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

Yosui Akaike for the CALET Collaboration
NASA/GSFC/CRESST/UMBC

CALET Collaboration Team

O. Adriani[25], Y. Akaike[2], K. Asano[7], Y. Asaoka[9,31], M.G. Bagliesi[29], E. Berti[25], G. Bigongiari[29], W.R. Binns[32], S. Bonechi[29], M. Bongi[25], P. Brogi[29], A. Bruno[15], J.H. Buckley[32], N. Cannady[13], G. Castellini[25], C. Checchia[26],M.L. Cherry[13], G. Collazuol[26], V. Di Felice[28], K. Ebisawa[8], H. Fuke[8], T.G. Guzik[13], T. Hams[3], N. Hasebe[31], K. Hibino[10], M. Ichimura[4], K. Ioka[34], W. Ishizaki[7], M.H. Israel[32], K. Kasahara[31], J. Kataoka[31], R. Kataoka[17], Y. Katayose[33], C. Kato[23], Y.Kawakubo[1], N. Kawanaka[30], K. Kohri [12], H.S. Krawczynski[32], J.F. Krizmanic[2], T. Lomtadze[27], P. Maestro[29], P.S. Marrocchesi[29], A.M. Messineo[27], J.W. Mitchell[15], S. Miyake[5], A.A. Moiseev[3], K. Mori[9,31], M. Mori[21], N. Mori[25], H.M. Motz[31], K. Munakata[23], H. Murakami[31], S. Nakahira[20], J. Nishimura[8], G.A De Nolfo[15], S. Okuno[10], J.F. Ormes[25], S. Ozawa[31], L. Pacini[25], F. Palma[28], V. Pal'shin[1], P. Papini[25], A.V. Penacchioni[29], B.F. Rauch[32], S.B. Ricciarini[25], K. Sakai[3], T. Sakamoto[1], M. Sasaki[3], Y. Shimizu[10], A. Shiomi[18], R. Sparvoli[28], P. Spillantini[25], F. Stolzi[29], S. Sugita[1], J.E. Suh[29], A. Sulaj[29], I. Takahashi[11], M. Takayanagi[8], M. Takita[7], T. Tamura[10], N. Tateyama[10], T. Terasawa[7], H. Tomida[8], S. Torii[9,31], Y. Tunesada[19], Y. Uchihori[16], S. Ueno[8], E. Vannuccini[25], J.P. Wefel[13], K. Yamaoka[14], S. Yanagita[6], A. Yoshida[1], and K. Yoshida[22]

1) Aoyama Gakuin University, Japan
2) CRESST/NASA/GSFC and Universities Space Research Association, USA
3) CRESST/NASA/GSFC and University of Maryland, USA
4) Hirosaki University, Japan
5) Ibaraki National College of Technology, Japan
6) Ibaraki University, Japan
7) ICRR, University of Tokyo, Japan
8) ISAS/JAXA Japan
9) JAXA, Japan
10) Kanagawa University, Japan
11) Kavli IPMU, University of Tokyo, Japan
12) KEK, Japan
13) Louisiana State University, USA
14) Nagoya University, Japan
15) NASA/GSFC, USA
16) National Inst. of Radiological Sciences, Japan
17) National Institute of Polar Research, Japan
18) Nihon University, Japan
19) Osaka City University, Japan
20) RIKEN, Japan
21) Ritsumeikan University, Japan
22) Shibaura Institute of Technology, Japan
23) Shinshu University, Japan
24) University of Denver, USA
25) University of Florence, IFAC (CNR) and INFN, Italy
26) University of Padova and INFN, Italy
27) University of Pisa and INFN, Italy
28) University of Rome Tor Vergata and INFN, Italy
29) University of Siena and INFN, Italy
30) University of Tokyo, Japan
31) Waseda University, Japan
32) Washington University-St. Louis, USA
33) Yokohama National University, Japan
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

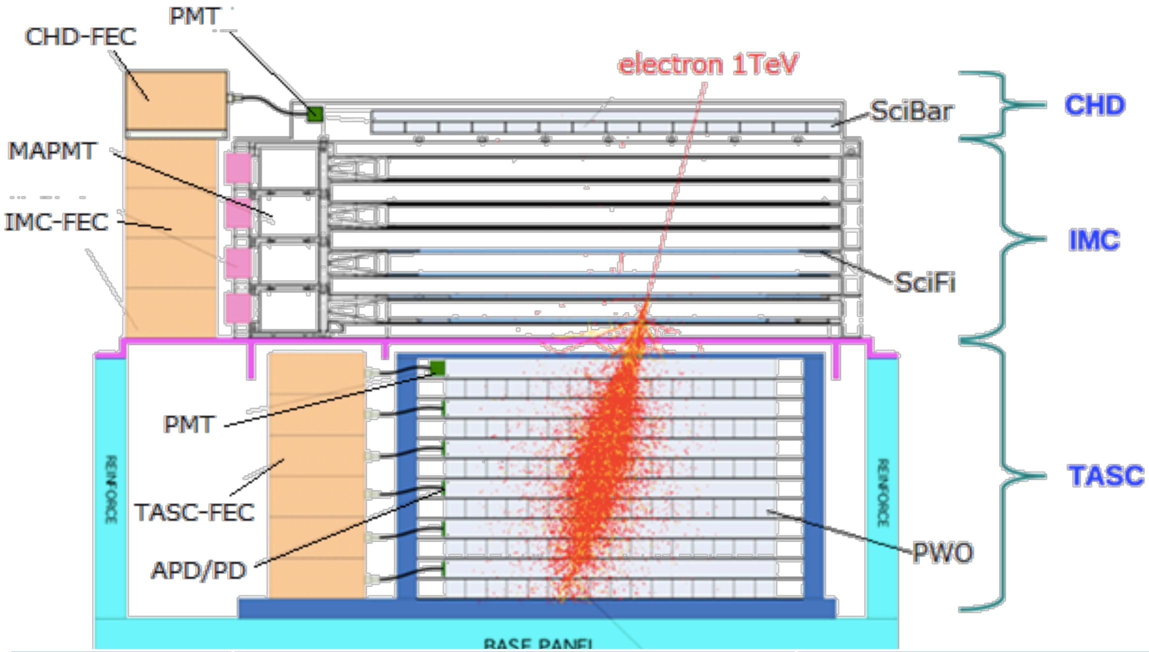
Direct measurements with CALET

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



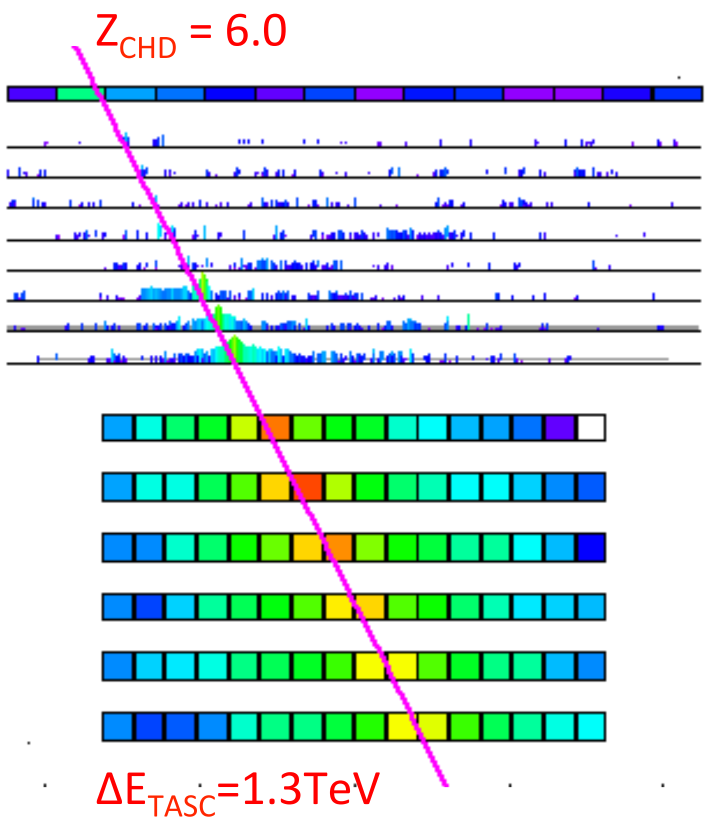
Performances

- 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

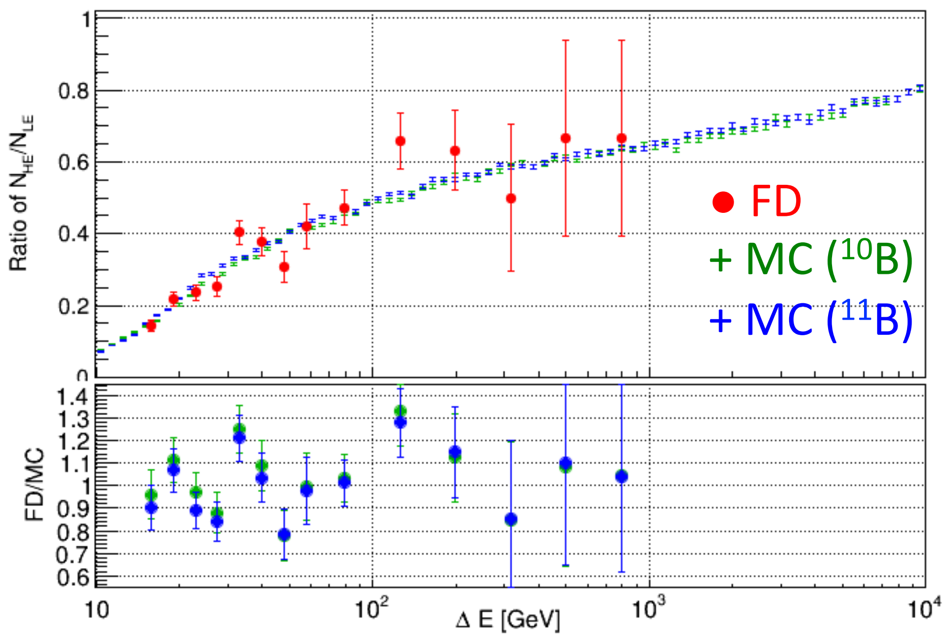
1. HE (High Energy) trigger
   - Period: Oct. 13 2015 - Oct. 31 2017 (750days)
2. Offline shower trigger
3. Tracking with IMC
   - select events satisfied Geom.A
   - identify the impact point
4. Charge consistency with CHD and IMC
   - remove backgrounds
   - maintain charge resolution
5. Charge selection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



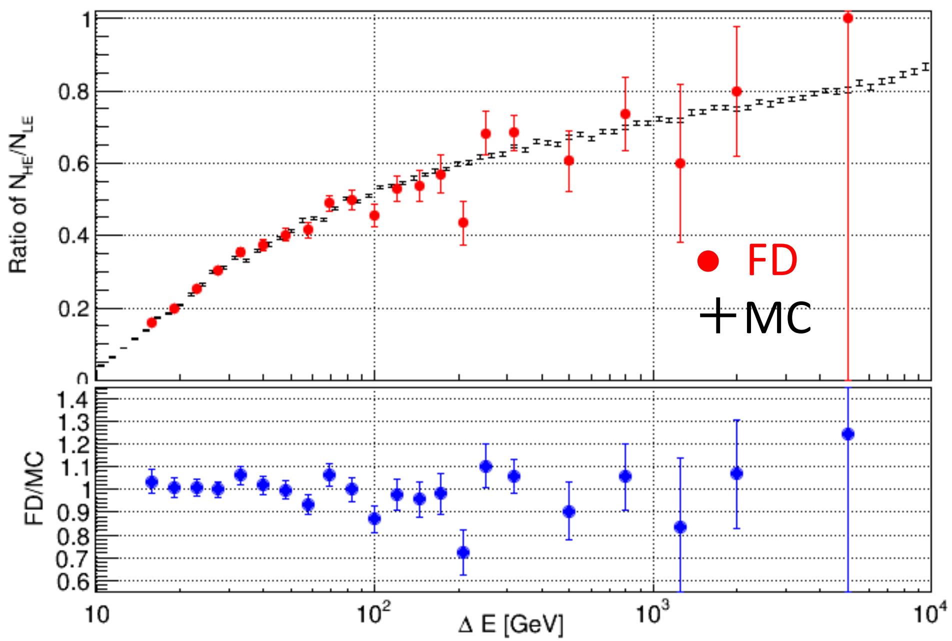
Trigger efficiency of HE trigger

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

HE Trigger Efficiency for Boron



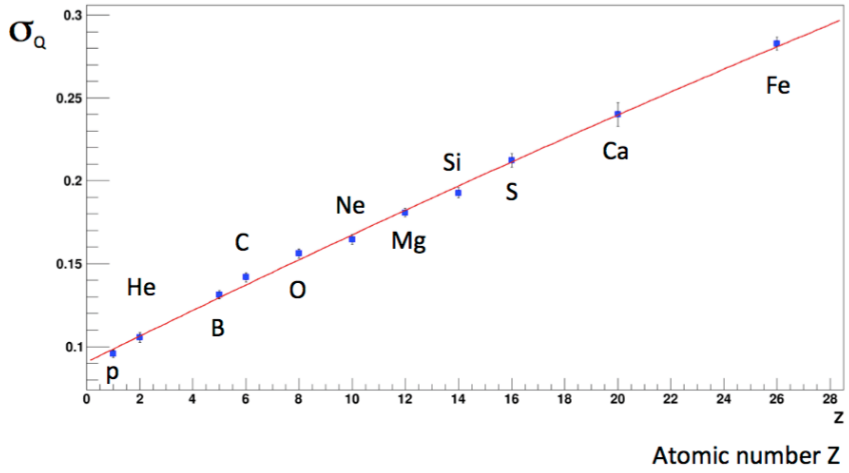
HE Trigger Efficiency for Carbon



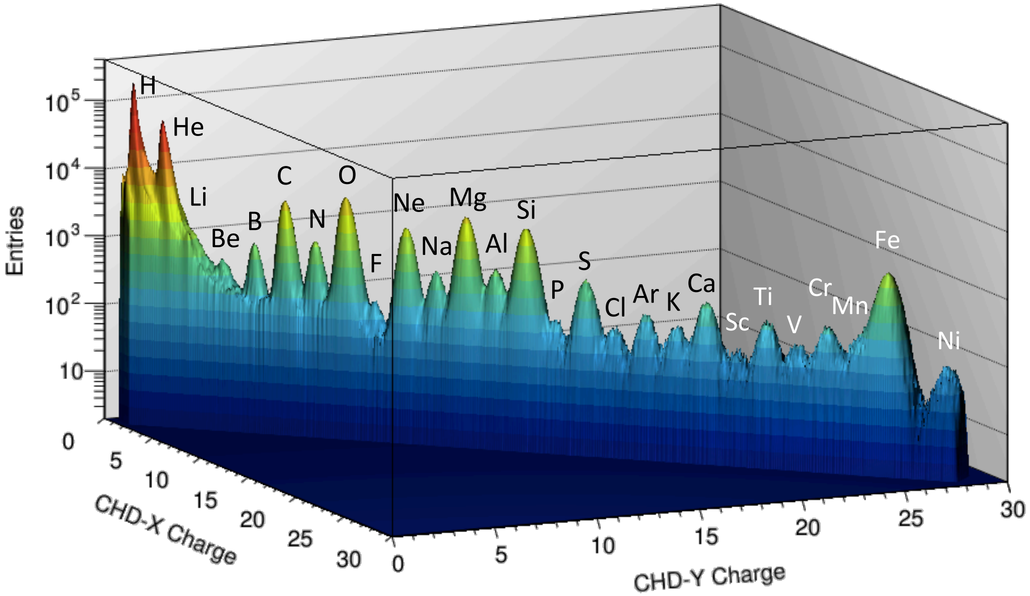
Charge resolution

- 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

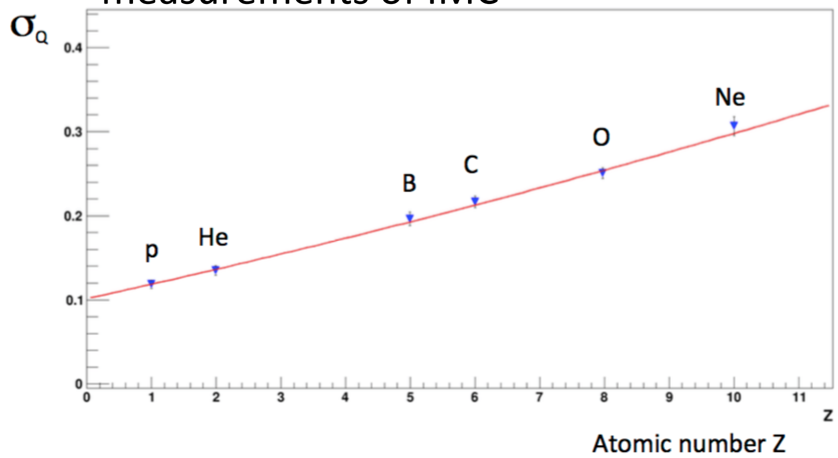
Charge resolution with 2layers of CHD



Charge with CHD-X vs CHD-Y



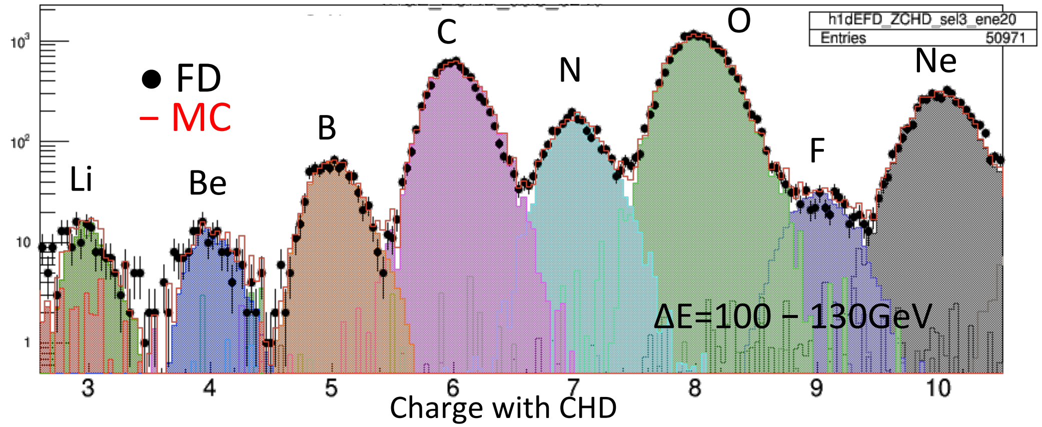
Charge resolution using multiple dE/dx measurements of IMC

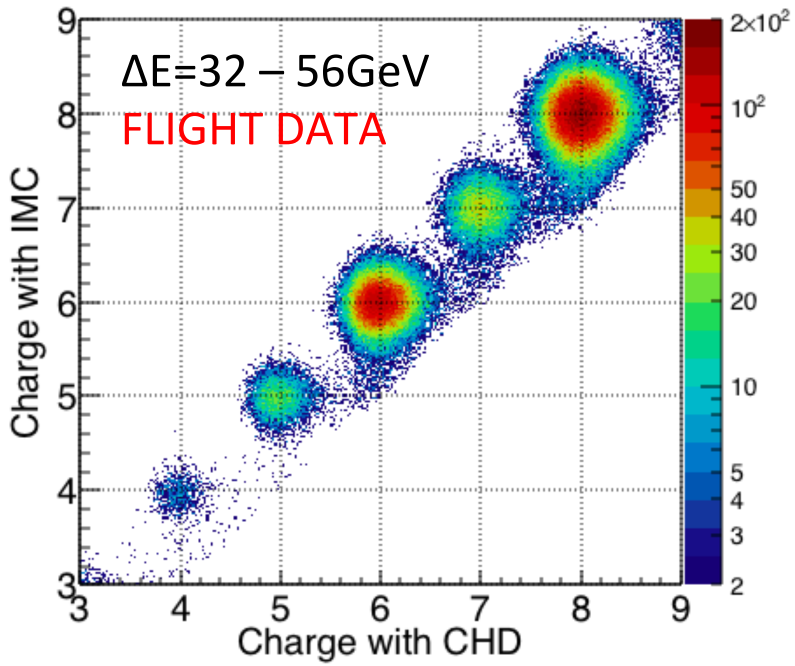


Charge identification of Carbon

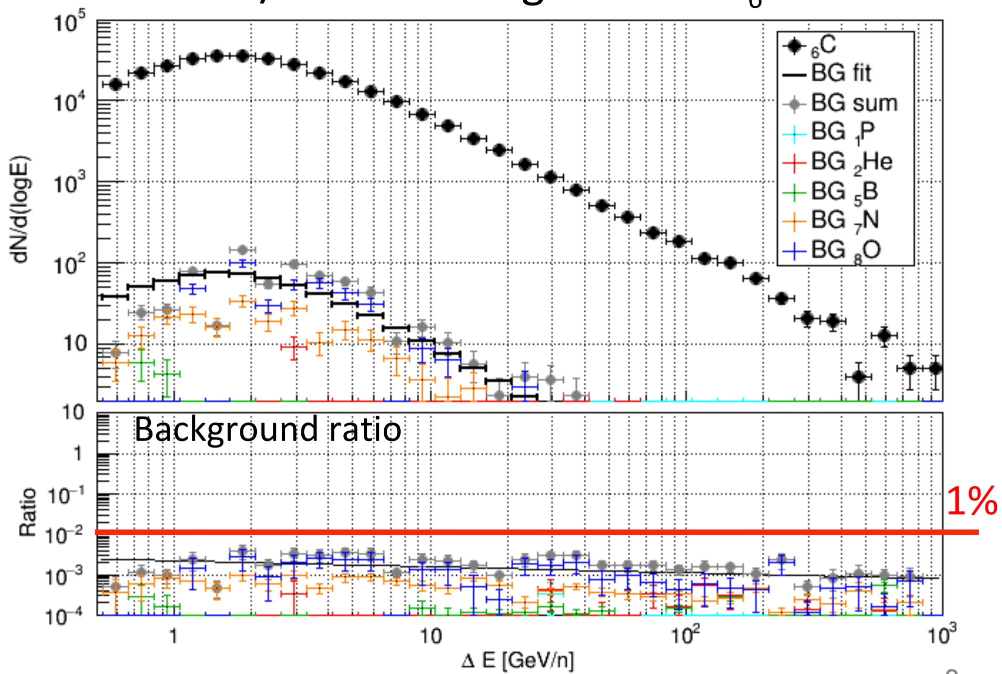
Pre-selection

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





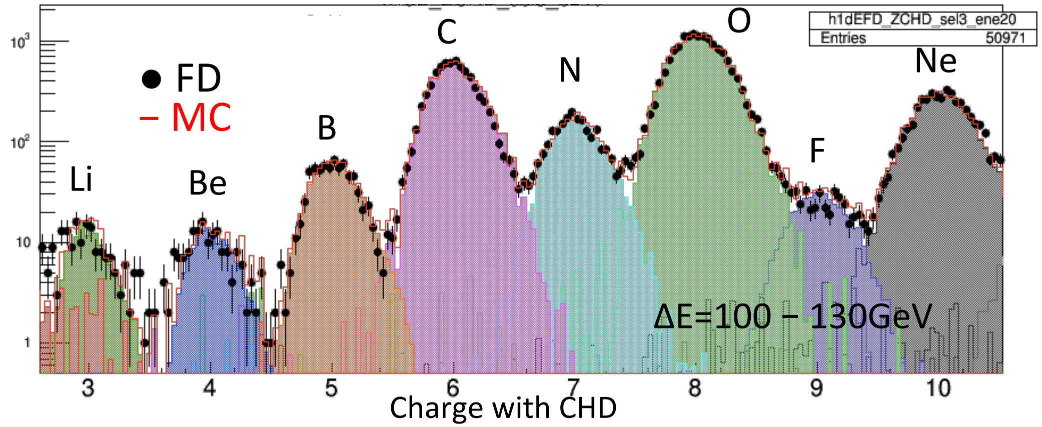
dN/dE and background for $_6$C

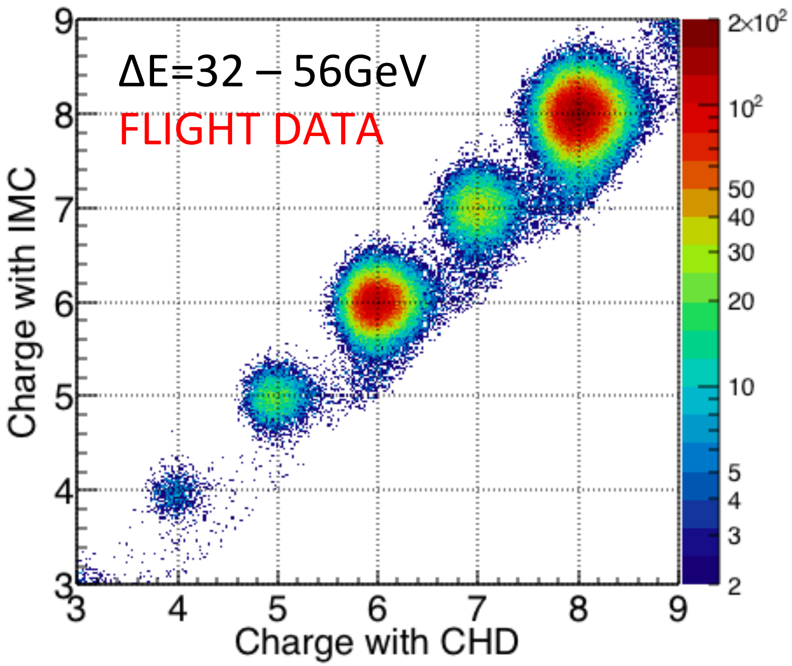


Charge identification of Boron

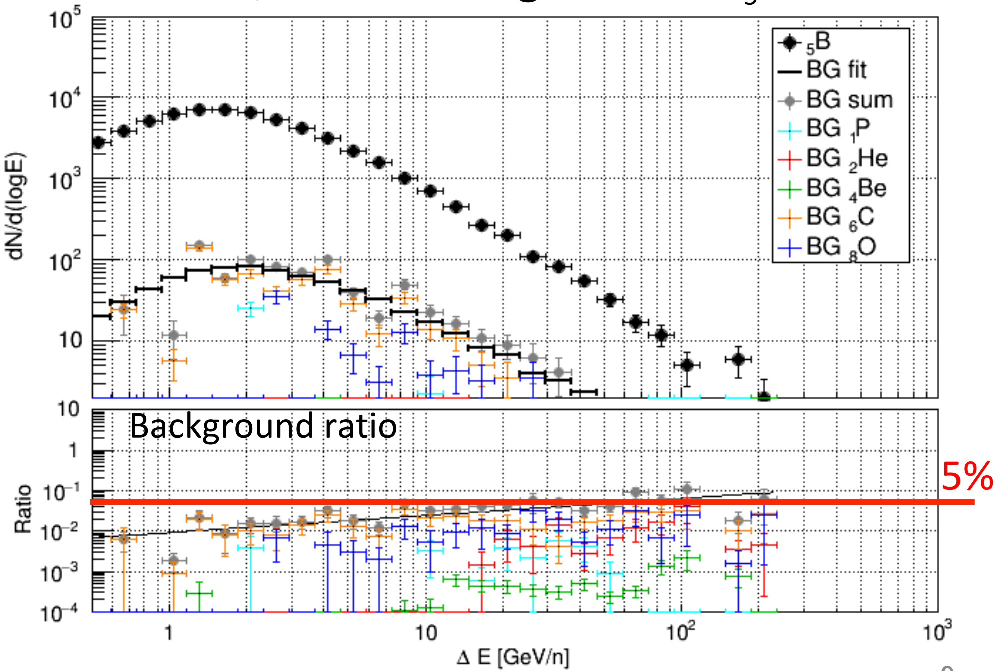
<u>Pre-selection</u>

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



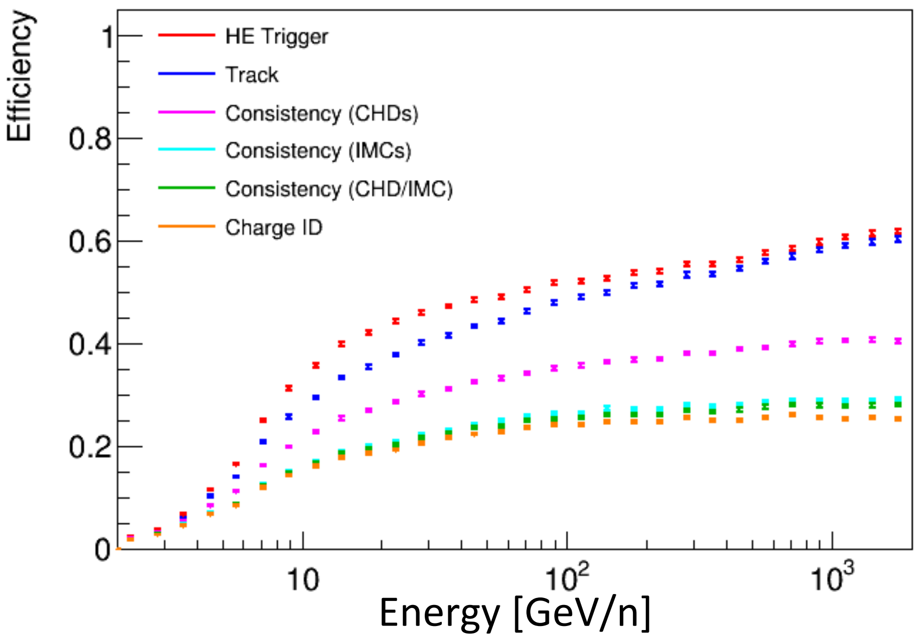


dN/dE and background for $_5$B

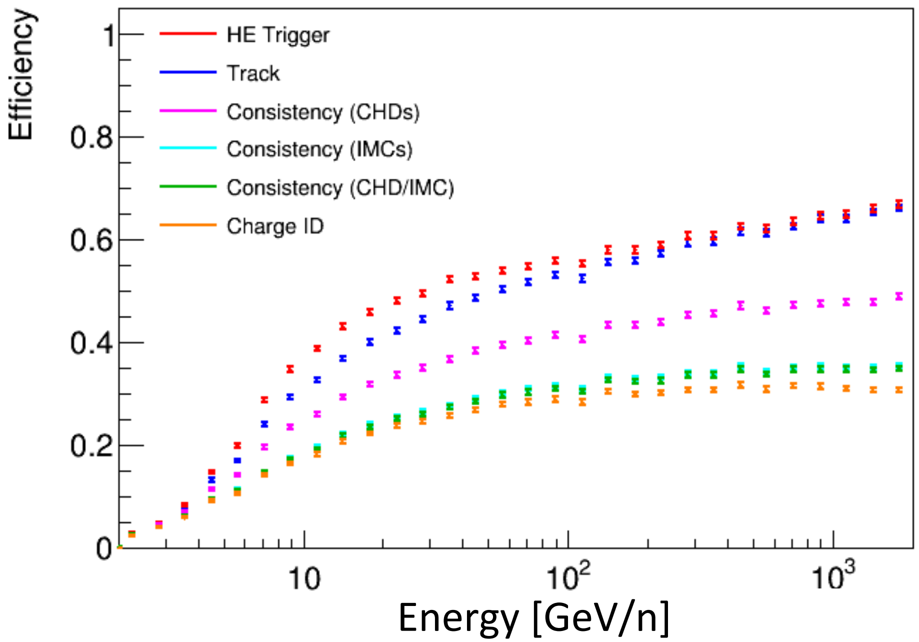


Efficiency

Efficiency for Boron



Efficiency for Carbon

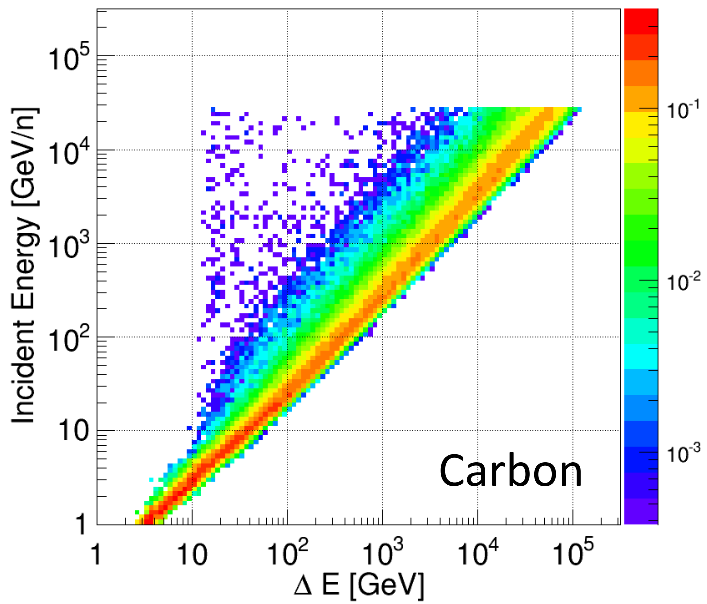


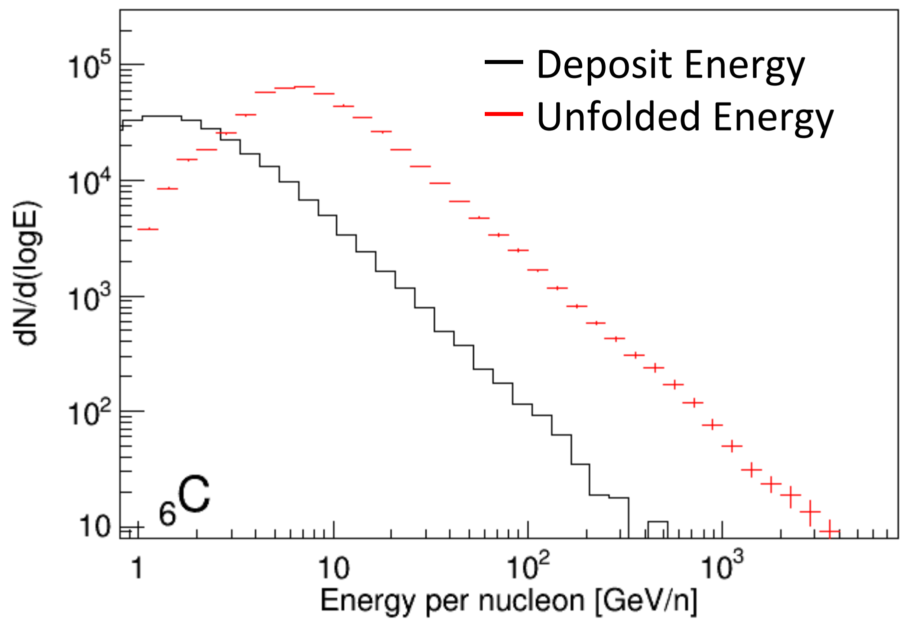
Energy unfolding

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

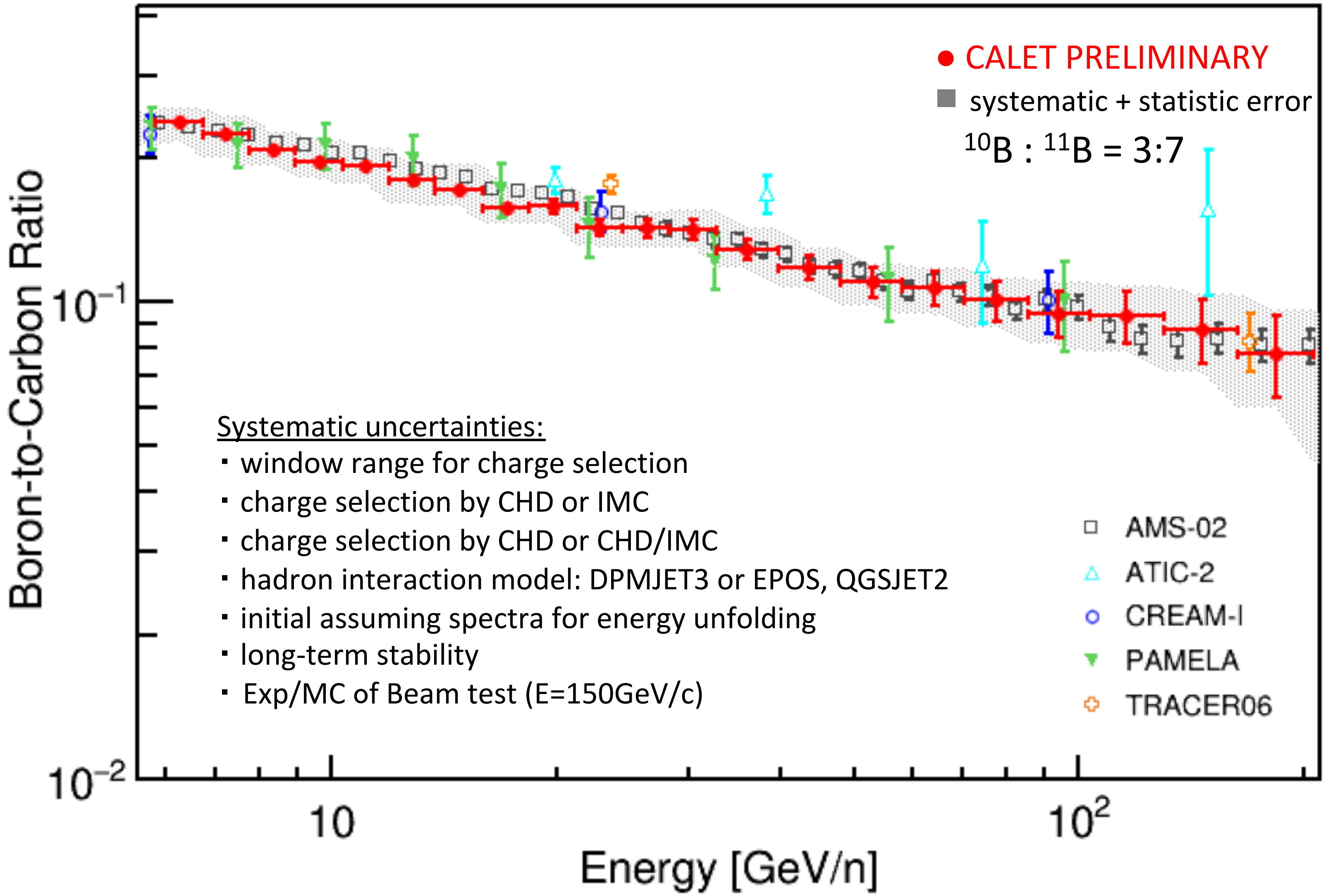
➡ Need energy unfolding for nuclei to obtain primary energy spectrum

- 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)



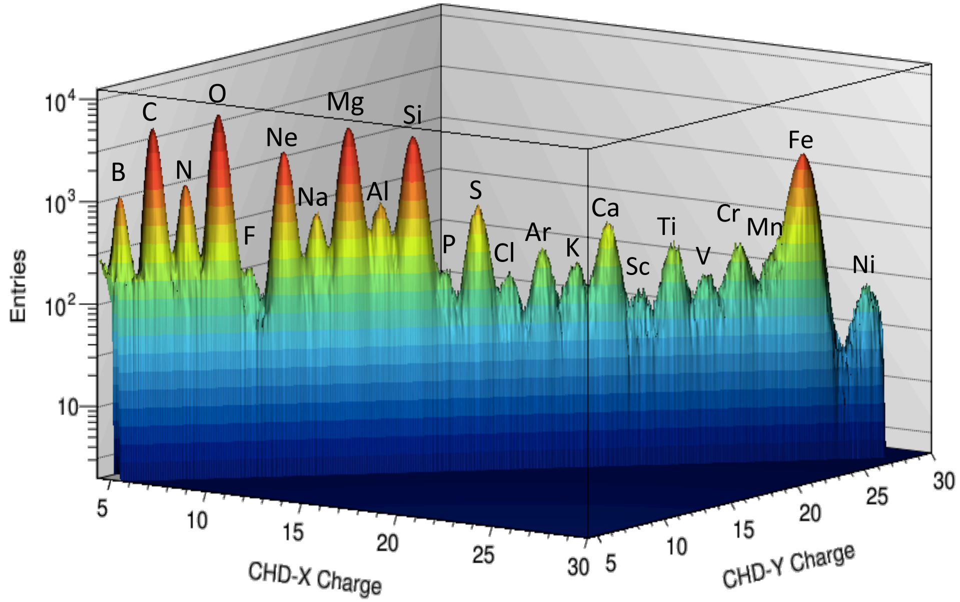


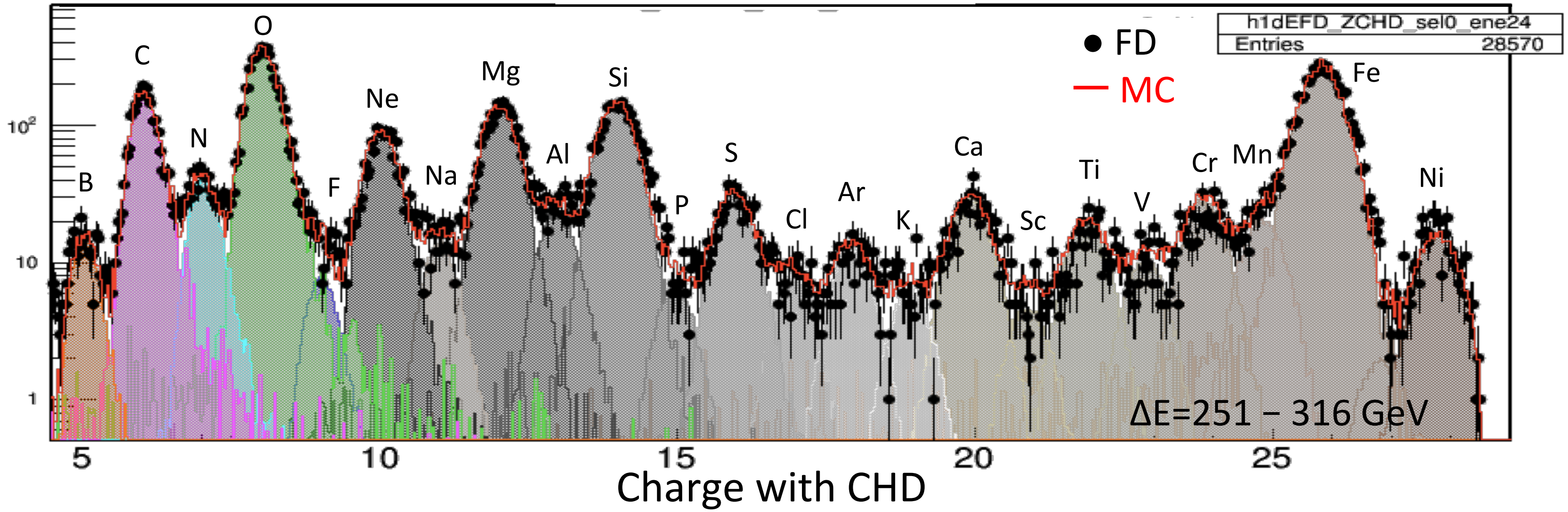
Preliminary Boron-to-Carbon Flux Ratio



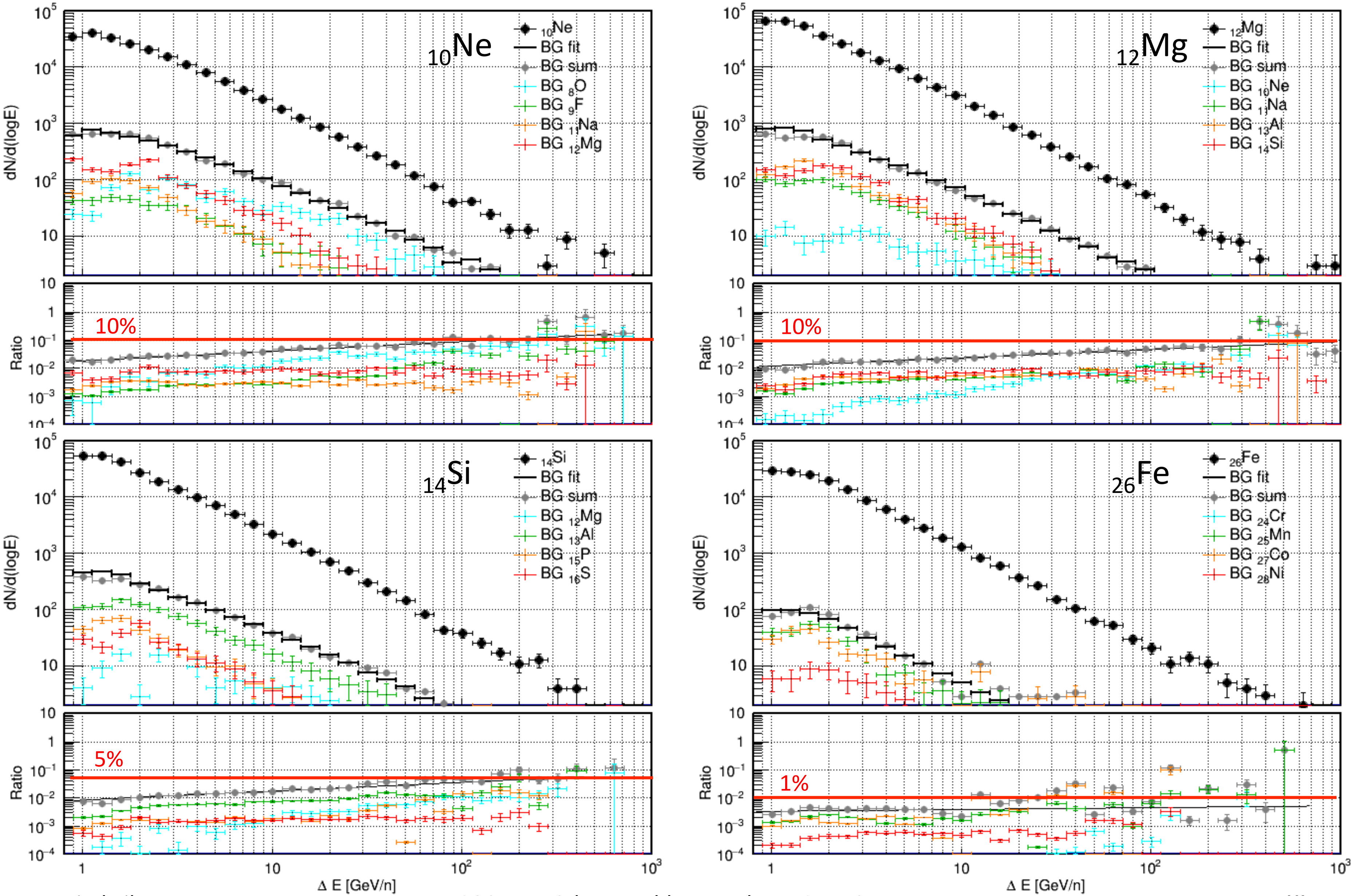
Analysis of heavy nuclei (Z>8)

- Characteristics of heavy nuclei analysis
  - trigger efficiency : ~100%
  - particle charge is identified by CHD

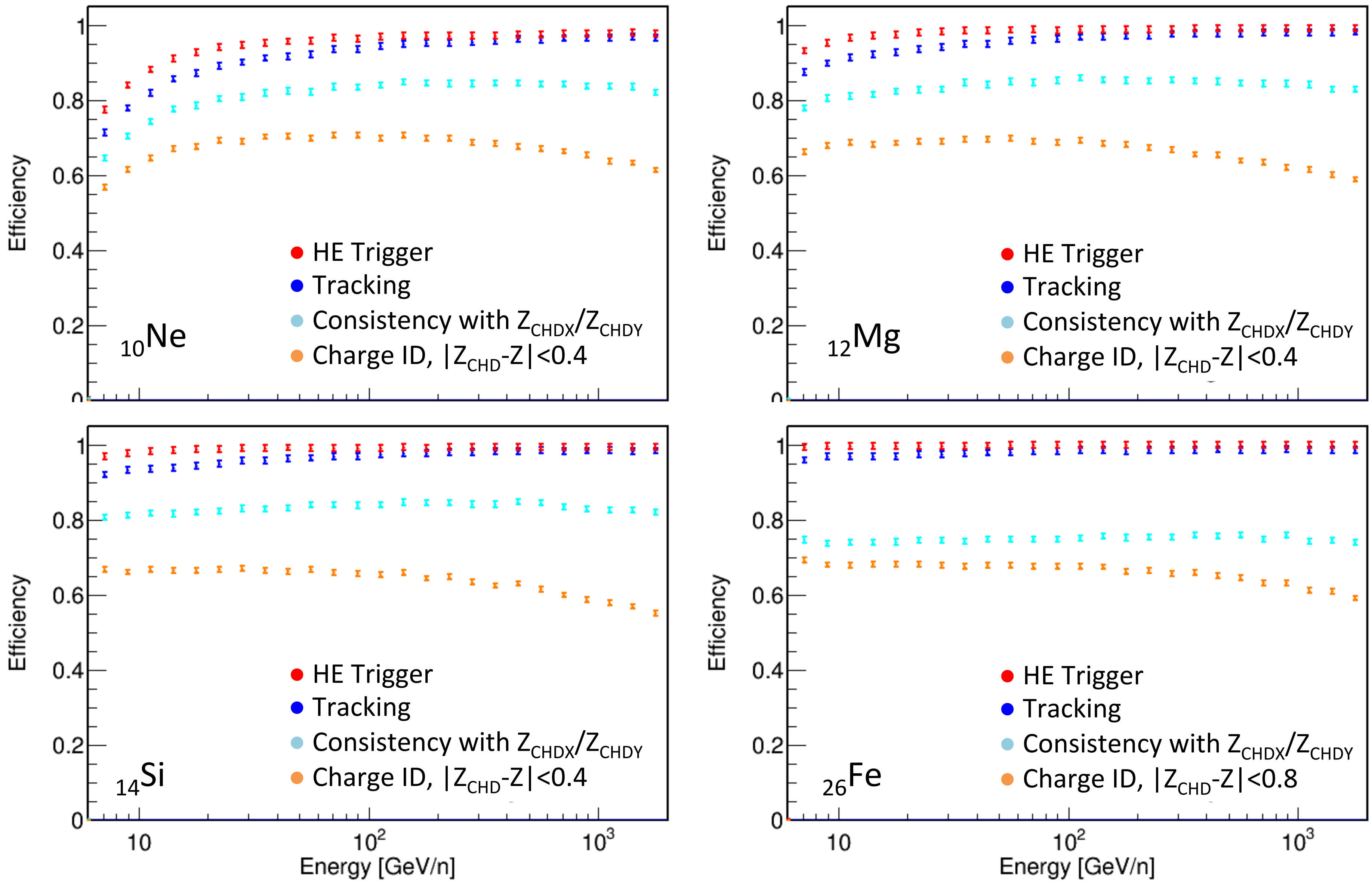




dN/dE and Background Estimation



Efficiency



Efficiency
HE Trigger
Tracking
Consistency with Z_CHDX/Z_CHDY
Charge ID, |Z_CHD-Z|<0.4
10Ne
12Mg
14Si
26Fe
Charge ID, |Z_CHD-Z|<0.8
0
0.2
0.4
0.6
0.8
1
10
10^2
10^3
Energy [GeV/n]

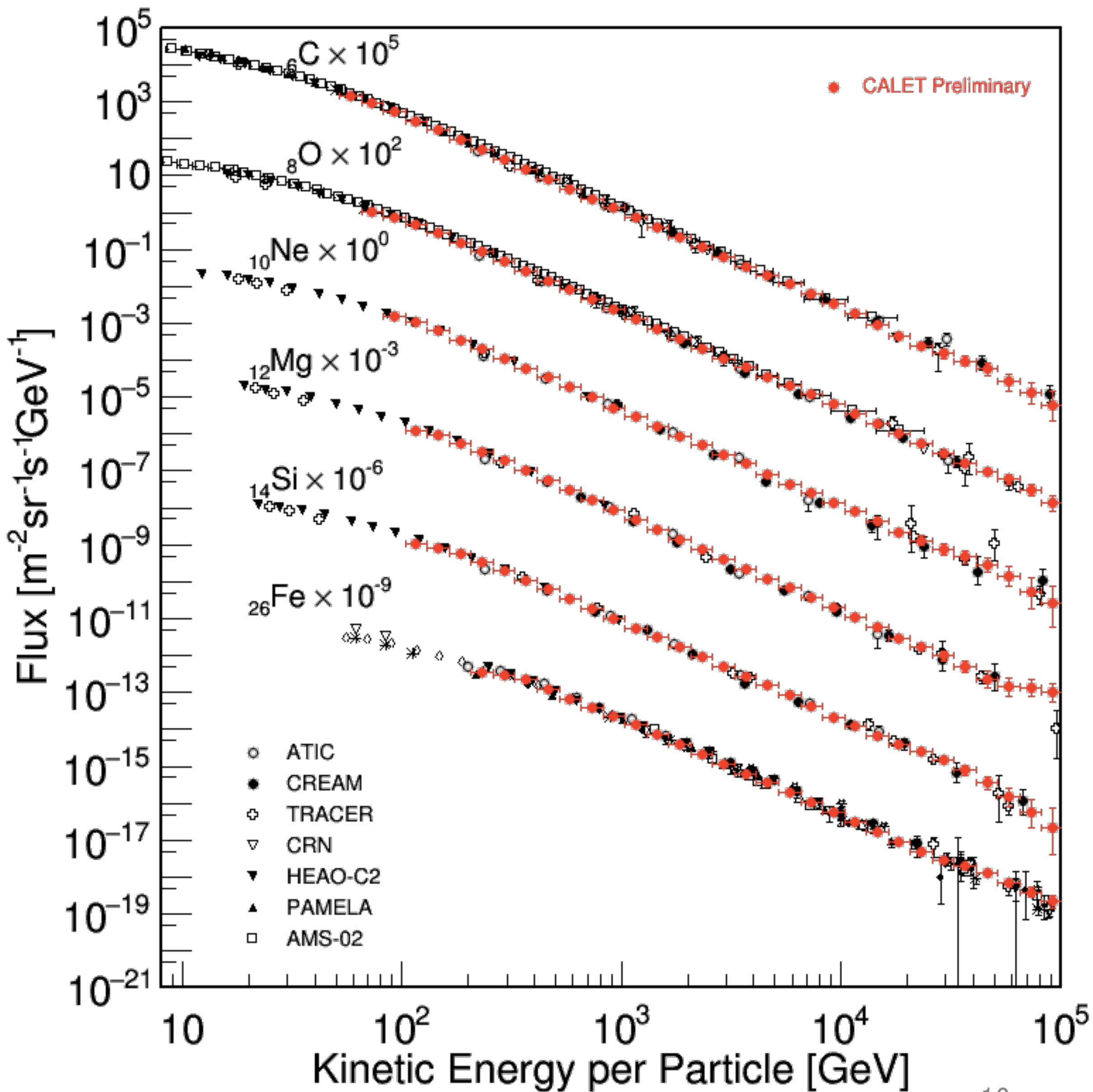
Preliminary Flux of Primary Components

Flux measurements:

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

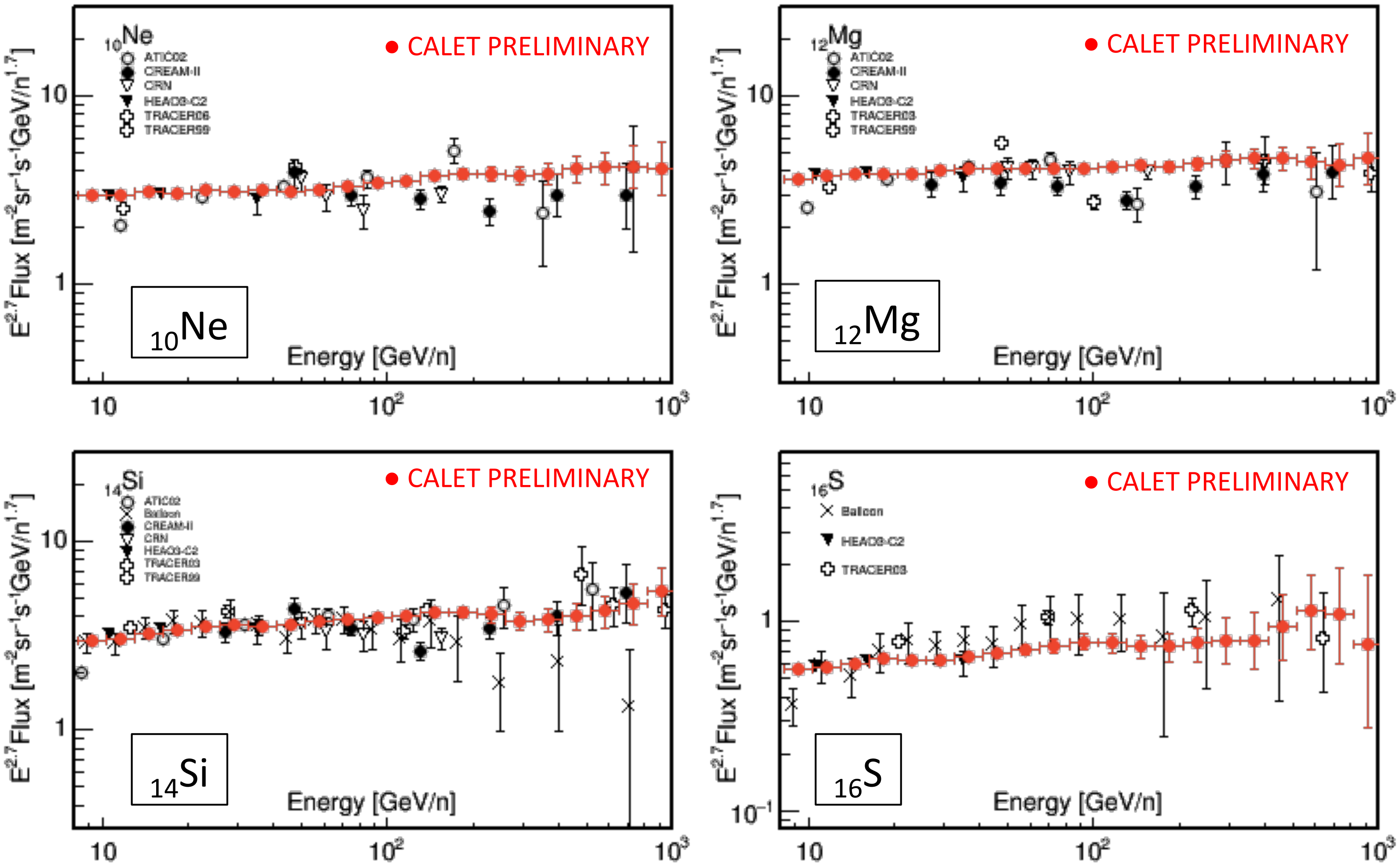
$N(E)$: Events in unfolded energy bin
$S\Omega$: Geometrical acceptance
$\varepsilon(E)$: Efficiency
T : Live Time
ΔE : Energy bin width

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



Preliminary 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

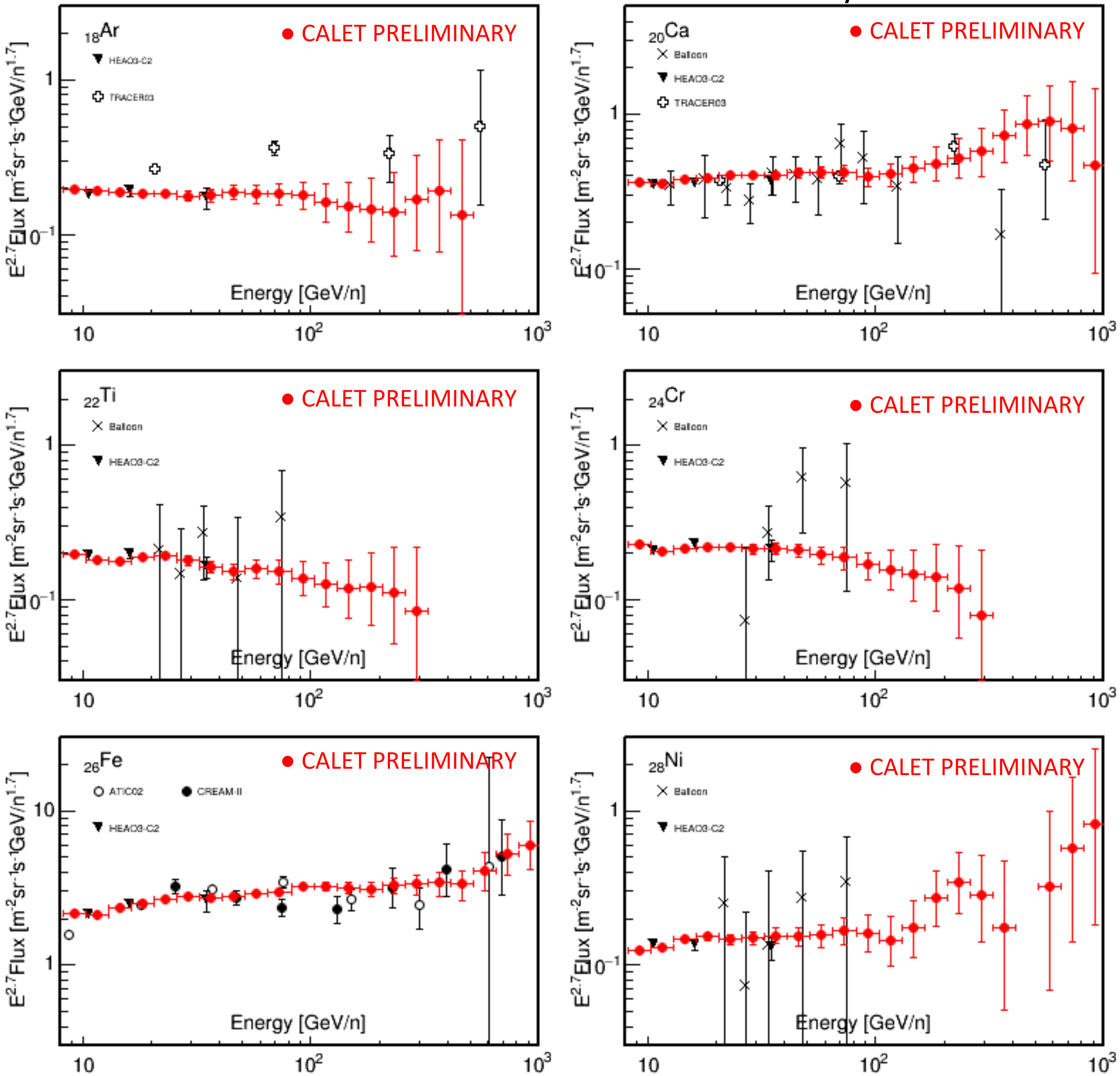
$_{20}$Ca

$_{22}$Ti

$_{24}$Cr

$_{26}$Fe

$_{28}$Ni



Yosui Akaike

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)

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

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