Energy spectra of carbon and oxygen cosmic rays with CALET on the International Space Station

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On behalf of the CALET collaboration

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THE ASTROPARTICLE PHYSICS CONFERENCE
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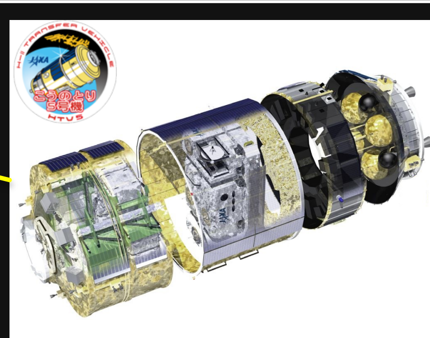
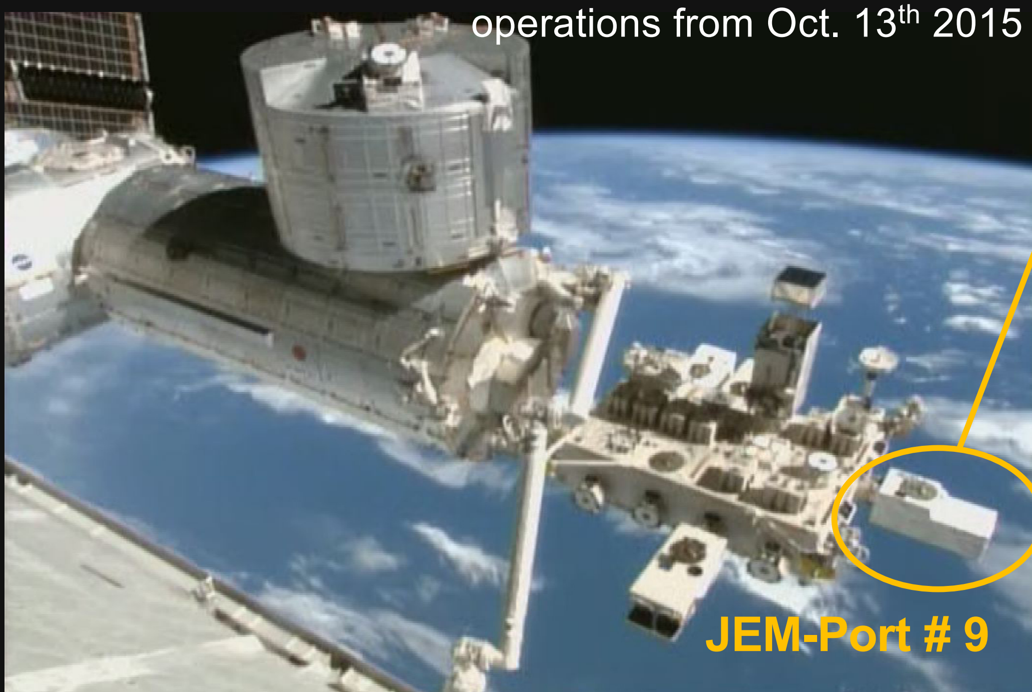
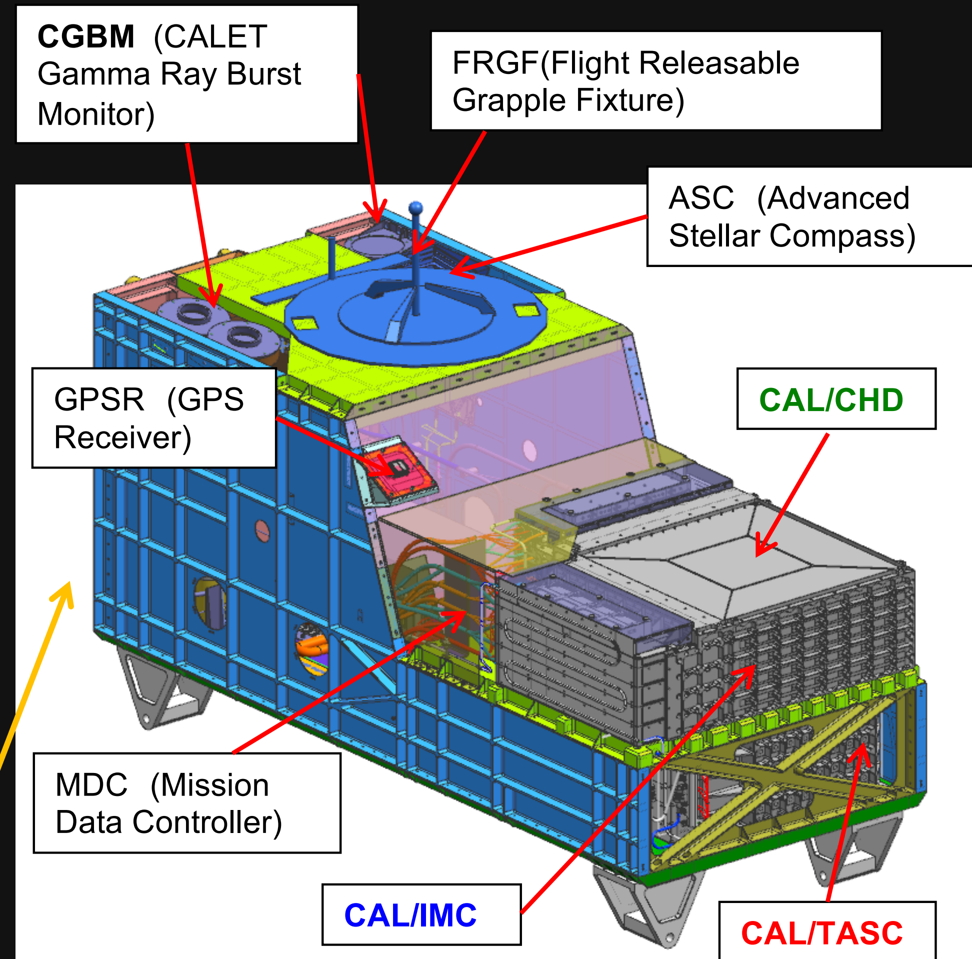
CALET payload



Launched on Aug. 19th 2015 on the Japanese H2-B rocket
Emplaced on JEM-EF port#9
On Aug. 25th 2015

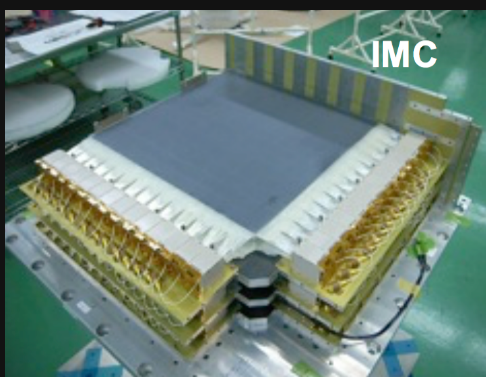
Continuous and stable operations from Oct. 13th 2015

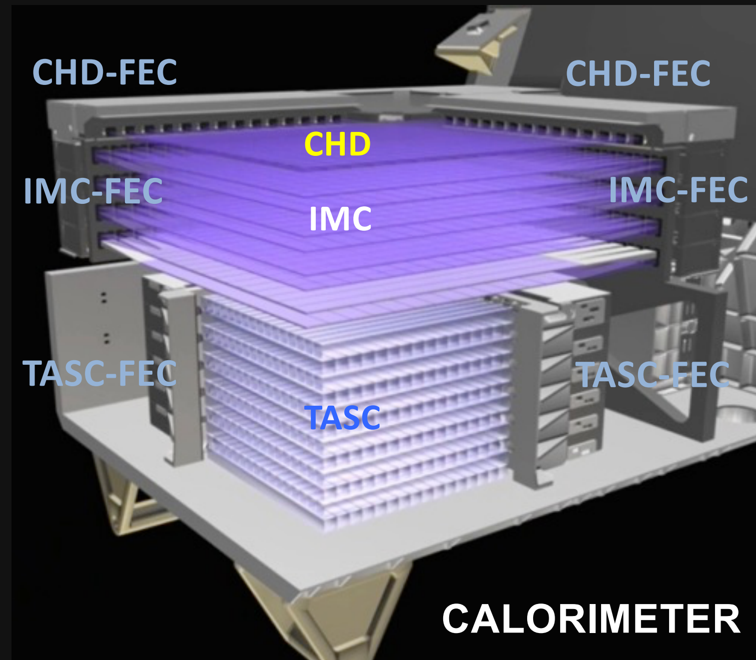




- Mass: 612.8 kg
- JEM Standard Payload Size
  1850 mm (L) × 800 mm (W) × 1000 mm (H)
- Power Consumption: 507 W（max）
- Telemetry: Medium (Low) 600 (50) kbps (6.5GB/day)

CALET instrument





CGBM

Detector	Measure	Geometry/Material	Readout
CHD (Charge Detector)	**Charge (Z=1-40)**	**Plastic Scintillator 14 paddles × 2 layers (X,Y) Paddle size: $3.2\times1\times45$ cm^3**	**PMT+CSA**
IMC (Imaging Calorimeter)	**Tracking Particle ID**	**448 Scifi × 16 layers (X,Y) 7 W layers (3 X_0) Scifi size: $1\times1\times448$ mm^3**	**64 MAPMT+ ASIC**
TASC (Total Absorption Calorimeter)	**Energy e/p separation**	**16 PWO logs × 12 layers (X,Y) log size: $1.9\times2\times32.6$ cm^3 Total thickness: 27 X_0 , ~1.2 λ**	**APD/PD + CSA PMT+CSA (for Trigger)**

CALET main scientific objectives

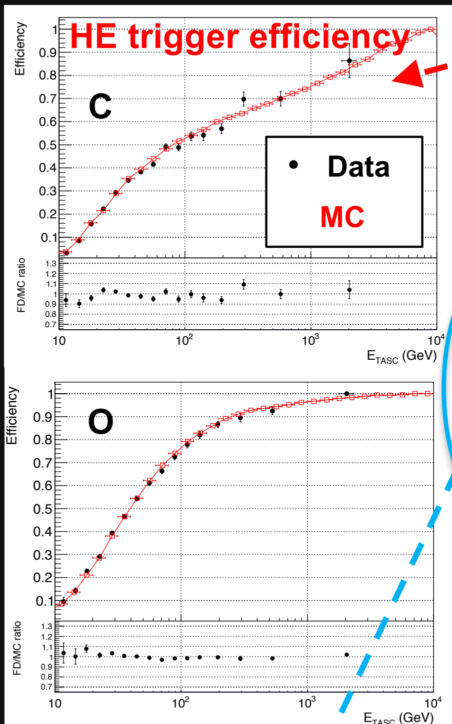
Science Objectives	Observation Targets	Energy range
Nearby CR sources	Electron spectrum	100 GeV – 20 TeV
Dark Matter	Signatures in e/γ spectra	100 GeV – 20 TeV
CR Origin and Acceleration	Electron spectrum	1 GeV – 20 TeV
	p-Fe individual spectra	10 GeV – 10^3 TeV
	Ultra Heavy Ions (26<Z≤40)	few GeV/n
Galactic CR Propagation	B/C sub-Fe/Fe ratios	Up to some TeV/n
Solar Physics	Electron flux	< 10 GeV
Transient phenomena (GRB, e.m. counterpart of GW)	Gamma and X-rays	7 keV – 20 MeV

Spectrum hardening: precise measurement of the transition region for each nuclear species and extension to TeV energy

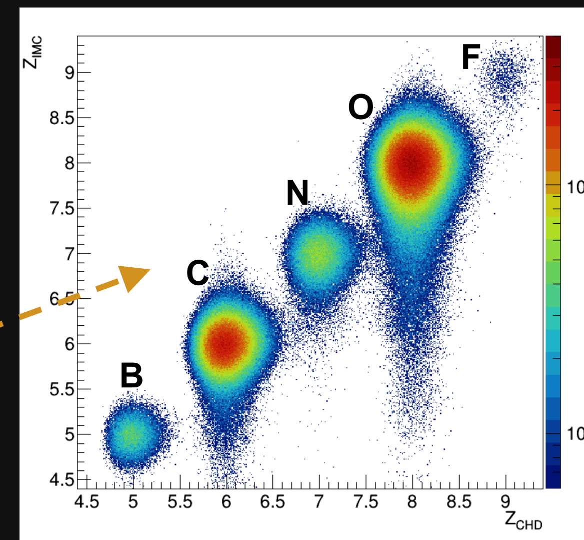
- Wide dynamic range (1-10^6 MIP)
- Large thickness (**30 X_0, ~1.3 λ**)
- Excellent charge ID (~0.2 e)

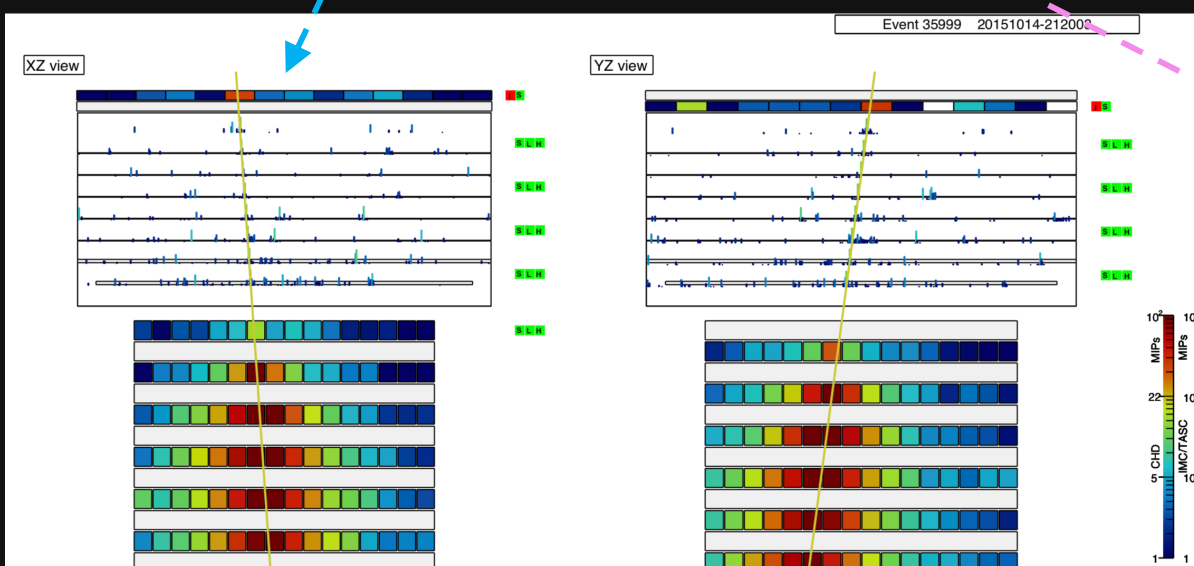
CALET can cover the whole energy range previously investigated in separate subranges by magnetic spectrometers and calorimeters.

Selection for C,O candidate events

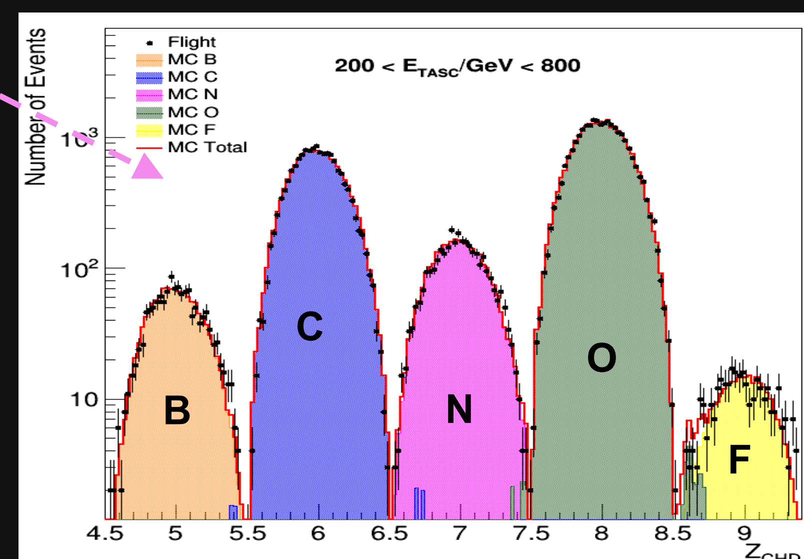


- High-Energy shower trigger: coincidence of signals (>50 MIP) in last IMC layers and signal (>100 MIP) in top TASC layer
- Rejection of events entering from lateral sides by analyzing longitudinal and lateral shower profiles
- Tracking with IMC: angular resolution 0.1°, spatial resolution 220 μm
- Acceptance (events crossing top CHD, TASC top and bottom excluding 2 cm from the edges)
- Charge ID: CHD σ_Z ~0.15 e, IMC σ_Z ~0.24 e
- Consistency of Z_{CHD} and Z_{IMC} → rejection of nuclear interactions at the top of instrument.

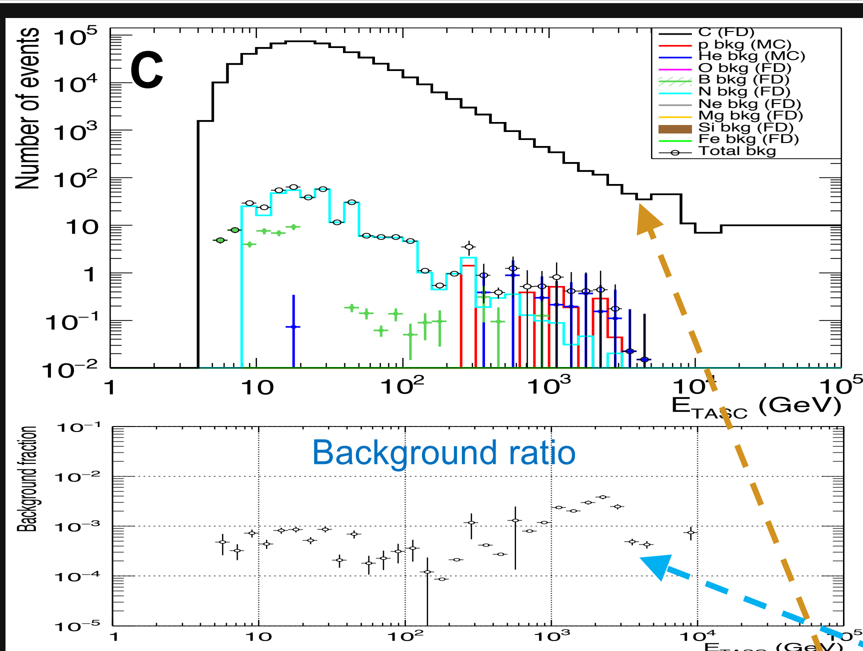


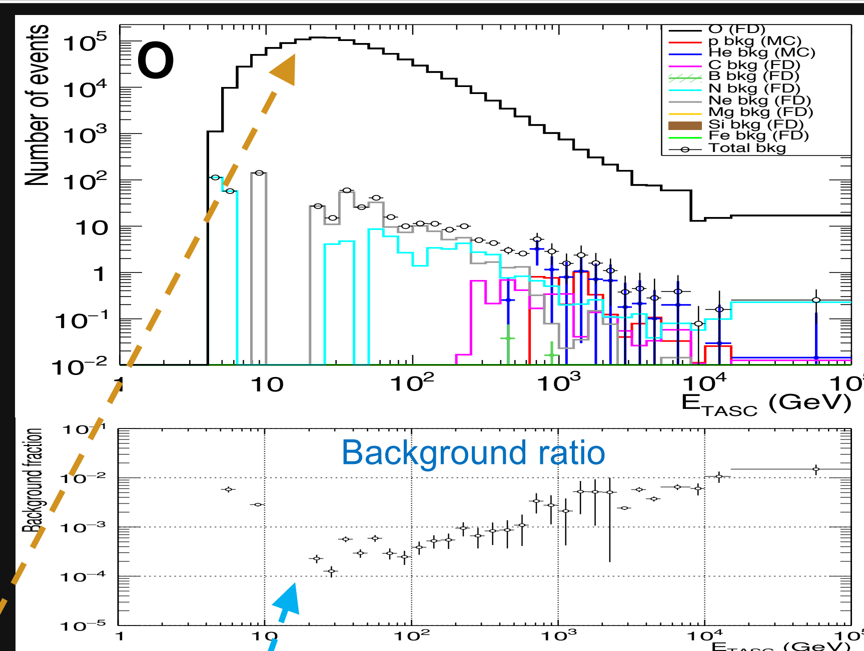


C candidate with E_{TASC}~2 TeV

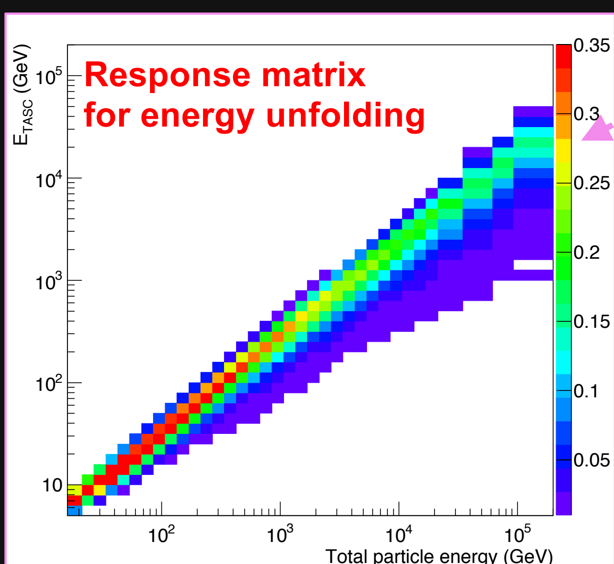


Flux measurement

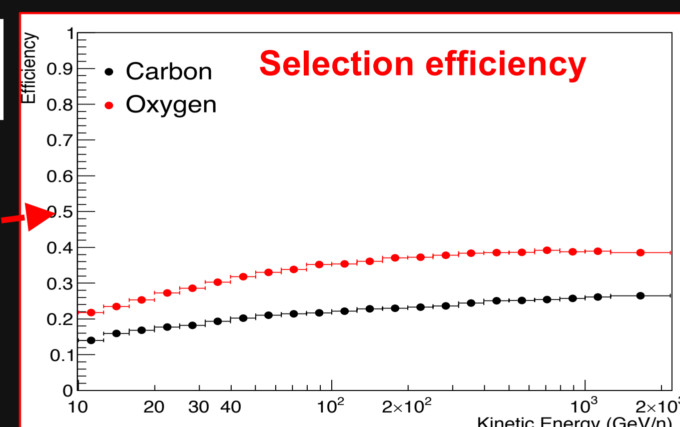




$$N(E) = U\left[N_{obs}(E_{\mathrm{TASC}}) - N_{bg}(E_{\mathrm{TASC}})\right]$$

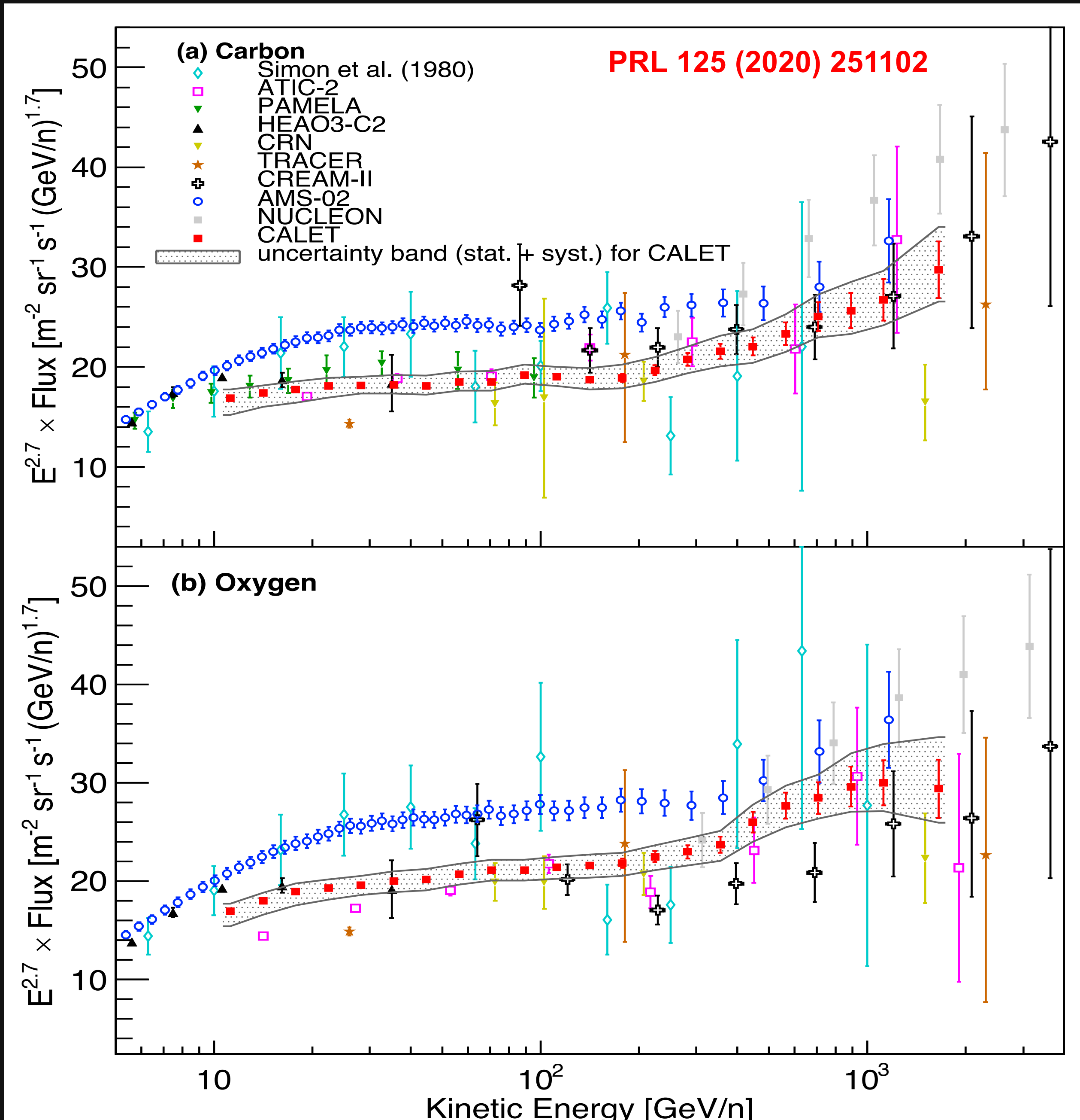


$$\Phi(E) = \frac{N(E)}{\varepsilon(E)\, S\Omega\, T\, \Delta E}$$



- Live time T=84.5% of observing time (1480 days)
- SΩ: 510 cm^2 sr
- Bin width ΔE commensurate with rms resolution of TASC , ~30% for nuclei

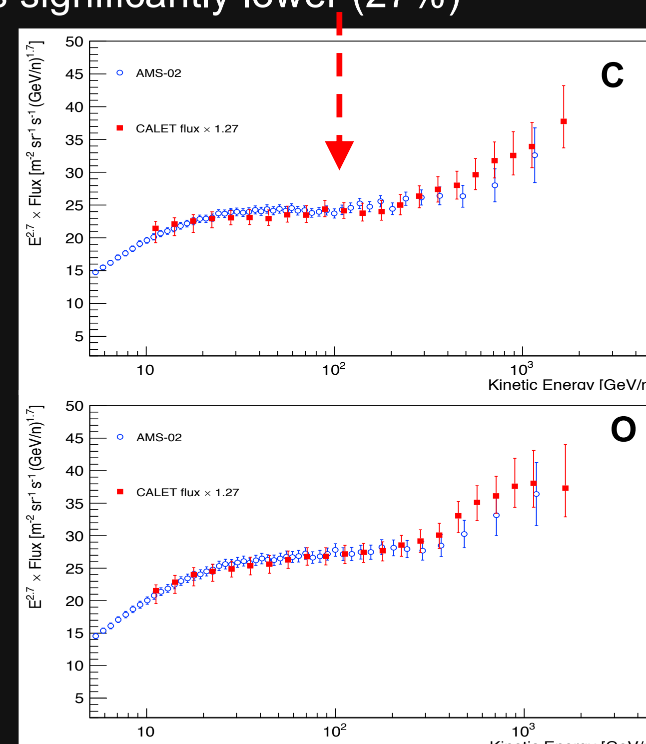
C and O energy spectra



C and O spectra measured from 10 GeV/n to 2.2 TeV/n.
They are consistent with PAMELA and most previous experiments.

They show a clear hardening around 200 GeV/n.

They have similar shape with AMS-02 spectra but the absolute normalization is significantly lower (27%)



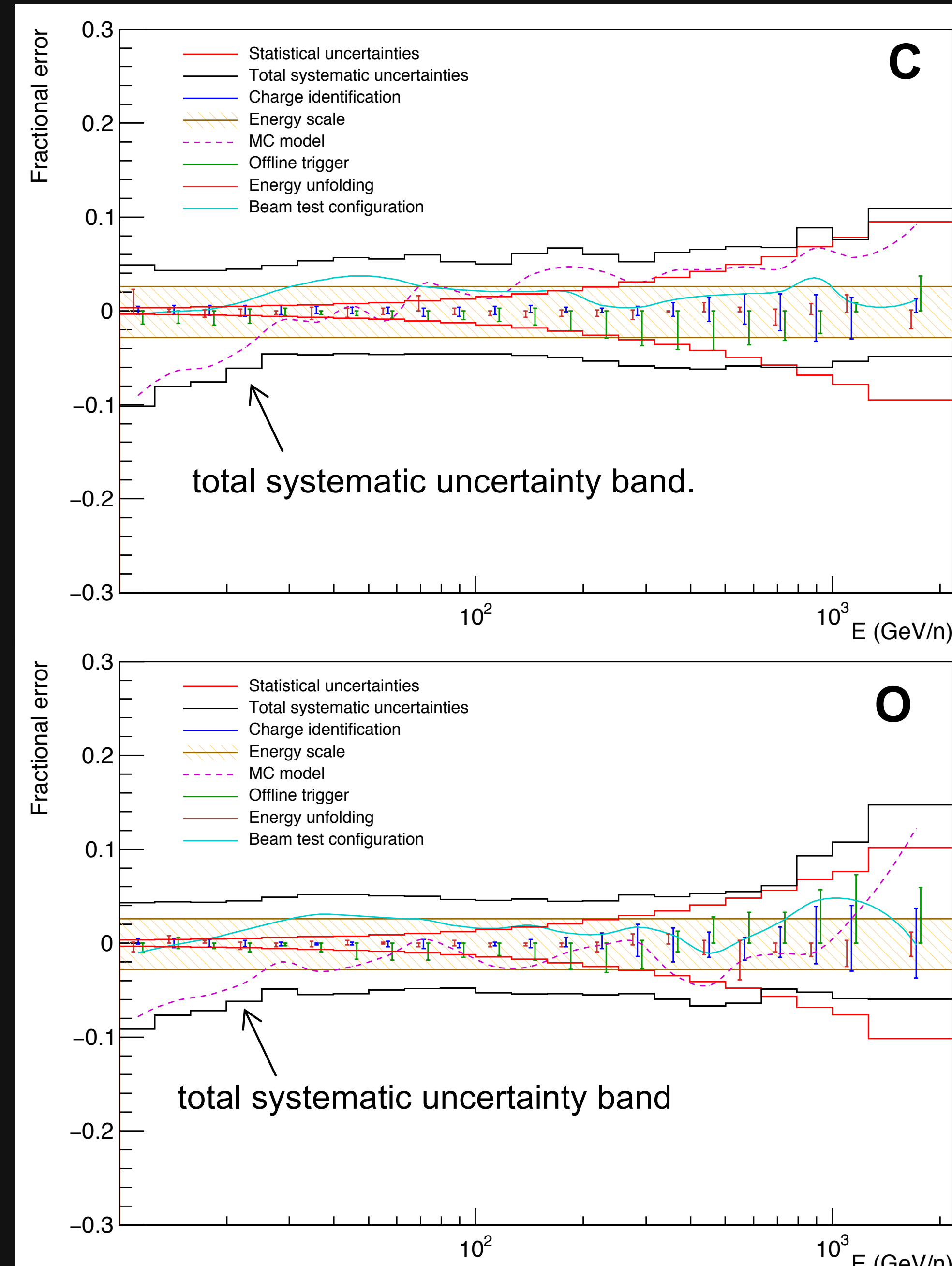
Systematic Uncertainties

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)

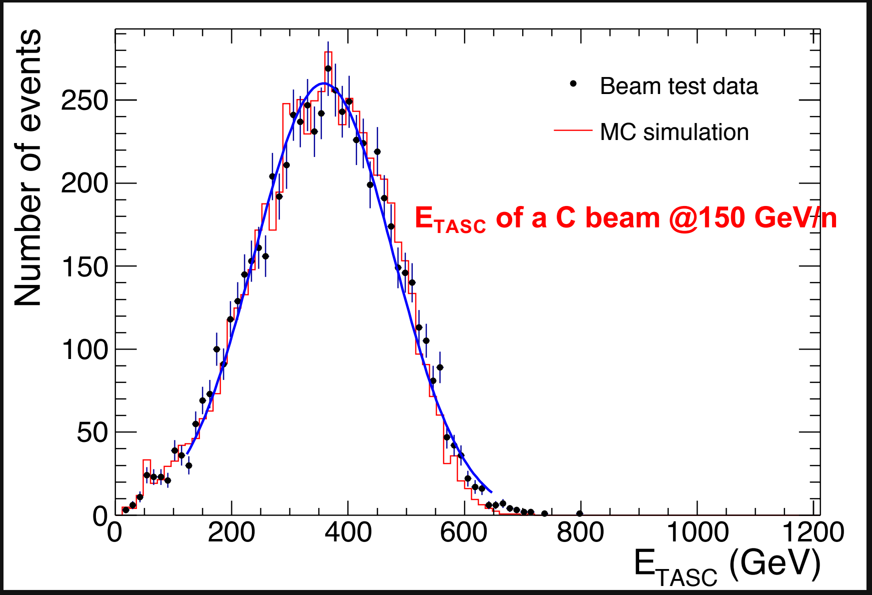
independent training: 100sets

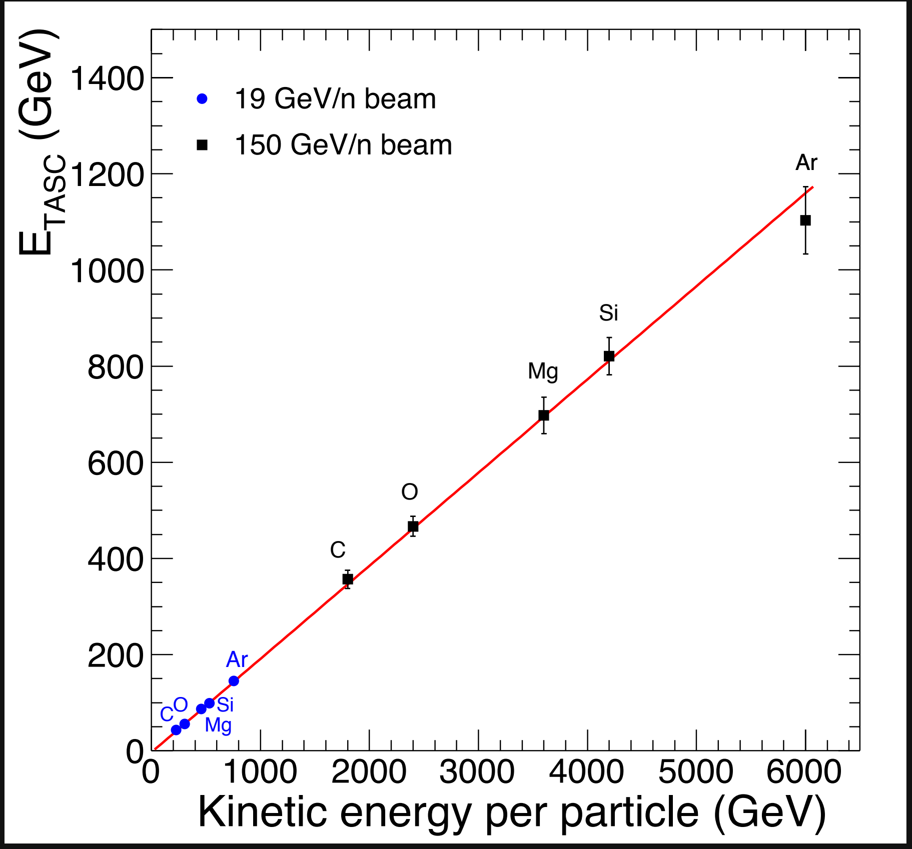


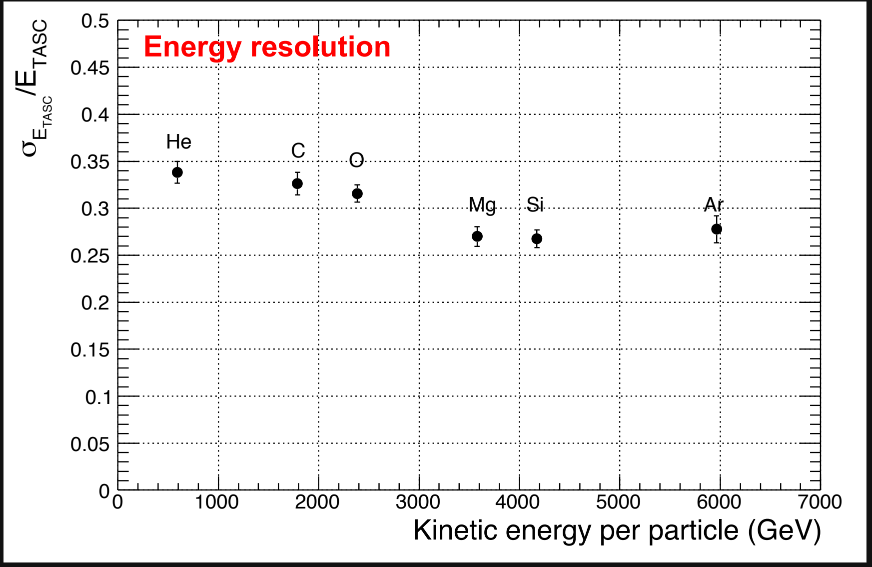
TASC energy scale

- 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%

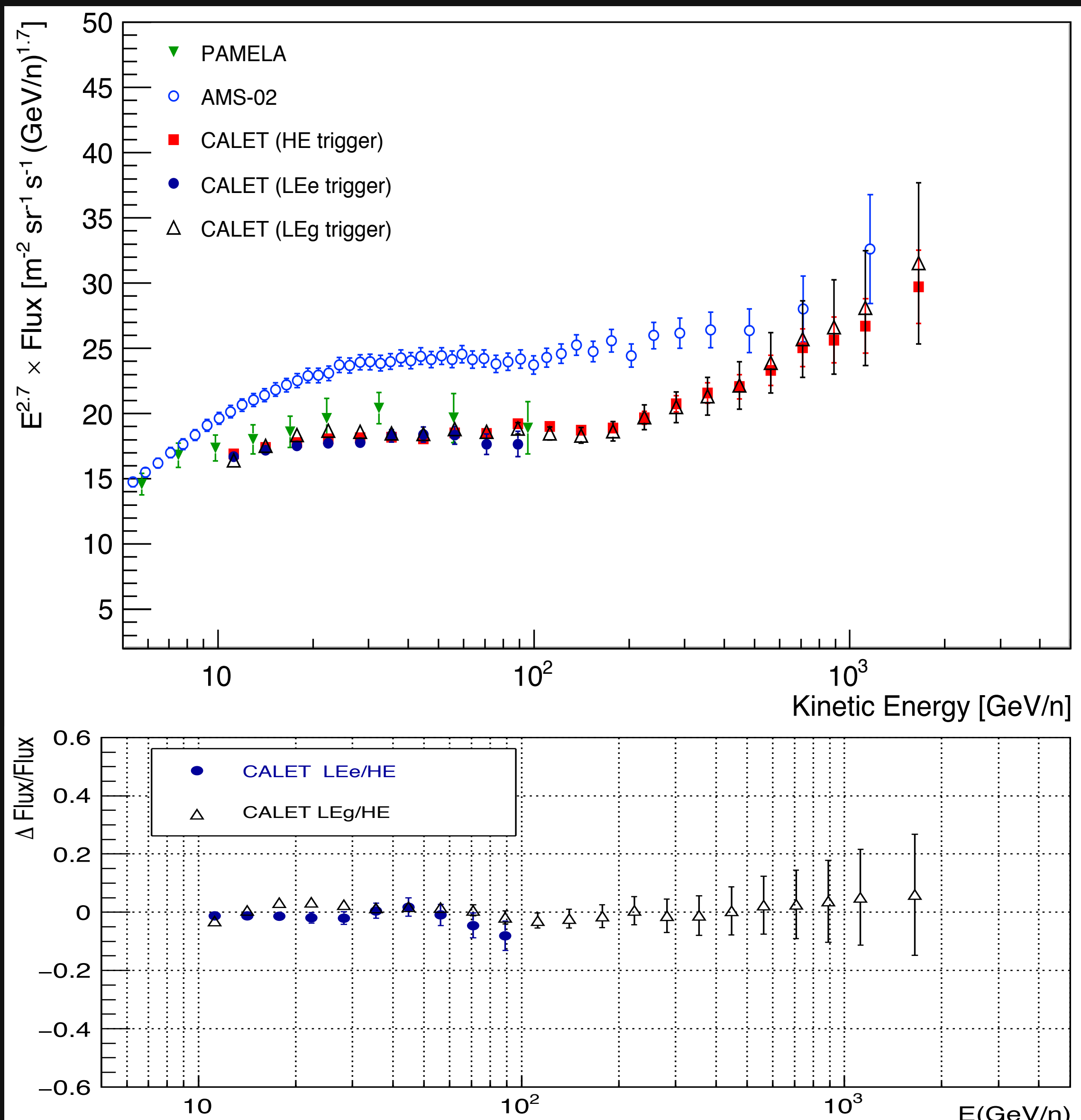
  Energy resolution ~30%
- The energy response derived from MC simulations was tuned using the beam test results.







High vs. low-energy triggers



Low-energy gamma (LEg) trigger

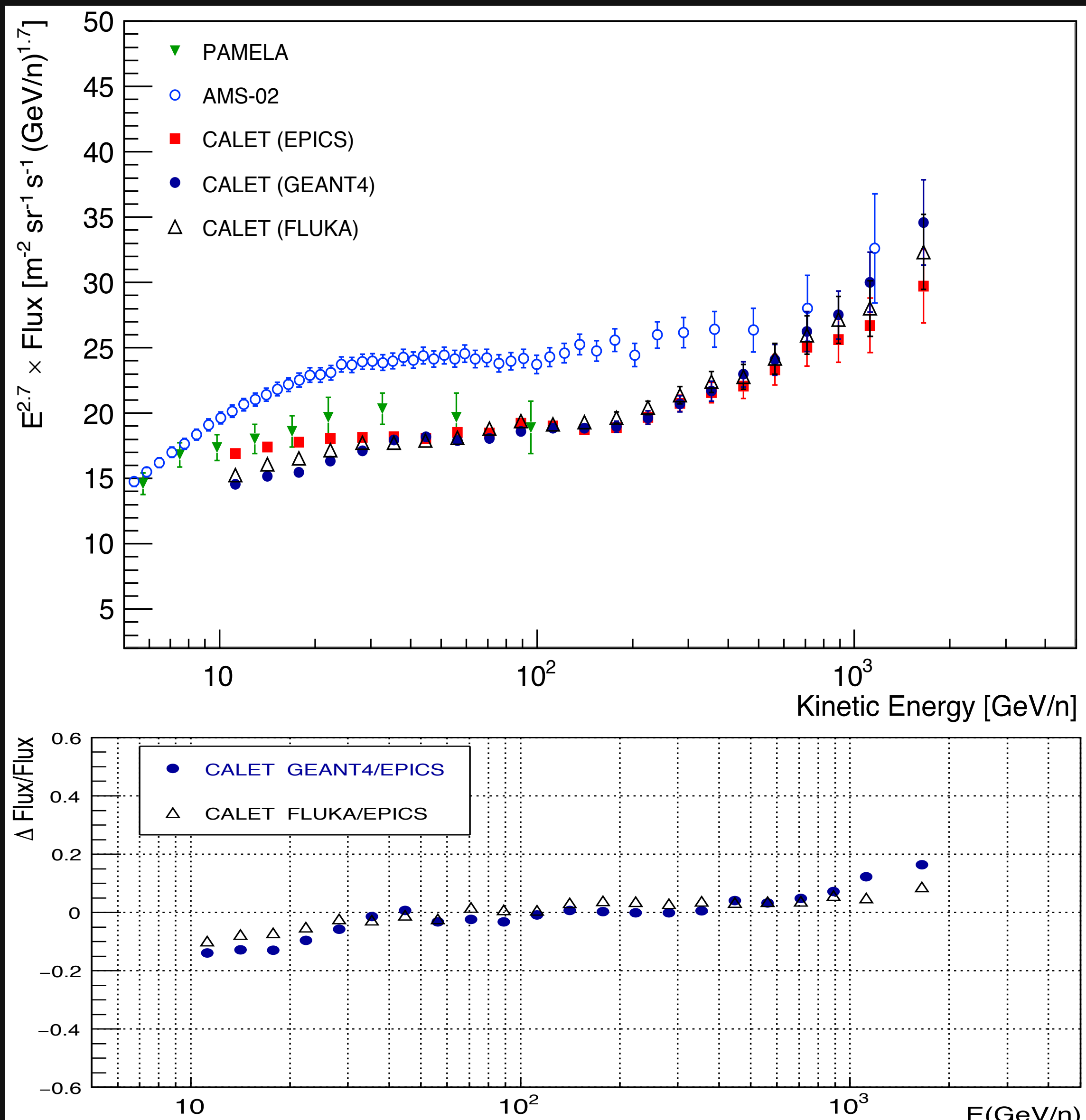
- Coincidence of last two pairs of IMC layers (5 MIP thr.) & top TASC layer (10 MIP thr.)
- livetime ~10% of HE livetime

Low-energy electron (LEe) trigger

- 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.

Monte 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

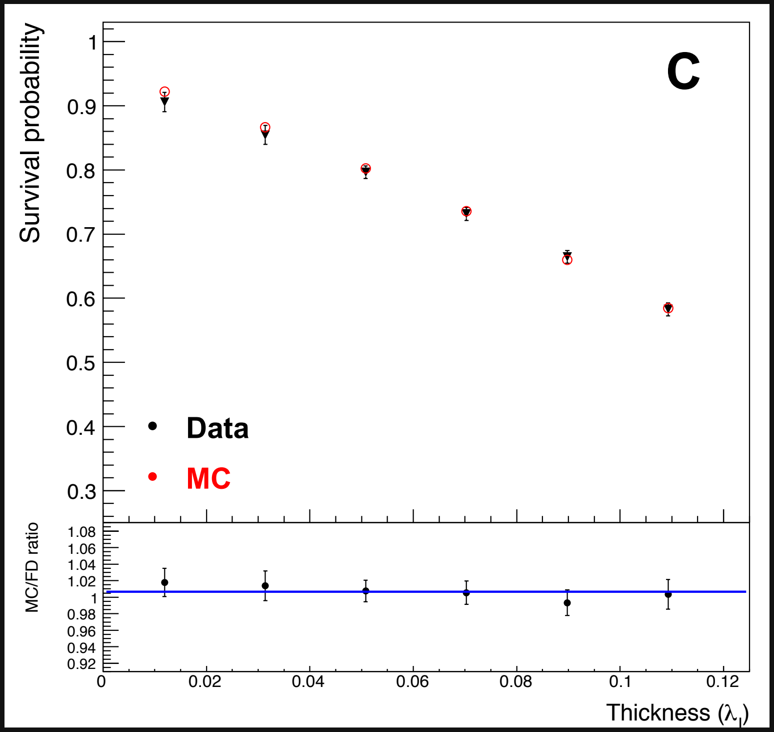
MC simulations were tuned using beam test and flight data.

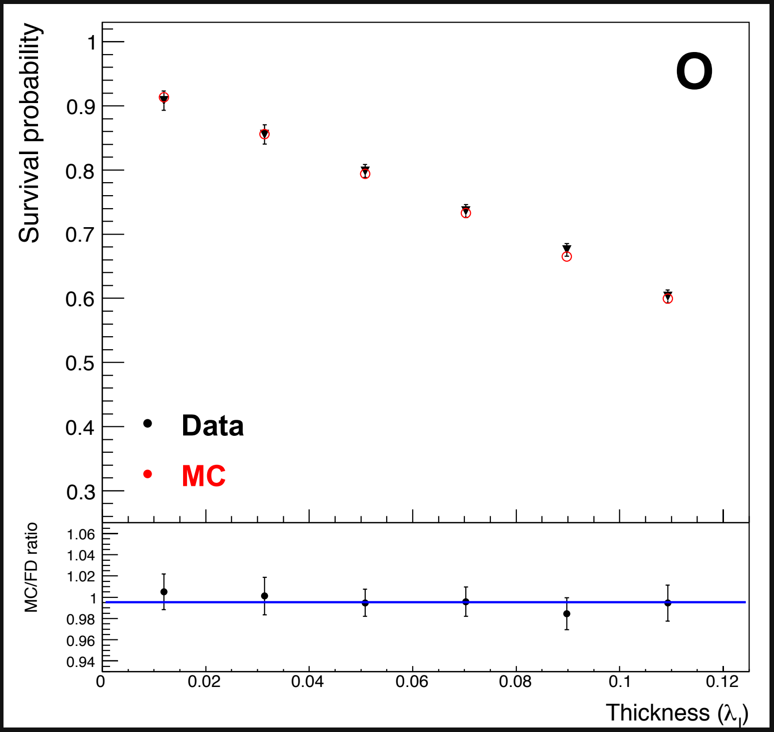
They are used to estimate selection efficiencies and response matrix.

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.

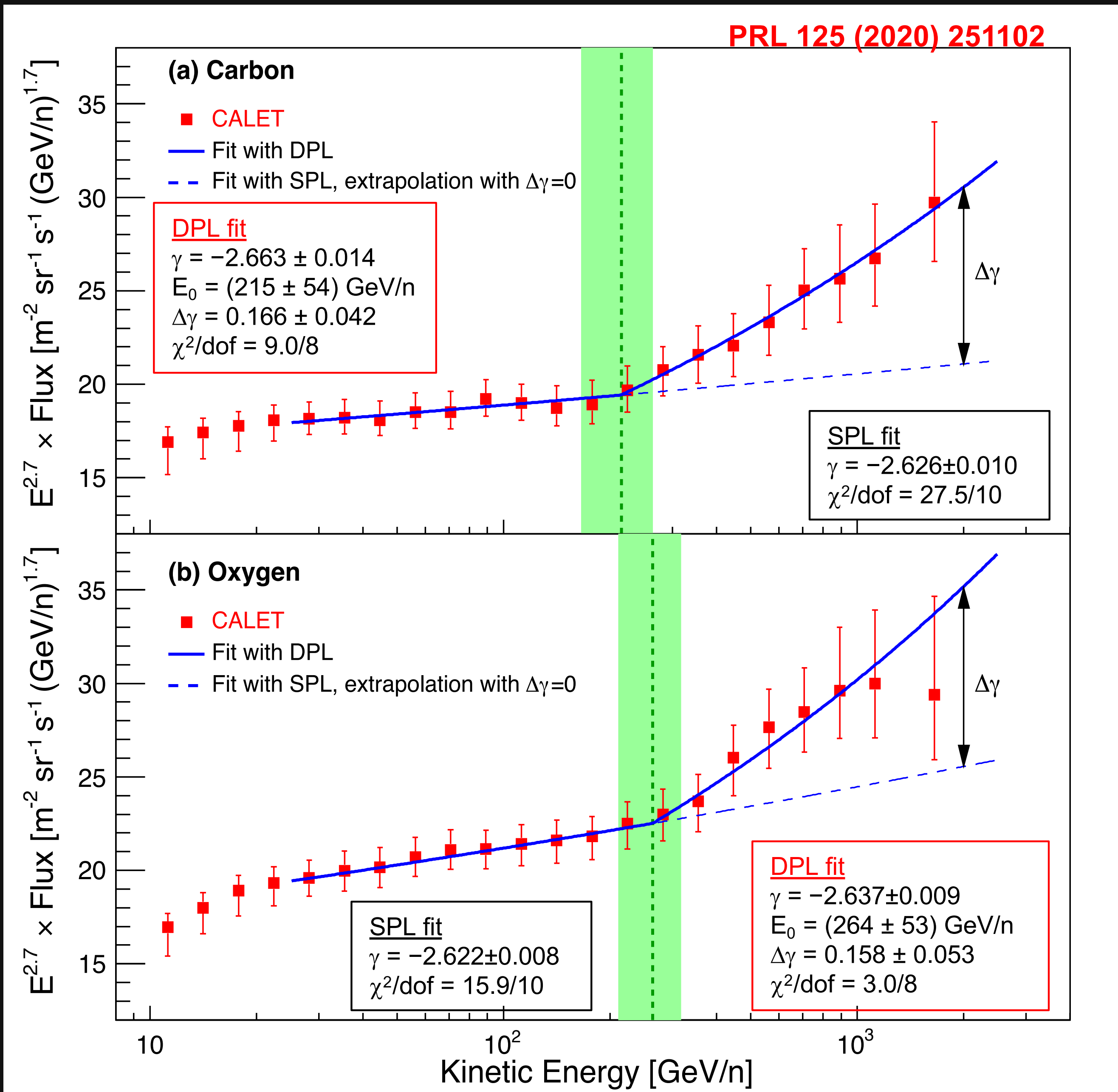
Survival probabilities





- We measured the survival probabilities of C and O nuclei at different depths in IMC to check that hadronic interactions in the detector are well simulated.
- In flight data, the survival probabilities are calculated as the ratio of the number of events selected as C (O) in the first six pairs of SciFi layers in IMC to the ones selected with CHD only. In MC (EPICS) data, the true information on the point where the first hadronic interaction occurs in the detector is used.
- Very good agreement between data and simulation (within <1%).

Spectral analysis



Double power-law (DPL) fit

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

Single power-law (SPL) fit

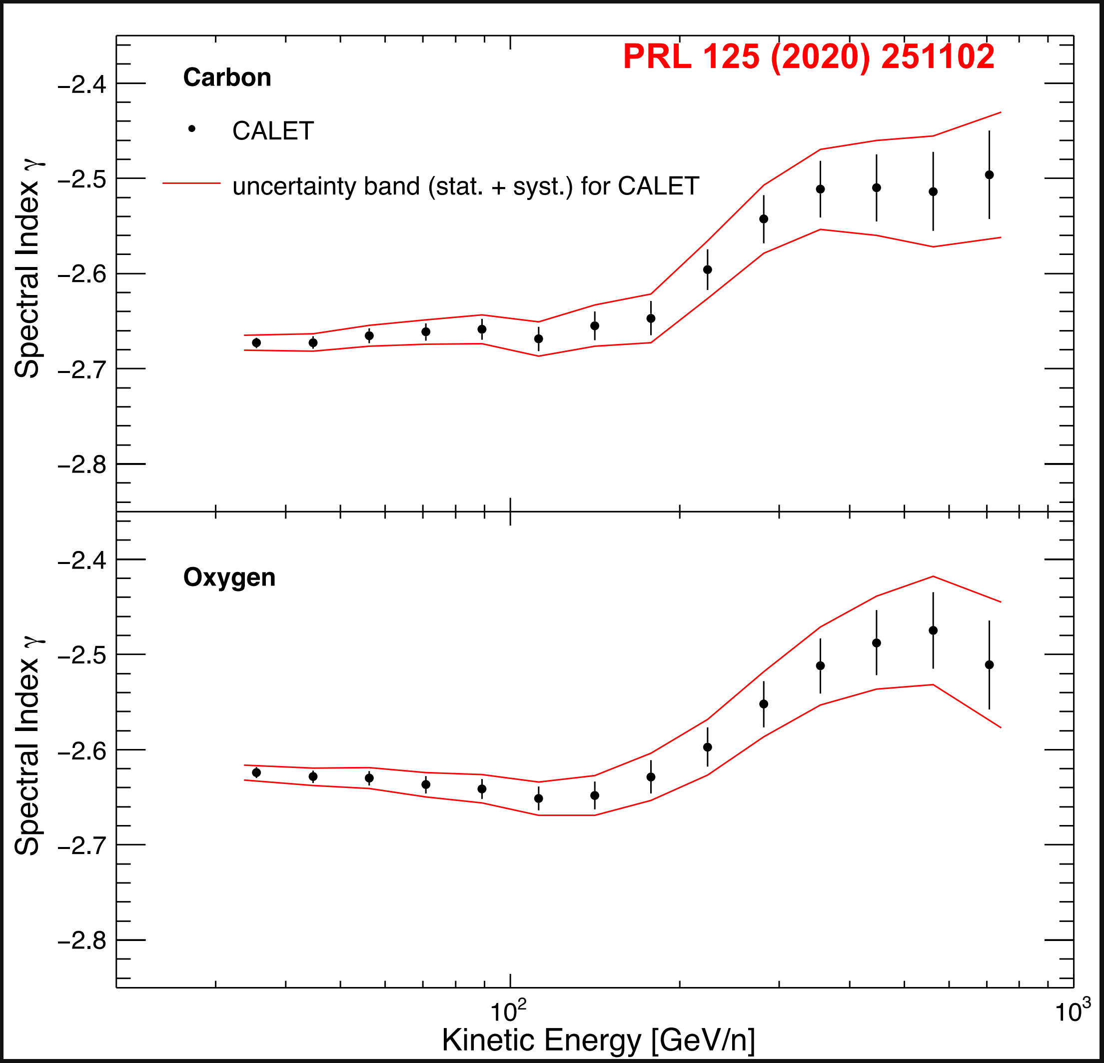
$$\Phi(E) = C\left(\frac{E}{\mathrm{GeV}}\right)^{\gamma}$$

The effect of systematic uncertainties in the spectrum is modelled in the χ^2 minimization function with a set of nuisance parameters.

$\Delta\chi^2$ SPL-DPL fits with 2 dof →

SPL hypothesis excluded at 3.9σ level for C and 3.2σ for O

Energy dependence of the spectral index



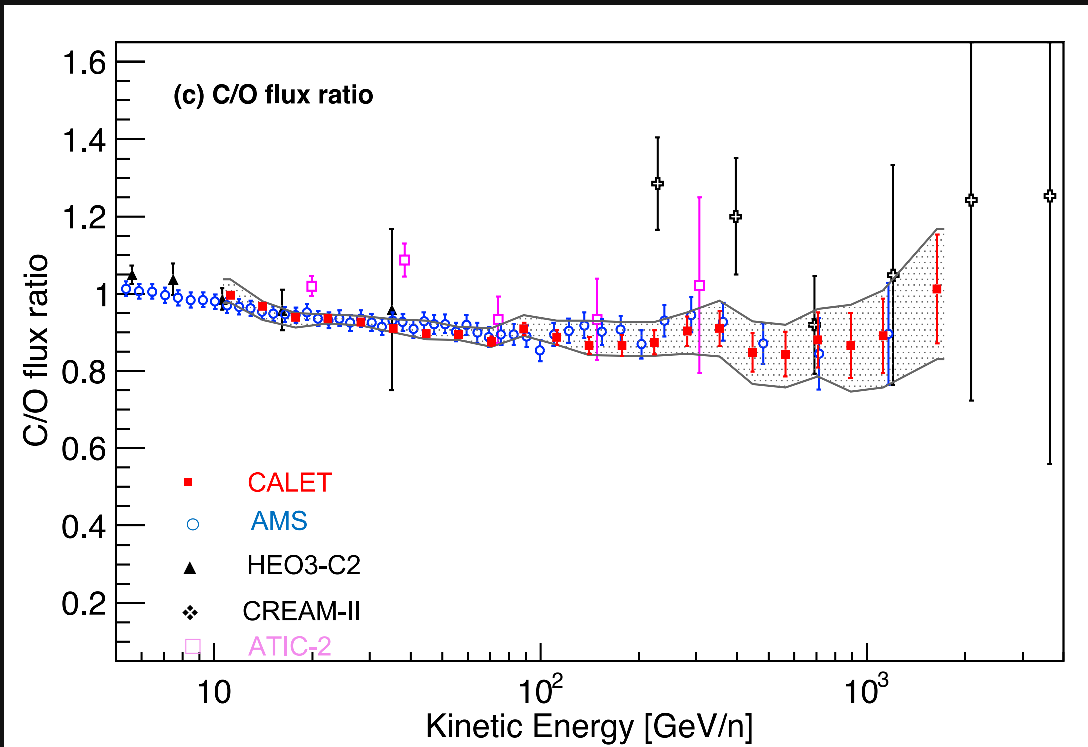
To study the energy dependence of the spectral index in a model independent way, the spectral index is calculated by a fit of

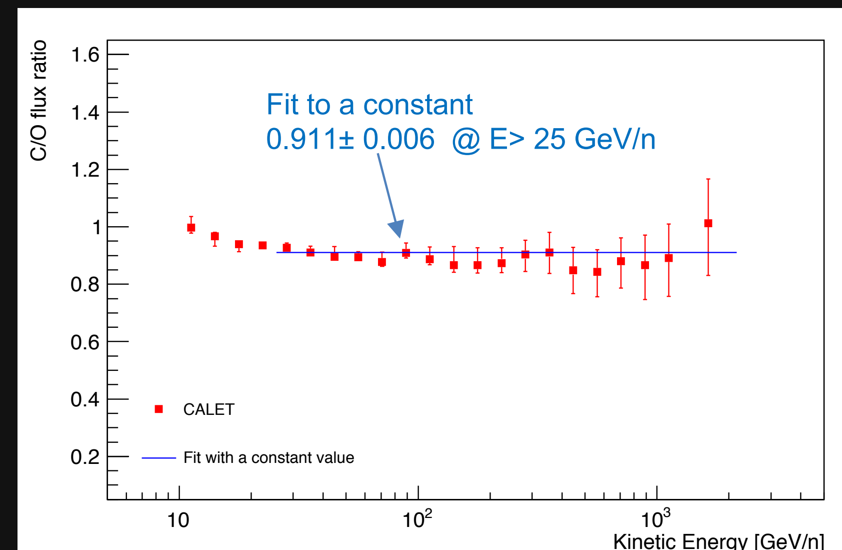
$$\gamma = \frac{d[\log(\Phi)]}{d[\log(E)]}$$

in energy windows centered in each bin and including the neighbor ± 3 bins.

→ Carbon and oxygen fluxes harden in a similar way above a few hundred GeV/n.

C/O flux ratio





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

Above 25 GeV/n the C/O ratio is well fitted to a constant value of 0.911 ± 0.006 with χ^2/dof = 8.3/17

→ C and O fluxes have the same energy dependence.

Conclusions

CALET measured the C and O energy spectra and their flux ratio in the energy interval from 10 GeV/n to 2.2 TeV/n

A single power law spectrum for C and O is excluded by more than 3σ

A spectral index increase $\Delta\gamma = 0.166 \pm 0.042$ for C and $\Delta\gamma = 0.158 \pm 0.053$ for O is measured above 200 GeV/n

C and O fluxes have the same energy dependence and a constant C/O flux ratio 0.911 ± 0.006 above 25 GeV/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 systematic 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 modelling of the instrument.