CALETによる炭素と酸素のエネルギースペクトル硬化の検出

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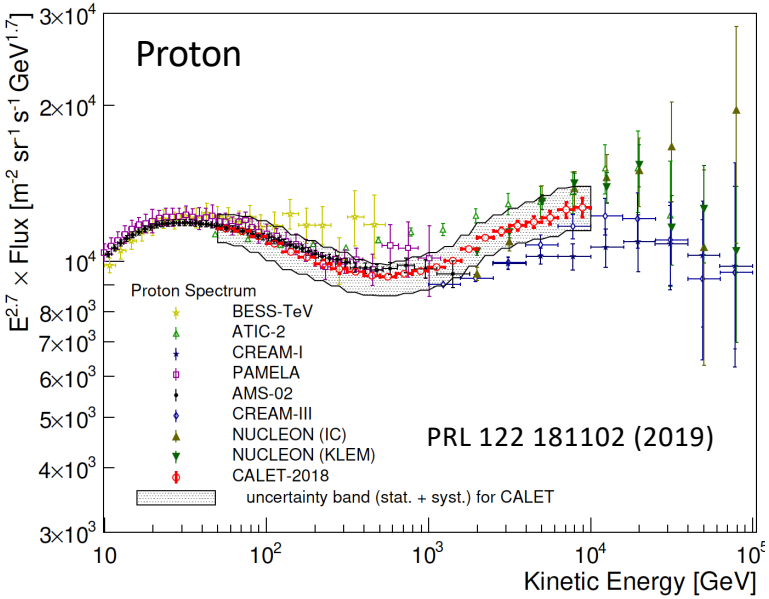
Energy Spectra of Galactic Cosmic Rays

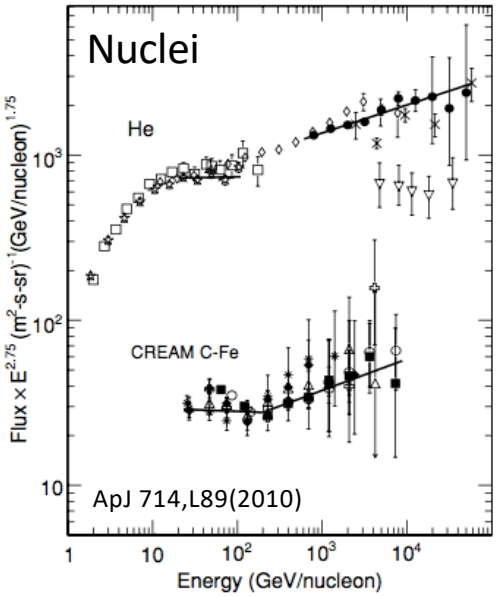
"Standard" model of galactic cosmic rays

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

Unexpected observation results

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





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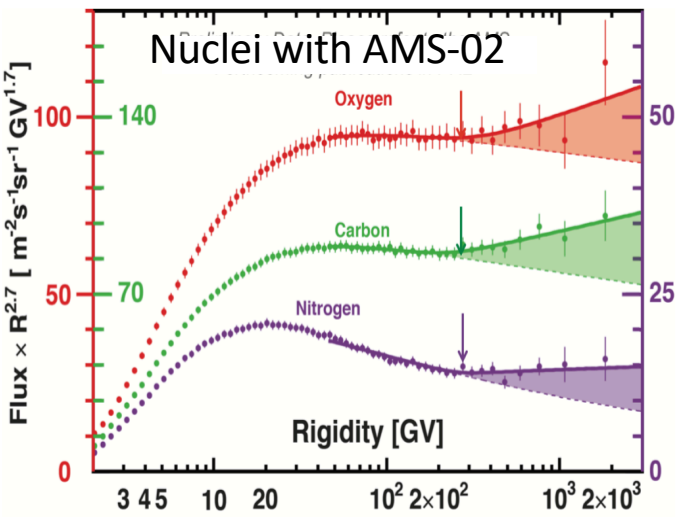
PRL 119 251101 (2017)



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

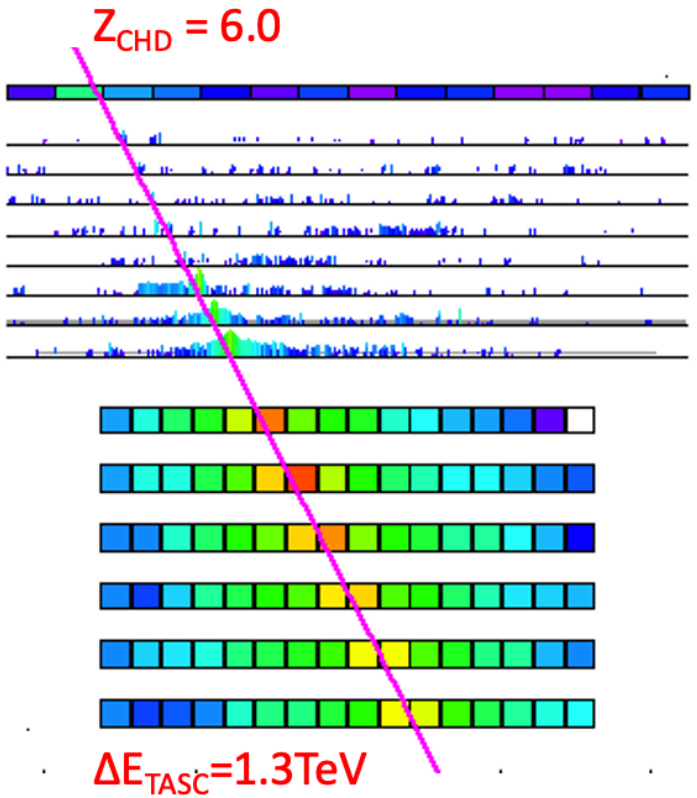
- HE + offline shower trigger
  - 50MIP in IMC-X/Y78, 100MIP in TASC-X1
- Tracking with IMC
- Acceptance cut
  - CHD, TASC top (2cm from edge) and bottom layers
- Charge identification with CHD and IMC
- Background estimation
- Energy measurement and unfolding
- Flux calculation

MC data

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

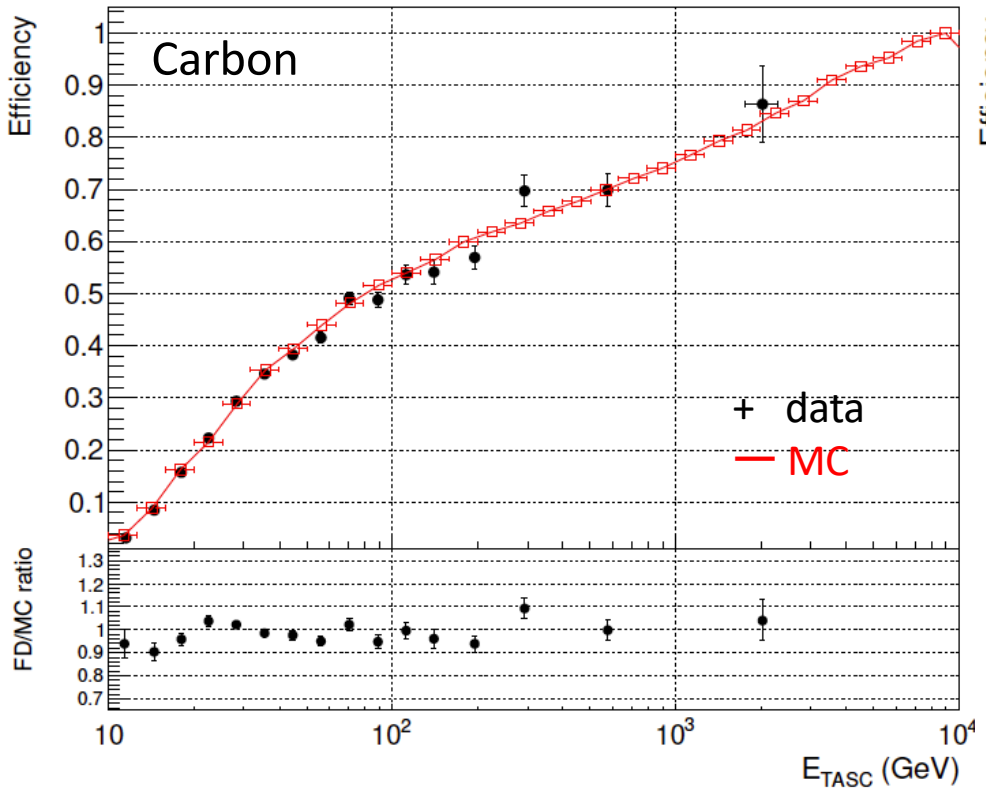
Digitization of signals in simulation are modelled and tuned by beam test results and flight data; quenching, noise and saturation.

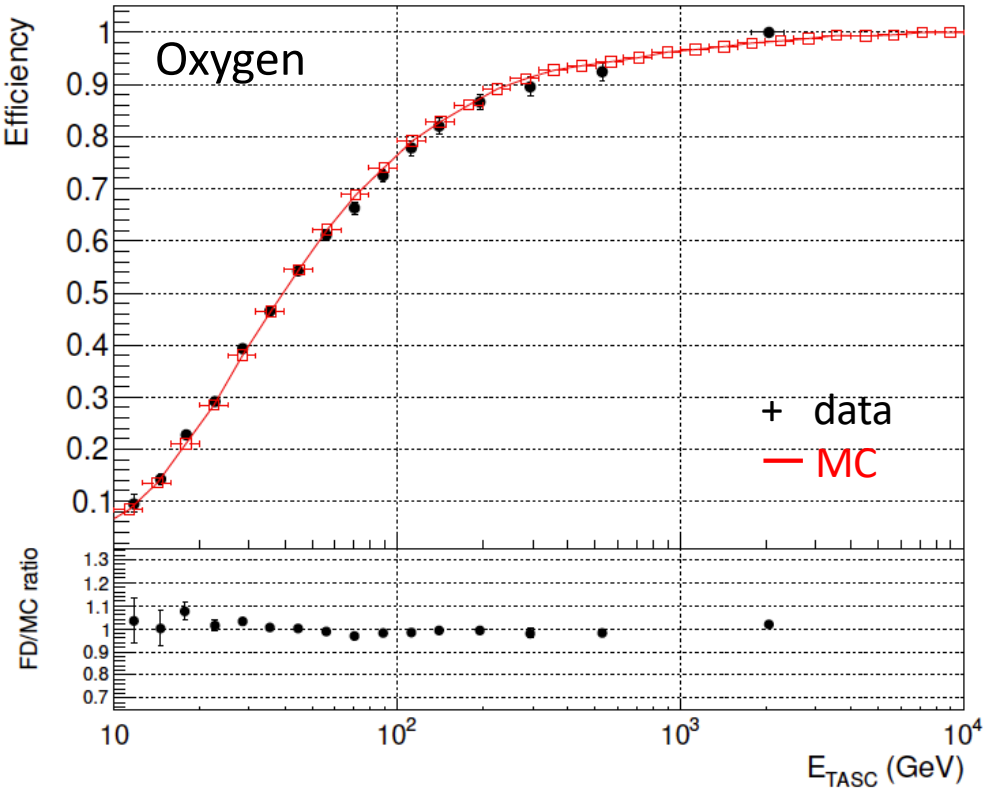
An example of Carbon event from Flight data



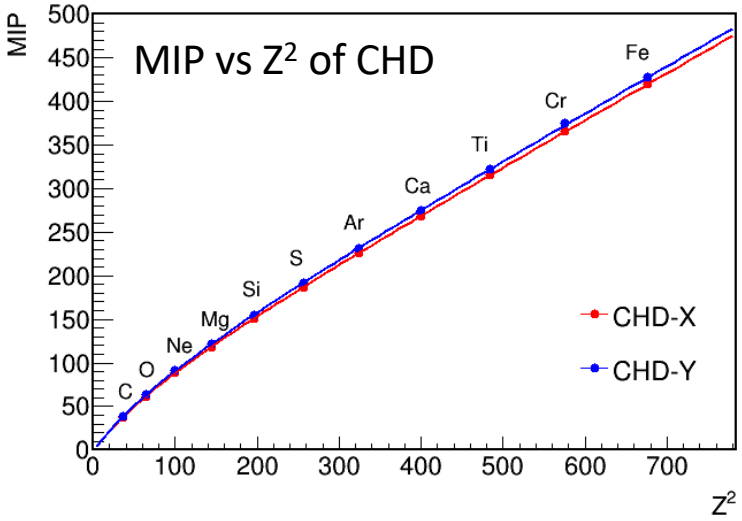
Study of trigger efficiency

- High-Energy Trigger (HET) is the primary CALET mission trigger, which is based on the coincidence of signals in last two IMC layers and top TASC layer
- HET efficiency for nuclei is measured using subset of data taken with the same trigger logic but lower threshold (allonging to trigger also penetrating particles)
- HET is modelled in simulation: good agreement between MC and flight data



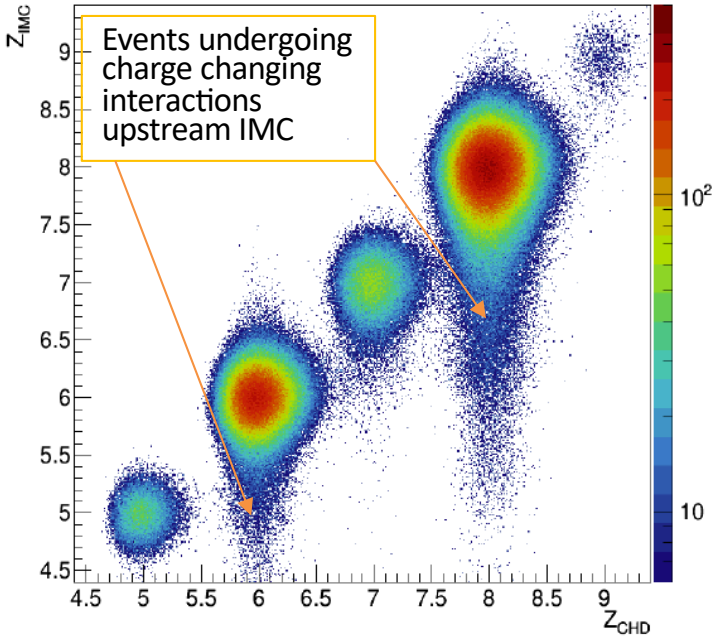


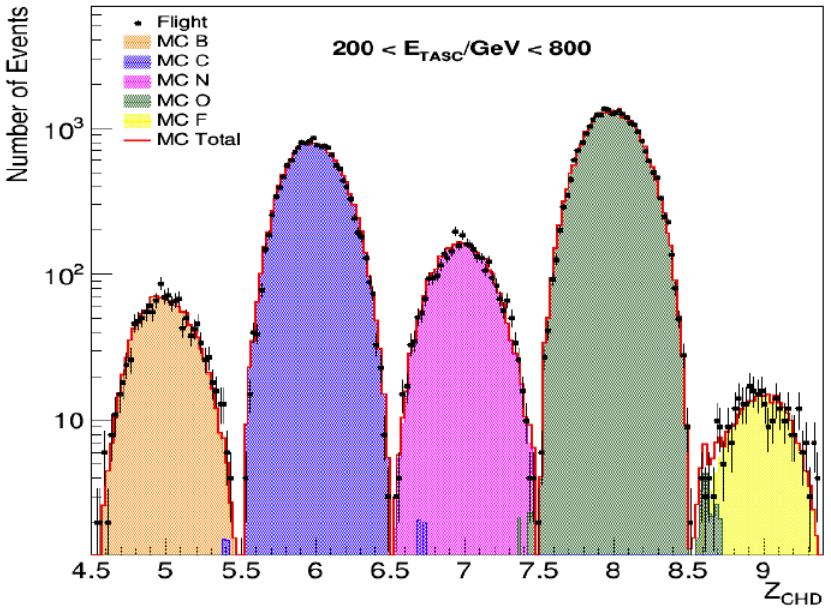
Charge identification



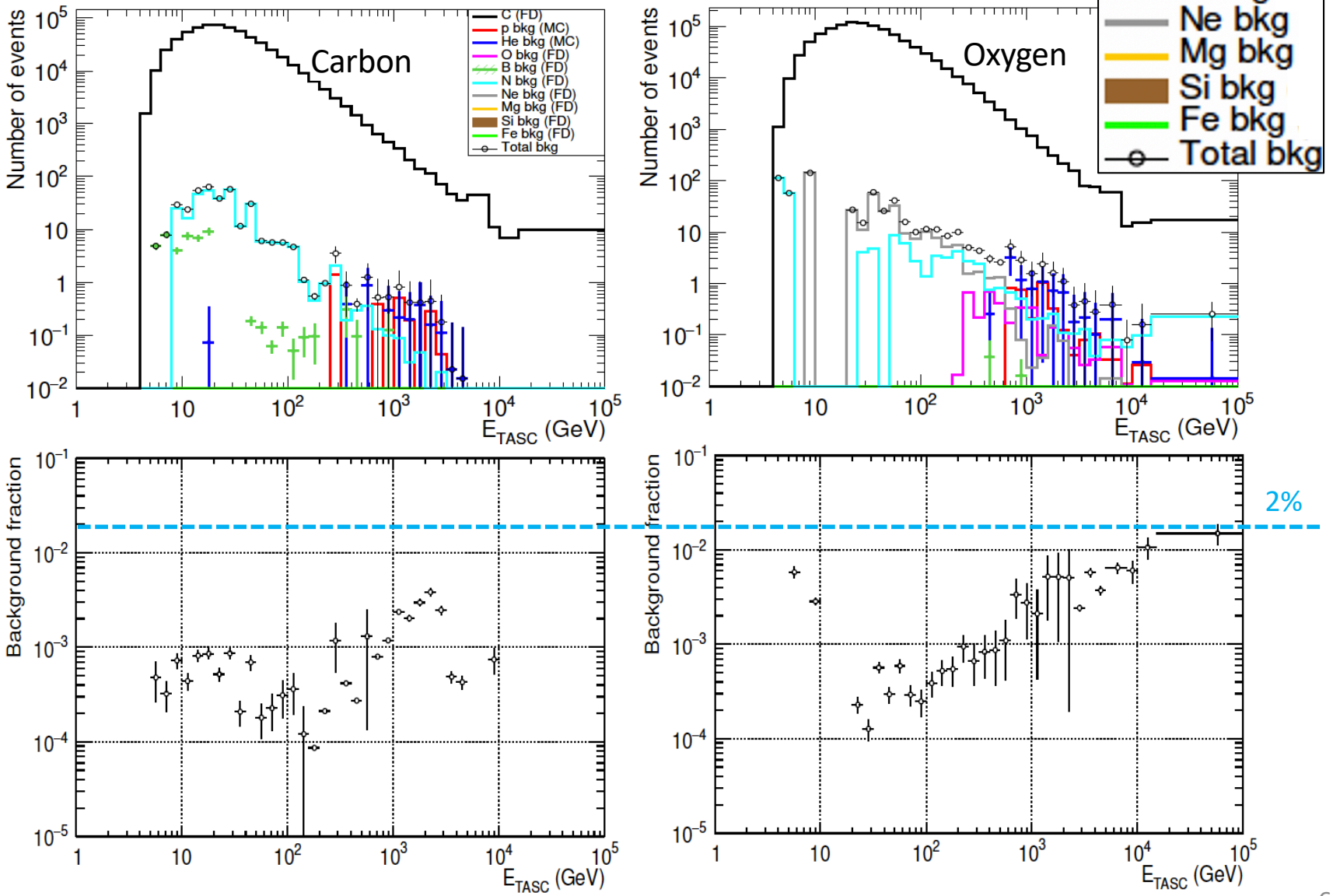
- Redundant charge measurements by combined CHD and multiple dE/dx in IMC fibers in the fast 4 X,Y layers
- Non-linear response to Z^2 due to light saturation in the scintillators is corrected from flight data
- Charge resolution;
  - CHD σ_Z ~ 0.15*e* in BCNO
  - IMC σ_Z ~ 0.20*e* in BCNO

→ Events with Z±0.4*e* are selected for flux calculation





dN/dE and background



Energy unfolding

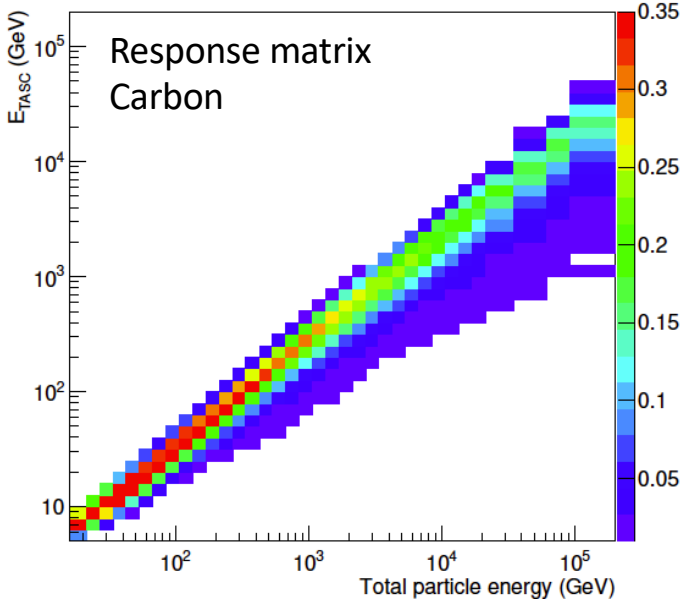
Characteristics of nuclei measurements with CALET calorimeter:

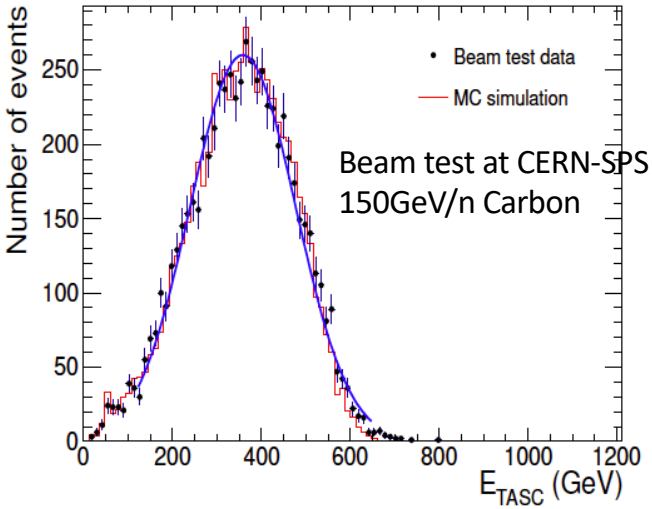
- thickness: 30 X_0 for electron, 1.3λ for proton
- σ(E)/E : 2% for electron, 30% for nuclei

➡ 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)



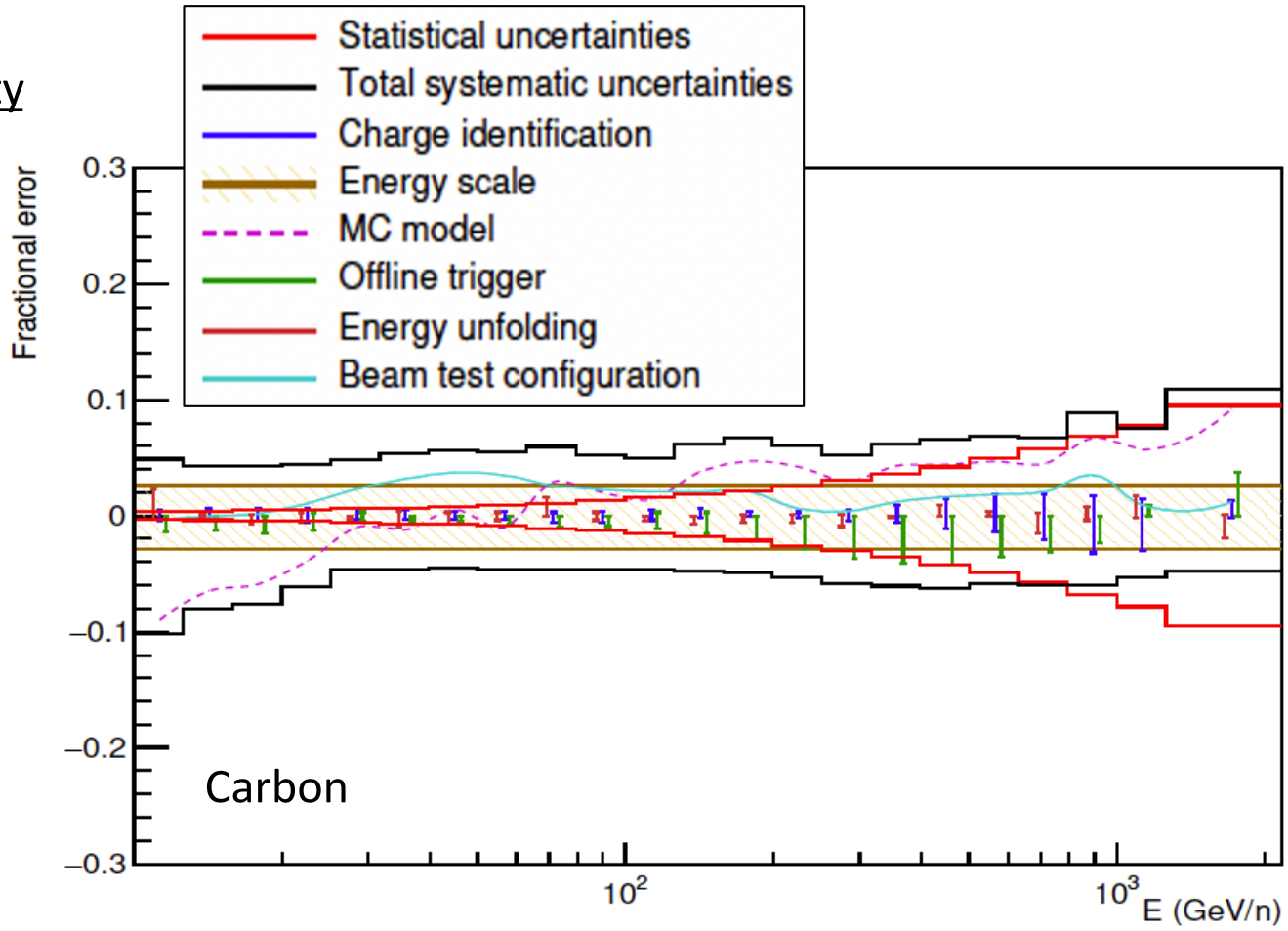


Correction factors of MC are 6.7% for E_{TASC}<45GeV and 3.5% for E_{TASC} >350GeV, respectively, while a simple linear interpolation Is used to determine the correction factor for intermediate energies

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
- MC model :
  EPICS vs FLUKA
- Energy unfolding :
  spectral index in 2.5 – 2.9
- Beam test configuration
- Live time
- Long-term stability



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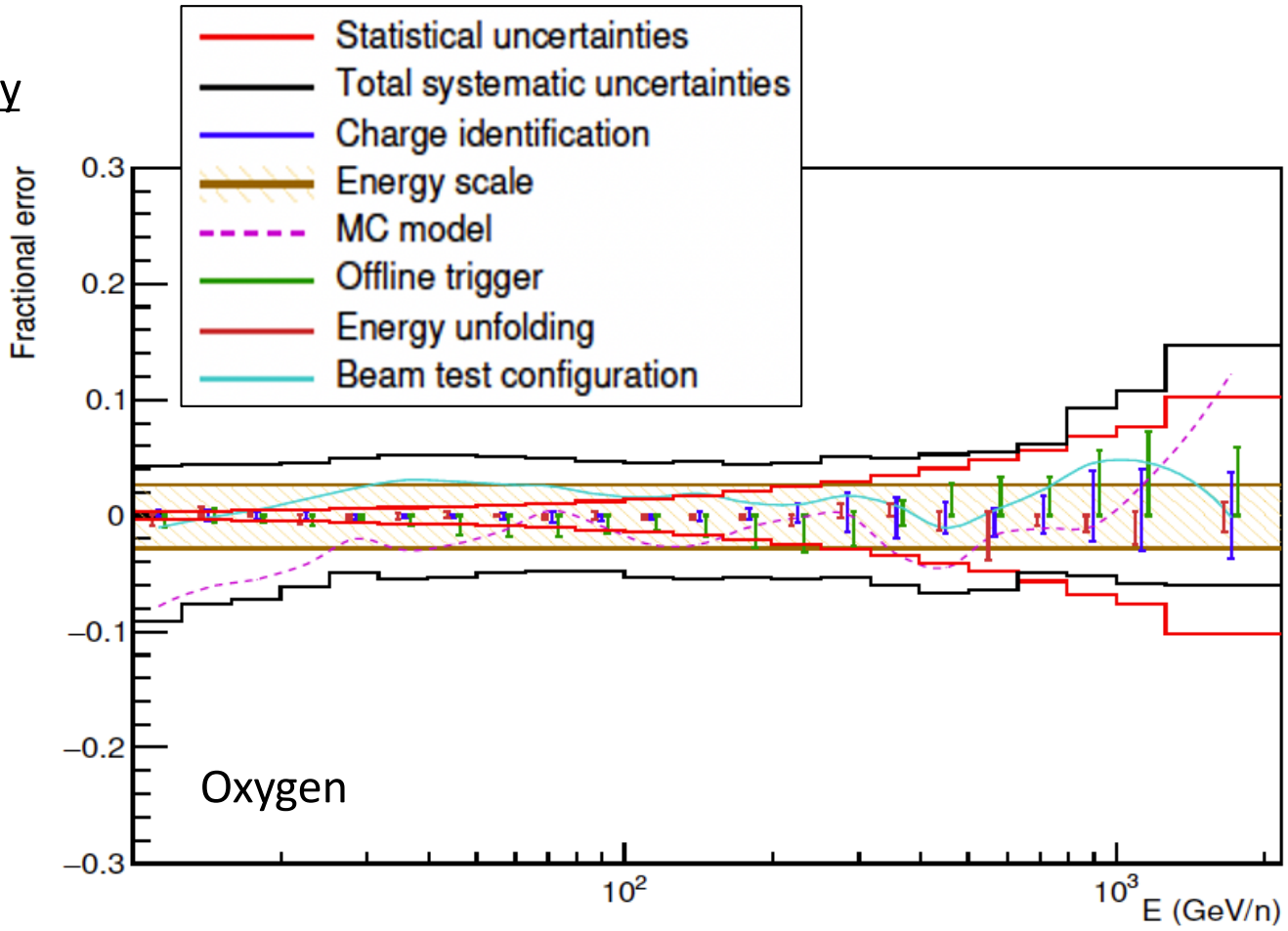


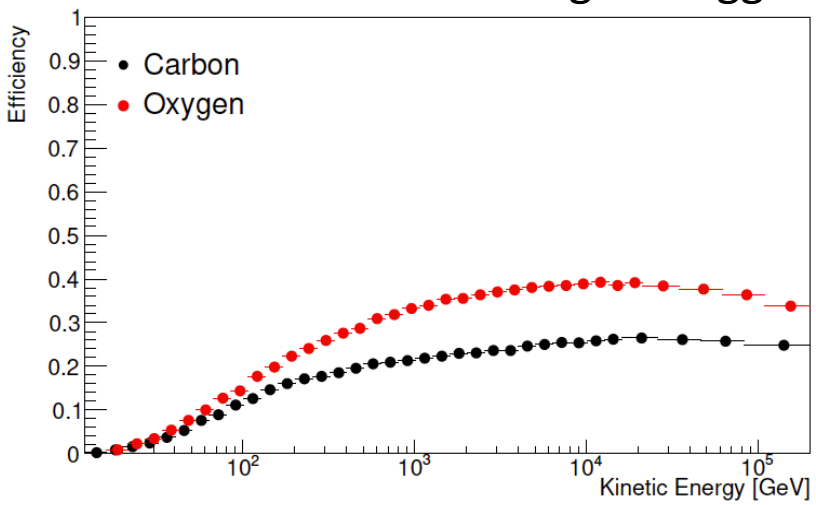
Energy spectra of C and O and the ratio

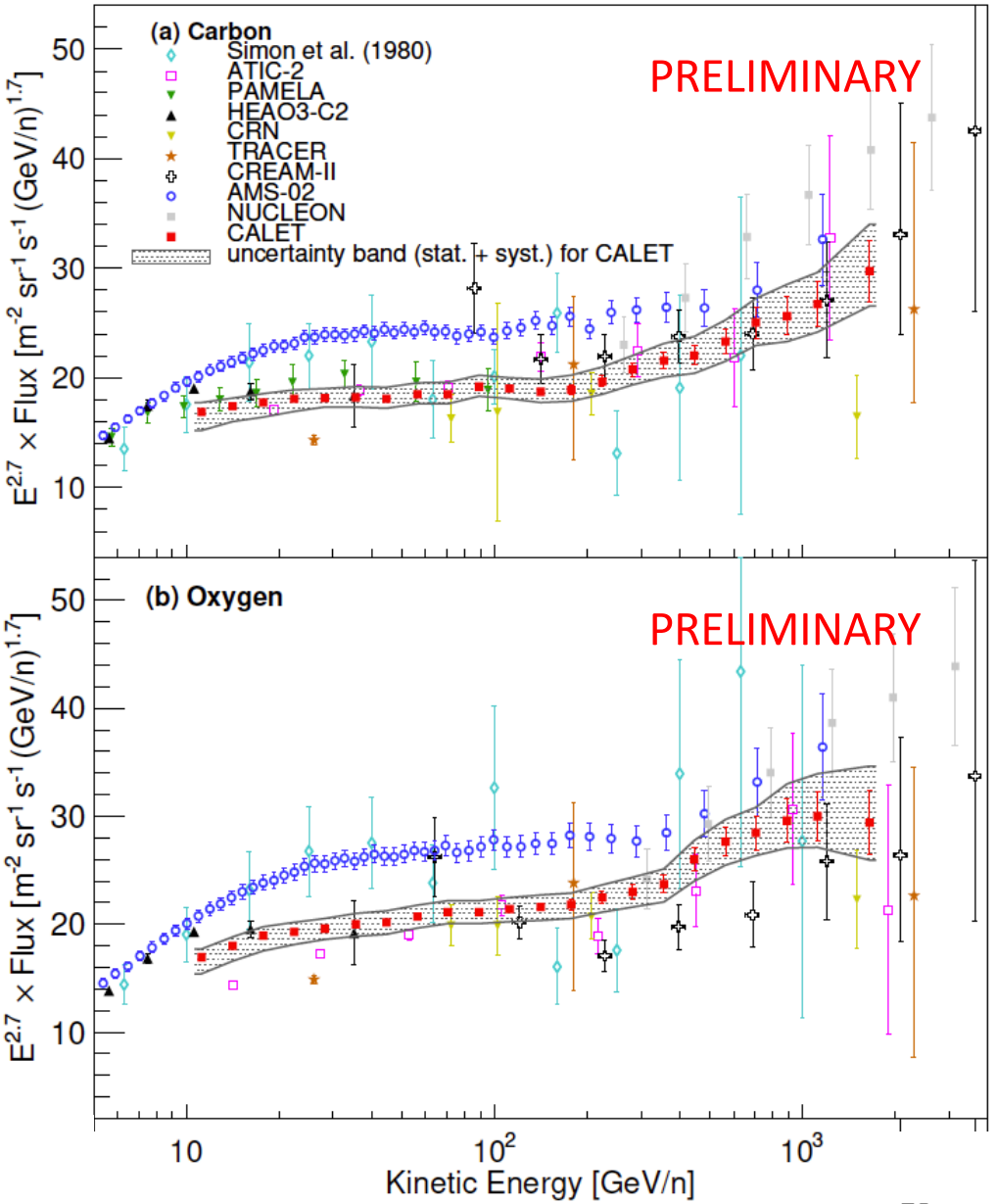
$$\Phi(E) = \frac{N(E)}{\Delta E\, \varepsilon(E)\, S\Omega\, T}$$

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

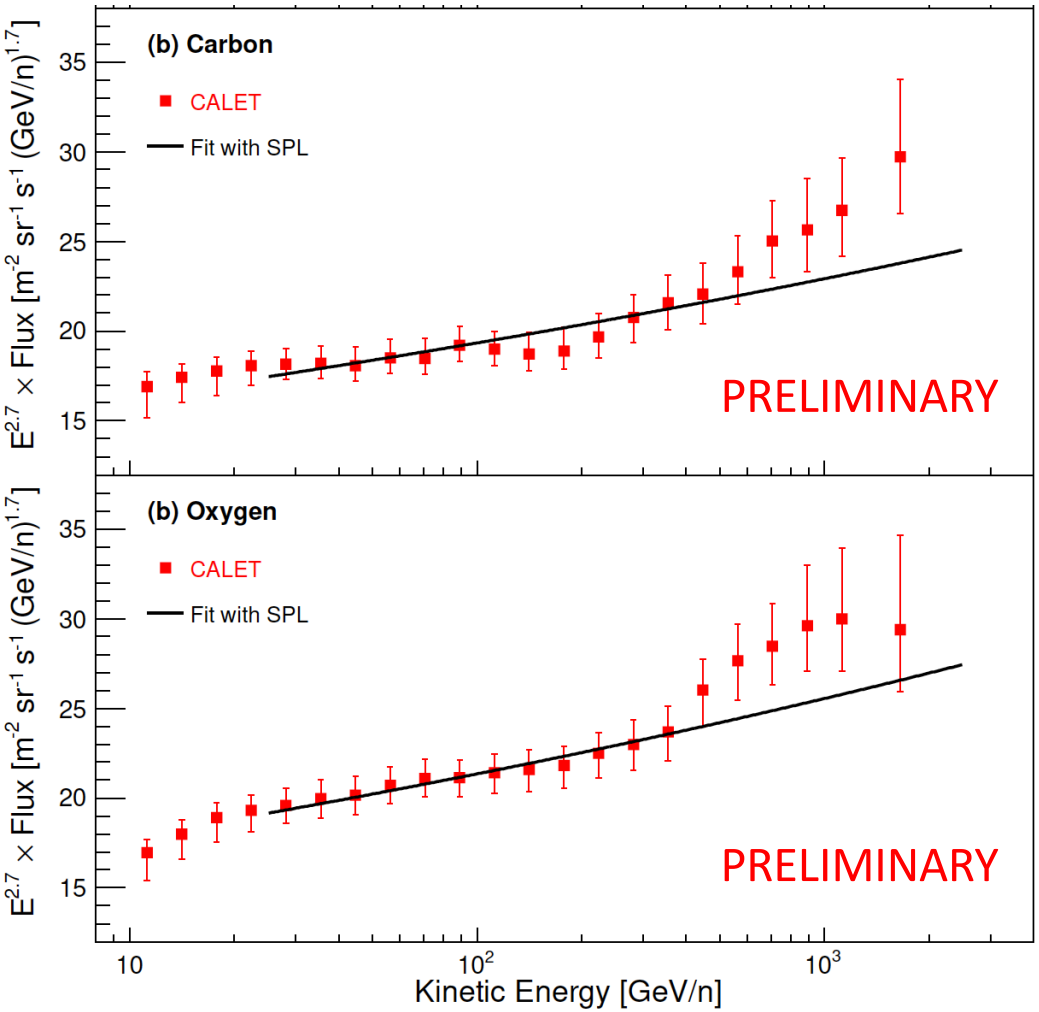
$N(E)$: Events in unfolded energy bin
ΔE : Energy bin width
$\varepsilon(E)$: Efficiency
$S\Omega$: Geometrical acceptance (510cm^{2}sr)
T : Live Time (3.00 x 10^9 hours)

Total efficiencies including HE trigger





Fitting with single power law function



$$\Phi(E) = C \left(\frac{E}{\mathrm{GeV}} \right)^{\gamma}$$

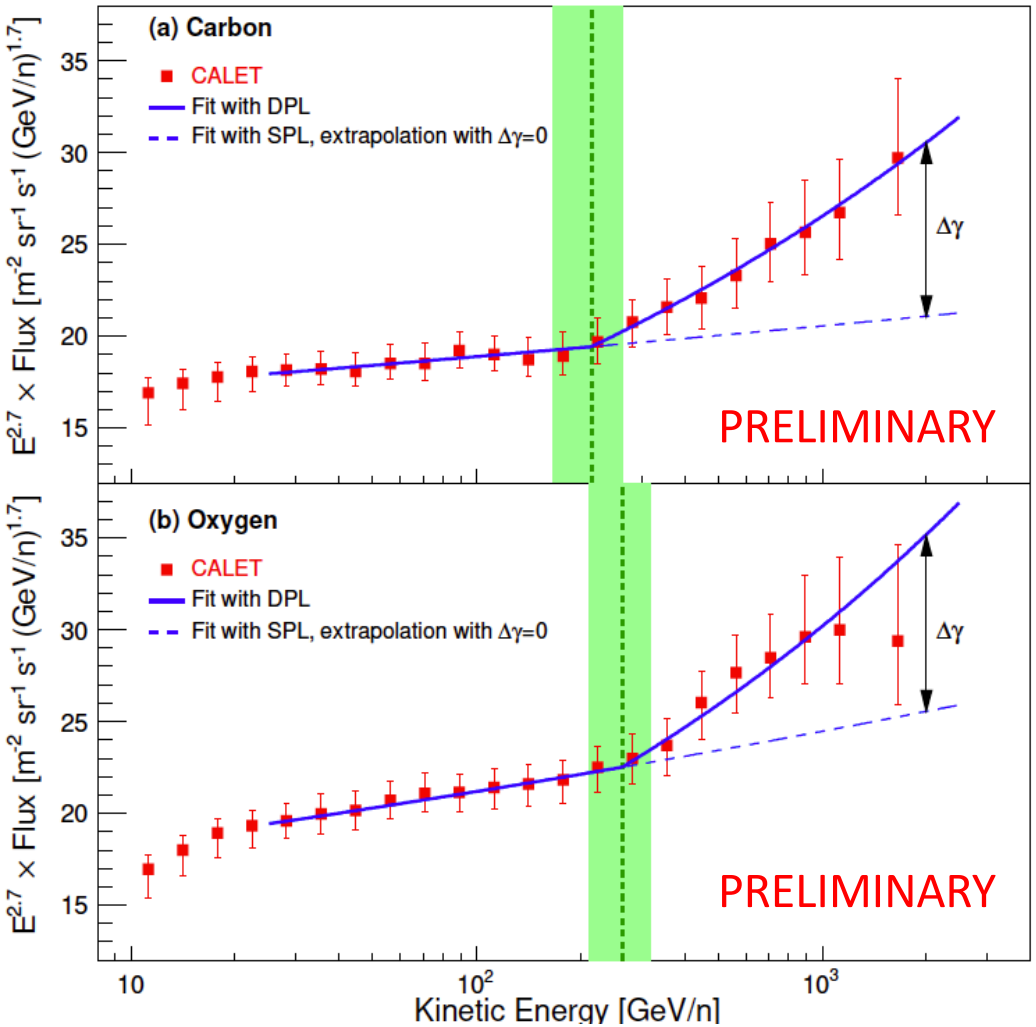
Fitting results of Carbon

$$\gamma = -2.626 \pm 0.010$$
$$\text{with } \chi^2/\text{d.o.f.} = 27.5/10$$

Fitting results of Oxygen

$$\gamma = -2.622 \pm 0.008$$
$$\text{with } \chi^2/\text{d.o.f.} = 15.9/10$$

Fitting with double power law function



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

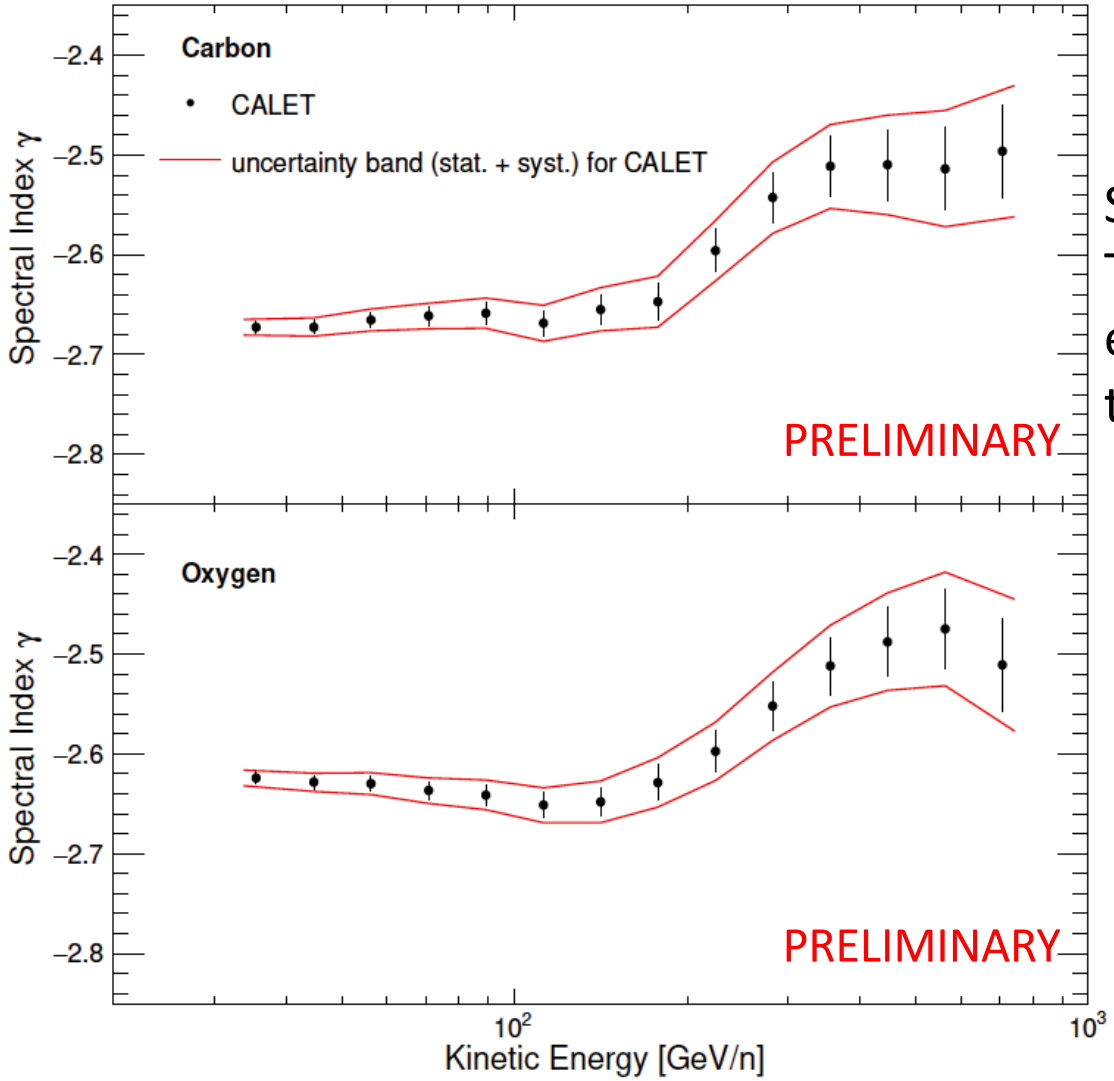
Fitting results of Carbon

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

Fitting results of Oxygen

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

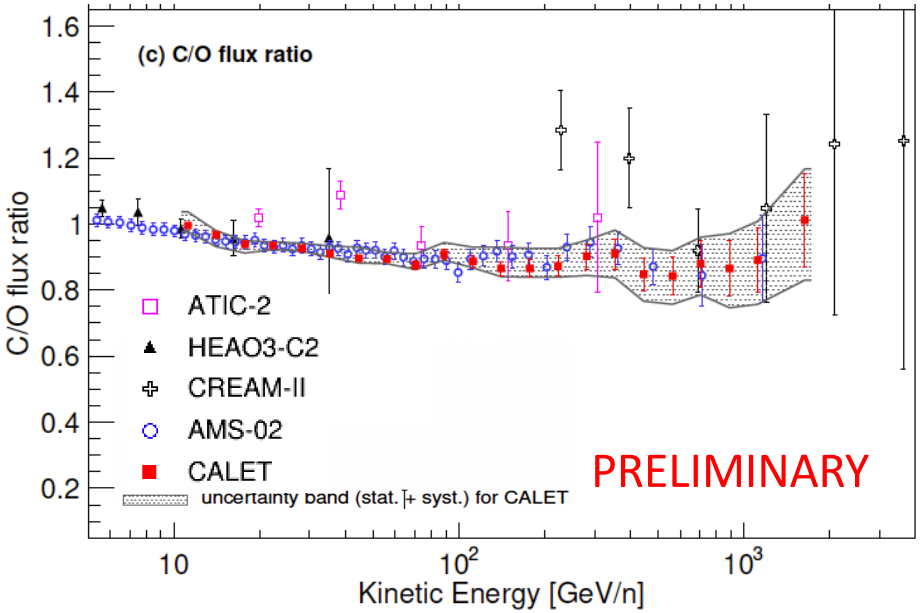
Spectral indies of C, O spectra

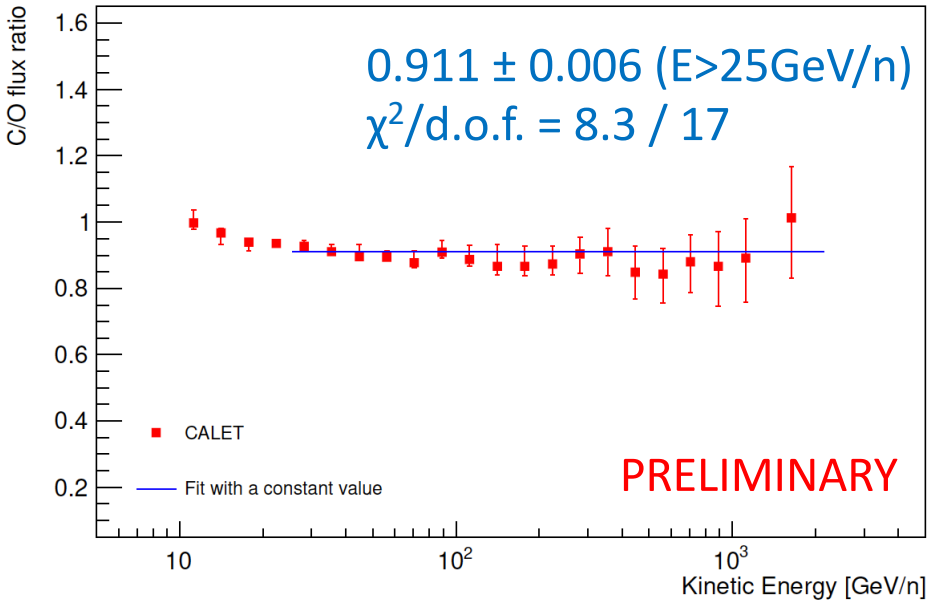


Sliding energy window method
The spectral index is computed for each bin by a fit to data including the neighbor ± 3 bins

Clear Hardening of the spectra above a few hundred GeV

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 with C: 6.154×10^5 and O: 1.047×10^6 events based on 1,480 days of operation

- Two independent analysis in CALET team was carried out, both of which are well consistent

- Our observations allow to exclude a single power law spectrum for C and O by more than 3σ; they show a spectral index increase and the same energy dependence above 25GeV/n
  - 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 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