CALETによる鉄とニッケルの エネルギースペクトルとB/C比の観測

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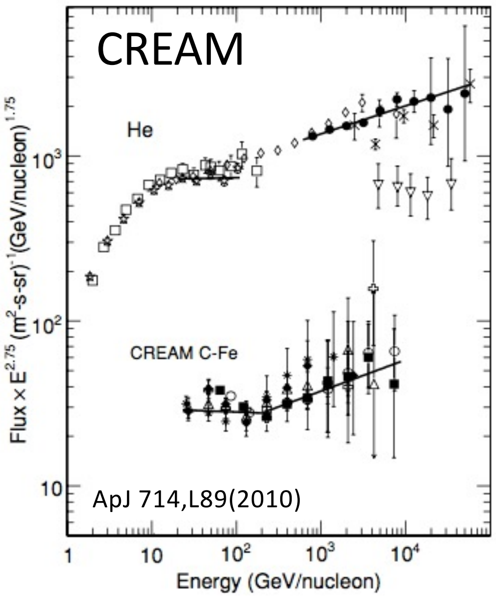
Nuclei observation with CALET

”Standard” model of galactic cosmic rays

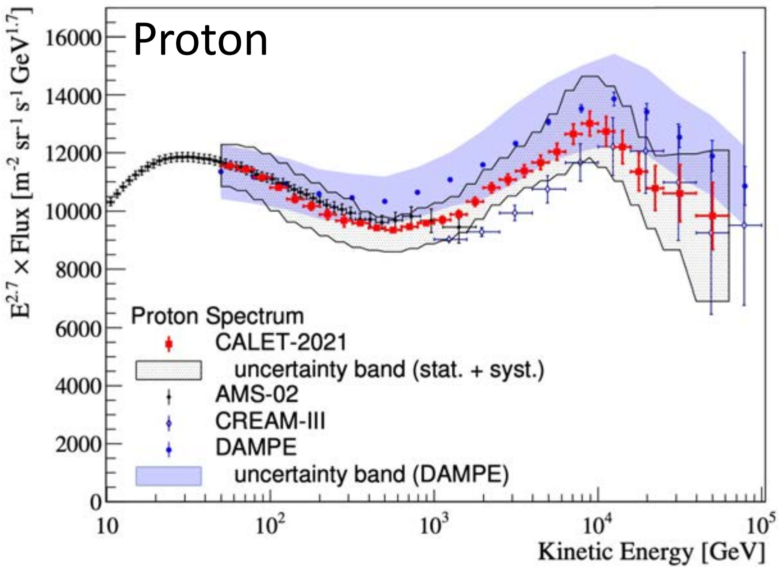
- Diffusive shock acceleration via supernovae remnant
- Diffusion propagation in our Galaxy
  - Same power law spectra for all primary cosmic rays (dN/dE ∝ $E^{-\gamma-\delta}$)
  - Acceleration limit proportional to the charge (Ec ∼ 100ZTeV), etc.

Unexpected observation results

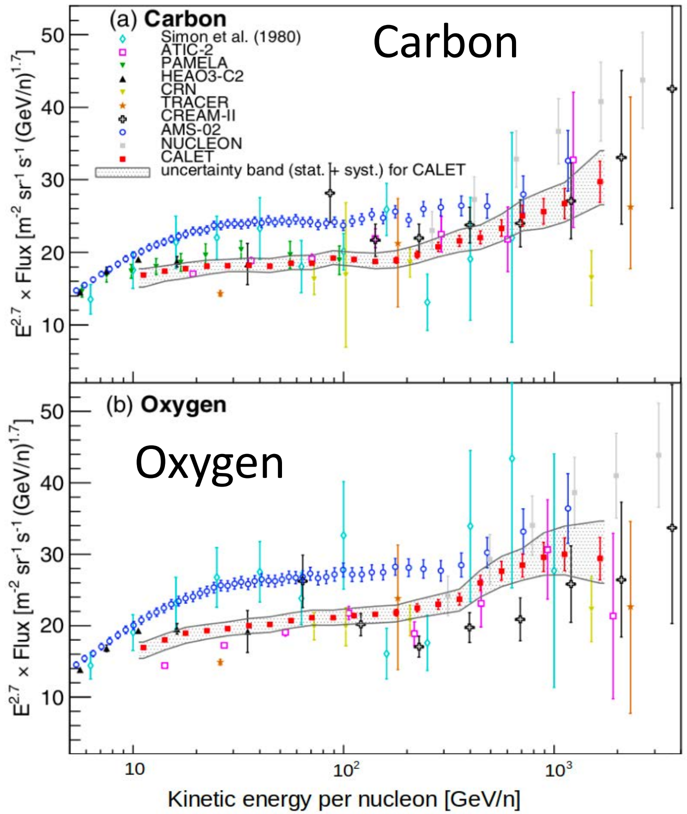
- Spectra of proton and nuclei break at R~600GV



PRL 129 101102 (2022)



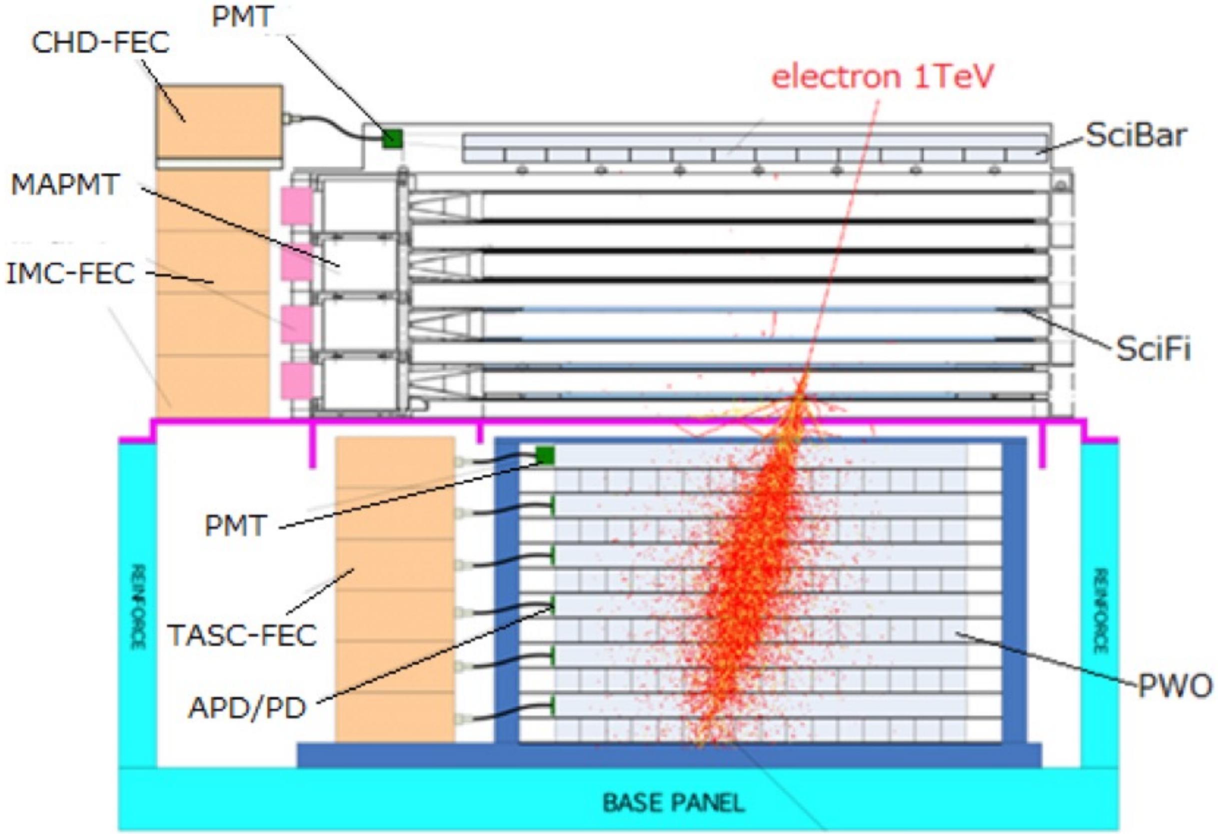
PRL 125 251102 (2020)



Detector for nuclei measurements

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

Since the start of operation on the ISS in October 2015,
CALET has been accumulating scientific data without any major interruption



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 = 0.15 for C, 0.30 for Fe

IMC: Imaging Calorimeter

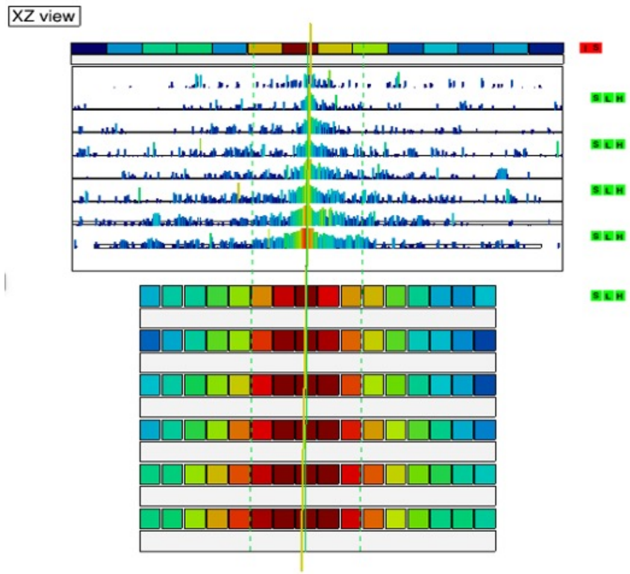
Arrival direction, Particle ID
- Scintillating fiber belts 448 x 16 layers
  Unit size: 1 mm^2 x 448 mm
- Tungsten plates 7 layers
  3 X_0 (=0.2 X_0 x 5 + 1.0 X_0x 2)
  ΔX at CHD = 200μm, ΔZ/Z = 0.20 for C

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

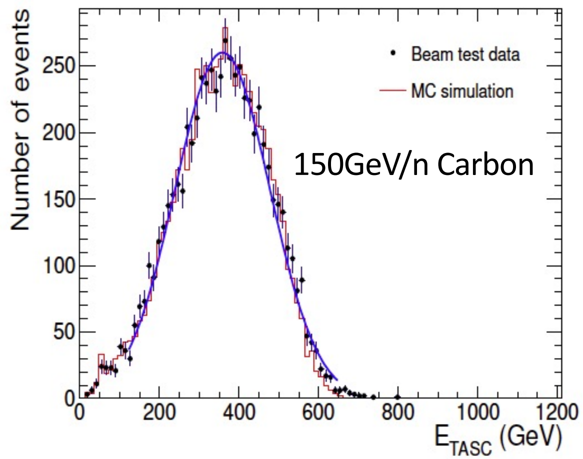
An example of Fe event, E_{TASC}=4TeV



Event selection;

1. High energy shower trigger
   Fe: 1,613 days
   Ni: 2,038 days
2. Shower event selection
   E_{TASC} at the top 4 layers > E_{MIP}
3. Track reconstruction with IMC
4. Acceptance cut
   Fe: CHD and TASC within 2cm from the edge
   Ni: CHD and TASC (looser condition to enhance statistics)
5. Charge consistency cut
   remove charge-changing particles interacting in the CHD
6. Charge selection

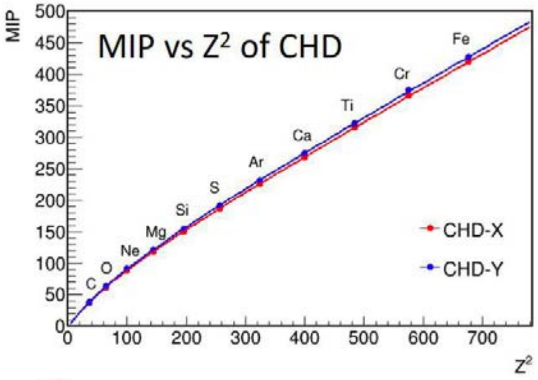
Energy distribution with beam test



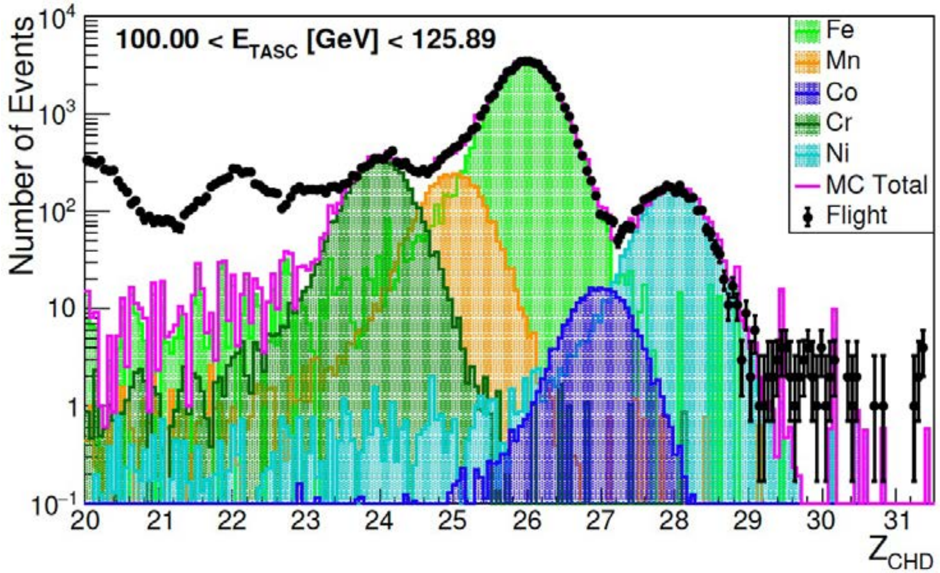
MC Simulations

- EPICS with DPMJET-III
  FLUKA(DPMJET-III) and Geant4(FEFP-BERT) are also used
  Accuracy of the MC was tested by beam test at CERN-SPS

Charge identification



Non-linear response to Z^2 due to the quenching effect in the scintillator is corrected

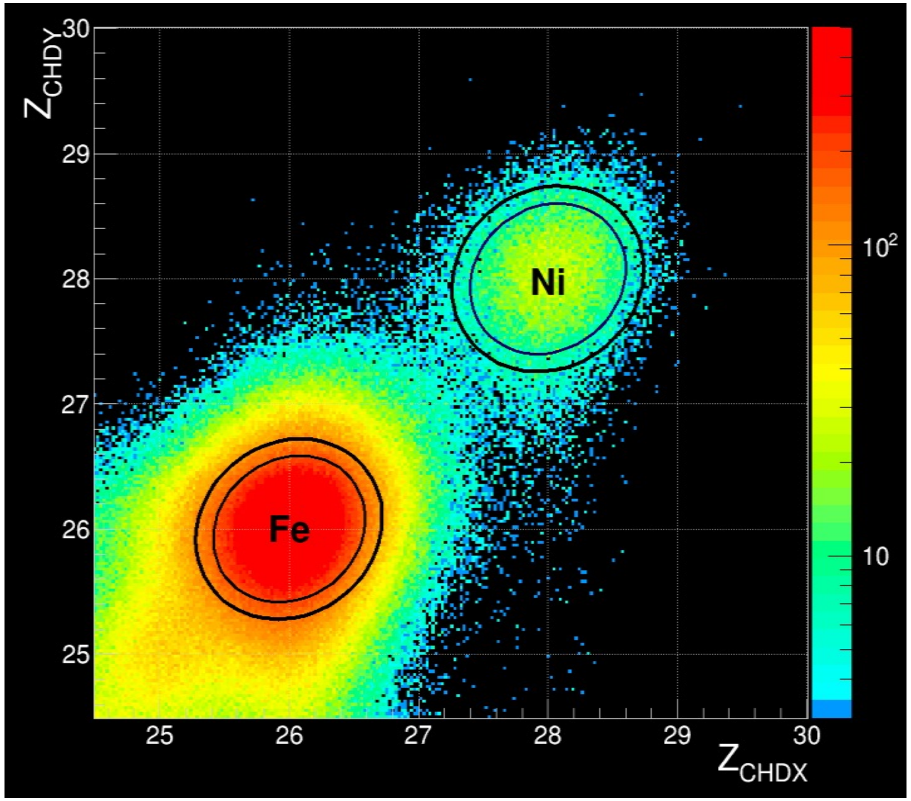


To remove background events interacting in CHD, a charge consistency cut is applied;

|ZCHDX – ZCHDY| < 1.5

Charge resolution σ_Z for iron(nickel) is 0.35*e*

Correlation between Z_{CHDX} and Z_{CHDY}

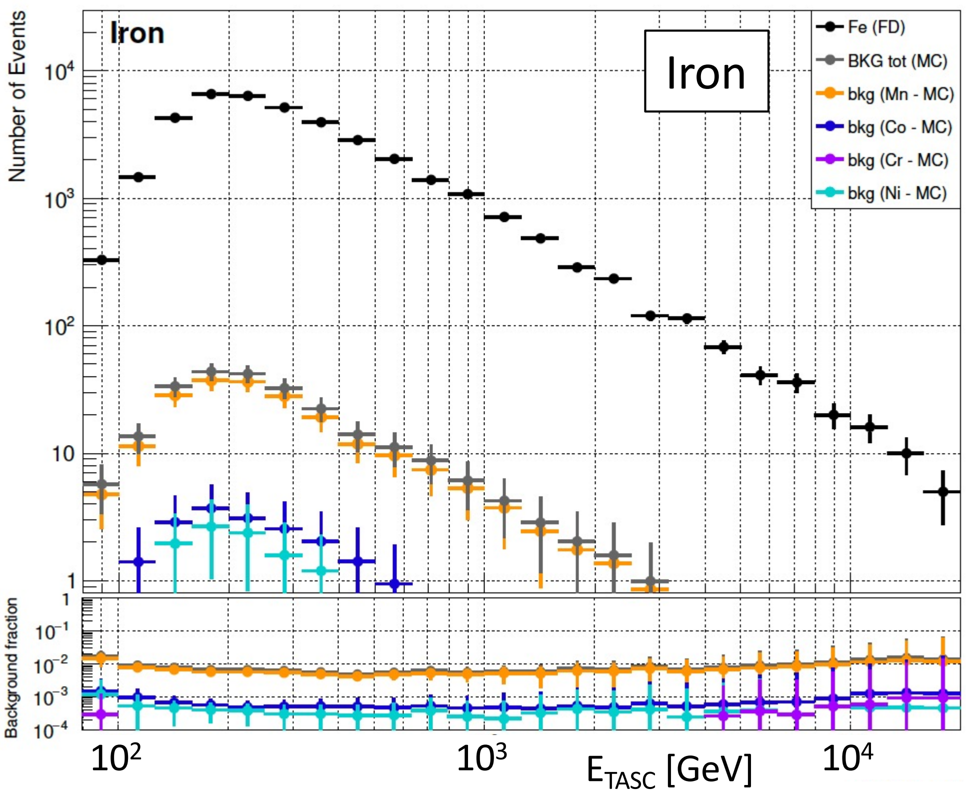


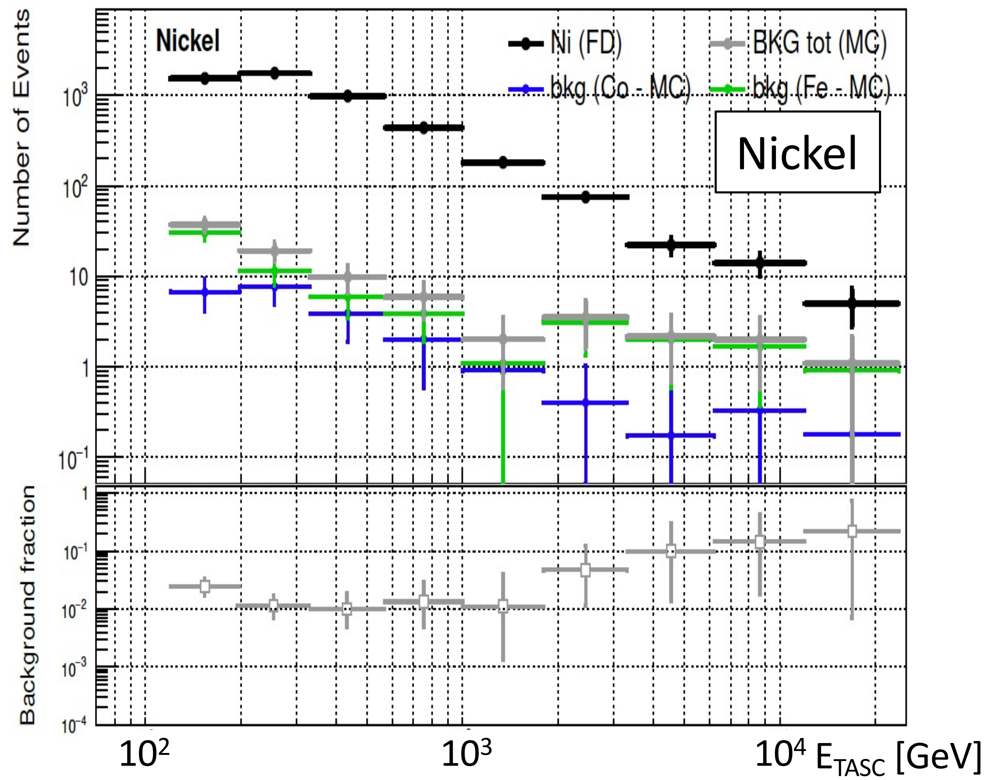
Iron (nickel) events are selected within an ellipse centered at Z=26(28), with 1.25 σ (1.4σ) wide semiaxes for Z_{CHDX} and Z_{CHDY} respectively, and rotated clockwise by 45°

dN/dE and background for Fe and Ni

The number of contaminating events is estimated by MC simulations
The total contamination is subtracted from the selected sample before doing the unfolding:

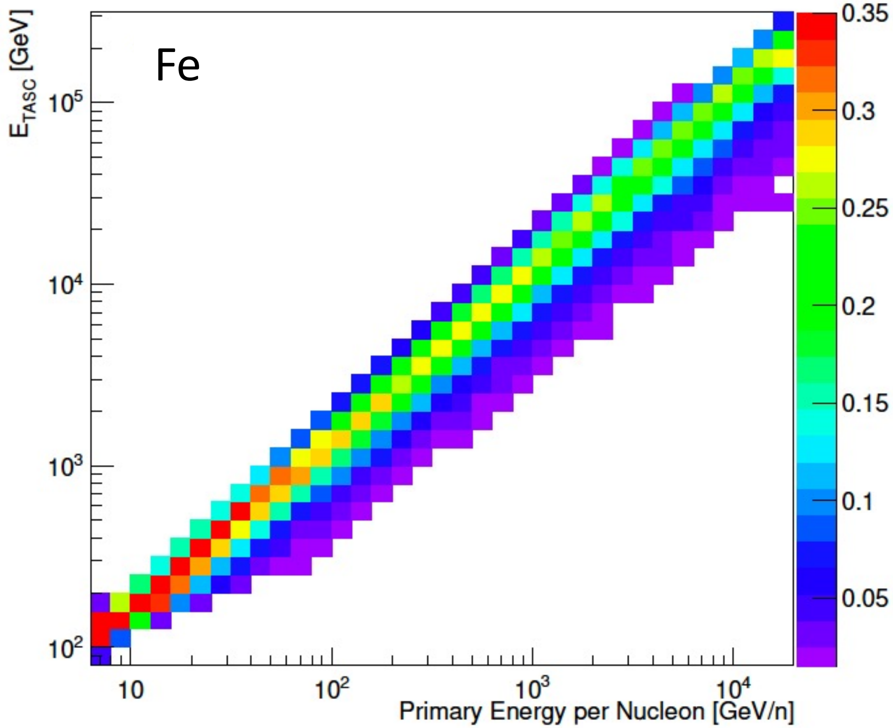
- N_{bg} for Fe: a few %
- N_{bg} for Ni: ~10%

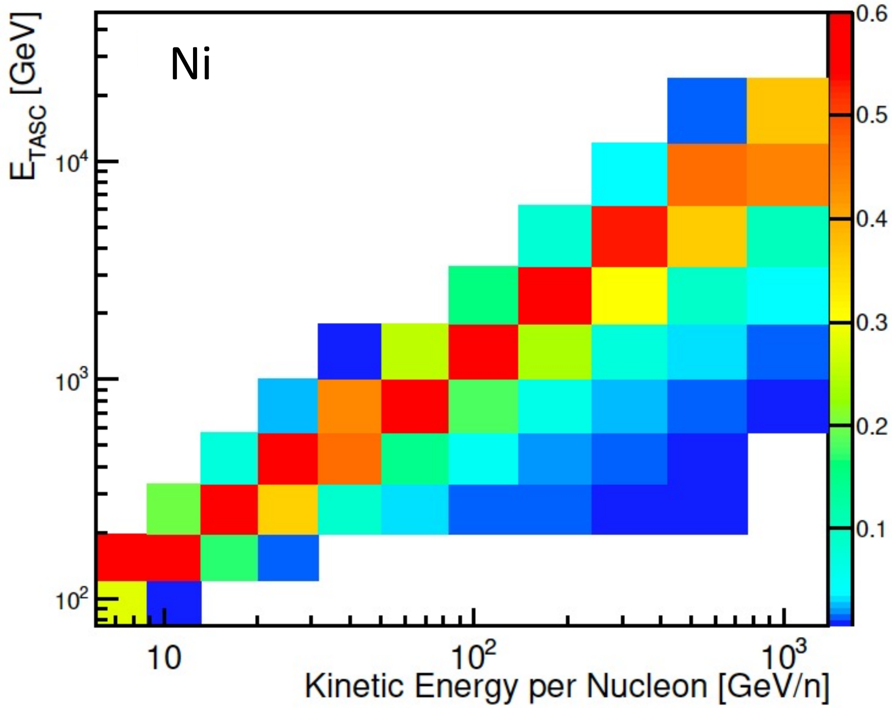




Energy unfolding

Energy unfolding is applied to correct bin-to-bin migration effect and obtain the primary energy spectrum. ΔE/E ~ 35%
The smearing matrix is computed using EPICS.
The unfolding is performed by an iterative method based on the Bayes theorem.





The flux measurement

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

$$N(E) = U[N_{\text{obs}}(E_{\text{TASC}}) - N_{bg}(E_{\text{TASC}})]$$

ΔE_i: energy bin width

$\varepsilon(E)$: efficiency

$S\Omega$: geometrical factor

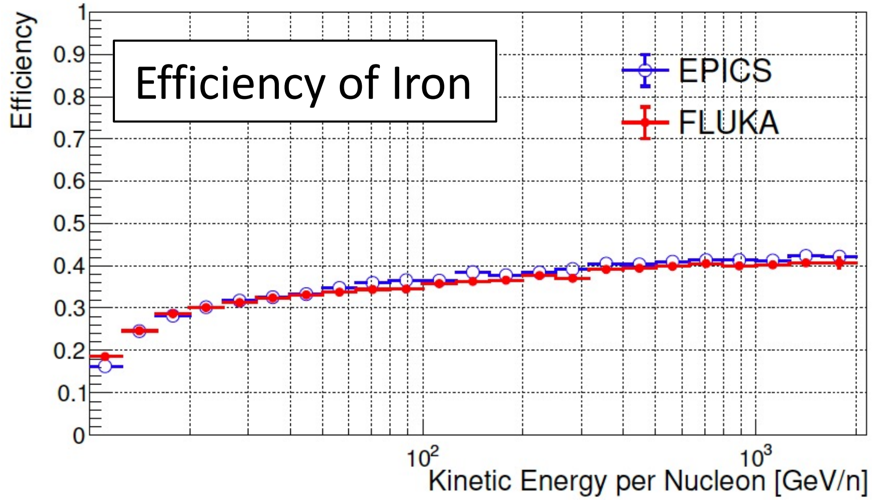
(Fe) 416 $cm^2 sr$

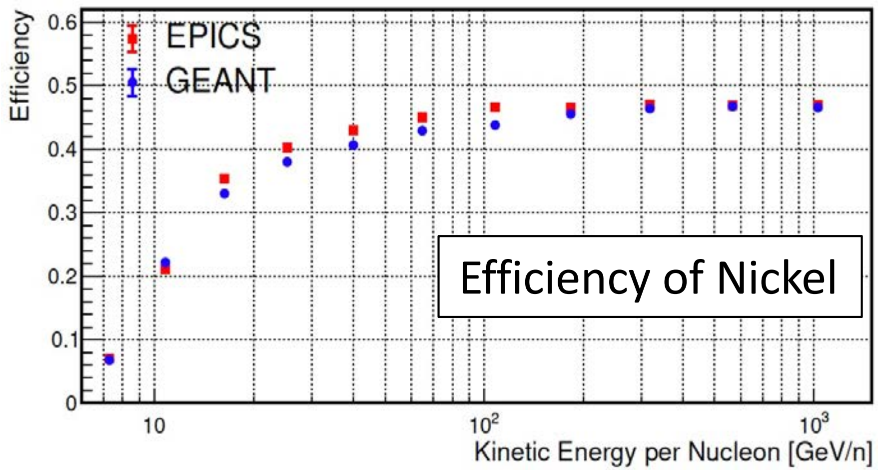
(Ni) 510 $cm^2 sr$

T: livetime

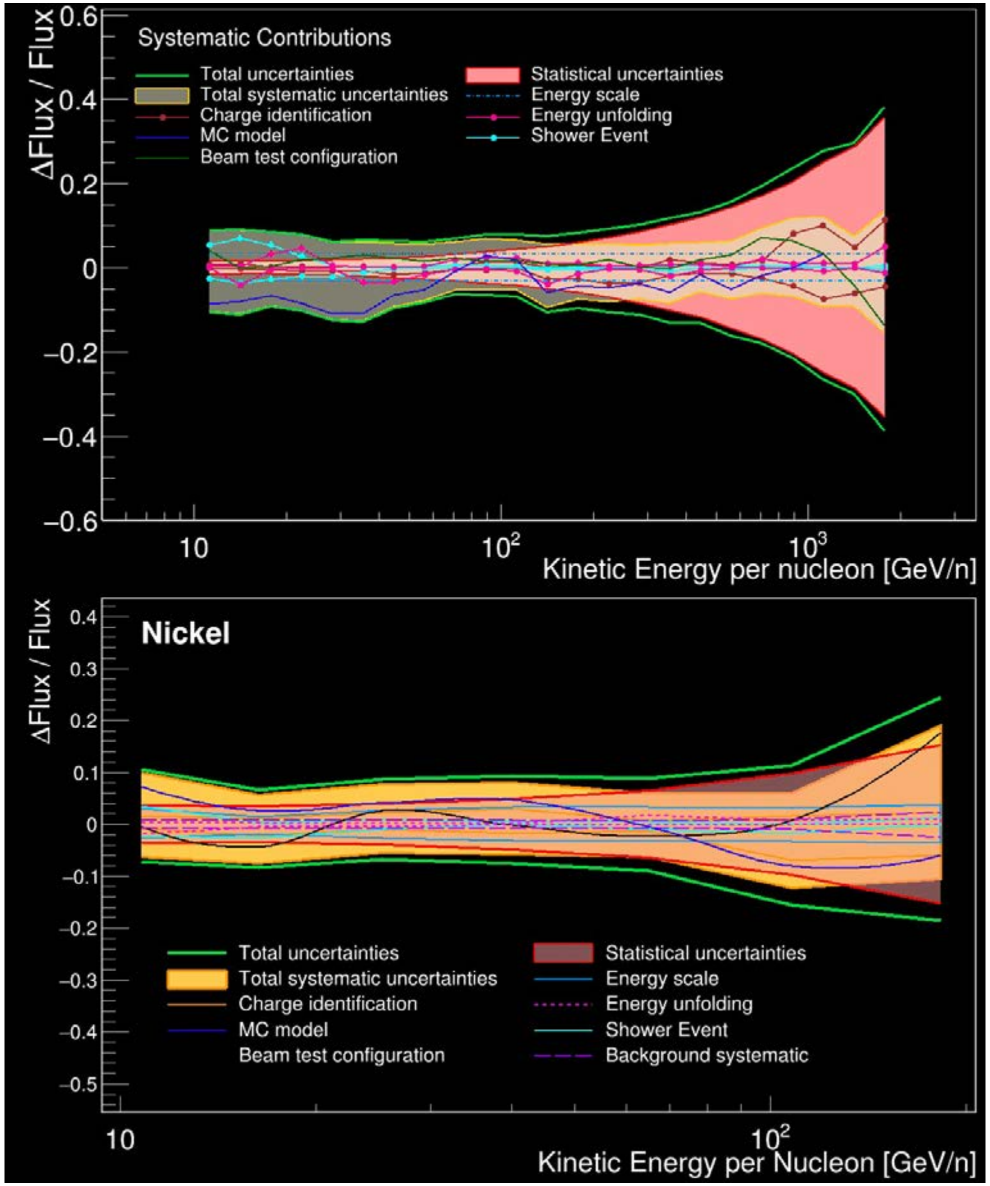
$N_{\text{obs}}(E_{\text{TASC}})$: # of observed events

$N_{bg}(E_{\text{TASC}})$: # of estimated background





Systematic uncertainties

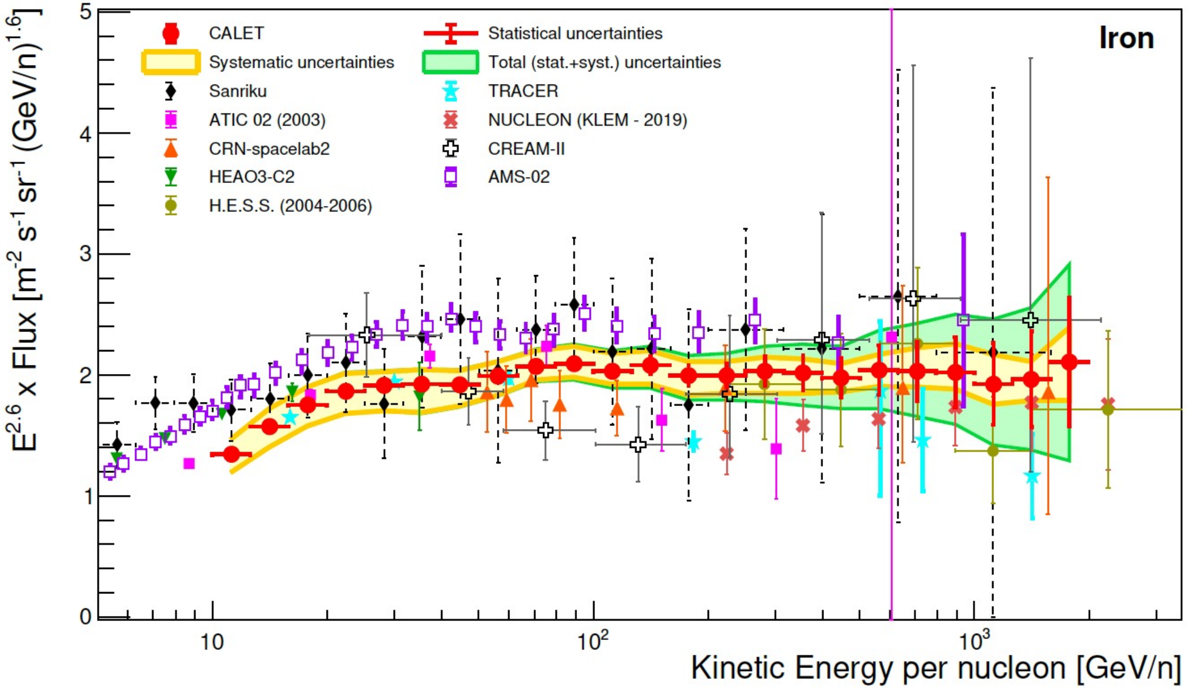


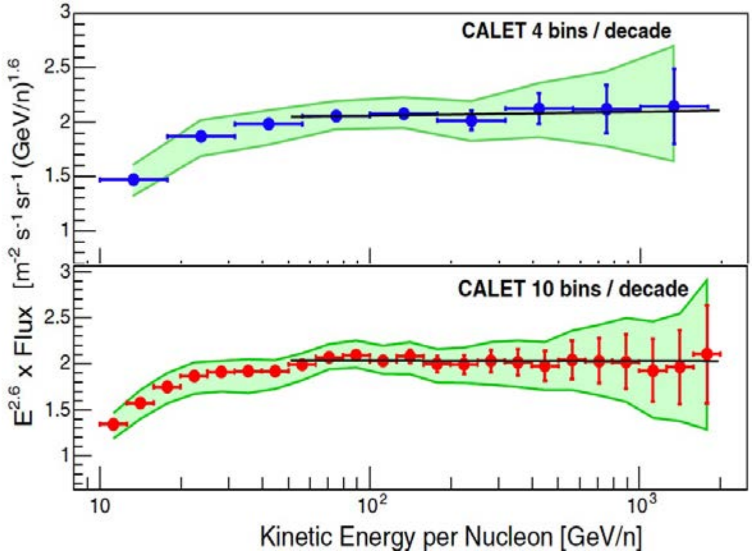
Energy dependent:
- Charge identification
- Energy scale correction
- Beam test configuration
- MC model
- Shower event
- Energy unfolding

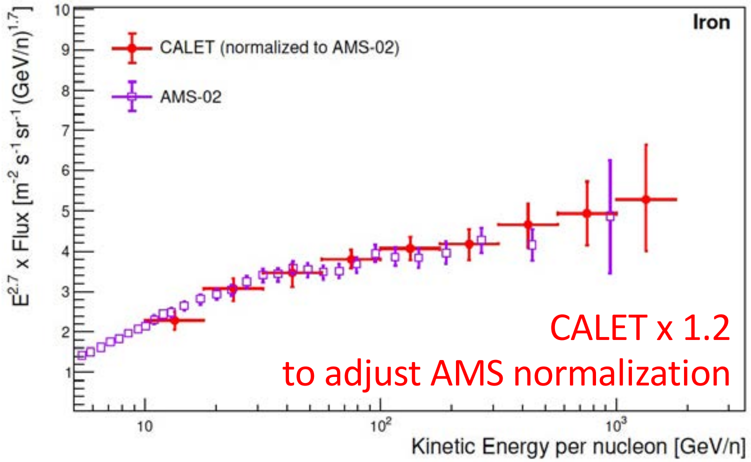
Energy Independent:
- Live time: 3.4%
- long-term stability: 2.0 – 2.7%
- Geometrical factor: 1.6%
- Isotopes composition: 2.2% (Ni only)

Iron spectrum

PRL 126 241101 (2021)



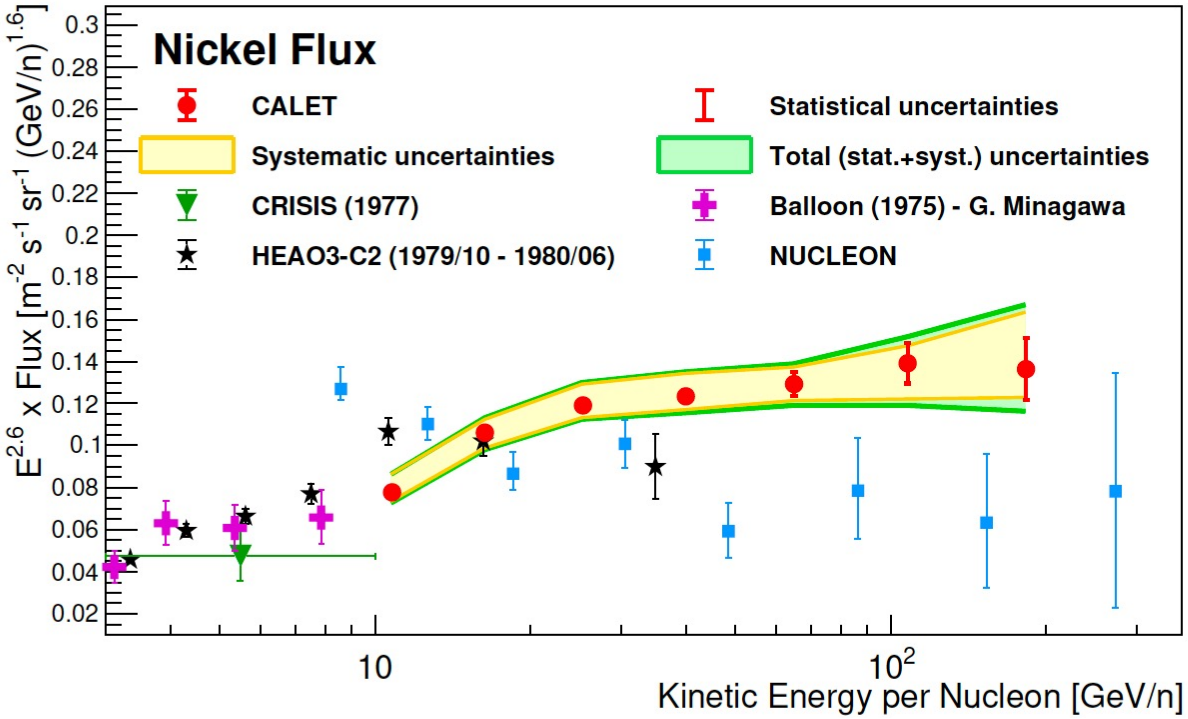


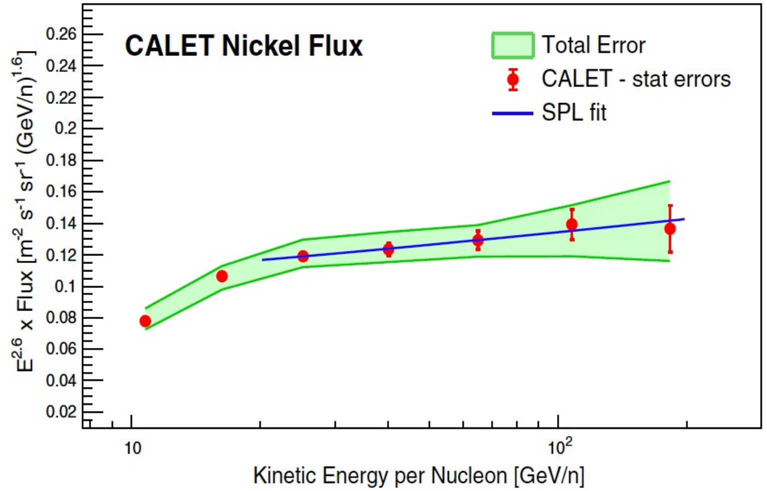


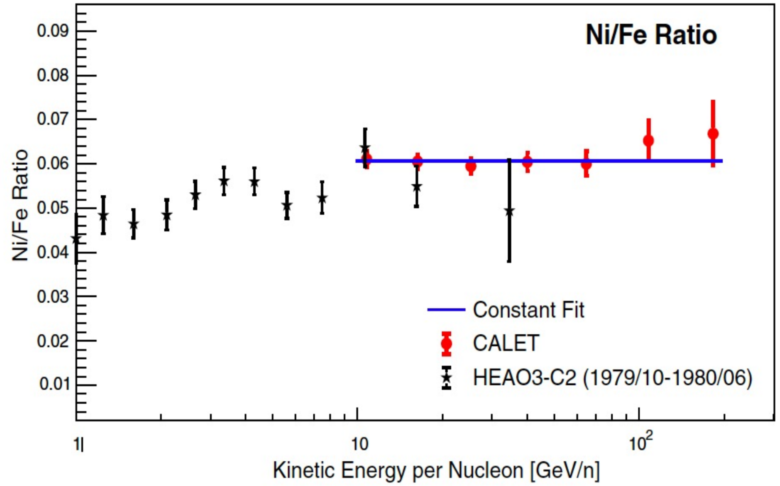
- Good agreement with ATIC, TRACER, HESS and CRN
- Normalization in tension with AMS-02
- A single power-law fit:
  γ = -2.60 ± 0.03 E > 50 GeV/n

Nickel spectrum

PRL 128 131103 (2022)



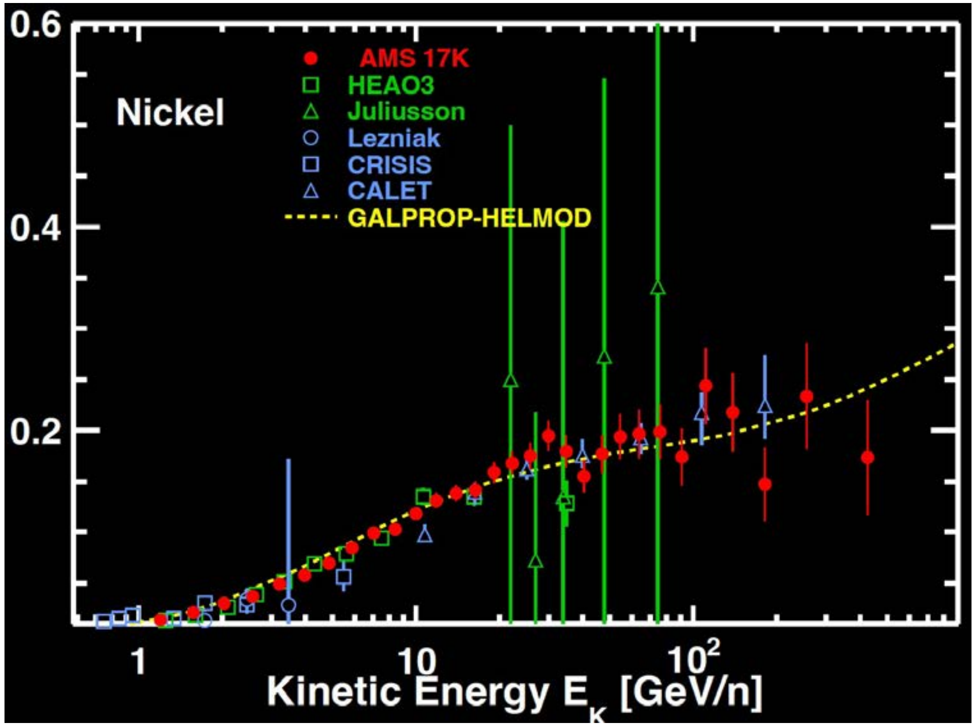


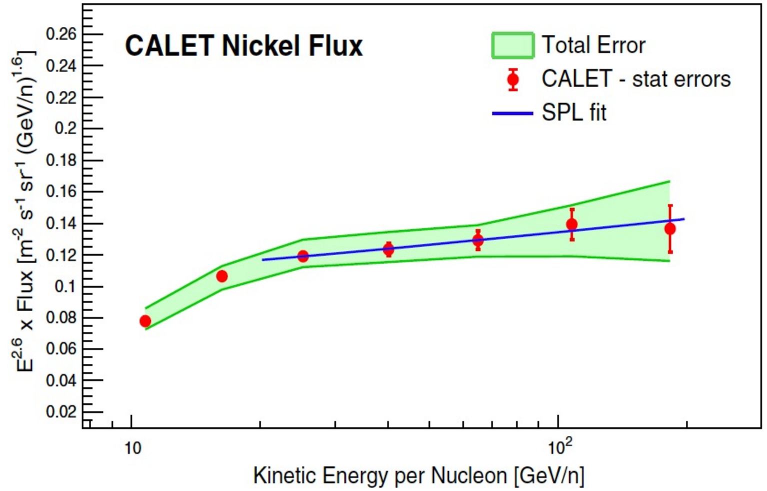


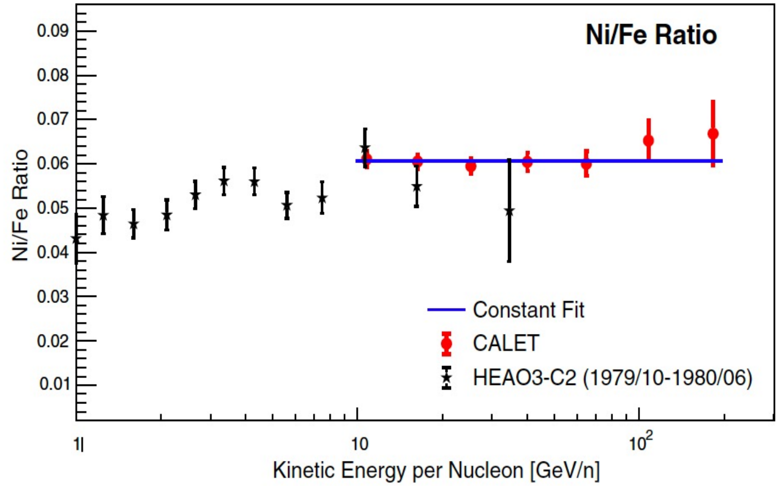
- Similar normalization with HEAO3-C2 and NUCLEON, through different spectral shape
- A single power-law fit:
  $\gamma = -2.51 \pm 0.07 \quad E > 20$ GeV/n
- Ni/Fe ratio gives a constant value;
  0.061 ± 0.001

Nickel spectrum

COSPAR 2022 (AMS Collaboration)



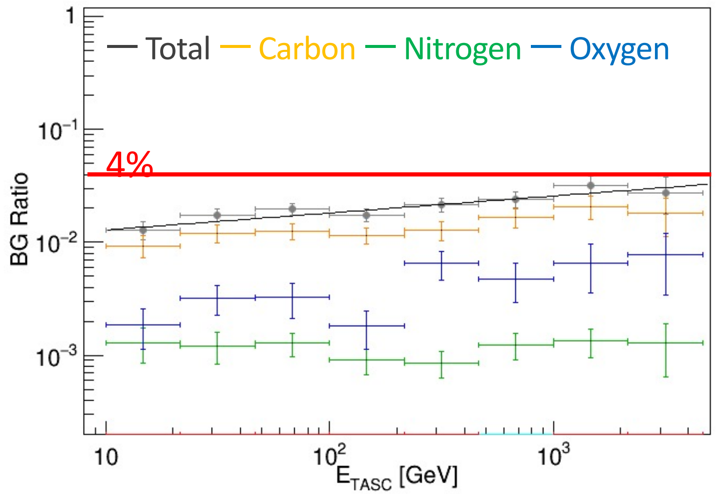


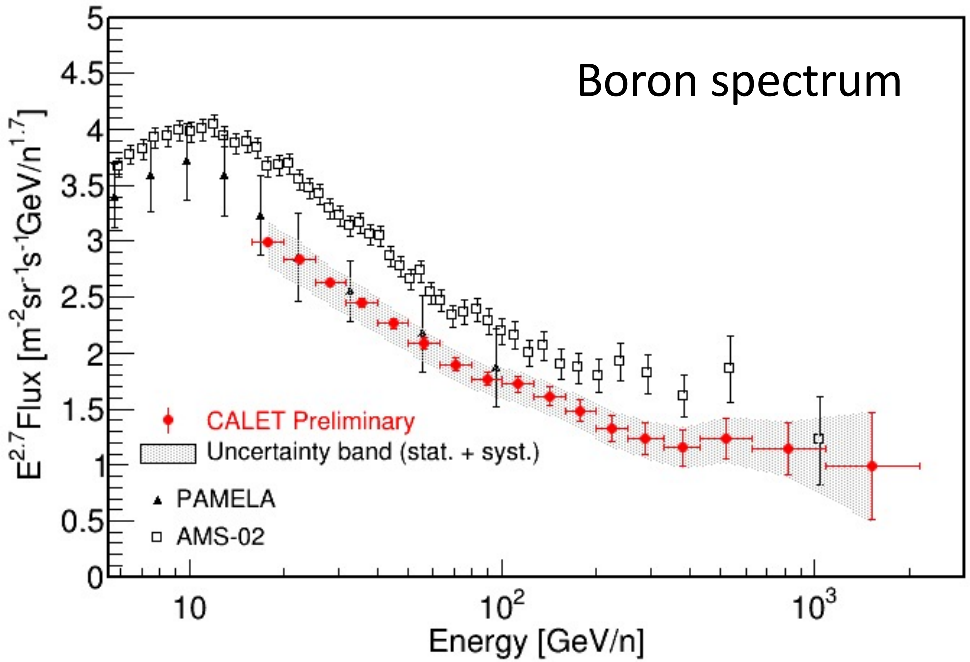


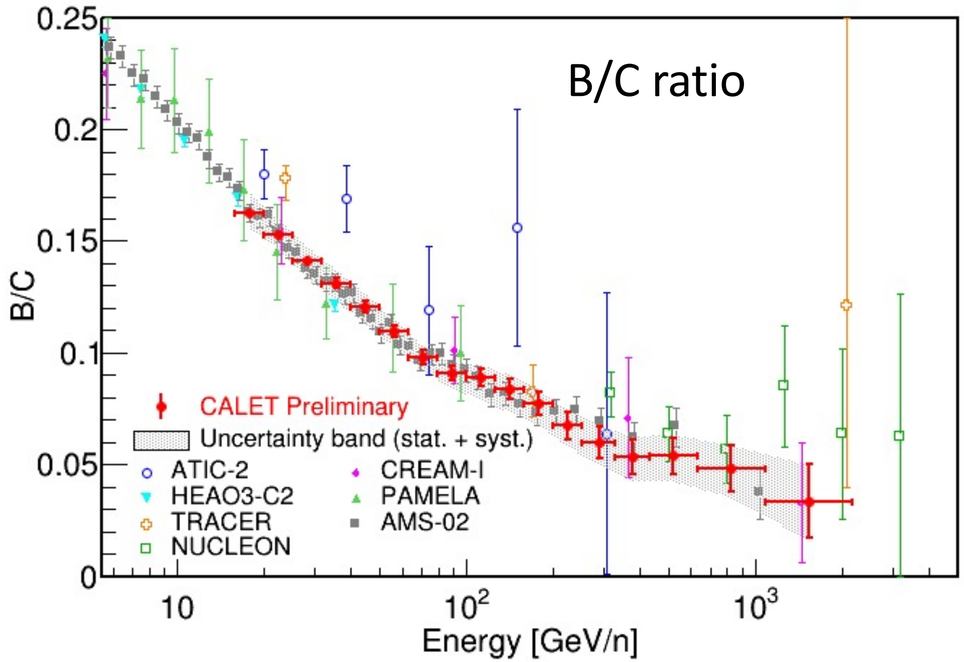
- Similar normalization with HEAO3-C2 and NUCLEON, through different spectral shape
- A single power-law fit:
  γ = -2.51 ± 0.07 E > 20 GeV/n
- Ni/Fe ratio gives a constant value;
  0.061 ± 0.001

Boron spectrum and B/C ratio

- Data period: 1,815 days
- Background for boron is less than 4%
- B spectrum is in good agreement with PAMELA, while ~20% lower than AMS-02 like C, O and Fe
- B/C ratio is in good agreement with the other results







Summary

- CALET measured iron and nickel fluxes between 10 GeV/n and 2.0 TeV/n and 8.8 GeV/n – 240 GeV/n respectively, with significantly better precision than most of the existing measurements.
  Fe: PRL 126 241101 (2021)
  Ni: PRL 128 131103 (2022)

- Above 50 GeV/n for iron and 20 GeV/n for nickel, the spectra are compatible with a single power law with a spectral index of -2.60 ± 0.03 for iron and -2.51 ± 0.07 for nickel

- The flat behavior of the nickel to iron ratio indicates that the spectral shapes of Fe and Ni are the same within the experimental accuracy, suggesting also that Fe and Ni have a similar acceleration and propagation behavior, as expected from the small difference in atomic number and wight between Fe and Ni nuclei

- The uncertainties given by our present statistics and large systematics do now allow us to draw a significant conclusion on a possible deviation from a single power law

- Preliminary boron and B/C ratio up to 2.2 TeV have been obtained