CALET5年間の観測による 炭素・酸素・鉄のエネルギースペクトルと B/C比の観測結果

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CALET5年間の観測による
炭素・酸素・鉄のエネルギースペクトルと
B/C比の観測結果

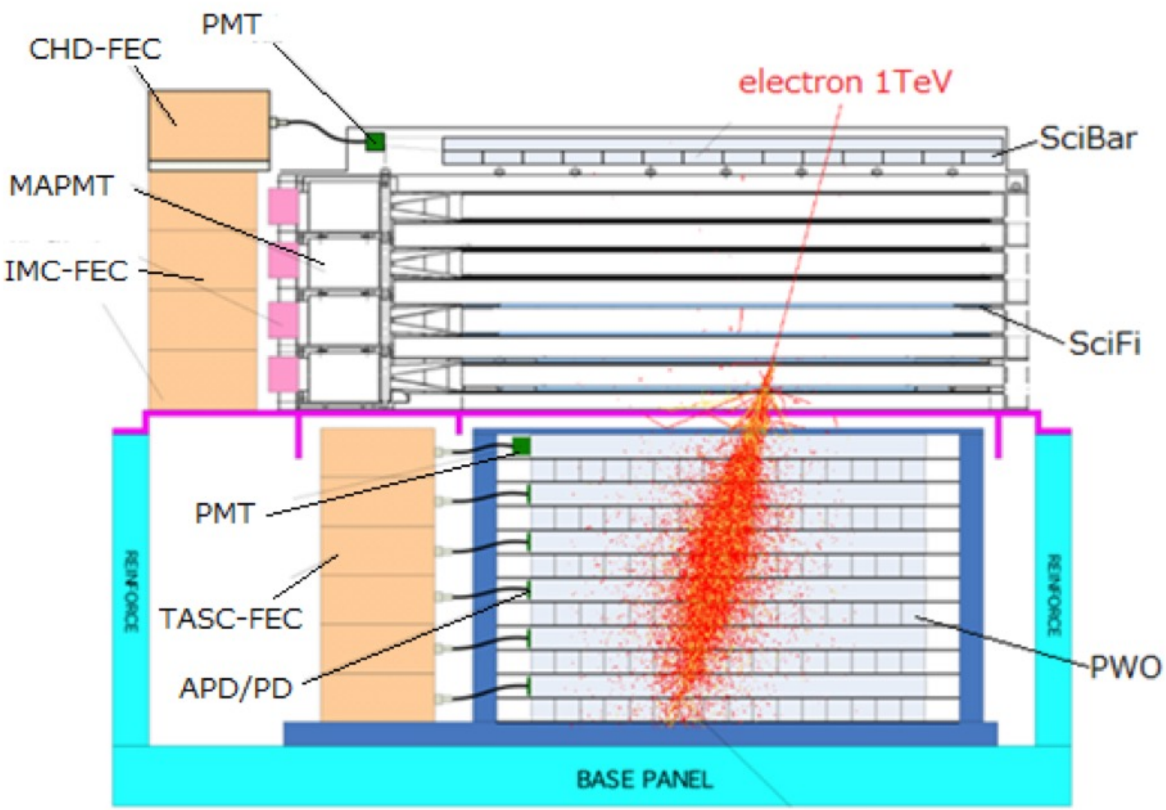
Publications:

- Carbon and oxygen
  - Phys. Rev. Lett. 125, 251102 (2020)
  - PoS (ICRC2021) 093
- Iron
  - Phys. Rev. Lett. 126, 241101 (2021)
  - PoS (ICRC2021) 109
- Boron and B/C ratio
  - PoS (ICRC2021) 112

Instrument of CALET

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
  $\Delta Z/Z$ = 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, $\Delta Z/Z$ = 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)

Data analysis for nuclei

Analyzed Flight Data

1,815 days (Oct. 13, 2015 – Sep. 30, 2020)

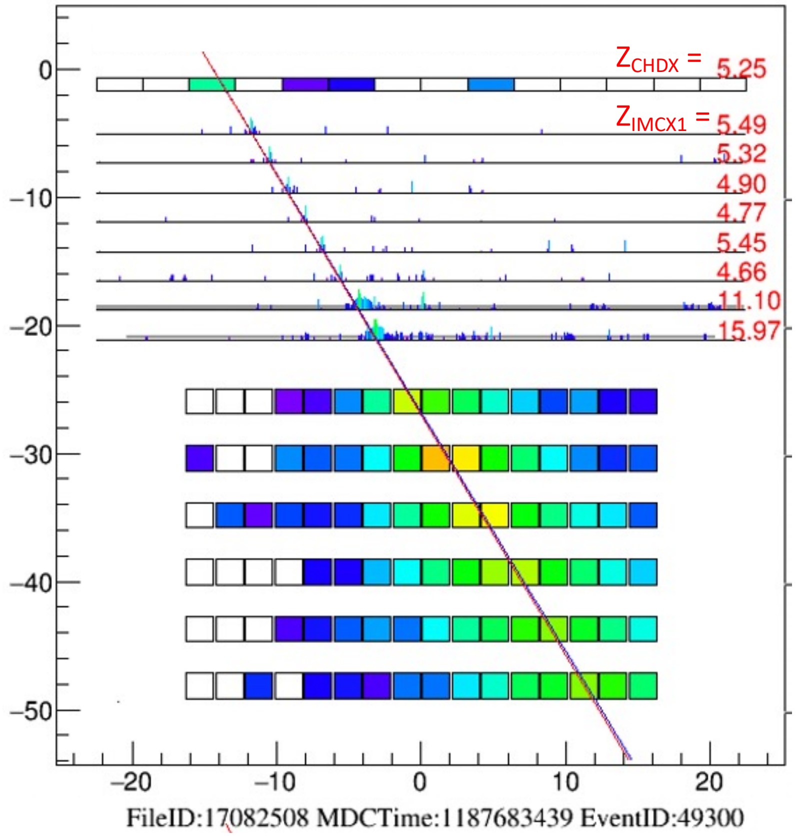
T_{live}=3.69 x 10^4 hours

Analysis procedure

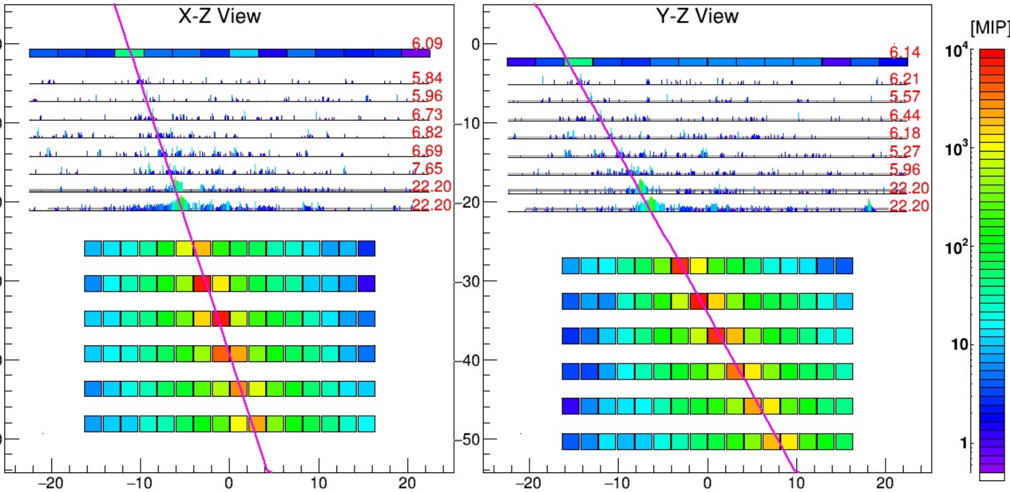
- HE + offline shower trigger
  50MIP in IMC-X/Y78, 100MIP in TASC-X1
- Tracking with IMC
- Field of view cut
  Remove shielded region by ISS structures
- Acceptance cut
  CHD, TASC top and bottom layers
- Charge identification
  Charge consistency among CHD and IMC layer
  Track width selection
- Estimate efficiency and background
- Apply energy unfolding
- Calculate flux and the ratio

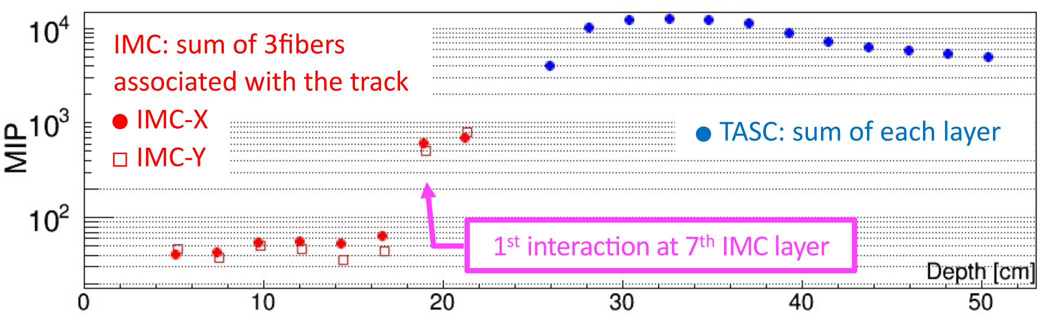
An example of Boron candidate (X-Z view)

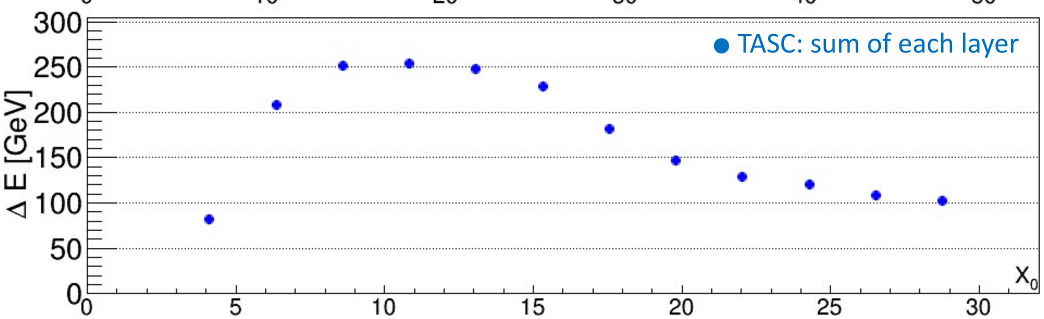
E_{TASC} = 475.8 GeV

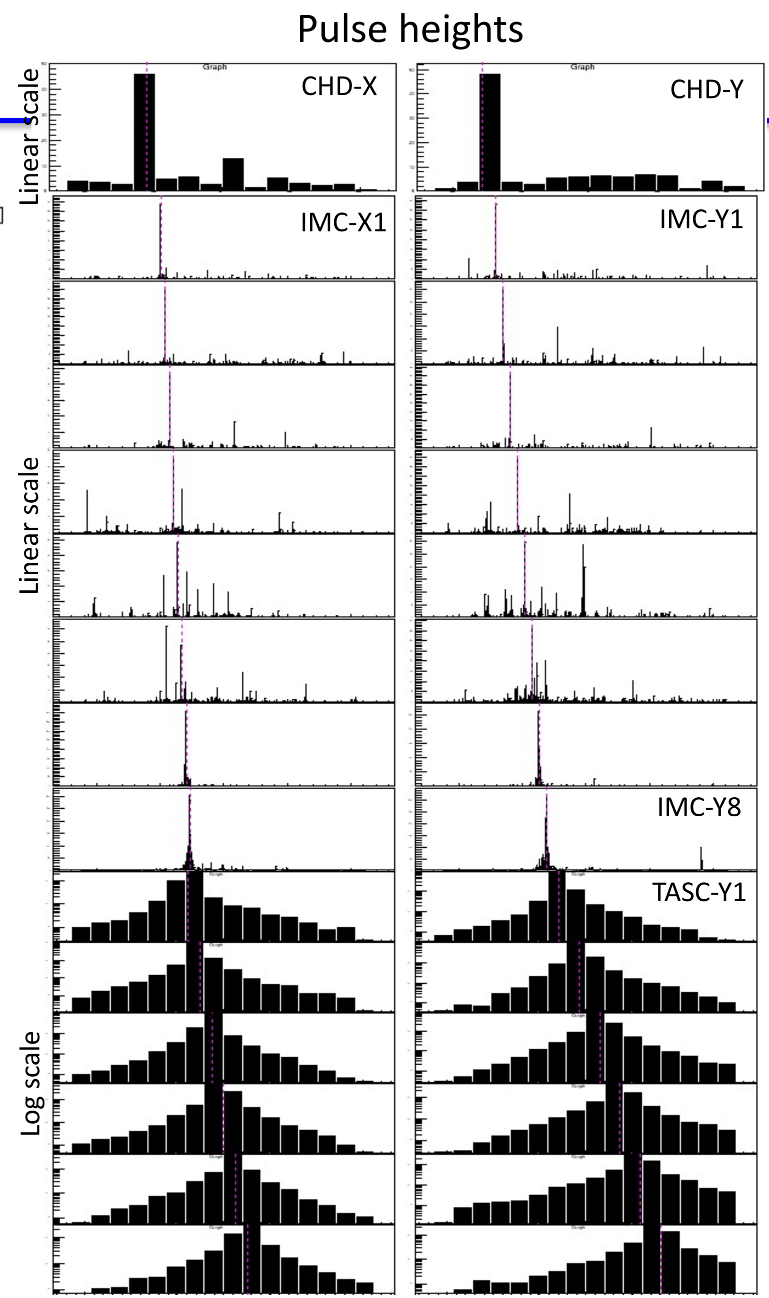


Event display: Carbon (ΔE_{TASC}=2.06TeV)









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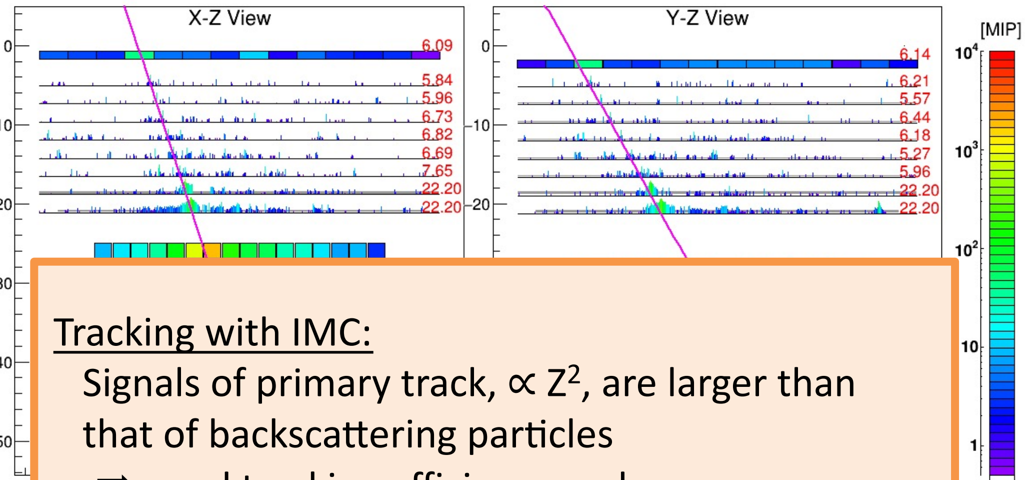
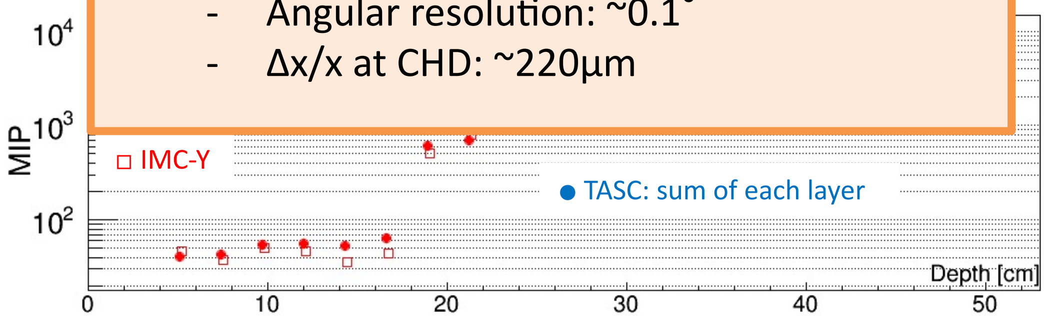


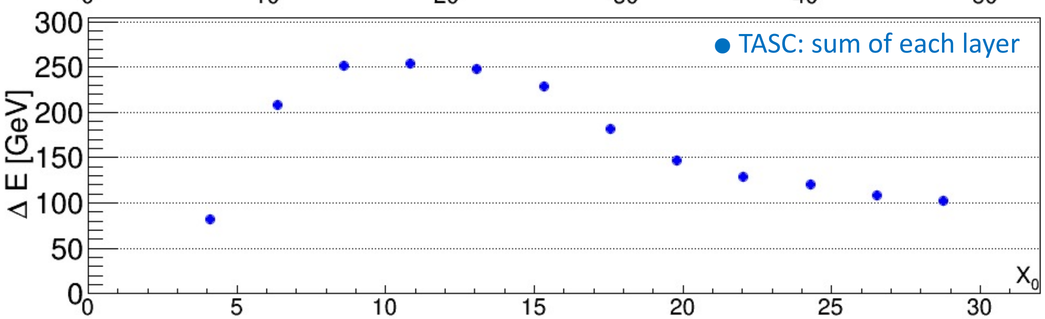
Tracking with IMC:

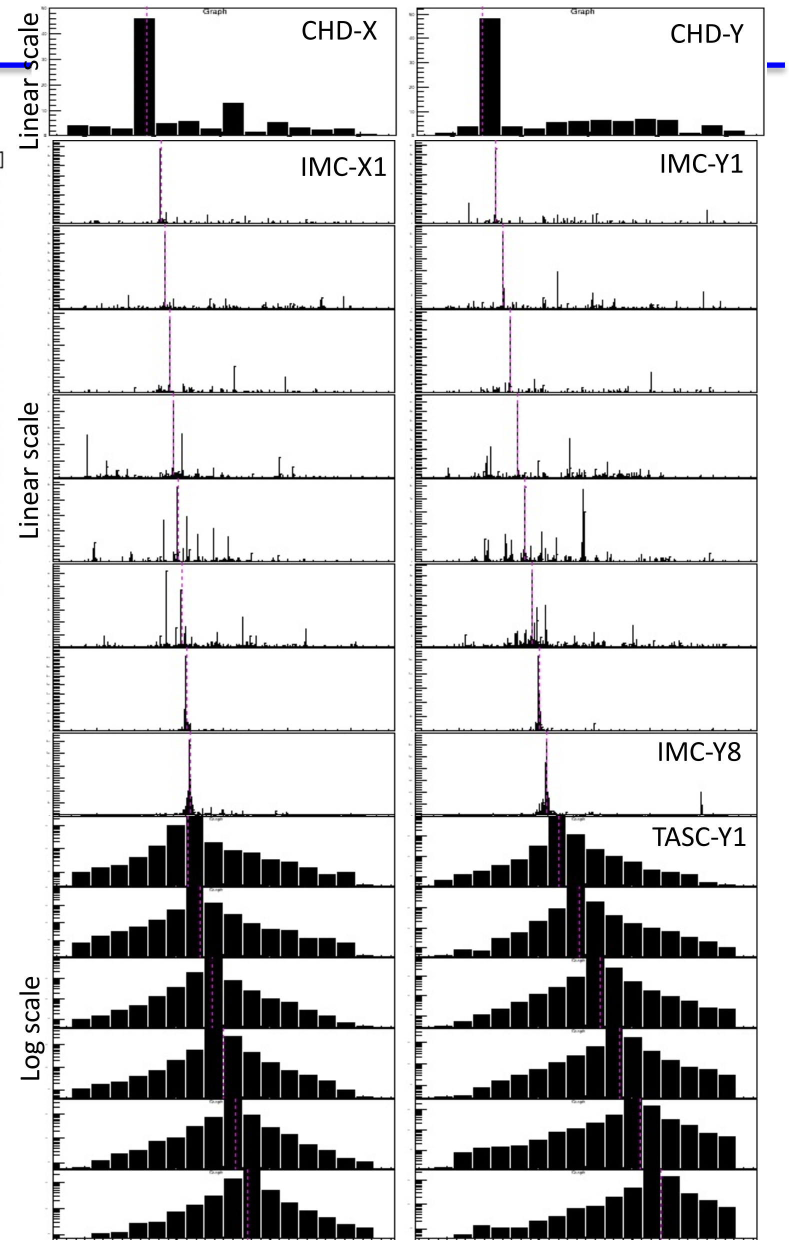
Signals of primary track, $\propto Z^2$, are larger than that of backscattering particles

➡ good tracking efficiency and accuracy

- Angular resolution: ~0.1˚
- $\Delta x/x$ at CHD: ~220µm

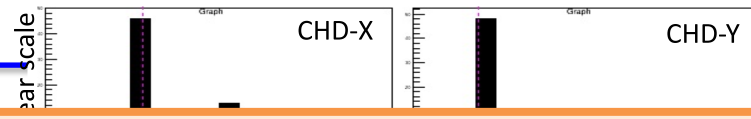


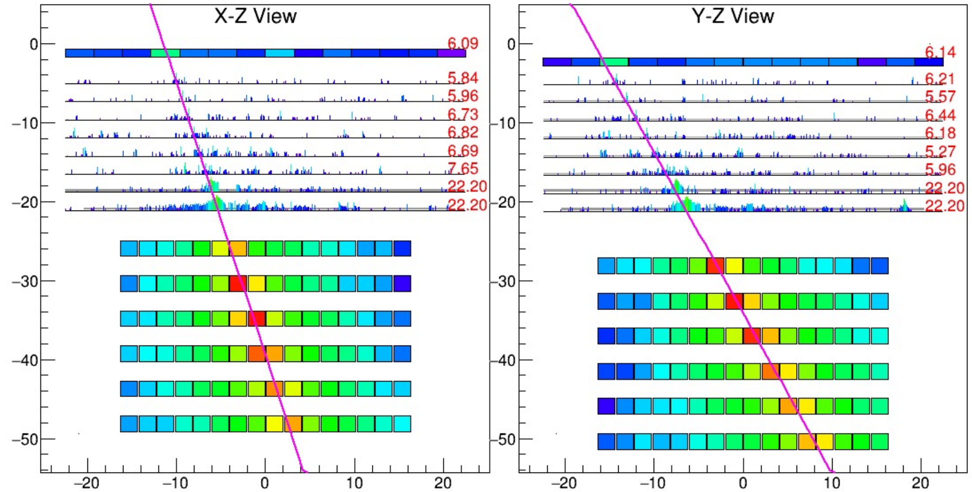


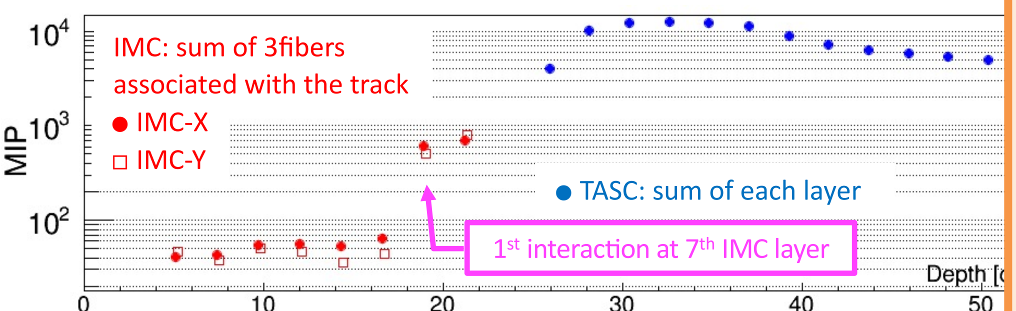


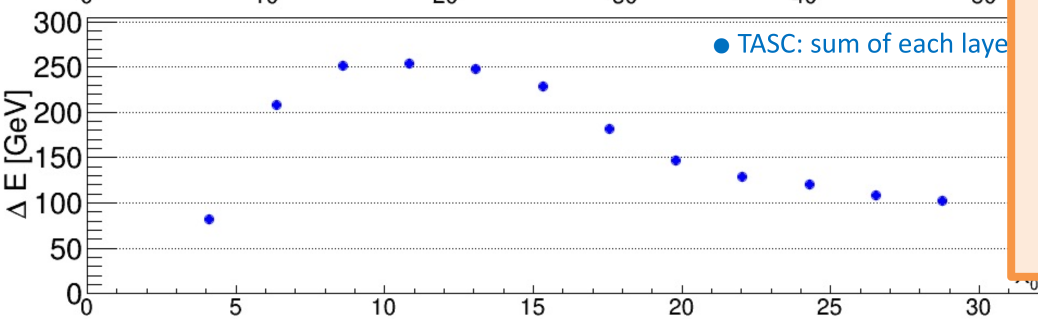
Event display: Carbon (ΔE_{TASC}=2.06TeV)

Pulse heights







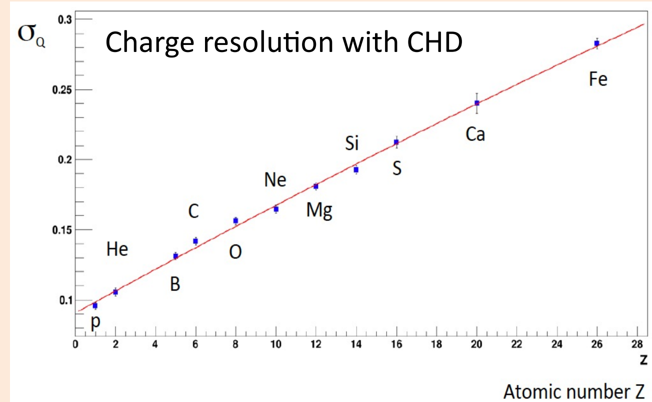


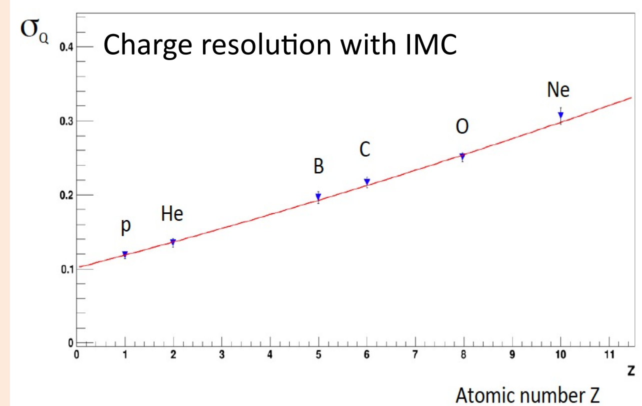
Charge measurement with CHD and IMC:

dE/dx measurement with CHD and IMC

IMC can identify the 1st interaction points

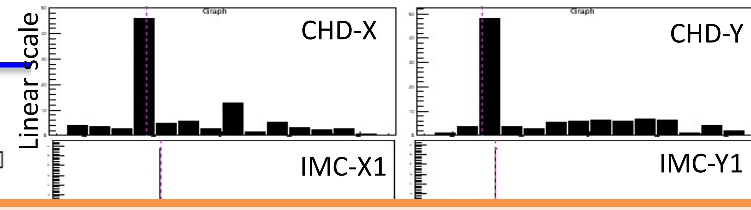
- $\Delta Z/Z$ (CHD): 0.15 for B, C, O, 0.30 for Fe
- $\Delta Z/Z$ (IMC): 0.20 for B, C, O

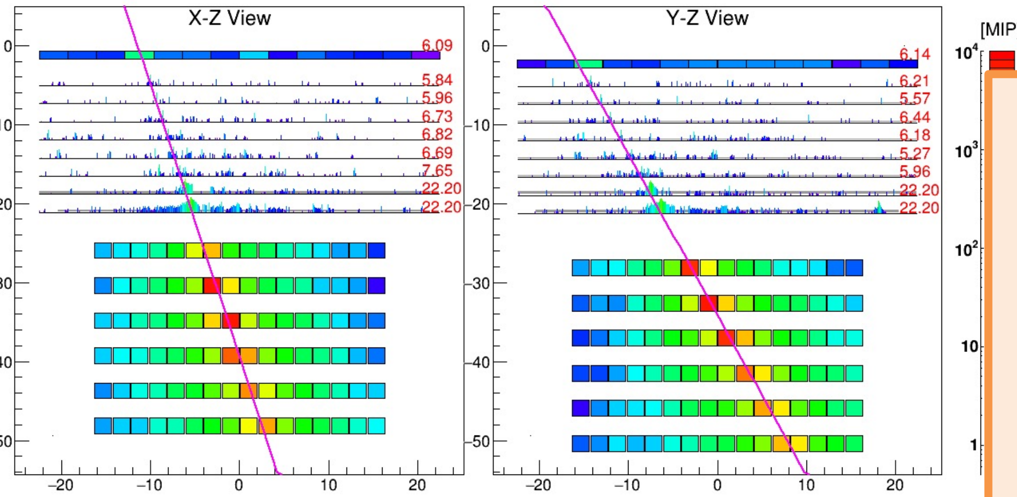


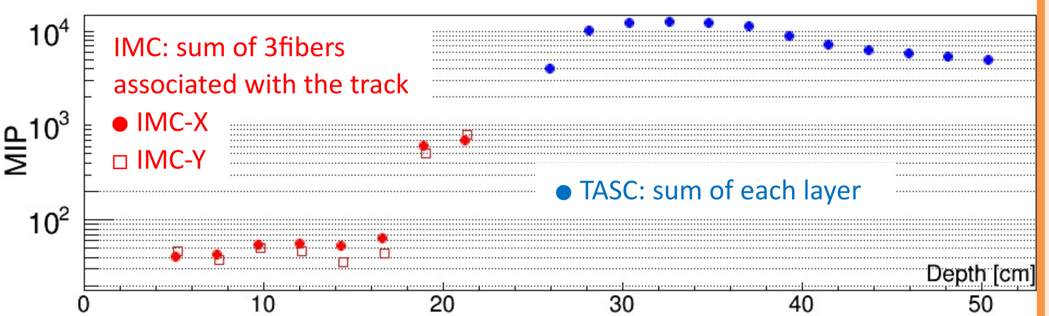


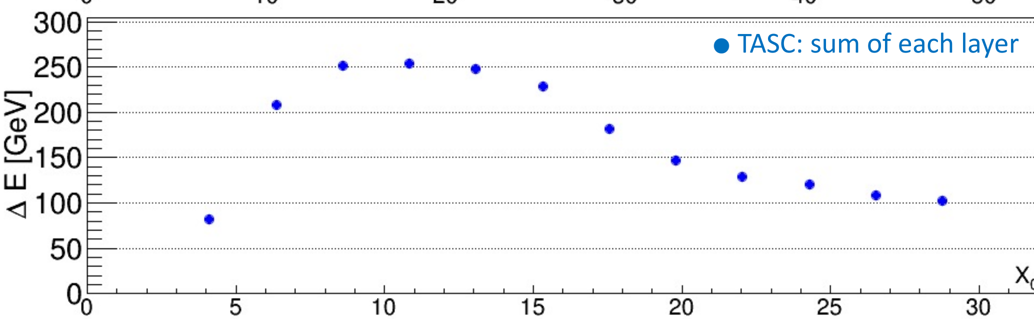
Event display: Carbon (ΔE_{TASC}=2.06TeV)

Pulse heights







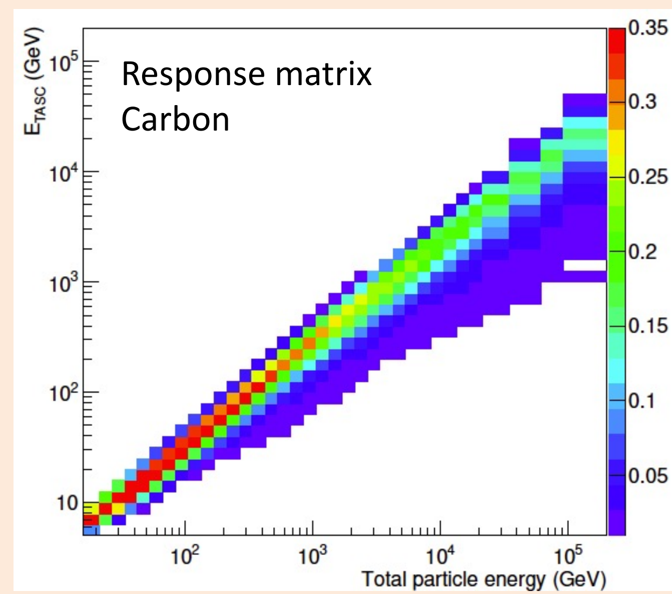


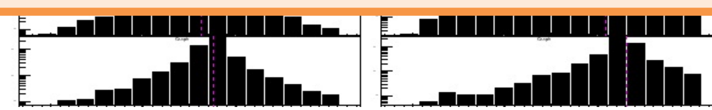
<u>Energy measurement with TASC:</u>

Calorimeter thickness: $1.3\lambda_I$ ($30X_0$)

- Energy resolution: ~30%

➡ Energy unfolding using MC simulation
Accuracy of the MC is tested
by 150 GeV/n ion beam at CERN-SPS





Flux measurement

$$\Phi(E) = \frac{N(E)}{\Delta E \varepsilon(E) S\Omega T} \qquad N(E) = U[N_{\mathrm{obs}}(E_{\mathrm{TASC}}) - N_{bg}(E_{\mathrm{TASC}})]$$

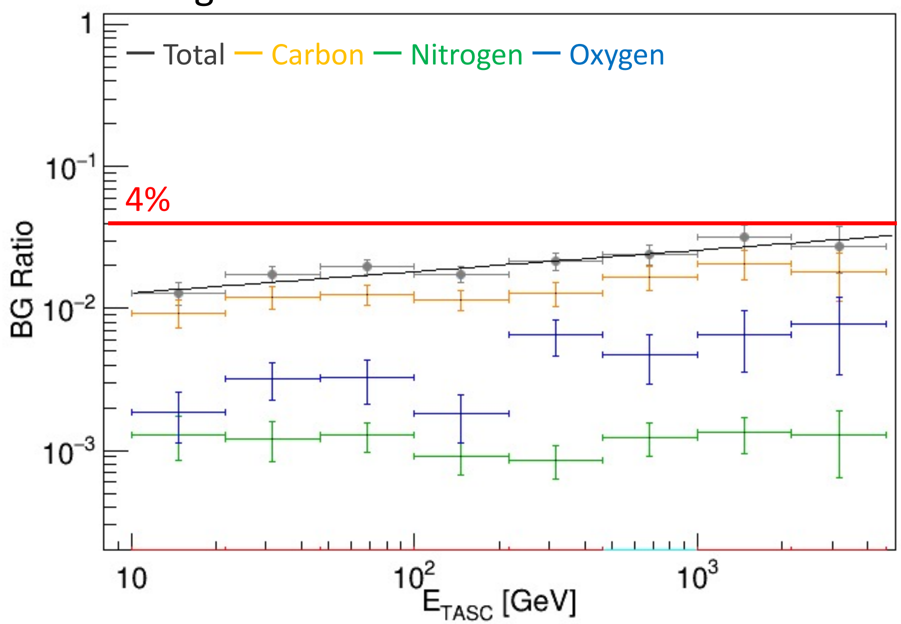
The number of observed events

Energy unfolding

The number of background events

- ε(E): Efficiency
  - 15-35% for B, C and O
  - 20-40% for Fe
- SΩ: Geometrical factor (510 $cm^2 sr$)
- T: livetime
  - 1,480 days for C and O
  - 1,613 days for Fe
  - 1,815 days for B

Background ratio for Boron



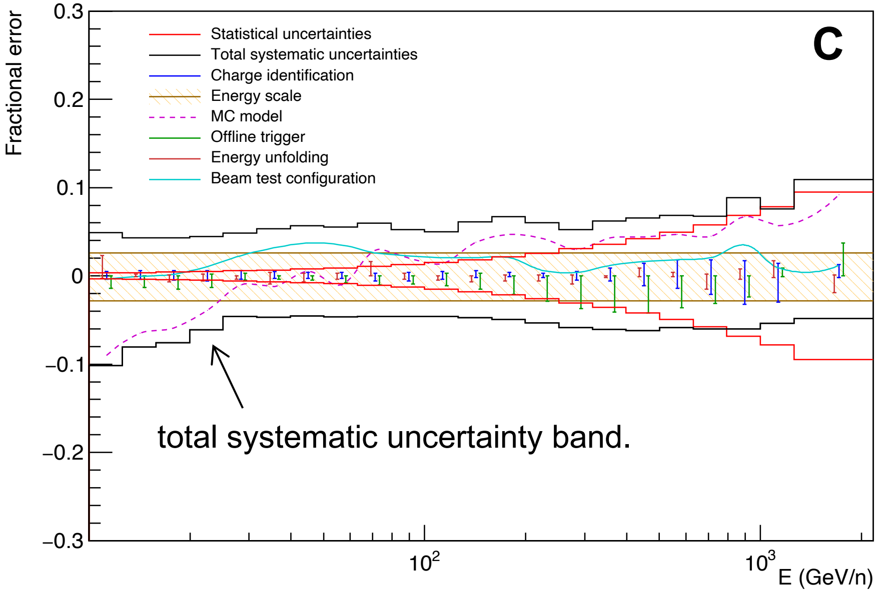
Background ratios of C, O and Fe are ~1 %

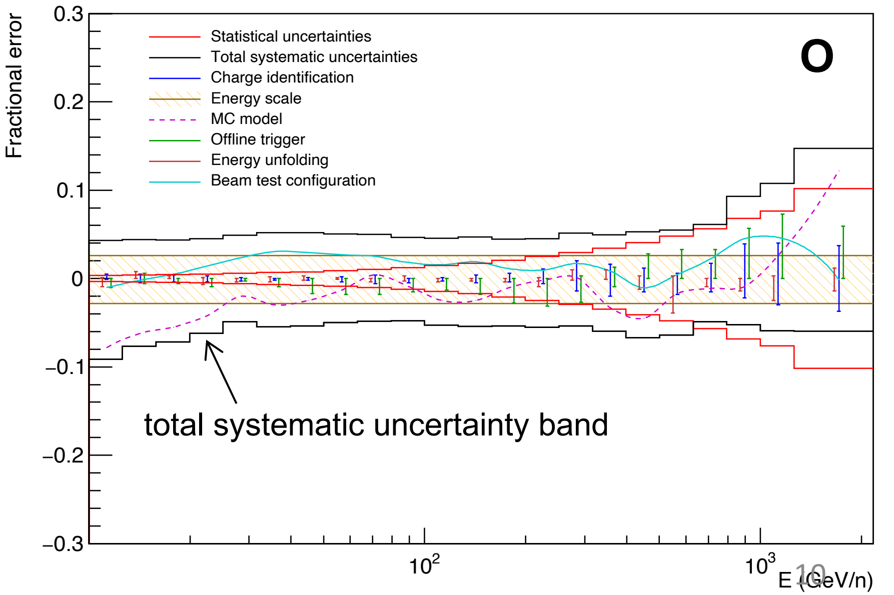
Systematic uncertainties

We check the stability of the spectrum by varying the analysis cuts and w/ different MC simulations for efficiencies and unfolding.

Main sources of systematics uncertainties:

- **Normalization:**
  - Live time
  - Long-term stability
  - Energy scale
- **Energy dependent:**
  - Tracking
  - Charge ID
  - Trigger
  - Unfolding
  - Beam test configuration
  - MC model (EPICS, FLUKA , GEANT4)





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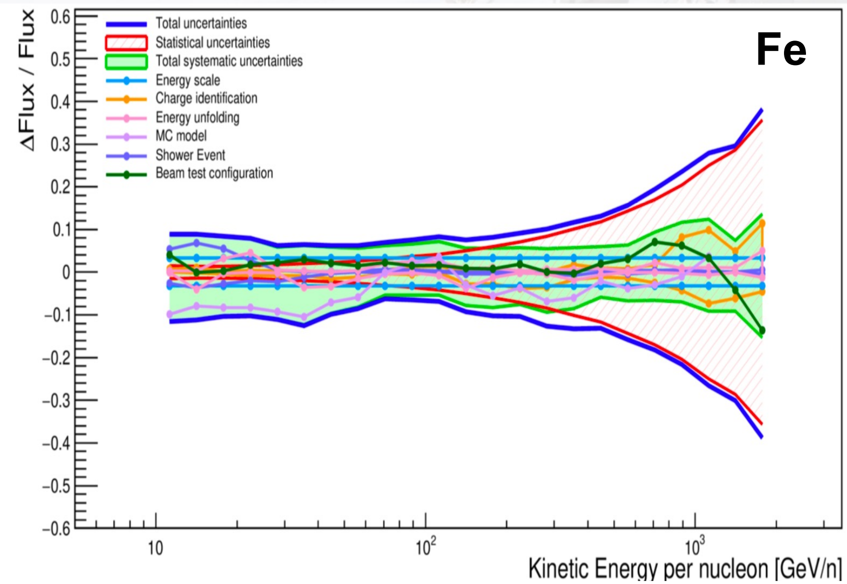
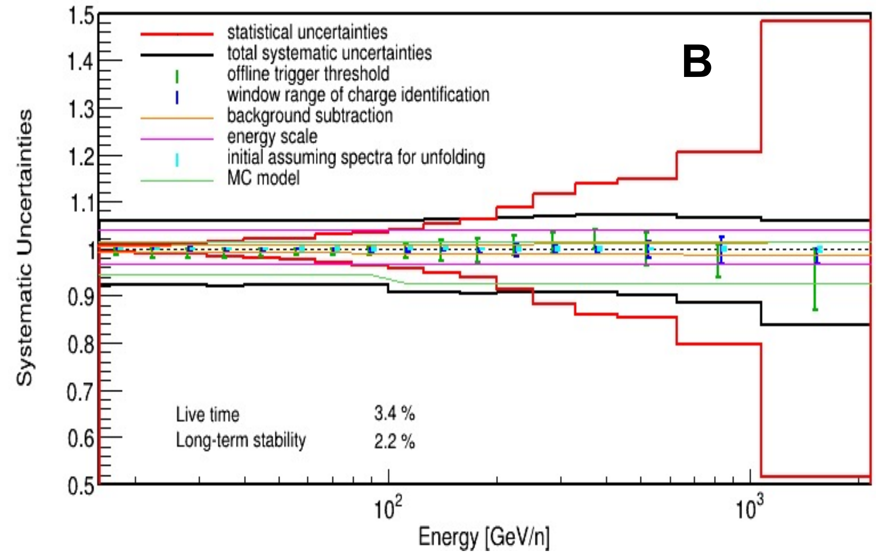
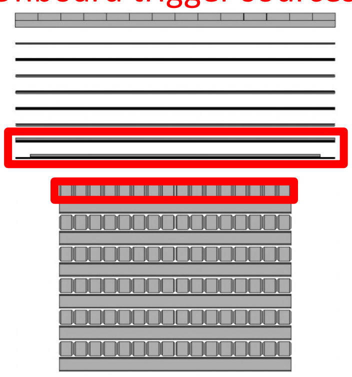


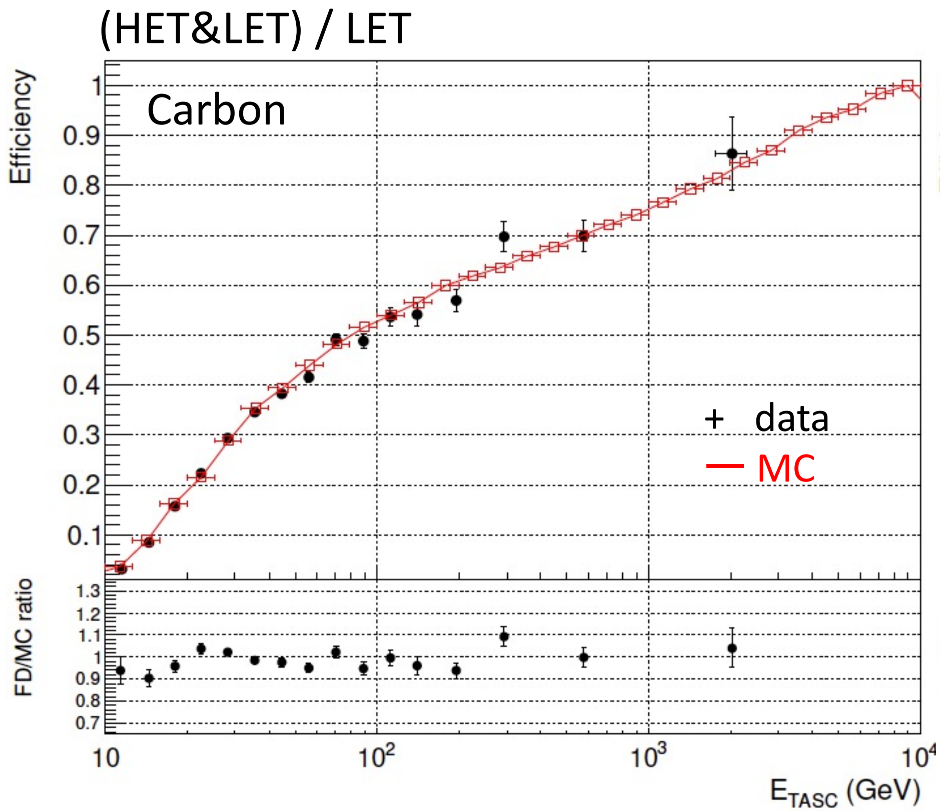


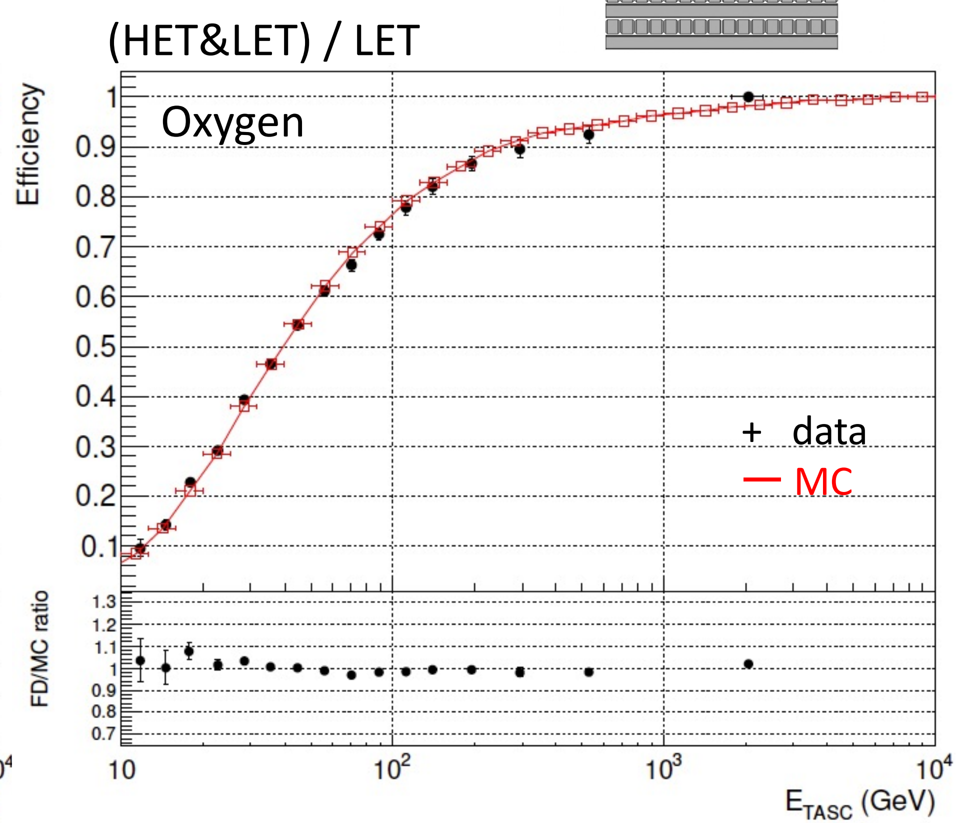
Trigger efficiency

- High-Energy Trigger (HET), which is the primary CALET mission trigger, is the coincidence of signals in last two IMC layers and top TASC layer
- Low-Energy Trigger (LET) is the same trigger logic as HET, but lower threshold allowing to trigger also penetrating particles of C and O

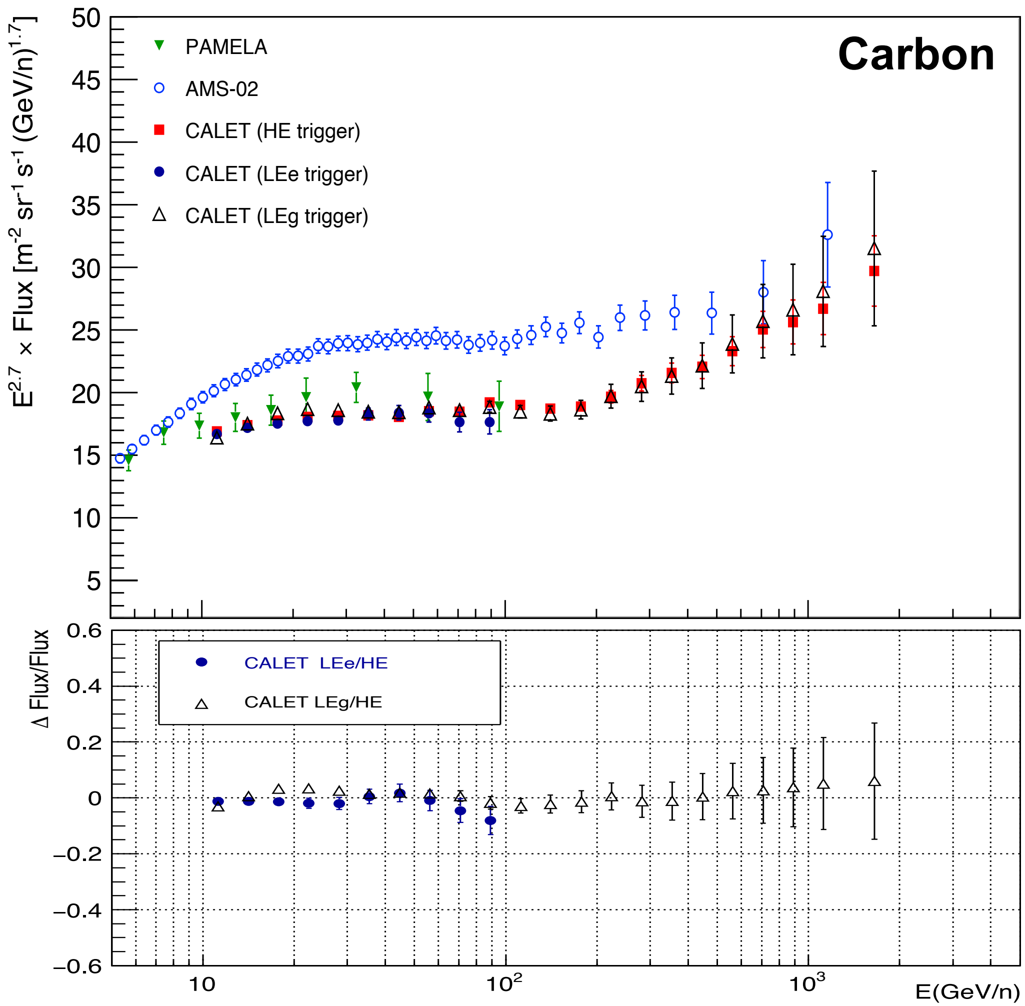
➡ HET is modelled in simulation: good agreement between MC and flight data







High vs. low energy triggers



High-energy (HE) trigger: E>10GeV

- Coincidence of last two pairs of IMC layers (50 MIP thr.) & top TASC layer (100 MIP thr.)

Low-energy gamma (LEg) trigger: E>1GeV

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

Low-energy electron (LEe) trigger: E>1GeV

- same as LEg with additional coincidence of CHD & upper IMC layers (0.3 MIP thr.)
- operated at a high geomagnetic latitude
- livetime ~2% of HE livetime

The resultant fluxes using data from the different trigger modes show consistent normalization and spectral shapes.

TASC energy scale

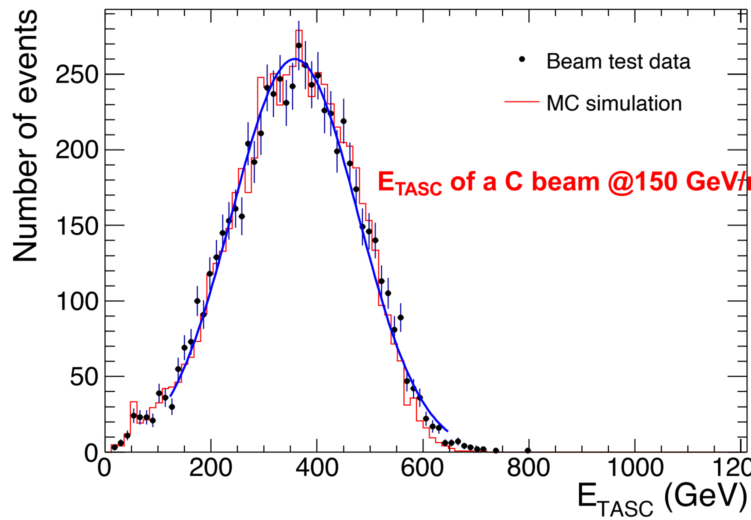
Beam test calibration at CERN-SPS with ion fragments beam (Z/A=2) at 13, 19 and 150 GeV/n.

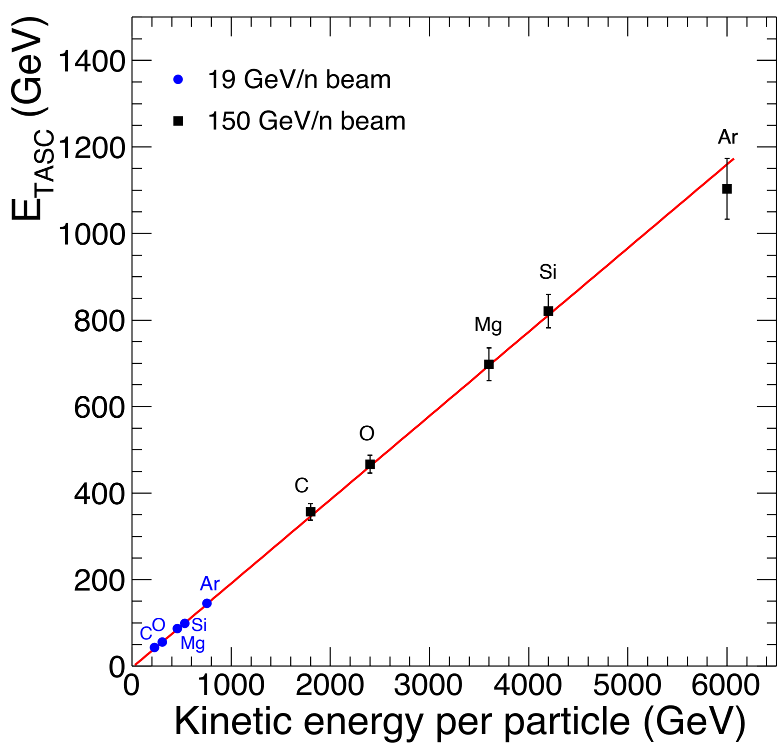
Good linearity up to max available beam energy (~ 6 TeV)

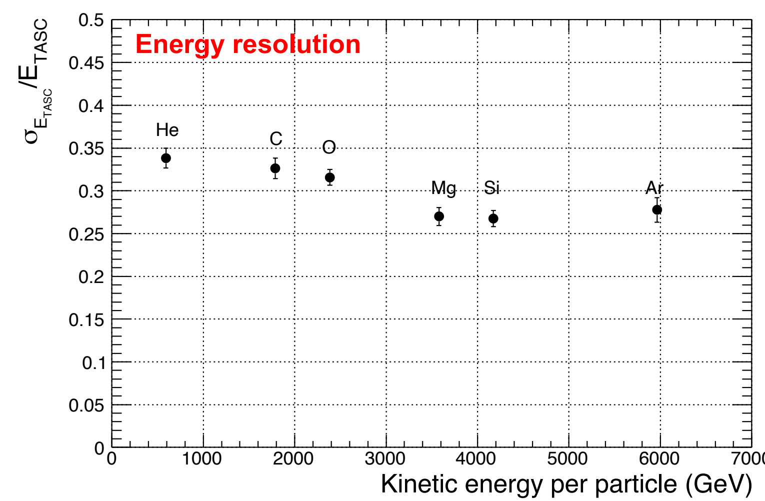
Fraction of particle energy released in TASC is ~20%

Energy resolution ~30%

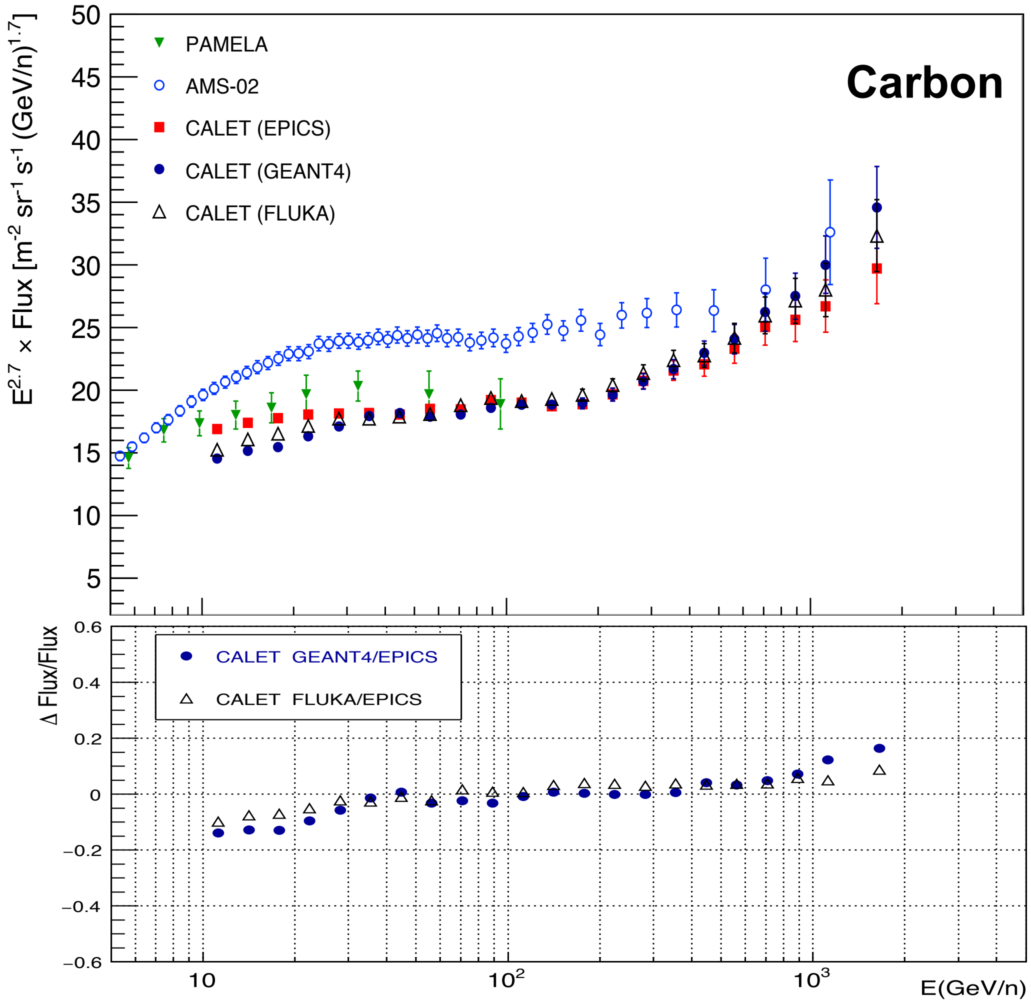
The energy response derived from MC simulations was tuned using the beam test results.







Mote Carlo models



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

- EPICS 9.21 w/ DPMJET-III
- Fluka 2011 2c.6 w/ DPMJET-III
- GEANT4 10.5 w/ FTFP_BERT

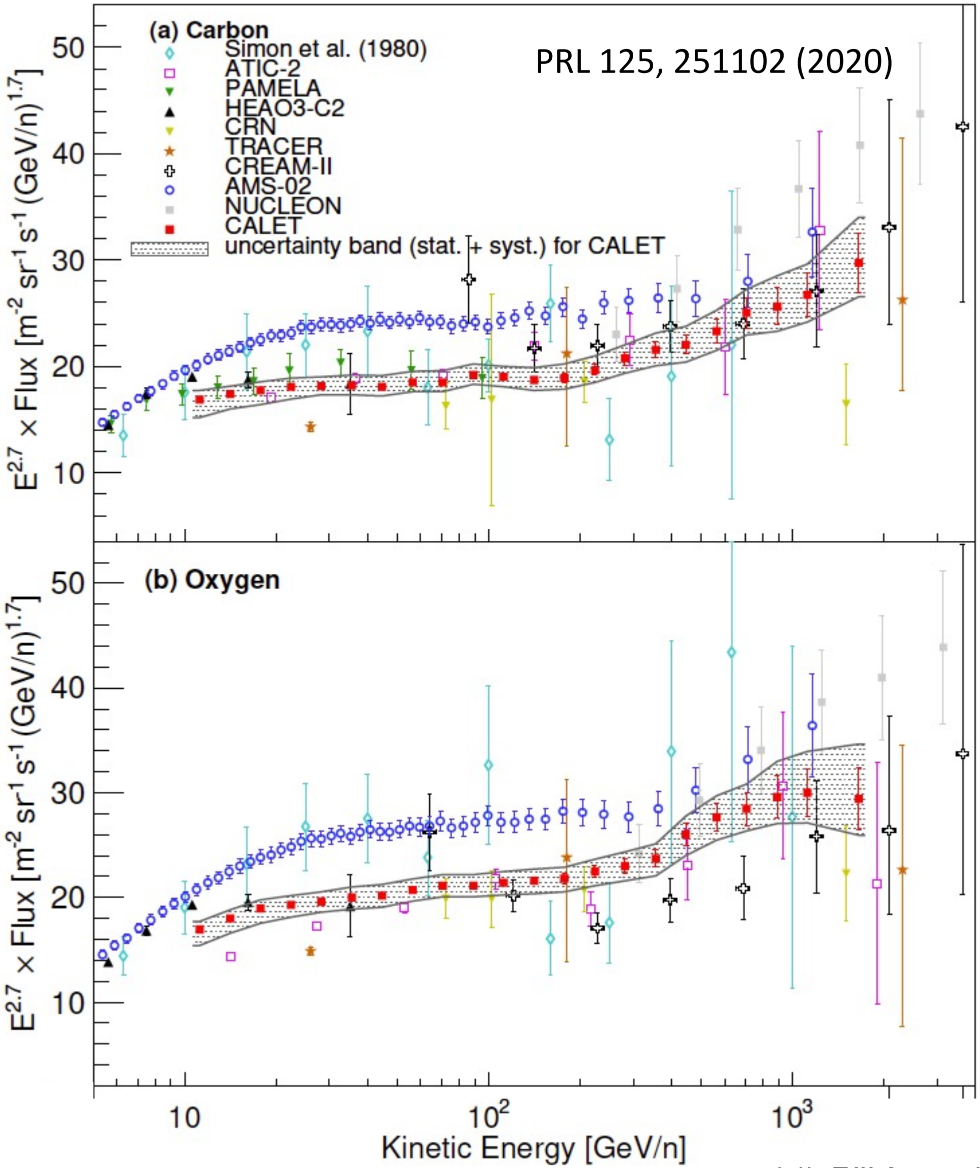
MC simulations were tuned using beam test and flight data.

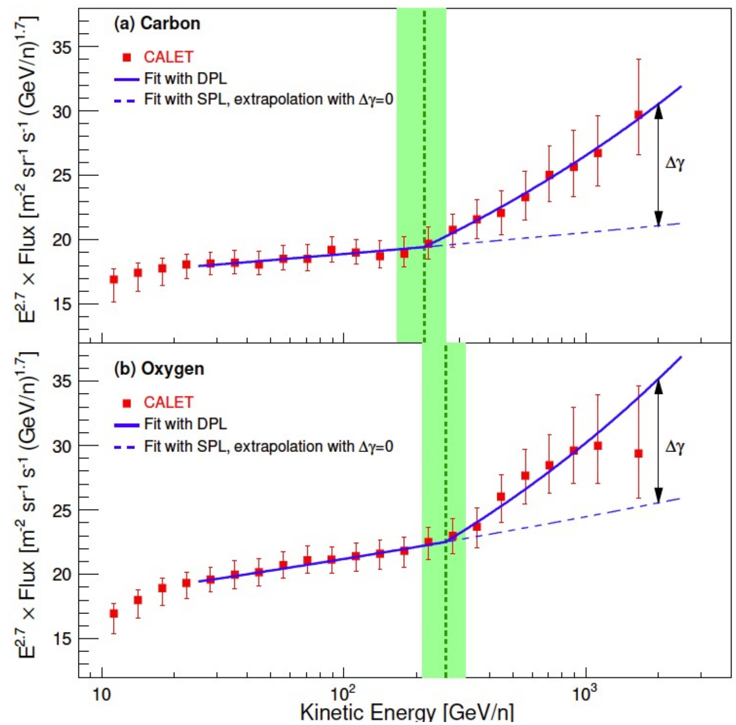
They are used to estimate selection efficiencies and response matrix.

Comparison of energy responses from different MC at high energy where no beam calibration is available.

The resultant fluxes from the analyses with different MC's show consistent normalization and spectral shapes.

Carbon and Oxygen Spectra





$$\Phi(E) = \begin{cases} C\left(\frac{E}{\mathrm{GeV}}\right)^{\gamma} & E \le E_0 \\ C\left(\frac{E}{\mathrm{GeV}}\right)^{\gamma}\left(\frac{E}{E_0}\right)^{\Delta\gamma} & E > E_0 \end{cases}$$

Carbon

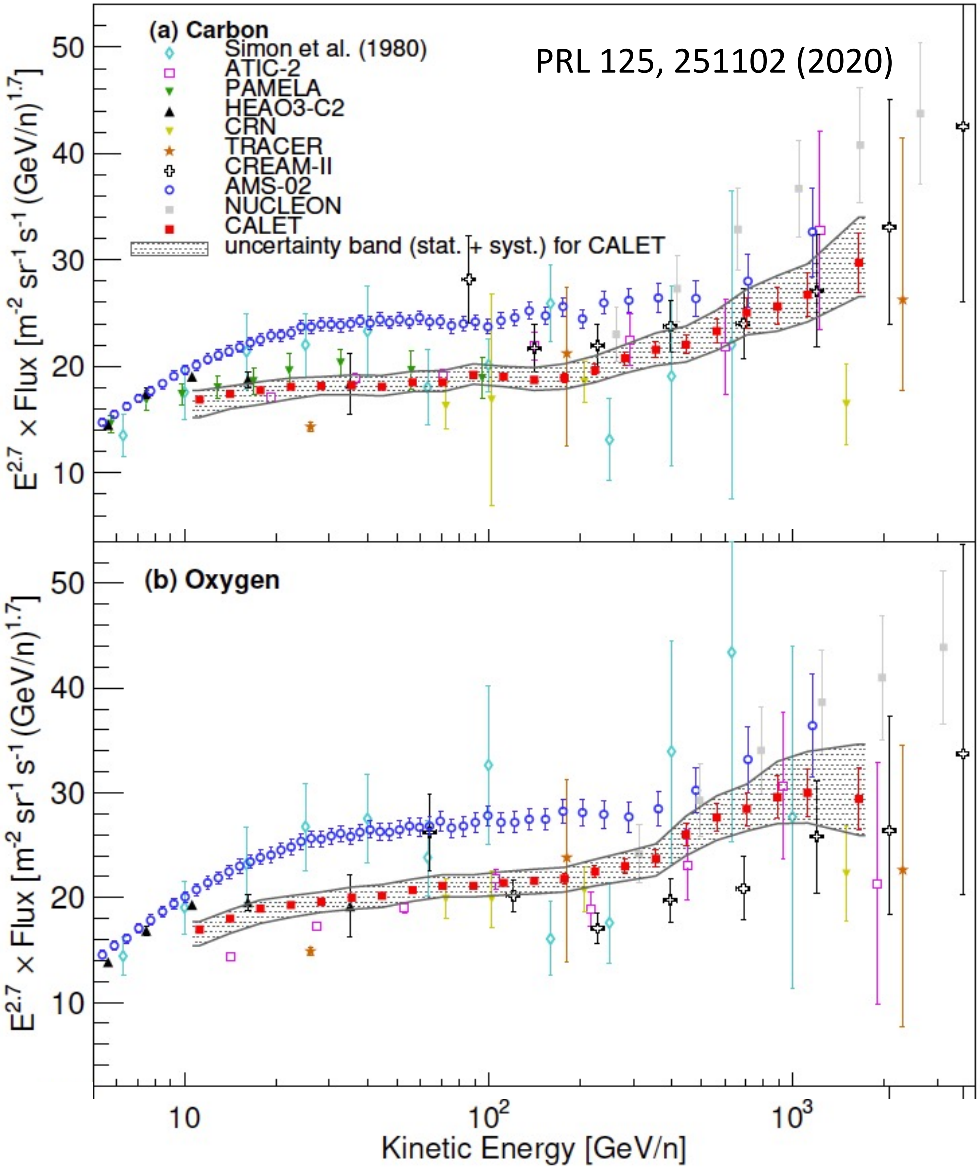
$$\begin{cases} \gamma = -2.663 \pm 0.014 \\ E_0 = 215 \pm 54\,\mathrm{GeV/n} \\ \Delta\gamma = 0.166 \pm 0.042\ \ (4.0\,\sigma) \\ \text{with}\ \ \chi^2/\text{d.o.f.} = 9.0/8 \end{cases}$$

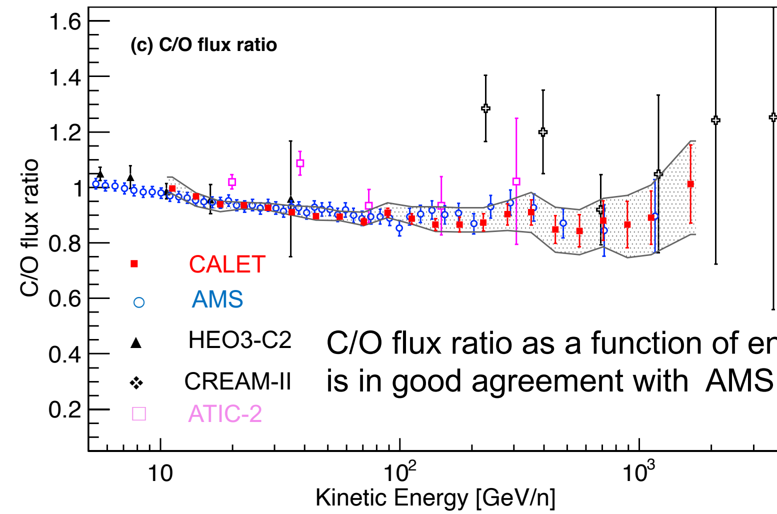
Oxygen

$$\begin{cases} \gamma = -2.637 \pm 0.009 \\ E_0 = 264 \pm 53\,\mathrm{GeV/n} \\ \Delta\gamma = 0.158 \pm 0.053\ \ (3.0\,\sigma) \\ \text{with}\ \ \chi^2/\text{d.o.f.} = 3.0/8 \end{cases}$$

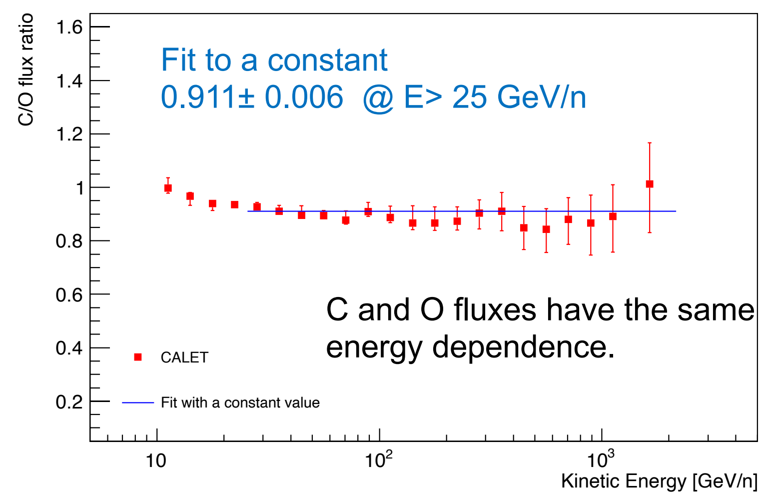
Carbon and Oxygen Spectra

PRL 125, 251102 (2020)





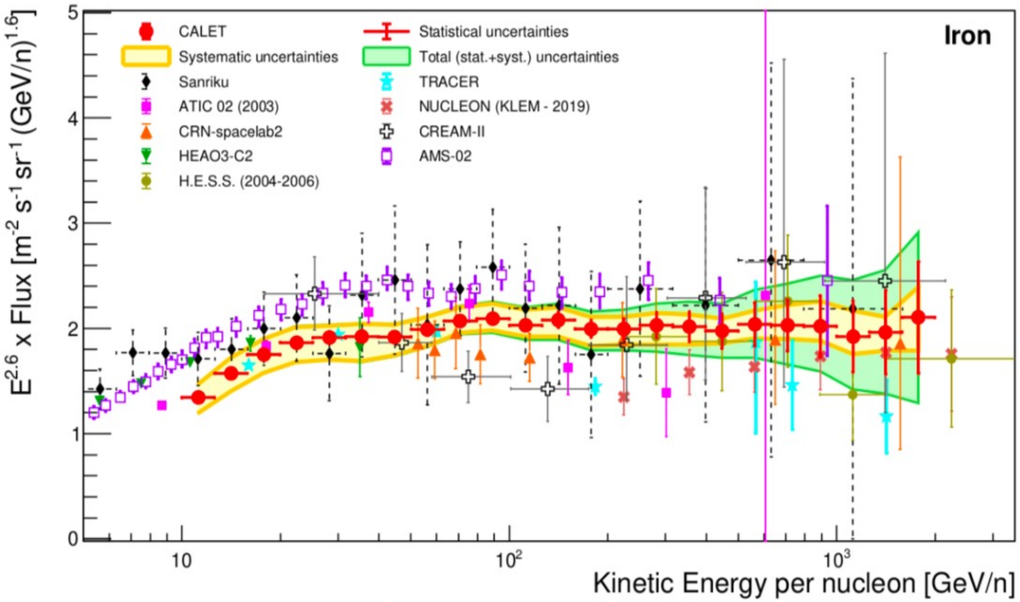
C/O flux ratio as a function of energy is in good agreement with AMS

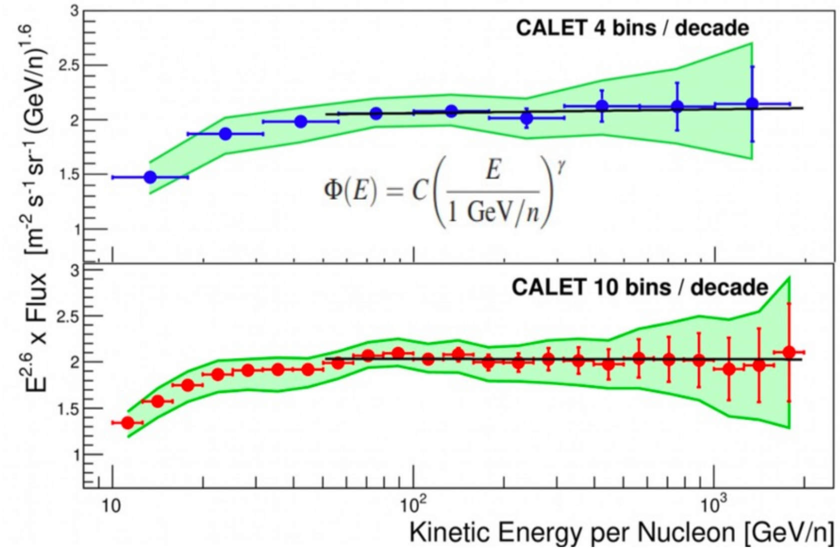


Fit to a constant
0.911± 0.006 @ E> 25 GeV/n

C and O fluxes have the same energy dependence.

Iron spectrum





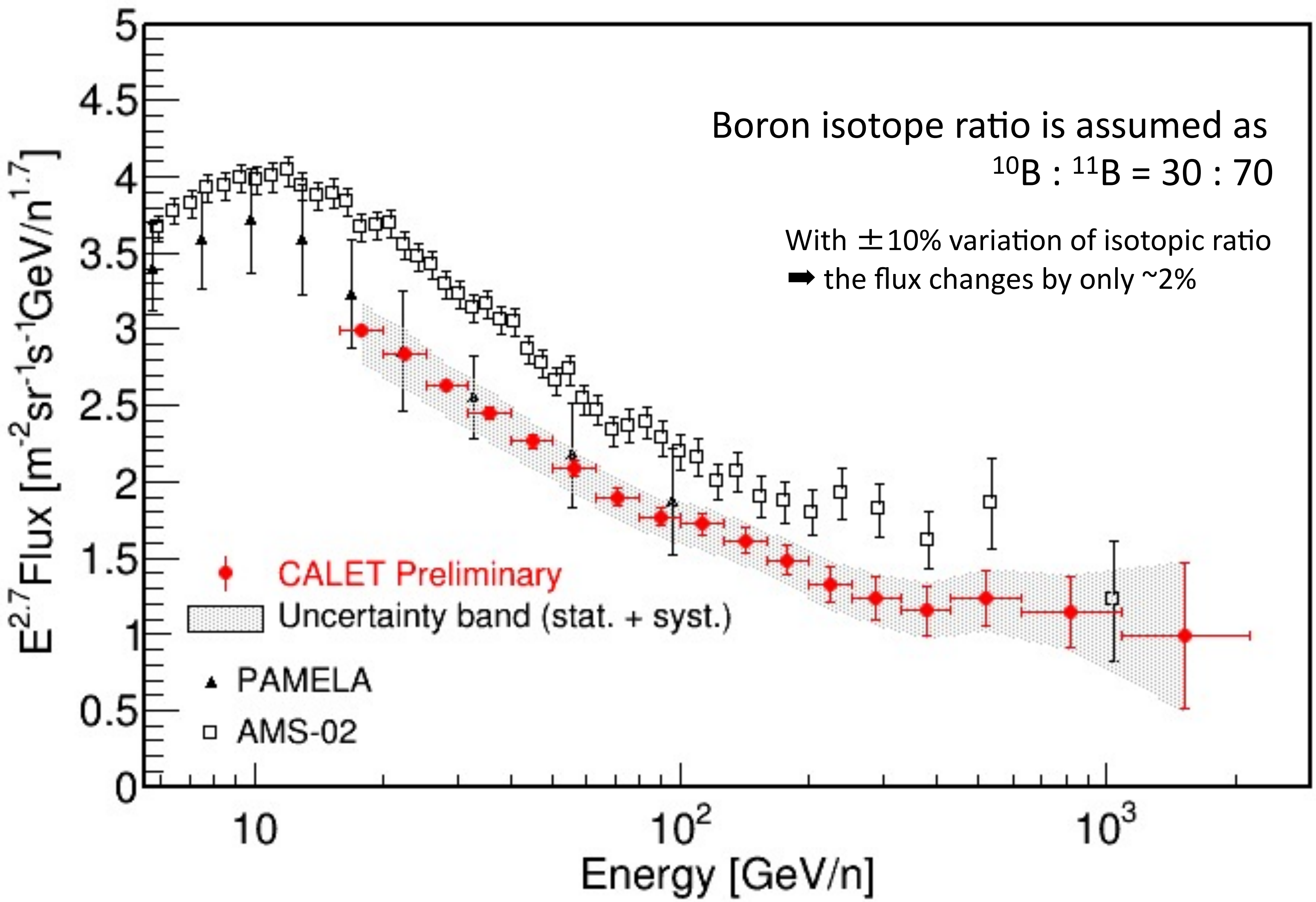
10bins/dec: γ=-2.60 ± 0.02 (stat) + 0.02 (sys)
4bins/dec: γ=-2.59 ± 0.02 (stat) + 0.04 (sys)

➡ stable when larger energy bins are used

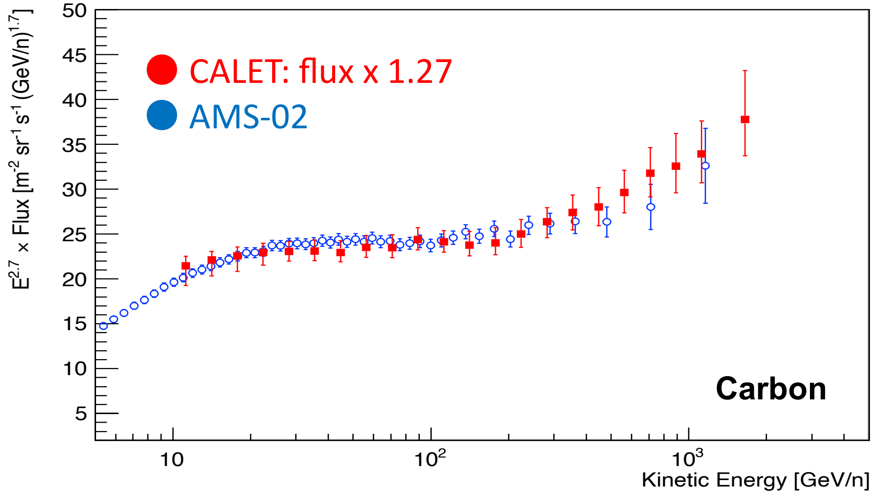
The iron flux, above 50 GeV/n, is compatible within the errors
With a single power law

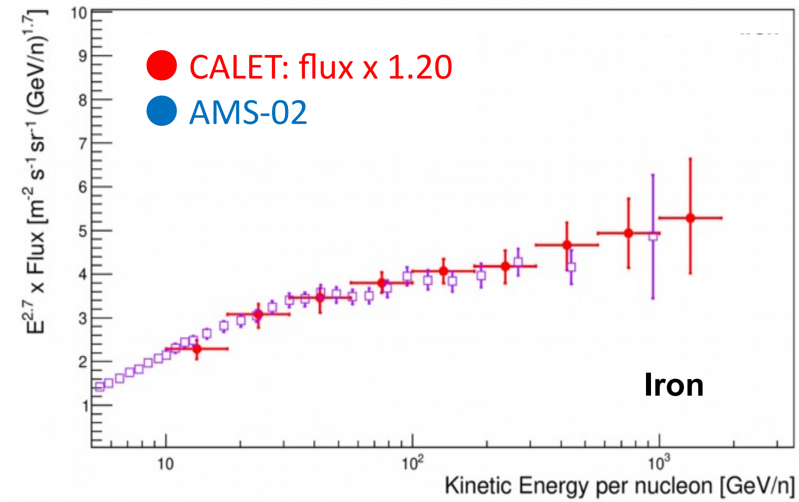
Boron spectrum

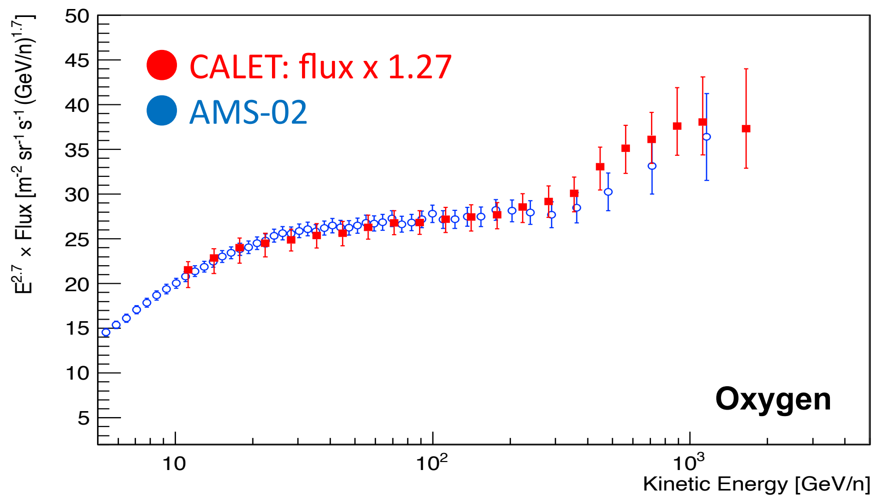
CALET preliminary result is consistent with PAMELA, but lower than AMS-02

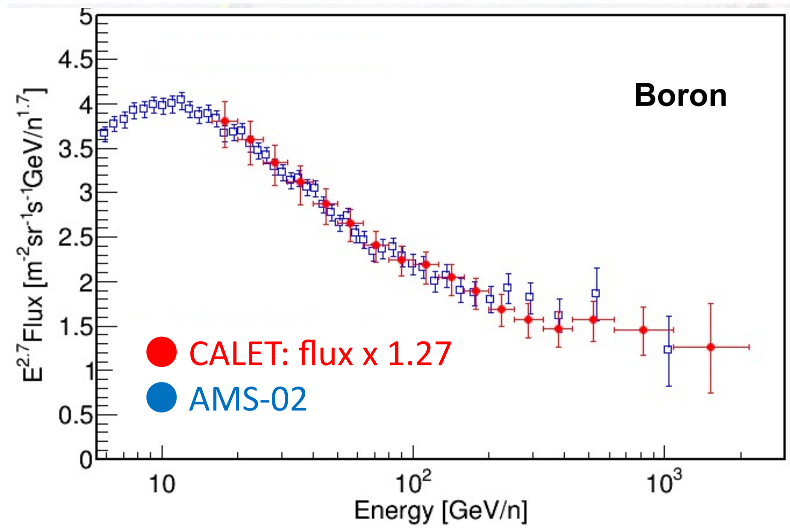


Fluxes normalized to AMS-02





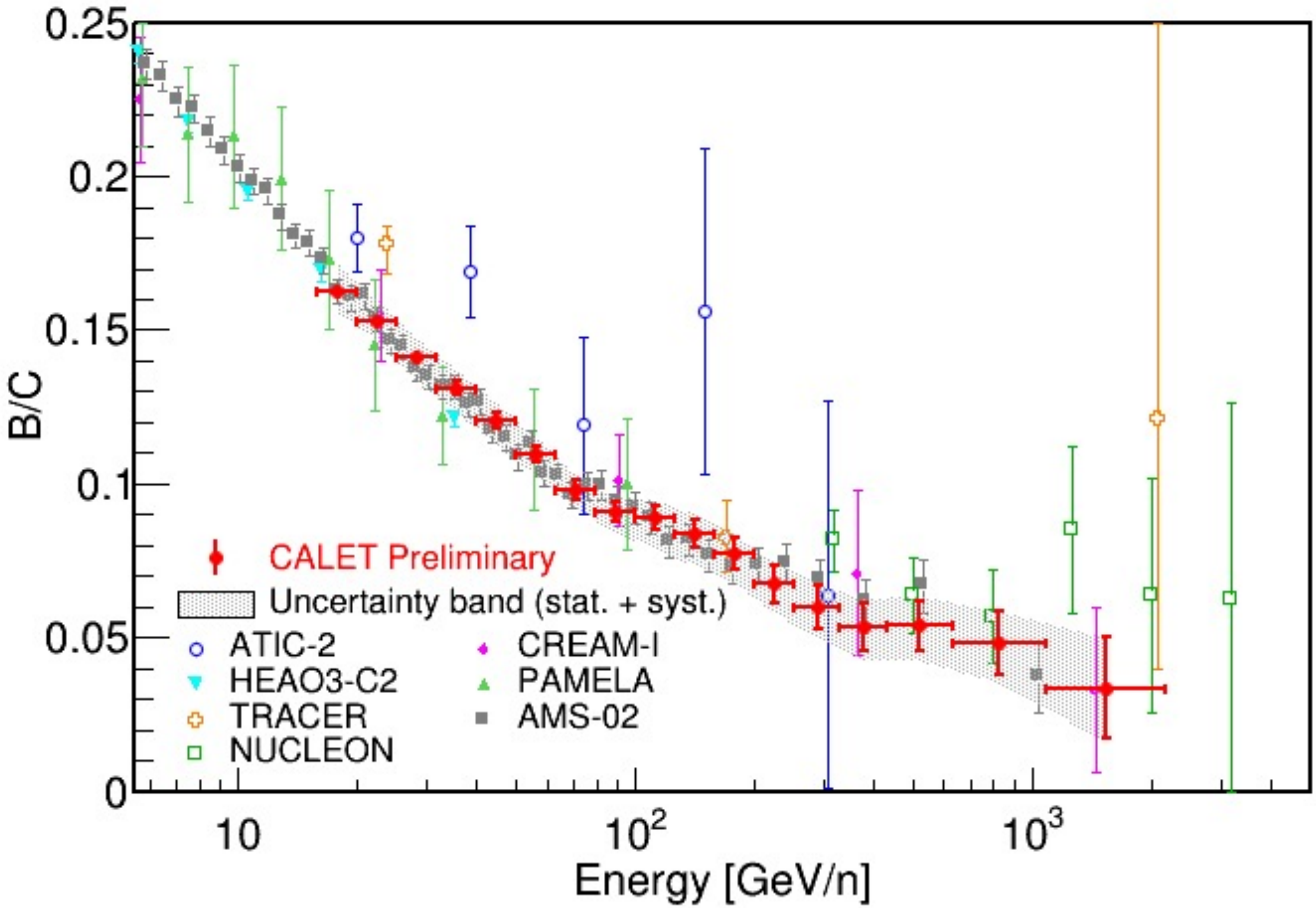




The spectral shapes and their spectral indices are consistent with AMS-02,
but the absolute normalizations are lower than AMS-02.

Preliminary result of B/C ratio

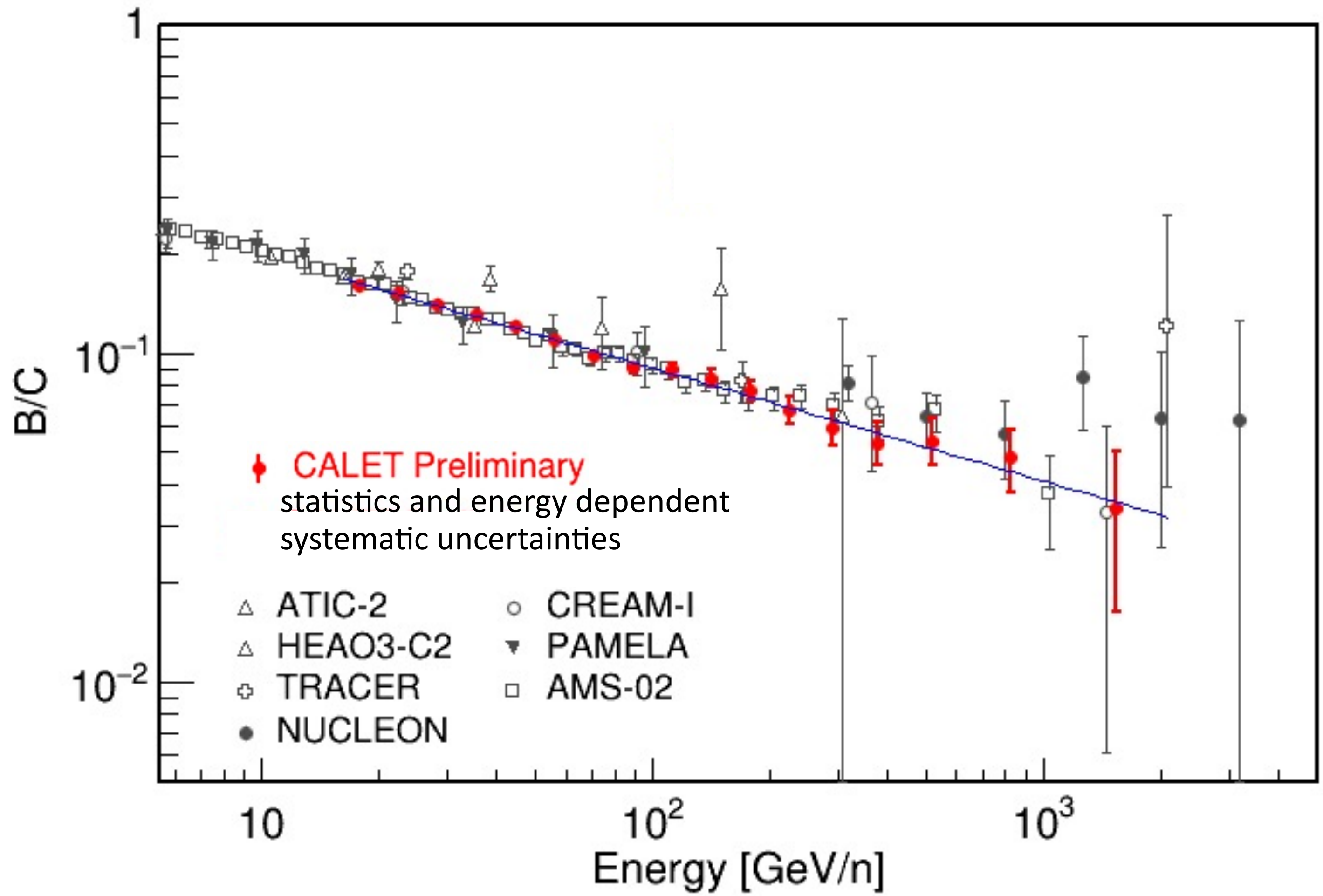
CALET preliminary result is well consistent with other experiments



Fit with a single power law function

The B/C ratio is fitted by a single power law function: $(\mathrm{B/C}) = AE^{\delta}$

$$\delta = -0.344 \pm 0.012 (E > 20\ \mathrm{GeV/n}), \quad \chi^2/\mathrm{ndf} = 5.6/15$$



Summary

- CALET measures carbon, oxygen, iron and boron spectra and B/C ratio from 10 GeV/n to 2.2 TeV/n with 5 years of operations

- A single power law spectrum for C and O is excluded by more than 3σ
- A spectral index increase $\Delta\gamma=0.166\pm0.042$ for C and $\Delta=0.158\pm0.053$ for O is measured above 200 GeV/n
- The Fe spectral spectrum is consistent with the hypothesis of a SPL spectrum up to 2 TeV/n with a spectral index $\gamma = -0.260\pm0.03$

- Preliminary result of B/C ratio can be fit with a SPL function of $E^{-\delta}$; $\delta=0.344\pm0.012$ (E>20GeV/n)

- Our results are consistent with the ones reported by AMS-02, as regards the spectrum shape and hardening. However, the absolute normalization of our data is significantly lower than AMS-02, but in agreement with other experiments

- We performed detailed systematics checks to search for possible causes of this normalization issue. We can exclude that it can stem from trigger inefficiencies, differences between MC simulation packages or hadronic models, or lacking modeling of the instrument.