CALET Ultra-Heavy Cosmic-Ray Observations Incorporating Trajectory Dependent Geomagnetic Rigidities

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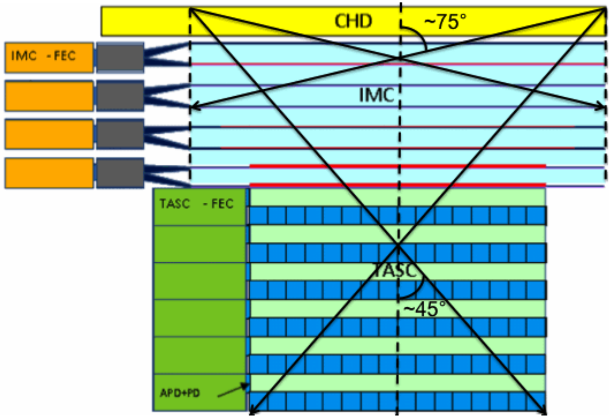
Ultra Heavy Cosmic Ray Analysis

- CALET has a special UH CR trigger utilizing the CHD and the top 4 layers of the IMC that:
  - has an expanded geometry factor of ~4000 cm^{2}sr
  - has a very high duty cycle due to low event rate
  - ISS obstructions in FOV reduce benefit and complicate analysis
- Analysis presented here uses data with UH triggers and good trajectories
- Relative abundances of elements below $_{14}$Si impacted as they only trigger at higher incidence angles
- UH analysis requires specialized data corrections and selections optimized for UH range using $_{26}$Fe

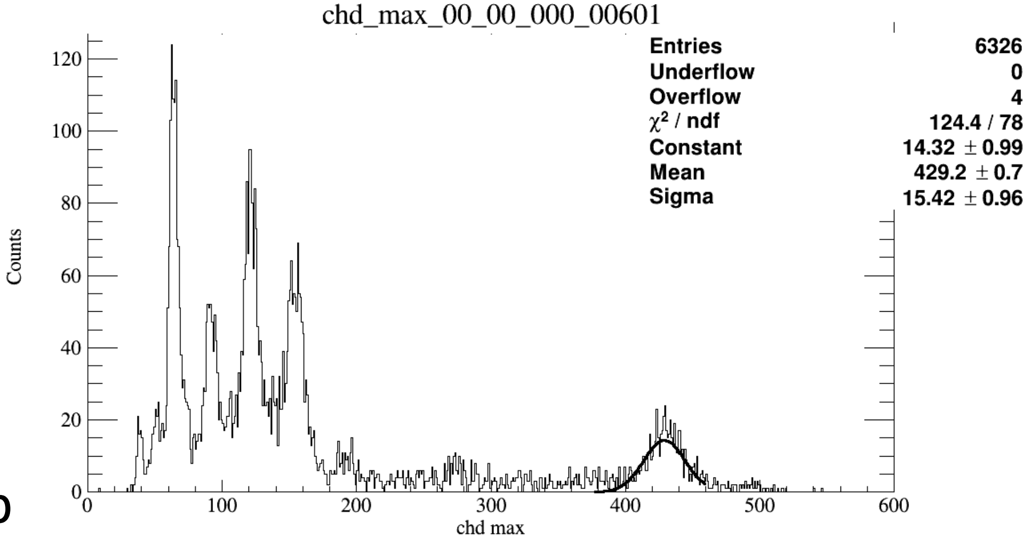


CALET UH Analysis Status

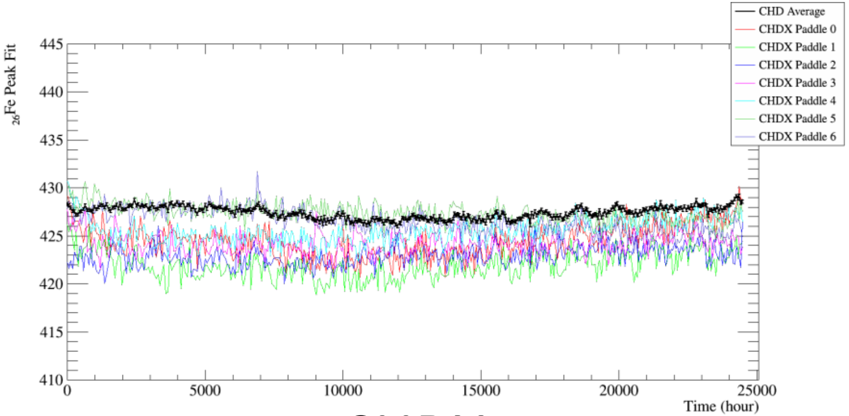
- Using ~3 years of CALET Level 2 PASS03.1 UH data
  - Analysis developed on previous 17 month data set applied
  - UH analysis CHD paddle time corrections
  - UH analysis CHD paddle position dependent corrections
  - Data selections for incidence angle, vertical cutoff rigidity, charge consistency, etc. applied
- Abundances fit for previous data sets agree within statistics with other UH measurements (SuperTIGER and ACE-CRIS)
- Work continues on trajectory dependent rigidity thresholds and ISS obstruction identification
- Analysis planned for CALET HE trigger data set with energy reconstruction in TASC – for Wolfgang Zober's PhD thesis project.

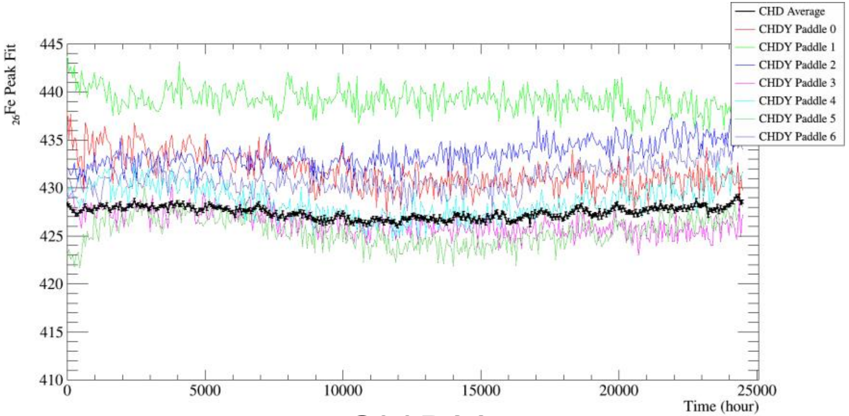
CHD $_{26}$Fe Time Corrections

- CHD time step histograms filled until at least 500 $_{26}$Fe range events in each CHD paddle
- In each time step $_{26}$Fe peaks fit with a Gaussian for each paddle and paddle average time steps calculated
- CHD paddle signals multiplied by the ratio of the mean of both layers over the full dataset to the paddle time step mean



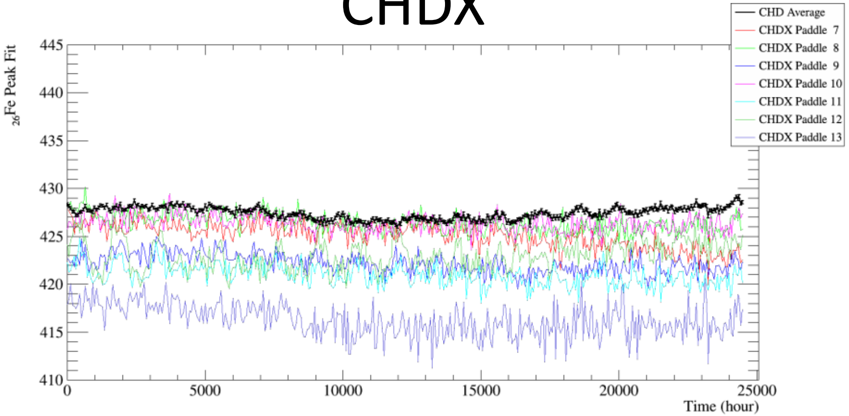
CHD $_{26}$Fe Time Contours

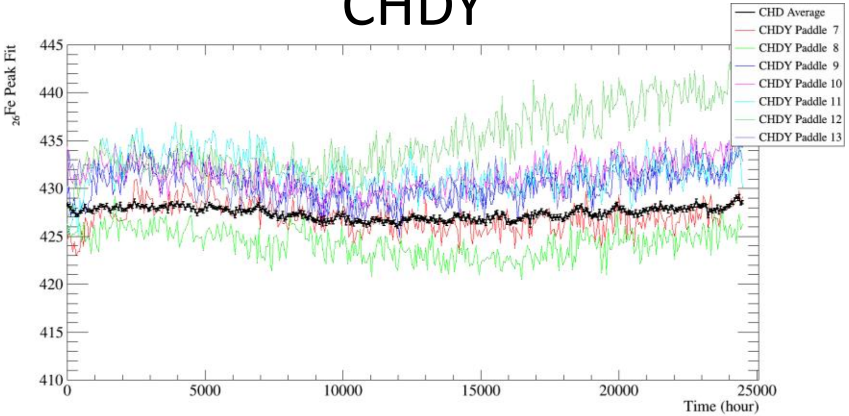




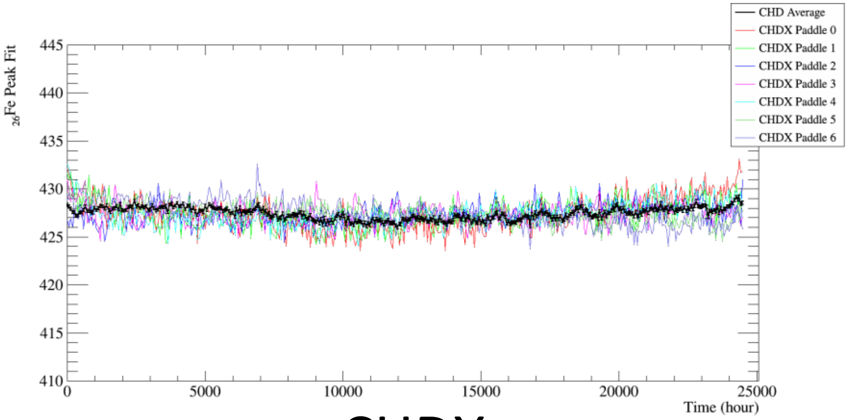
CHDX

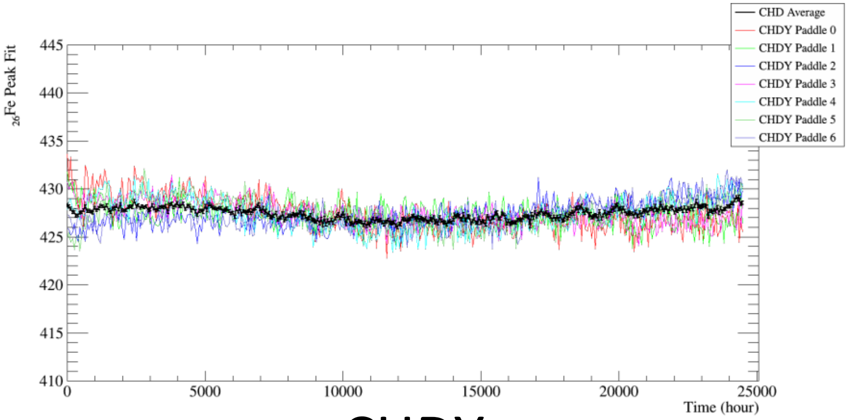
CHDY





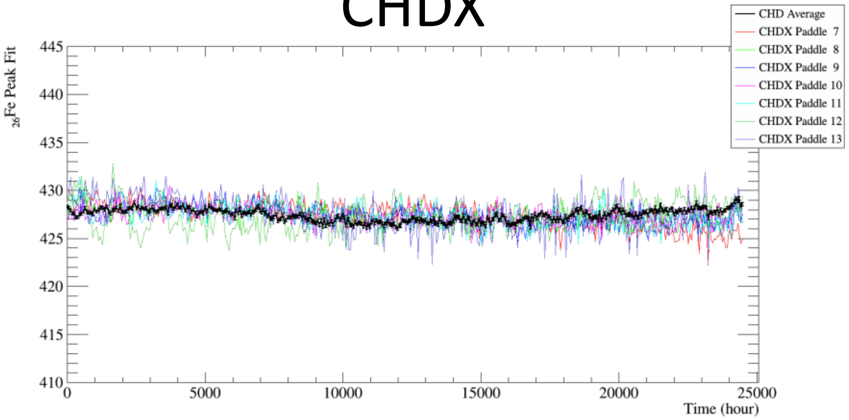
Corrected Time Contours

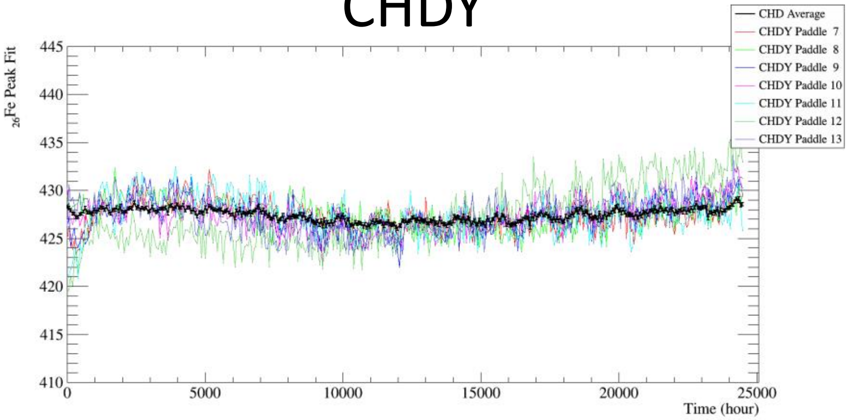




CHDX

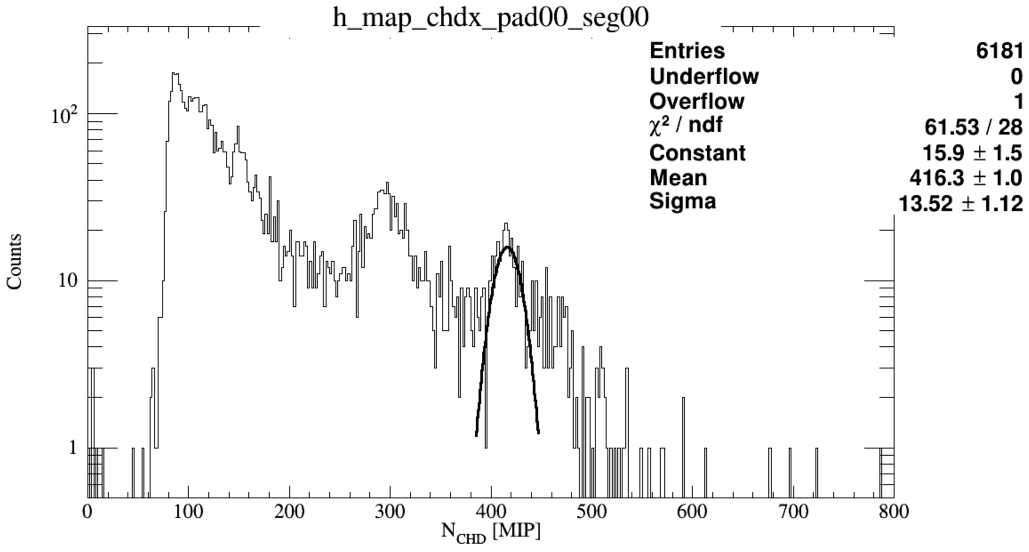
CHDY





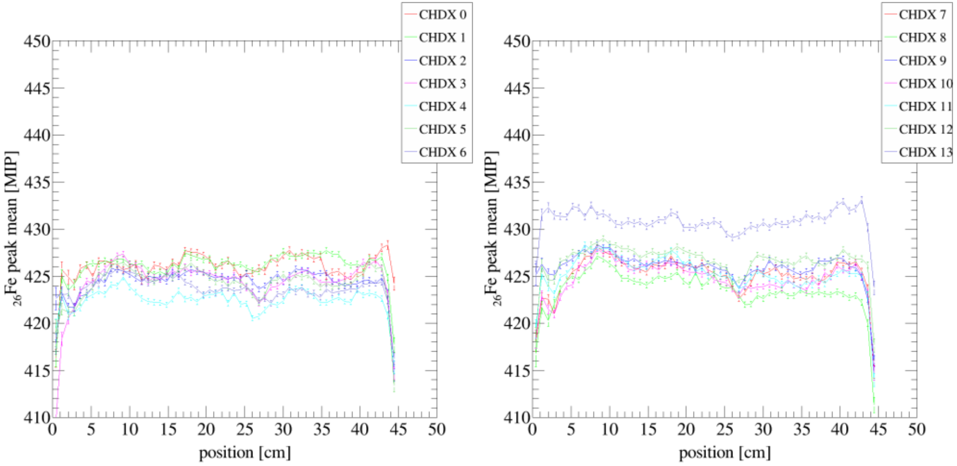
CHD Position Correction Method

- CHD paddles divided into thirds of the paddle width (1.07 cm) segments
- $_{14}$Si and $_{26}$Fe peaks fit with Gaussian for each segment
- CHD paddle signal multiplied by the ratio of each layer mean to the segment mean

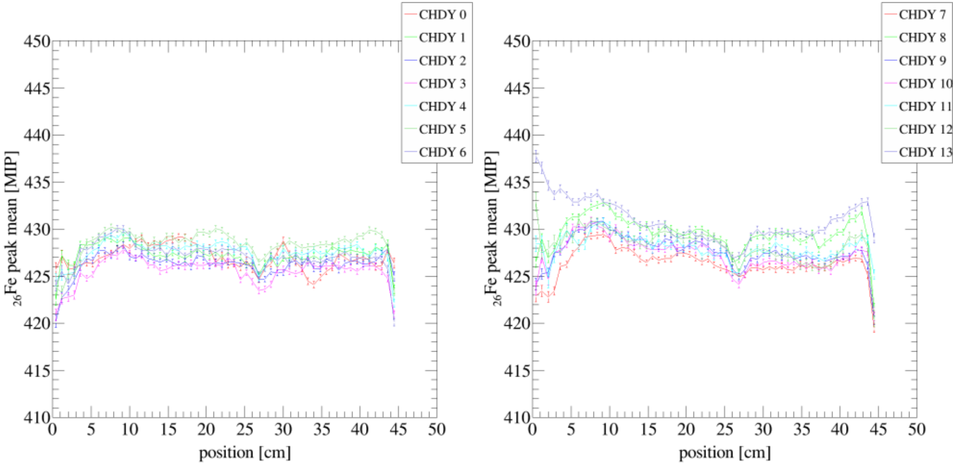


CHD $_{26}$Fe Position Dependence

CHDX



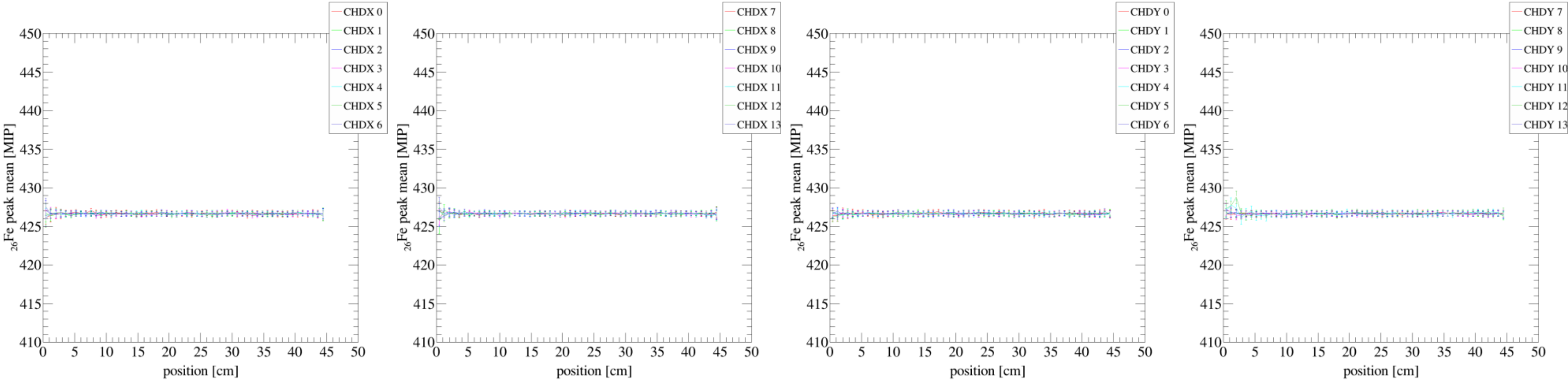
CHDY



CHD $_{26}$Fe After Position Correction

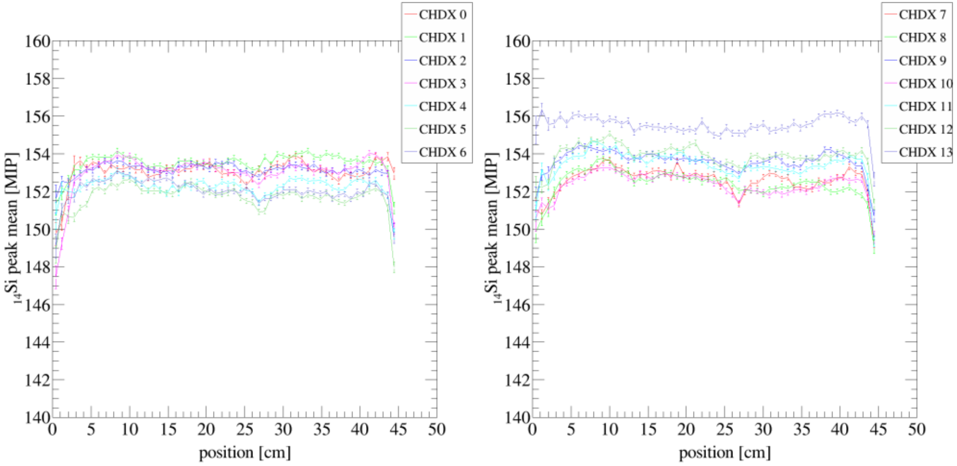
CHDX

CHDY

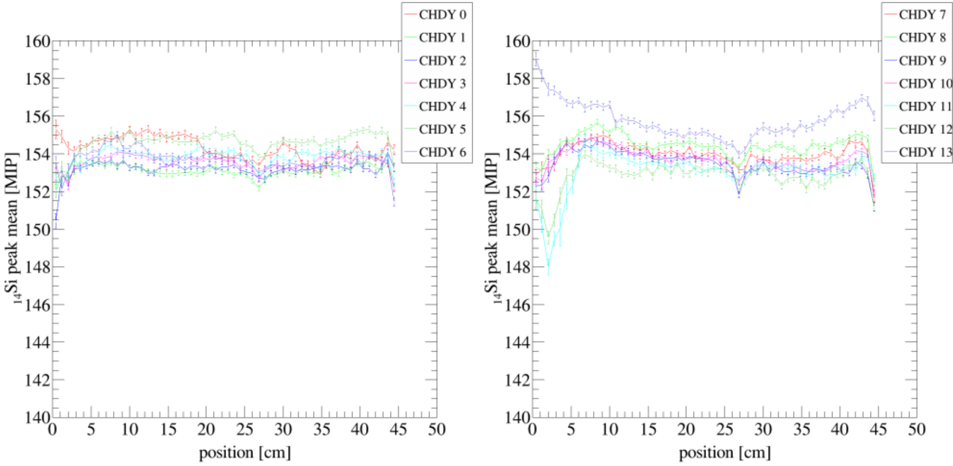


CHD $_{14}$Si Position Dependence

CHDX

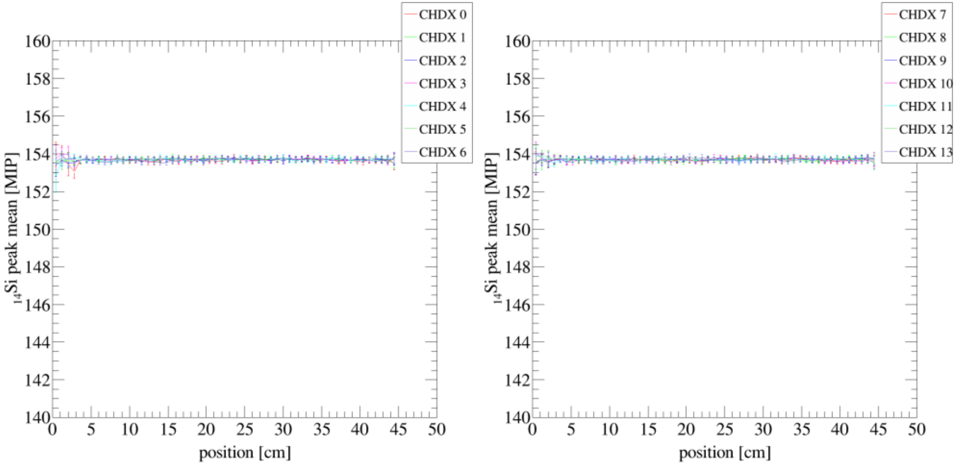


CHDY

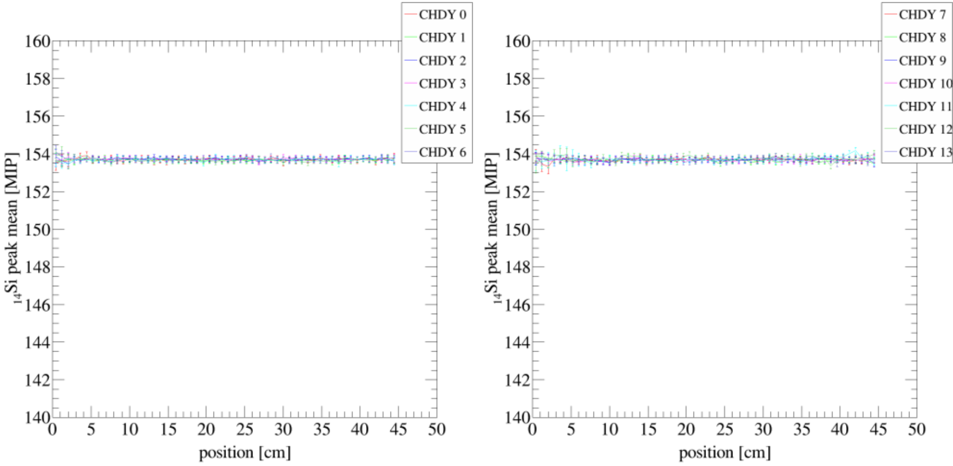


CHD $_{14}$Si After Position Correction

CHDX



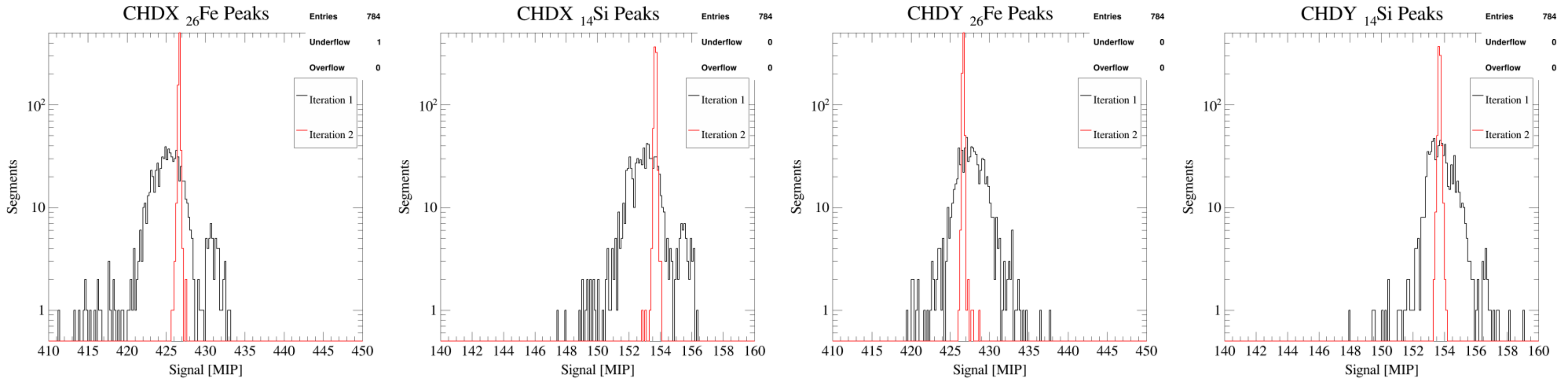
CHDY



CHD $_{14}$Si and $_{26}$Fe Peak Means

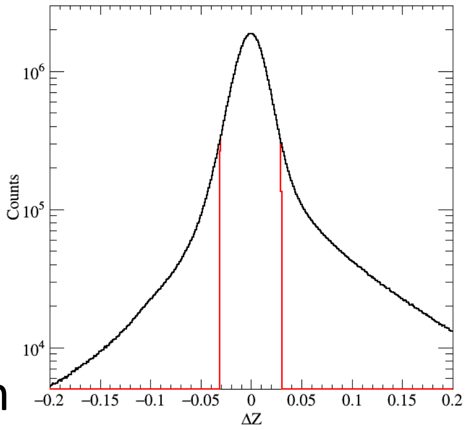
CHDX

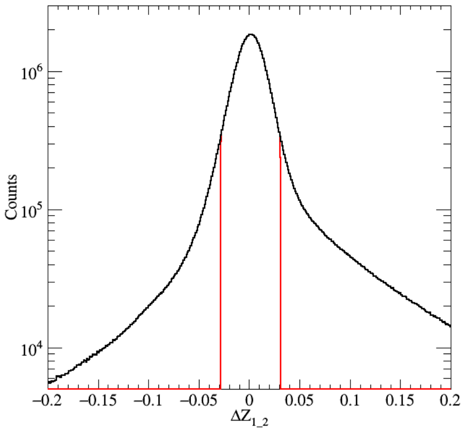
CHDY



Charge Consistency Selections

- Selection cut is made for charge estimate consistency between CHDX and CHDY
- $Z_{est} \propto \mathrm{CHD}^{1/1.7}$
- $\Delta Z=(Z_{CHDX}-Z_{CHDY})/(Z_{CHDX}+Z_{CHDY})$ for Z_{CHDX} and Z_{CHDY} total layer signals
- ΔZ_{1_2} uses Z_{CHDX} and Z_{CHDY} for sum of signals from two highest layer paddles
- ±2σ selections applied



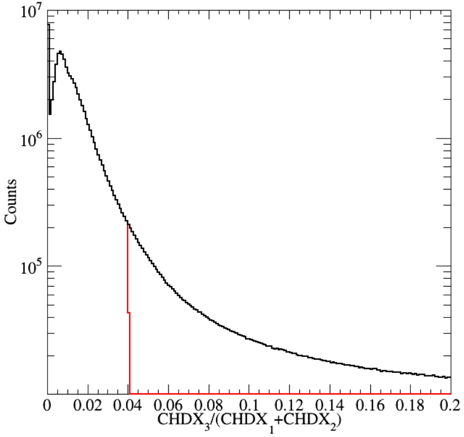


ΔZ selection Includes more signal from backscatter
ΔZ_{1_2} selection focused on primary particle track

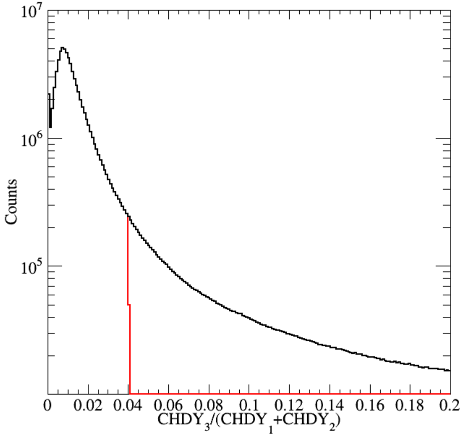
Paddle Dominance Selections

- Best charge estimate uses CHDX and CHDY signals from the two highest paddles
- Events with disproportionately high third paddle signals are selected
- $CHDX_3/(CHDX_1+CHDX_2) < 0.04$
- $CHDY_3/(CHDY_1+CHDY_2) < 0.04$

CHDX

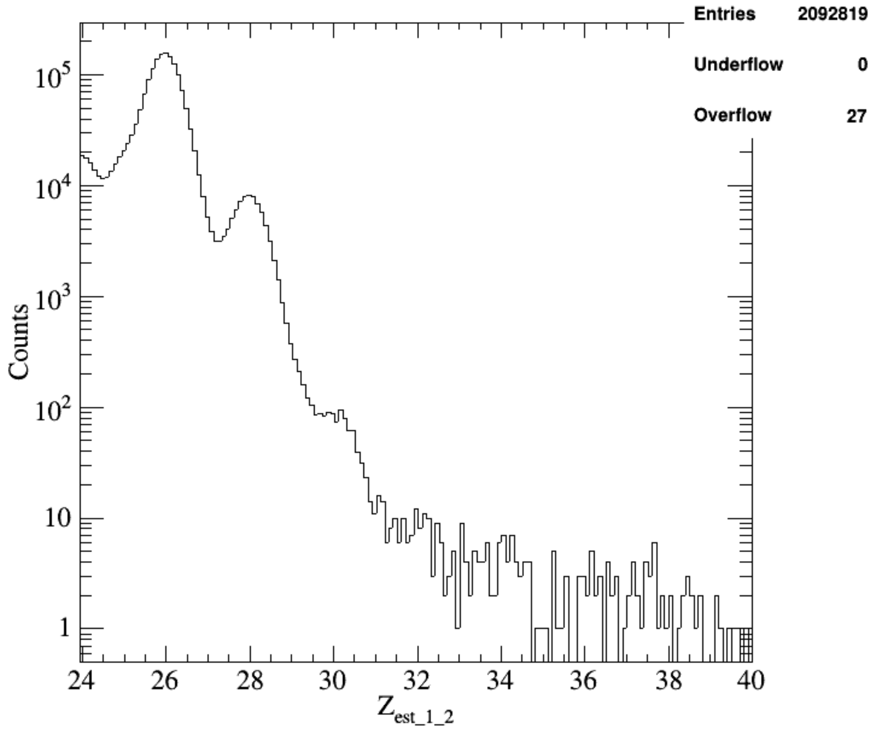


CHDY



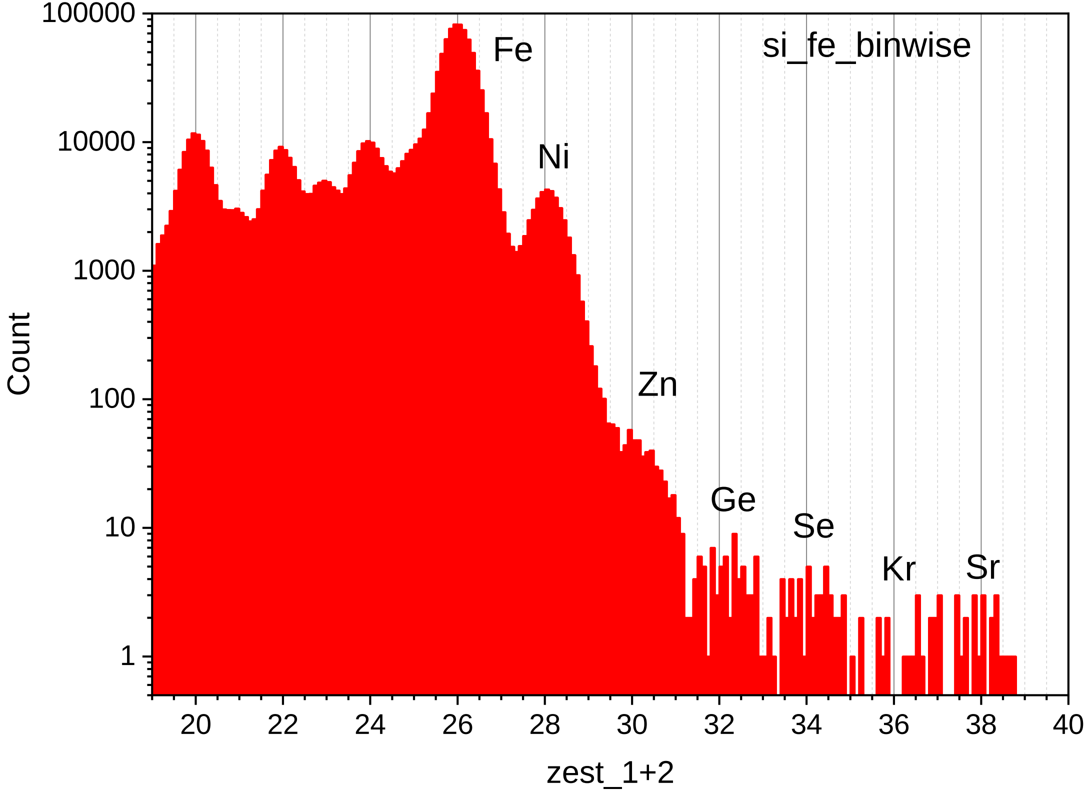
Current Analysis Charge Histogram

- Selections on ~3 year dataset:
  - Zest > 24
  - Theta < 45 deg
  - STRM > 4.0 GV
  - Z Consistency
  - Paddle dominance
  - IMC minimum
- We can clearly see well resolved peaks for $_{32}$Ge, $_{34}$Se, and $_{38}$Sr.
- $_{30}$Zn is more than a shoulder, but is not clearly resolved. Even a small improvement in resolution would help a lot here.
- More statistics should be a major help in better defining the peaks
- Geomagnetic cutoff for each trajectory should help in rejecting low energy particles that are very likely broadening the distributions.



Reduced Dataset Charge Histogram

- Selections on 17 month dataset:
  - Zest > 19
  - Theta < 45 deg
  - STRM > 4.5 GV
  - Z Consistency
  - IMC Energy Correction
- We can clearly see well resolved peaks for $_{32}$Ge, $_{34}$Se, and $_{38}$Sr.
- $_{30}$Zn is more than a shoulder, but is not clearly resolved. Even a small improvement in resolution would help a lot here.
- More statistics should be a major help in better defining the peaks
- Geomagnetic cutoff for each trajectory should help in rejecting low energy particles that are very likely broadening the distributions.



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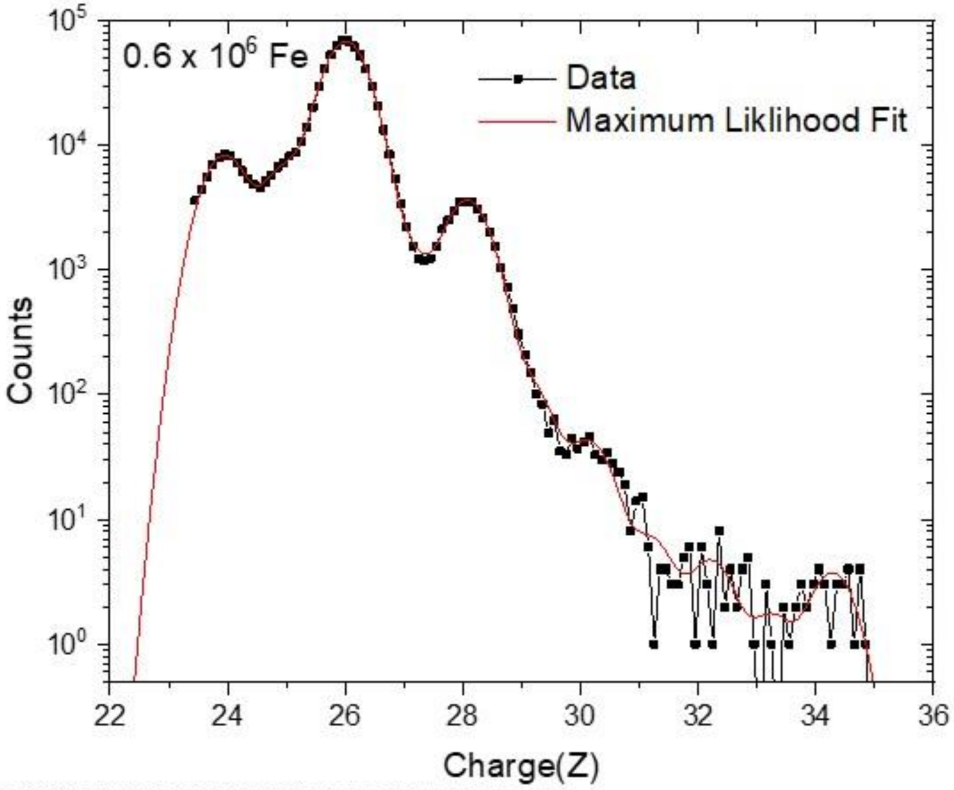
Event Distribution

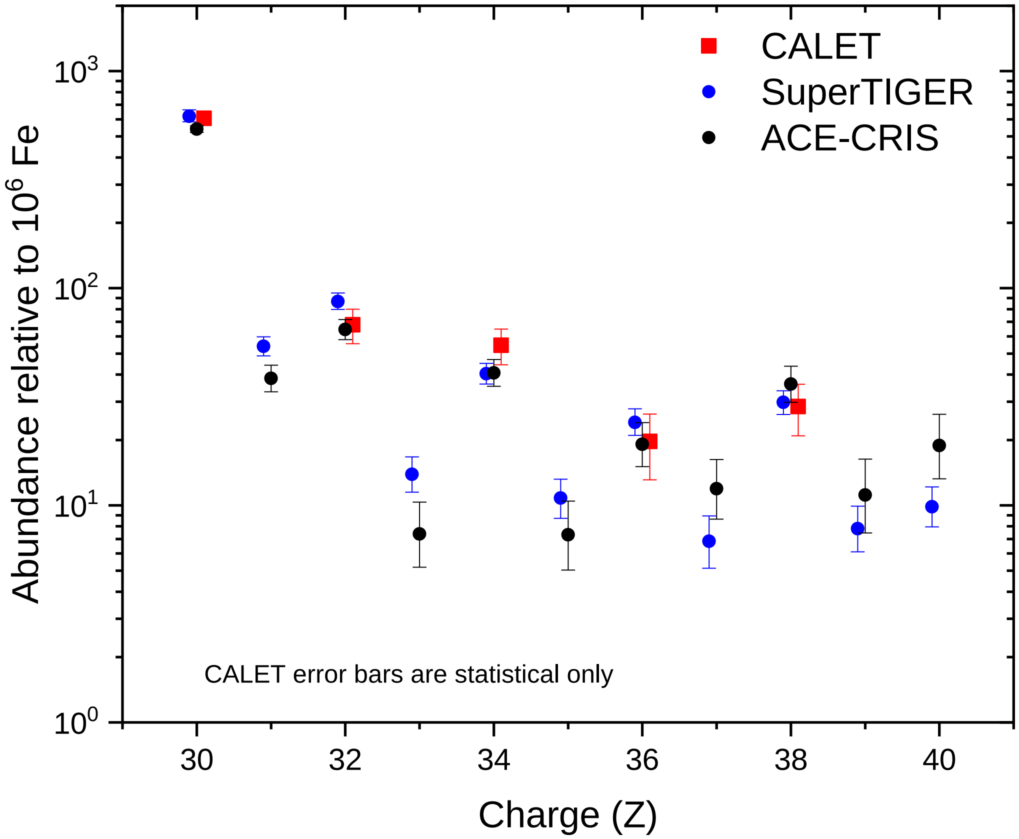
- To estimate the abundances detected, we used a maximum likelihood fitting routine to fit the data.
- Fits reasonably good up to $_{34}$Se.
- For higher charges, the low statistics resulted in poor fits.
- For even-Zs above $_{34}$Se ($_{36}$Kr & $_{38}$Sr) the abundances were initially estimated by taking cuts in the valleys.
- Using SuperTIGER abundances, half of the odd-Zs on either side of the even-Z charge was subtracted off of the $_{36}$Kr & $_{38}$Sr numbers to estimate their abundances.



E:\CALET\Data Brian 12.17.2018 interpolated\si fe binwise correction\4th try selections\5th try at fitting\Fit figure

Comparing Relative Abundances

- The ACE and ST data are "in-space" abundances.
- The CALET data have not yet been corrected to the top of the instrument.
  - Those corrections will be small, so they will not change things materially.
- The agreement with ST and ACE-CRIS appears to be quite good.
- Additional data and anticipated improved resolution should result in reduced error bars.



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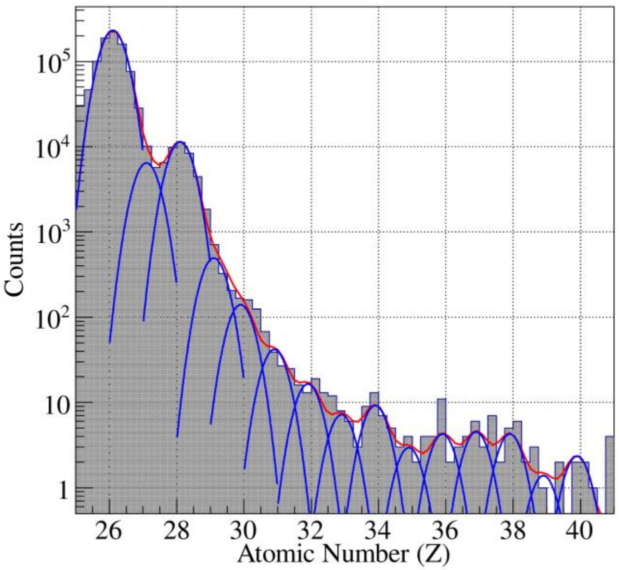
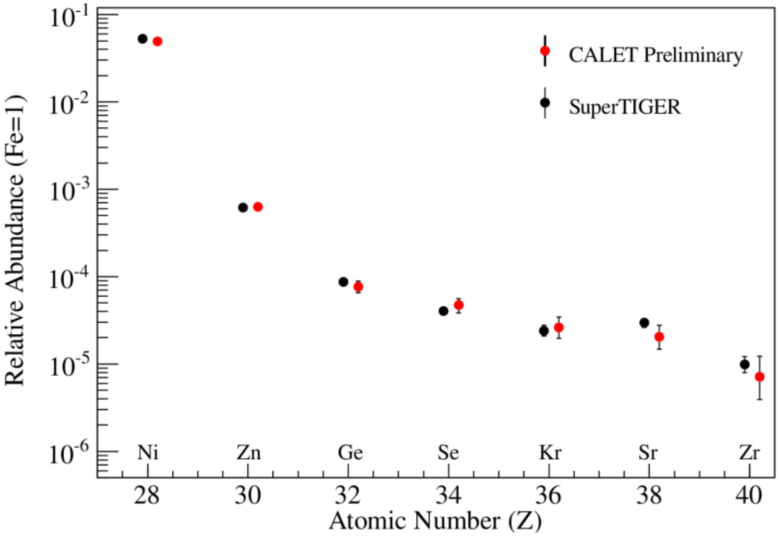
2017 CALET UH ICRC Results

Selections on ~13 month dataset:

- Zest > 24
- Theta < 60 deg
- STRM > 4.0 GV
- Z Consistency

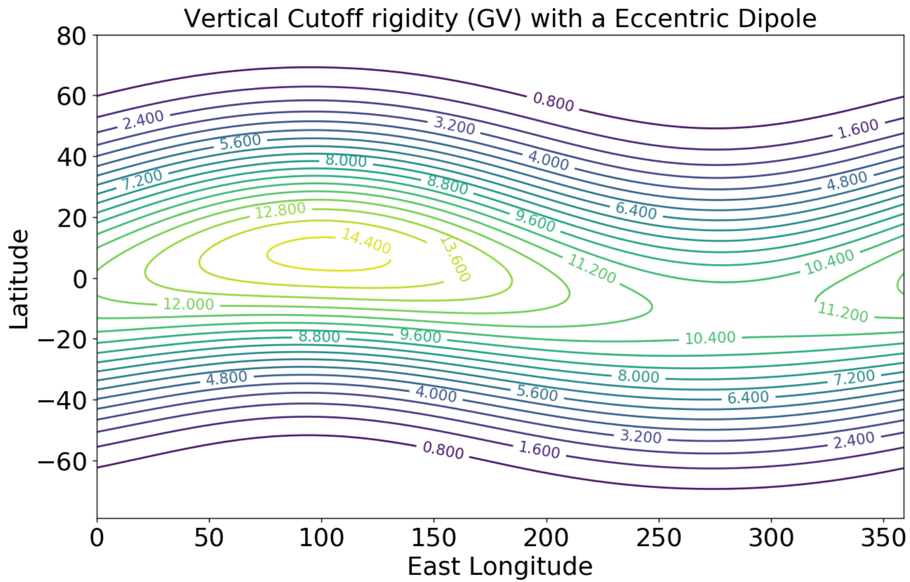
Abundances fit to integer centered charges with fixed σ = 0.35

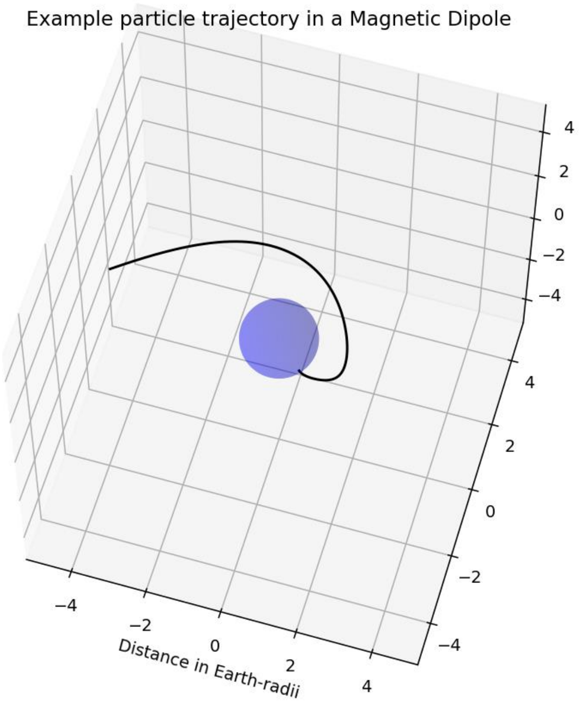




Trajectory Based Rigidity Threshold

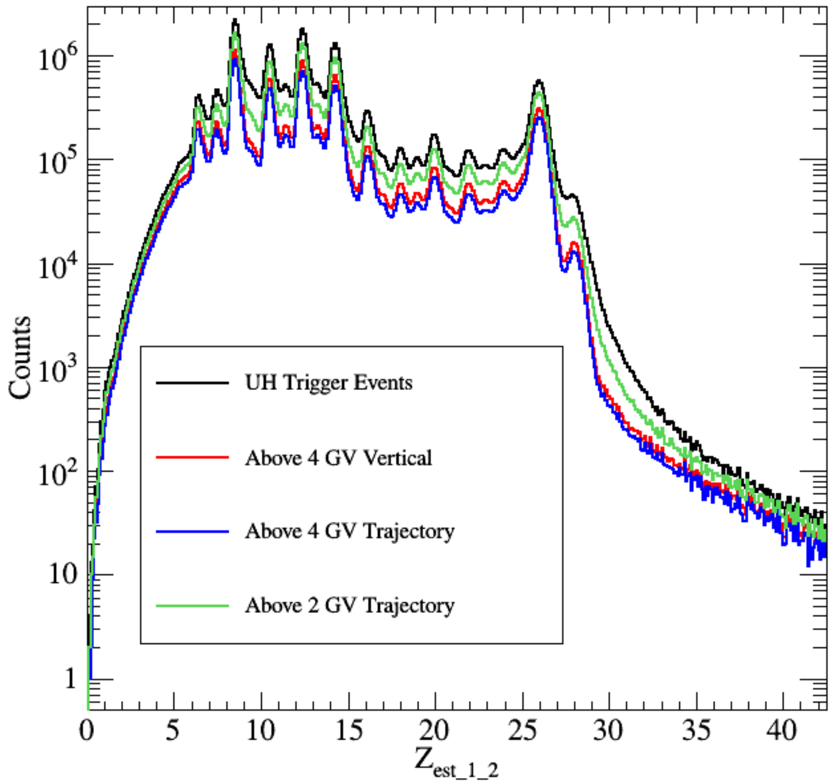
Work is ongoing on determining event trajectory based geomagnetic rigidity cutoffs. These will allow a more targeted energy threshold selection that will maximize statistics.





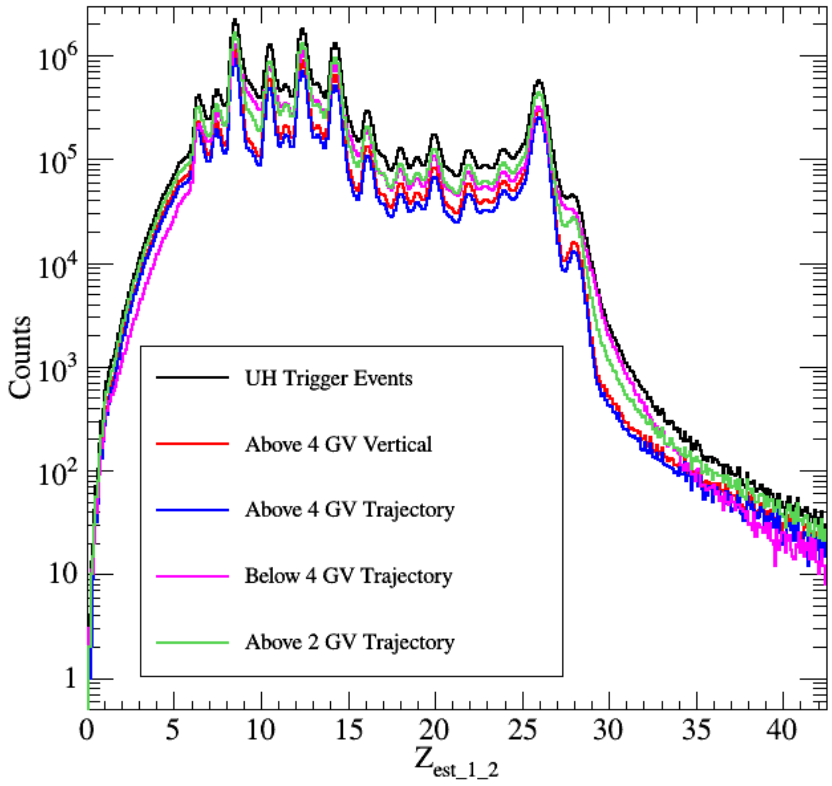
Trajectory Dependent Rigidity!

- Trajectory dependent rigidity using Wolfgang Zober's approximate geomagnetic model works!
- Can be used instead of vertical rigidity selection.



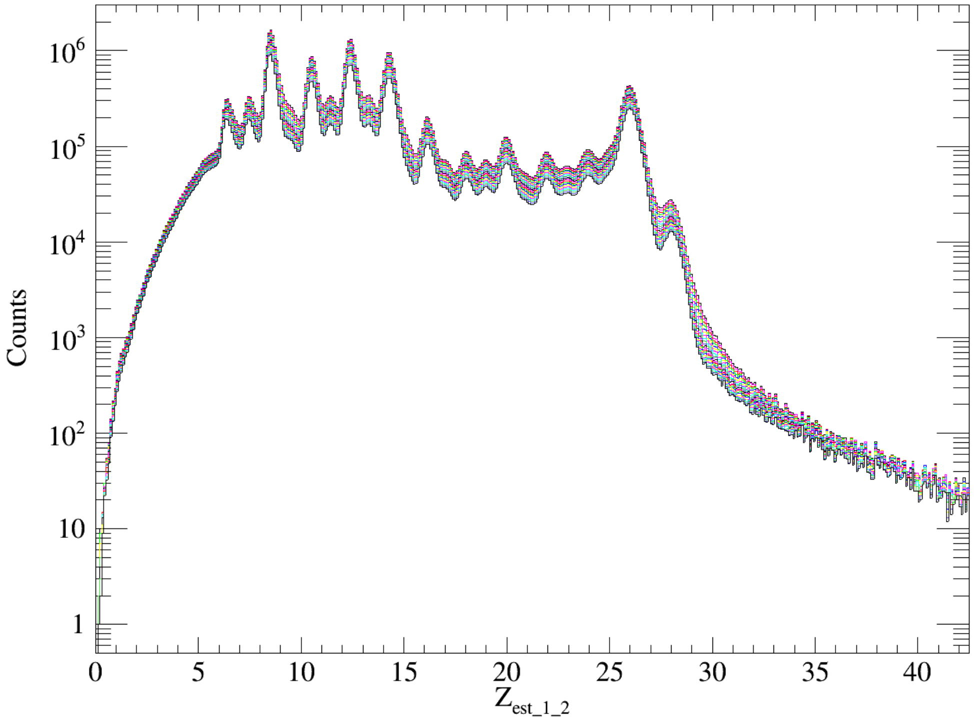
Trajectory Dependent Rigidity!

- Trajectory dependent rigidity using Wolfgang Zober's approximate geomagnetic model works!
- Can be used instead of vertical rigidity selection.
- Resolution better at higher rigidities.



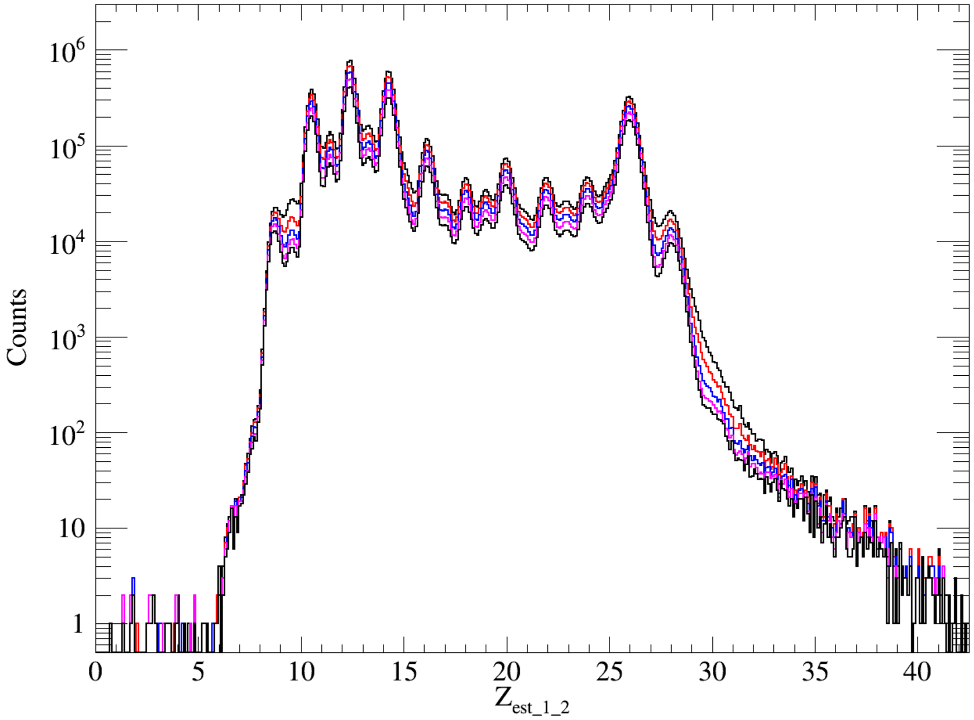
Trajectory Dependent Rigidity 2-4 GV

- UH Trigger histograms for events above 2 to 4 GV in 0.1 GV steps.
- Need to optimize rigidity cut to balance statistics with tail spillover.
- No other selections here.



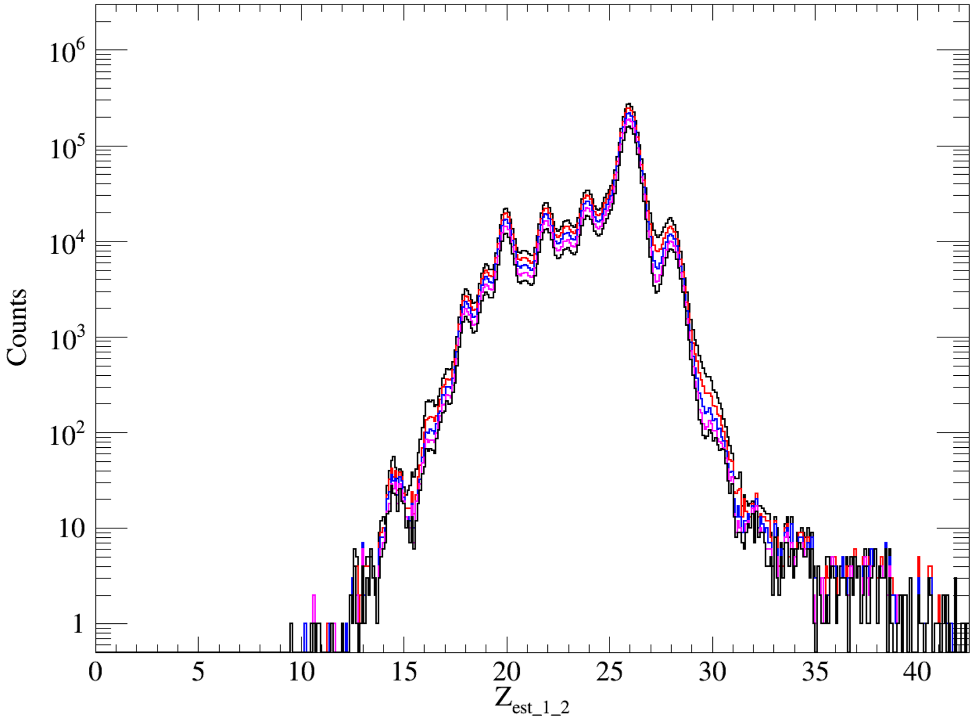
Trajectory Dependent Rigidity 2-4 GV

- UH Trigger histograms for events above 2 to 4 GV in 0.5 GV steps.
- Applied most of Bob's selections:
  - Theta < 45 deg
  - STRM > 4.0 GV
  - Z Consistency
  - Paddle dominance
- Still major tails



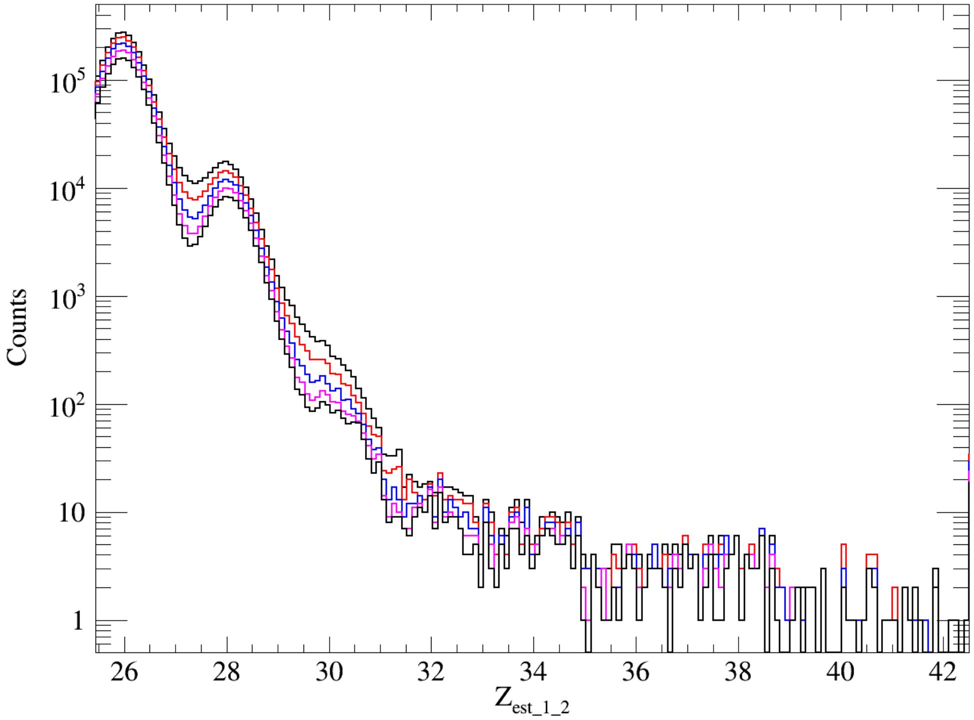
Trajectory Dependent Rigidity 2-4 GV

- UH Trigger histograms for events above 2 to 4 GV in 0.5 GV steps.
- Applied most of Bob's selections:
  - Theta < 45 deg
  - STRM > 4.0 GV
  - Z Consistency
  - Paddle dominance
  - IMC minimum
- Strong cut on tails and on lower charges.



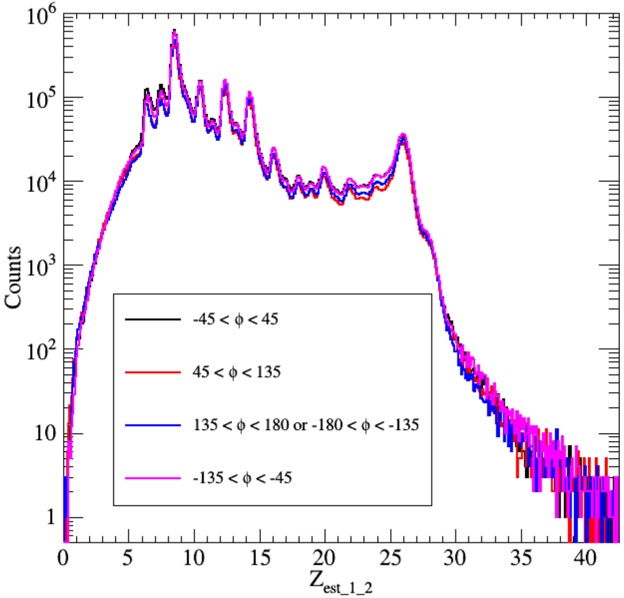
Trajectory Dependent 2-4 GV: UH Range

- UH Trigger histograms for events above 2 to 4 GV in 0.5 GV steps.
- Applied most of Bob's selections:
  - Theta < 45 deg
  - STRM > 4.0 GV
  - Z Consistency
  - Paddle dominance
  - IMC minimum
- Need refined IMC selection that reduces tails without charge bias.

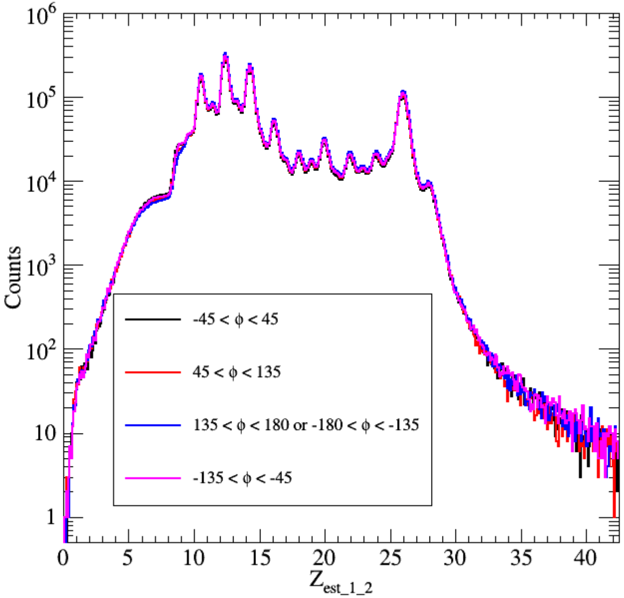


UH Sensitivity to Obstructions

Incidence Angle > 45˚



Incidence Angle < 45˚



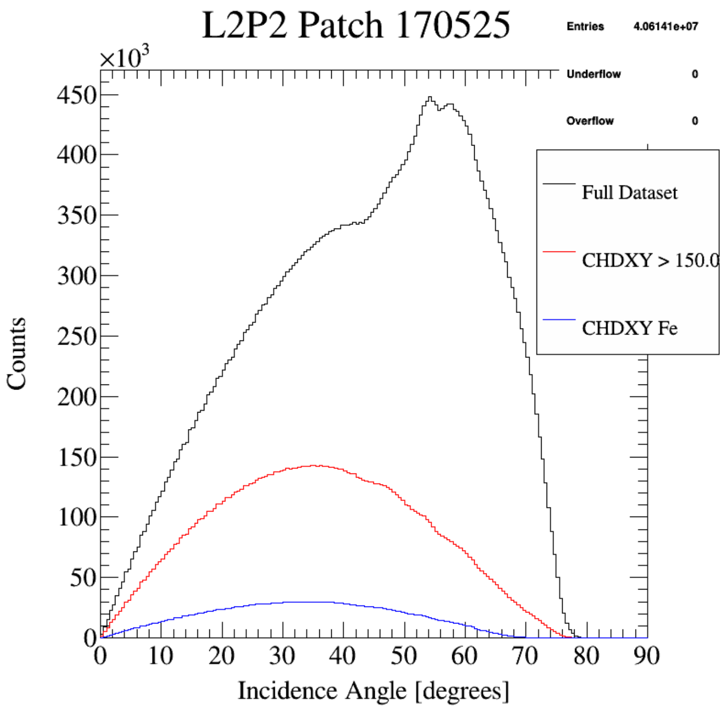
Future Work

- Acquire and analyze Level 2 Pass 4 data. Generate new:
  - CHD $_{26}$Fe peak based time corrections
  - CHD $_{14}$Si and $_{26}$Fe peaks position corrections
  - Charge assignments Z(ΔCHD,θ)
  - CHD charge consistency selections
  - IMC selection.
- Implement selection cuts to eliminate ISS obstructions.
- With Wolfgang Zober:
  - Trajectory based rigidity selections using individual event ray-tracing.
  - UHCR analysis using HE trigger events with TASC information.

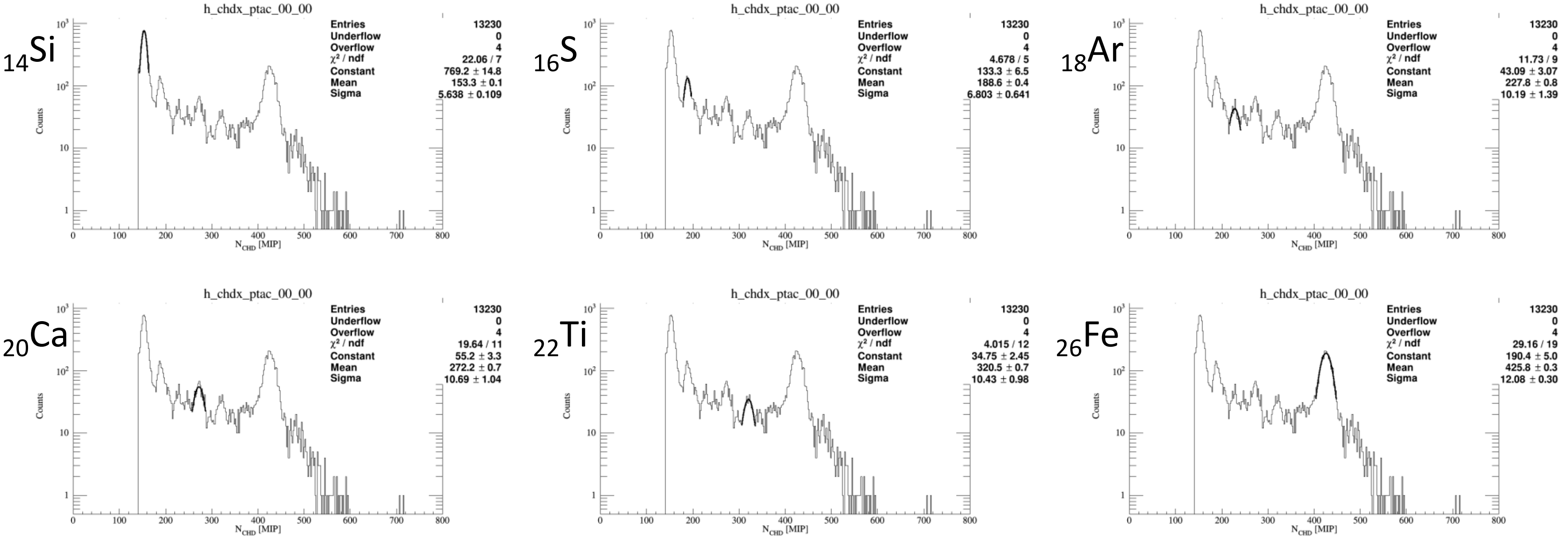
Backup Slides

ΔCHD/<CHD> vs ϴ Dataset

- Partition UH dataset
  - Limit to $_{14}$Si and up to limit incidence angle dependence by selecting:
    CHDX > 150 and CHDY > 150
  - 30 equal statistics bins in incidence angle:
    $0° < \theta < 68°$
  - 30 equal statistics bins in relative CHD signal:
    $$-0.076 < \frac{\Delta CHD}{\langle CHD \rangle} < 0.076$$

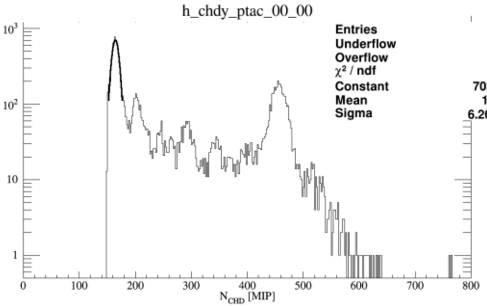


CHDX Selected Even Peak Fitting

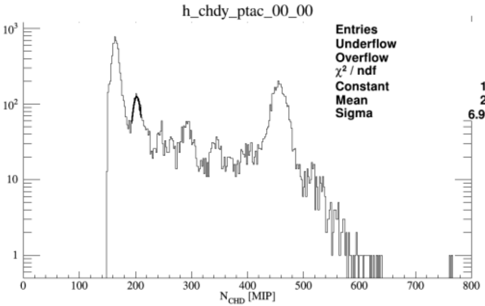


CHDY Selected Even Peak Fitting

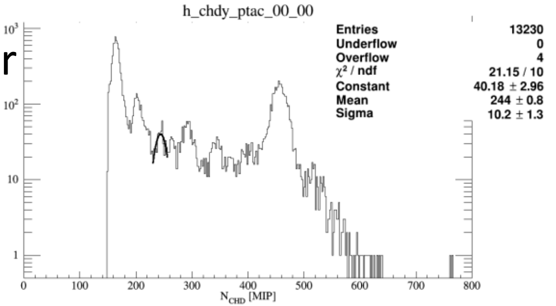
$_{14}$Si



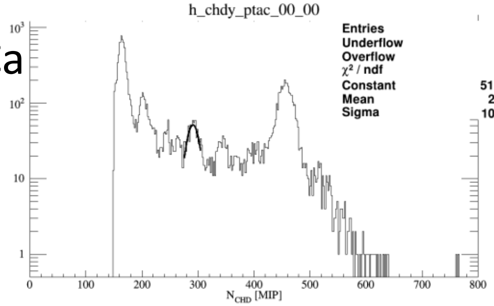
$_{16}$S



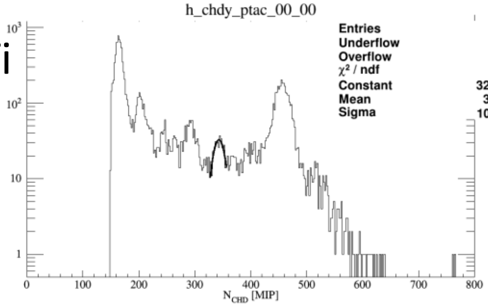
$_{18}$Ar



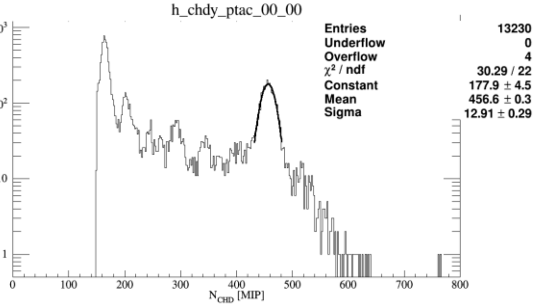
$_{20}$Ca



$_{22}$Ti



$_{26}$Fe



Selected Charge Models

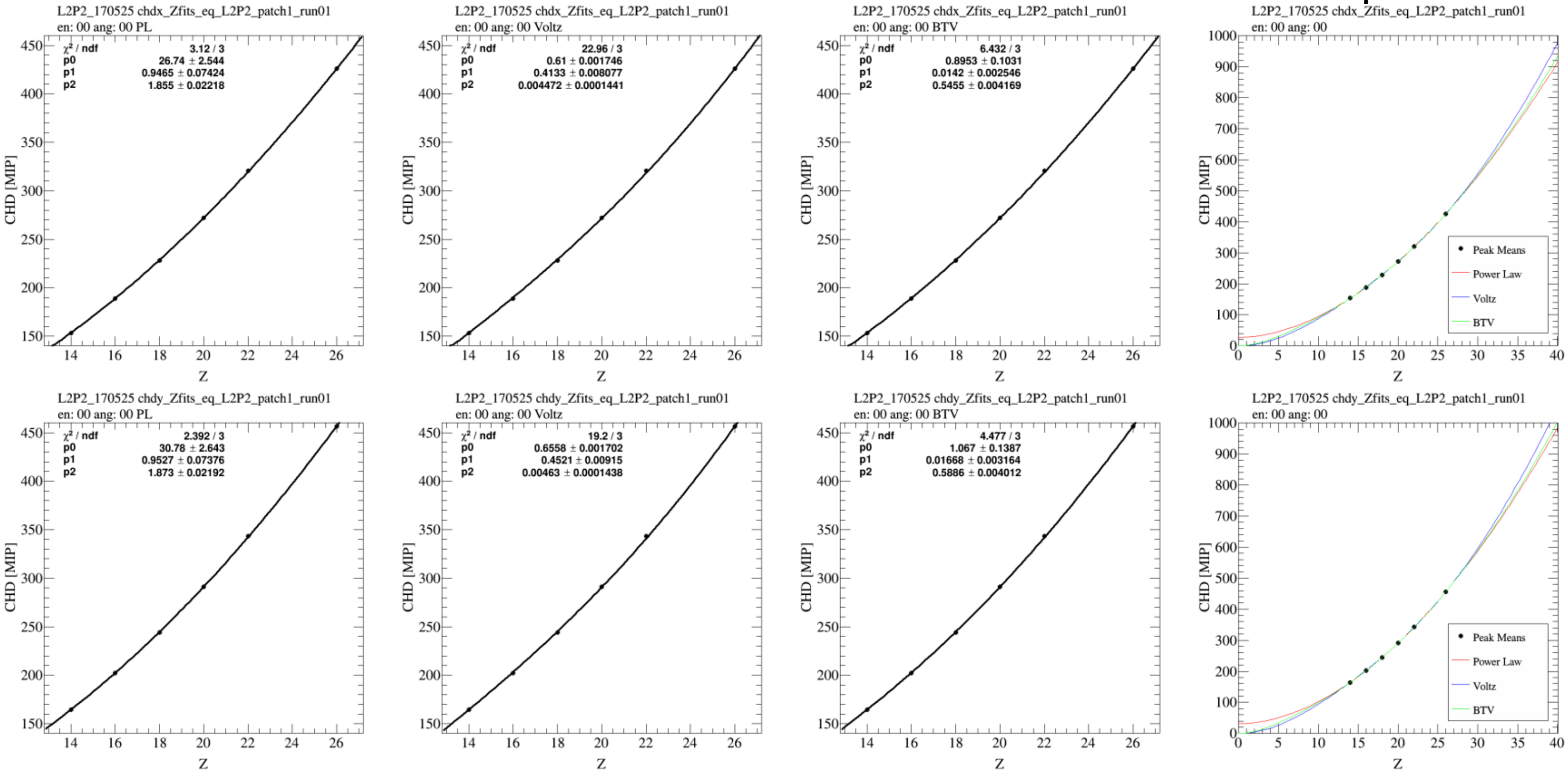
- Power Law - CALET NIM:
  $CHD = A + BZ^C$
- Voltz Model - TIGER/SuperTIGER analysis:
  $$\frac{dL}{dx} = As\frac{dE}{dx}(1 - Fs)e^{-B_s(1-Fs)\frac{dE}{dx}} + A_s\frac{dE}{dx}\mathrm{F_s}$$
  Assuming constant energy: $CHD = AZ^2\, e^{BZ^2} + CZ^2$
- BTV Model - CALET NIM/SuperTIGER analysis:
  $$\frac{dL}{dx} = As\frac{dE}{dx}(1 - Fs)/(1 + Bs\frac{dE}{dx}(1 - Fs)) + A_s\frac{dE}{dx}\mathrm{F_s}$$
  Assuming constant energy: $CHD = AZ^2/(1 + BZ^2) + CZ^2$

Charge Model Fits

Power Law | Voltz | BTV | Comparison

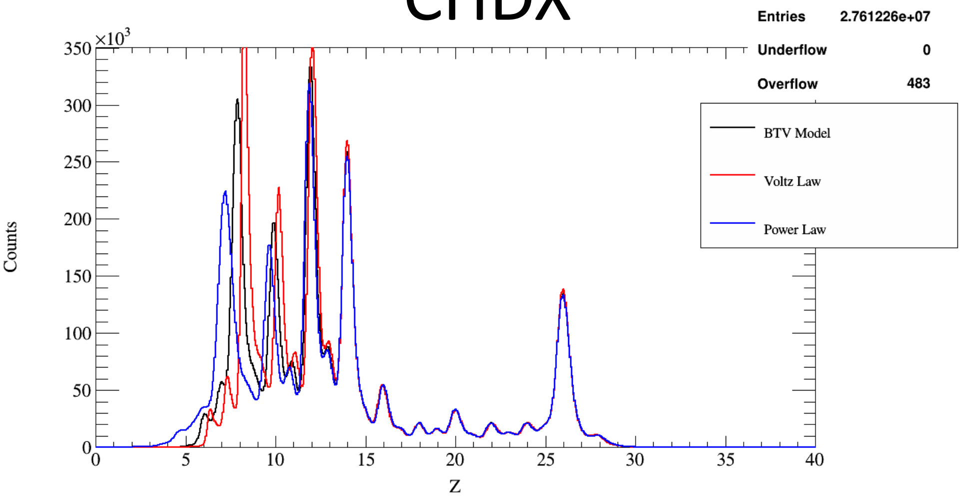
CHDX

CHDY

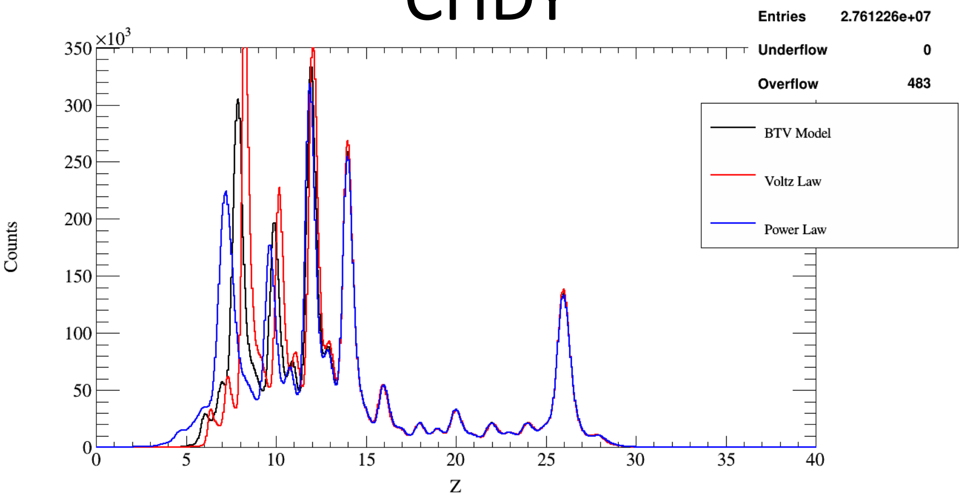


Comparing Charge Assignments

CHDX

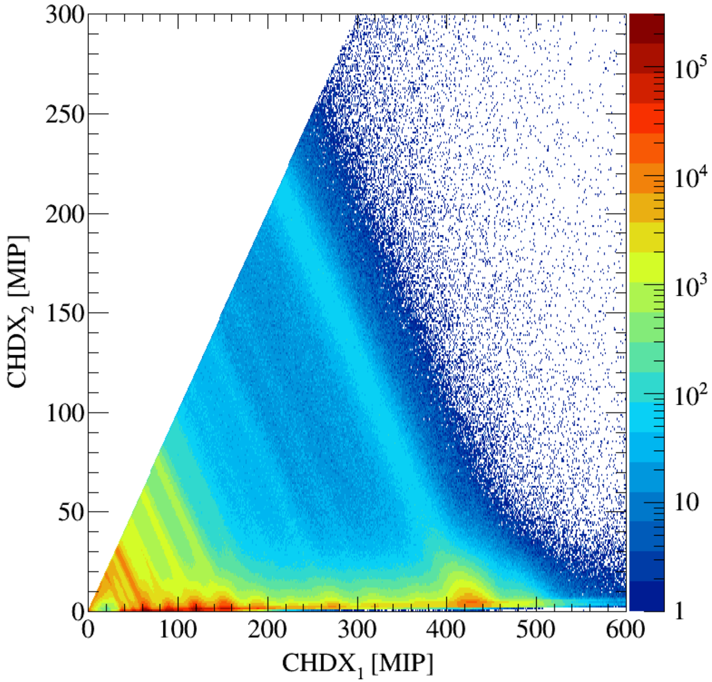


CHDY

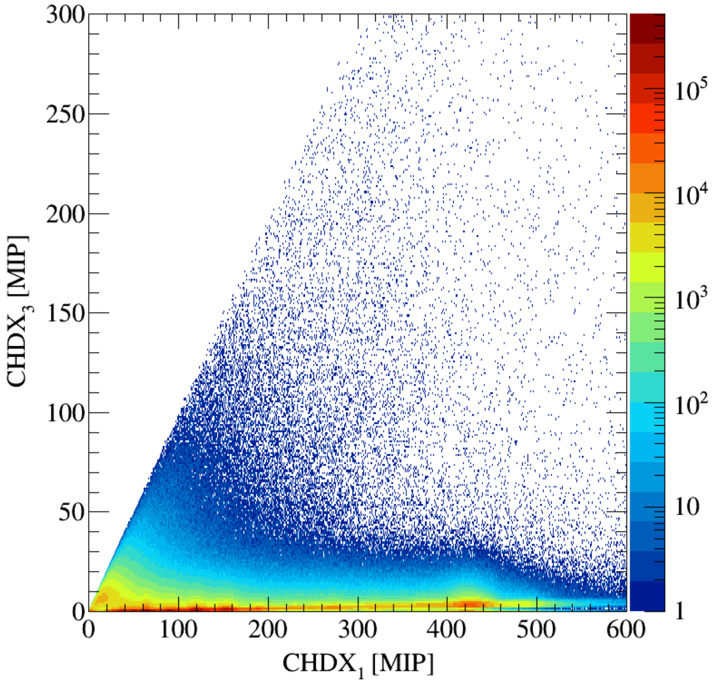


- Three charge assignments agree well within the range of the peaks fit for the models, but diverge outside of this region.
- None of the models has peaks aligned with the appropriate low-Z charges.
- Voltz model charge assignment has best low-Z resolution, which is why it has been used previously in TIGER and SuperTIGER UH analyses.

Handling Cross Paddle Events

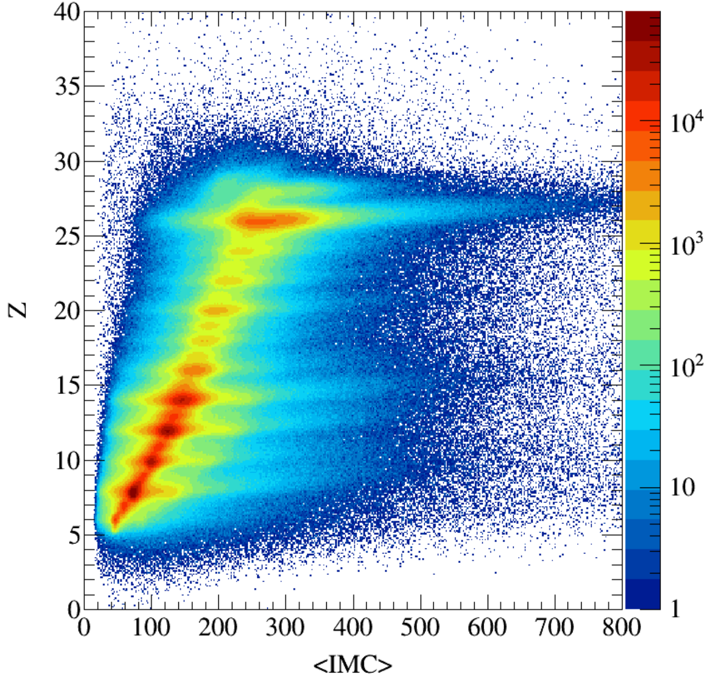


Second highest paddle versus first showing cross paddle events.

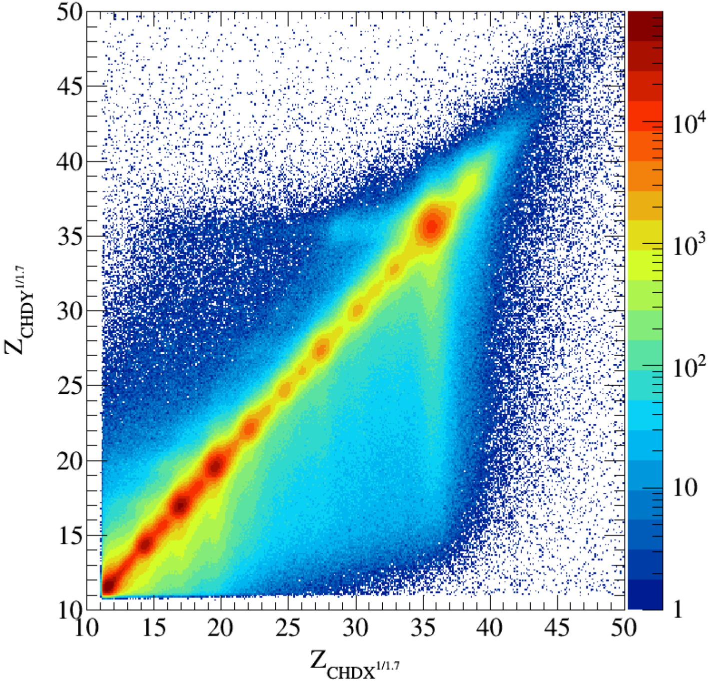


Third highest paddle versus first showing background.

Next Corrections and Selections



There is some IMC dependence in the latest charge assignment that might be corrected.



Use charge consistency selections earlier in the analysis.