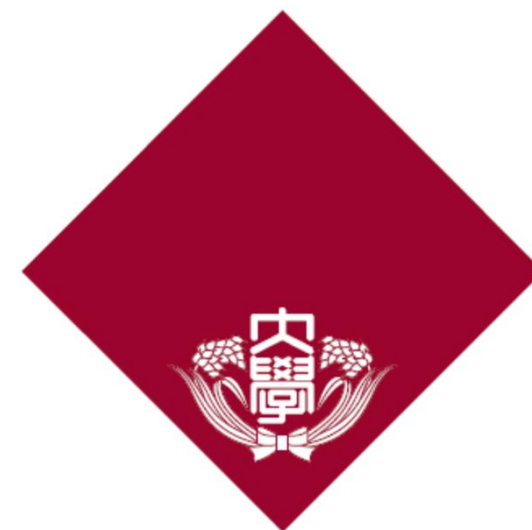


CALETによる全粒子スペクトルの直接観測



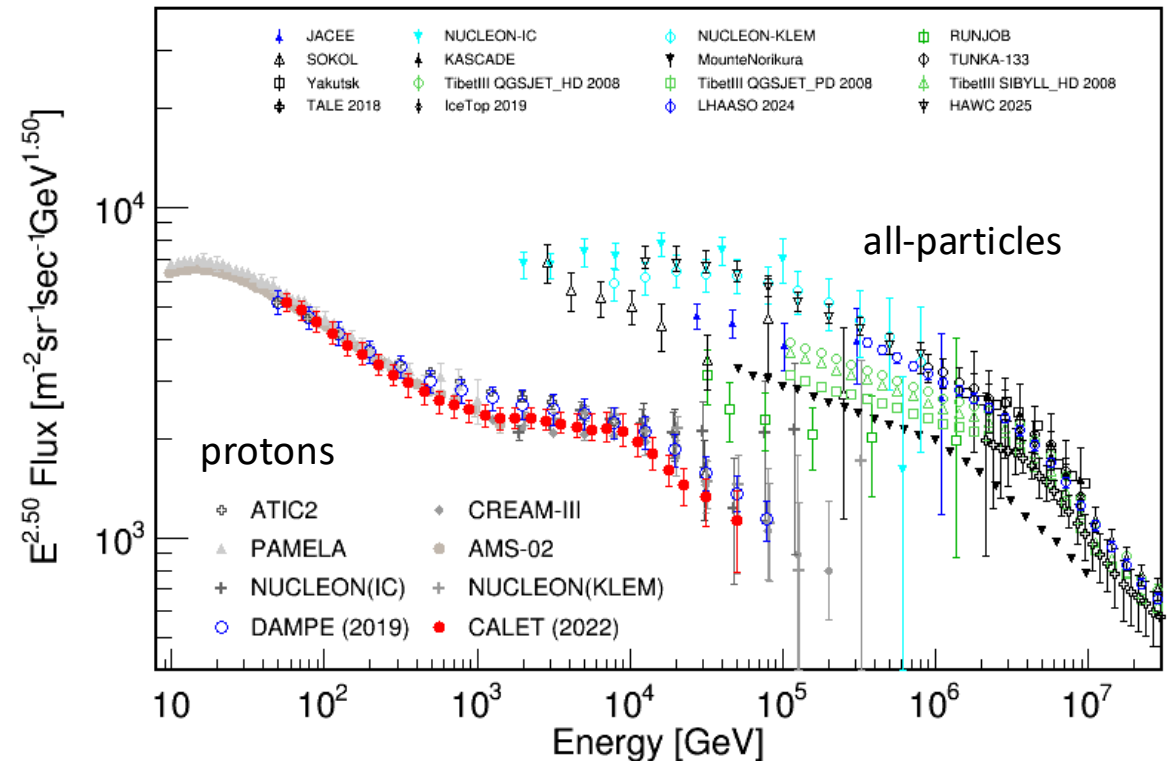
早大理工総研, 芝工大シエ^A

赤池陽水,
鳥居祥二, 小林兼好, 笠原克昌^A
他 CALET チーム



Measurement of all-particle spectrum with CALET

- Above ~ 1 PeV, cosmic rays are mainly studied via indirect measurements.
 - \Rightarrow Require assumptions on composition and hadronic models.
- Direct observations in this region are limited by statistics and exposure.
- A direct measurement to the PeV region can:
 - Provide a model-independent spectrum,
 - Serve as a reference to cross-check indirect measurements.
- In this study, we extend CALET's all-particle spectrum up to 1 PeV by combining events across a wide charge range and loosening the selection criteria.



Capabilities for proton and nuclei measurements

Charge measurement

- CHD enables individual charge identification from $Z=1 - 40$
- Charge resolution ranges from 0.15 e to 0.3 e for protons to iron

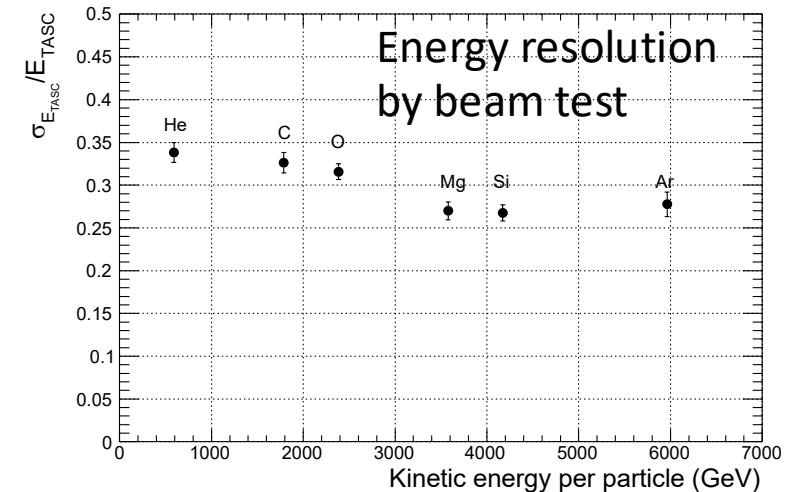
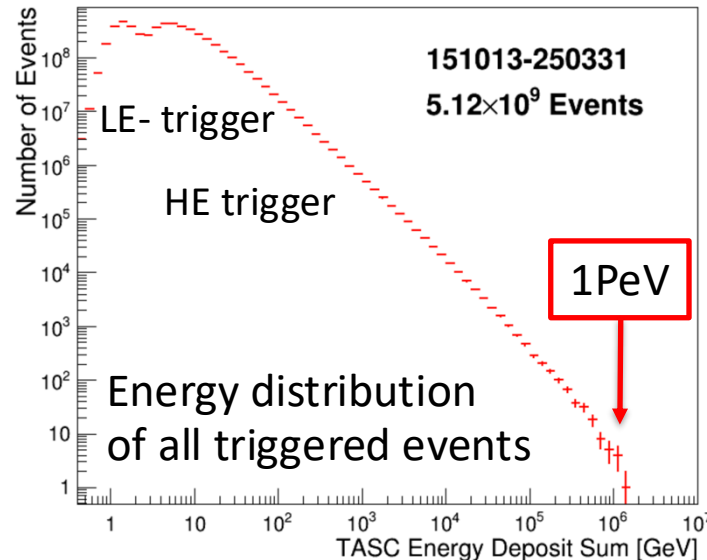
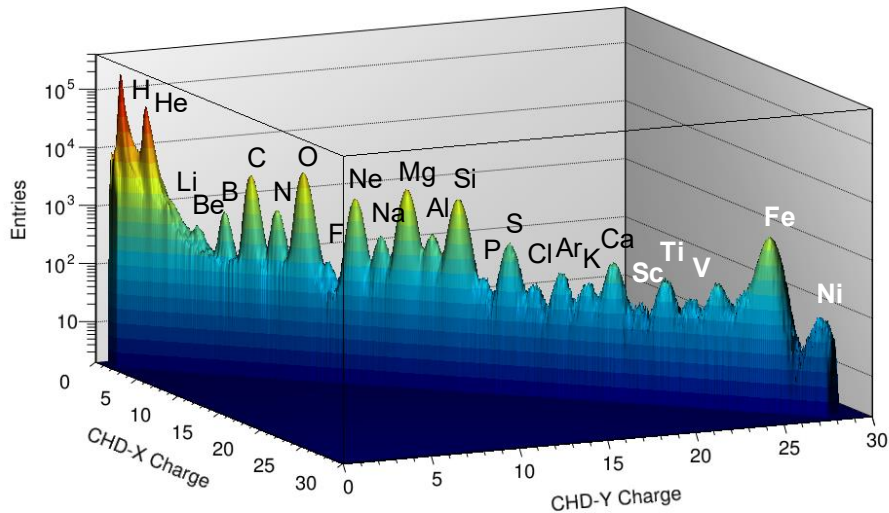
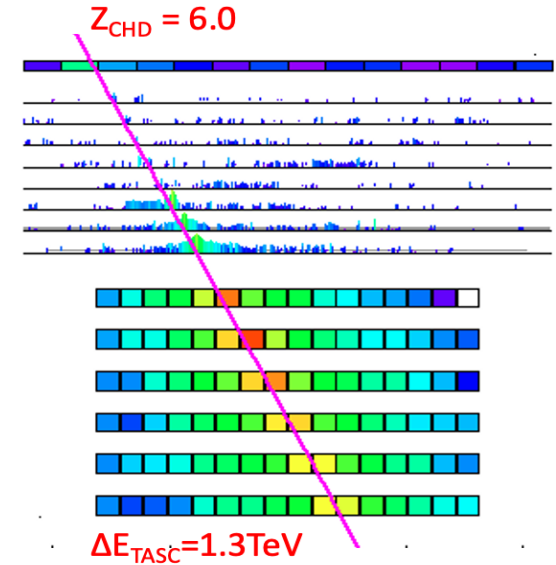
Tracking

- The imaging capability of the IMC enables precise reconstruction of the incident particle's trajectory and entry point.

Energy measurement

- Capable of measuring nuclei over a wide energy range: 1 GeV to 1 PeV.
- Energy resolution for nuclei: 30 – 35%

An example of Carbon event



Event selection

Data period

- Oct. 13, 2015 – Oct. 31, 2025 (3672days; 10 years)

Trigger condition

- High-energy (HE) trigger ($E_{\text{TASC}} > \sim 10\text{GeV}$)
- Offline trigger with stricter thresholds than onboard

Tracking

- Kalman Filter (KF) tracking applied
 - ⇒ Unified reconstruction for all nuclei (p – Ni)

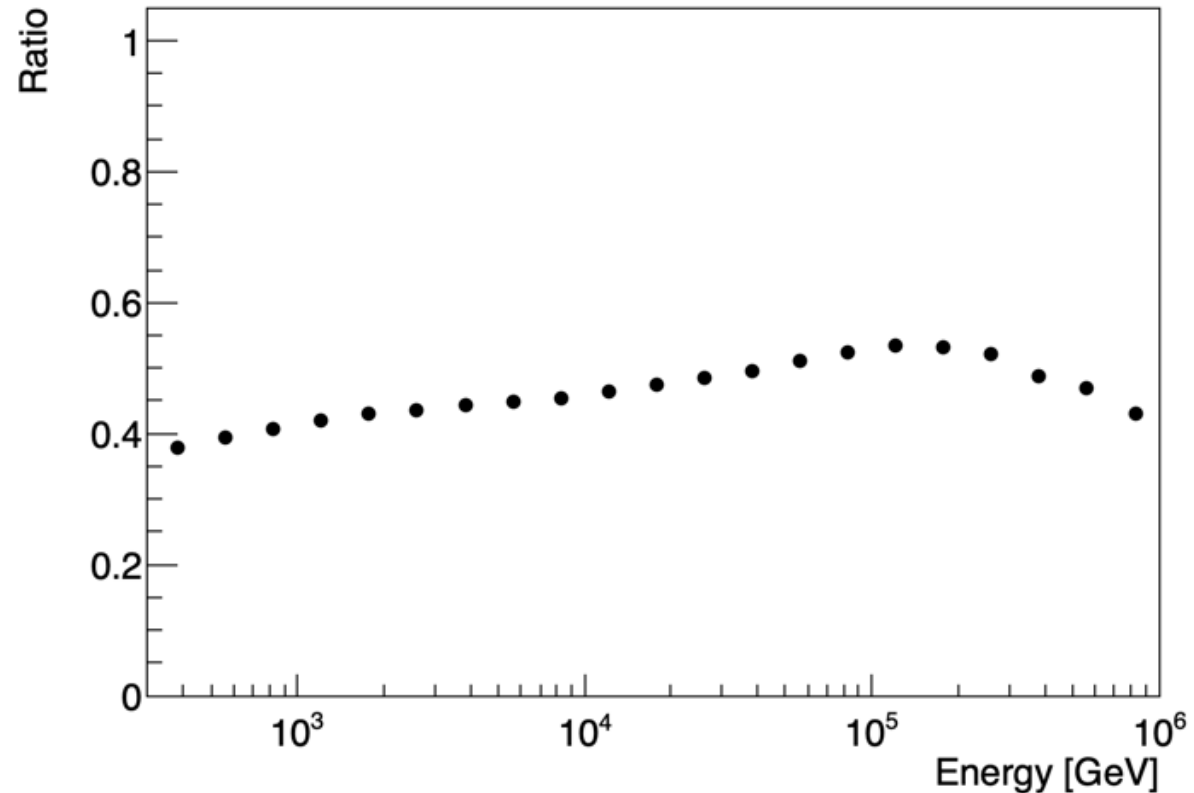
Geometrical condition

- Traversing both the top and bottom of CHD and TASC

Event selection

- Consistency between the IMC tracking axis and the energy centroid in TASC ($\Delta < 3\text{ cm}$)
 - ⇒ suppress mis-reconstructed events
- Charge consistency: $|Z_{\text{CHDX}} - Z_{\text{CHDY}}| < 1$
- Reconstructed charge $Z > 0.3$ to reject photons

Total efficiency
including trigger and selection efficiency



No species are separated:

- All nuclei are combined for the all-particle analysis

MC Simulation

Detector simulation:

- EPICS code with DPMJET-III as the hadron interaction model.

⇒ Validated by beam test results at CERN-SPS

The discrepancies are accounted for as systematic uncertainties.
Compared to Geant4 and FLUKA, EPICS best agrees with data.

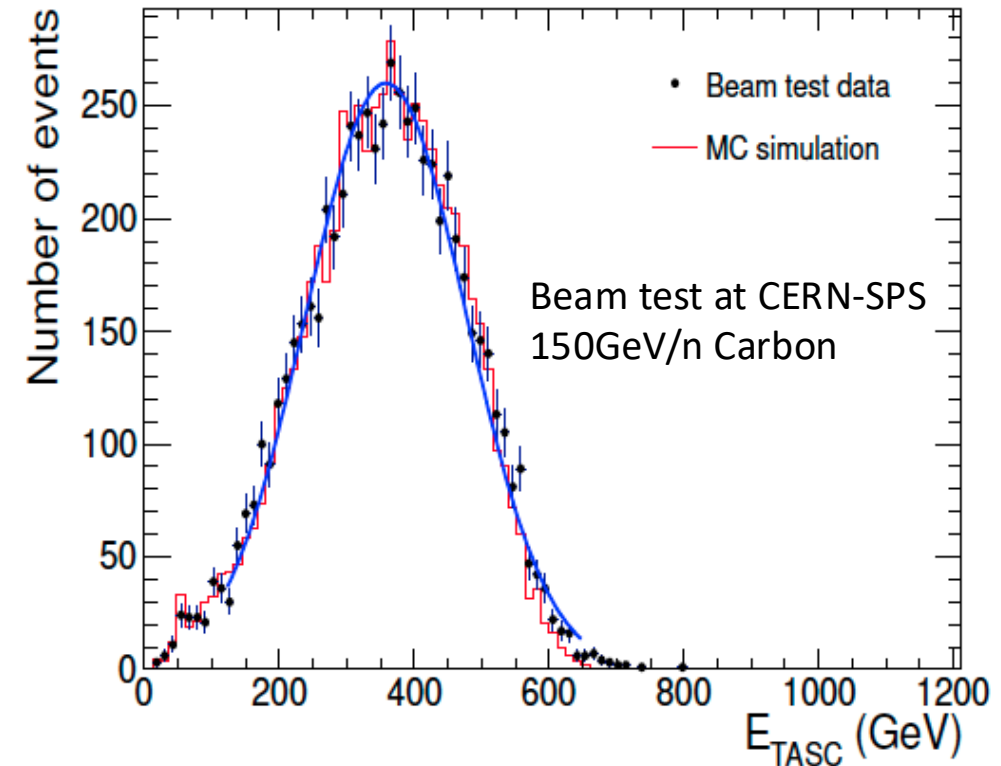
MC data set

- Events are generated for each element from $Z = 1$ to 28 with an input spectrum of E^{-1} over the range
 - 1 GeV – 1 PeV for p, He, C, O and Fe
 - 1 GeV – 316 TeV for the others

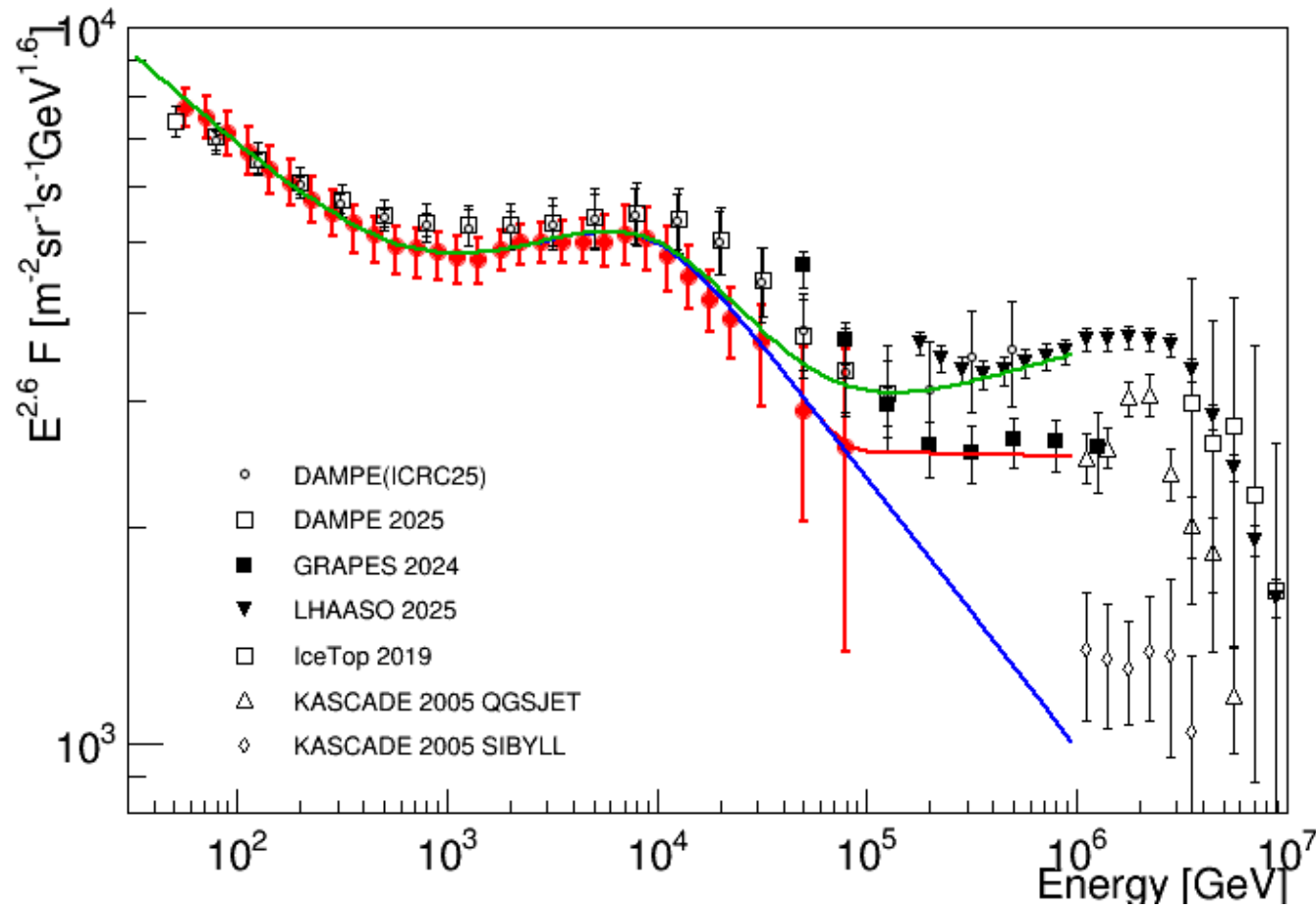
Weighting to measured fluxes

Each MC event is weighted to reproduce the fluxes observed by CALET

An example of the energy distribution of beam-test



Proton flux

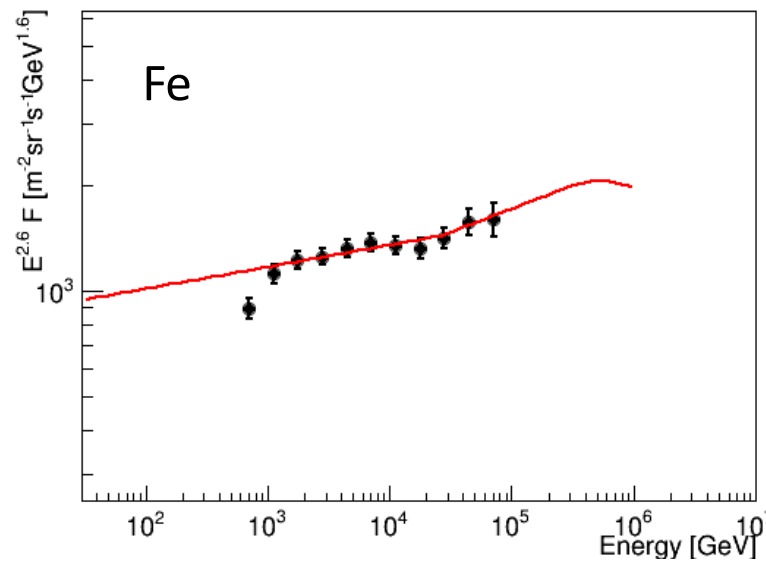
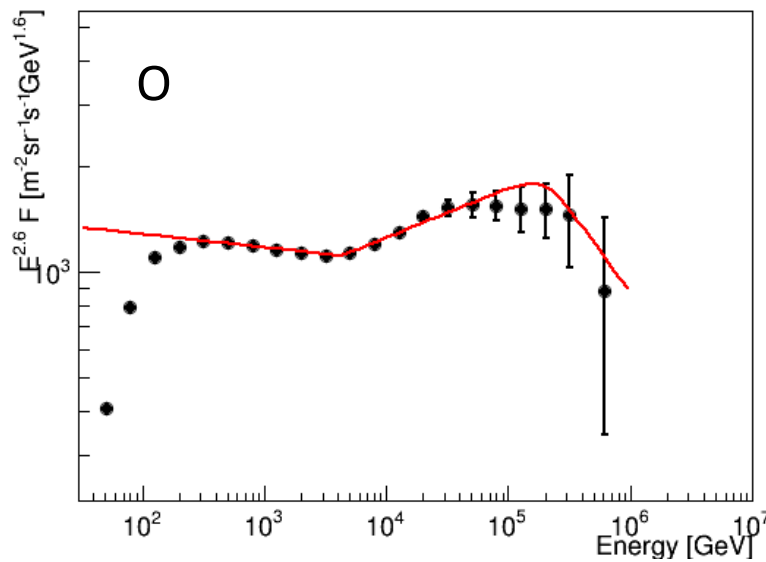
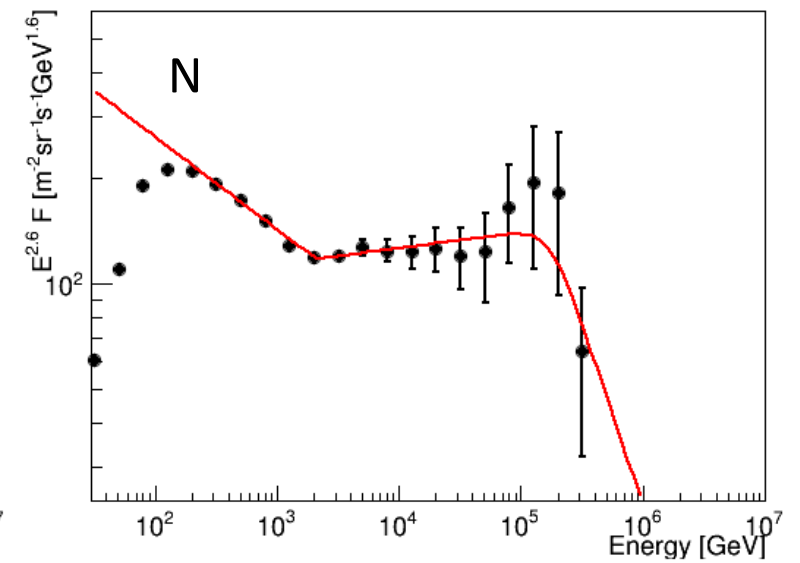
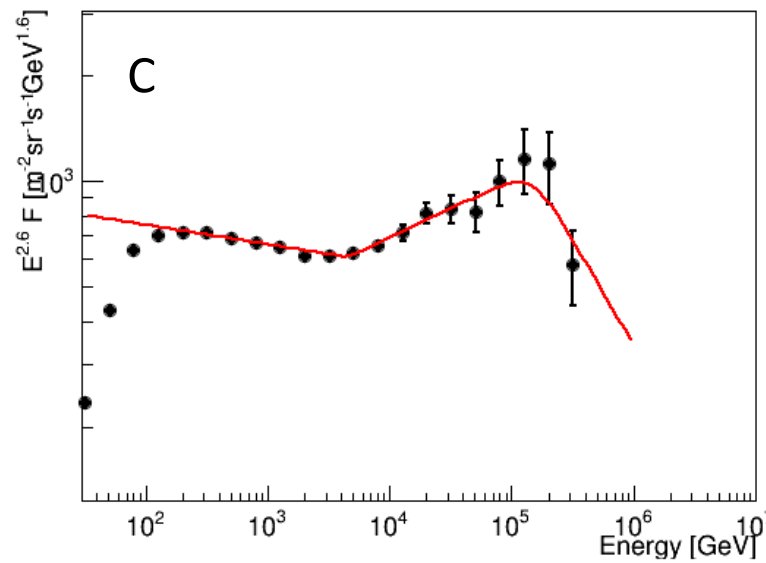
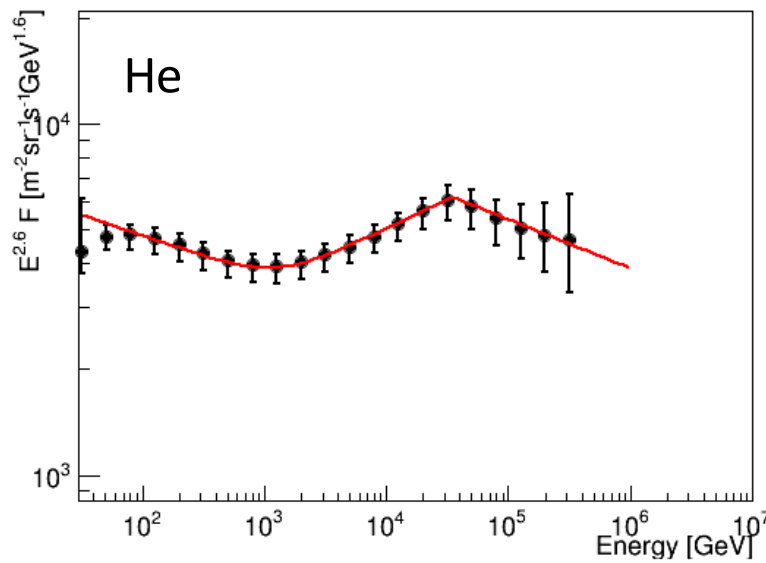


- CALET proton spectrum up to 100 TeV is well described by a double smoothly broken power-law function

$$\Phi(E) = C \left(\frac{E}{\text{GeV}} \right)^\gamma \left[1 + \left(\frac{E}{E_0} \right)^S \right]^{\frac{\Delta\gamma}{S}} \left[1 + \left(\frac{E}{E_1} \right)^{S_1} \right]^{\frac{\Delta\gamma_1}{S_1}}$$

- Above 100 TeV, three models are considered
 - Simple extrapolation
 - 2nd hardening consistent with GRAPES results
 - 2nd hardening consistent with LHAASO results

Nuclei fluxes

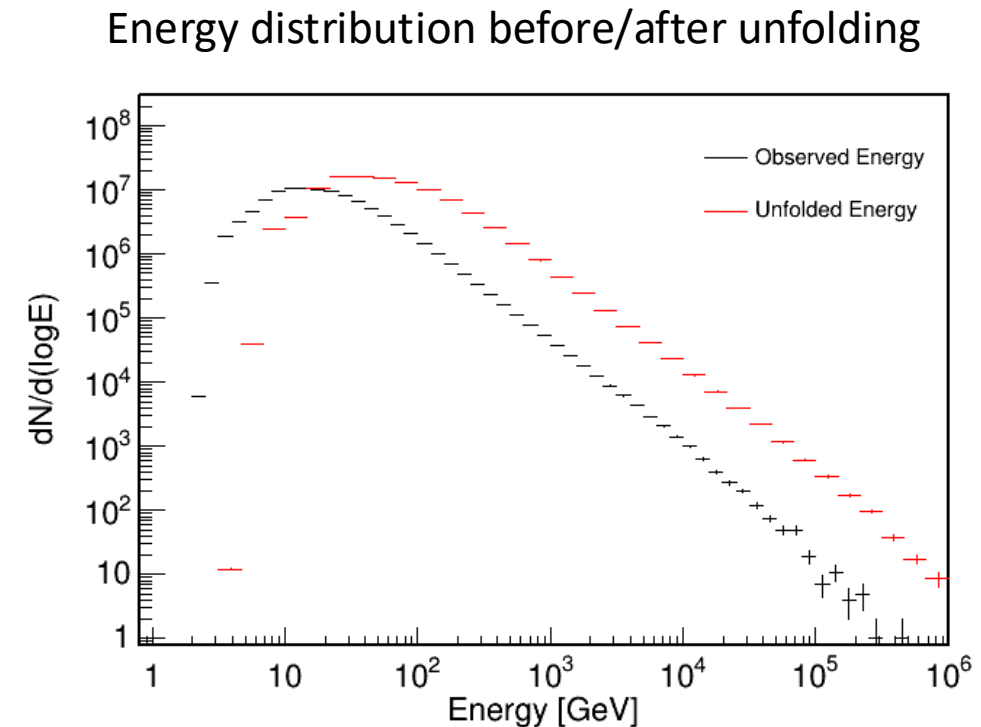
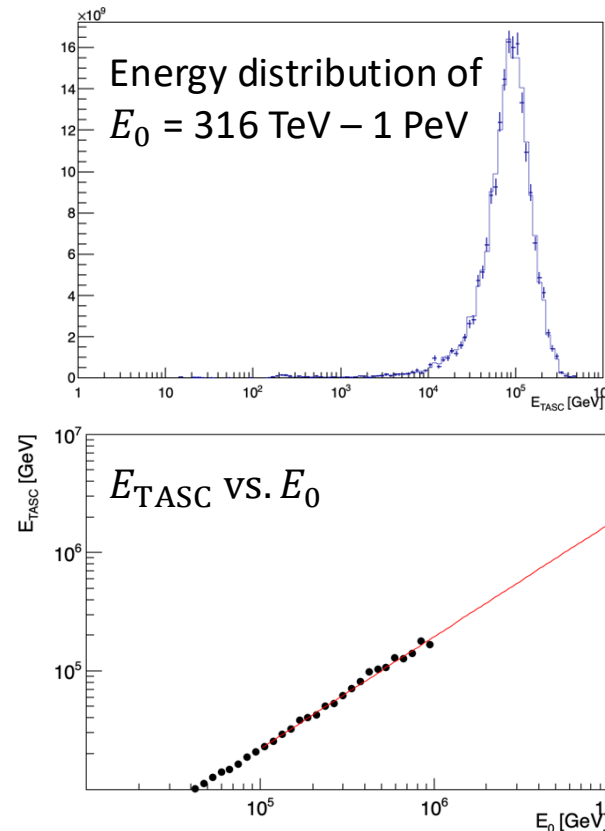
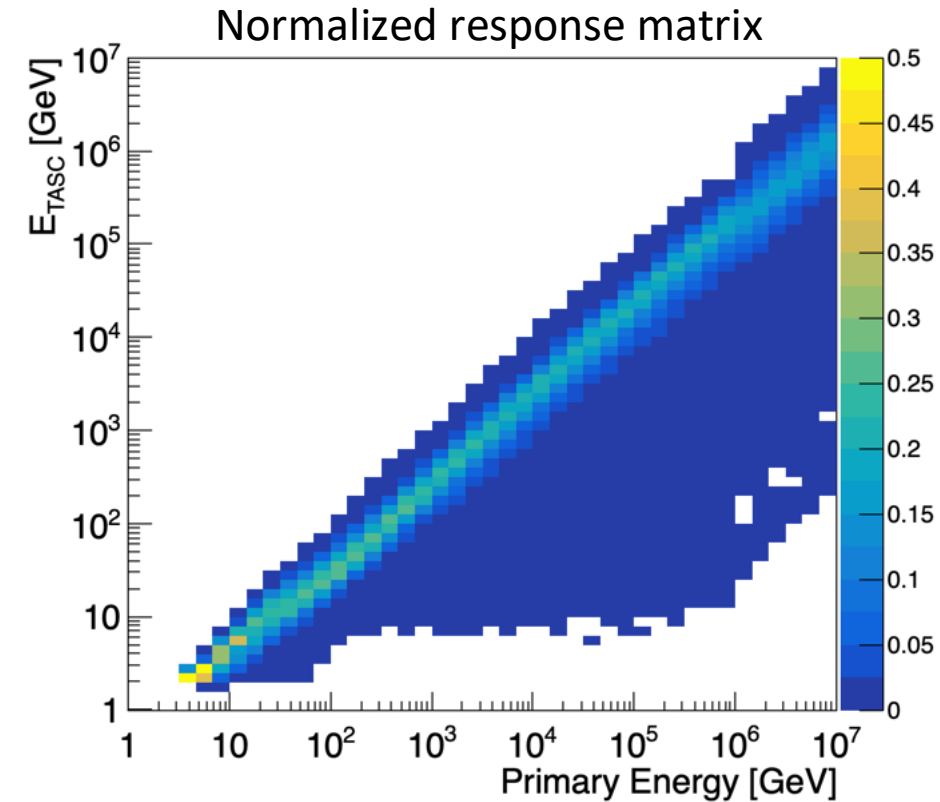


The CALET data are fitted with the following function, extrapolated to 1 PeV, and used to weight MC events

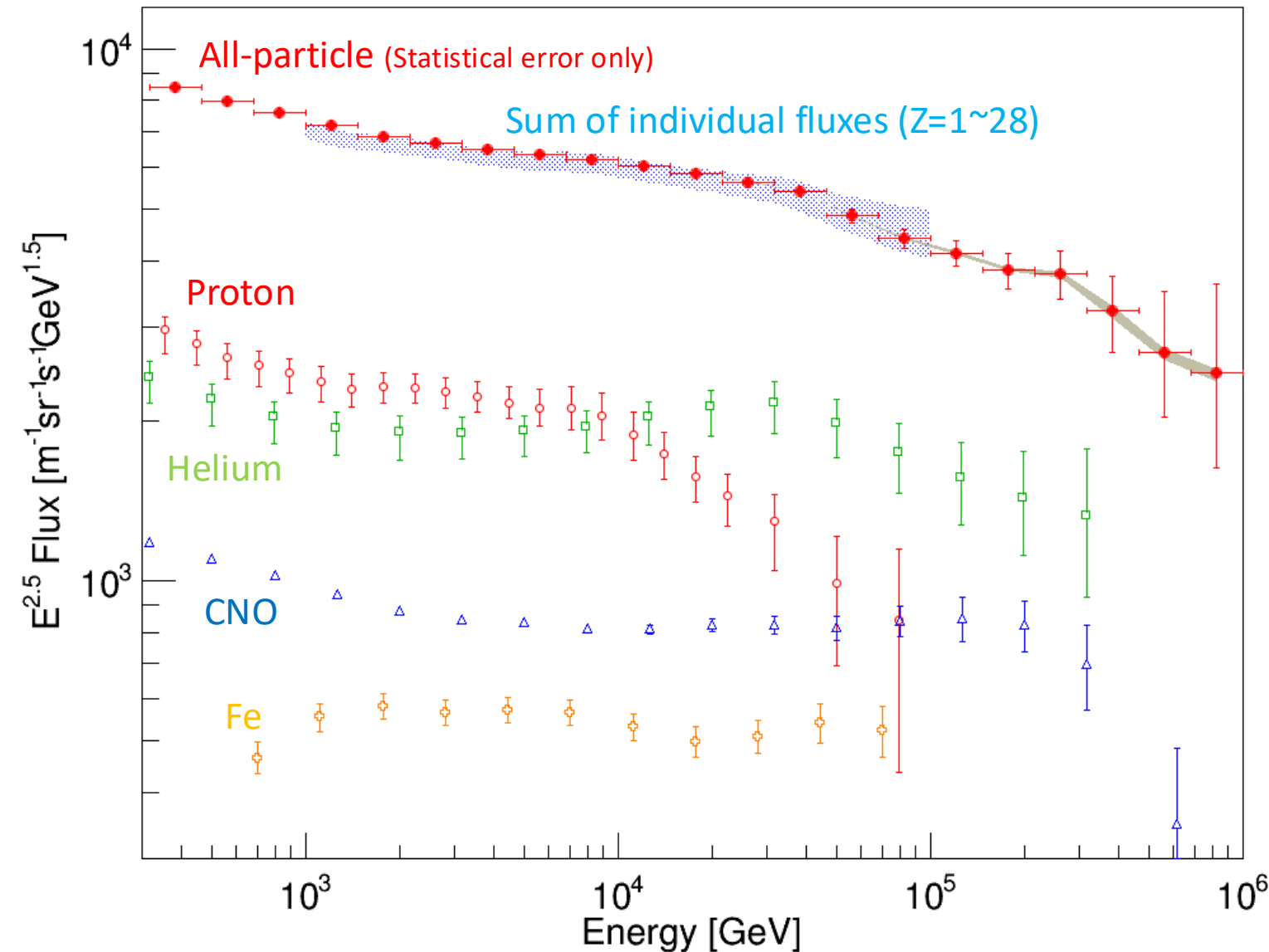
- $Z=2\sim 14, 16, 18, 20, 26$: DBPL
 E_1 (energy at softening) is fixed as
25 x Z TeV for CNO,
20 x Z TeV for $Z>8$
- Others: SPL

Energy reconstruction and unfolding

- Shower energy: total energy deposit in TASC
- Response matrix: combined from $Z=1 - 28$
- Above 10^6 GeV; extrapolated using template from 316 TeV – 1 PeV, scaled by energy
- Bayesian iterative unfolding applied
⇒ corrects resolution and migration effects

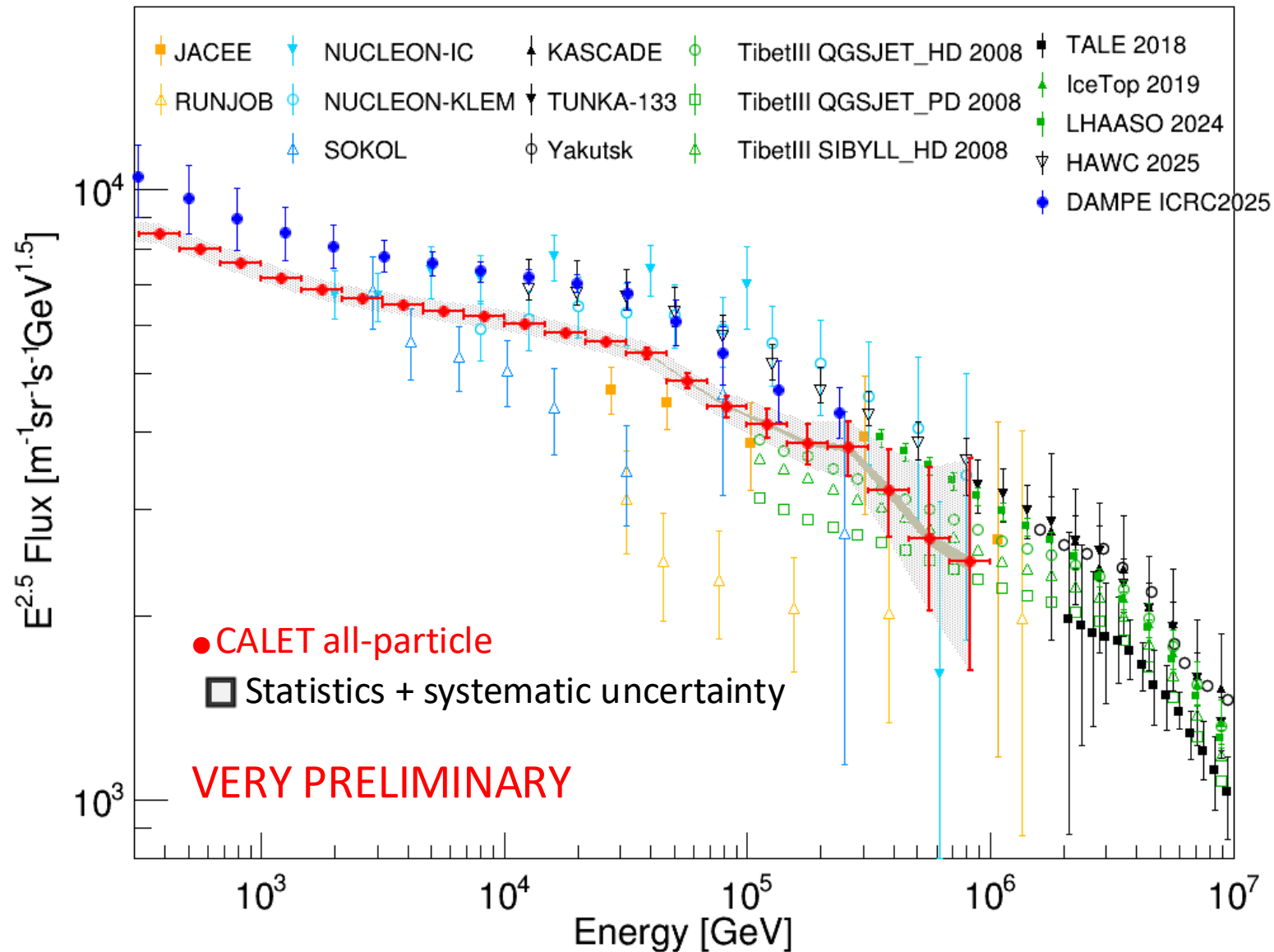


All-particle spectrum from 316 GeV to 1 PeV



- All-particle spectrum is consistent to the sum on individual spectra observed by CALET in the energy range 1 TeV – 1 PeV
- Below ~ 100 TeV, the result is based on the composition measured by CALET.
- Above ~ 100 TeV, the model-dependent uncertainty from extrapolation must be considered.
- The uncertainty from the proton spectrum extrapolation above ~ 100 TeV is small compared to the statistical errors.
- Further studies including heavier components are ongoing.

All-particle spectrum with other measurements

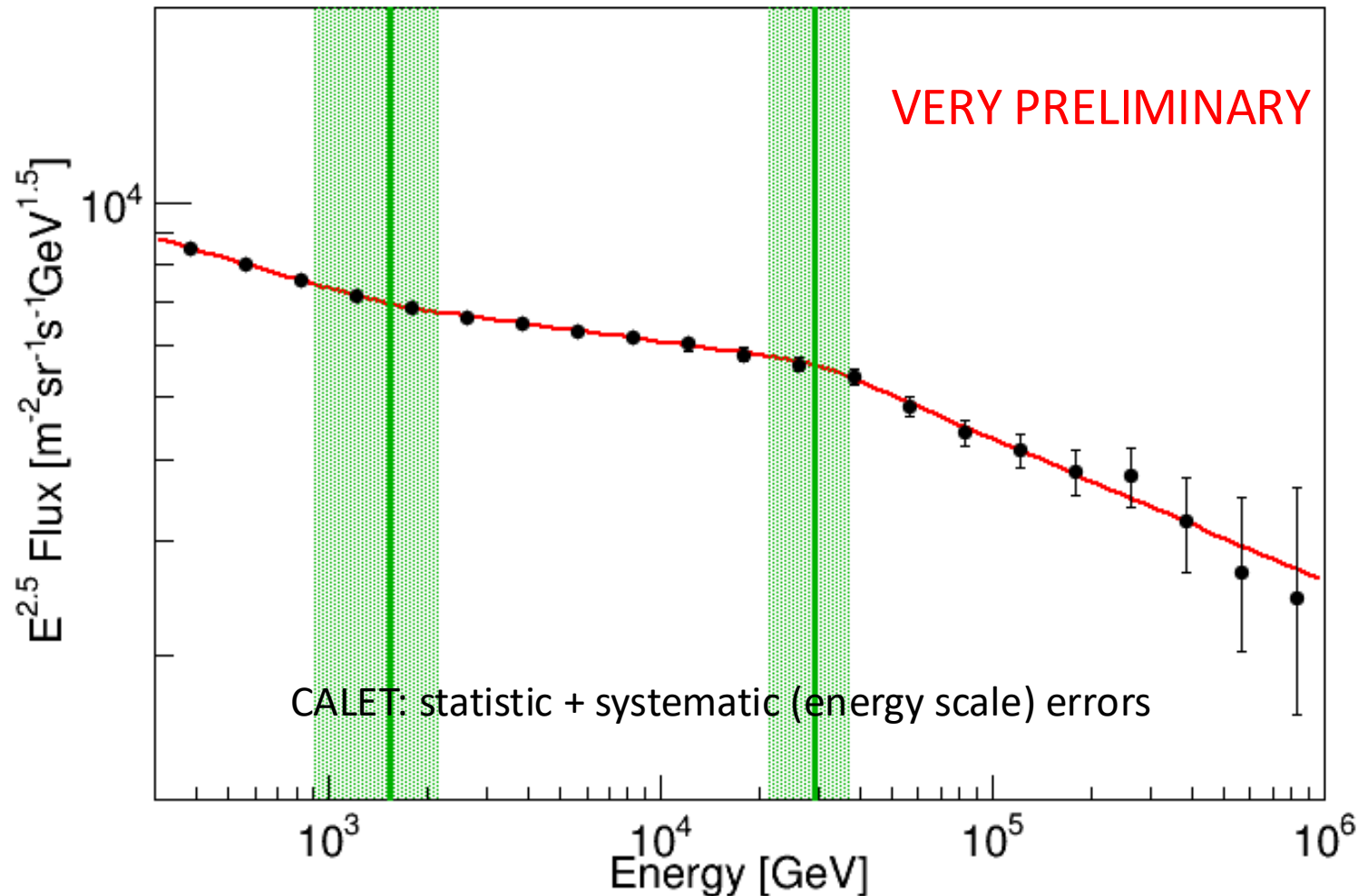


- Systematic uncertainties in all-particle:
- Energy scale based on the beam test
 - Live time

Further details are currently being evaluating.

Fit with Double Broken Power-Law function

$$\Phi(E) = C \left(\frac{E}{\text{GeV}} \right)^\gamma \left[1 + \left(\frac{E}{E_0} \right)^s \right]^{\frac{\Delta\gamma}{s}} \left[1 + \left(\frac{E}{E_1} \right)^{s_1} \right]^{\frac{\Delta\gamma_1}{s_1}}$$



Fitting Parameters

$$\gamma = -2.65 \pm 0.02$$

$$E_0 = 1.53 \pm 0.62 \text{ TeV}$$

$$\Delta\gamma = 0.08 \pm 0.03$$

$$s = 6.6 \text{ (Fix)}$$

$$E_1 = 29.2 \pm 8.1 \text{ TeV}$$

$$\Delta\gamma_1 = -0.15 \pm 0.03$$

$$s_1 = 10 \text{ (Fix)}$$

Summary

- ❑ CALET has been operating stably since October 2015 for more than 10 years.
 - ❑ Wide dynamic range from MIPs to the PeV scale
 - ❑ Direct, high-precision measurements of cosmic-ray nuclei from proton to nickel
- ❑ A preliminary all-particle spectrum in the range of 316 GeV – 1 PeV has been derived by combining events over a wide charge range.
- ❑ Further refinement of systematic uncertainties is ongoing.
- ❑ The updated CALET spectrum is expected to help bridge the observational gap between direct and indirect measurements in the TeV – PeV region.
- ❑ Extended operations have been approved by JAXA, NASA, and ASI through the end of 2030.