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Measurements of Heavy Cosmic-Ray Nuclei Spectra with CALET on the ISS

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34) Yukawa Institute for Theoretical Physics, Kyoto University, Japan

Measurements of Cosmic-Ray Nuclei

Nuclei measurements in GeV – TeV energy region

- Primary individual spectra
  - cosmic-ray acceleration and propagation
  - hardening of spectra
- Secondary-to-primary flux ratio
  - cosmic-ray propagation
  - energy dependence of diffusion coefficient

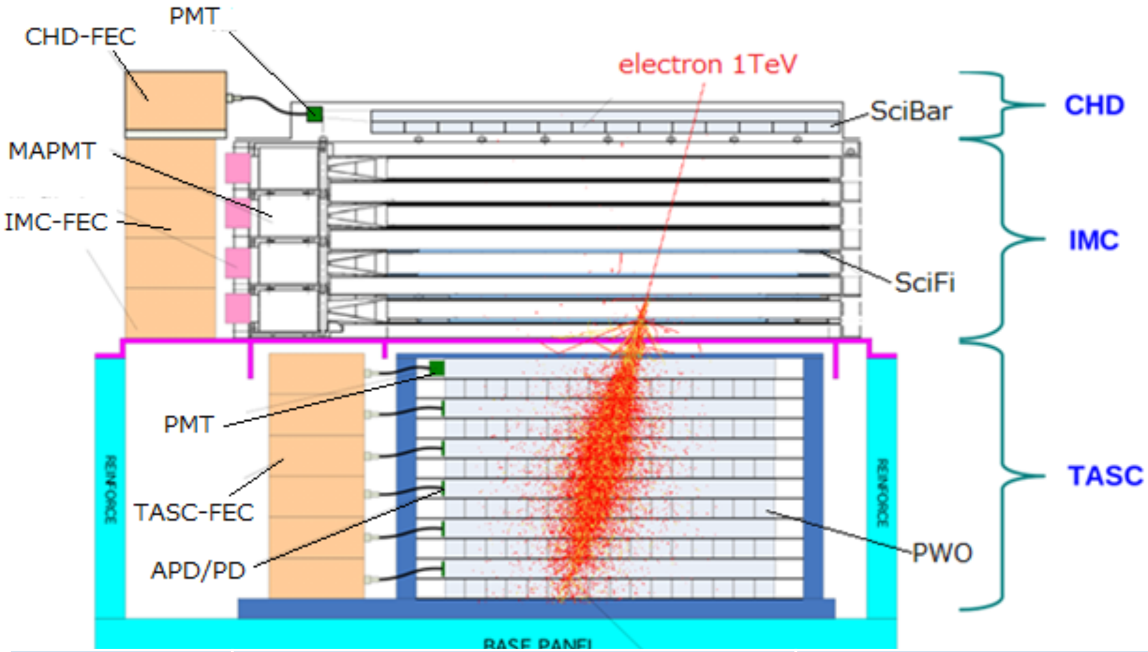
Direct measurements with CALET

Energy spectra from Proton to Iron

- Charge measurement in Z = 1 – 40
  - charge resolution: 0.15*e*(C)-0.3*e*(Fe)
- Energy measurement in 10GeV − 1PeV
  - dynamic range : 1 − 10^6MIP (~1PeV)

CALET-CAL Detector

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



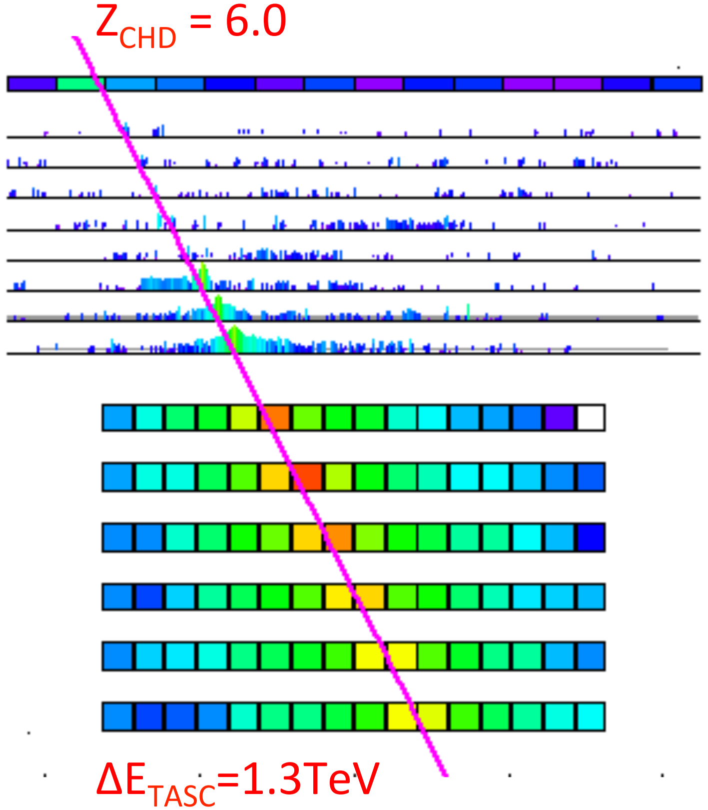
Performances

- Energy resolution
  - 2% (>100GeV) for electron, γ
  - 30~35% for protons, nuclei
- Charge resolution
  - 0.15 – 0.3*e*
- Angular resolution
  - 0.2 deg for electron, γ > ~50GeV

	CHD (Charge Detector)	IMC (Imaging Calorimeter)	TASC (Total Absorption Calorimeter)
Function	Charge Measurement (Z=1-40)	Arrival Direction, Particle ID	Energy Measurement, Particle ID
Sensor (+ Absorber)	**Plastic Scintillator : 14 × 2layers** Unit Size: 32mm x 10mm x 450mm	**Scintillating fibers: 448 x 16 layers** Unit size: $1mm^2$ x 448 mm **Total thickness of Tungsten: 3 X_0**	**PWO log: 16 x 12 layers** Unit size: 19mm x 20mm x 326mm **Total Thickness of PWO: 27 X_0**
Readout	PMT+CSA	64 -anode MAPMT + ASIC	APD/PD+CSA PMT+CSA (for Trigger)@top layer

Analysis procedure for nuclei

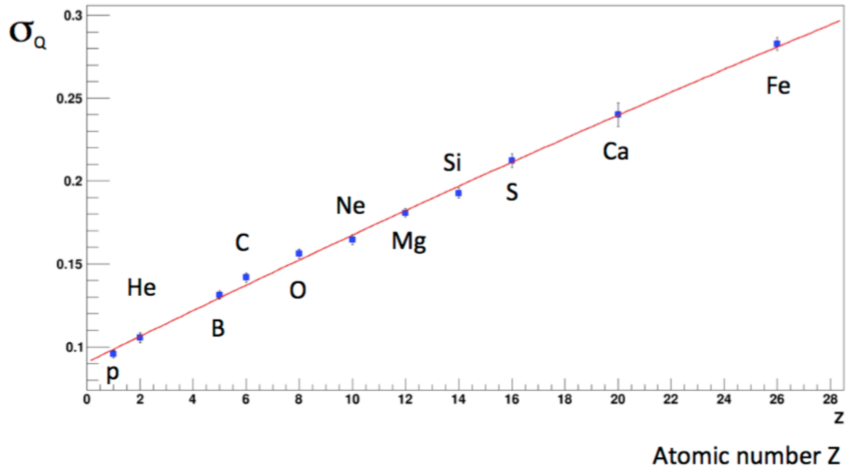
1. HE (High Energy) trigger
   - Period: Oct. 13 2015 - Oct. 31 2017 (750days)
2. Offline shower trigger
3. Tracking with IMC
   - select events satisfied Geom.A
   - identify the impact point
4. Charge consistency with CHD and IMC
   - remove backgrounds
   - maintain charge resolution
5. Charge selection with CHD
   - estimate background
6. Energy measurements and unfolding
   - measure energy with TASC
   - unfold energy spectrum by Iterative Bayesian process
7. Flux Calculation



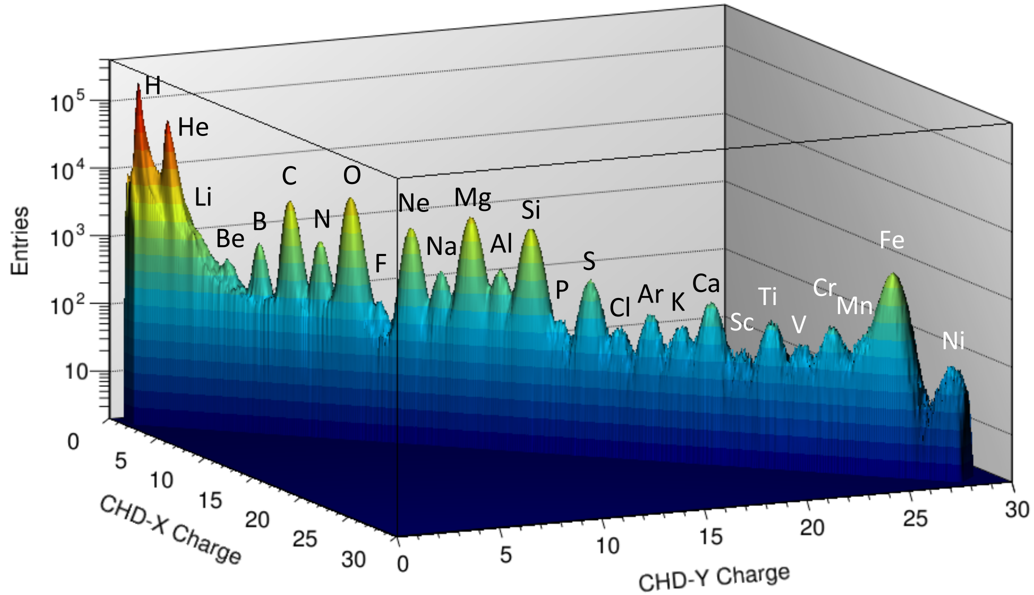
Charge resolution

- Non-linear response to Z^2 is corrected both in CHD and IMC using a model
- A clear separation between p, He, ~Z=8, can be seen from CHD+IMC data analysis

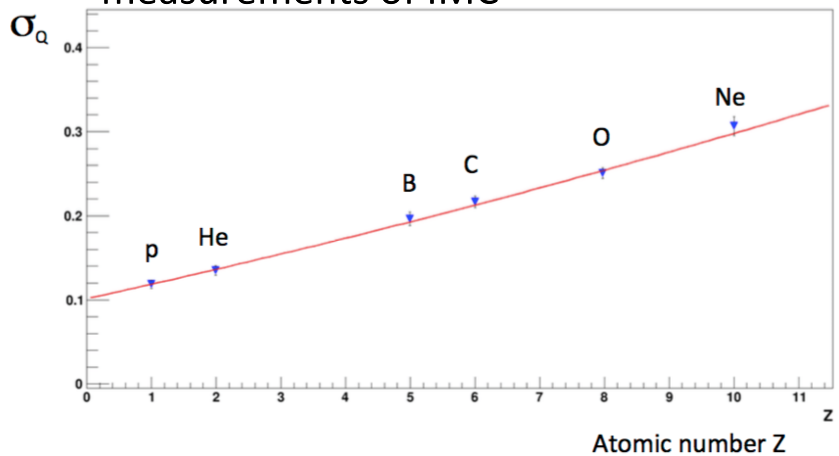
Charge resolution with 2layers of CHD



Charge with CHD-X vs CHD-Y



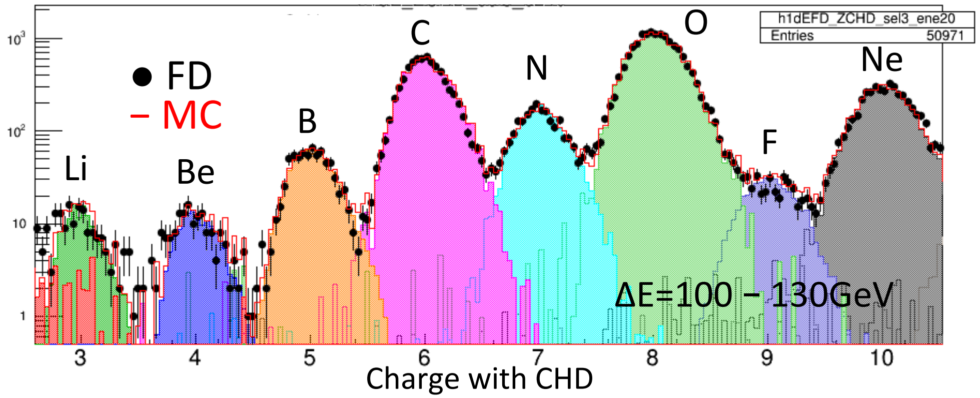
Charge resolution using multiple dE/dx measurements of IMC

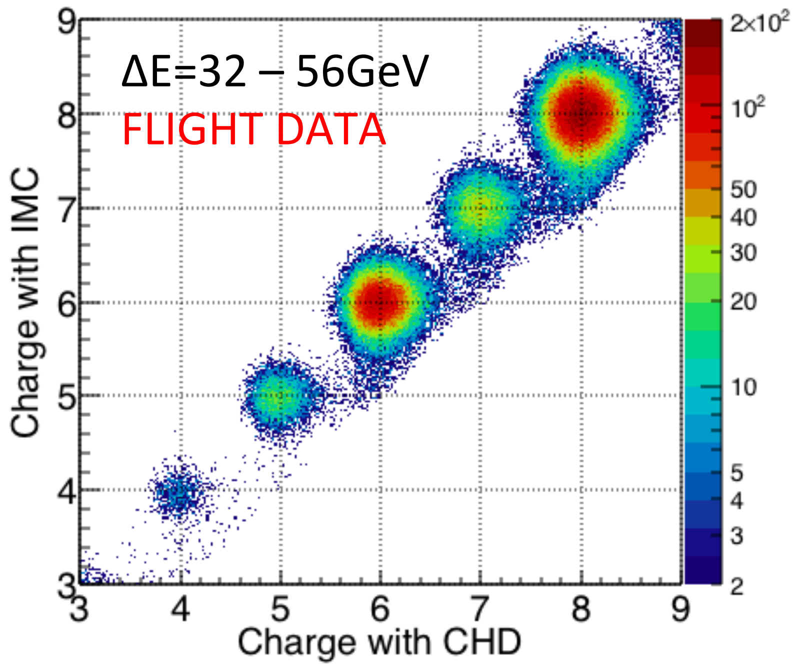


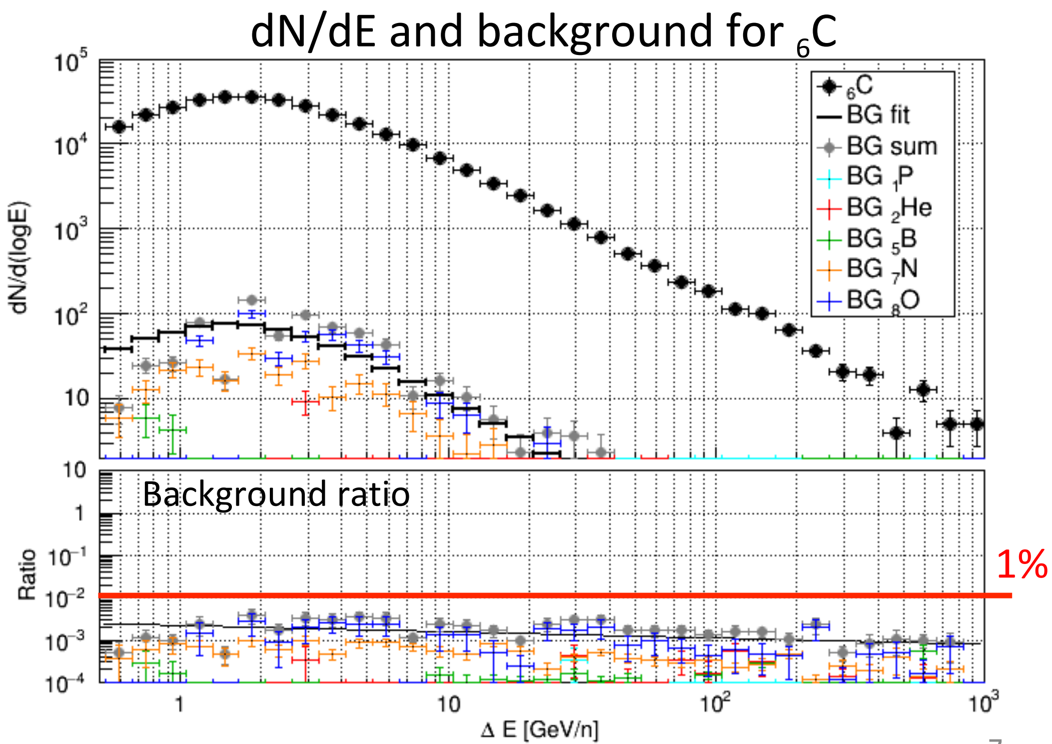
Charge identification of Carbon

<u>Pre-selection</u>

- HE trigger
- Tracking + geometrical condition
- Z-consistency with CHD-X and CHD-Y
- Z-consistency with CHD and IMC







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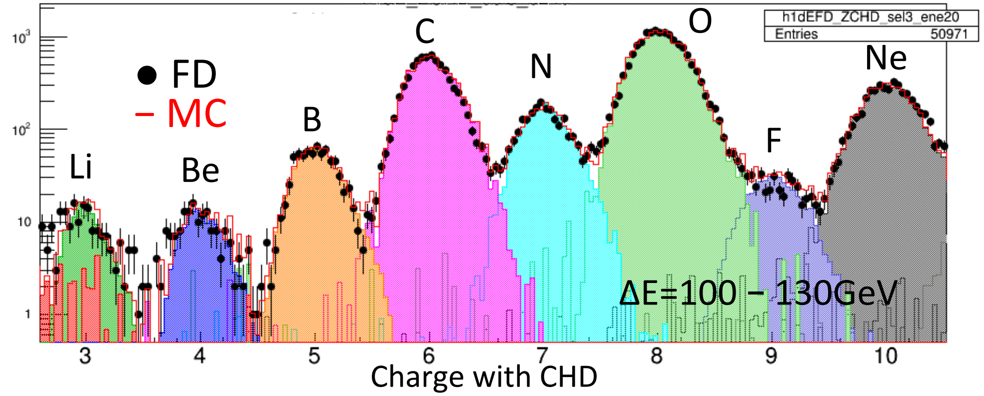
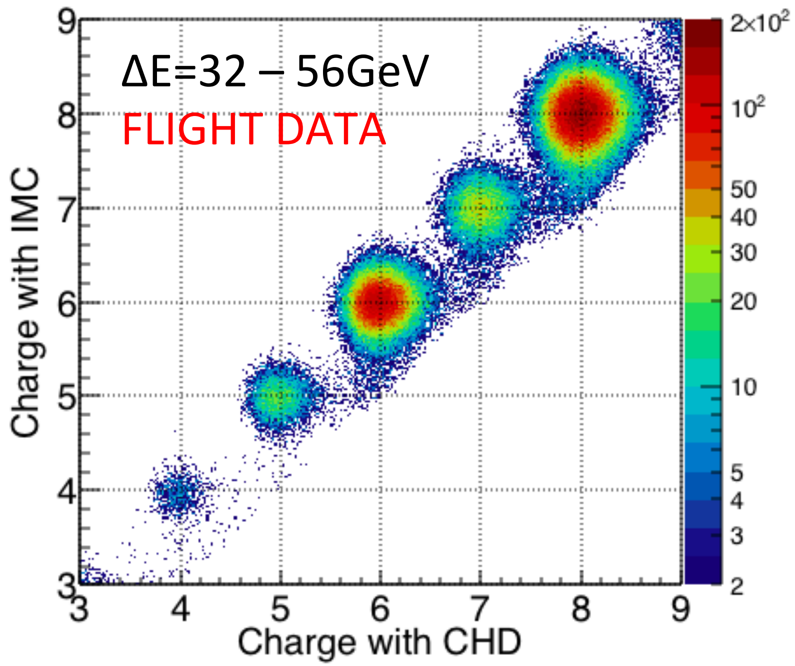
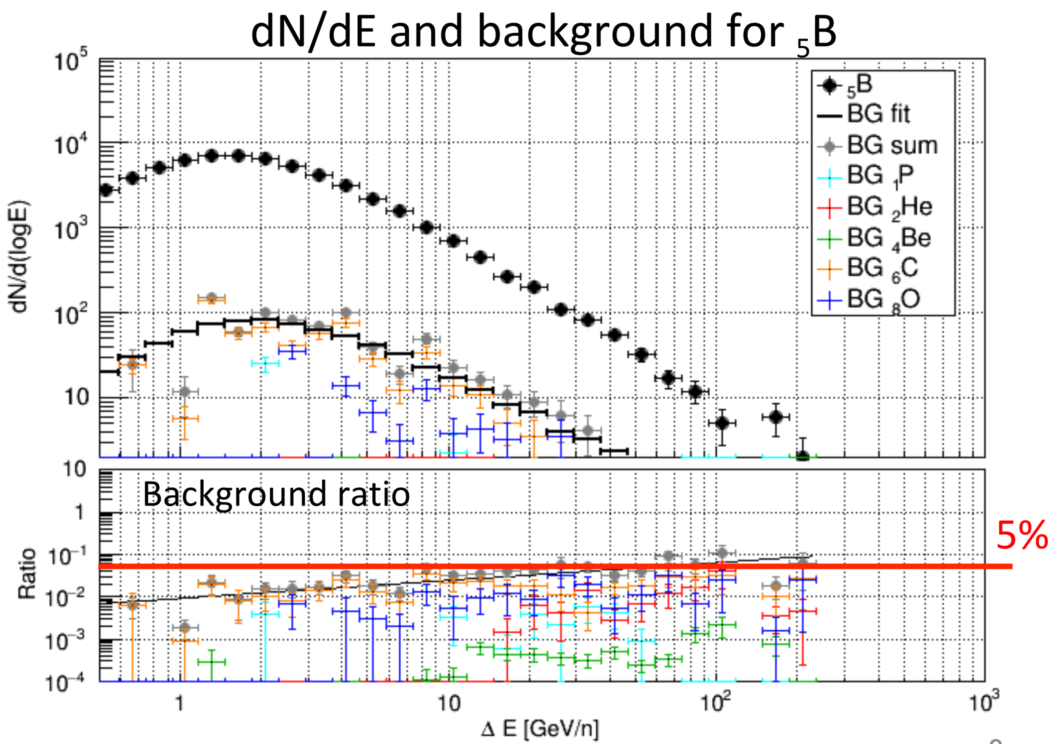
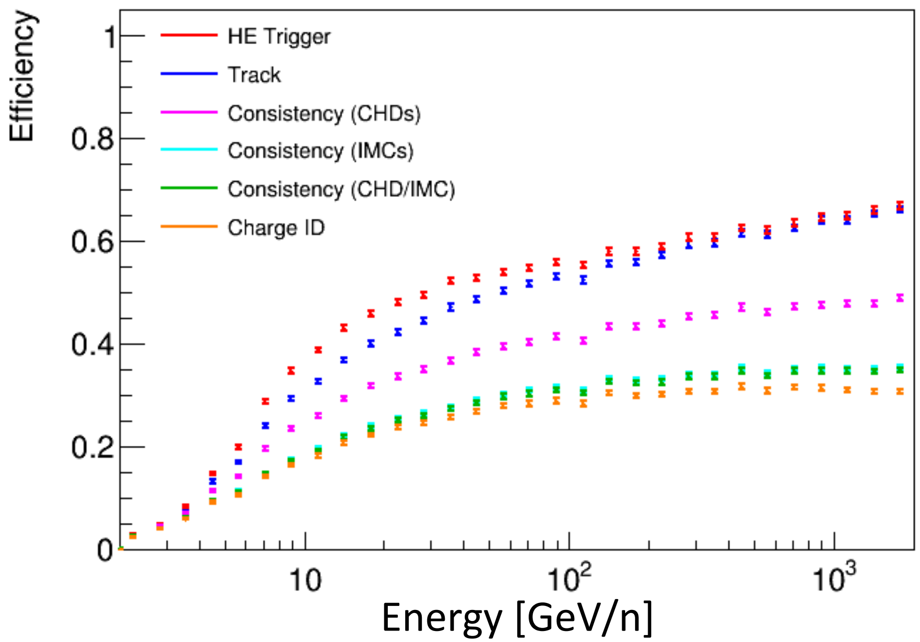




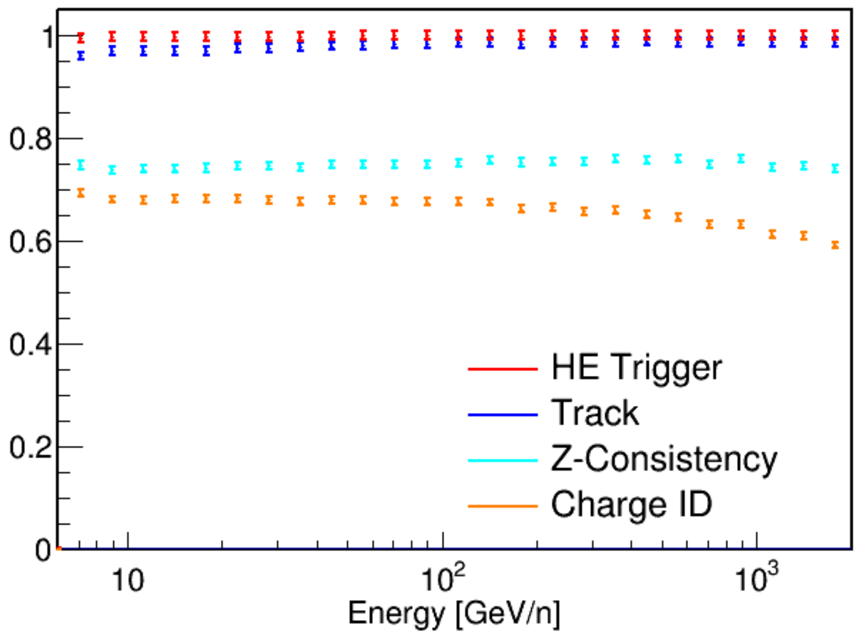


Efficiency

Efficiency for Carbon



Efficiency for Iron

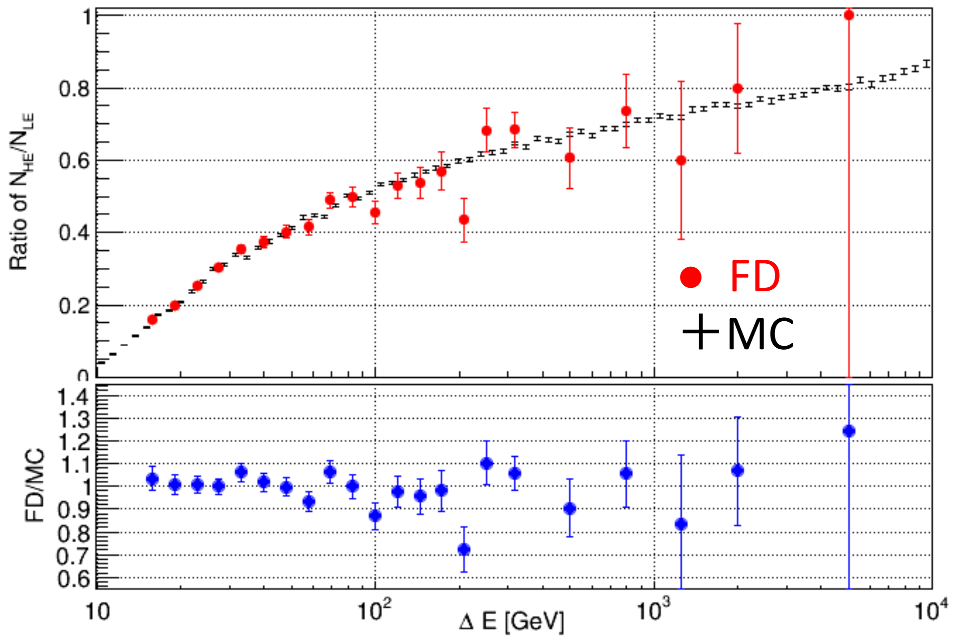


Trigger efficiency of heavy nuclei (Z>10) is ~1, due to the large dE/dx

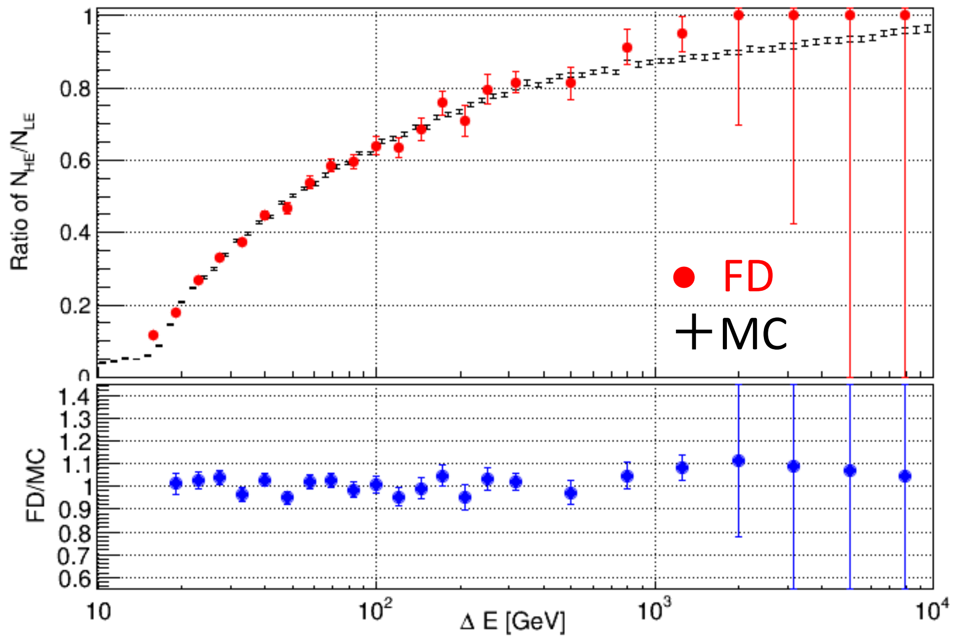
Trigger efficiency of HE trigger

HE trigger is a shower trigger to detect 10 GeV shower events
The HE trigger efficiency was evaluated using data by low threshold trigger (LE-GAM) which can be detected all events of Z>=5 including penetrating particles because of the large dE/dx

HE Trigger Efficiency for Carbon



HE Trigger Efficiency for Oxygen



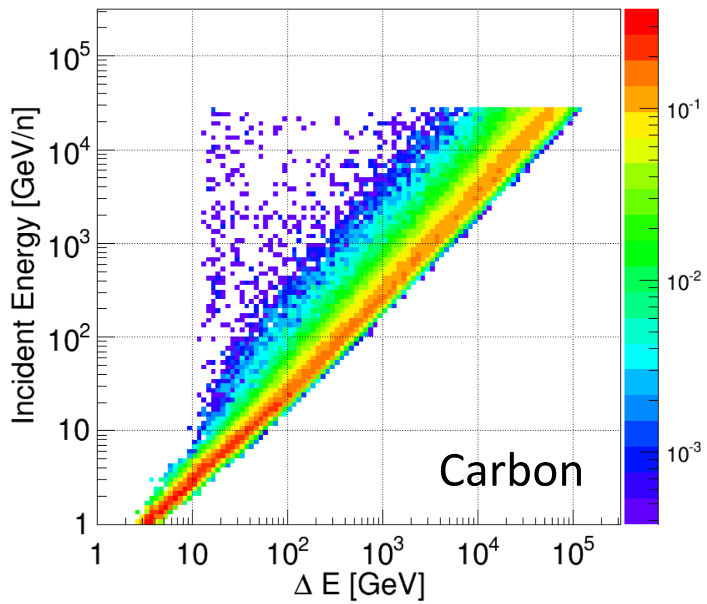
Energy unfolding

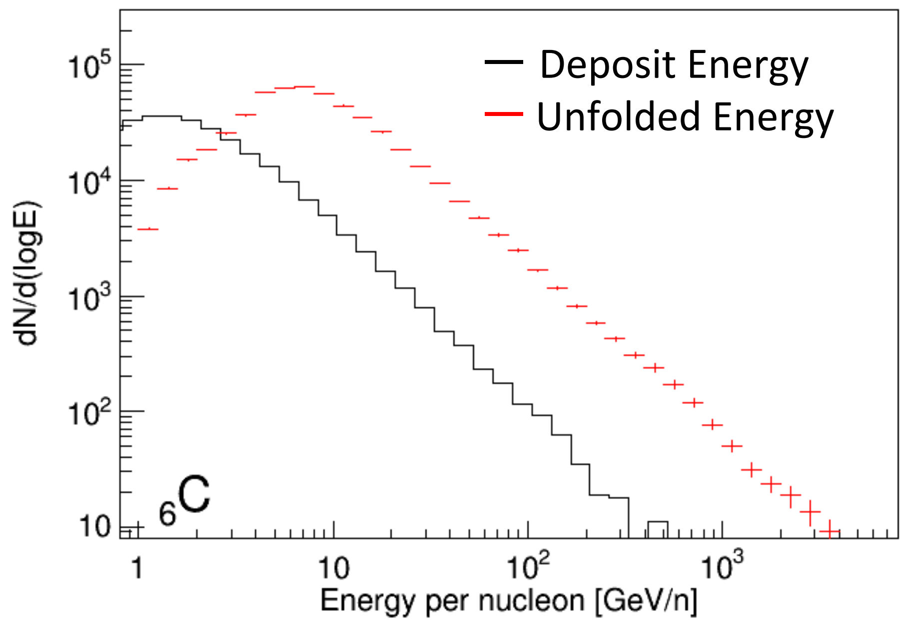
Characteristics of nuclei measurements with CALET calorimeter:

- 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:
    ΔE [GeV] (deposit energy in calorimeter) vs E_0 [GeV] (primary energy)





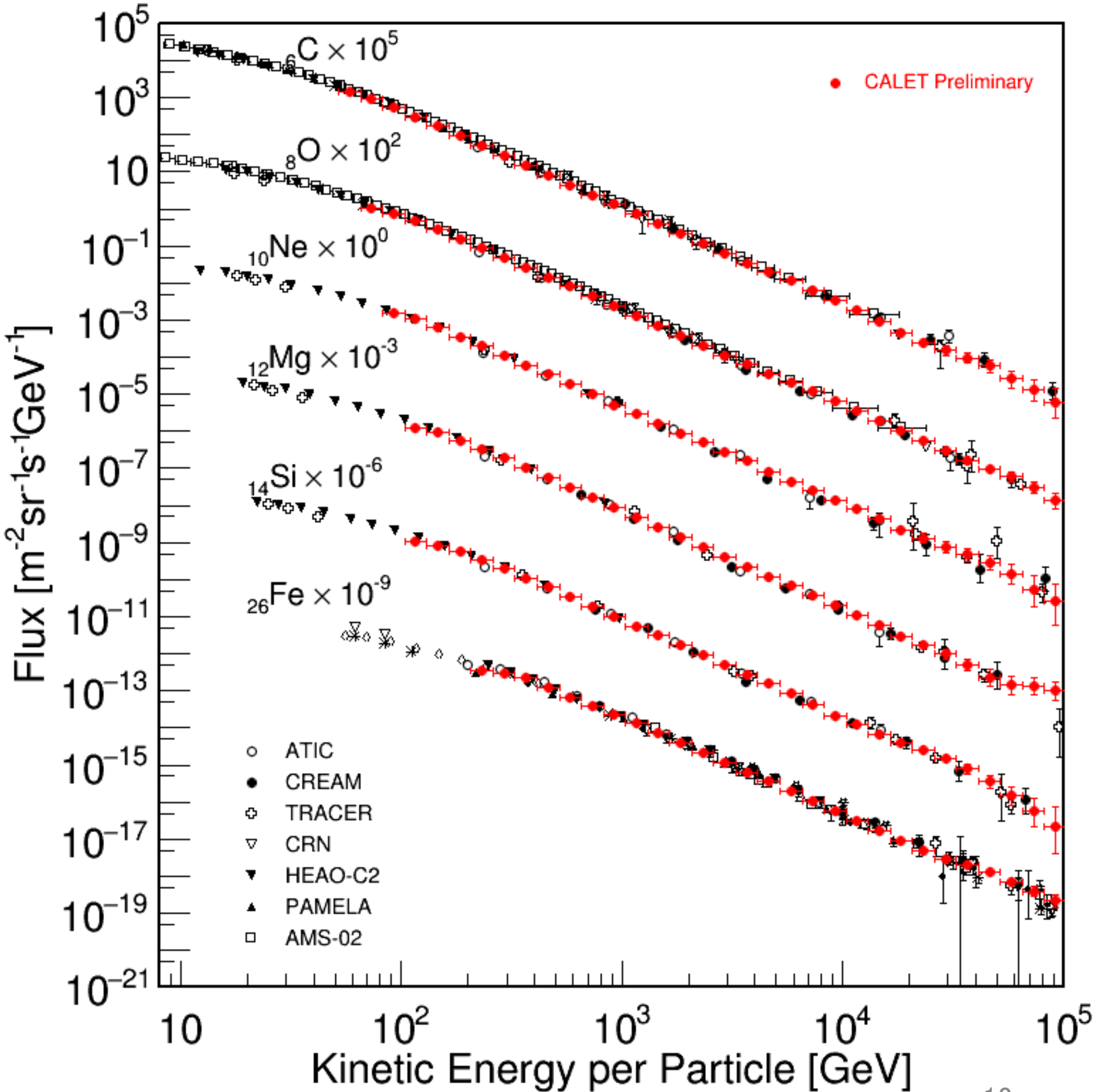
Preliminary Flux of Primary Components

Flux measurements:

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

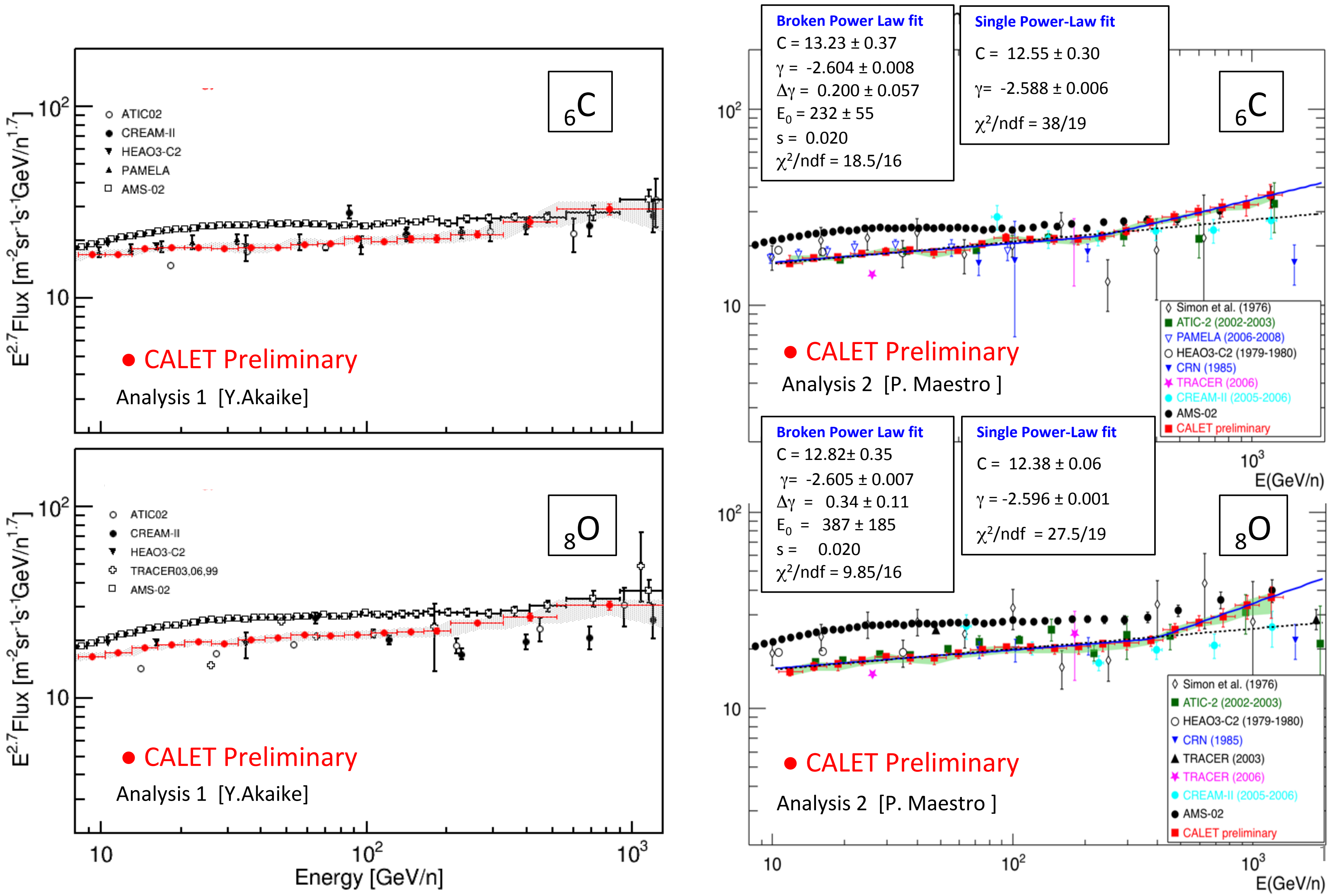
$N(E)$: Events in unfolded energy bin
$S\Omega$: Geometrical acceptance
$\varepsilon(E)$: Efficiency
T : Live Time
ΔE : Energy bin width

Observation period:
Oct.13 2015 – Oct.31 2018
(750 days)

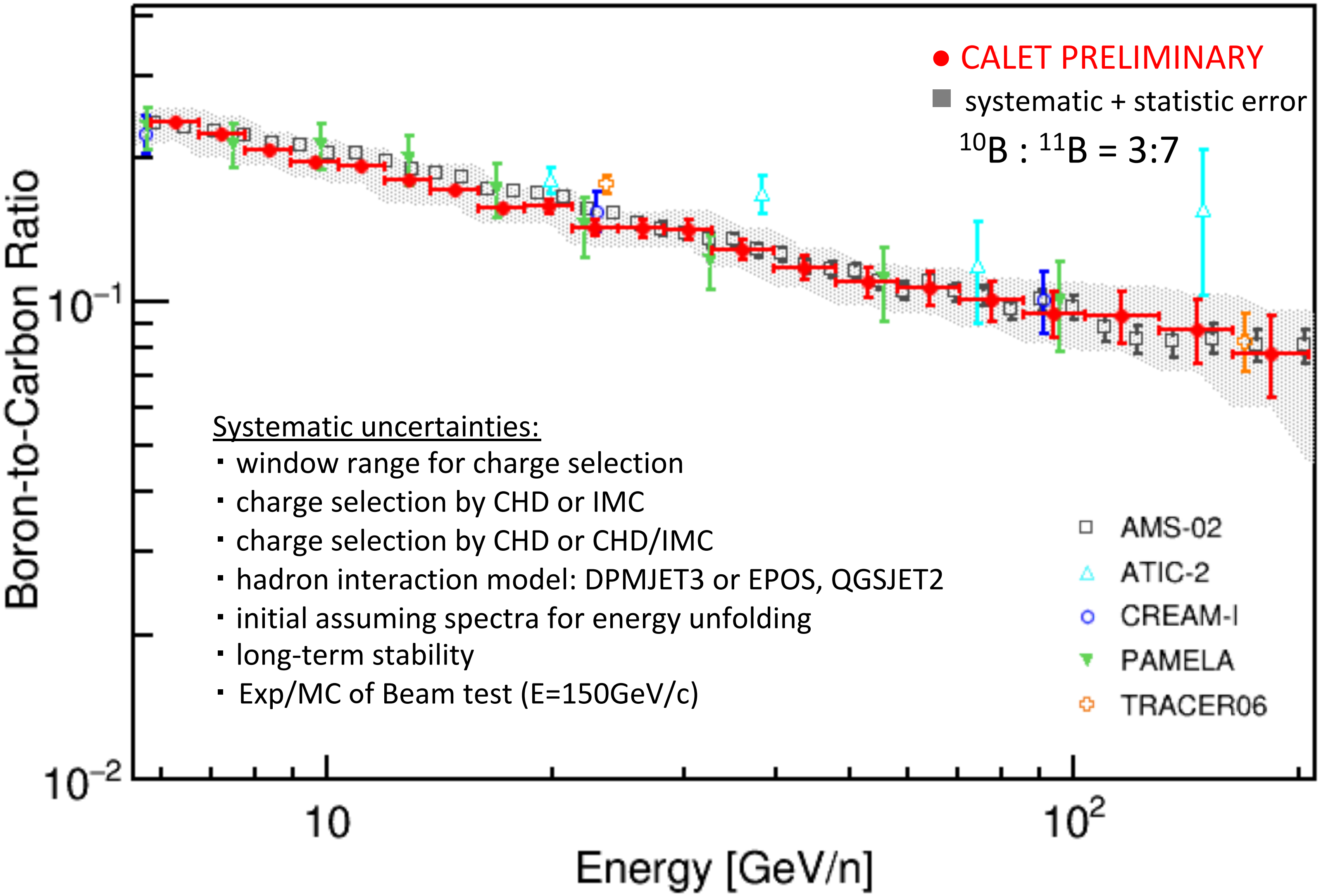


Preliminary Carbon and Oxygen Spectra

(2 independent CALET analysis)

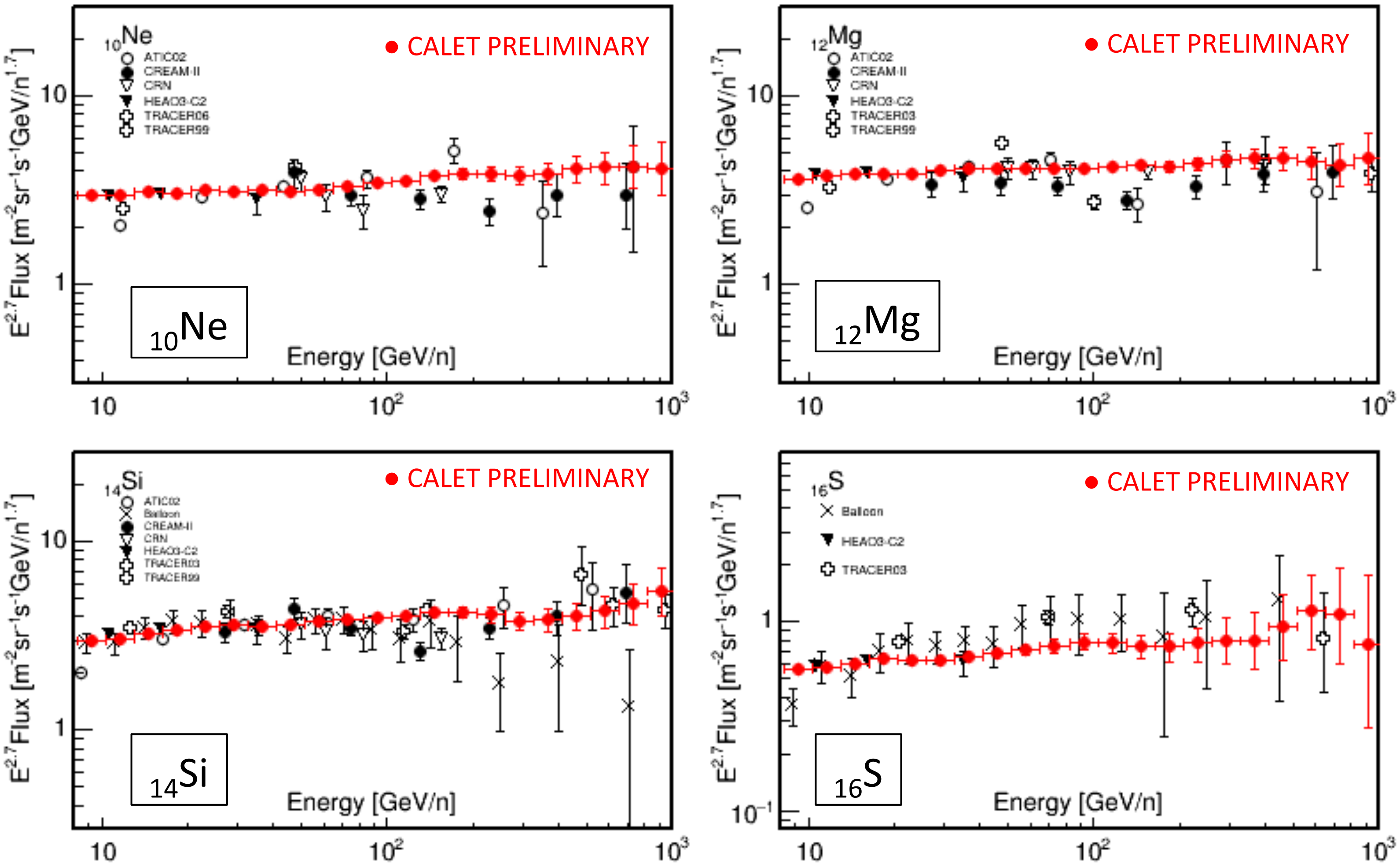


Preliminary Boron-to-Carbon Flux Ratio



Preliminary Spectra of Nuclei with **Even** Atomic Number (Z=10-16)

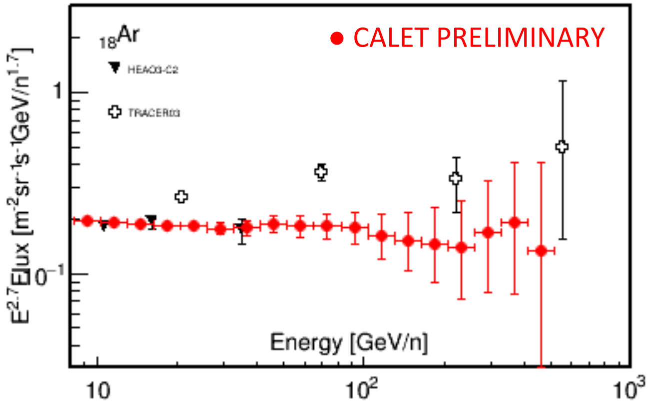
Only statistical error are shown



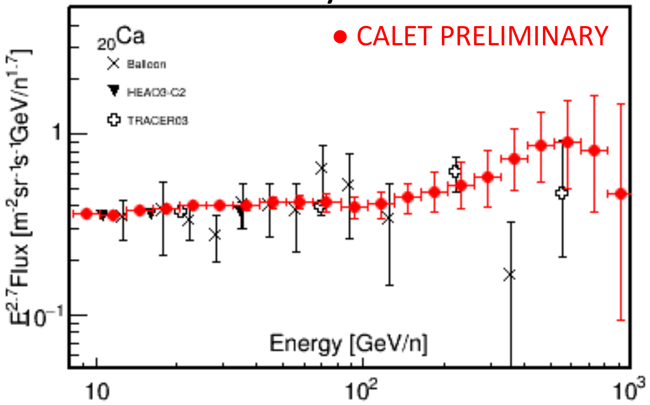
Preliminary Spectra of Nuclei with **Even** Atomic Number (Z=18-28)

Only statistical error are shown

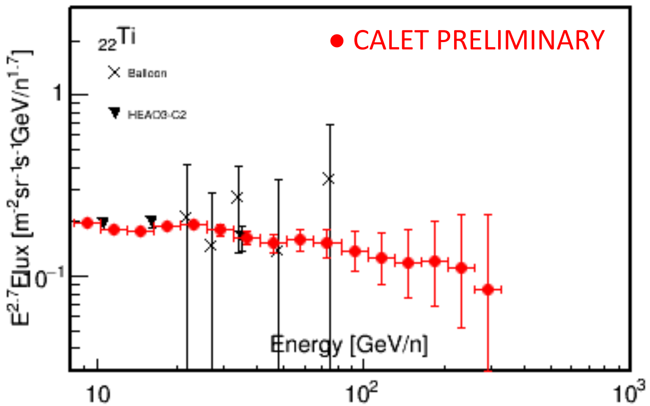
$_{18}Ar$



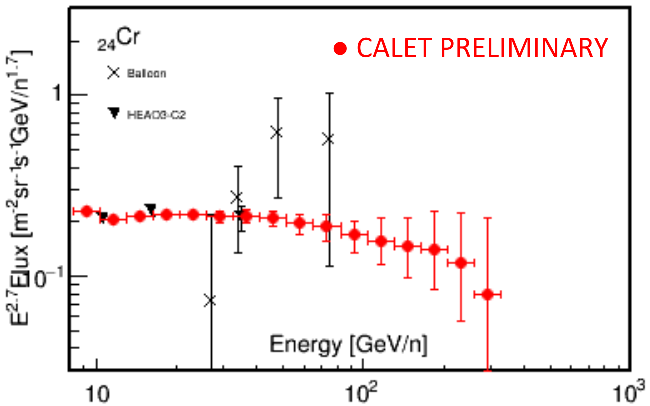
$_{20}Ca$



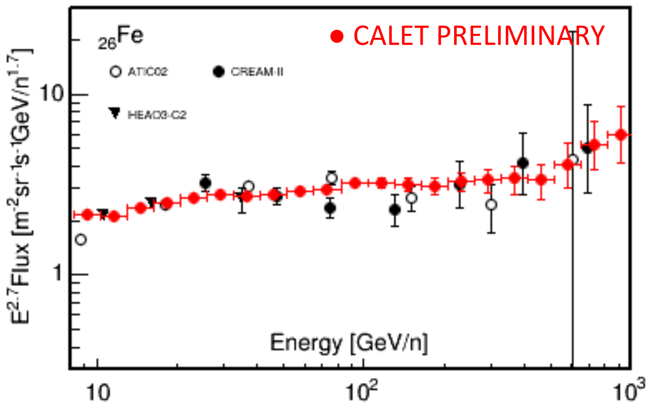
$_{22}Ti$



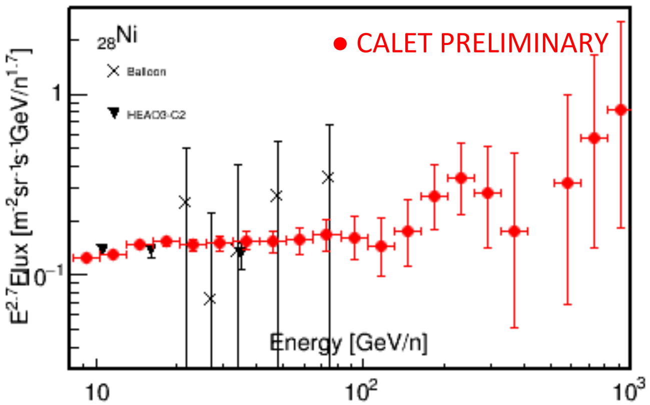
$_{24}Cr$



$_{26}Fe$



$_{28}Ni$



Conclusion

- The ability of CALET to measure heavy cosmic-ray nuclei has been successfully demonstrated
  - Charge resolution: 0.15 for carbon, 0.30 for iron
  - Dynamic range for energy measurement: 1-10^6 MIP (1GeV − 1PeV)

- Preliminary analysis of nuclei have successfully carried out for the primary cosmic-ray elements up to 100 TeV and B/C ratio up to 200 GeV/n using data from the 750 days of operation

- Further studies will provide the excellent energy spectra with high statistics in a wide energy range, and reveal details spectral features