# CALETによる10GeV/nから2.2TeV/nの炭素と酸素のエネルギースペクトル観測結果

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O. Adriani et al., (CALET Collaboration), Phys. Rev. Lett. **125**, 251102 (2020)
“Direct Measurement of the Cosmic-Ray Carbon and Oxygen Spectra from 10 GeV/n to 2.2TeV/n with the Calorimetric Electron Telescope on the International Space Station”

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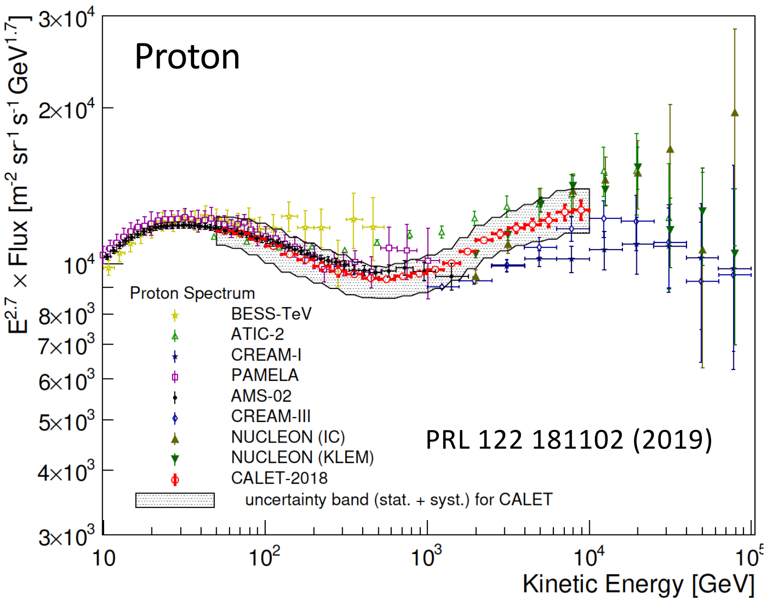
# Energy Spectra of Galactic Cosmic Rays

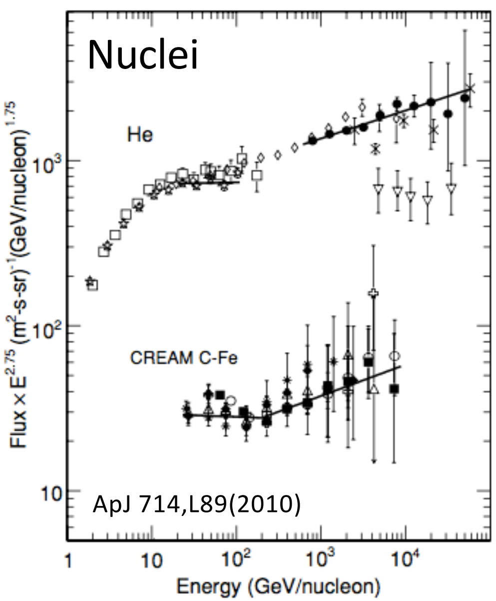
<u>"Standard" model of galactic cosmic rays</u>

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

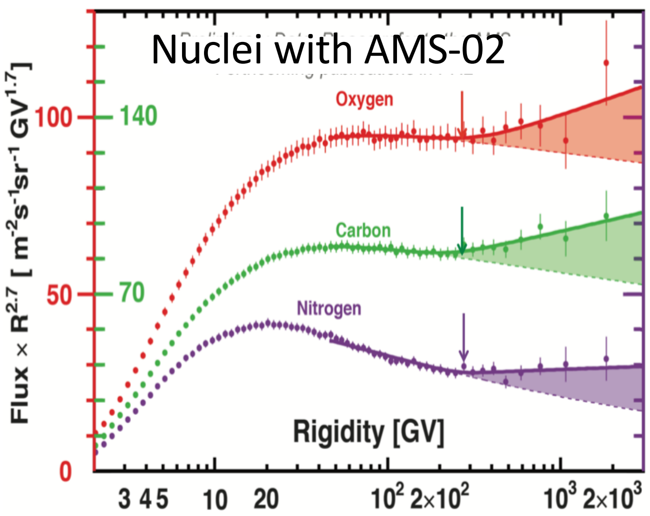
<u>Unexpected observation results</u>

- Spectra of proton and nuclei break at R~300GV



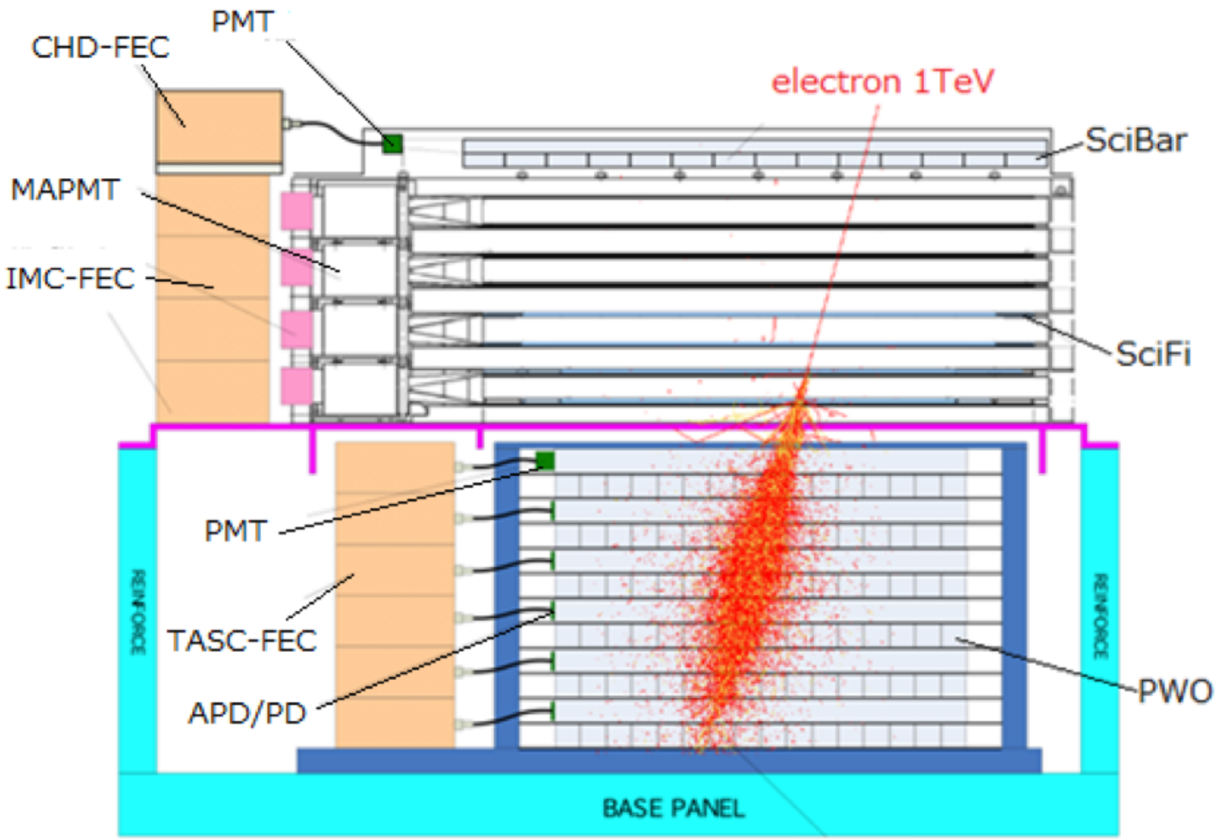




PoS(ICRC2017)1093
PRL 119 251101 (2017)



# 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**




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 $X_0$x 2)
  ΔX at CHD = 200μm, ΔZ/Z = 0.20 for C

TASC: Total Absorption Calorimeter

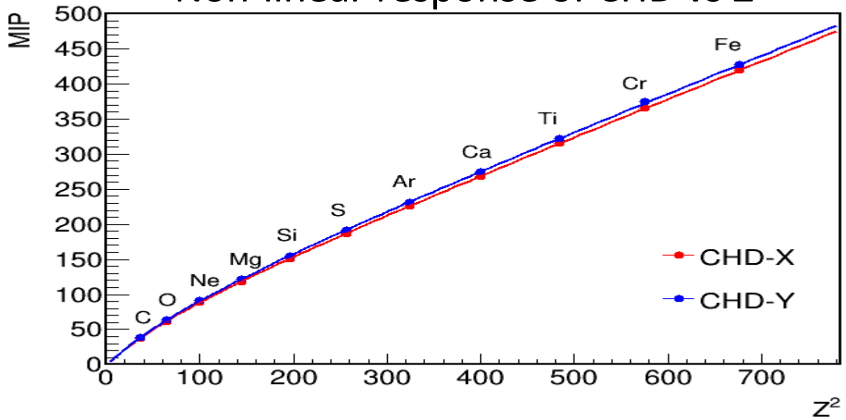
Energy measurement, Particle ID

- 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)

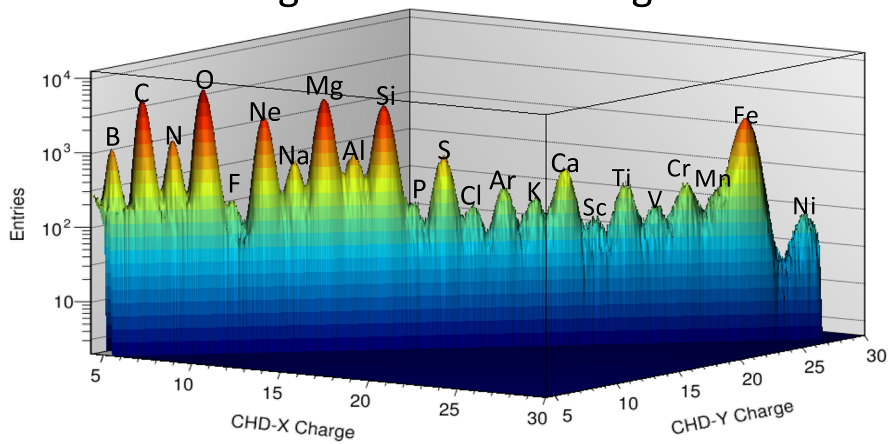
# Charge measurement with CALET

- Charge range: Z=1 – 40
- Charge resolution:
  - CHD: 0.15*e* for C, 0.30*e* for Fe
  - IMC : 0.20*e* for C

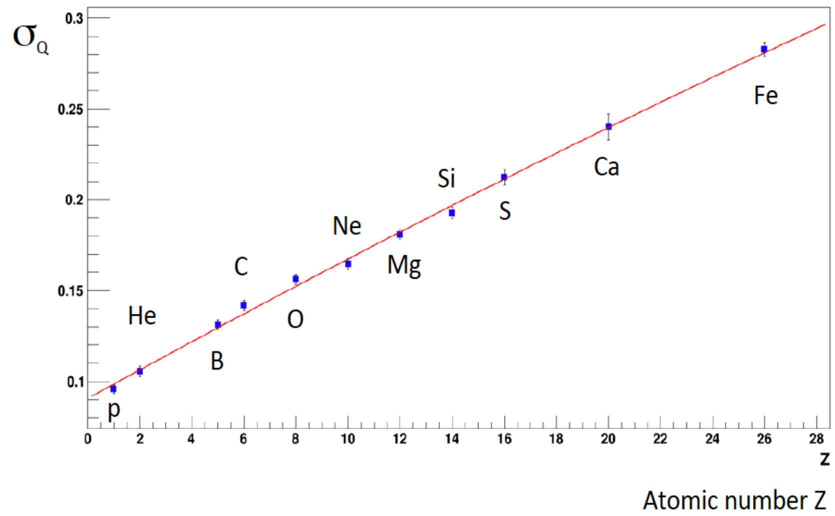
Non-linear response of CHD vs $Z^2$



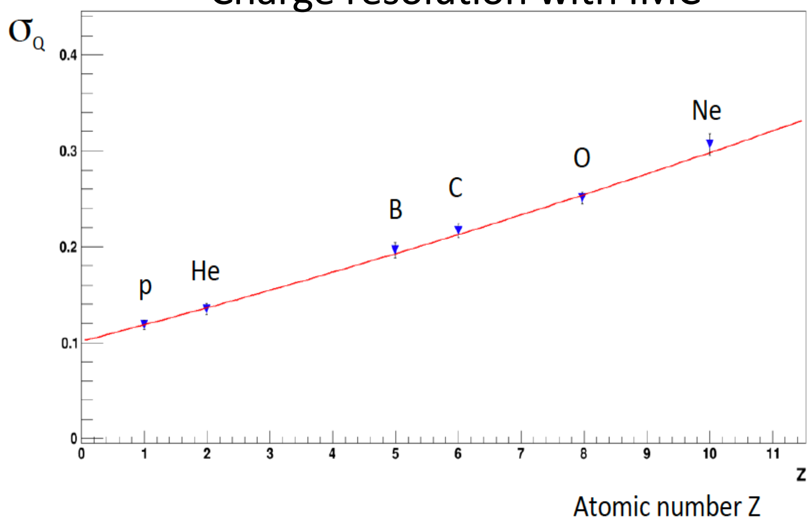

Charge distribution of flight data




Charge resolution with CHD



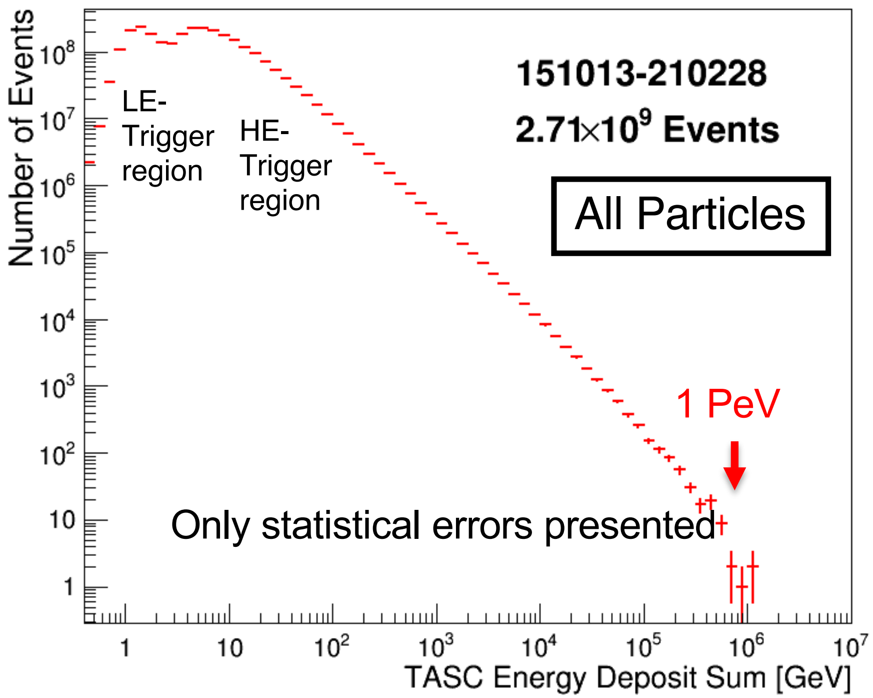

Charge resolution with IMC



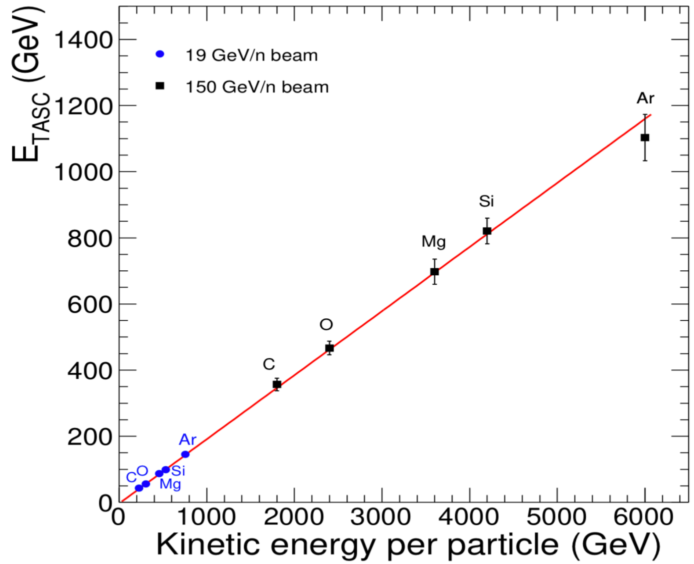
# Energy measurement with CALET

- Dynamic range: 1 – $10^6$MIP (1GeV – 1PeV)
- MIP calibration have performed on space
- Energy resolution: 30% for nuclei

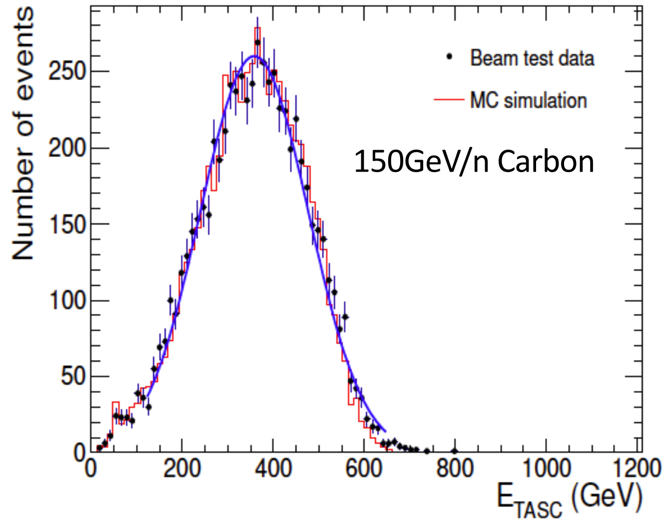
Distribution of deposit energies (ΔE) in TASC




Linearity with beam test




Energy distribution with beam test



# Selection for C, O candidate events

## Analyzed Flight Data

1,480 days (Oct. 13, 2015 – Oct. 31, 2019)

$T_{live}$=3.00 x $10^4$ hours

## Analysis procedure

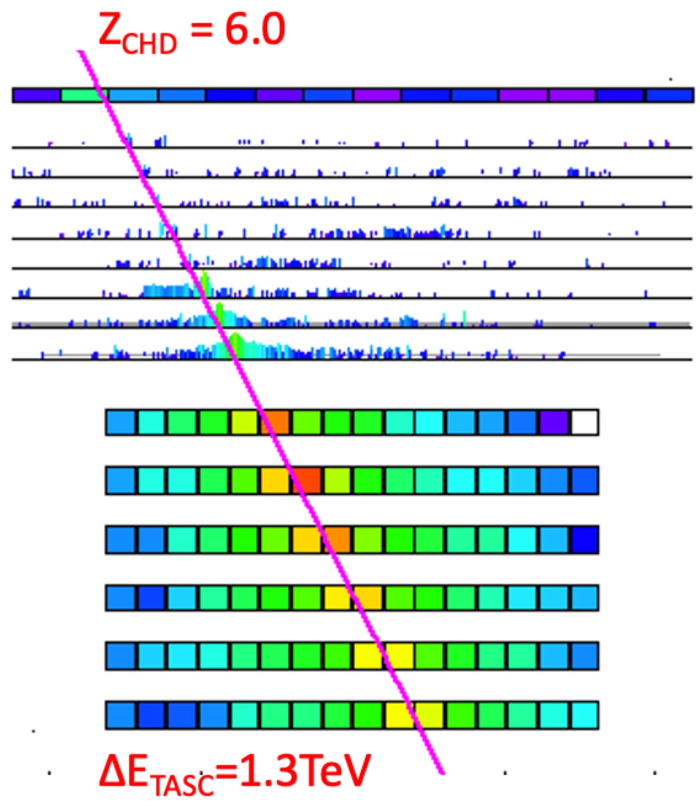
- HE + offline shower trigger
  - 50MIP in IMC-X/Y78, 100MIP in TASC-X1
- Tracking with IMC
- Acceptance cut
  - CHD, TASC top (2cm from edge) and bottom layers
- Charge identification with CHD and IMC
- Background estimation
- Energy measurement and unfolding
- Flux calculation

## MC data

- EPICS v9.22, Cosmos8.02, DPMJET-III
- proton – Ni in 1 GeV – 1 PeV

Digitization of signals in simulation are modelled and tuned by beam test results and flight data; quenching, noise and saturation.

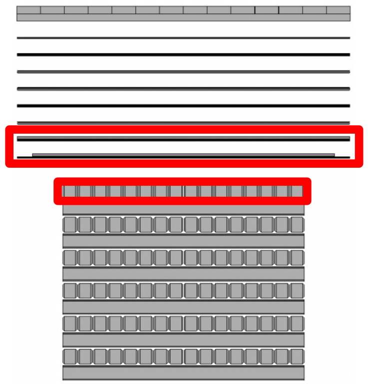
An example of Carbon event from Flight data



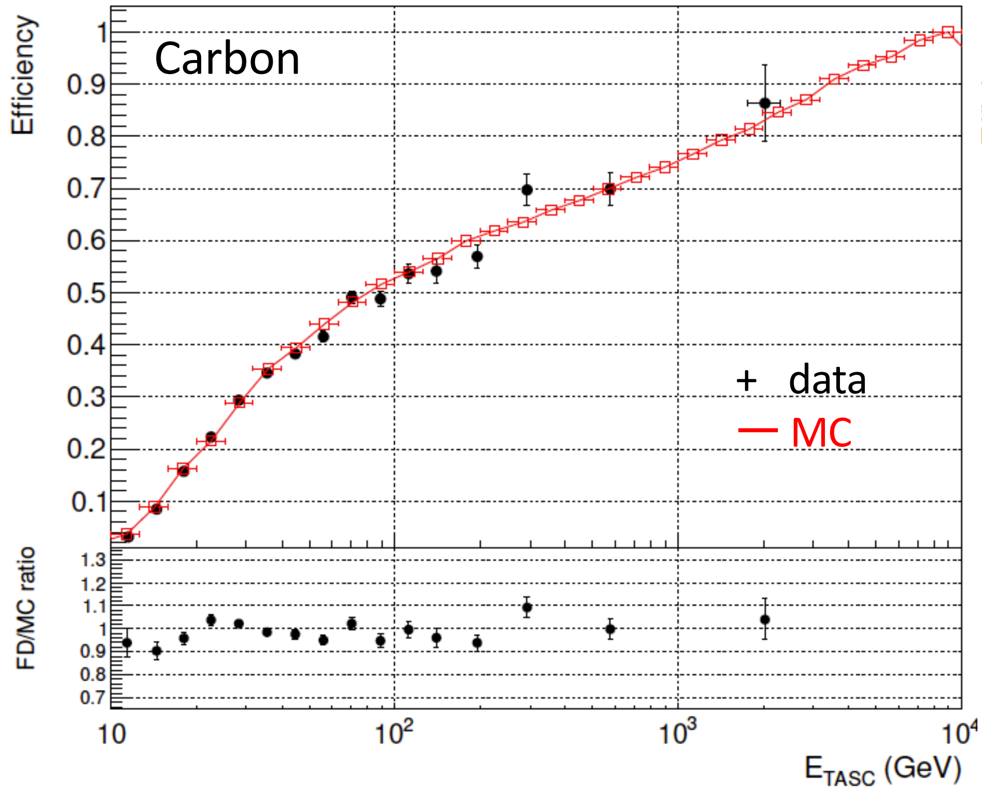
# Study of trigger efficiency

- 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

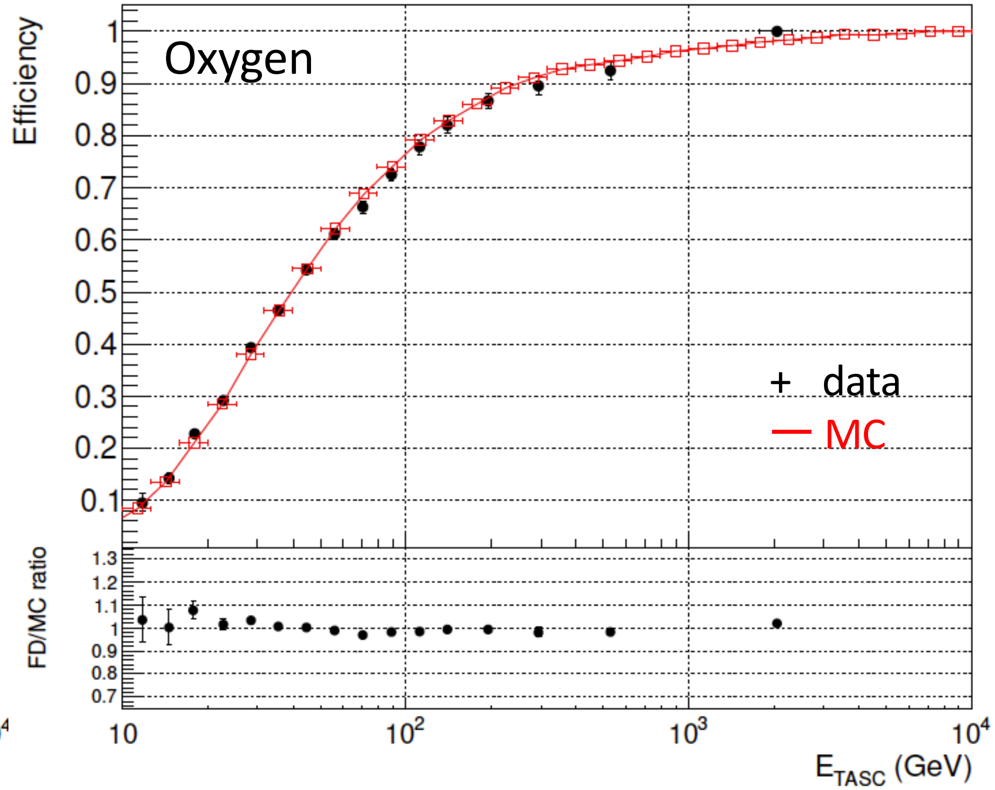
➡ HET is modelled in simulation: good agreement between MC and flight data



(HET&LET) / LET




(HET&LET) / LET



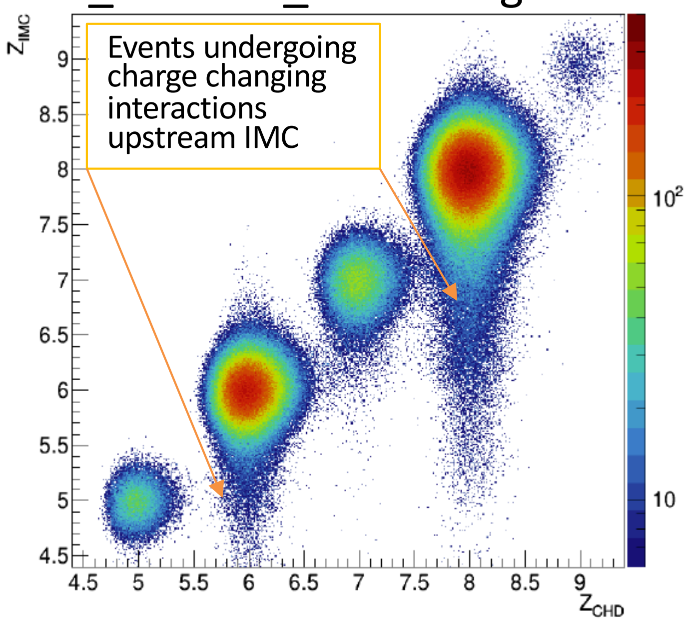
# Charge identification

Event selection

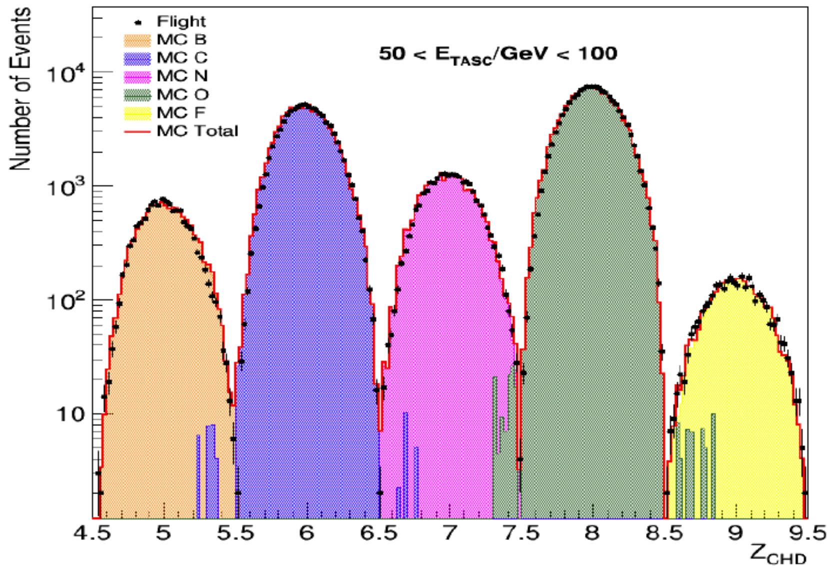
- Offline trigger confirmation
  - $N_{IMC78}$>50MIP, $N_{TASCX1}$>100MIP
- TASC lateral leakage fraction
  - $E_{TASCX1} < 0.4\ E_{TASC}$
- Remove late-interacting events
  - $E_{TASC\text{-}bottom} < 0.4\ E_{TASC}$
- Charge consistency with CHD and IMCs
  - $|Z_{CHD} - Z| < 0.4e$ & $|Z_{IMC} - Z| < 2\sigma_{IMC}$

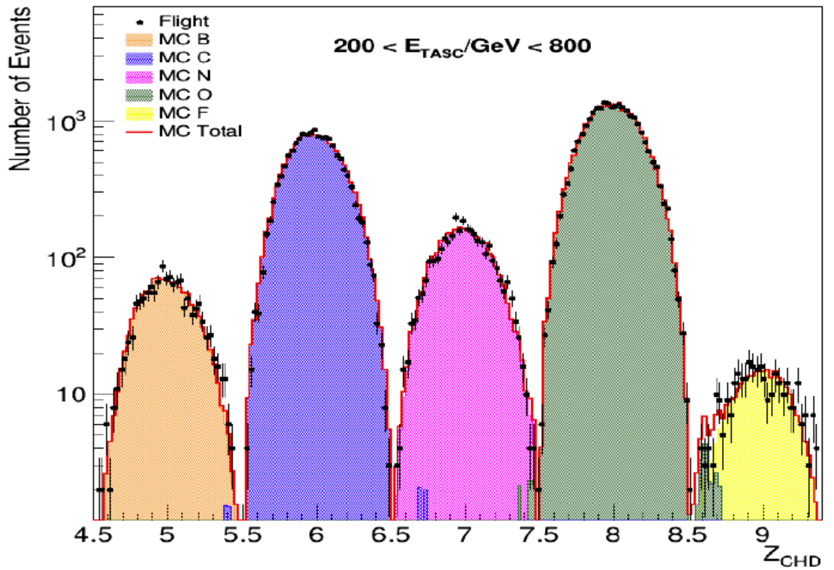
→ $6.15 \times 10^5$ events for Carbon, and
$1.05 \times 10^6$ events for Oxygen are selected

Z_IMC vs Z_CHD of flight data

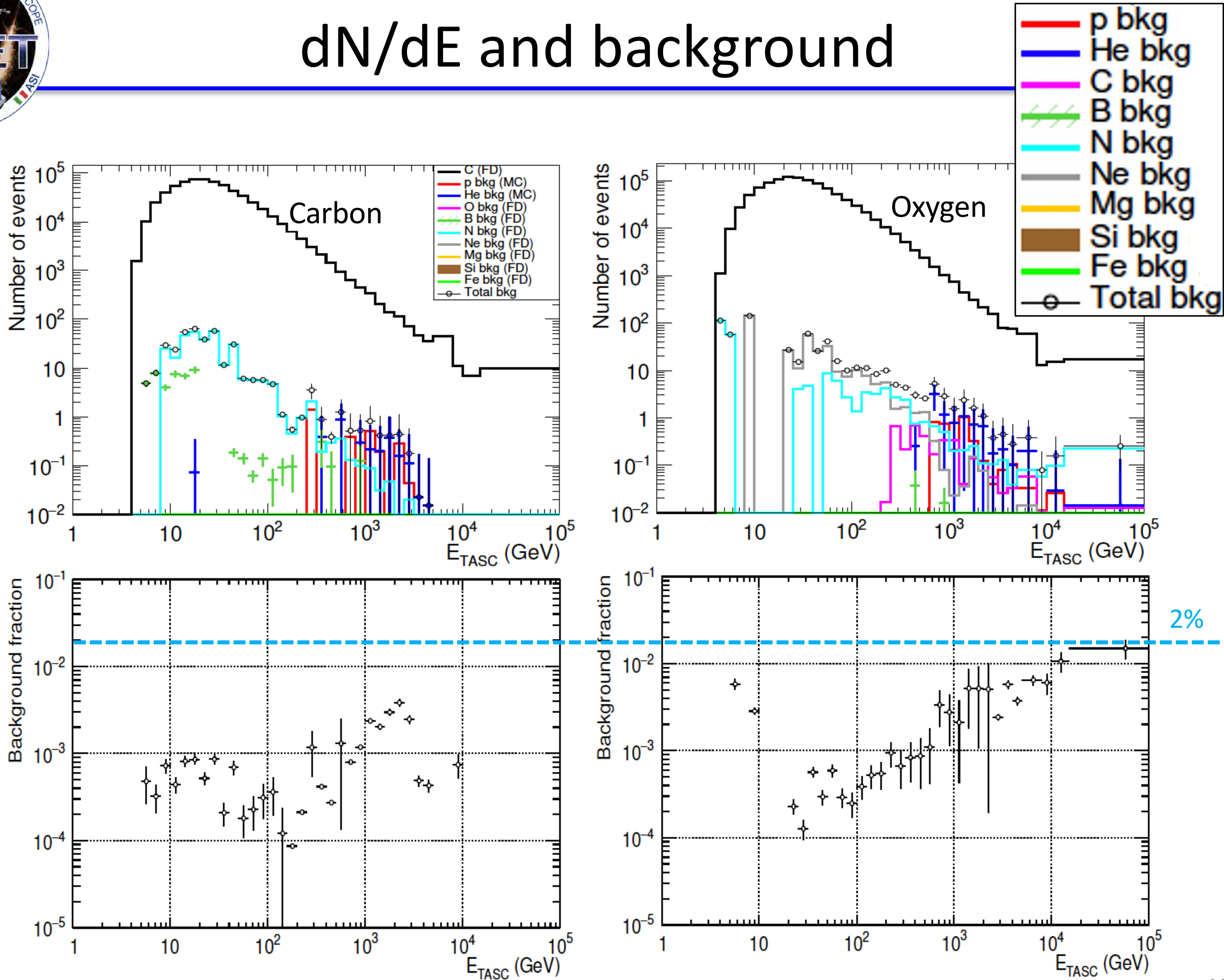



Charge distribution of CHD compared with MC



# dN/dE and background



# Energy unfolding

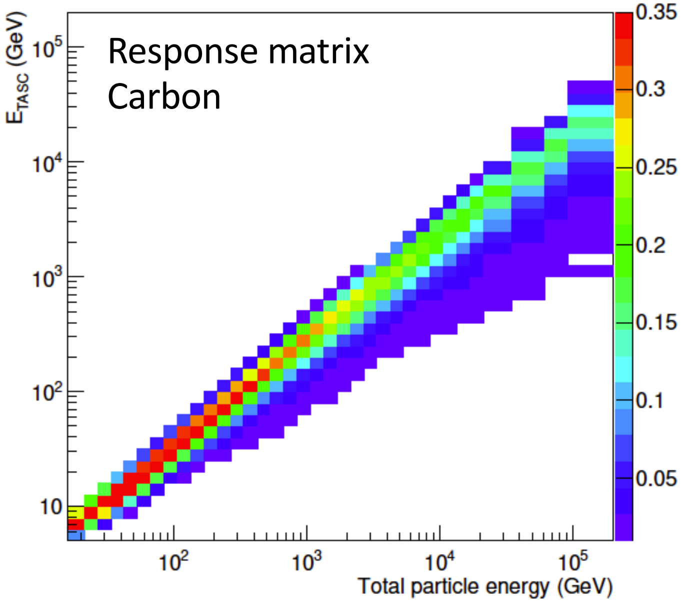
Characteristics of nuclei measurements with CALET calorimeter:

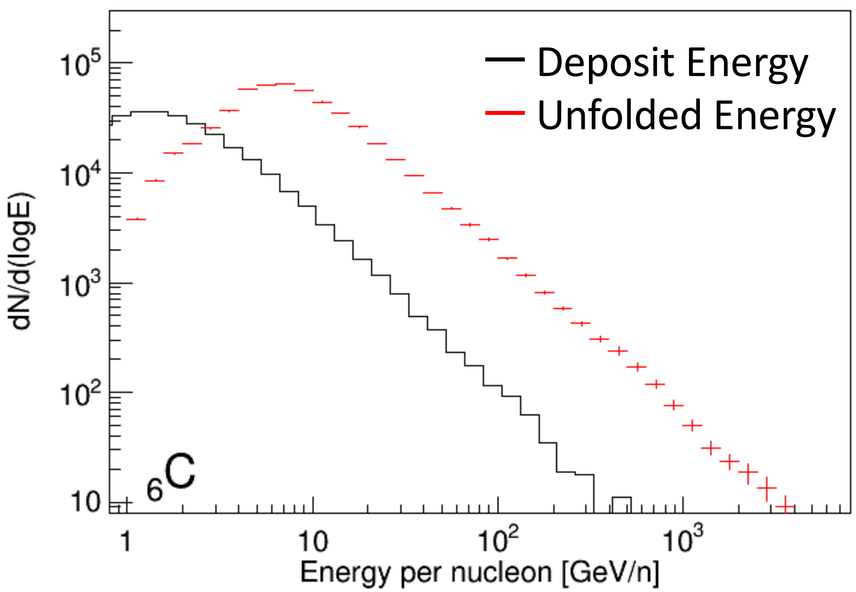
- thickness: 30 $X_0$ for electron, 1.3λ for proton
- σ(E)/E : 2% for electron, 30% for nuclei

➡ Need energy unfolding for nuclei to obtain primary energy spectrum

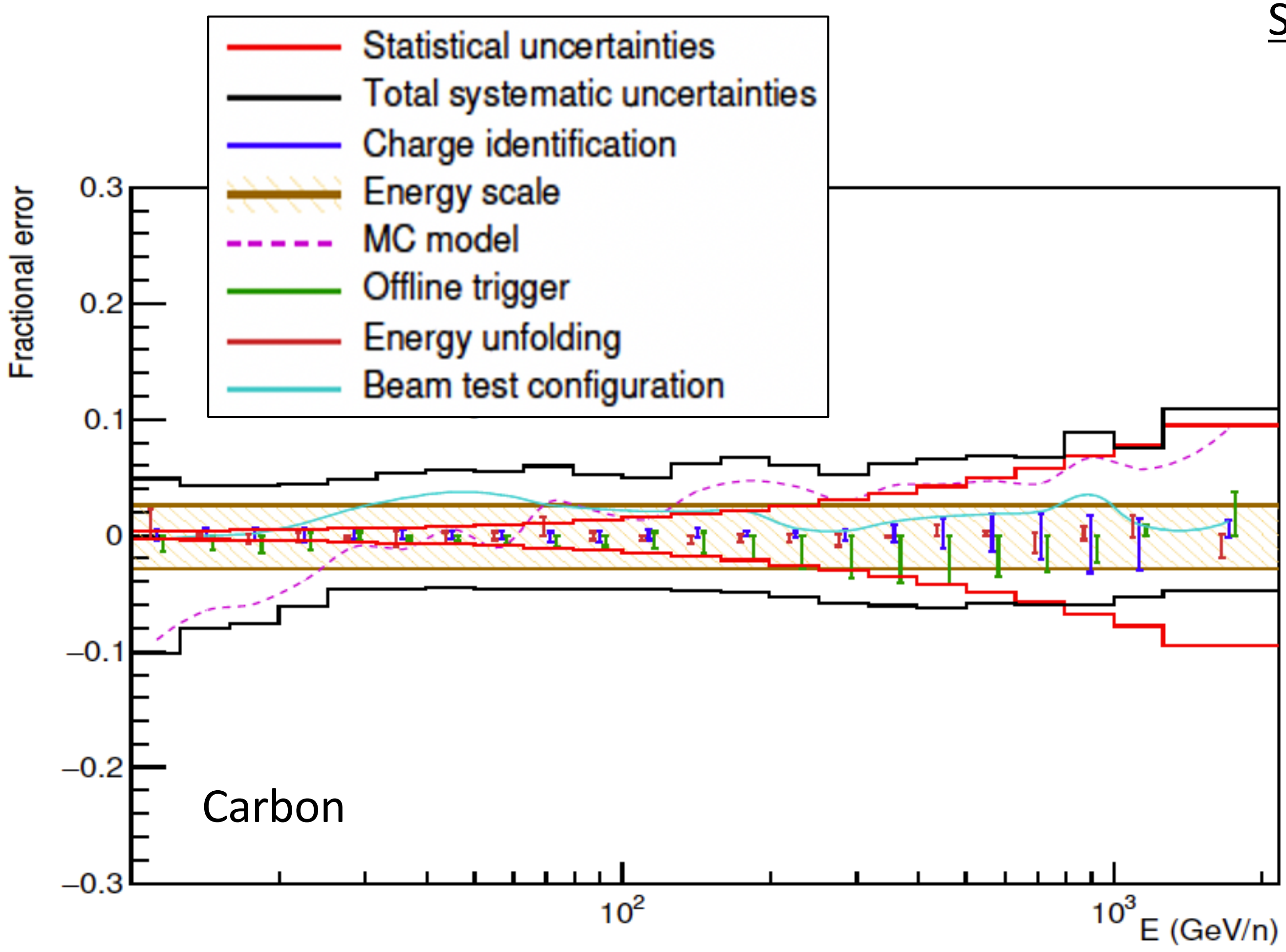
Iterative Bayesian unfolding

- Initial assuming spectra: f(E)=A x $E^{-2.60}$
  A is normalized by charge distribution in CHD
- Response function:
  $E_{TASC}$ [GeV] (deposit energy in calorimeter) vs $E_0$ [GeV] (primary energy)



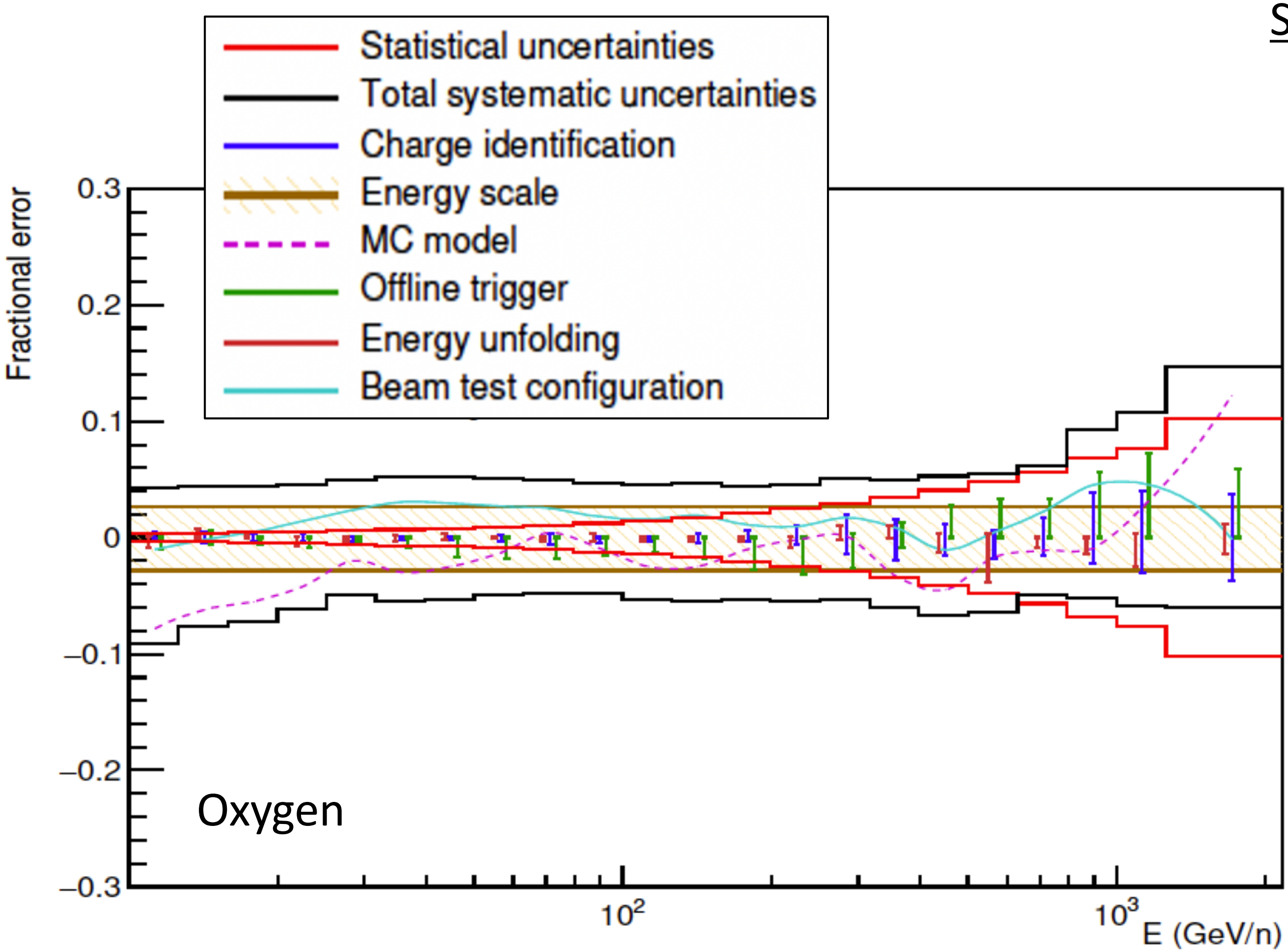
# Systematic uncertainty




Sources of systematic uncertainty

- Offline trigger threshold : 100-150MIP at TASC-X1
- Charge identification: 0.35e – 0.45e for CHD 1.75σ – 2.2σ for IMC
- Energy scale : ±2% from beam test
- Beam test configuration
- Energy unfolding : spectral index in 2.5 – 2.9
- MC model : EPICS vs FLUKA
- Live time
- Long-term stability

# Systematic uncertainty

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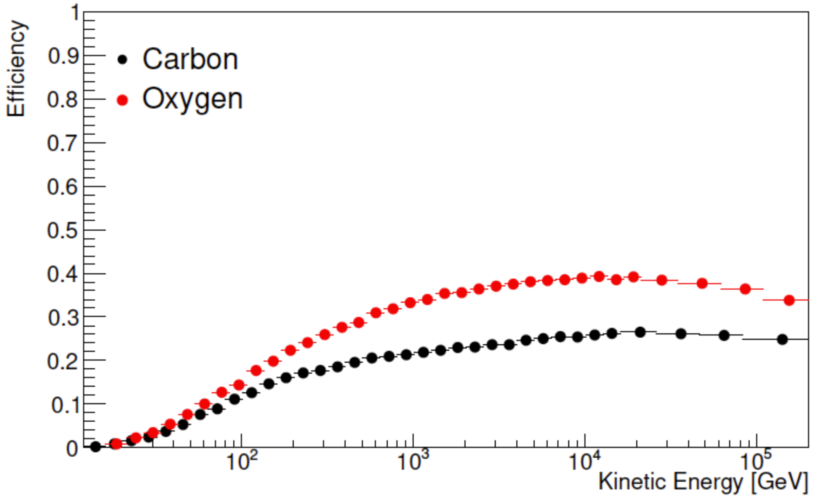
# Energy Spectra of Carbon and Oxygen

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

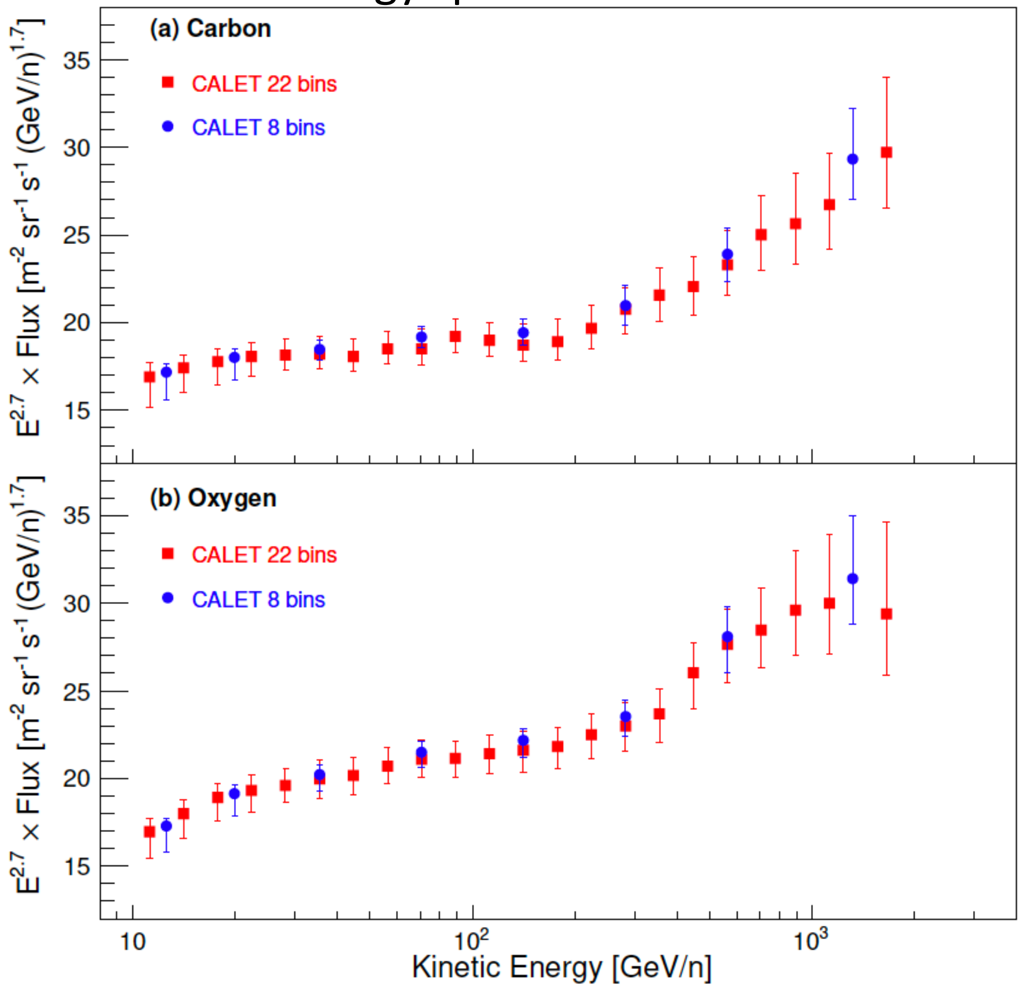
$$N(E) = U\left[N_{obs}(E_{\mathrm{TASC}}) - N_{bg}(E_{\mathrm{TASC}})\right]$$

$N(E)$ : Events in unfolded energy bin
$\Delta E$ : Energy bin width
$\varepsilon(E)$ : Efficiency
$S\Omega$ : Geometrical acceptance (510cm$^2$sr)
$T$ : Live Time (3.00 x $10^9$ hours)

Total efficiencies including HE trigger

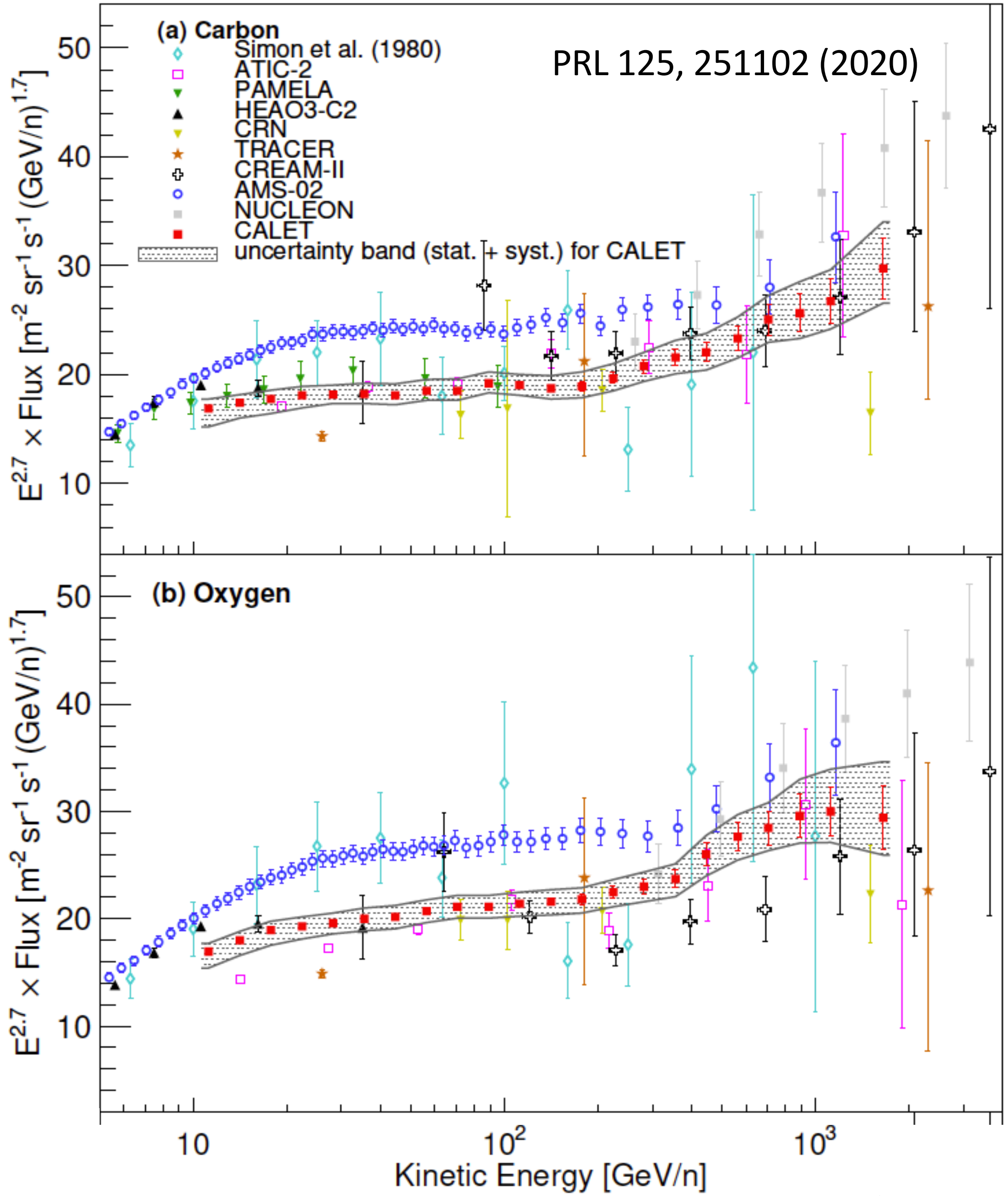


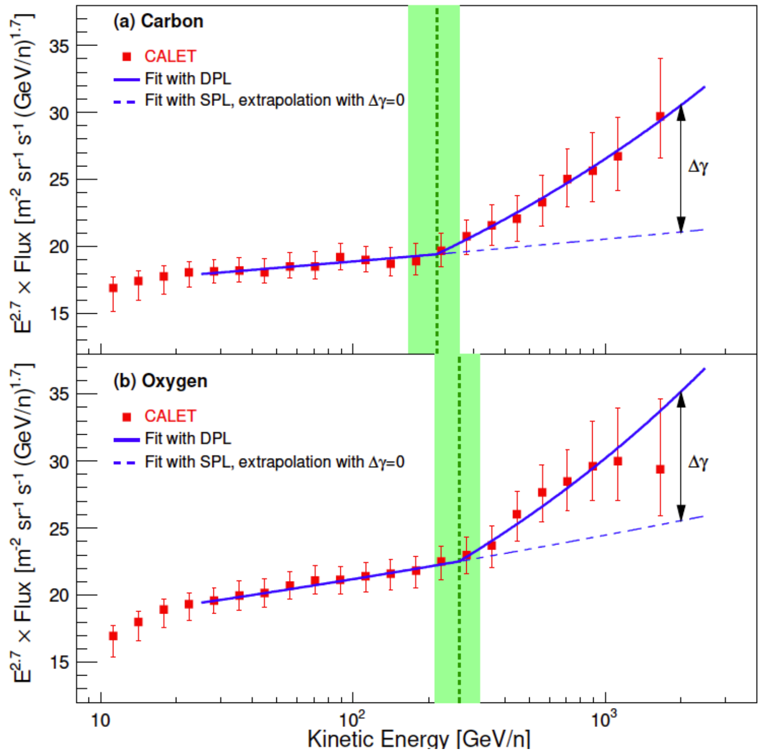

Energy spectra with CALET




The wide-bin spectra have the same shape.

# Carbon and Oxygen Spectra




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

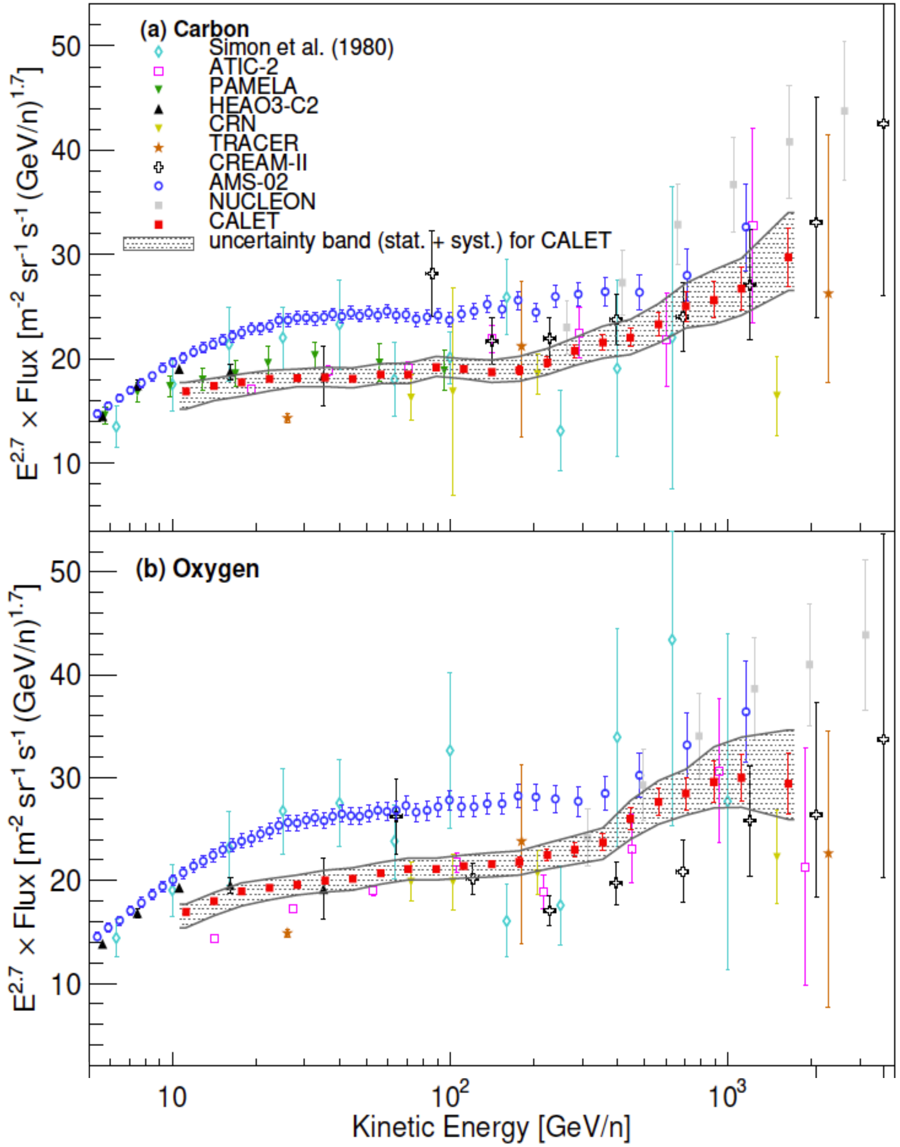
**Carbon**

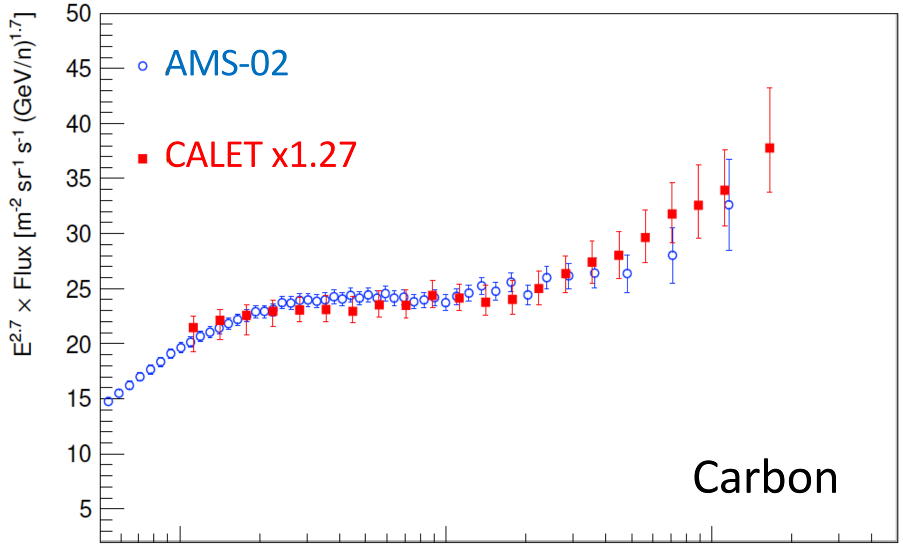
$$\begin{cases} \gamma = -2.663 \pm 0.014 \\ E_0 = 215 \pm 54\,\mathrm{GeV/n} \\ \Delta\gamma = 0.166 \pm 0.042 \;\; (4.0\,\sigma) \\ \text{with } \; \chi^2/\mathrm{d.o.f.} = 9.0/8 \end{cases}$$

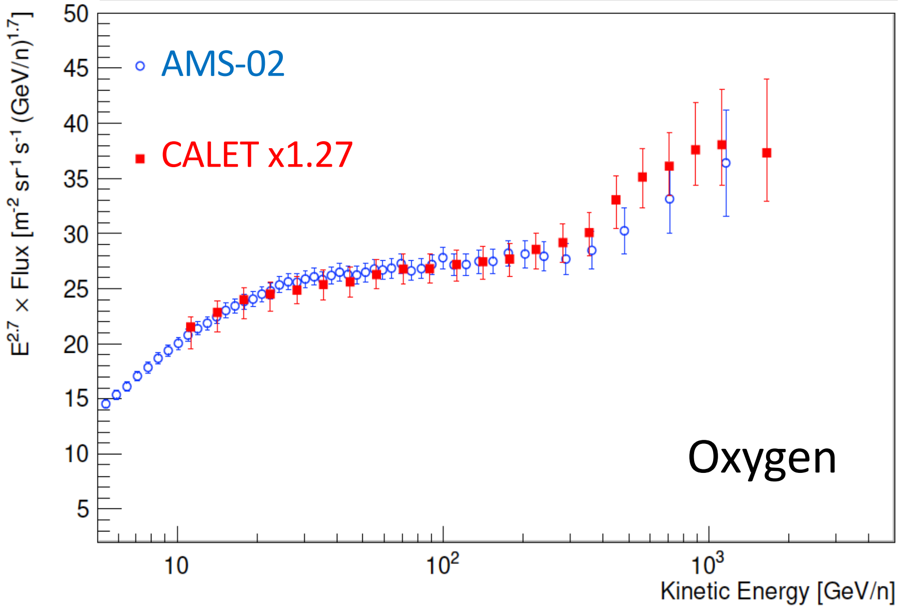
**Oxygen**

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

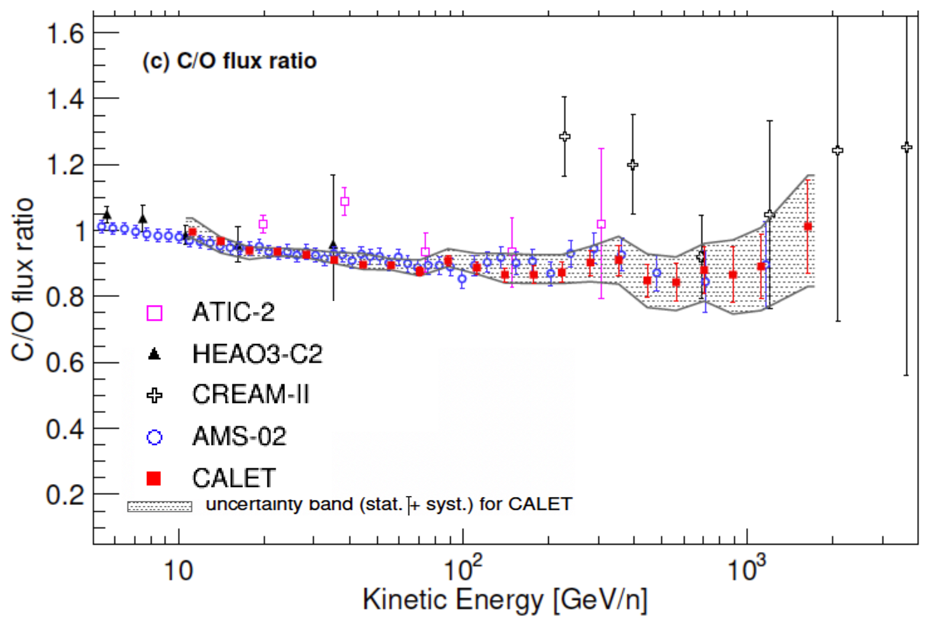
# Comparison with AMS-02

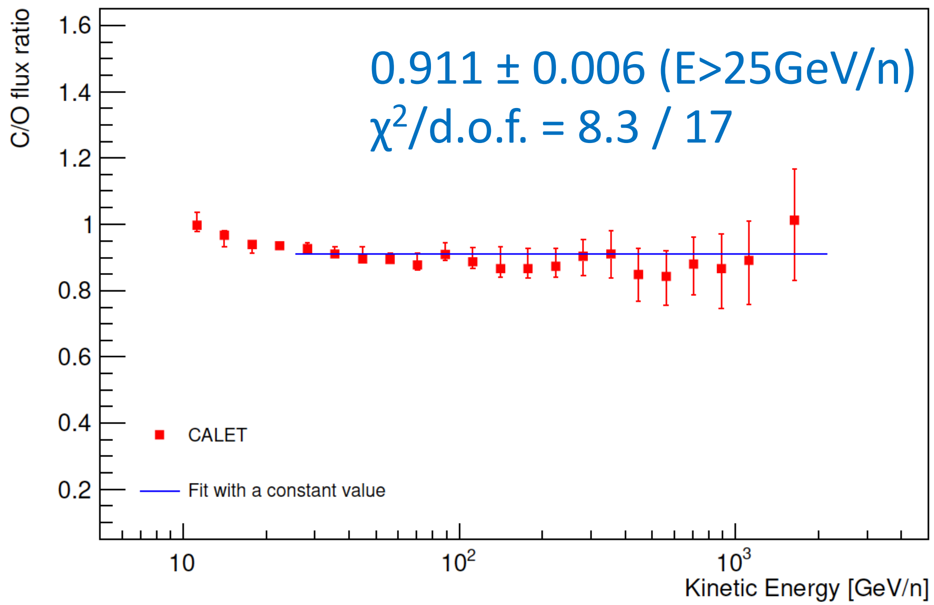


# C/O flux ratio




The carbon to oxygen flux ratio is well fitted to a constant value above 25 GeV/n, indicating that the two fluxes have the same energy dependence

# Summary

- CALET has measured the energy spectra of carbon and oxygen from 10 GeV/n to 2.2 TeV/n, and the results was published from PRL 125, 251102 (2020)
  - $6.154 \times 10^5$ events for carbon and $1.047 \times 10^6$ events for oxygen are selected in the data during 1,480 days of operation
  - Our observations allow to exclude a single power law spectrum for C and O by more than $3\sigma$
    - C : $\gamma = -2.663 \pm 0.014$, $E_0 = 215 \pm 54$ GeV/n, $\Delta\gamma = 0.166 \pm 0.042$
    - O: $\gamma = -2.637 \pm 0.009$, $E_0 = 264 \pm 53$ GeV/n, $\Delta\gamma = 0.158 \pm 0.053$
  - The spectra of C and O show the same energy dependence above 25 GeV/n
  - The spectral hardening is consistent with that measured by AMS-02, but the absolute normalization of the flux is about 27% lower, though in agreement with observations from previous experiments including the PAMELA spectrometer

- To understand the spectral hardening, the measurements of the spectra of heavier nuclei such as Fe and the secondary-to-primary ratio such as B/C would be important, and the analysis is ongoing