国際宇宙ステーション搭載CALETによる宇宙線原子核の観測

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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 ~ 100ZTeV), etc.

Unexpected observation results

- Proton spectrum is harder than helium
- Spectra of proton and nuclei break at R~300GV

Direct measurements with CALET

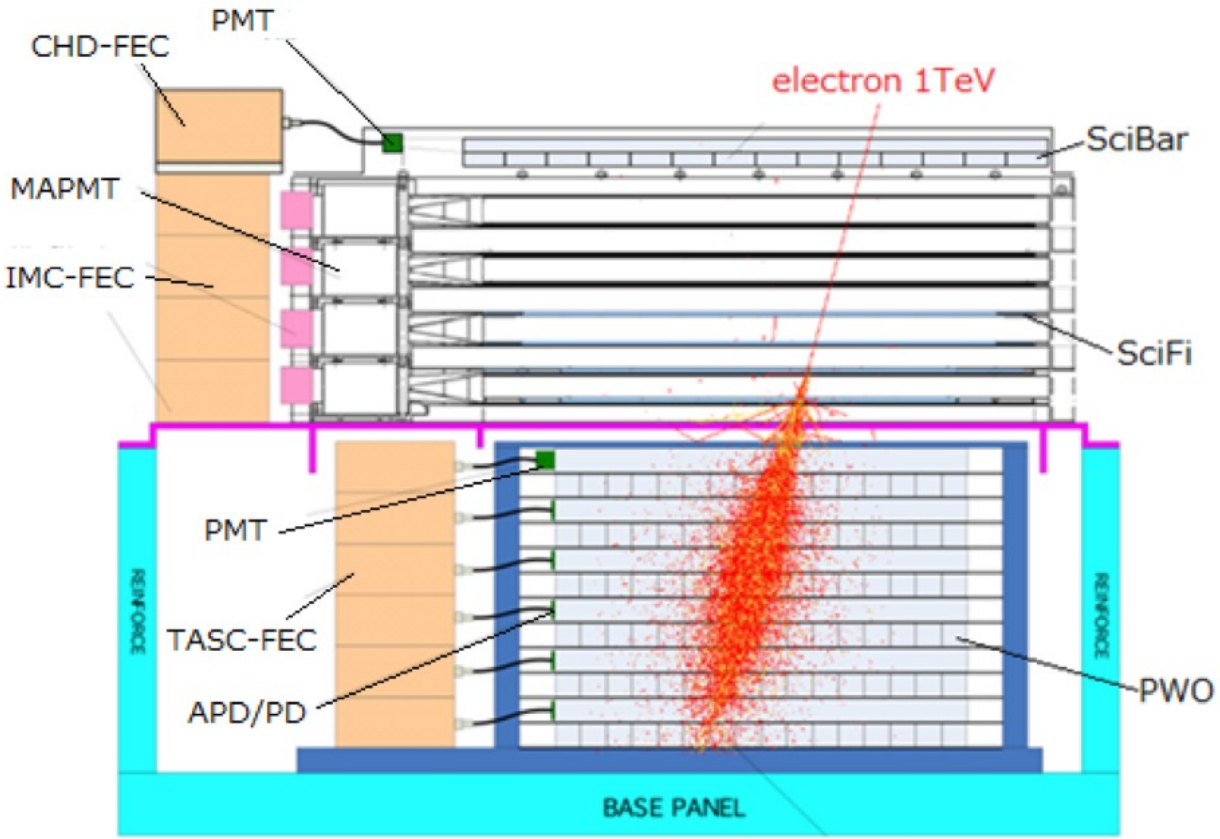
Precisely measure the energy spectra from proton through iron

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

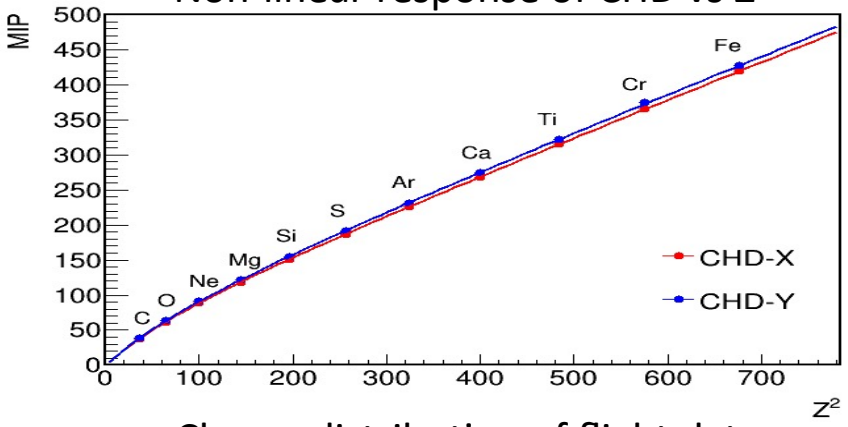
Energy measurement, Particle ID

- 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)

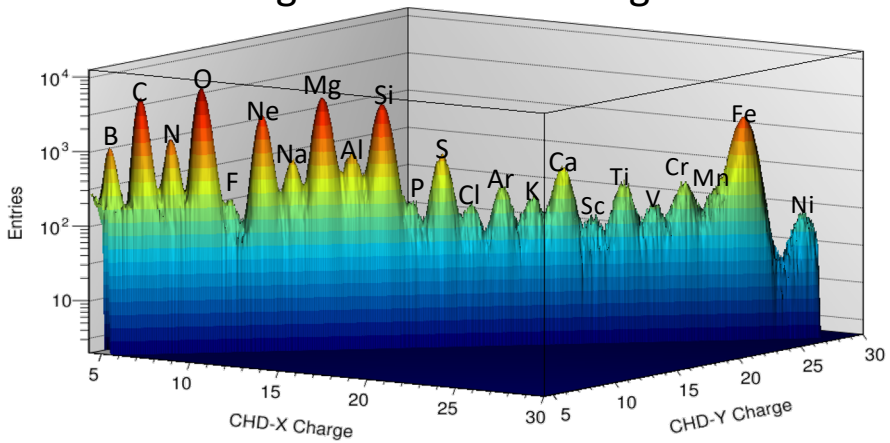
Charge measurement with CALET

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

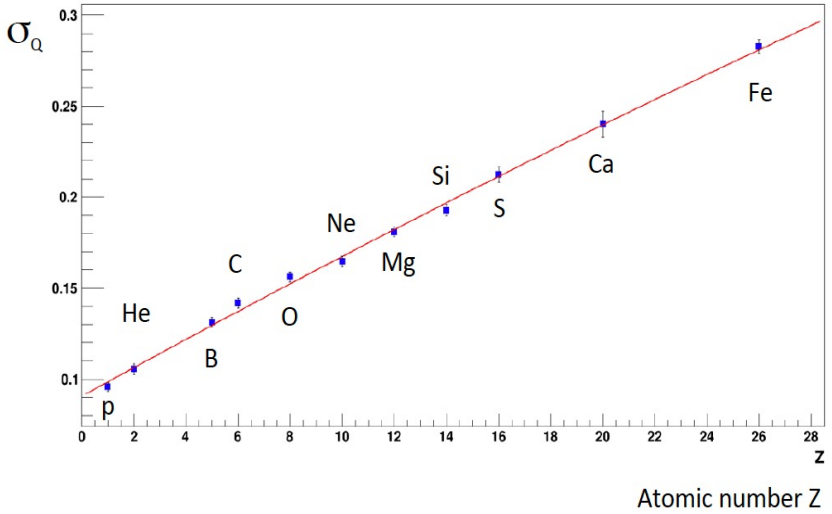
Non-linear response of CHD vs Z^2



Charge distribution of flight data

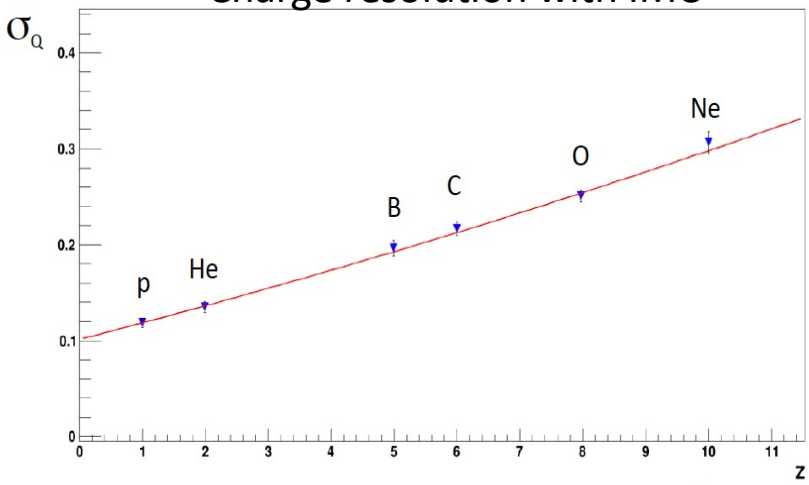


Charge resolution with CHD



Atomic number Z

Charge resolution with IMC

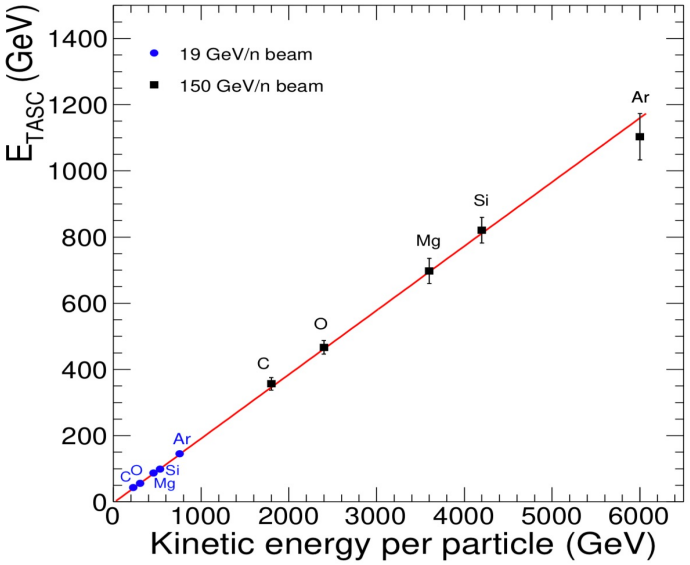


Atomic number Z

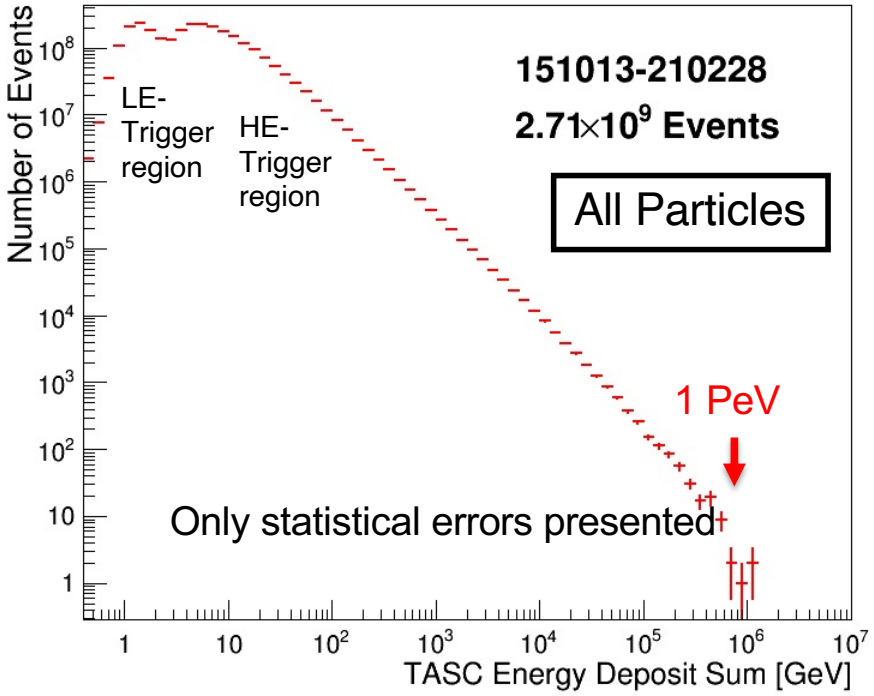
Energy measurement with CALET

- Dynamic range: 1 – 10^6MIP (1GeV – 1PeV)
- MIP calibration have performed on space
- Energy resolution: 30% for nuclei

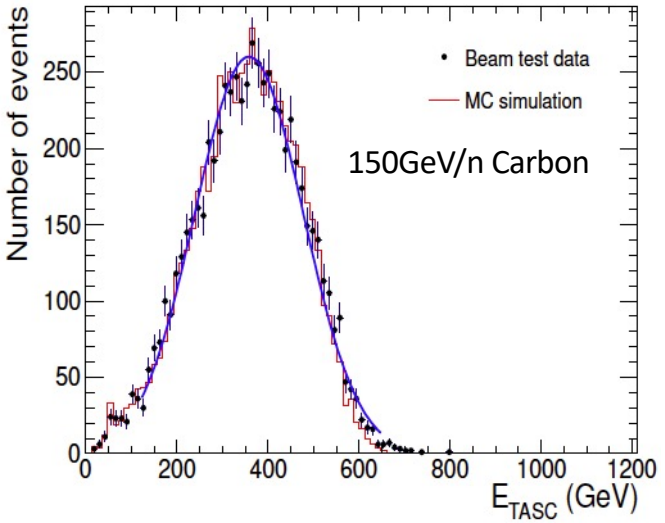
Linearity with beam test



Distribution of deposit energies (ΔE) in TASC



Energy distribution with beam test

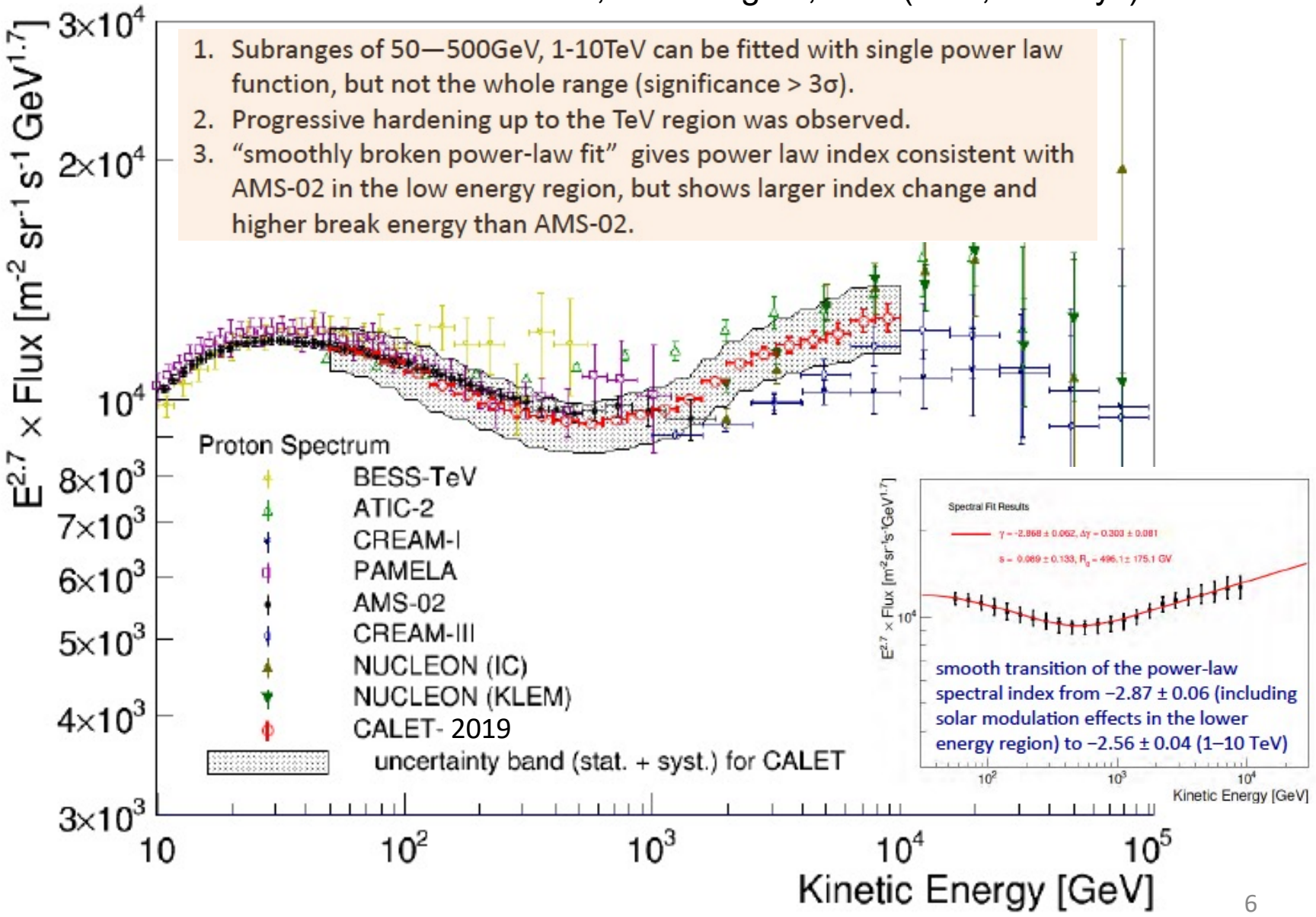


Proton Spectrum

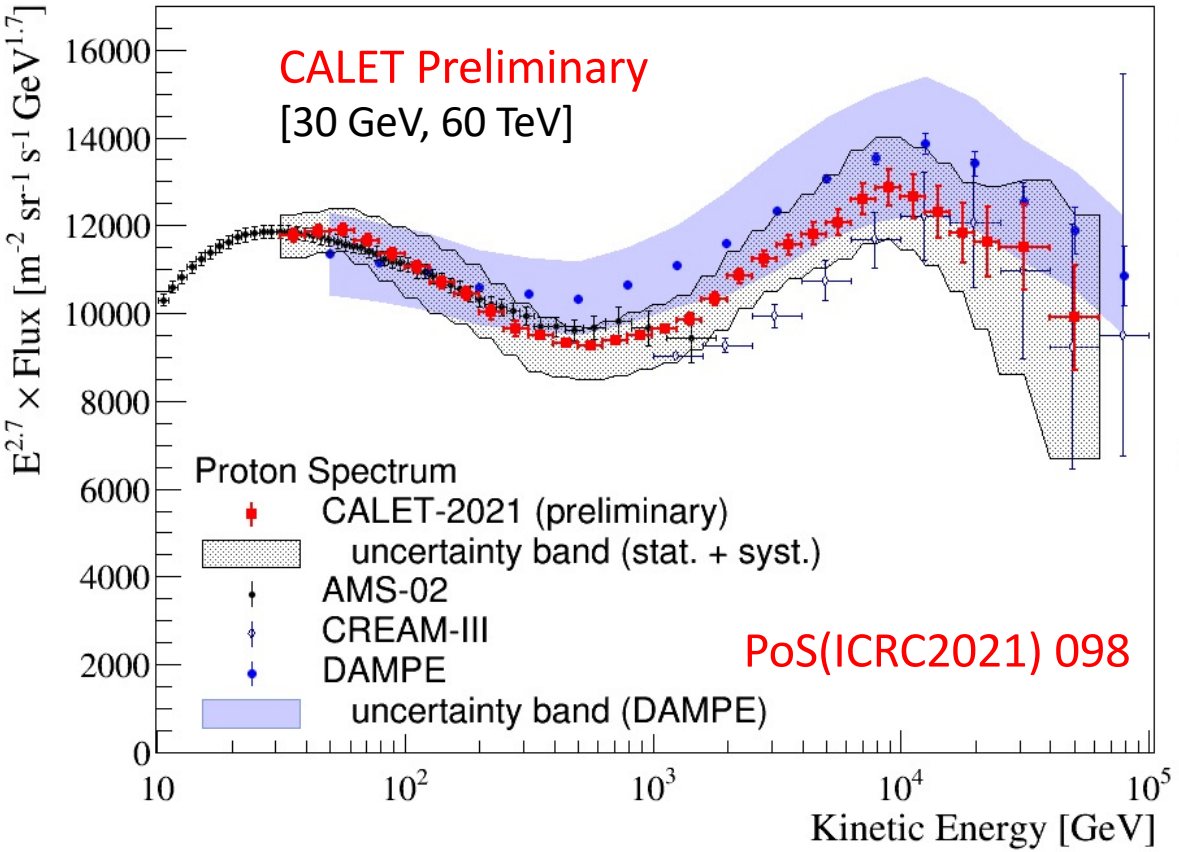
PRL **125**, 251102 (2020)

CALET Observations: Oct.13,2015- Aug.31,2018 (for 1,056 days)

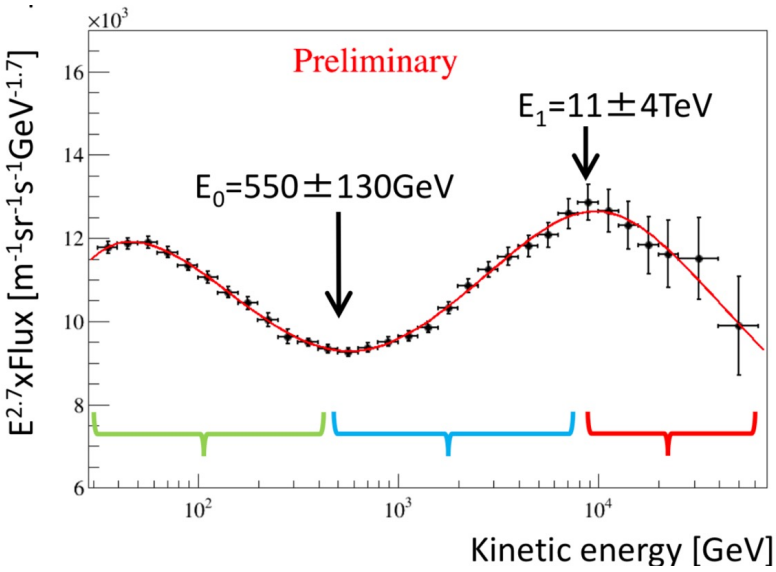
1. Subranges of 50—500GeV, 1-10TeV can be fitted with single power law function, but not the whole range (significance > 3σ).
2. Progressive hardening up to the TeV region was observed.
3. "smoothly broken power-law fit" gives power law index consistent with AMS-02 in the low energy region, but shows larger index change and higher break energy than AMS-02.



Proton spectrum (update: as of Sep.30 2020)



Spectral fit with double broken power law



$$\Phi = E^{2.7} \times C \times \left(1 - \frac{p_0}{E} - \frac{p_1}{E^2}\right) \times \left(\frac{E}{45}\right)^{\gamma} \times \left(1 + \left(\frac{E}{E_0}\right)^{s}\right)^{\frac{\Delta\gamma}{s}} \times \left(1 + \left(\frac{E}{E_1}\right)^{s}\right)^{\frac{\Delta\gamma_1}{s}}$$

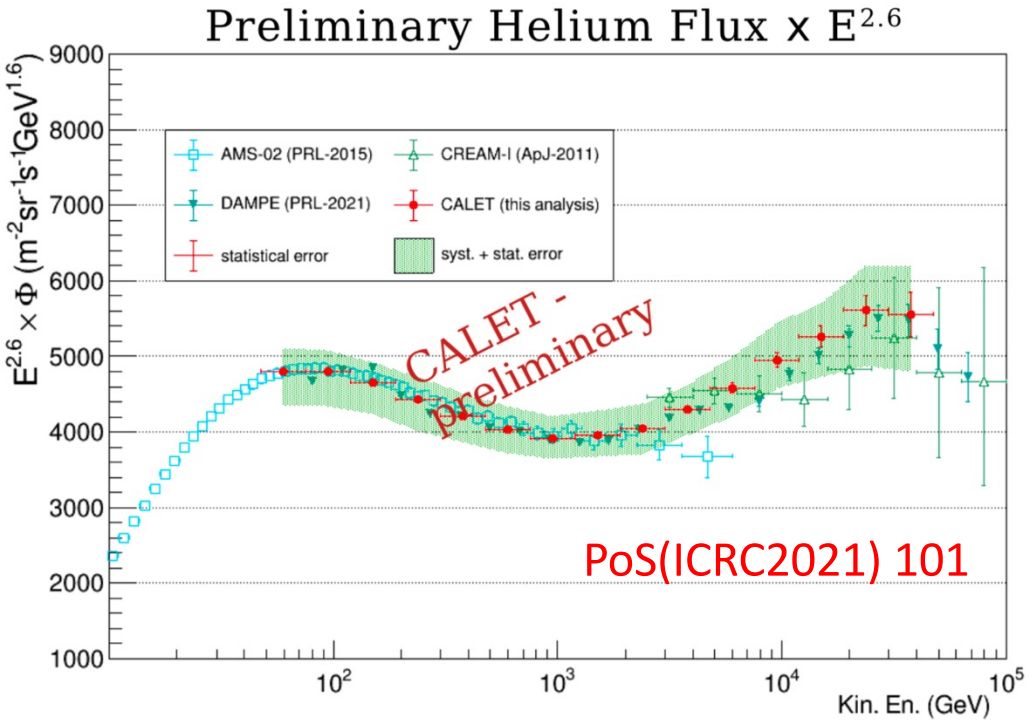
Low energy hardening softening

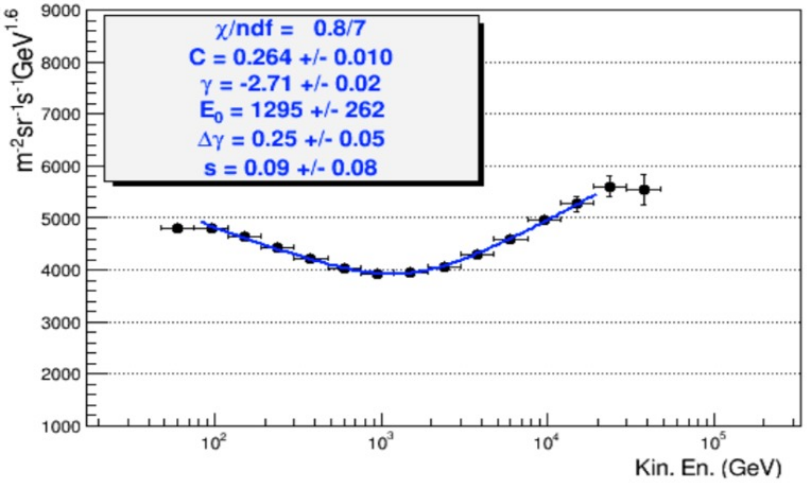
C	(5.1±2.1)x10^{-1}	S	2.1±2.0
p_0	9.1±26	Δγ	(4.4±3.8)x10^{-1}
P_1	-6.6±470	E_0	(5.5±1.3)x10^{2}
γ	-2.9±0.3	$\Delta\gamma_1$	(-4.4±3.0)x10^{-1}
		E_1	(1.1±0.4)x10^{4}

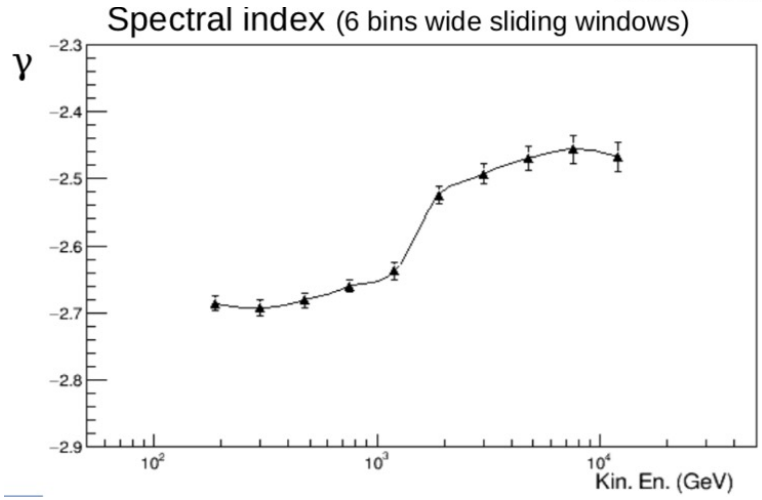
$\chi^2 = 2.9/22$

- CALET expands the energy region to 60 TeV and a spectral softening in E>10 TeV as well.
- DAMPE flux is consistent with AMS=02 and CALET up to 200 GeV. Above, the flux is higher (close to the limit of the systematic error band)

Helium spectrum



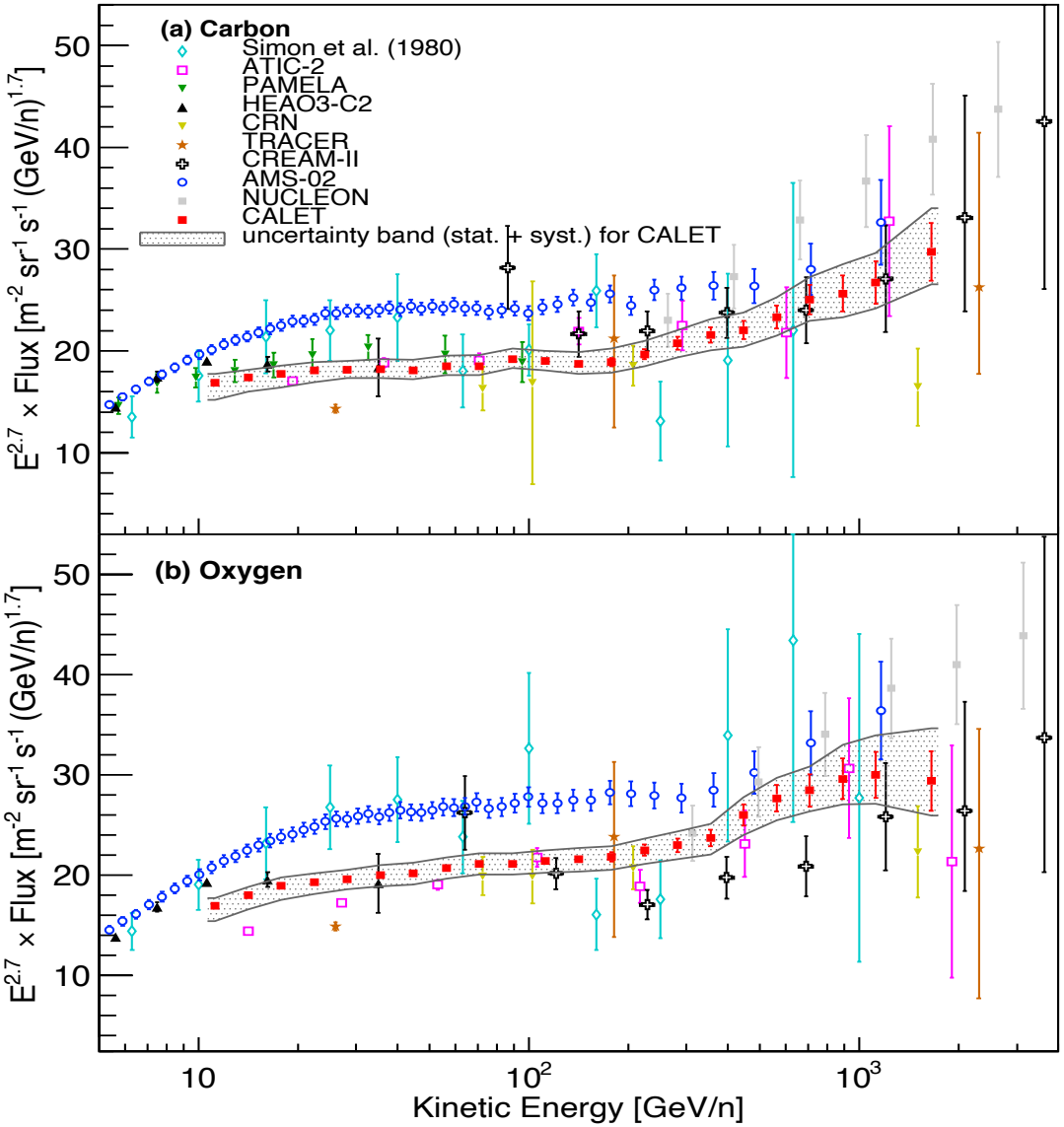




- Progressive hardening up to the multi-TeV region was observed
- Smoothly brloken power-law fit gives power law index (γ), Δγ and break energy (E_0) consistent with the recent results from DAMPE

Carbon and Oxygen spectra

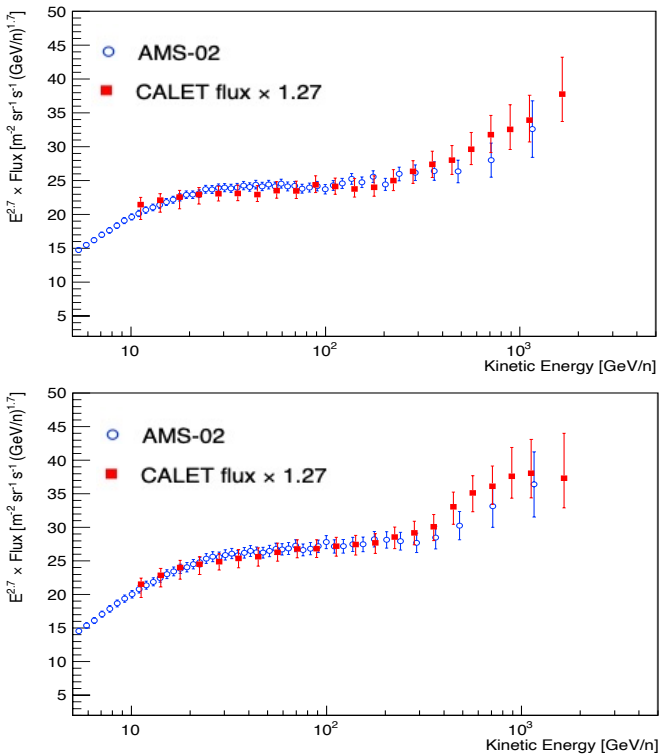
PRL **125**, 251102 (2020)



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

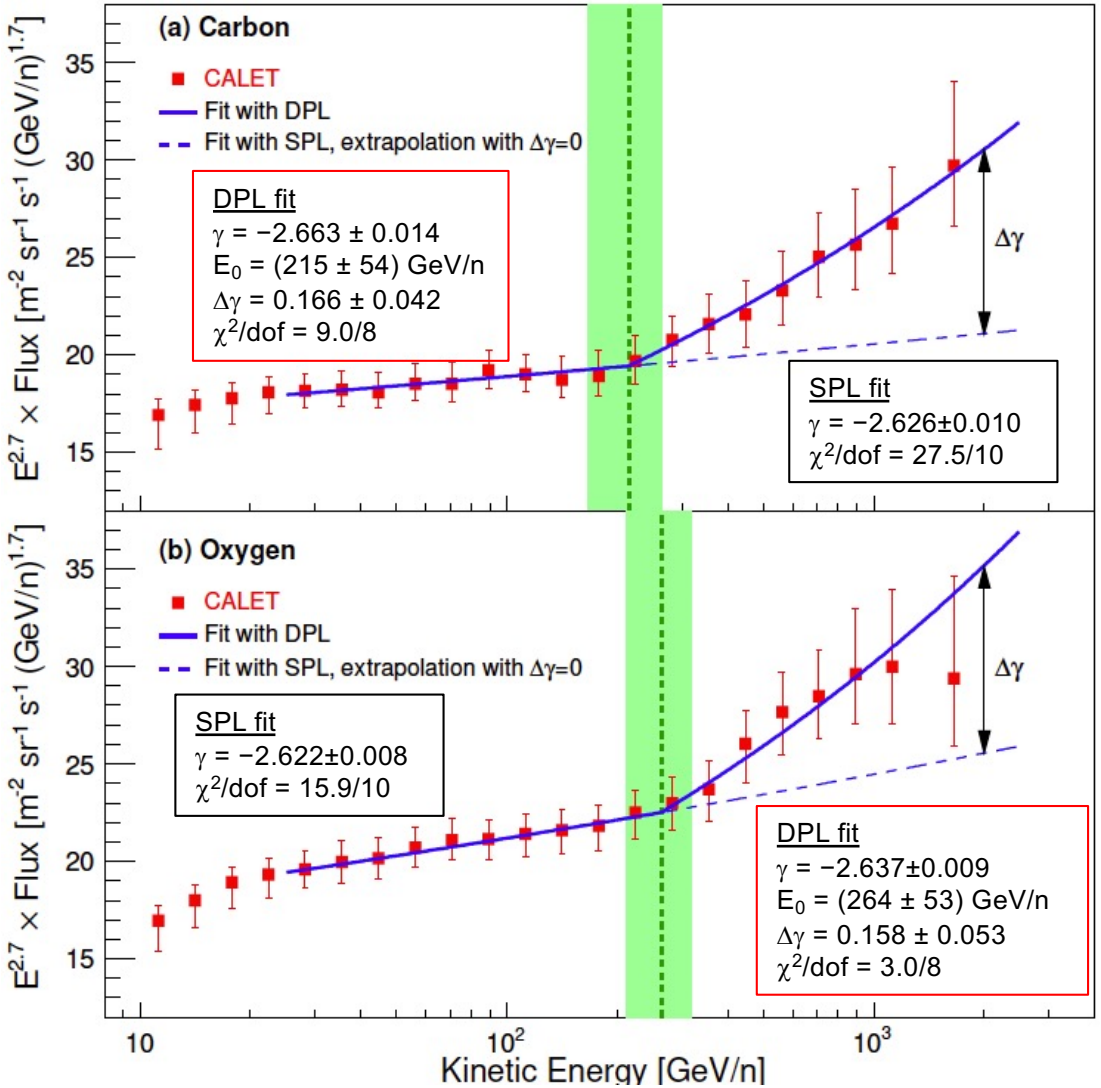
The spectra show a clear hardening around 200 GeV/n.

They have shapes similar to 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:

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

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

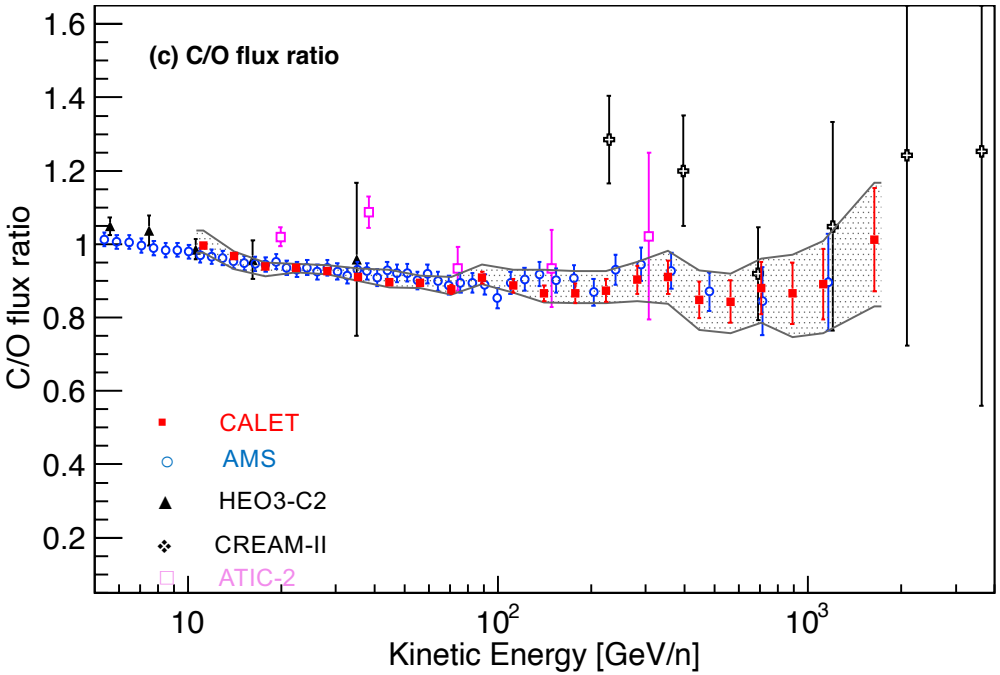
$\Delta\chi^2$ SPL-DPL fits with 2 dof →

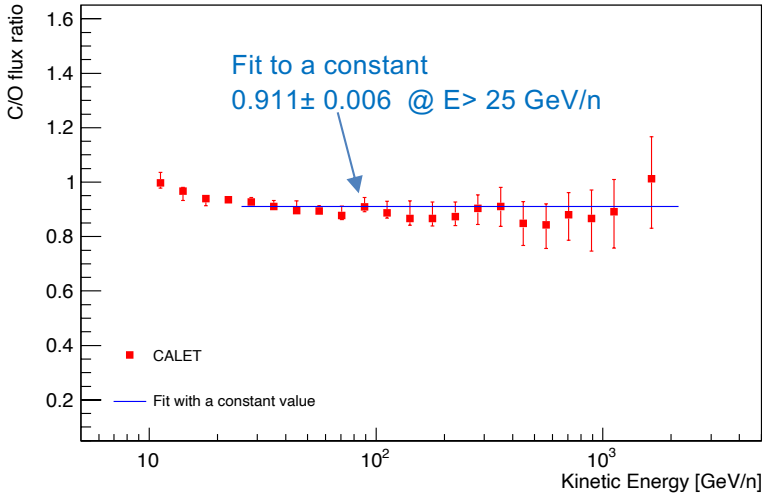
SPL hypothesis excluded at 3.9σ level for C and 3.2σ for O

C/O flux ratio

PRL **125**, 251102 (2020)

C/O ratio





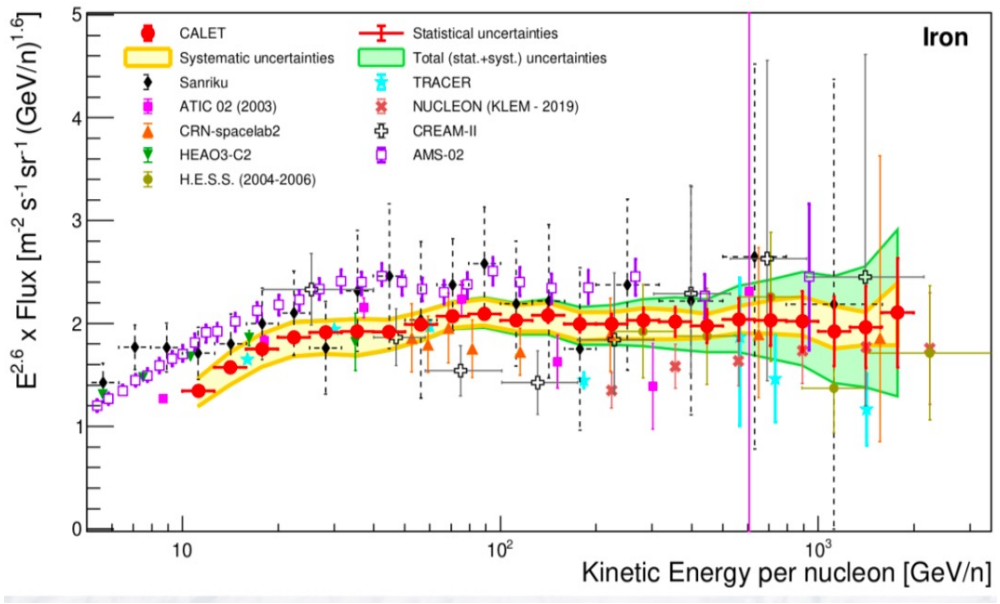
- C/O flux ratio as a function of energy is in good agreement with the one reported by AMS
- Above 25 GeV/n the C/O ratio is well fitted to a constant value of 0.911 ± 0.006 with χ^2/dof = 8.3/17

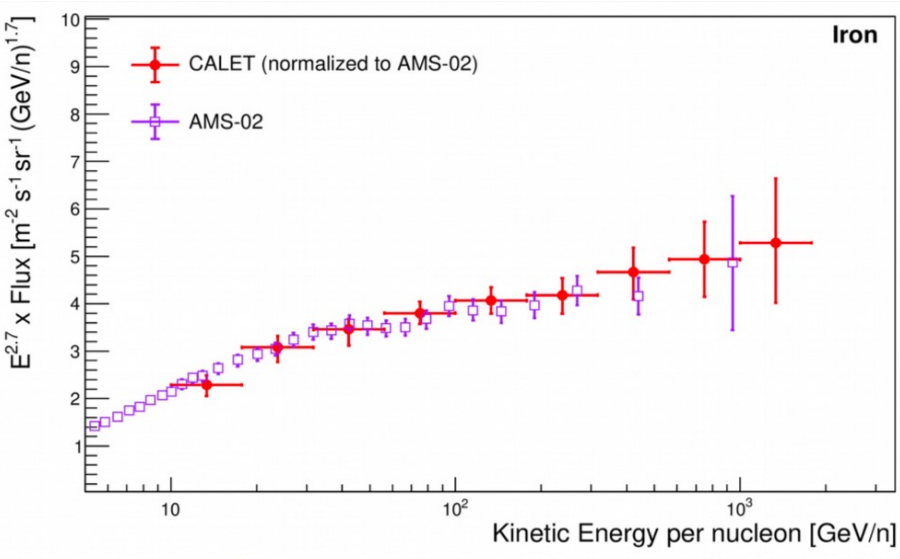
→ C and O fluxes have the same energy dependence.

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%

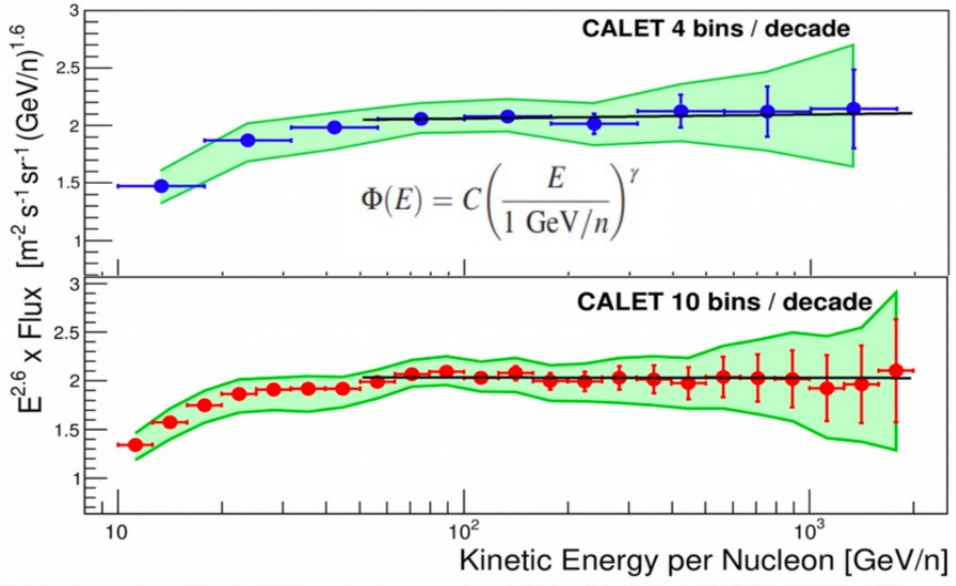




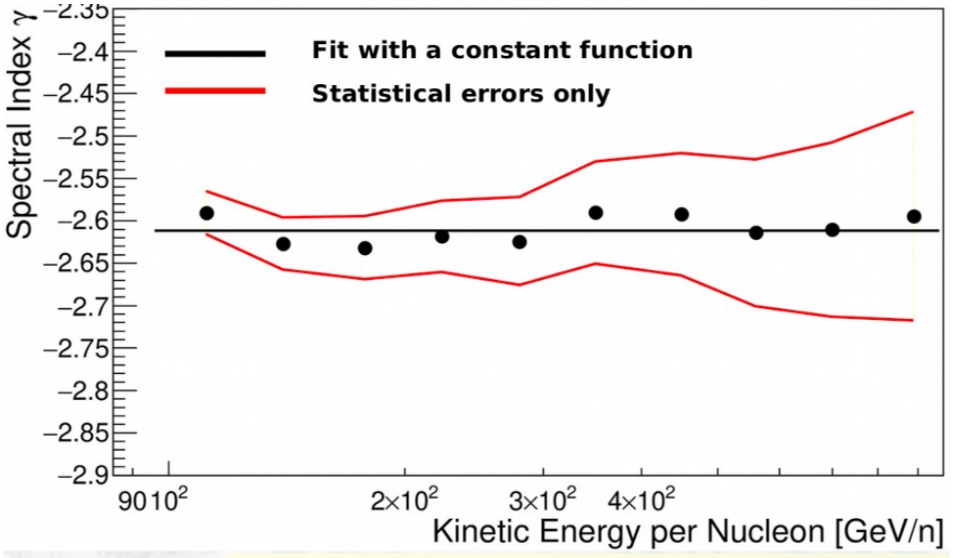
Spectral index of iron

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**

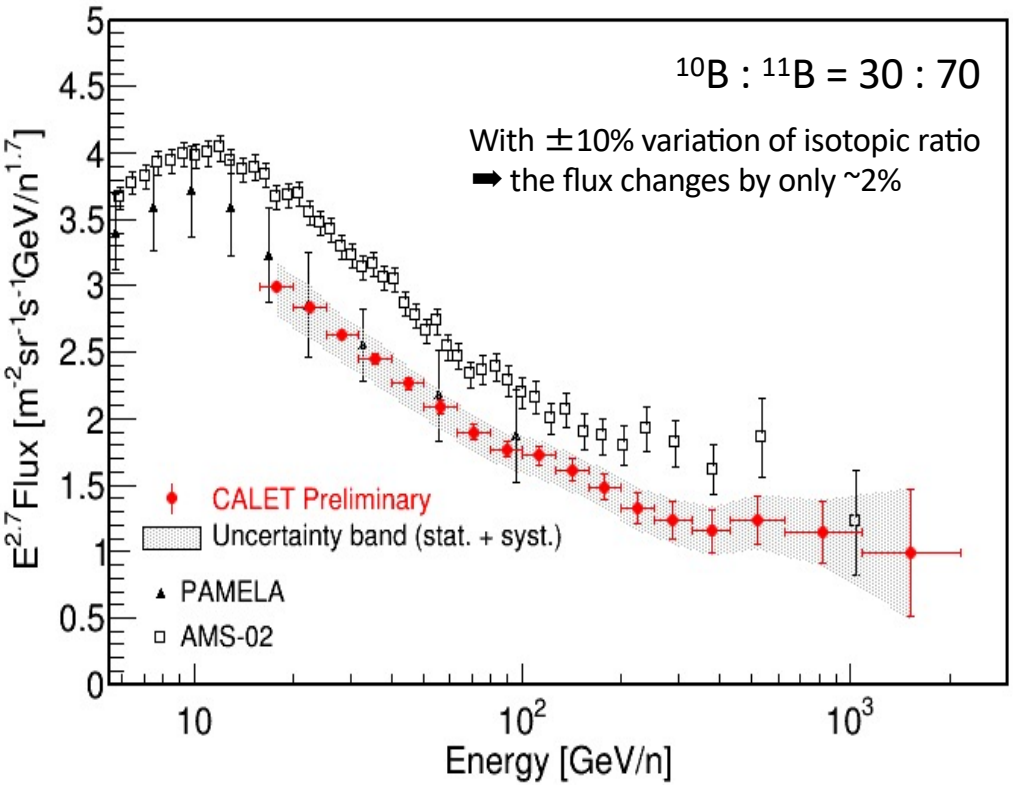
- Spectral index γ determined for each bin by fitting the data using ± 3 bins
- <γ> = -2.61 ± 0.01

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

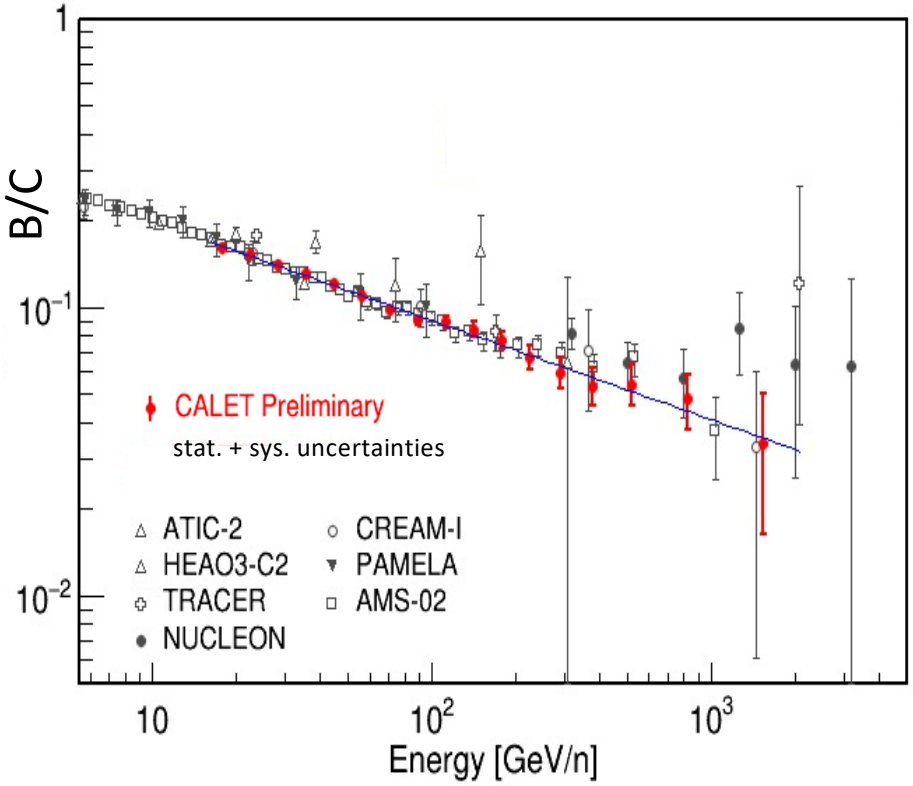
Boron spectrum and B/C ratio

PoS (ICRC2021) 112

Boron energy spectrum



B/C ratio



- Flux normalization is consistent with PAMELA, while ~20% lower than AMS-02.
- Fit with a single power law function: $\delta = -0.344 \pm 0.012$ (E>20GeV/n), χ^2/ndf = 5.6/15

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.

- 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.