Results of the Ultra-Heavy Cosmic-Ray Analysis with CALET on the International Space Station

Wolfgang V. Zober and Brian F. Rauch

for the CALET Collaboration

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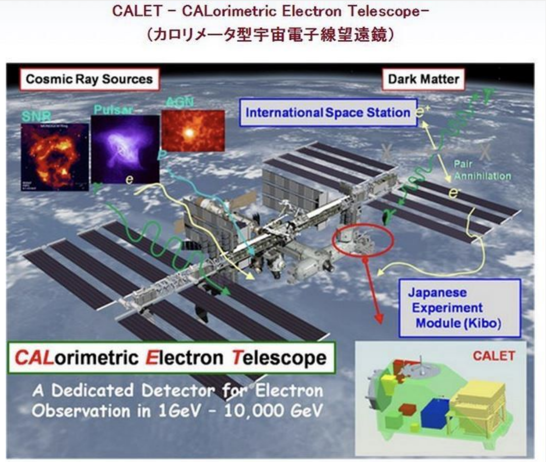
CALET Member list

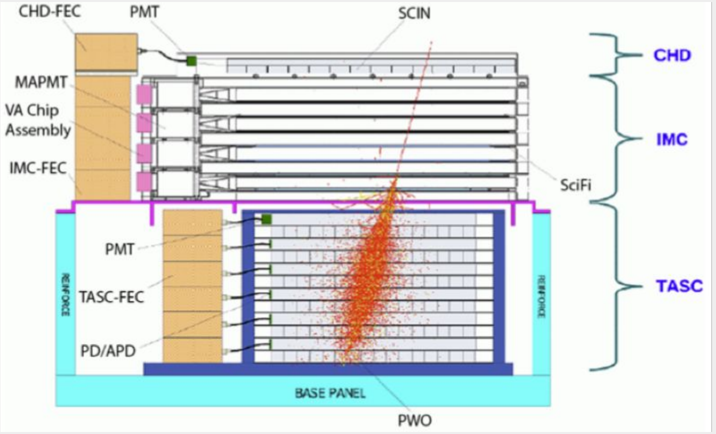
O. Adriani,[1,2] Y. Akaike,[3,4] K. Asano,[5] Y. Asaoka,[5] E. Berti,[2,13] G. Bigongiari,[6,7] W.R. Binns,[8] M. Bongi,[1,2] P. Brogi,[6,7] A. Bruno,[9] N. Cannady,[10,11,12] G. Castellini,[13] C. Checchia,[6,7] M.L. Cherry,[14] G. Collazuol,[15,16] G.A. de Nolfo,[9] K. Ebisawa,[17] A. W. Ficklin,[14]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

1) University of Florence, Italy
2) INFN Florence, Italy
3) WISE, Waseda University, Japan
4) JEM Utilization Center, JAXA, Japan
5) ICRR, University of Tokyo, Japan
6) University of Siena, Italy
7) INFN Pisa, Italy
8) Washington University, St. Louis, USA
9) Heliospheric Physics Laboratory, NASA/GSFC, USA
10) University of Maryland, Baltimore County, USA
11) Astroparticle Physics Laboratory, NASA/GSFC, USA
12) CRESST, NASA/GSFC, USA
13) IFAC, CNR, Italy
14) Louisiana State University, USA
15) University of Padova, Italy
16) INFN Padova, Italy
17) ISAS, JAXA, Japan
18) Kanagawa University, Japan
19) Hirosaki University, Japan
20) YITP, Kyoto University, Japan
21) Shibaura Institute of Technology, Japan
22) ASE, Waseda University, Japan
23) NIPR, Japan
24) Yokohama National University, Japan
25) Shinshu University, Japan
26) IPNS, KEK, Japan
27) University of Pisa
28) NIT(KOSEN), Ibaraki College, Japan
29) University of Maryland, College Park, USA
30) Ritsumeikan University, Japan
31) GCSE, Waseda University, Japan
32) University of Denver, USA
33) NICT, Japan
34) Aoyama Gakuin University, Japan
35) Nihon University, Japan
36) Osaka Metropolitan University, Japan
37) NITEP, Osaka Metropolitan University, Japan
38) QST, Japan
39) Nagoya University, Japan
40) Ibaraki University, Japan

The Calorimetric Electron Telescope

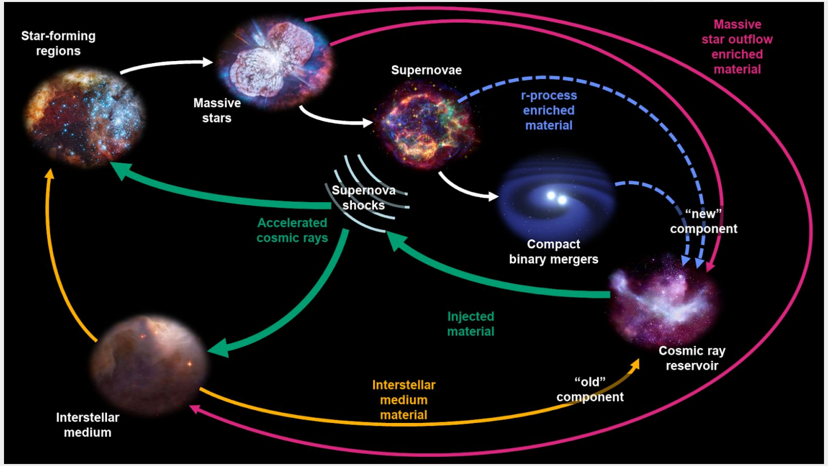
- CALET launched to the ISS in August 2015 to determine the spectra of the electron-flux up to TeV energies.
    - While CALET was designed for electrons and possesses a normal incidence depth of 30 radiation lengths, it also has the dynamic range that's capable of measuring elemental charge up to Z=40.
- The instrument consists of two layers of segmented plastic scintillators for the cosmic-ray charge identification (CHD), a 3 radiation length thick tungsten-scintillating fiber imaging calorimeter (IMC) and a 27 radiation length thick lead-tungstate calorimeter (TASC).
- Its main calorimeter is designed to measure the fluxes of the highest energy cosmic-ray electrons, but has also made excellent measurements of cosmic-ray (CR) nuclei and gamma rays.





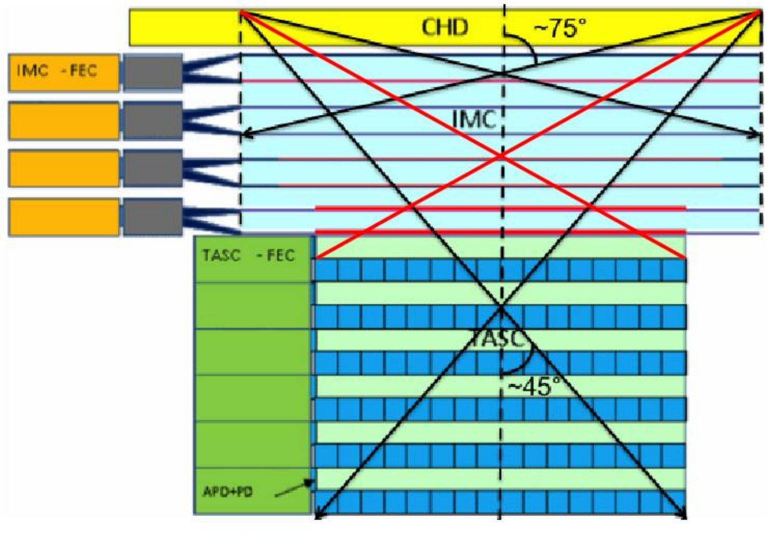
Ultra-Heavy Cosmic Ray Science

- Ultra-heavy cosmic rays (UHCR) provide clues into the source of all CR, their mechanism, and nucleosynthetic sources, which include the most energetic processes in the universe: supernova, binary neutron star mergers, etc.
- Instruments that can do UHCR measurements for $30 \leq Z \leq 40$ with single element resolution:
  - CALET on ISS within earth's magnetosphere with an energy range, E > 1 GeV/nucleon
  - SuperTIGER which measures at similar energies to CALET.
    - Note, that as a stratospheric balloon payload, it has different systematics that include requiring atmospheric corrections.
  - ACE-CRIS at the L1 Lagrange point outside Earth's magnetosphere and an energy range ~100 – 500 MeV/nucleon.



Ultra-Heavy Cosmic Ray Science

- This analysis uses 7.5 years of CALET UH-trigger data from 10/2015 through 04/2023. This UH-trigger dataset has ~4× the geometry factor of the standard nuclei trigger. (~260 million events)
- We add a constraint to the analysis that events pass through the top of the TASC. (~65 million events)
- This reduces statistics but the energy information allows for an improved charge assignment.
    - Allowing us to trade statistics for better resolution.



CHD Corrections

Please see the second ICRC: PoS(ICRC2023)089 for more details.

- This analysis has two secondary corrections for optimizing CHD signal for UH events:
- Position
  - Each CHD paddle is divided into 42 subsections, which are then normalized to the full layer mean for both the $_{14}$Si and $_{26}$Fe peaks.
    - For clarity we define a event for $_{14}$Si and $_{26}$Fe as an event within 1 sigma of the respective peak mean in a preliminary charge assignment.
- Time
  - Using the position corrected signal, the CHD paddles are normalized to the full layer $_{14}$Si and $_{26}$Fe peaks over time increments that have 550 events occur in each individual paddle.

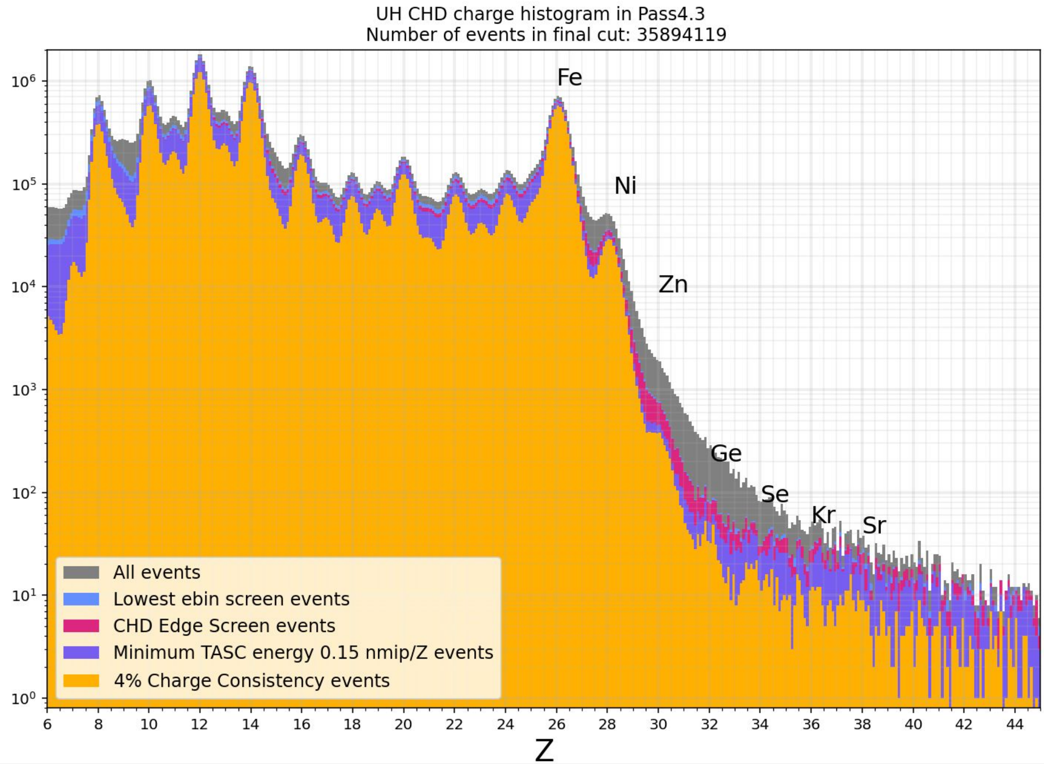
After these corrections we perform a charge assignment based on Deposited Energy in the TASC

- UH events are divided into energy bins of ~61000 $_{26}$Fe candidate events and we perform a peak fitting routine on each energy bin to determine charge assignment.

Event Screening

Please see the second ICRC: PoS(ICRC2023)089 for more details.

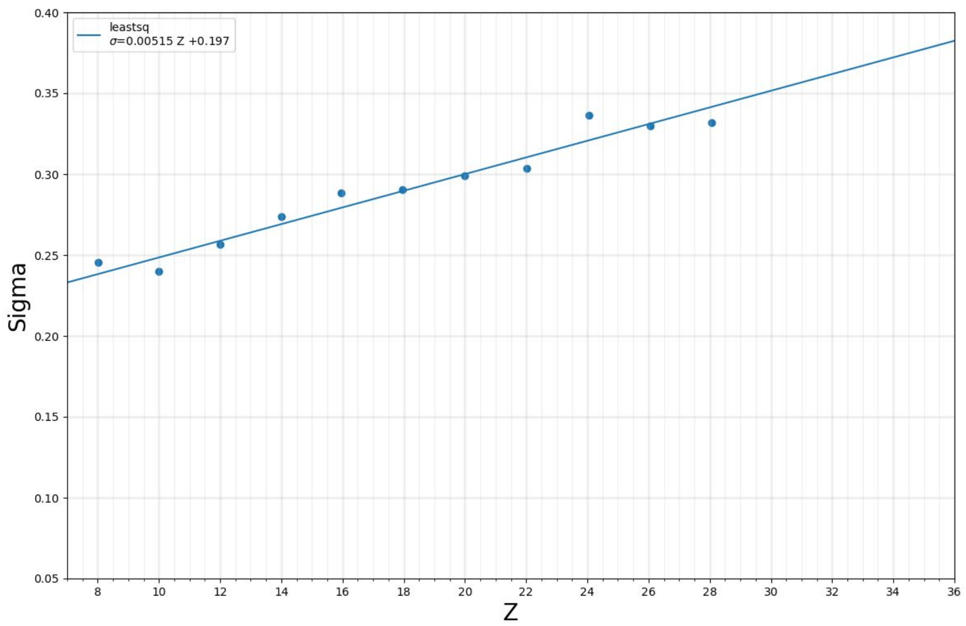
- For consistency the following events are screened in the analysis
  - Events with a deposited energy less than 1.53 nmip. Bins below that energy were smeared and prevented a reliable peak fitting from being performed.
  - A position screen to account for the lack of statistics in the edge cases of the individual paddles.
  - A consistency screen that requires CHDX and CHDY to be within a 4% percent difference.
  - A minimum deposited energy in the the TASC based on 0.15 nmip/Z.



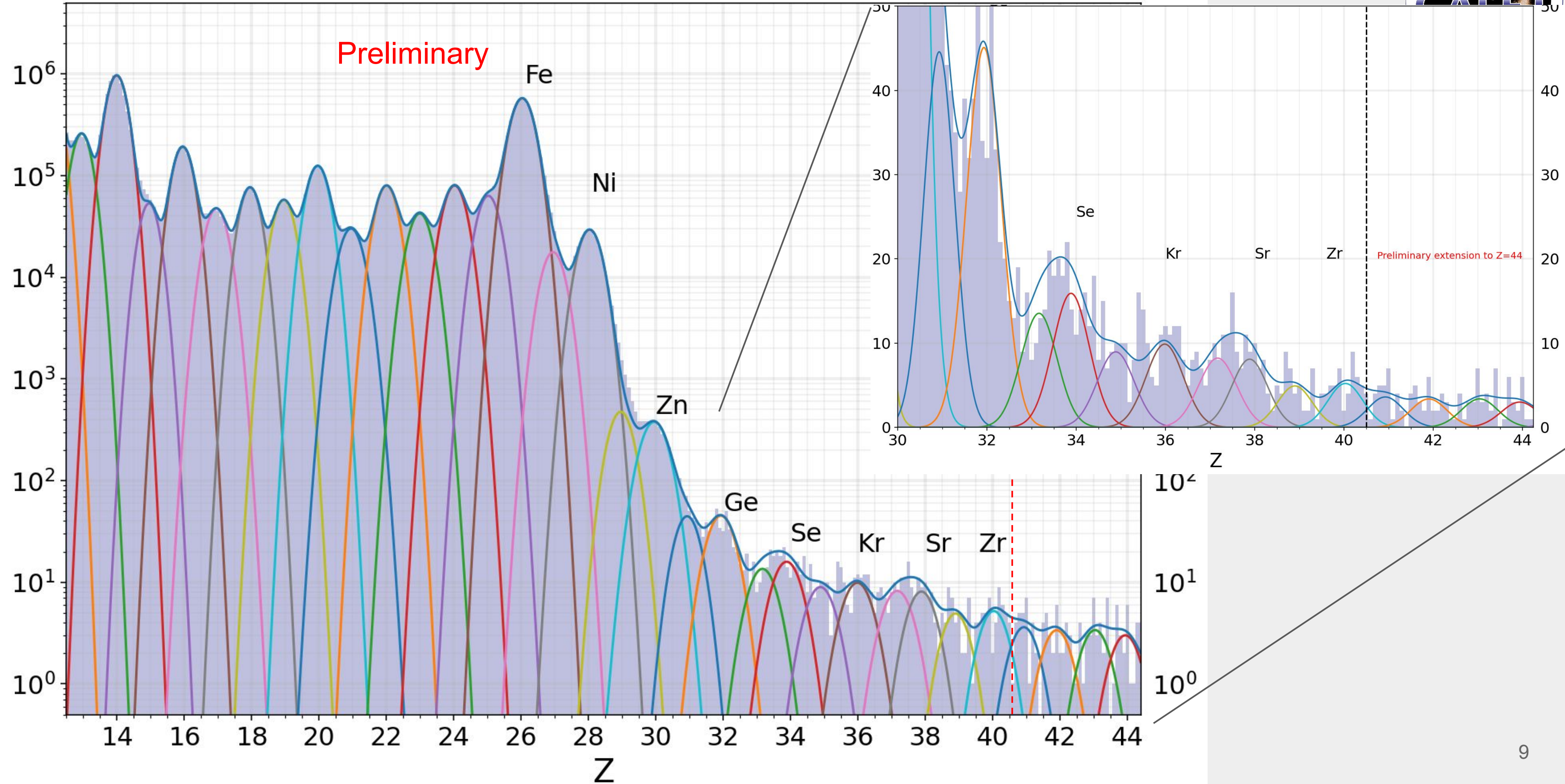
Determination of Abundances

Peak fitting is done over multiple steps.

- Fit step one has minimal constraints to determine sigmas for each peak.
- The sigmas from the even peaks over $8 \leq Z \leq 28$ are then linearly fit to extrapolate a sigma for all peaks
- Second multi-gaussian uses that linearized sigma equation with a maximum-likelihood multiple-Gaussian fit for all elements in CALET's charge range.
- Final fit uses a fixed position and sigma from the second fit to determine error bars on the abundances.



UH CHD charge histogram with TASC filter in Pass4.3
Number of events shown: 36228859



Determination of Error

We have three error sources:

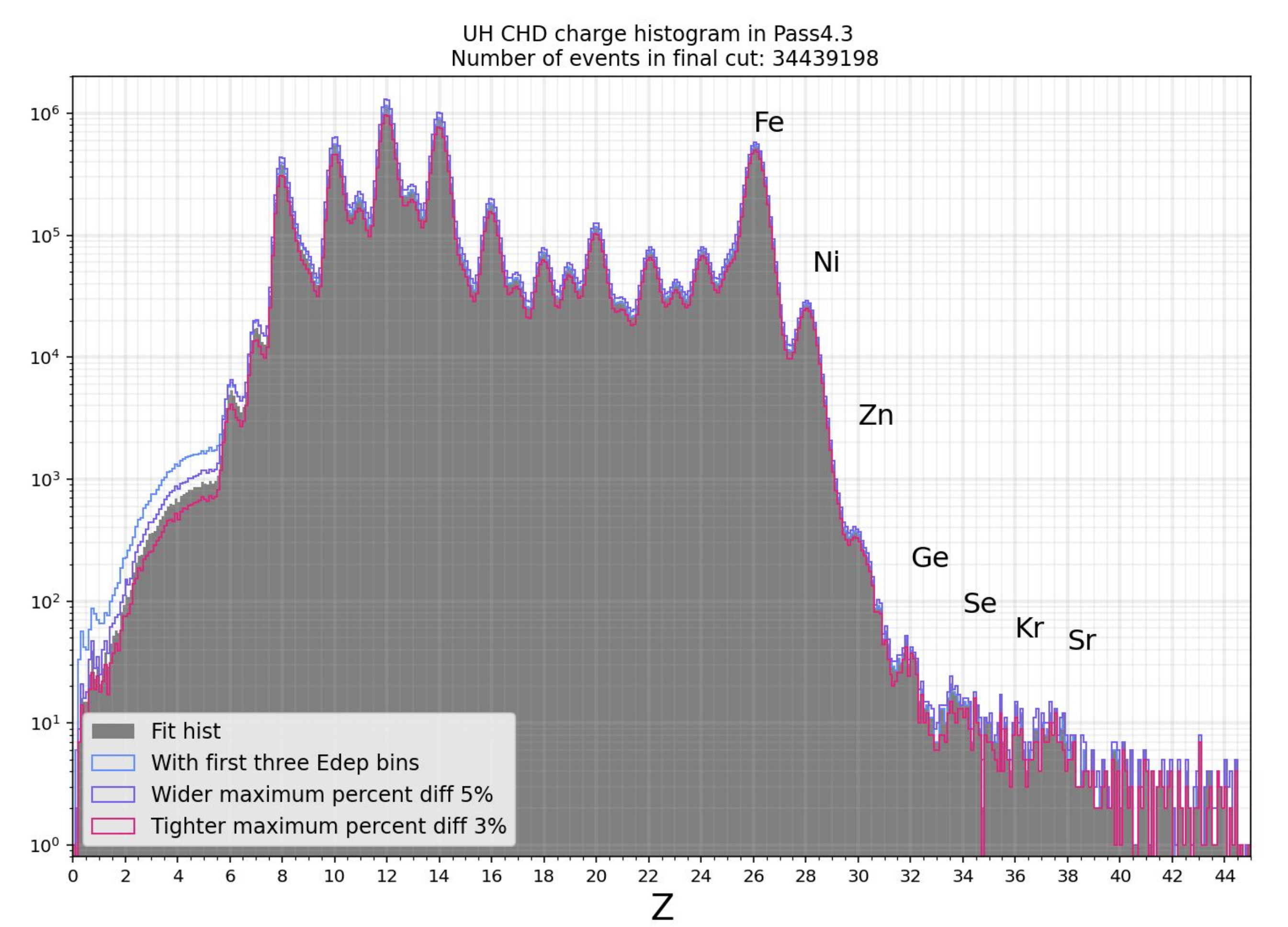
- Error from the fitting error. This is calculated from the correlation matrix.
- Gehrels's treatment of poissonian statistical error.
- A systematic error based on the variations in peak resolution from the chosen screens

Errors are then combined in quadrature

Determination of Variational Error

- Reuse the fixed parameters from the second fit (sigma and peak position) on a set of alternative histograms. The only thing allowed to vary is peak amplitude.
- For the UH TASC analysis the variations are primarily on charge consistency and energy bin screening
- We take the maximum differences between the original histogram and the variations.

Determination of Variational Error

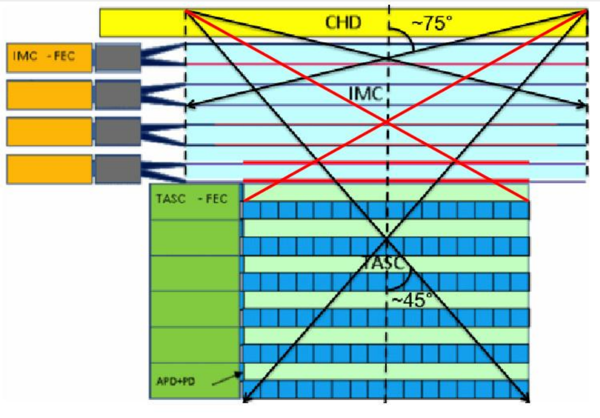


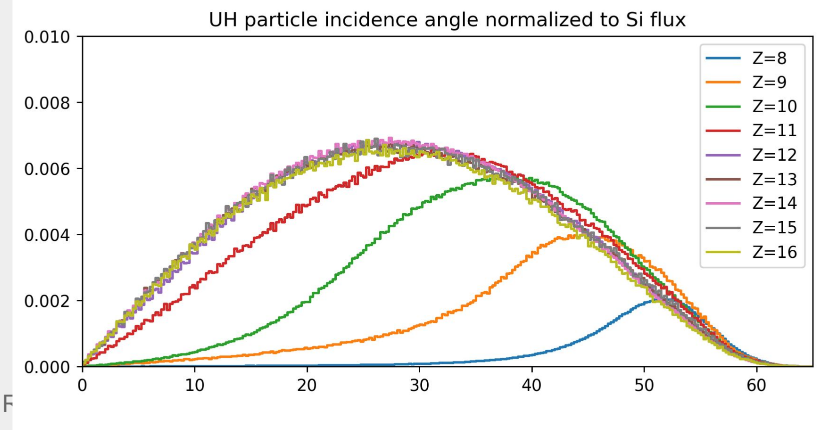
Rescaling lower Z for geometry constraints

As stated earlier the maximum angle for event acceptance in the TASC analysis is 60 degrees. (Red line in top right diagram)

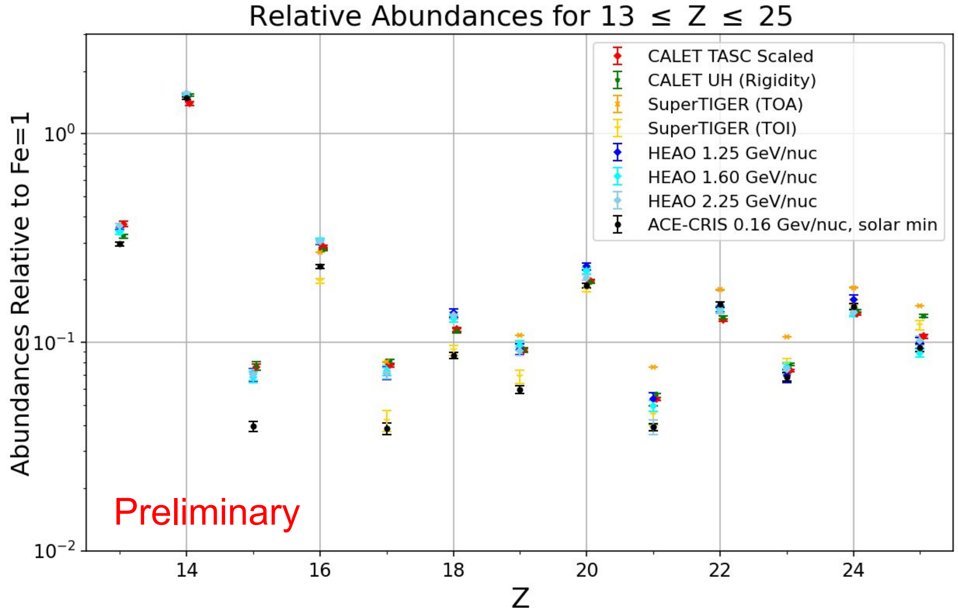
Events coming in at tracks closer to the red line can get lower Z events to exceed the UH trigger.

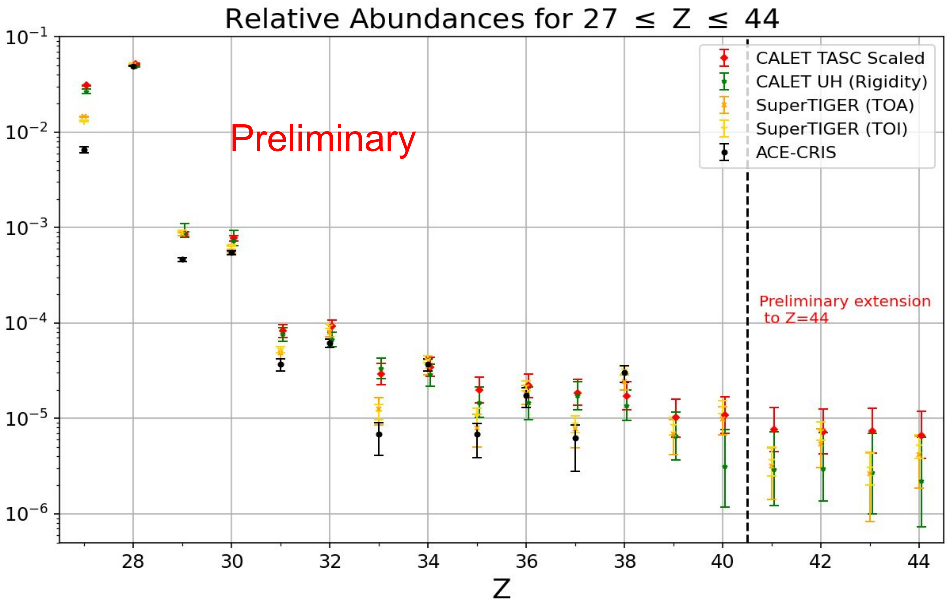
If we examine how event incidence angle varies with Z, we can rescale abundances and correct for this systematic. (Bottom right)



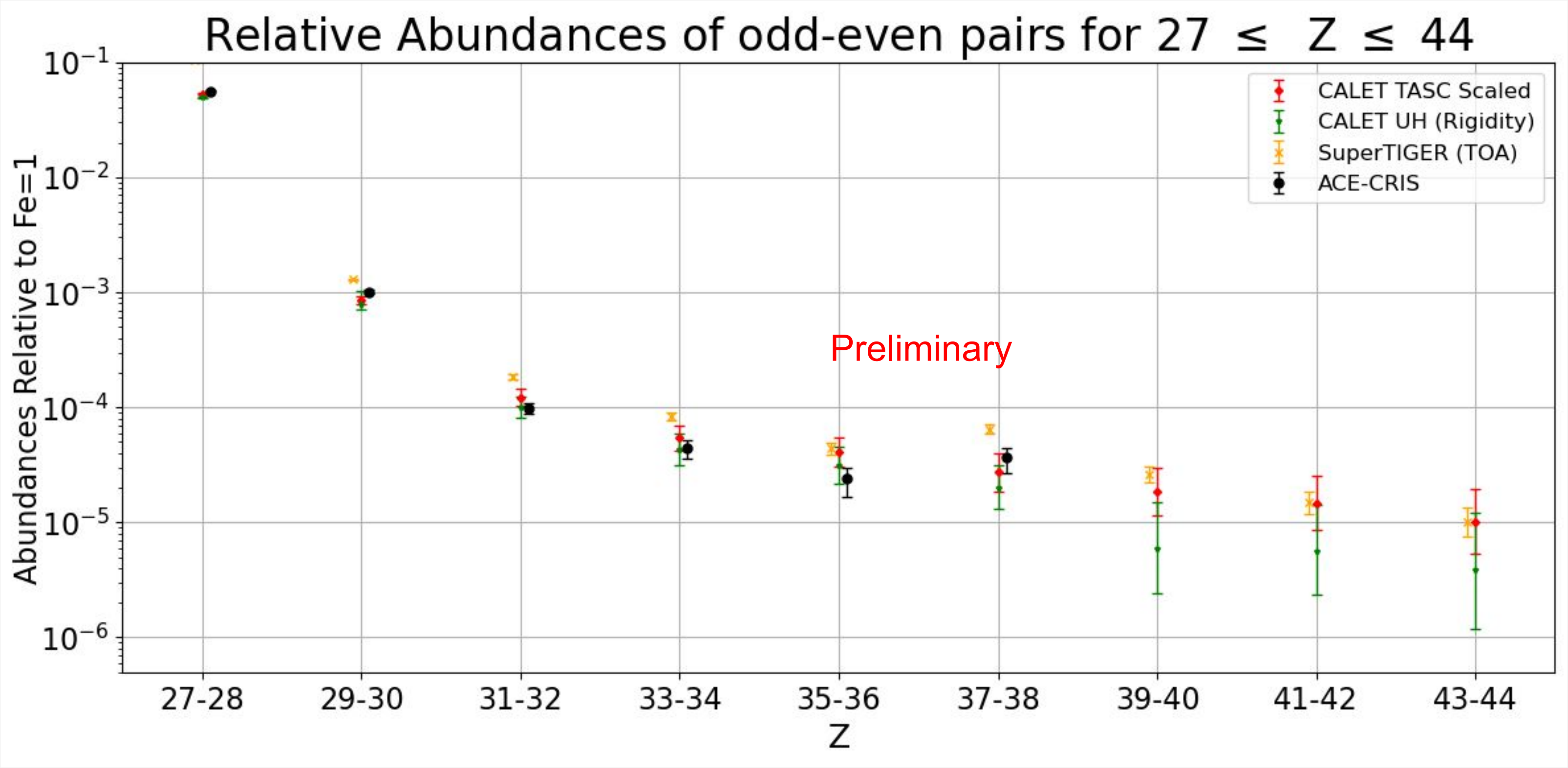


Relative Abundances





Even-Odd pair Abundances



Future Work for CALET UH

- A paper for the relative abundances of $13 \leq Z \leq 44$ is in prep.
- With CALET planned to continue operations, we do expect our resolution of odd-even peaks to improve.

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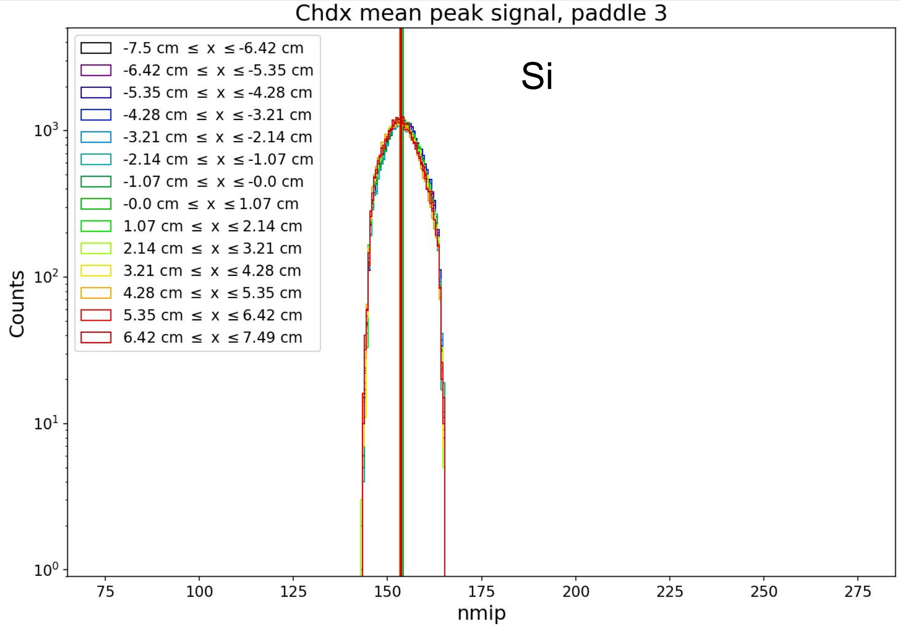
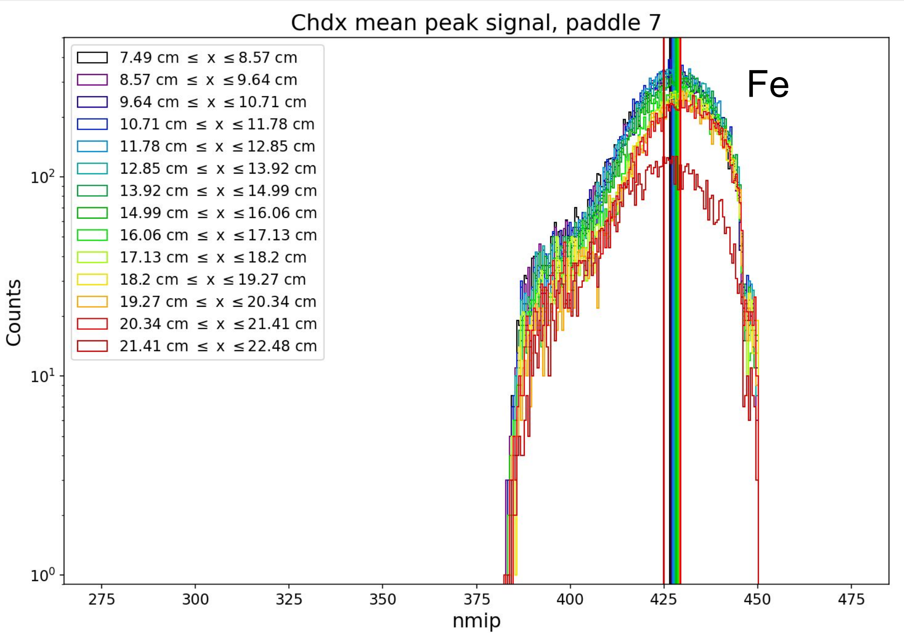
Backup Slides

Example paddle segment signals seen for in the position Corrections





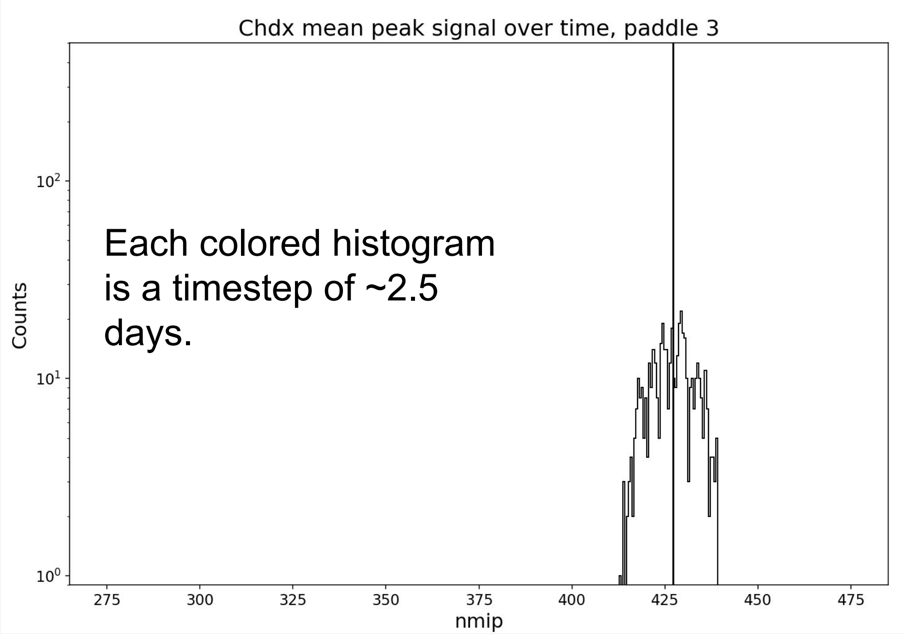
Each histogram represents one paddle segment of the larger paddle

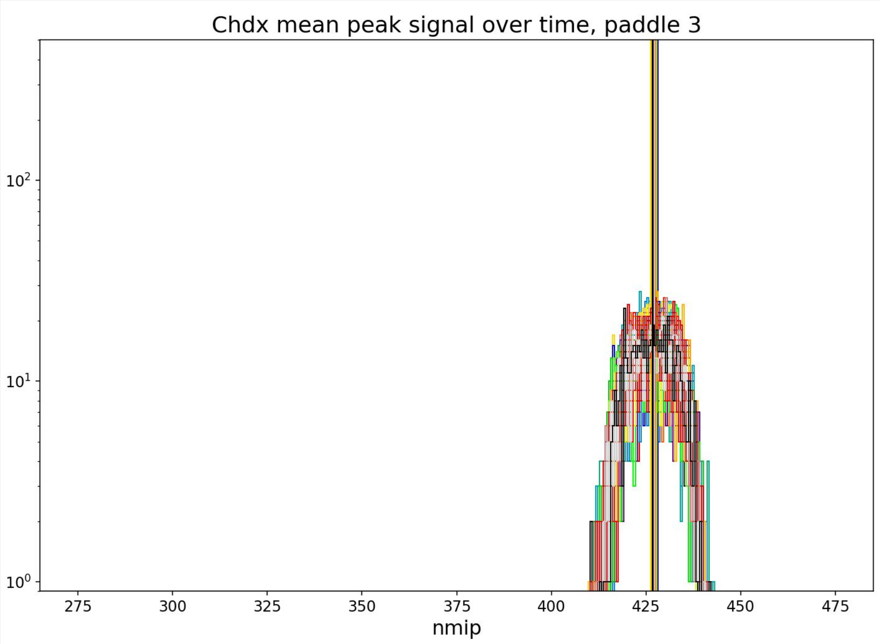
On the Iron paddle segment you can see how the peak shifts and is contaminated by Mn

Time Correction Peaks

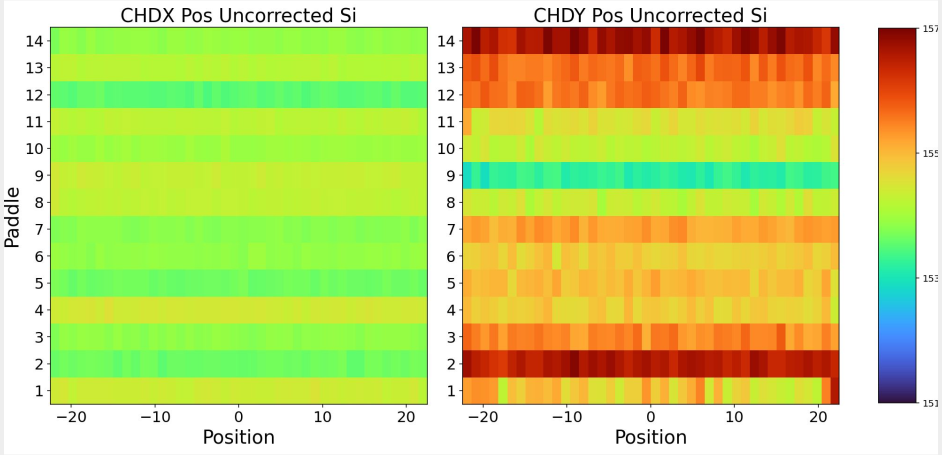
Example peaks from the time correction process

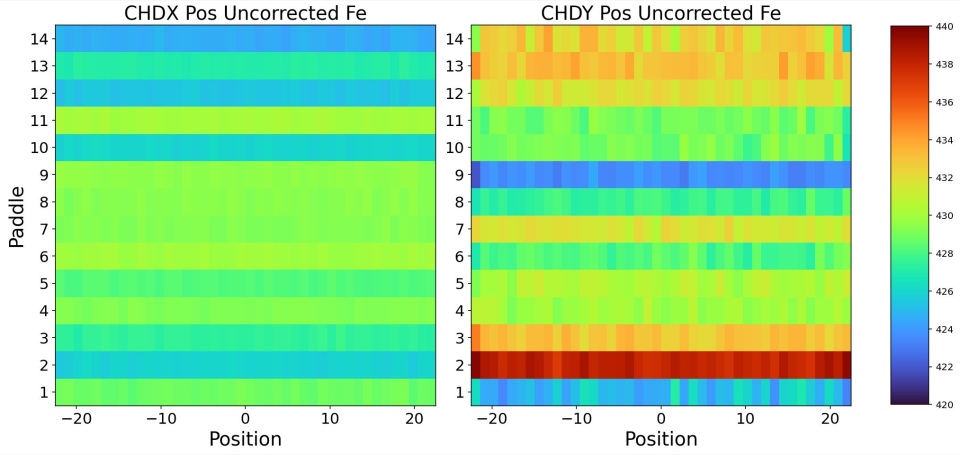
Each colored histogram is a timestep of ~2.5 days.



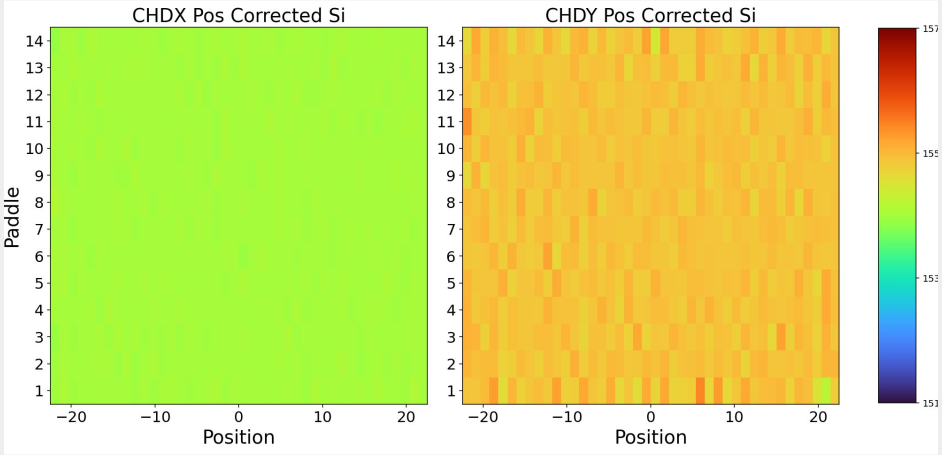


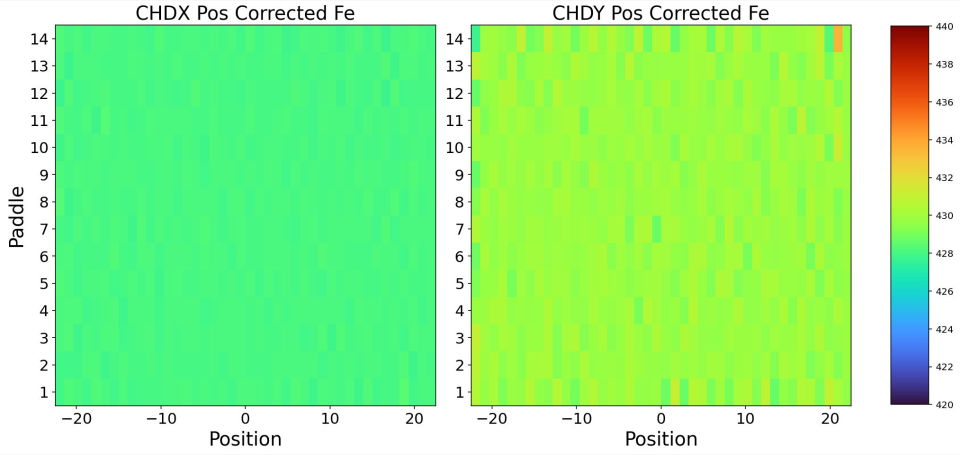
CHD $_{14}$Si and $_{26}$Fe Signal Before Position Corrections





CHD $_{14}$Si and $_{26}$Fe Signal After Position Corrections

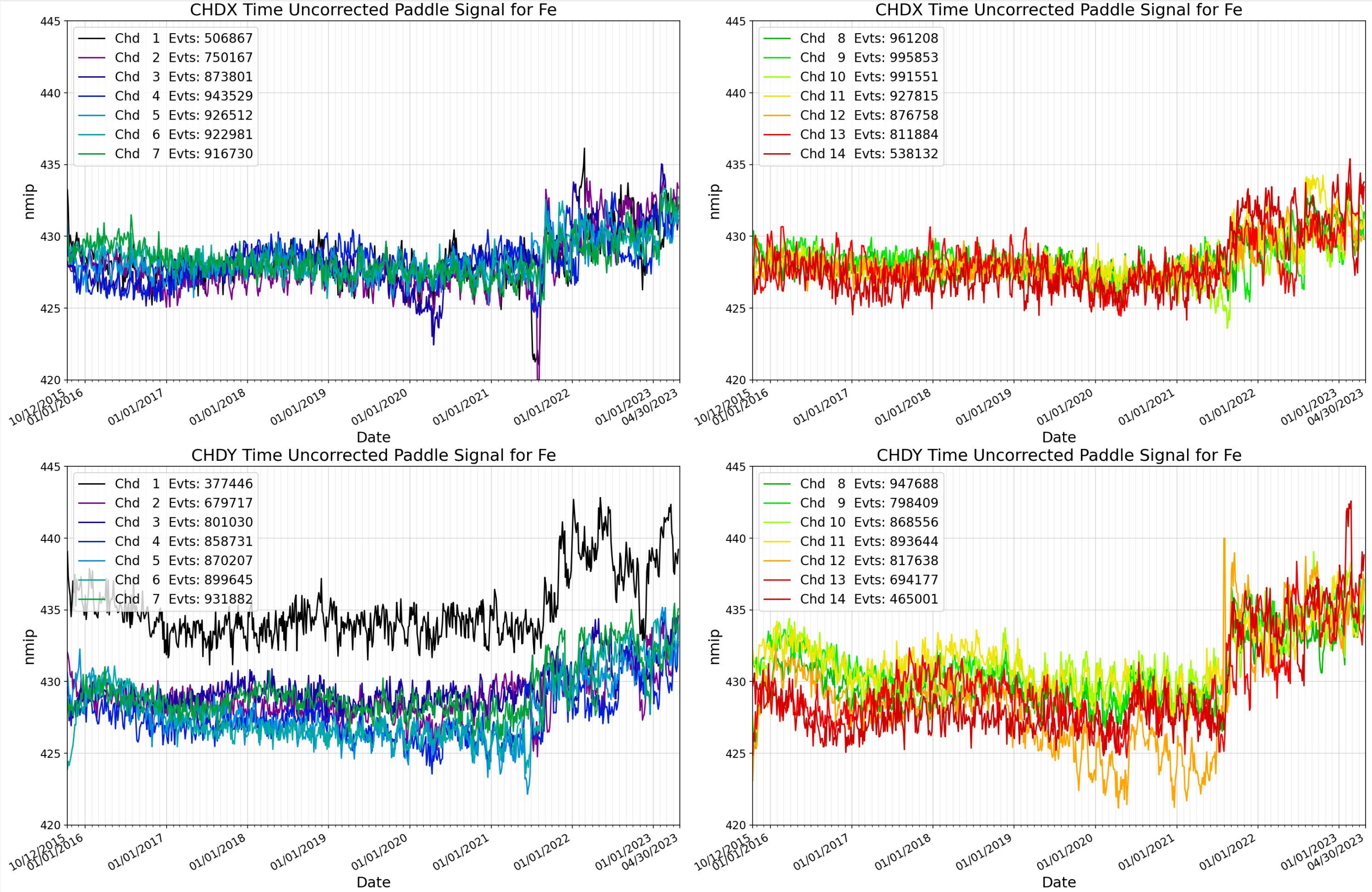




CHD $_{26}$Fe Signal Before Time Corrections

CHDX

CHDY

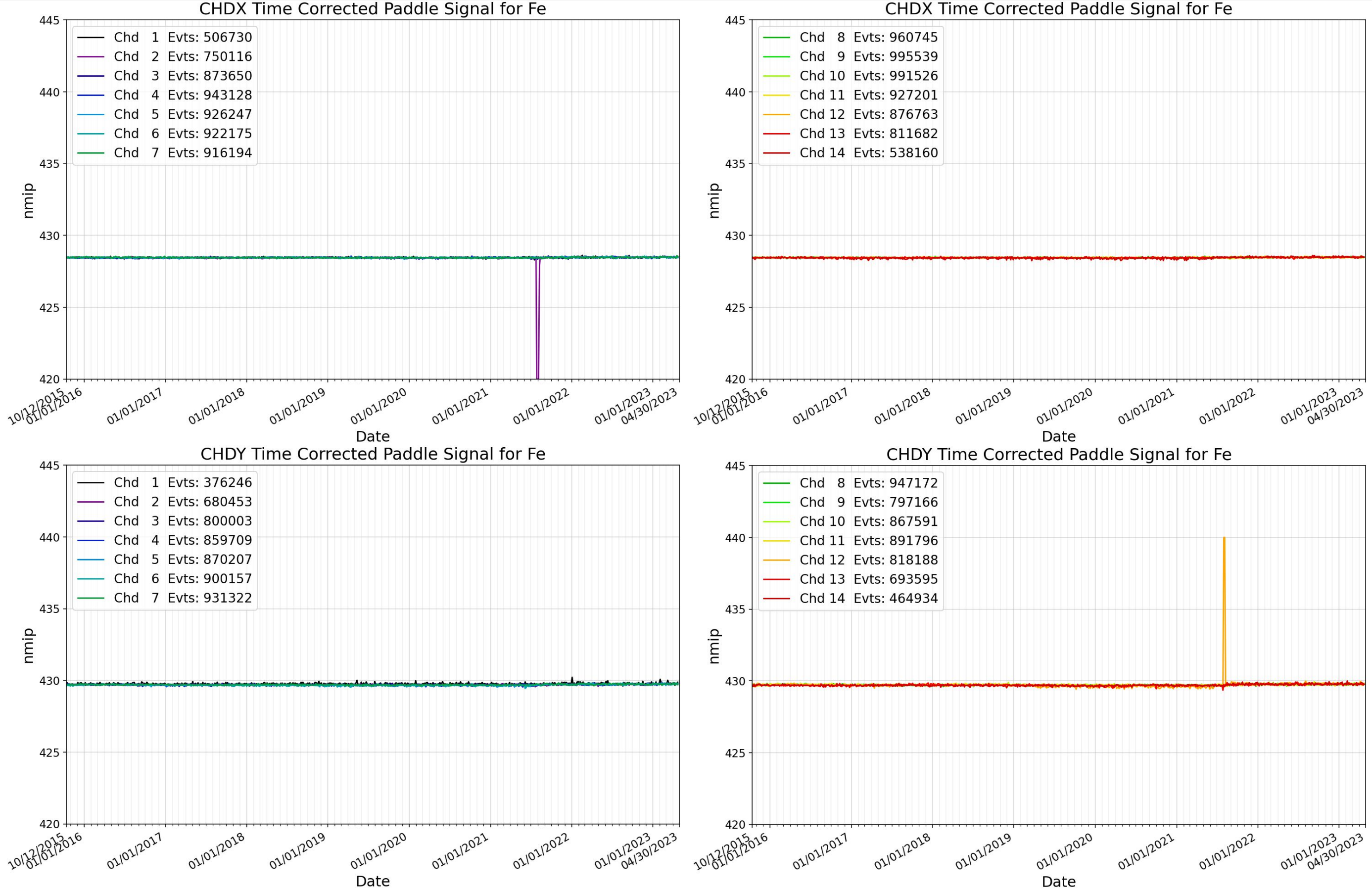


Each timestep is ~3 days

CHD $_{26}$Fe Signal After Time Corrections

CHDX

CHDY



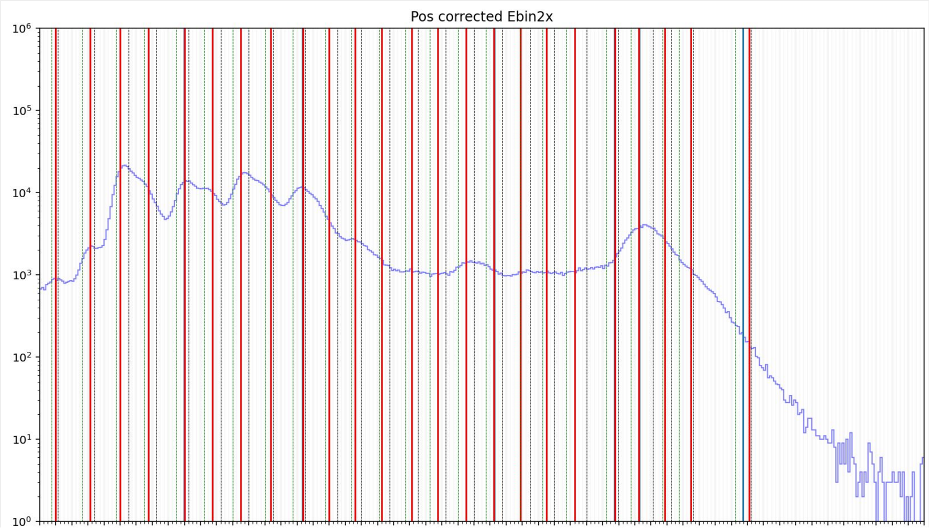
Each timestep is ~3 days

Charge Smearing

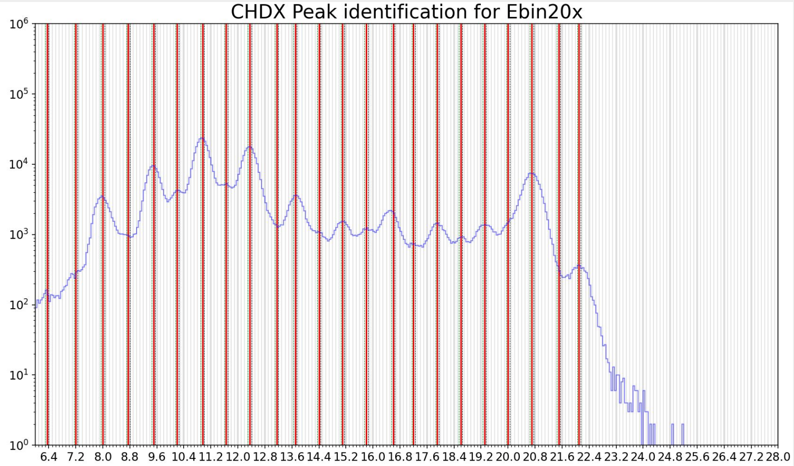
Charge smearing at lower energy is shown on top
Lower plot shows a higher energy bin.

Red lines show peak fitting routine's attempt at finding peak position for Tarle charge assignment.

Very noticeable differences in resolving peaks.



CHD Energy Binned Charge Assignment

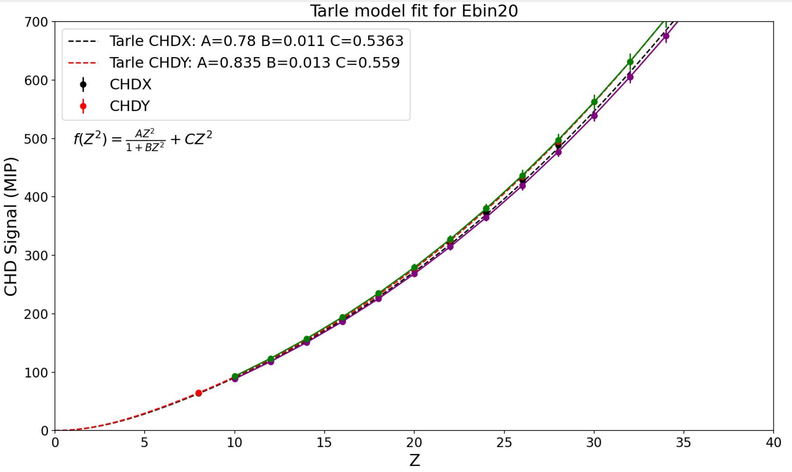


As an example, this the 20th energy bin.

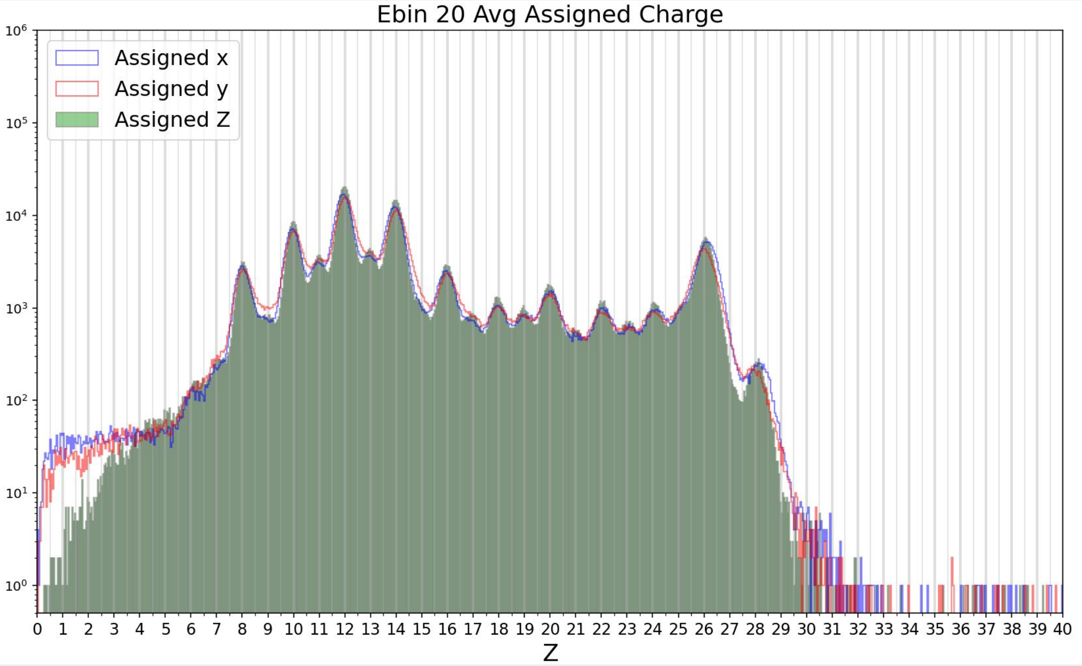
We identify mean peak signal for CHDX (top left) and CHDY.

Plot those peak positions with their respective Z and perform a Tarle Model fit (Bottom Left)

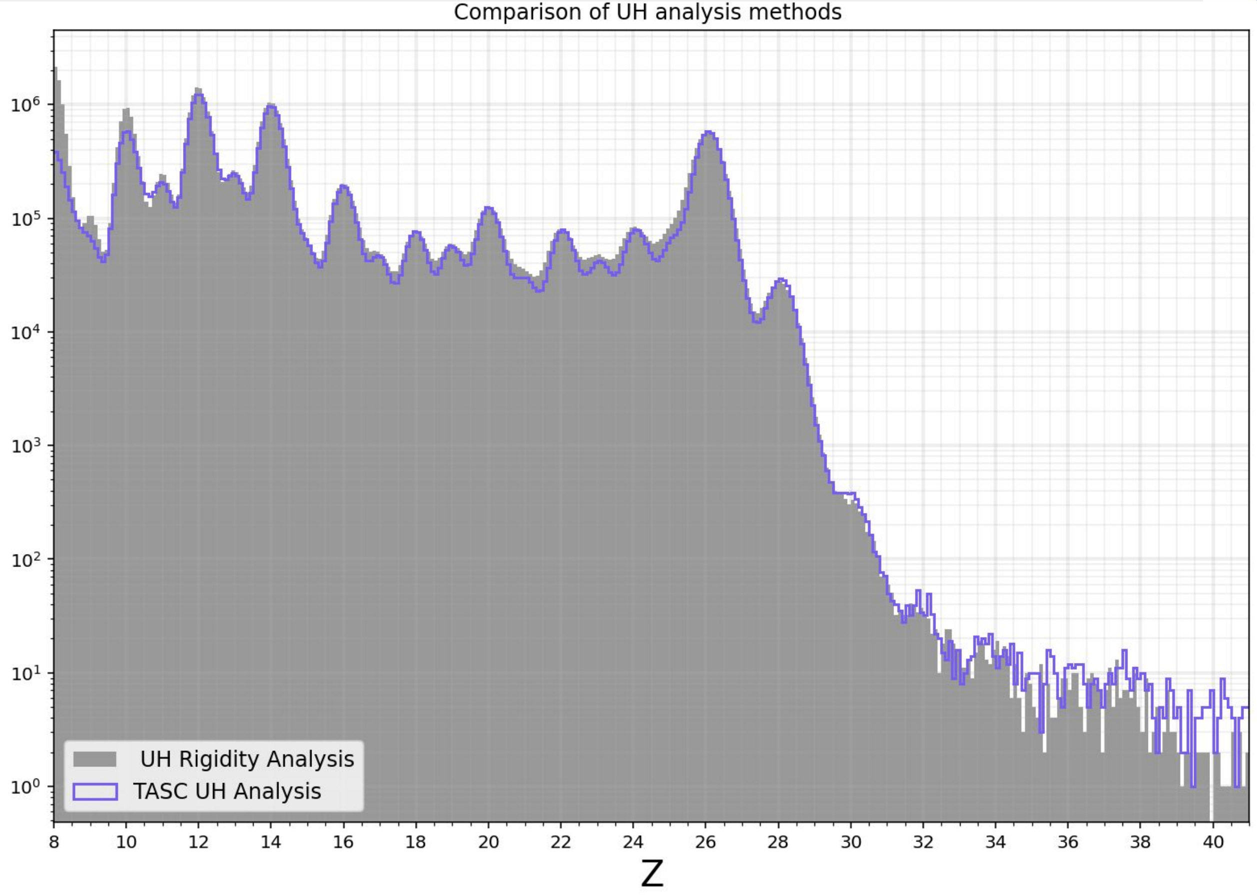
That equation is then used to convert all events within that bin to Z. (Right)



W Z



Comparison of TASC based analysis to rigidity



Rationale for higher Z

Previous work for determining maximum Z looked at the max Z and incident angle for detector saturation.

For 45 degrees the constraint is the ADC around Z = ~46

Both the TASC and UH trigger analyses have shallower entry angles (~60 and 75 degrees respectively).

This lowers the max Z for both. It should be around 44 or 45 for TASC. Rigidity may be closer to 42 or 43.