Boron flux in cosmic rays and its flux ratio to primary species measured with CALET on the International Space Station

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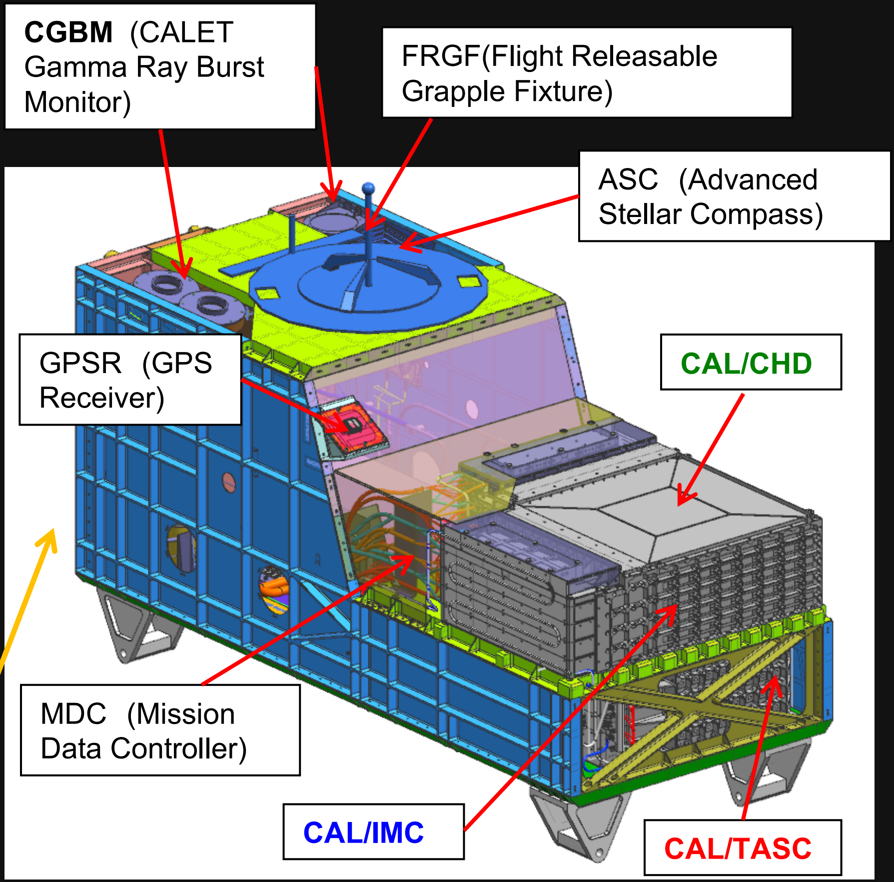
On behalf of the CALET collaboration

ICRC2023
The Astroparticle Physics Conference
Nagoya, Japan, Jul 26–Aug 3, 2023

CALET payload

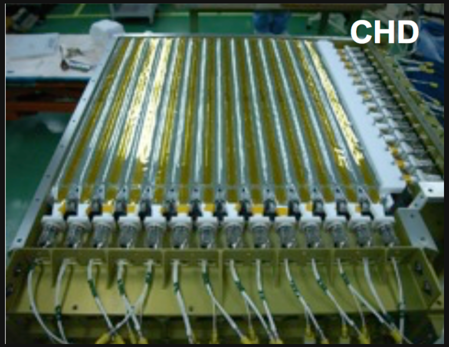
Launched on Aug. 19th 2015 on the Japanese H2-B rocket
Emplaced on JEM-EF port#9 On Aug. 25th 2015

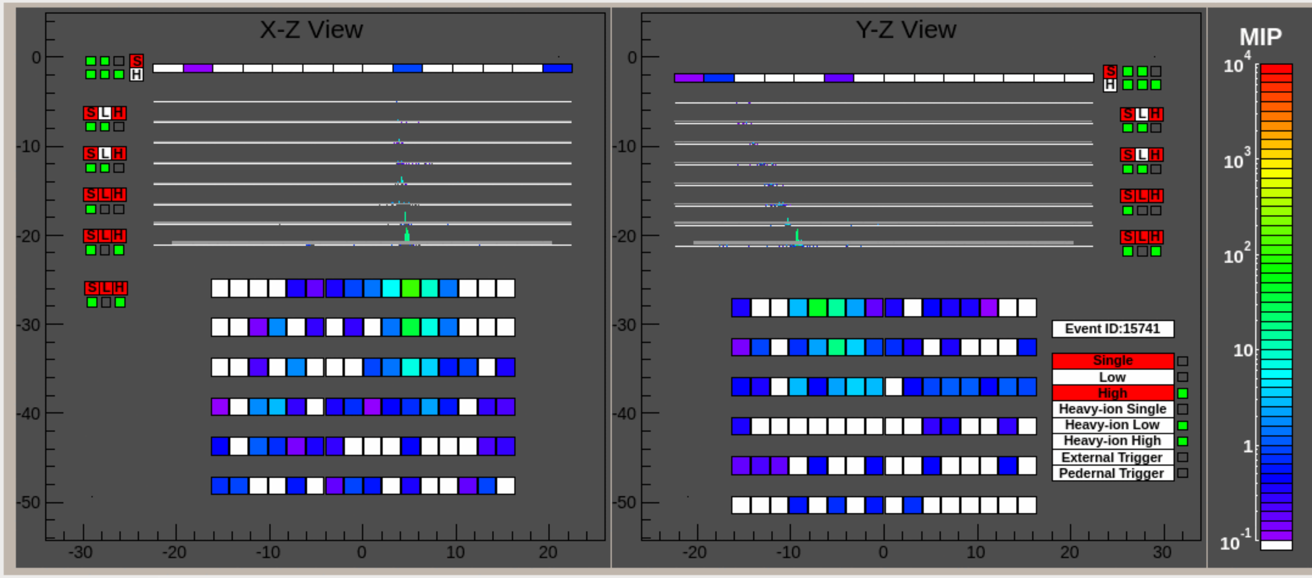
Continuous and stable operations from Oct. 13th 2015



- 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 Calorimeter





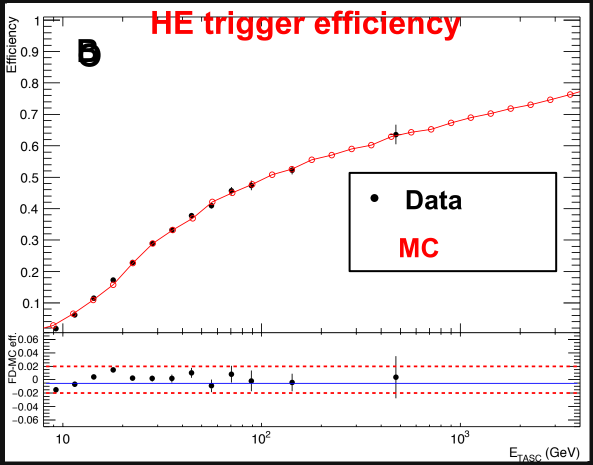
YYMMDDHH:15101303 EventID:1128743511-15741 UTCTime:2015/10/13/03:52:18.41342 KE 7.45[GeV] RE 4.5079[cm] FE 0.0036 Entry: 30883

No.	dirX	dirY	dirZ	posX	posY	posZ	Chi2_x	Np_x	Chi2_y	Np_y	Zenith[deg]	Azimuth[deg]	Color ID
0	0.07	0.37	0.93	3.26	-17.83	0.00	0.55	7	1.23	8	22.09	-79.64	2
1	0.05	0.37	0.93	3.82	-17.83	0.00	0.31	7	0.29	8	21.92	-77.90	3
2	0.05	0.37	0.93	3.82	-17.83	0.00	0.31	7	0.29	8	21.92	-77.90	4
3	0.07	0.37	0.93	3.25	-17.83	0.00	0.08	8	0.28	8	22.08	-79.67	5

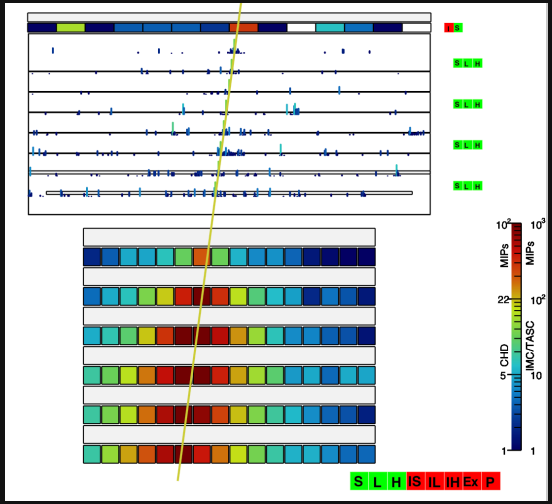
CHD **Charge Detector**	2 layers x 14 plastic scintillating paddles **single element charge ID** from p to Fe and up to Z = 40 charge resolution ~0.1-0.3 e
IMC **Imaging Calorimeter**	Scifi + W absorbers: 3 X_0 at normal incidence 8 x 2 x 448 plastic scifi (1mm^2) readout individually **Tracking** (~0.1° angular resolution) + **Shower imaging**
TASC **Total Absorption Calorimeter**	Total thickness 27 X_0, 1.2 λ_I 6 x 2 x 16 lead tungstate ($PbWO_4$) logs **Energy res.**: ~2% (>10 GeV) for e,γ ~30% for p,nuclei **e/p separation**: ~10^{-5}

Selection for B,C,O candidate events

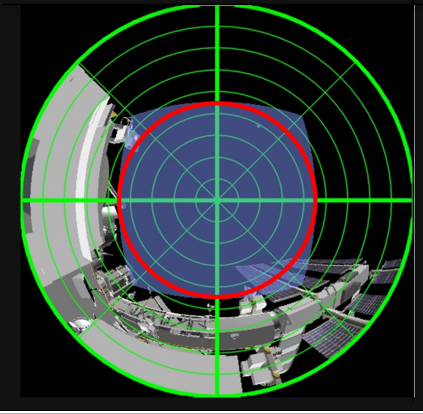
- High-Energy shower trigger: coincidence of signals (>50 MIP) in last IMC layers and signal (>100 MIP) in top TASC layer.



- Rejection of events entering from lateral sides by analyzing longitudinal and lateral shower profiles



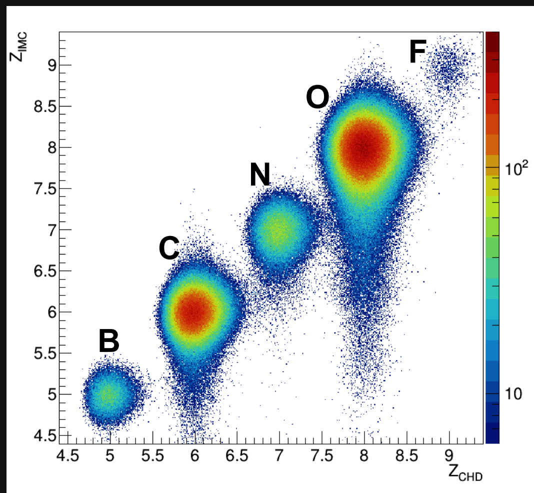
- KF tracking. Track quality cuts.
- Acceptance (events crossing top CHD, TASC top and bottom excluding 2 cm from the edges)
- FOV cut: events (8%) pointing to ISS structures are discarded based on FOV maps



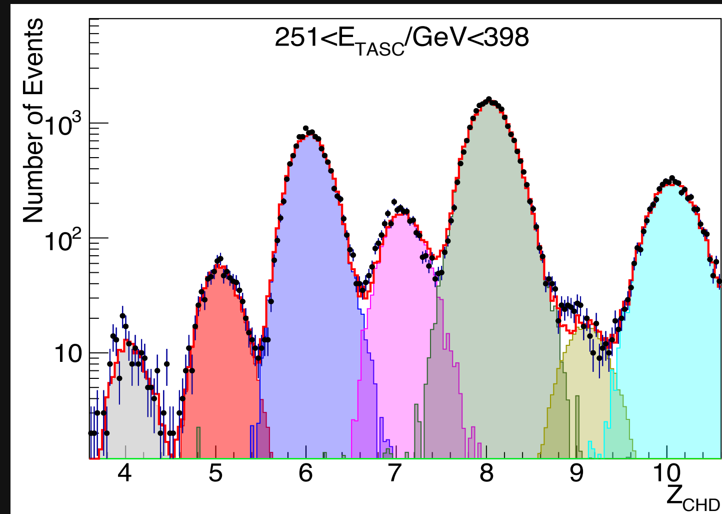
See Poster PCRD3-07

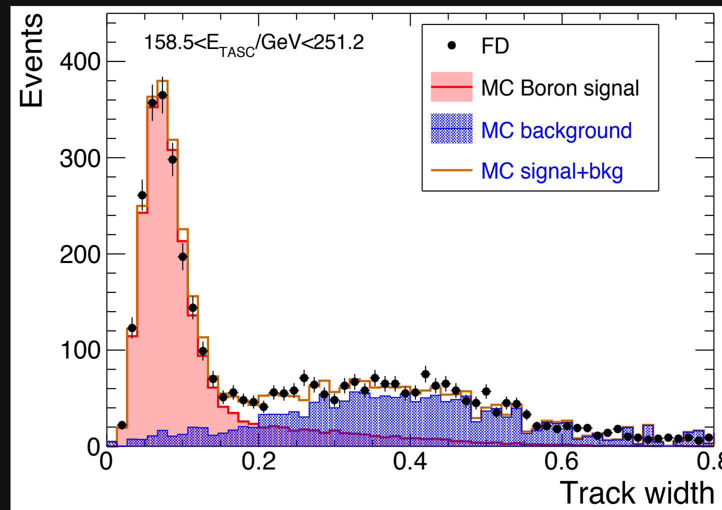
Selection for B,C,O candidate events

- 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.

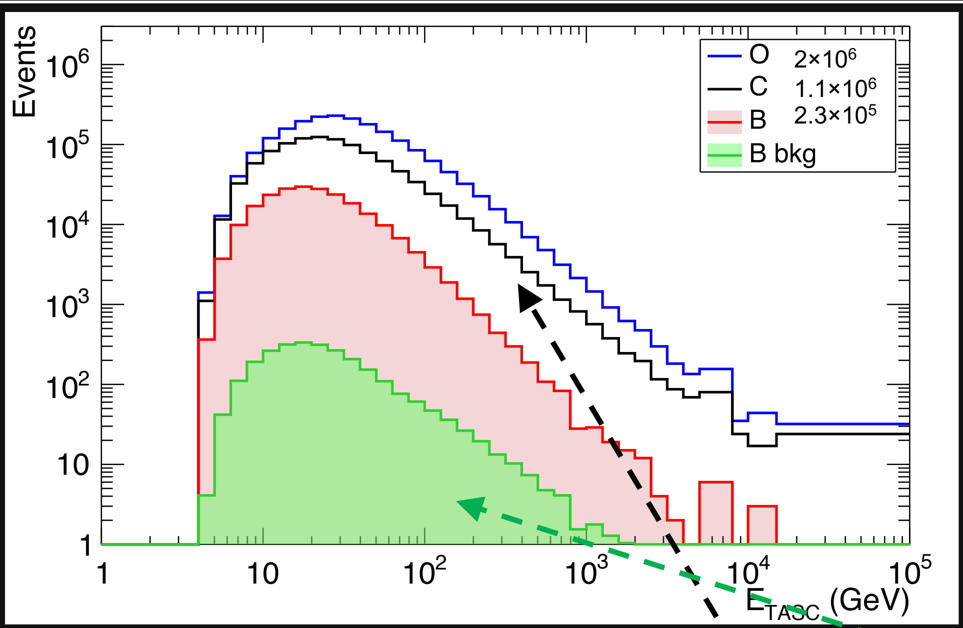


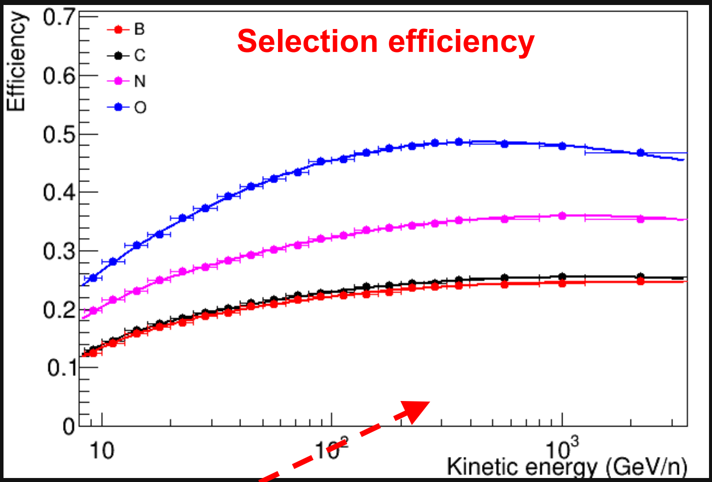
- Track width cut (<0.2) rejects early interacting proton and He events misidentified as B.
- Background contamination estimated from TW and Z_{CHD} distributions in different E_{TASC} bins (1% @100 GeV, 7% @1.5 TeV)

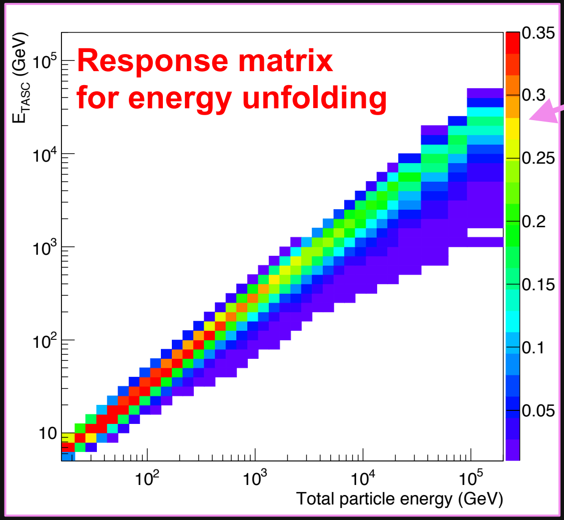




Flux measurement







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

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

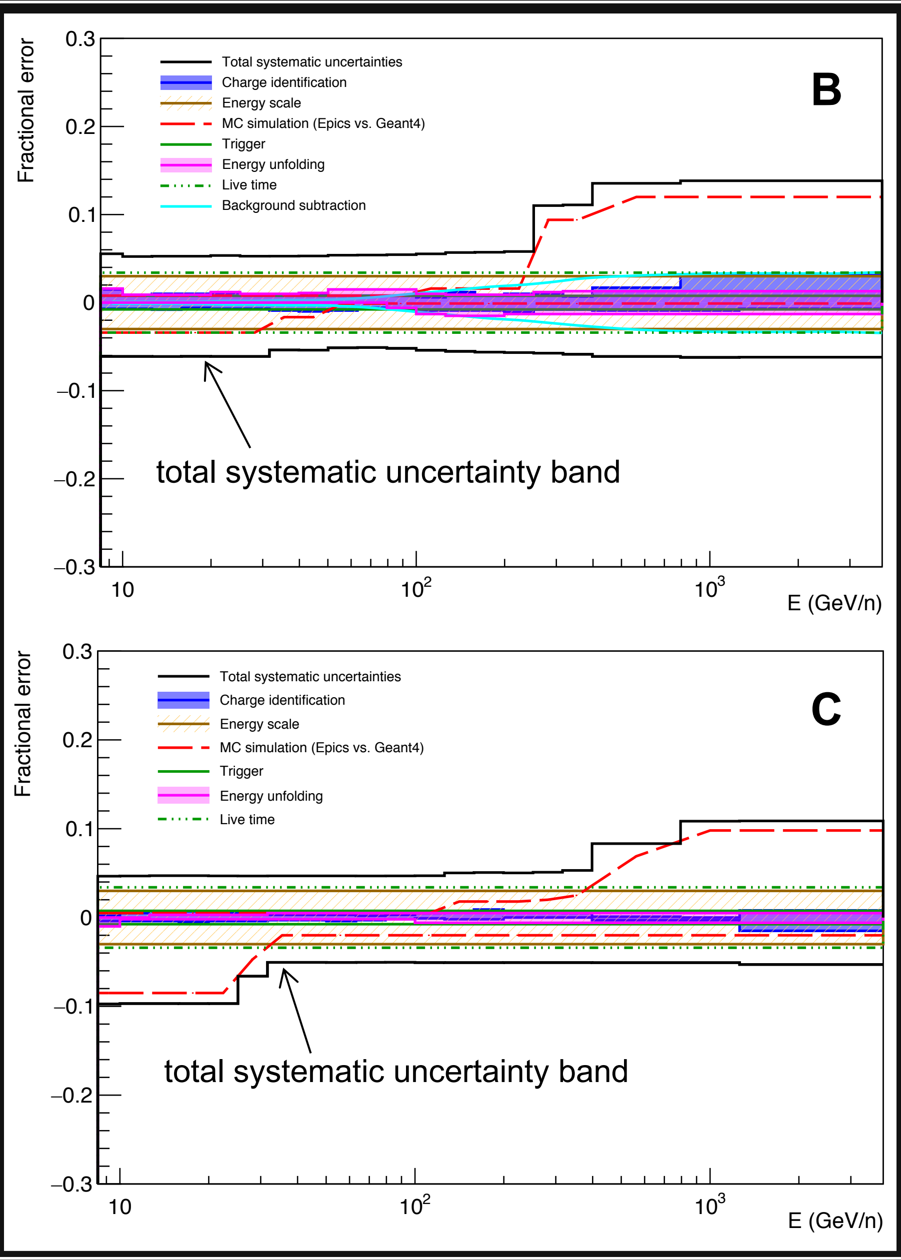
- Live time T=86% of observing time (2554 days)
- SΩ: 510 cm^2 sr
- Bin width ΔE commensurate with rms resolution of TASC , ~30% for nuclei

Systematic Uncertainties

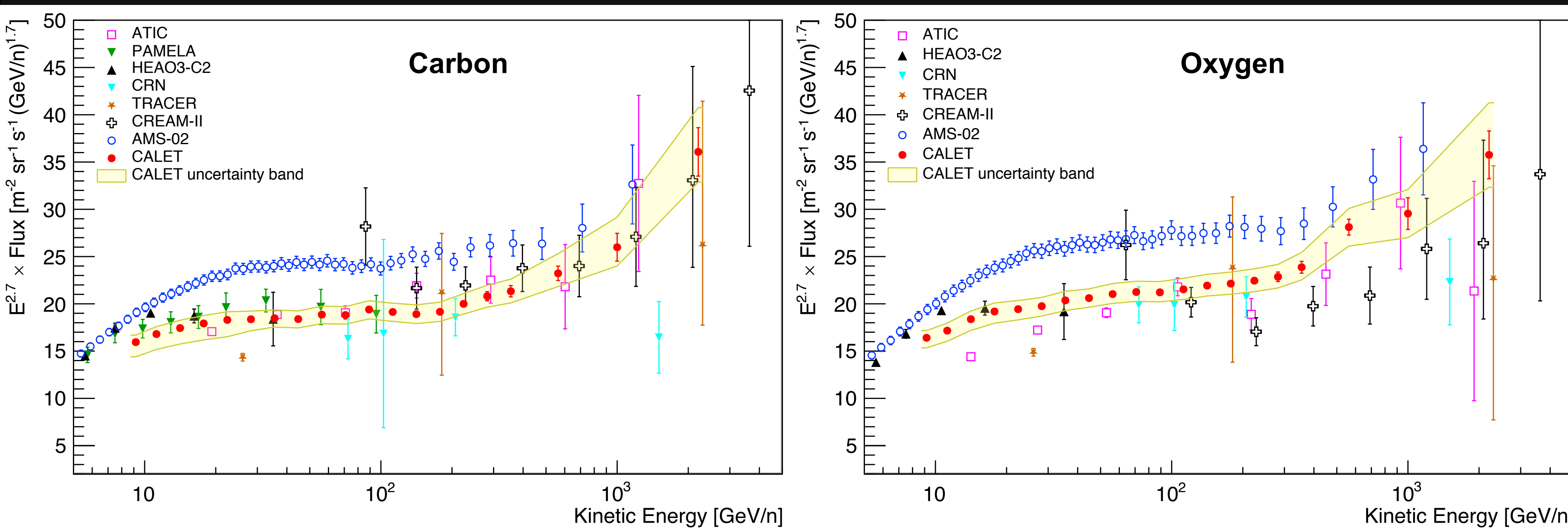
We check the stability of the spectrum by varying the analysis cuts and w/ different MC simulations for efficiencies and unfolding.

Main sources of systematics uncertainties:

- **Normalization:**
  - Live time
  - Long-term stability
  - Energy scale
- **Energy dependent:**
  - Tracking
  - Charge ID
  - Trigger
  - Unfolding
  - MC model (EPICS, GEANT4)
  - Background subtraction
  - B isotopic composition (ref. $^{11}B:^{10}B = 0.7:0.3$)



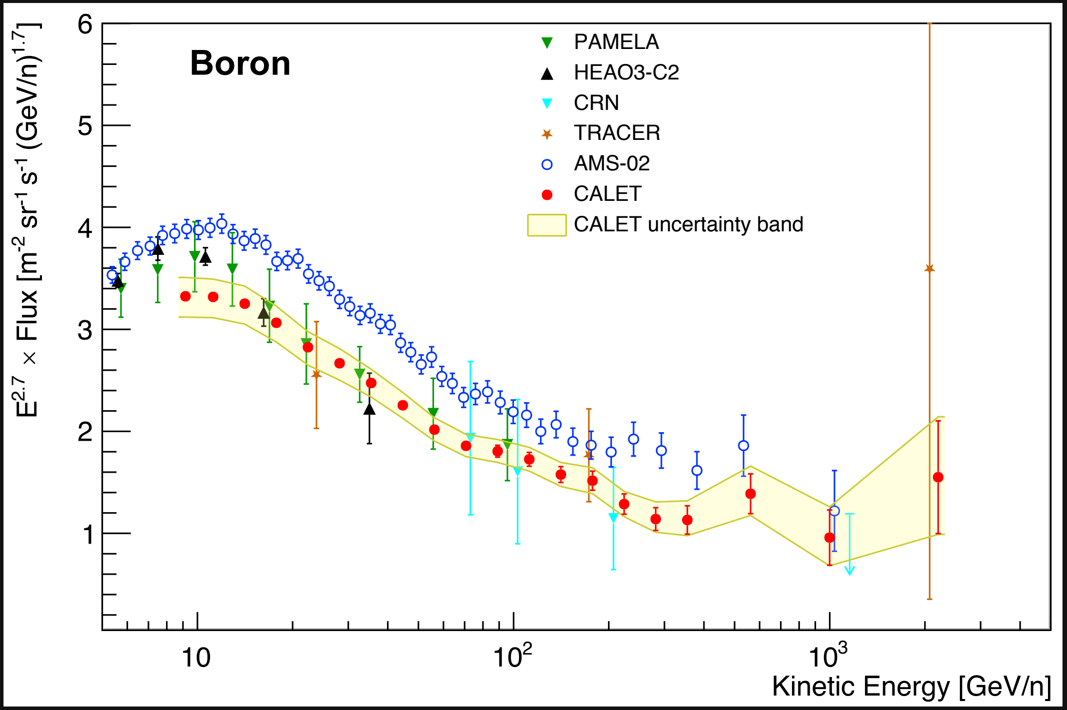
C and O energy spectra



- C and O spectra measured from 8.4 GeV/n to 3.8 TeV/n
- Larger dataset (44% more data), improved systematics assessment

  Agreement with our early result **PRL 125 (2020) 251102**
- Consistent with PAMELA and most previous experiments.
- Clear hardening around 200 GeV/n
- Similar shape with AMS-02 spectra but the absolute normalization is lower

Boron energy spectrum



Measured from 8.4 GeV/n to 3.8 TeV/n

Agreement with our recent result **PRL 129 (2022) 251103**

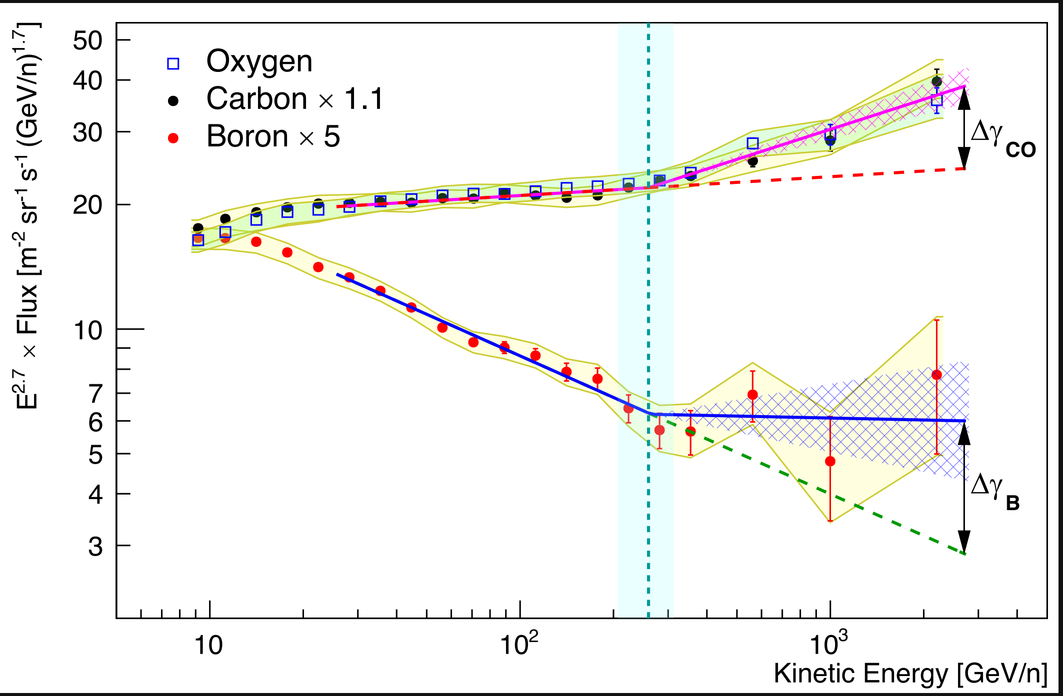
Consistent with PAMELA and most previous experiments.

Similar shape with AMS-02 spectra but the absolute normalization is lower

Spectral analysis

Simultaneous fit to C,O (w/ same parameters, except normalizazion)
DPL fit to B with E_0 fixed at fitted value from C-O fit

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

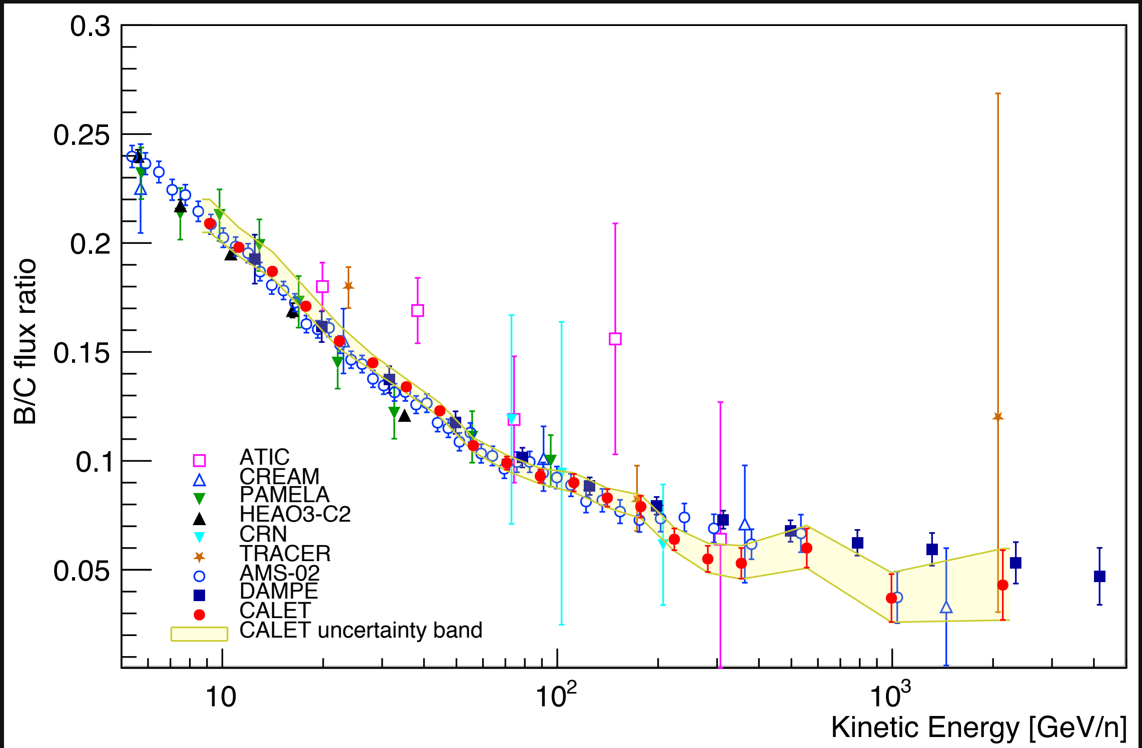


C-O fit
$\gamma = -2.66 \pm 0.02$
$E_0 = (260 \pm 50)$ GeV/n
$\Delta\gamma = 0.19 \pm 0.04$
$\chi^2/\mathrm{dof} = 23/25$

B fit
$\gamma = -3.03 \pm 0.03$
E_0 fixed from C-O
$\Delta\gamma = 0.32 \pm 0.14$
$\chi^2/\mathrm{dof} = 5.2/11$

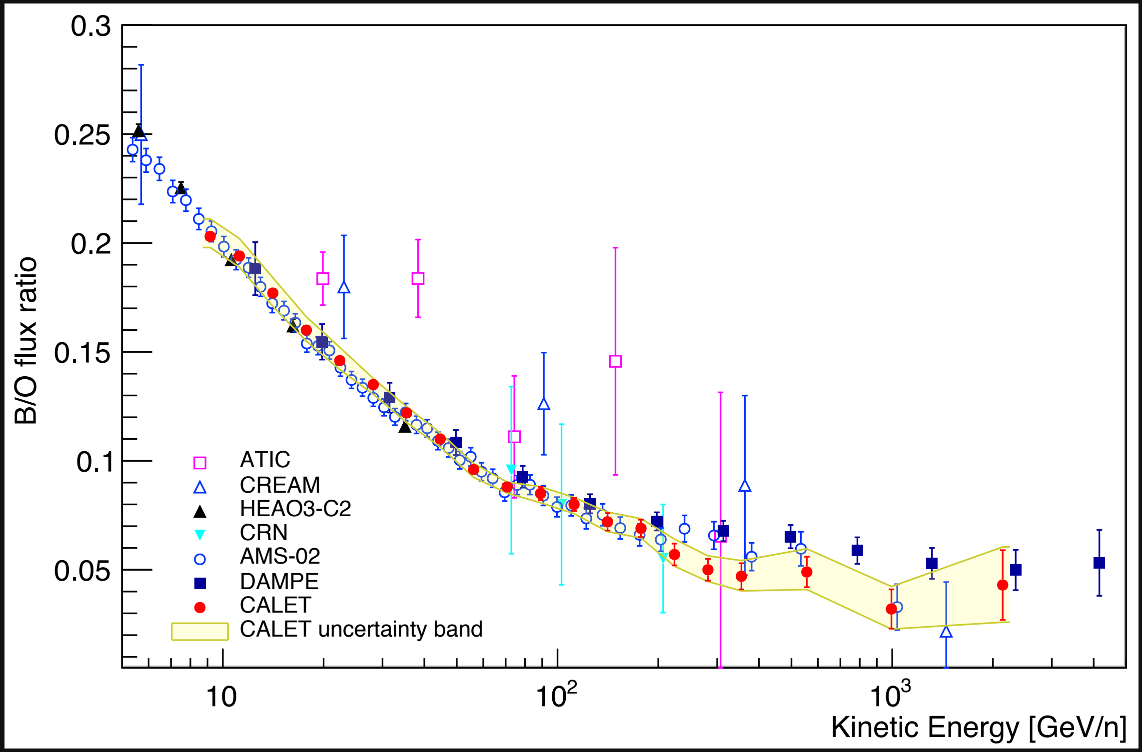
- C and O fluxes harden in a similar way above 200 GeV/n
- B spectrum clearly different from C-O as expected for primary and secondary CR
- Fit results seem to indicate, albeit with low statistical significance, that the flux hardens more for B than for C and O above 200 GeV/*n*.

B/C flux ratio



- B/C and B/O in agreement with AMS02
- Flux ratios are lower than DAMPE result above 300 GeV/n, although consistent within the error bars

B/O flux ratio



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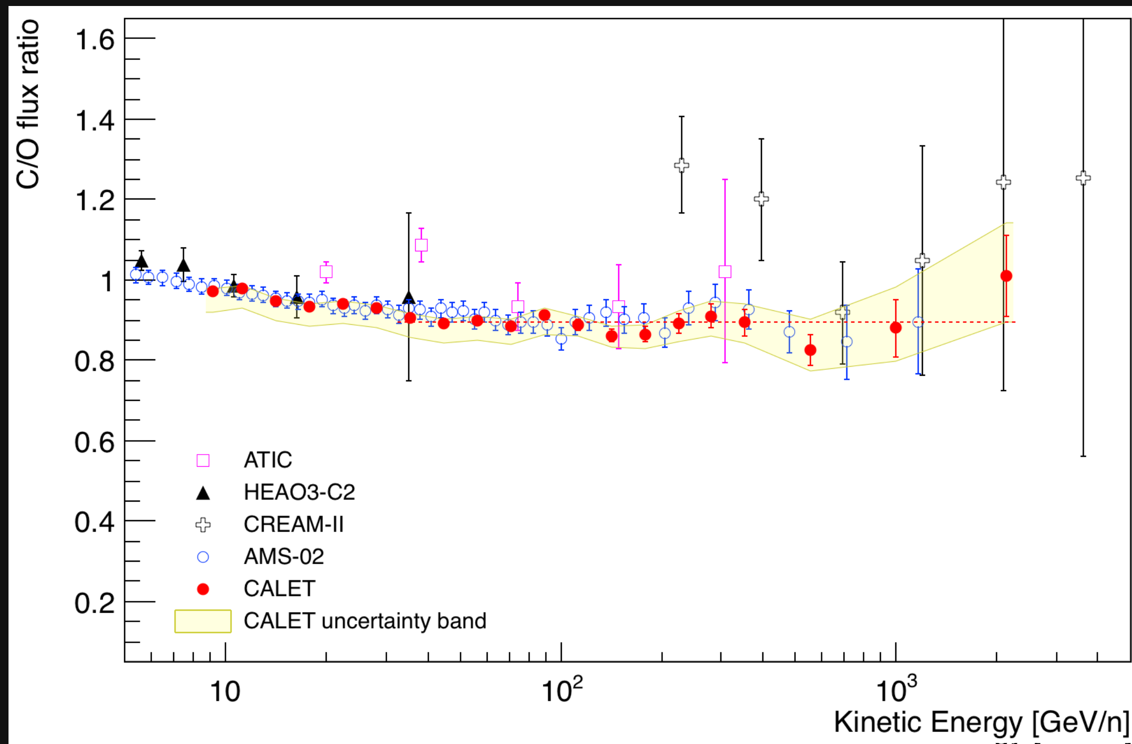
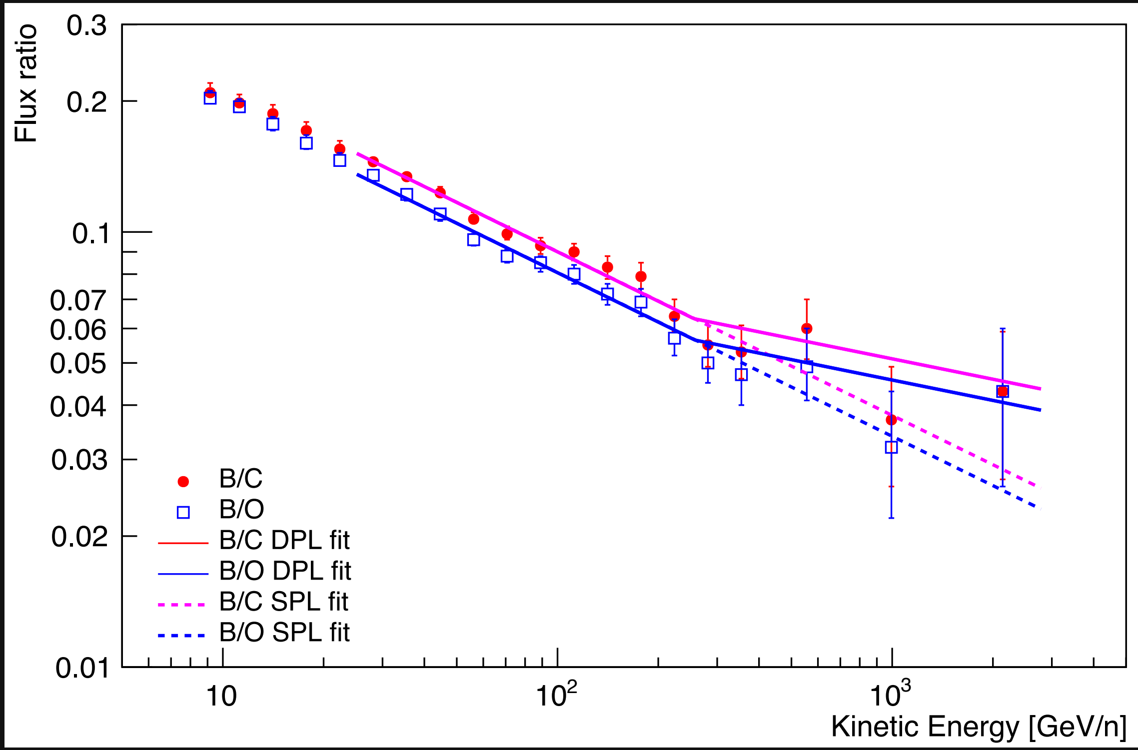
C/O flux ratio



- C/O flux ratio as a function of energy is in good agreement with AMS-02
- At E>30 GeV/n the C/O ratio is well fitted to a constant value 0.90 ± 0.03 χ^2/dof = 8.1/13
→ C and O fluxes have the same energy dependence.
- At E<30 GeV/n C/O ratio is slightly softer → secondary C from O and heavier nuclei spallation

B/C B/O spectral fit



- Simultaneous fit to B/C and B/O (E>25 GeV/n) with same parameters except normalization

  SPL fit $\Gamma = -0.376 \pm 0.014$ (χ^2/dof = 19/27)

  DPL fit $\Delta\Gamma = 0.22 \pm 0.10$ (χ^2/dof = 15/26)
- Consistent with hardening reported by AMS-02 and DAMPE
- Need more B statistics to reduce large uncertainty at high energy

Leaky Box model

In a Leaky Box model of CR transport in the Galaxy, B/C and B/O can be expressed as

$$\frac{\Phi_B(E)}{\Phi_C(E)} = \frac{\lambda(E)\lambda_B}{\lambda(E)+\lambda_B}\left[\frac{1}{\lambda_{C\to B}} + \frac{\Phi_O(E)}{\Phi_C(E)}\frac{1}{\lambda_{O\to B}}\right]$$

$$\frac{\Phi_B(E)}{\Phi_O(E)} = \frac{\lambda(E)\lambda_B}{\lambda(E)+\lambda_B}\left[\frac{1}{\lambda_{O\to B}} + \frac{\Phi_C(E)}{\Phi_O(E)}\frac{1}{\lambda_{C\to B}}\right]$$

ApJ 752, 69 (2012)

- Parametrization of the total and partial charge-changing cross sections by Webber et al. (Phys. Rev. C 41, 520 (1990)), used to calculate interaction lengths λ_B $\lambda_{O\to B}$ $\lambda_{C\to B}$
- ISM composition of 90% hydrogen and 10% helium.
- Contribution to B flux due to spallation of heavier nuclei (Ne, Mg, Si, Fe) is neglected (<10%)
- Use CALET measurement for C/O ratio in the formula

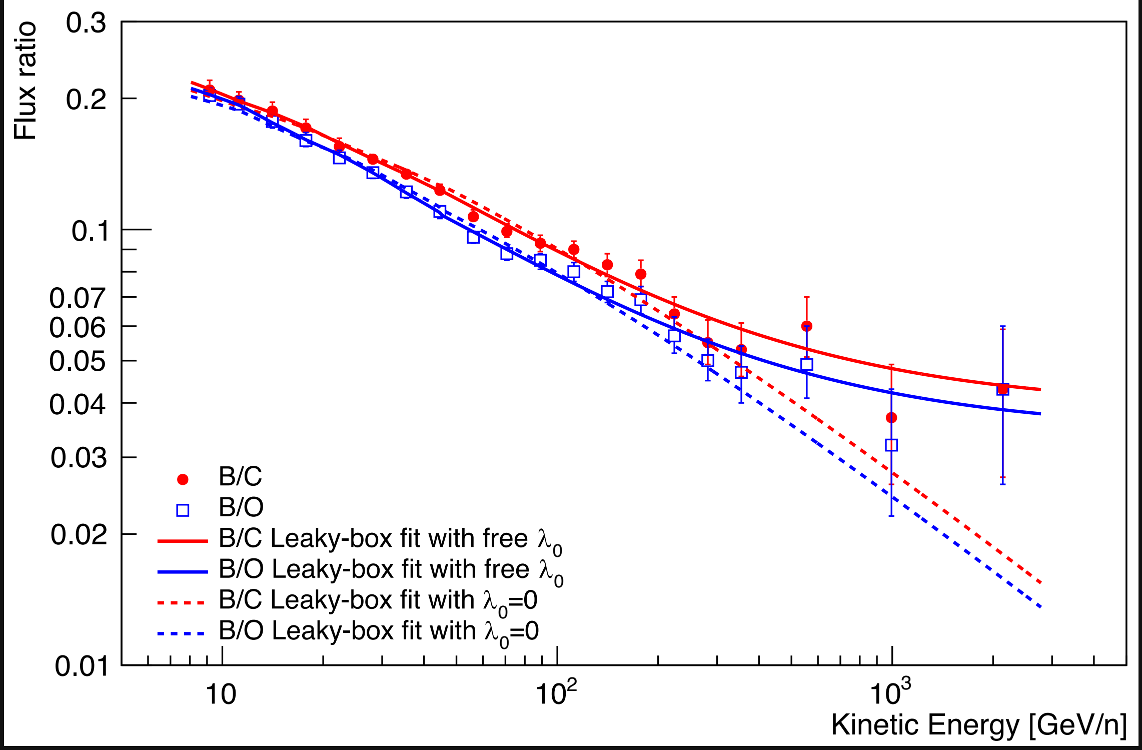
The escape pathlength can be parametrized as

$$\lambda(E) = kE^{-\delta} + \lambda_0$$

δ : diffusion coefficient spectral index

λ_0 : residual path length, i.e. the amount of matter traversed by CR inside the acceleration region (source grammage)

Leaky Box fit



Fit parameters	λ_0 =0 fixed	λ_0 free
k (g/cm$^{2)}$)	13.1 ± 0.2	13.0 ± 0.3
δ	0.61 ± 0.01	0.81 ± 0.04
λ_0 (g/cm^2)	0	1.17 ± 0.16
χ^2/dof	58.3/38	17.9/37

Significance of $\lambda_0 \neq 0$ > 5σ

→ residual path length could explain the flattening of B/C, B/O ratios at high energy.

Conclusions

CALET measured the B,C,O energy spectra and their flux ratios in the energy interval from 8.4 GeV/n to 3.8 TeV/n with 87 months of data.

C and O spectra have the same energy dependence and show a spectral index increase $\Delta\gamma = 0.19 \pm 0.04$ above 200 GeV/n

Boron spectrum exhibits a slightly larger spectral hardening (by ~0.1-0.2) than C and O fluxes occurring at about the same energy.

Within the limitations of our data's present statistical significance, this trend supports the hypothesis that secondary CRs harden more than the primaries.

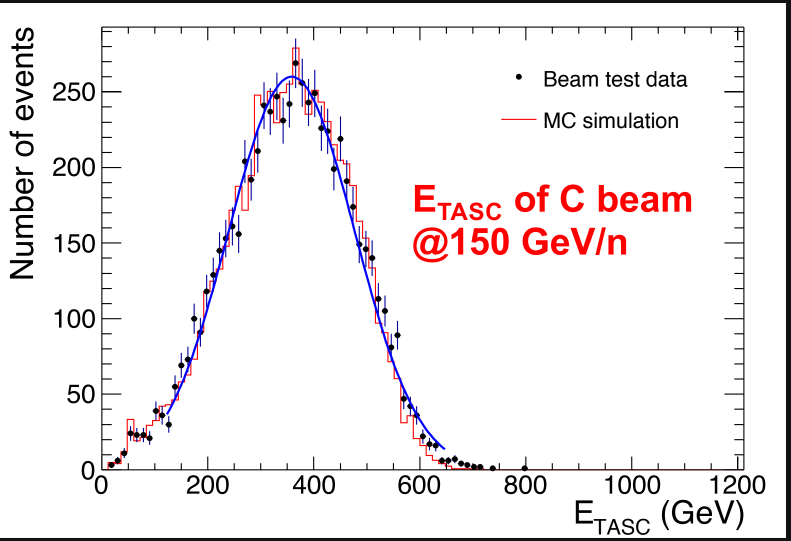
Interpreting our data with a Leaky Box model, the flattening of B/C and B/O ratios in the TeV/n region could be explained as due to a residual propagation path length (λ_0~1 g/cm^2), compatible with the hypothesis that a fraction of secondary B nuclei can be produced near the CR source.

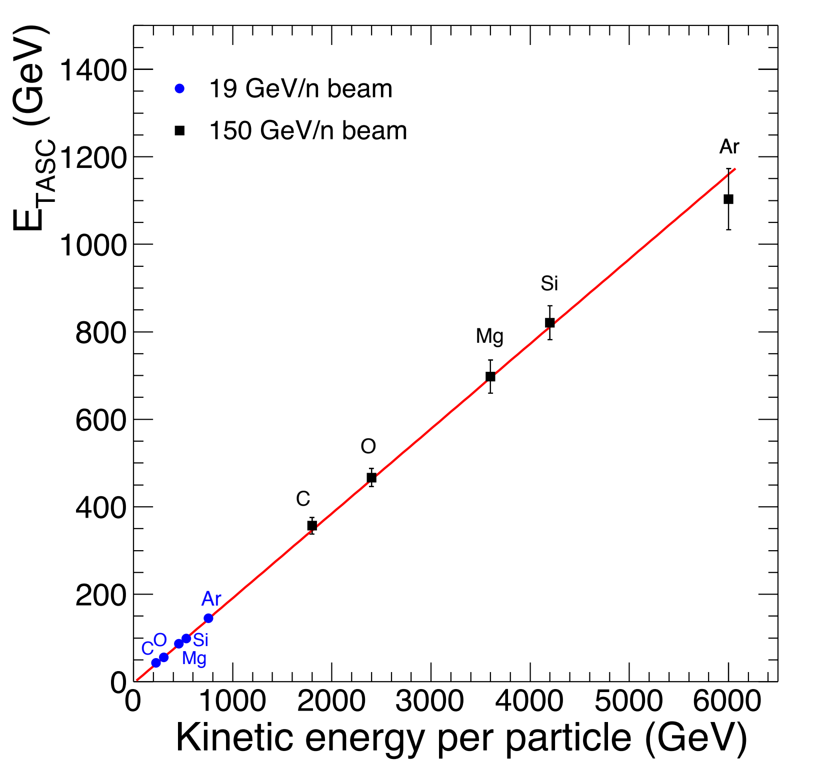
Backup slides

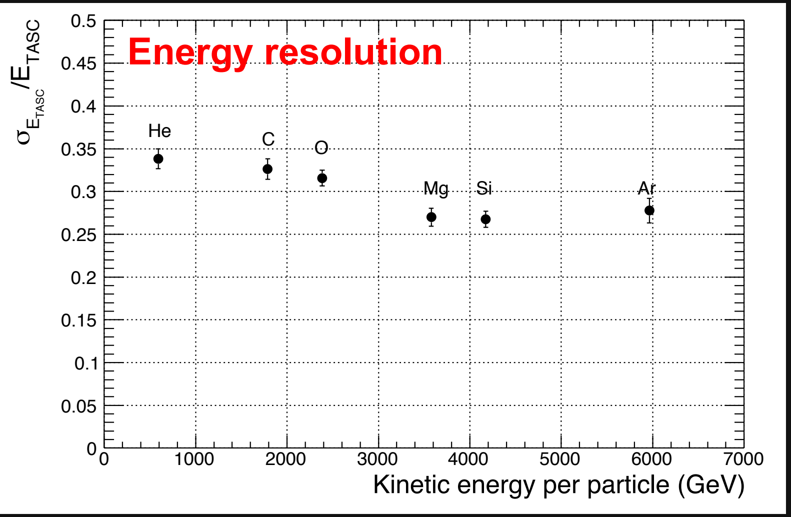
TASC energy scale

- 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%

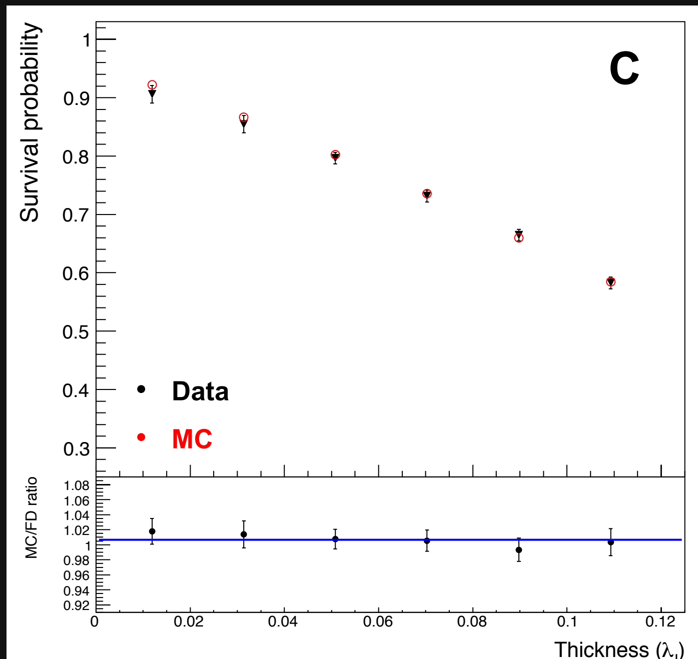
  Energy resolution ~30%
- The energy response derived from MC simulations was tuned using the beam test results.

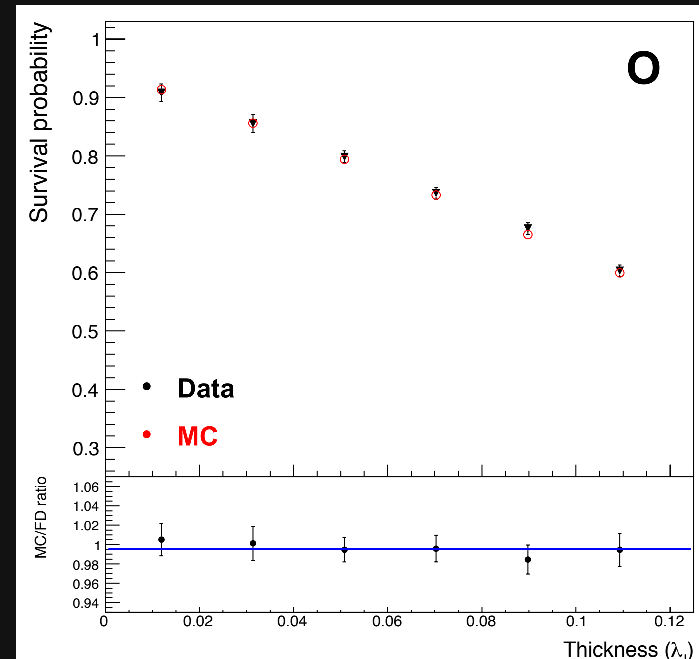






Survival probabilities





- 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%).