Helium flux and its ratio to proton flux in cosmic rays measured with CALET on the International Space Station

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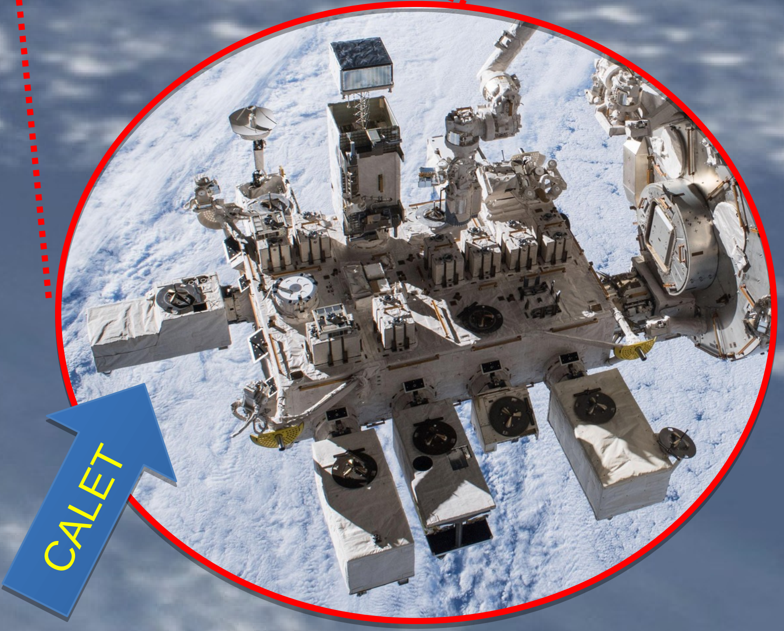
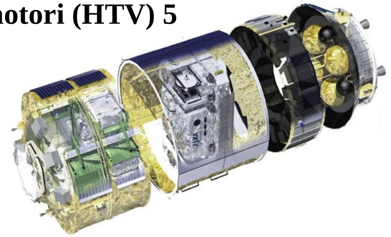
for the CALET collaboration

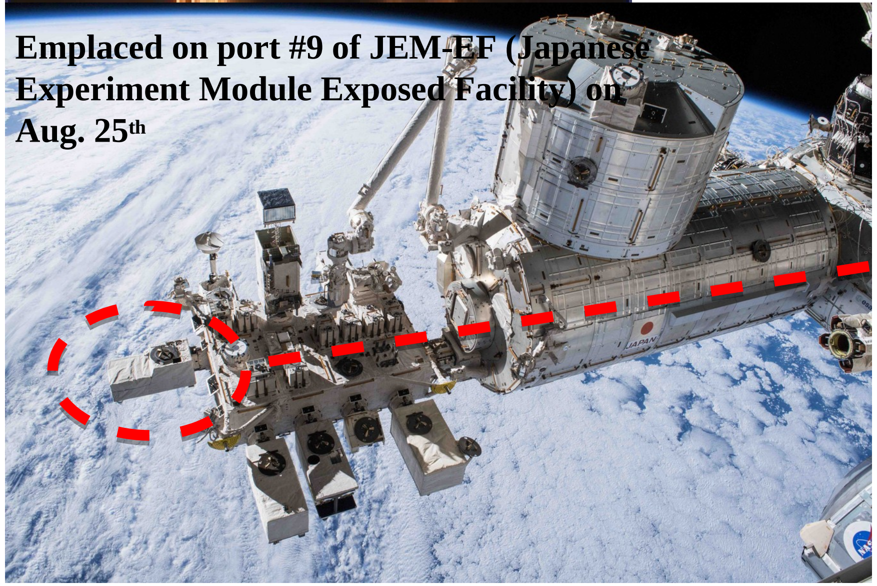


CALET payload

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

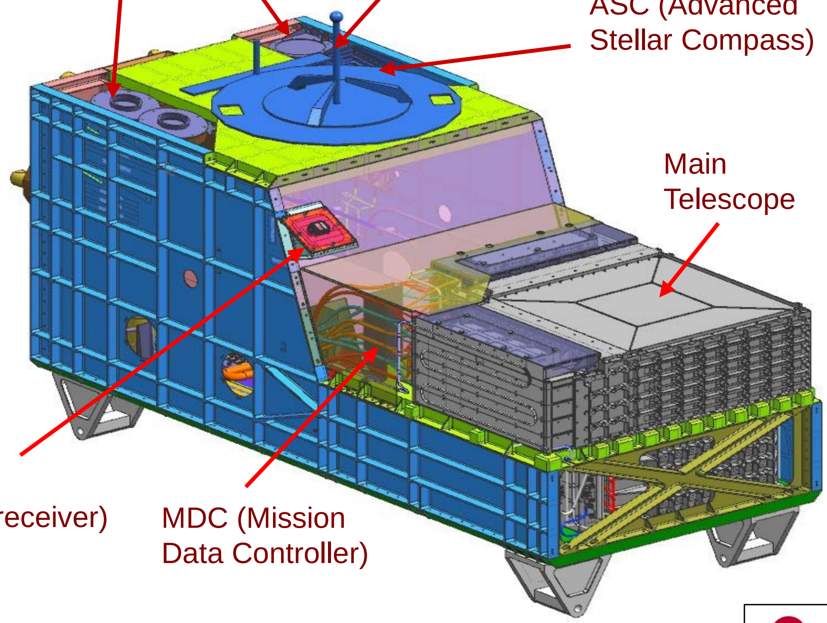
Kounotori (HTV) 5





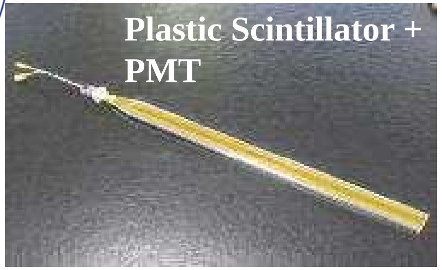
Emplaced on port #9 of JEM-EF (Japanese Experiment Module Exposed Facility) on Aug. 25th

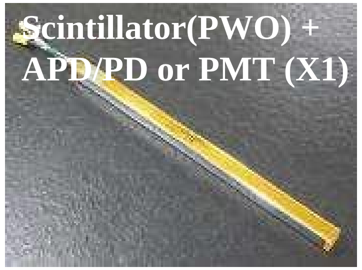
- Mass: 612.8 kg (JEM Standard Payload)
- Size: 1850mm (L) × 800mm (W) × 1000mm (H)
- Power: 507 W (max)
- Telemetry: Medium 600 kbps (6.5GB/day)

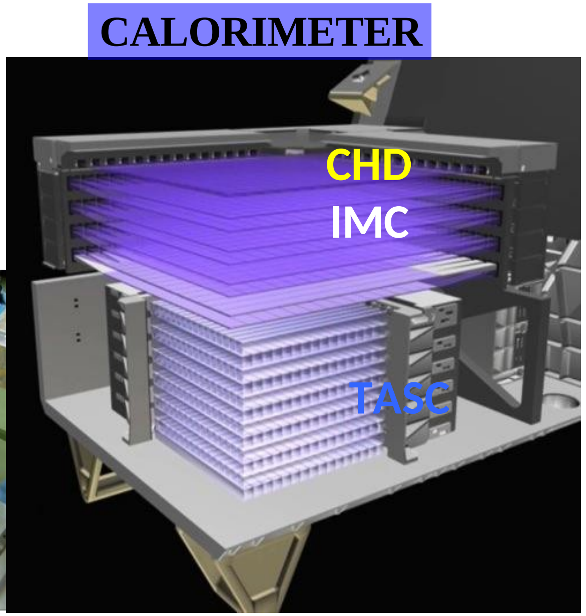


Continues stable observation since Oct. 13, 2015 and collected >3.6 billions (HET) events so far.

Detector overview







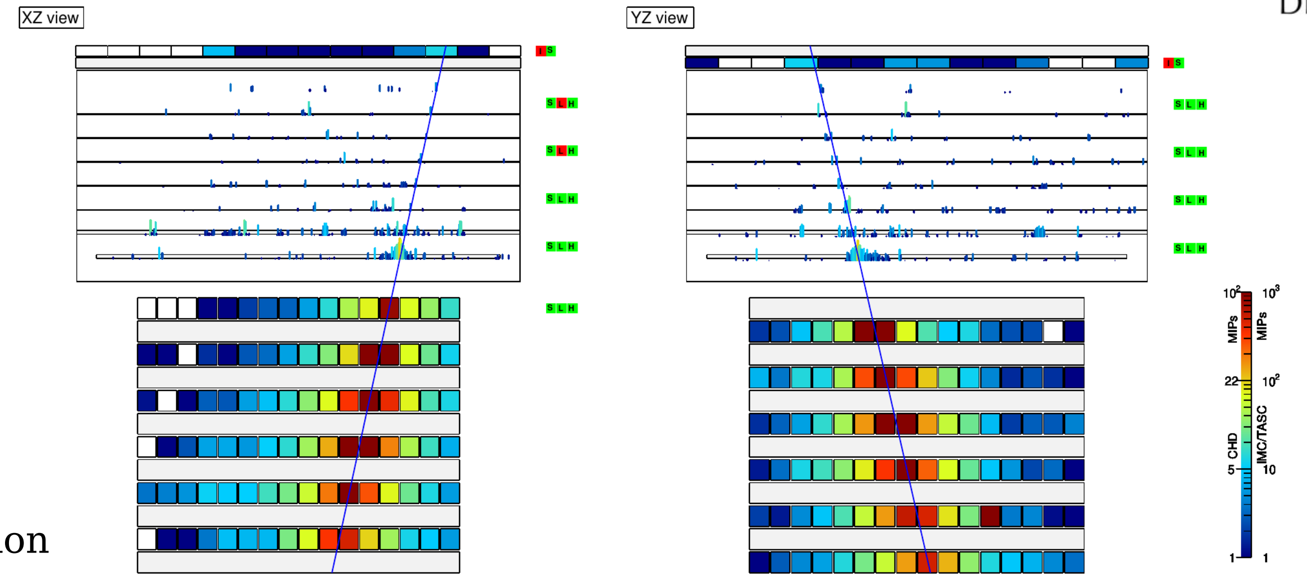
	CHD (Charge Detector)	IMC (Imaging Calorimeter)	TASC (Total Absorption Calorimeter)
Measure	Charge (Z=1-40)	Tracking , Particle ID	Energy, e/p Separation
Geometry (Material)	Plastic Scintillator 14 paddles x 2 layers (X,Y): 28 paddles Paddle Size: 32 x 10 x 450 mm³	448 Scifi x 16 layers (X,Y) : 7168 Scifi 7 W layers ($3X_0$): $0.2X_0$ x 5 + $1X_0$ x2 Scifi size : 1 x 1 x 448 mm³	16 PWO logs x 12 layers (x,y): 192 logs log size: 19 x 20 x 326 mm³ Total Thickness : 27 X_0 , ~1.2 λ_I
Readout	PMT+CSA	64-anode PMT+ ASIC	APD/PD+CSA PMT+CSA (for Trigger)@top layer

Selection of Helium candidate

Analyzed flight data:

- 2392 days (October 13, 2015 to April 30 2022)
- live time fraction ~84.4% of the accumulated observation time

Event display of a selected He candidate (~700 GeV TASC dep. en.)



Selection criteria:

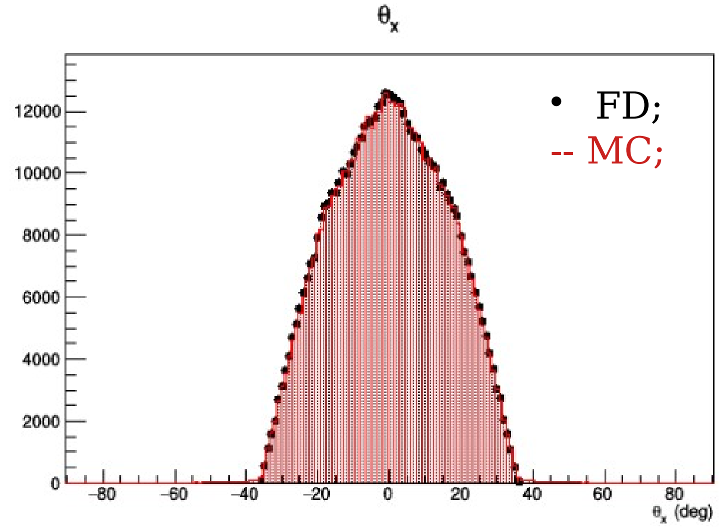
- HE shower trigger + off-line trigger confirmation
- IMC reconstructed track + track quality cut
- acceptance cut (events crossing CHD, TASC top layer within 2 cm from the edge and TASC bottom layer)
- off-acceptance rejection cuts (additional cuts to remove contamination from mis-reconstructed off-acceptance events)
- charge ID (identification of the primary particle through the dE/dx measurements in CHD and along the IMC track)

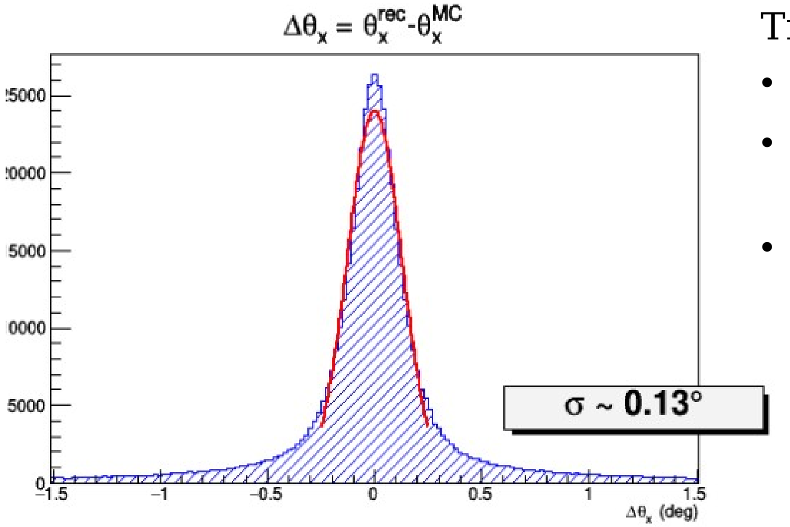
MC simulation:

- Two detailed MC simulations of the instrument were developed based on Fluka and Epics (w/ DPMJET-III).
- Digitization of signals and trigger were modelled accurately in simulation and tuned using beam test results and flight data.
- MC is used to estimate: tracking and selection efficiencies; the energy response (“smearing”) matrix.

Tracking performance

Robust track finding, through combinatorial Kalman Filter algorithm, that exploits the IMC fine granularity and imaging capability.



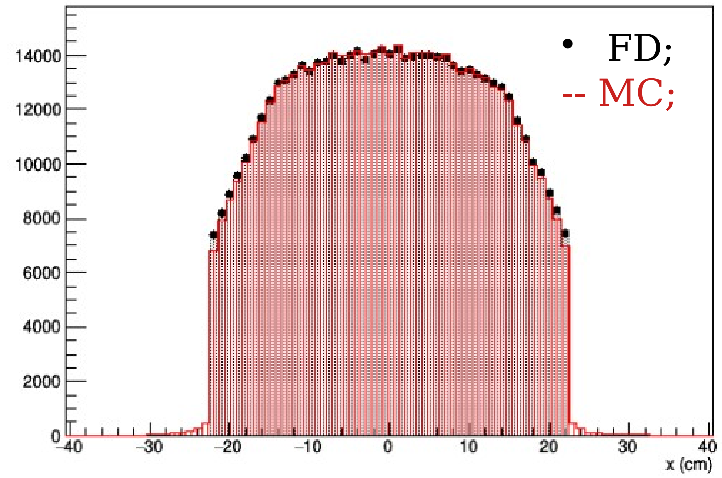


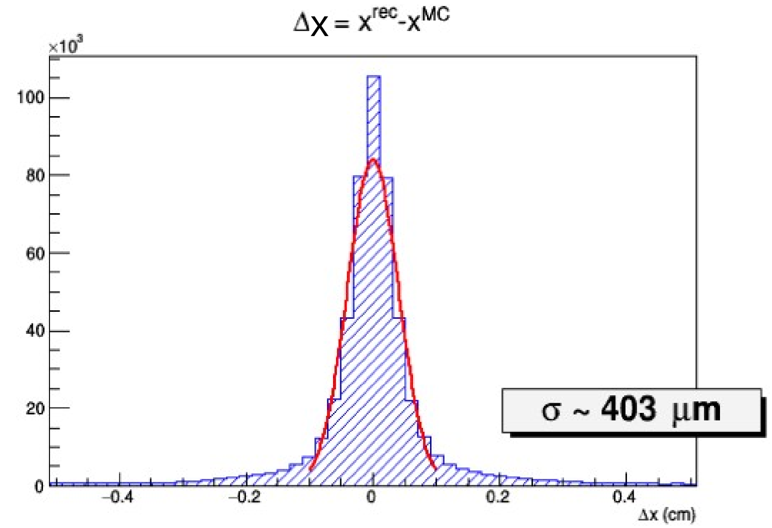
Tracking provides:

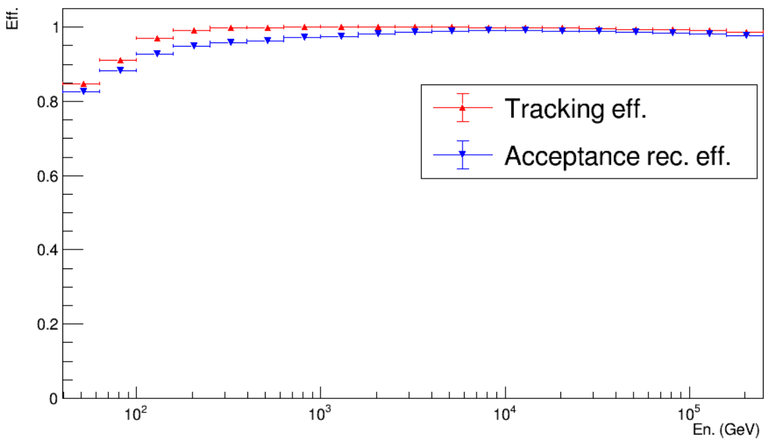
- CR arrival direction
- the geometrical acceptance of reconstructed events
- the CHD paddles and IMC scifi's crossed by CR particle (for particle ID)

- Angular resolution: ~0.13°
- IP resolution on CHD: ~400 μm

Impact Point on CHD x





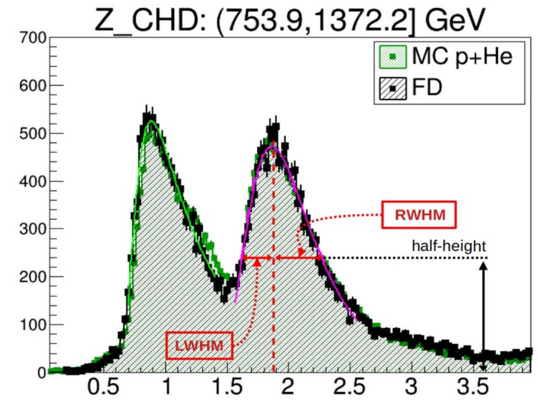


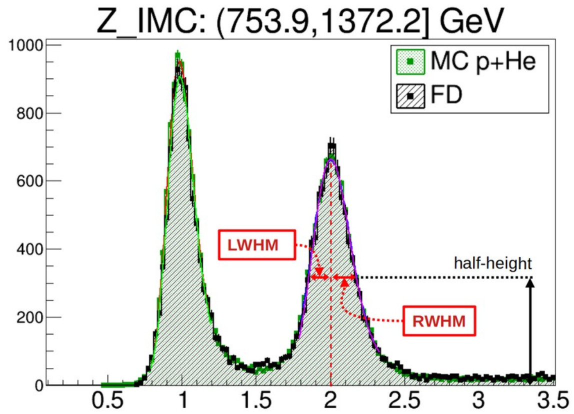
Charge identification of Nuclei

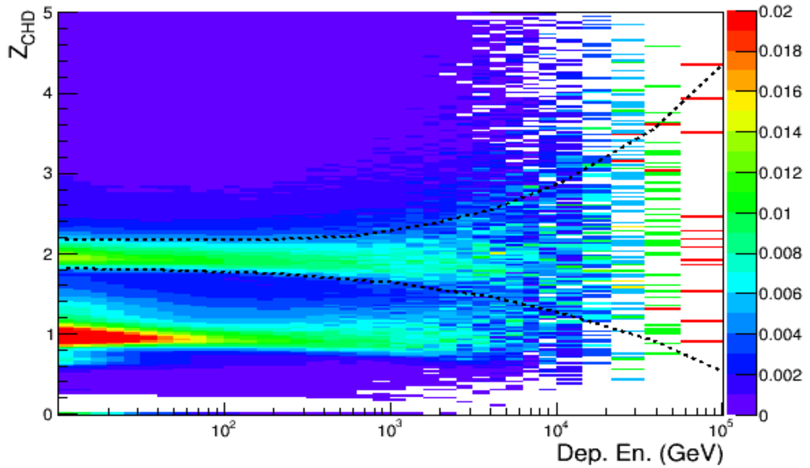
Single element selection for He nuclei is achieved by CHD + IMC charge analysis.

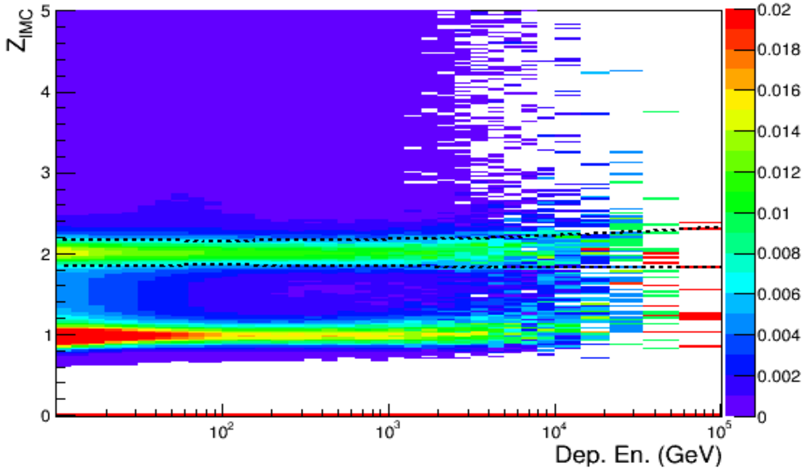
Deviation from Z^2 response is corrected both in CHD and IMC using a “Voltz” ionization model.

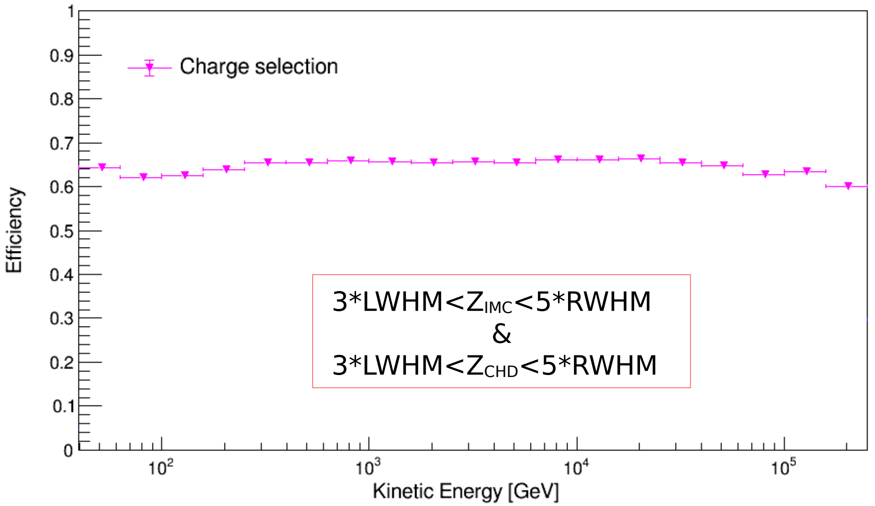
Almost flat helium selection efficiency is achieved via an energy dependent cut, that follows the energy dependence of the peak position and the asymmetric (Left and Right) Width at Half Maximum of the charge distributions.







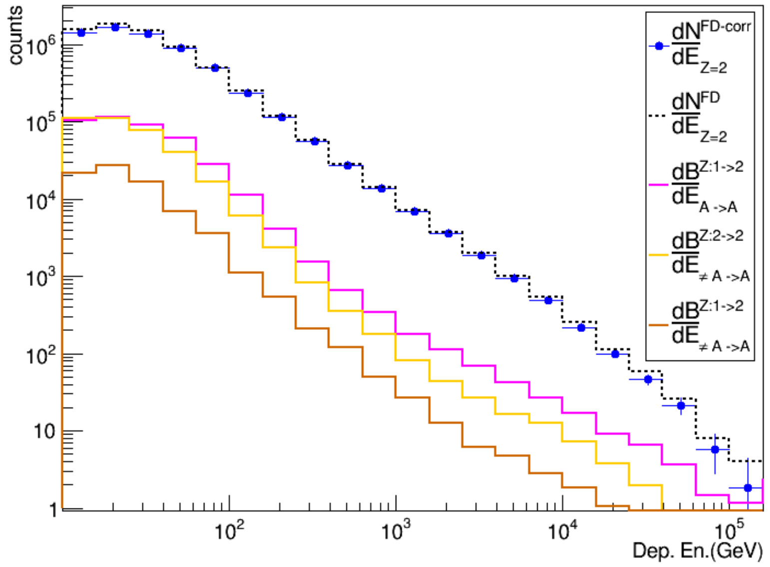


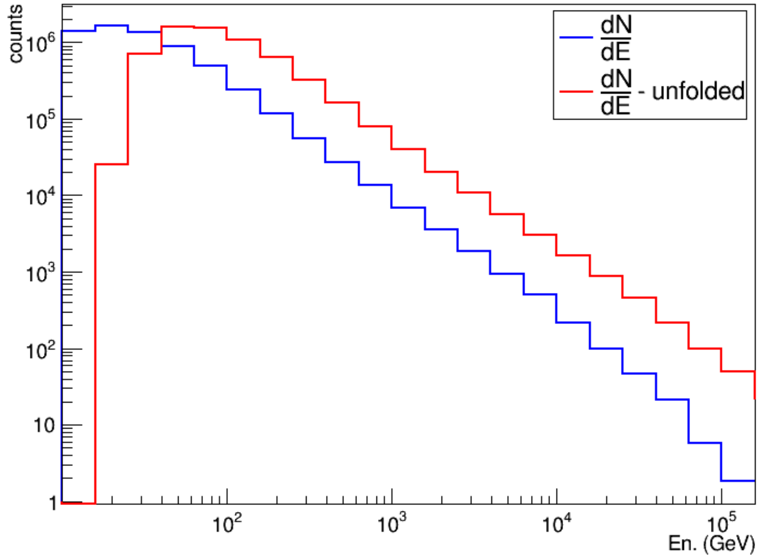


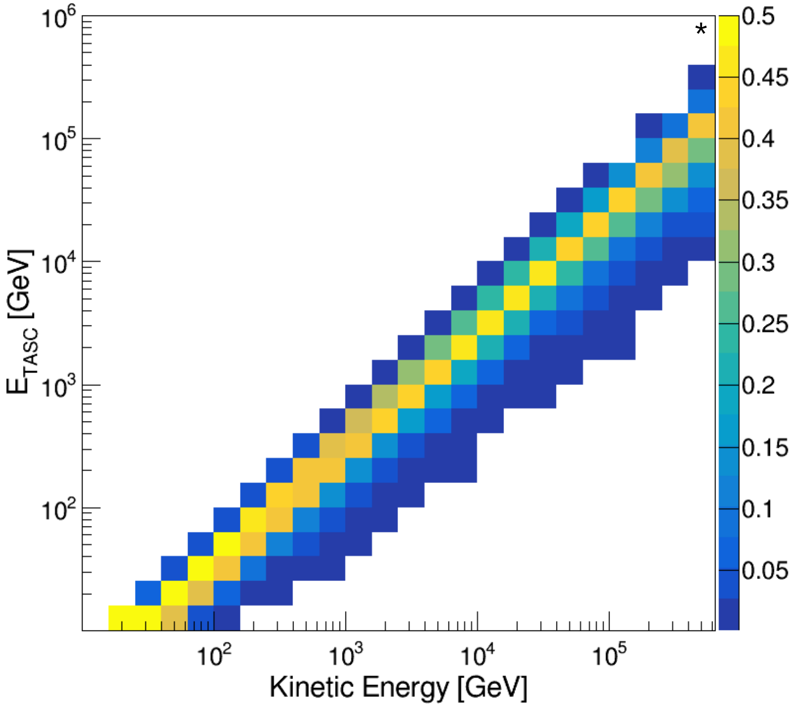
Background Estimation and Unfolding

The main background in the He selected sample (dN/dE) is charge contamination from misidentified protons, followed by off-acceptance contamination from mis-reconstructed protons and helium events.

The number of contaminating events (dB/dE) is estimated using both MC (to evaluate the background ratio) and the FD (to evaluate the helium and proton abundances) and then subtracted.





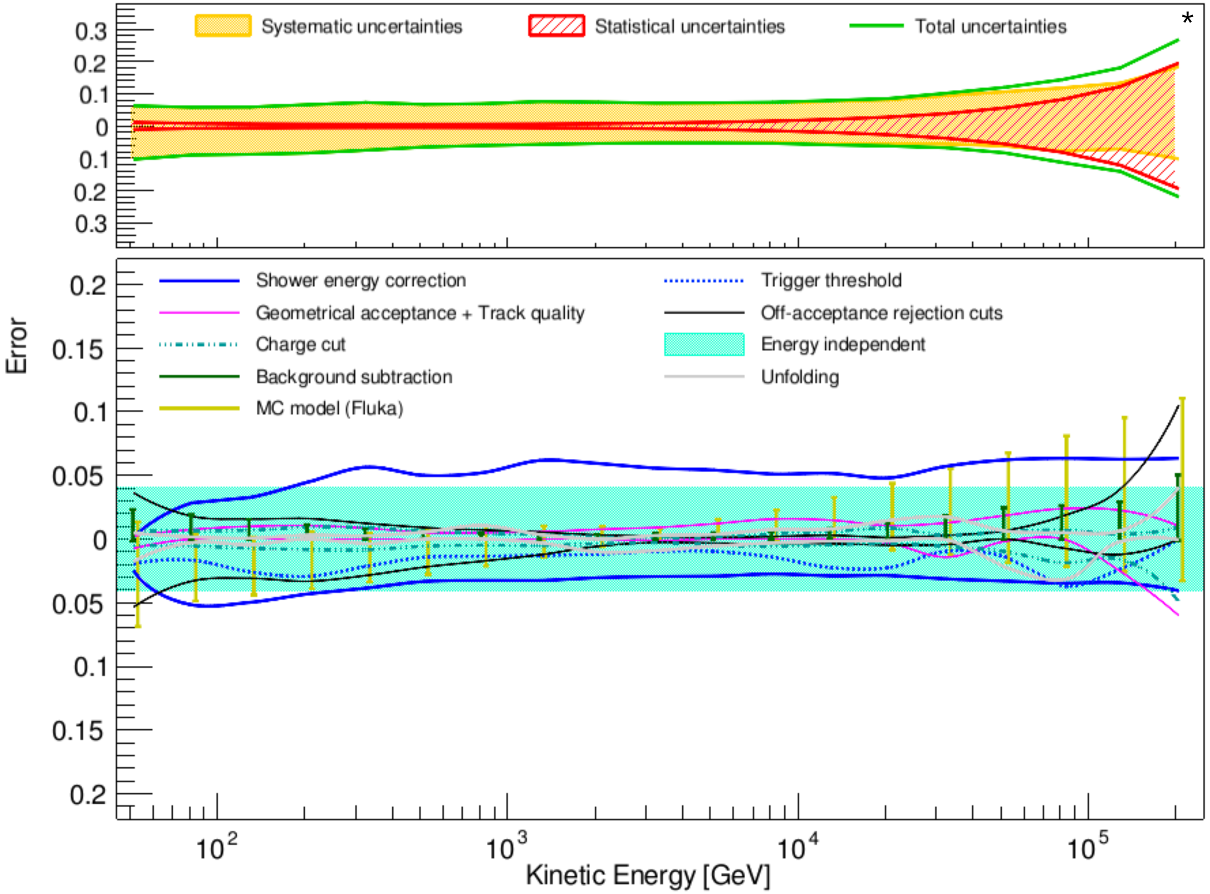


- The smearing matrix is computed using Epics MC.
- The unfolding is performed by an iterative method based on the Bayes theorem.
- Energy bins are commensurate with RMS resolution of TASC (~30% for nuclei).

**Supplemental Material of O. Adriani et al., Phys. Rev. Lett. 130, 101102 (2022)*

Evaluation of systematic

Breakdown of systematic uncertainties.



Energy dependent:

- shower energy correction (Beam test calibration)
- off-acceptance rejection cuts
- charge cut
- unfolding
- background subtraction
- tracking
- trigger
- MC model (Fluka)

Energy independent:

- live time
- long term stability
- radiation environment

**Supplemental Material of O. Adriani et al., Phys. Rev. Lett. 130, 101102 (2022)*

Helium Flux Measurement

CALET results in the energy range from ~40 GeV to ~250 TeV.

Flux measurement:

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

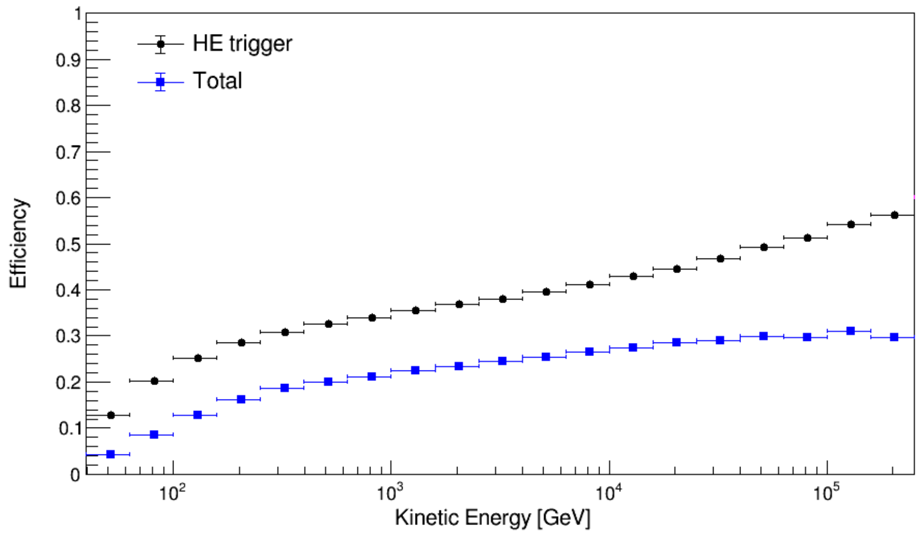
$N(E)$: events in unfolded energy bin

$S\Omega$: geometrical acceptance (510 cm^{2}sr)

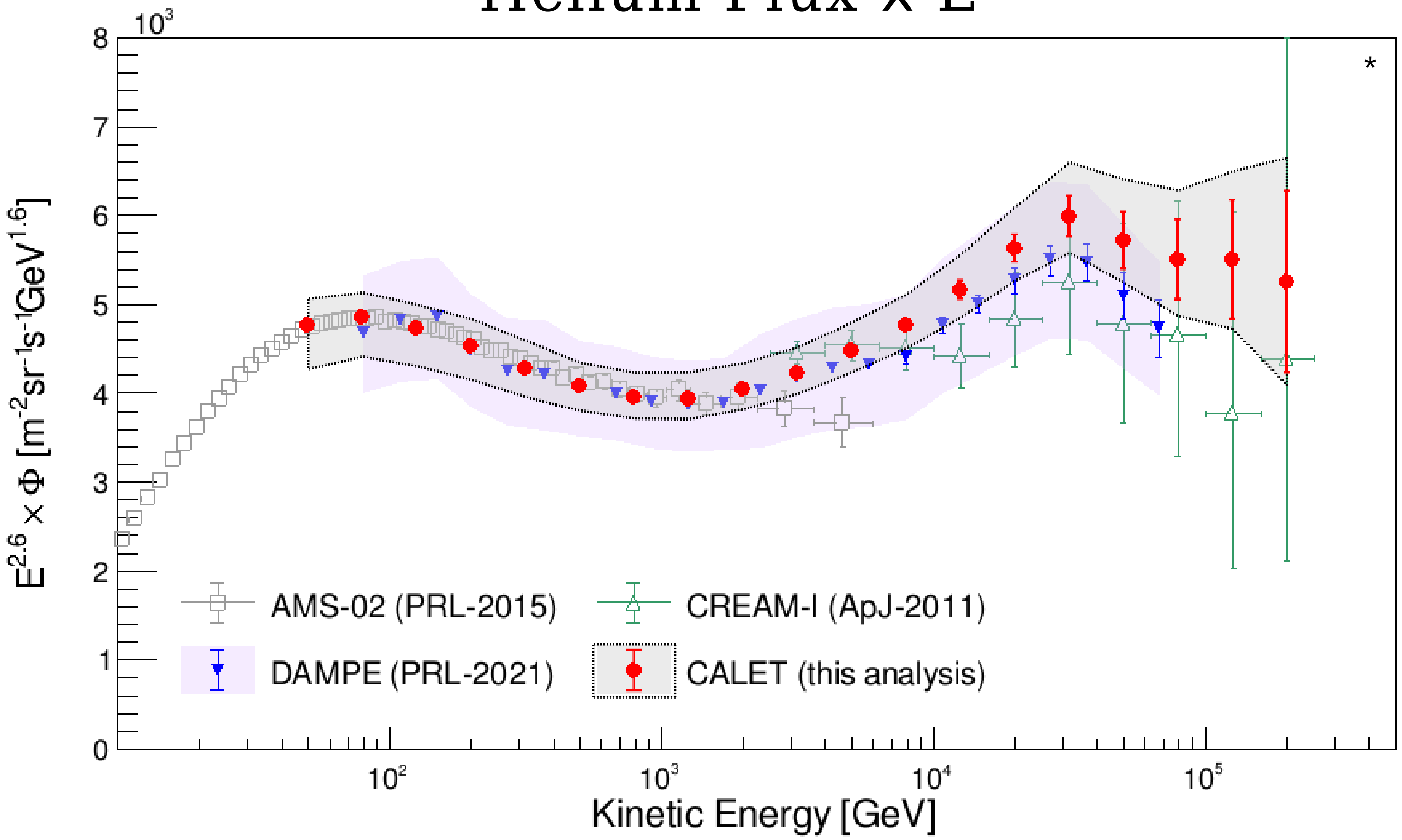
$\varepsilon(E)$: efficiency

T: live Time

ΔE: energy bin width



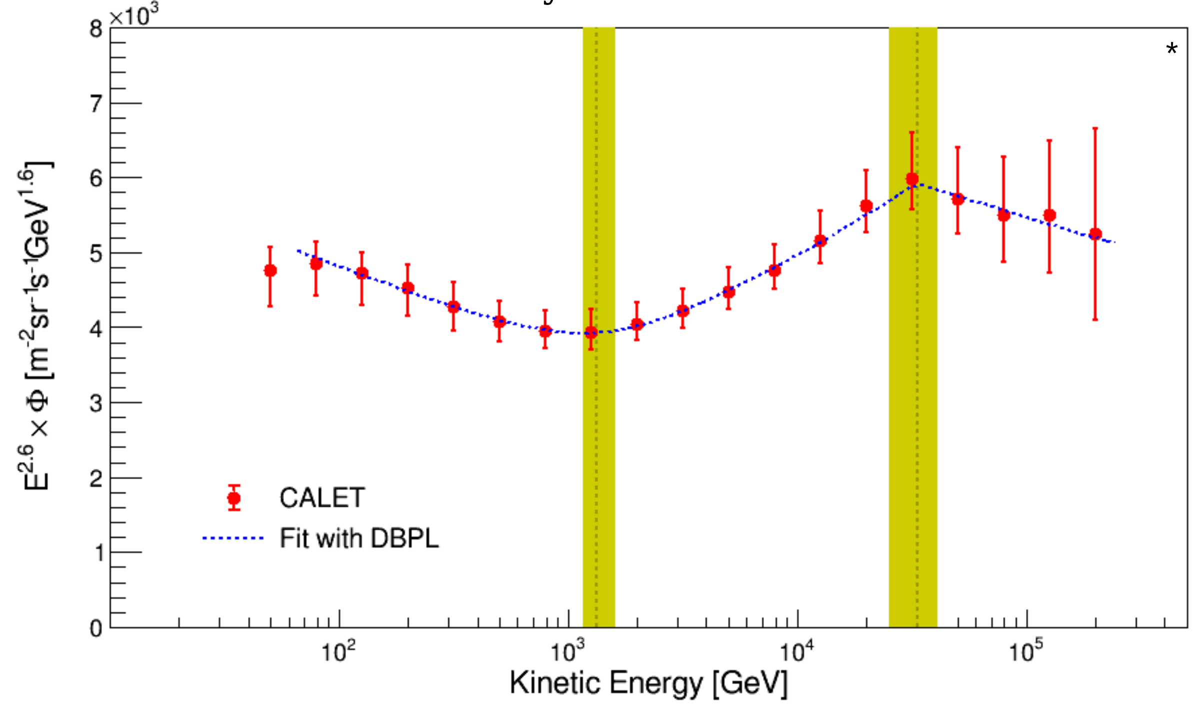
Helium Flux x $E^{2.6}$



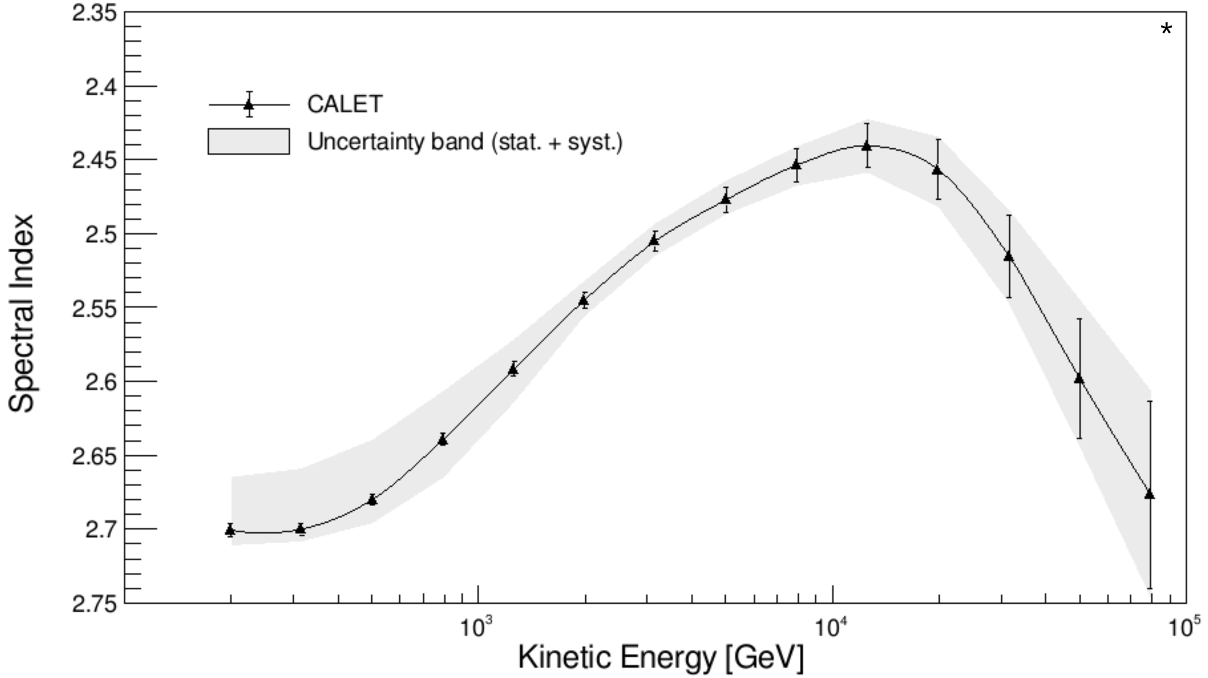
*O. Adriani et al., Phys. Rev. Lett. 130, 101102 (2022)

Spectral Behavior of Helium Flux

"Double Smoothly Broken Power-law fit"



Spectral index (5 bins wide sliding windows)



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

$\gamma=-2.703^{+0.005}_{-0.006}(stat)^{+0.032}_{-0.009}(syst)$; $\Delta\gamma=-0.25^{+0.02}_{-0.01}(stat)^{+0.02}_{-0.03}(syst)$;
$E_0=1319^{+113}_{-93}(stat)^{+267}_{-124}(syst)\,GeV$; $S=2.7^{+0.6}_{-0.5}(stat)^{+3.0}_{-0.9}(syst)$;
$\Delta\gamma_1=-0.22^{+0.07}_{-0.10}(stat)^{+0.03}_{-0.04}(syst)$; $E_1=33.2^{+9.8}_{-6.2}(stat)^{+1.8}_{-2.3}(syst)\,TeV$;

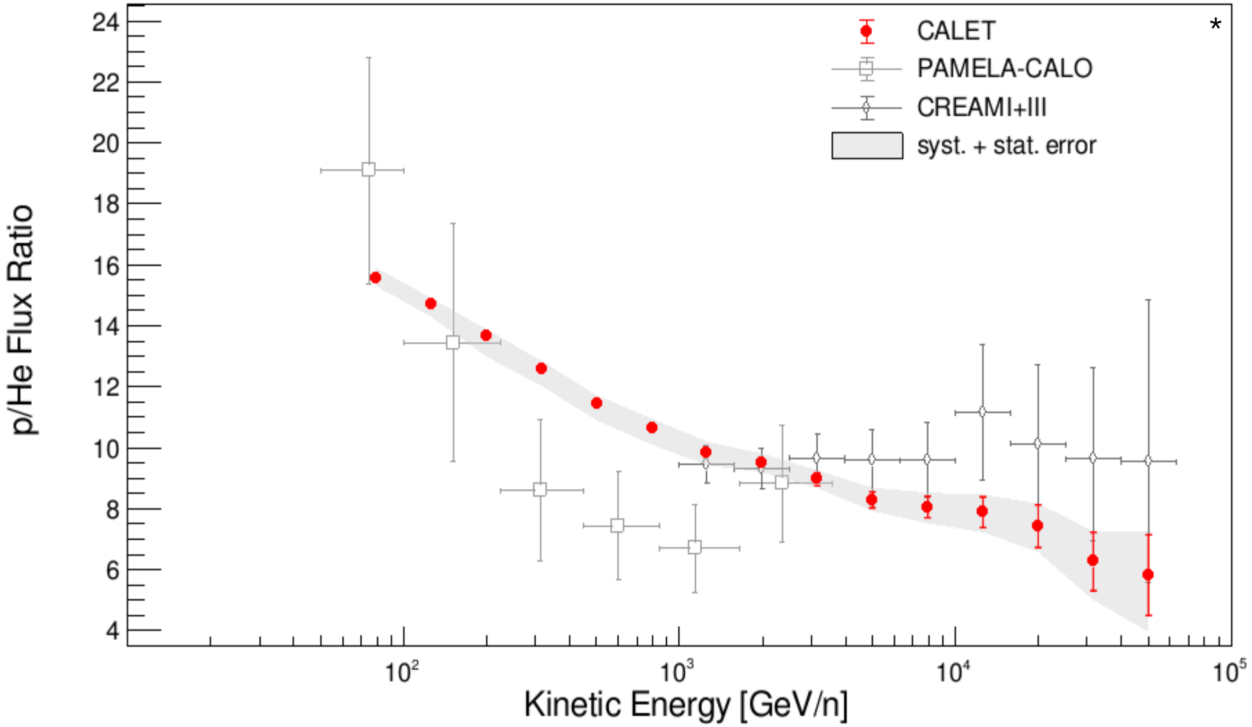
The spectral hardening and softening can be easily seen in the figure above where the spectral index is shown as a function of the particle kinetic energy.

*O. Adriani et al., Phys. Rev. Lett. 130, 101102 (2022)

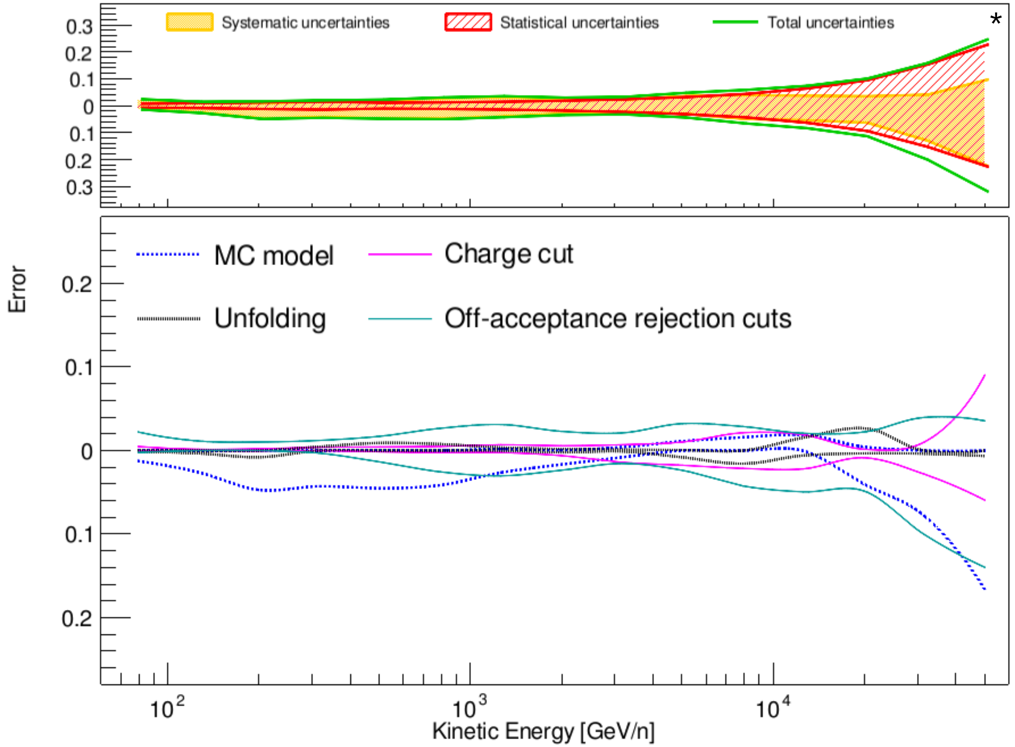
Proton over Helium ratio

Using the CALET proton flux from *"O. Adriani et al., Phys. Rev. Lett. 129, 101102 (2022)"*, the p/He flux ratio has been measured in a wide energy range from 60 GeV/n to ~60 TeV/n.
The ^{3}He contribution to the flux is taken into account assuming the same ^{3}He/^{4}He ratio as measured by spectrometers** and extrapolating it to higher energies with the use of a single power-law fit.

p/He ratio



Breakdown of systematic uncertainties.



*O. Adriani et al., Phys. Rev. Lett. 130, 101102 (2022) and its Supplemental Material

** M. Aguilar et al., Phys. Rev. Lett. 123, 181102 (2019)

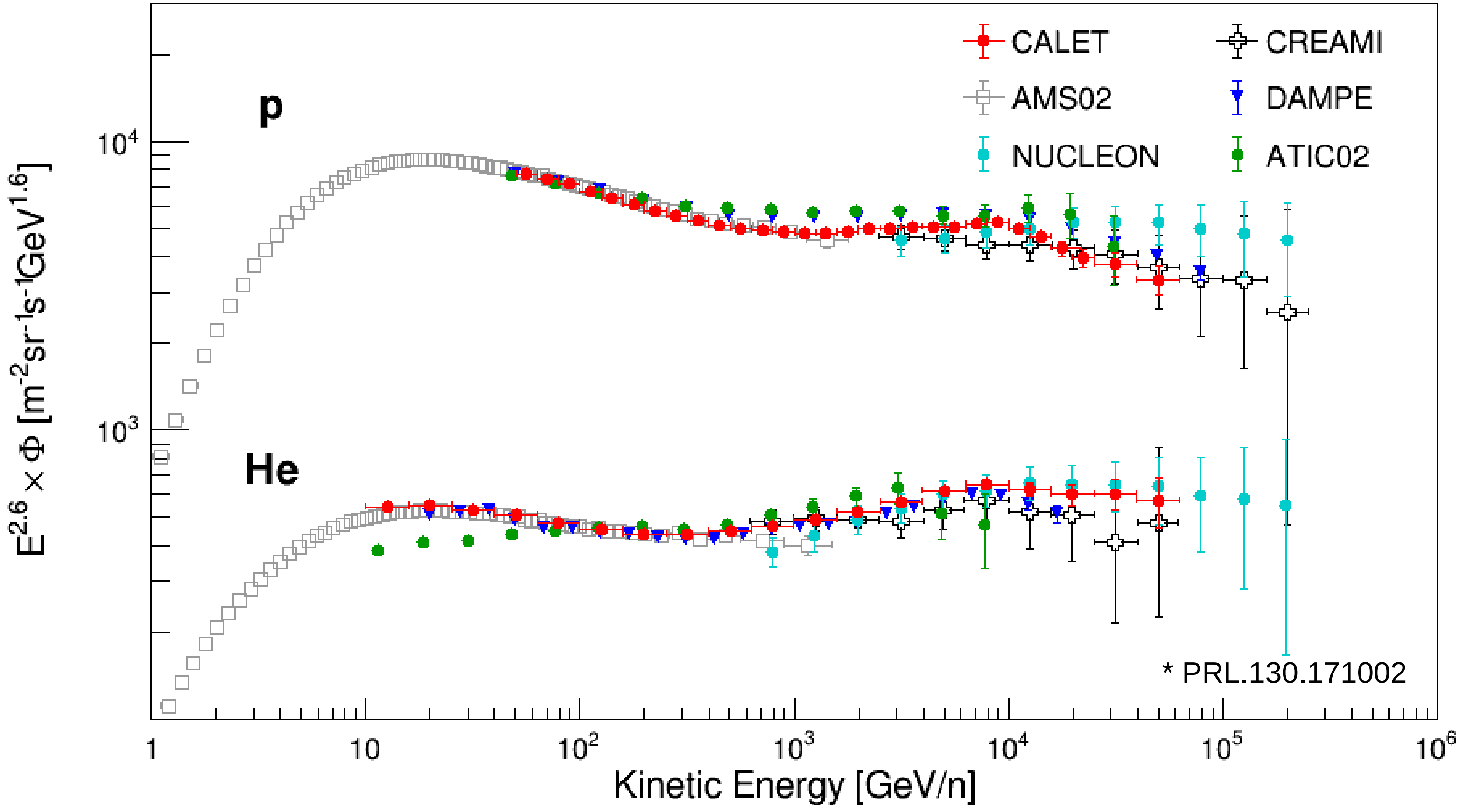
Conclusions

- CALET measured light nuclei in CRs from few tens of GeV up to tens of TeV.
- Excellent performances and remarkable stability of the instrument have been achieved.
- The measurement of He flux has been carried out up to 250 TeV of particle energy with ~6.6 years of data and recently published in "*O. Adriani et al., Physical Review Letters 130, 171002 (2023)*".
- This result confirms the presence of a hardening above a few hundred GeV (at > 8σ level) and the onset of a flux softening above a few tens TeV.
- A double smoothly broken power law fits both spectral features with parameters that are found to be consistent, within the errors, with the most recent results of DAMPE.
- The proton over helium ratio has been measured with high precision from ~60 GeV/n to ~60 TeV/n, extending the energy reach of previous measurements with magnetic spectrometers by more than one order of magnitude.
- ^{3}He contribution to the ratio has been taken into account.
- Independent analyses were carried out using different event selection and background rejection procedures, results are consistent within the errors.
- Further studies to increase statistics at high energies and possibly reduce the systematic uncertainty are ongoing.

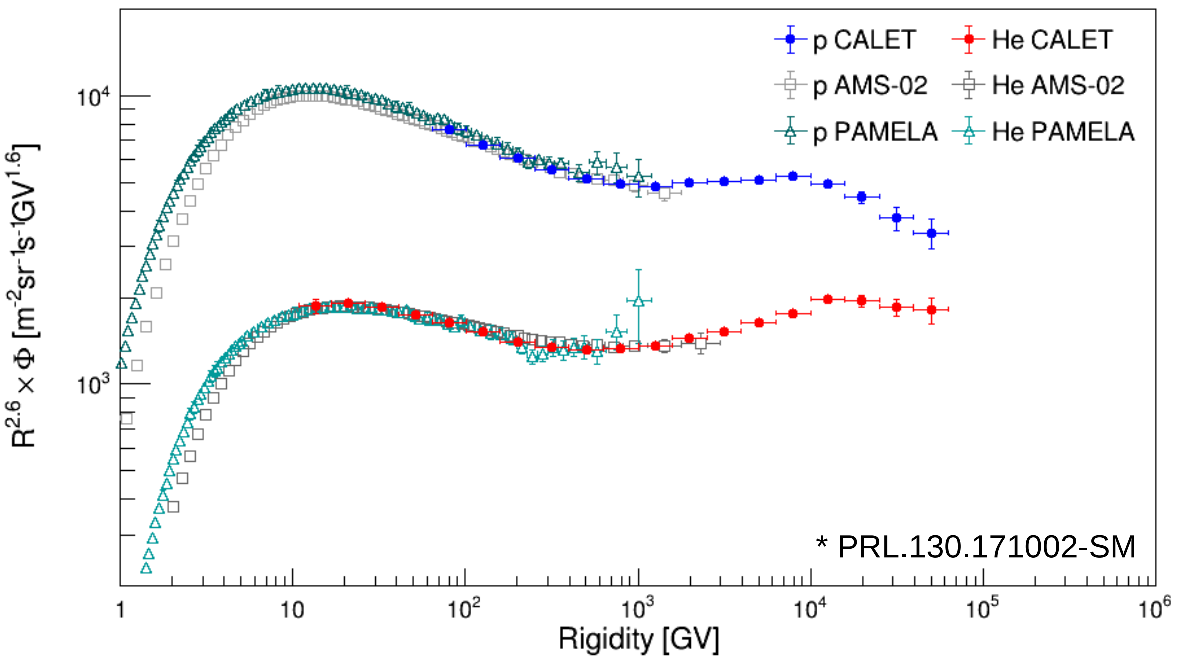
Thanks for your attention!

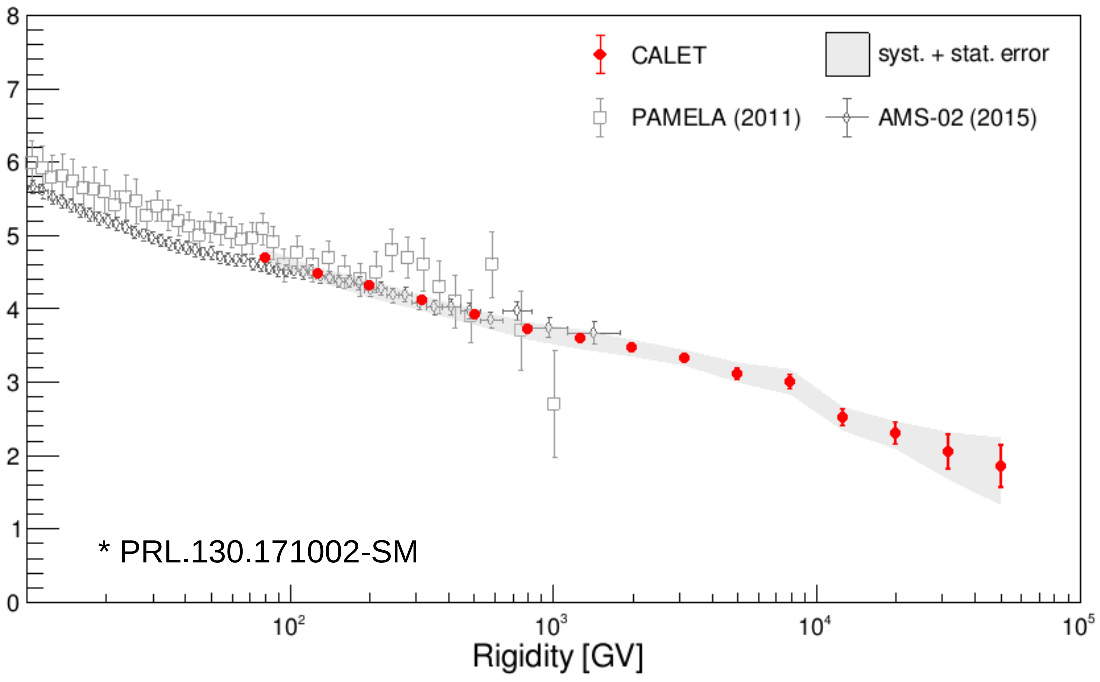
BACKUP

Proton and Helium [Kinetic energy per nucleon]



Proton over Helium ratio [rigidity]





The CALET Collaboration Team

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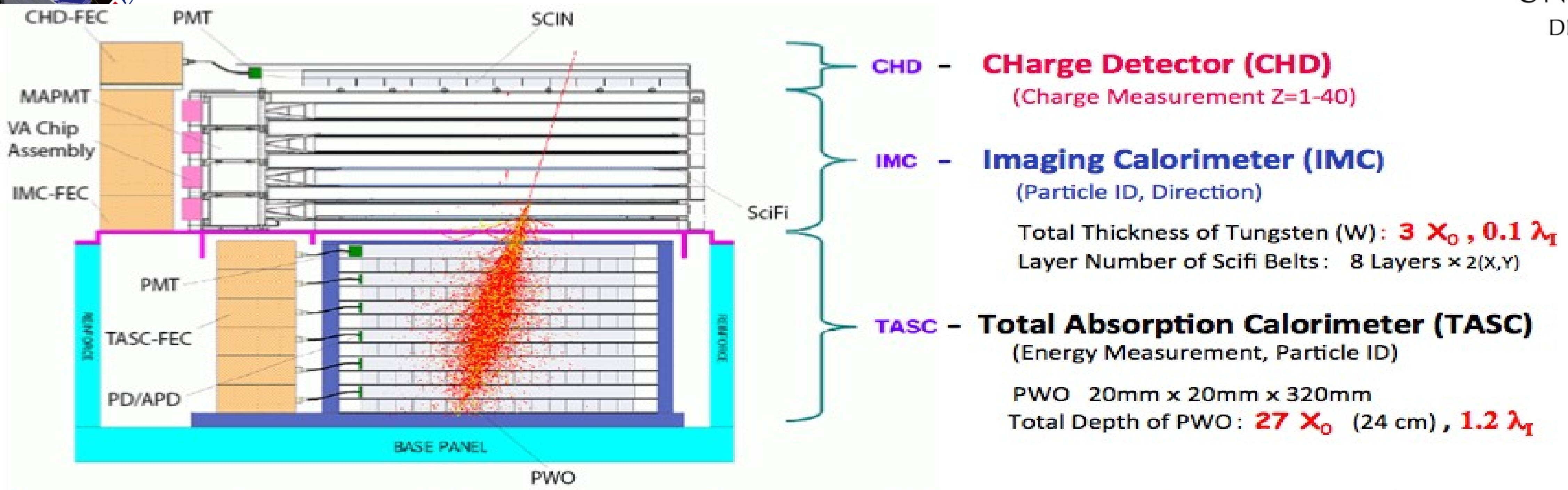
Instrument overview

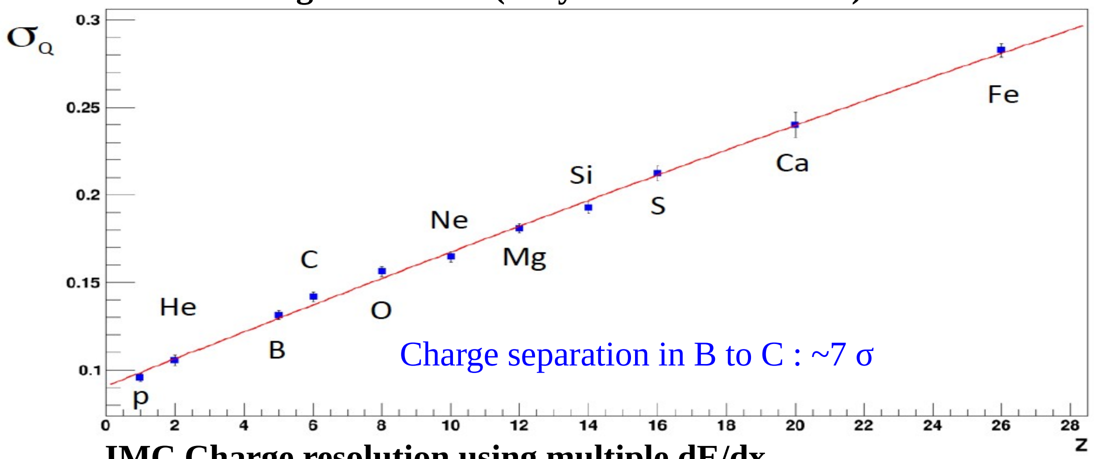


	CHD (Charge Detector)	IMC (Imaging Calorimeter)	TASC (Total Absorption Calorimeter)
Function	Charge Measurement (Z = 1 - 40)	Arrival Direction, Particle ID	Energy Measurement, Particle ID
Sensor (+ Absorber)	Plastic Scintillator : 2 layers Unit Size: 32mm x 10mm x 450mm	SciFi : 16 layers Unit size: $1mm^2$ x 448 mm Total thickness of Tungsten: $3\ X_0$	PWO log: 12 layers Unit size: 19mm x 20mm x 326mm Total Thickness of PWO: $27\ X_0$
Readout	PMT+CSA	64 -anode PMT+ ASIC	APD/PD+CSA PMT+CSA (for Trigger)

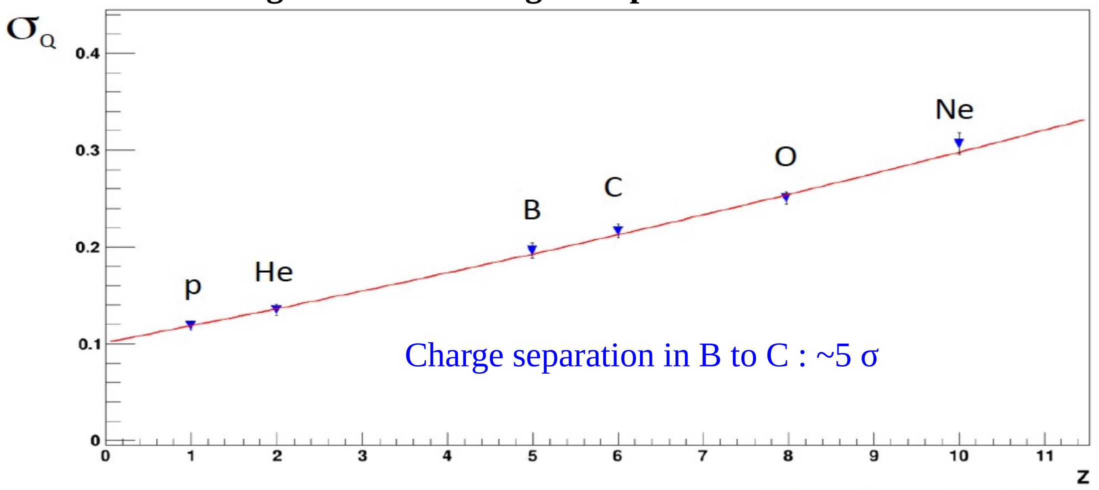
Charge identification of Nuclei

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

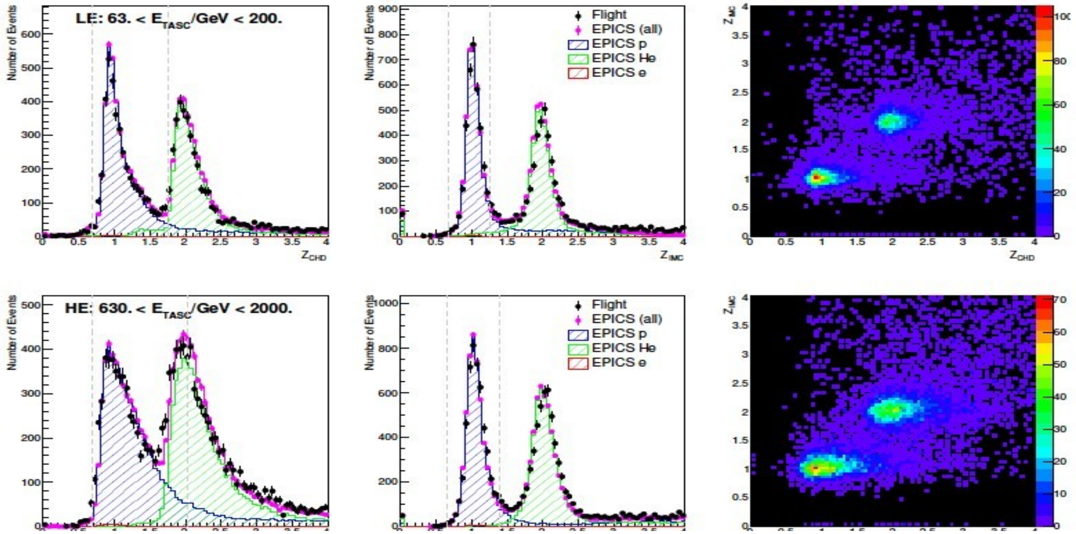
CHD charge resolution (2 layers combined vs. Z)



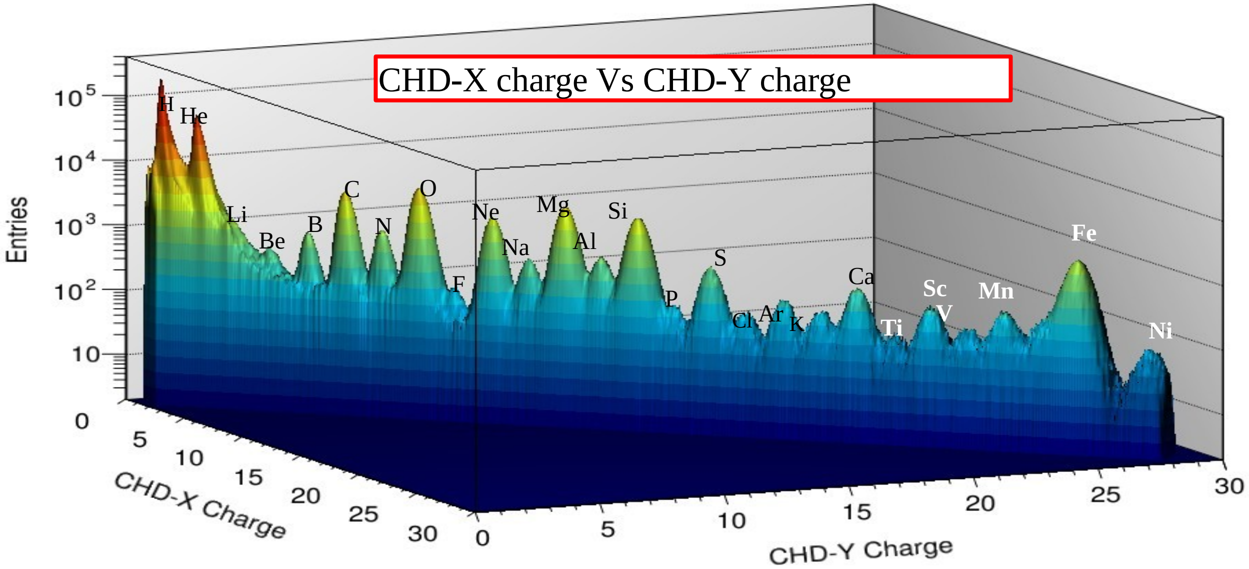
IMC Charge resolution using multiple dE/dx.



Combined CHD-IMC proton-Helium charge-ID



CHD-X charge Vs CHD-Y charge



Deviation from Z^2 response is corrected both in CHD and IMC using a core + halo ionization model (Voltz)

CALET overview

Overview of detector performances:

Geometric Factor :
1200 $cm^2 sr$ for electrons, light nuclei
1000 $cm^2 sr$ for gamma-rays
4000 $cm^2 sr$ for ultra-heavy nuclei

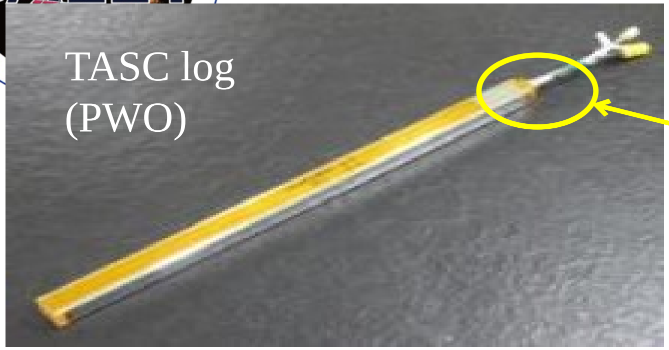
- **$\Delta E/E$:**
  ~2% (>10 GeV) for e, gamma
  ~30-35 % for protons, nuclei
- **e/p separation :** 10^{-5}
- **Charge resolution :** 0.15 - 0.3 e
- **Angular resolution :**
  0.2° for gamma-rays > ~50 GeV

Main CALET science objectives:

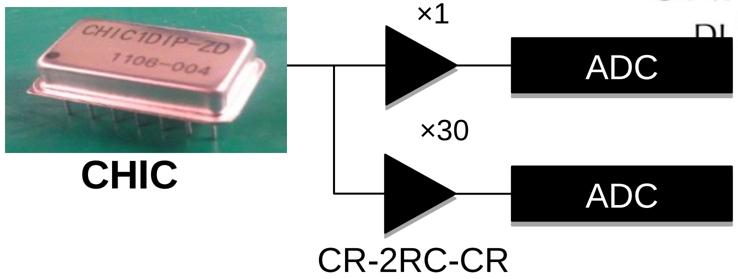
- Electron observation in the 1 GeV - 20 TeV energy range. Design optimized for electron detection: high energy resolution and large e/p separation power + e.m. shower containment.
  - Search for Dark Matter and Nearby Sources
- Observation of cosmic-ray nuclei in the 10 GeV - 1 PeV energy range.
  - Unraveling the CR acceleration and propagation mechanism(s)
- Detection of transient phenomena in space Gamma-ray bursts, e.m. GW counterparts, Solar flares, Space Weather

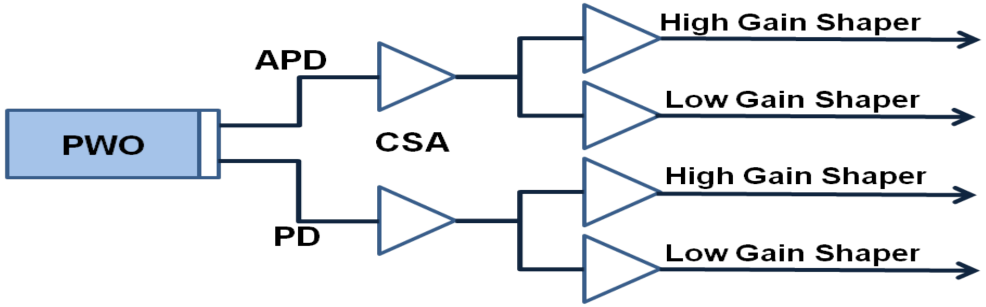
Scientific Objectives	Observation Targets	Energy Range
CR Origin and Acceleration	Electron spectrum Individual spectra of elements from proton to Fe Ultra Heavy Ions (26 < Z ≤ 40) Gamma-rays (Diffuse + Point sources)	1GeV - 20 TeV 10 GeV - 1000 TeV > 600 MeV/n 1 GeV - 1 TeV
Galactic CR Propagation	B/C 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-ray spectra	100 GeV - 20 TeV
Solar Physics	Electron flux (1GeV-10GeV)	< 10 GeV
Gamma-ray Transients	Gamma-rays and X-rays	7 keV - 20 MeV

Energy measurement: in a wide dynamic range of 1-10^6 MIPs



APD gain ～50



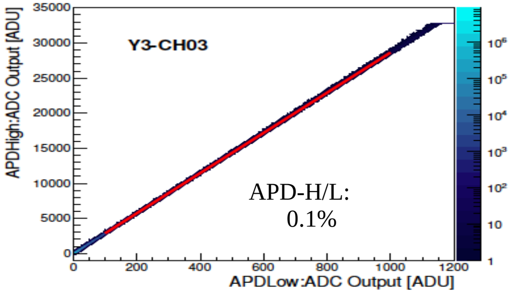


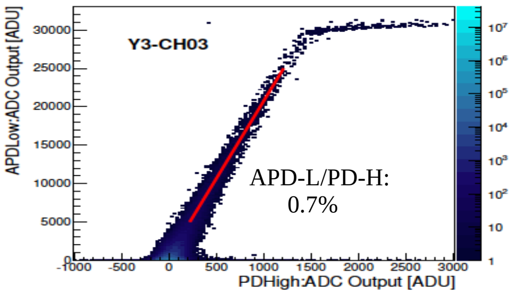
The whole dynamic range was calibrated by UV laser irradiation on ground :

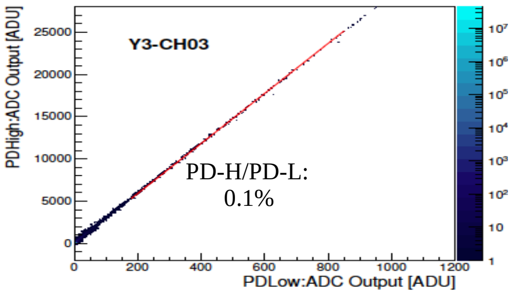
1) The linearity is confirmed in the range of 1.4-2.5 %.

2) The whole dynamic range is confirmed to cover from 1 MIP to 10^6 MIPs.

The correlation between adjacent gain ranges is calibrated by using in-flight data in each channel.







Example of energy distribution in one PWO log