Results from the first 8.5 years of operation with CALET

CALET

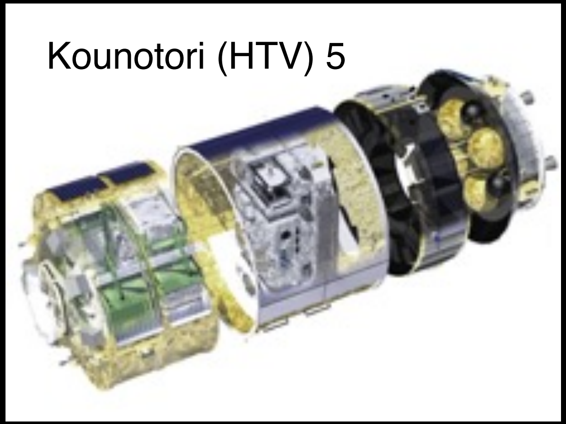
Yosui Akaike
Waseda University, Japan
for the CALET Collaboration

The CALET Collaboration Member

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] G.A. de Nolfo,[10] K. Ebisawa,[17] A. W. Ficklin,[14] H. Fuke,[17] S. Gonzi,[1,2,6] T.G. Guzik,[14] T. Hams,[11] K. Hibino,[18] 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] and W. V. Zober [9]

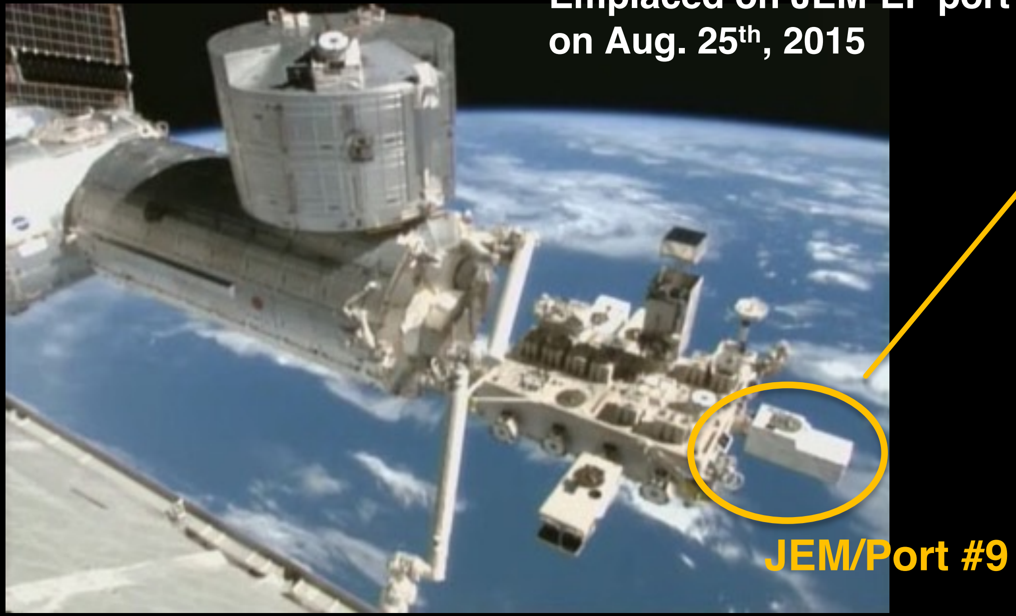
1) University of Florence, Italy
2) INFN Sezione di Firenze, Italy
3) WISE Waseda University, Japan
4) JEM Utilization Center, Japan
5) ICRR, University of Tokyo, Japan
6) IFAC, CNR, Italy
7) University of Siena, Italy
8) INFN Sezione di Pisa, Italy
9) Washington University, St. Louis, USA
10) Heliospheric Physics Laboratory, NASA/GSFC, USA
11) University of Maryland Baltimore County, USA
12) Astroparticle Physics Laboratory, NASA/GSFC, USA
13) CRESST, 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, Japan
26) National Astronomical Observatory of Japan, Japan
27) IPNS, KEK, Japan
28) University of Pisa, Italy
29) NIT, Ibaraki College, 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

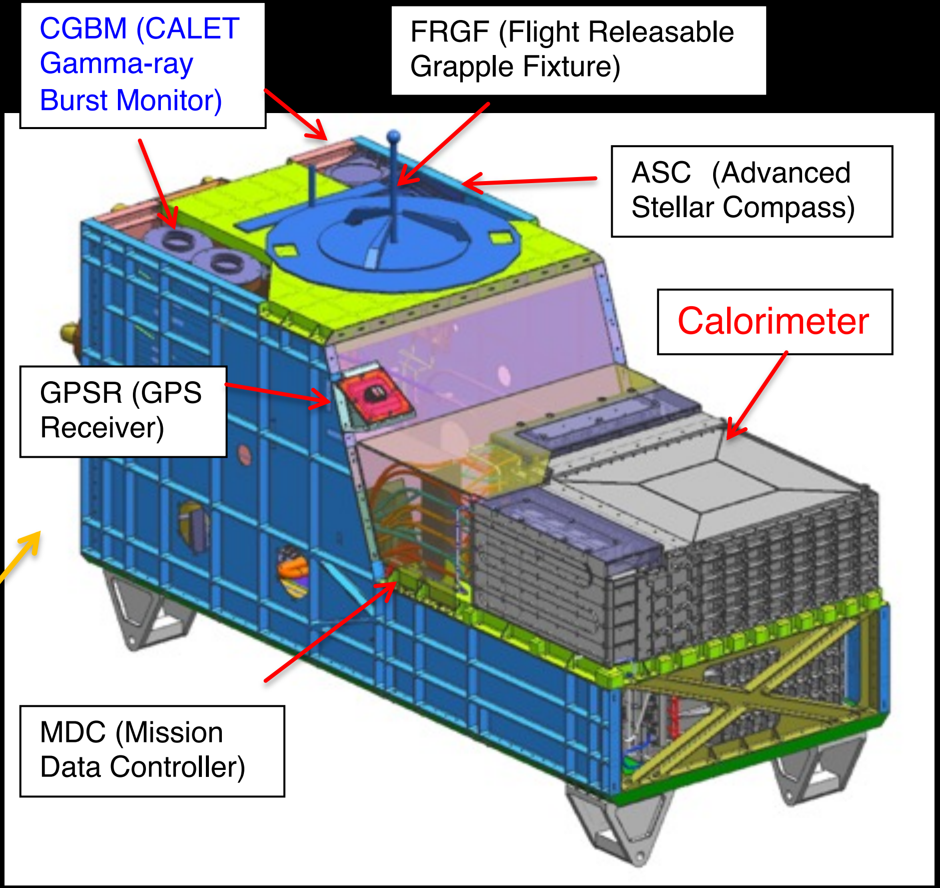
CALET Payload



Launched on Aug. 19th, 2015 by the Japanese H2-B rocket

Emplaced on JEM-EF port #9 on Aug. 25th, 2015



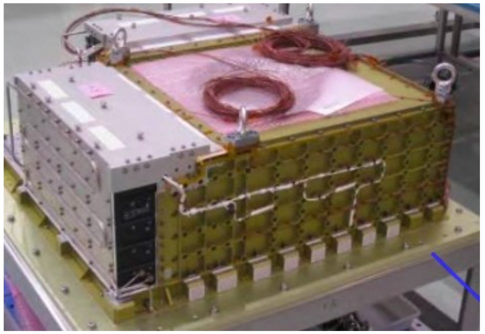


- **Mass: 612.8 kg**
- **JEM Standard Payload Size:**
  1850mm(L) × 800mm(W) × 1000mm(H)
- **Power Consumption: 507 W（max）**
- **Telemetry:**
  Medium 600 kbps (6.5GB/day) / Low 50 kbps

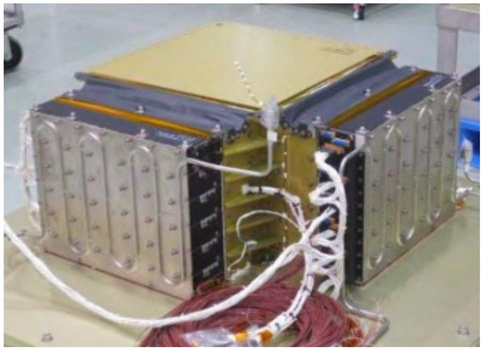
Overview of the CALET Detector

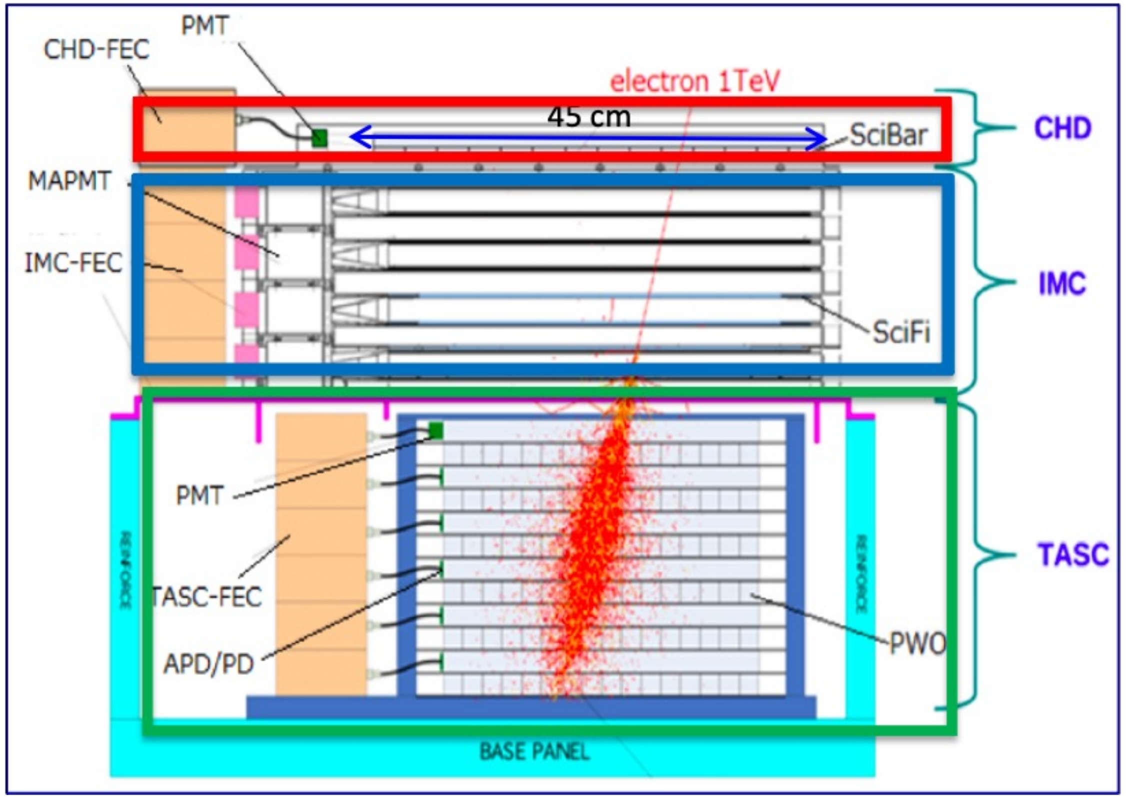
A 30-radiation length deep calorimeter designed to detect electrons and gamma-rays to 20 TeV and cosmic rays up to 1 PeV

CHD/IMC



TASC





CHD – Charge Detector

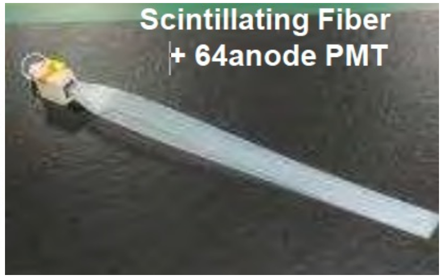
- 2 layers x 14 plastic scintillating paddles
- **single element charge ID** from p to Fe and above (Z = 40)
- charge resolution ~0.1-0.3 e

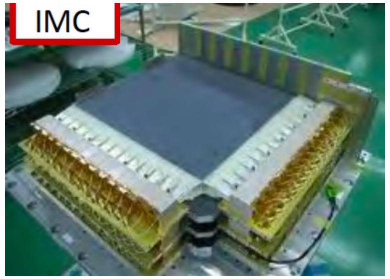
IMC – Imaging Calorimeter

- Scifi. + tungsten absorbers: **3 X_0**
- 8 x 2 x 448 plastic scintillating fibers (1mm) **readout individually**
- **tracking** (~0.1° angular resolution) + **Shower imaging**
- **angular resolution:** 0.2° for gamma-rays > ~50 GeV

TASC – Total Absorption Calorimeter

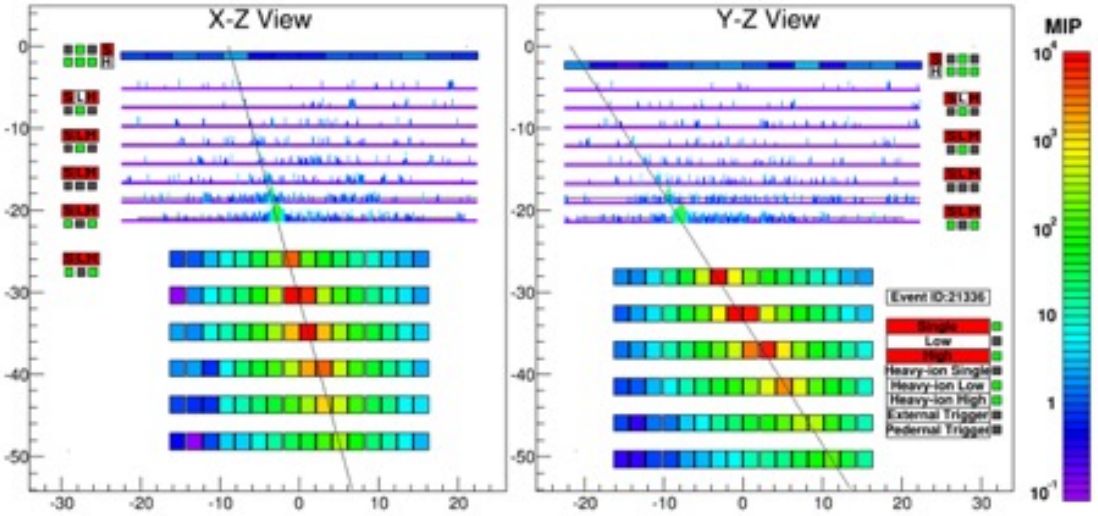
- 6 x 2 x 16 lead tungstate ($PbWO_4$) logs: **27 X_0, 1.2 λ_I**
- **energy resolution:** ~2 % (>10GeV) for e , γ
  ~30-35% for p, nuclei
- **e/p separation:** ~10^{-5}



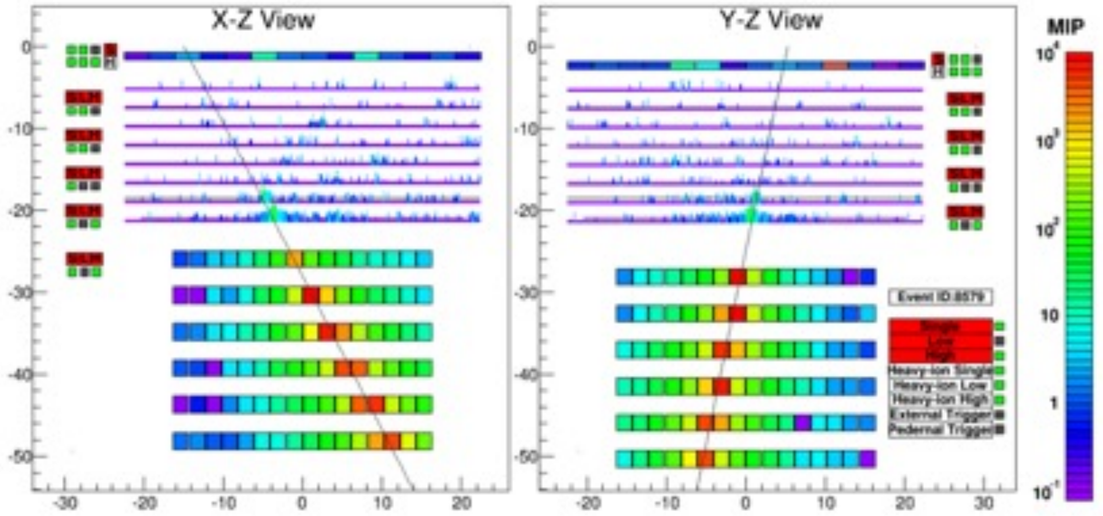


Examples of Event Candidates

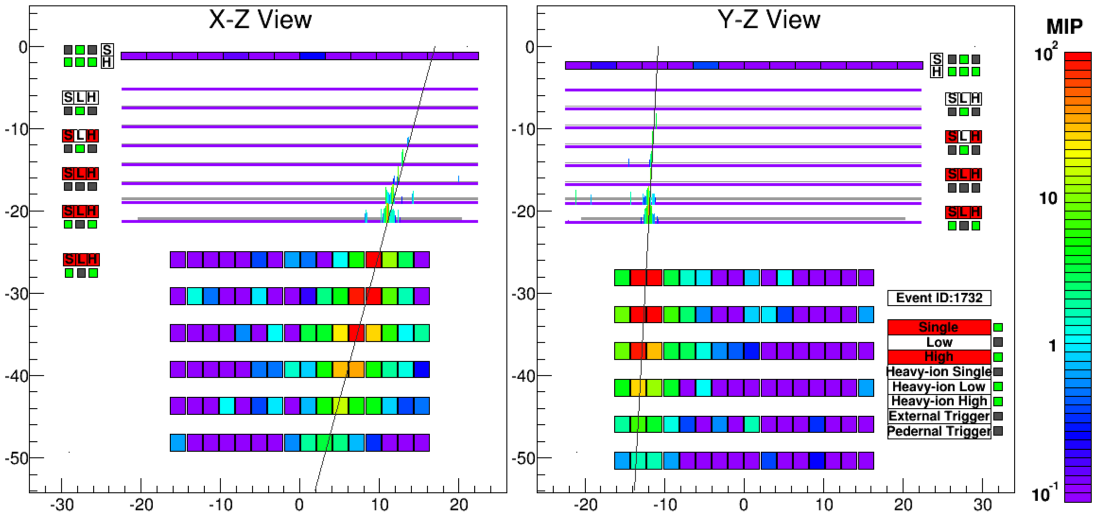
Electron, E=3.05 TeV



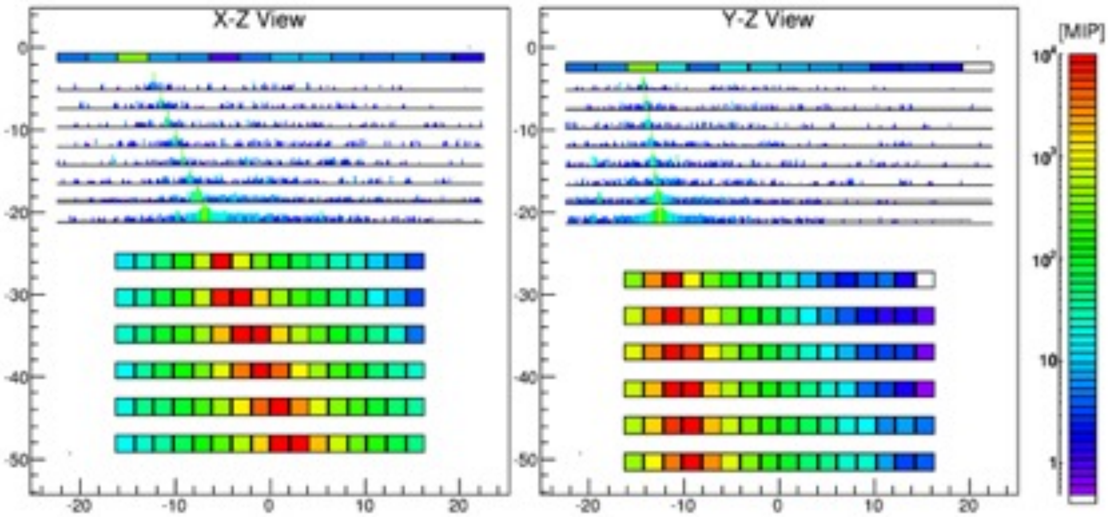
Proton, E_{TASC}=2.89 TeV



Gamma-ray, E=44.3 GeV



Iron, E_{TASC} =9.3 TeV



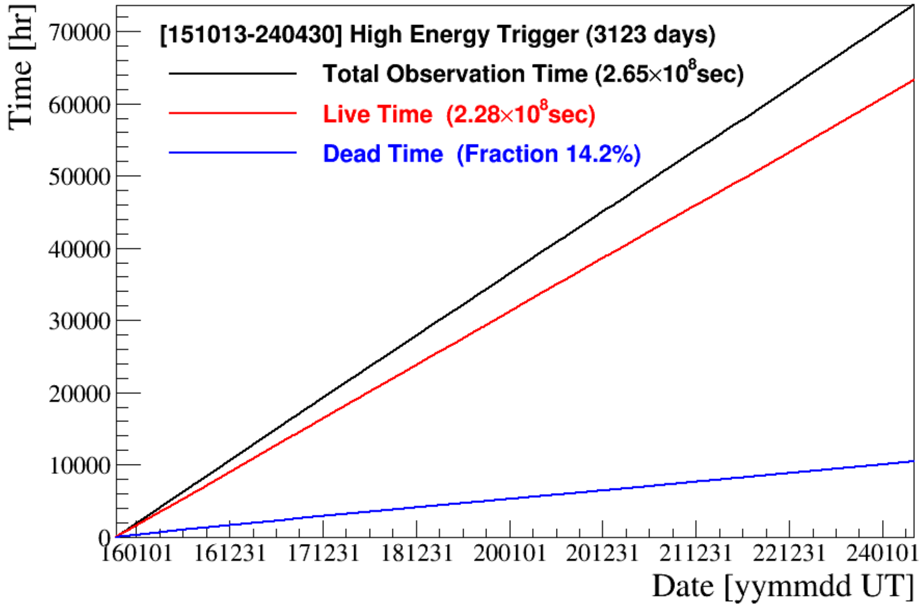
Orbital operation for the first over 8.5 years

Geometrical Factor:

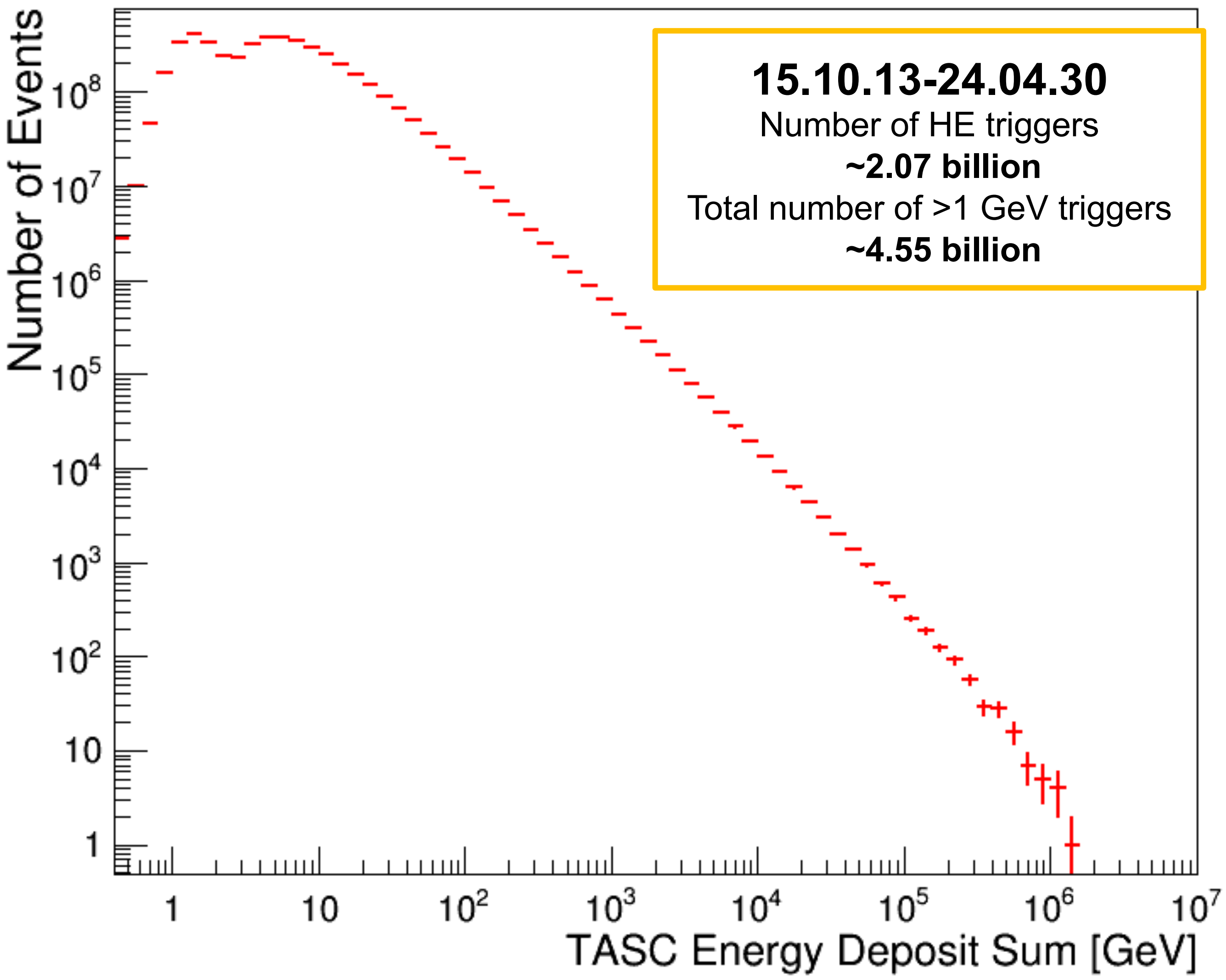
- 1040 cm^2 sr for electrons, light nuclei
- 1000 cm^2 sr for gamma-rays
- 4000 cm^2sr for ultra-heavy nuclei

High-energy trigger (> 10 GeV) statistics:

- Orbital operations : **3123 days (>8 years)** as of April 30, 2024
- Observation time : 2.65×10^8 sec
- Live time fraction: ~ **86%**
- Exposure of HE trigger : **~320 $\mathbf{m^2}$ sr day**



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



15.10.13-24.04.30

Number of HE triggers

~2.07 billion

Total number of >1 GeV triggers

~4.55 billion

Capabilities of the electron measurements

- Energy calibration in space have been done by the penetrate particles of cosmic-ray protons and helium nuclei
- Very-wide range read out of energy deposited in TASC was calibrated by a UV pulse laser on the ground

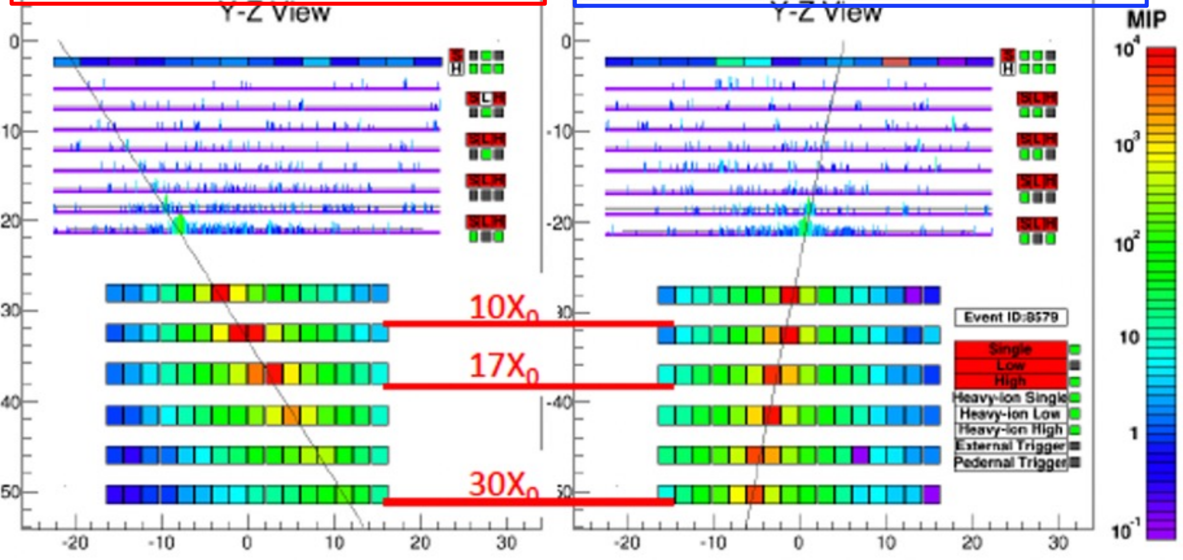
➡ The energy resolution of electrons is <2% above 20 GeV

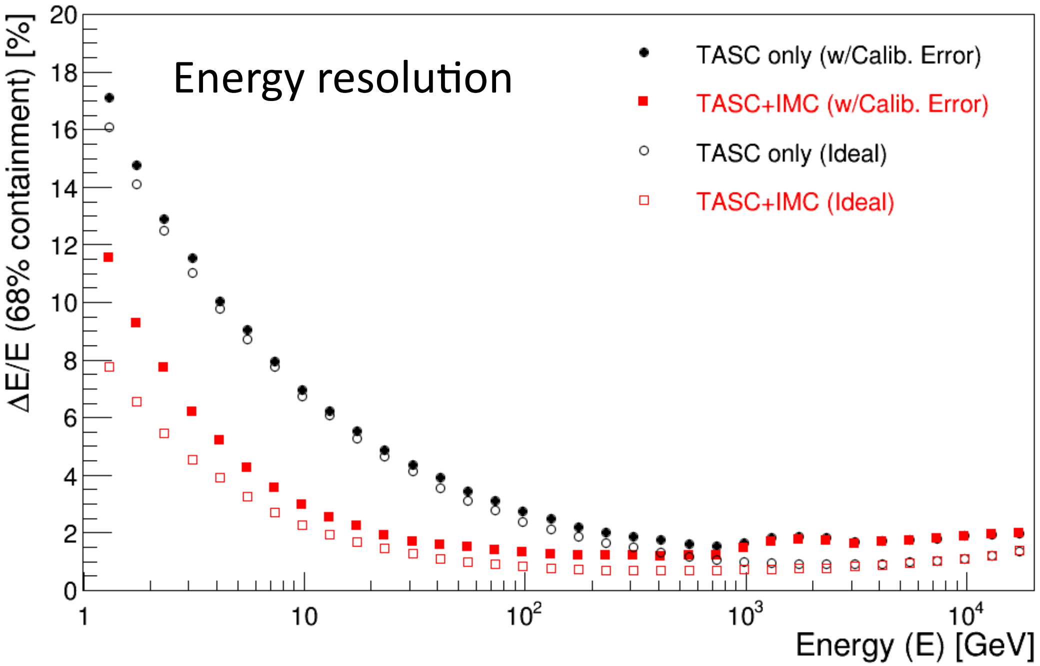
- Imaging capability with thick calorimeter provides powerful electron/proton identification

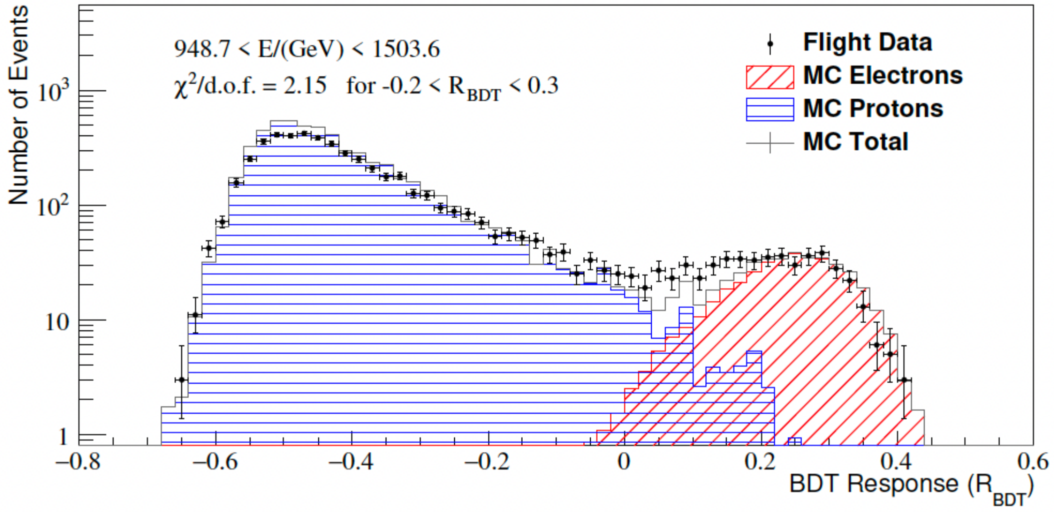
➡ The total BG protons are less than 10% up to 7.5 TeV with 70% electron efficiencies

3TeV electron candidates

Corresponding background

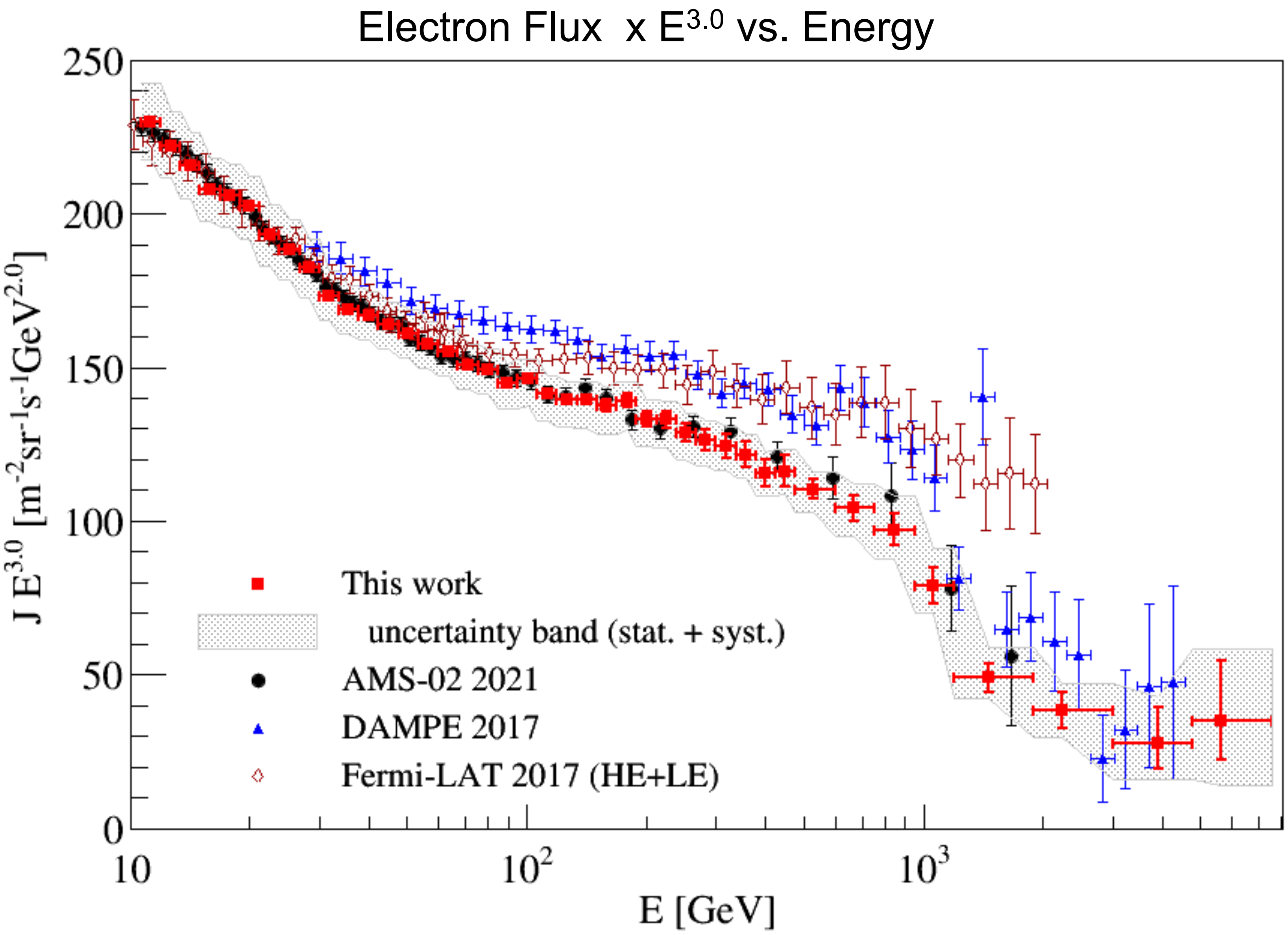






Electron + positron spectrum

PRL 131, 191001 (2023)



2537 days of CALET observations:

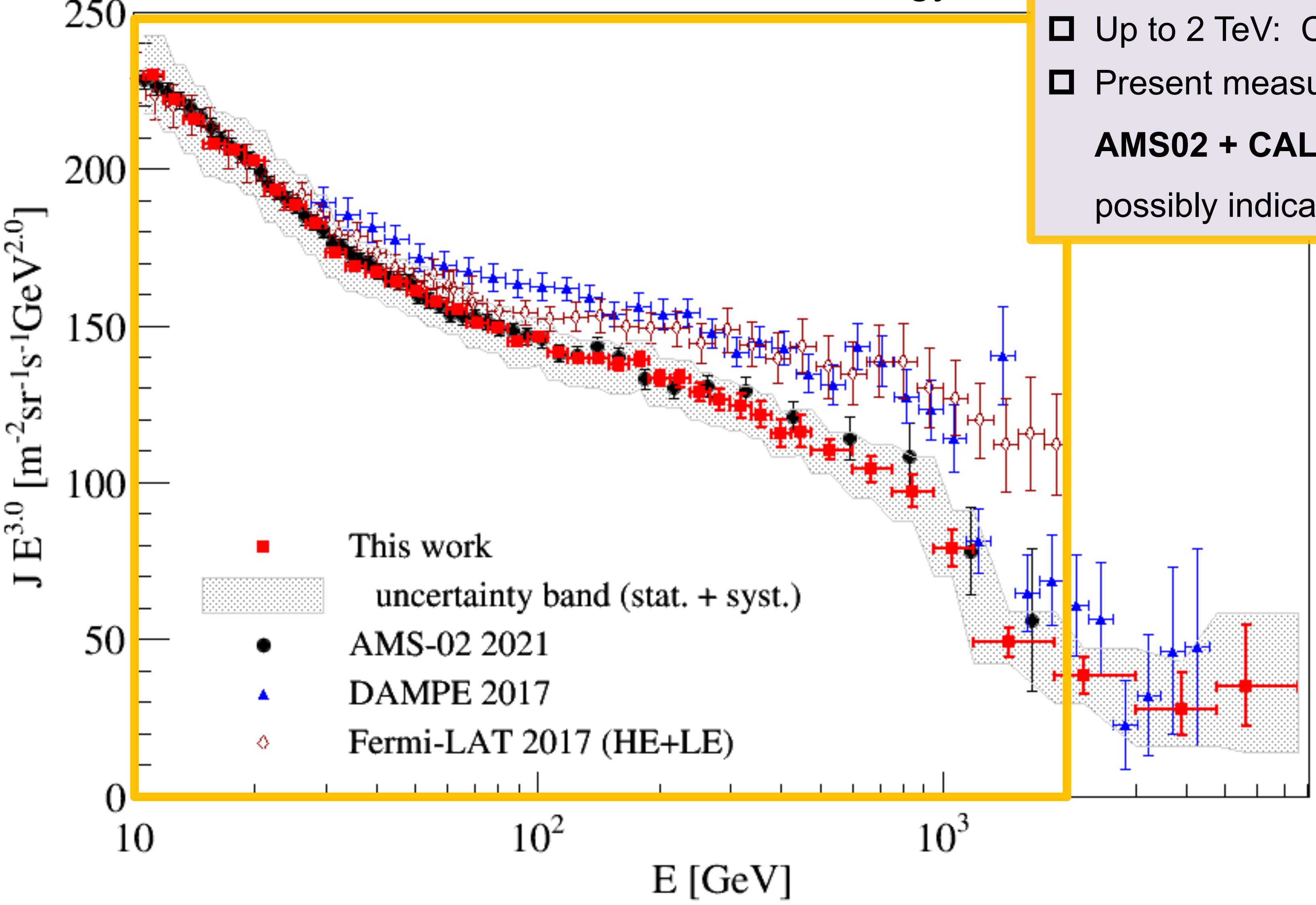
Oct.13, 2015 – Dec. 31, 2022

7.02 million events > 10 GeV

Electron + positron spectrum

PRL 131, 191001 (2023)

Electron Flux x $E^{3.0}$ vs. Energy



☐ Up to 2 TeV: CALET spectrum is consistent with AMS-02

☐ Present measurements cluster into 2 groups:

AMS02 + CALET and **FERMI + DAMPE**

possibly indicating the presence of unknown systematics

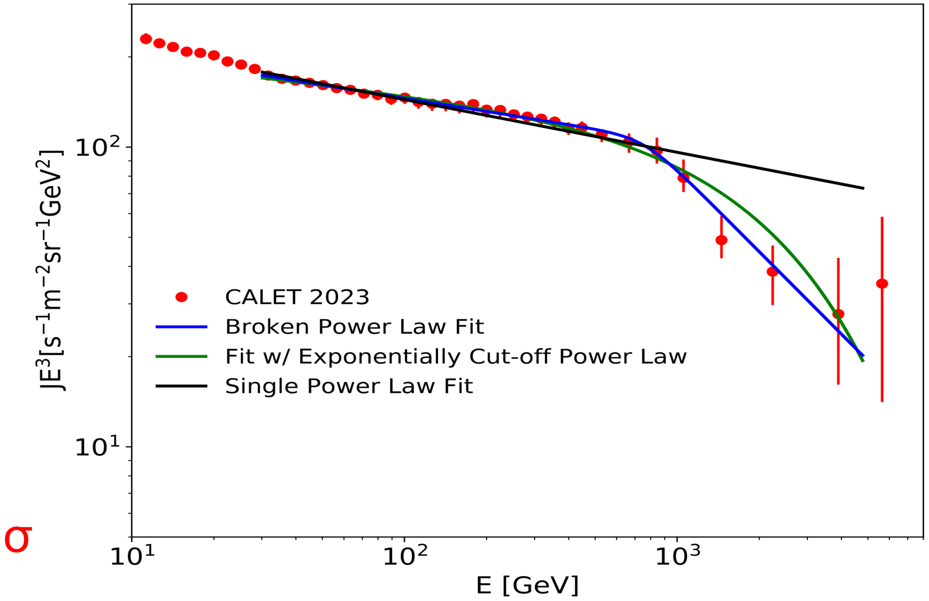
2537 days of CALET observations:
Oct.13, 2015 – Dec. 31, 2022
7.02 million events > 10 GeV

Towards an interpretation of all-electron spectrum

☐ Fits of the CALET all-electron spectrum in 30 GeV – 4.8 TeV

- Broken power law
  - $\gamma = -3.15 \pm 0.01$, $\Delta\gamma = -0.77 \pm 0.22$
  - $E_b = 761 \pm 115$ GeV (χ^2/NDF=3.6/27)
- Exponential cut-off power law
  - $\gamma = -3.10 \pm 0.01$
  - $E_c = 2.854 \pm 0.305$ TeV (χ^2/NDF=12/28)
- Single power law
  - $\gamma = -3.18 \pm 0.01$ (χ^2/NDF=56/29)

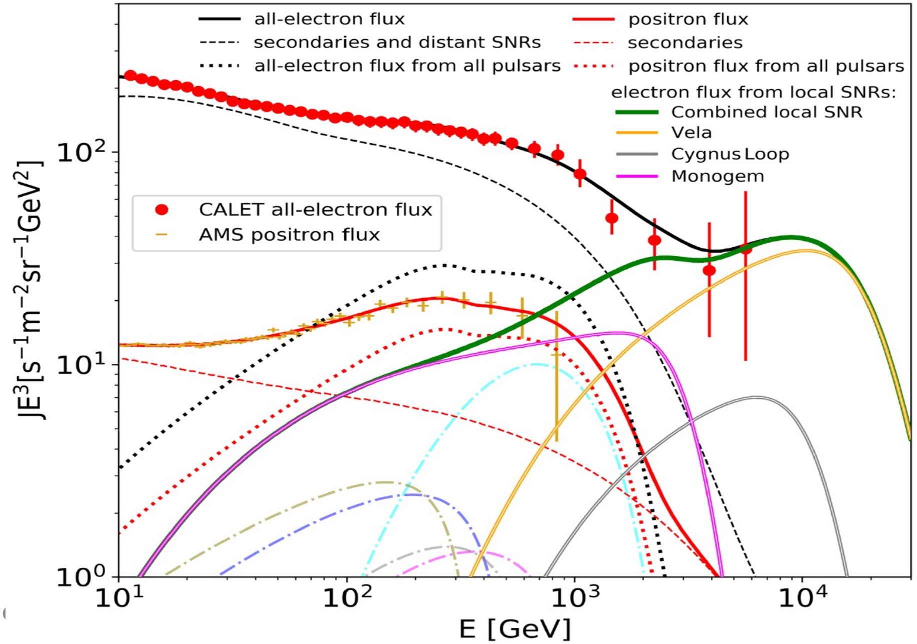
The significance of both fits of softening spectrum is more than 6 σ



☐ Possible spectral fit in whole energy region

- Positron contribution is fitted using AMS-02 flux with secondaries + pulsars
- CALET electron + positron flux is fitted with secondaries + pulsars + SNRs

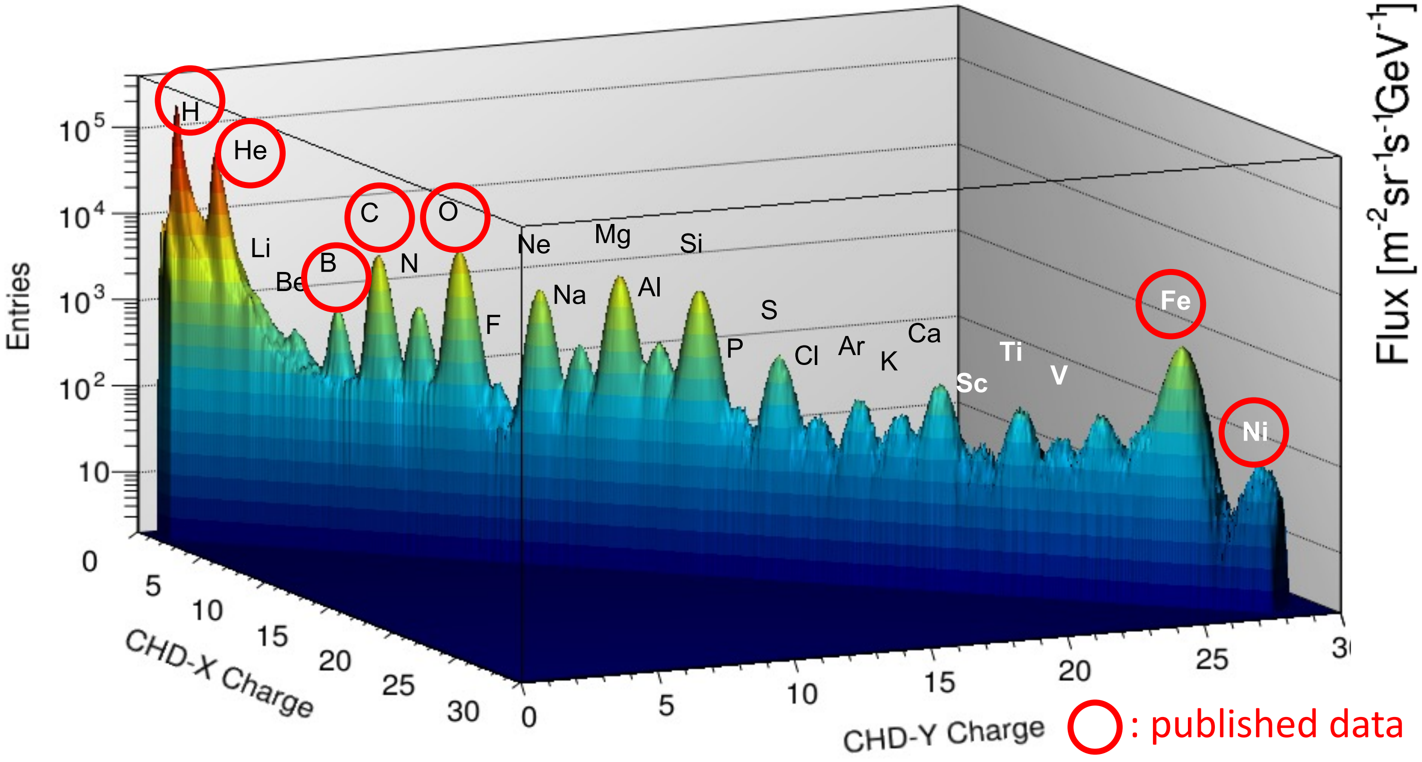
A possible contribution from the Vela SNR:
Energy output of 0.8 x 10^{48} erg in electron CRs above 1 GeV



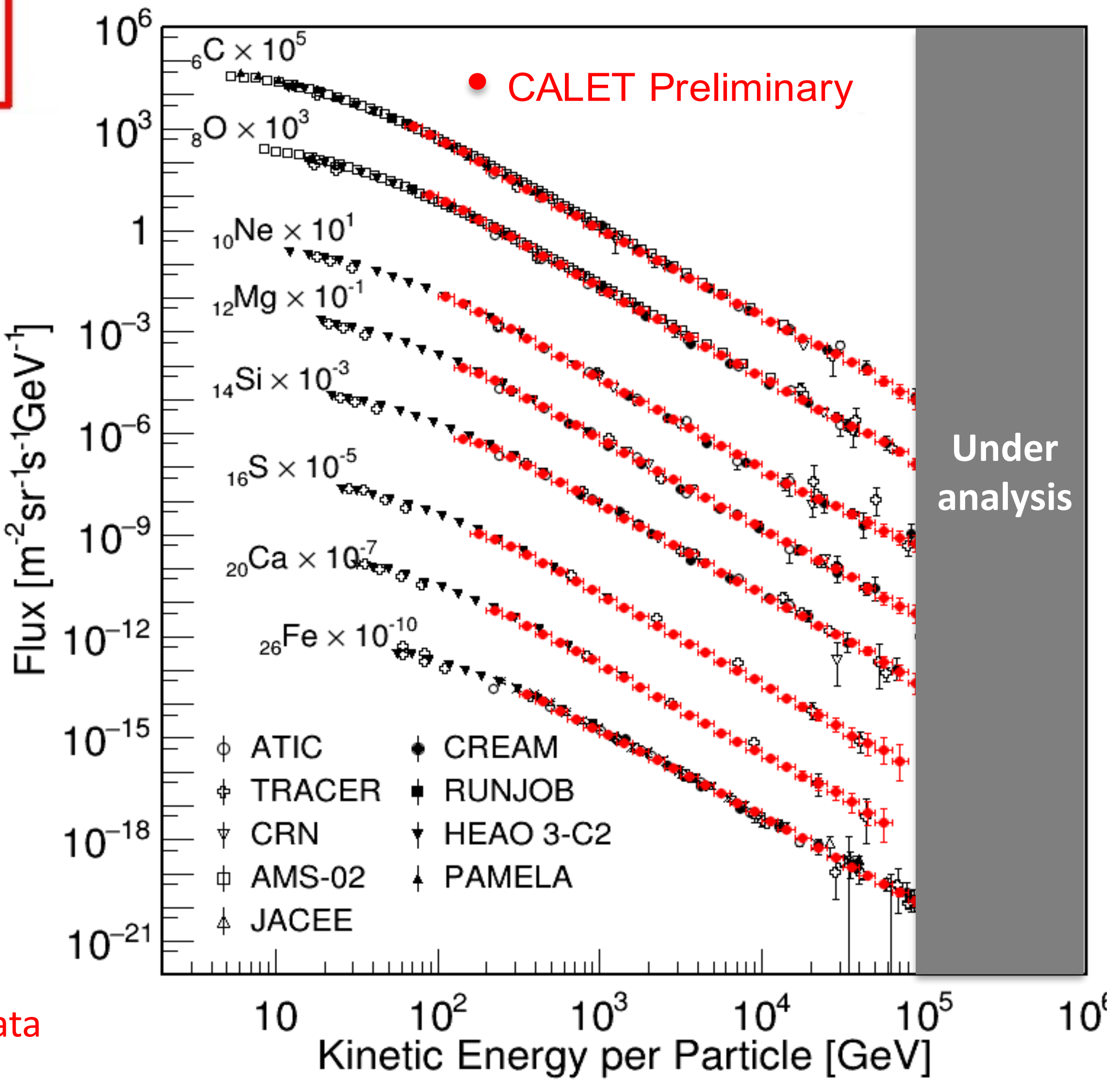
Observations of Cosmic-ray Nuclei

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

Charge distribution from Proton to Nickel
(periodic table of elements by CALET)

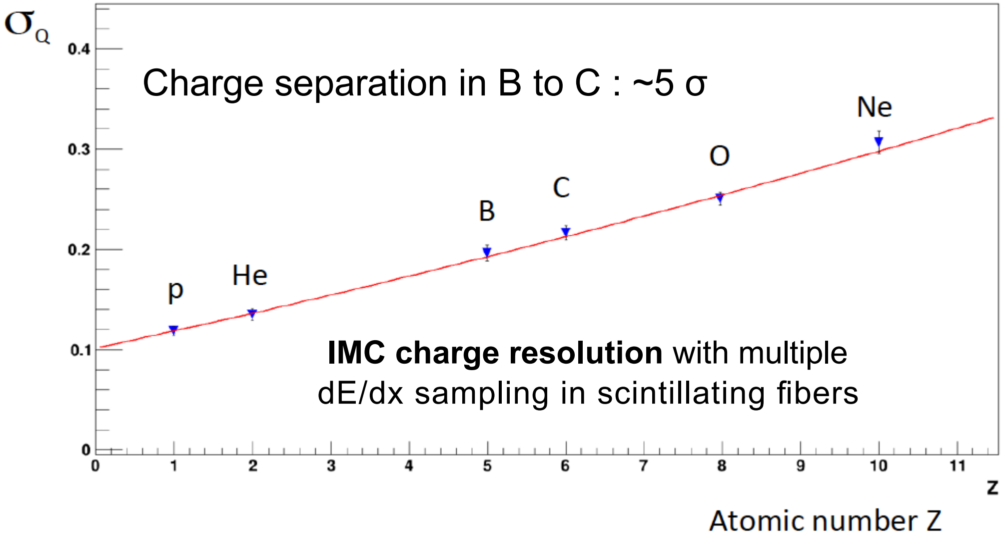


Preliminary spectra of Carbon – Iron



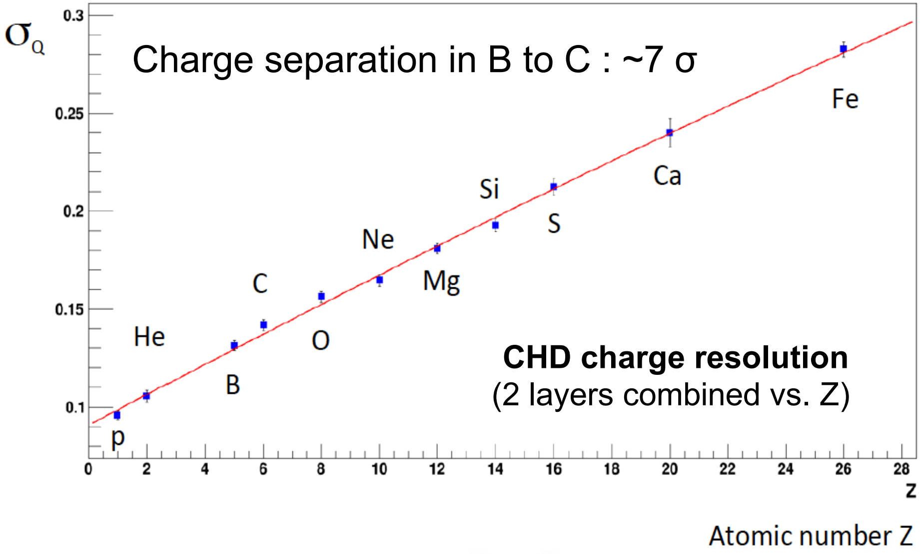
Charge Identification with CHD and IMC

Single element identification for p, He and light nuclei is achieved by CHD+IMC charge analysis.



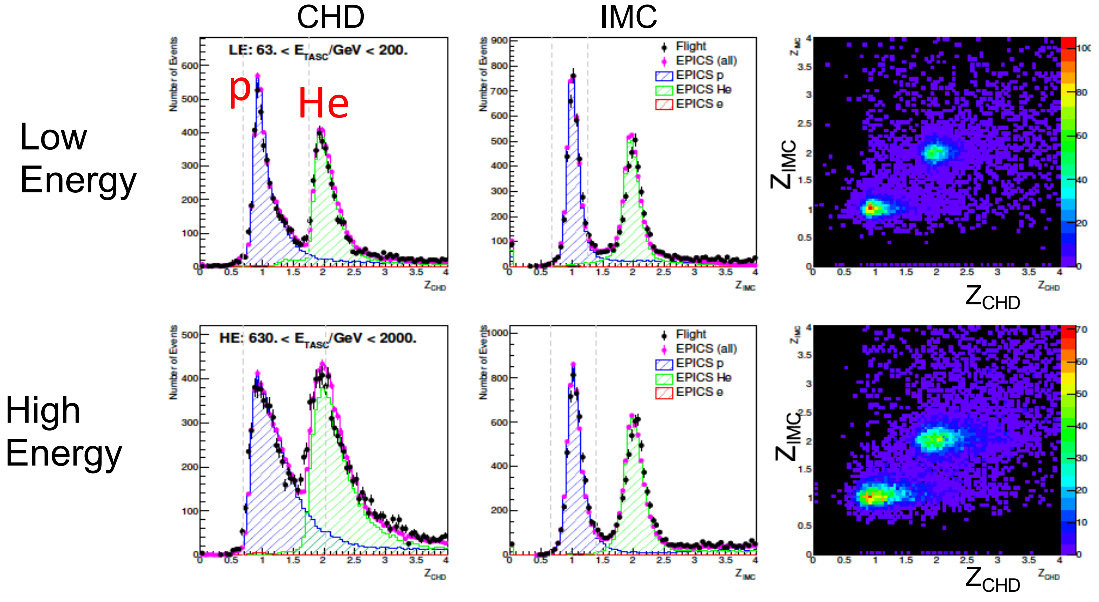
Charge separation in B to C : ~5 σ

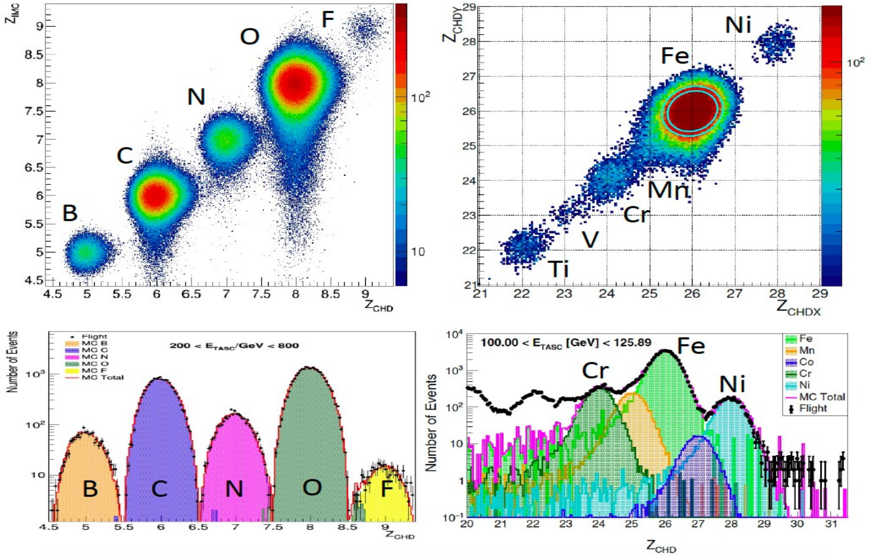
IMC charge resolution with multiple dE/dx sampling in scintillating fibers



Charge separation in B to C : ~7 σ

CHD charge resolution (2 layers combined vs. Z)





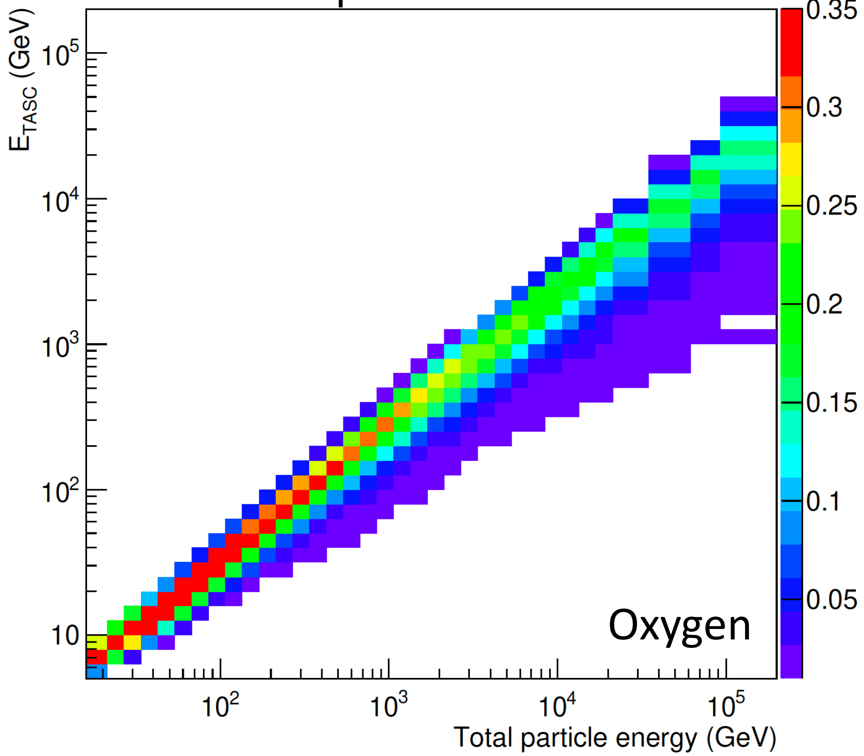
Energy measurements for nuclei

Characteristics of CALET calorimeter:
- thickness: 30 X_0 for electron, 1.3λ for proton
- σ(E)/E : 2% for electron, 30% for nuclei
  ➡ Apply the energy unfolding for nuclei to obtain primary energy spectrum

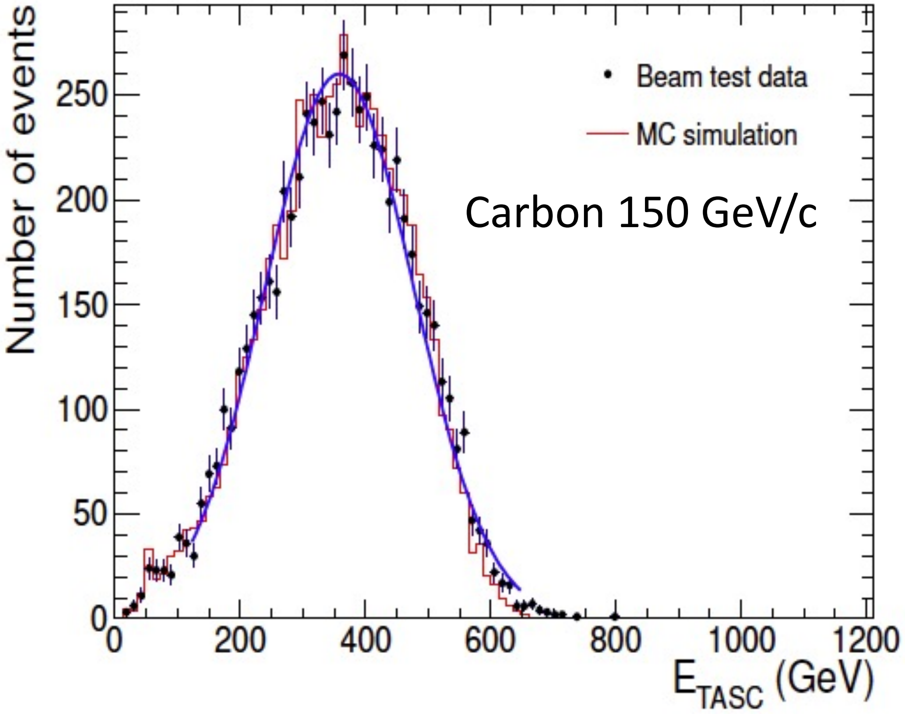
Beam calibration at CERN-SPS with Ion fragments at 13, 19 150 GeV/n to assess our MC simulations

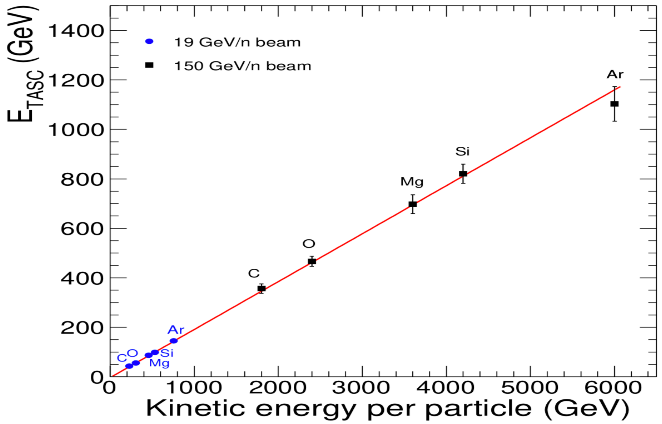
➡ Discrepancies are included into the systematic uncertainties

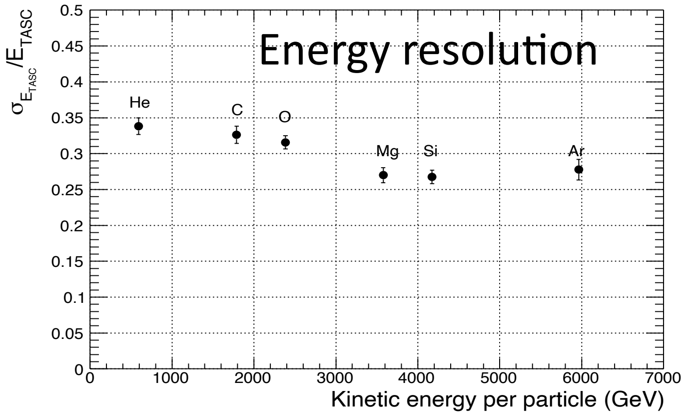
Response matrix



Energy distribution







Energy resolution

Systematic uncertainties

The stability of the spectra by varying the analysis cuts and different MC simulations for efficiencies and unfolding.

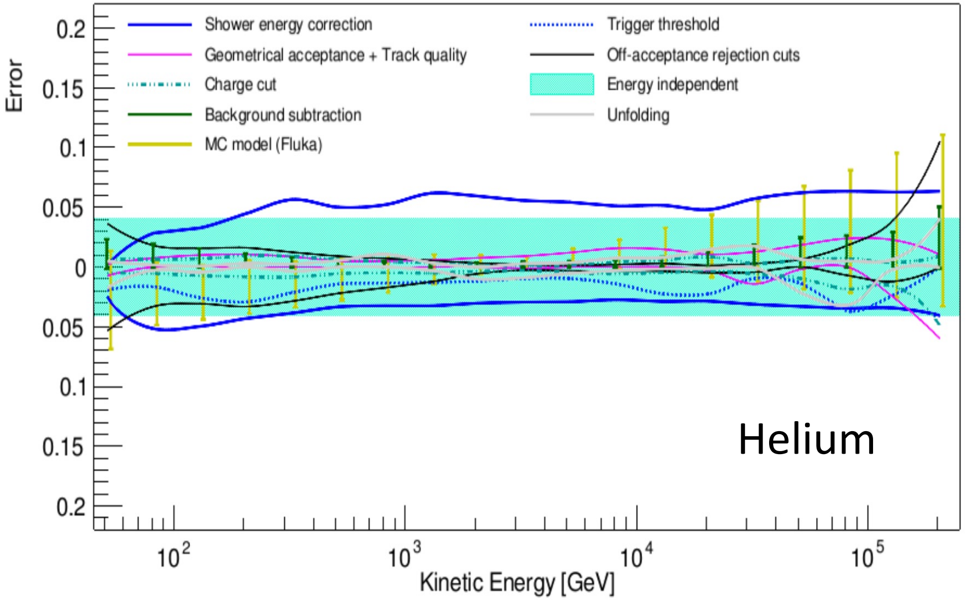
Main sources of systematic uncertainties:

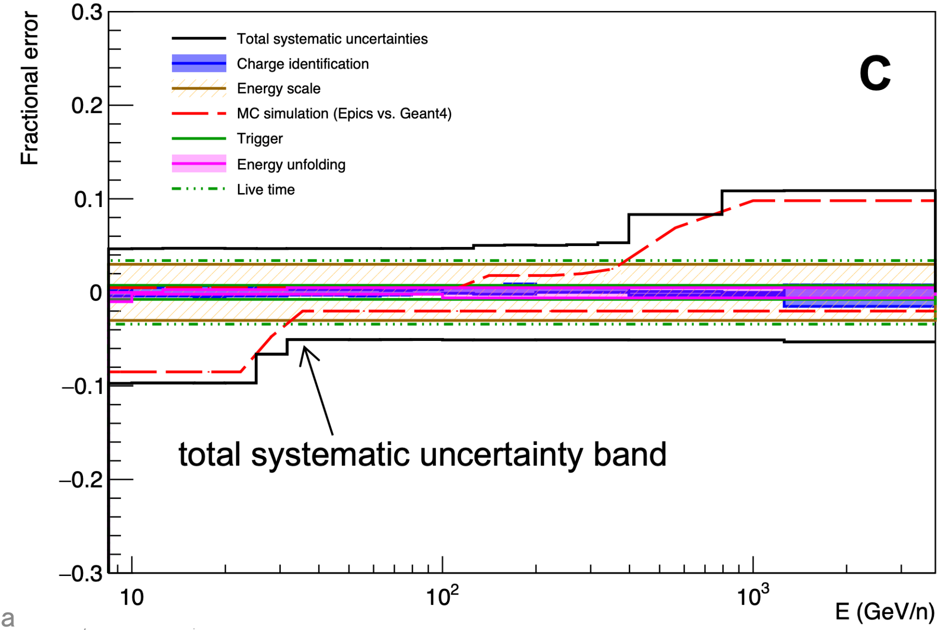
Normalization:

- Live time
- Long-term stability
- Energy scale

Energy dependent:

- Trigger
- Tracking
- Off-acceptance rejection cuts
- Charge ID
- Background subtraction
- Energy unfolding
- MC model (EPICS, FLUKA, Geant4)



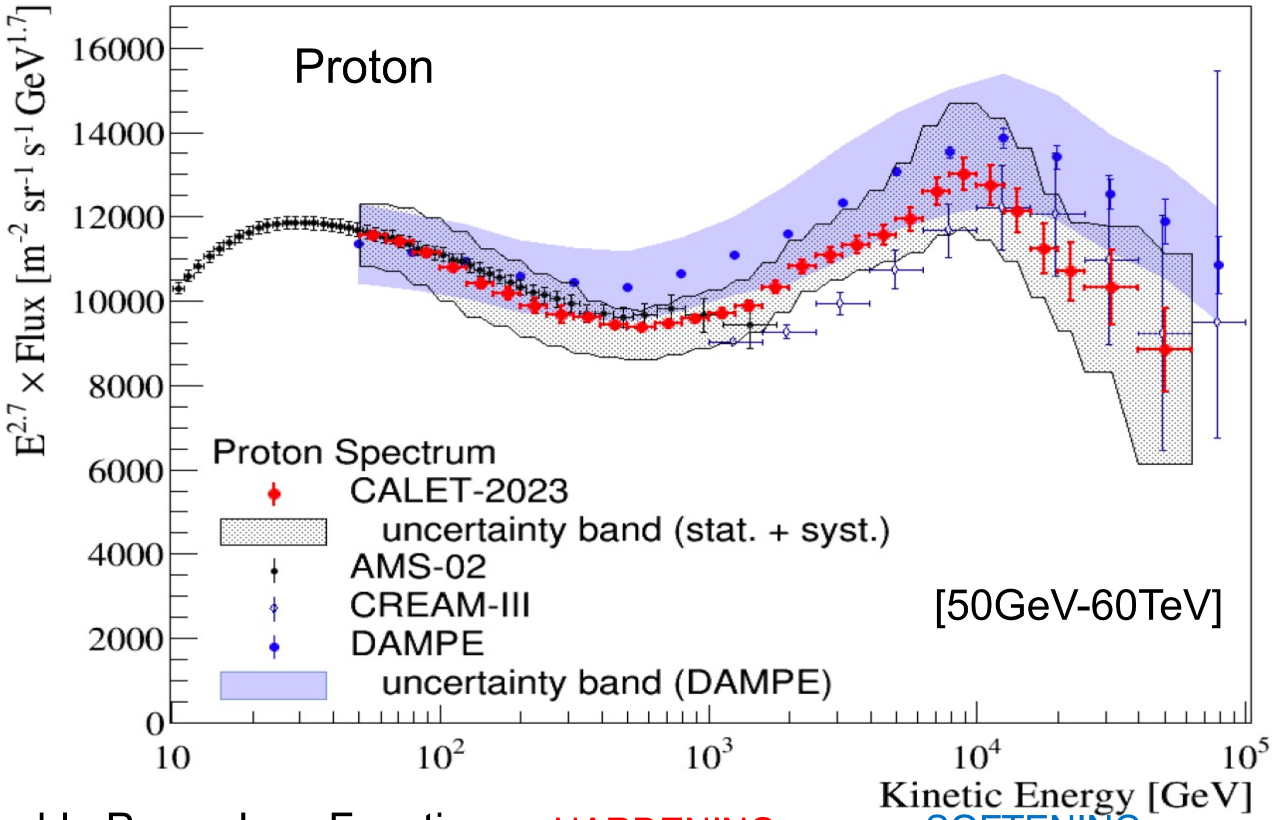


total systematic uncertainty band

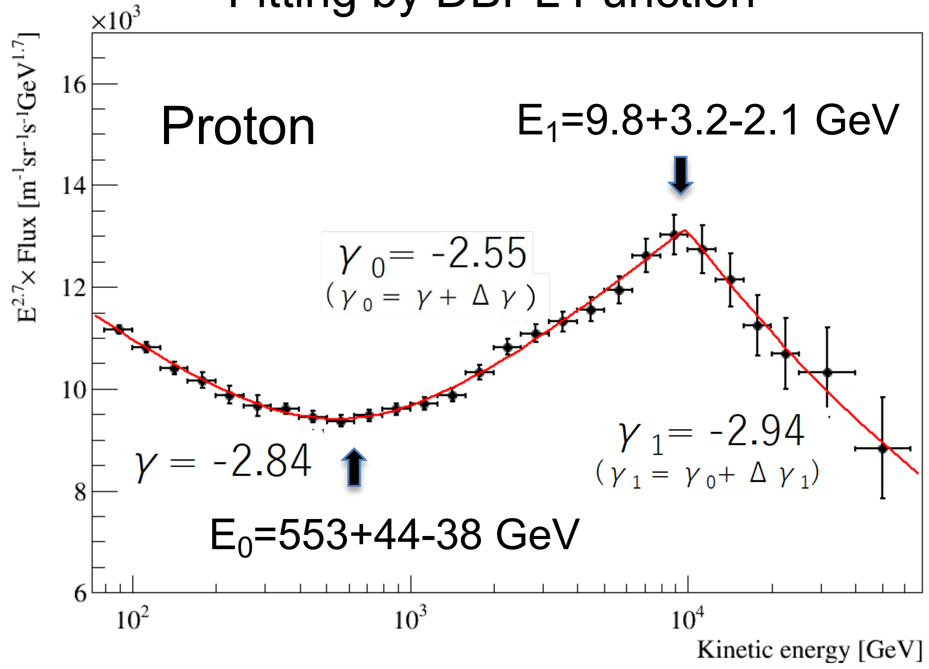
Proton spectrum

PRL 129, 101102 (2022)
+ PoS(ICRC2023) 092

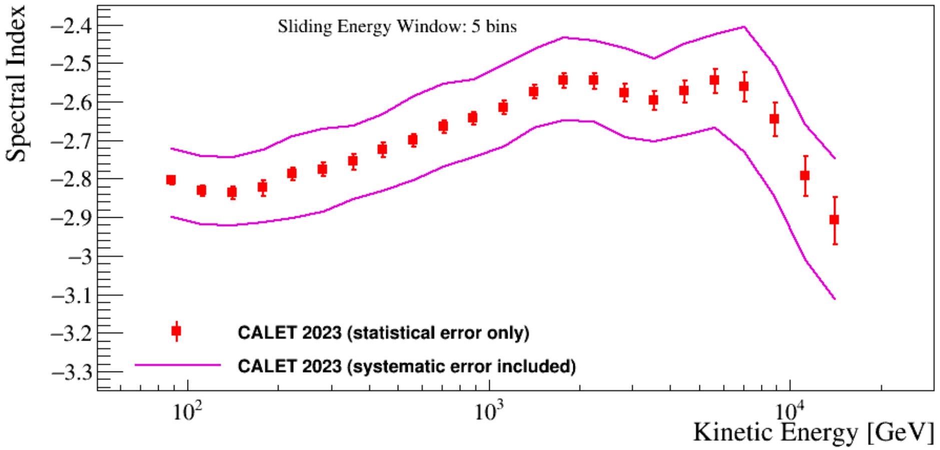
Flux x $E^{2.7}$ vs. Kinetic energy [Oct.2015- Apr.2023]



Fitting by DBPL Function



Energy dependence of power index



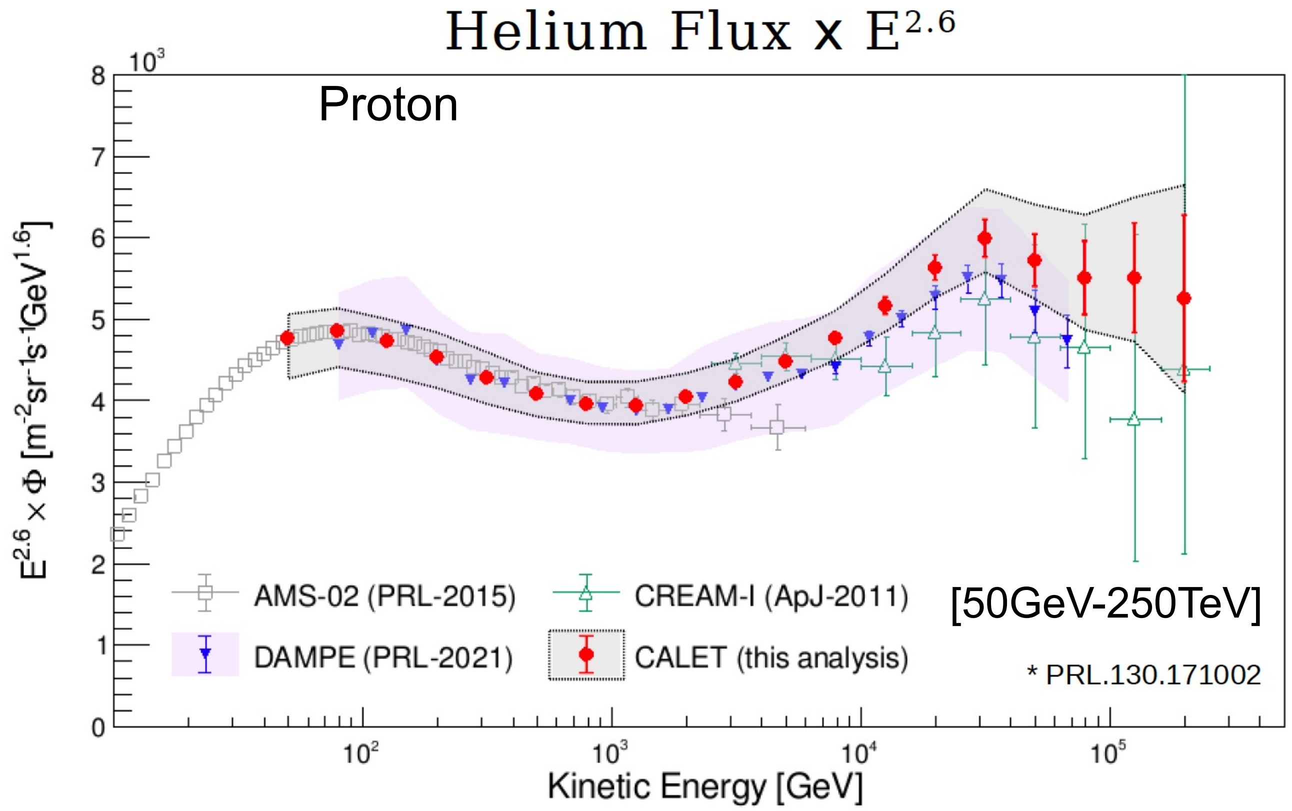
Double Power Law Function: HARDENING SOFTENING

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

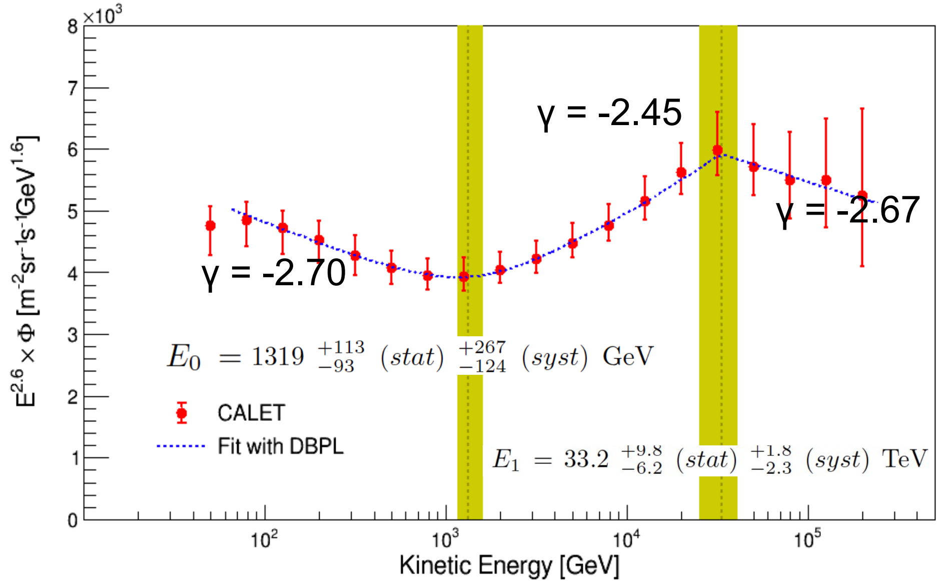
Helium spectrum

PRL 130, 171002 (2023)

Flux x $E^{2.6}$ vs. Kinetic energy [Oct. 2015 - Apr. 2022]



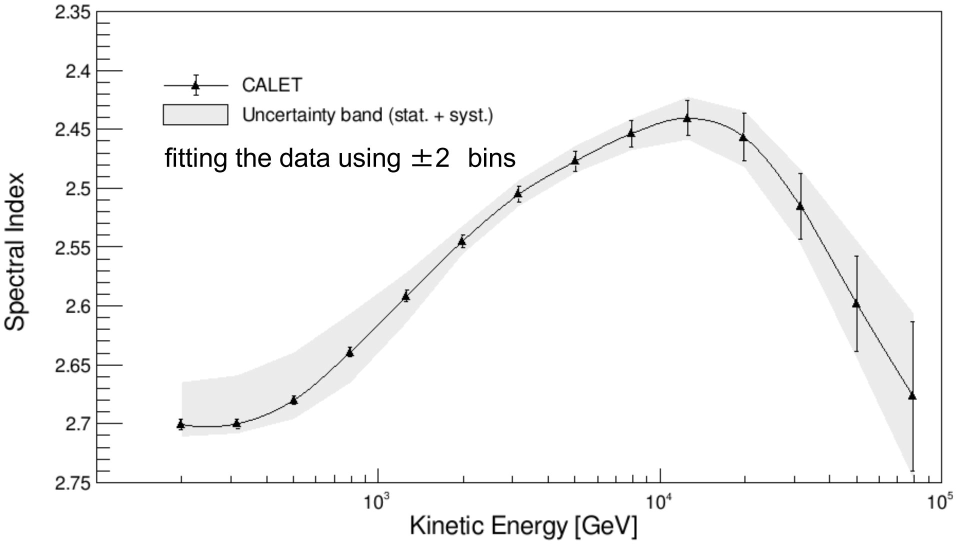
Fitting by Double Power Law (DBPL) function



$E_0 = 1319\ ^{+113}_{-93}\ (stat)\ ^{+267}_{-124}\ (syst)$ GeV

$E_1 = 33.2\ ^{+9.8}_{-6.2}\ (stat)\ ^{+1.8}_{-2.3}\ (syst)$ TeV

Energy dependence of power index



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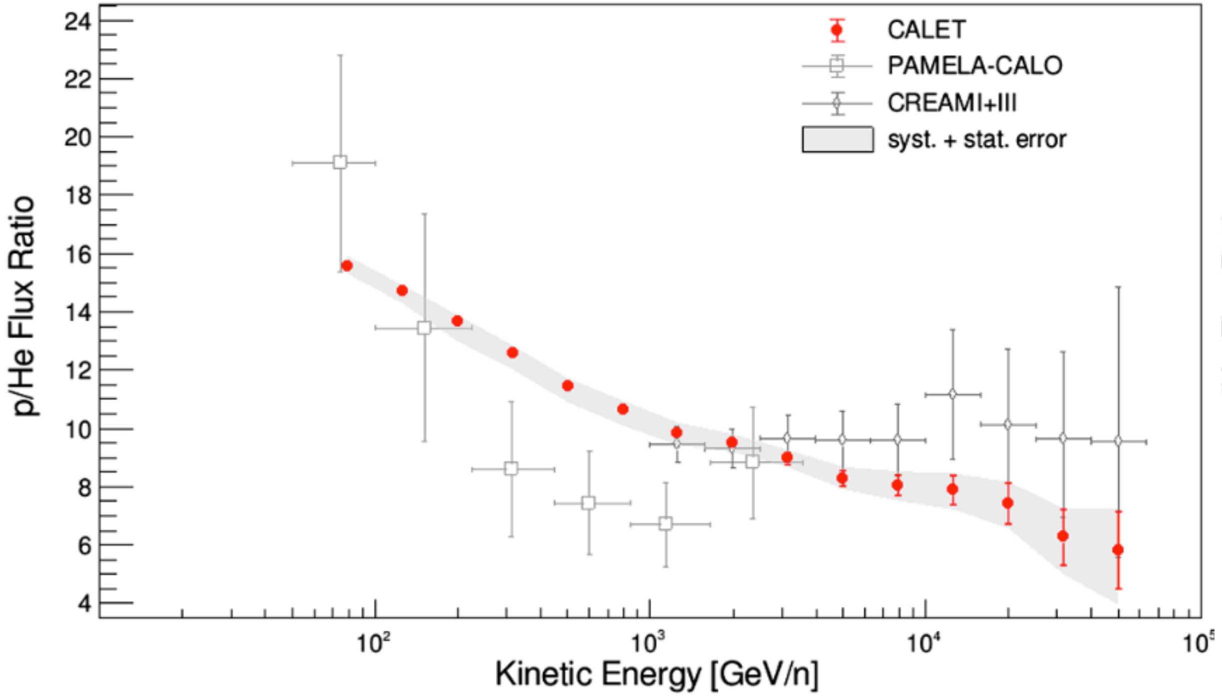
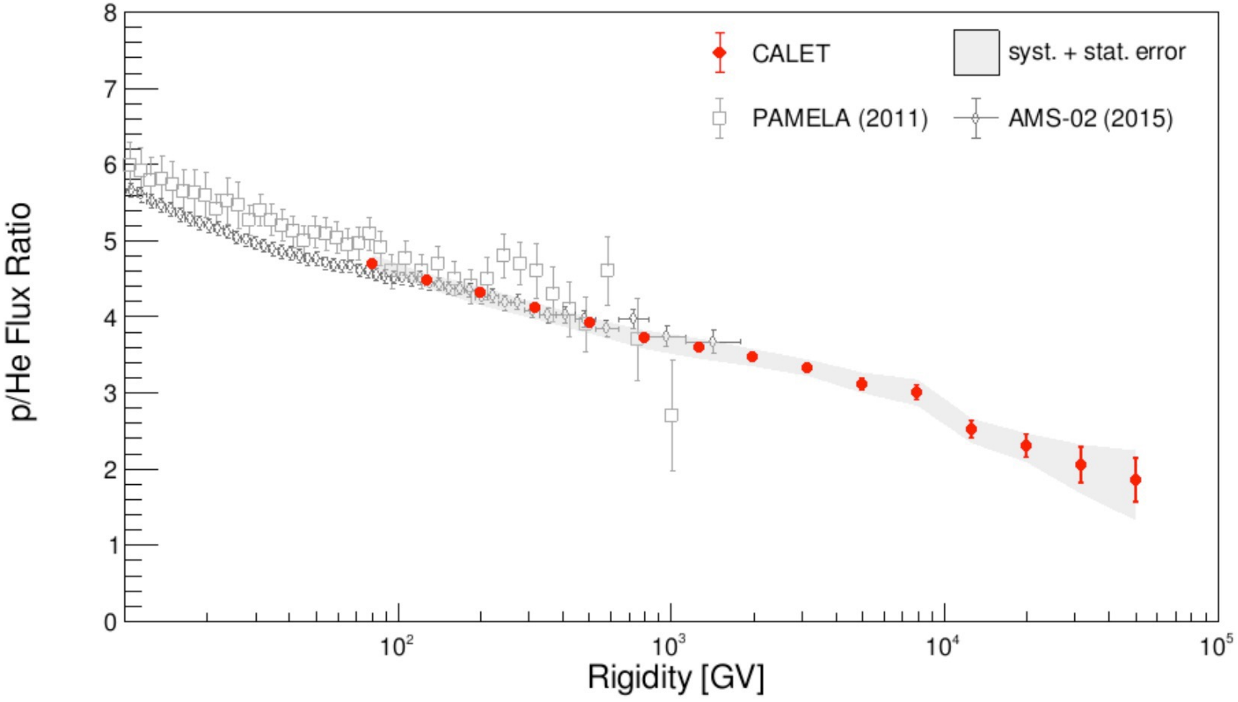
Proton / Helium Ratio

PRL 130, 171002 (2023)

Proton/Helium Ratio vs. Energy/nucleon



Proton/Helium Ratio vs. Rigidity

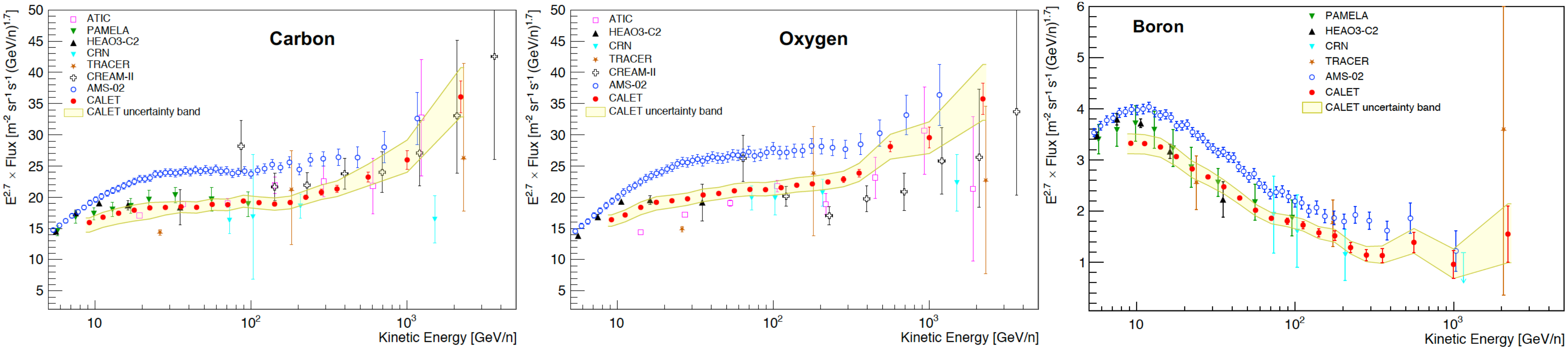


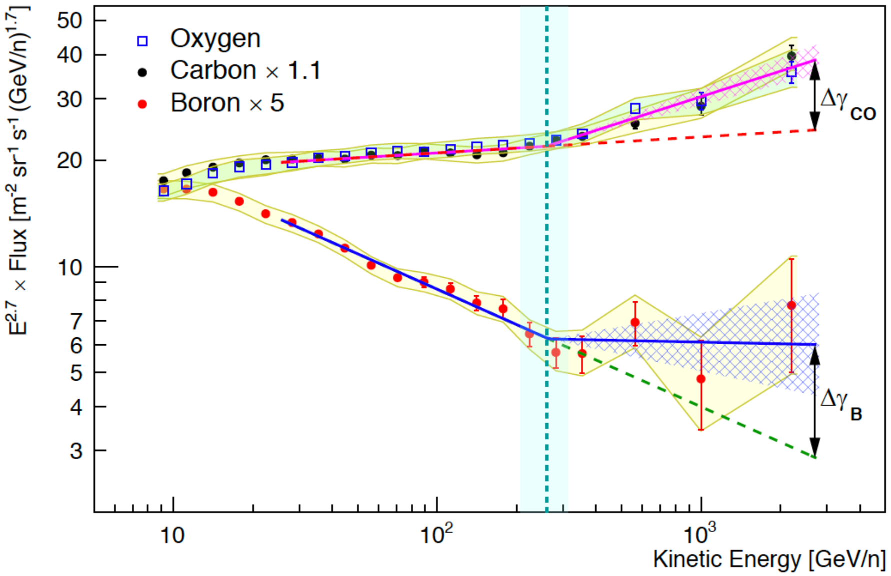
- The spectral index of helium is harder than that of proton (by ~0.1) in the whole rigidity range.
- Possible change of the spectral index of p/He ratio seen above 10 TV will be carefully checked by analyzing higher statistics data in future.

Energy Spectra of B, C and O

PRL 129, 251103 (2022)
+ PoS(ICRC2023) 058

Flux x $E^{2.7}$ vs kinetic energy per nucleon [8.4 GeV- 3.8 TeV]





Fitting with double power law function

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

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.
- The flux hardens more for B than for C and O above 200 GeV/n, albeit with low statistical significance.

B/C, B/O and C/O ratio

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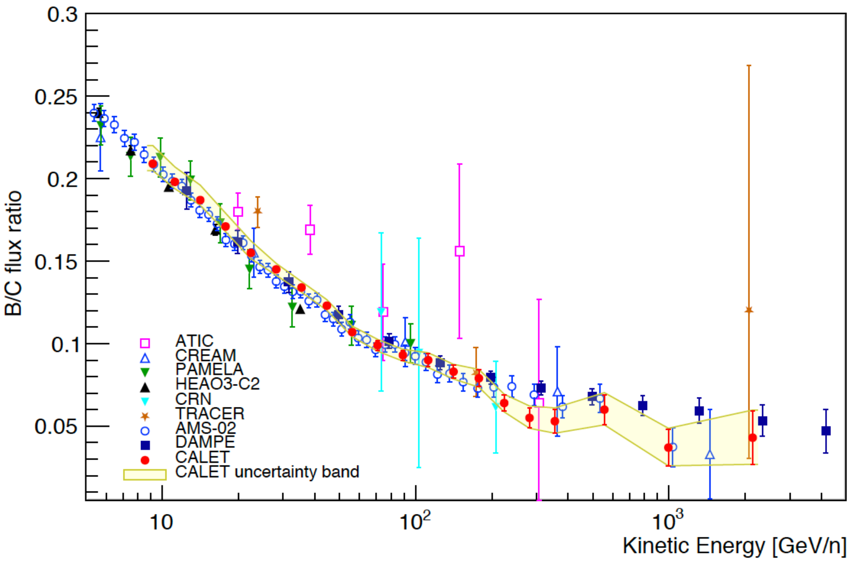
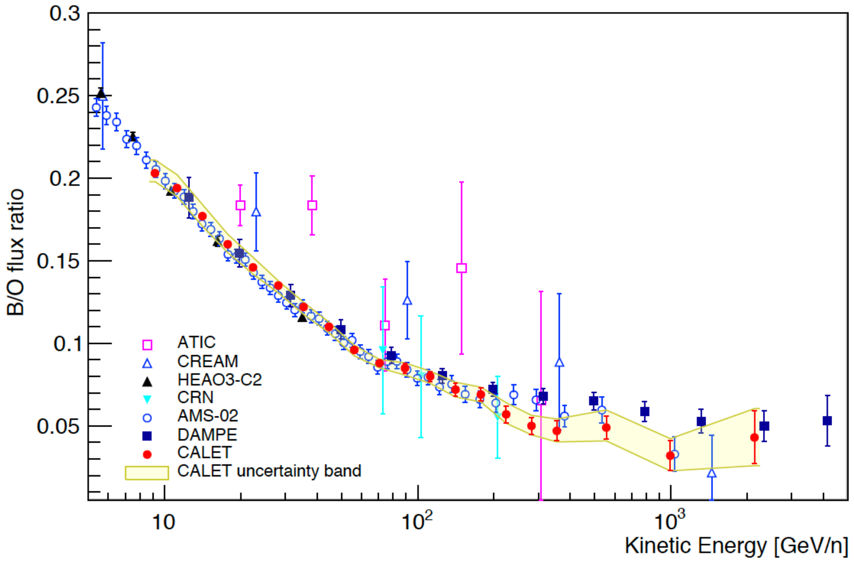
+ PoS(ICRC2023) 058

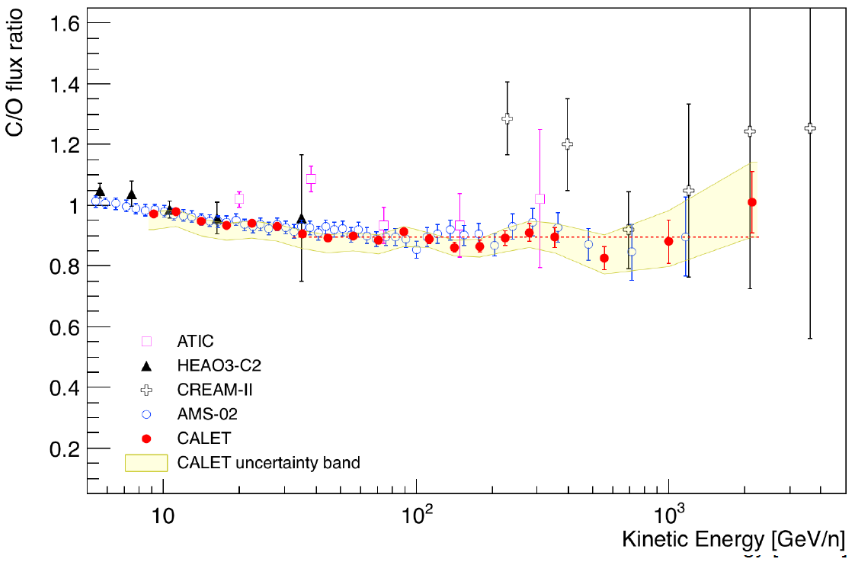
B/C flux ratio



B/O flux ratio



C/O flux ratio



- Flux ratios of B/C and B/O are in good agreement with AMS-02 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 with 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

Spectral fit of B/C and B/O

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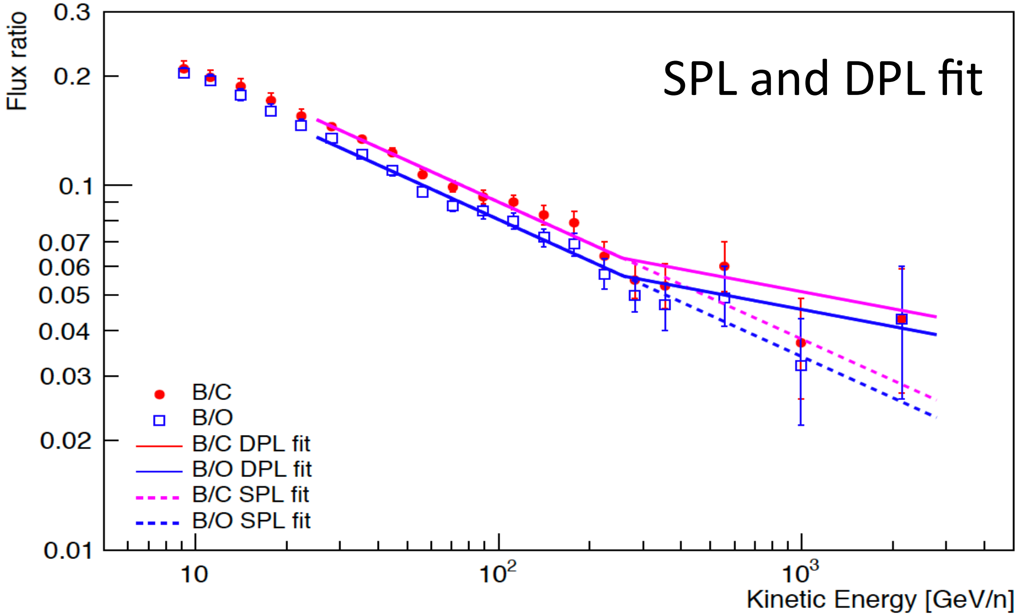

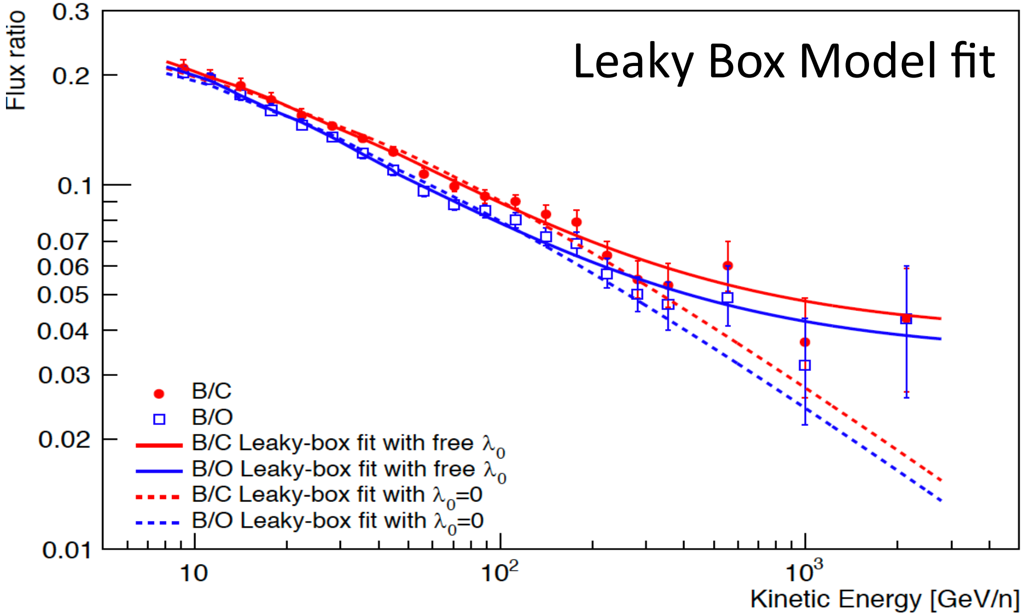

Simultaneous fit to B/C and B/O (E>25 GeV/n) with same parameters except normalization

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 = 19/26)

Leaky-box model fit [ApJ **752** 69 (2012)]

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

$\lambda(E)$: mean escape path length

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

λ_0 : residual path length

δ : diffusion coefficient spectral index

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 energies.

Energy spectra of Fe and Ni

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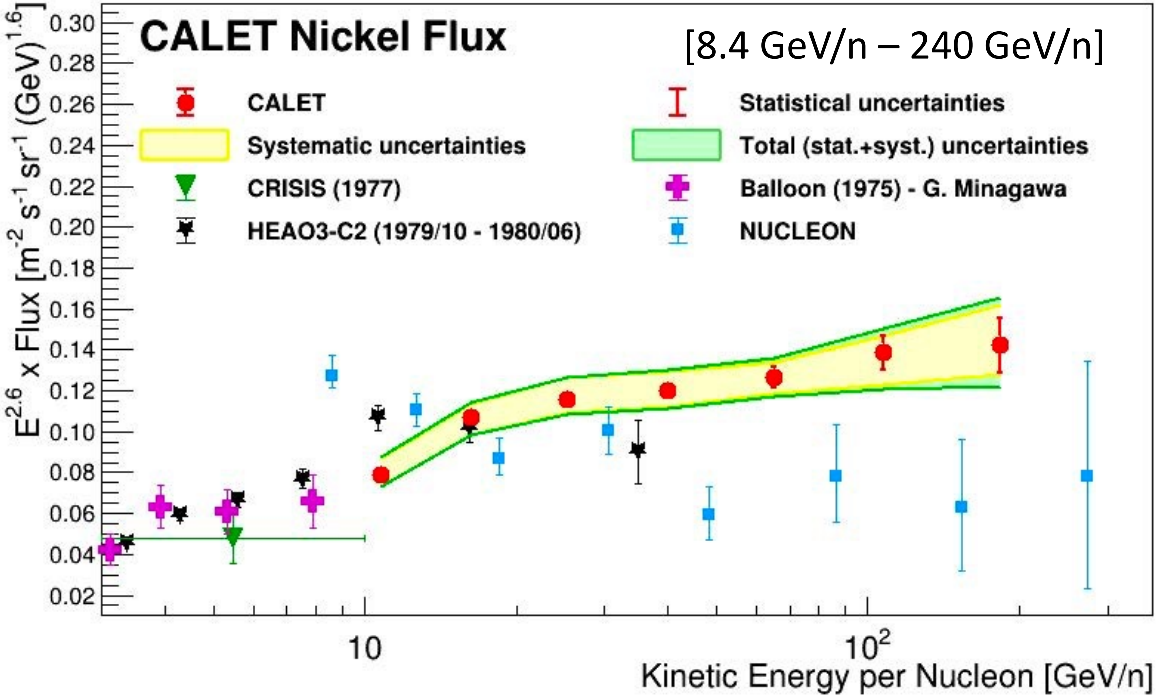
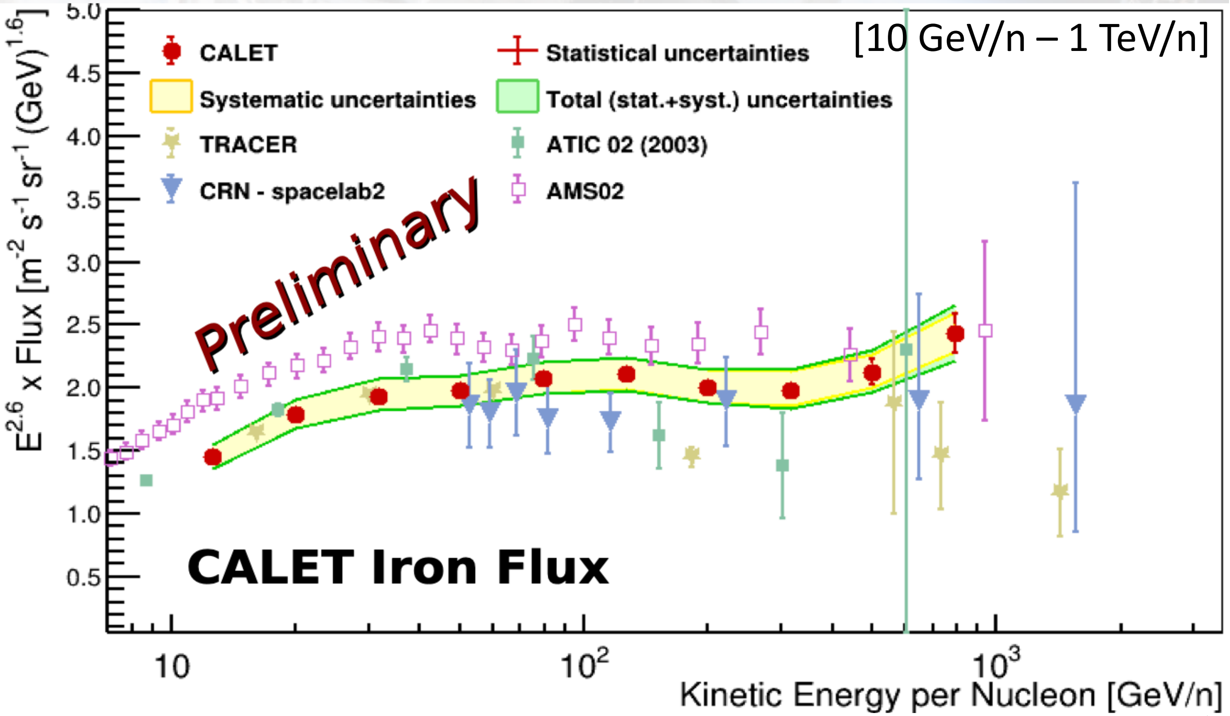
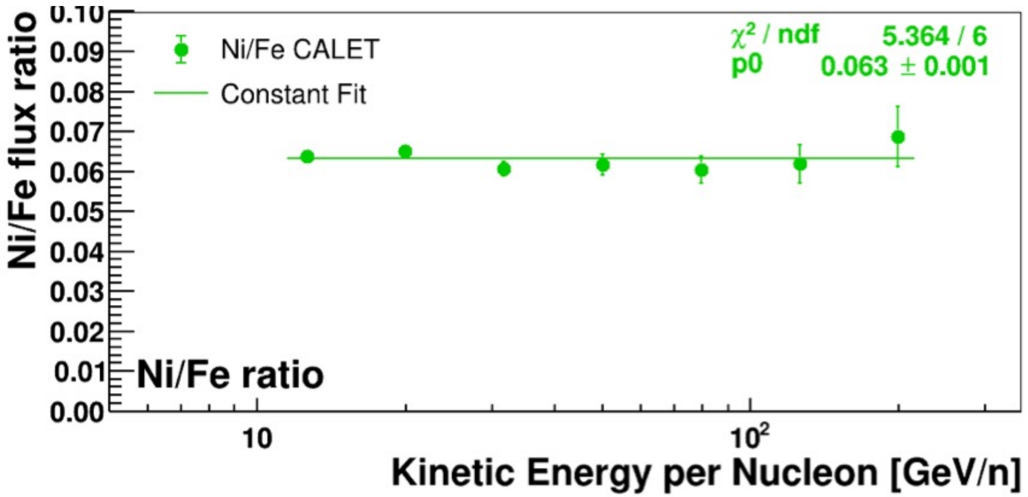
- Larger (60% more) data set from PRL (2021)
- The absolute normalization is lower than AMS-02 like B, C, O
- Ni/Fe ratio is constant with respect to the energy



[8.4 GeV/n – 240 GeV/n]



[10 GeV/n – 1 TeV/n]



Fit to the Spectra of Fe and Ni

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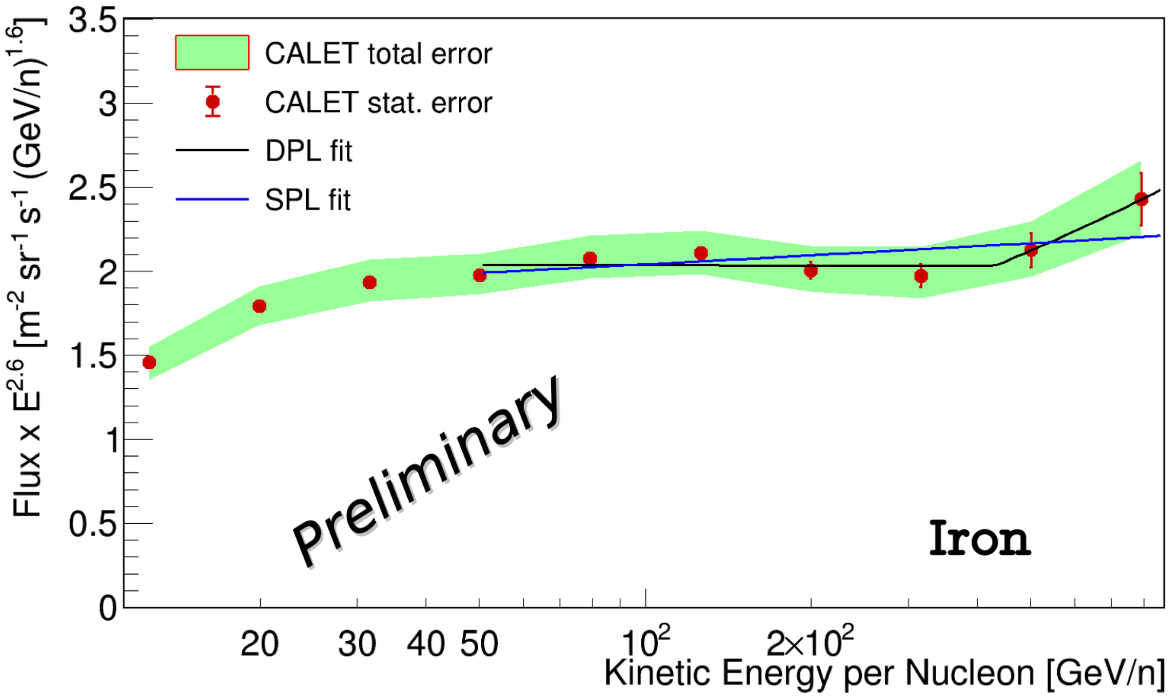

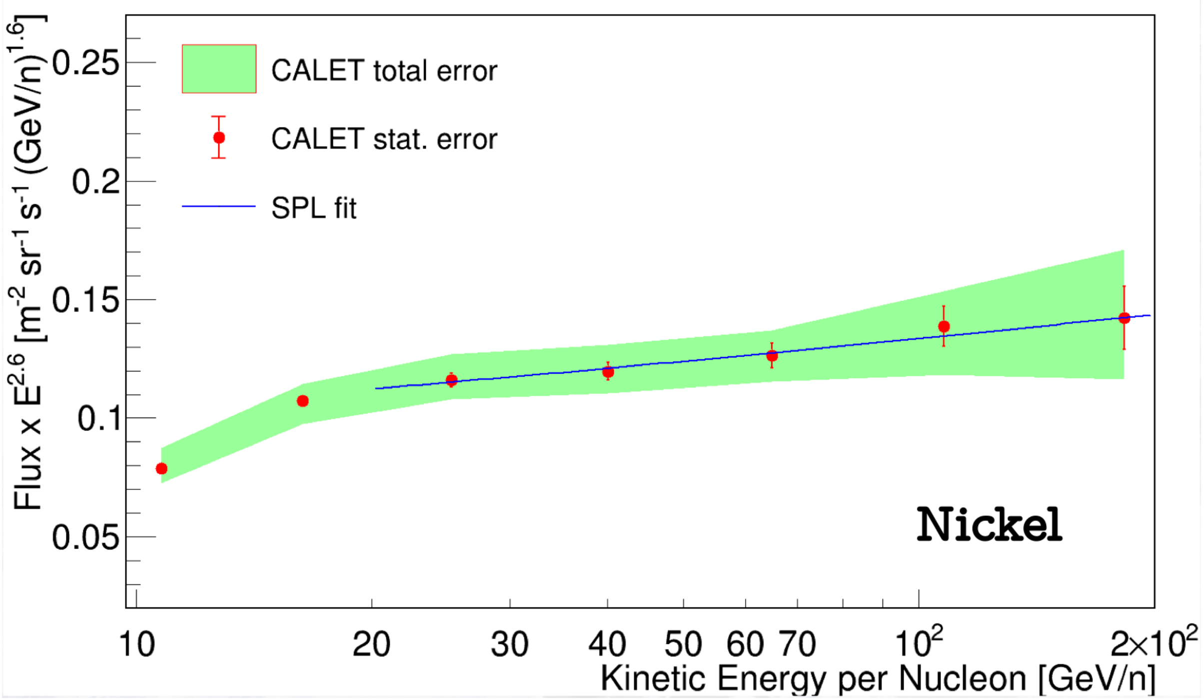

Fe (SPL)

$\gamma = -2.56 \pm 0.03$

$\chi^2/\mathrm{dof} = 2.7/5$

Fe (DPL)

$\gamma = -2.60 \pm 0.08$

$E_0 = (428 \pm 314)$ GeV/n

$\Delta\gamma = 0.29 \pm 0.27$

$\chi^2/\mathrm{dof} = 0.8/3$

Ni (SPL)

$\gamma = -2.49 \pm 0.08$

$\chi^2/\mathrm{dof} = 0.1/3$

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

- The significance of the fit with the DPL in the studied energy range for Fe is not sufficient to exclude the possibility of a single power law
- Ni flux is consistent with the hypothesis of an SPL spectrum in 20 – 240 GeV/n

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 Apr. 30, 2024, total observation time is 3123 days (> 8.5 years) with live time fraction close to 86%. Nearly 4.55 billion events collected with low energy trigger (> 1 GeV) and 2.07 billion events with high energy trigger (> 10 GeV).

☐ Accurate calibrations have been performed in the energy measurements established in 1 GeV-1PeV.

☐ Following results of the cosmic-ray spectra have been obtained by now.

- Measurement of electron + positron spectrum in 10 GeV- 7.5 TeV.
- Direct measurement of proton and Helium in 50 GeV ~ 60 and 250 TeV energy range, respectively and of Carbon and Oxygen spectra in 8.4 GeV/n -3.8 TeV/n: Spectral hardening was consistently observed around a few hundred GeV/n. B/C flux is precisely measured up to 3.8 TeV/n.
- Iron and Nickel spectra, and the ratios to light elements were measured to energies beyond those covered by previous experiments..

☐ Continuous observations of GRBs, Solar Modulation and REP events have being carried out.

☐ CALET observation has successfully been carried out over 8.5 years, and is extended to 2030 with the approval of JAXA.