# Ultra-Heavy Cosmic Ray Analysis with CALET on the International Space Station: Established and Developing Procedures

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## The CALorimetric Electron Telescope (CALET)[1]

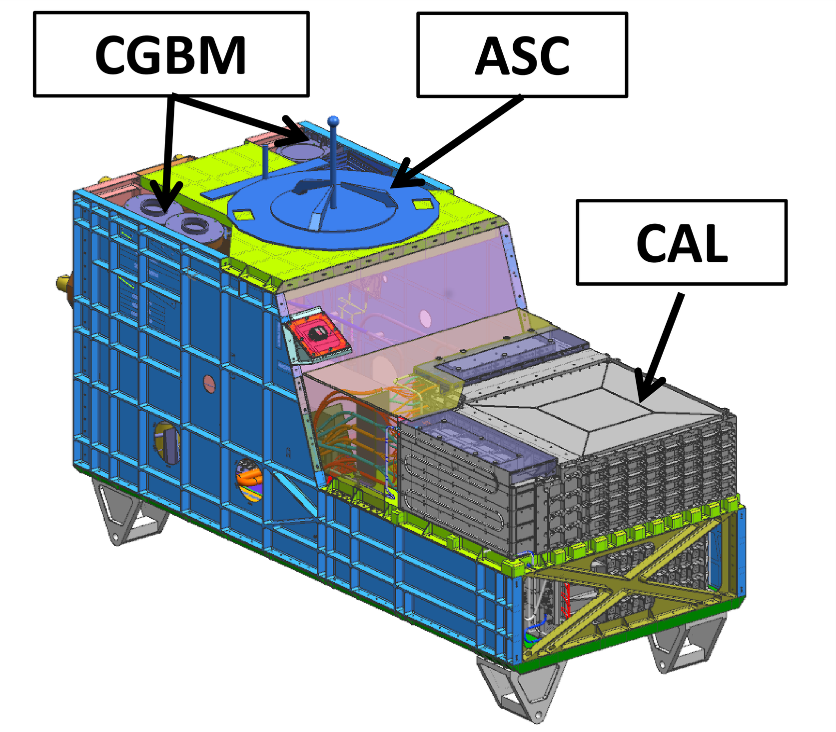


***Figure 1:*** CALET structure indicating the CALET Gamma-ray Burst Monitor (CGBM), Advanced Stellar Compass (ASC), and CALET Calorimeter (CAL).

| | | |
|---|---|---|
| **CHD** | • Plastic scintillating paddles<br>• 14 paddles x 2 layers (X, Y) = 28 paddles<br>• Each paddle: 32 x 10 x 450 mm$^3$ | Charge Measurement |
| **IMC** | • Plastic scintillating fibers & tungsten plates<br>• 448 fibers x 16 layers (8X, 8Y) = 7168 fibers<br>• Each fiber: 1 x 1 x 448 mm$^3$<br>• 7 W layers: (5 x 0.2 $X_0$) + (2 x 1 $X_0$) = 3 $X_0$ | Particle Tracking |
| **TASC** | • Lead tungstate ($PbWO_4$; PWO) logs<br>• 16 logs x 12 layers (6X, 6Y) = 192 logs<br>• Each log: 19 x 20 x 326 mm$^3$<br>• Total thickness: 27 $X_0$, ~1.2 $\lambda_I$ | Energy reconstruction |

## CALET Ultra-Heavy Analysis Dataset

- CALET uses dedicated UH trigger[2] which only requires events pass through CHD and top of IMC
- FOV increased from ~45 to ~75 degrees, increasing geometric factor to ~4000 cm$^2$ sr
- 1.8 x 10$^8$ UH events collected between October 2015 and September 2020

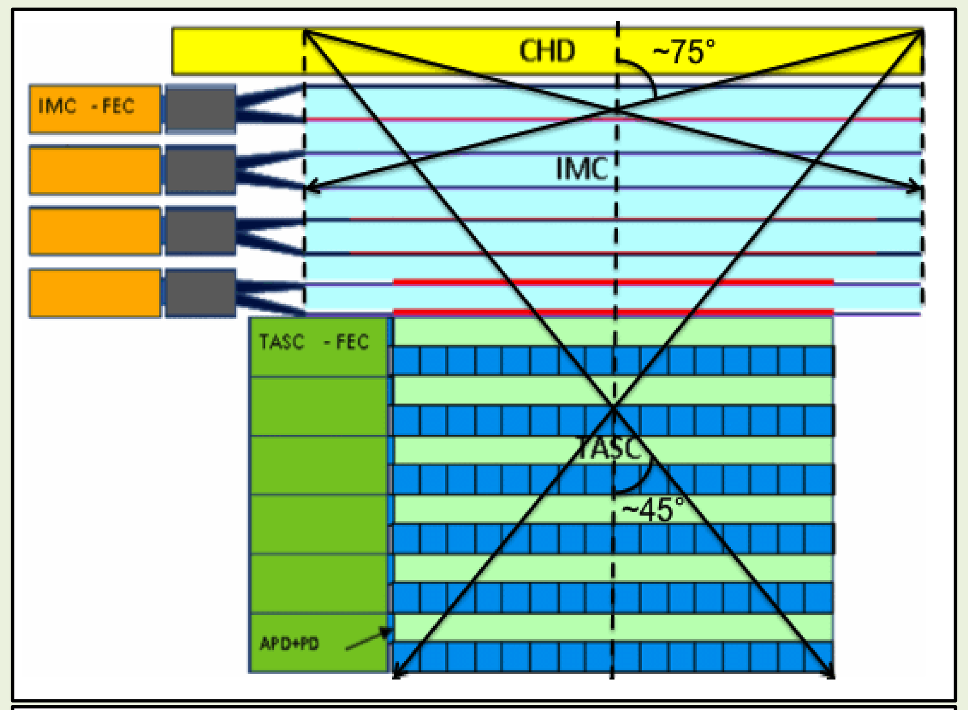


***Figure 2:*** Diagram of the CAL showing the approximate geometry requirements of the standard and UH trigger modes.

## Event Selection

- Theta Cut[3]: Events must have a reconstructed UH track with incidence angle of less than 60 degrees
- Charge Consistency[3]: Difference in estimated charges in the CHDX and CHDY for each event can not exceed 1.5%

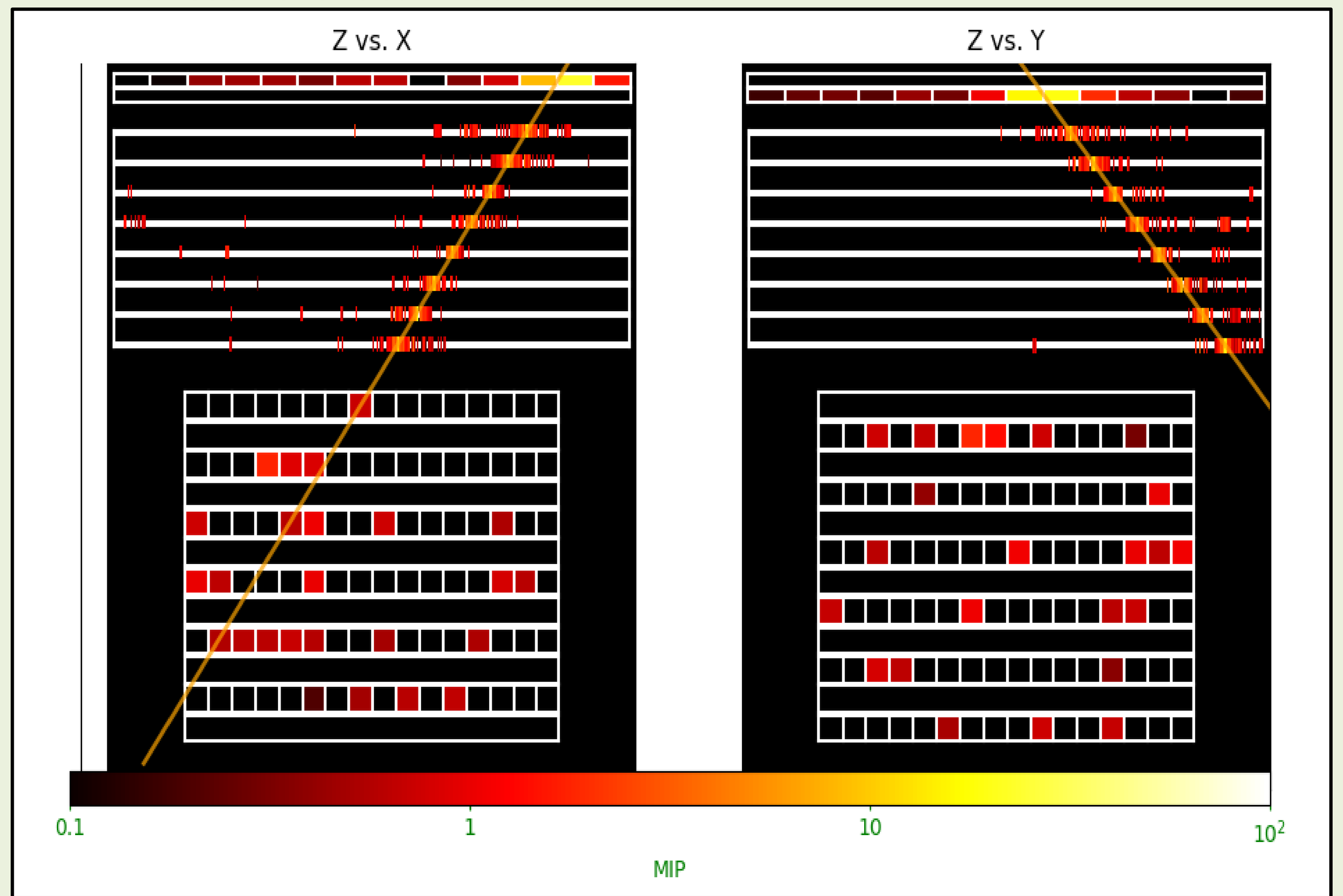


***Figure 3:*** Ultra-heavy nuclei event cadidate visualized with the CALET event viewer.

## Charge Correction of Ultra-heavy Events

### Time Dependence

**Cause:**

- Changes in temperature
- Long-term gain drift

**Correction:**

- Perform Si and Fe peak fits in 1-day bins
- Apply linear correction

### Spatial Dependence

**Cause:**

- Light propagation effects
- Material non-uniformity

**Correction**

- Perform Si and Fe peak fits in 3.2 x 3.2 cm bins in the CHDX and CHDY.
- Apply linear correction

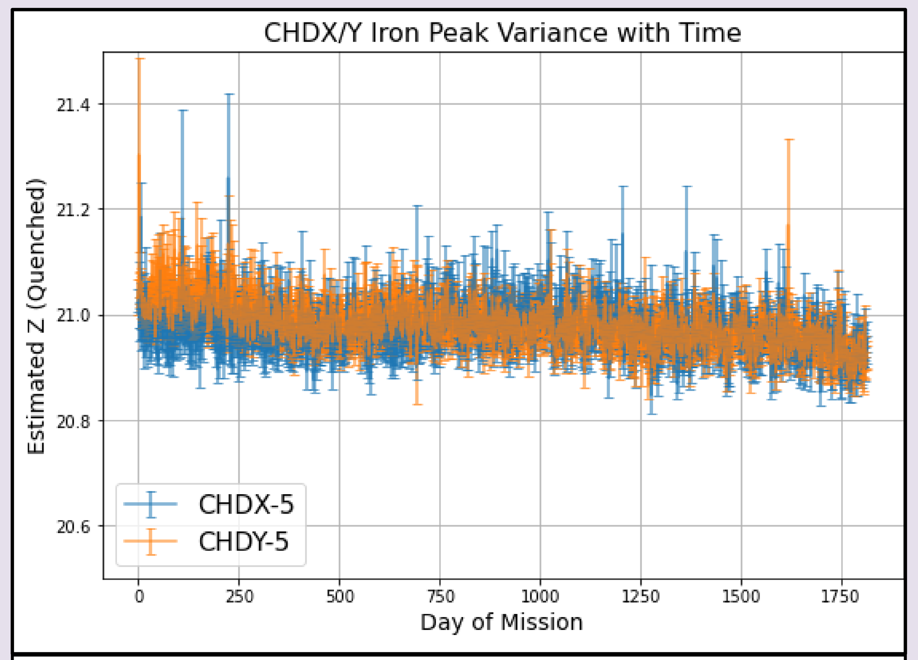


***Figure 4:*** Location of the fitted Fe peak for CHDX and CHDY for each day in the UH dataset.

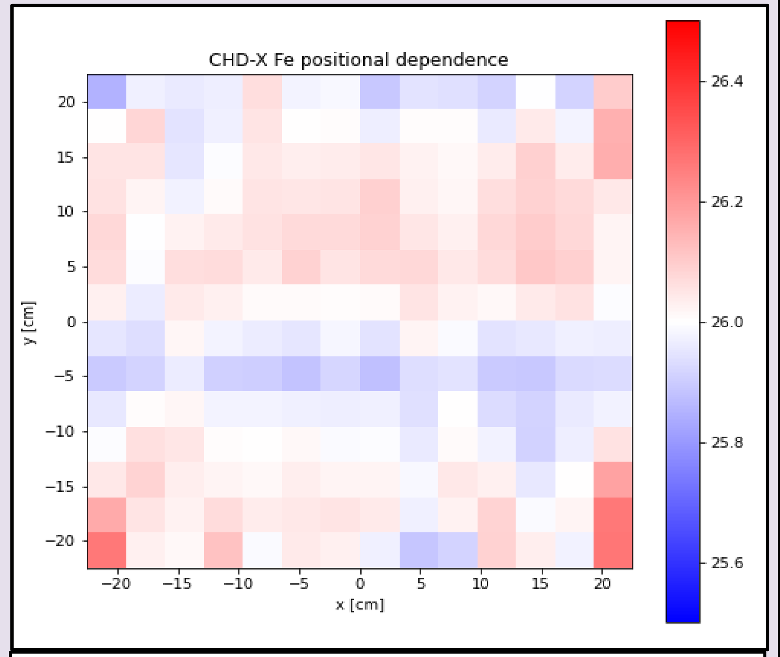


***Figure 5:*** Location of the fitted Fe peak for each position bin of the CHDX.

### Quenching Correction

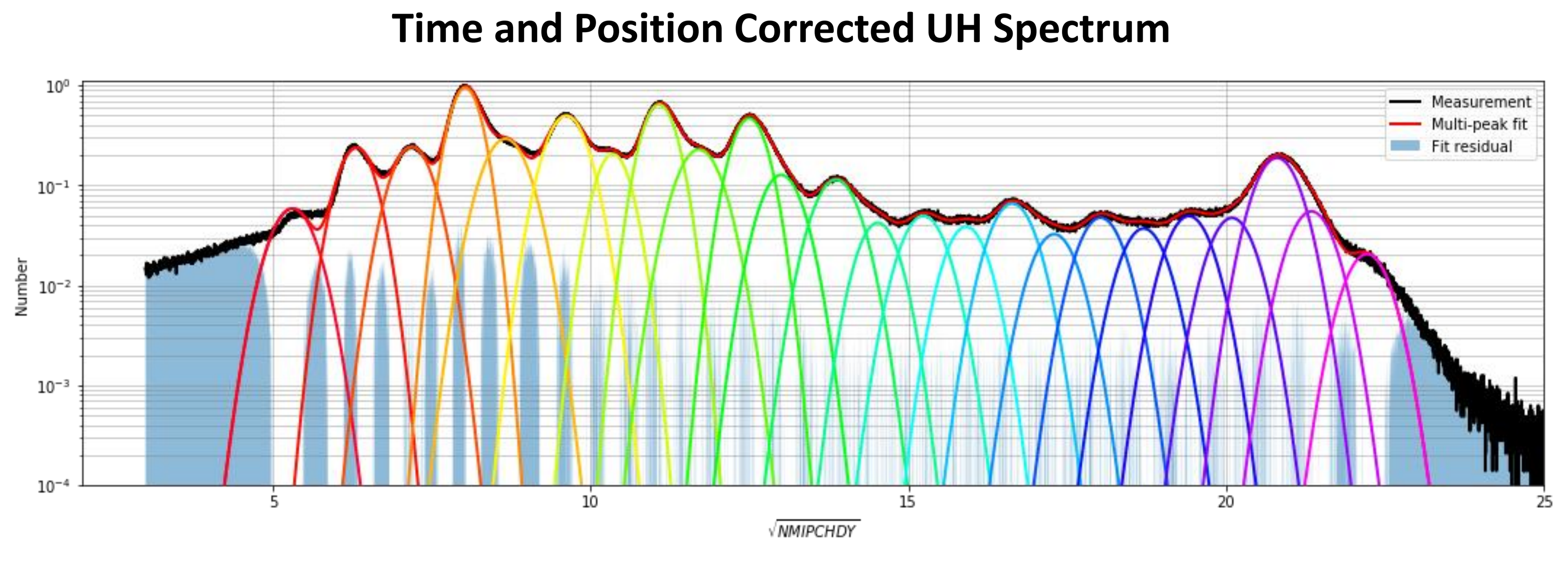


***Figure 6:*** Resulting quenched UH spectrum following time and position corrections.

- 1. Multi-peak fit from C to Ni
- 2. Fit Tarle function to peaks to find parameters.
- 3. Invert Tarle function to return corrected dE/dx values

$$\frac{dE}{dx} = \frac{B_1 Z^2}{1 + B_2 Z^2} + B_3 Z^2$$

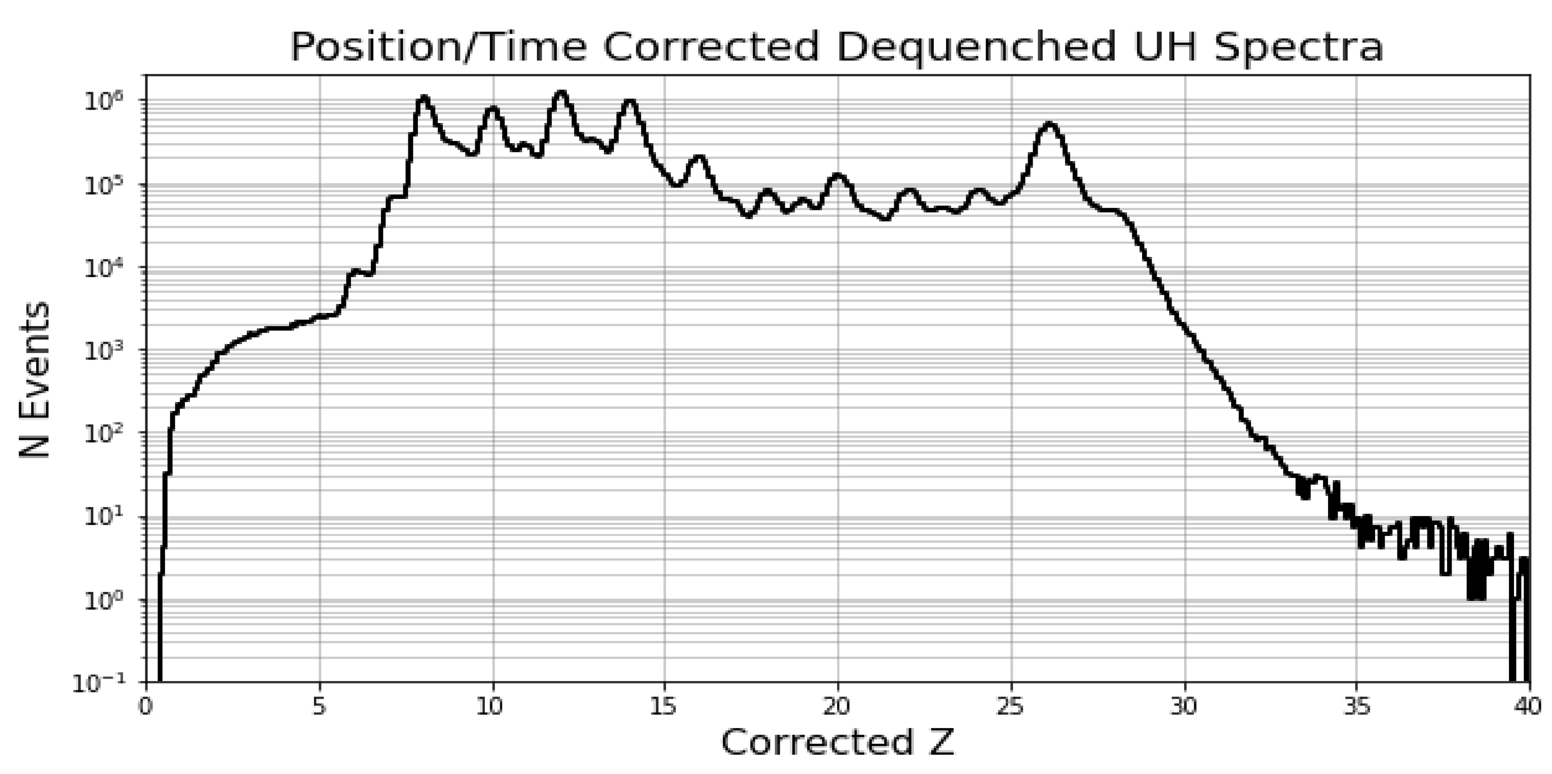


***Figure 7:*** Resulting charge corrected UH spectrum following time and position corrections.

## Removing Non-relativistic and Low Z Nuclei Contamination

**Challenge**

- Non-relativistic nuclei lead to higher ionization energy deposits
- Along with low Z nuclei, this causes contamination in the UH dataset

**Methods**

- Remove observations made at times of low cutoff rigidity
- Make direct cut on energy deposits in the TASC (see reference 6), limiting geometry

### Vertical Cutoff Rigidity

**Method:**

- Stoermer approximation
- $\mathbf{R = 14.3 \times cos^4(lat_m)}$[4]

**Weaknesses:**

- Uses dipole approximation for Earth's geomagnetic field
- Assumes particle trajectory with normal incidence

**Result:**

- Improves charge resolution, but limits statistics in UH range

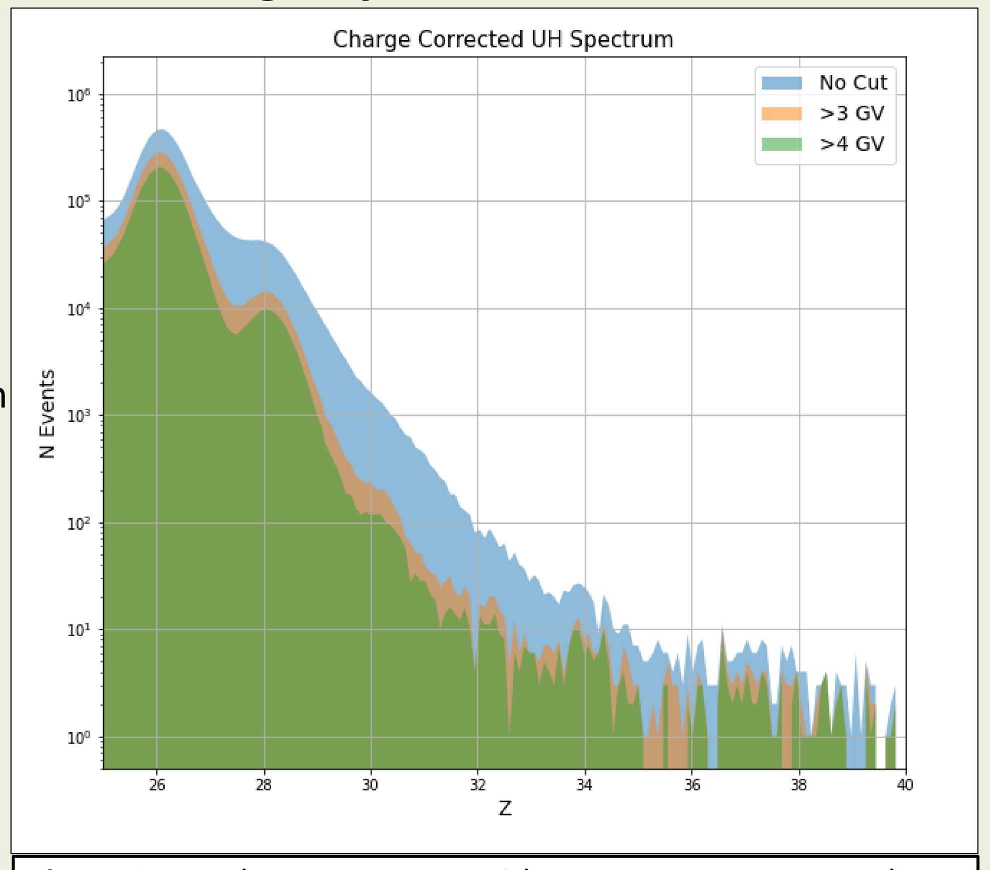


***Figure 8:*** UH charge spectrum with no cut, a >3 GV cut, and a >4 GV cut.

### Calculating Effective Cutoff Rigidities

**Method**

- Numerically solve the equations of motion along a given trajectory for a range of rigidities to find allowed/forbidden trajectories[5]
  - Geomagnetic information calculated at each step using the IGRF13 and Tsyganenko 05 internal/external models
- Compute an effective cutoff rigidity[5] that considers the effect of the penumbra.
  - $R_E = R_L + (R_U - R_L) \times N_{Forbidden} / N_{Total}$

**Result**

- Updated rigidity cut improves charge resolution in the UH region, resulting in clearly resolved peaks for evenly charge nuclei up to Z=38
- Results are consistent with those using the TASC deposit method[6] despite the datasets having roughly 50 percent of events in common
- Future optimization and implementation of both methods will look to increase statistics while maintaining charge resolution

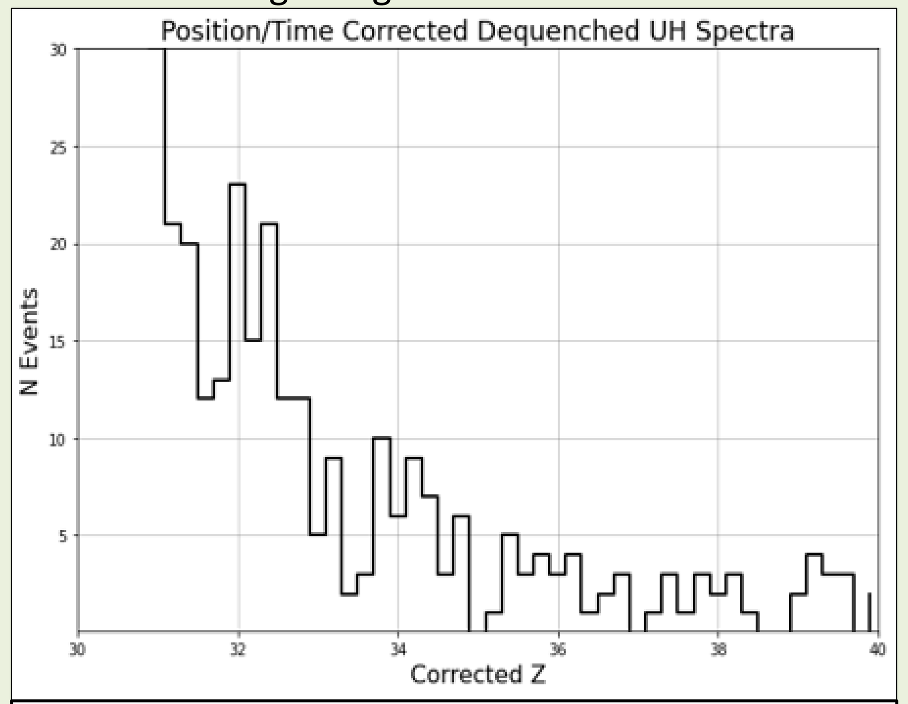


***Figure 9:*** UH charge spectrum with a >4 GV rigidity cut using the calculated effect cutoff rigidities.

## References

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