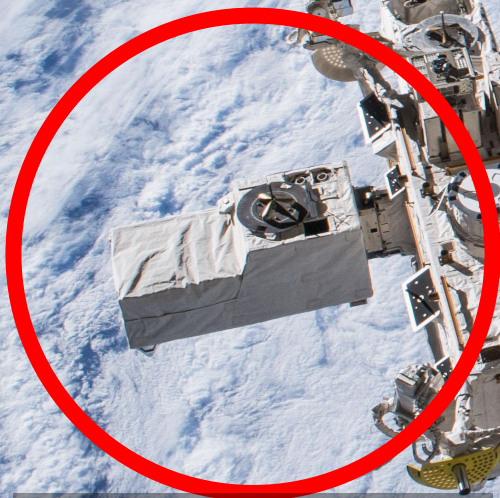


9 years of charged cosmic-ray measurements with CALET on the International Space Station



Calorimetric Electron Telescope (CALET)

Paolo Maestro
University of Siena and INFN
for the CALET Collaboration



PI: Japan
Co-PI: Italy
Co-PI: USA

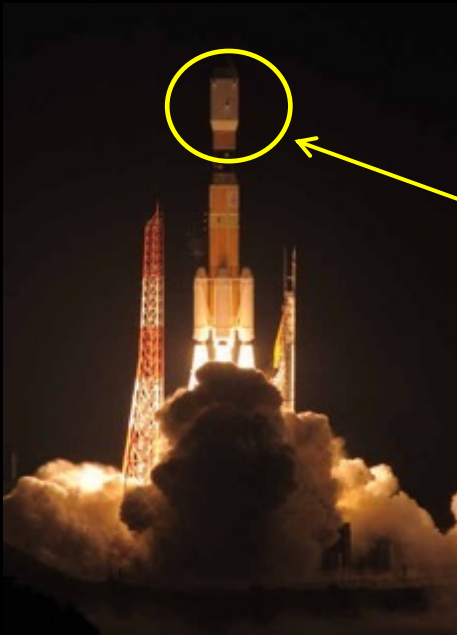
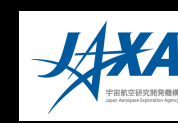
O. Adriani,^{1,2} Y. Akaike,^{3,4} K. Asano,⁵ Y. Asaoka,⁵ E. Berti,^{2,6} G. Bigongiari,^{7,8} W. R. Binns,⁹ M. Bongi,^{1,2}
P. Brogi,^{7,8} A. Bruno,¹⁰ N. Cannady,^{11,12,13} G. Castellini,⁶ C. Checchia,^{7,8} M. L. Cherry,¹⁴ G. Collazuol,^{15,16}
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M. Ichimura,¹⁹ W. Ishizaki,⁵ M. H. Israel,⁹ K. Kasahara,²⁰ J. Kataoka,²¹ R. Kataoka,²² Y. Katayose,²³
C. Kato,²⁴ N. Kawanaka,^{25,26} Y. Kawakubo,¹⁴ K. Kobayashi,^{3,4} K. Kohri,^{26,27} H. S. Krawczynski,⁹
J. F. Krizmanic,¹² P. Maestro,^{7,8} P. S. Marrocchesi,^{7,8} A. M. Messineo,^{8,28} J. W. Mitchell,¹² S. Miyake,²⁹
A. A. Moiseev,^{12,13,30} M. Mori,³¹ N. Mori,² H. M. Motz,³² K. Munakata,²⁴ S. Nakahira,¹⁷ J. Nishimura,¹⁷
M. Negro,¹⁴ S. Okuno,¹⁸ J. F. Ormes,³³ S. Ozawa,³⁴ L. Pacini,^{2,6} P. Papini,² B. F. Rauch,⁹ S. B. Ricciarini,^{2,6}
K. Sakai,^{11,12,13} T. Sakamoto,³⁵ M. Sasaki,^{12,13,30} Y. Shimizu,¹⁸ A. Shiomi,³⁶ P. Spillantini,¹ F. Stolzi,^{7,8}
S. Sugita,³⁵ A. Sulaj,^{7,8} M. Takita,⁵ T. Tamura,¹⁸ T. Terasawa,⁵ S. Torii,³ Y. Tsunesada,^{37,38} Y. Uchihori,³⁹
E. Vannuccini,² J. P. Wefel,¹⁴ K. Yamaoka,⁴⁰ S. Yanagita,⁴¹ A. Yoshida,³⁵ K. Yoshida,²⁰ W. V. Zober⁹

- 1) University of Florence, Italy
- 2) INFN Sezione di Firenze, Italy
- 3) RISE, Waseda University, Japan
- 4) JEM Utilization Center, JAXA, Japan
- 5) ICRR, University of Tokyo, Japan
- 6) IFAC, CNR, Italy
- 7) University of Siena, Italy
- 8) INFN Sezione di Pisa, Italy
- 9) Washington University in St. Louis, USA
- 10) Heliospheric Physics Laboratory, NASA GSFC, USA
- 11) University of Maryland, Baltimore County, USA
- 12) Astroparticle Physics Laboratory, NASA GSFC, USA
- 13) CRESST II, NASA GSFC, USA
- 14) Louisiana State University, USA

- 15) University of Padova, Italy
- 16) INFN Sezione di Padova, Italy
- 17) ISAS, JAXA, Japan
- 18) Kanagawa University, Japan
- 19) Hirosaki University, Japan
- 20) Shibaura Institute of Technology, Japan
- 21) ASE, Waseda University, Japan
- 22) NIPR, Japan
- 23) Yokohama National University, Japan
- 24) Shinshu University, Japan
- 25) Tokyo Metropolitan University
- 26) NAO, Japan
- 27) IPNS, KEK, Japan
- 28) University of Pisa, Italy

- 29) KOSEN, NIT, Japan
- 30) University of Maryland, College Park, USA
- 31) Ritsumeikan University, Japan
- 32) GCSE, Waseda University, Japan
- 33) University of Denver, USA
- 34) NICT, Japan
- 35) Aoyama Gakuin University, Japan
- 36) Nihon University, Japan
- 37) Osaka Metropolitan University, Japan
- 38) NITEP, Osaka Metropolitan University, Japan
- 39) QST, Japan
- 40) Nagoya University, Japan
- 41) Ibaraki University, Japan

CALET payload



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

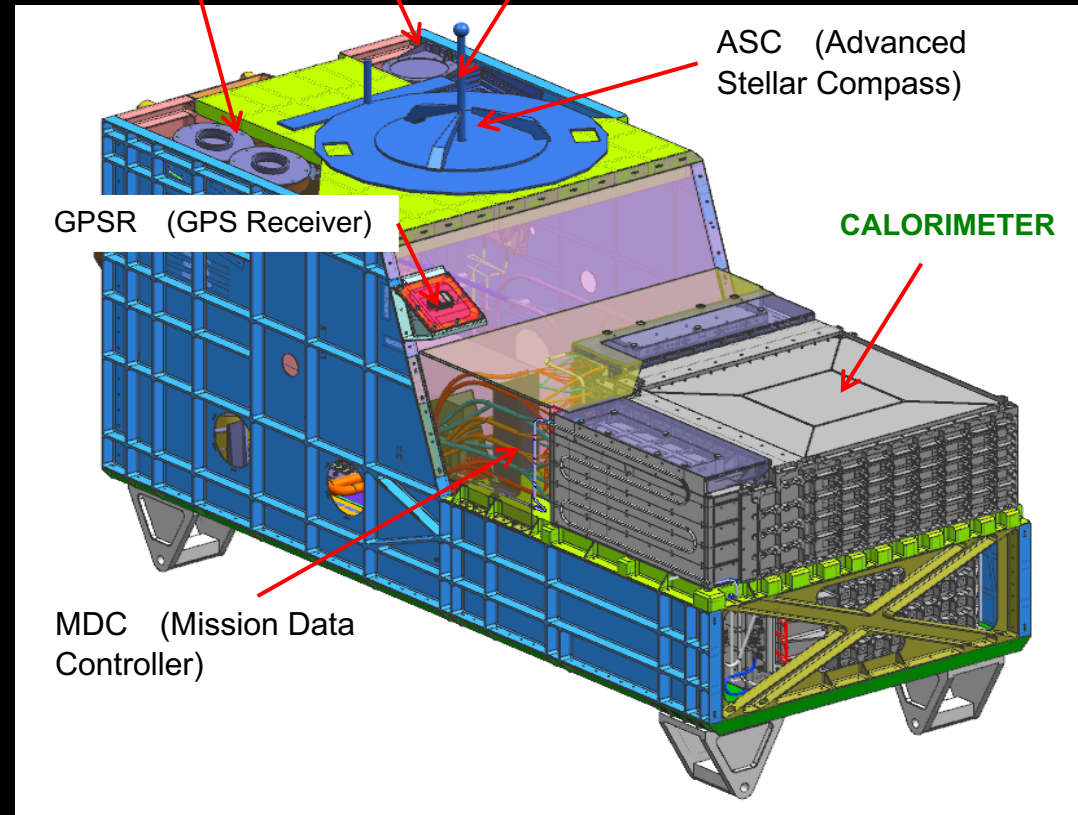


Continuous and stable operations from Oct. 13th 2015

JEM-Port # 9

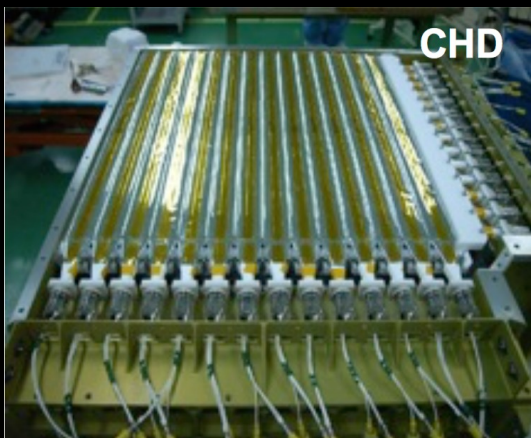
CGBM (CALET Gamma Ray Burst Monitor)

FRGF (Flight Releasable Grapple Fixture)

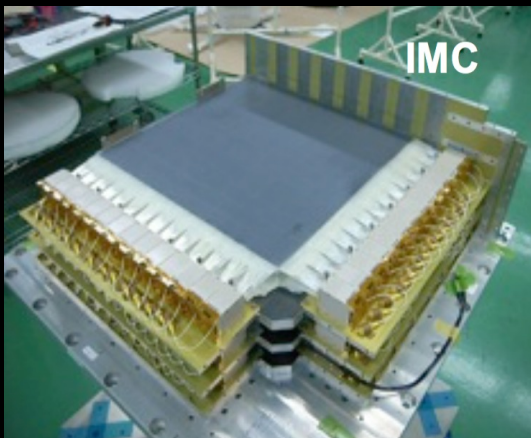


- Mass: 612.8 kg
- JEM Standard Payload Size
1850 mm (L) × 800 mm (W) × 1000 mm (H)
- Power Consumption: 507 W (max)
- Telemetry: Medium (Low) 600 (50) kbps (6.5GB/day)

CALET Calorimeter



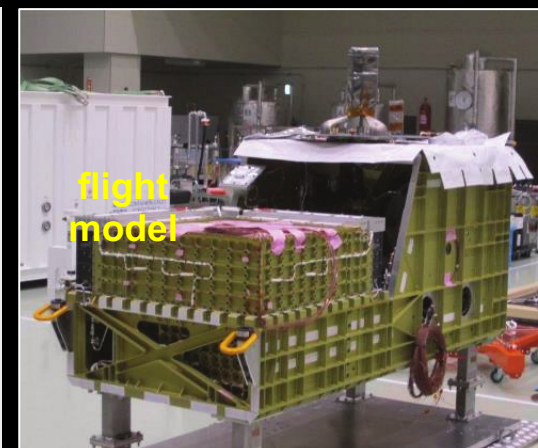
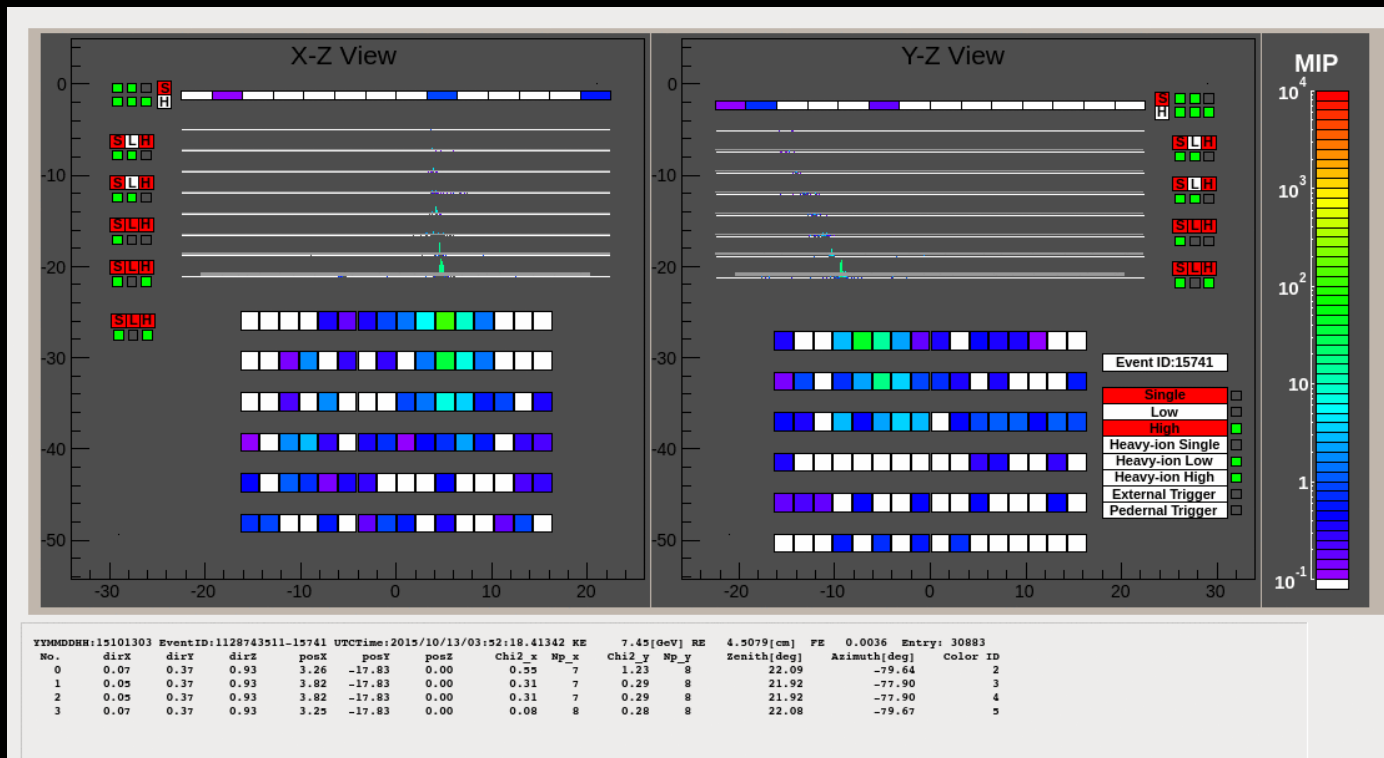
CHD



IMC



TASC



flight model

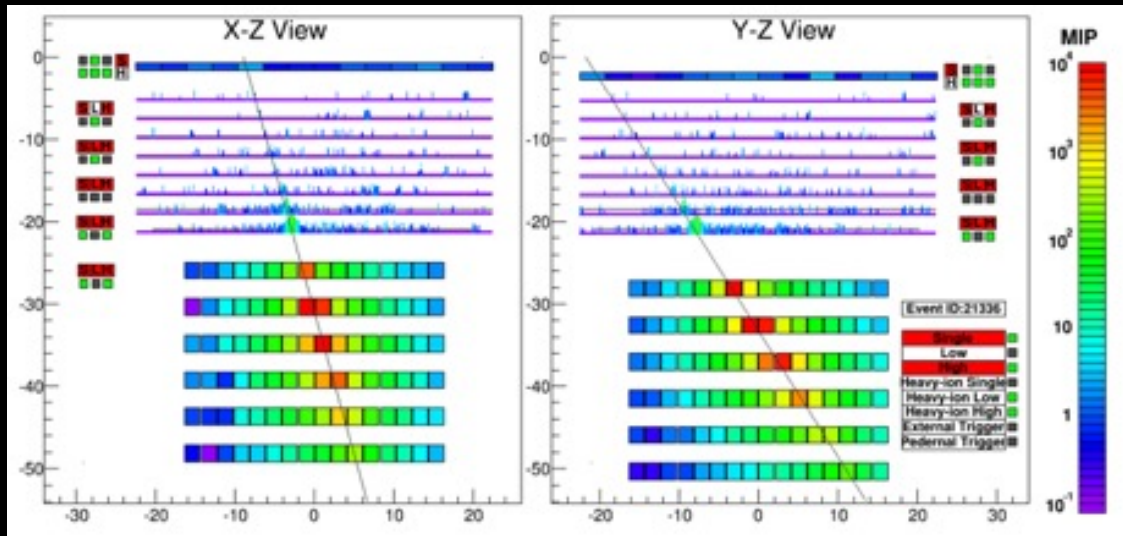
<p>CHD Charge Detector</p>	<p>2 layers x 14 plastic scintillating paddles single element charge ID from p to Fe and up to Z = 40 charge resolution ~0.1-0.3 e</p>	<p>PMT+CSA</p>
<p>IMC Imaging Calorimeter</p>	<p>Scifi + 7 W absorbers: 3 X₀ at normal incidence 8 x 2 x 448 plastic scifi (1mm²) readout individually Tracking (~0.1° angular resolution) + Shower imaging</p>	<p>64 MAPMT+ ASIC</p>
<p>TASC Total Absorption Calorimeter</p>	<p>Total thickness 27 X₀, 1.2 λ_i 6 x 2 x 16 lead tungstate (PbWO₄) logs Energy res.: ~2% (>10 GeV) for e,γ ~30% for p,nuclei e/p separation: ~10⁵</p>	<p>APD/PD + CSA PMT+CSA Dynamic range:10⁶</p>

CALET scientific objectives

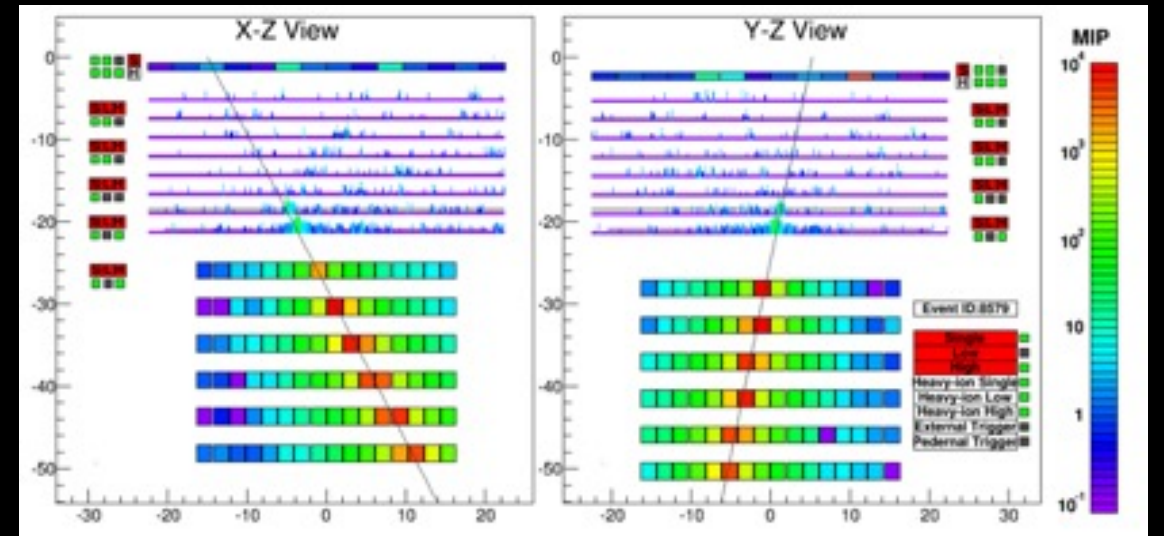
Scientific Objectives	Observable Quantity	Energy Range
Cosmic-ray origin and acceleration	Electron spectrum	1 GeV – 20 TeV
	Elemental spectra	10 GeV – 1 PeV
	Ultra-heavy abundances	> 600 MeV/n
	Gamma rays (diffuse & point source)	1 GeV – 1 TeV
Galactic CR propagation	B/C and sub-Fe/Fe ratios	Up to some TeV/n
Nearby CR sources	Electron spectrum	100 GeV – 20 TeV
Dark matter	Signatures in electron/gamma spectra	100 GeV – 20 TeV
Solar physics	Electron flux	1 GeV – 10 GeV
Gamma-ray transients, GW counterparts	LE gamma rays and X-rays	7 keV – 20 MeV

Examples of CALET event candidates

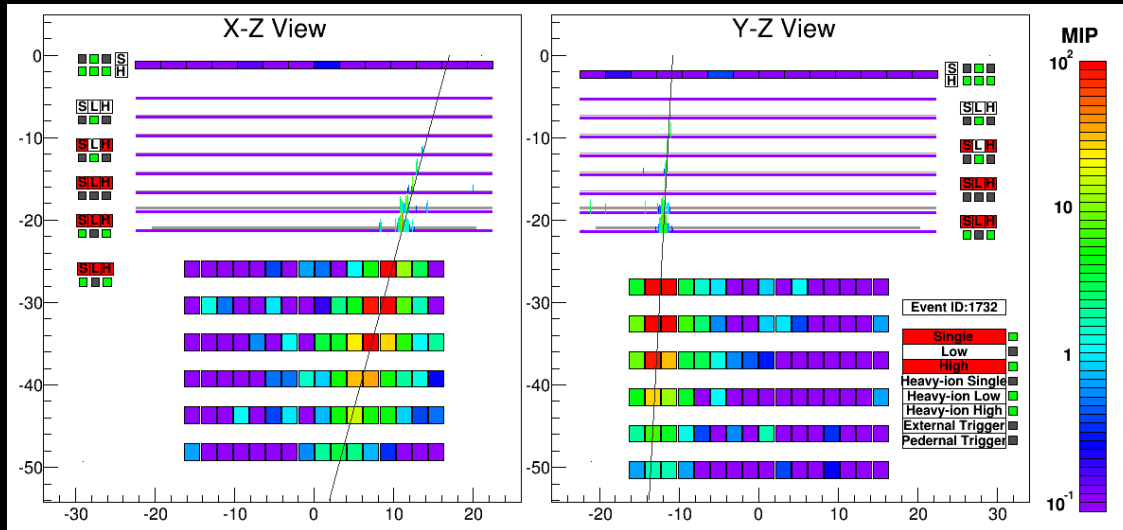
Electron, $E=3.05$ TeV



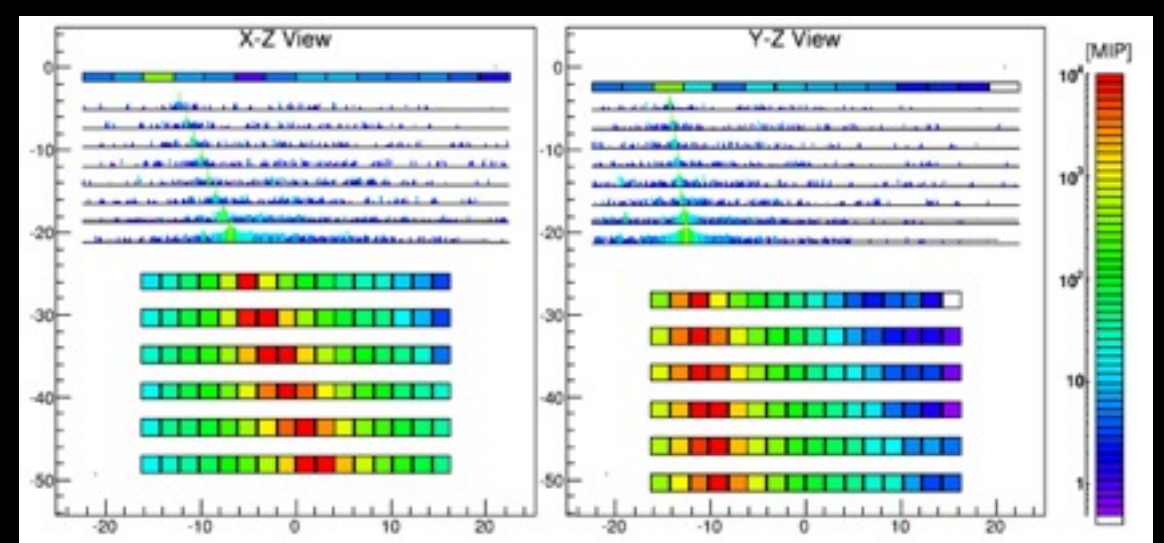
Proton, $E_{TASC}=2.89$ TeV



Gamma-ray, $E=44.3$ GeV

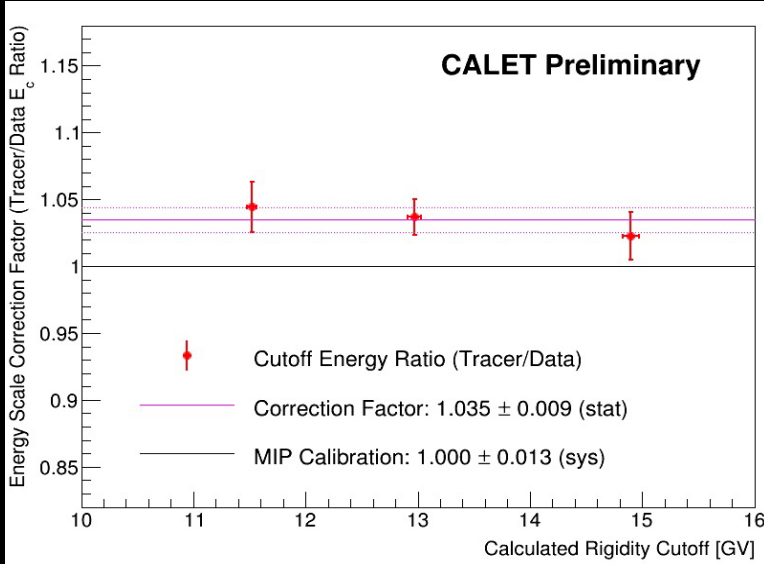


Iron, $E_{TASC}=9.3$ TeV



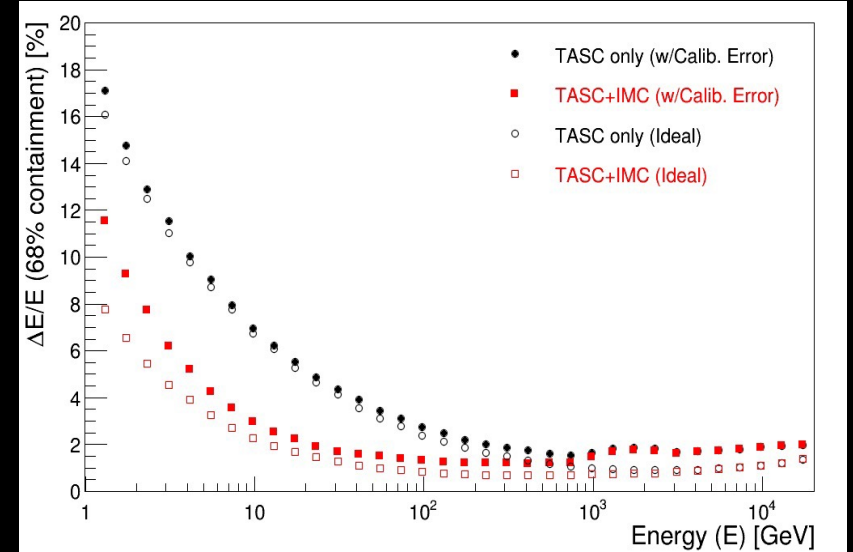
Energy measurement: energy scale and resolution

ELECTRONS

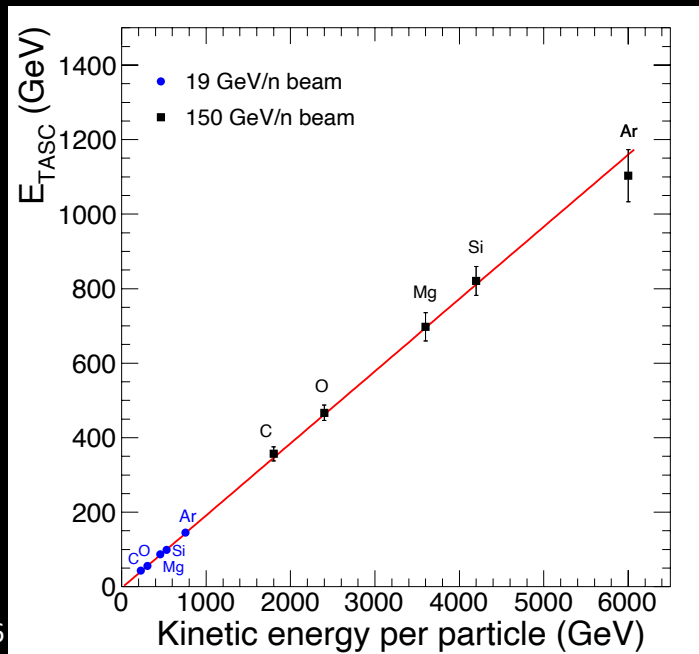


Beam calibration at CERN-SPS + rigidity cutoff

Energy resolution: < 2% above 20 GeV with both TASC and IMC including calibration errors



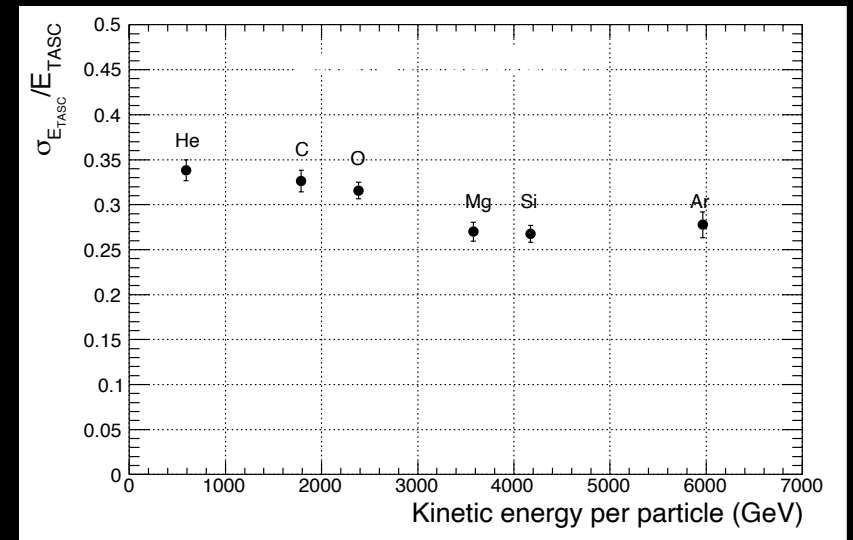
HADRONS



Beam calibration at CERN-SPS with ion fragments from primary Ar beam at 13, 19 150 GeV/n

Linearity assessed up to ~6 TeV
Fraction of particle energy released in TASC is ~20%

Energy resolution ~30%



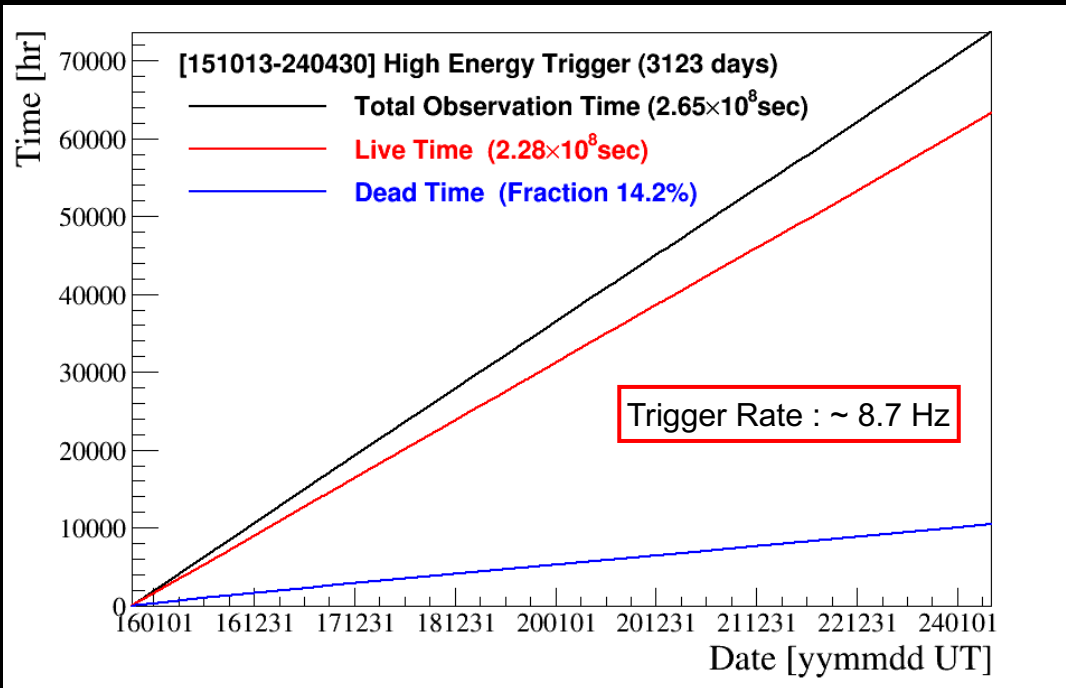
CALET Orbital Operations

Geometrical Factor:

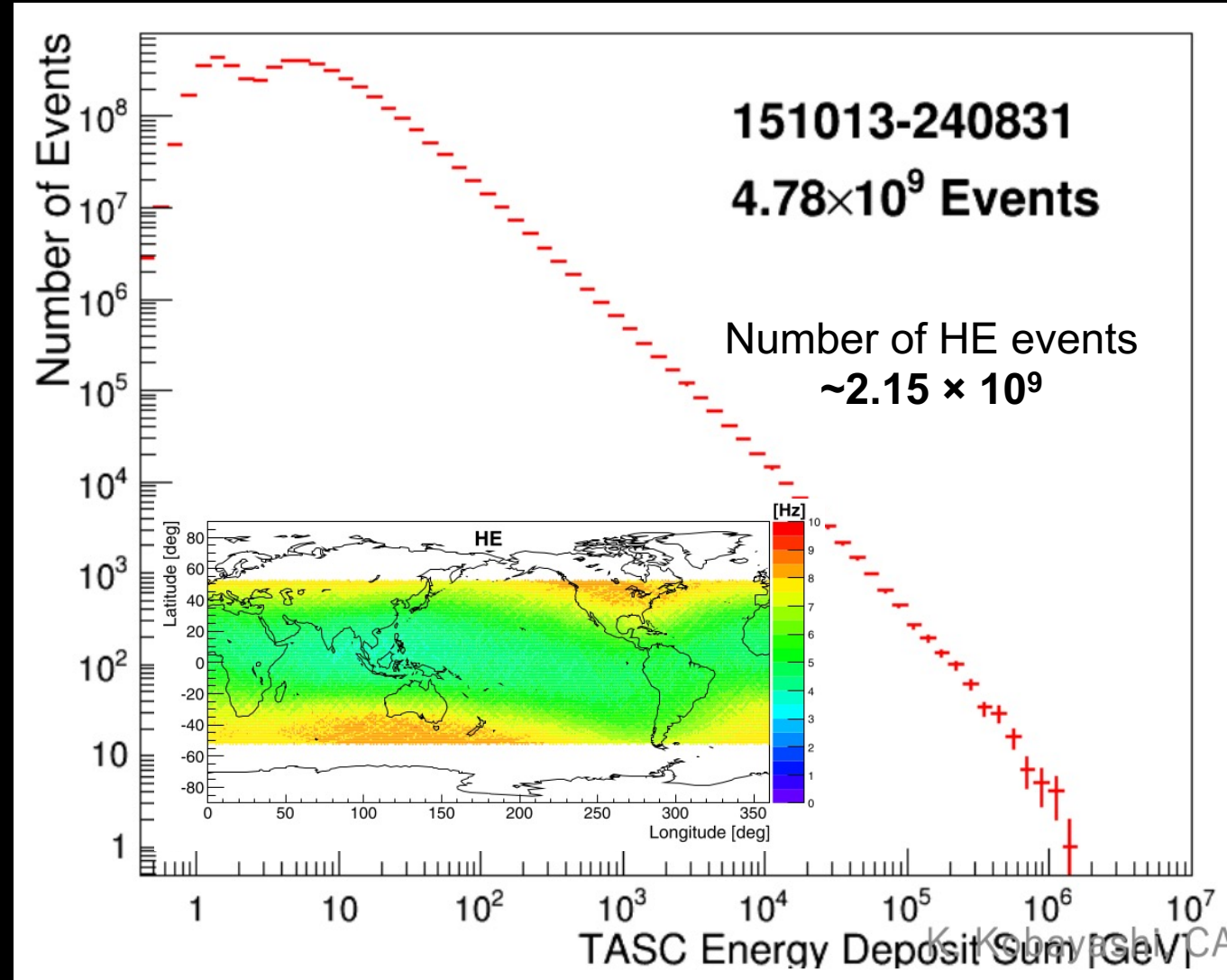
- 1040 cm² sr for electrons, light nuclei
- 1000 cm² sr for gamma-rays
- 4000 cm²sr for ultra-heavy nuclei

High-energy trigger (> 10 GeV) statistics:

- Orbital operations **>3200 days**
- Live time fraction **~ 86%**
- Exposure of HE trigger **~300 m² sr day**

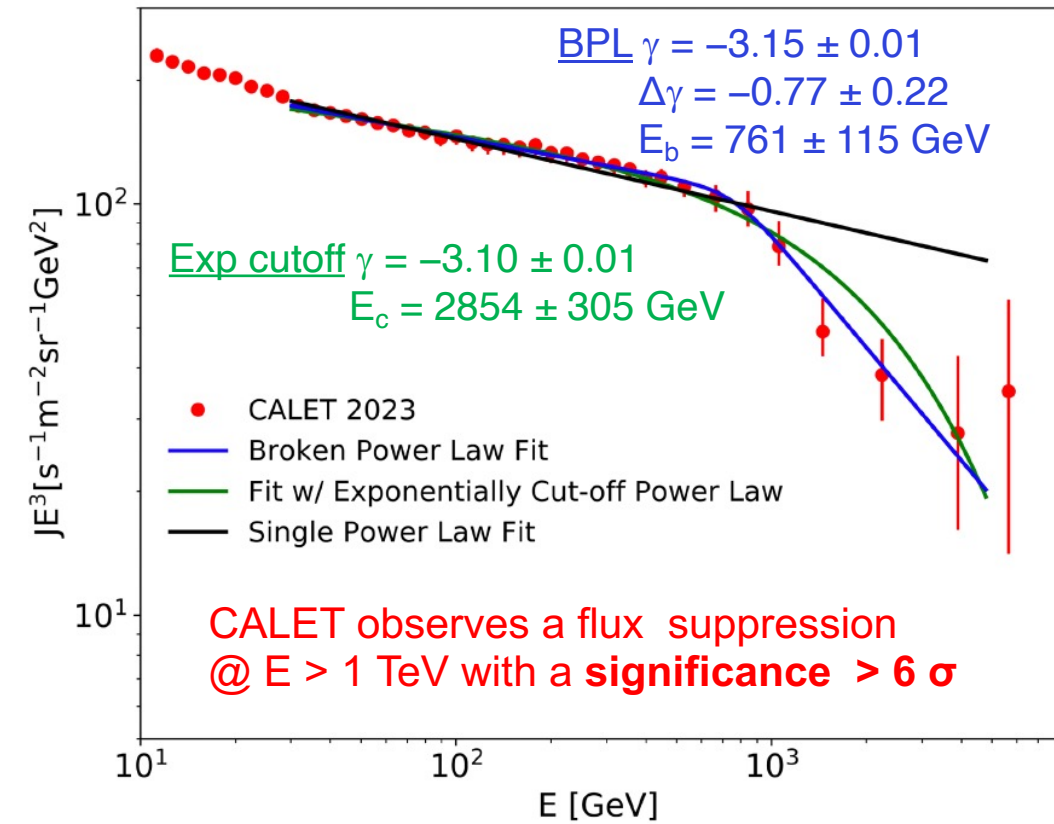
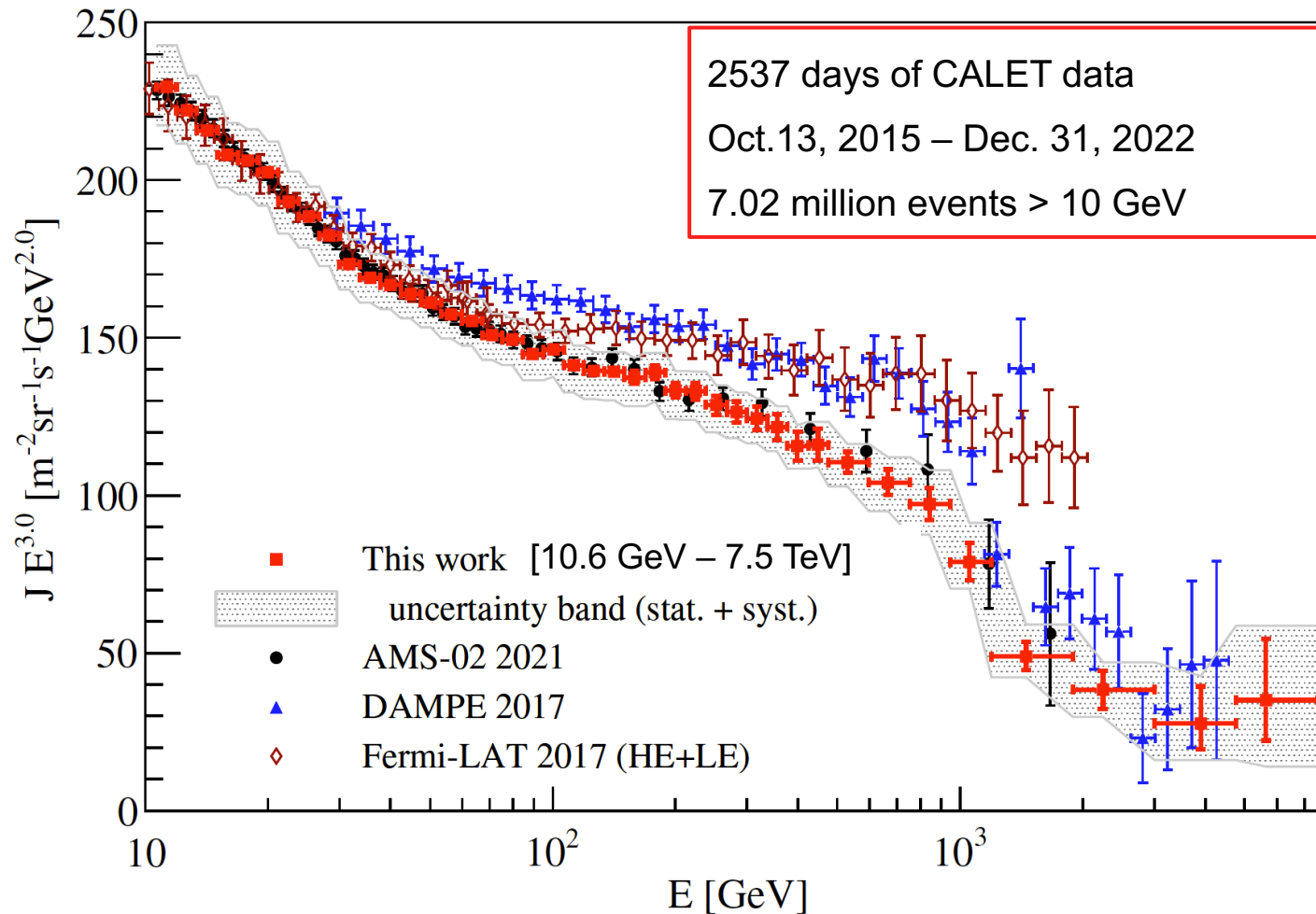


Energy deposit (in TASC) spectrum: 1 GeV-1 PeV



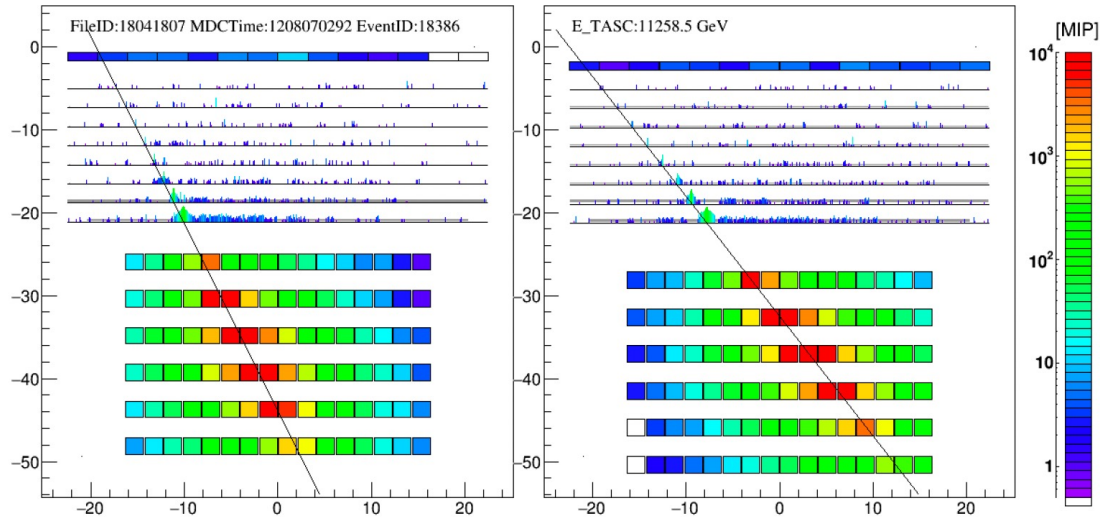
Cosmic-ray all electron spectrum

PRL 131 191001 (2023)
ICRC2023 Pos 071

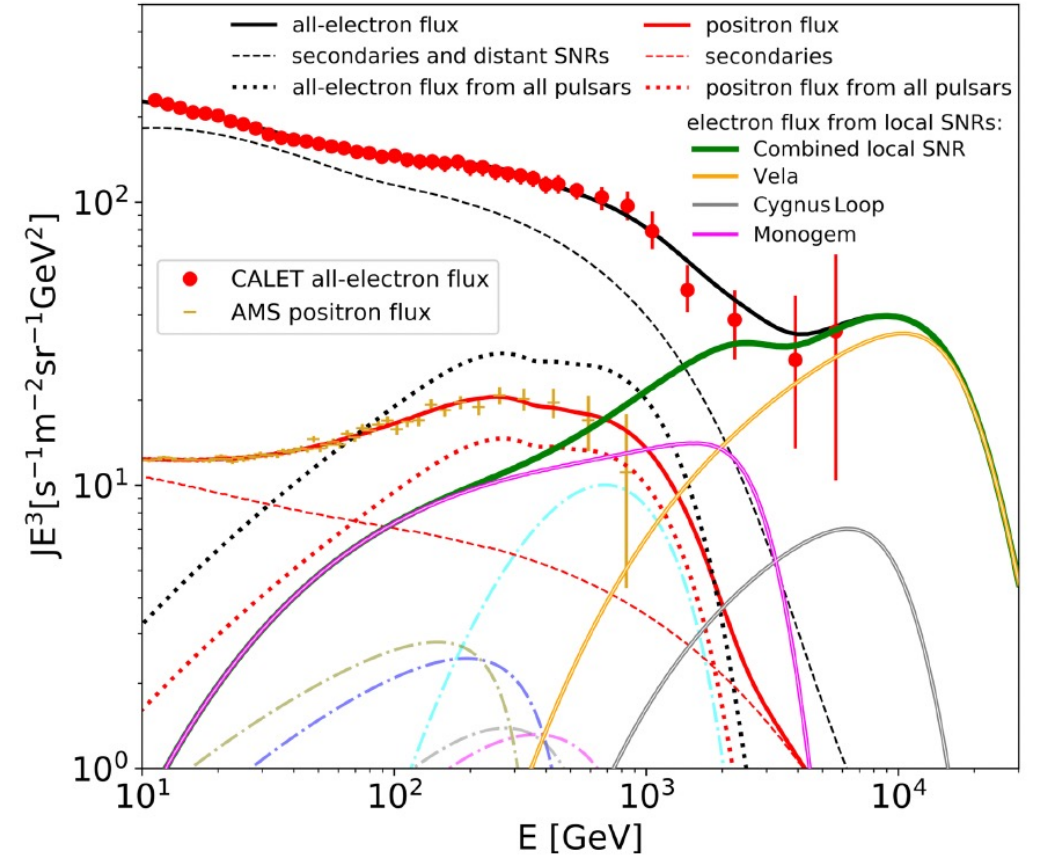


Continued observation has reduced statistical and systematic errors in the all-electron spectrum.
Systematic discrepancy between CALET/AMS-02 and DAMPE/Fermi-LAT persists beyond tabulated error.

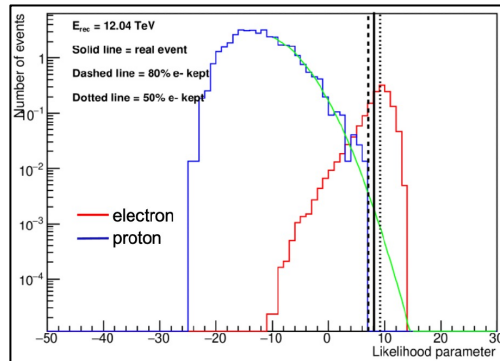
Energy losses due to Synchrotron and Inverse Compton → Observable sources of the electrons in the TeV region located at a distance $< \sim 1 \text{ kpc}$ and produced $< \sim 10^5 \text{ yr}$ ago.
→ **Softening of the spectrum is expected above 1 TeV**



Nearby accelerators could leave observable features in the spectrum in the TeV region.



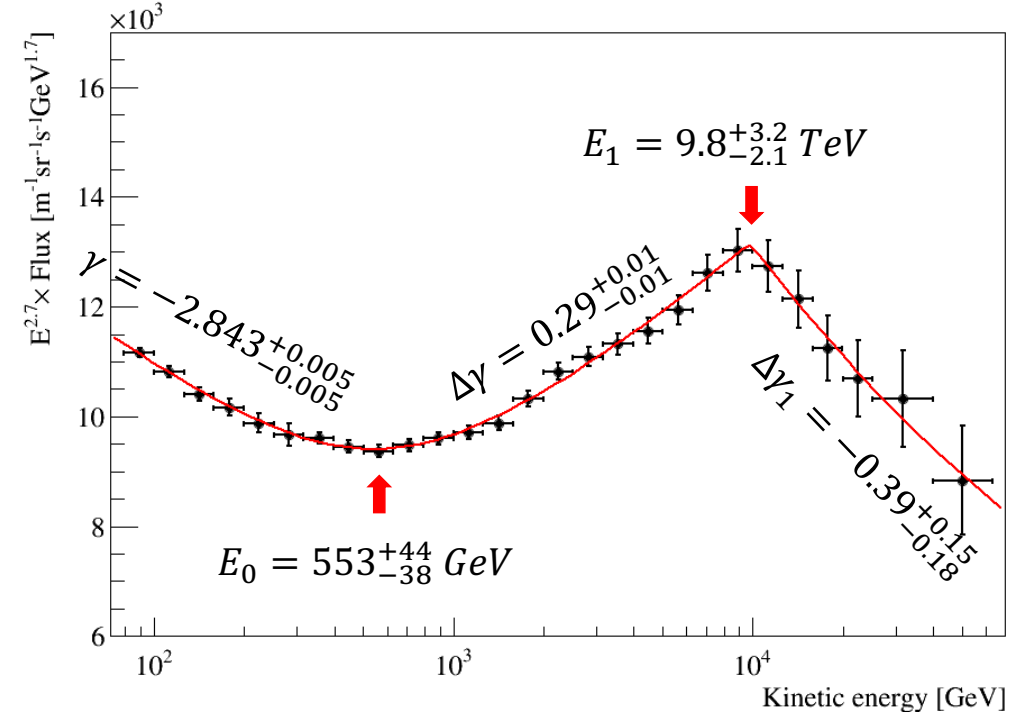
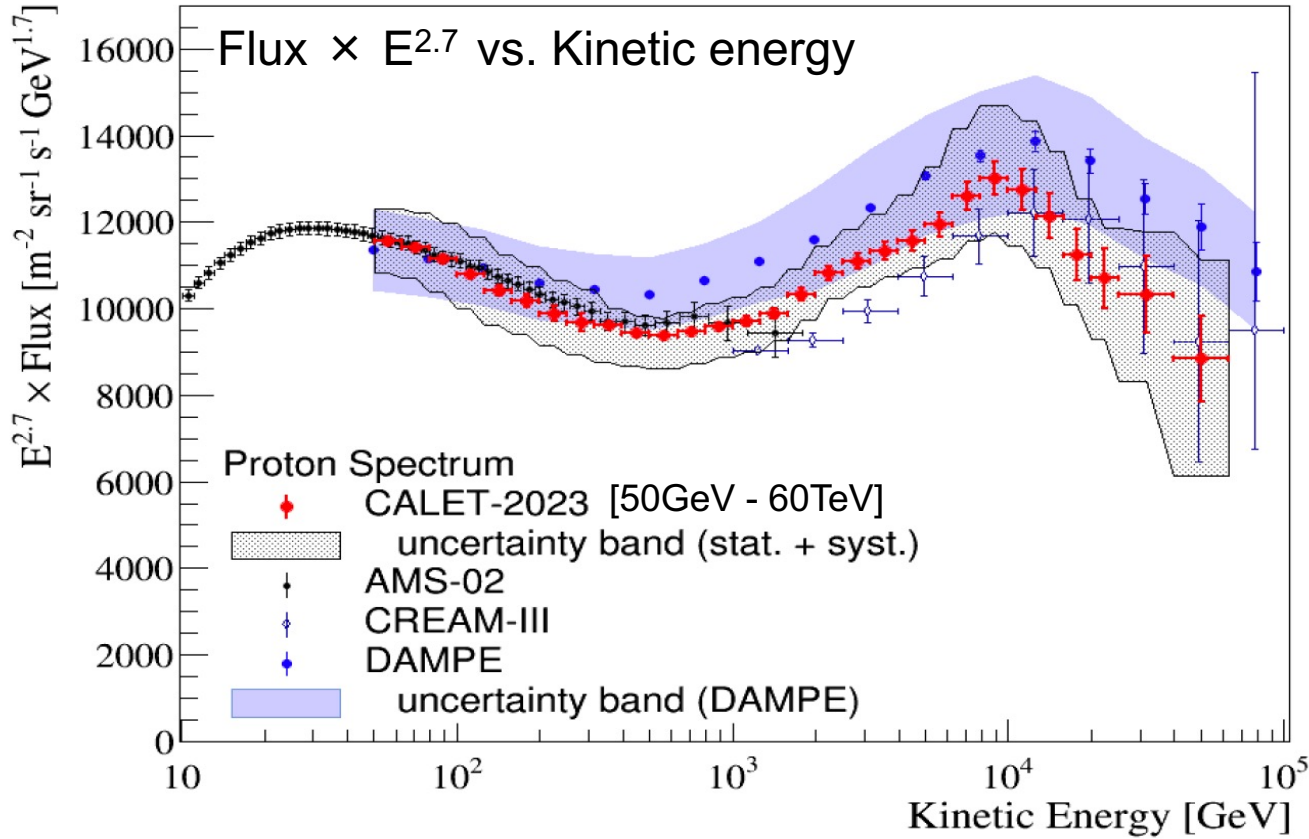
Advanced analysis is going on for electron identification @ $E > 5$ TeV.



The observed numbers of electron candidates obtained by the event-by-event analysis are 9 (4) above 4.8 TeV (7.5 TeV), compatible with the expected contribution from the nearby SNRs

Cosmic-ray proton spectrum

PRL 129 101102 (2022)
ICRC2023 Pos 092

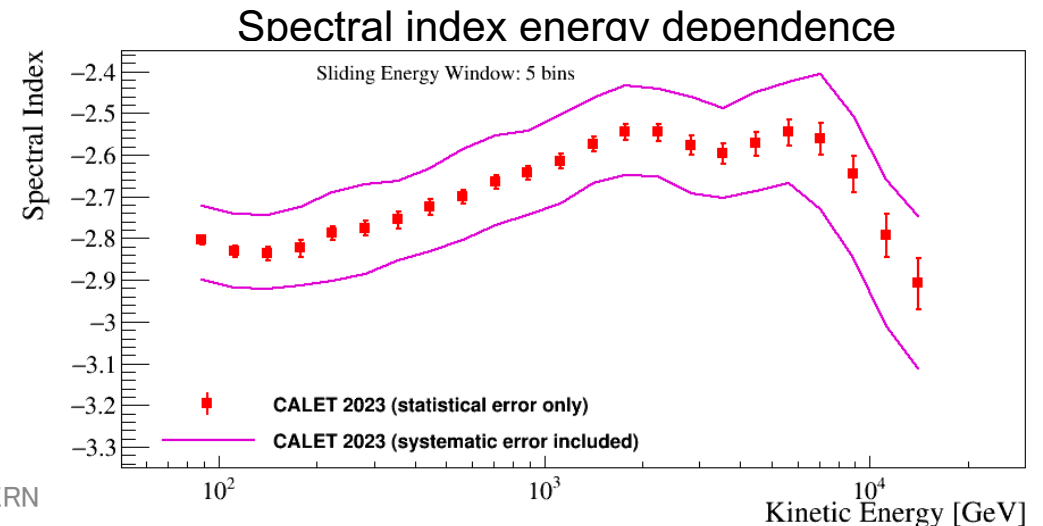


Double Power Law Function:

HARDENING

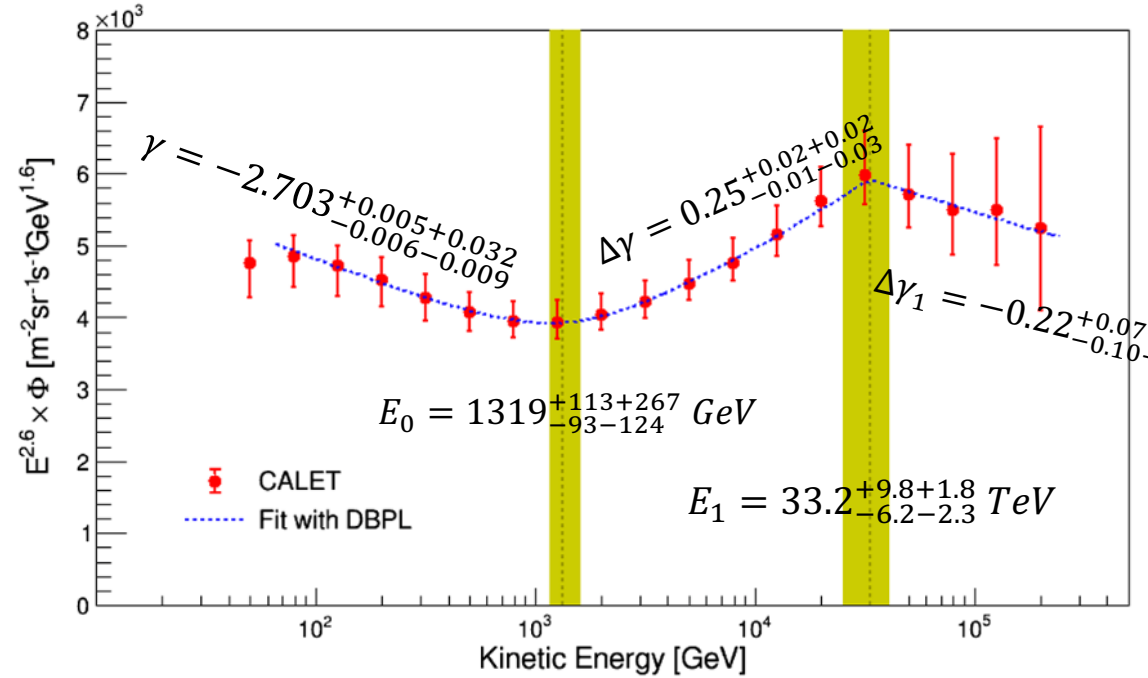
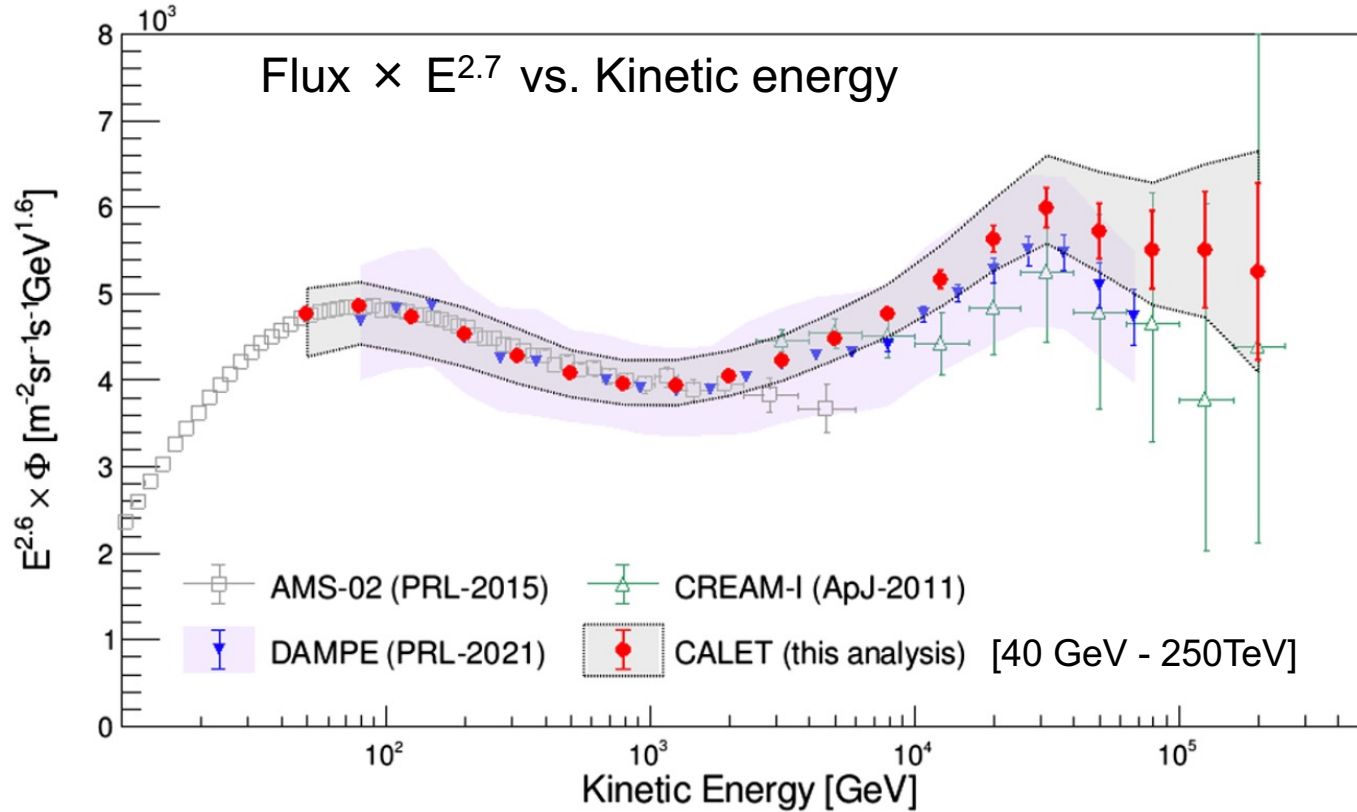
SOFTENING

$$\Phi(E) = C \left(\frac{E}{\text{GeV}} \right)^\gamma \left[1 + \left(\frac{E}{E_0} \right)^S \right]^{\frac{\Delta\gamma}{S}} \left[1 + \left(\frac{E}{E_1} \right)^{S_1} \right]^{\frac{\Delta\gamma_1}{S_1}}$$



Cosmic-ray helium spectrum

PRL 130 171002 (2023)

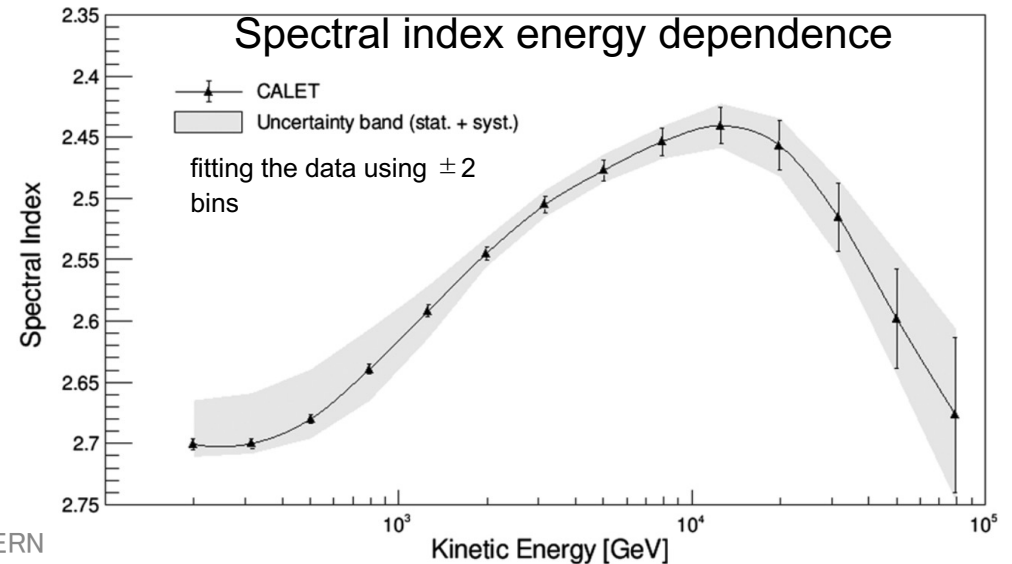


Double Power Law Function:

HARDENING

SOFTENING

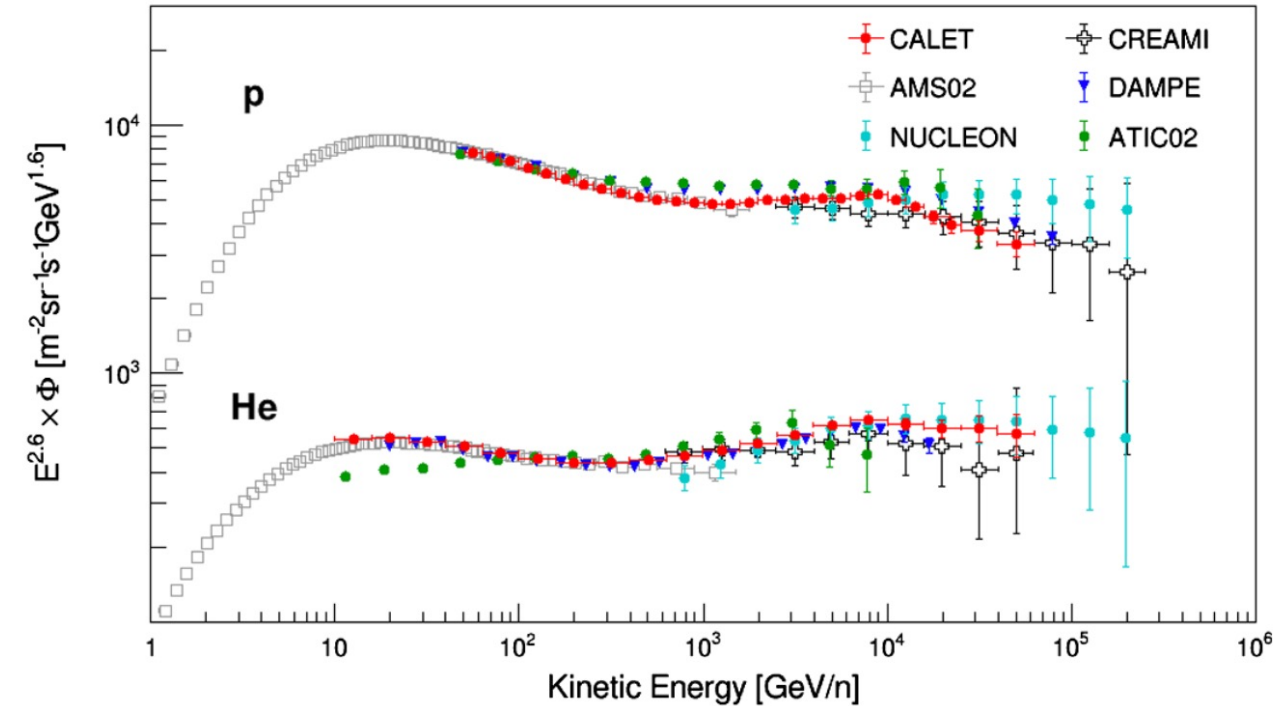
$$\Phi(E) = C \left(\frac{E}{GeV} \right)^\gamma \left[1 + \left(\frac{E}{E_0} \right)^S \right]^{\frac{\Delta\gamma}{S}} \left[1 + \left(\frac{E}{E_1} \right)^{S_1} \right]^{\frac{\Delta\gamma_1}{S_1}}$$



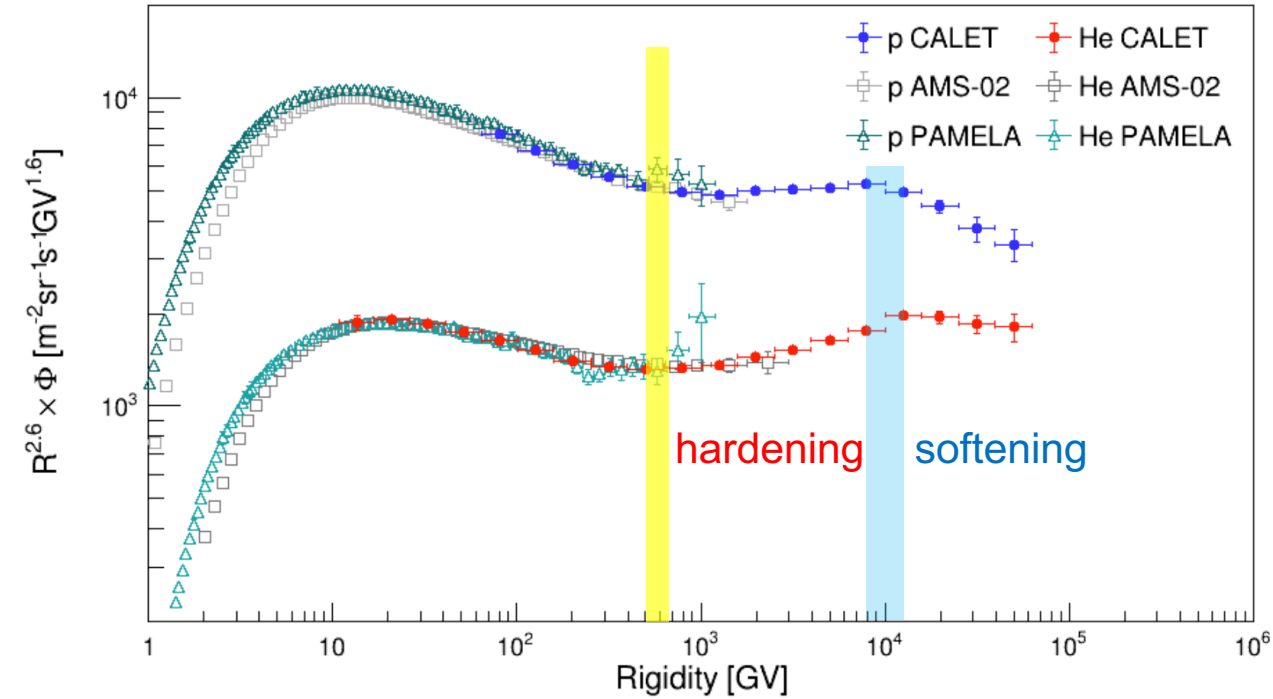
Proton vs. Helium Spectrum

PRL 130 171002 (2023)

Proton & Helium Spectrum vs **Enerav/nucleon**



Proton & Helium Spectrum vs **Rigidiy**

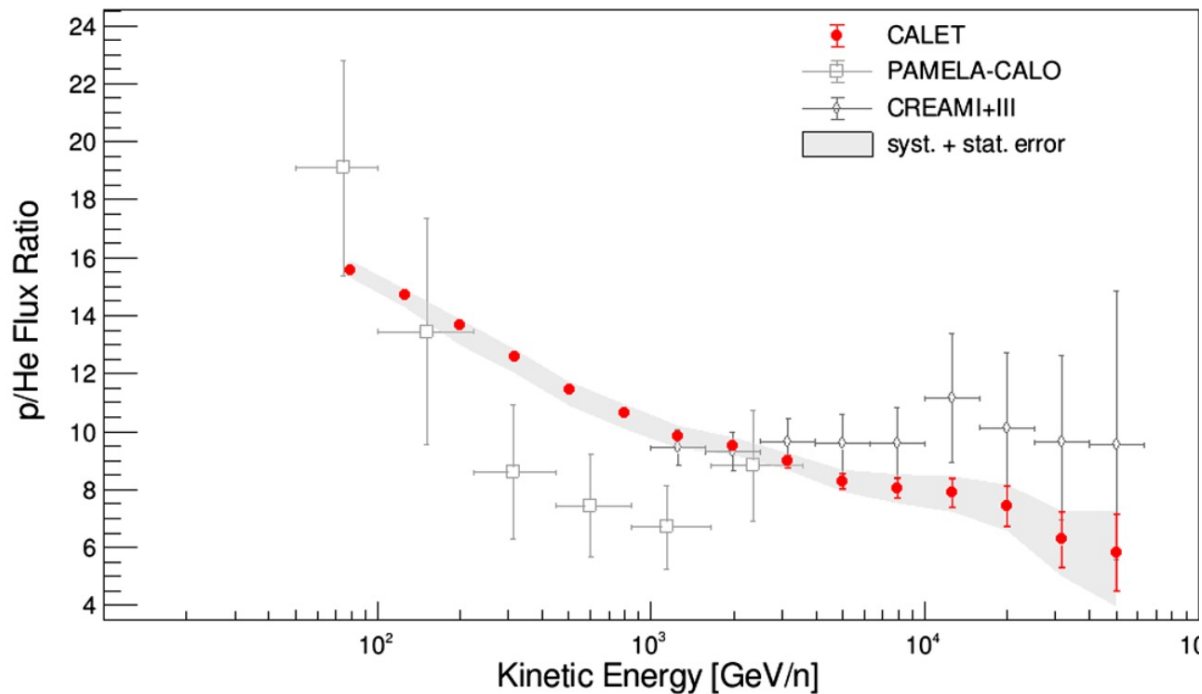


- Both of proton and helium spectrum have a similar structure of **hardening** and **softening** around the same region of rigidities.
- The softening of p & He spectrum around 10 TV indicates a possible relation to the energy limit of shock wave acceleration in SNR.

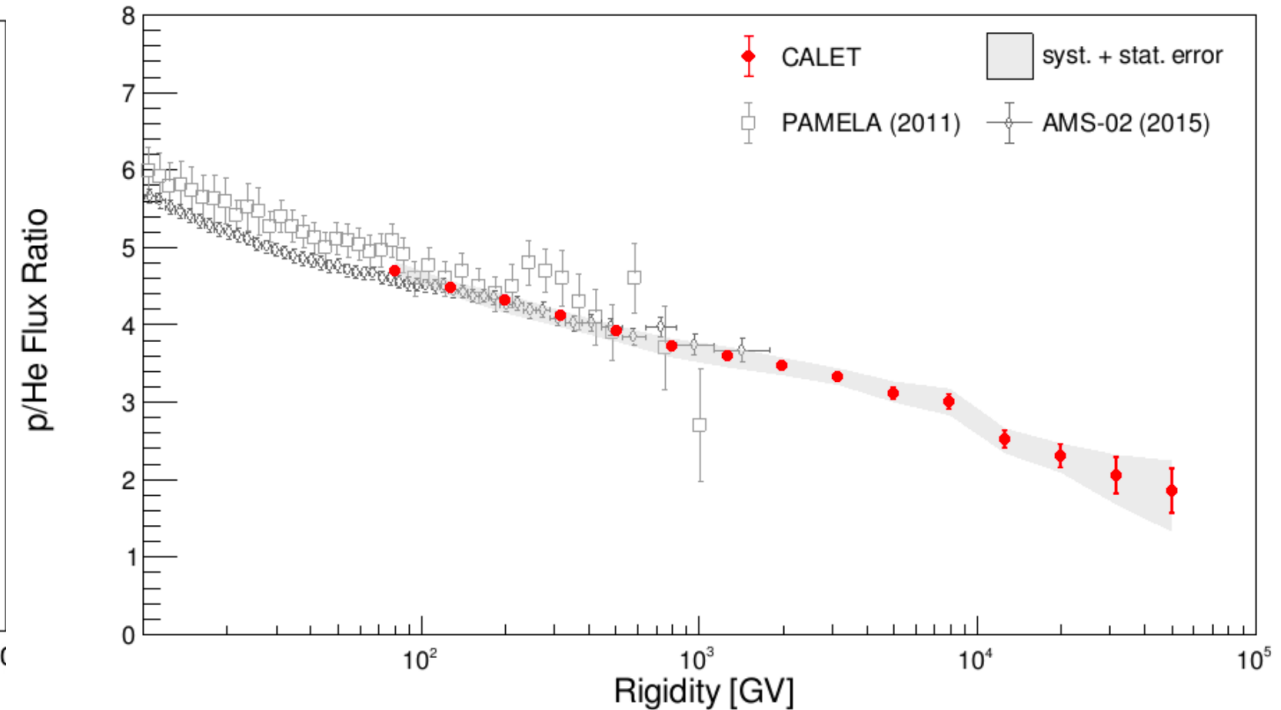
Proton/Helium Ratio

PRL 130 171002 (2023)

Proton/Helium Ratio vs. **Energy/nucleon**



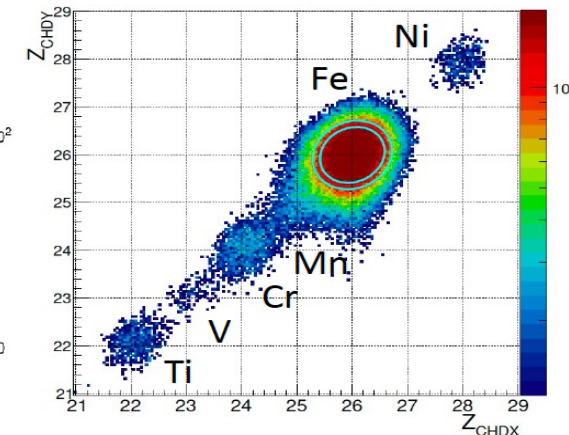
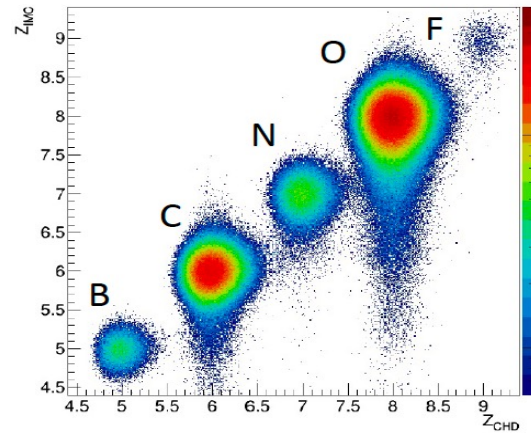
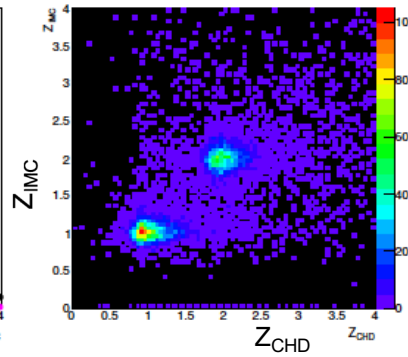
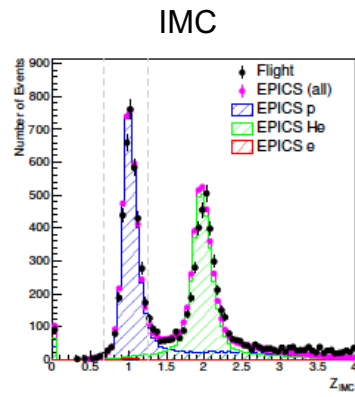
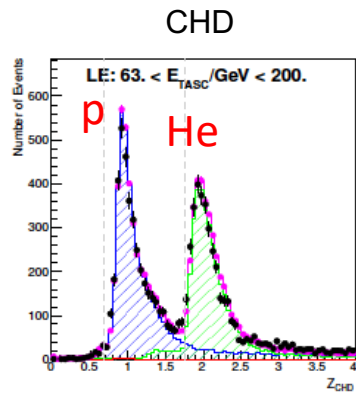
Proton/Helium Ratio vs. **Rigidity**



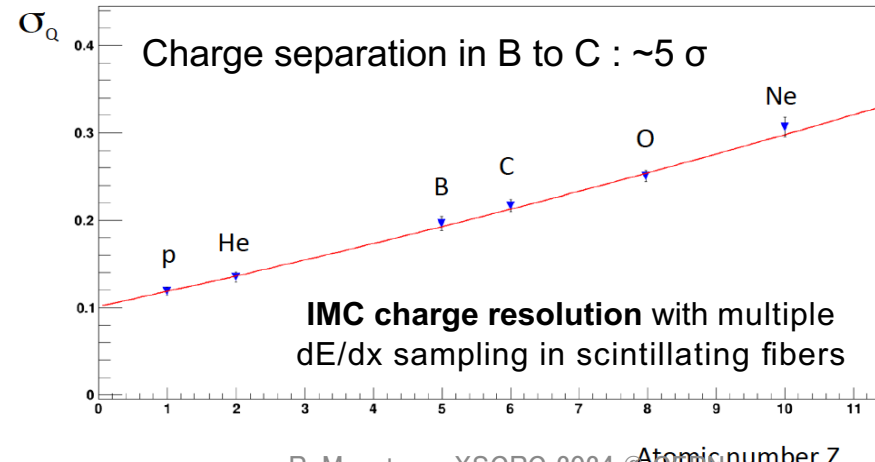
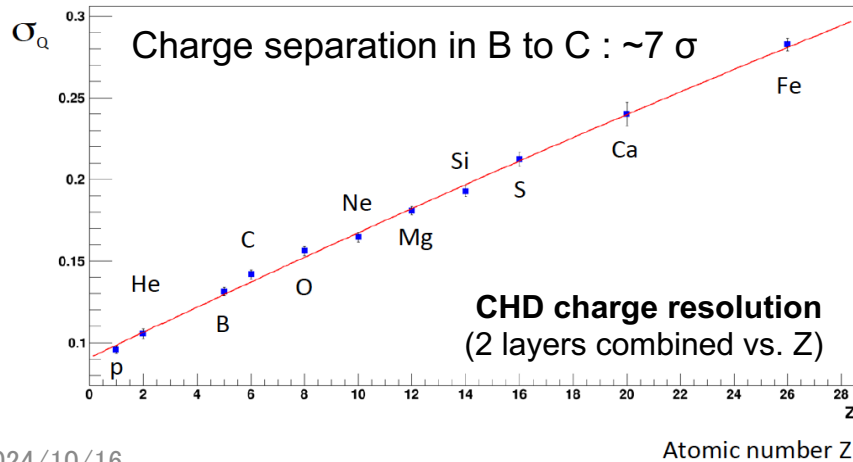
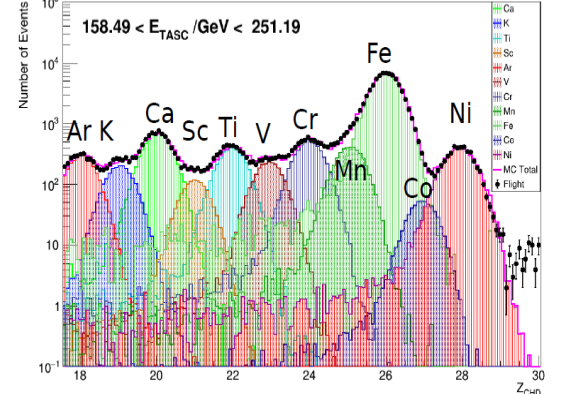
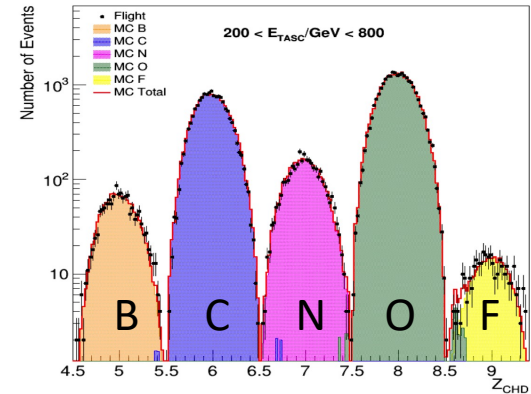
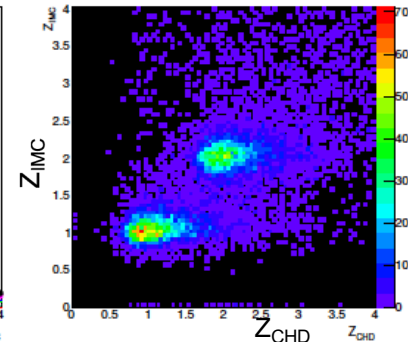
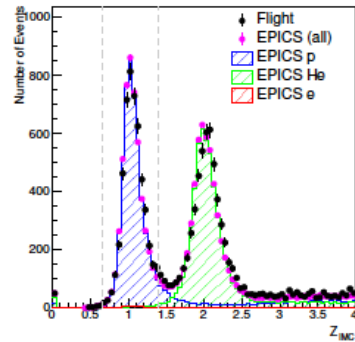
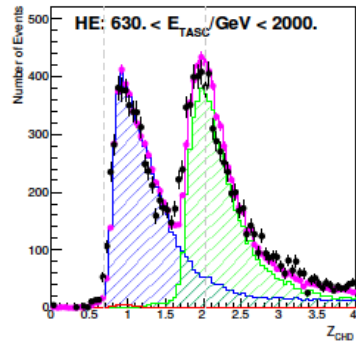
- The spectral index of helium is harder than that of proton (by ~ 0.1) in the whole rigidity range.
- Possible change of the spectral index of p/He ratio seen above 10 TV will be carefully checked by analyzing higher statistics data in future.

Charge Identification with CHD and IMC

Low Energy



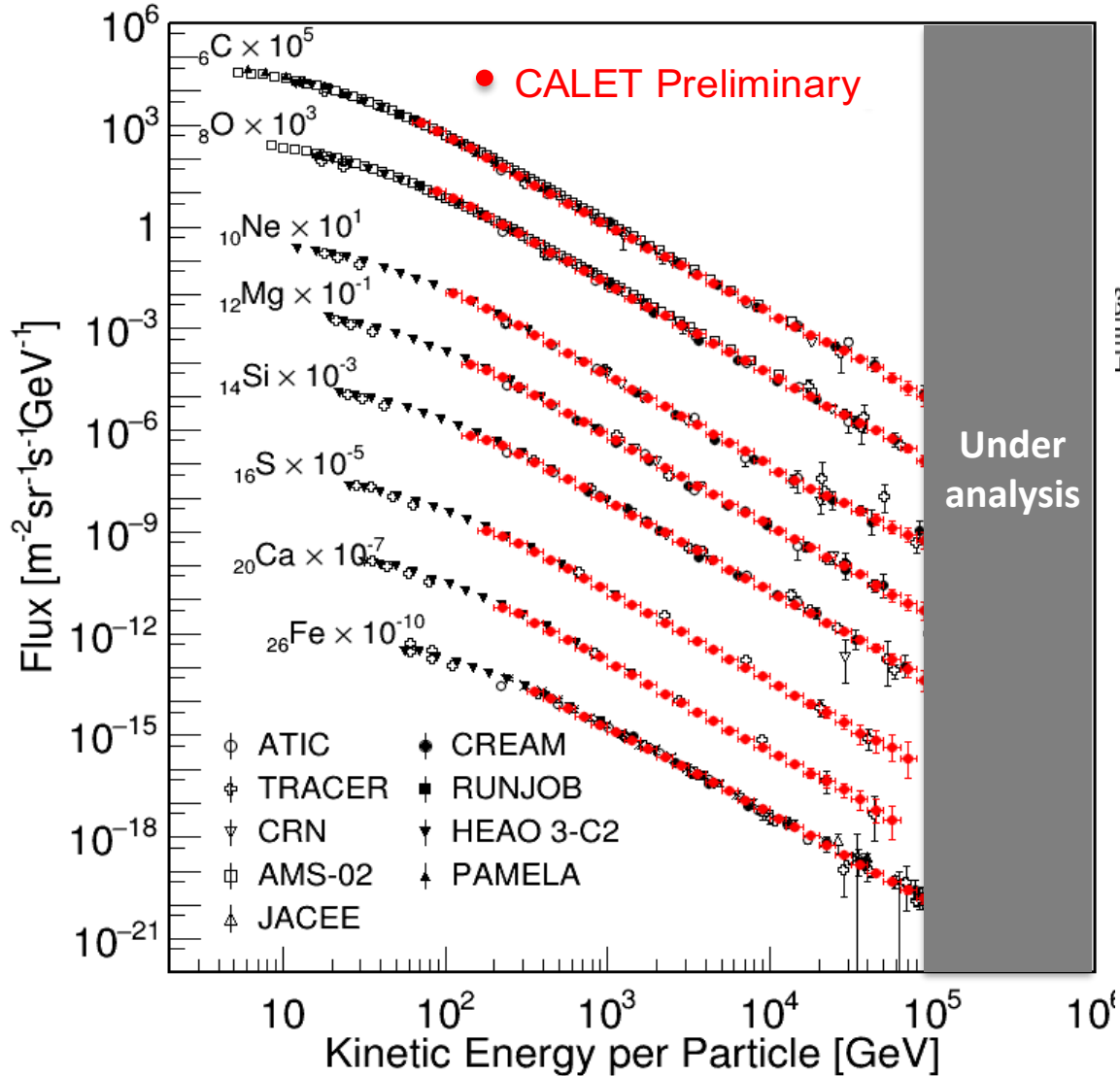
High Energy



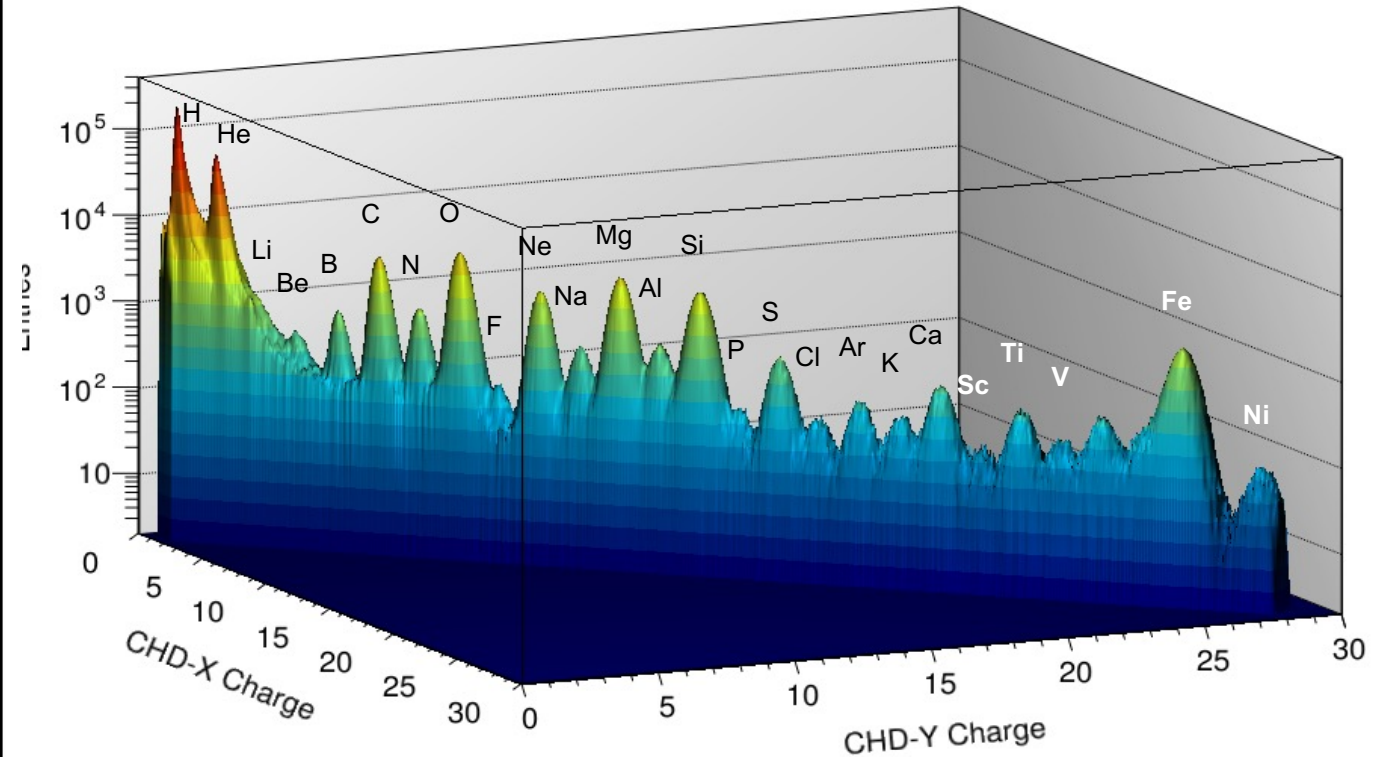
- Single element identification for p, He and light nuclei is achieved by CHD+IMC charge analysis.
- Deviation from Z^2 response is corrected using a core + halo ionization model (Voltz)
- Excellent charge resolution
 CHD σ_Z 0.15 e (BCNO) 0.28 (Fe)
 IMC σ_Z 0.20 e (BCNO)

Observations of cosmic-ray nuclei from C to Fe

Preliminary spectra of Carbon – Iron

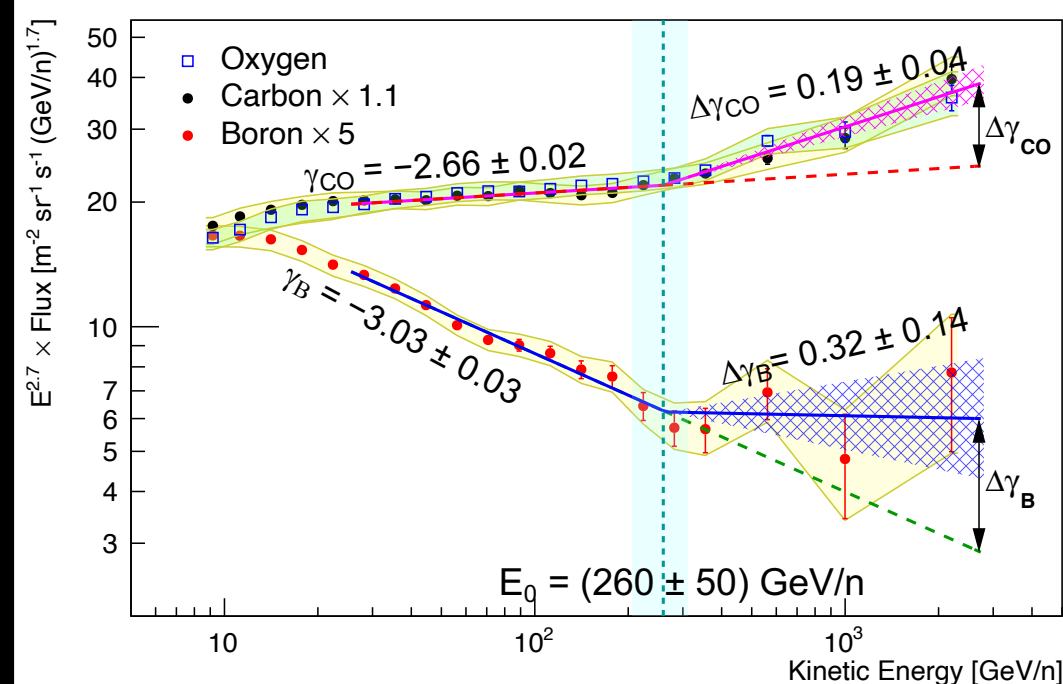
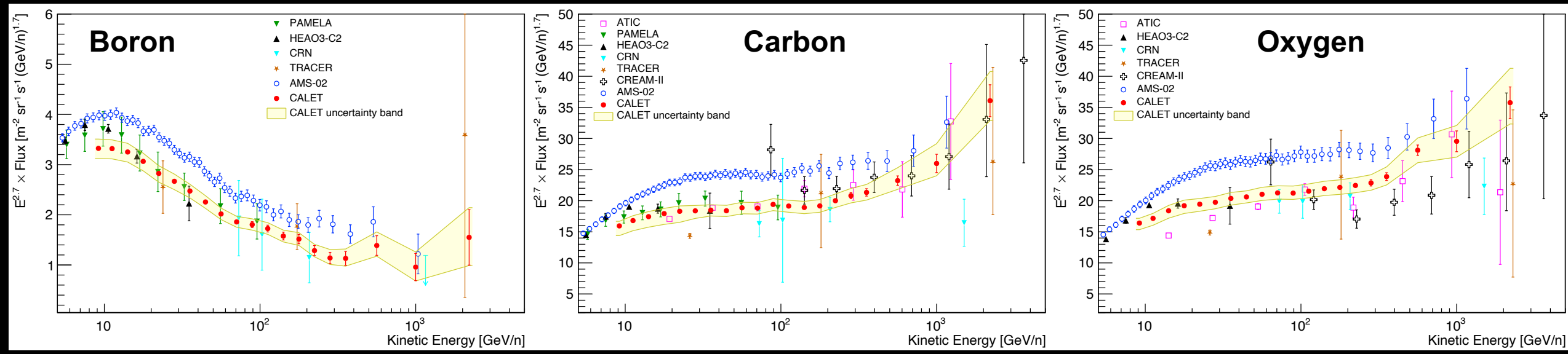


Charge distribution from H to Ni



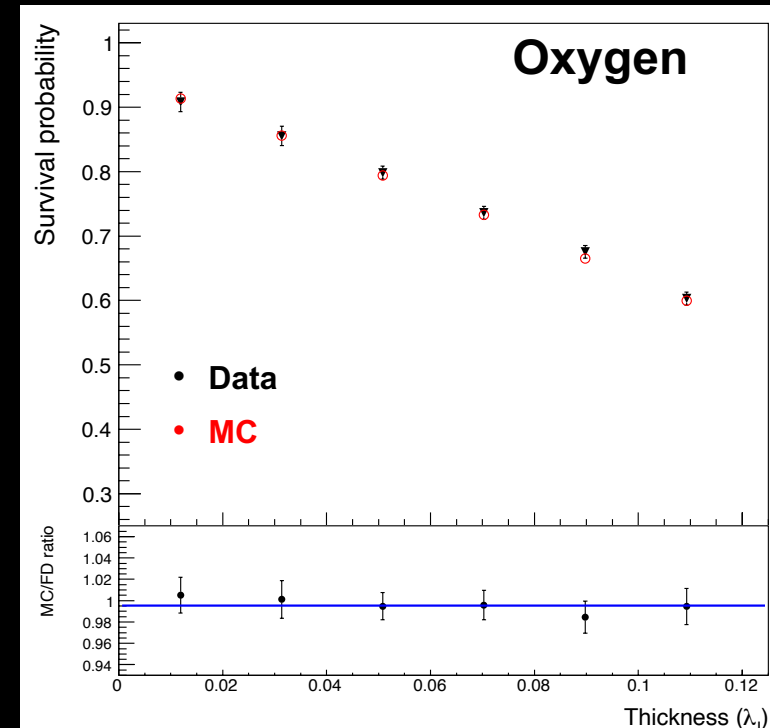
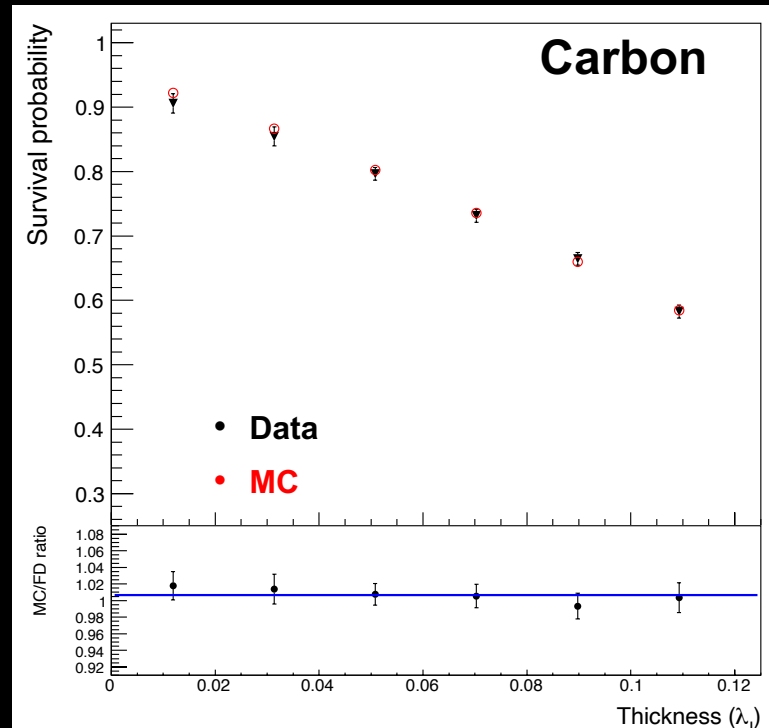
With excellent charge-ID of individual elements CALET is exploring the Table of Elements in the multi-TeV domain

B C O energy spectra



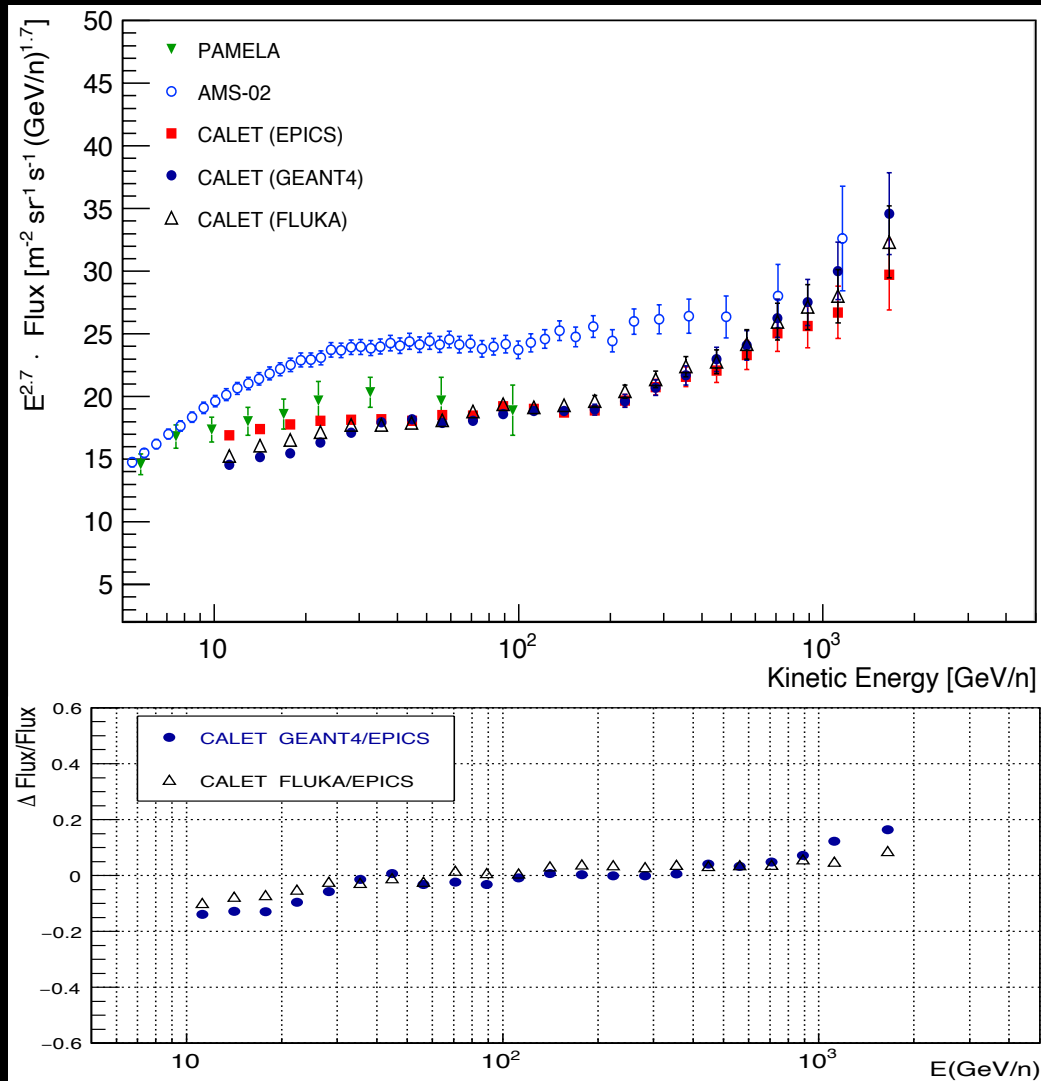
- BCO spectra measured from 8.4 GeV/n to 3.8 TeV/n
- BC fluxes consistent with PAMELA and most previous experiments.
- Similar shape with AMS-02 spectra but lower absolute normalization
- C and O fluxes harden in a similar way above 200 GeV/n
- B spectrum clearly different from C-O as expected for primary 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.

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%).

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

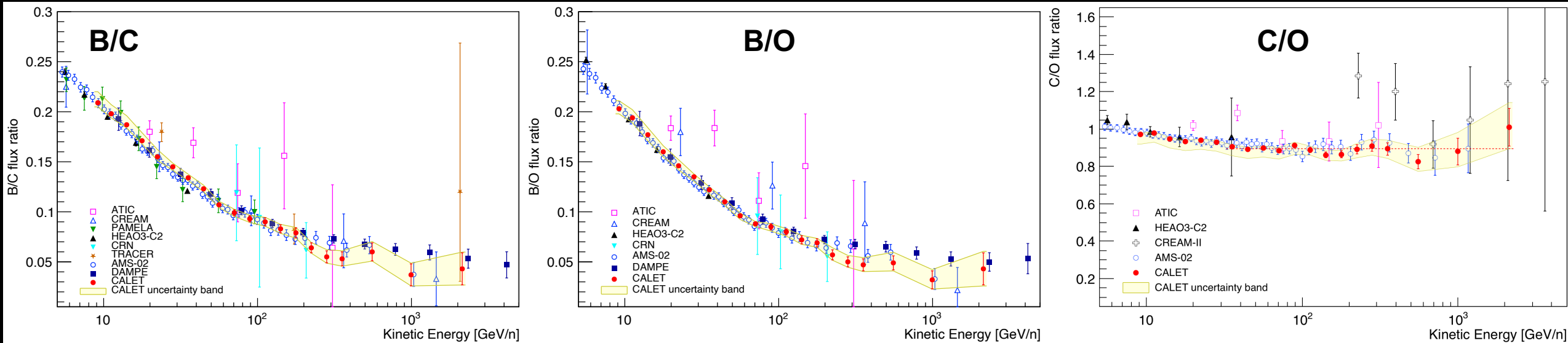
MC simulations were tuned using beam test and flight data.

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.

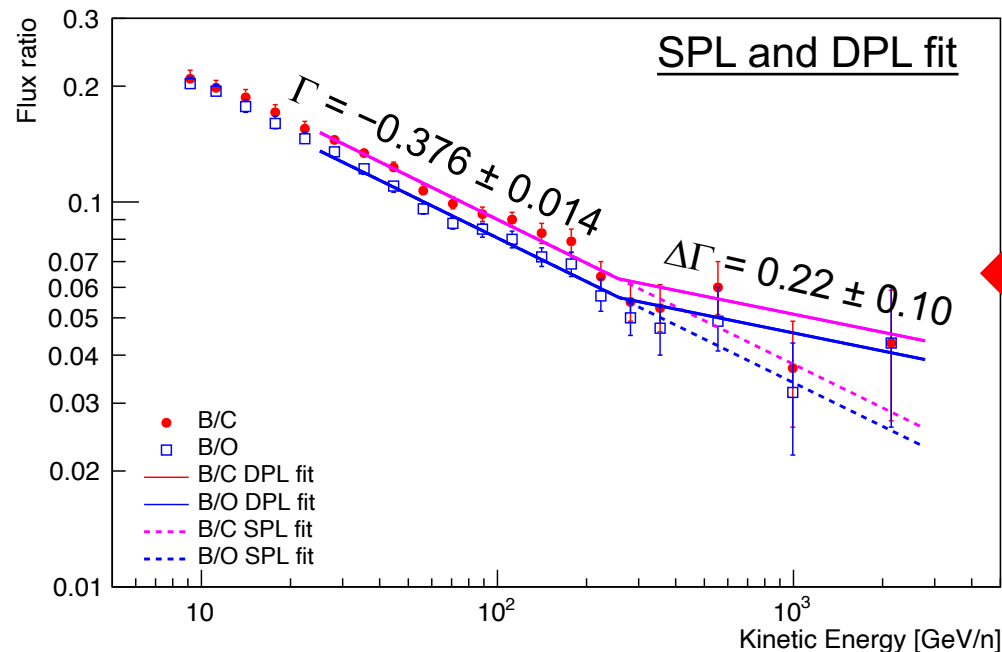
The resultant fluxes from the analyses with different MC's show consistent normalization and spectral shapes.

B C O flux ratios

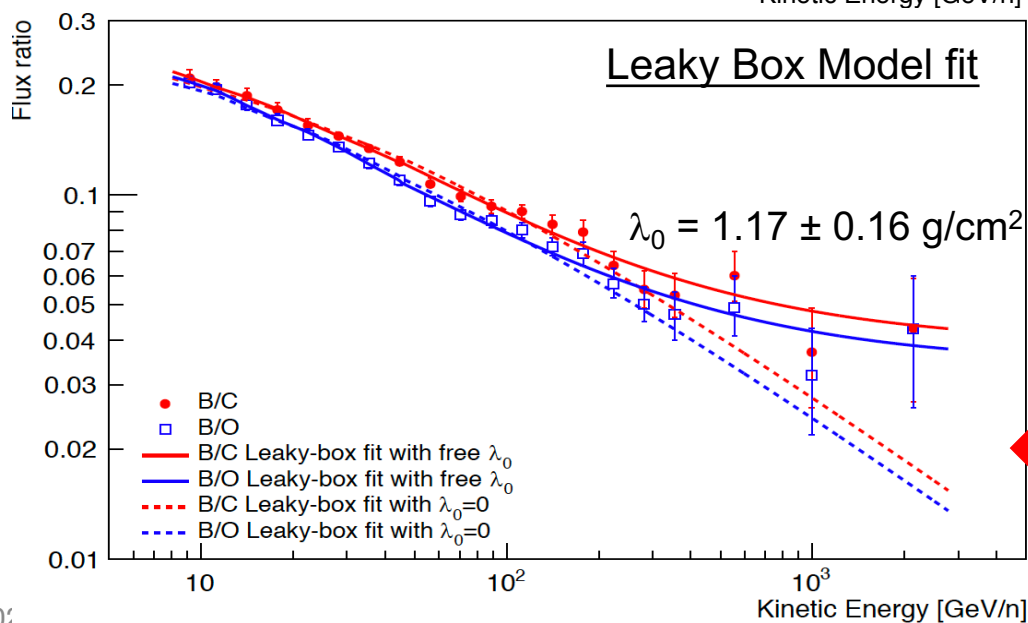


- Flux ratios of **B/C** and **B/O** are in agreement with AMS02 and lower than DAMPE result above 300 GeV/n, although consistent within the error bars.
- **C/O** flux ratio as a function of energy is in good agreement with AMS-02.
- At $E > 30$ GeV/n the **C/O ratio** is well fitted to a constant value 0.90 ± 0.03 \rightarrow C and O fluxes have the same energy dependence.
- At $E < 30$ GeV/n **C/O ratio** is slightly softer \rightarrow secondary C from O and heavier nuclei spallation

Spectral fit of B/C and B/O



Simultaneous fit to B/C and B/O ($E > 25$ GeV/n) with same parameters except normalization.
 DPL fit suggests, though with currently limited statistical significance, a flattening of the B/C ratio at high energy, consistent with AMS-02 and DAMPE.
 This supports the hypothesis that secondary B exhibits a stronger hardening than primary C and O.



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

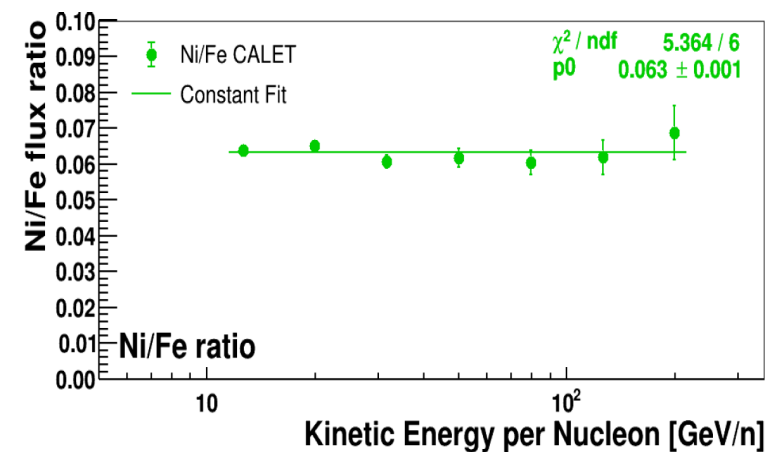
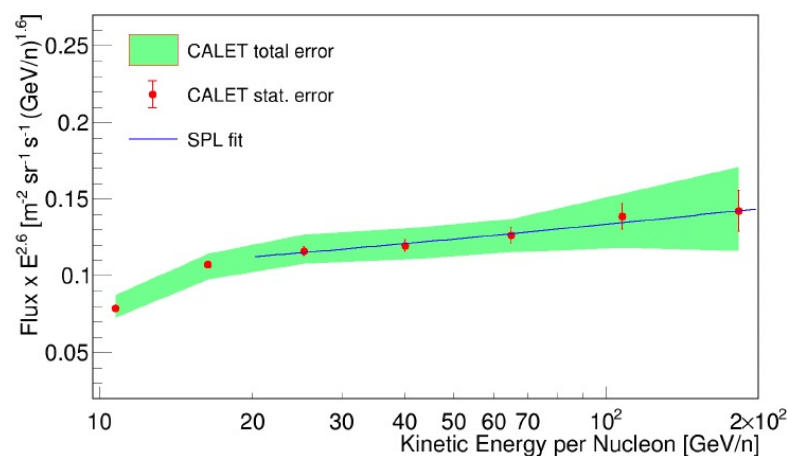
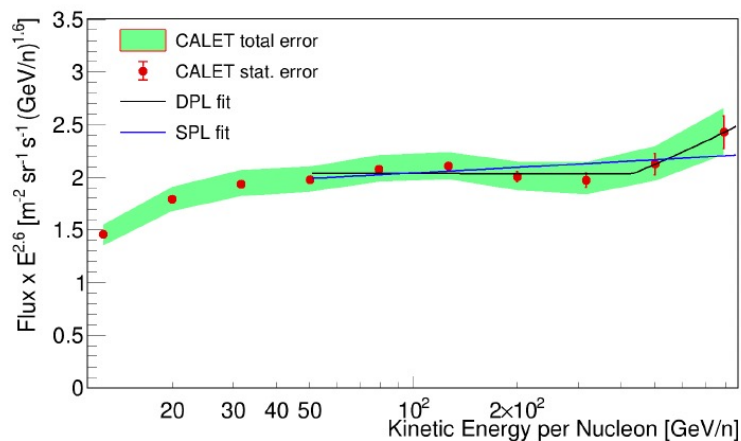
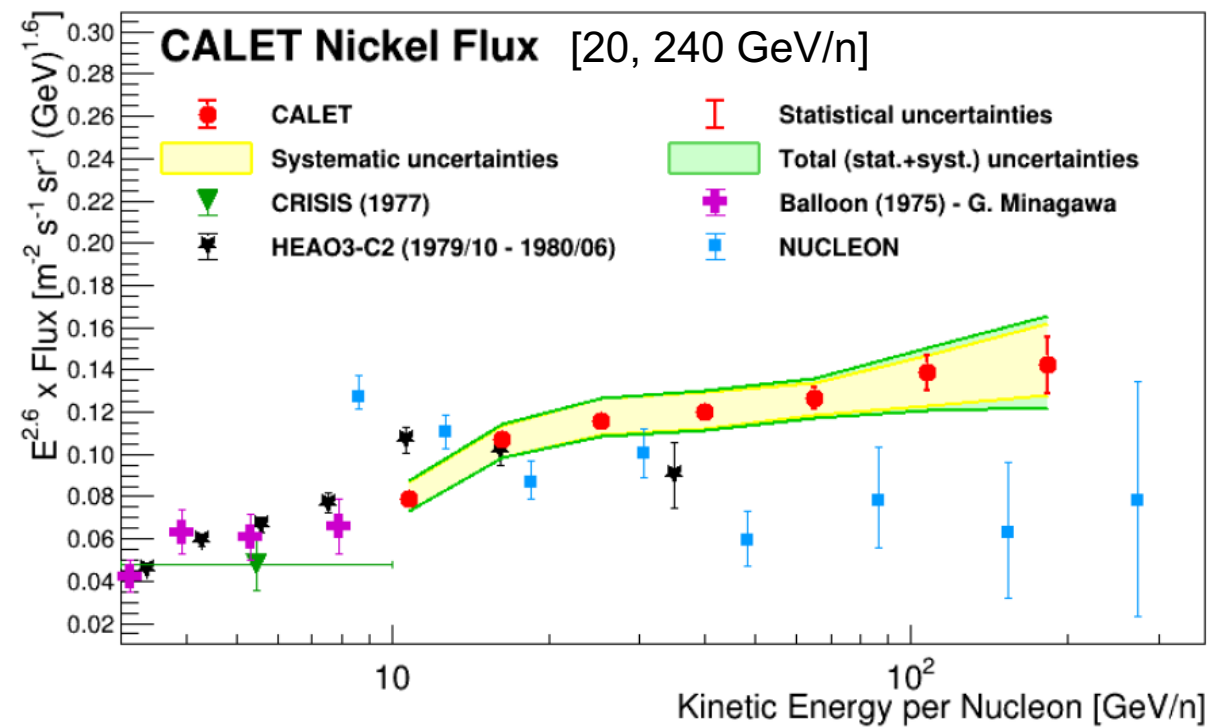
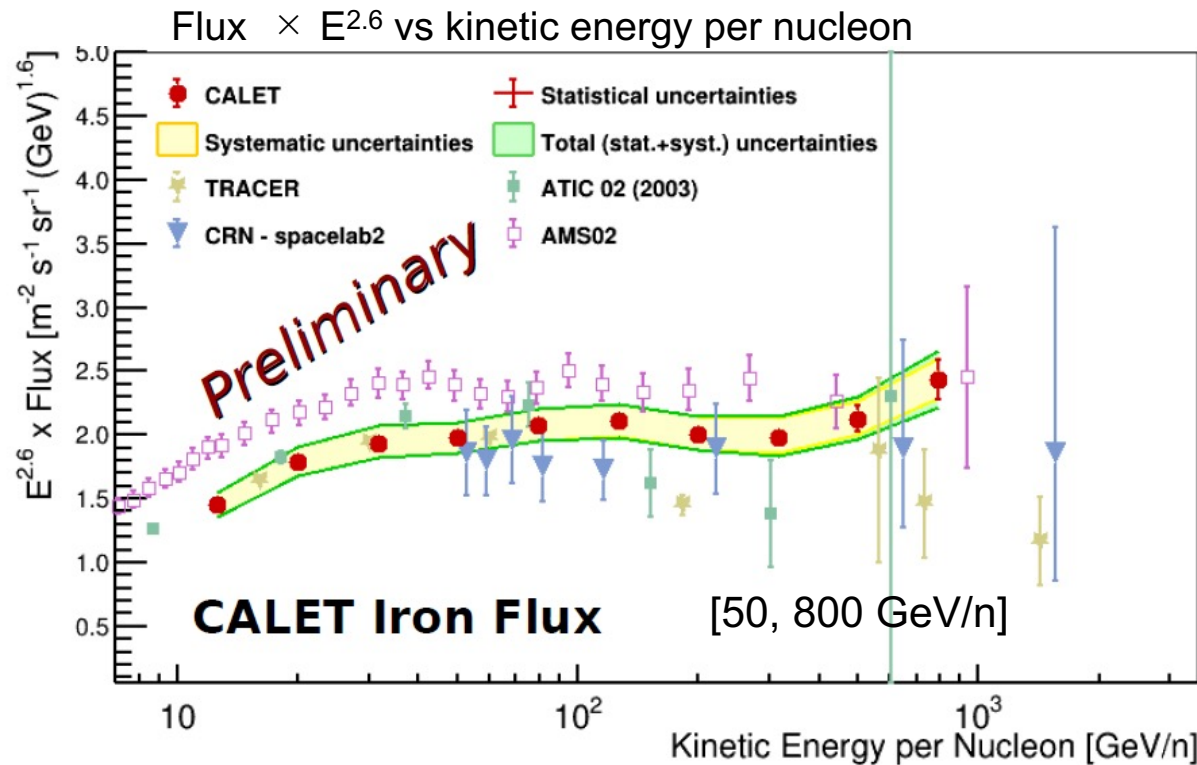
$$\frac{\Phi_B(E)}{\Phi_O(E)} = \frac{\lambda(E)\lambda_B}{\lambda(E) + \lambda_B} \left[\frac{1}{\lambda_{O \rightarrow B}} + \frac{\Phi_C(E)}{\Phi_O(E)} \frac{1}{\lambda_{C \rightarrow B}} \right]$$

The escape pathlength can be parametrized as $\lambda(E) = kE^{-\delta} + \lambda_0$

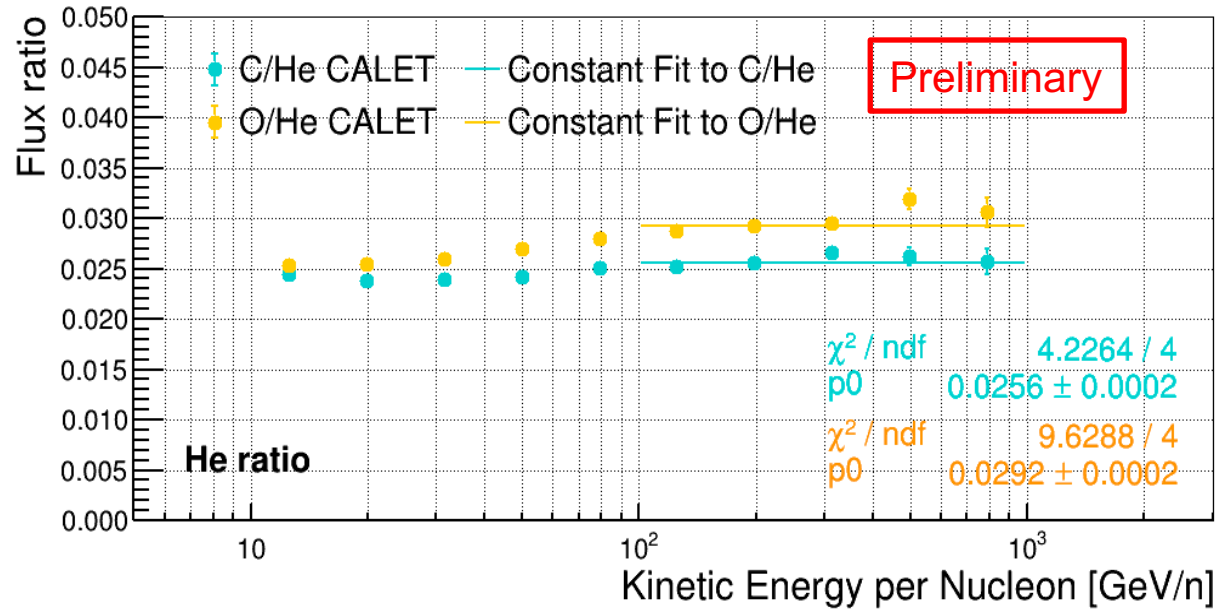
Significance of $\lambda_0 \neq 0 > 5\sigma \rightarrow$ Residual path length could explain the flattening of B/C, B/O ratios at high energies.

Iron and nickel spectra

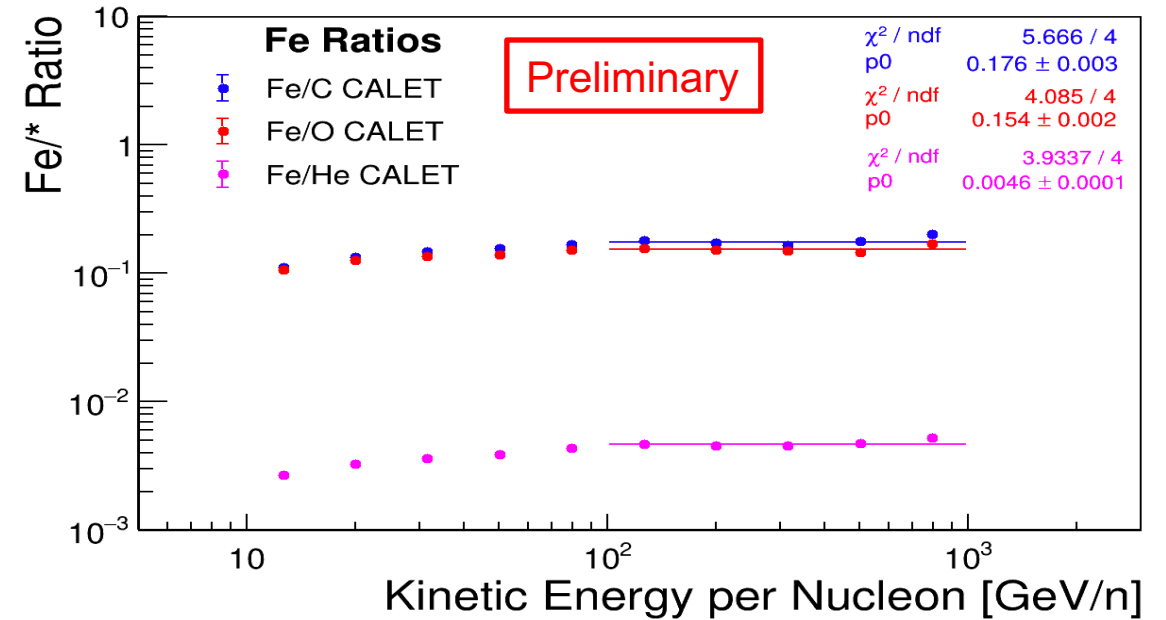
PRL 126 241101 (2022)
 PRL 128 131103 (2023)
 ICRC2023 PoS 061



C/He and O/He ratio

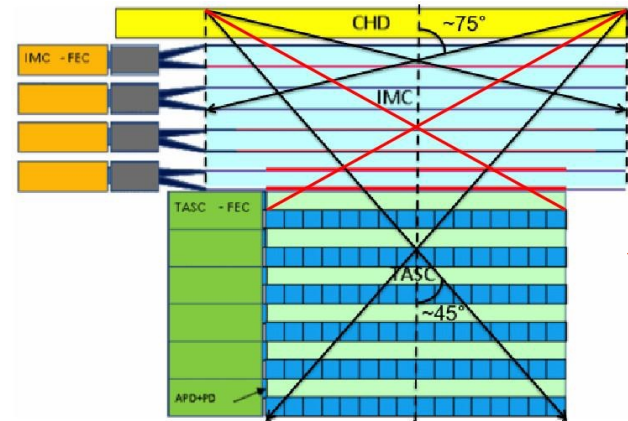


Fe/C Fe/O Fe/He ratios

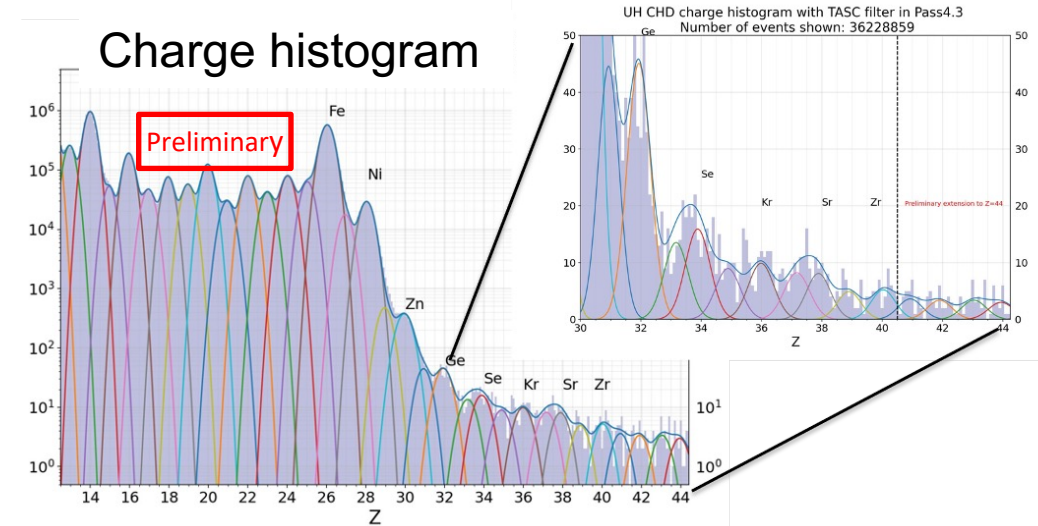


The flux ratio between light nuclei (He, C, O) is constant above 100 GeV/n
 Fe/O, Fe/C and Fe/He ratios are compatible with a constant above 100 GeV/n within errors → similar propagation

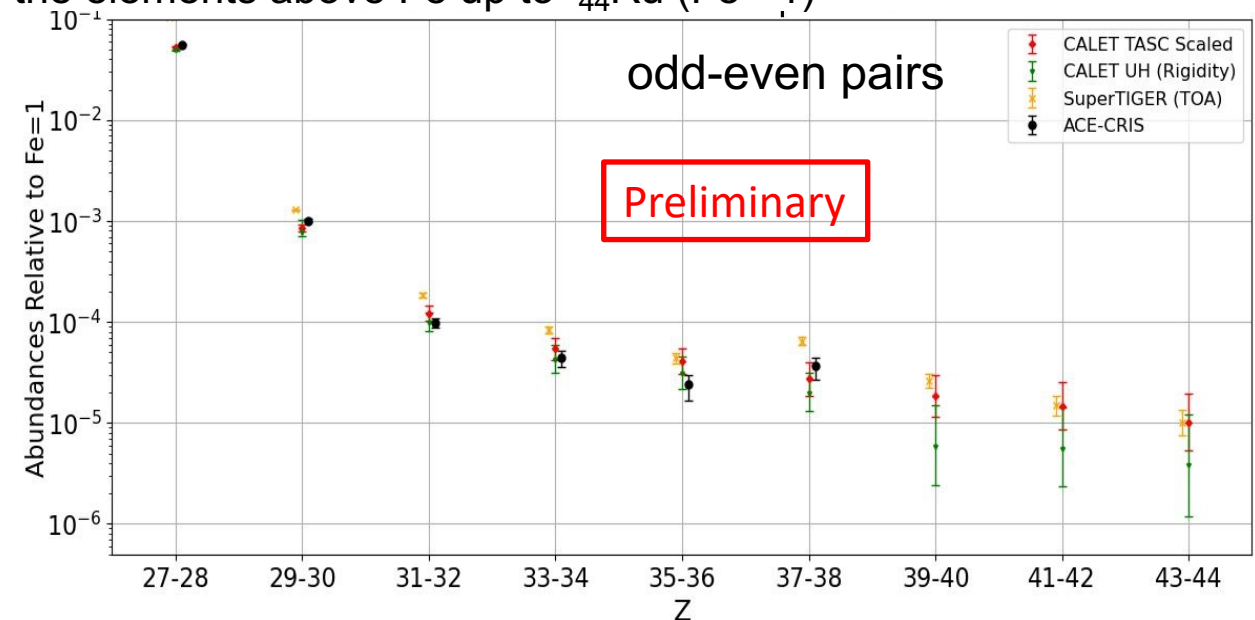
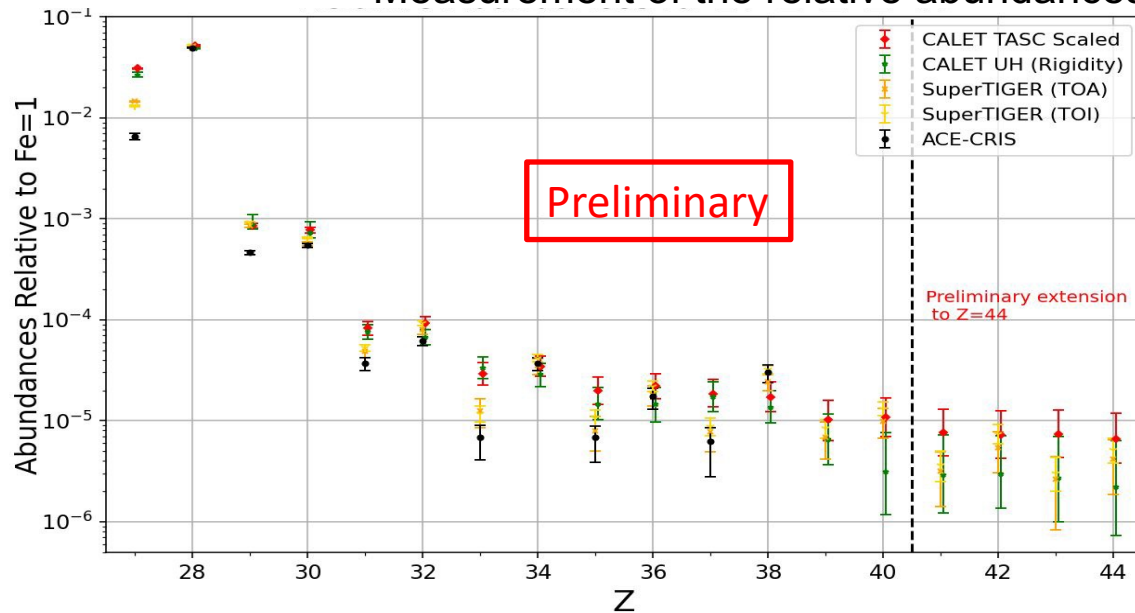
Ultra-heavy cosmic-ray nuclei ($26 < Z \leq 44$)



- Special UH trigger with **GF ~ 4400 cm²**
- ~260 million events collected
- Energy measurement based on rigidity cutoff. TASC used for a sub-sample of events (65 million)



Measurement of the relative abundances of the elements above Fe up to ${}_{44}\text{Ru}$ ($\text{Fe} = 1$)

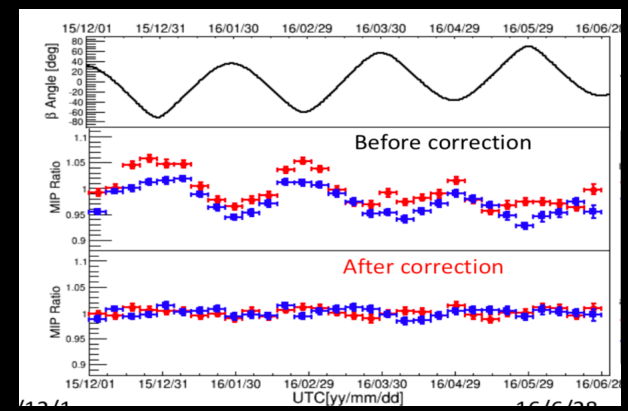
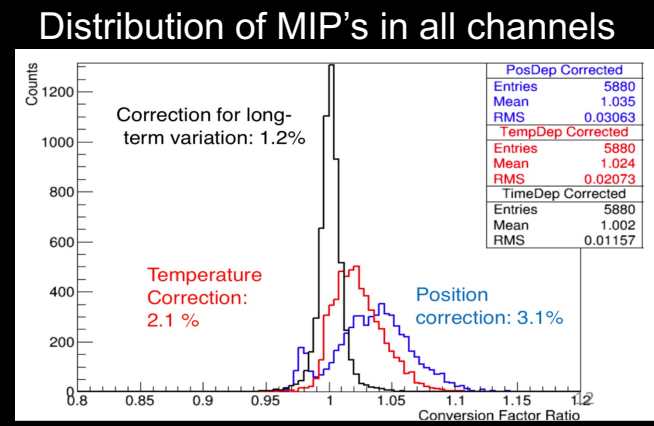
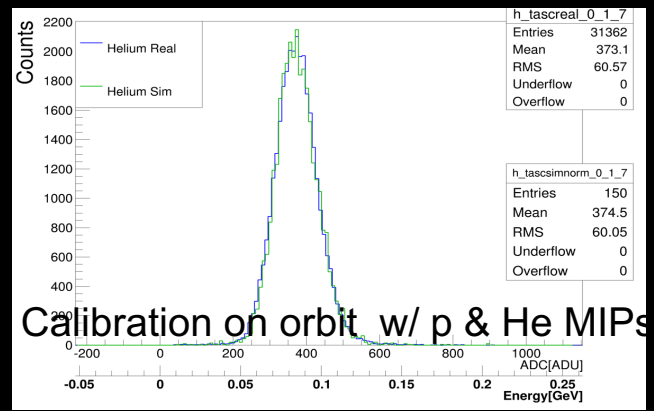
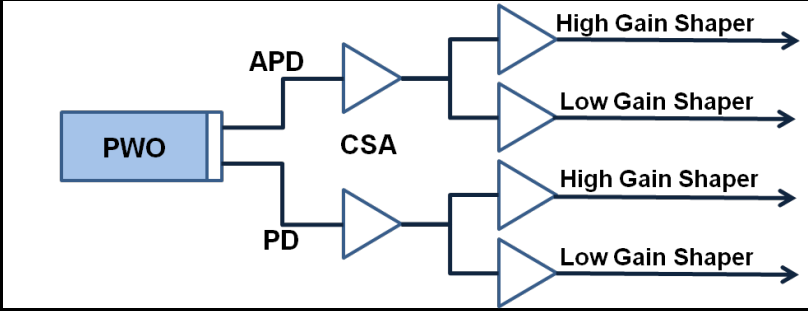
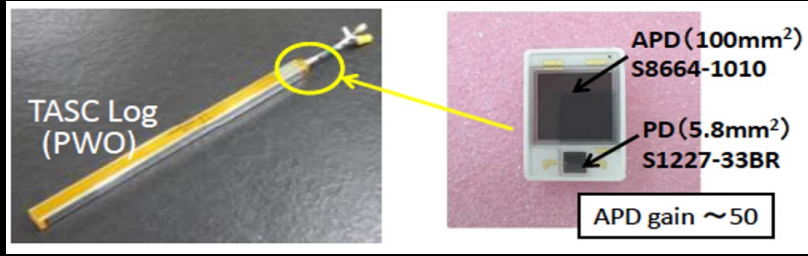


CALET: Summary and Future Prospects

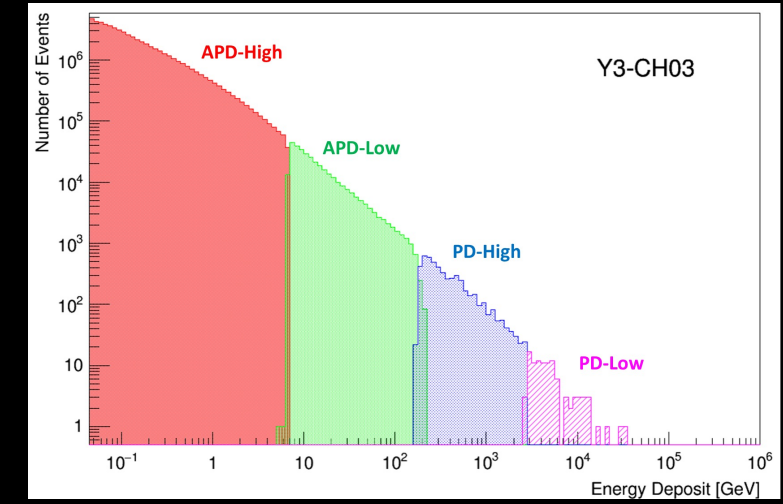
- CALET was launched on Aug. 19th, 2015. The observation campaign started on Oct. 13th, 2015. Excellent performance and remarkable stability of the instrument have been confirmed.
- As of Aug. 31, 2024, total observation time is 3200 days with live time fraction close to 86%. Nearly 4.78 billion events collected with low energy trigger (> 1 GeV) and 2.15 billion events with high energy trigger
- Accurate calibrations have been performed in the energy measurements established in 1 GeV-1PeV.
- Analysis of cosmic-ray events continues, extending to higher energies and charges
 - All electron spectrum in the range 10.6 GeV – 7.5 TeV.
 - Proton spectrum in the range 50 GeV – 60 TeV
 - Helium spectrum in the range 40 GeV – 250 TeV
 - BCO spectra in the range 8.4 GeV/n – 3.8 TeV/n
 - B/C flux ratio up to 3.8 TeV/n
 - Iron spectrum in the range 50 GeV/n – 2 TeV/n
 - Nickel spectrum in the range 8.8 GeV/n – 240 GeV/n
 - Abundances of heavy and ultra-heavy nuclei ($13 \leq Z \leq 44$)
- CALET has successfully completed 9 years of observations and has been **approved by JAXA/NASA/ASI for extended operations until 2030!**

Backup slides

TASC calibration

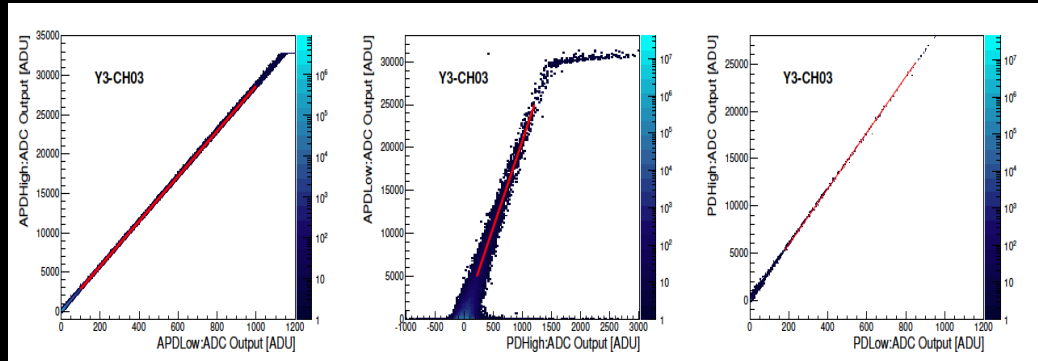


Corrections for position, temperature, latitude (due to rigidity) dependence



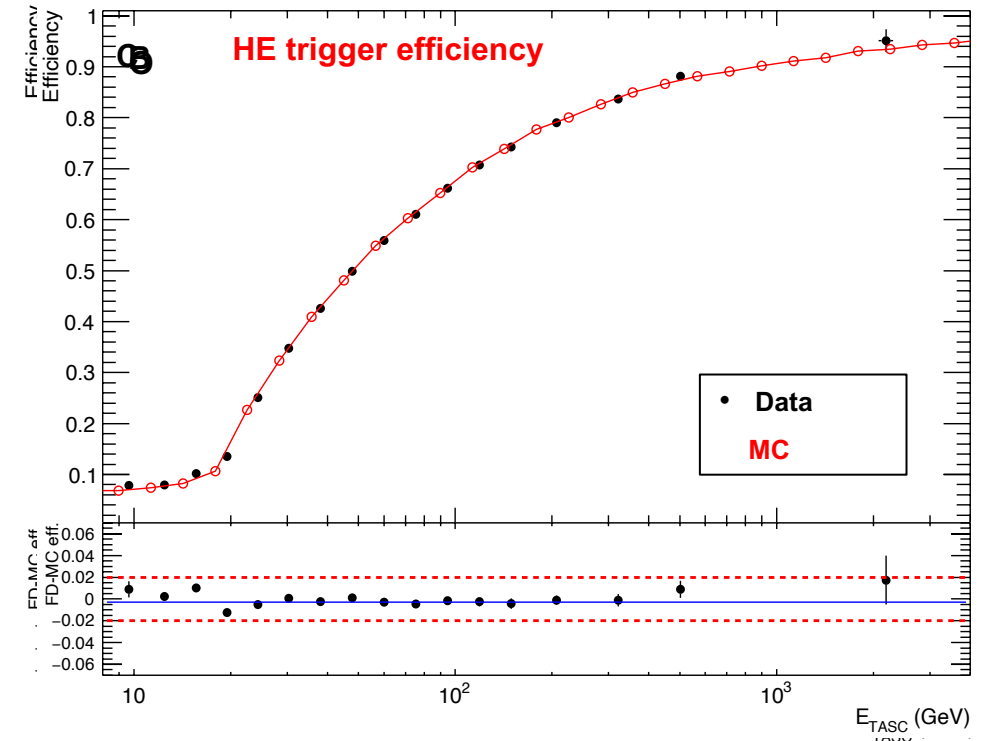
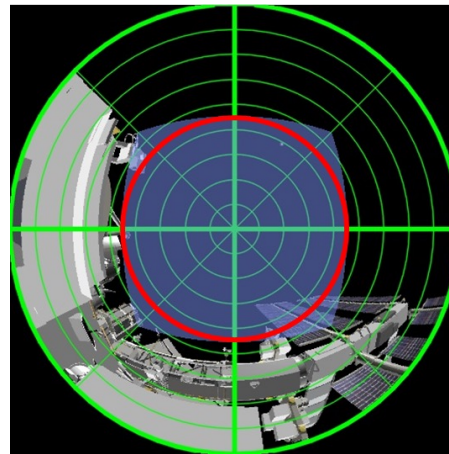
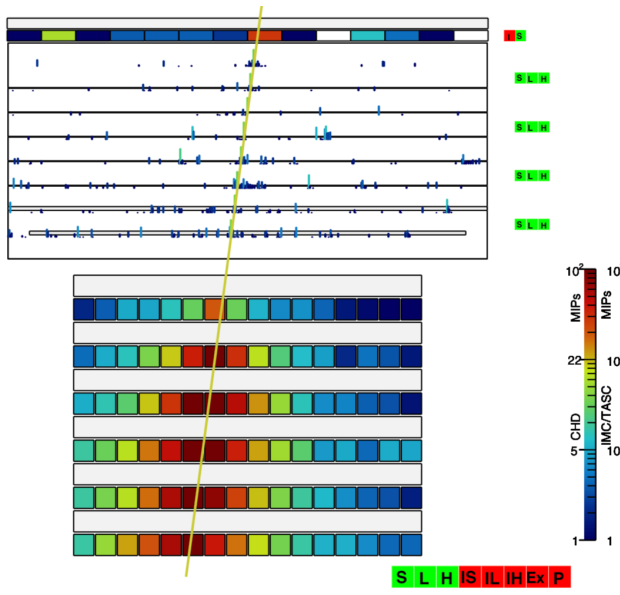
Energy distribution in one PWO log.
Dynamic range of each channel: 1 - 10⁶ MIP

Gain ranges calibrated by UV laser irradiation on ground.
Correlation of gain ranges calibrated in-flight

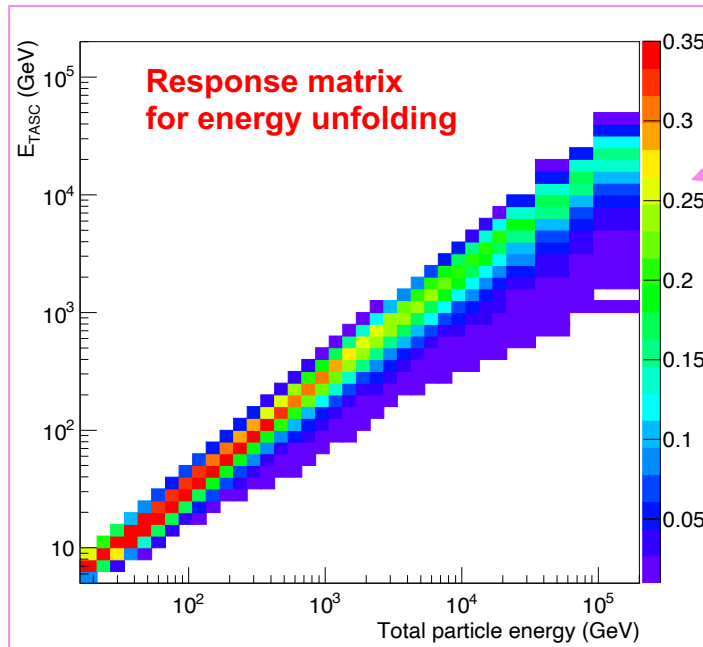
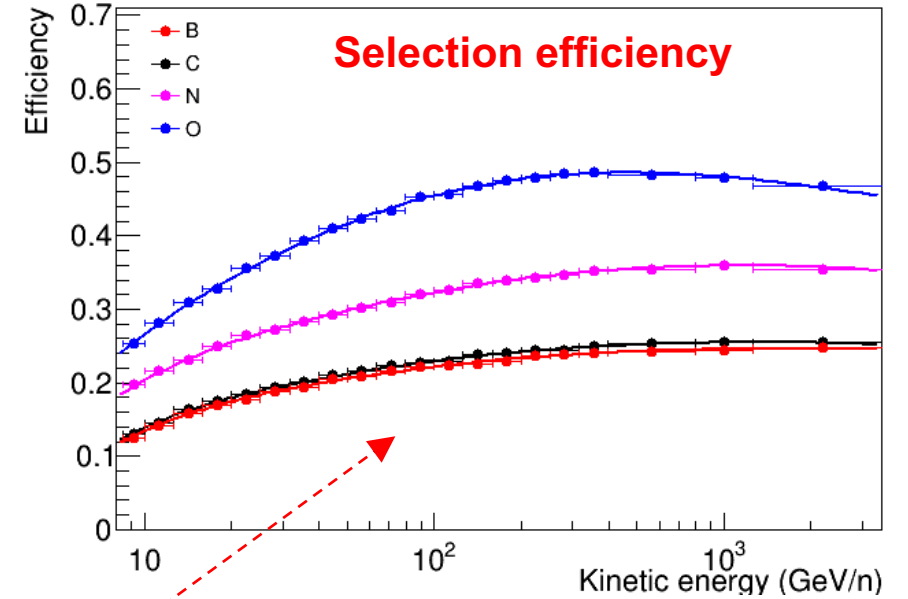
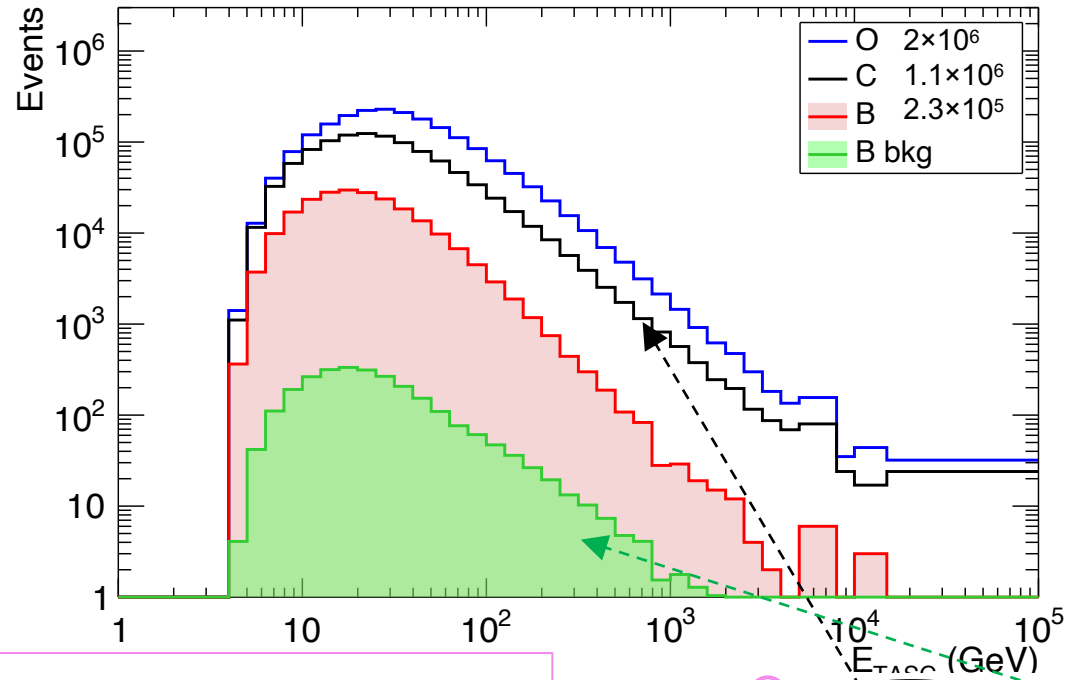


Selection for B,C,O candidate events

- 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



Flux measurement



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

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

Live time $T=86\%$ of observing time (2554 days)
 $S\Omega$: $510 \text{ cm}^2 \text{ sr}$
 Bin width ΔE commensurate with rms resolution of TASC , $\sim 30\%$ 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.

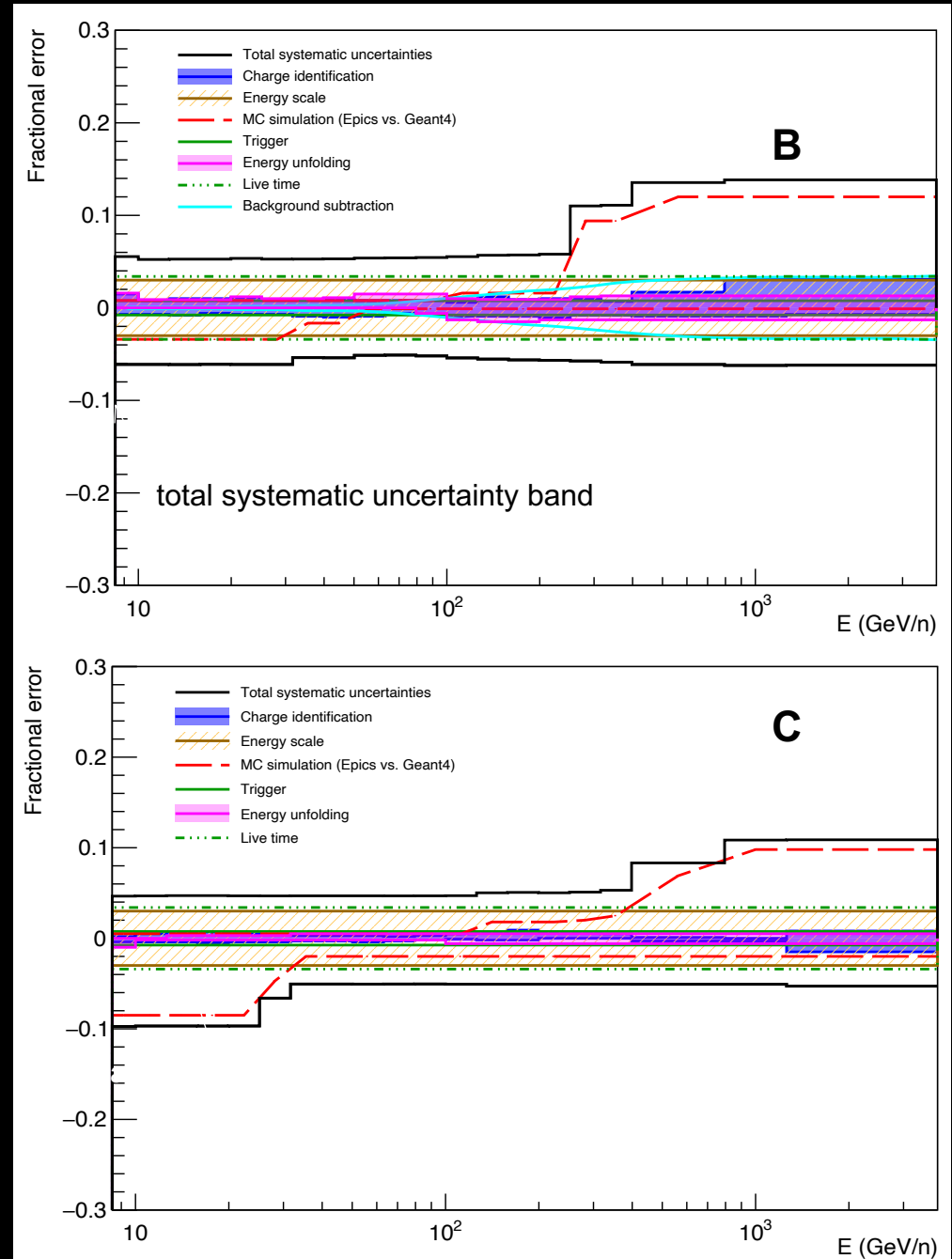
Main sources of systematics uncertainties:

➤ **Normalization:**

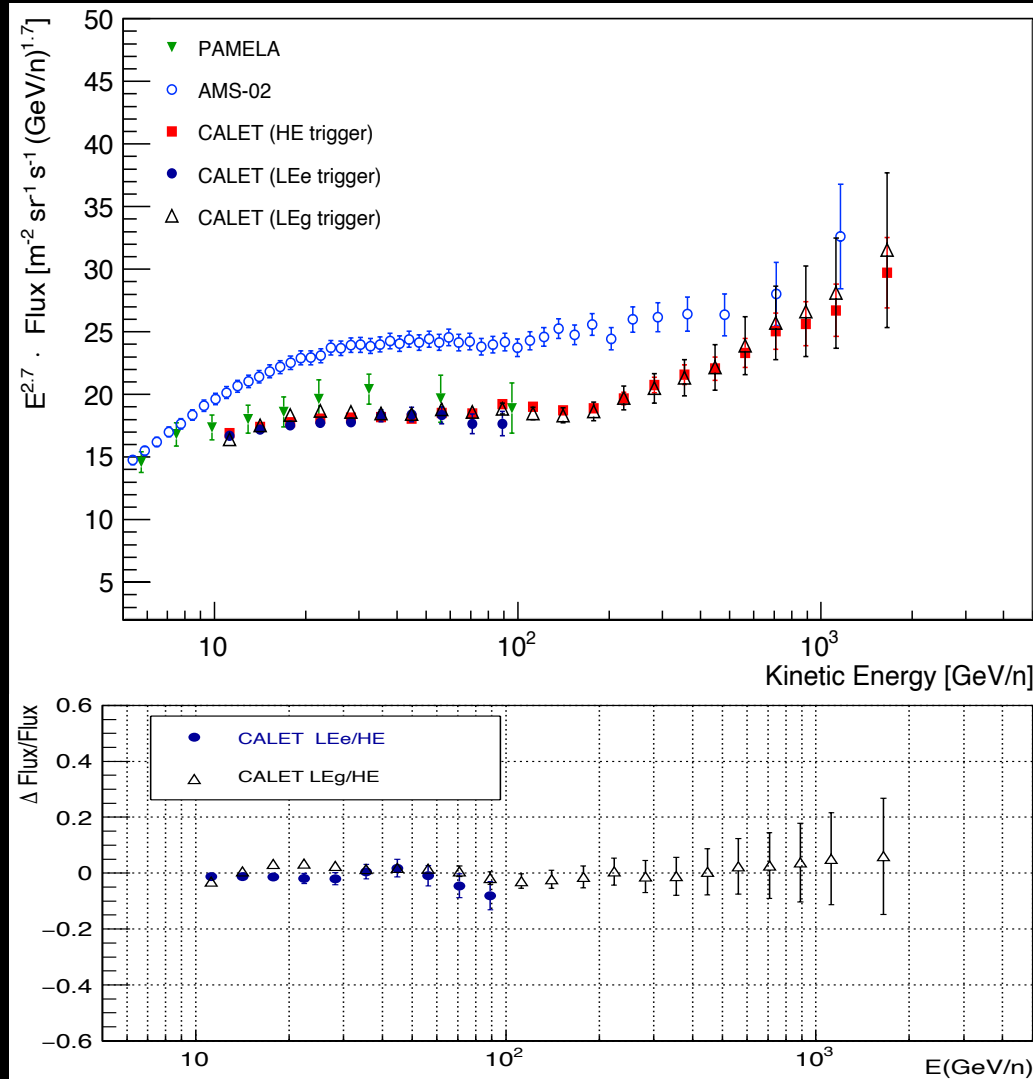
- Live time
- Long-term stability
- Energy scale

➤ **Energy dependent:**

- Tracking
- Charge ID
- Trigger
- Unfolding
- MC model (EPICS, GEANT4)
- Background subtraction
- B isotopic composition (ref. $^{11}\text{B}:^{10}\text{B} = 0.7:0.3$)



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 $\sim 10\%$ of HE livetime

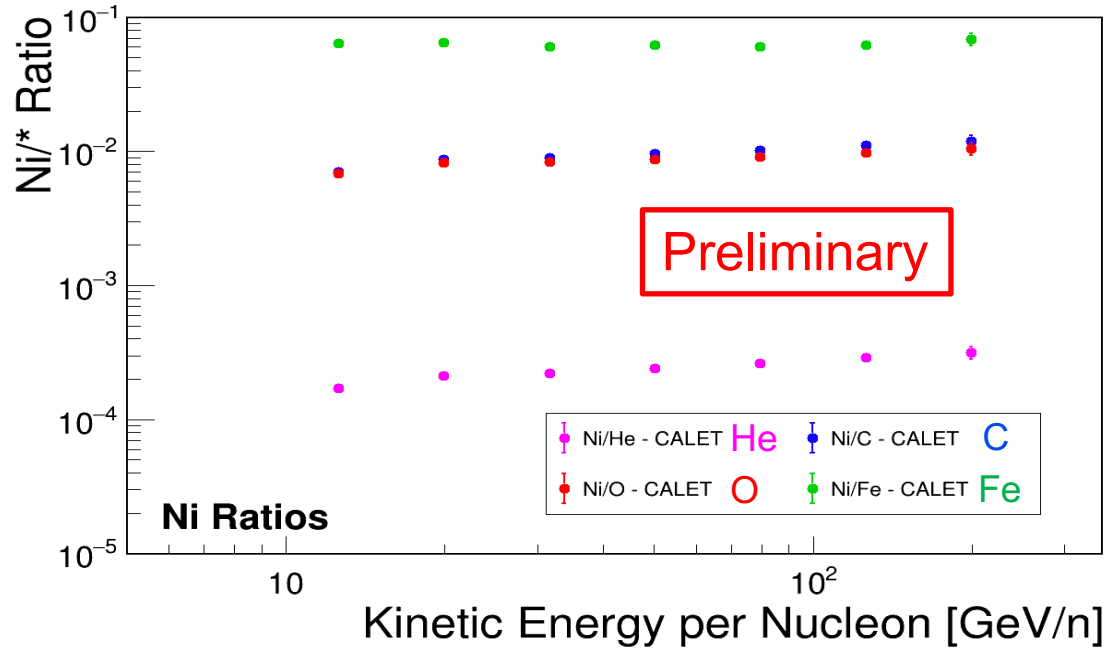
Low-energy electron (LEe) trigger

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

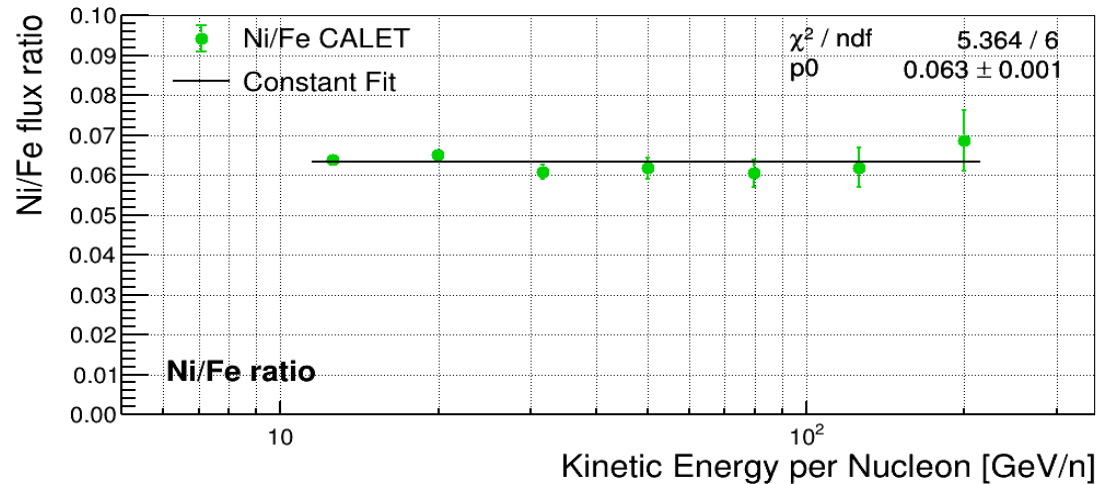
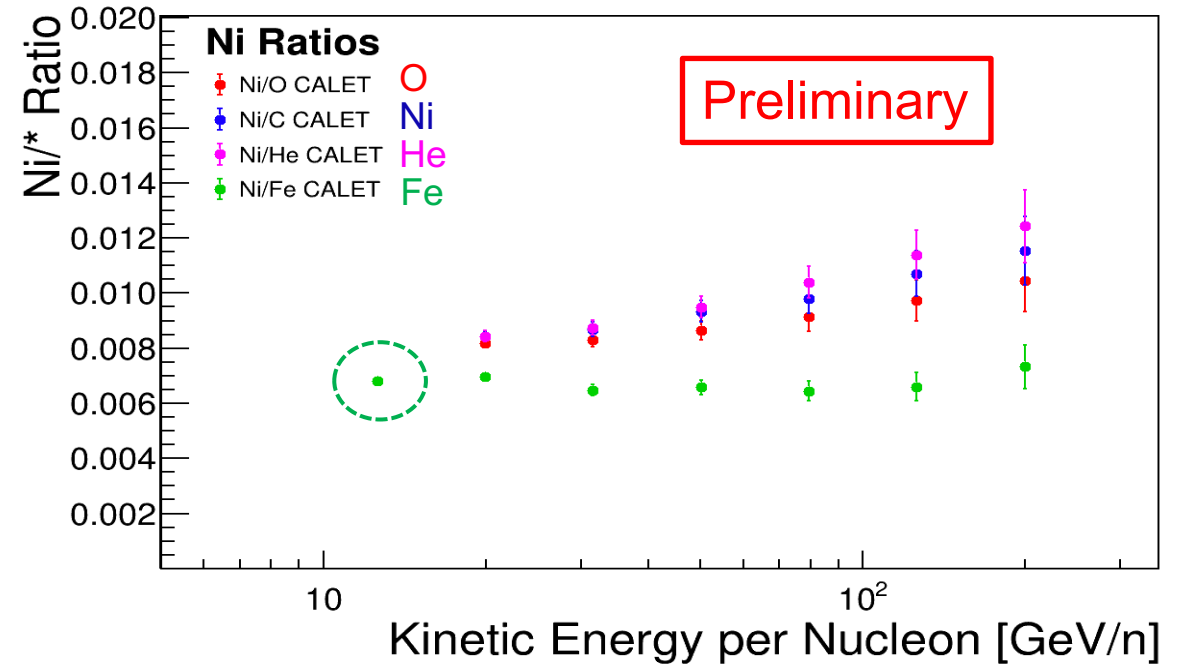
The resultant fluxes using data from the different trigger modes show consistent normalization and spectral shapes.

Flux Ratios of Nickel to Primary Elements

Ni ratios to He, C, O and Fe



Ni ratios normalized at around 10 GeV/n



- The Ni/Fe flux ratio is constant in all the energy range thus Ni and Fe have very similar behavior in all the energy range.
- The present energy range of nickel flux does not allow to fit the Ni/* ratios with a constant above 100 GeV/n.
- At low energy the Ni/O, Ni/C, Ni/He flux ratio show an increasing trend also visible in Fe/* ratios.