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Measurements of Heavy Cosmic Ray Nuclei Fluxes with CALET

Yosui Akaike for the CALET Collaboration

NASA Goddard Space Flight Center
Center for Research and Exploration in Space Science & Technology II
University of Maryland Baltimore County

Nuclei measurement with CALET

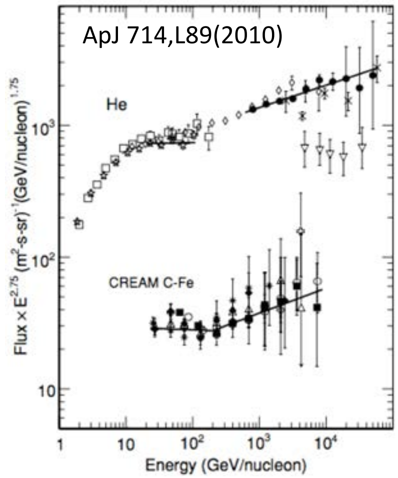
Nuclei measurements in GeV – TeV

Primary individual spectra

- cosmic-ray acceleration and propagation
- hardening of spectra

Secondary-to-primary flux ratio

- cosmic-ray propagation
- energy dependence of diffusion coefficient



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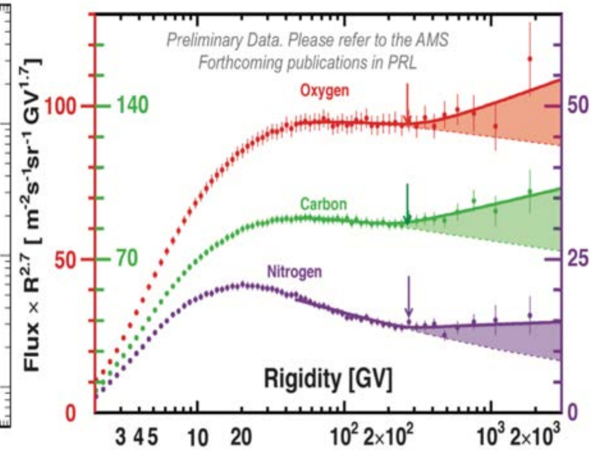


Direct measurements with CALET

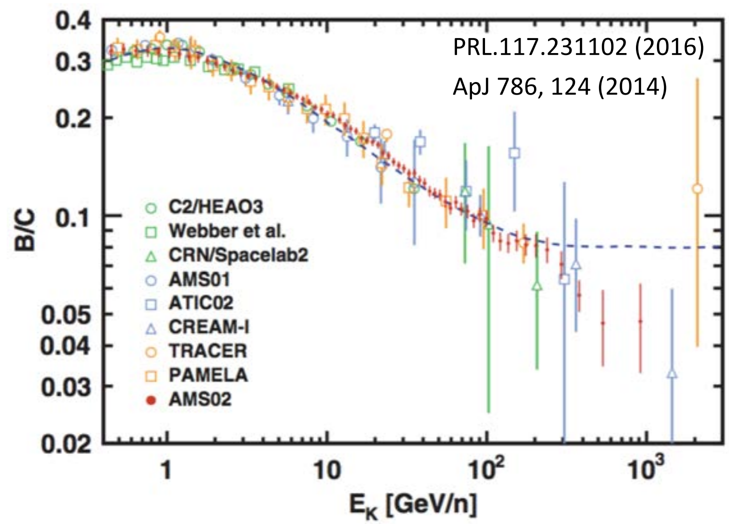
Energy spectra from Proton to Iron

Energy measurement in 10 GeV – 1PeV

- dynamic range : 1 – 10^6MIP

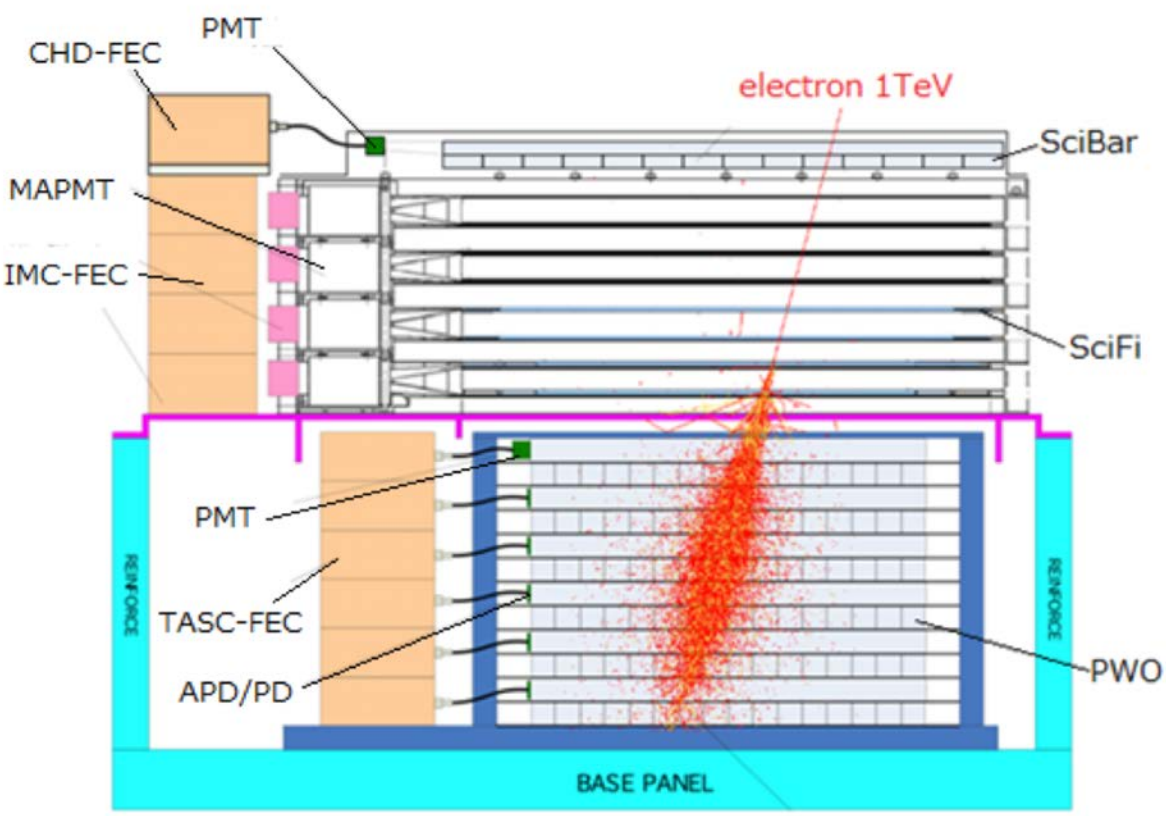
Charge measurement in Z = 1 – 40

- charge resolution: 0.18*e*(C)-0.3*e*(Fe)



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 = 0.18 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 = 300μm

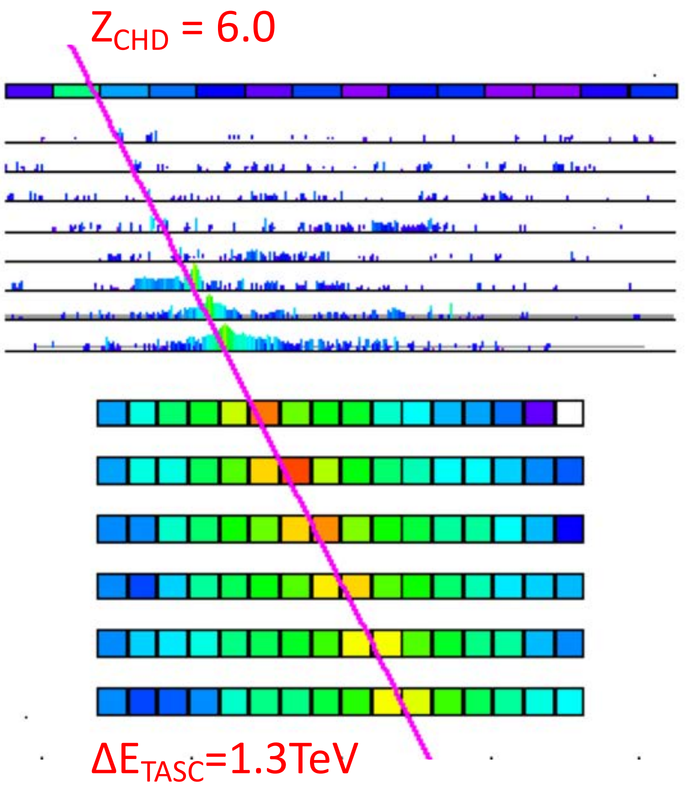
TASC: Total Absorption Calorimeter

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

1. HE (High Energy) trigger
   - Period: Oct. 13 2015 - Dec. 31 2018 (1,176 days)
2. Offline shower trigger
3. Tracking with IMC
   - select events satisfied Geom.A+B
   - 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

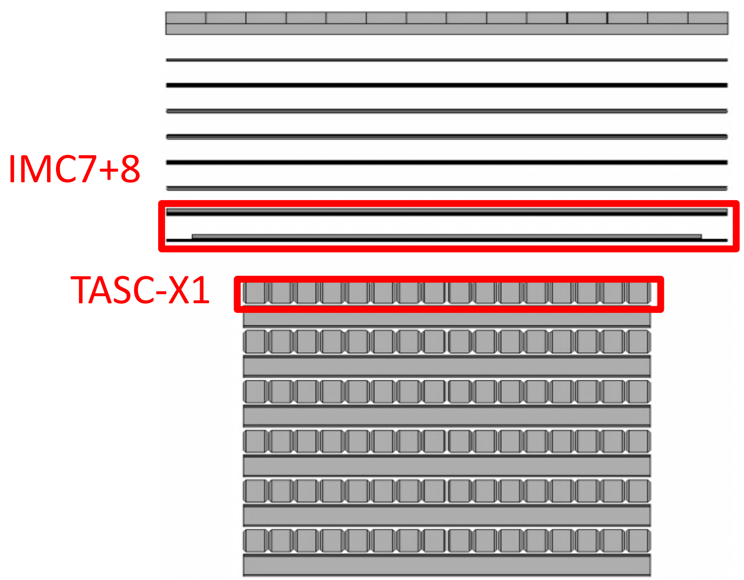


Onboard trigger for heavy nuclei

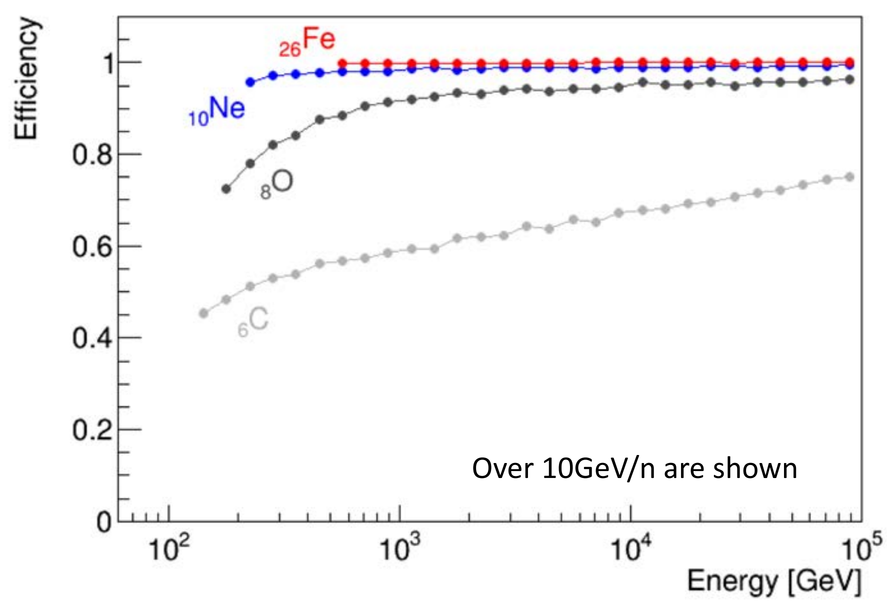
On-board High Energy shower trigger (HE Trigger):
- The energy thresholds are set to detect shower events with energies over 10GeV

For light nuclei (Z<10), only events interacting in the detector are triggered.
For heavy nuclei, most events including events interacting in deep layers are triggered because of the large dE/dx ($\propto Z^2$) ➡ trigger efficiency is almost 100%.

Onboard HE Trigger



HE trigger efficiency

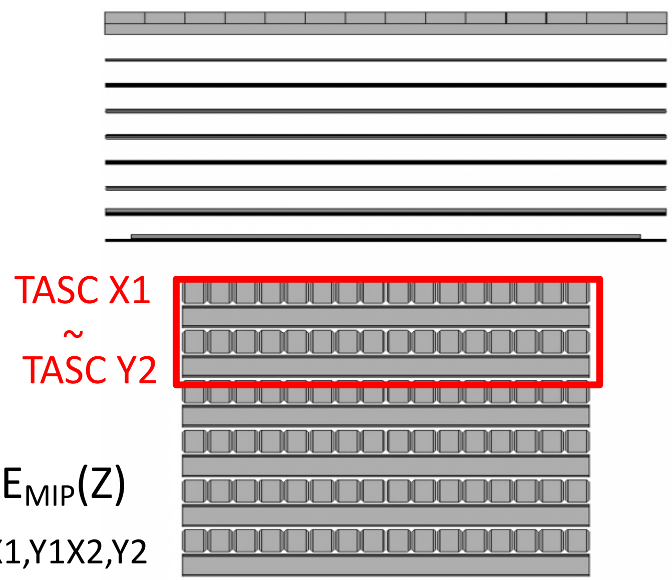


Shower event selection for heavy nuclei

On-board High Energy shower trigger (HE Trigger):
- The energy thresholds are set to detect shower events with energies over 10GeV

For light nuclei (Z<10), only events interacting in the detector are triggered.
For heavy nuclei, most events including events interacting in deep layers are triggered because of the large dE/dx ($\propto Z^2$) ➡ trigger efficiency is almost 100%.
➡ Apply shower event selection in offline analysis

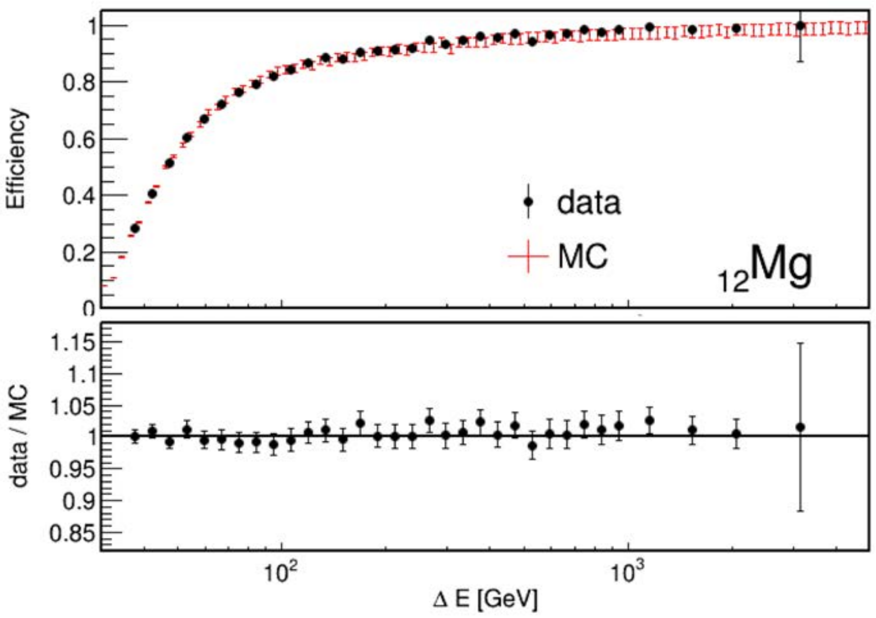
Shower event selection



$\Delta E_i > E_{MIP}(Z)$

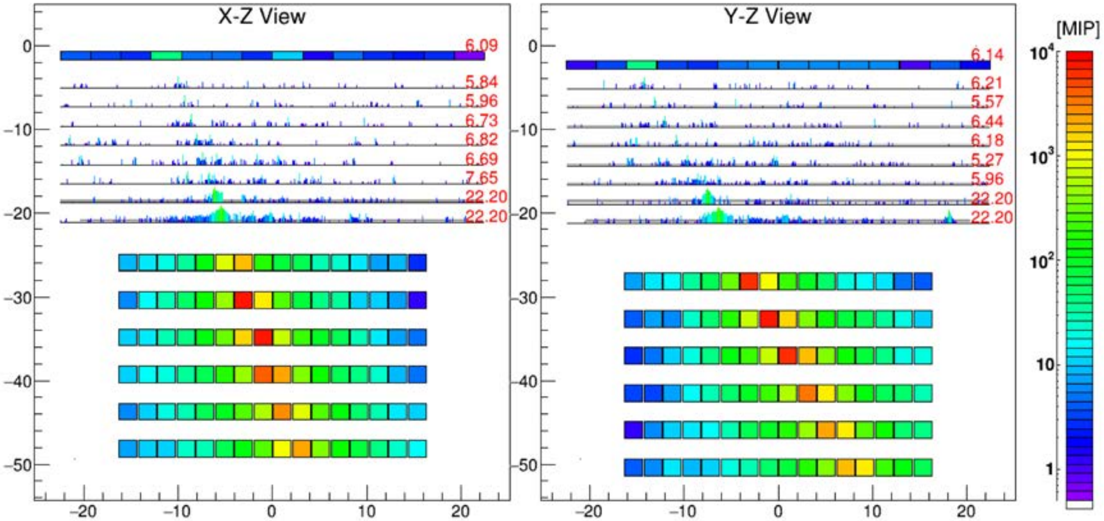
i: X1,Y1X2,Y2

Efficiency of shower event selection

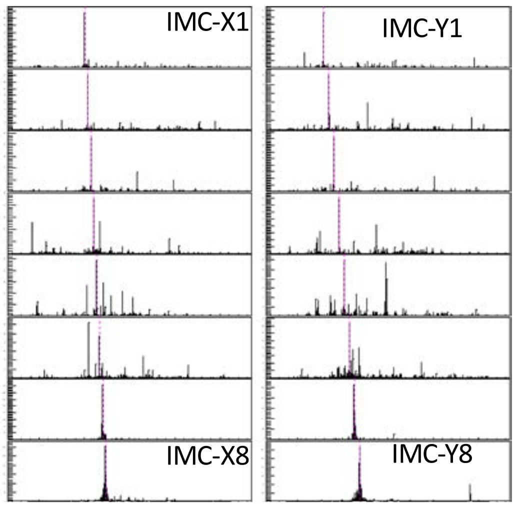


Tracking with IMC

Carbon ΔE_{TASC} = 2.06 TeV



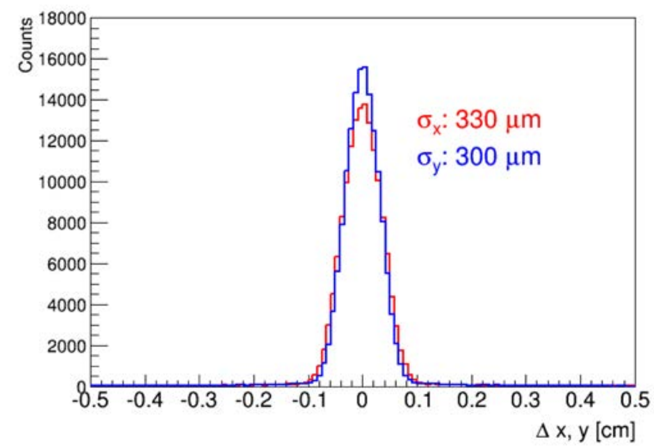
Pulse height of IMC



- Reconstruct shower axis with IMC signals
- Heavy nuclei can make many shower particles in IMC, which could be a large background for track; the signal of primary particle is commonly larger than the signals of the shower particles; $dE/dx \propto Z^2$

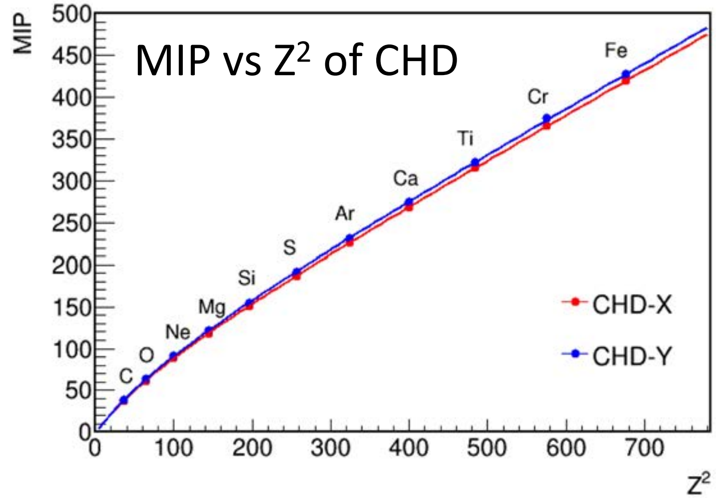
⇨ Simple tracking methods: Least chi-square fitting is applied for the maximum clusters in upper 4 IMC layers.

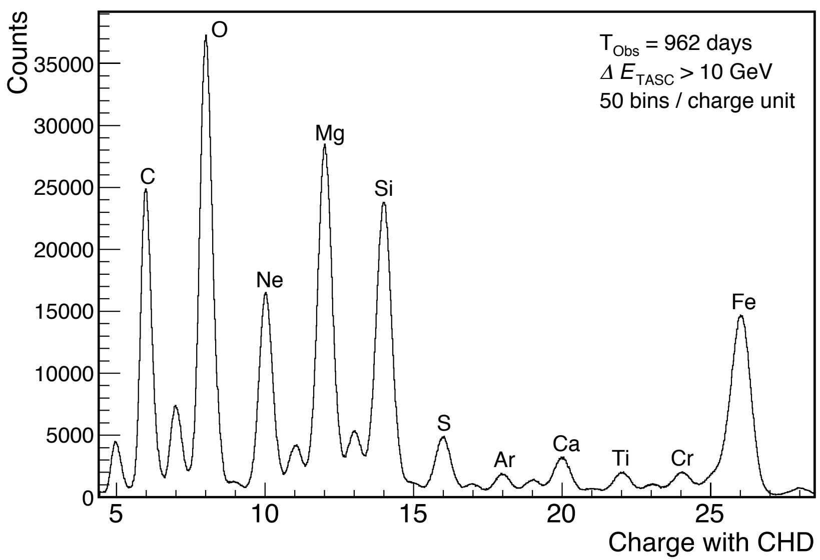
Accuracy of impact point at CHD

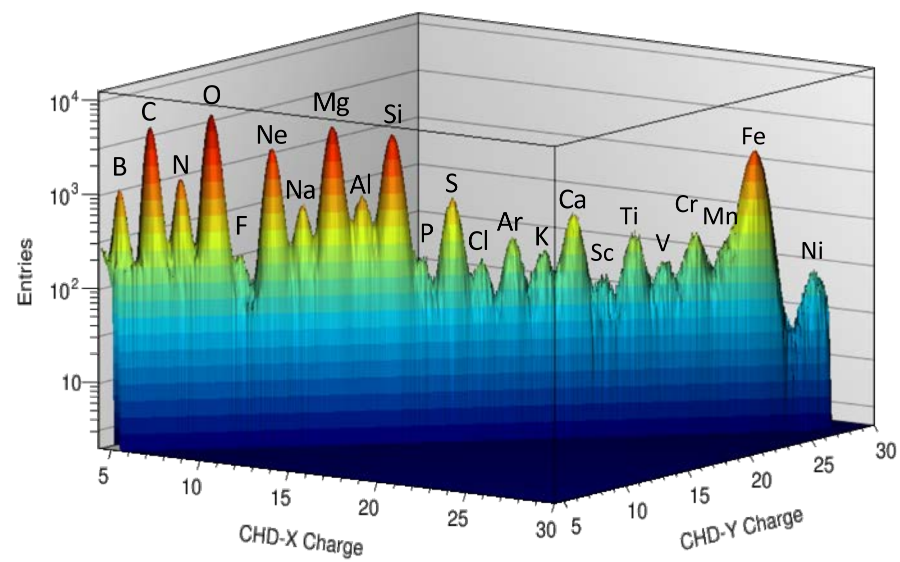


Charge measurement

- Non-linearity response toZ^2 is corrected both in CHD and IMC from flight data
- Charge resolution with CHD : 0.18 for C
  0.30 for Fe
- Charge resolution with IMC : 0.19 for C



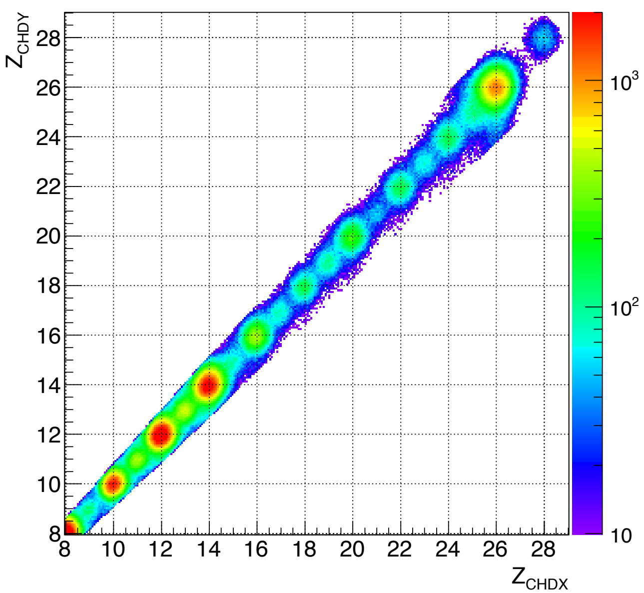




Event selection

Two selections are applied
to remove events with mis-reconstructed track such as particles entering from the detector side, and to remove background events interacting in the CHD

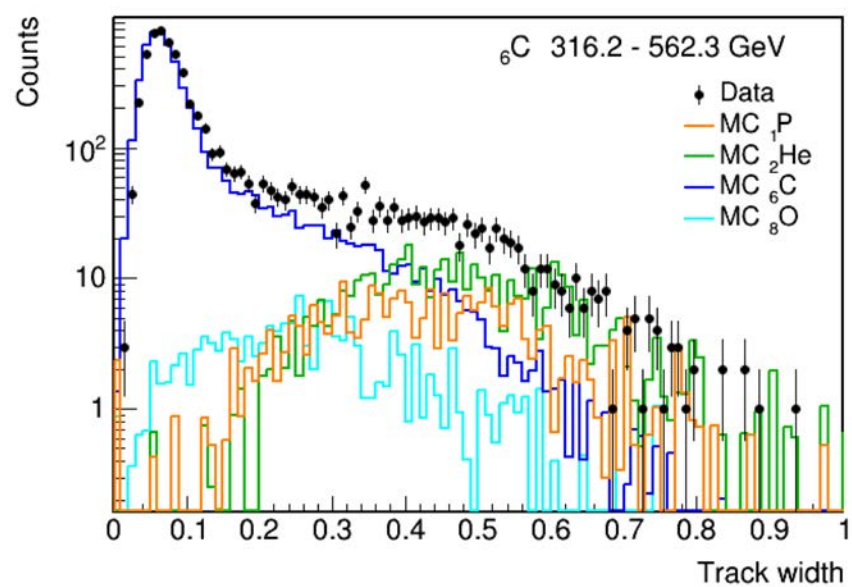
- Charge consistency cuts
  - $|Z_{CHDX} - Z_{CHDY}| < 10\%$
  - $|Z_{CHD} - Z_{IMC}| < 15\%$
  - $|Z_{IMC12} - Z_{IMC34}| < 15\%$



- Track width

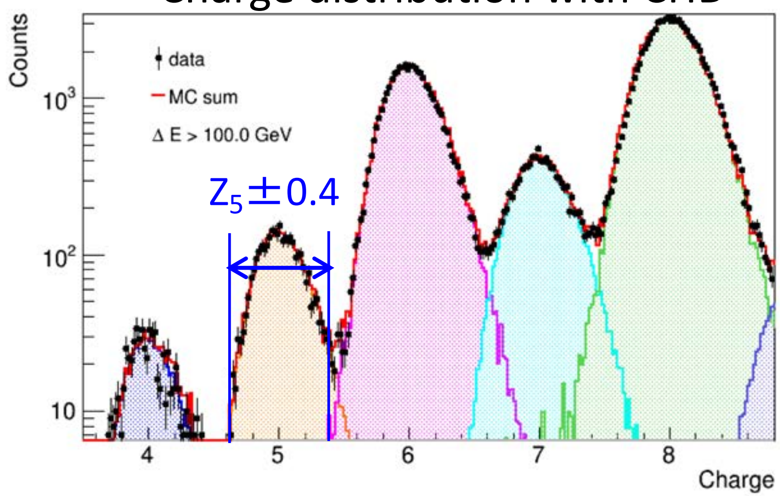
$$B_{\mathrm{IMCi}} = \left(\sum_{j=-k}^{k} N_{\mathrm{IMCi,j}} - \sum_{j=-1}^{1} N_{\mathrm{IMCi,j}}\right)\frac{1}{Z^2_{\mathrm{IMCi}}}$$

Sum of 7 SciFis　　Sum of 3 SciFis

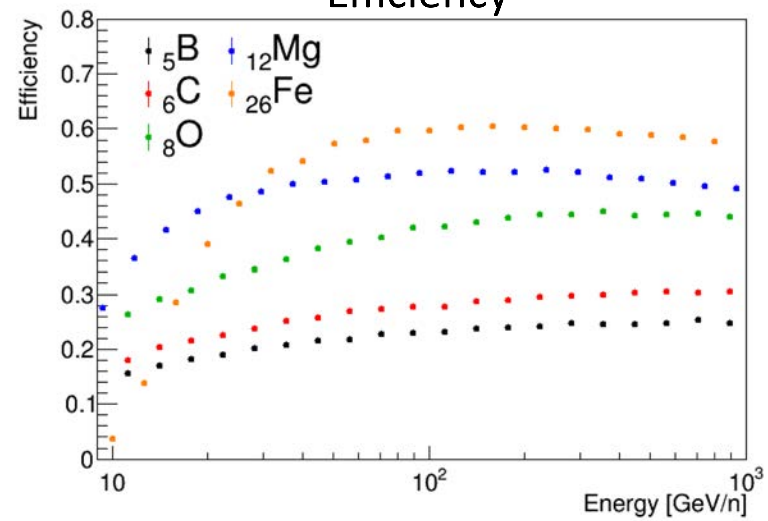


Efficiency and Background

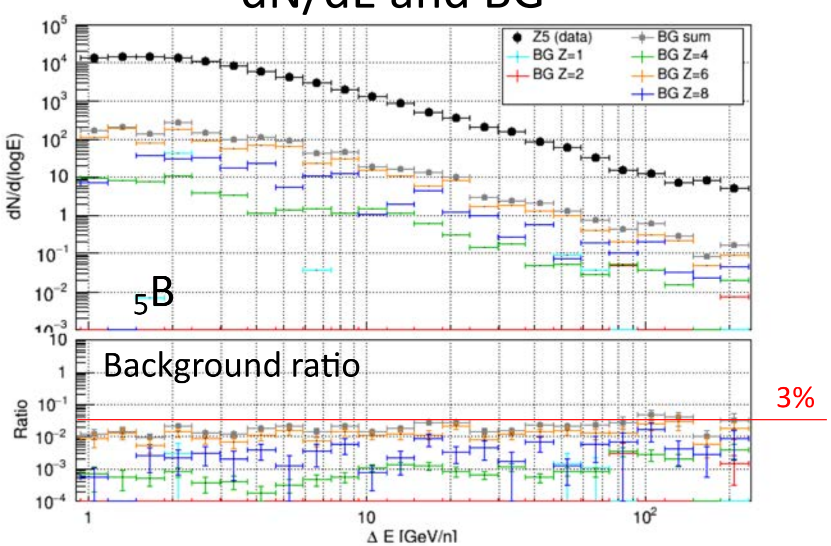
Charge distribution with CHD

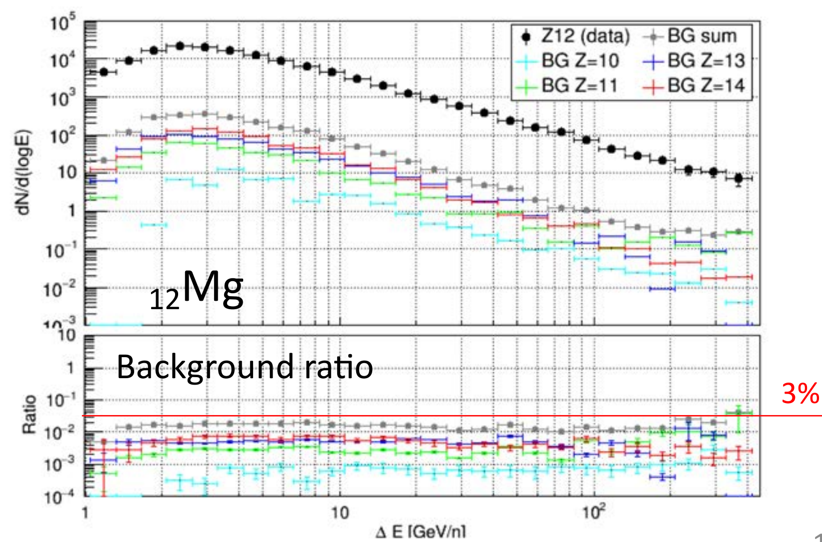


Efficiency



dN/dE and BG





Energy unfolding

Characteristics of nuclei measurements with CALET calorimeter:

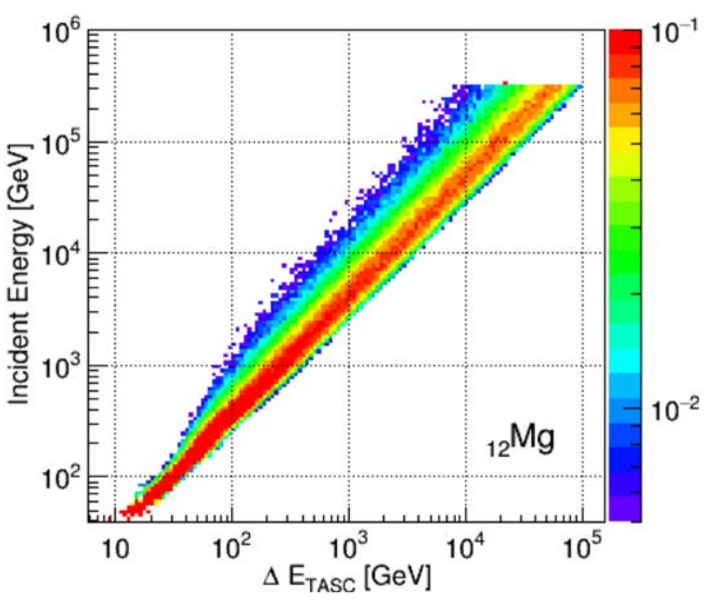
- thickness: 30 X_0 for electron, 1.3λ for proton
- σ(E)/E : 2% for electron, 30% for nuclei

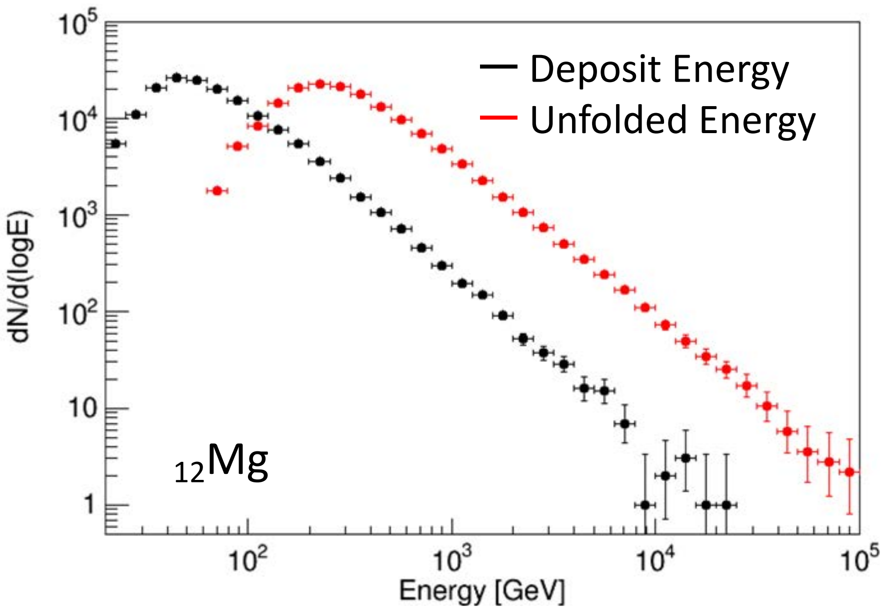
➡ Need energy unfolding for nuclei to obtain primary energy spectrum

● Iterative Bayesian unfolding
- Initial assuming spectra: $f(E)=A \times E^{-2.60}$

  A is normalized by charge distribution in CHD
- Response function:

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





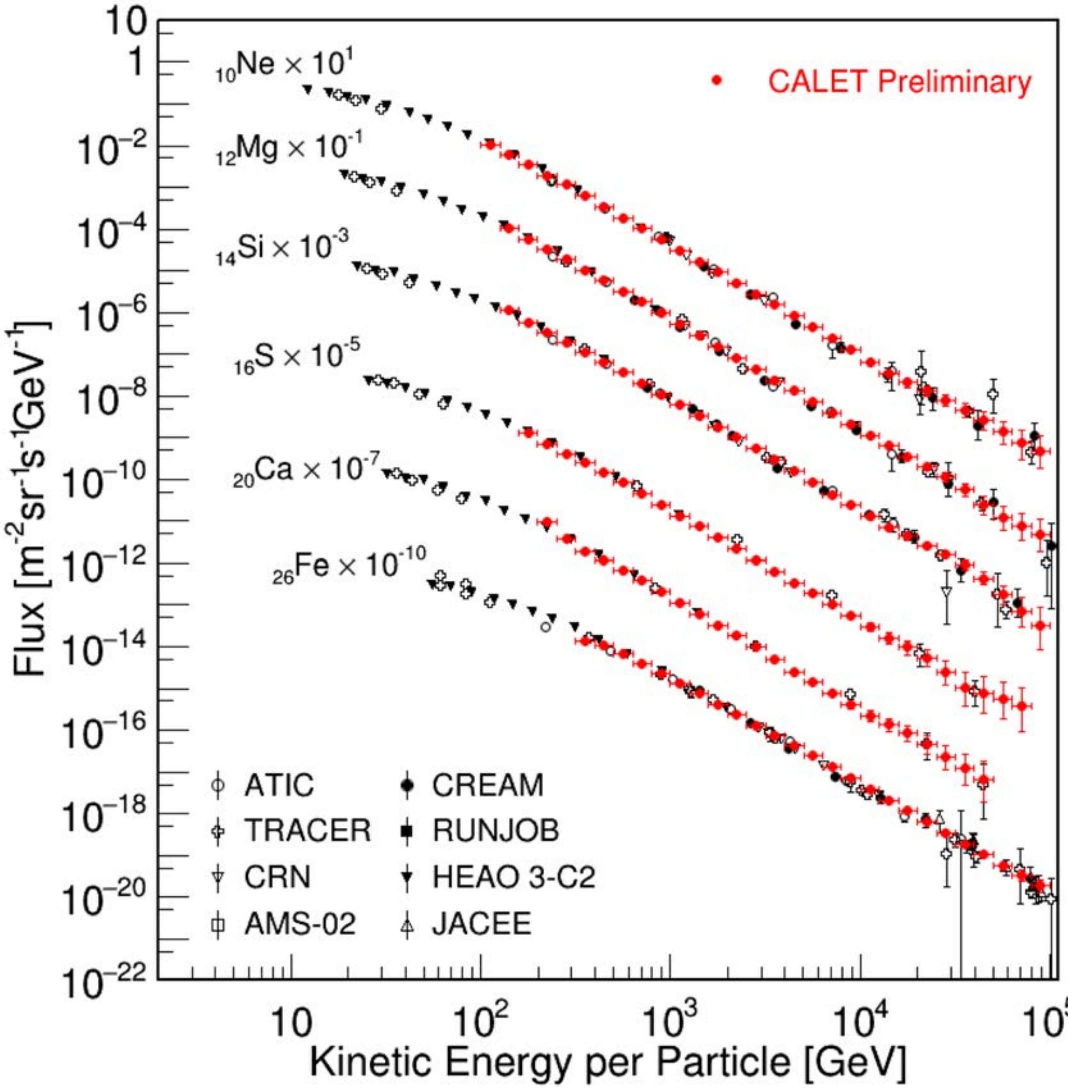
Energy spectra of primary components

Flux measurements:

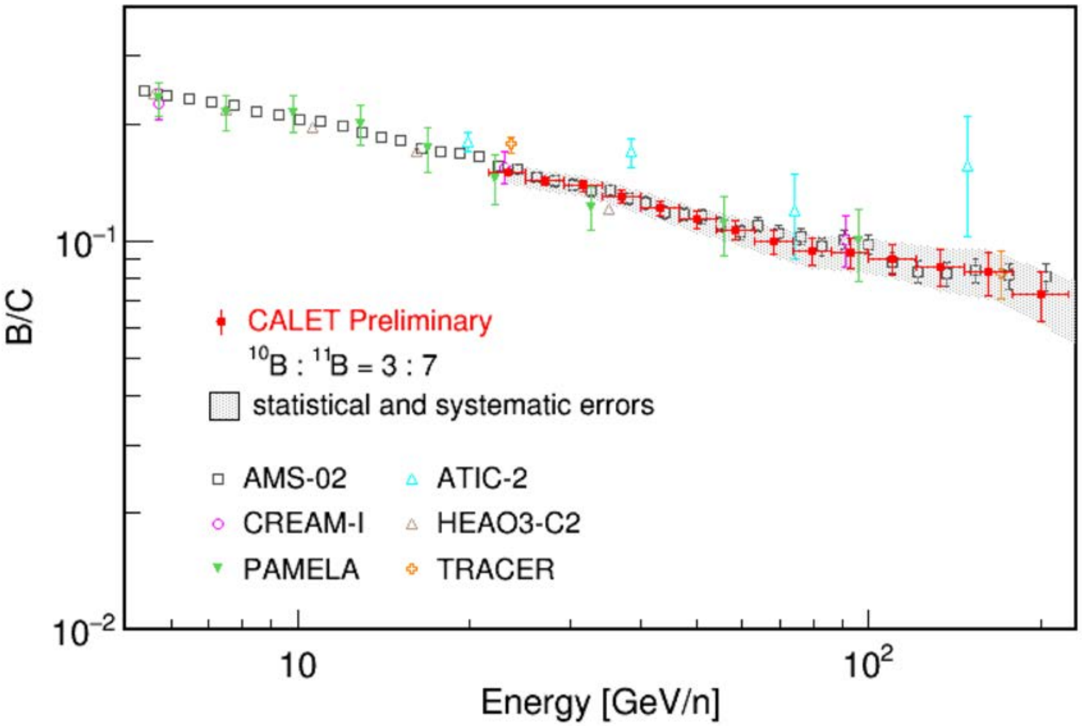
$$\Phi(E) = \frac{N(E)}{S\Omega\varepsilon(E)T\Delta E}$$

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

Observation period:
Oct.13 2015 – Dec.31 2018
(1,176 days)



Boron-to-carbon ratio



Source of systematic uncertainties

- Trigger efficiency
- Charge consistency cuts
- Track width selection
- Window range for charge identification
- Background model of p and He spectra
- Initial prior spectra of energy unfolding
- Energy correction with beam test results
- Difference of beam test model and flight model
- Long term stability

Summary

- The ability of CALET to measure cosmic-ray nuclei has been successfully demonstrated
  - Dynamic range for energy measurement: 1-10^6 MIP (1GeV – 1PeV)
  - Charge resolution: 0.18 for carbon, 0.30 for iron
- Using data from the 1,176 days of operation, preliminary analysis of nuclei has been successfully carried out
  - primary cosmic-ray elements up to 100 TeV
  - B/C ratio up to 200 GeV/n
- Independent analyses were carried out using different event selection procedures and MC simulations. Preliminary results are consistent.
- Further studies on an increased data set and detailed systematic study will increase the sensitivity to detailed spectral features, which may provide a key to solve questions about galactic cosmic-ray acceleration and propagation.