# CALETによる重原子核・全粒子スペクトルの観測

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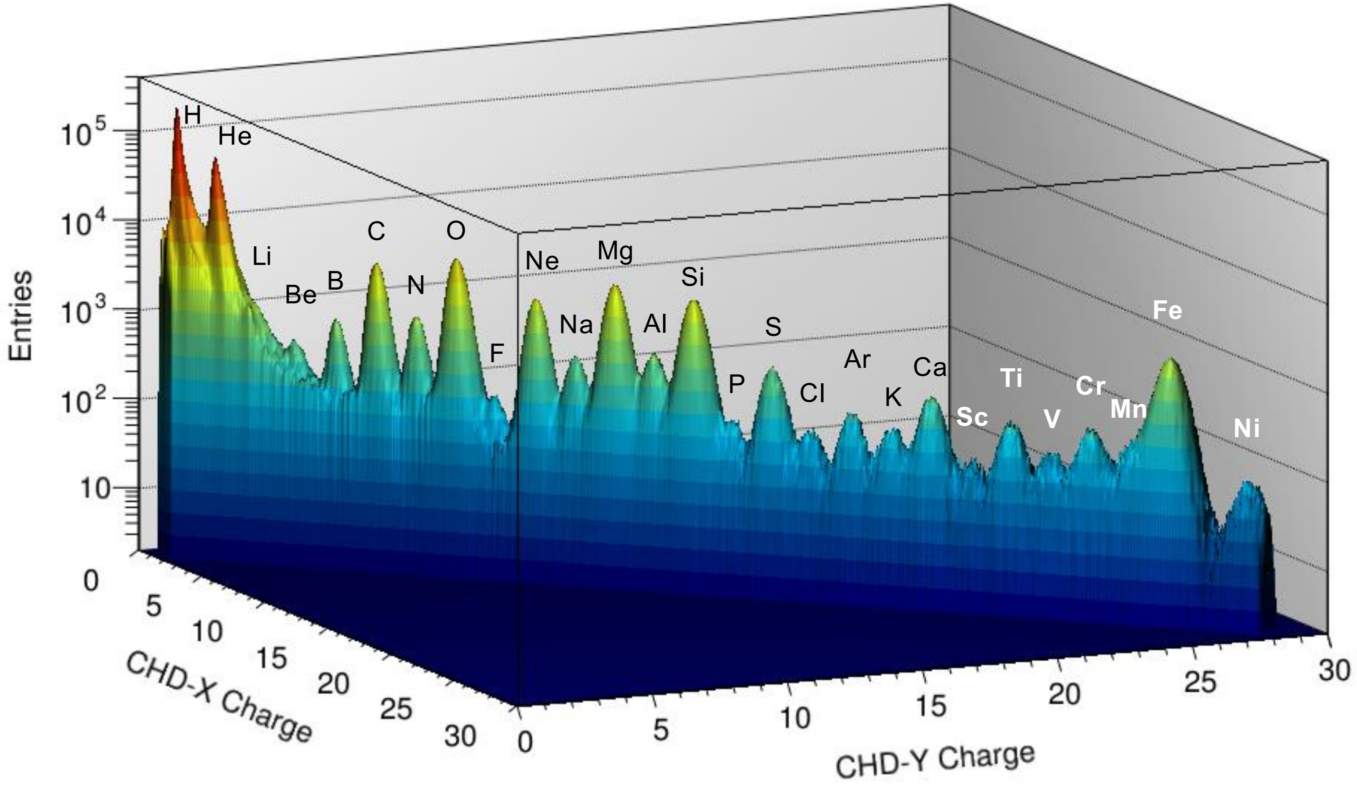
3. All-particle spectrum
4. Study on the flux normalization



# Capabilities for nuclei measurements with CALET

**Tracking**

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

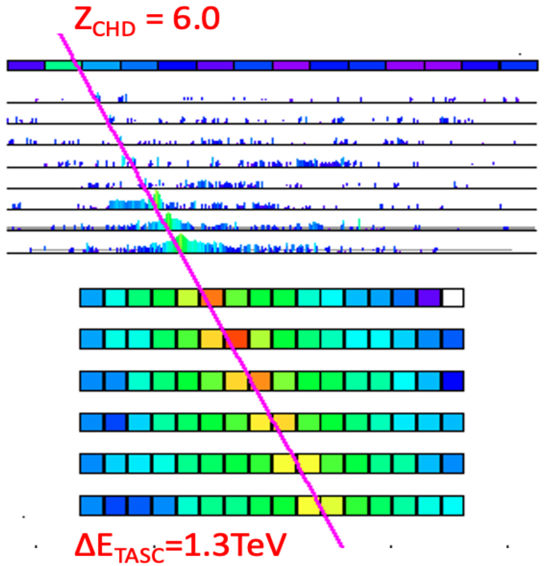
**Charge measurement**

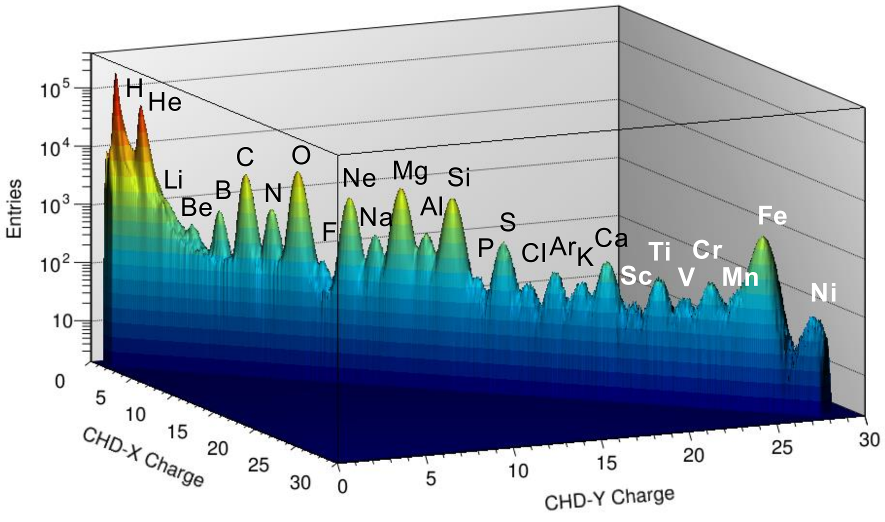
- CHD enables individual charge identification from Z=1 – 40
- Charge resolution ranges from 0.15 e to 0.3 e for protons to iron

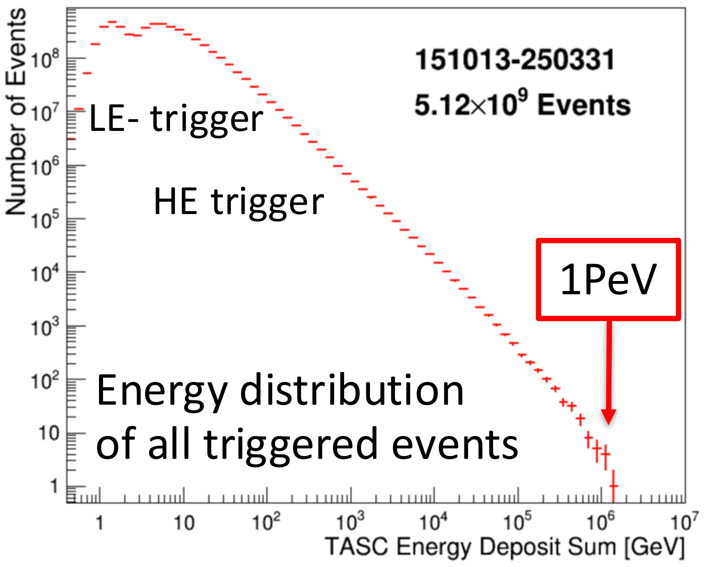
**Energy measurement**

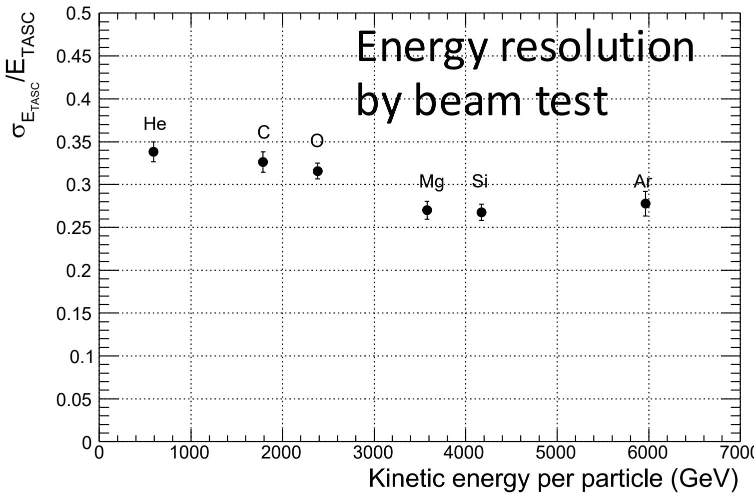
- Capable of measuring nuclei over a wide energy range: 1 GeV to 1 PeV.
- Energy resolution for nuclei: 30 – 35%

An example of Carbon event

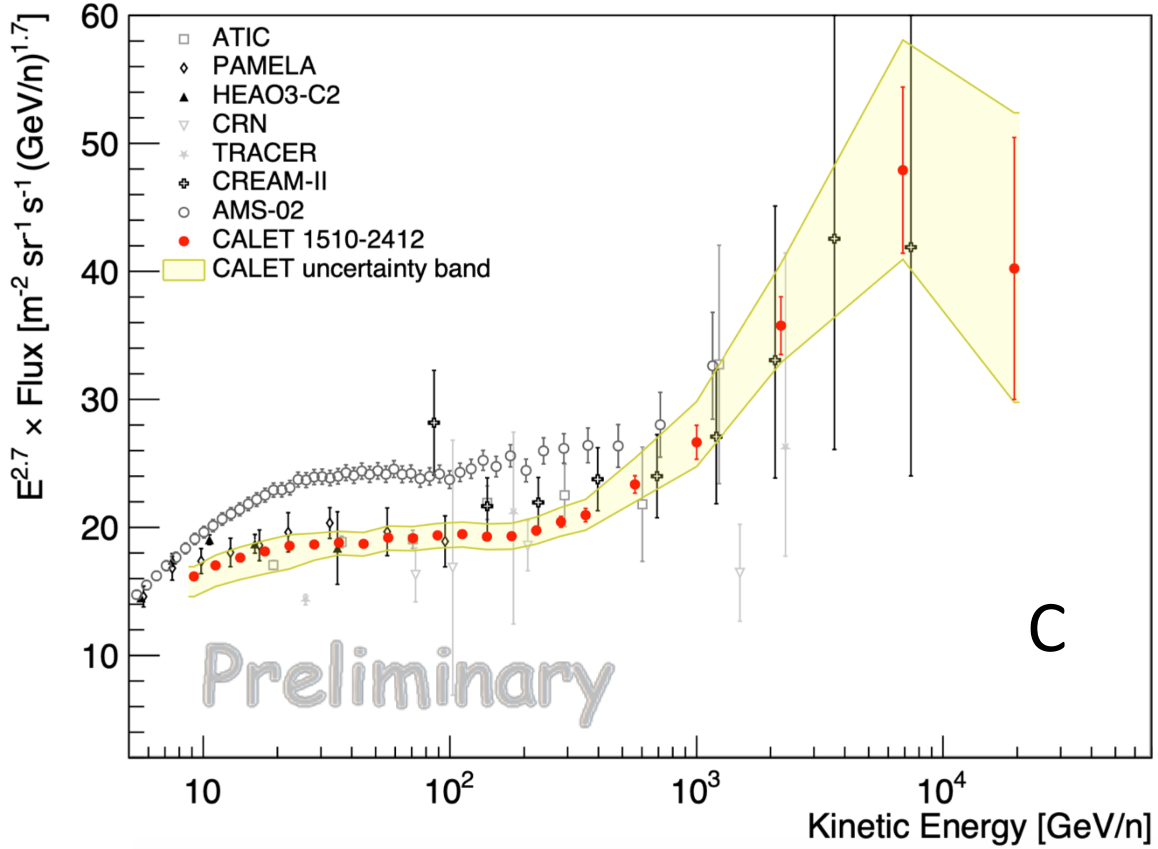


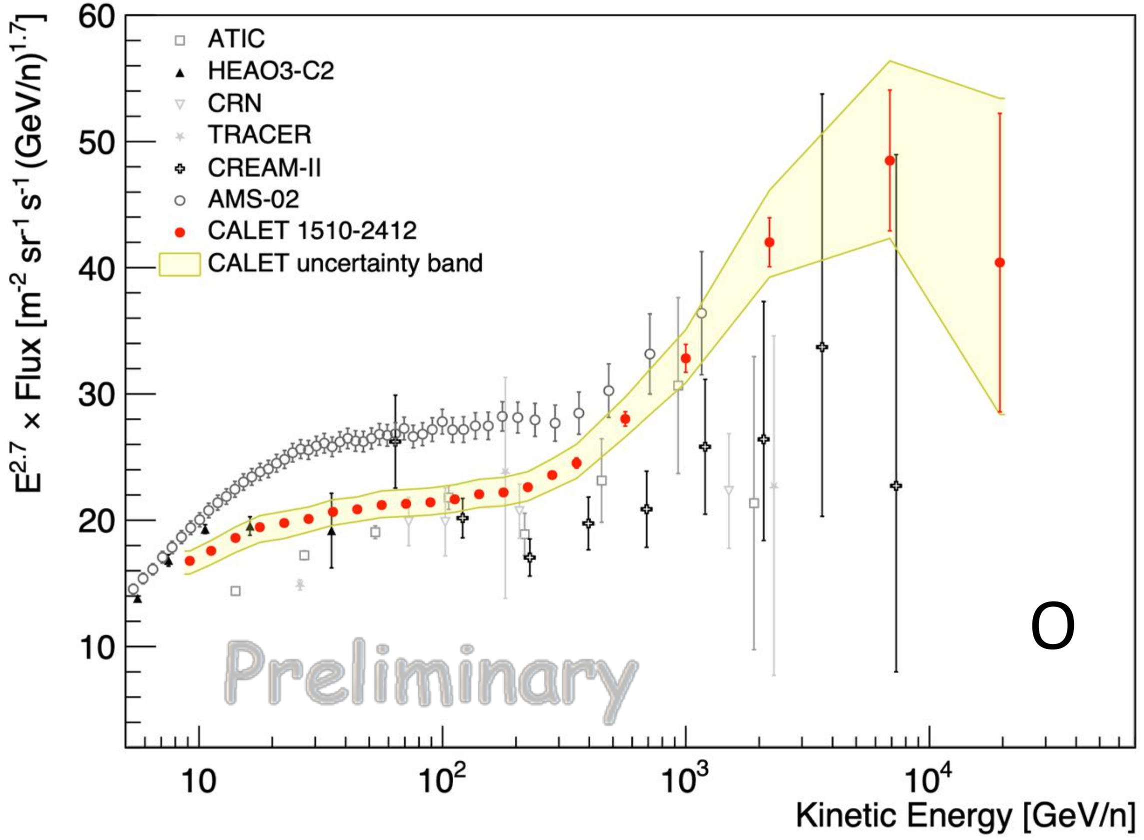



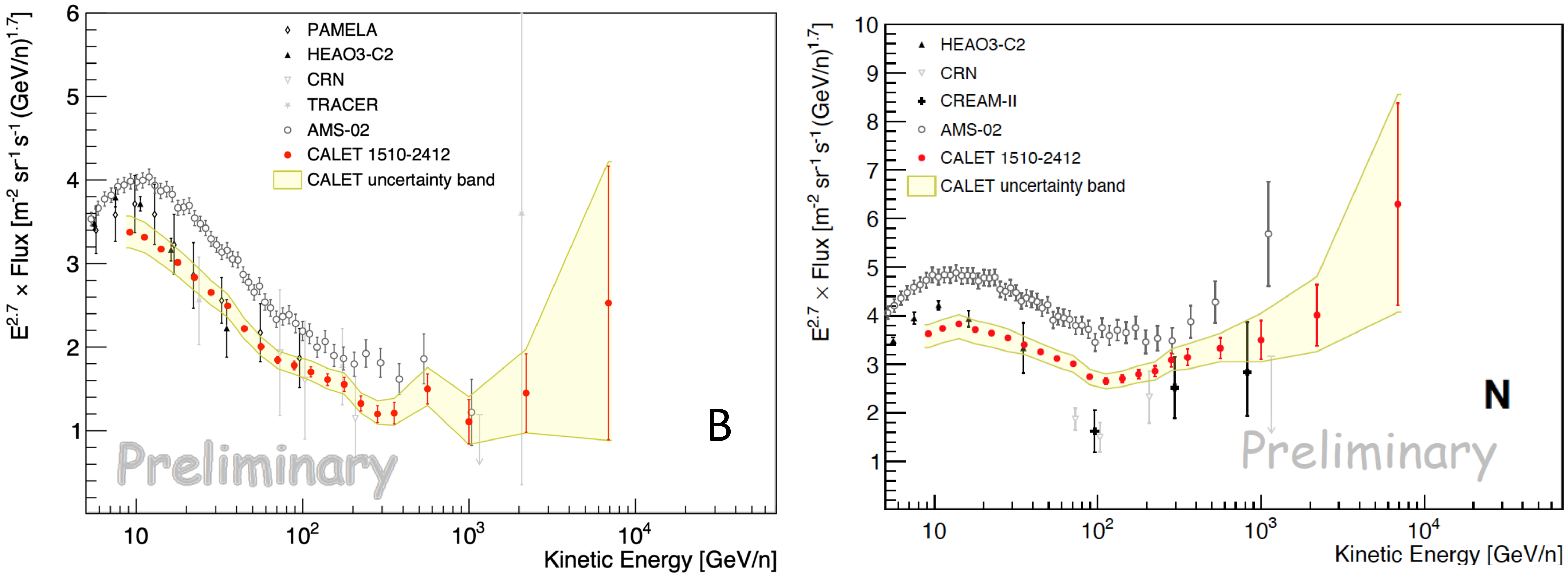
# Carbon and Oxygen energy spectra



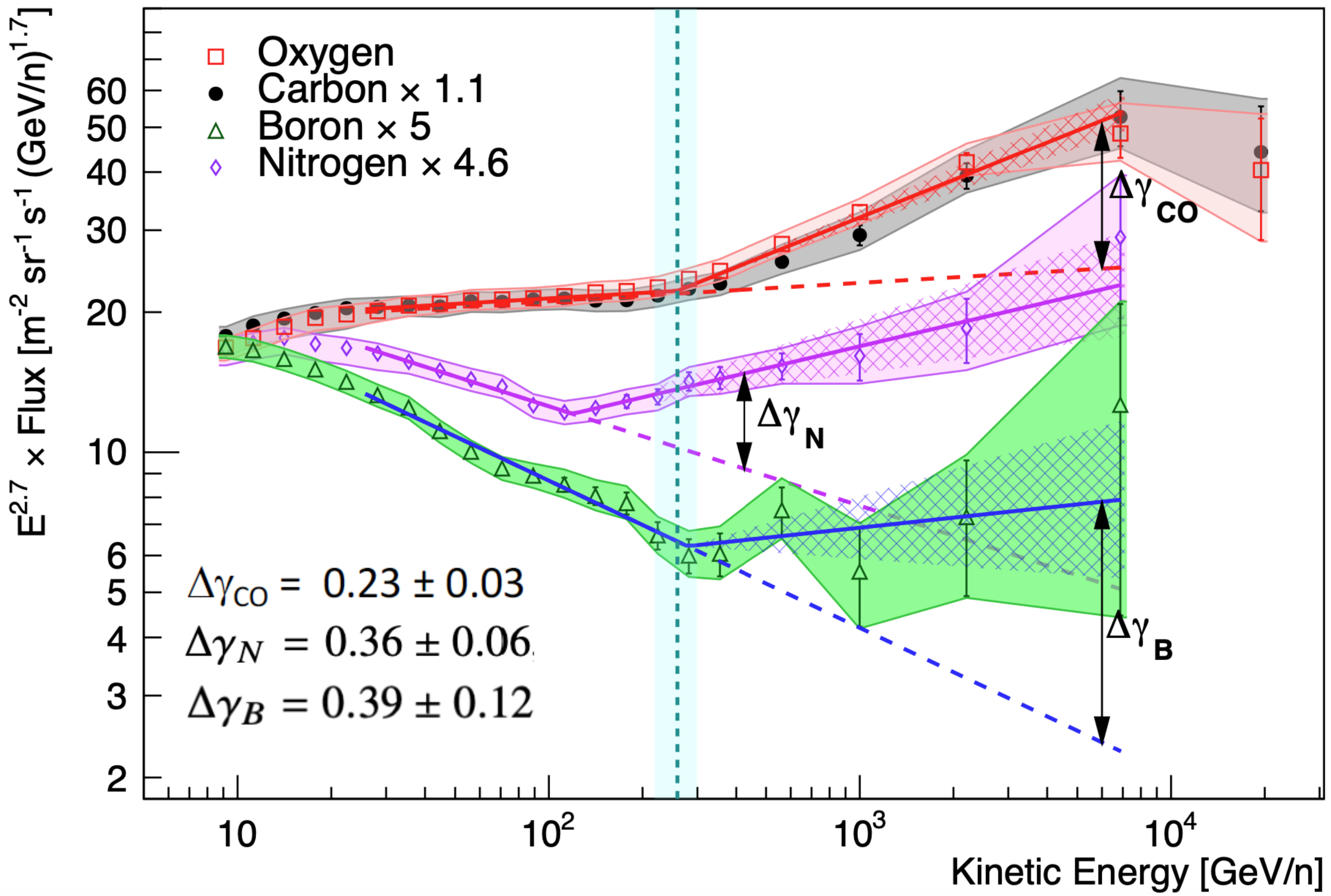

- C and O spectra measured from 8.4 GeV/n to ~19 TeV/n
- Main systematic uncertainties from MC models (EPICS/FLUKA/Geant4)
- Consistent with PAMELA data. Similar shape but lower normalization compared to AMS-02 data.
- Clear hardening around 200 GeV/n. Hint of a softening around 10 TeV/n

# Boron and Nitrogen energy spectra



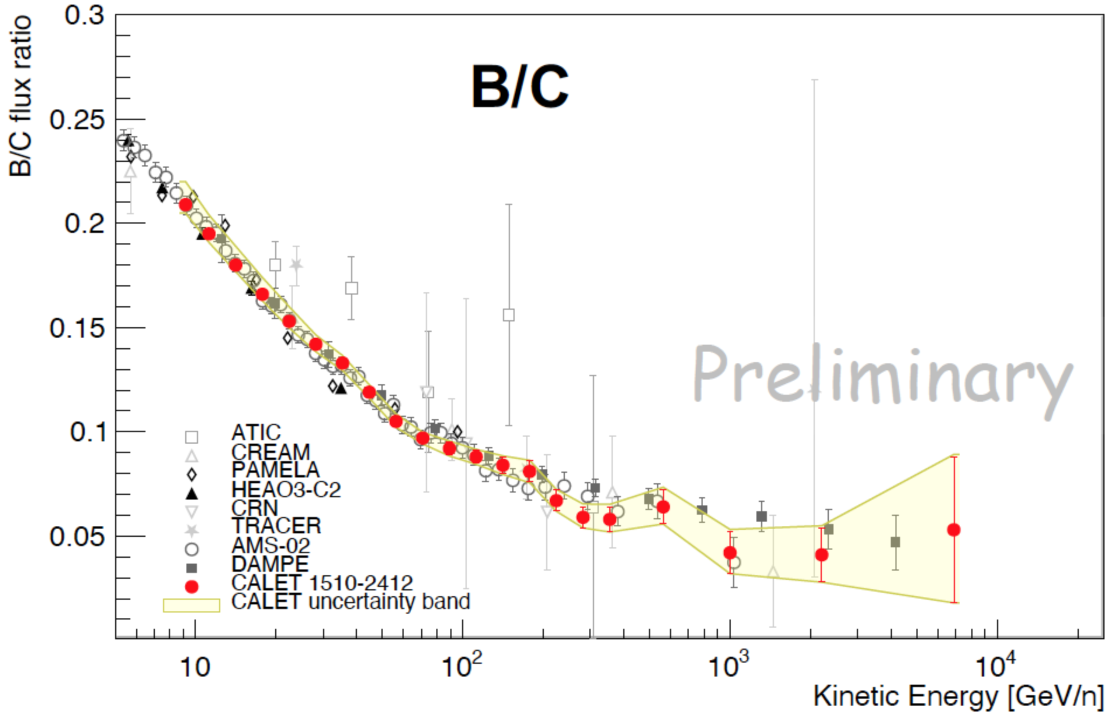

- B and N spectra measured from 8.4 GeV/n to ~6.7 TeV/n
- Main systematic uncertainties from MC models (EPICS/FLUKA/Geant4)
- Consistent with PAMELA data. Similar shape but lower normalization compared to AMS-02 data.

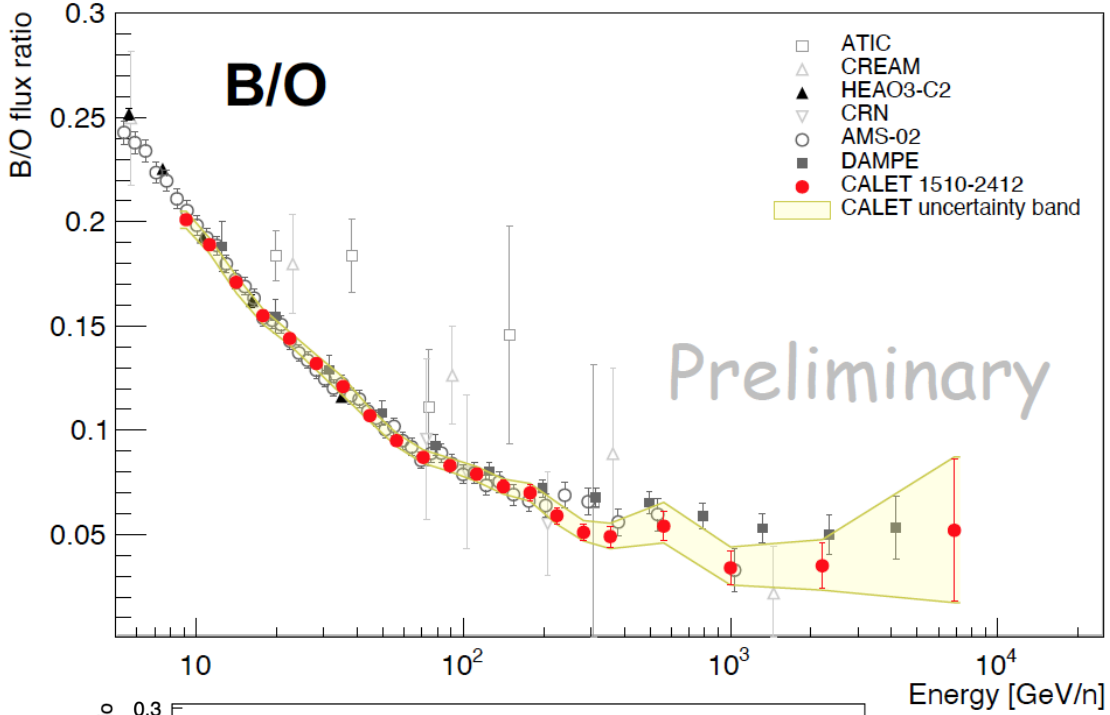
# Spectral analysis for BCNO

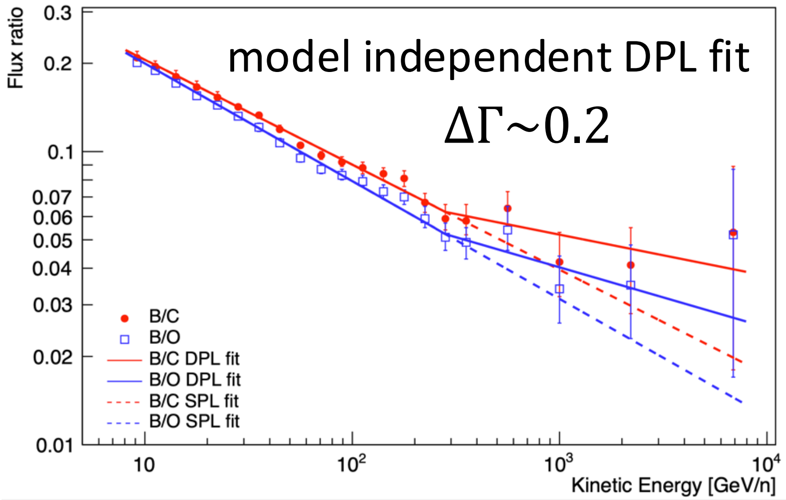



- C and O fluxes harden similarly above 200 GeV/n (significance 7σ)
- B hardens almost twice as C, O (significance 2.5σ) as expected from propagation of a purely secondary element.
- N consistent with a mixed composition of primary and secondary: hardens more than C, O but less than B (significance 5σ)

# Boron flux ratios

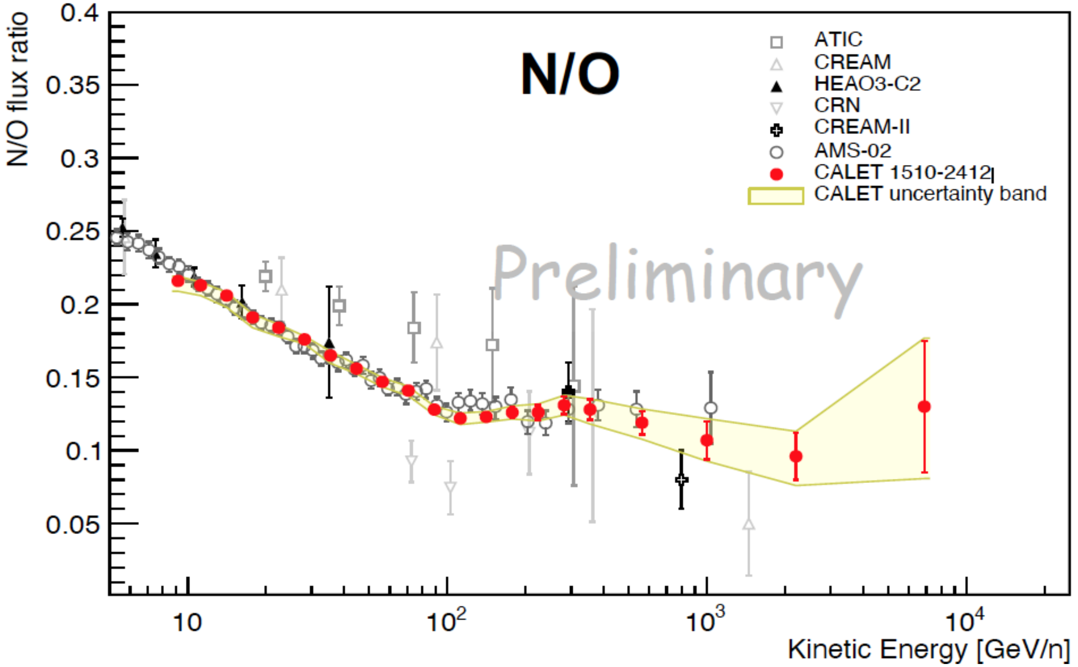


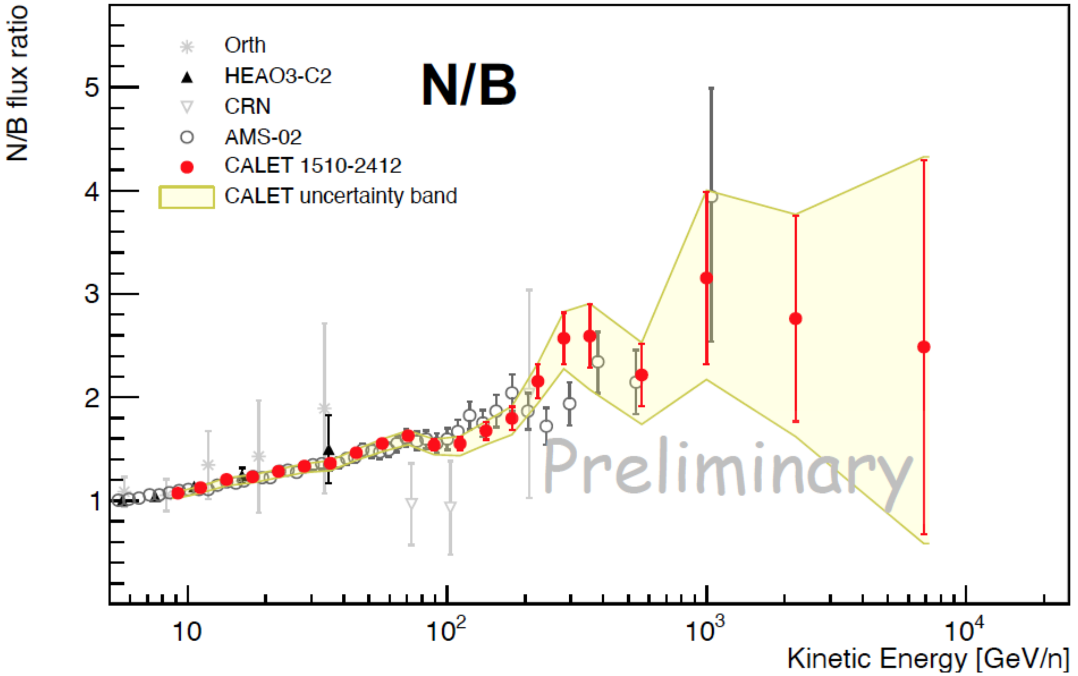



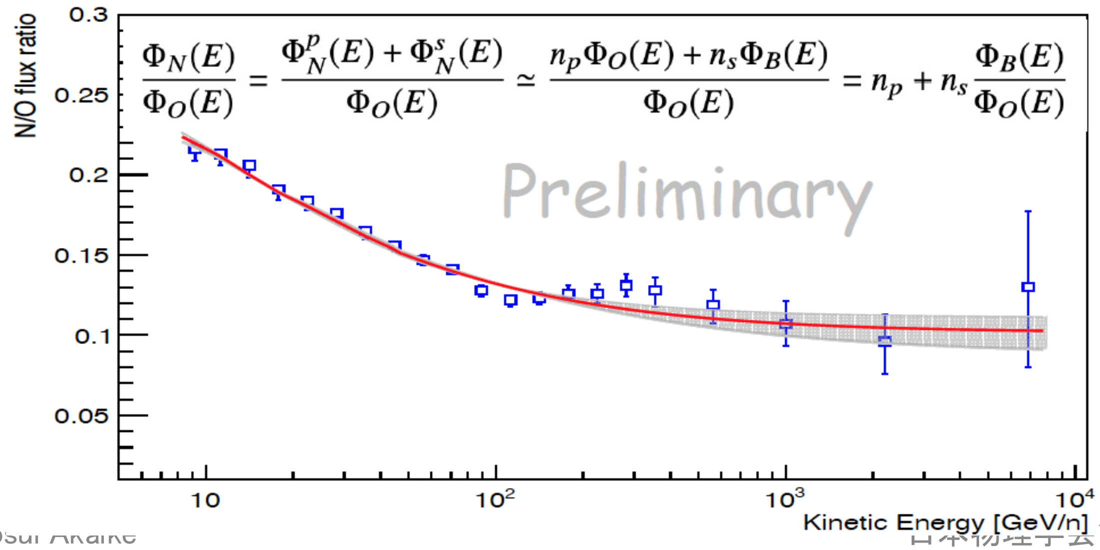




- Observe of a flattening of B/C and B/O with energy
- The observed flattening at TeV/n might be due to a change in the spectral index of δ of the diffusion coefficient or the presence of source grammage (~1.3 g/cm$^2$)

# Nitrogen flux ratios



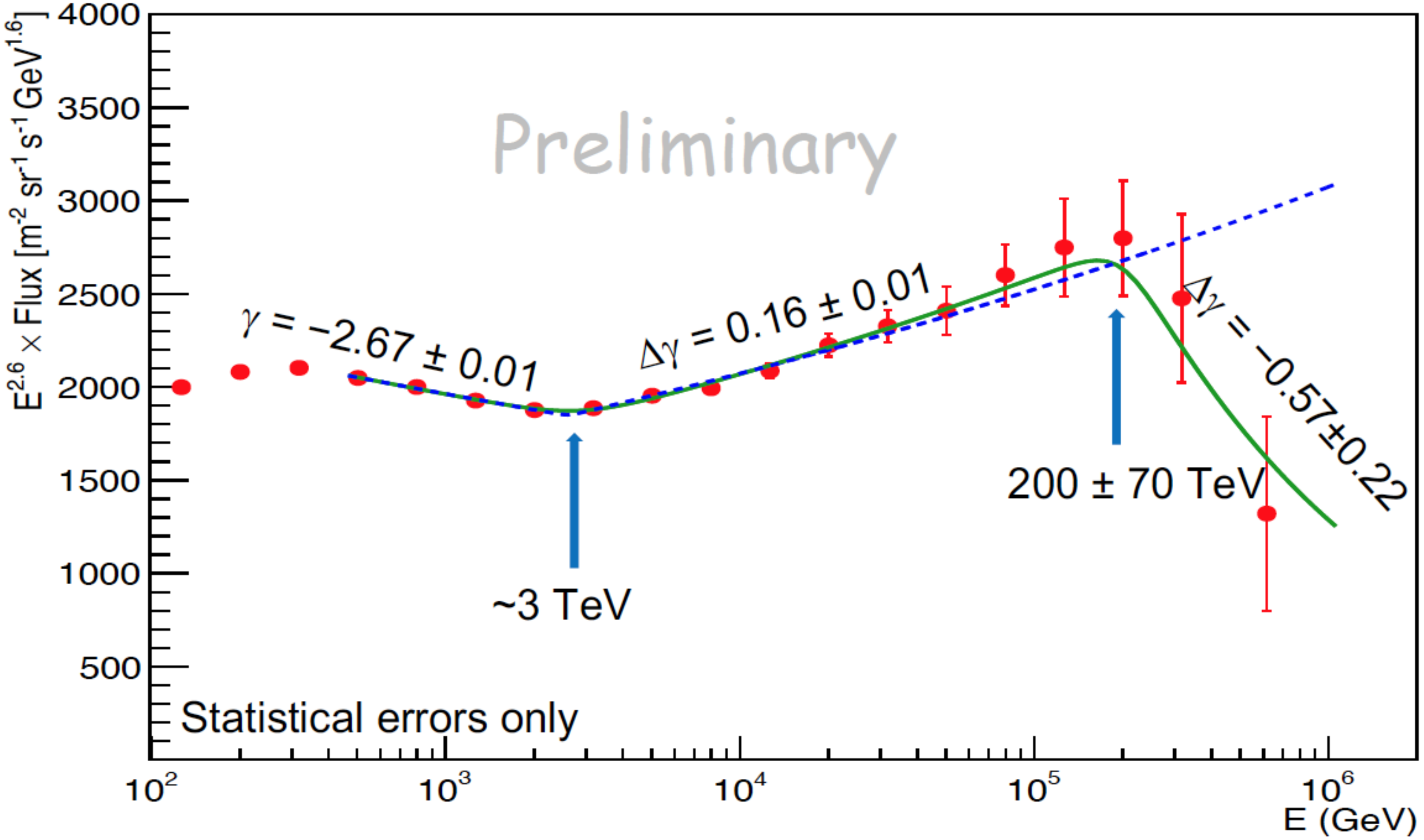




- N/O ratio decreases with E and flattens above 100 GeV/n, while N/B continues to rise
  ⇨ N components: primary $\Phi_N^P = n_P\Phi_O$
  + secondary $\Phi_N^S = n_S\Phi_B$

$\rightarrow n_P = 0.074 \pm 0.003\,(\text{stat}) \pm 0.02\,(\text{sys})$

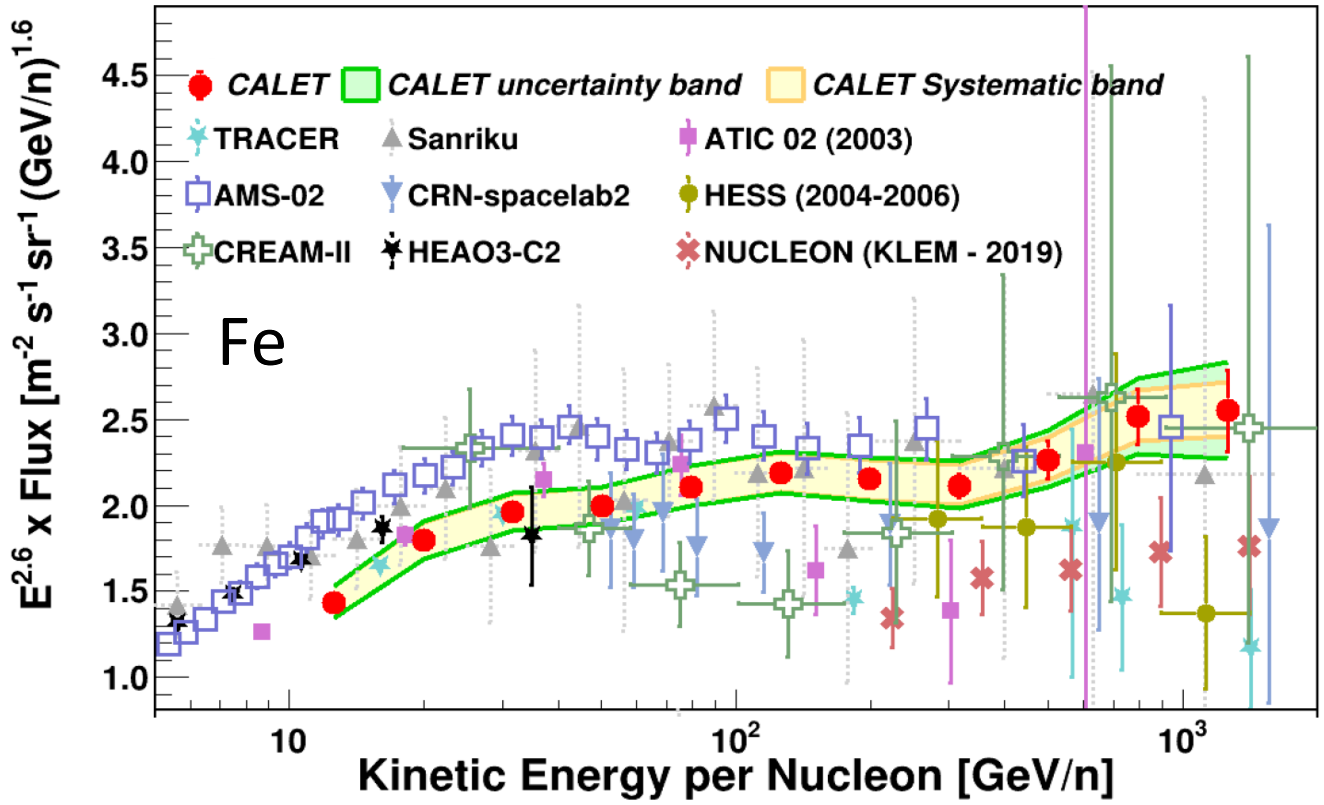
$n_S = 0.74 \pm 0.02\,(\text{stat}) \pm 0.05\,(\text{sys})$

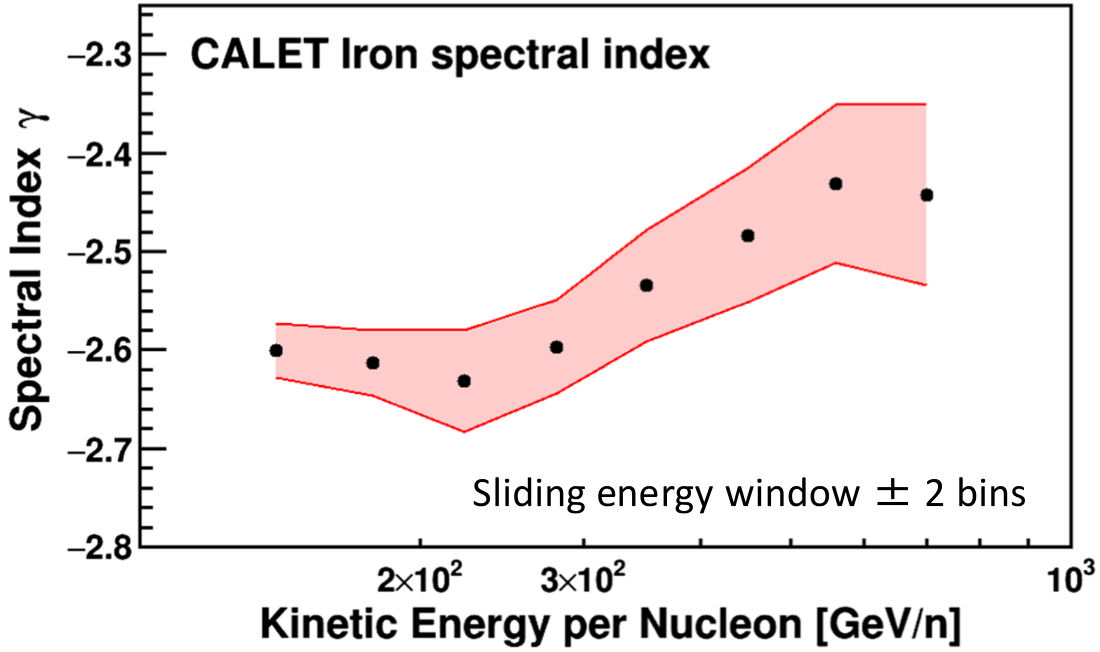
# Combined CNO spectrum




- Combined C, N, O sample selected with large charge cuts
- MC datasets merged using relative abundances consistent with measured C/O and N/O ratios.
- Hint of a softening around 200 TeV, albeit with low statistical significance

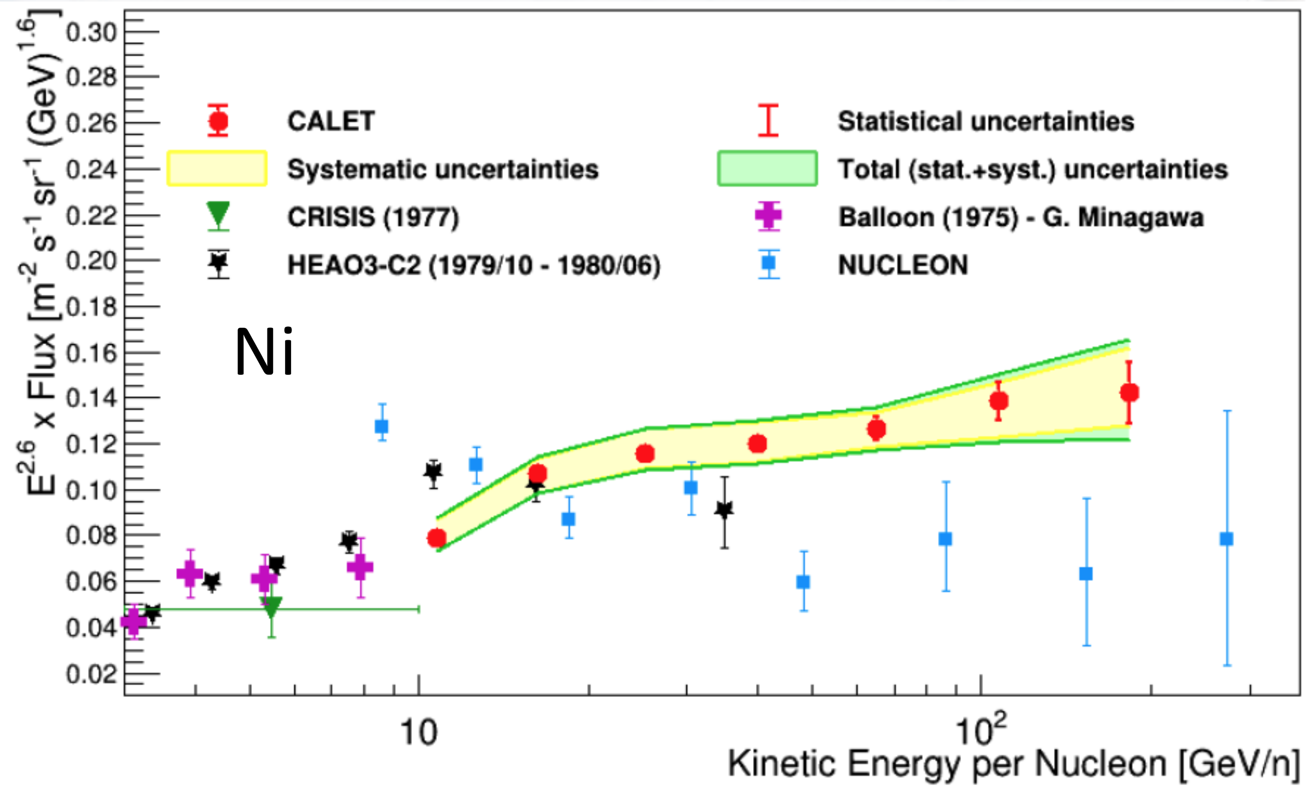
# Iron spectrum

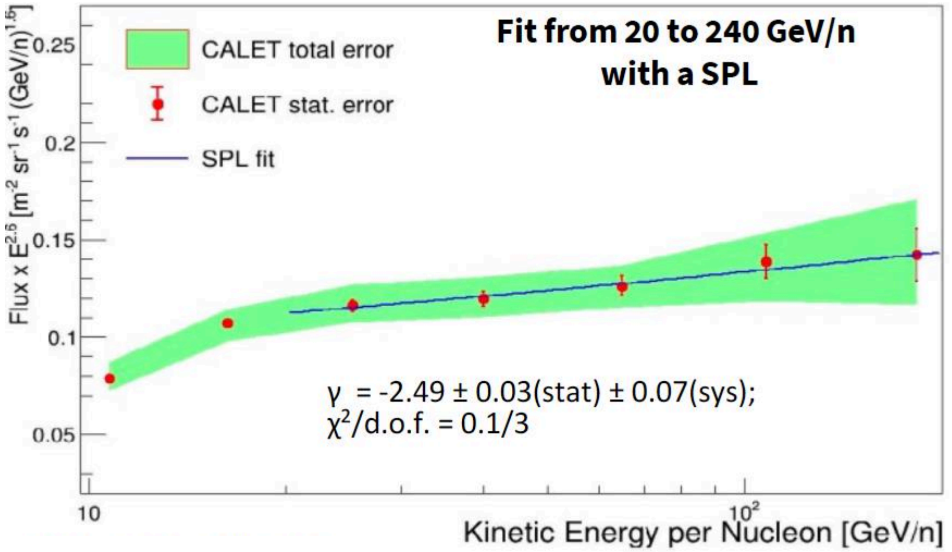


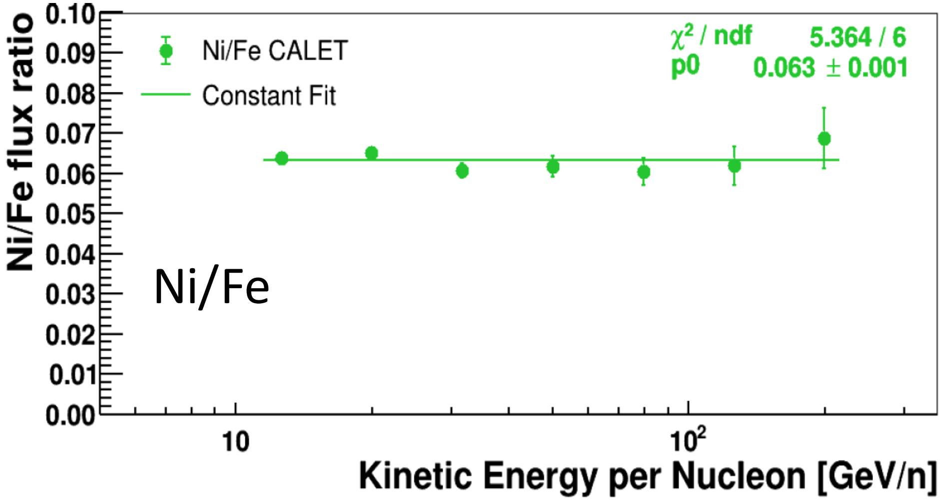




- Possible hardening of the spectrum above a few hundred GeV/n
- CALET spectrum has similar shape with AMS-02 data, but the absolute normalization is lower

# Nickel spectrum

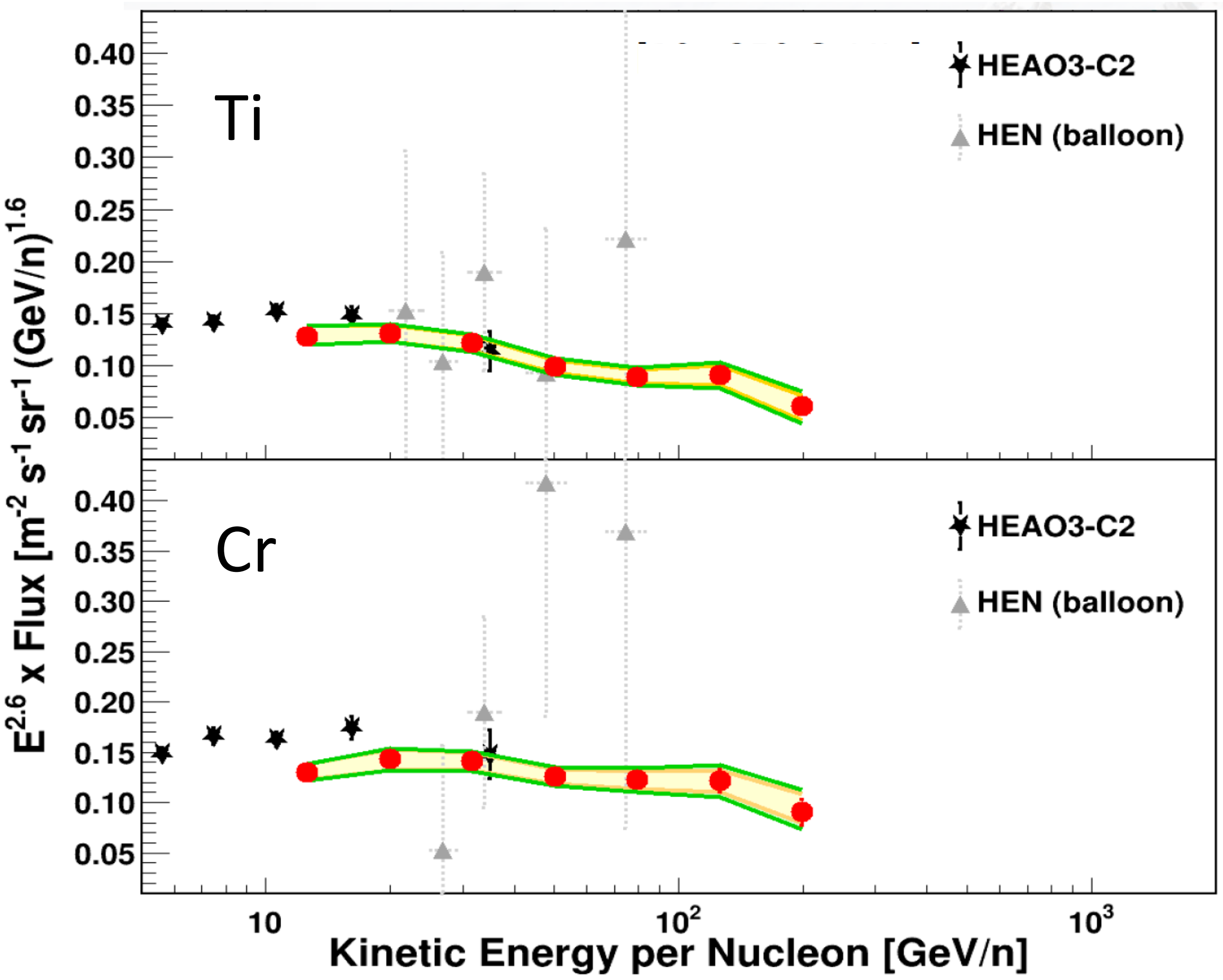


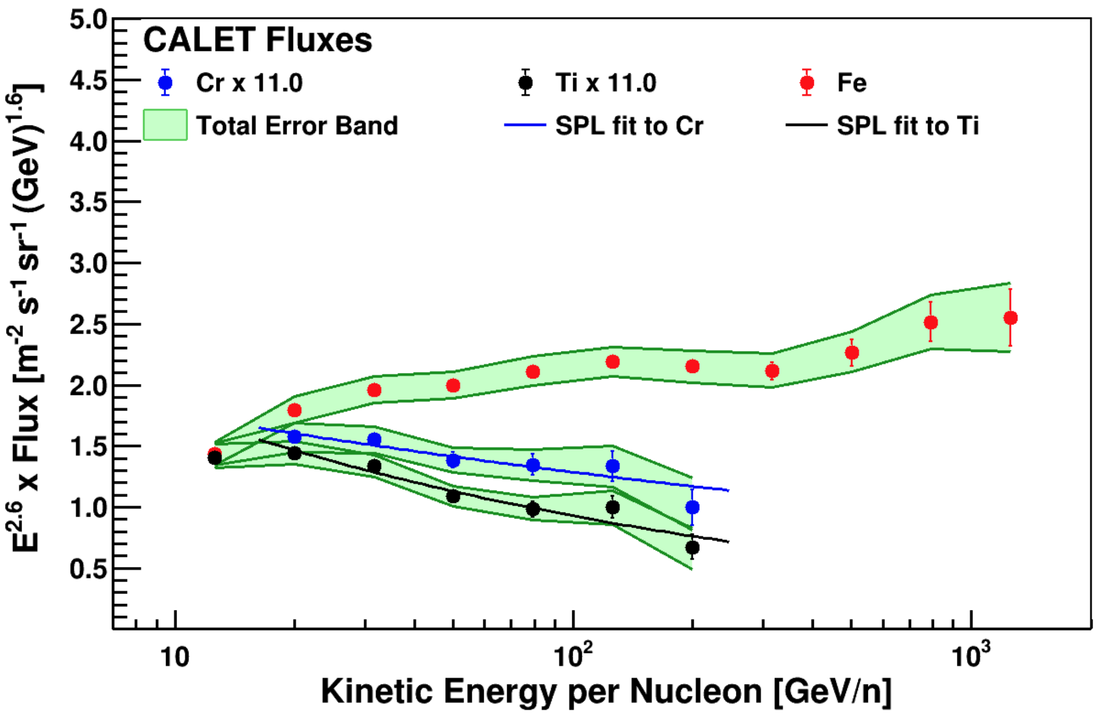




- The Ni/Fe flux ratio is constant in 10 - 240 GeV/n confirming that Ni and Fe have a similar behavior

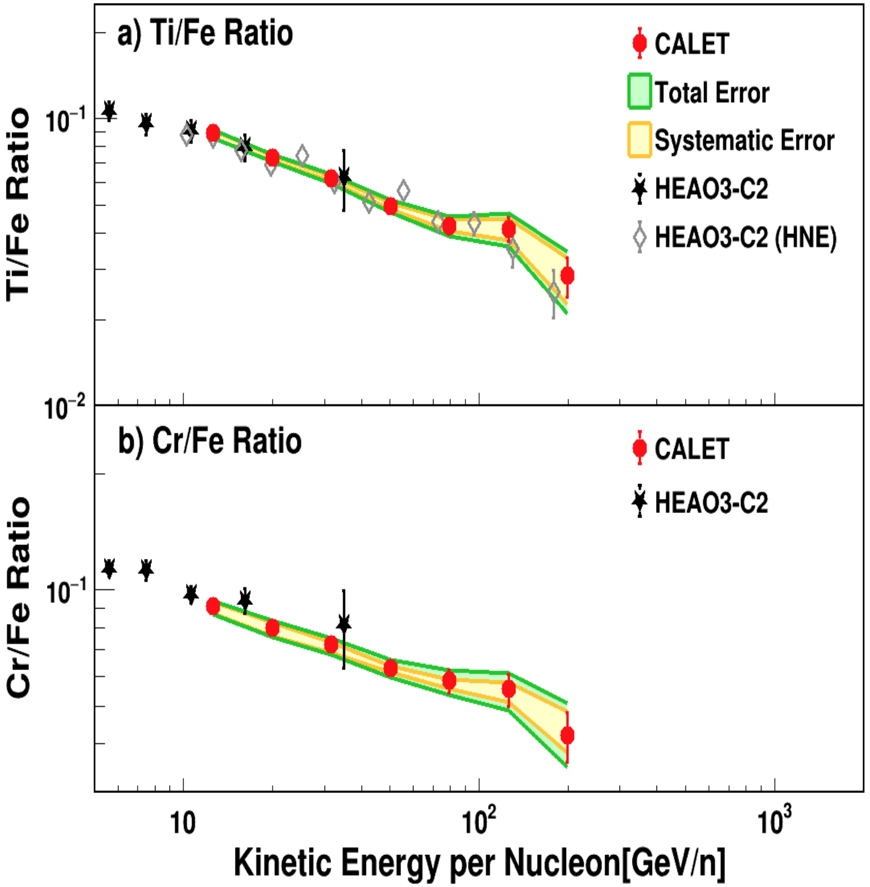
# Titanium and Chromium spectra

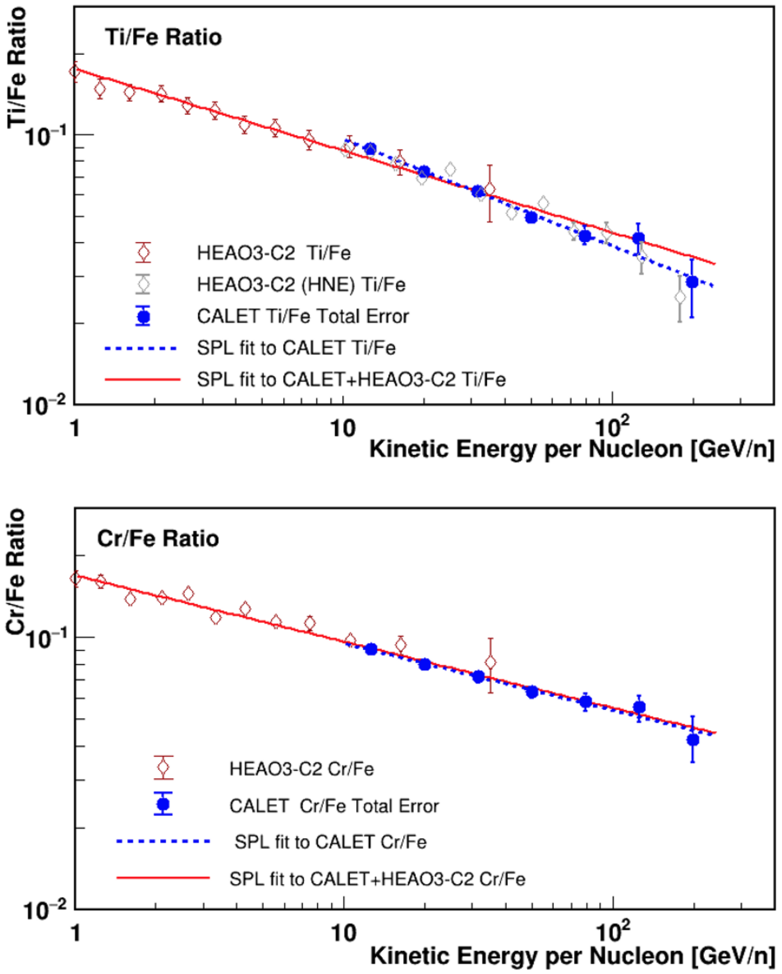



$$\gamma_{Ti} = -2.88 \pm 0.06\ (\text{stat.} \oplus\ \text{syst.}), \chi^2/\text{ndf} = 1.8/4$$
$$\gamma_{Cr} = -2.74 \pm 0.06\ (\text{stat.} \oplus\ \text{syst.}), \chi^2/\text{ndf} = 1.1/4$$

# Sub-Iron to Iron Ratios: Ti/Fe, Cr/Fe




SPL fit for CALET data

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

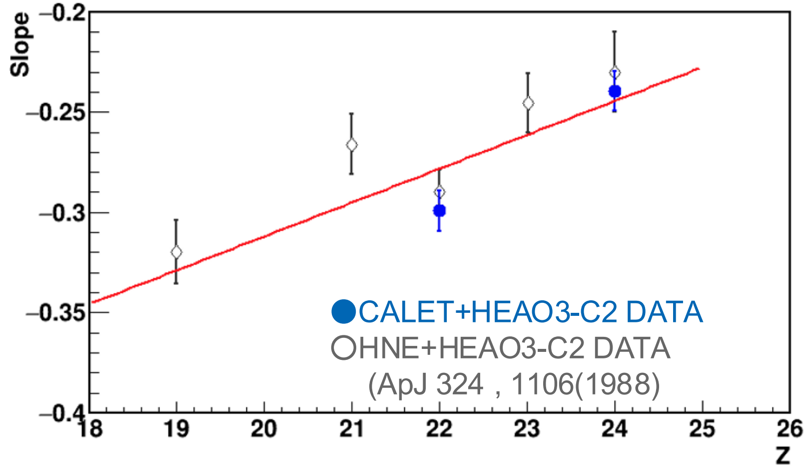
$\gamma_{\mathrm{Cr/Fe}} = -0.24 \pm 0.03, \chi^2/\mathrm{ndf} = 0.8/5$

SPL fit for CALET + HEAO3-C2

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

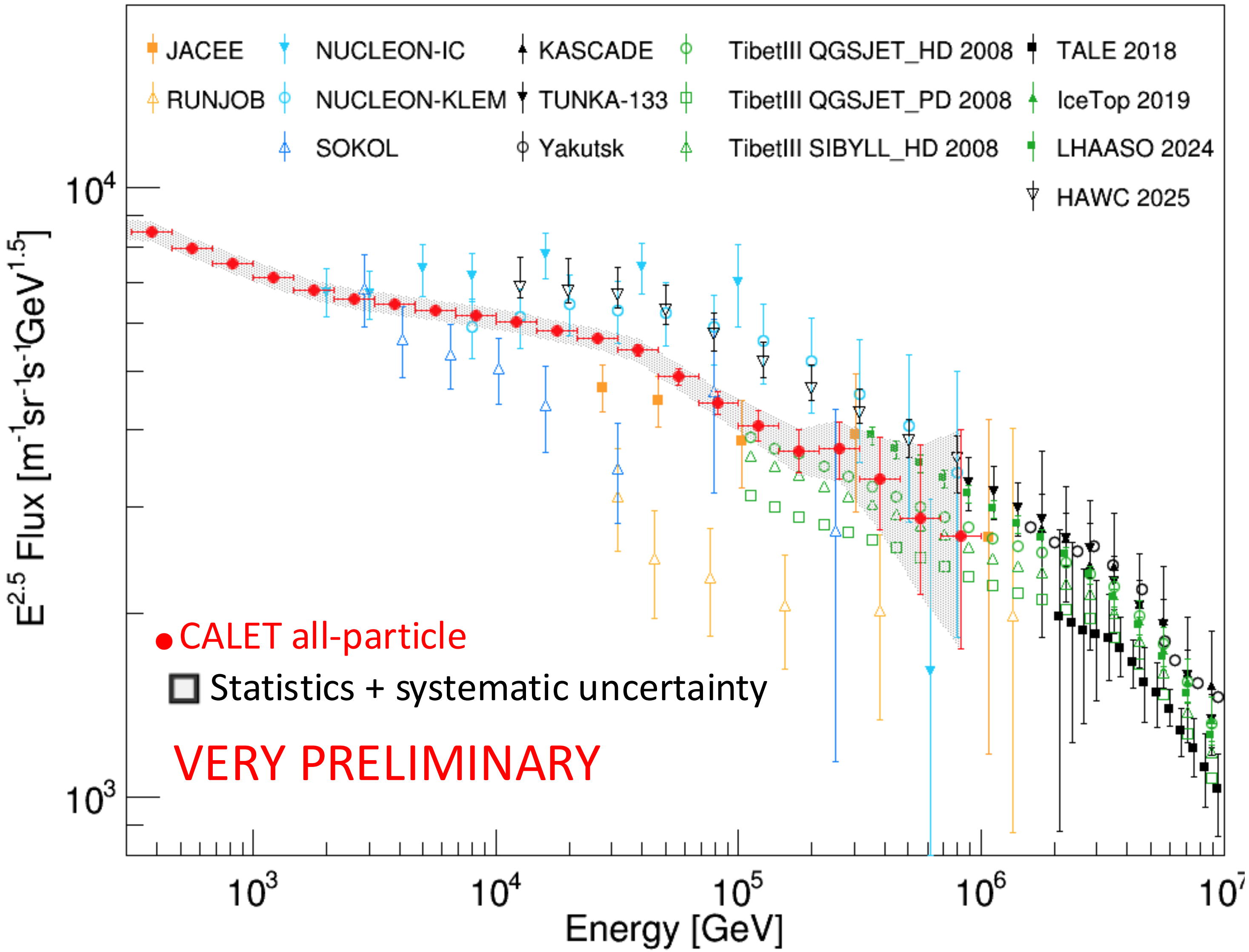
$\gamma_{\mathrm{Cr/Fe}} = -0.24 \pm 0.01, \chi^2/\mathrm{ndf} = 17/17$

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



# All-particle spectrum

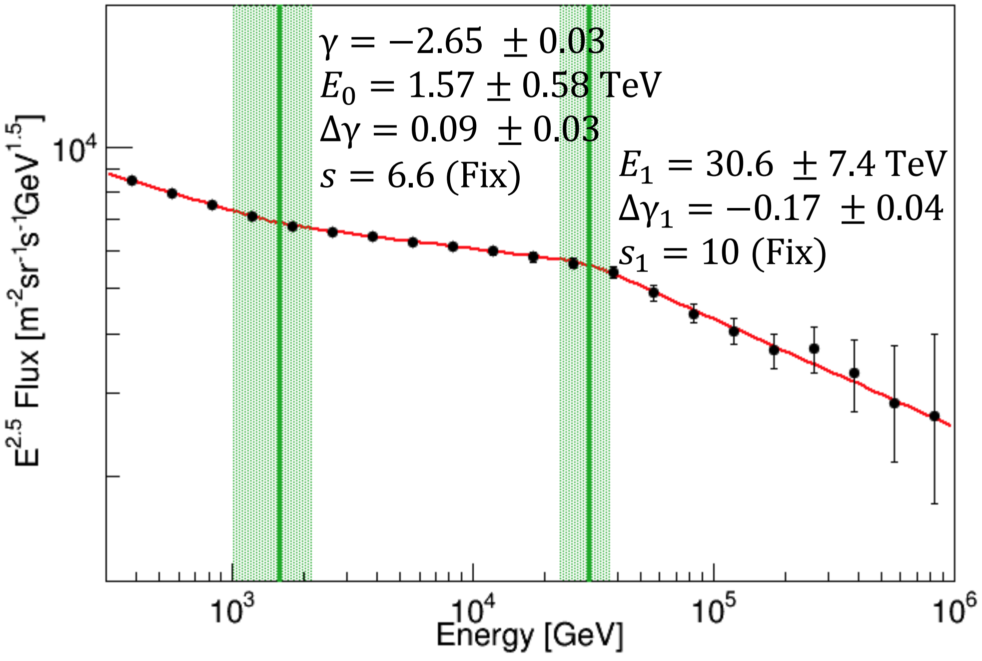
CALET closes the gap with indirect measurements from ground experiments



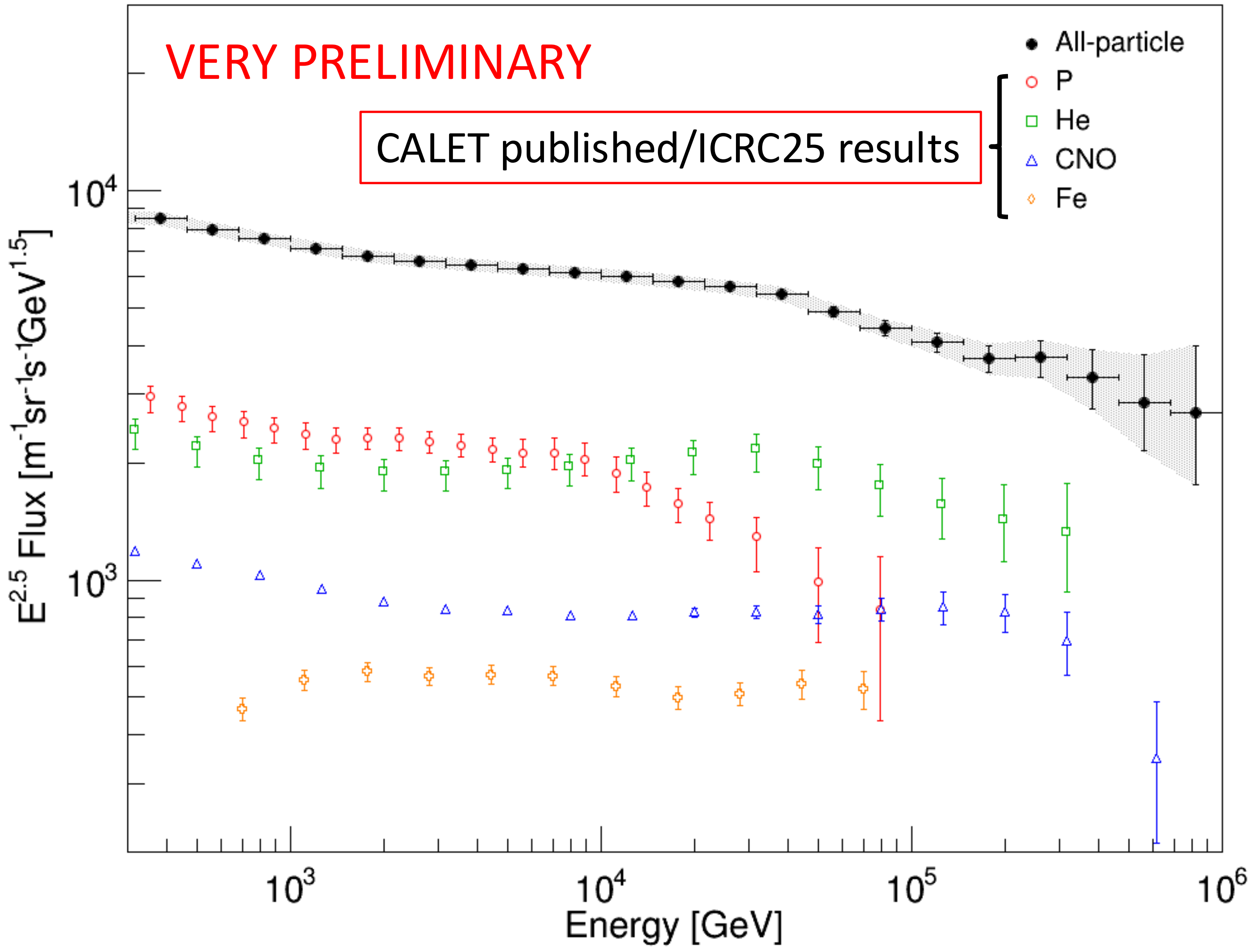

MC events are weighted to reproduce the fit results of each energy spectrum by CALET
The response matrix from MC is based on aa weighted mixture of nuclei from Z = 1 to 28

Smoothly broken-power law fit:

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



# Relative flux of observed nuclei to all-particle spectrum

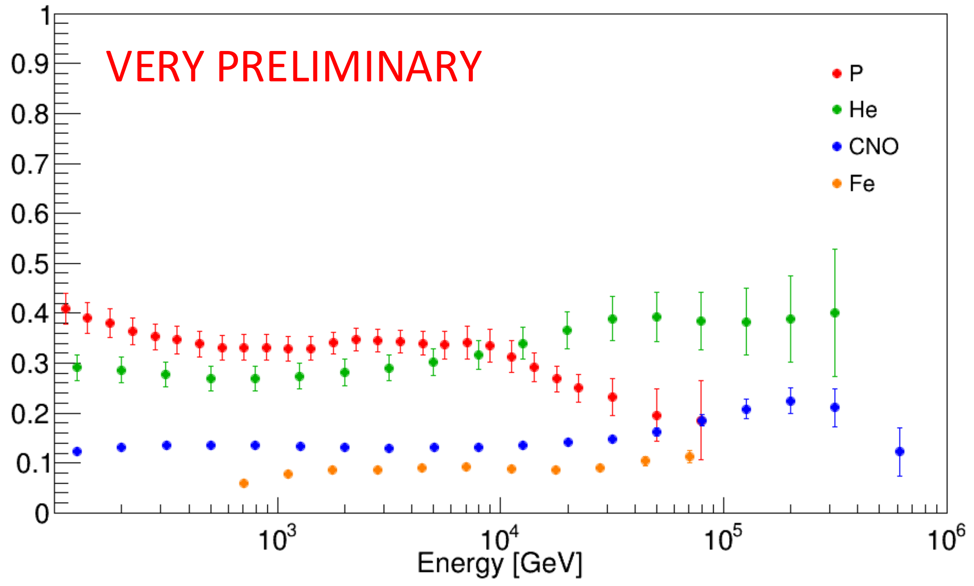



Systematic uncertainties in all-particle:

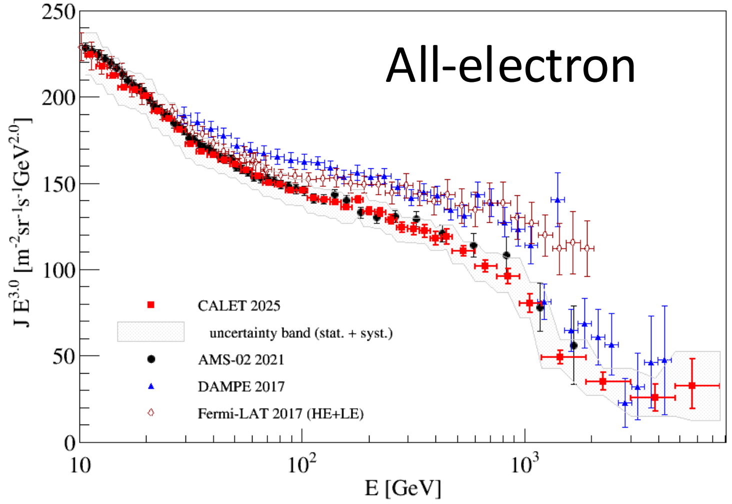
- Energy scale based on the beam test
- Live time

Further details are currently being evaluating.

Abundance flux ratio



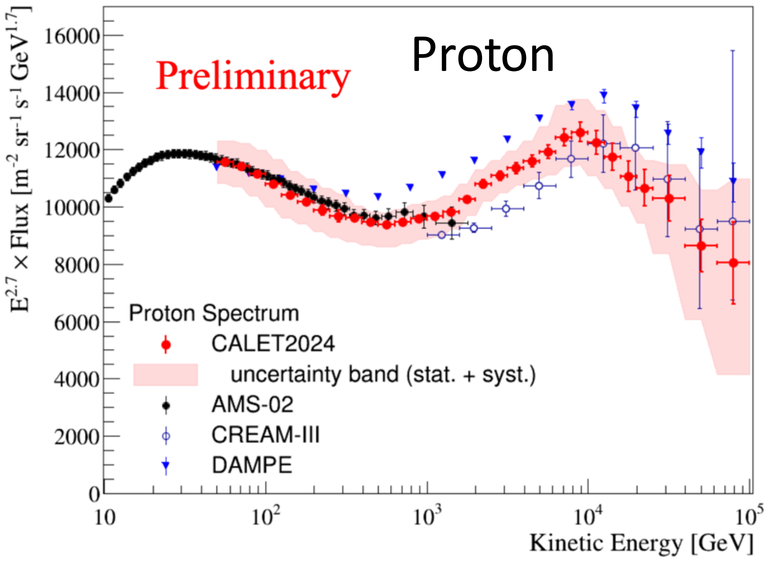
# Absolute normalization puzzles

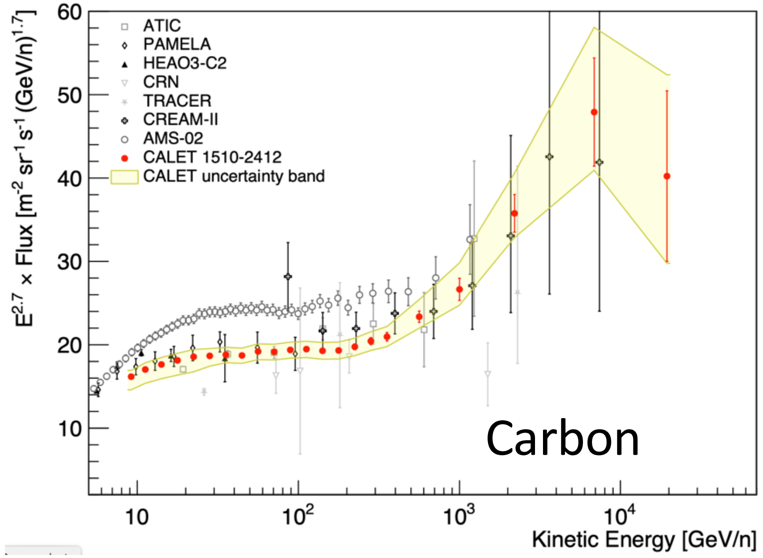


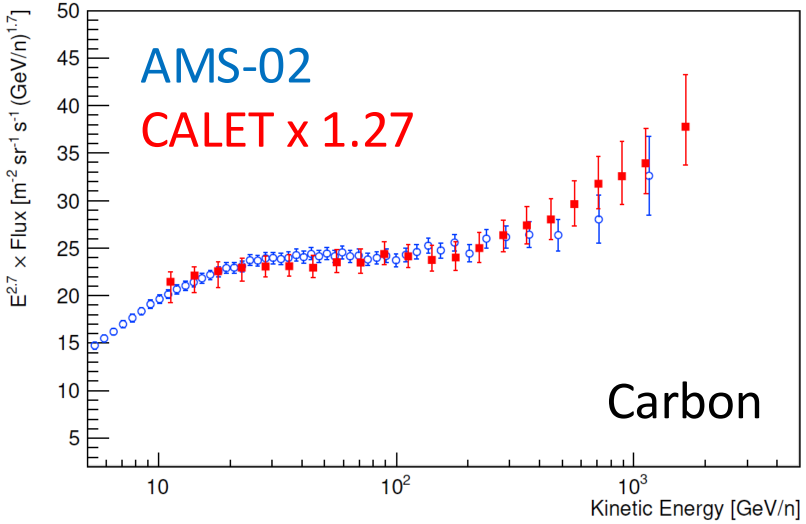

For **electron, p, He and Ni,**
CALET data are well consistent with AMS-02 data, while DAMPE data are higher.

For **nuclei with Z =5 – 26**,
CALET data are consistent with PAMELA CREAM and etc.,
while ~25% lower than AMS-02 (and DAMPE) in the normalization.
The spectral shapes are well consistent with AMS-02

⇨ Is there any systematic issue behind the flux normalization puzzle?



# Summary

- Thanks to ~10 years of excellent performance and remarkable stability of the instrument on the ISS, the following results have been obtained:
  - B, C, N, O nuclei:
    - Clear spectral hardening at a few hundred GeV/n. Especially, $\Delta\gamma_B \sim 2\Delta\gamma_{CO}$
    - B/C and B/O show flattening at ~ 1 TeV/n, which may suggest a change of the diffusion coefficient or indicate the presence of source grammage.
    - A softening feature is observed around 100 TeV for C and O
  - Fe, Ni, and sub-Fe (Ti, Cr)
    - Fe shows hints of spectral hardening around a few hundred GeV/n
    - Fe and Ni shows the same energy dependence up to 250 GeV/n
  - All-particle spectrum
    - Measured up to 1 PeV
- Various sources of systematic uncertainty have been investigated in detail

# END

# Study on the normalization

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

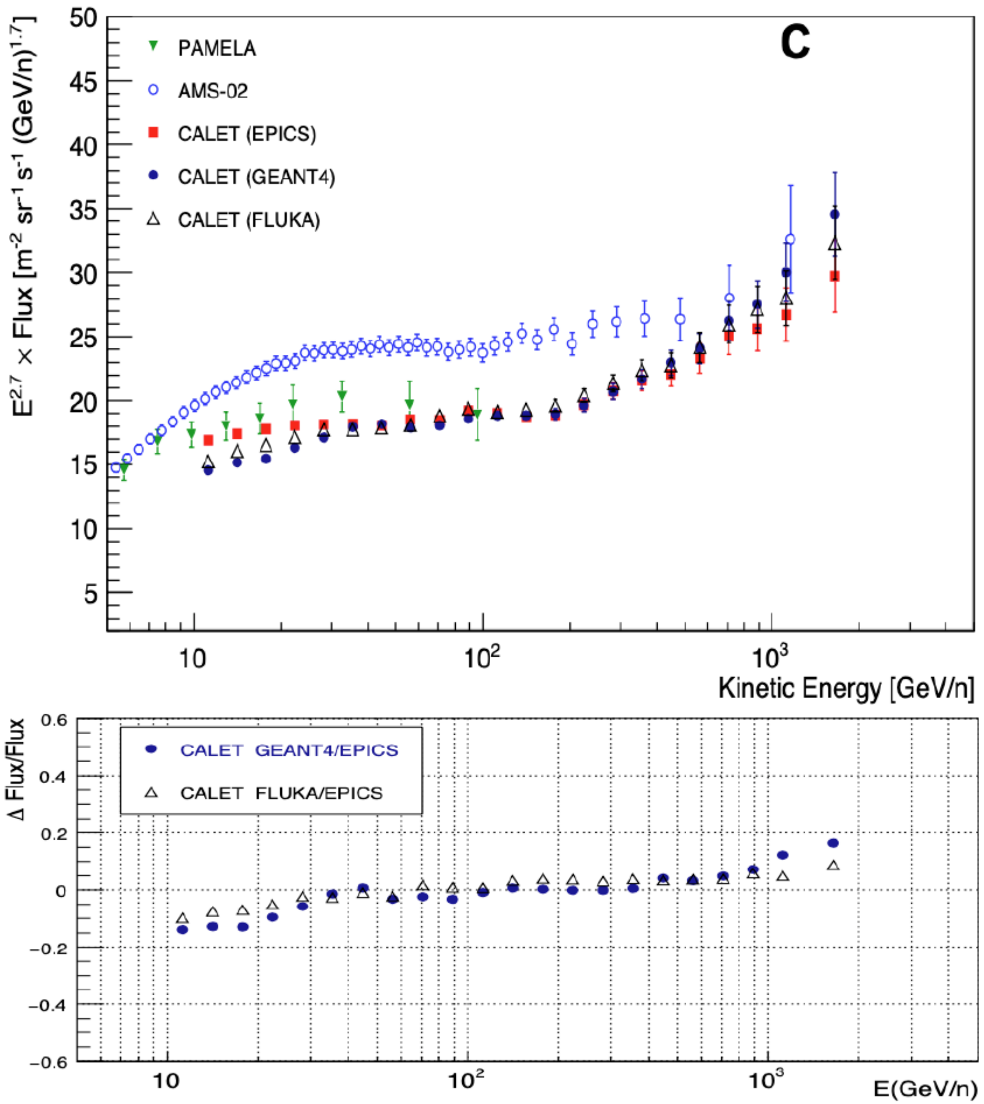
The main studies carried out to data include:

- 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

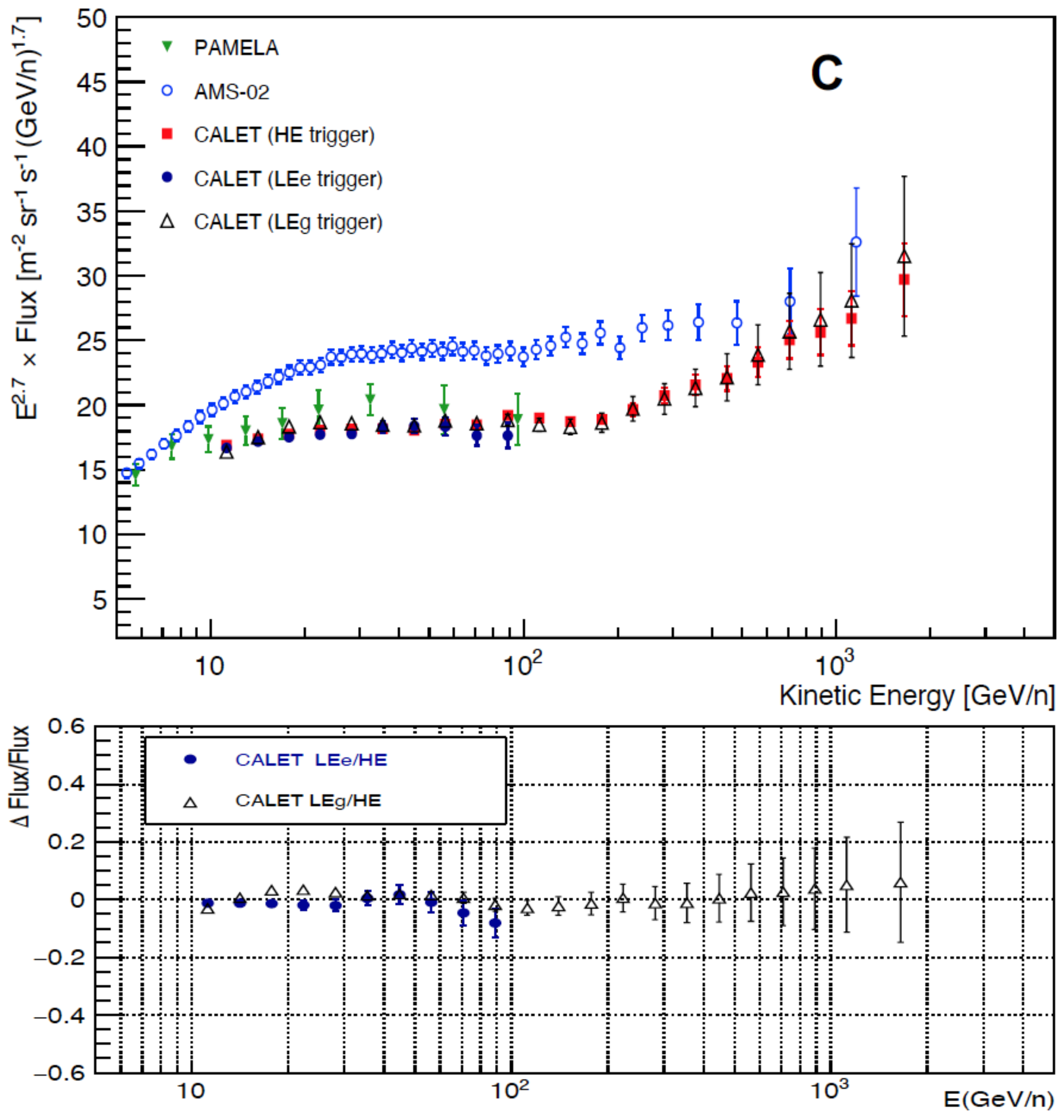
- EPICS 9.21 w/ DPMJET-III
- FLUKA 2011 2x.6 w/ DPMJET-III
- Geant4 10.5 w/ FTFP_BERT

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

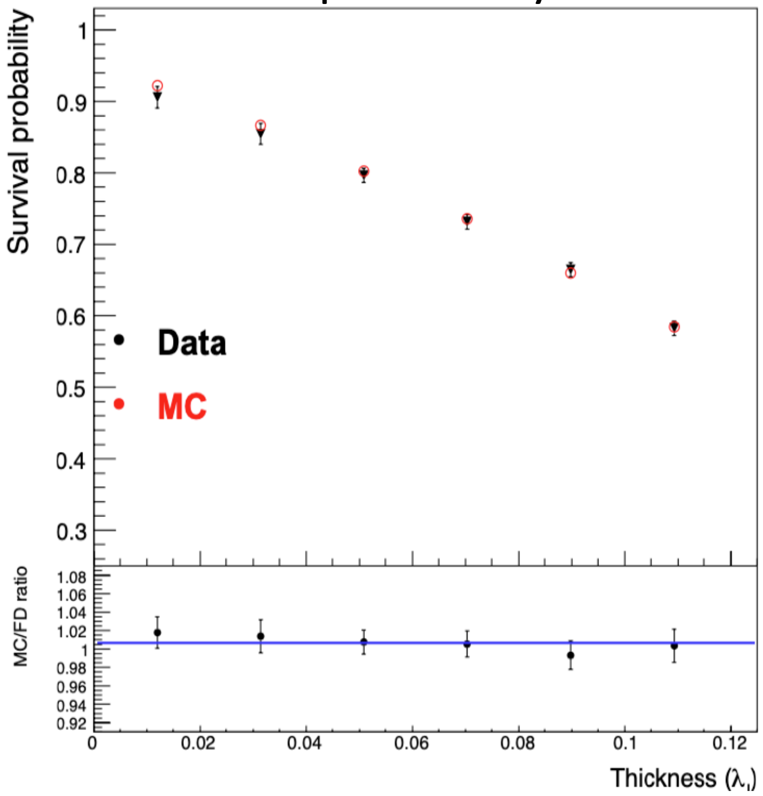
Low-energy electron (LEe) trigger

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

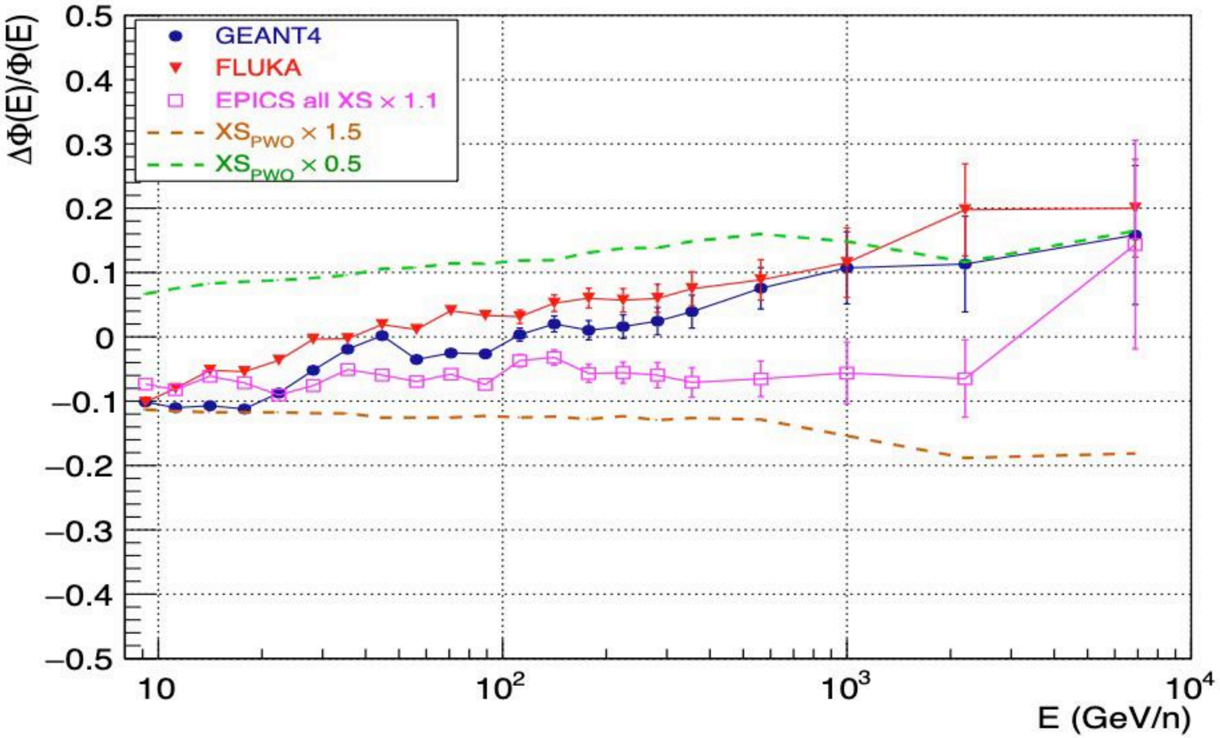
The fluxes obtained using different trigger modes show consistent normalization and spectral shapes

# Efficiency: cross-section

Survival probability in IMC




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

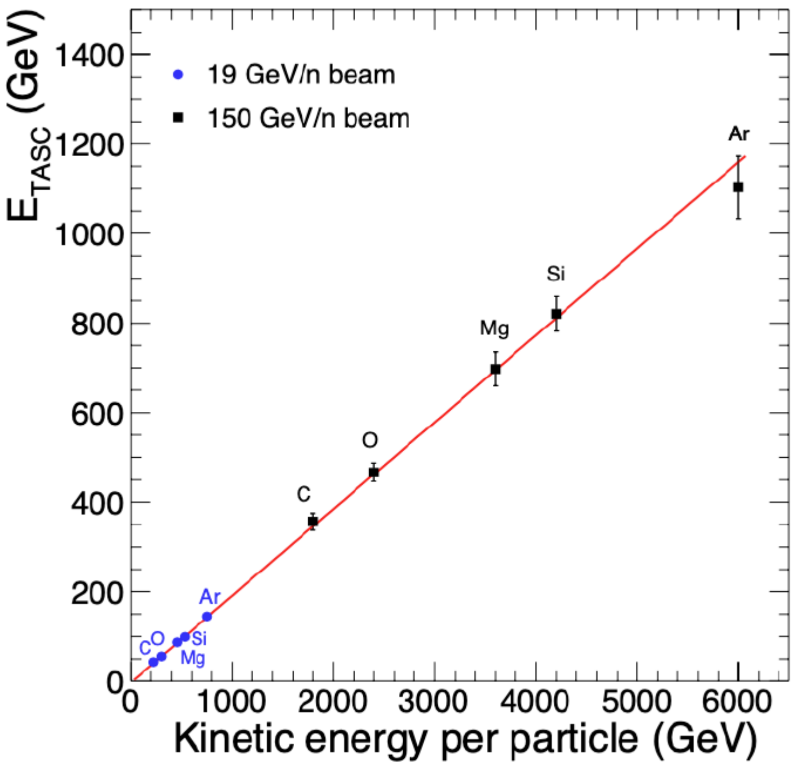


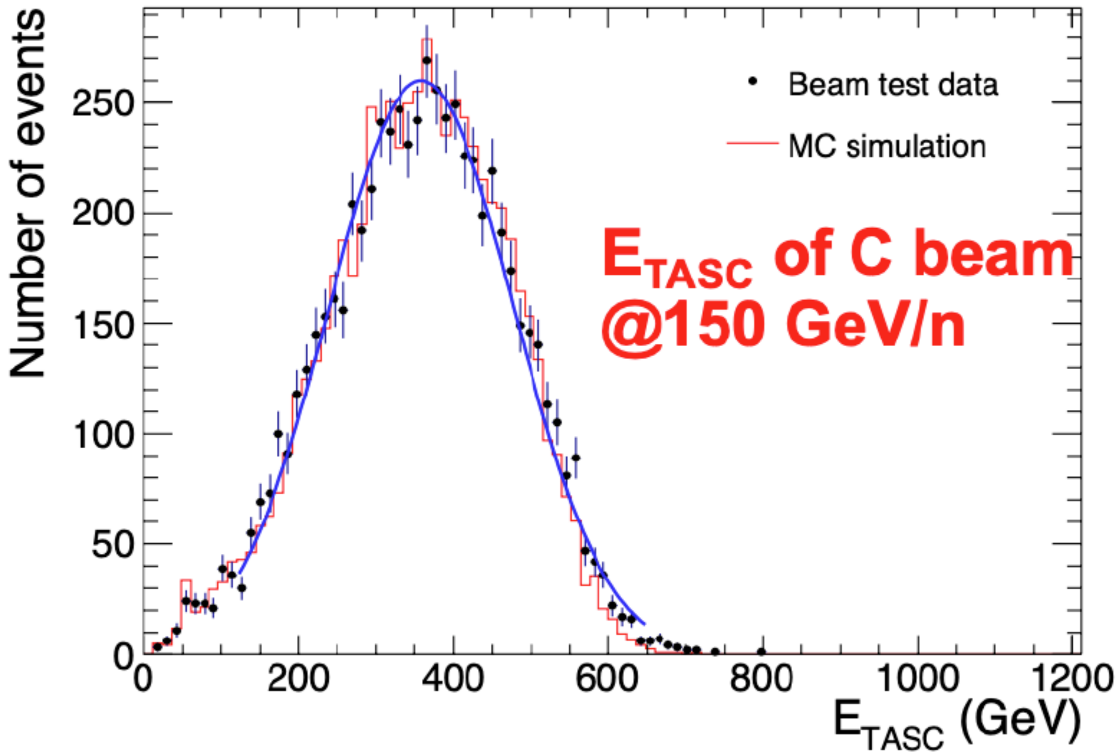

Comparison of spectra obtained different MC simulations: EPICS (reference), FLUKA, Geant4

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.

# Spectral analysis (SBPL fit)

Smoothed broken power law

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