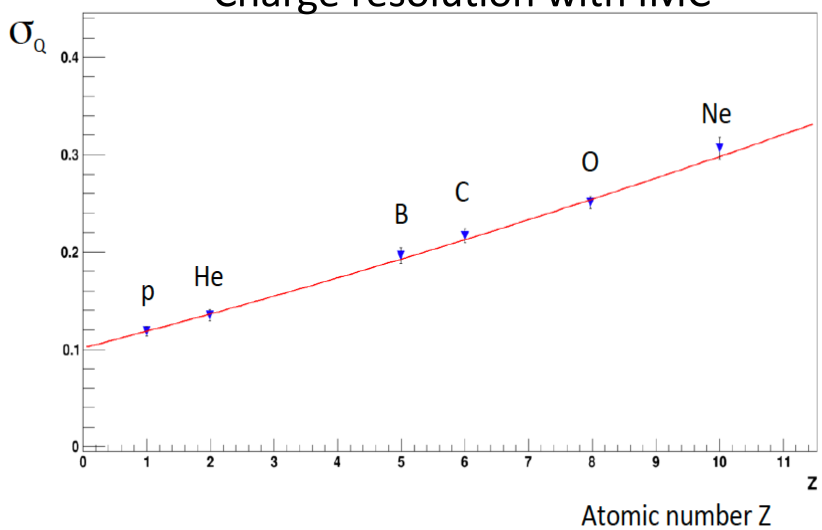
Charge distribution of flight data



Charge resolution with CHD



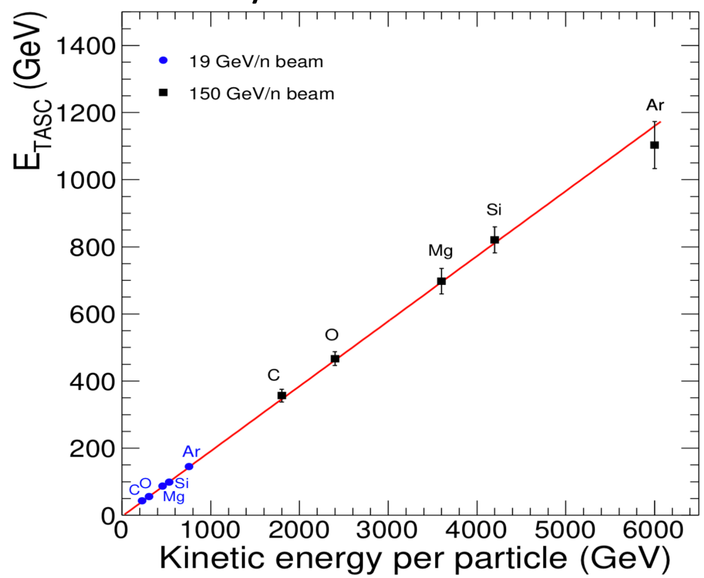
Charge resolution with IMC



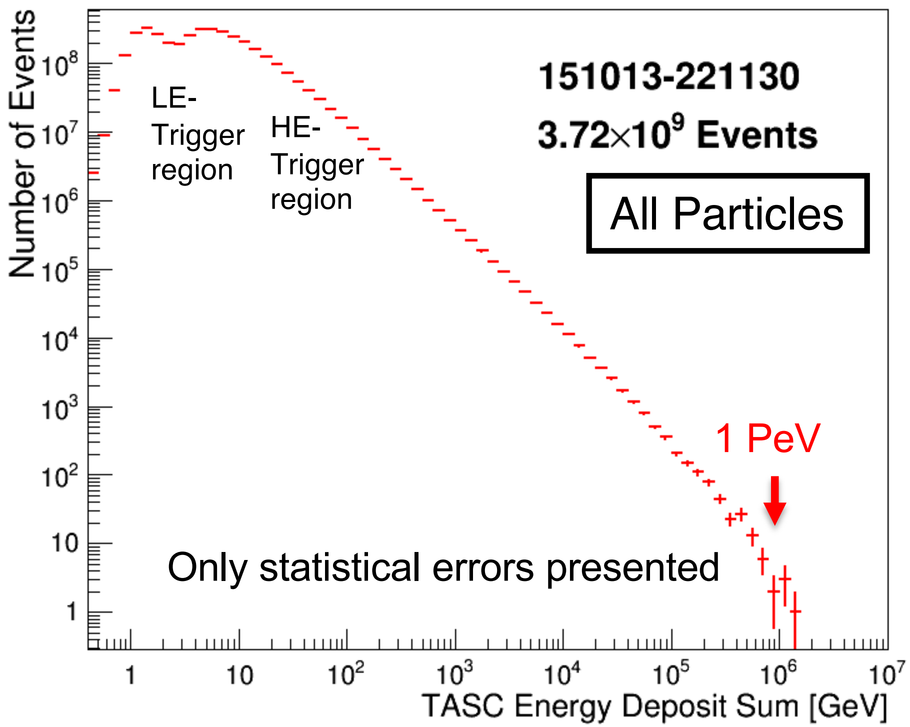
Energy measurement with CALET

- Dynamic range: 1 – 10⁶MIP (1GeV – 1PeV)
- MIP calibration have performed on space
- Energy resolution: 30% for nuclei

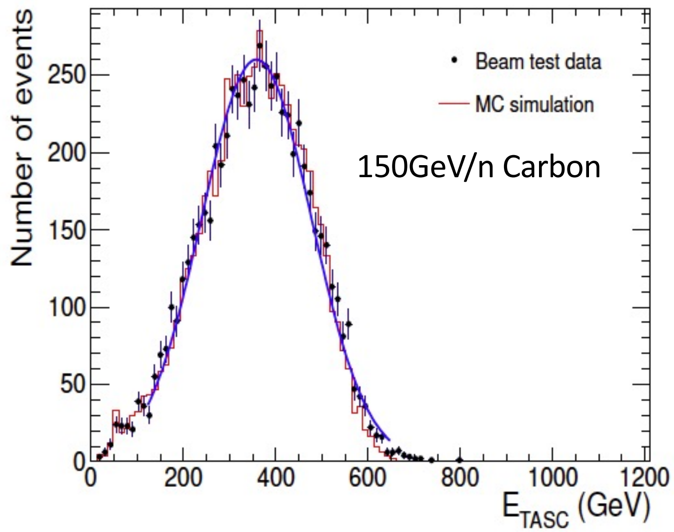
Linearity with beam test



Distribution of deposit energies (ΔE) in TASC



Energy distribution with beam test



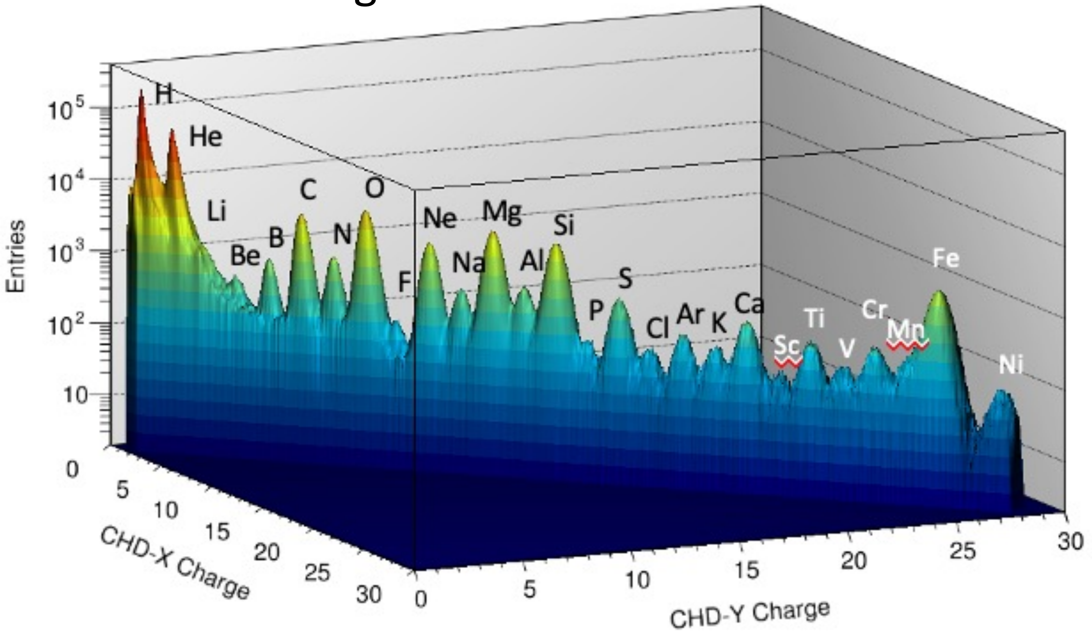
Publications of Nuclei Spectra by CALET

CALET is exploring the Table of Elements in the multi-TeV domain
with excellent charge-ID of individual elements

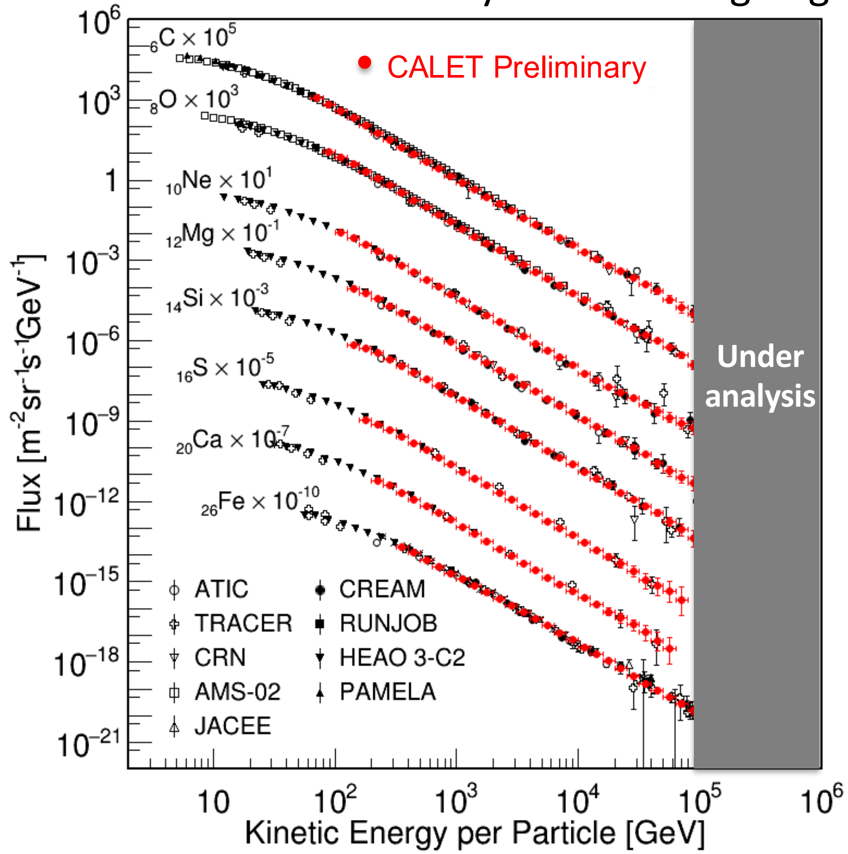
Proton: PRL **122** 181102 (2019)
PRL **129** 101102 (2022) New!
} Poster P-003 by K. Kobayashi in this symposium

C, O and C/O: PRL **125** 251102 (2020)
Fe: PRL **126** 241101 (2021)
Ni and Ni/Fe: PRL **128** 131103 (2022) New!
B and B/C: PRL **129** 251103 (2022) New!
} This presentation

Charge distribution with CALET

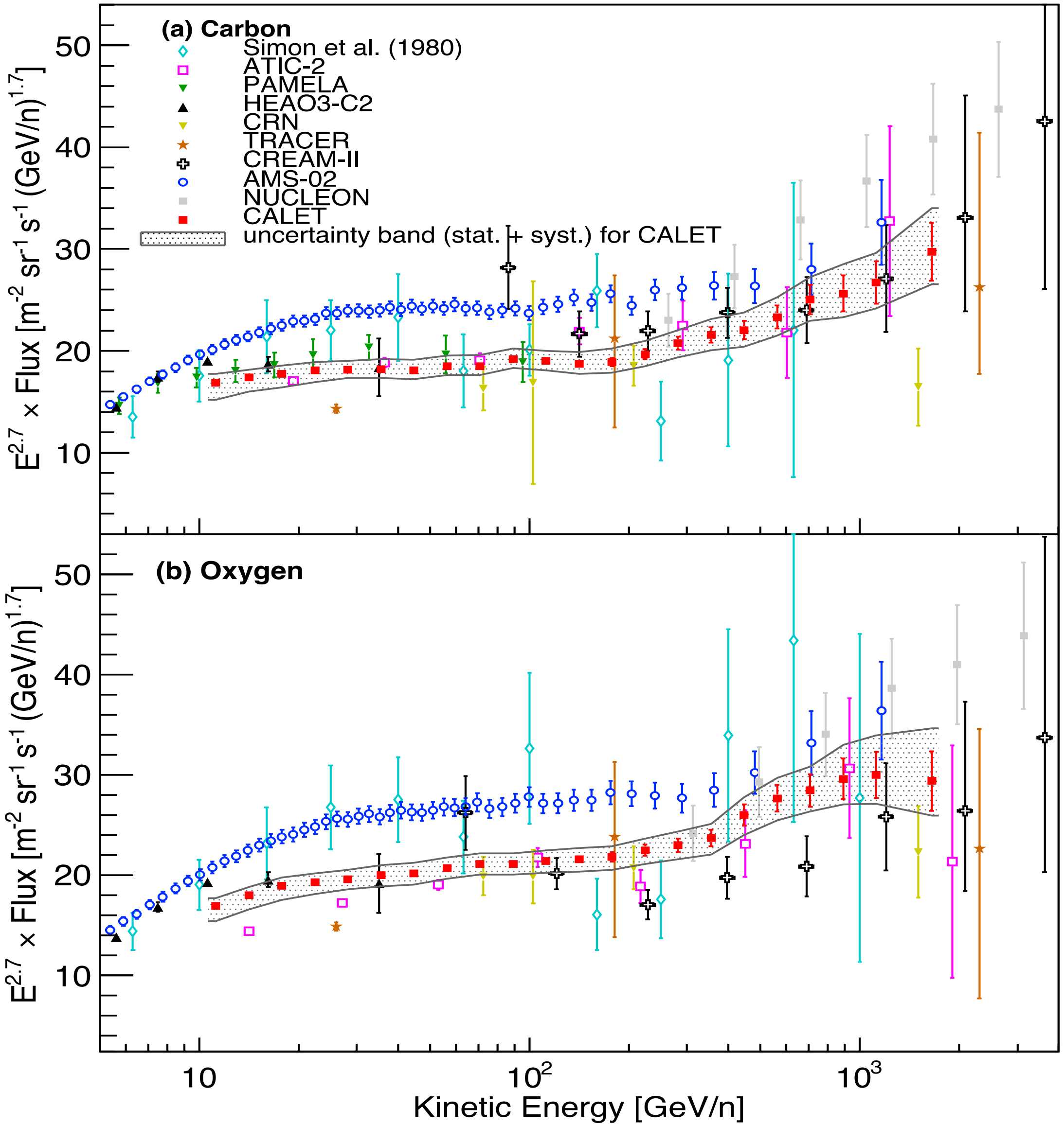


Other nuclei analysis is now ongoing



Carbon and Oxygen spectra

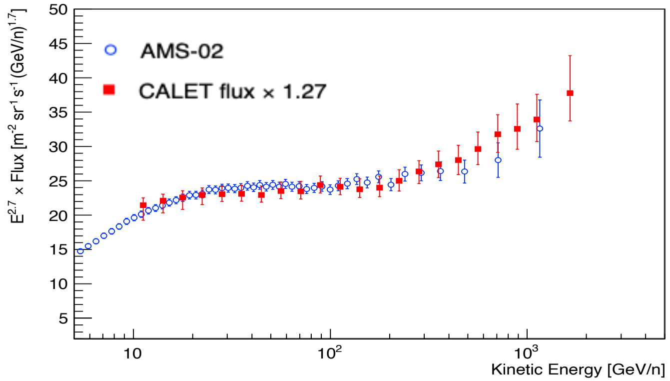
PRL **125**, 251102 (2020)

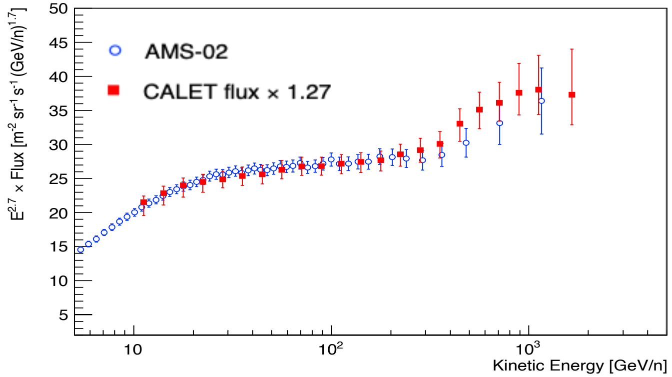


CALET C is consistent with PAMELA and most of the previous experiments. PAMELA did not publish oxygen.

The spectra show a clear hardening around 200 GeV/n.

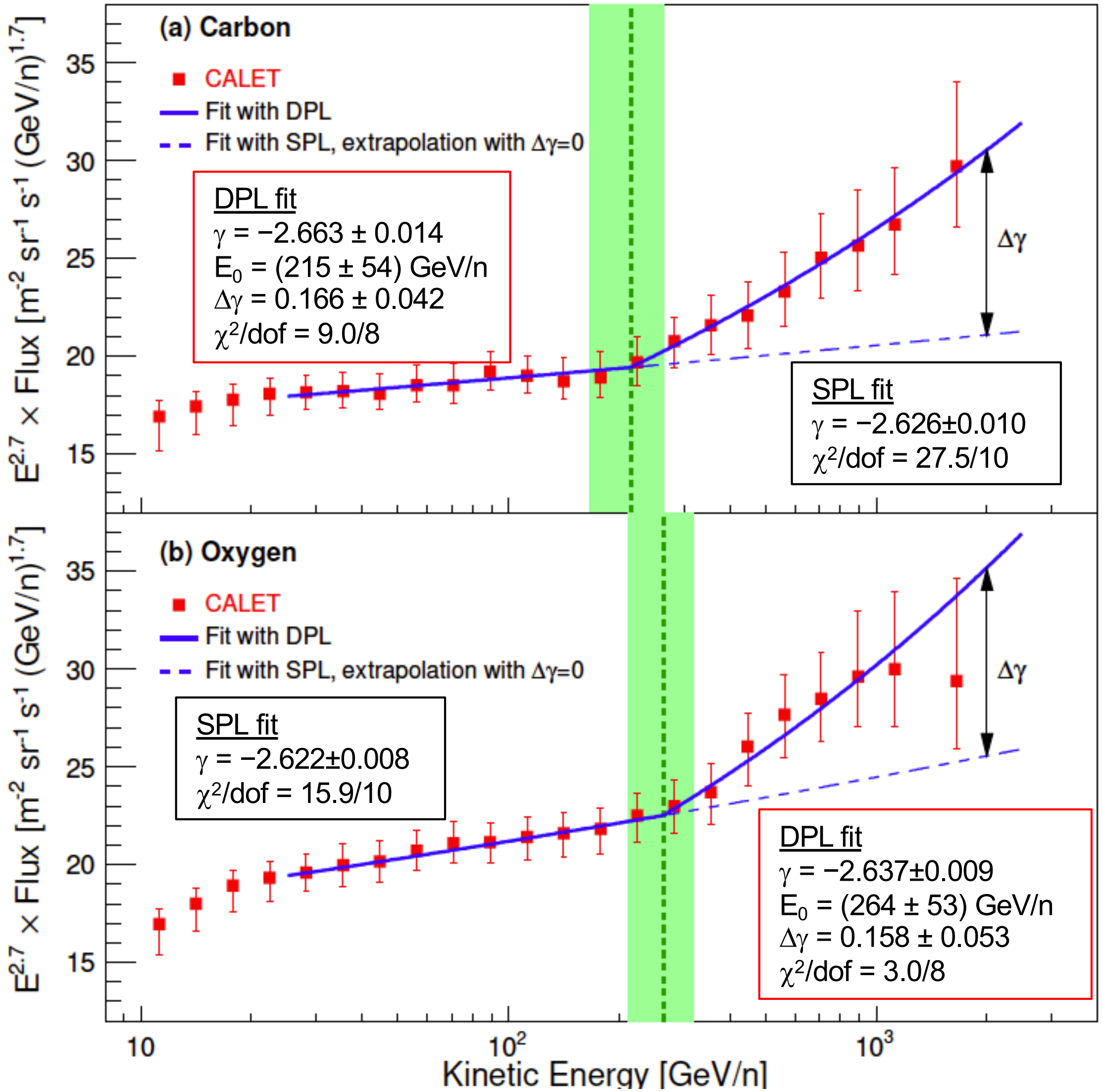
They have shapes like AMS-02 but the absolute normalization is significantly lower (~27%)





Spectral hardening in the carbon and oxygen spectra

PRL **125**, 251102 (2020)



Double power-law (BPL) fit:

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

Single power-law (SPL) fit:

$$\Phi(E) = C\left(\frac{E}{\mathrm{GeV}}\right)^{\gamma}$$

The effect of systematic uncertainties in the spectrum is modelled in the χ^2 minimization function with a set of nuisance parameters

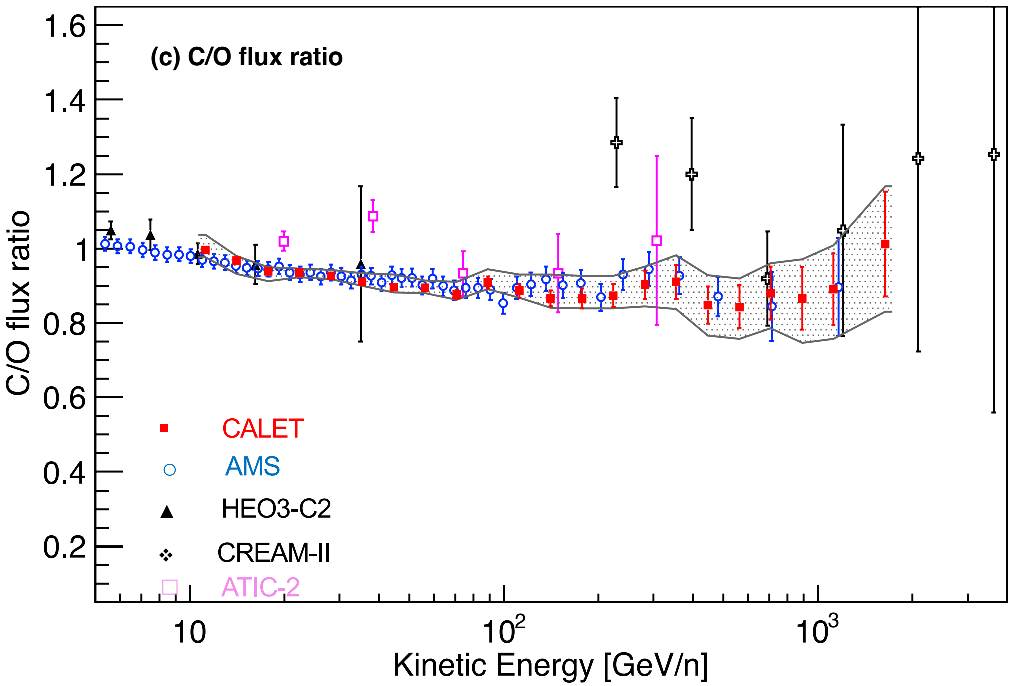
$\Delta\chi^2$ SPL-DPL fits with 2 dof →

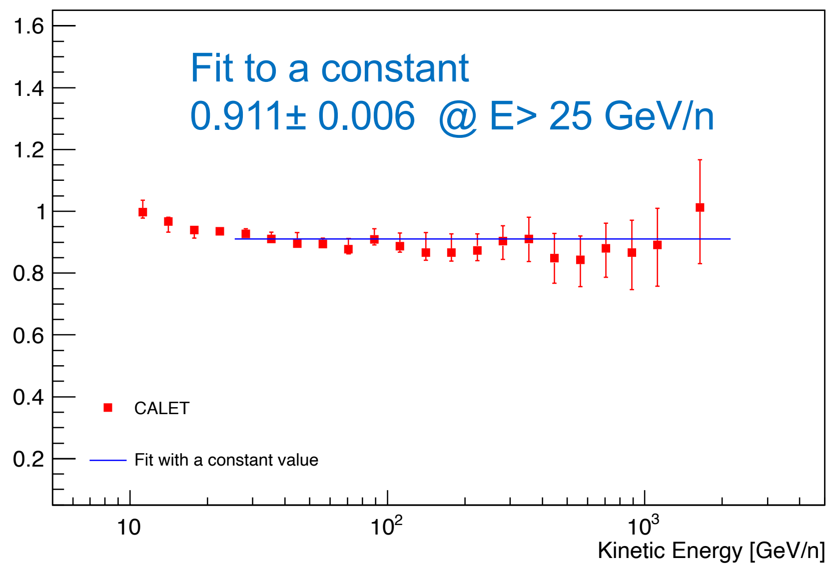
SPL hypothesis excluded at 3.9σ level for C and 3.2σ for O

C/O flux ratio

PRL **125**, 251102 (2020)

C/O ratio





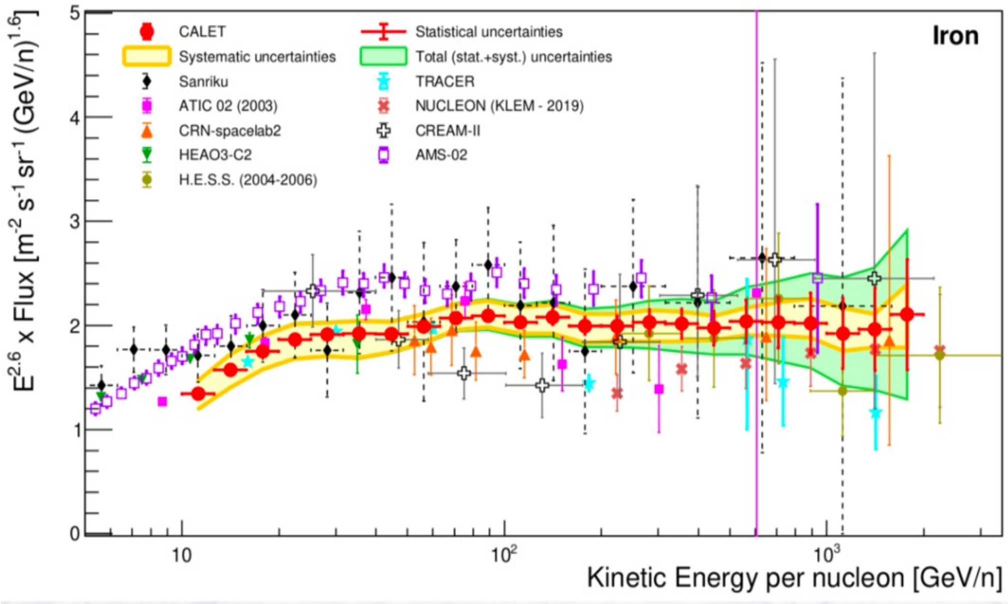
- C/O flux ratio as a function of energy is in good agreement with the one reported by AMS
- Above 25 GeV/n the C/O ratio is well fitted to a constant value of 0.911 ± 0.006 with χ^2/dof = 8.3/17

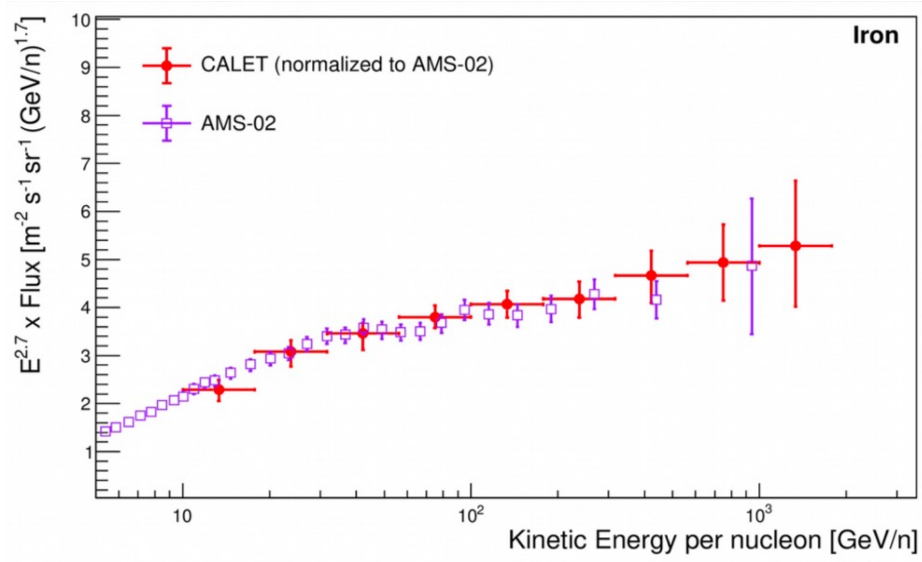
→ C and O fluxes have the same energy dependence.

Iron spectrum

PRL **126**, 241101 (2021)

- CALET spectrum is consistent with
  - ATIC-02 and TRACER at low energy
  - CRN and HESS at high energy
- CALET and NUCLEON iron spectra have similar shape, but different normalization
- CALET and AMS-02 iron spectra have a very similar shape, but differ in the absolute normalization of the flux by ~20%

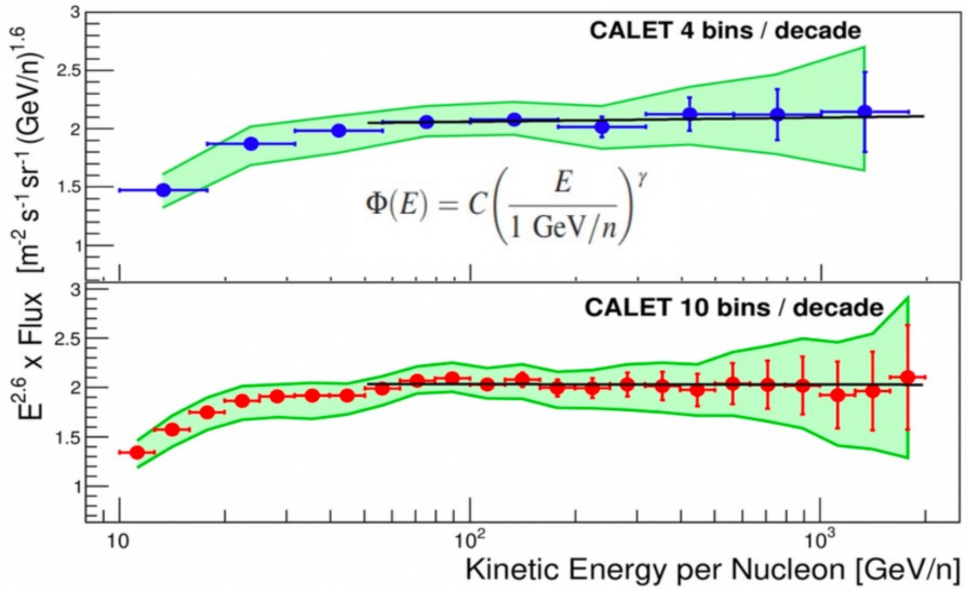




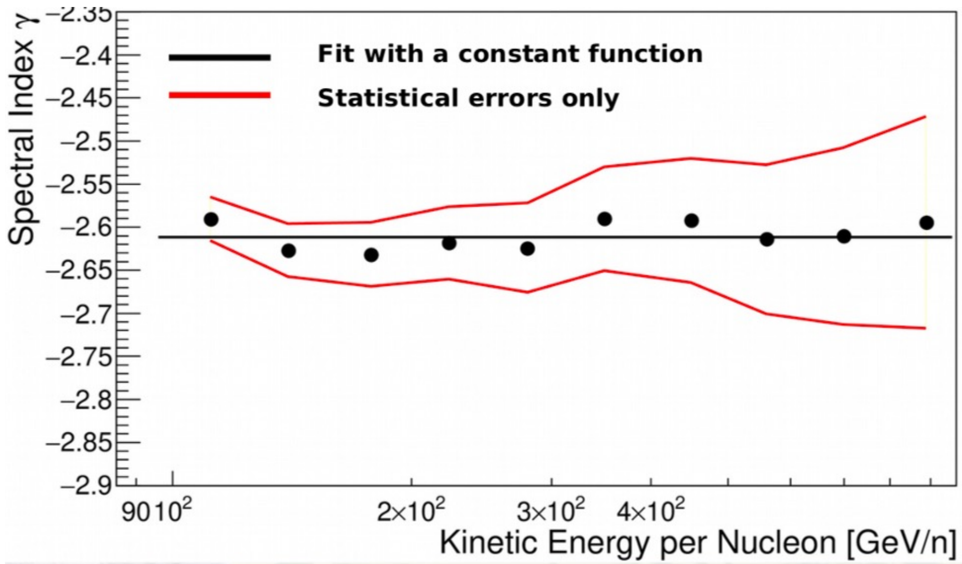
Spectral index of iron

PRL **126**, 241101 (2021)

Fit from 50 GeV/n to 2.0 TeV/n,
with a single power law function



Sliding window



- **10 bin/dec**: γ = -2.60 ± 0.02 (stat) ± 0.02 (sys)
- **4 bin/dec:** γ = -2.59 ± 0.02 (stat) ± 0.04 (sys)

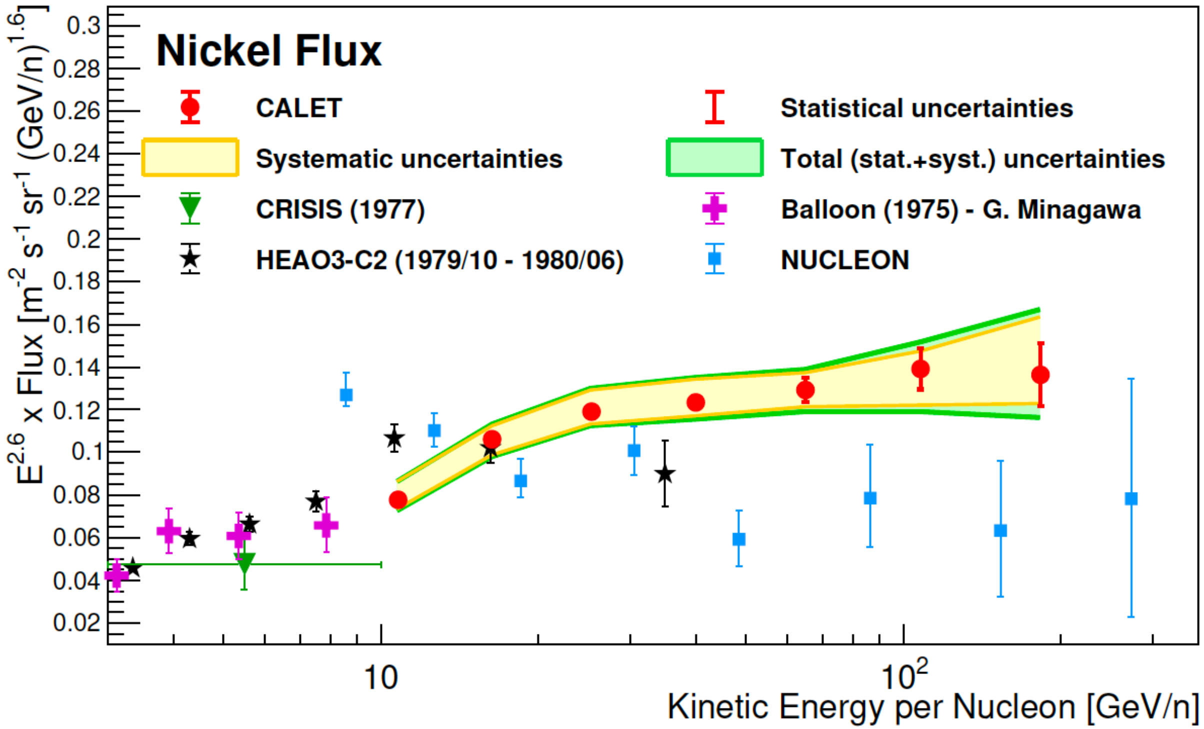
➡ **Stable when larger energy bins are used**

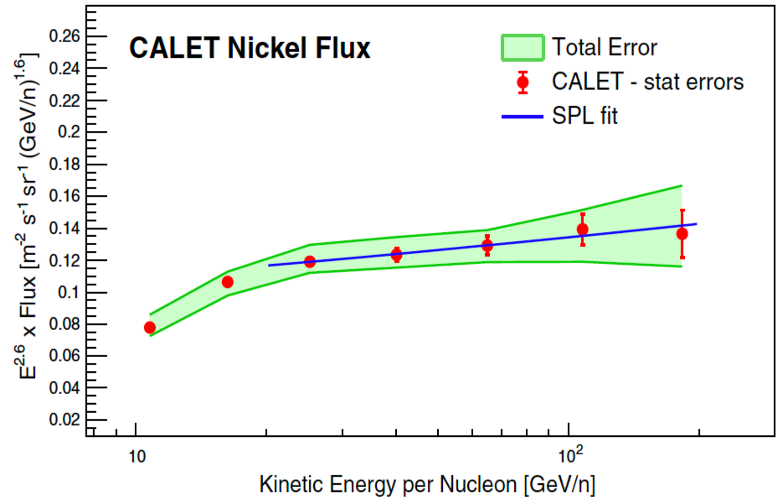
- Spectral index γ determined for each bin by fitting the data using ± 3 bins
- <γ> = -2.61 ± 0.01

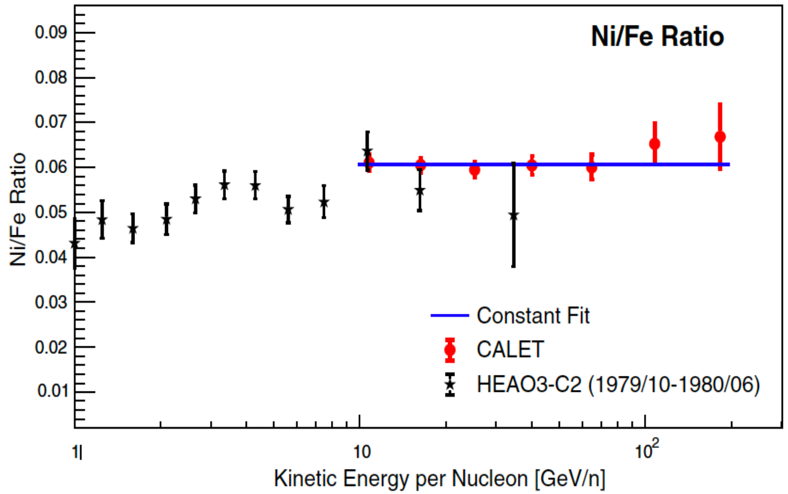
The iron flux, above 50 GeV/n, is compatible within the errors with a single power law

Nickel spectrum

PRL 128 131103 (2022)





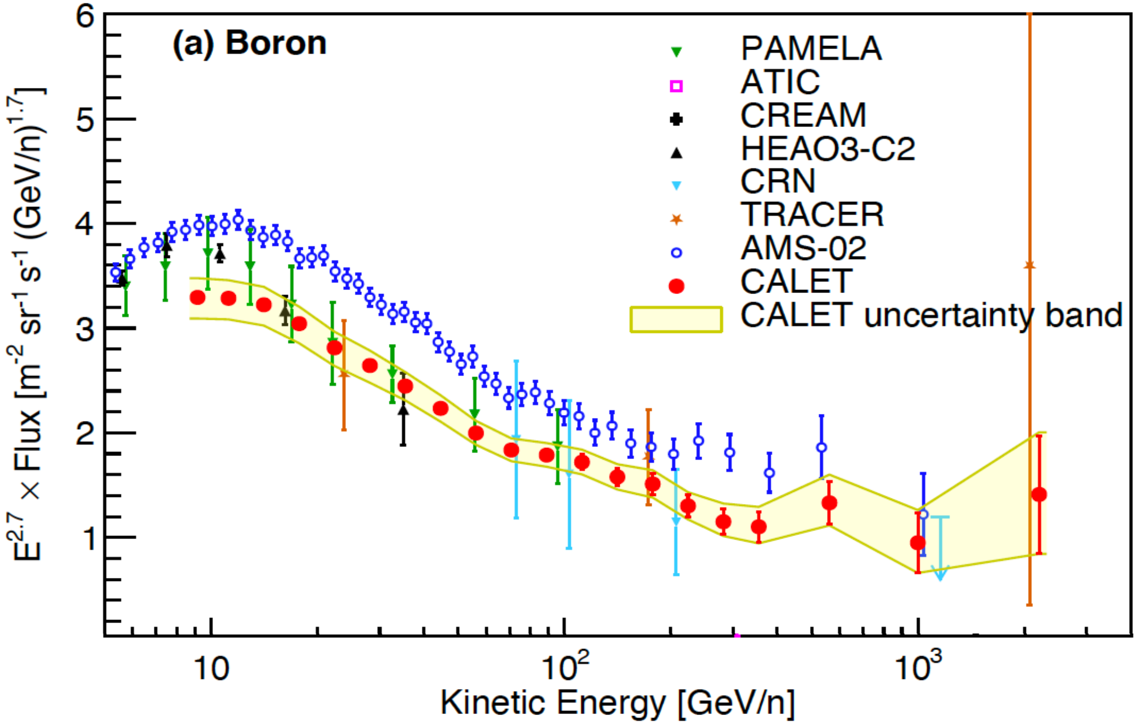


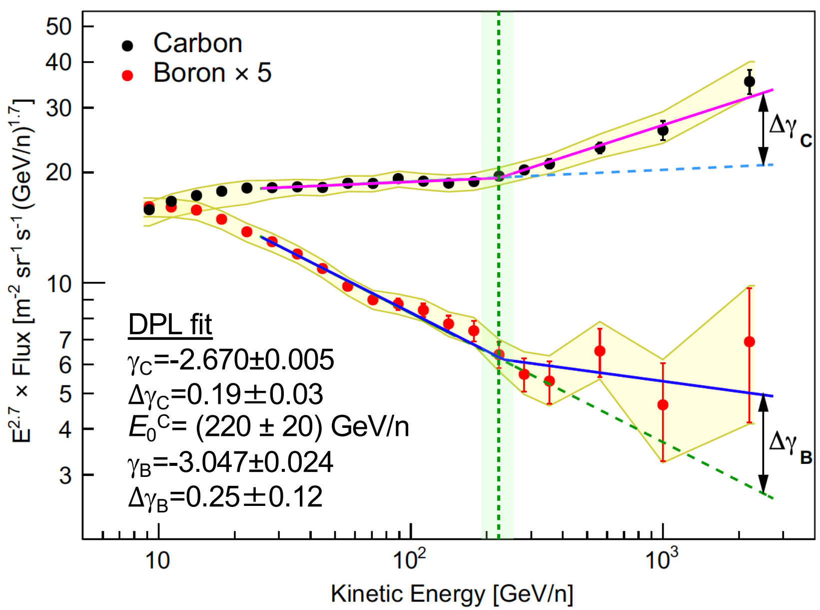
- Similar normalization with HEAO3-C2 and NUCLEON, through different spectral shape
- A single power-law fit:
  $\gamma = -2.51 \pm 0.07$ $E > 20$ GeV/n
- Ni/Fe ratio gives a constant value;
  0.061 ± 0.001

The nickel flux, above 20 GeV/n, is compatible within the errors with a single power law

Boron Spectrum

PRL 129 251103 (2022)





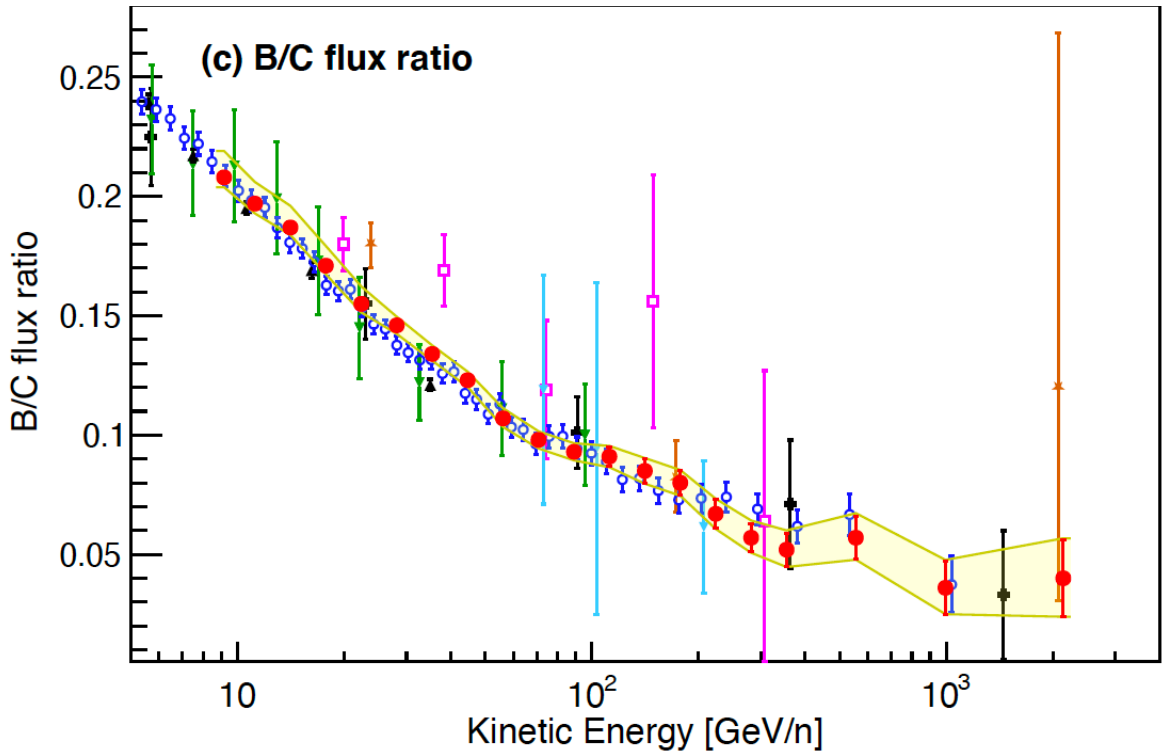
- The B spectrum is consistent with that of PAMELA and most of the earlier experiments, but the absolute normalization is in tension with that of AMS-02 like C, O and Fe fluxes.

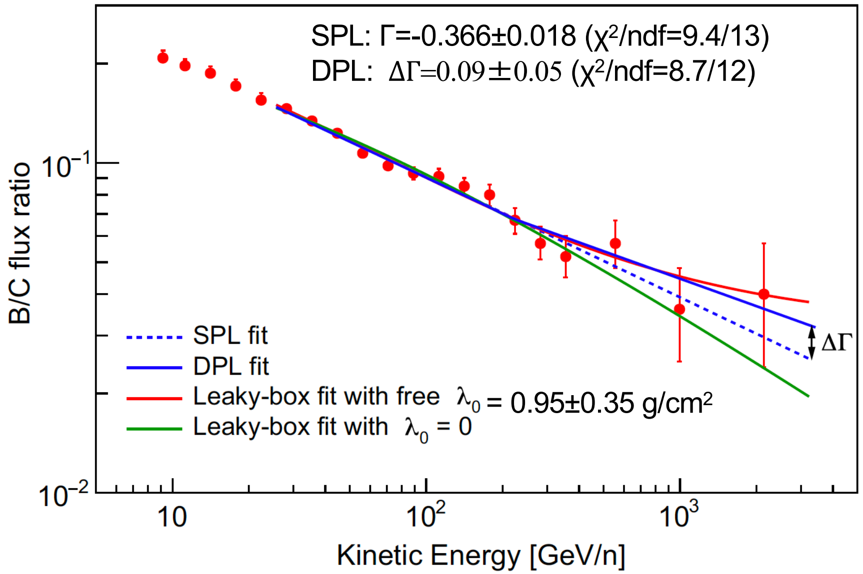
The energy spectra are clearly different as expected for primary and secondary CRs, albeit with low statistical significance, that the flux hardens more for B than for C above 200GeV/n

Boron-to-carbon ratio

PRL 129 251103 (2022)

Boron in cosmic rays are produced by the spallation reactions of primary CRs such as carbon
⇨ The B/C (primary-to-secondary) ratio includes a history of the propagation in the Galaxy.





- The B/C ratio with CALET is consistent with the one measured by AMS-02
- A DPL function provides a better fit, suggesting a trend of the data toward a flatting of the B/C ratio at high energy
- “Leaky-box” (LB) approximate fit suggests the possibility of a non-null value of the residual path length

Summary

- The measurement of the nuclei energy spectra with CALET has been performed with a significantly better precision than most of the existing measurements.
- CALET confirmed the spectral hardening in the spectra of proton, helium, carbon and oxygen, while iron spectrum is hypothesis of single power law function.
- The measurements of boron and B/C ratio indicates a harden more for B than for C above 200 GeV/n
- Our results are consistent with the ones reported by AMS-02, as regards the spectrum shape and hardening. However, the absolute normalization of our heavy nuclei data is significantly lower than AMS-02, but in agreement with other experiments.
- We performed detailed systematics checks to search for possible causes of this normalization issue. We can exclude that it can stem from trigger inefficiencies differences between MC simulation packages or hadronic models, or lacking modeling of the instrument.