Extending Cosmic-Ray Measurements over a Decade with CALET

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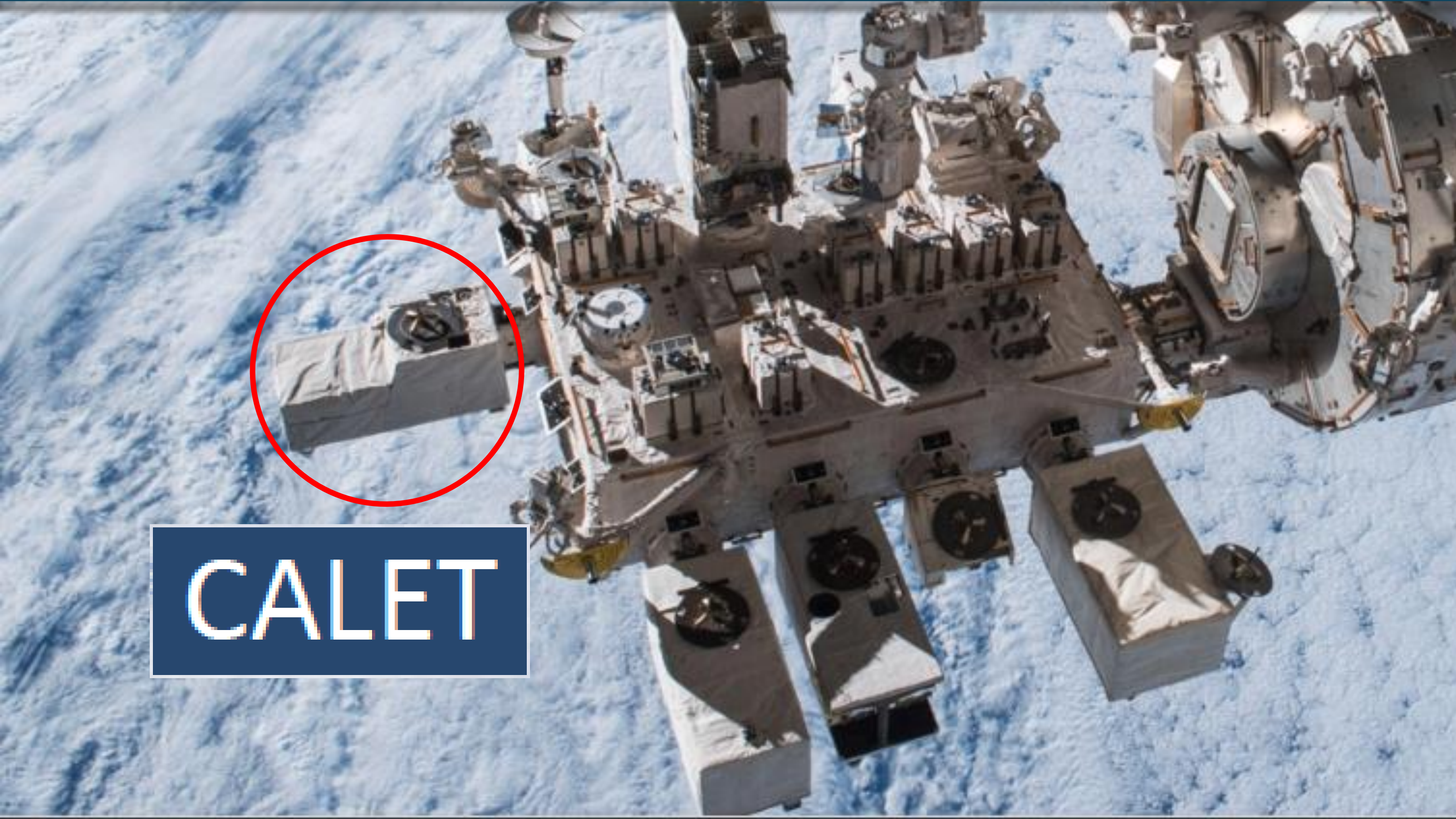
Space Environment Utilization Center Human Spaceflight Technology Directorate, JAXA



CALORIMETRIC ELECTRON TELESCOPE
CALET
NASA ASI JAXA

TeV Particle Astrophysics
TeVPA 2026
Tendo Japan
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The CALET Collaboration

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33) GCSE, Waseda University, Japan
34) University of Denver, USA
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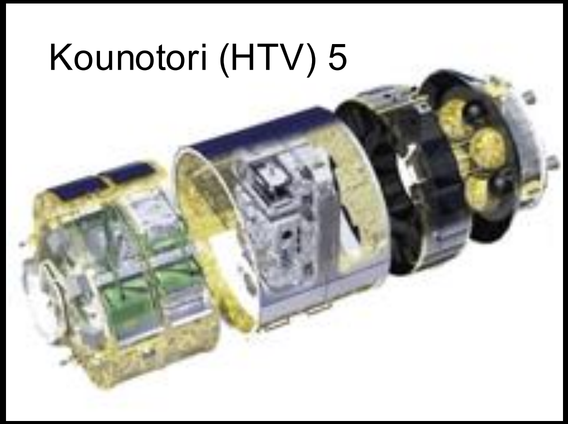
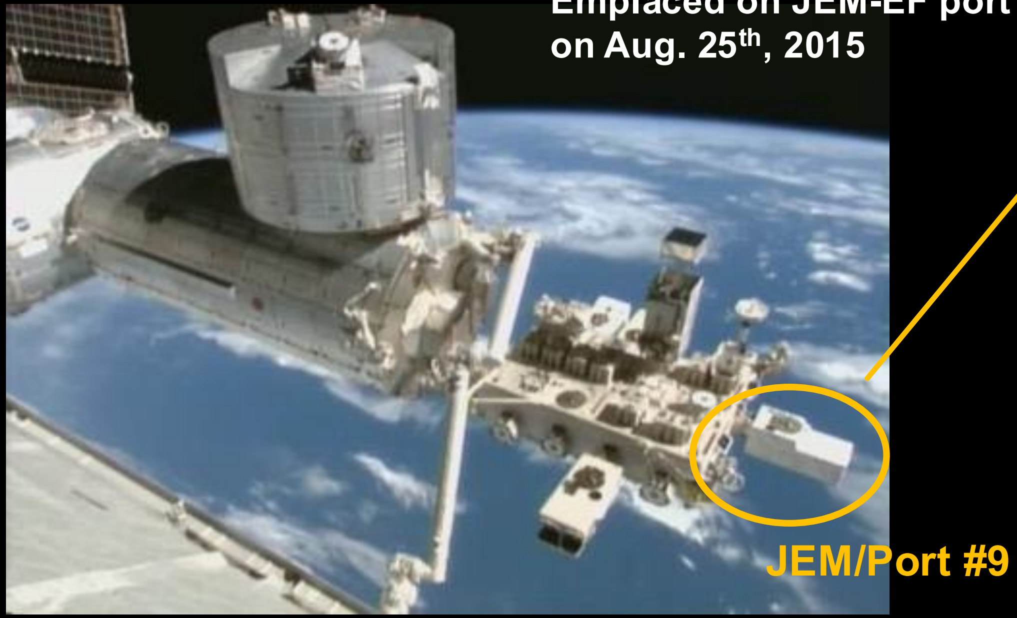
38) Osaka Metropolitan University, Japan
39) NITEP, Osaka Metropolitan University, Japan
40) QST, Japan
41) Nagoya University, Japan
42) Ibaraki University, Japan

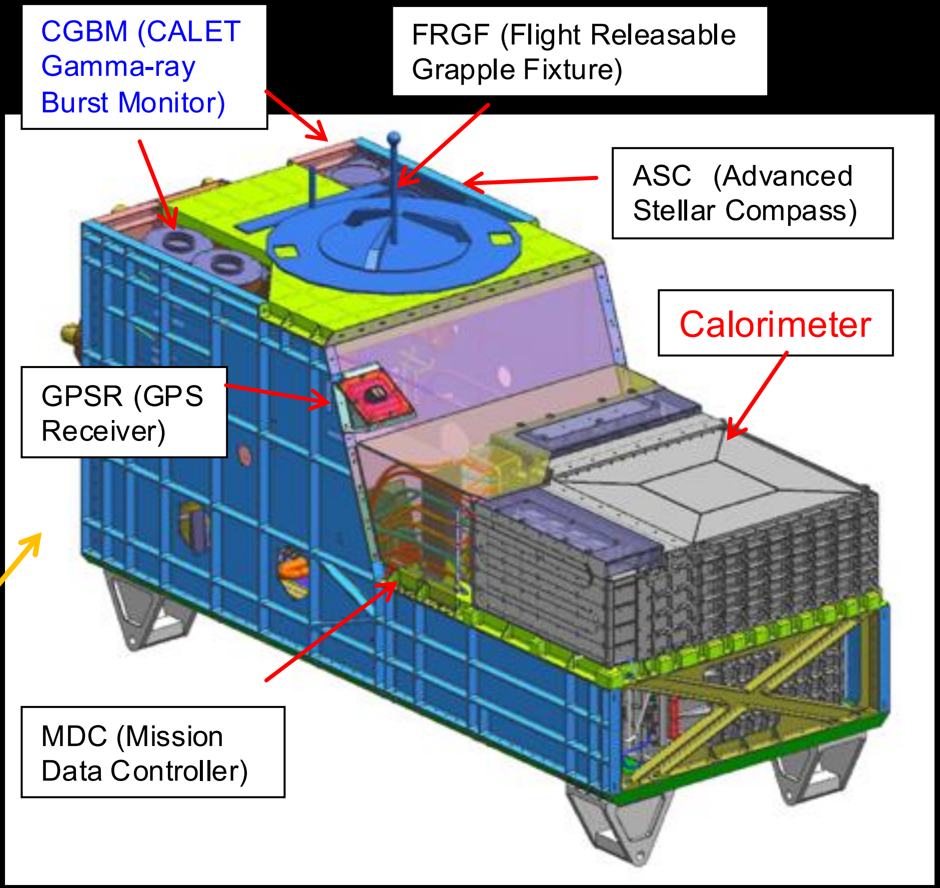
CALET Payload



Launched on Aug. 19th, 2015 by the Japanese H2-B rocket

Emplaced on JEM-EF port #9 on Aug. 25th, 2015



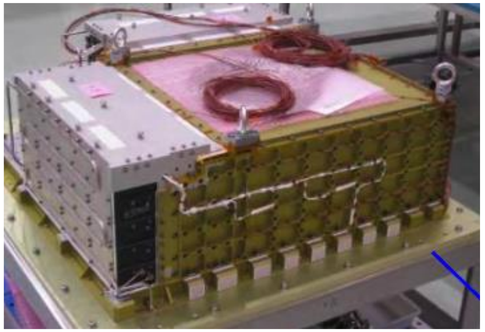


- **Mass: 612.8 kg**
- **JEM Standard Payload Size:**
  1850mm(L) × 800mm(W) × 1000mm(H)
- **Power Consumption: 507 W（max）**
- **Telemetry:**
  Medium 600 kbps (6.5GB/day) / Low 50 kbps

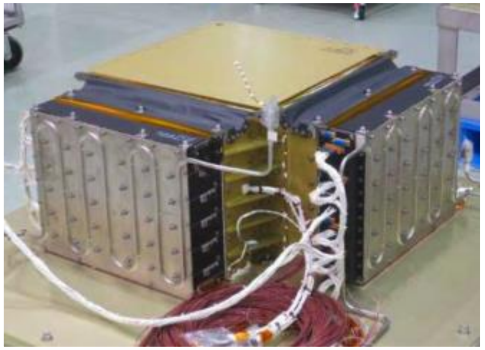
Overview of the CALET Calorimeter

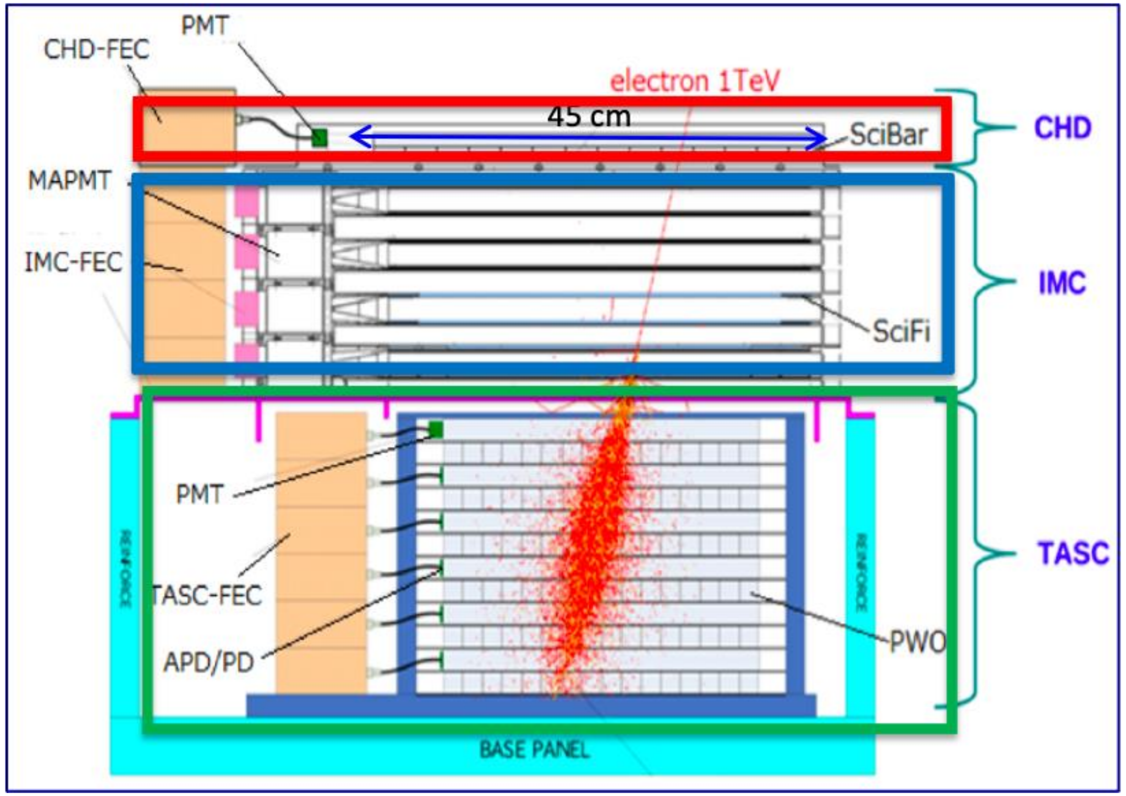
A 30-radiation length deep calorimeter designed to detect electrons and gamma-rays to 20 TeV and cosmic rays up to 1 PeV

CHD/IMC



TASC





CHD – Charge Detector

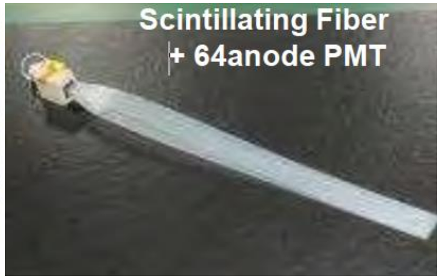
- 2 layers x 14 plastic scintillating paddles
- **single element charge ID** from p to Fe and above (Z = 40)
- charge resolution ~0.1-0.3 e

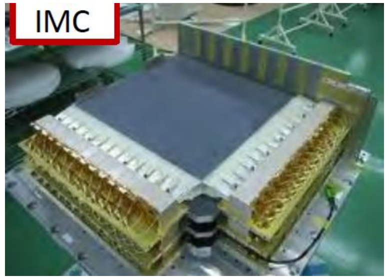
IMC – Imaging Calorimeter

- Scifi. + tungsten absorbers: **3 X_0**
- 8 x 2 x 448 plastic scintillating fibers (1mm) **readout individually**
- **tracking** (~0.1° angular resolution) + **Shower imaging**
- **angular resolution:** 0.2° for gamma-rays > ~50 GeV

TASC – Total Absorption Calorimeter

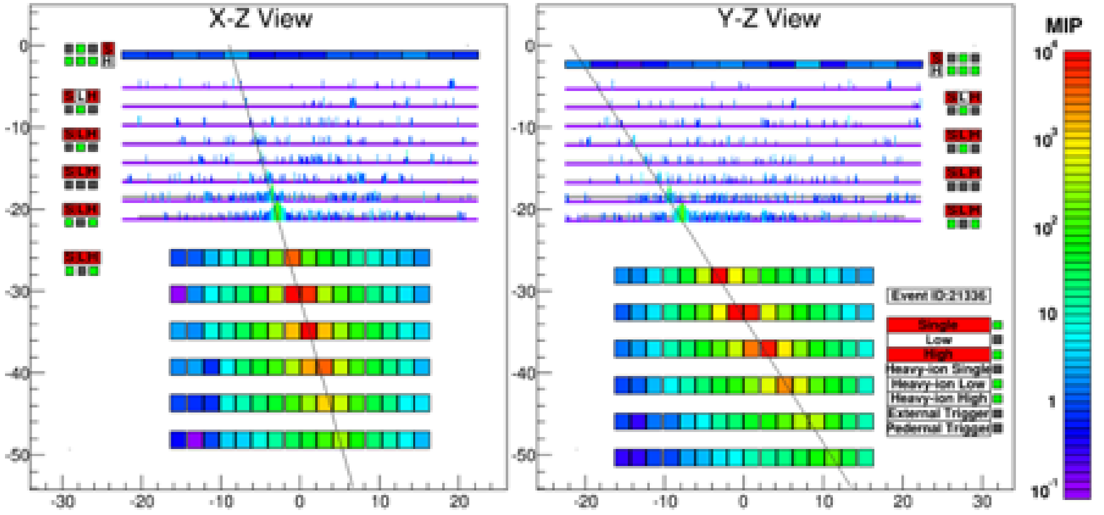
- 6 x 2 x 16 lead tungstate ($PbWO_4$) logs: **27 X_0, 1.2 λ_I**
- **energy resolution:** ~2 % (>10GeV) for e , γ
  ~30-35% for p, nuclei
- **e/p separation:** ~10^{-5}



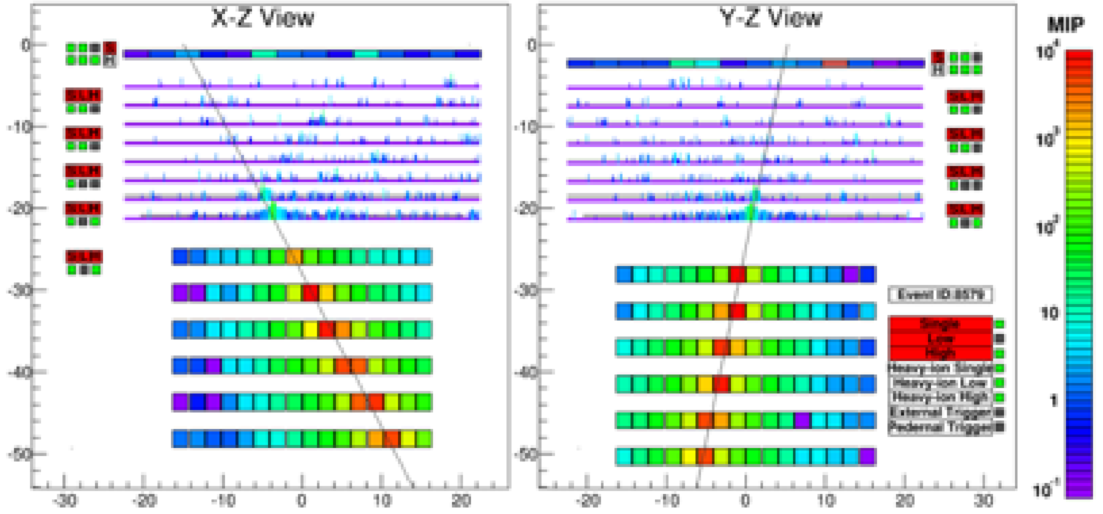


Examples of Event Candidates

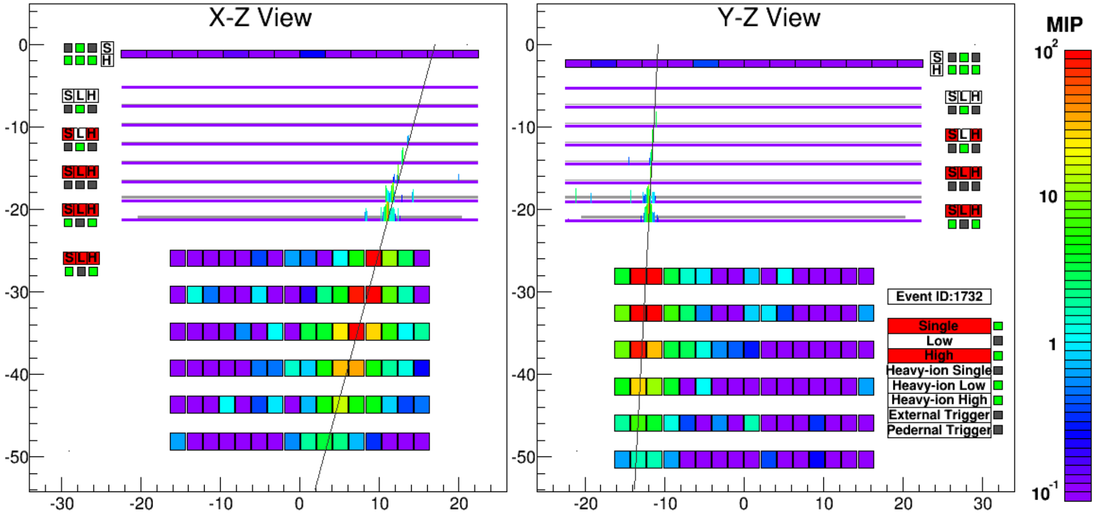
Electron, E=3.05 TeV



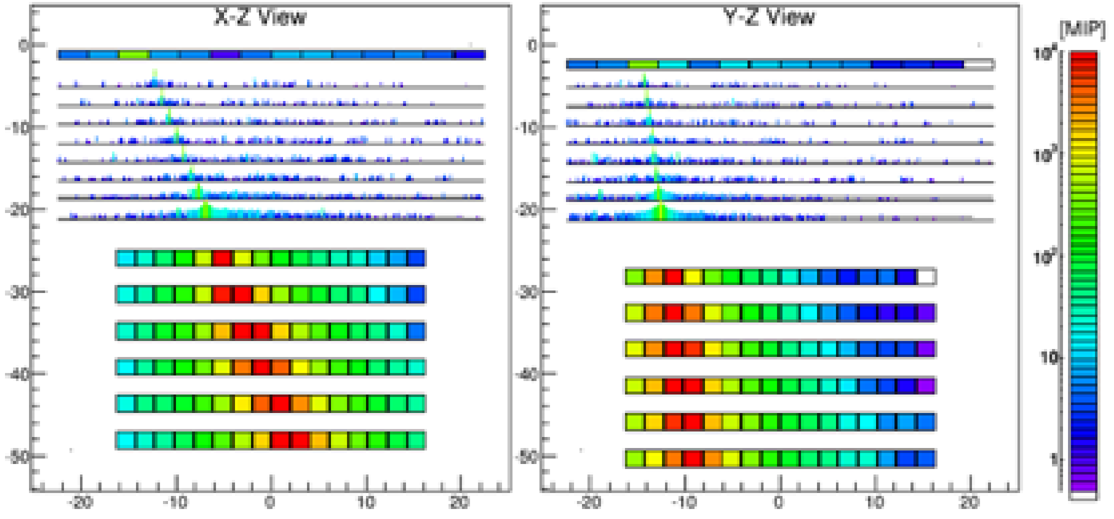
Proton, E_{TASC}=2.89 TeV



Gamma-ray, E=44.3 GeV



Iron, E_{TASC} =9.3 TeV



Capabilities of the electron measurements

- Energy calibration in space has been performed with penetrating cosmic-ray protons and helium nuclei
- High dynamic range readout of energy deposited in TASC was calibrated by a UV pulse laser on the ground

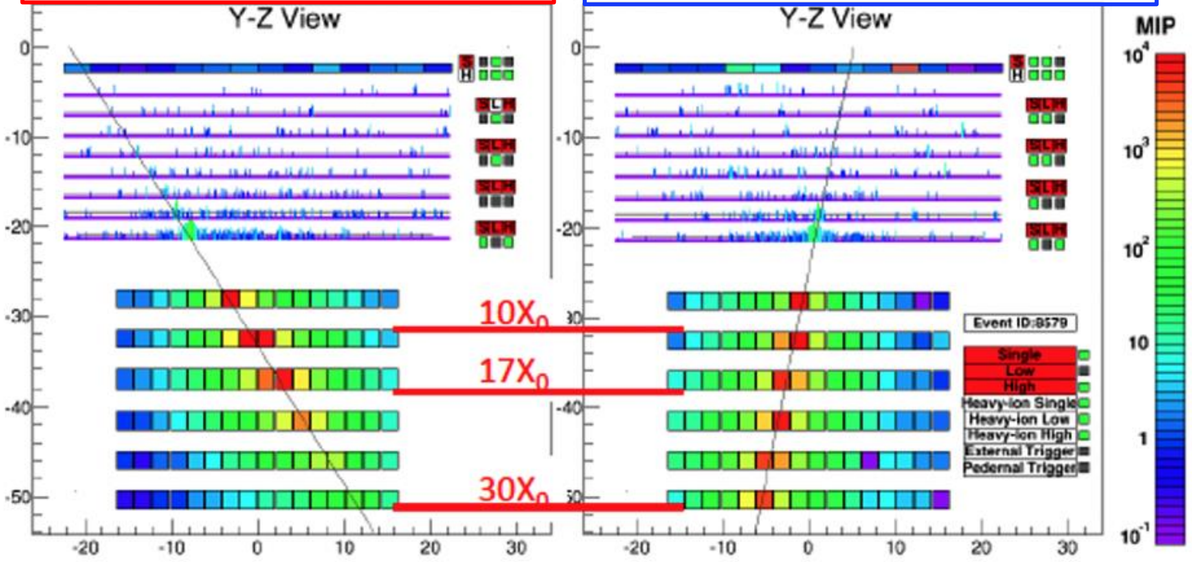
➡ The energy resolution of electrons is <2% above 20 GeV

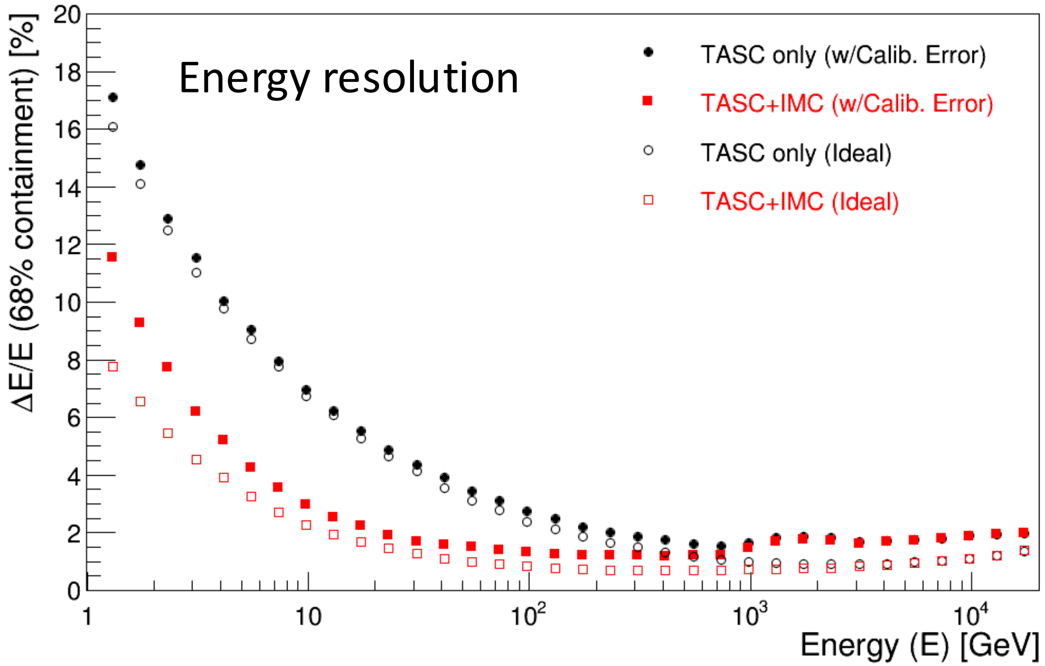
- Imaging capability with thick calorimeter provides powerful electron/proton identification

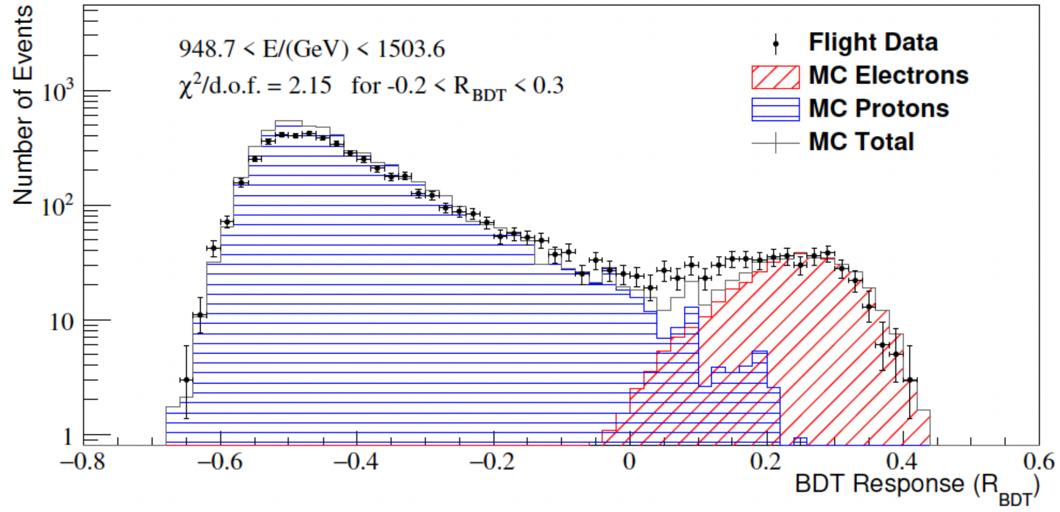
➡ The total BG protons are less than 10% up to 7.5 TeV with 70% electron efficiencies

3TeV electron candidates

Corresponding background

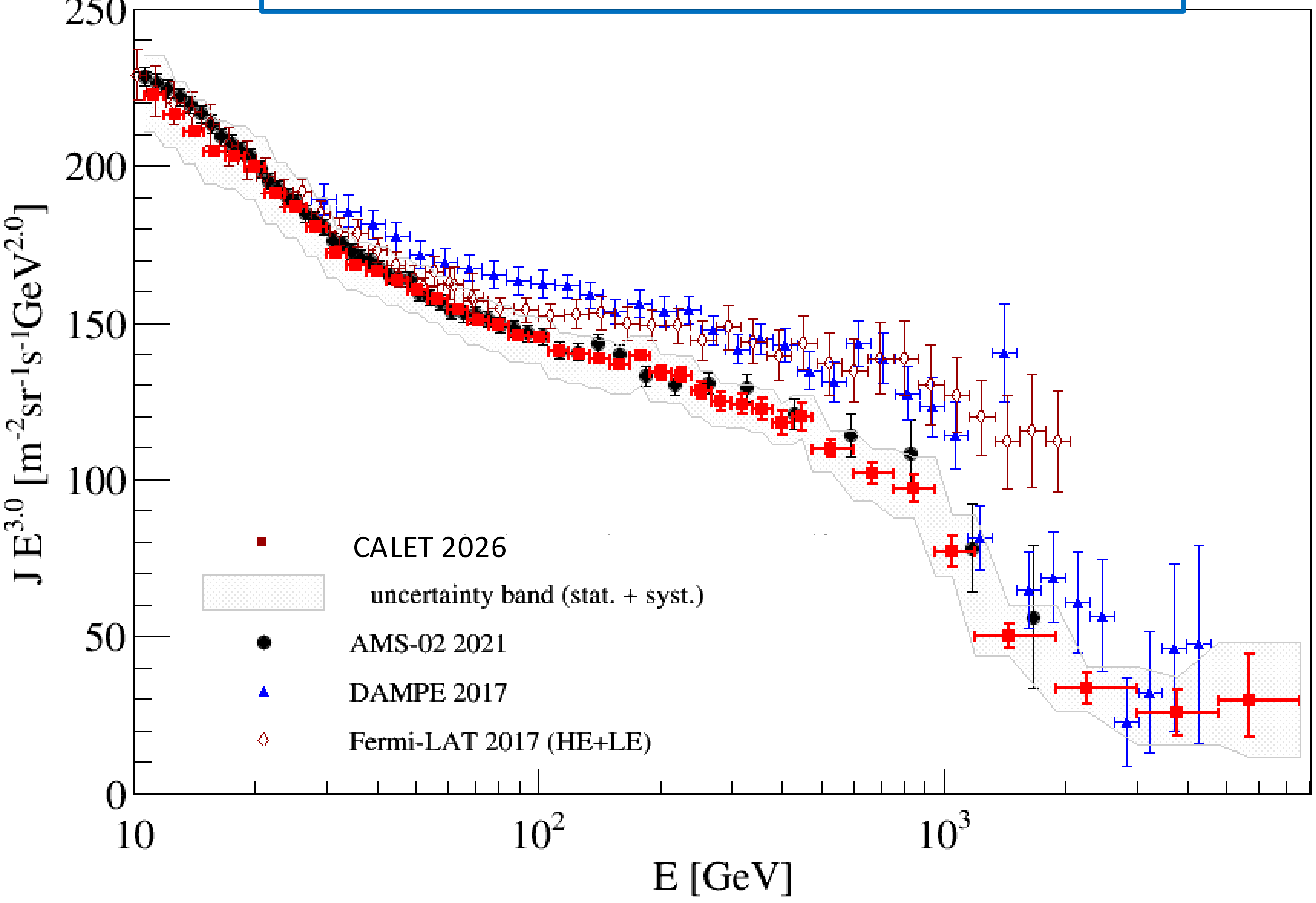






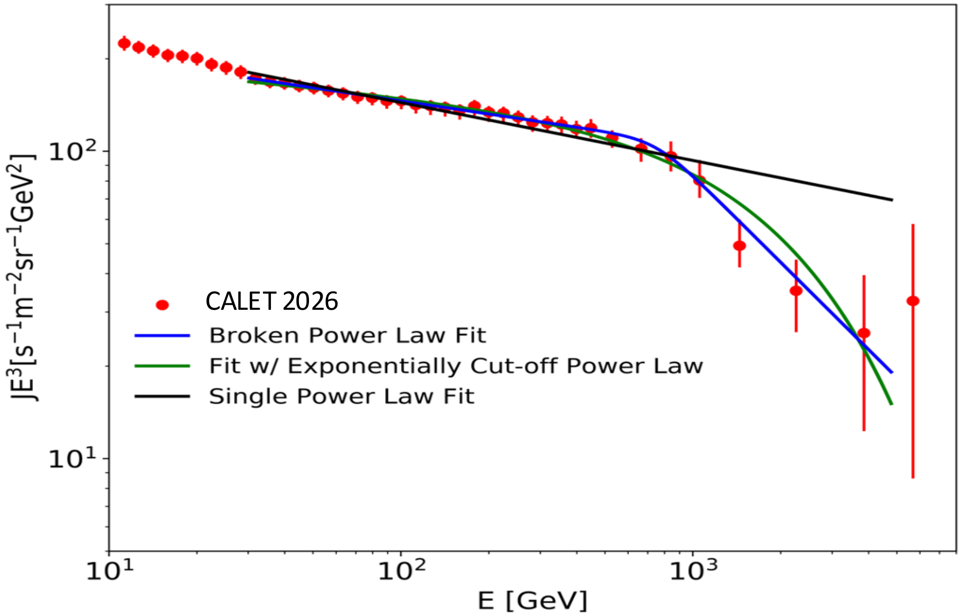
All-electron spectrum

Preliminary update: statistics increased by 42% + 3 years w.r.t. PRL 131, 191001 (2023)



Expected cutoff around 1 TeV based on the decrease in the number of sources significantly contributing to the all-electron spectrum

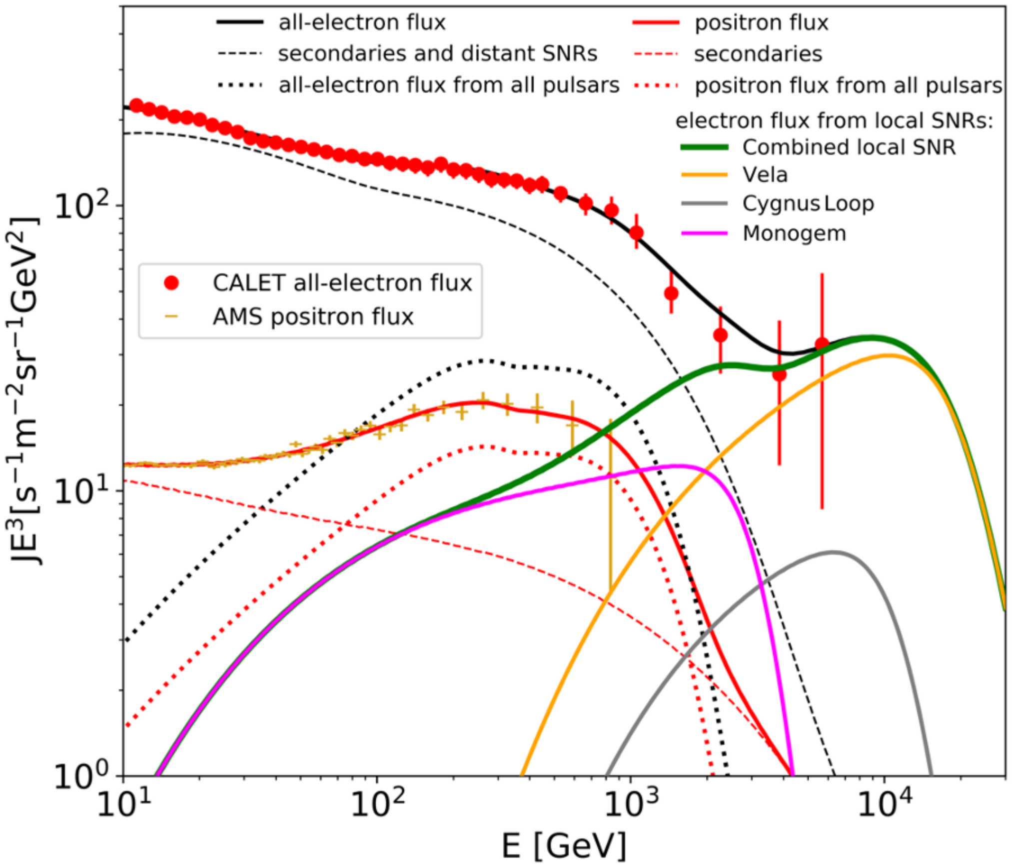
CALET observed a flux suppression above 1 TeV with a significance ~6.7σ



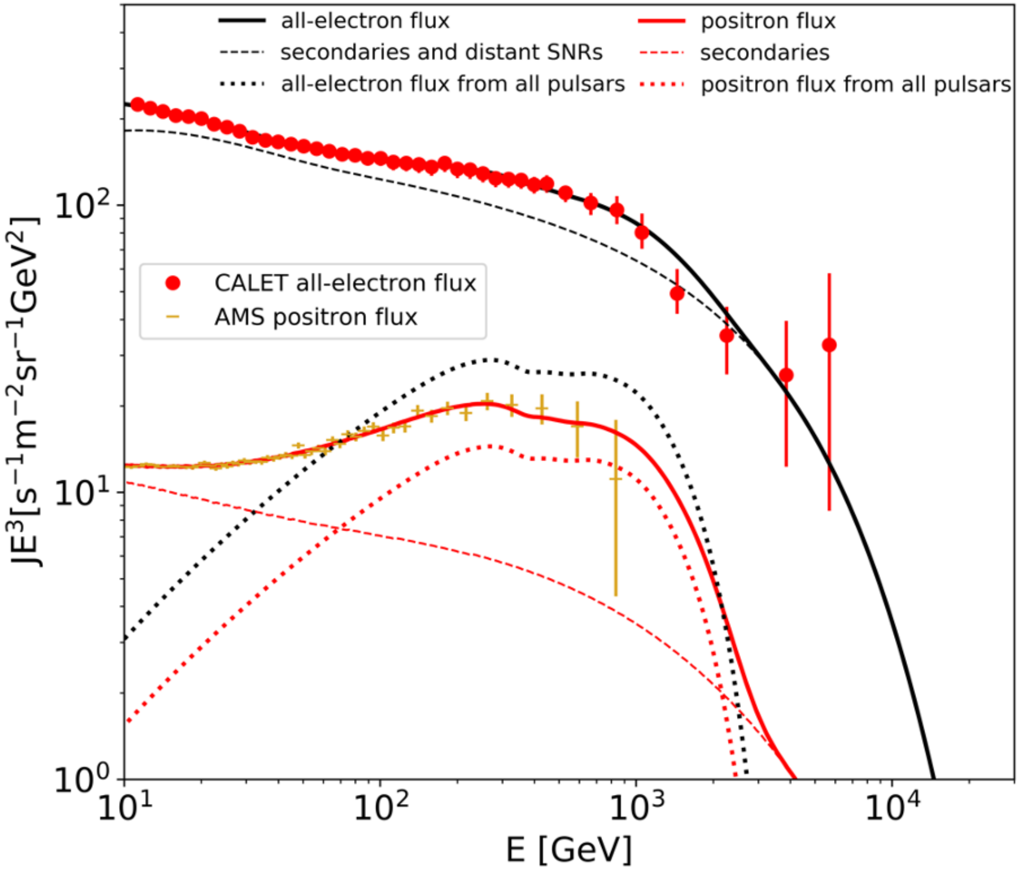
Fit with/without nearby sources

- In the TeV region and above, nearby accelerators may produce observable features in the spectrum.
- The all-electron spectrum is modeled as combination of $e^{\pm}$ fluxes from pulsars, secondaries and distant SNRs
- Fit with and without nearby sources yield similar X^2/d.o.f., but including nearby sources provides a better spectral agreement in the TeV region

Fit WITH local SNRs

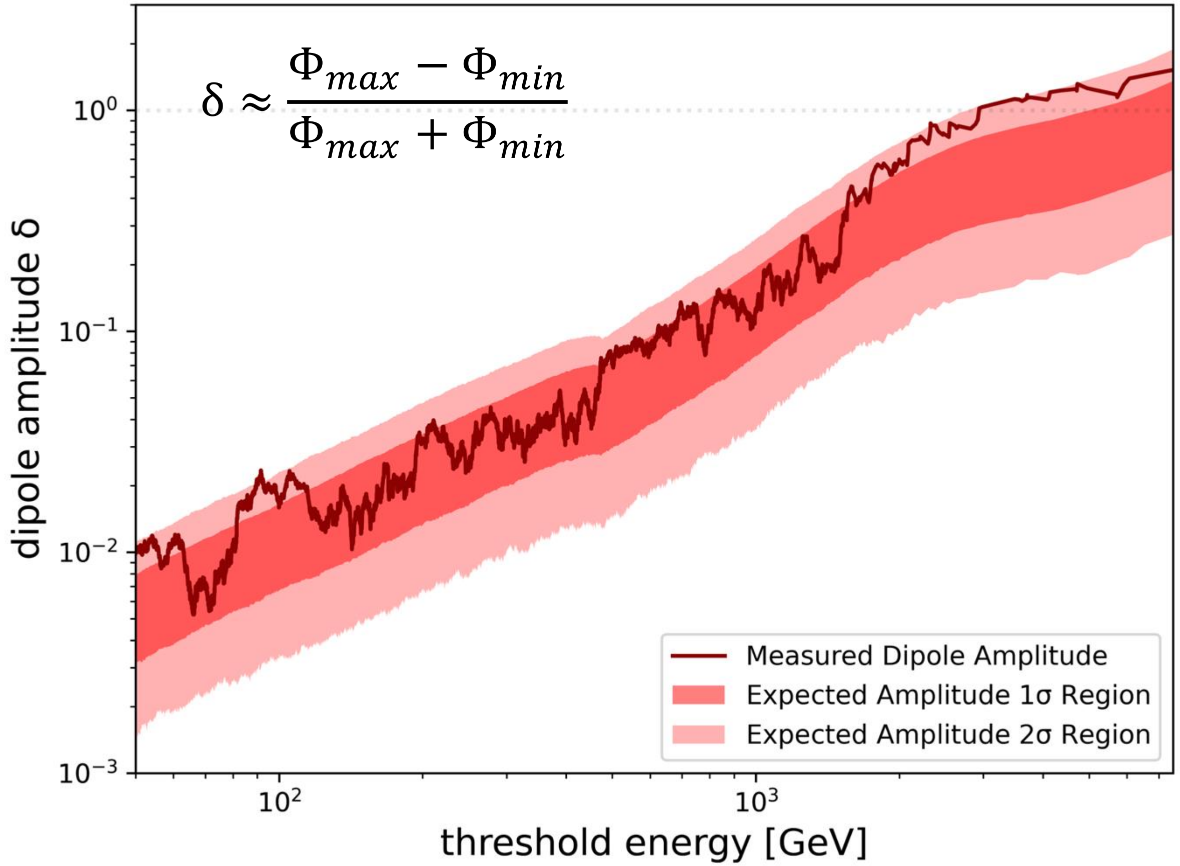


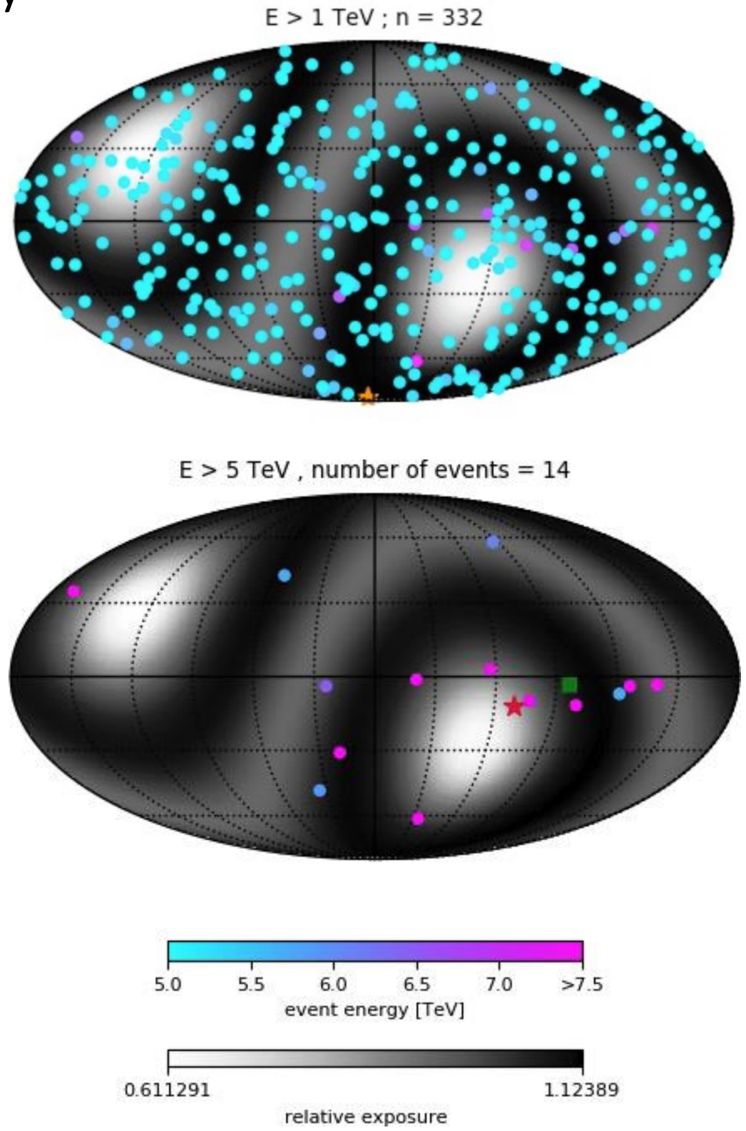
Fit WITHOUT local SNRs



Dipole anisotropy measurement

Measurement of the dipole amplitude as a function of lower threshold energy





- Dipole amplitude within 2σ band expected from white noise, but close to upper boundary above ~2 TeV
- Highest energy events cluster in one part of the sky with dipole direction close to the direction towards the Vela SNR

Capabilities of nuclei measurements

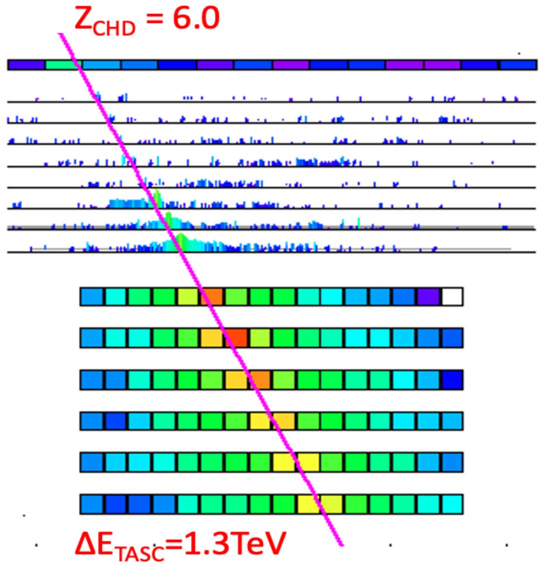
Charge measurement

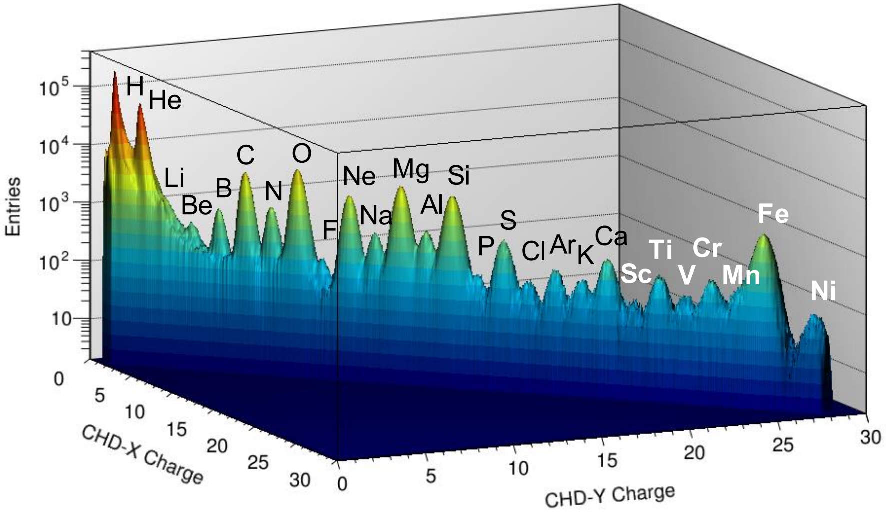
- CHD enables individual charge identification from Z=1 – 40
- Charge resolution ranges from 0.15*e* to 0.3*e* for protons to iron

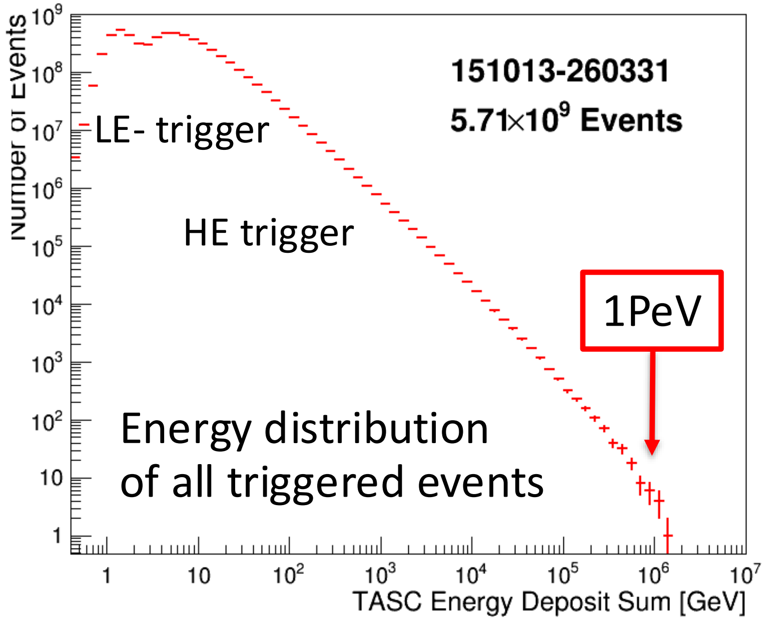
Energy measurement

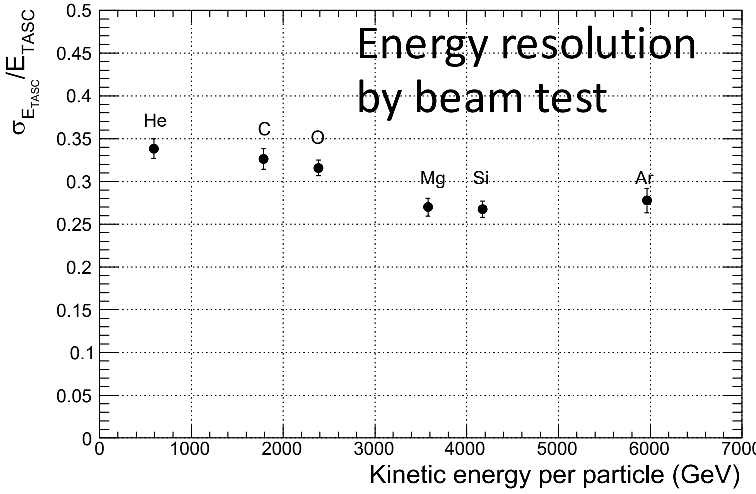
- Capable of measuring nuclei over a wide energy range: 1 GeV to 1 PeV.
- Energy resolution for nuclei: 30 – 35%

An example of Carbon event



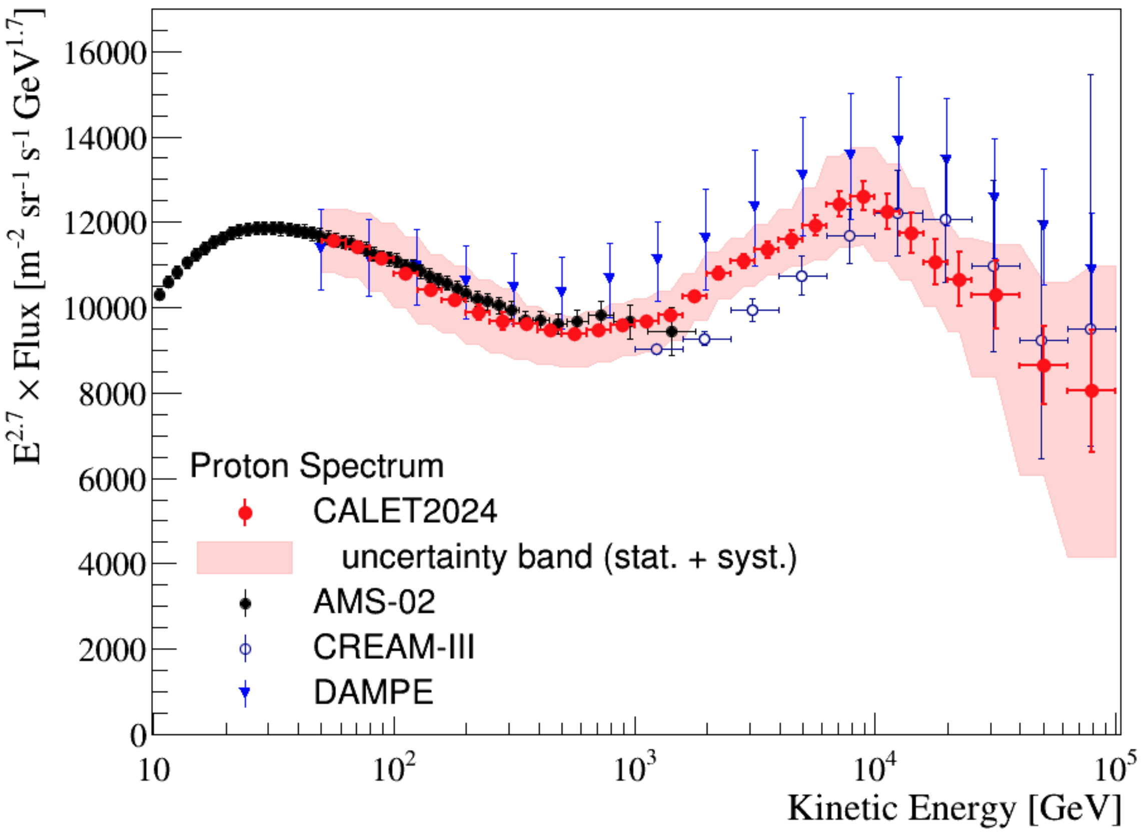




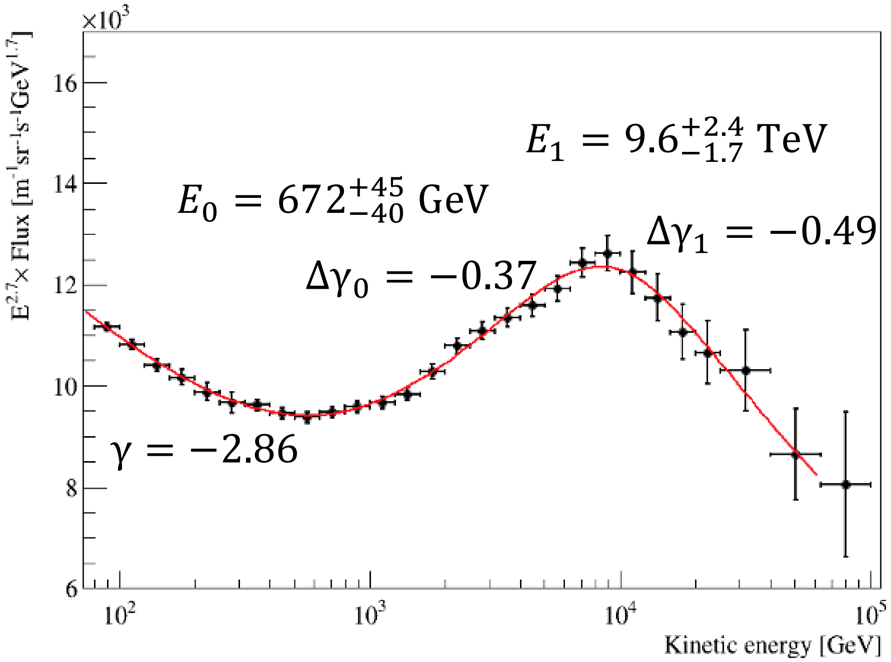


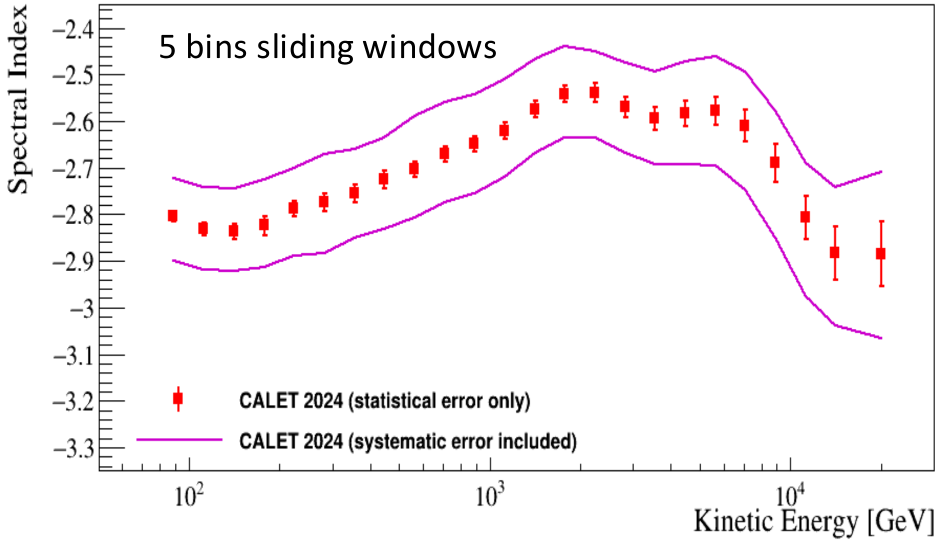
Proton Spectrum

Proton Flux × $E^{2.7}$



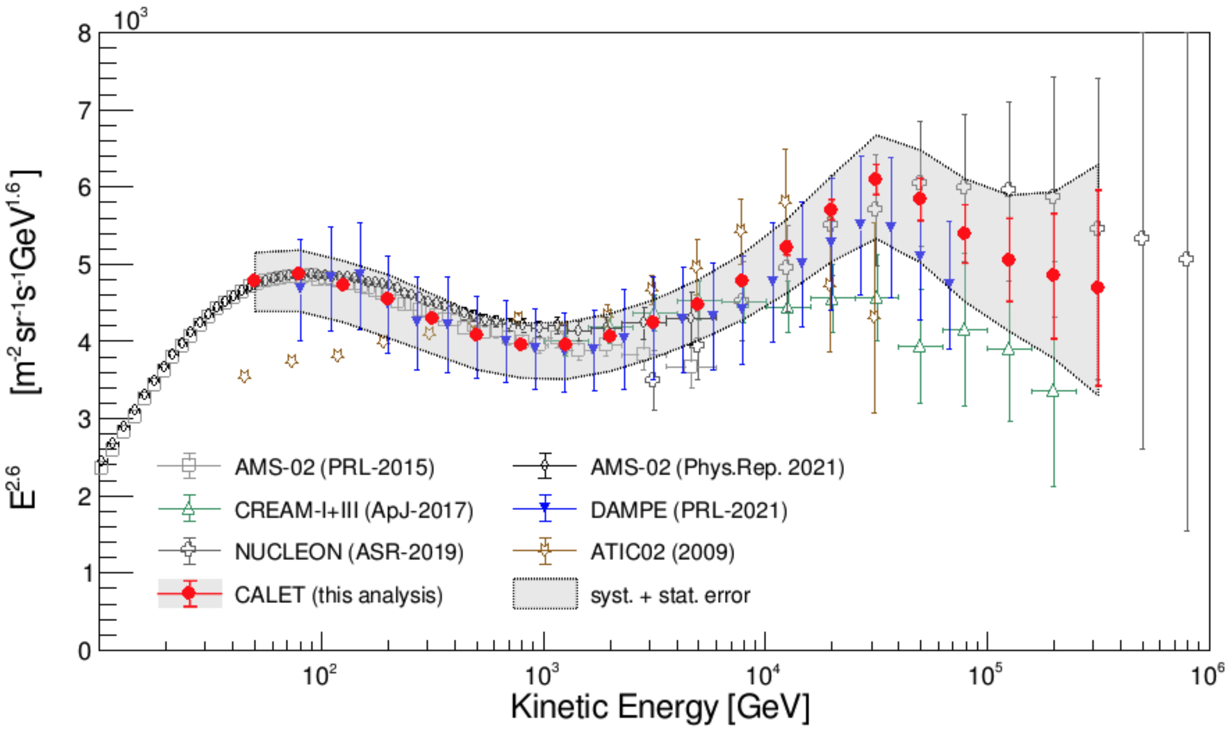
$$\Phi(E) = C\left(\frac{E}{\mathrm{GeV}}\right)^{\gamma}\left[1+\left(\frac{E}{E_0}\right)^{S}\right]^{\frac{\Delta\gamma}{S}}\left[1+\left(\frac{E}{E_1}\right)^{S_1}\right]^{\frac{\Delta\gamma_1}{S_1}}$$



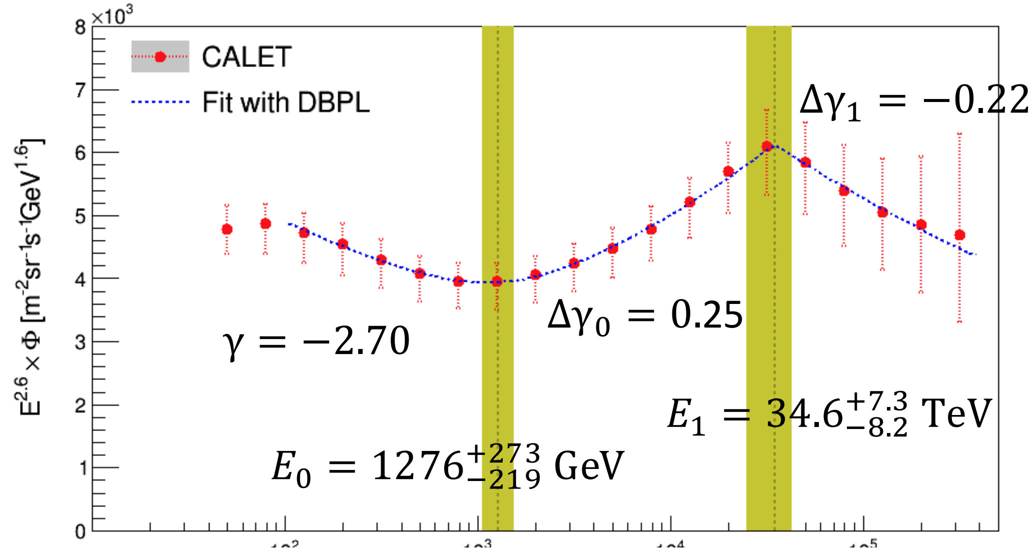


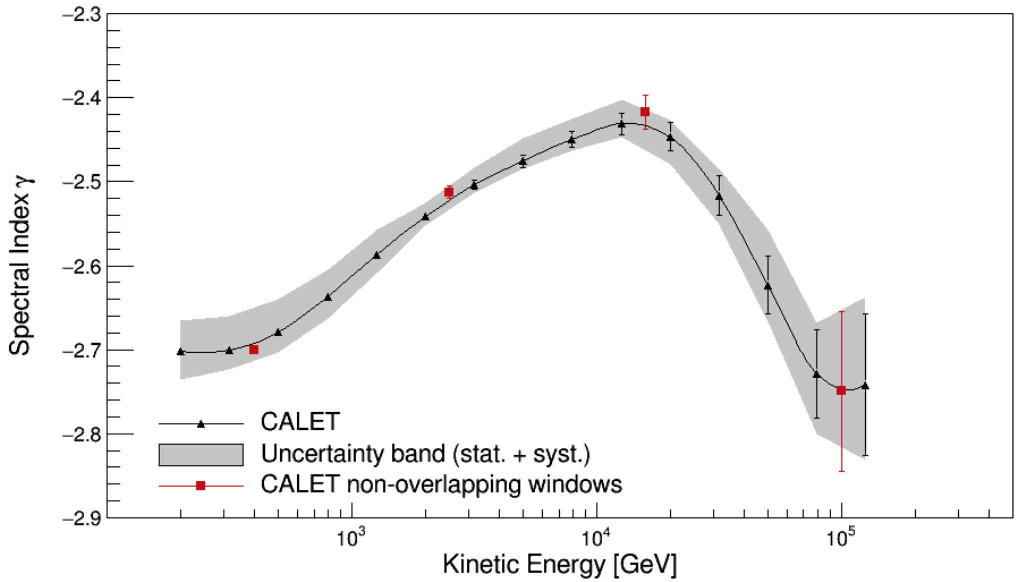
Helium Spectrum

Helium Flux × $E^{2.6}$



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

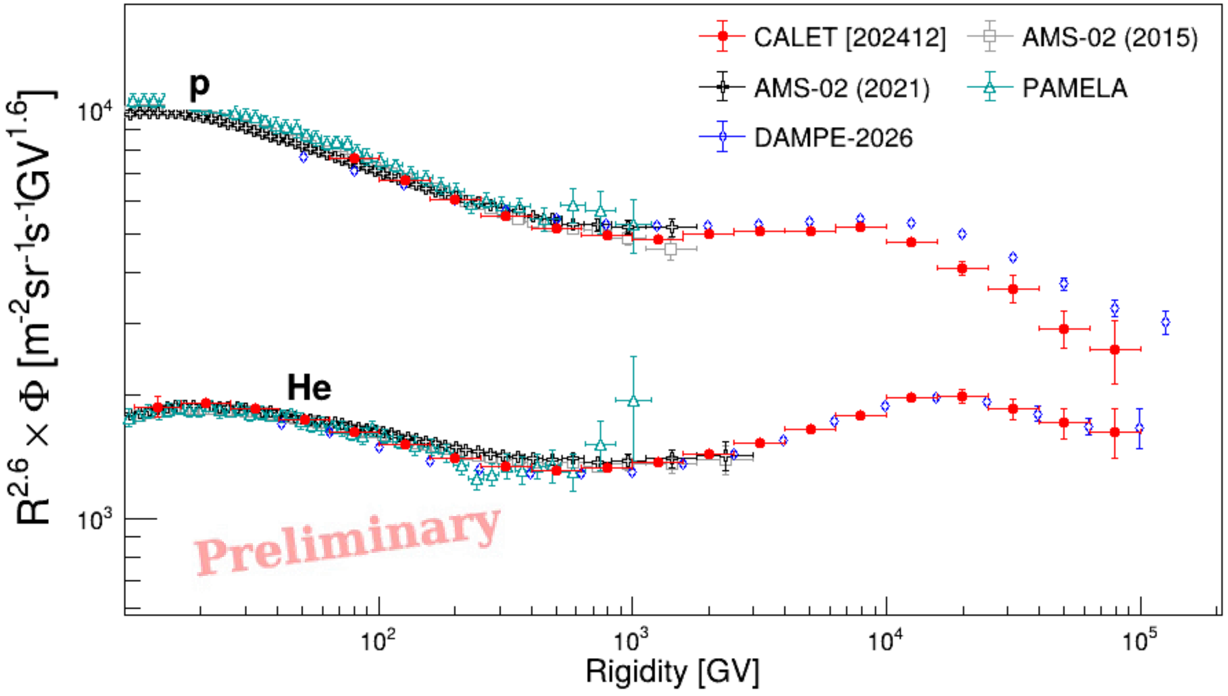




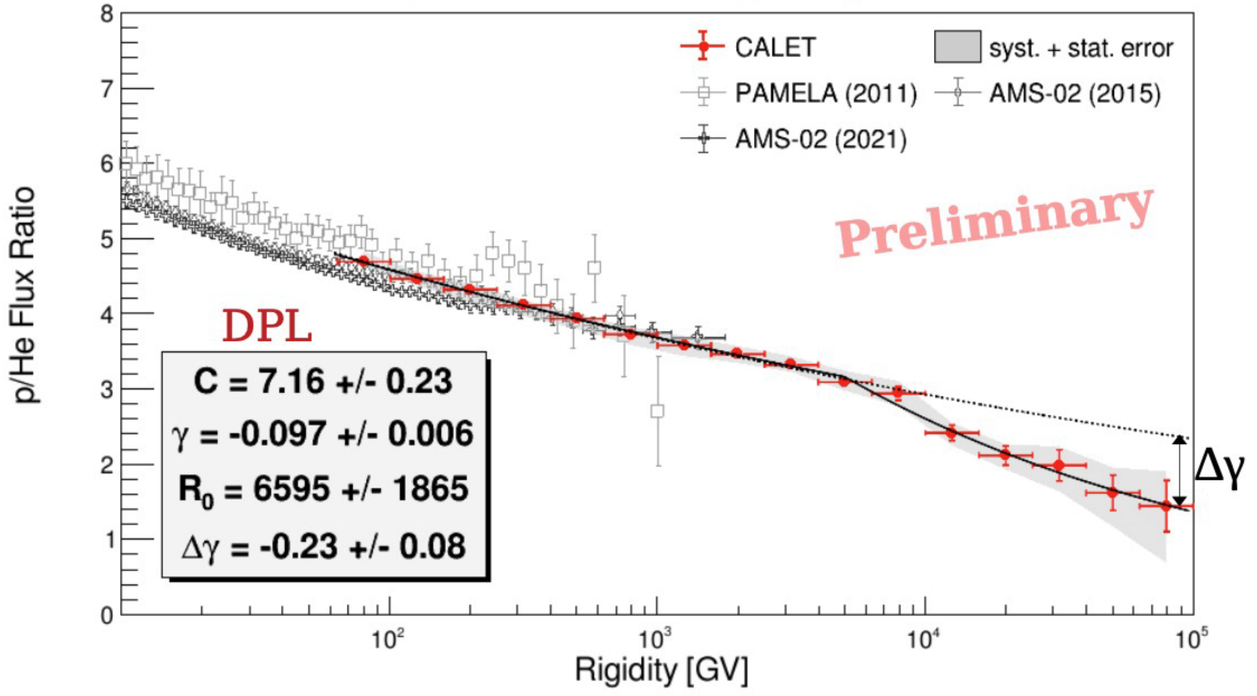
Proton and Helium Spectra

- P and He spectral break positions scale well with RIGIDITY.
- The energy dependence of p/He ratio is consistent with a single power law with index of -0.1 up to 10 TV.
- A double power law is favored with a significance of 4.8σ compared to SPL from 60 GV to 100 TV.
  - Further analysis are ongoing to confirm this results.

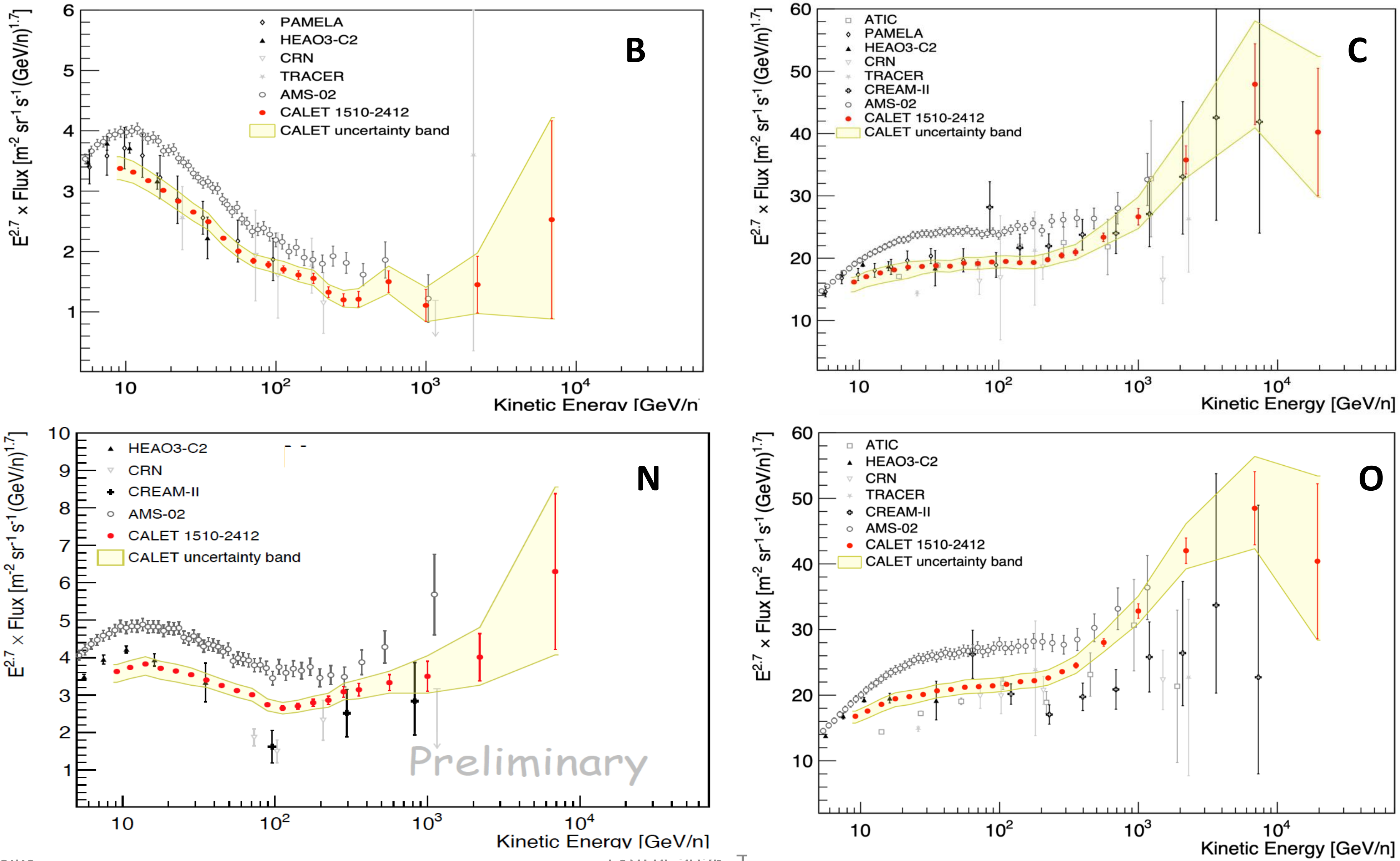
P and He spectra × $R^{2.6}$ [Rigidity]



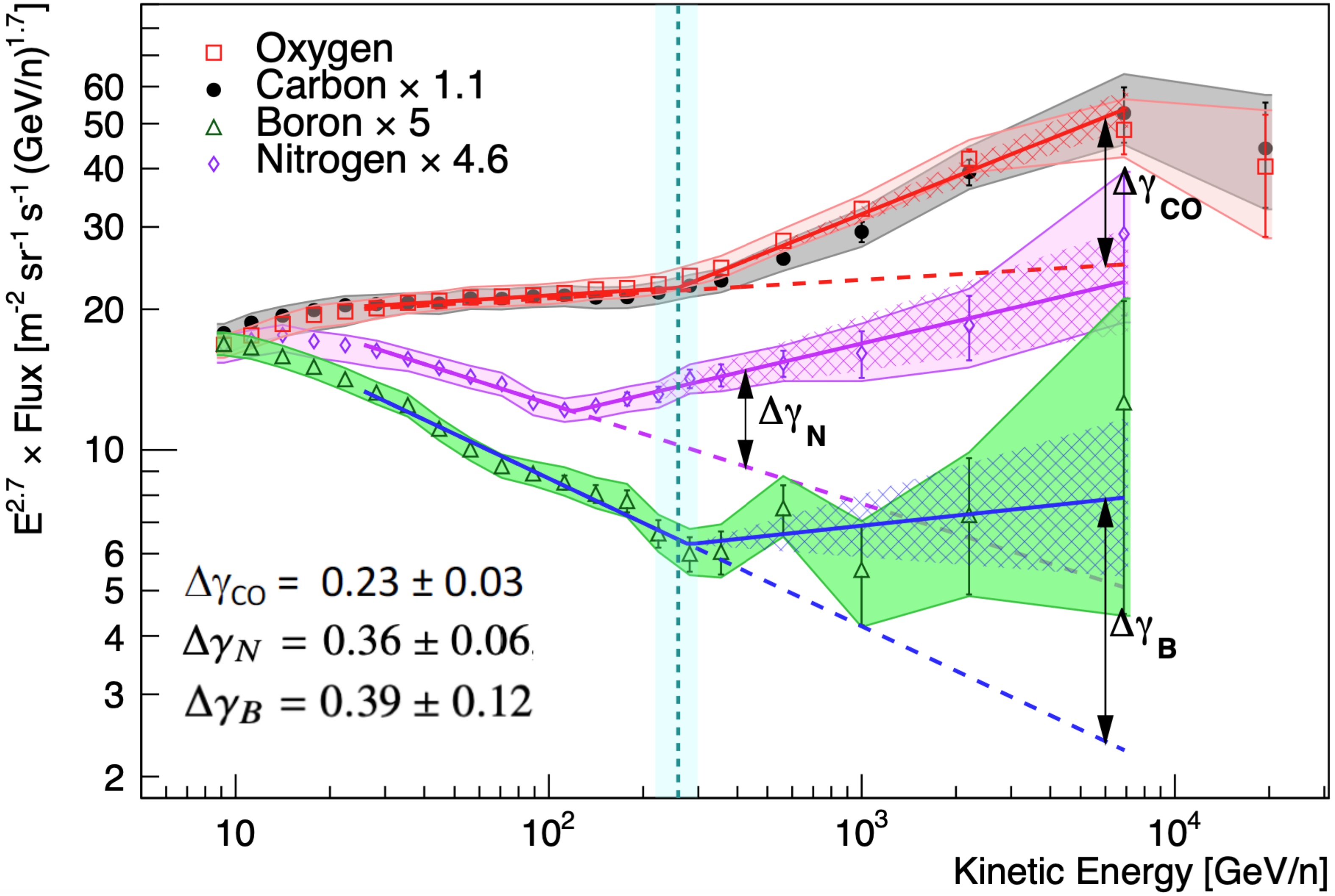
p/He ratio [Rigidity]



Energy spectra of B, C, N, and O

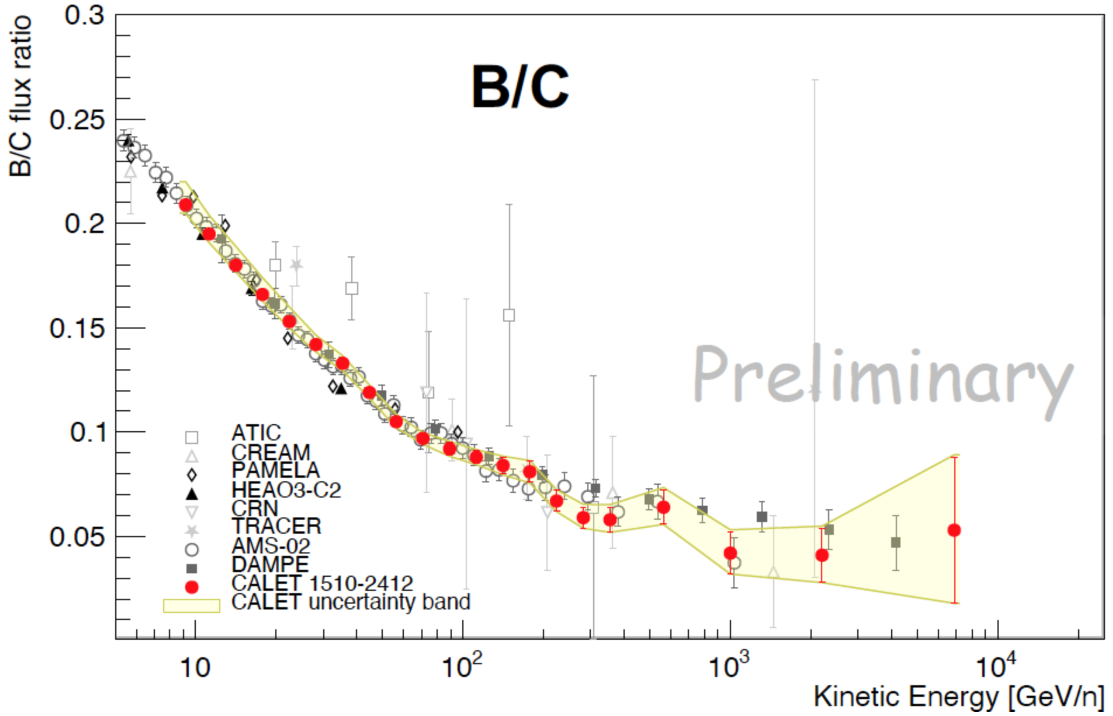


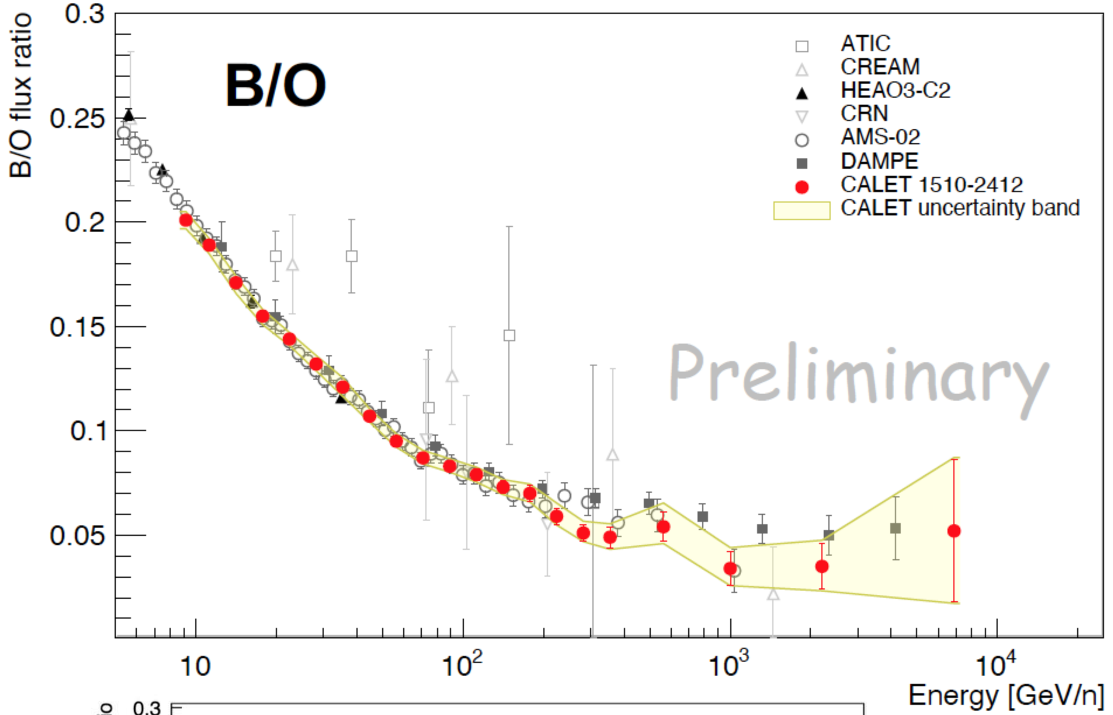
Spectral analysis for BCNO



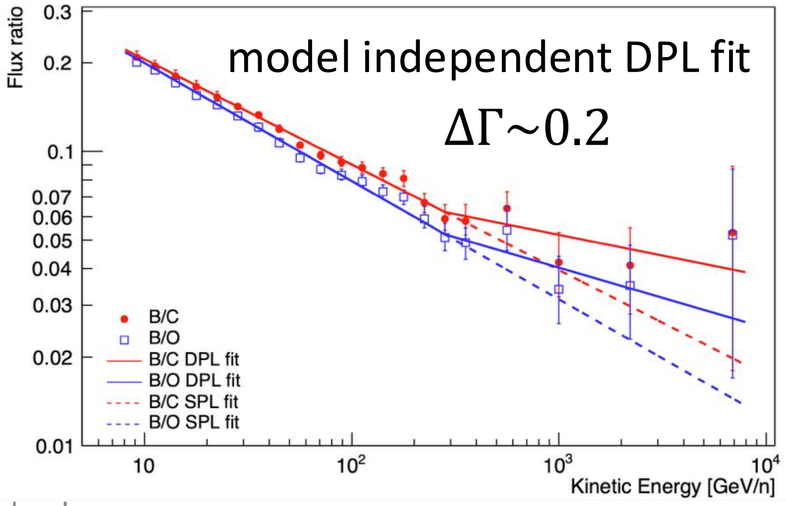
- C and O fluxes harden similarly above 200 GeV/n (significance 7σ)
- B hardens ~twice as much as C, O (significance 2.5σ) as expected from propagation of a purely secondary element.
- N consistent with a mixed composition of primary and secondary: hardens more than C, O but less than B, (significance 5σ) with hardening starting at lower energy than for C, O and B.

Boron flux ratios

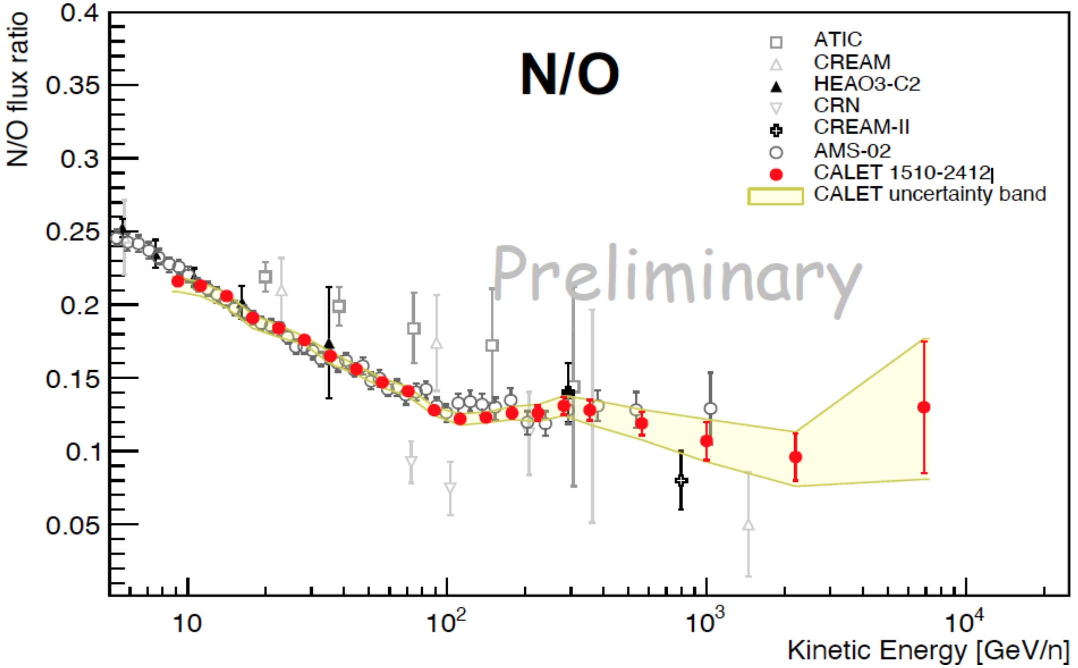


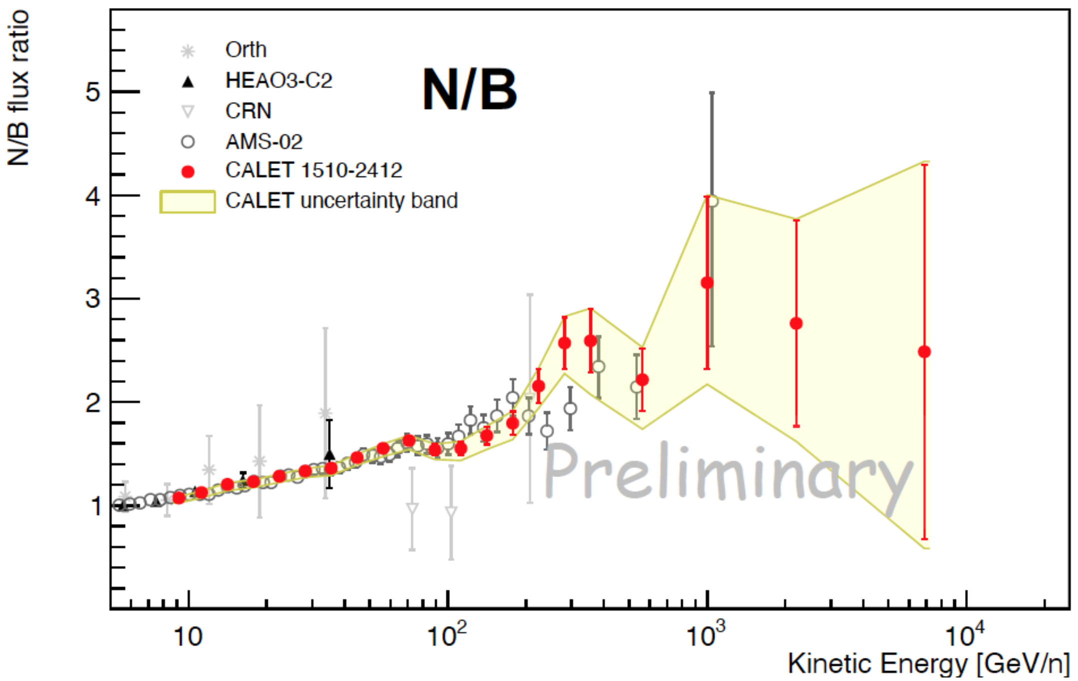


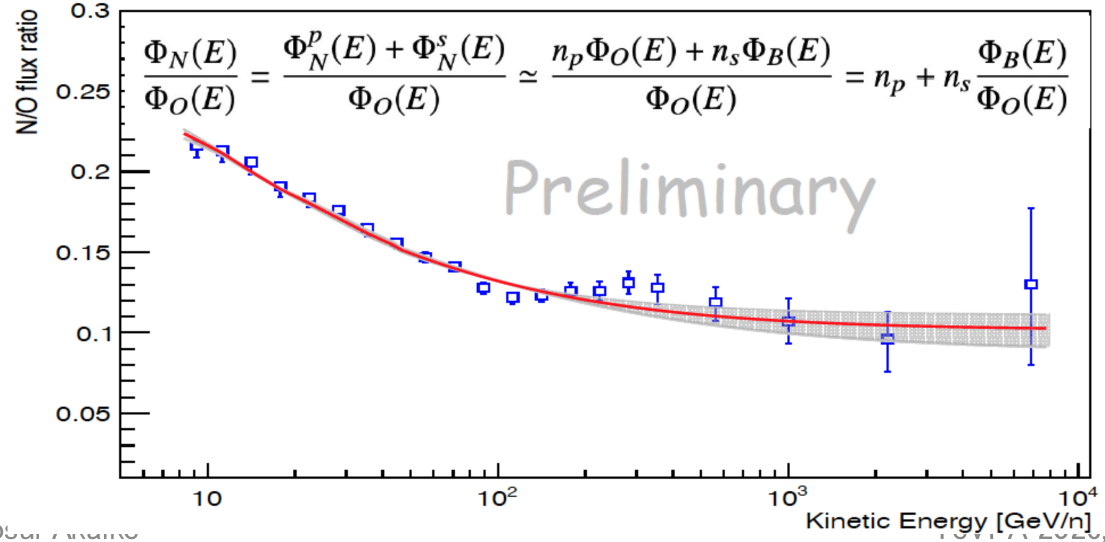
- Observe of a flattening of B/C and B/O with energy
- The observed flattening at TeV/n might be due to a change in the spectral index of δ of the diffusion coefficient or the presence of source grammage (~1.3 g/cm^2)



Nitrogen flux ratios



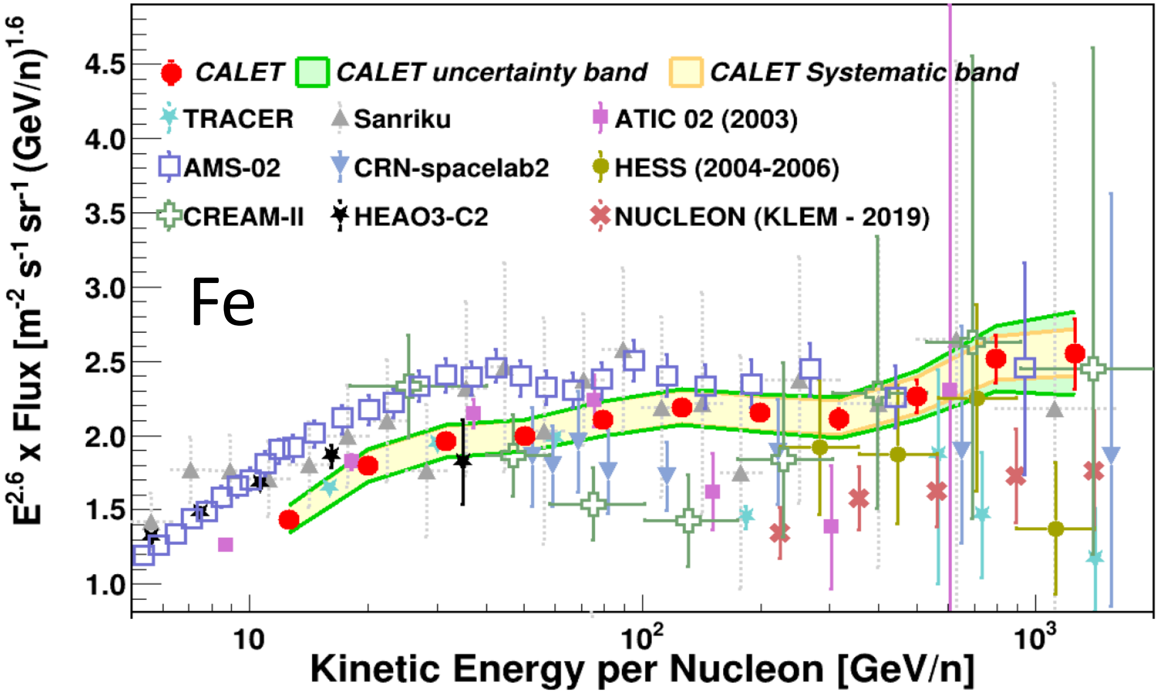


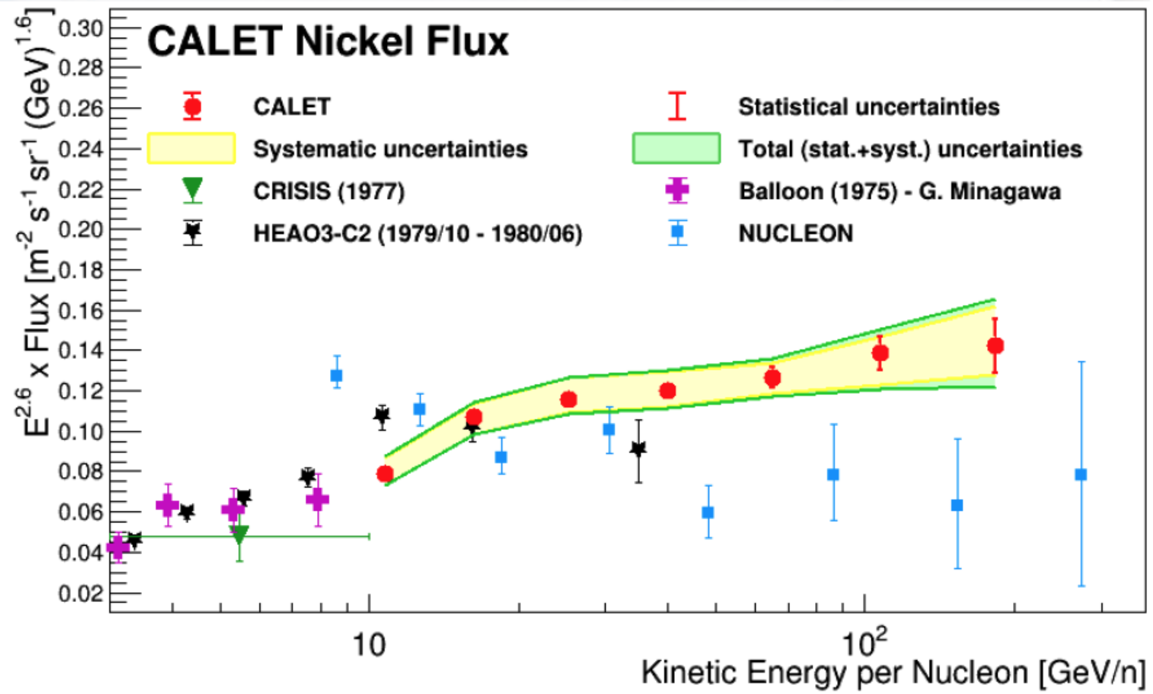


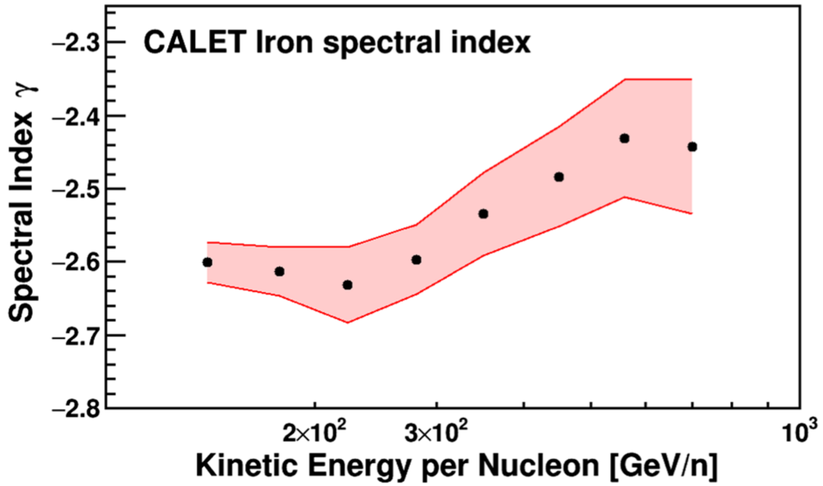
- N/O ratio decreases with E and flattens above 100 GeV/n, while N/B continues to rise
  ⇨ N components: primary $\Phi_N^P = n_P\Phi_O$
  \+ secondary $\Phi_N^S = n_S\Phi_B$

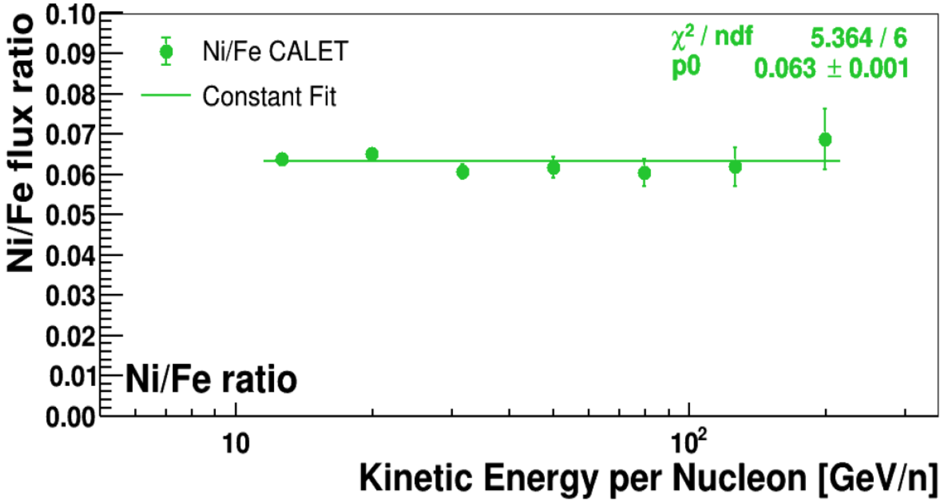
→ $n_P = 0.074 \pm 0.003\ (\text{stat}) \pm 0.02\ (\text{sys})$
$n_S = 0.74 \pm 0.02\ (\text{stat}) \pm 0.05\ (\text{sys})$

Energy spectra of Fe and Ni

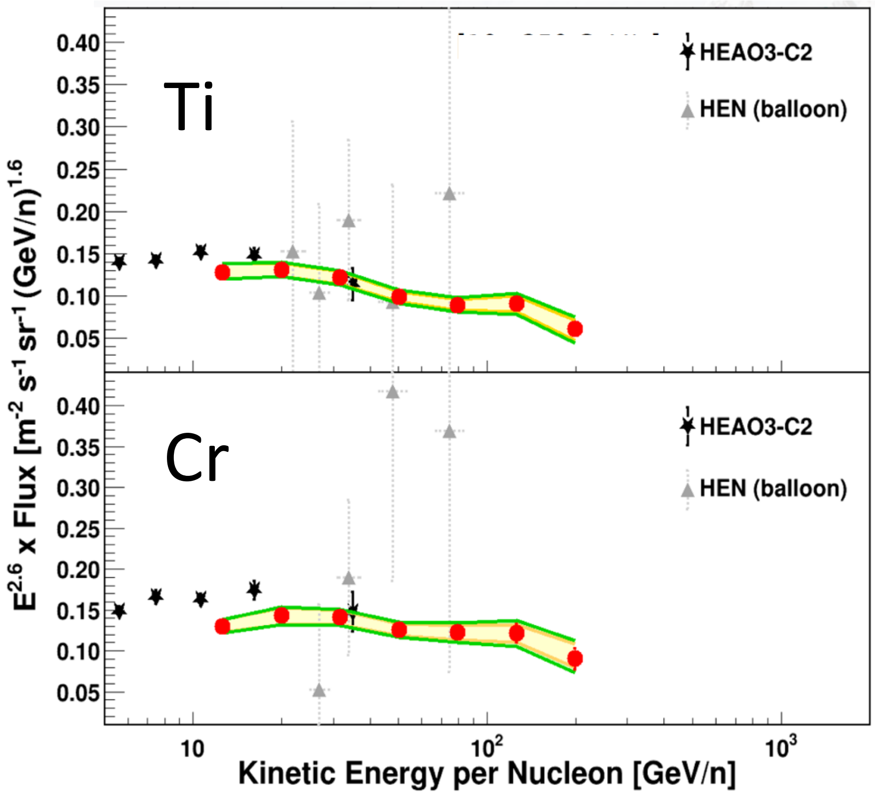


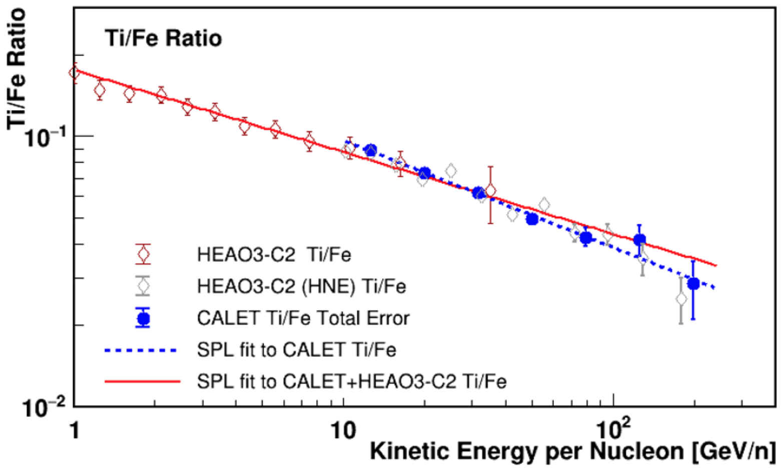


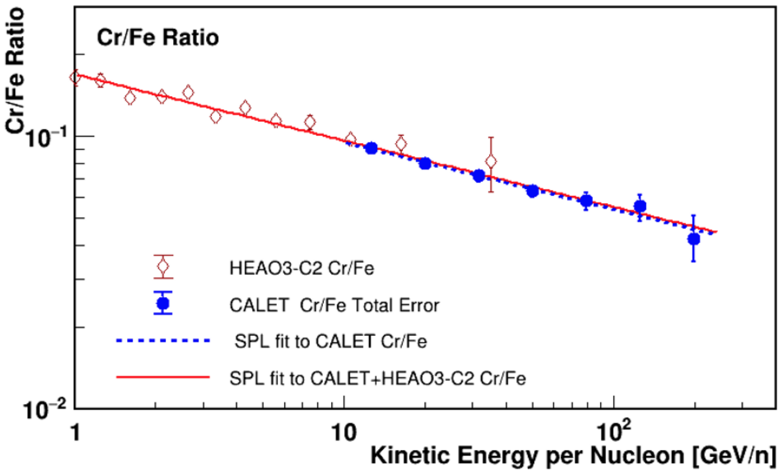




Energy spectra of Ti and Cr, and their ratios to Fe







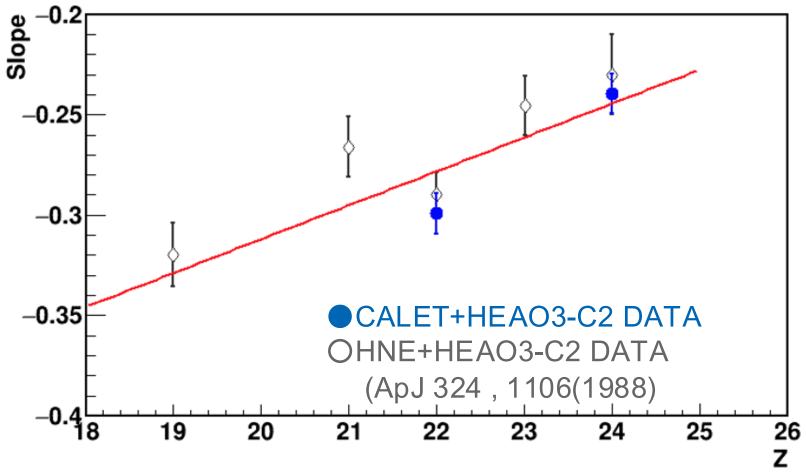
SPL fit for CALET data

$$\gamma_{\mathrm{Ti/Fe}} = -0.39 \pm 0.03, \chi^2/\mathrm{ndf} = 1.9/5$$
$$\gamma_{\mathrm{Cr/Fe}} = -0.24 \pm 0.03, \chi^2/\mathrm{ndf} = 0.8/5$$

SPL fit for CALET + HEAO3-C2

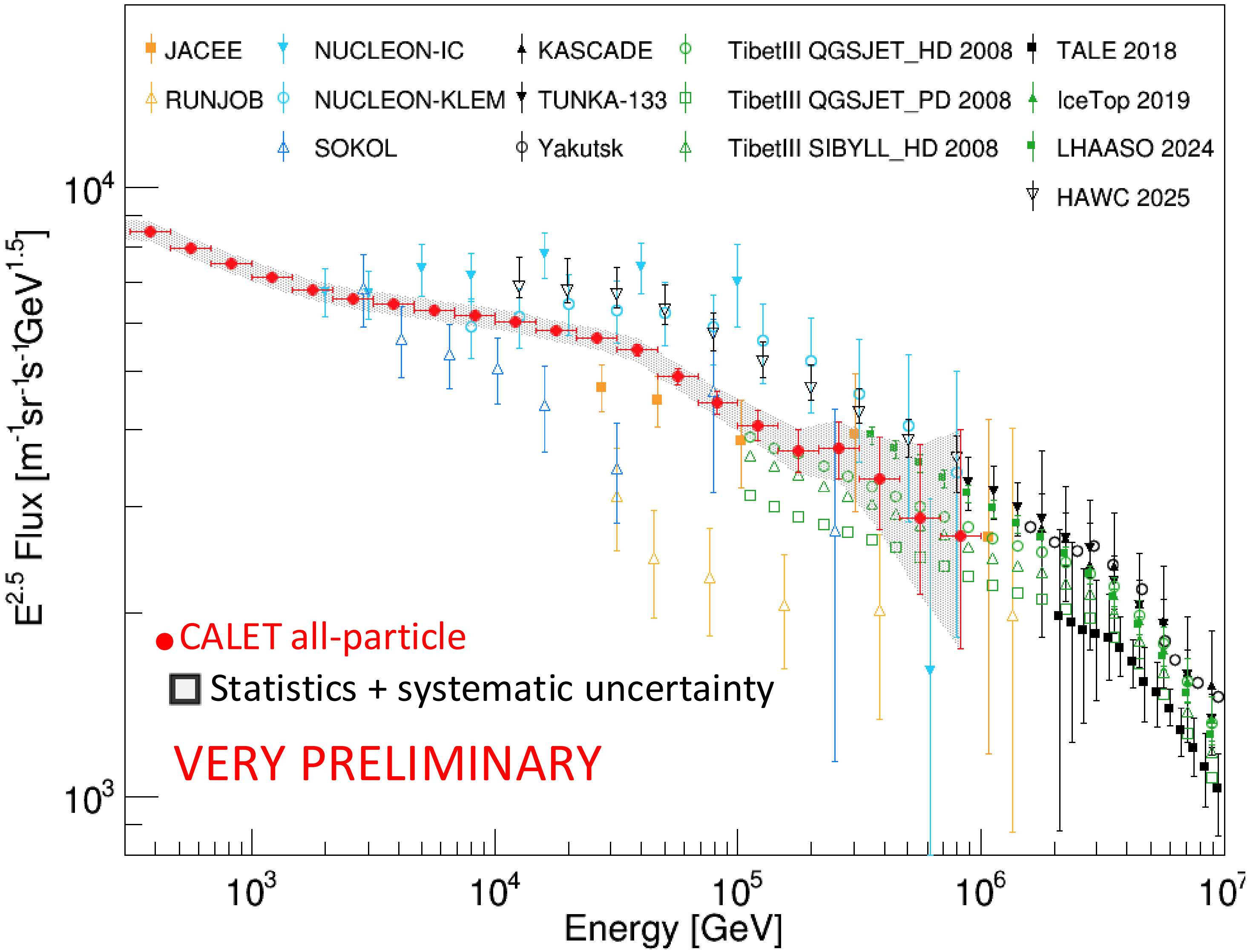
$$\gamma_{\mathrm{Ti/Fe}} = -0.30 \pm 0.01, \chi^2/\mathrm{ndf} = 15/17$$
$$\gamma_{\mathrm{Cr/Fe}} = -0.24 \pm 0.01, \chi^2/\mathrm{ndf} = 17/17$$

Dependence of the spectral indices of flux ratios to iron vs atomic number Z



All-particle spectrum

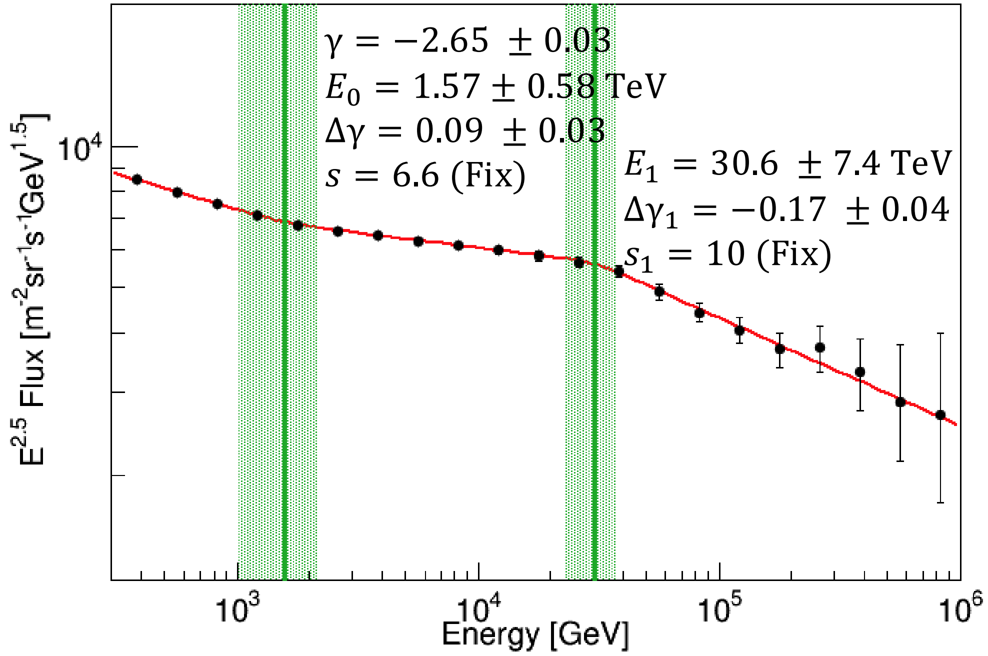
CALET closes the gap with indirect measurements from ground experiments



MC events are weighted to reproduce the fit results of each energy spectrum by CALET
The response matrix from MC is based on a weighted mixture of nuclei from Z = 1 to 28

Smoothly broken-power law fit:

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



Summary

- CALET was launched on Aug. 19th, 2015. The observation campaign started on Oct. 13th, 2015. Excellent performance and remarkable stability of the instrument have been confirmed for over 10 years.

- Accurate calibrations have been performed in the energy measurements established in 1 GeV-1PeV.

- Following cosmic-ray spectra have been measured so far:
  - **Electron + positrons:** 10 GeV – 7.5 TeV.
  - **Protons and Helium**: 50 GeV – 100 TeV and 250 TeV, respectively
  - **BCNO group**: 8.4 GeV/n – 19 TeV/n (C, O) and up to 5.7 TeV/n (B, N)
  - **Iron and Nickel**: 10 GeV/n – 1 TeV/n and 240 GeV/n
  - **sub-Fe (Ti, Cr):** 10 GeV/n – 250 GeV/n and ratios to Fe
  - **All-particle spectrum: up to 1 PeV**

- Continuous all-sky monitoring of gamma rays, GRBs, solar modulation and REP events is ongoing.

- CALET observation has successfully been carried out over 10 years and is extended to 2030 with the approval of JAXA.

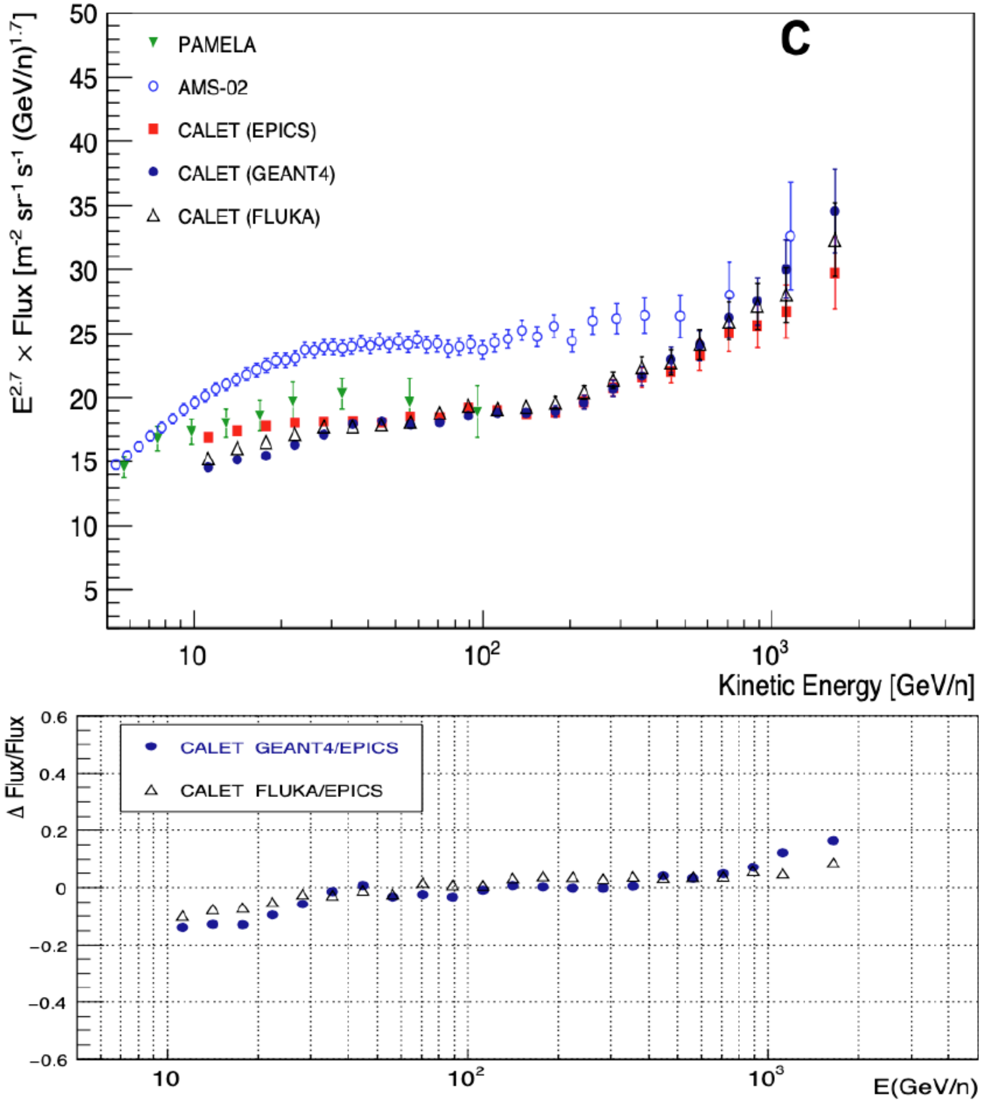
Study on the normalization

CALET have been investigated several areas where potential sources of systematic error could affect flux normalization

The main studies carried out to data include:

- Monte Carlo models
  - ⇨ EPICS (reference), FLUKA, Genat4
- Efficiency
  - Trigger
    - ⇨ Studies with different trigger logic and energy threshold
  - Cross-sections in MC
    - ⇨ Check by varying cross sections in MC
  - Event election criteria
    - ⇨ various selection criteria were tested and compared
- Energy scale calibration
  - ⇨ Validated through beam test results;
    corresponding uncertainties are included in the systematic errors

Monte Carlo models



MC simulations, reproducing detector configuration, physics processes and detector signals, where developed based on three simulation packages

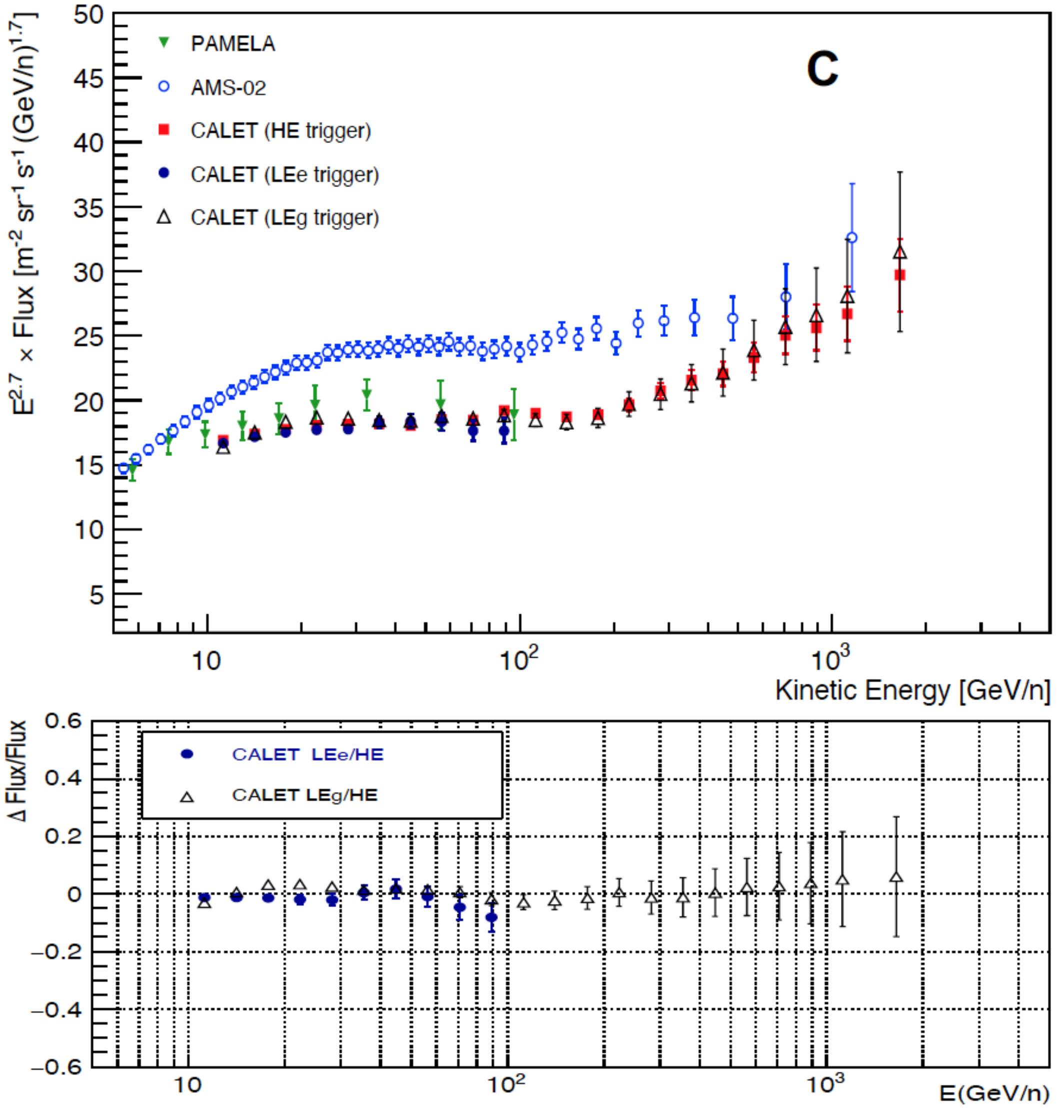
- EPICS 9.21 w/ DPMJET-III
- FLUKA 2011 2x.6 w/ DPMJET-III
- Geant4 10.5 w/ FTFP_BERT

MC simulations were tuned using beam test data and flight data

They are used to estimate selection efficiencies and response matrix.

The fluxes obtained using different MC simulations show consistent normalization and spectral shapes.

Efficiency: Trigger



Low-energy gamma (LEg) trigger

- Coincidence of last two pairs of IMC layers (5MIP thr.) % top TASC layer (10 MIPthr.)
- Livetime ~ 10% of HE-livetime

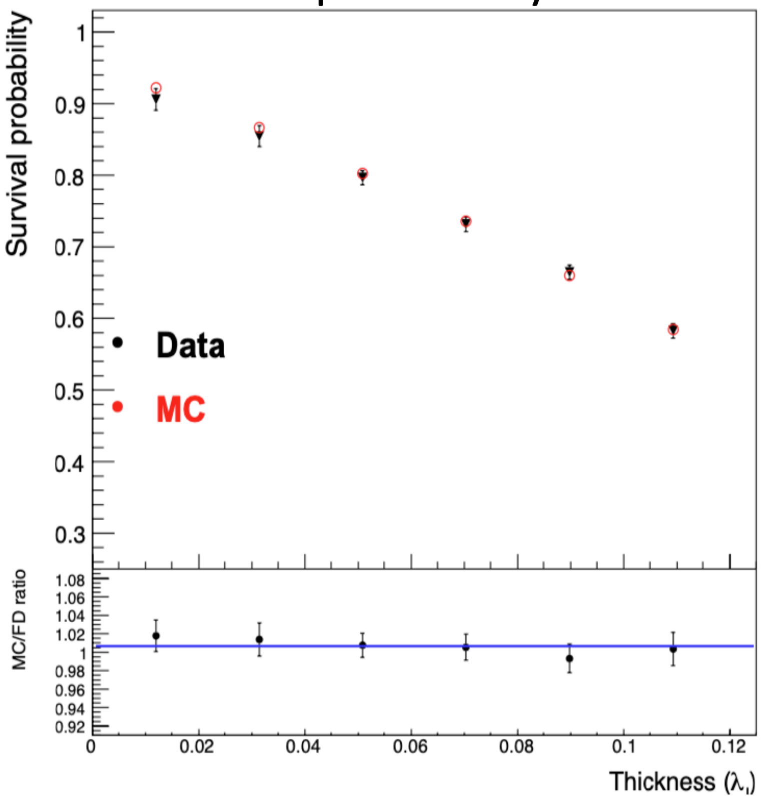
Low-energy electron (LEe) trigger

- Same as LEg with additional coincidence of CHD & upper IMC layer (0.3 MIP thr.)
- Livetime ~ 2% of HE-livetime

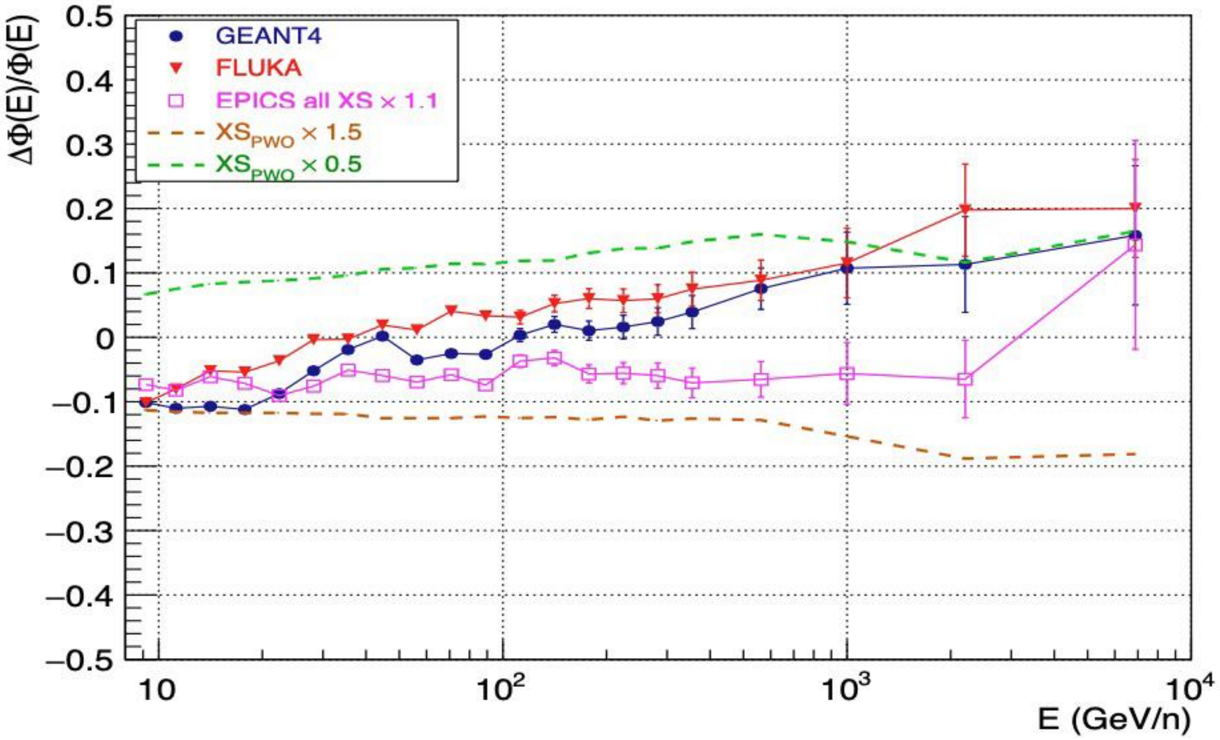
The fluxes obtained using different trigger modes show consistent normalization and spectral shapes

Efficiency: cross-section

Survival probability in IMC



Very good agreement between data and simulation (within <1%)

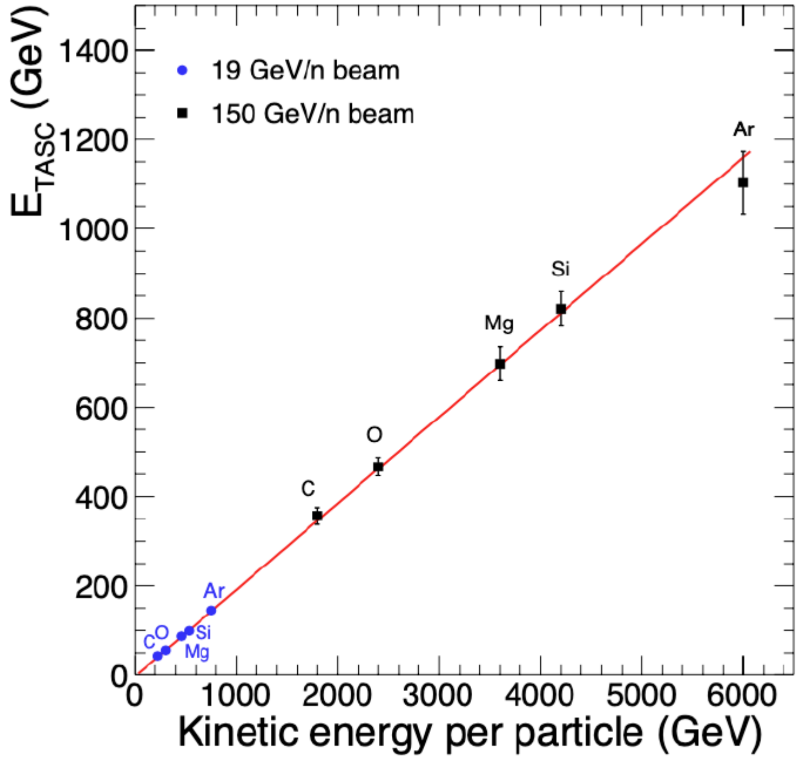


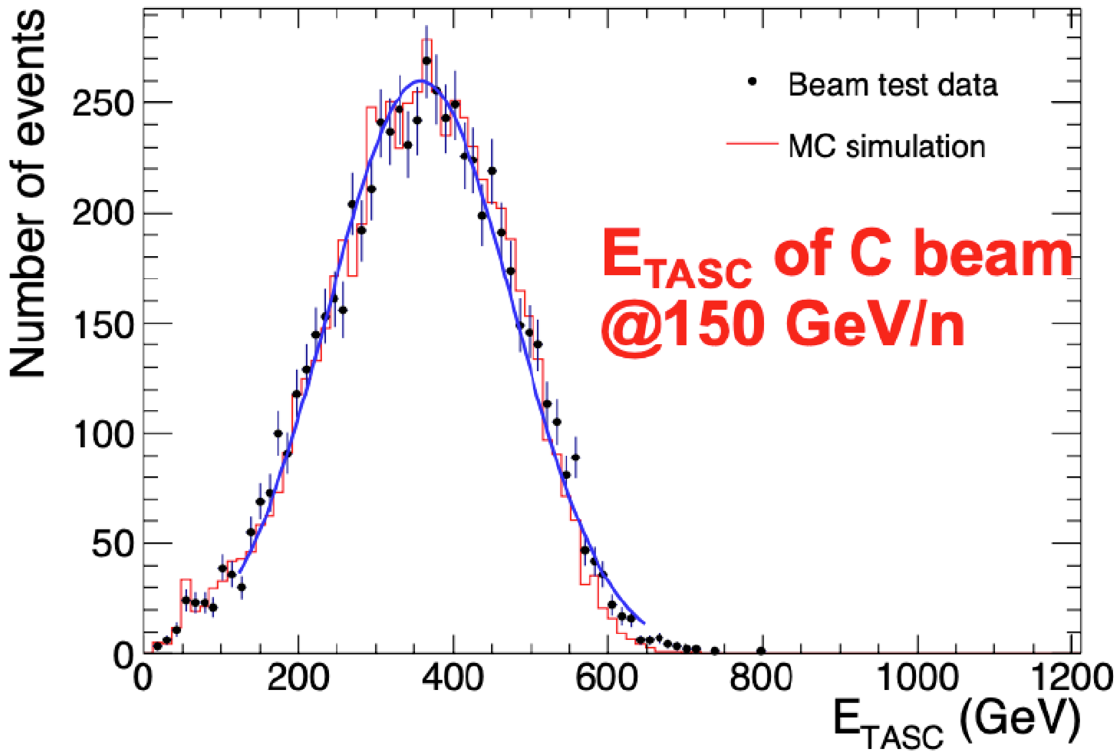
Comparison of spectra obtained different MC simulations: EPICS (reference), FLUKA, Geant4

Cross-section × 1.5 (dashed orange): -10%

× 0.5 (dashed green): + 10%

Energy scale: beam test





- Beam test calibration at CERN-SPS with ion fragments (Z/A = 2)
- Good linearity up to max available beam energy (6TeV)
- The energy response derived from MC simulations was tuned using the beam test results, and the errors have been included into the systematic uncertainties.