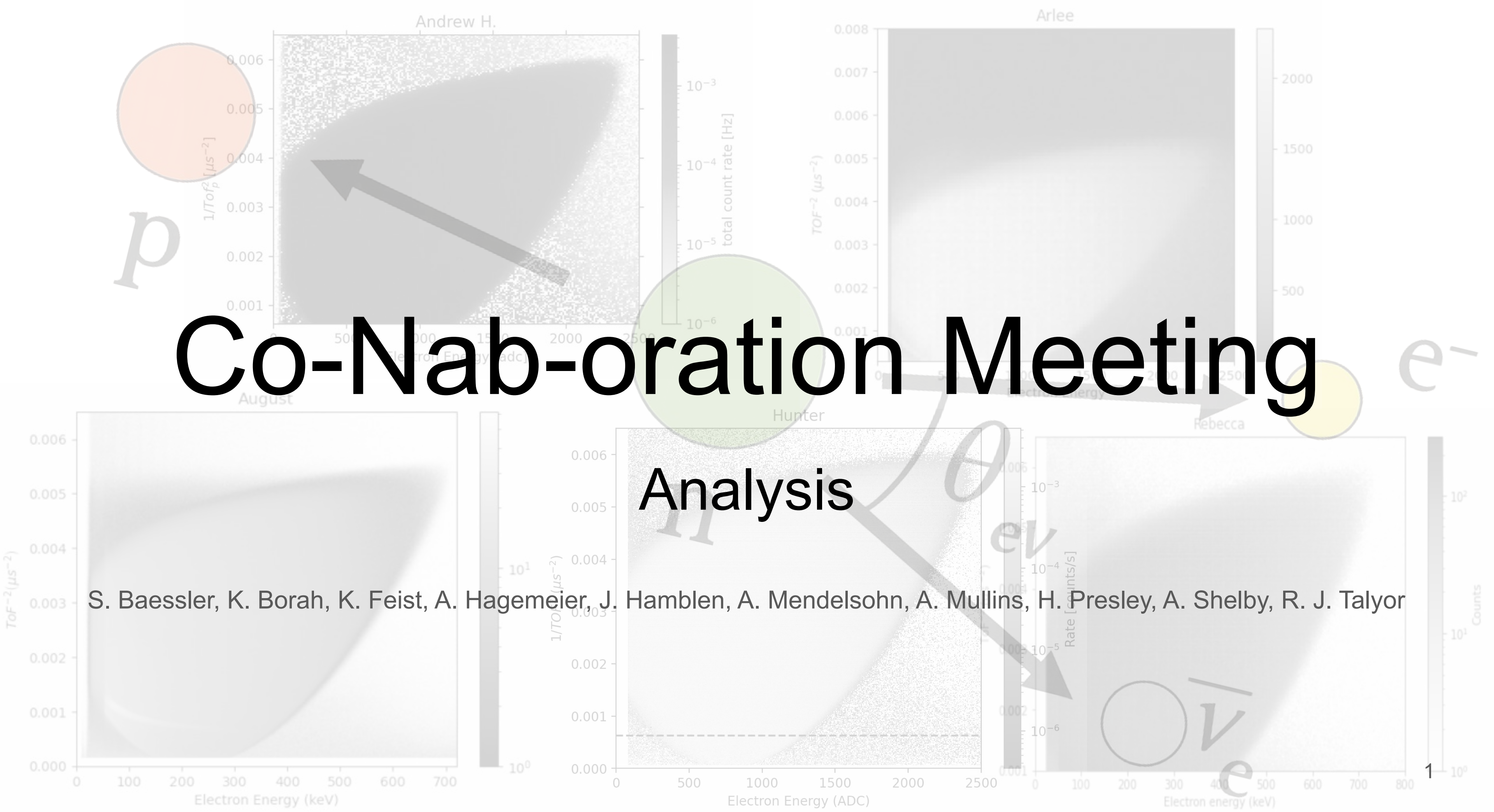


Co-Nab-oration Meeting

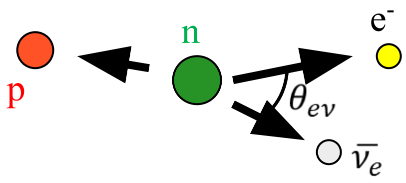
Analysis

S. Baessler, K. Borah, K. Feist, A. Hagemeier, J. Hamblen, A. Mendelsohn, A. Mullins, H. Presley, A. Shelby, R. J. Talyor

Intro To Analysis

Stefan Baeßler

Idea of Nab experiment



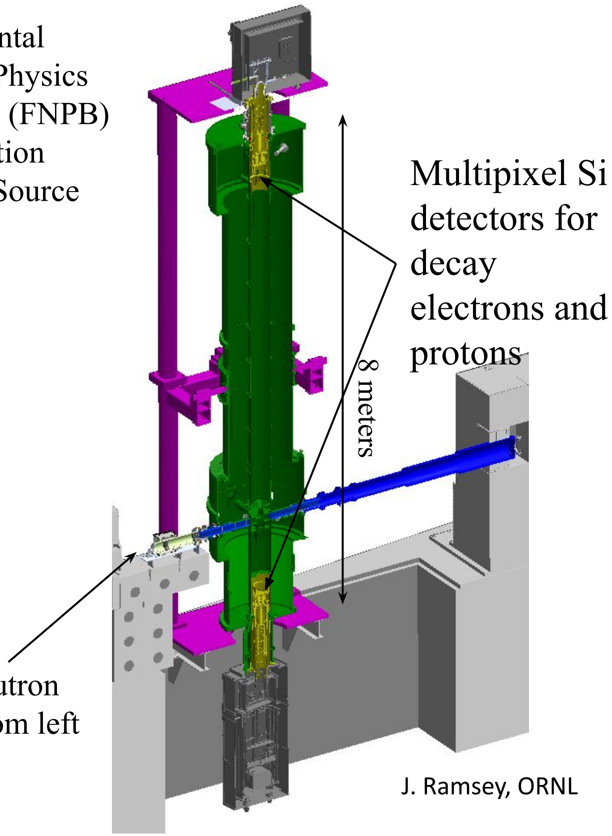
$$d\Gamma \propto \varrho(E_e)\left(1 + a\frac{p_e}{E_e}\cos\theta_{ev} + b\frac{m_e}{E_e}\right)$$

Measurement of electron energy spectrum gives the Fierz term b.

Measurement of a from measurement of proton and electron energy.

General Idea: J.D. Bowman, Journ. Res. NIST 110, 40 (2005)
Original configuration: D. Počanić et al., NIM A 611, 211 (2009)
Asymmetric configuration: S. Baeßler et al., J. Phys. G 41, 114003 (2014)
Si Detector: L.J. Broussard et al., Nucl. Inst. Meth. A 849, 83 (2017) and Hyperfine Int. 240,1 (2019)
Simulated Spectrometer Performance: J. Fry et al., EPJ WOC 219, 04002 (2019)

Nab @ Fundamental Neutron Physics Beamline (FNPB) @ Spallation Neutron Source (SNS)



J. Ramsey, ORNL

pNab: Measurement of correlation coefficients with polarized neutrons

b or b_ν may indicate S,T

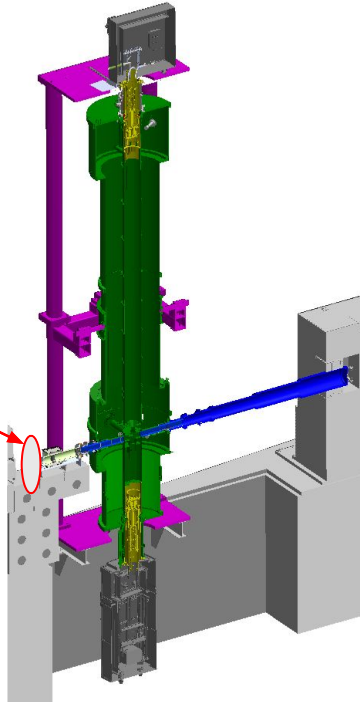
$B_0 \neq B_0(\lambda)$ may indicate V+A

$$d\Gamma \propto \varrho(E_e)\left(1 + a\frac{p_e}{E_e}\cos(\vec{p}_\nu,\vec{p}_e) + b\frac{m_e}{E_e} + A\frac{p_e}{E_e}\cos(\vec{\sigma}_n,\vec{p}_e) + \left(B_0 + b_\nu\frac{m_e}{E_e}\right)\cos(\vec{\sigma}_n,\vec{p}_\nu)\right)$$

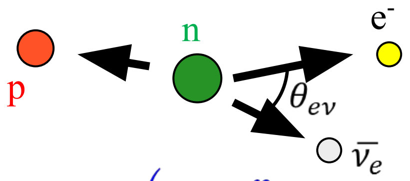
$a = a(\lambda)$

$A = A(\lambda)$

New addition: Neutron beam polarizer



Idea of the cos θ_{ev} spectrometer Nab @ SNS

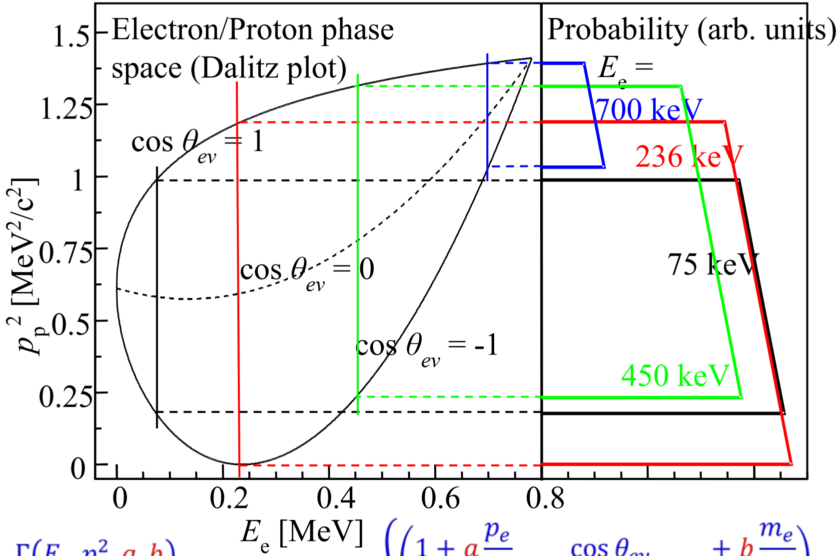


$$d\Gamma \propto \varrho(E_e)\left(1 + a\frac{p_e}{E_e}\cos\theta_{ev} + b\frac{m_e}{E_e}\right)$$

- Energy Conservation in Infinite Nuclear Mass Approximation: $E_\nu = E_{e,max} - E_e$
- Momentum Conservation:

$$p_p^2 = p_e^2 + p_\nu^2 + 2p_e p_\nu \cos\theta_{ev}$$

(p_p is inferred from proton time-of-flight)



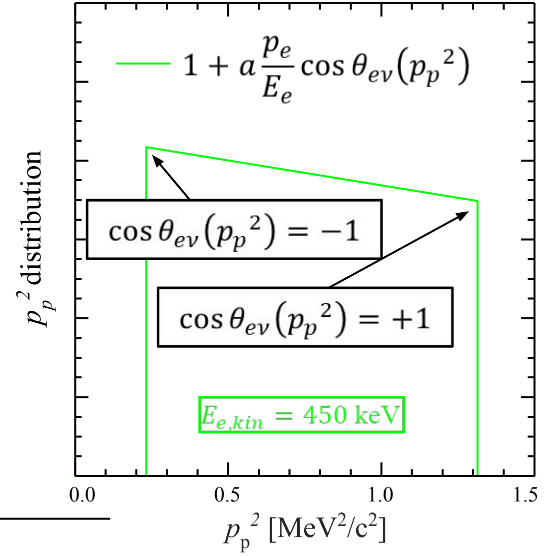
Properties of $p_p{}^2$ distribution for fixed E_e:

Edges $\left(p_p{}^2\right)_{min,max} = (p_e \pm p_\nu)^2$

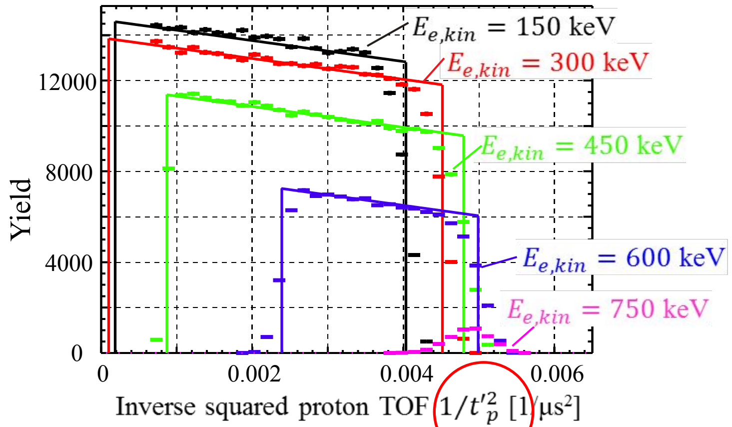
Slope $\propto a$

$$\frac{\Gamma(E_e, p_p^2, a, b)}{dE_e\, dp_p^2} = \underbrace{\frac{\varrho'(E_e)}{\varrho(E_e)\cdot\frac{d\cos\theta_{ev}}{dp_p^2}}} \cdot \begin{cases} \left(1 + a\frac{p_e}{E_e}\underbrace{\cos\theta_{ev}}_{(p_p^2 - p_e^2 - p_\nu^2)/2p_e p_\nu} + b\frac{m_e}{E_e}\right) & \text{for } -1 \le \underbrace{\cos\theta_{ev}}_{(p_p^2 - p_e^2 - p_\nu^2)/2p_e p_\nu} \le 1 \\ 0 & \text{otherwise} \end{cases}$$

Simulated Nab data analysis



Full GEANT4 spectrometer simulation:



$$t_p = \frac{m_p \cdot \text{spectrometer length}}{p_p\text{−component along } \vec{B}}$$ (see here)

We will discuss the mapping $t_p \to t_p'$ later

(w/o, we don't have trapeziums)

Connections to observables

Neither E_e nor p_p^2 is actually observable. The actual determination of a requires a fit to

$$P\left(\frac{1}{t_p^2}, E_{e,rec}\right) = N \int_0^{E_{e,max}} \Phi_E(E_{e,rec}, E_e) \int_{p_{p,min}^2}^{p_{p,max}^2} \Phi_t\left(\frac{1}{t_p^2}, p_p^2\right) \Gamma(E_e, p_p^2, a, b) dp_p^2 \, dE_e$$

Electron energy response function $\boldsymbol{\Phi_E(E_{e,rec}, E_e)}$: We try to reconstruct electron energy from the energy deposit of the electrons in the detector, eventually by summing over multiple hits. This can be described with an electron energy response function $\Phi_E(E_{e,rec}, E_e)$, which connects reconstructed $E_{e,rec}$ and electron energy at decay E_e.

Proton momentum response function $\boldsymbol{\Phi_t(1/t_p^2, p_p^2)}$: Similarly, we estimate the squared proton momentum from a measurement of the squared inverse proton time-of-flight. We advertised our spectrometer with the statement that the width of $\Phi_t(1/t_p^2, p_p^2)$ for given p_p^2 is only a few percent. The various fit methods differ by how they obtain this function.

Latest writeups: Method A, Method B, Method F (Frank), Method C (David B.)

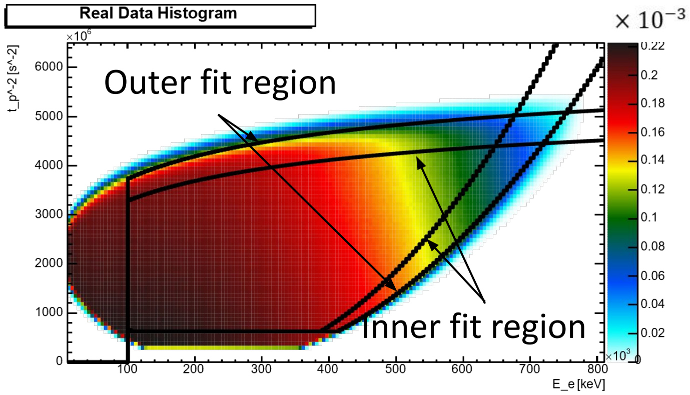
(Frank's recent summary of his use of methods A and F is here)

Equation above needs verification from Monte-Carlo, it misses correlation of the response function due to the correlations between proton and electron impact angle, and due to radial coordinate of impact position. So far, that passes only for the case w/o electric field (although the issue may be in the fit model and the mapping that is part of that, not in the equation above – Jason, Stefan, needs work)

Data processing: the path to "filling a teardrop", cont.

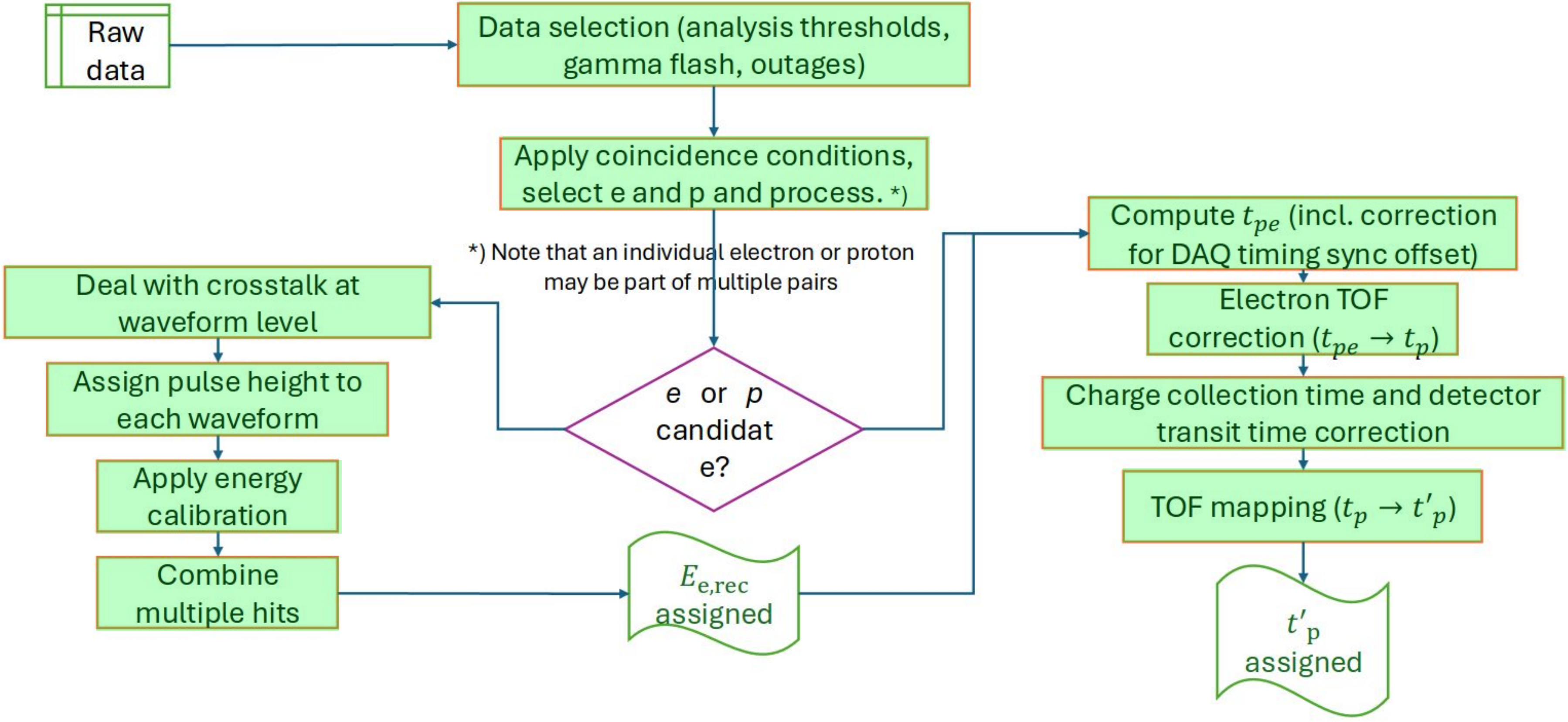
And finally, we have to choose the fit region. Different fit methods have different requirements.

- Inner fit region: Not very sensitive to detector response, but to "a" coefficient (the "slopes")
- Difference between inner and outer fit region: The edges, sensitive to detector TOF response.

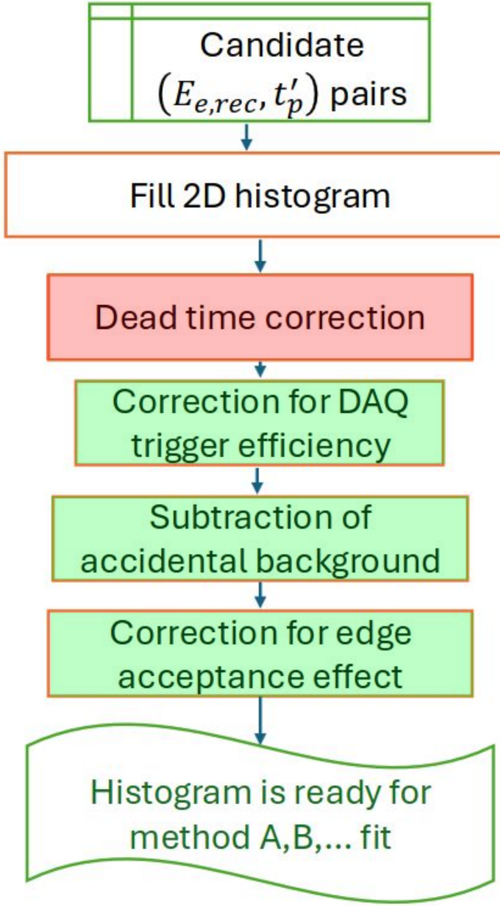


Simulated data from F. Gonzalez, ORNL

Offline physics analysis workflow



Physics analysis workflow, cont.



Nab Starter Exercise

- High barrier to entry with regards to data analysis
  - # of accounts required - many
  - Data and file structures to understand - also many
  - Undergrads don’t always have the free time to get over the initial analysis hump
- Simple exercise that lets new members of the group make a teardrop!
  - Link to theory teardrop code on the wiki
  - Small csv file with processed data
  - Coincidence and backscatter logic already included
  - Goal of exercise: produce a teardrop similar to that from the theory code with the included data
    - README includes guidance and tips for getting there

Starter Exercise (Irony: you need an account to access)

Analysis Teams

- Student-centric analysis meetings started 08/19/2025
- Two analysis teams formed (not finalized) with onsite folks interested in analyzing data all the way to little ‘a’
  - Anyone is welcome to join a team! Not limited to onsite personnel of course.
- The boundaries for what teams share/silo are completely undefined as of now
- Our goal is to have each team member **develop analysis machinery** to produce **physics corrected teardrop** ready for ‘a’ fitting before truly branching off into separate teams

Flowchart
(Click me)

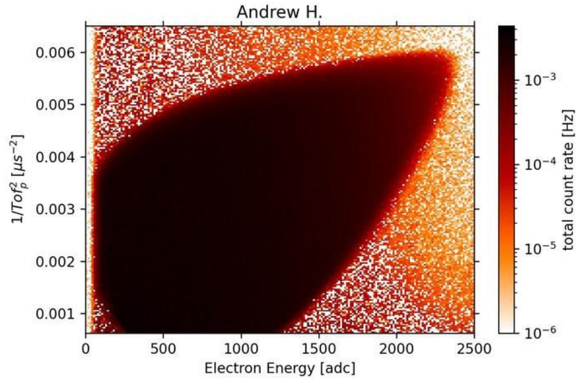
Analysis Teams

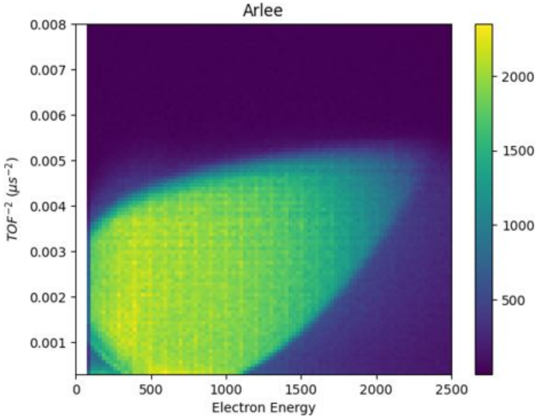
Group 1:
Andrew H.
Arlee S.
Andrew M.

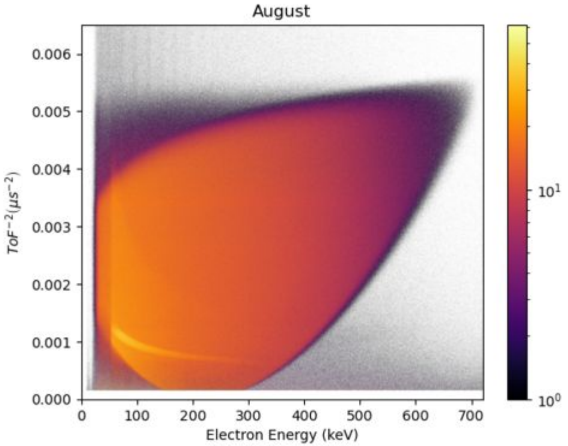
Group 2:
August M.
Rebecca **G**.
Hunter P.

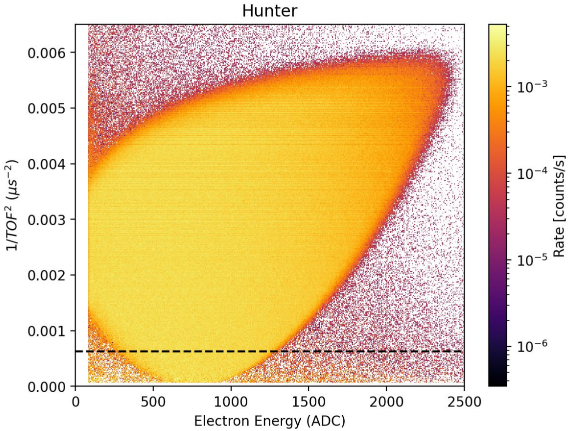
Flowchart
(Click me)

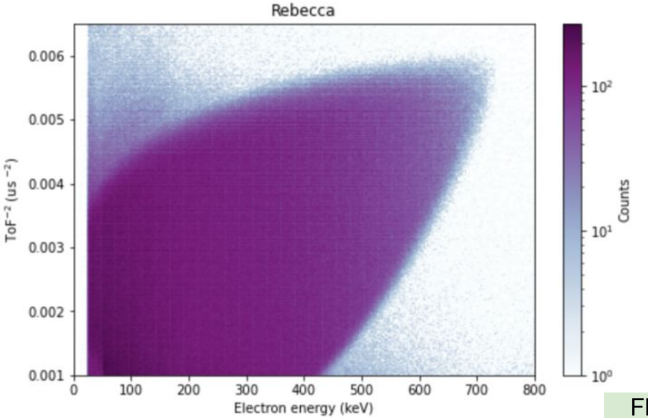
Tear Drops











Flowchart
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Data Selection

Hunter Presley and Andrew Hagemeier

Flowchart
(Click me)

Data Selection (non-exhaustive)

1. Gamma flash
2. Proton peak
3. T_{pe}
4. Pulser cut
5. Outages
6. Beginning and end of subruns

Flowchart
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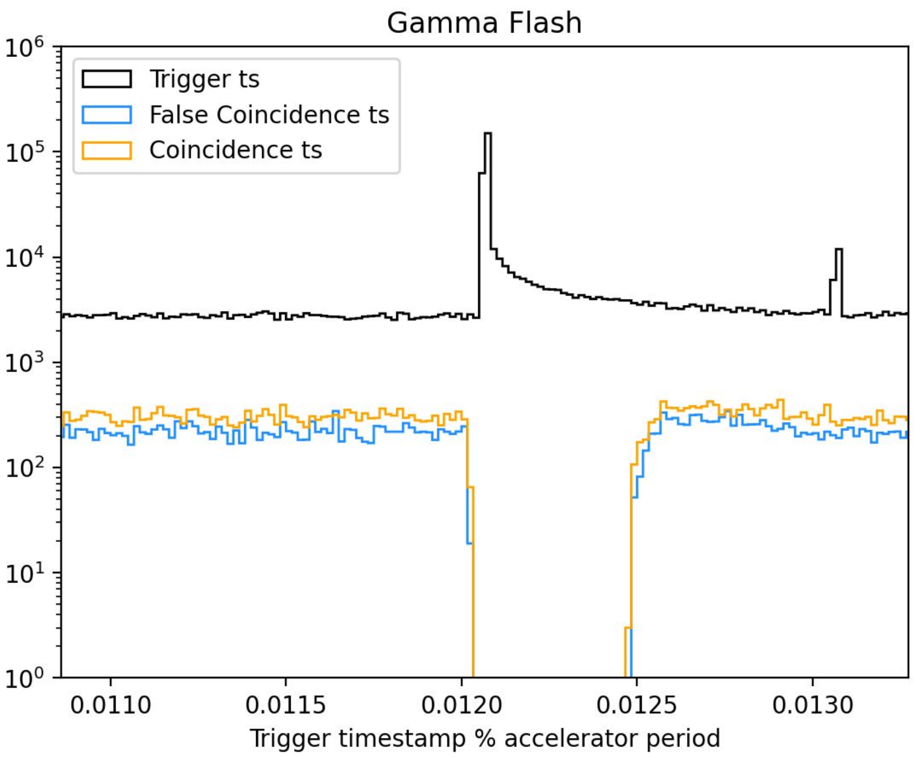
Data Selection - Gamma Flash

- Spike in events corresponding to accelerator pulse
- Use board channel 227 (accelerator t0) to determine accelerator period
- Modulo timestamps with accelerator period



Flowchart
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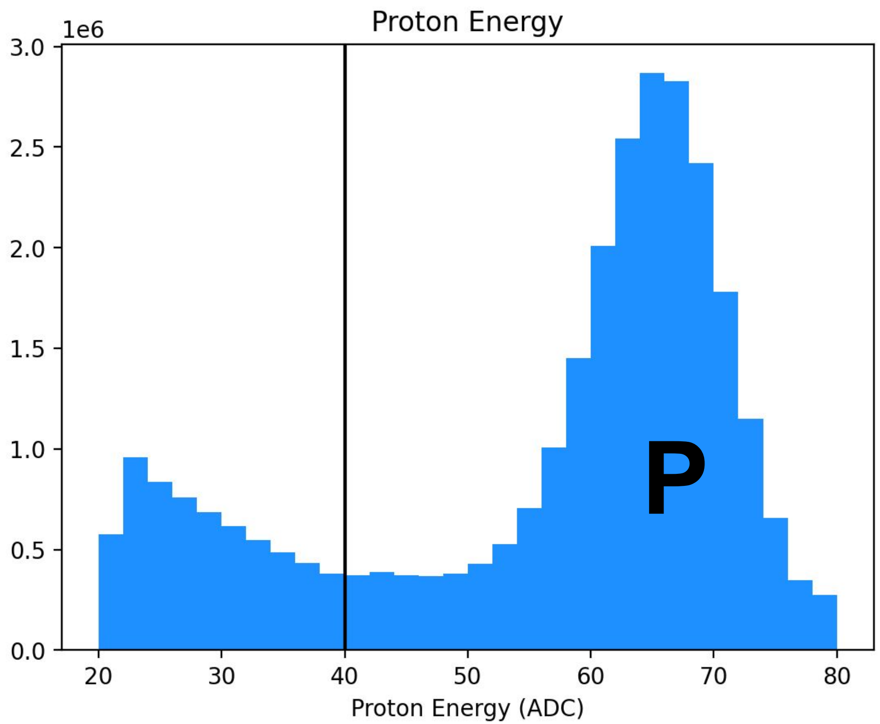
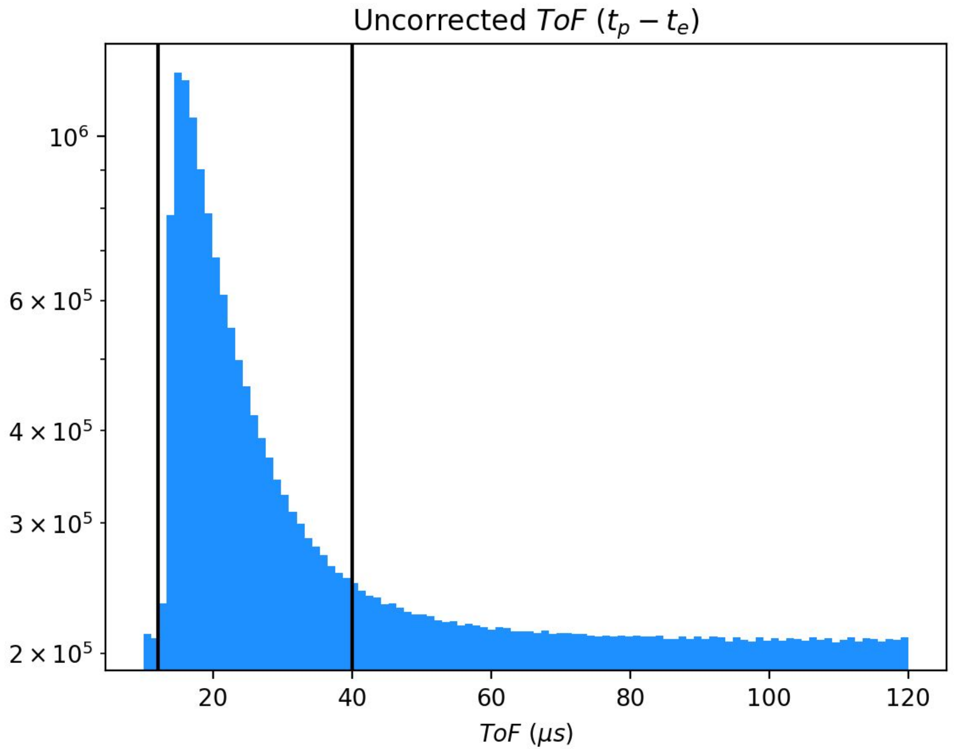
Data Selection - Proton Energy and Time of Flight





Flowchart
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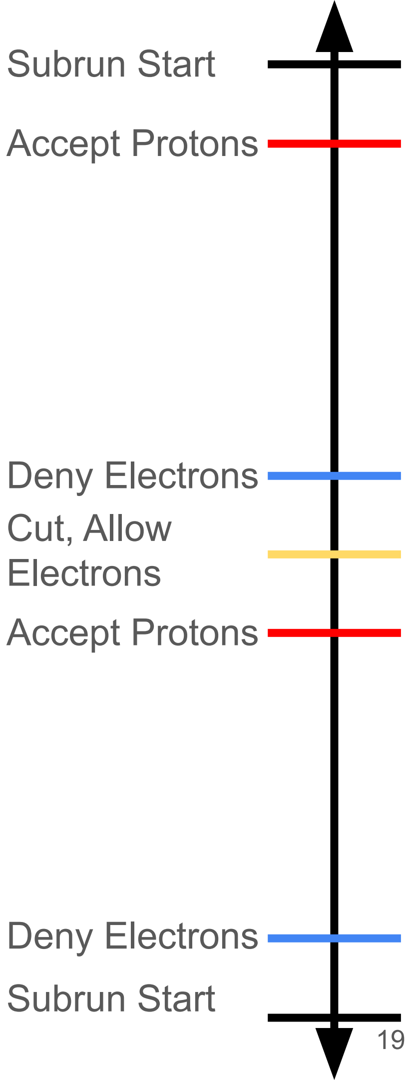
Data Selection-Temporal Cuts Bias Adjustment

- Temporal cuts, without adjusting can cause a bias in proton tof
- Two Types of Temporal Cuts
  - Cuts longer than a coincidence window
    - Subruns, Outages
  - Cuts Shorter than a coincidence window
    - Gamma Flash, Pulser
- How to deal with this effect
  - Study this effect with simulations to determine bias
  - Not accept coincidences where this would be a problem
    - Cut out proton hits within a coincidence window after the cut
    - Cut out electron hits within a coincidence window before the cut



Flowchart
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Waveform Processing

Andrew Mullins

Sliding Least Squares – Method (Each Channel)

- Use waveforms to generate template
- Fit waveforms with basis functions using a sliding window:
  - Constant
  - Linear
  - Template
- Fit parabola around minimum in chi squared
  - Sub time bin timing resolution
  - Sub ADC Unit energy resolution

Flowchart
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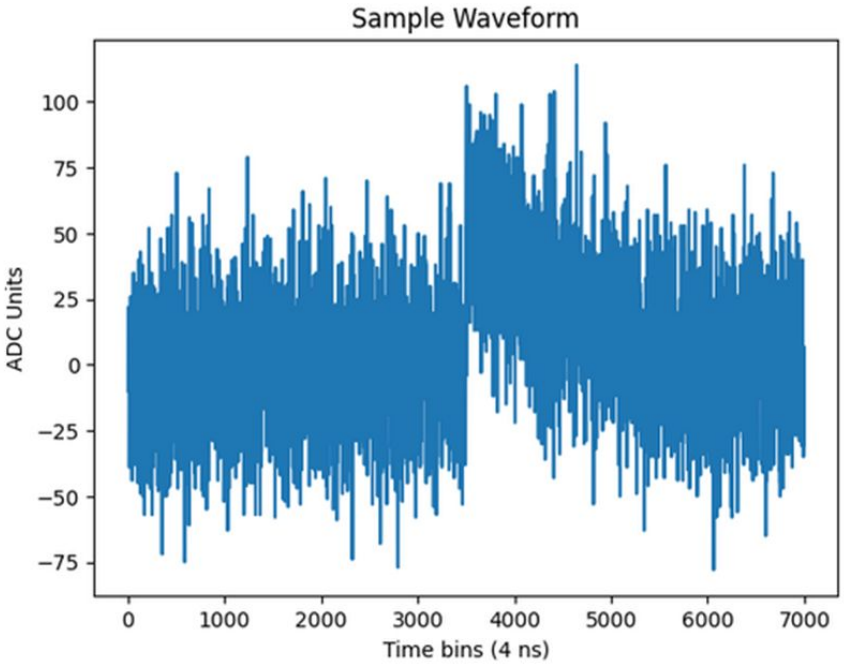
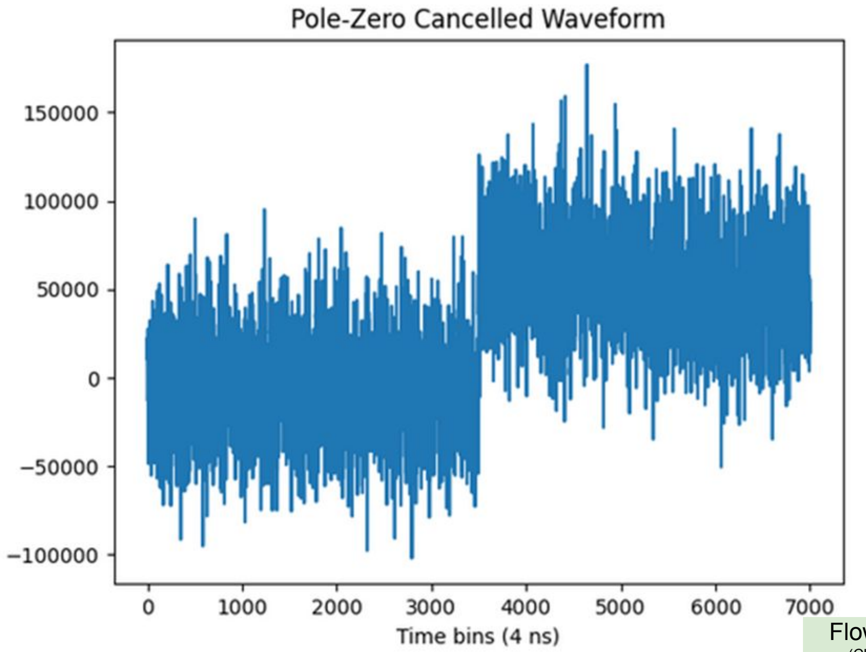
Sliding Least Squares – Waveform Preparation

- Pole-Zero Cancellation
    - Exponential Background -> constant offset
    - Constant offset -> linear background
    - Pulse -> step function





Flowchart
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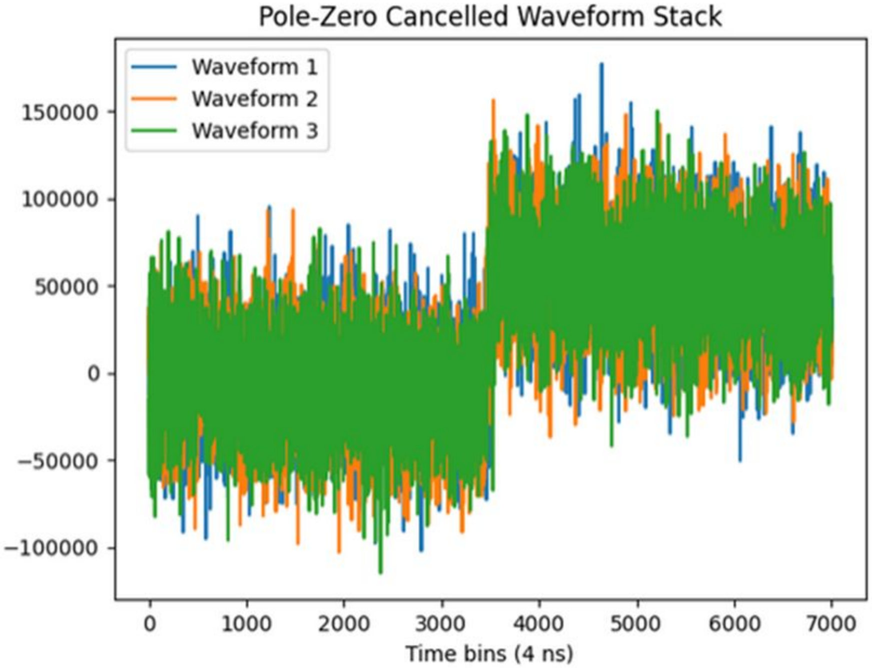
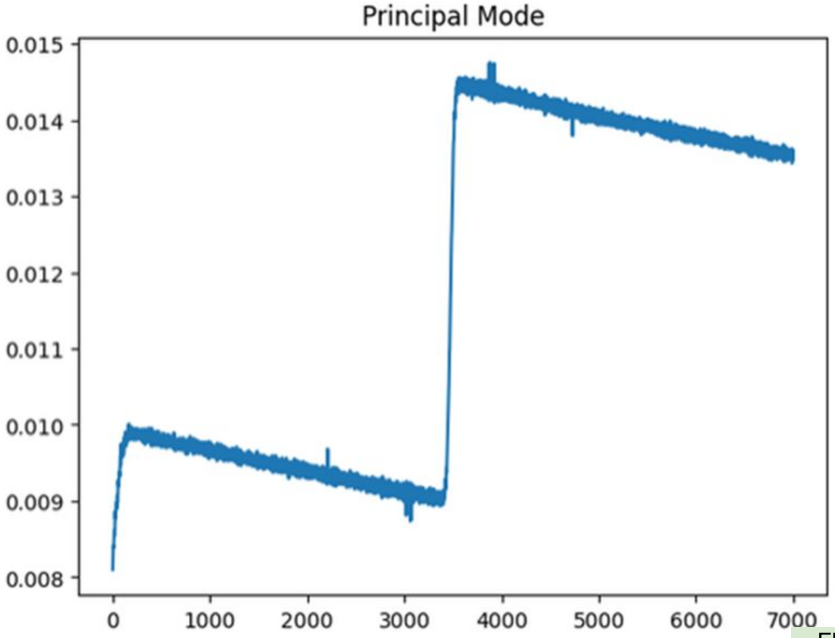
Sliding Least Squares – Template Extraction

- Stack waveforms in a matrix
- Compute Singular Value Decomposition (SVD)
- Extract template waveform from principal mode





Flowchart
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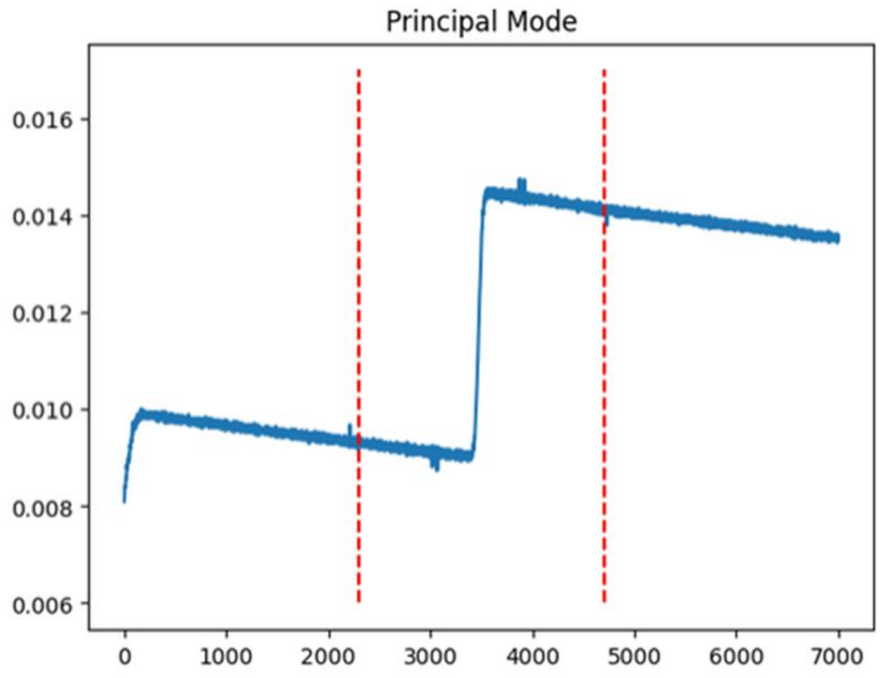
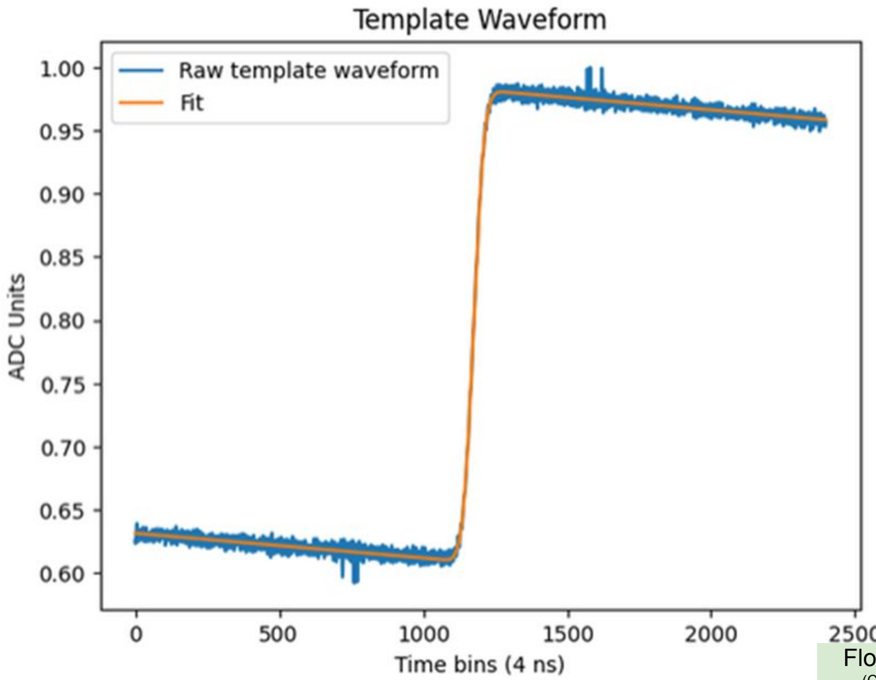
Sliding Least Squares – Template Extraction

- Exclude artifacts from template pulse
- Trim waveform by a configurable amount
- Fit waveform to constant offset, linear, integrated gaussian





Flowchart
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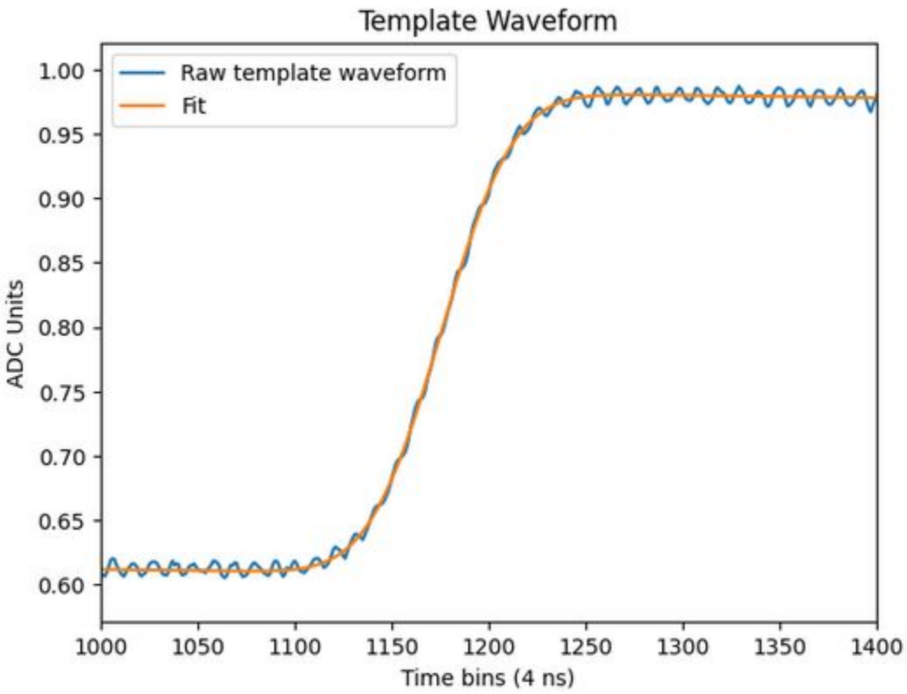
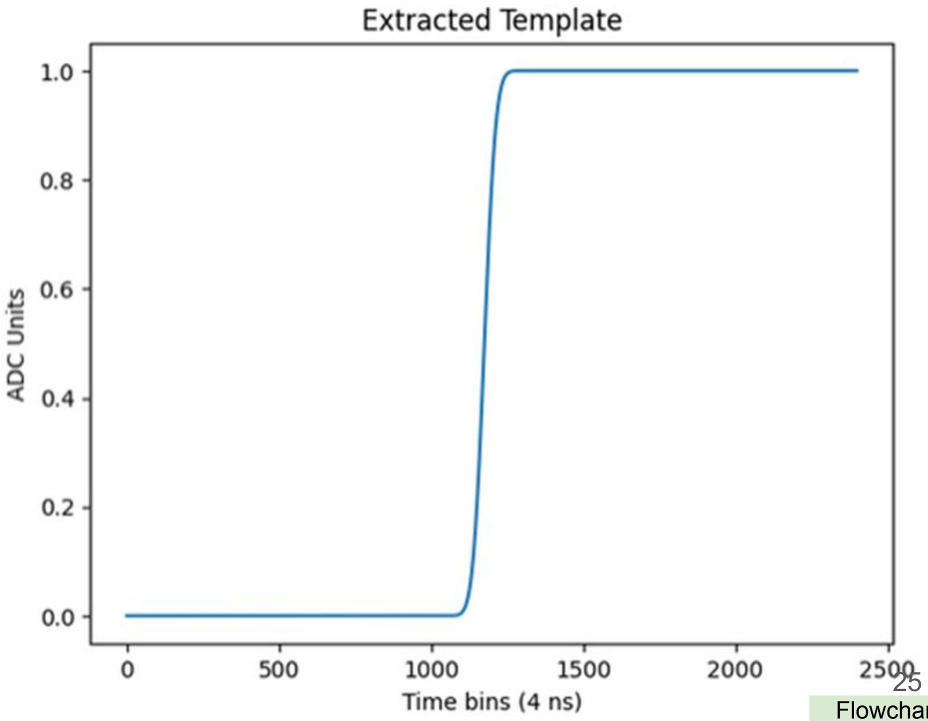
Sliding Least Squares – Template Extraction

- Remove linear component and constant offset
- Set amplitude to 1 for easier energy extraction





Flowchart
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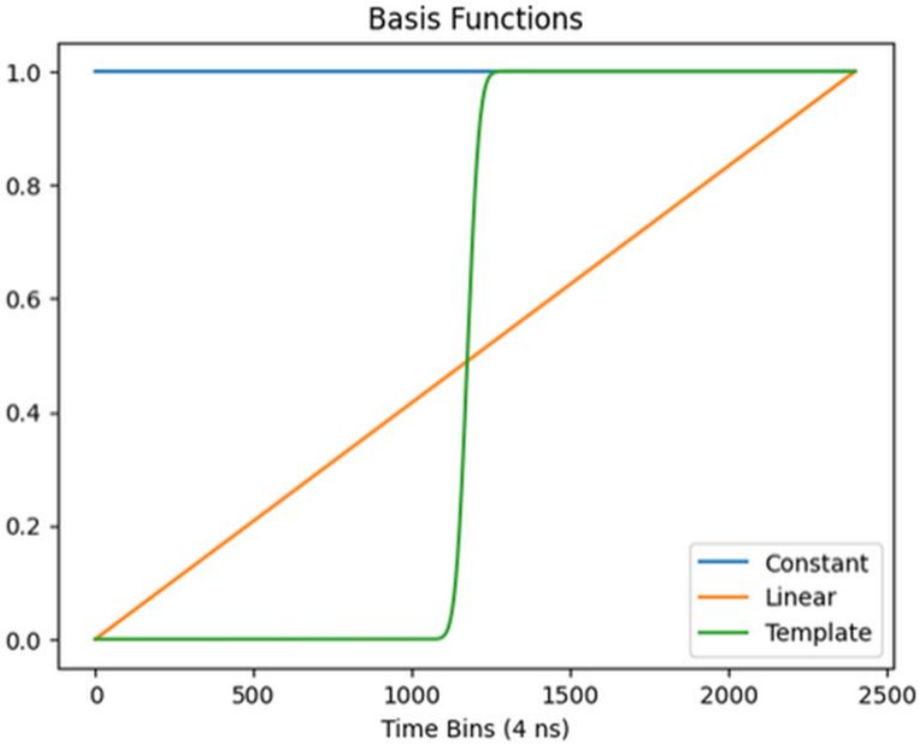
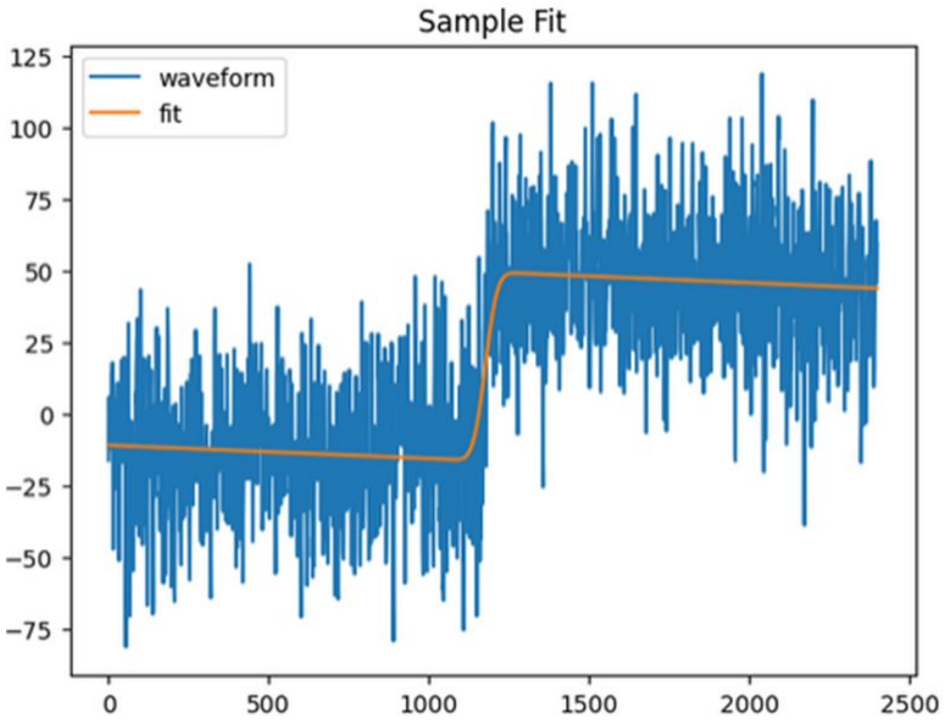
Sliding Least Squares – Fitting as a Convolution

- Least Squares Fit using basis functions
- Constant, Linear, Template





Flowchart
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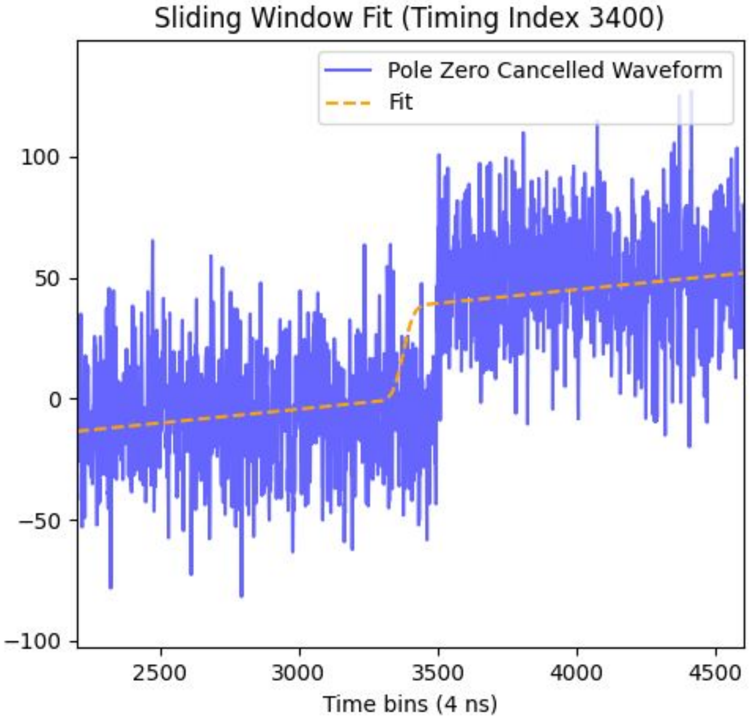
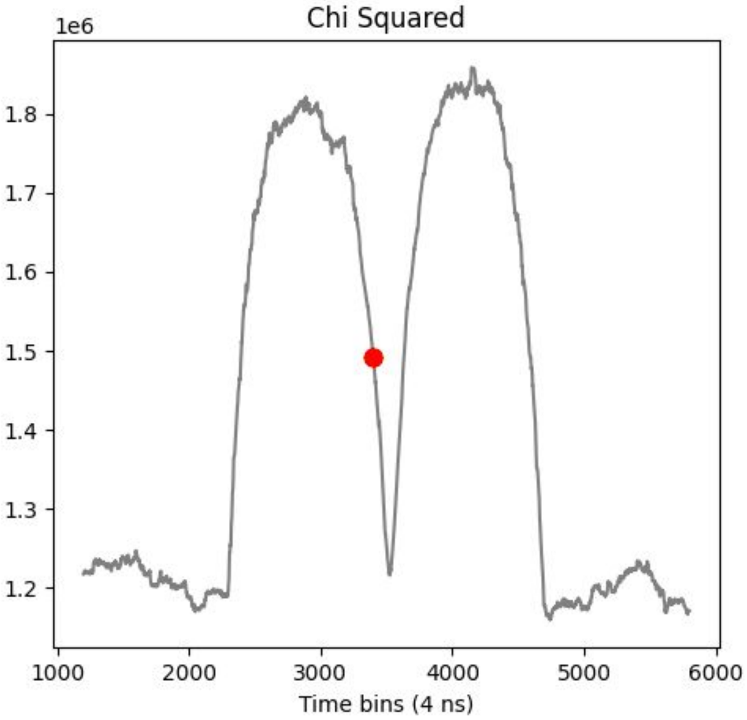
Sliding Least Squares – Fitting as a Convolution

- Use convolutions to ‘slide’ basis functions along waveform
- Calculate Chi Squared as a function of position along the waveform





Flowchart
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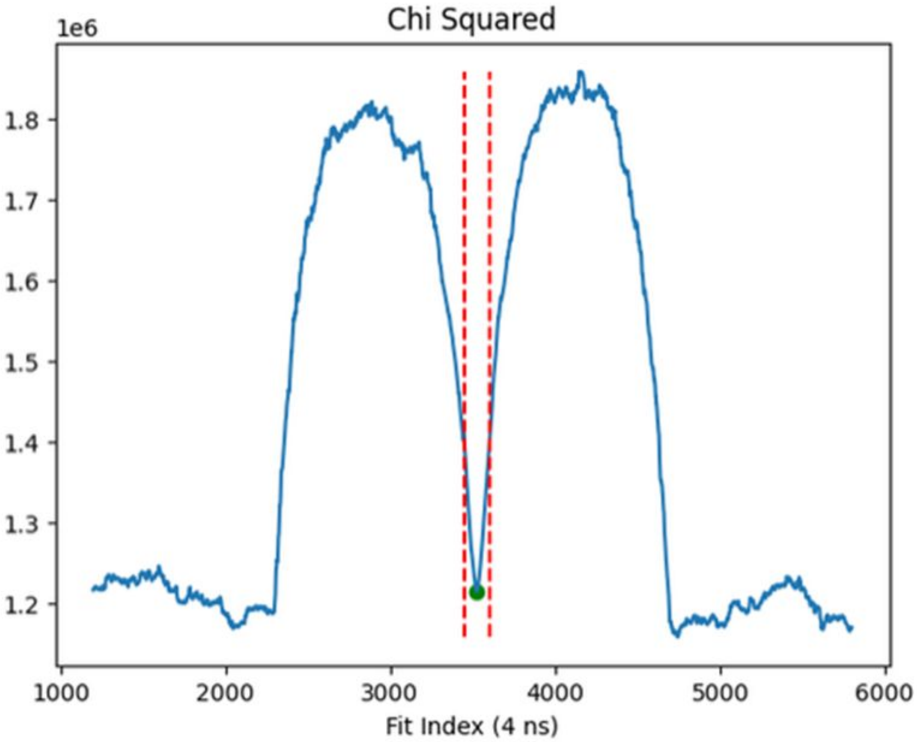
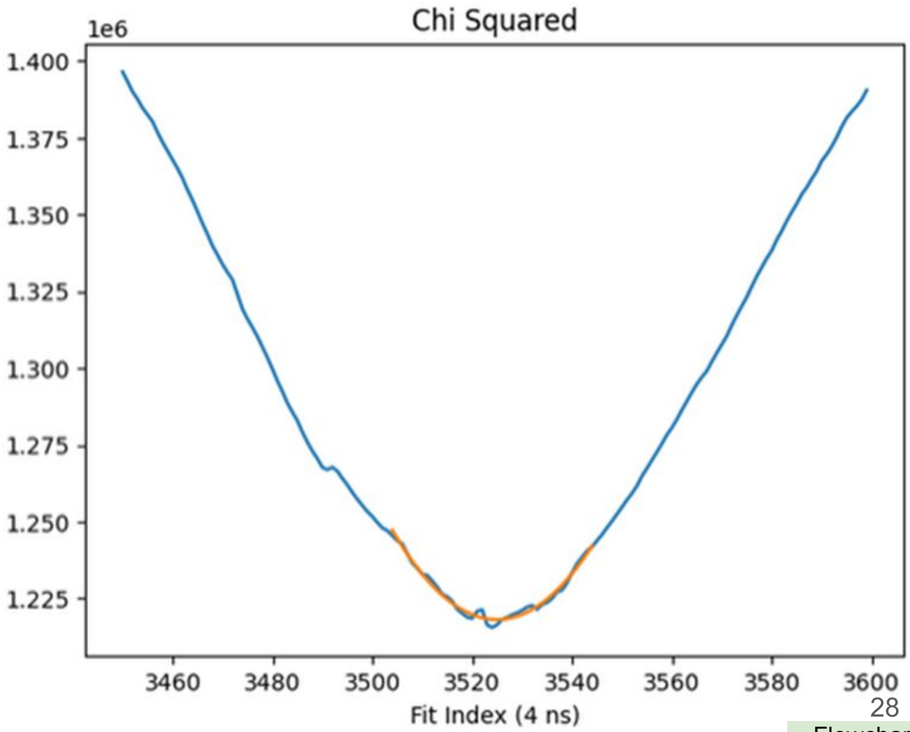
Sliding Least Squares – Fitting as a Convolution

- Quadratic fit around minimum for sub time bin timing resolution





Flowchart
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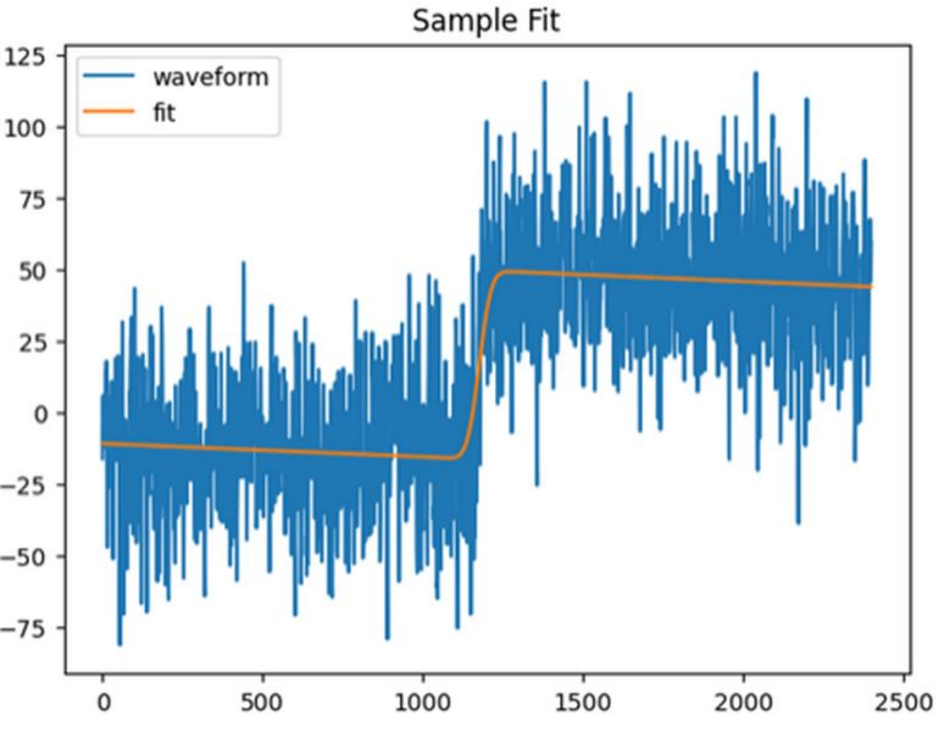
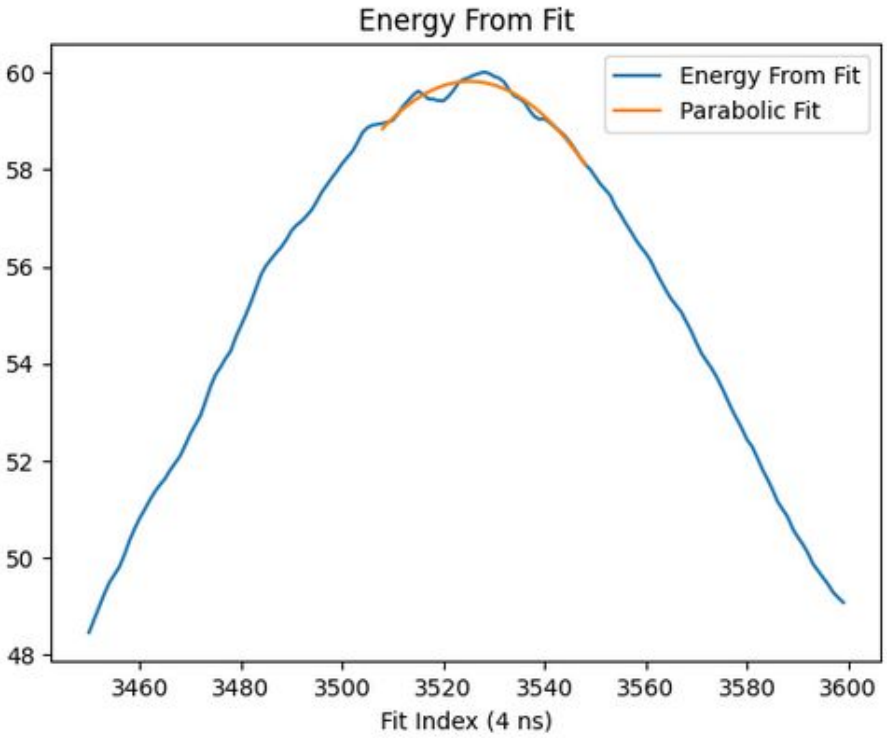
Sliding Least Squares – Fitting as a Convolution

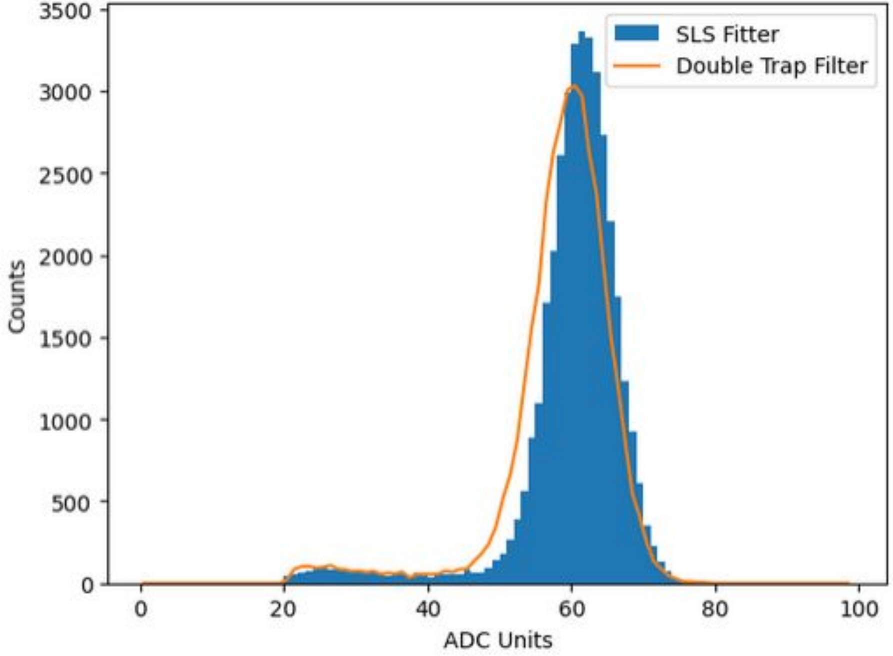
- Quadratic fit around minimum for sub time bin timing resolution

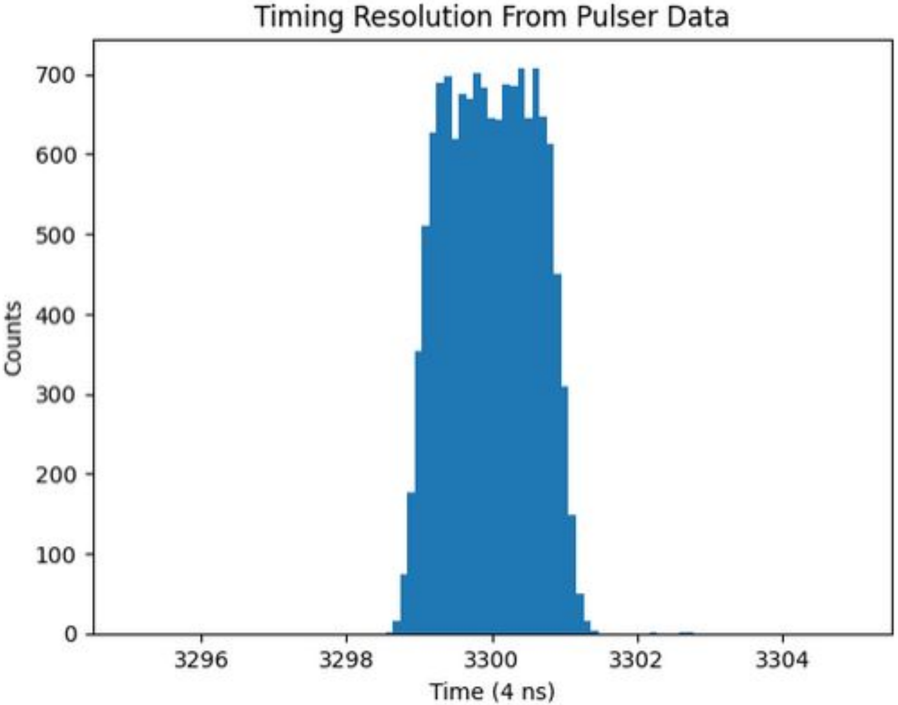




Sliding Least Squares – Results

- Timing Resolution validated with pulser data (different waveform template)
- Energy Resolution better than double trap filter





Flowchart
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Sliding Least Squares – Work in progress

- Possible improvements
  - Fitting out oscillations in baseline
  - Improved weights in template fits (currently boxcar weights)
  - Adjust tau for pole-zero cancellation
  - Adjust window width
  - Exclude artifacts from baseline
- Validation Methods
  - Use pulser data between two channels to measure timing offset free from hardware trigger influence
  - Synthetic data on realistic noise to accurately test SLS fitter vs double trap or single trap filters

Flowchart
(Click me)

Energy Calibration

Arlee Shelby

Flowchart
(Click me)

^{207}Bi Peaks

- Fit routine broken up into 3 regions:
  - Auger electron peaks:
    - 56 keV
    - 68 keV
  - Intermediate conversion electron peaks:
    - 482 keV
    - 554 keV
    - 566 keV
  - High-lying conversion electron peaks
    - 976 keV
    - 1048 keV
    - 1060 keV
- Optimal case: 8 peaks

		Energy keV			Electrons per 100 disint.
e_{AL}	(Pb)	5,2	-	15,7	54,8 (7)
e_{AK}	(Pb)				2,9 (4)
	KLL	56,028	-	61,669	}
	KLX	68,181	-	74,969	}
	KXY	80,3	-	88,0	}
$ec_{1,0}$ T	(Pb)	481,694	-	569,680	2,112 (29)
$ec_{1,0}$ K	(Pb)	481,694		(2)	1,548 (22)
$ec_{1,0}$ L	(Pb)	553,838	-	556,664	0,429 (7)
$ec_{1,0}$ M	(Pb)	565,848	-	567,215	0,1057 (16)
$ec_{3,1}$ T	(Pb)	975,655	-	1063,640	9,53 (18)
$ec_{3,1}$ K	(Pb)	975,655		(3)	7,11 (17)
$ec_{3,1}$ L	(Pb)	1047,798	-	1050,624	1,84 (5)
$ec_{3,1}$ M	(Pb)	1059,808	-	1061,175	0,441 (25)
$ec_{3,1}$ N	(Pb)	1062,765	-	1063,523	0,1193 (30)
$\beta^+_{0,1}$	max:	805,8		(21)	0,012 (2)
$\beta^+_{0,1}$	avg:	383,4		(9)	

^{207}Bi Fit

- For each peak:

$$z_1 = \frac{(x - c_1)}{\sigma_1}$$

F = Gaussian + lower exponential + step function

$$F_1 = A_1 \cdot e^{-\frac{1}{2}(z_1)^2} + R_A \cdot A_1 \cdot \frac{e^{R_\sigma \cdot \sigma_1 \cdot z_1}}{(1 + e^{z_1})^4} + \frac{R_s \cdot A_1}{(1 + e^{z_1})^2}$$

- Parameters:
  - c: peak centroid
  - σ: peak width
  - A: peak amplitude
  - R_A: global amplitude ratio between lower expo amplitude ($A_{lower\ expo}$) and peak amplitude (A_{peak})
    - Constraint: $A_{lower\ expo} < A_{peak}$
    - For multiple peaks fit simultaneously, constrains $A_{lower\ expo}$ to be same fraction of A_{peak}
  - R_σ: global width ratio between lower expo width ($\sigma_{lower\ expo}$) and peak width (σ_{peak})
    - For multiple peaks fit simultaneously, constrains $\sigma_{lower\ expo}$ to be same fraction of σ_{peak}
  - R_s: amplitude ratio between each step function and each peak (A_{step} / A_{peak})
    - Constrans $A_{step} < A_{peak}$

Flowchart
(Click me)

Auger Peaks Fit Example: Pixel 60

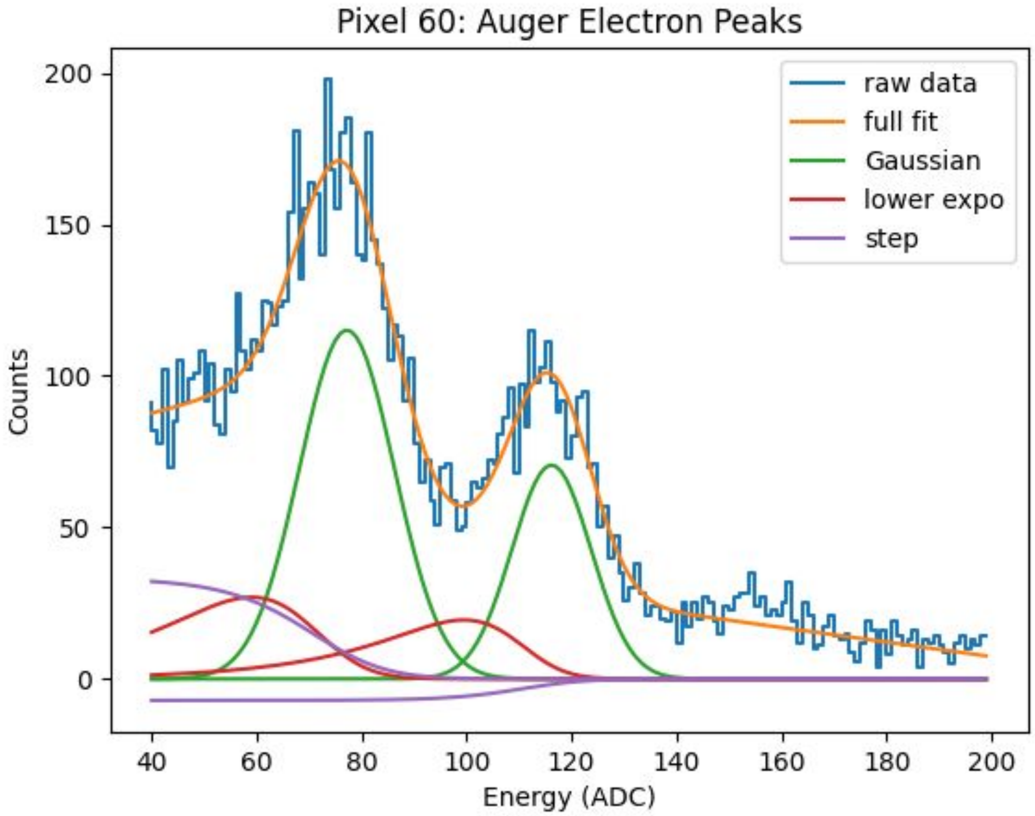
Flowchart
(Click me)

- For each energy line (56 and 68 keV):

  $F_{1/2}$ = Gaussian + lower exponential + step function

- Full fit: $F = F_1 + F_2$

$$z_1 = \frac{(x - c_1)}{\sigma_1} \qquad z_2 = \frac{(x - c_2)}{\sigma_2}$$



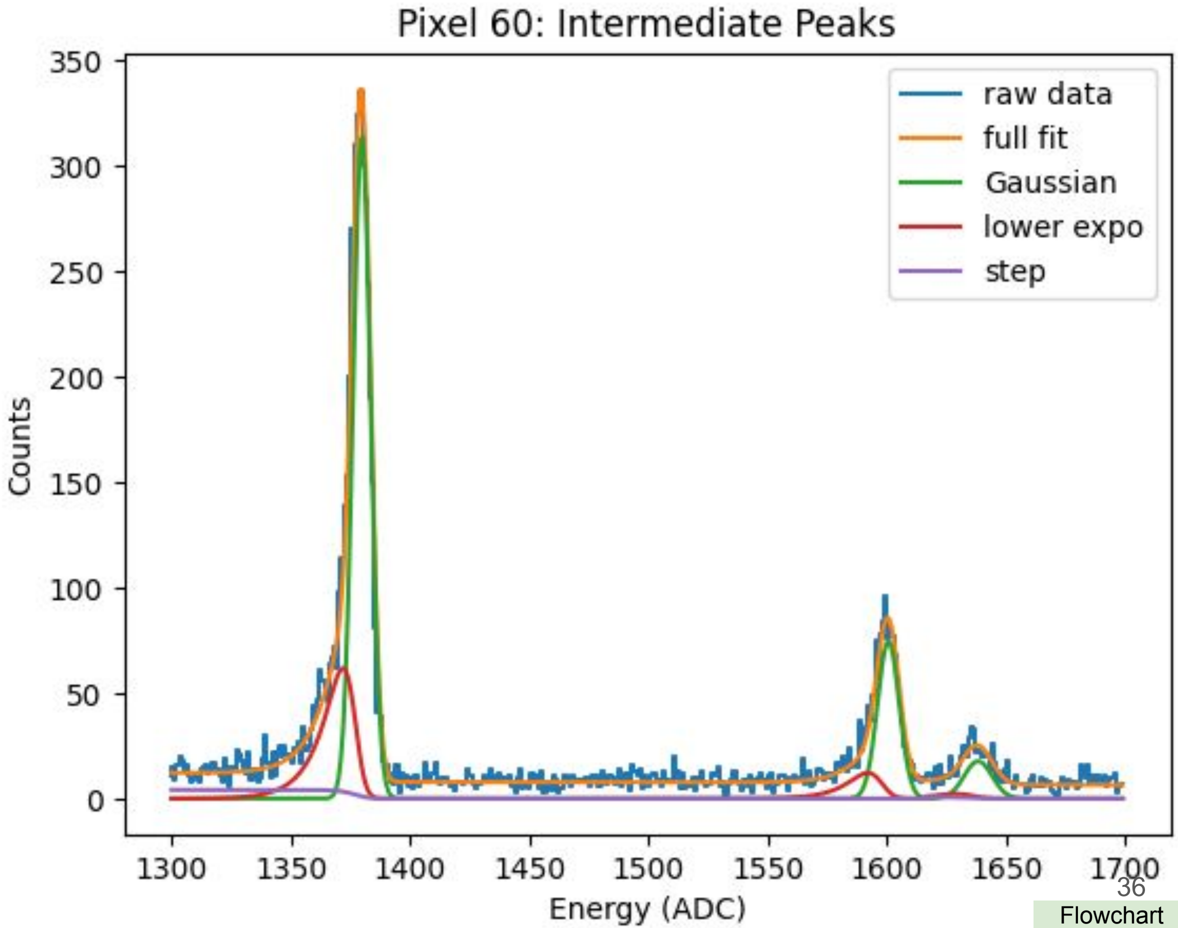
$$F = A_1 \cdot e^{-\frac{1}{2}(z_1)^2} + R_A \cdot A_1 \cdot \frac{e^{R_\sigma \cdot \sigma_1 \cdot z_1}}{(1+e^{z_1})^4} + \frac{R_{s_1} \cdot A_1}{(1+e^{z_1})^2} + A_2 \cdot e^{-\frac{1}{2}(z_2)^2} + R_A \cdot A_2 \cdot \frac{e^{R_\sigma \cdot \sigma_2 \cdot z_2}}{(1+e^{z_2})^4} + \frac{R_{s_2} \cdot A_2}{(1+e^{z_2})^2}$$

Intermediate Conversion Electron Fit Example: Pixel 60

- For each energy line (482, 554, and 566 keV):

  $F_{1/2/3}$ = Gaussian + lower exponential + step function

- Full fit: $F = F_1 + F_2 + F_3$



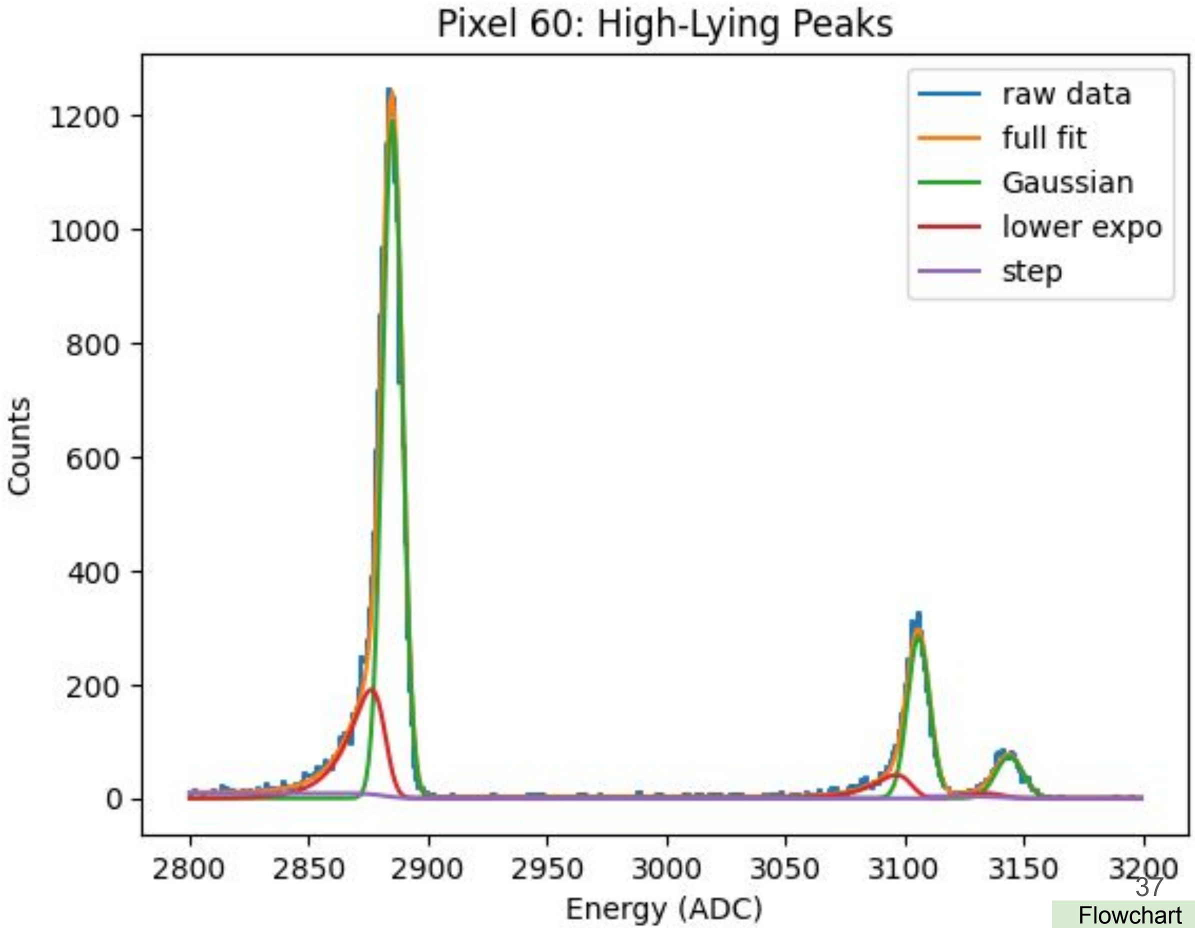
Flowchart
(Click me)

High-Lying Conversion Electron Fit Example: Pixel 60

- For each energy line (976, 1048, and 1060 keV):

  $F_{1/2/3}$ = Gaussian + lower exponential + step function

- Full fit: $F = F_1 + F_2 + F_3$



Flowchart
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^{109}Cd Peaks

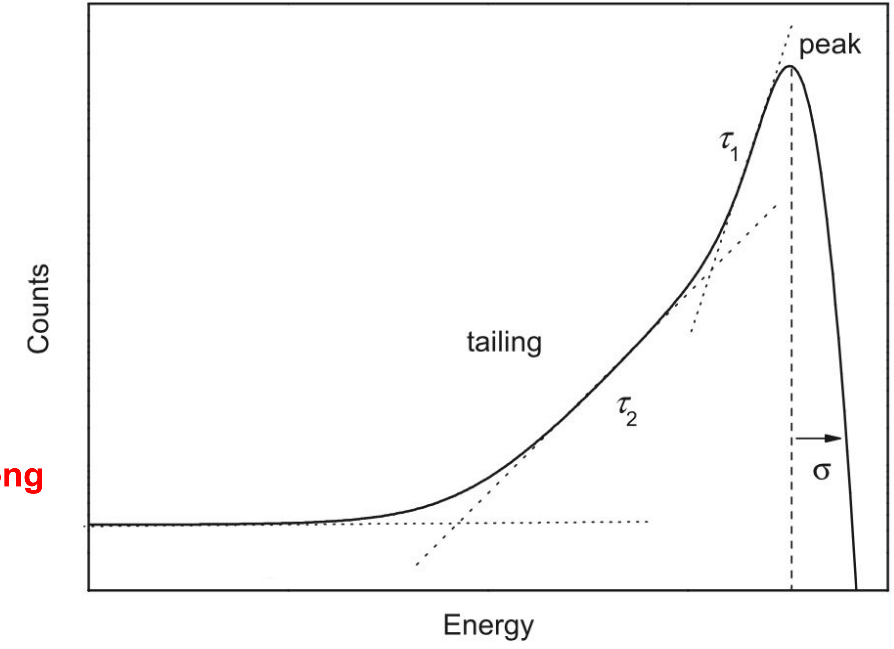
- Fit routine has one region
  - Conversion electron energy lines:
    - 63 keV
    - 84 keV
    - 87.3 keV
    - 87.9 keV
- Optimal case: 2 peaks
  - Detector resolution cannot resolve the L, M and N shell energy lines

		Energy (keV)	Electrons (per 100 disint.)
e_{AL}	(Ag)	1,8 - 3,8	167,3 (8)
e_{AK}	(Ag)		
	KLL	17,79 - 18,69	20,8 (6)
	KLX	20,945 - 22,160	
	KXY	24,079 - 25,507	
$ec_{1,0}$ K	(Ag)	62,520 (1)	41,8 (8)
$ec_{1,0}$ L	(Ag)	84,2279 - 84,6826	44,1 (9)
$ec_{1,0}$ M	(Ag)	87,3162 - 87,6670	9,04 (19)
$ec_{1,0}$ N	(Ag)	87,9385 - 88,0304	1,413 (29)

^{109}Cd Fit

- ^{109}Cd spectra has a much larger tail contribution
  - Fit function for ^{207}Bi doesn't work
  - Use a modified exponential with two components for each peak
- For each peak:

F = modified expo (short tailing) + modified expo (long tailing)



- Parameters:
  - c: peak centroid
  - σ: peak width
  - η: fraction of peak area
    - Constraint: $\eta_{PEAK} > \eta_2$
    - Normalization Constraint: $\eta_{PEAK} + \eta_{2/3} = 1$
    - For multiple peaks: η_{PEAK} same for all peaks
  - τ: tailing parameter
    - Constraint: $\tau_1 < \tau_2$

$$F_1 = \eta_{PEAK} \cdot A_1 \cdot e^{\frac{(x-c_1)}{\tau_1}} \cdot \left(1 - \mathrm{erf}\left(\frac{(x-c_1)}{\sqrt{2}\cdot\sigma_1} + \frac{\sigma_1}{\sqrt{2}\cdot\tau_1}\right)\right) + \eta_2 \cdot A_1 \cdot e^{\frac{(x-c_1)}{\tau_2}} \cdot \left(1 - \mathrm{erf}\left(\frac{(x-c_1)}{\sqrt{2}\cdot\sigma_1} + \frac{\sigma_1}{\sqrt{2}\cdot\tau_2}\right)\right)$$

Flowchart
(Click me)

Conversion Electron Fit Example: Pixel 106

$$F_1 = \eta_{PEAK} \cdot A_1 \cdot e^{\frac{(x-c_1)}{\tau_1}} \cdot \left(1 - \mathrm{erf}\left(\frac{(x-c_1)}{\sqrt{2 \cdot \sigma_1}} + \frac{\sigma_1}{\sqrt{2 \cdot \tau_1}}\right)\right) + \eta_2 \cdot A_1 \cdot e^{\frac{(x-c_1)}{\tau_2}} \cdot \left(1 - \mathrm{erf}\left(\frac{(x-c_1)}{\sqrt{2 \cdot \sigma_1}} + \frac{\sigma_1}{\sqrt{2 \cdot \tau_2}}\right)\right) + \eta_{PEAK} \cdot A_2 \cdot e^{\frac{(x-c_2)}{\tau_1}} \cdot \left(1 - \mathrm{erf}\left(\frac{(x-c_2)}{\sqrt{2 \cdot \sigma_2}} + \frac{\sigma_2}{\sqrt{2 \cdot \tau_1}}\right)\right) + \eta_3 \cdot A_2 \cdot e^{\frac{(x-c_2)}{\tau_2}} \cdot \left(1 - \mathrm{erf}\left(\frac{(x-c_2)}{\sqrt{2 \cdot \sigma_2}} + \frac{\sigma_1}{\sqrt{2 \cdot \tau_2}}\right)\right)$$

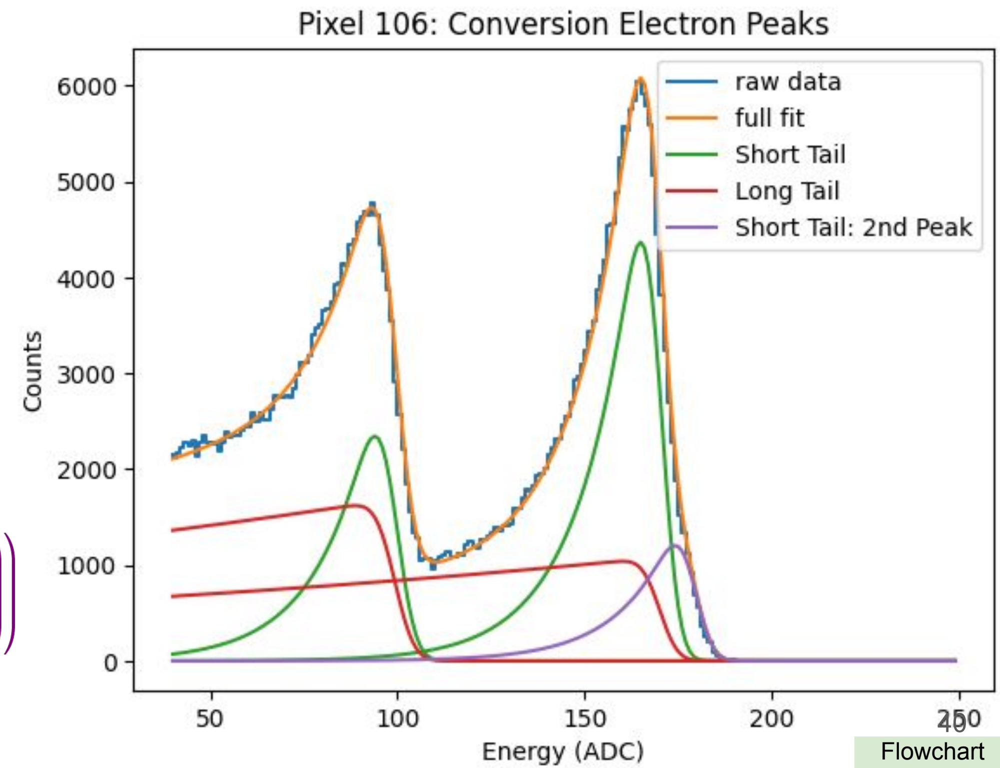
- For the two main energy lines (63 and 84 keV):

  F = modified expo (short tailing) + modified expo (long tailing)

  - Also have two energy lines ~87 keV constrained to 84 keV line:
    - R_A: area ratio constraint
    - R_c: centroid ratio constraint

$$F_3 = R_A \cdot \eta_{PEAK} \cdot A_2 \cdot e^{\frac{(x - R_c \cdot c_2)}{\tau_2}} \cdot \left(1 - \mathrm{erf}\left(\frac{(x - R_c \cdot c_2)}{\sqrt{2 \cdot \sigma_2}} + \frac{\sigma_2}{\sqrt{2 \cdot \tau_2}}\right)\right)$$

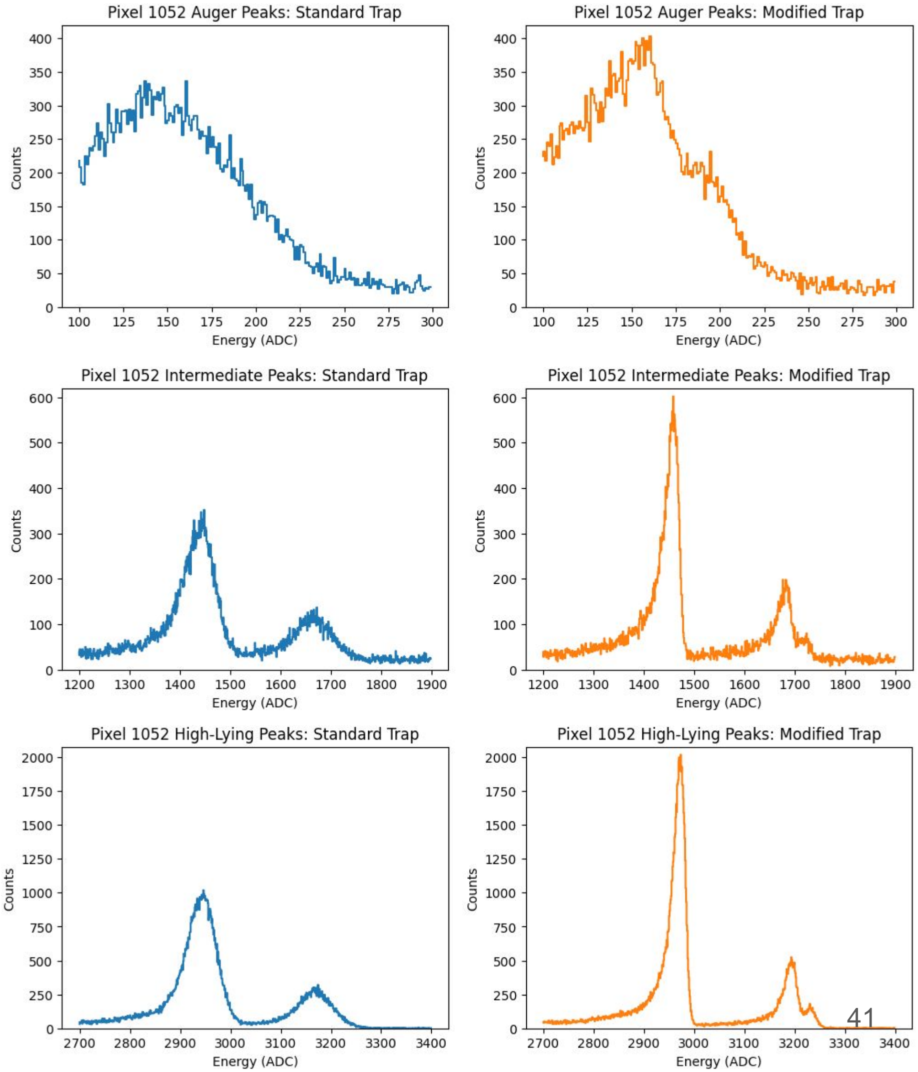
- Full fit: $F = F_1 + F_2 + F_3$



Flowchart
(Click me)

UDET vs. LDET Energy Extraction: ^{207}Bi peaks

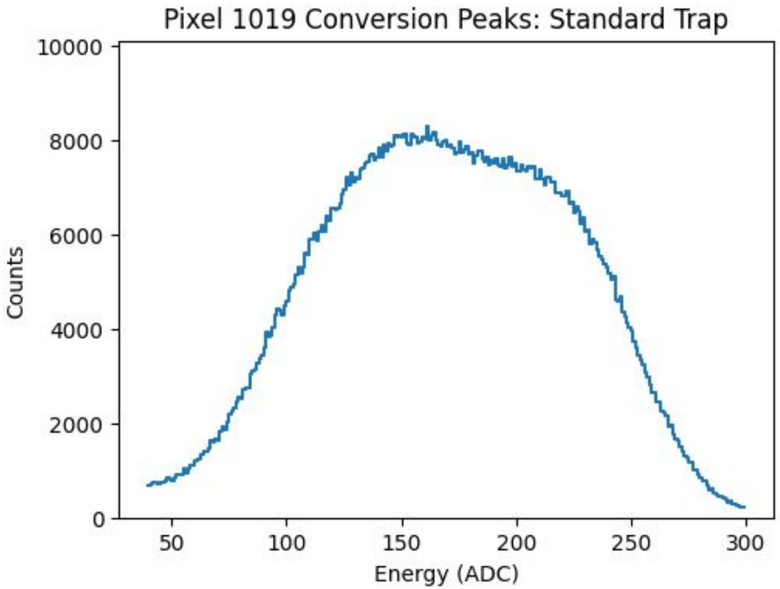
- UDET: fit function works well
  - I use the "standard" nabPy single trap filter to extract energy
    - Trap parameters (1250, 50, 1250) (risetime, flat top length, decay rate)
- LDET: fit function works well with modified trap filter parameters
  - Using the **"standard"** filter parameters many peaks unresolved
  - Using **"modified"** trap filter parameters, peaks can be resolved and fit function works
    - Modified trap parameters: (150, 20, 1250) (risetime, flat top length, decay rate)

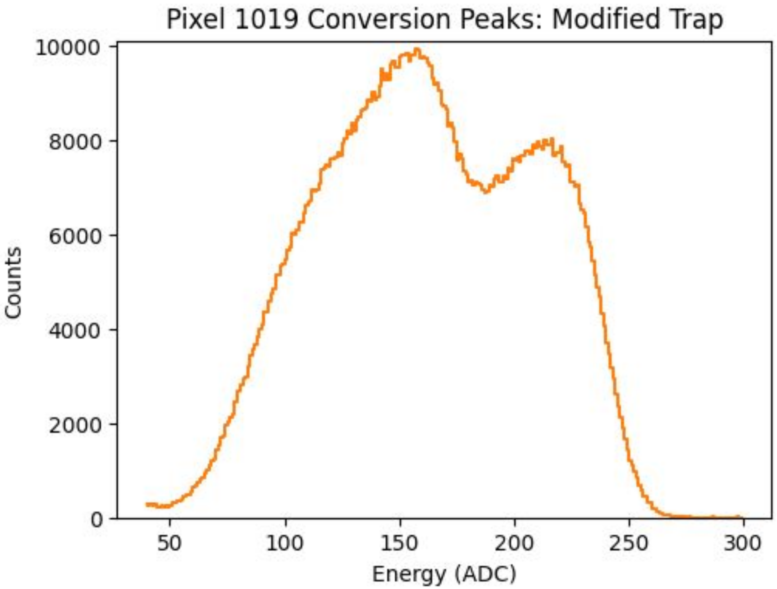


Flowchart
(Click me)

UDET vs. LDET Energy Extraction: ^{109}Cd peaks

- **Standard** trap parameters (1250, 50, 1250) (risetime, flat top length, decay rate)
- **Modified** trap parameters: (150, 20, 1250) (risetime, flat top length, decay rate)





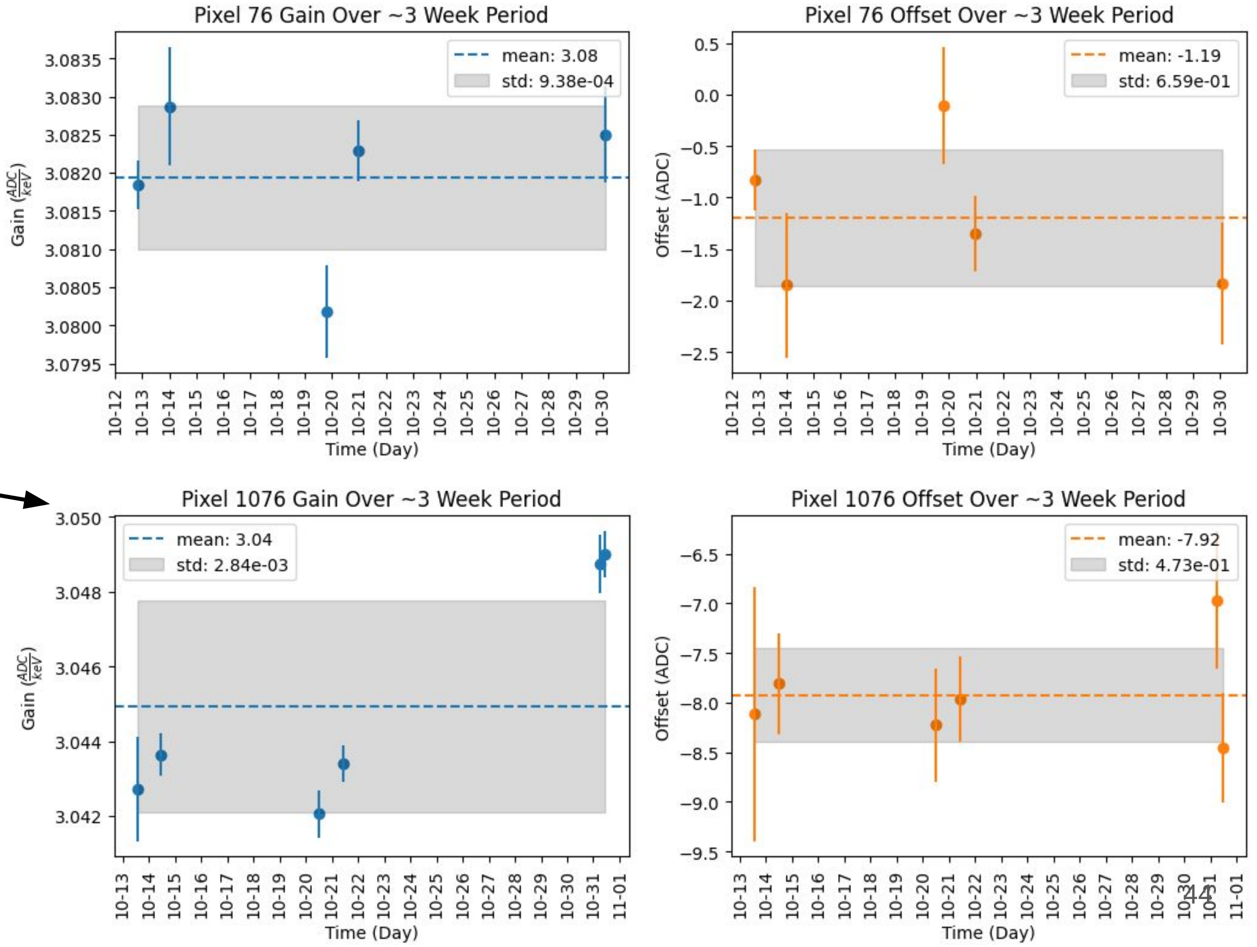
Fall 2025 Calibration Data (with RSIS)

- 80% field (MAIN/UDET: -110 A):
  - Oct 7 - Oct 8
- **Full field (MAIN/UDET: -137.2 A):**
  - **Oct 13 - 14**
  - **Oct 20 - Oct 22**
  - **Oct 29 - Oct 31**
- Reverse full field (MAIN/UDET: 137.2 A):
  - Nov 5, Nov 10 - Nov 11

Flowchart
(Click me)

Linear Calibration Results from ^{207}Bi: Example Pixel 76

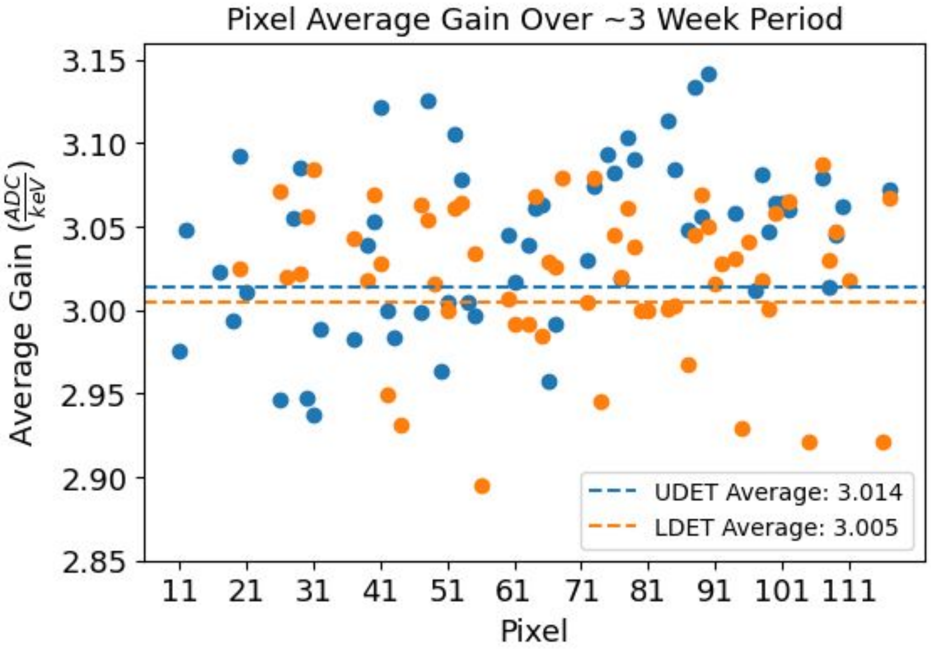
- Linear calibration: $y = mx+b$
  - **m: gain (ADC/keV)**
  - **b: offset (ADC)**
- Examples shown for pixel 76
  - Top: UDET
  - Bottom: LDET
- “std”: standard deviation of each distribution (i.e. gain/offset)

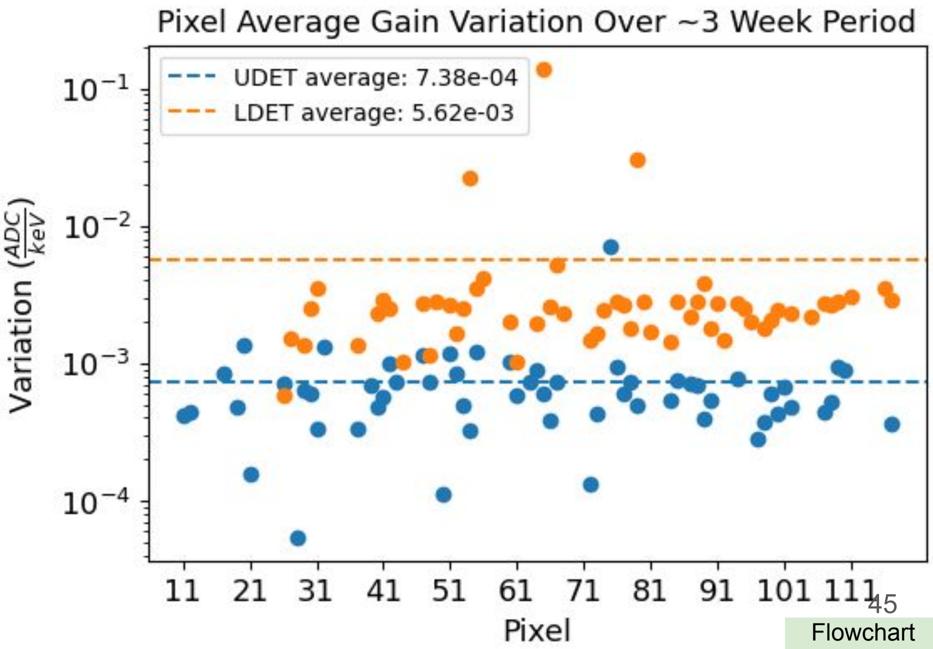


Flowchart
(Click me)

Average Linear Calibration Results from ^{207}Bi: Gain

- Linear calibration: y = mx+b
  - m: gain (ADC/keV)
- Variation = standard deviation of distribution for each pixel
  - **UDET** and **LDET**
  - Two outliers not shown in left plot: UDET pixel 95 and LDET pixel 1054 (low gain pixels)

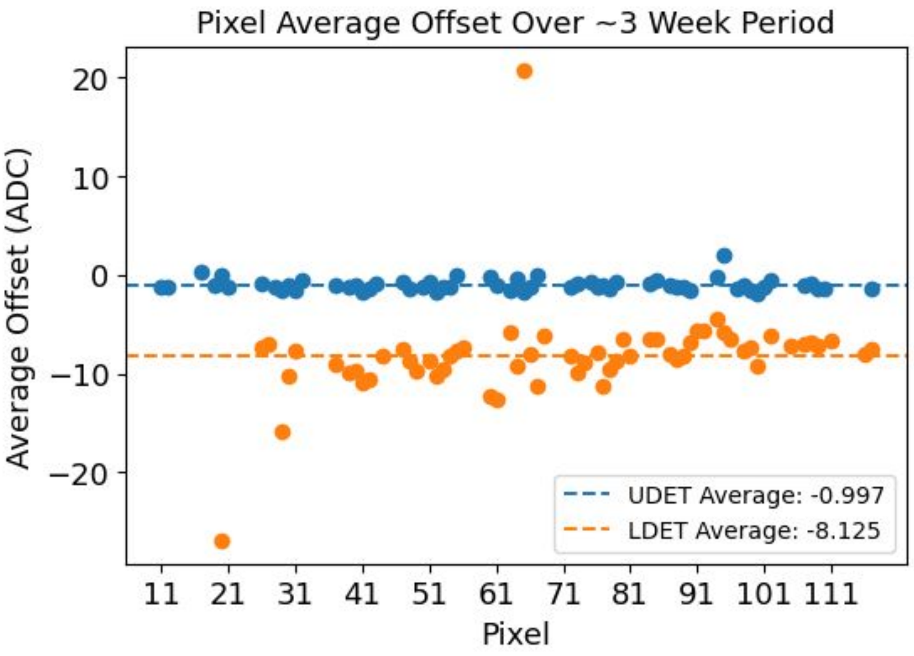


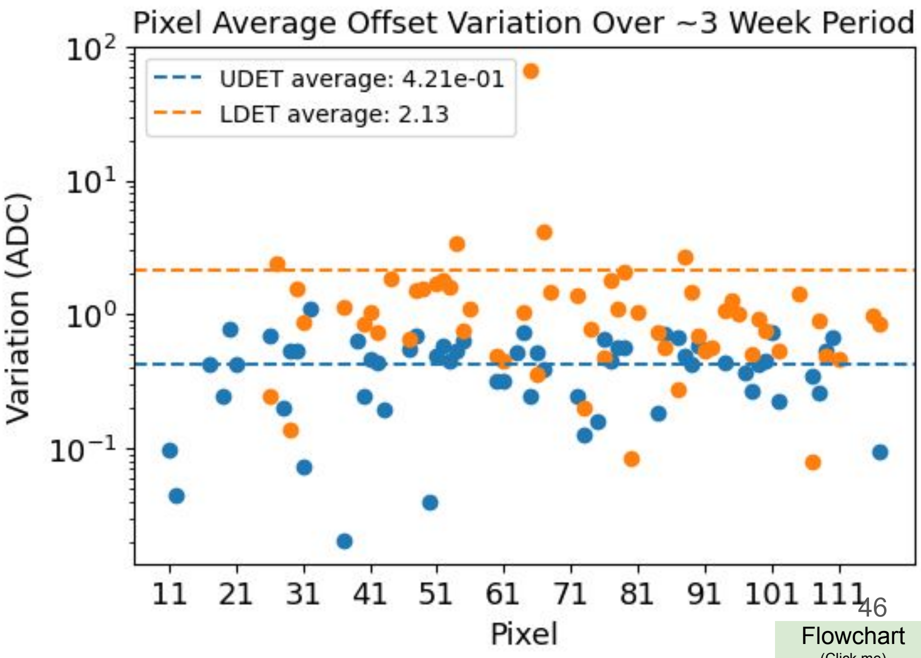


Flowchart
(Click me)

Average Linear Calibration Results from ^{207}Bi: Offset

- Linear calibration: y = mx+b
  - b: offset (ADC)
- Variation = standard deviation of distribution for each pixel
  - **UDET** and **LDET**

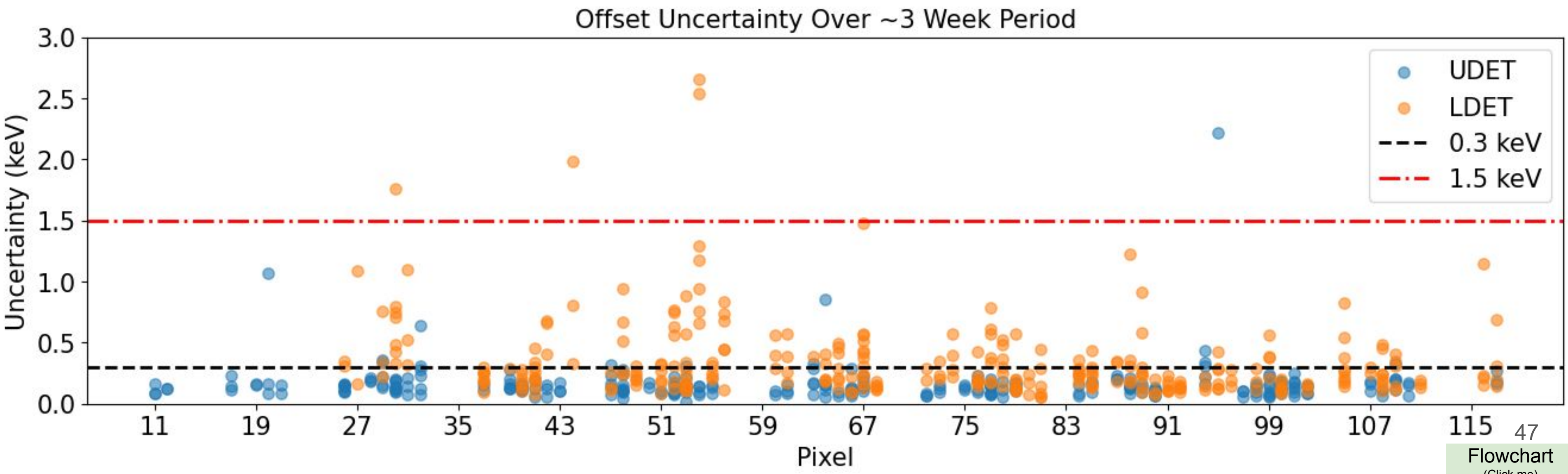




Flowchart
(Click me)

Linear Calibration Results from ^{207}Bi: Nab Requirements

- To meet Nab "little a" precision goals:
  - For 0.1% ultimate goal: offset uncertainty <**0.3 keV**
  - Estimate for 0.5% result: offset uncertainty <**1.5 keV** (5 times larger)
- Each dot is an individual run: all UDET and most LDET pixels have at least one run that meets Nab requirements
  - 5 outlier runs not shown

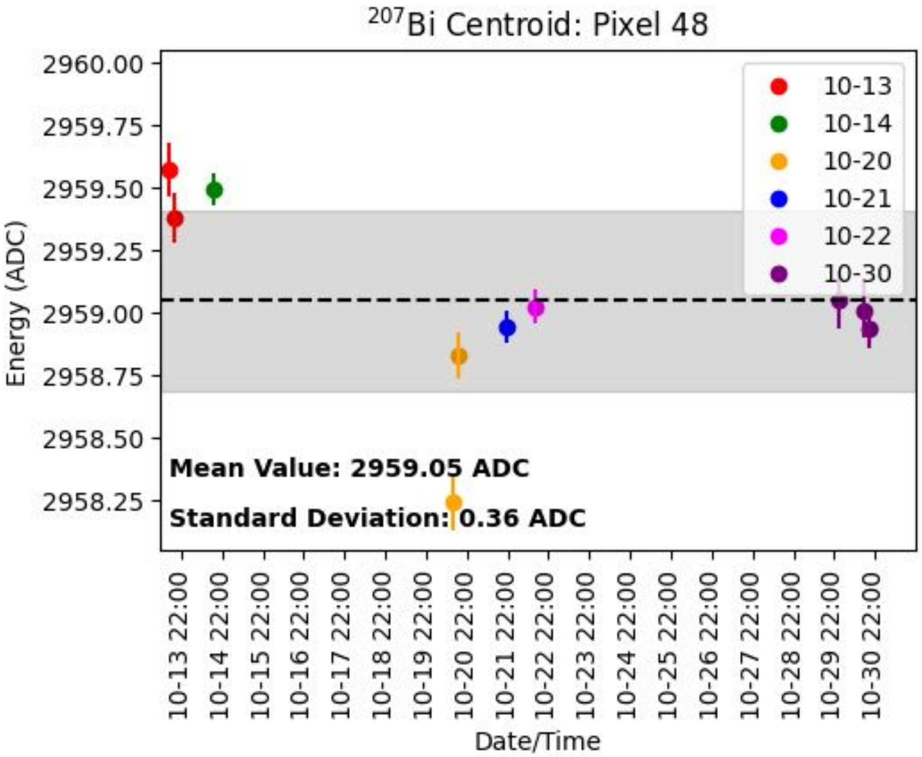


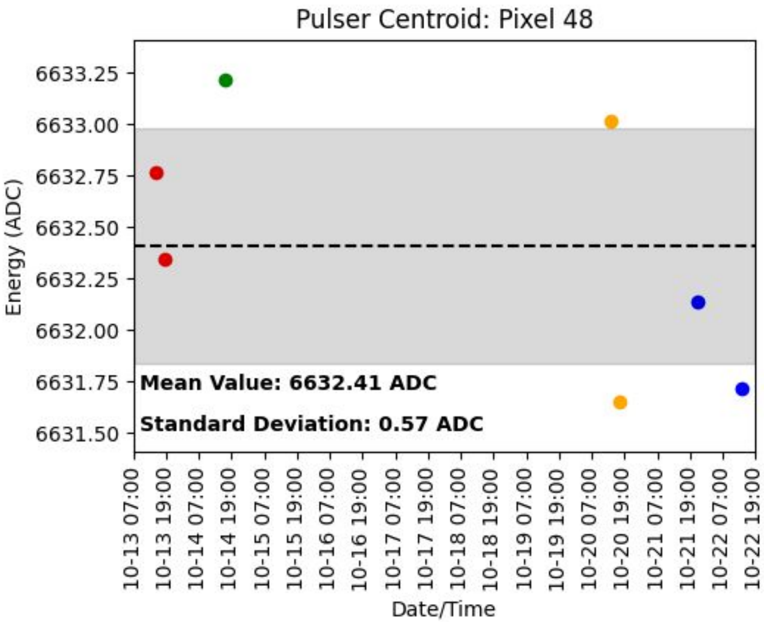
Flowchart
(Click me)

Pulser Data

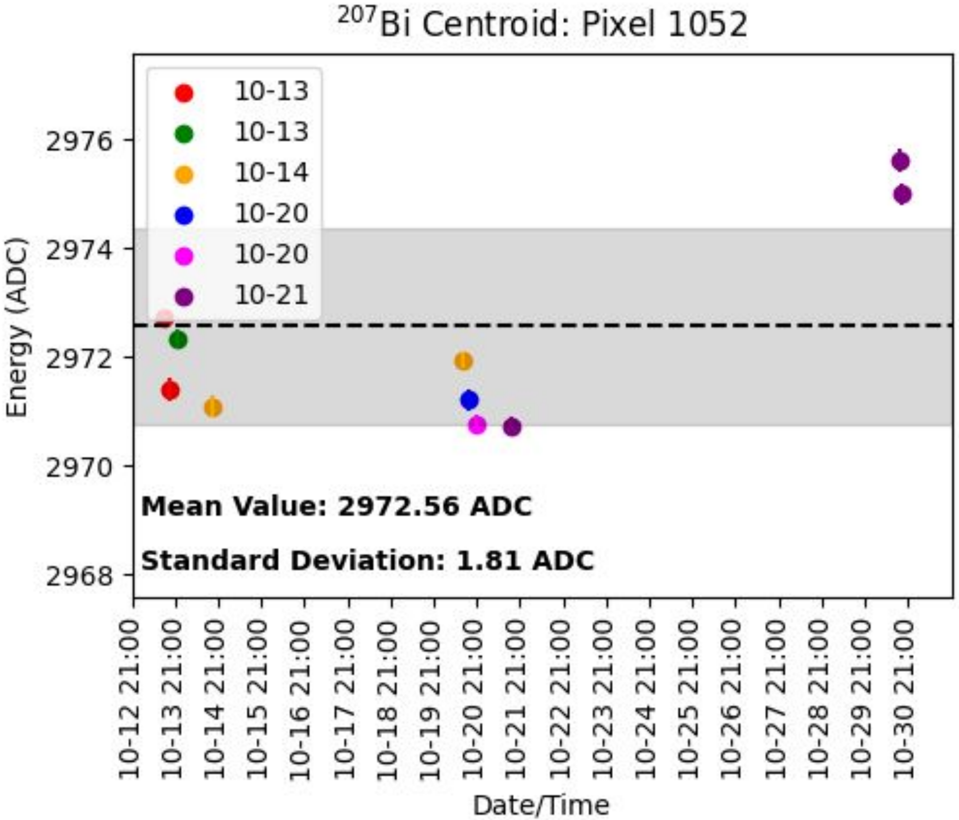
- Pulser signal sent through detector electronics chain
- Fall 2025, pulser data:
  - Every pixel
  - Raw pulser output signal (which is what is sent through electronics)
    - Used to determine if pulser itself contributes to trends in pulser and source data
    - Board channel (BC):
      - UDET: 112, LDET: 223
  - Pulser trigger signal
    - BC:
      - UDET: 118, LDET: 230
- I fit pulser peaks to a Gaussian
- **Impact for calibrations:**
  - **Way to determine if trends in source peak centroids are due to electronics vs. detector effects**
  - **Goal: determine if source trends can be adequately tracked with pulser**
    - **Reduce frequency of calibration suites**
  - **Fall 2025:**
    - **Pulser (for the most part) always on**
    - **Temperature study done (Nov.) to determine if pulser tracks source data with temperature**

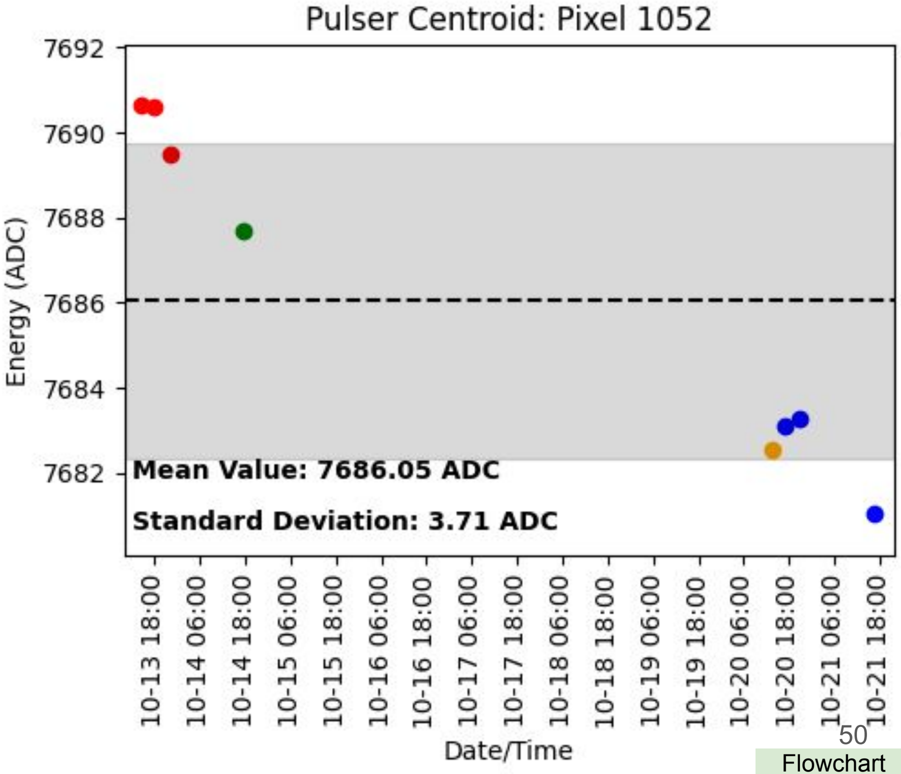
UDET Pixel 48





LDET Pixel 1052

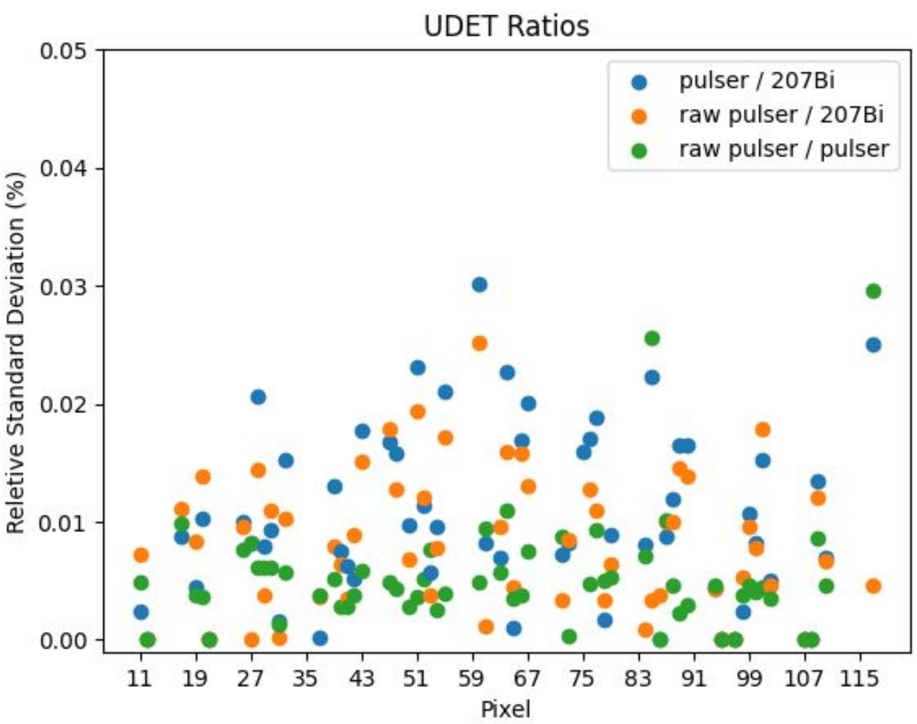


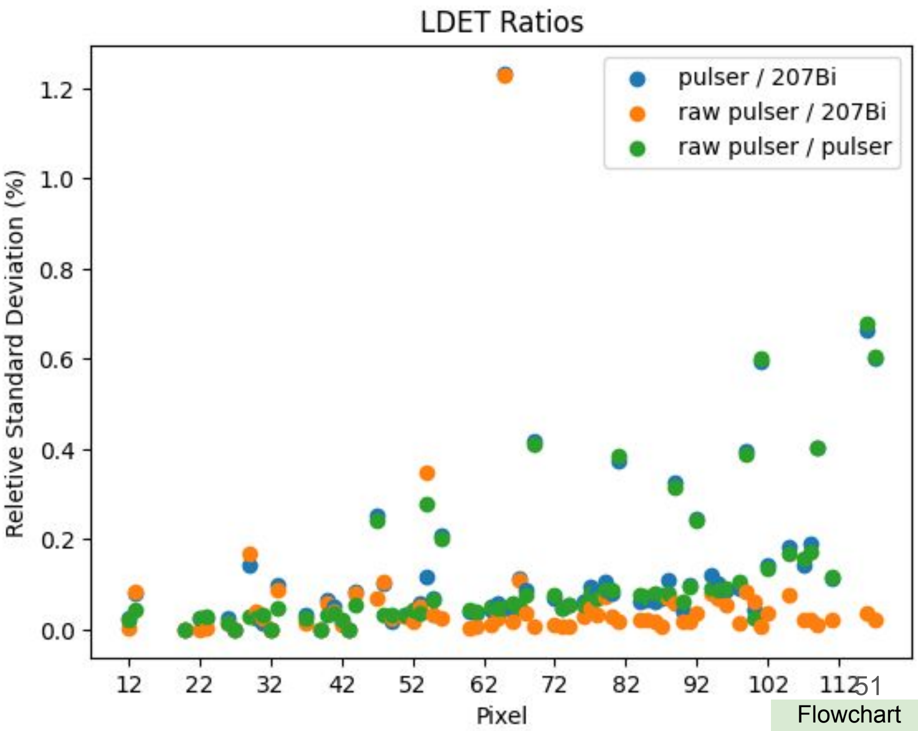


Flowchart
(Click me)

Stability

- Only over ~ 2 week (pulser settings accidentally changed during last week of data)

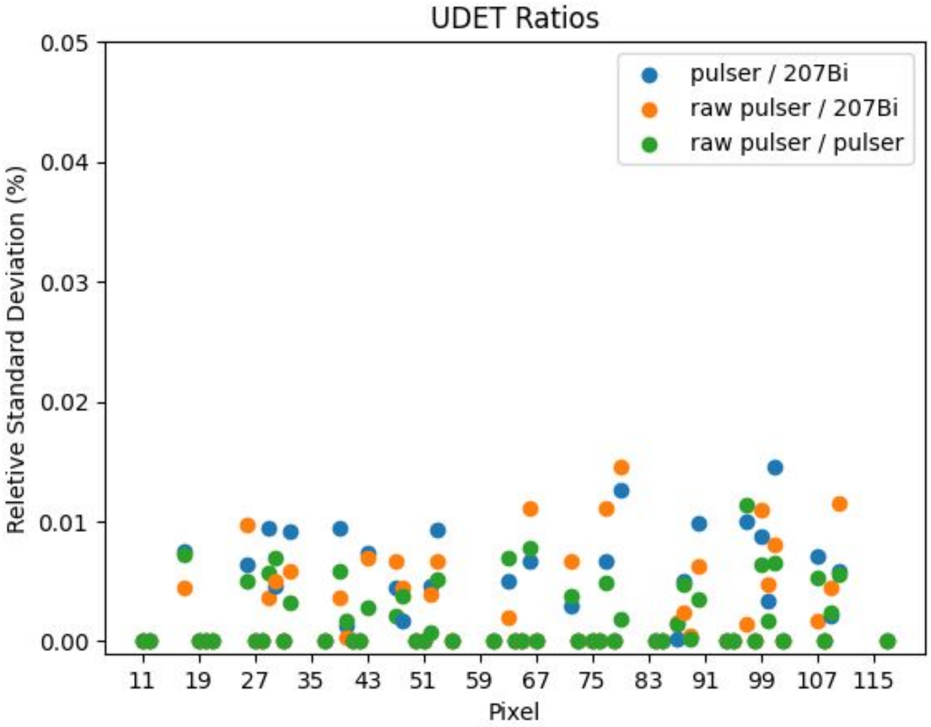


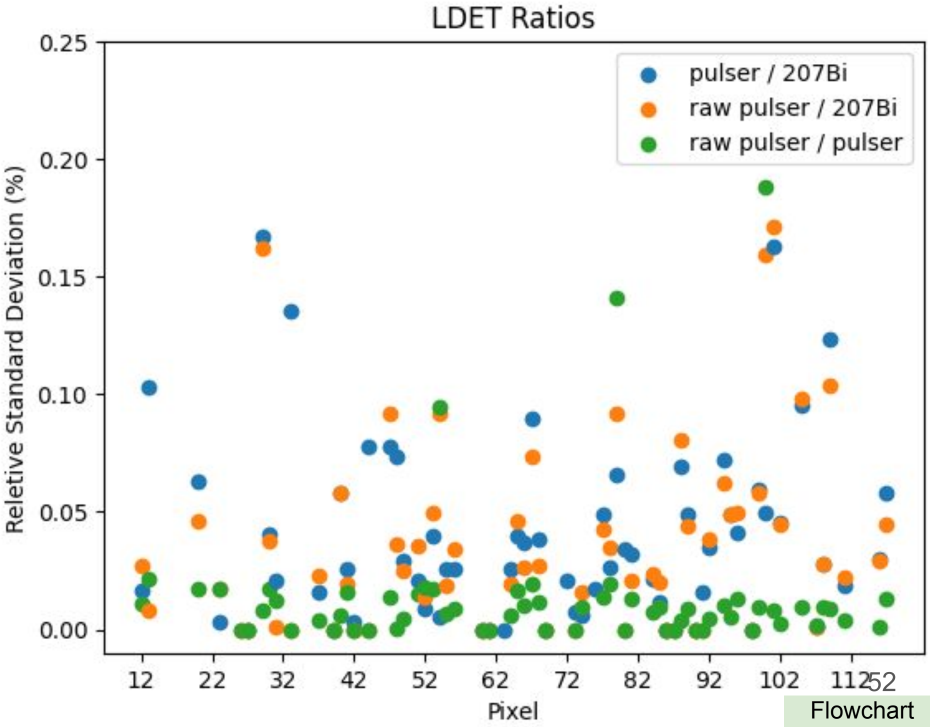


Flowchart
(Click me)

Stability

- Over last week (pulser settings accidentally changed during last week of data)
- One outlier not shown in LDET plot (right)





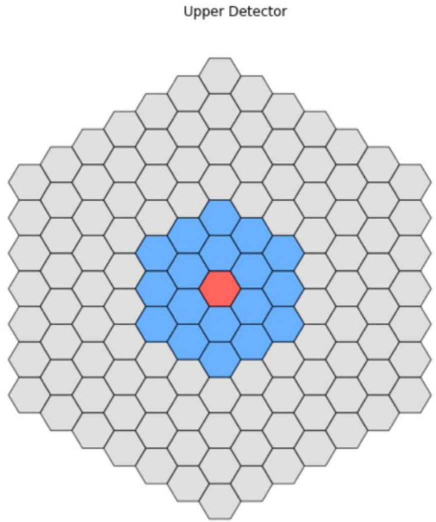
Flowchart
(Click me)

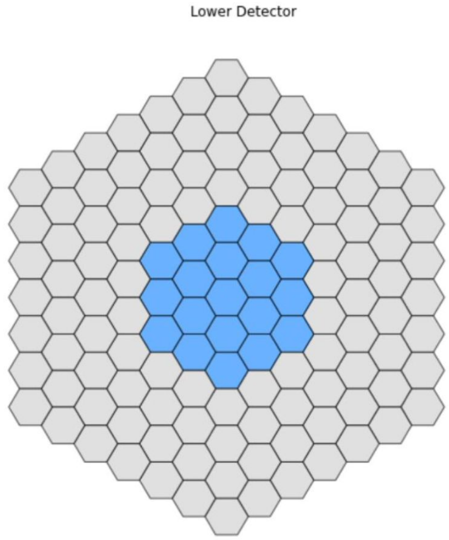
Energy Reconstruction

Andrew Hagemeier

Flowchart
(Click me)

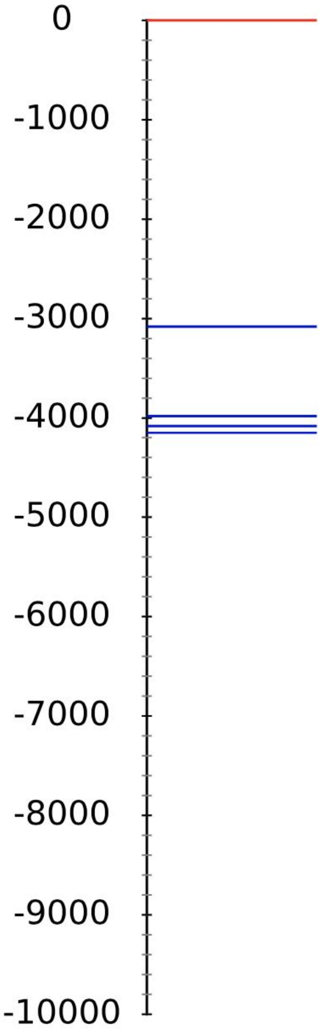
What Is a Coincidence Event





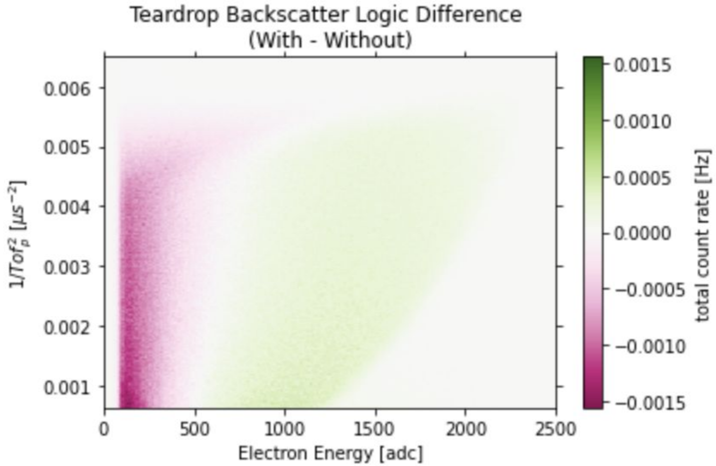
- Electron & Proton Candidate
  - Determined by Energy, must be distinct in DAQ v1.5
    - Proton Energy Window 2025 Fall
      - 20-90 ADC (~ 6 - 27 keV)
    - Electron Energy Window 2025 Fall
      - >90 ADC (~ 27 keV)
- Tof Window
  - Electron Candidate within coincident pixels of proton candidate occurs within the coincidence time window of that proton candidate
- An electron can be coincident with multiple protons

Flowchart
(Click me)



Electron Energy Reconstruction

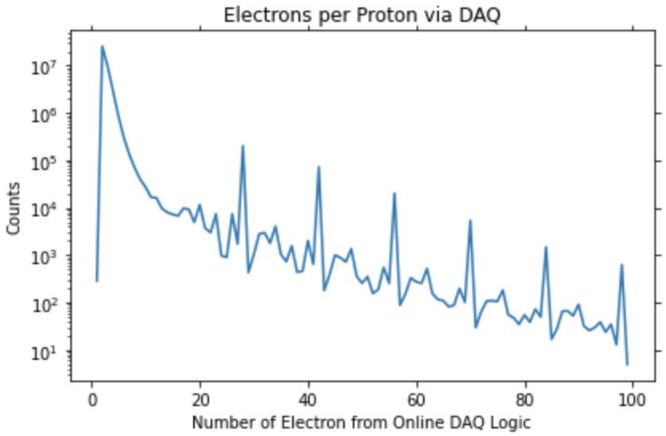
- Backscattered electrons occur within the backscatter window of a previous electron, can be telescoping
  - Call these electron events
- Multiple electron event possible per proton
  - Determining if distinguishable is yet to be determined
- Energy sum of electron events for total electron energy
  - Add the HV of the detector to the last electron hit to the energy
- Timing of electron event is taken from first electron hit

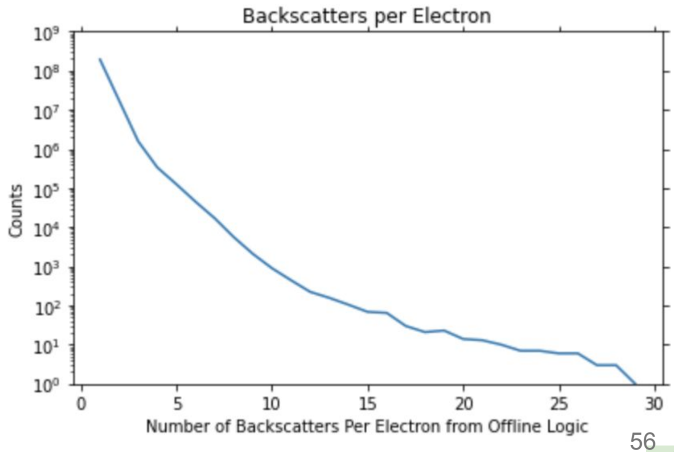


Flowchart
(Click me)

Backscatter Rate

- ~9% of events have at least one electron candidate within my backscatter window (200 ns) of another
- <1% of all events have more than two backscattered electrons
  - Plots & percentages do include backgrounds

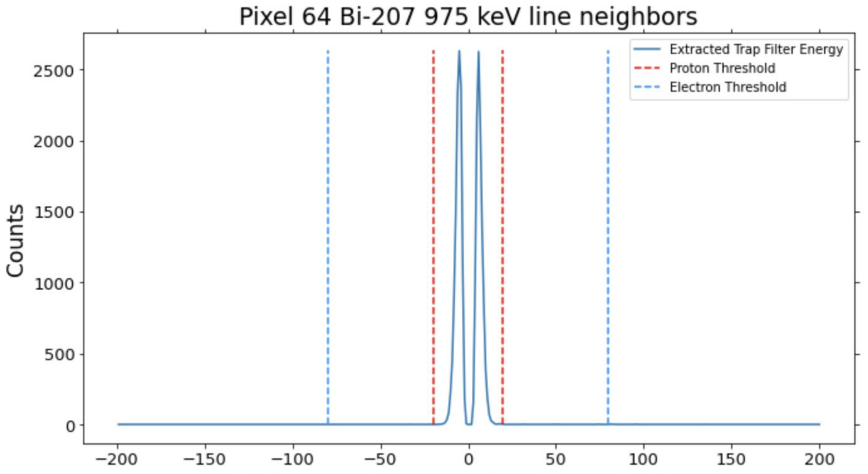


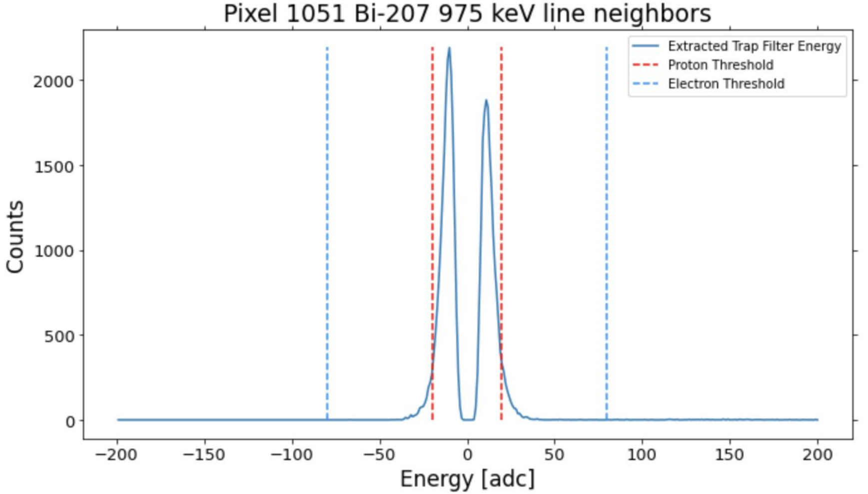


Flowchart
(Click me)

Cross Talk

- Taken from peak of calibration line during overnight source run, looking at triggers within 100 ns of electron hit
- See no significant counts above background noise
- Not above electron threshold on Goop! (LDET)
- Not in proton threshold region on VALENTINE(UDET)





Flowchart
(Click me)

Background Subtraction

Hunter Presley

Flowchart
(Click me)

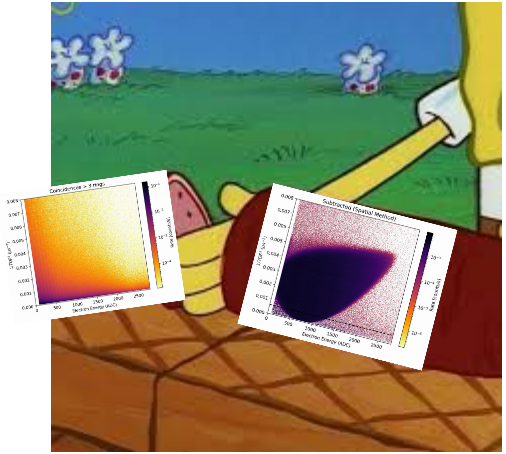
Background Subtraction

What to expect?

- Brief explanation of false coincidences (background)
- Two subtraction methods (WIP)
    - Time shifting
    - Spatial cut

What not to expect

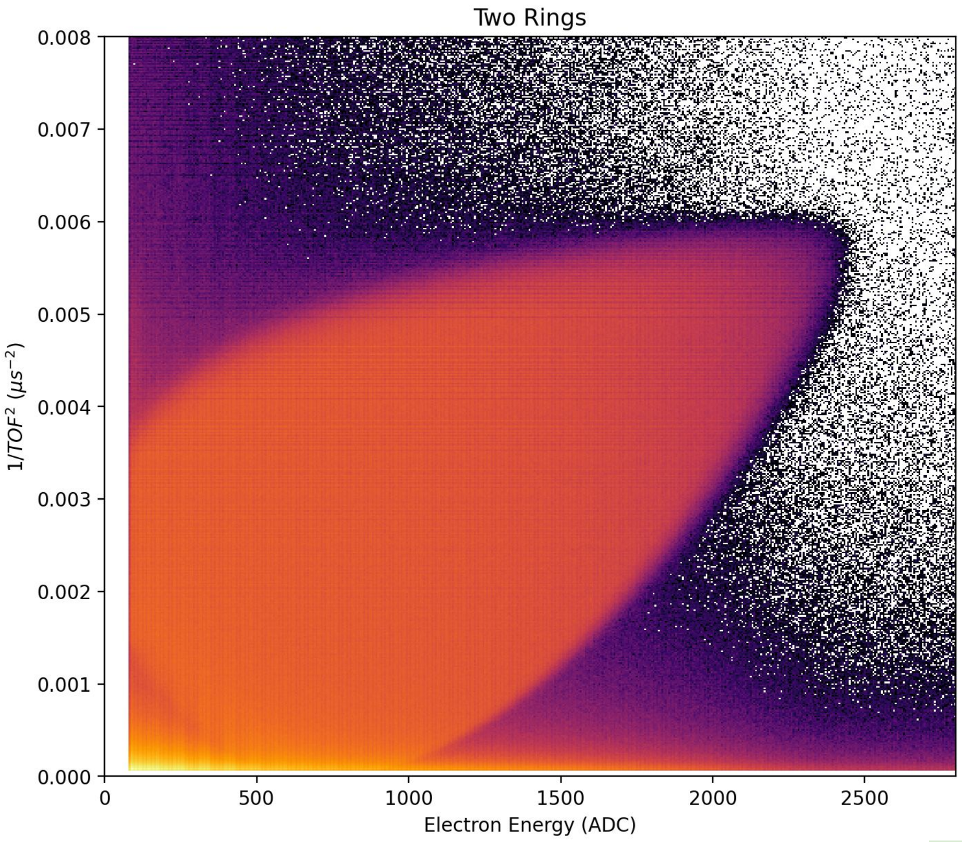
- Finalized results :)



Trigger stream teardrop

- **Coincidence logic** on triggers
- **Backscatter logic** (see previous talk)

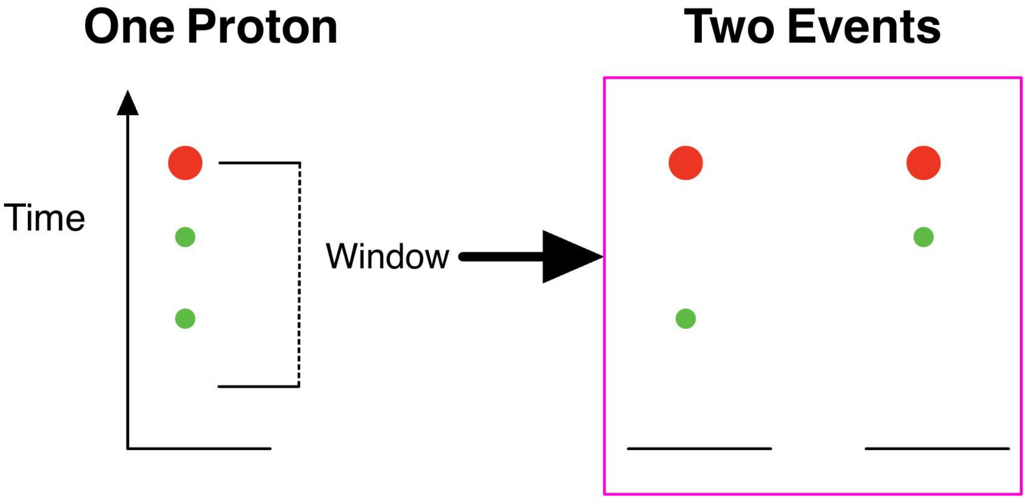
	timestamp	bc	energy	pixel
0	61084632036886	35	614	101
1	61084632036890	73	3123	111
2	61084632043368	63	222	23
3	61084632045386	178	574	1049
4	61084632101314	142	392	1078



Flowchart
(Click me)

False Coincidences

- In a perfect world we detect every proton-electron pair born from each neutron decay within our decay volume with 100% accuracy ⟶ 0 false coincidences
- Coincidence events
  - PID: Energy window and detector location
  - Identify proton and look back in time for electron signals
  - In many cases, a single proton will have multiple equally qualified electron candidates



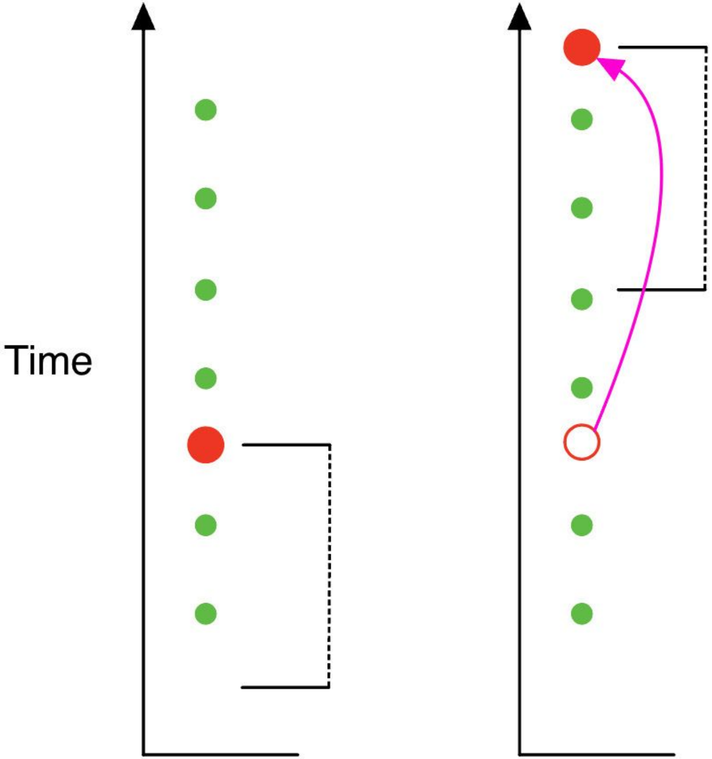
Flowchart
(Click me)

How to subtract out the background?

- There is **no way** to isolate **true coincidences** in the data (would be nice)
- We **CAN** isolate **false coincidences** by looking at regions of data where true coincidences are physically impossible to occur
    - **Temporal isolation**
    - **Spatial isolation**
- Background subtraction procedure:
    - Produce false coincidence distribution
    - Normalize and subtract from signal distribution

Temporal Isolation

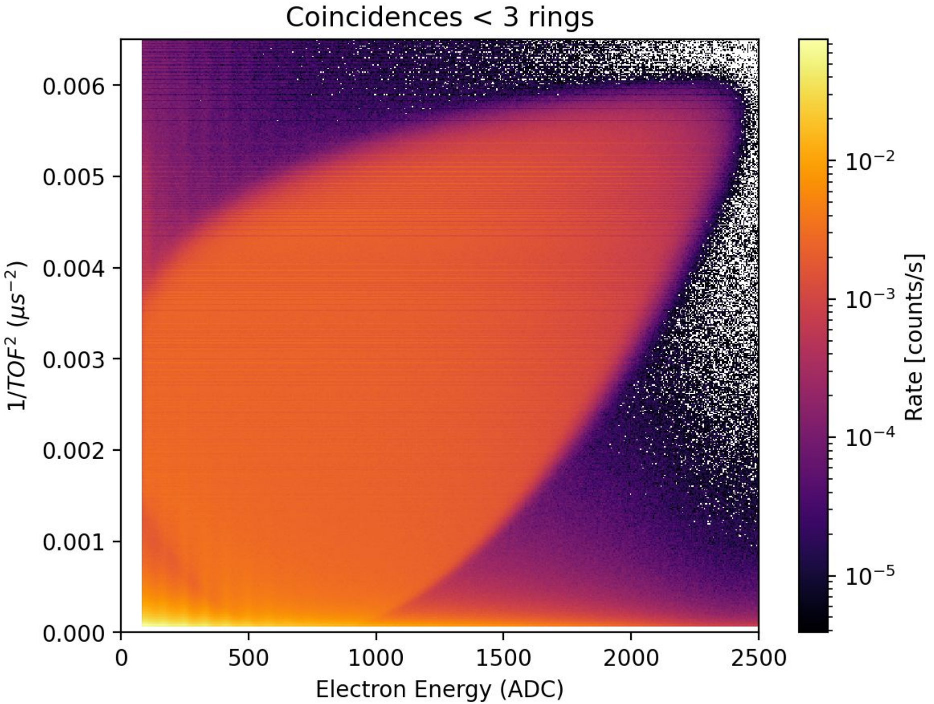
- Add an **offset to all proton times** prior to running the coincidence logic and energy reconstruction
- Offset should be large enough that **no electrons** in any particular proton lookback window **could physically be coincident** with that particular proton

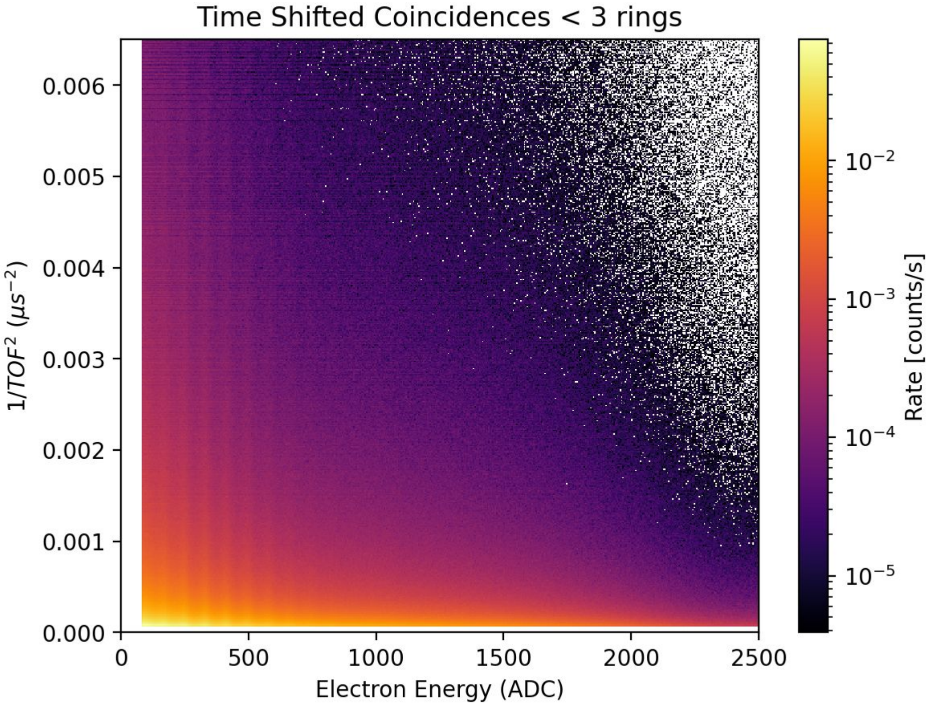


Temporal Isolation

- Rerun coincidence logic with timeshifted protons
  - For this I used **1 beam period** ~(.0167s)
  - Apply **identical cuts/corrections**
    - Timing synchronization
    - Gamma flash
    - Energy and timing windows
    - Coincidence < 3 rings
  - Subtract time-shifted teardrop from original

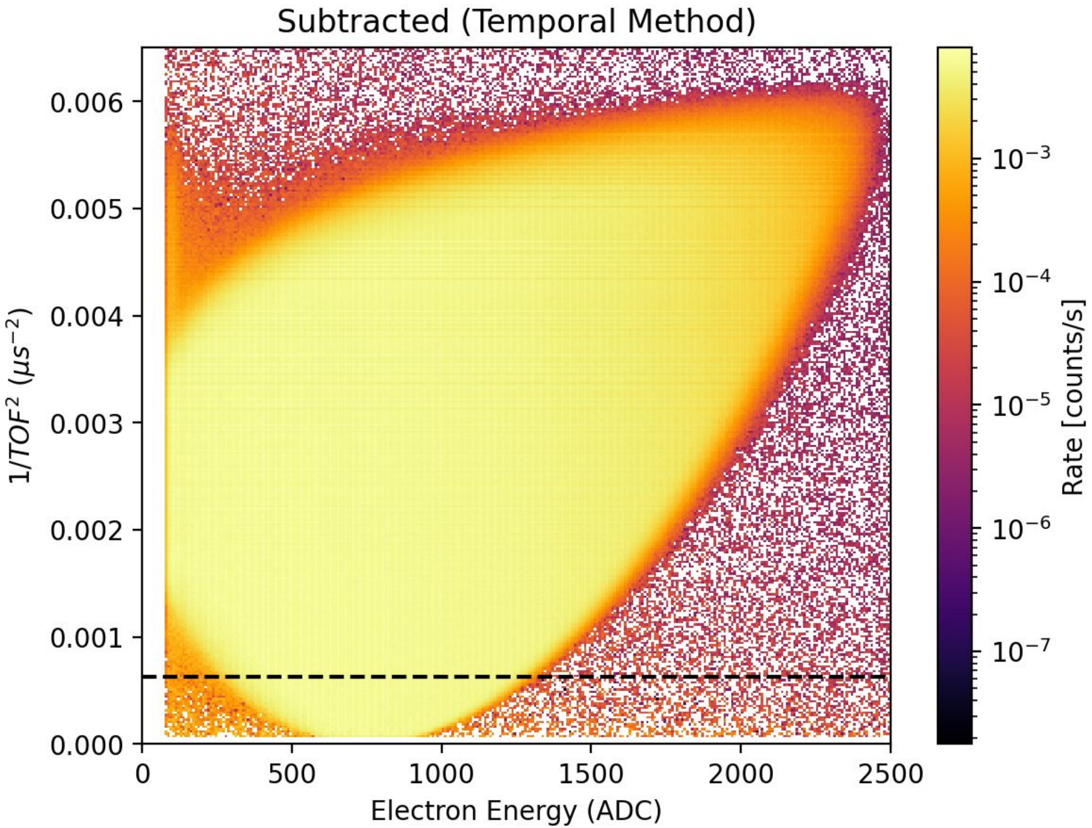
Temporal Isolation





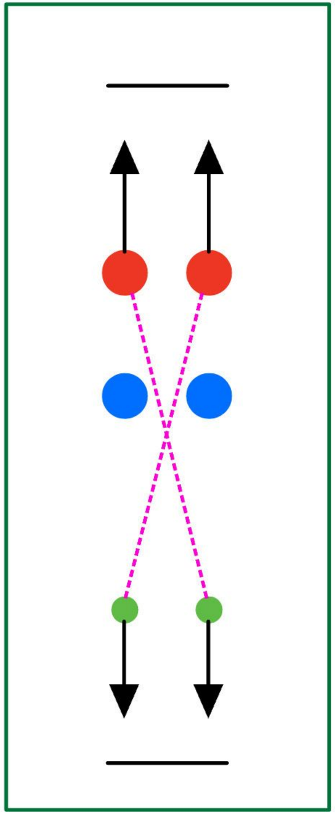
Flowchart
(Click me)

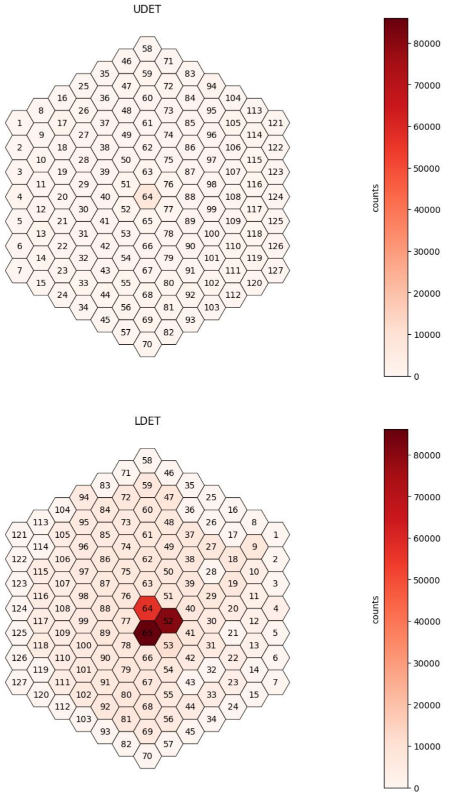
Temporal Isolation



Spatial Isolation

- Create new “distance” variable for **every coincident event** that gives the number of rings between the proton and electron (initial hit)
- Cut on a region of the data where coincidence is **spatially very unlikely** (more than 3 ring separation from electron and proton) to isolate false coincidences

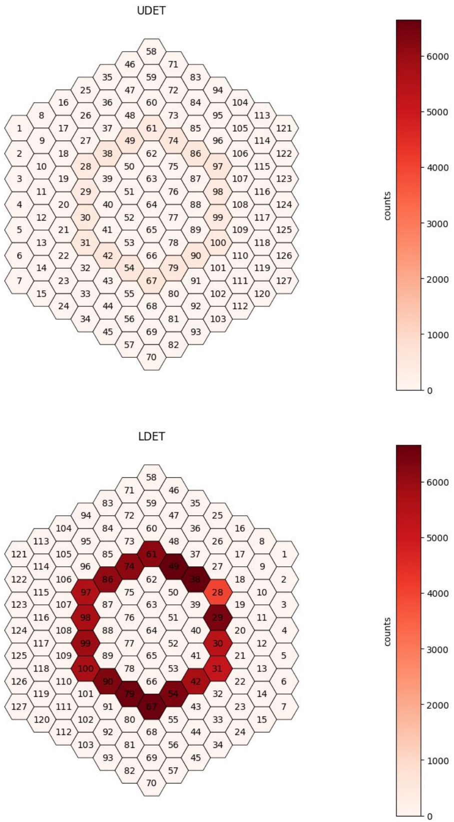




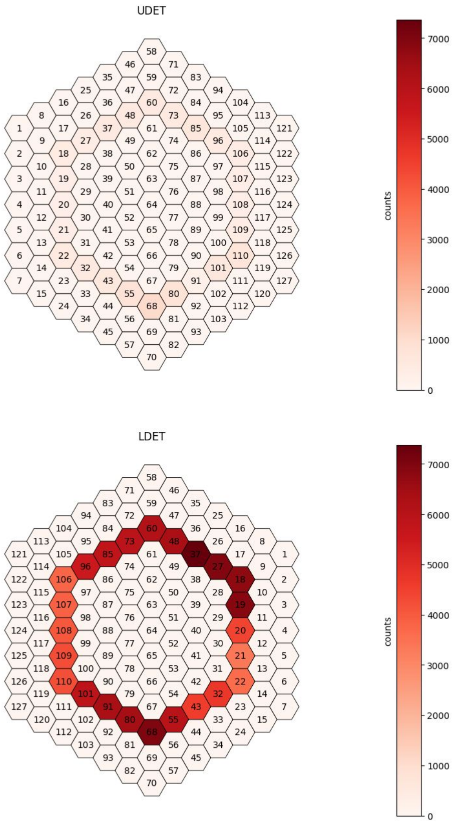
Distance Variable

Electron coincidences for protons on pixel 64

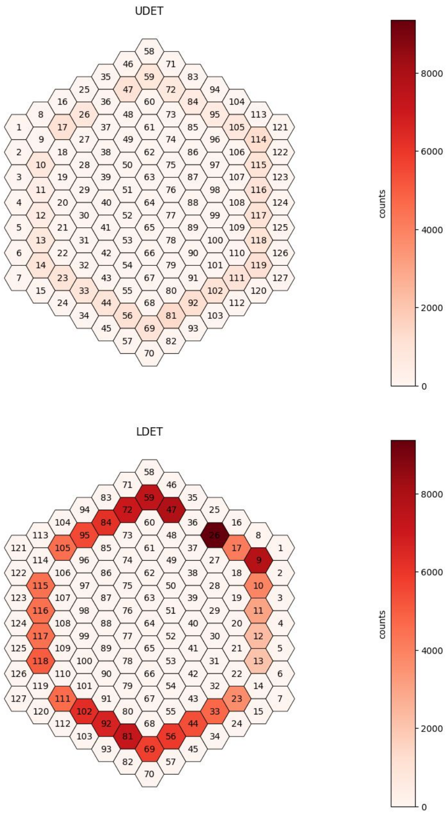
Dist==3



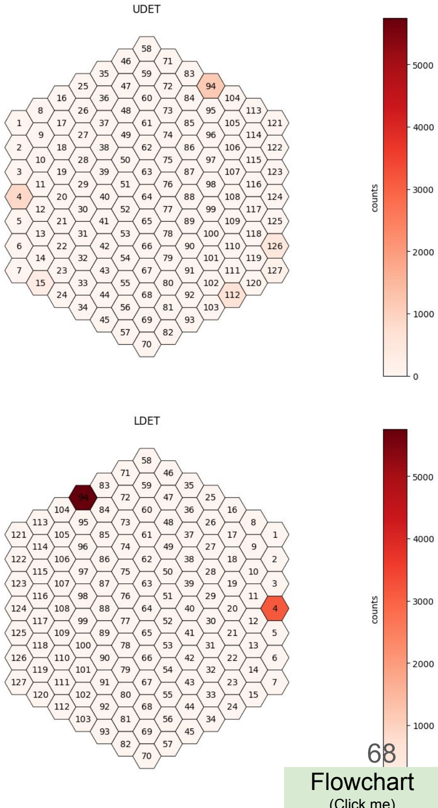
Dist==4



Dist==5



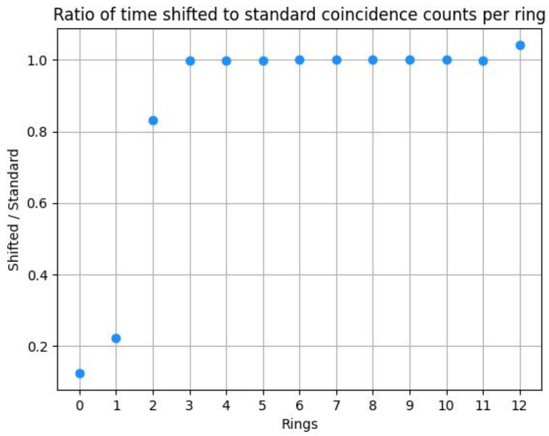
Dist==6

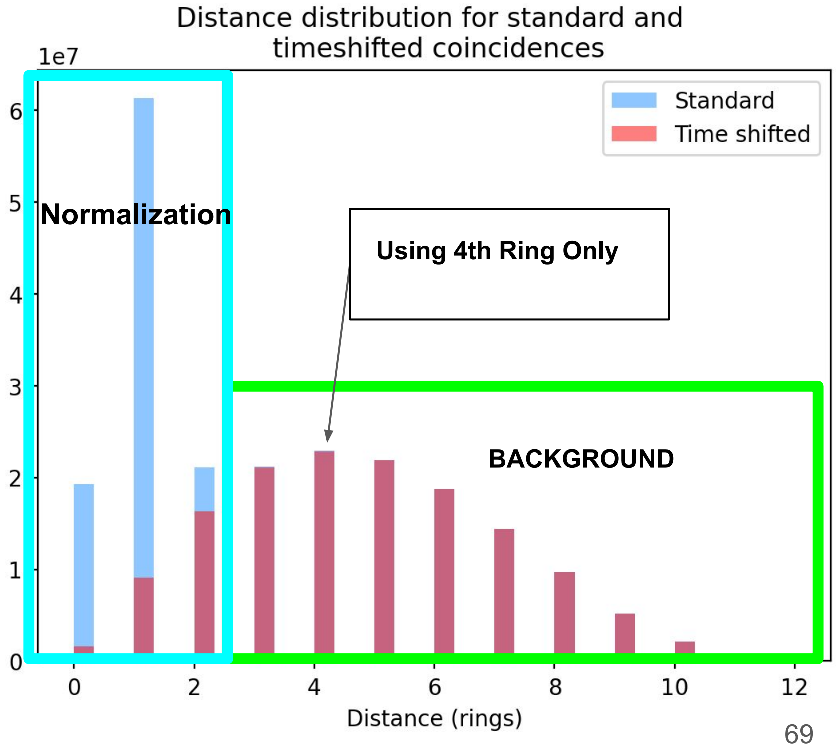


Flowchart
(Click me)

Spatial Isolation

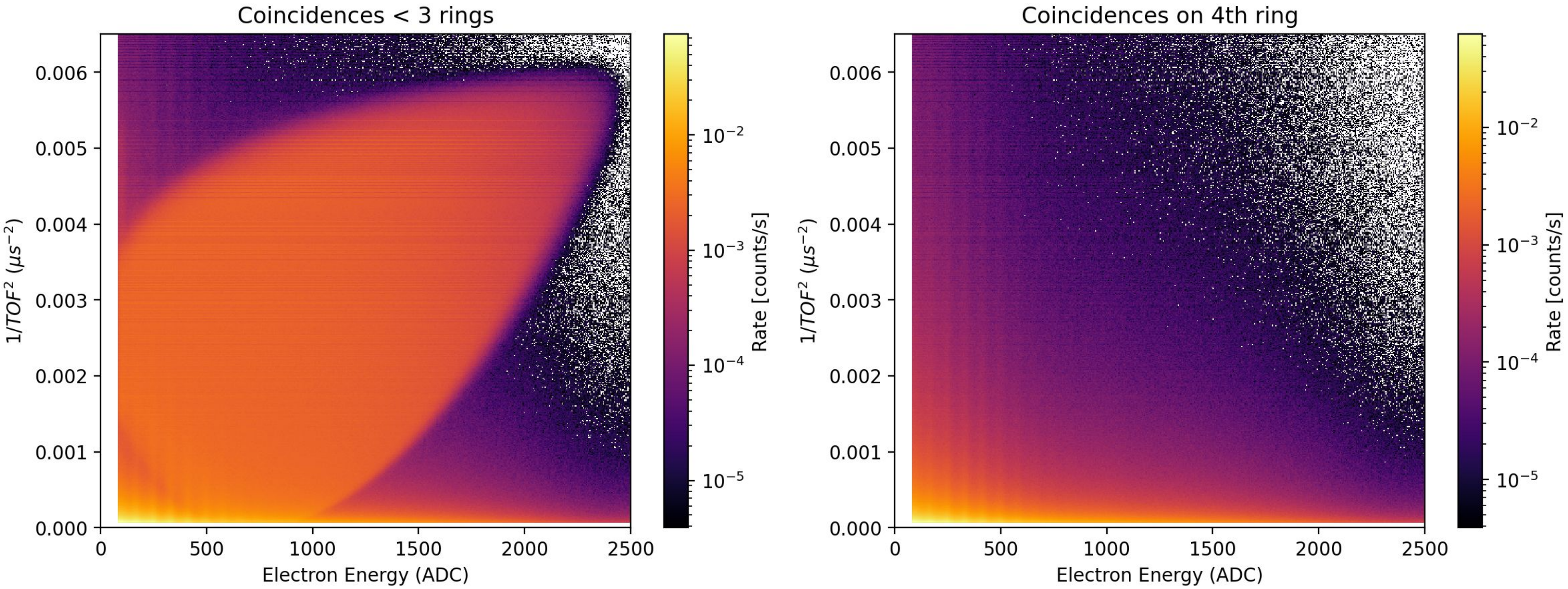
- Normalized using timeshifted data
- Number of events passing cuts under two rings for time shifted vs standard
  - Probably better way to normalize
  - WIP





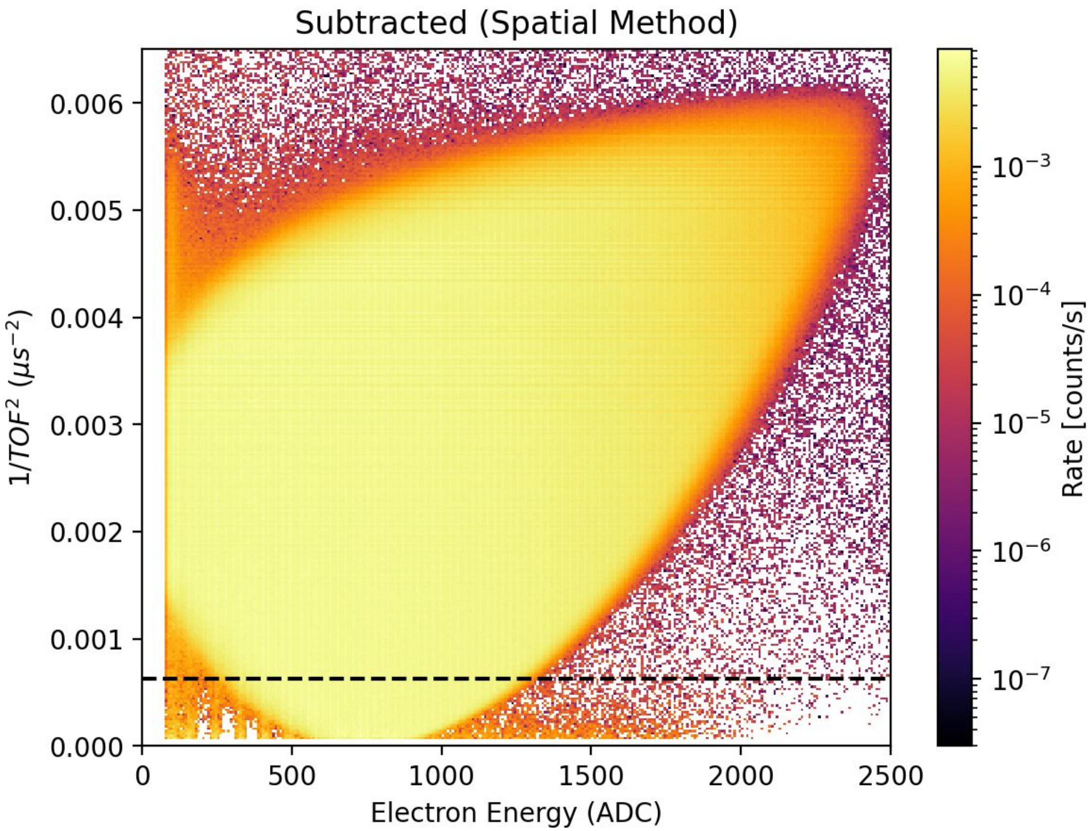
Flowchart
(Click me)

Spatial Isolation



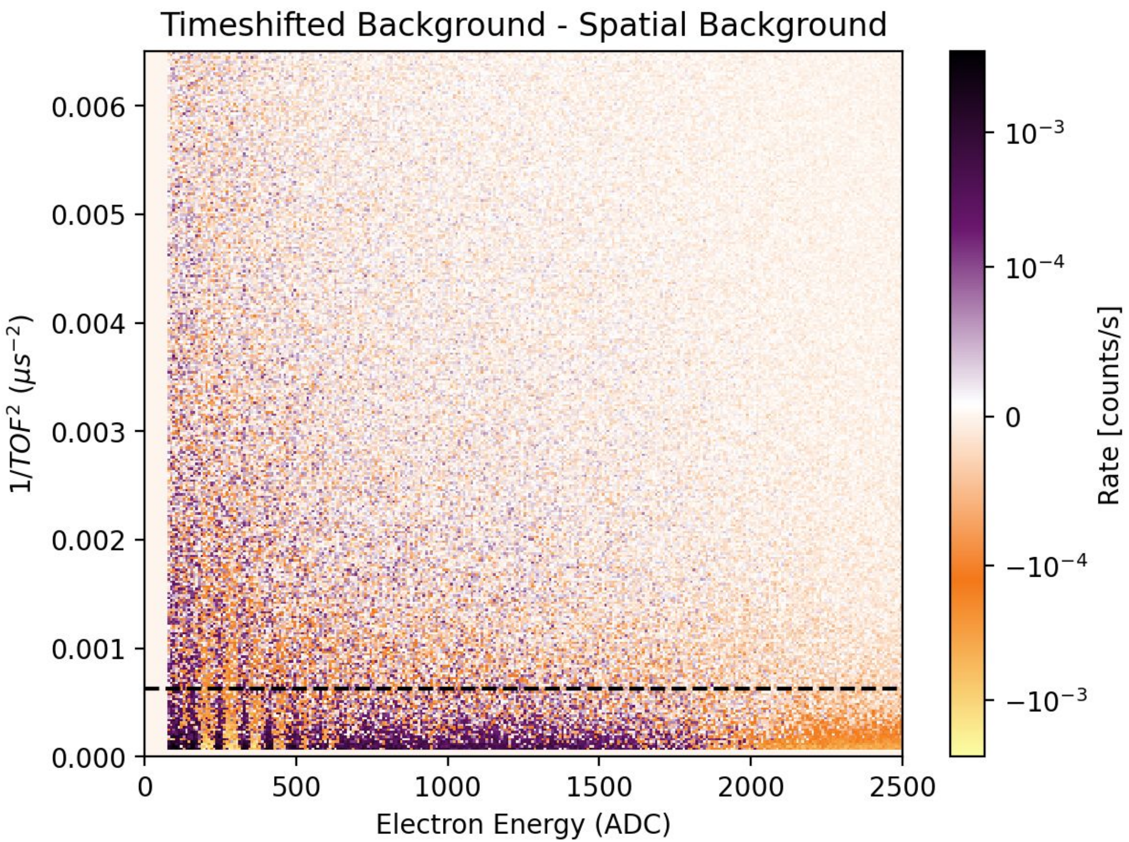
Flowchart
(Click me)

Spatial Isolation



Flowchart
(Click me)

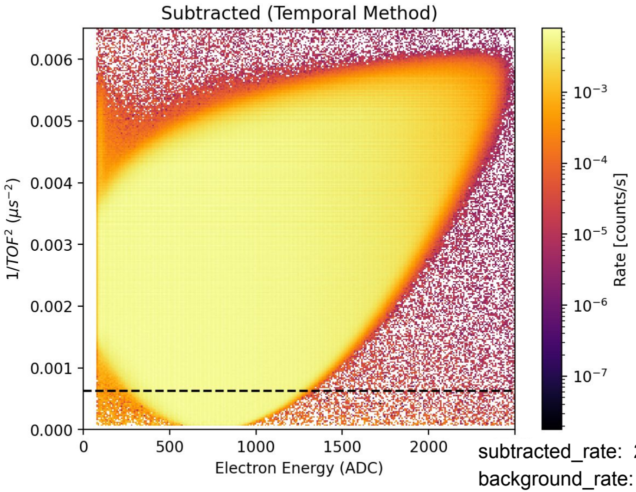
Comparison



Flowchart
(Click me)

Summary

- Plots shown created from trigger stream
  - Filter parameters optimized for trigger efficiency, not energy and timing resolution
- Spatial method
  - Normalization needs work to be independent of temporal method
- Both methods should be used on processed waveforms with optimal filter parameters
  - Need non-prescaled singles
- Not the only methods in development!



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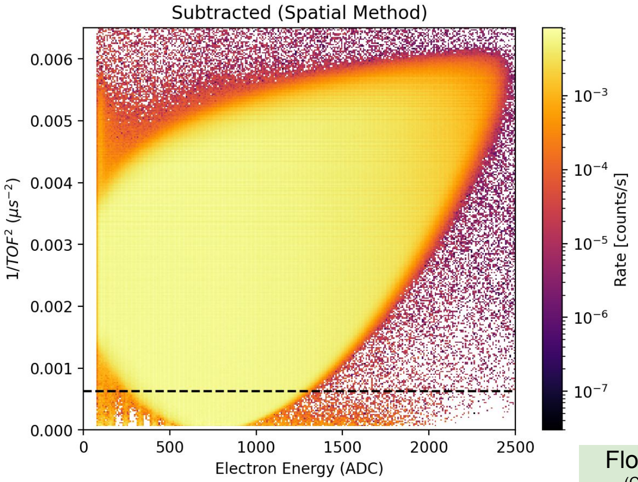
background_rate: 18



Flowchart
(Click me)

Charge collection time & Detector transit

RJ Taylor

Flowchart
(Click me)

Charge collection time theory

After electron-hole pairs are created their movement is determined by

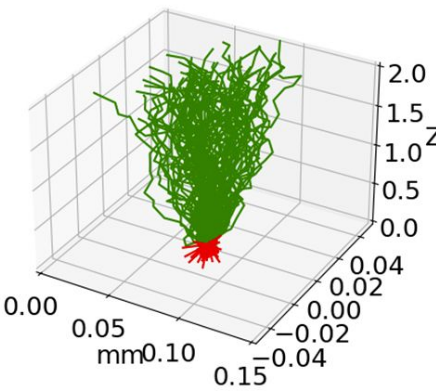
$$\boldsymbol{v}_d = \frac{\mu_0 \boldsymbol{E}}{[1 + (\mu_0 E/v_s)^{1/\beta}]^{\beta}}$$

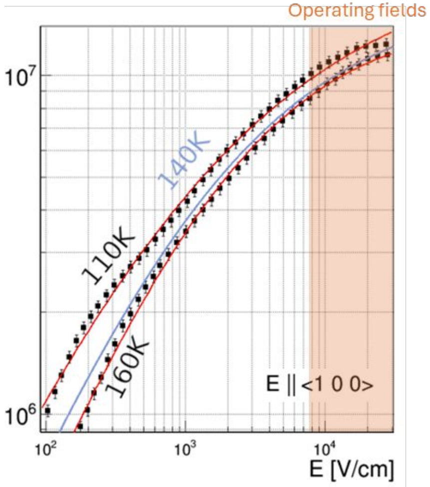
$$|\boldsymbol{E}(z)| = \begin{cases} \sqrt{\frac{2VNq}{\varepsilon}} - \frac{Nq}{\varepsilon}z & \text{undepleted} \\ \frac{V}{L} + \frac{NqL}{2\varepsilon} - \frac{Nq}{\varepsilon}z & \text{depleted} \end{cases}$$

Empirical fit constants dependent on T,E, crystal axis, and charge

Bias voltage

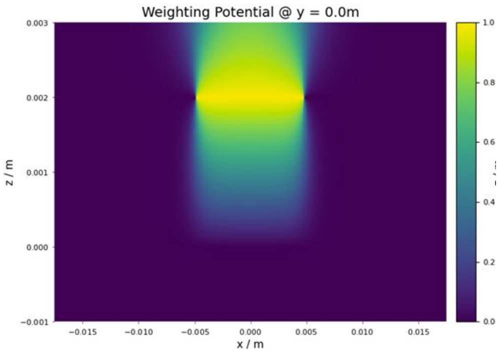
Impurity density

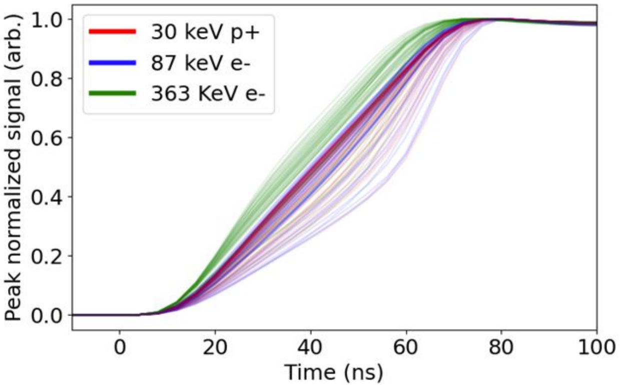




Drift trajectories of charges and weighting field determine signal shape.

$$i = q\vec{v} \cdot \vec{W}$$





Flowchart
(Click me)

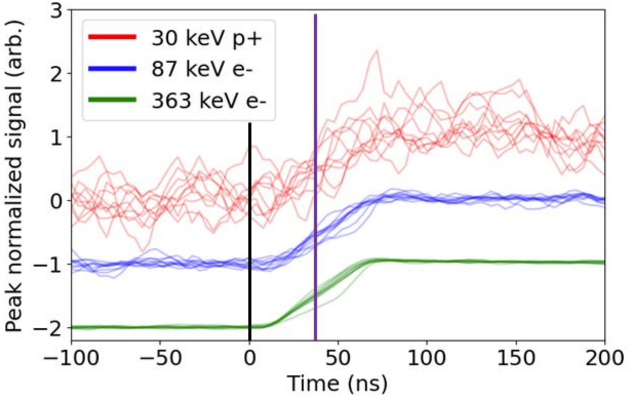
Charge collection time bias

Once detector has been characterized, we can simulate signals with NESSE to determine the detector timing bias.

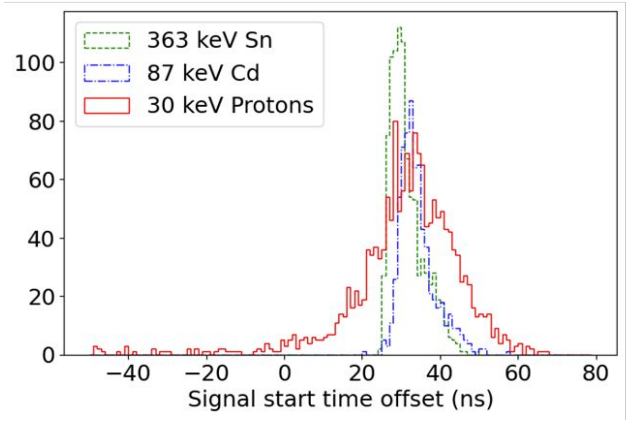
Note that increased bias voltage and SNR decrease timing uncertainty.

Unless timing offset is known for every event, there will be a timing bias….
Notice timing offset variation between electrons and protons.

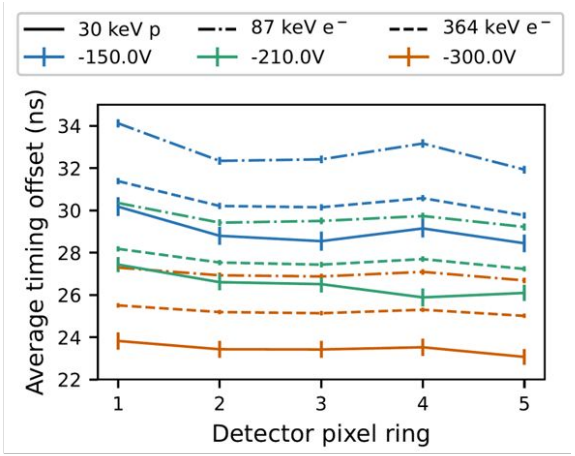
With noise signal start is obscured, timestamp is assigned after true start.



Distributions of the timing extraction offset using a logistic fit to determine t_0.



Timing offset varies for event type and voltage. IDP causes 0.8 ns timing range at -300 V.

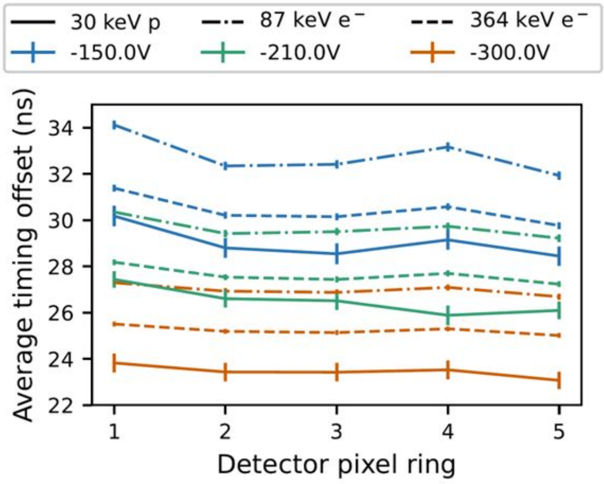


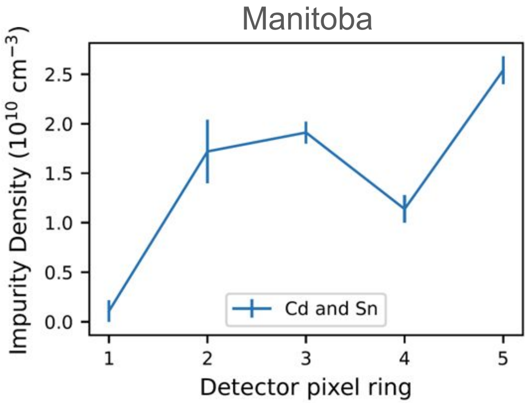
Flowchart
(Click me)

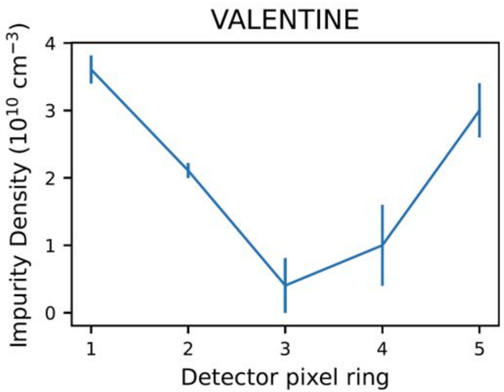
Charge collection time correction

What do we need to know to reach <0.3 timing bias due to charge collection time?

- Expected offset as function of electron energy (~5 ns)
  - Accurate energy calibration and extraction
  - Requires signal shape simulations for full energy range
  - NESSE must be tuned to detectors (correct mobility, geometry, bias voltage, scattering input, etc.)
- Impurity density of every pixel (~1 ns)
  - Determined by comparing calibration signal risetimes to detector simulations







Preliminary assessment using manitoba simulations

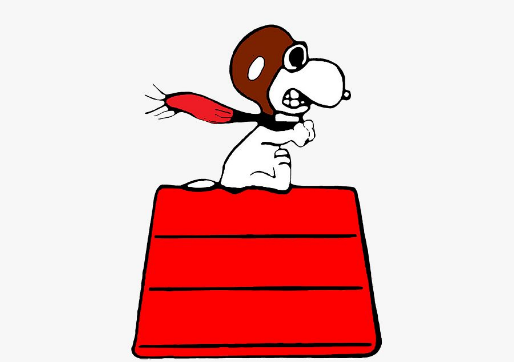
Flowchart
(Click me)

Proton Time of Flight Correction

August Mendelsohn

The Situation

- ➔ Raw data: detected t_0^p and t_0^e timestamps
- ➔ Create "tof" by: $t_0^p - t_0^e$
  - ◆ (complicated by backscatters - take **first** electron timestamp)
- ➔ Need to correct "tof" and ascribe uncertainties due to the proton interactions
  - ◆ Or include as fit parameters - either way, need to keep track
- ➔ Does **not** take into account path length variations due to:
  - ◆ Birth location (neutron beam)
  - ◆ Magnetic field interactions
  - ◆ Electric field interaction
  - ◆ Charge collection time in silicon
  - ◆ Amplifier uncertainties
  - ◆ Electron time-of-flight
  - ◆ Missed (below threshold) electron backscatters
- ➔ Table to follow, based on this list.



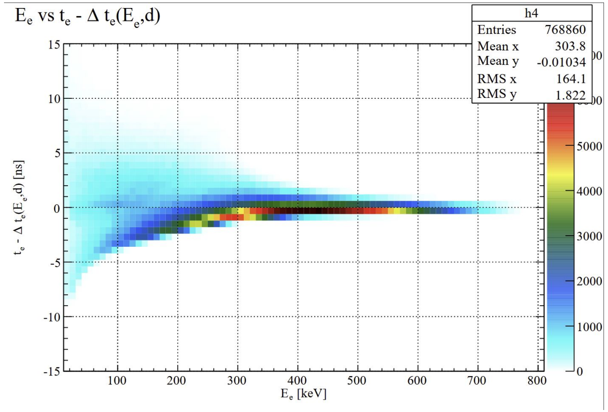
ToF Contribution (Spectrometer)	Sub-Effect	Contribution to ToF Uncertainty	Analysis Status
Electric Field	Simulated Field	~2 us (on vs off) (5% on effective length)	Considered
	Inhomogeneity / Stability	-	Planning Stage
ExB Field	Reflected Protons	negligible	Measured
Magnetic Field	Adiabaticity	negligible	Considered
	Stability	1% field change/day	Considered
Neutron Beam	Position	Need to know beam size to 3%/cm (vert), 1 mm (horizontal)	Measured
	Profile		
Electron ToF	Electron ToF	5-25 ns	Considered

ToF Contribution (Detector/DAQ)	Sub-Effect	Contribution to ToF Uncertainty	Analysis Status
Timing Resolution	Rise time (IDP, silicon parameter dependence)	~ 4 ns (analyzed up to 390 keV)	Considered And Here
	Impact angle/ Energy Dependence		Considered
Detector Position	Position of detector face wrt spectrometer axis	-	Planning Stage
Detector Synchronization	Offset	465 ns	Analyzed See next few slides!
	Stability	4-50 ns during spring cycle	

Flowchart
(Click me)

Largest Uncertainties

- UDET E-Field
  - Toy model is simulated - want to improve
  - COMLSOL simulation of the electrode implemented in GEANT4
- DAQ timing synchronization
  - Actually quite easy to implement: measure the timing offset between the two chassis, and add the offset to the offending chassis, noting the uncertainty in that offset.
- Electron ToF
  - J. Fry + S. Baeßler studied this extensively in 2019-onwards
  - E_e dependent, ranges from 5-25 ns
  - Can trust simulation to 1%



Flowchart
(Click me)

Applying the corrections

- Range from simple to impossible
  - Timing synch (**easy**): add to all lower detector channel timestamps
  - E field effects/ edge effects (**intermediate**): Spatially dependent function, need simulations (see later slides)
  - Neutron beam/proton birth location (**impossible**): unknowable
- Can also leave as fit parameters (*kind of* side-steps the issue)
- Implementation depends on fitting order of operations, folds in with the systematics discussion

Timing Synchronization

Kaushik Borah

Flowchart
(Click me)

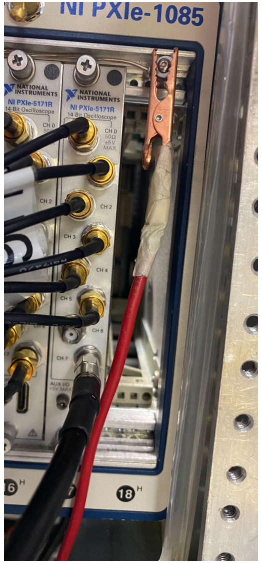
Timing Synchronization

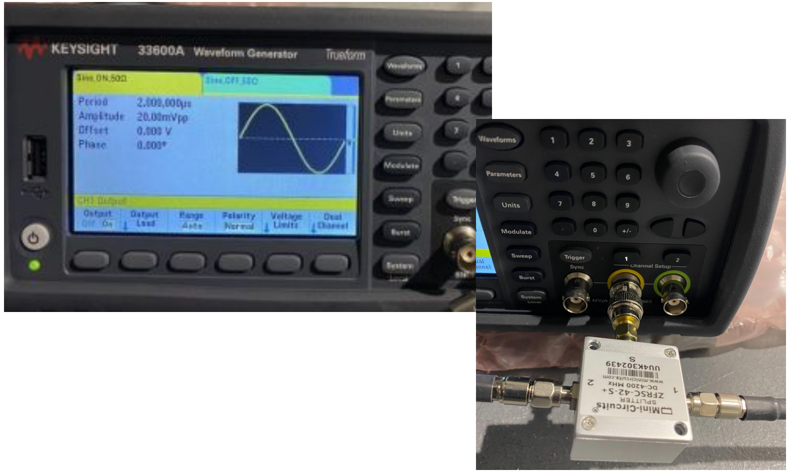
DAQ Synchronization

- Upper Chassis to Lower Chassis
- No Detectors and No Electronics

Detector Synchronization

- Chassis + Detectors + Electronics





Flowchart
(Click me)

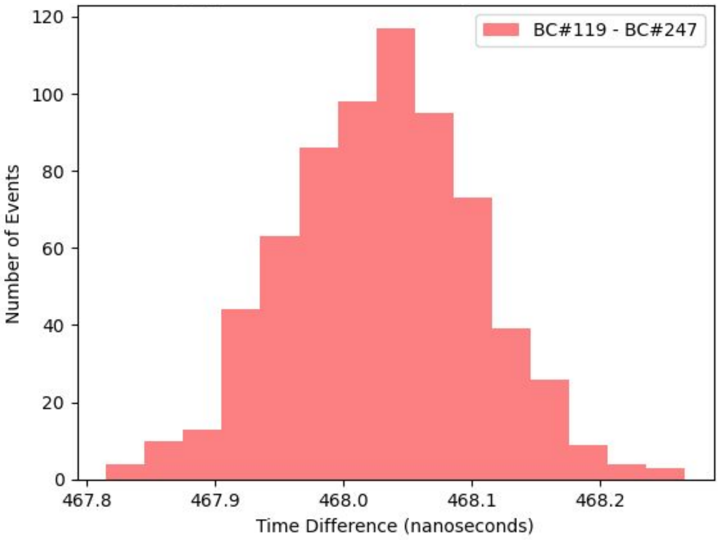
Error Analysis in Timing Synchronization

- Linear Fitting to the waveform with a chosen frequency
- Gaussian Fitting to the Histogram for Timing Difference

$$f(t; B, C, D) = B + C\cos(\omega t) + D\sin(\omega t)$$

$$A = \sqrt{C^2 + D^2}$$

$$\phi = \arctan\left(\frac{D}{C}\right)$$



Standard Error $= \dfrac{\sigma}{\sqrt{N}}$

N is Number of Events

Flowchart
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Detector Synchronization for Fall 2025

- Run# 8382 (Taken on September 24th)
- Run# 8877 (Taken on November 3rd)
- Run# 8998 (Taken on November 19th)

Flowchart
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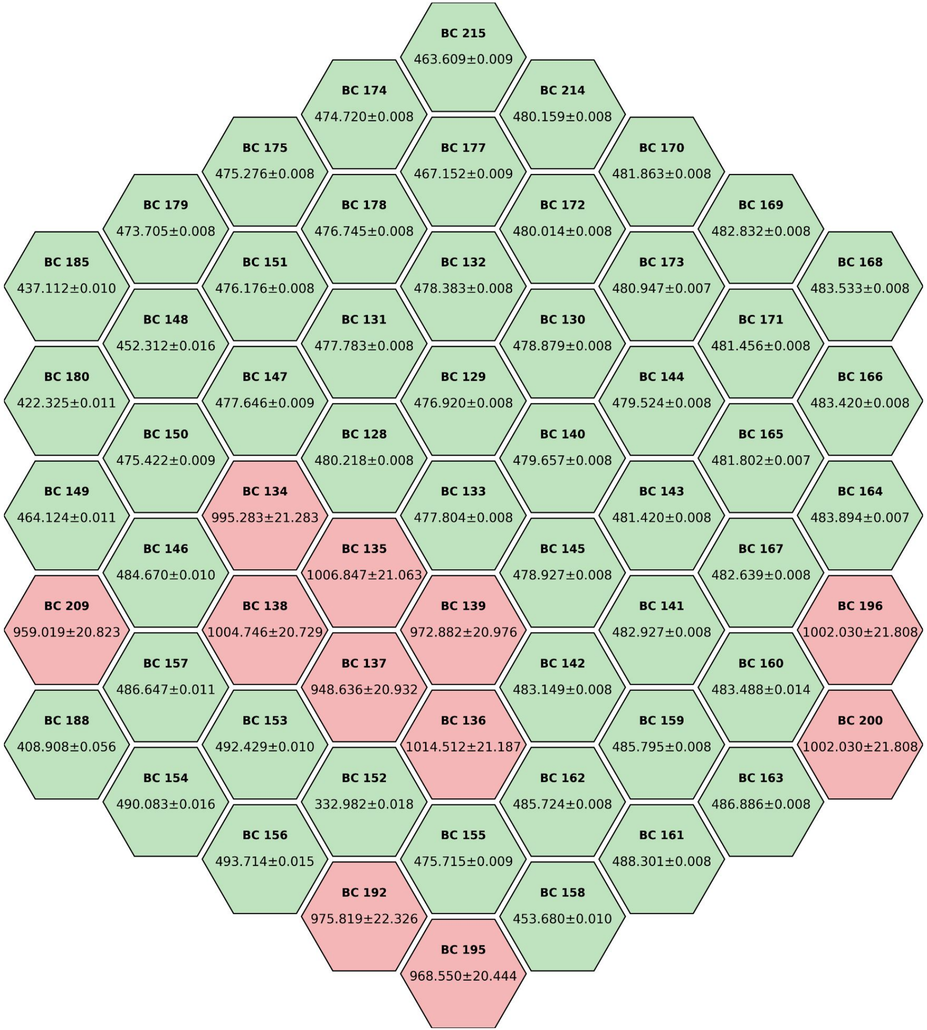
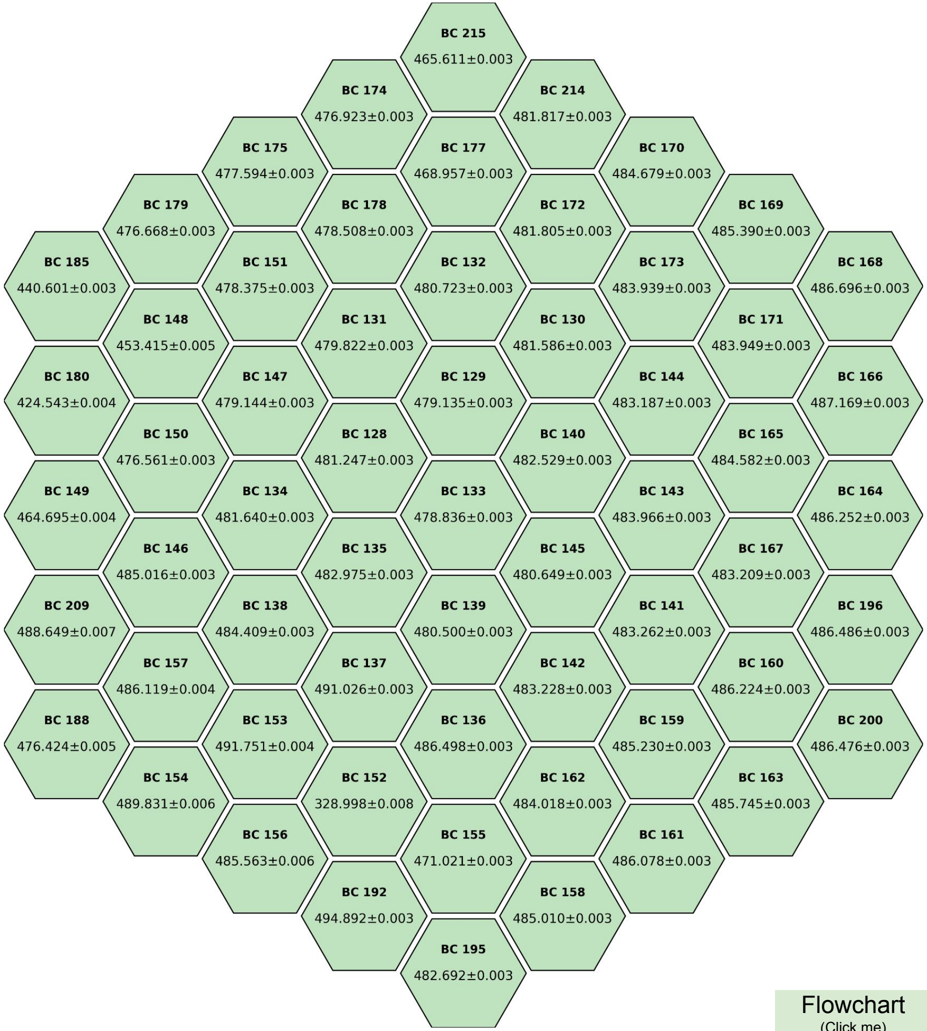
September, Run#8382, Upper BC 5 vs all Lower BC

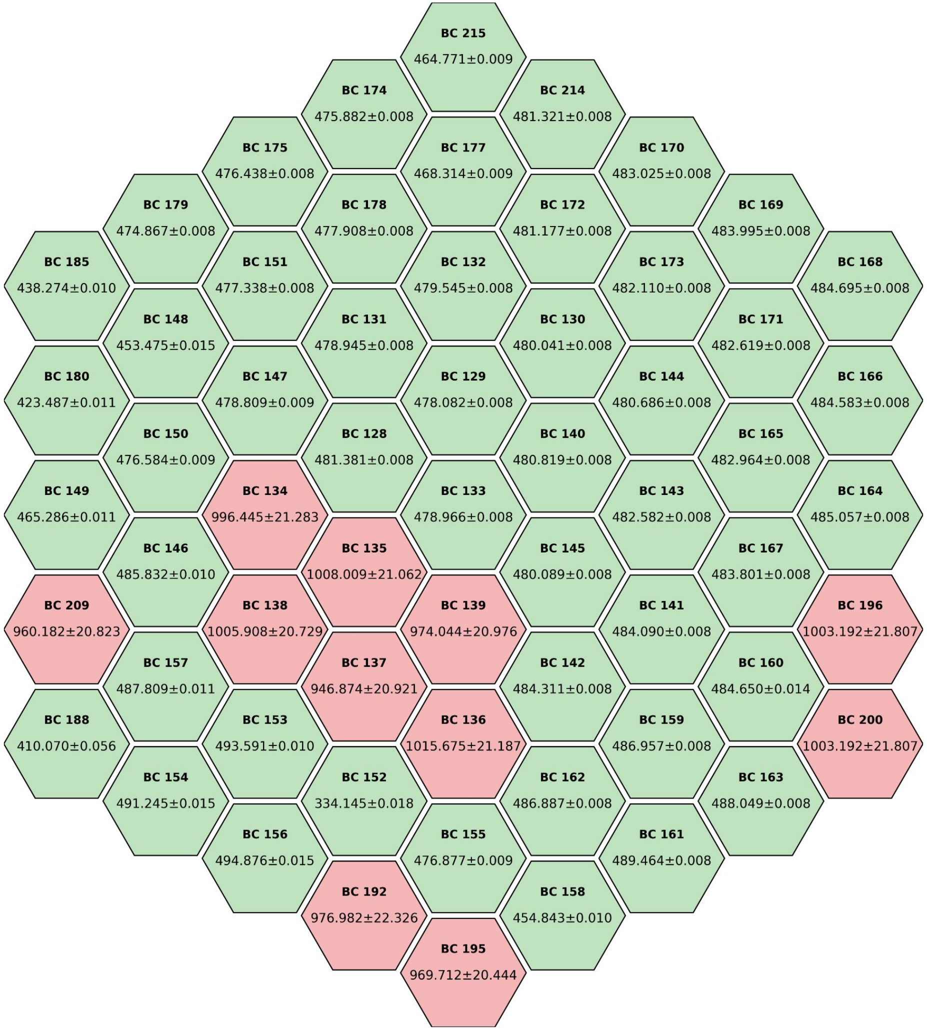


November, Run#8877, Upper BC 5 vs all Lower BC

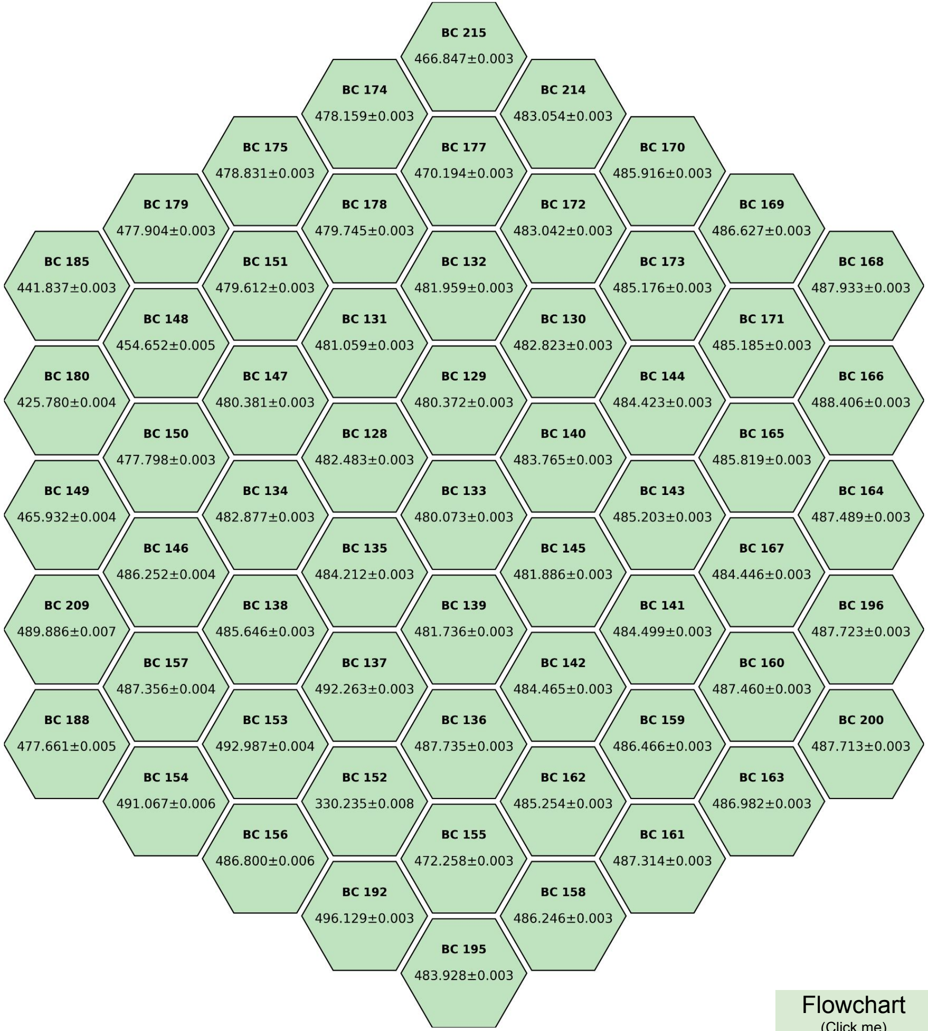


Flowchart
(Click me)

September, Run#8382, Upper BC 1 vs all Lower BC

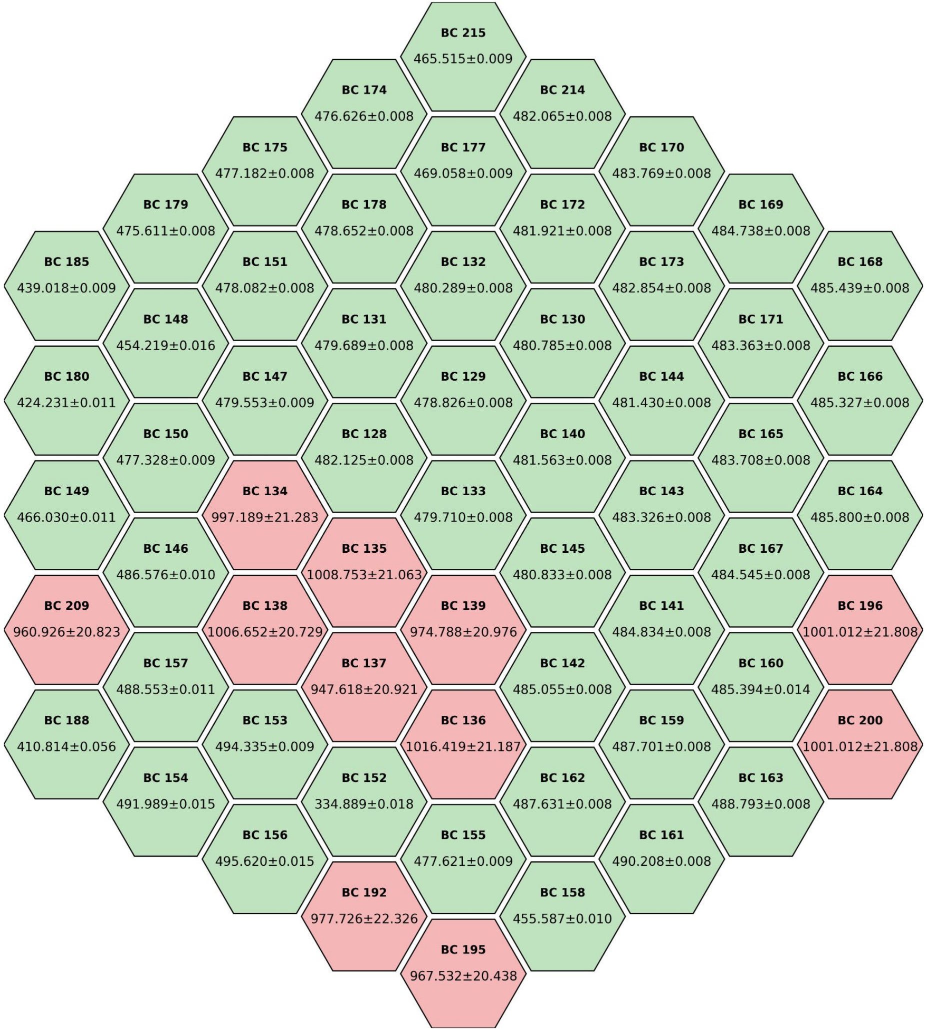


November, Run#8877, Upper BC 1 vs all Lower BC

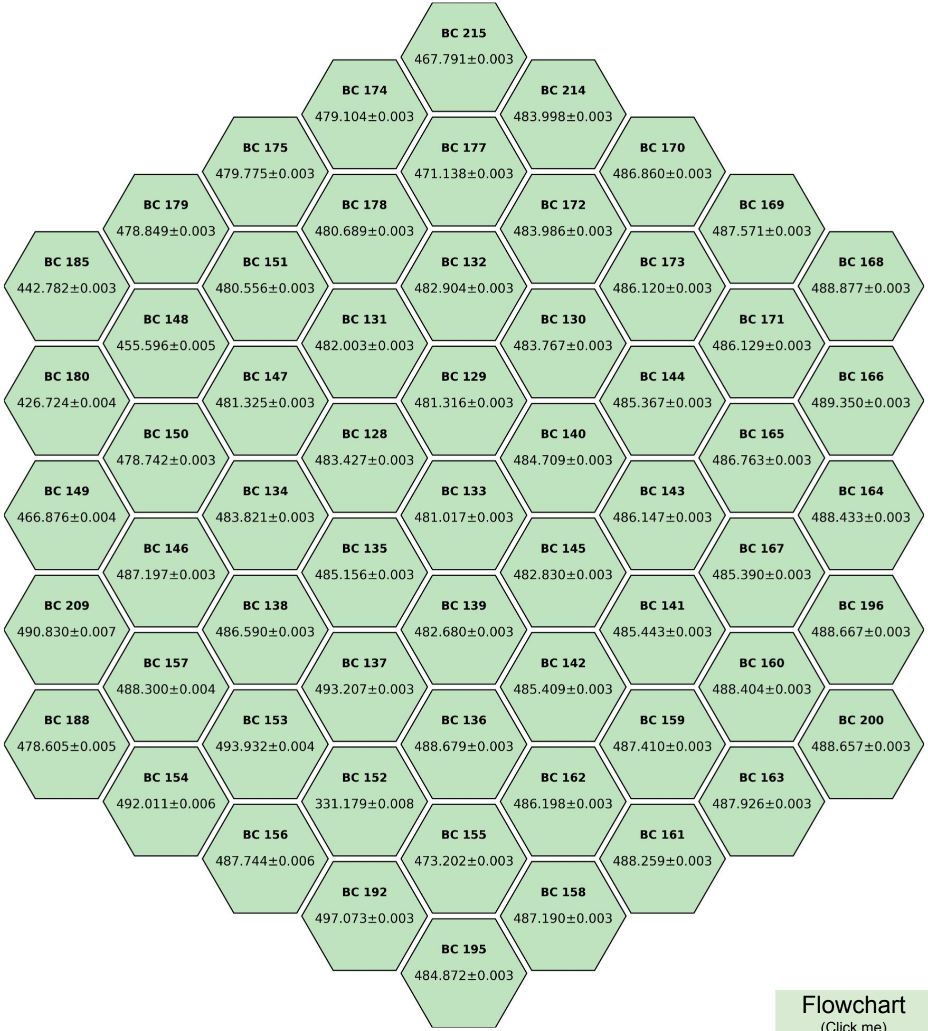


Flowchart
(Click me)

September, Run#8382, Upper BC 12 vs all Lower BC



November, Run#8877, Upper BC 12 vs all Lower BC



Flowchart
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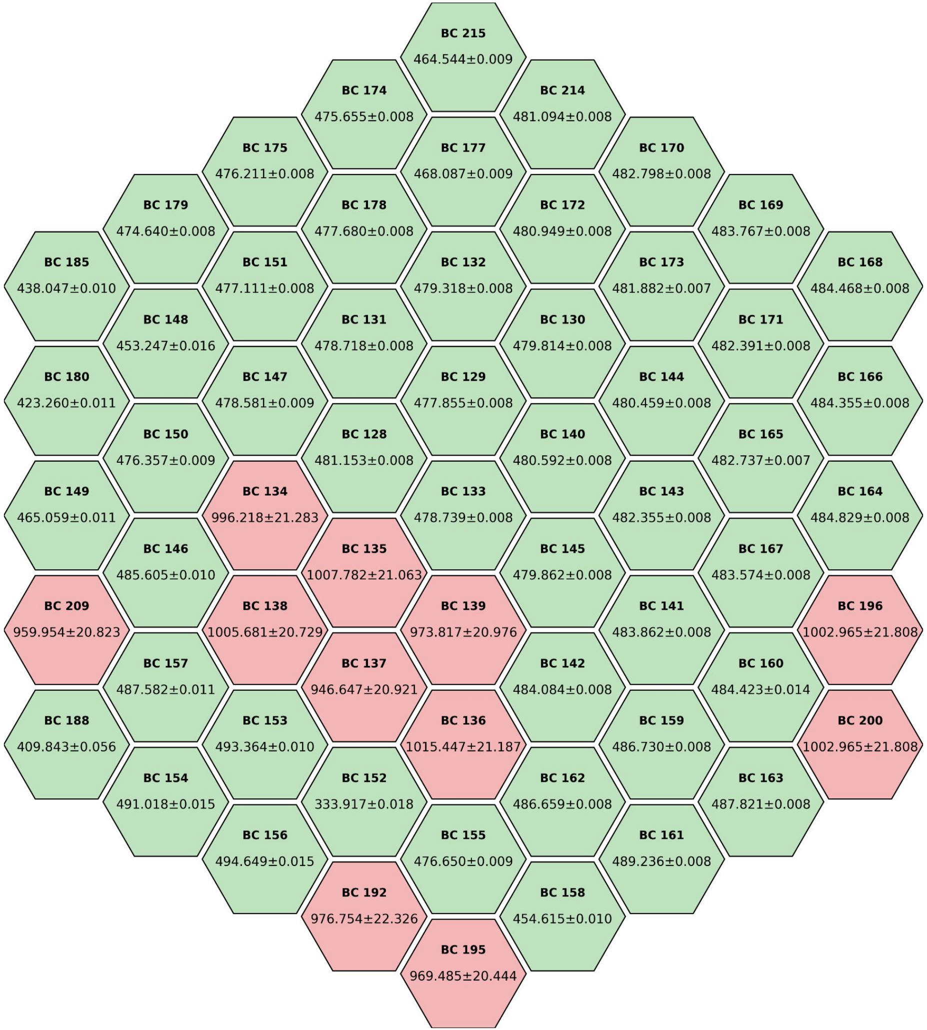
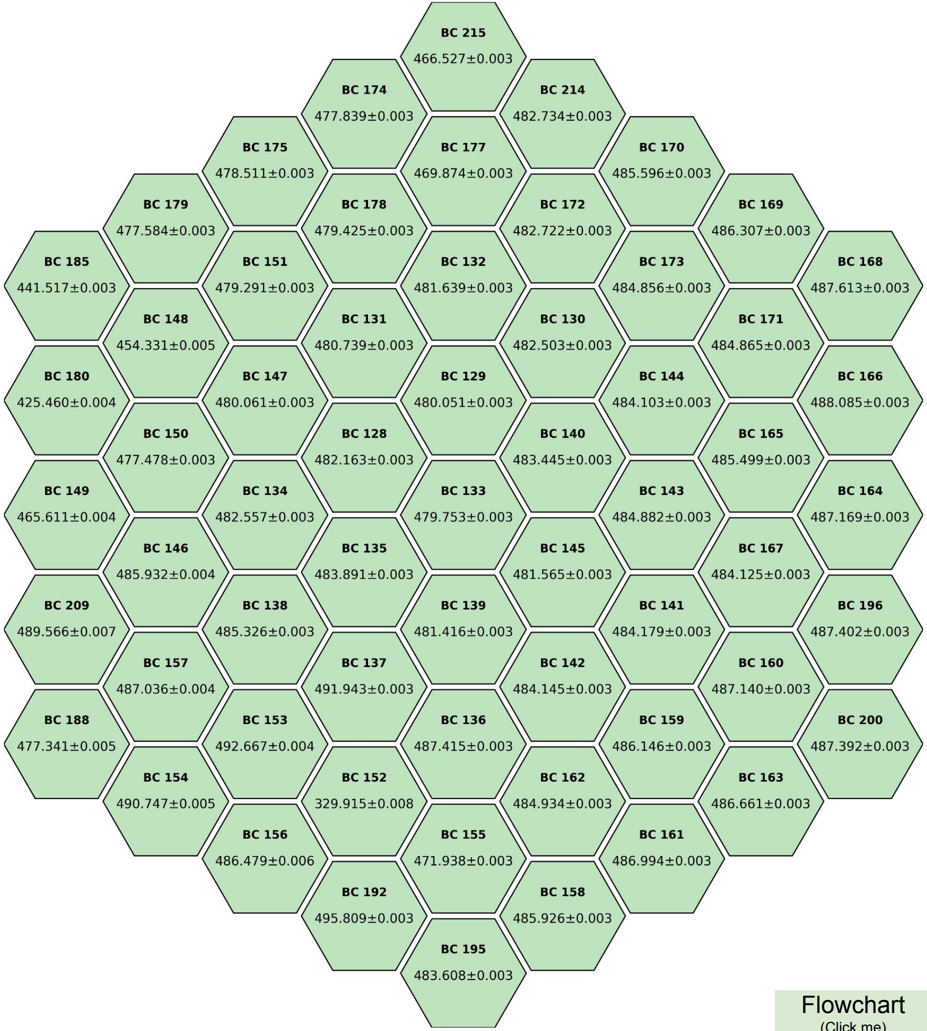
September, Run#8382, Upper BC 17 vs all Lower BC



November, Run#8877, Upper BC 17 vs all Lower BC



Flowchart
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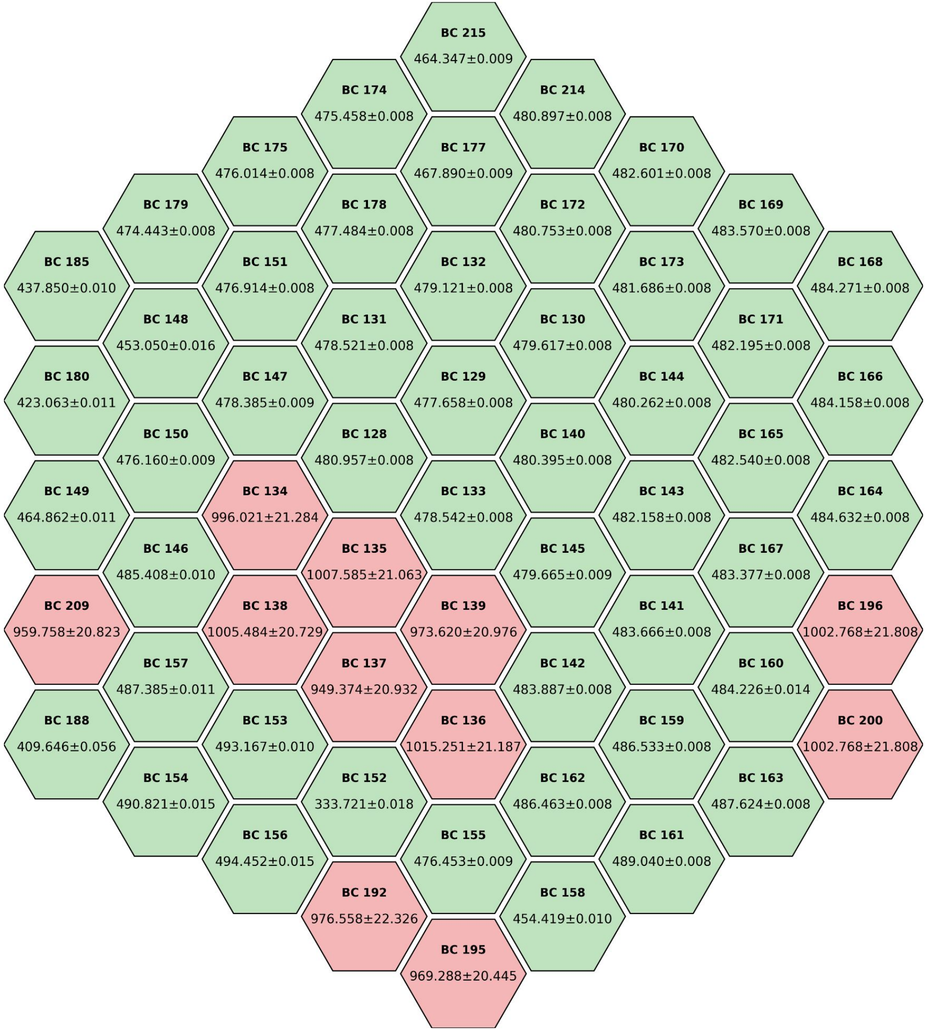
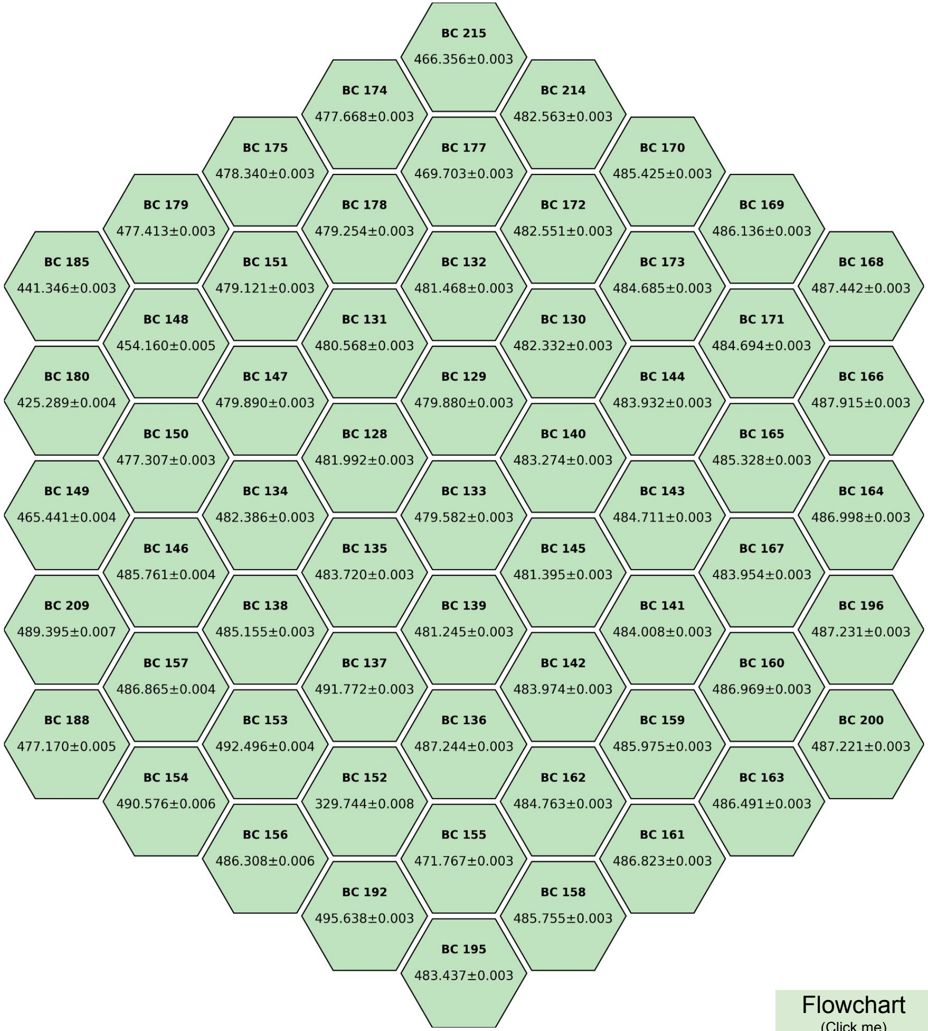
September, Run#8382, Upper BC 11 vs all Lower BC

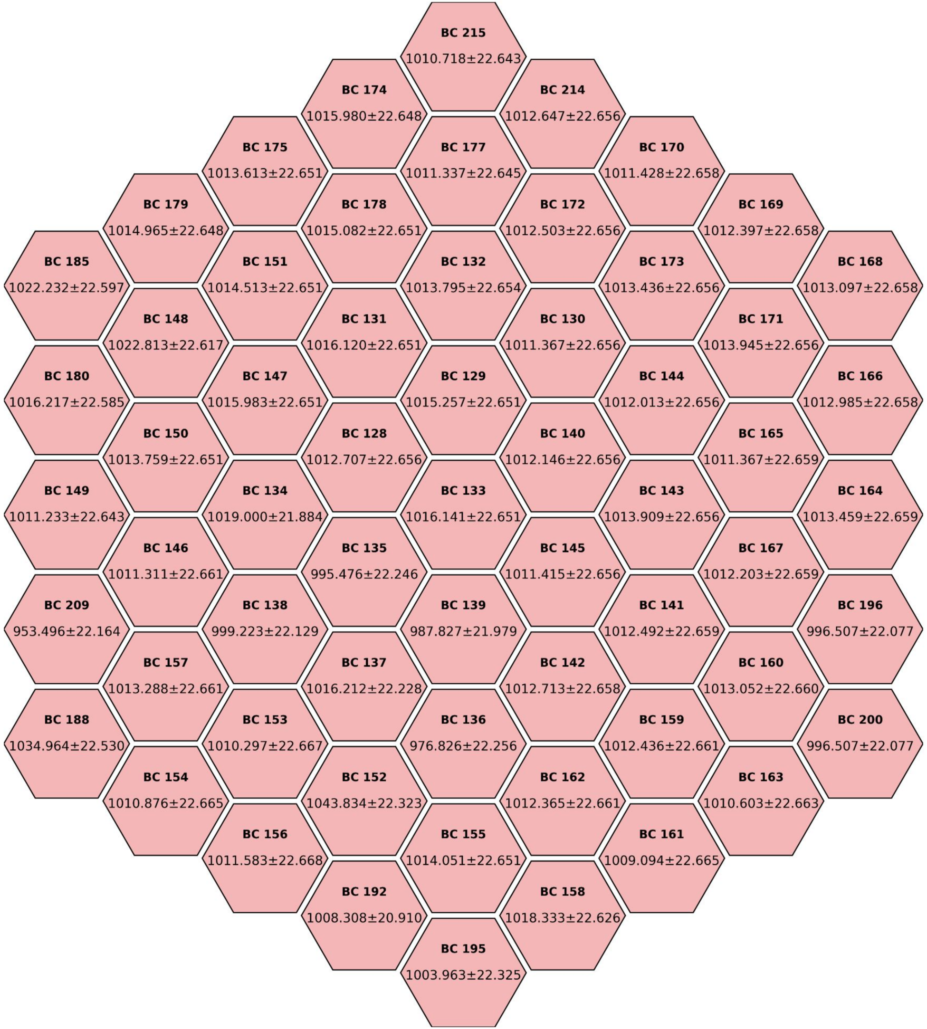


November, Run#8877, Upper BC 11 vs all Lower BC

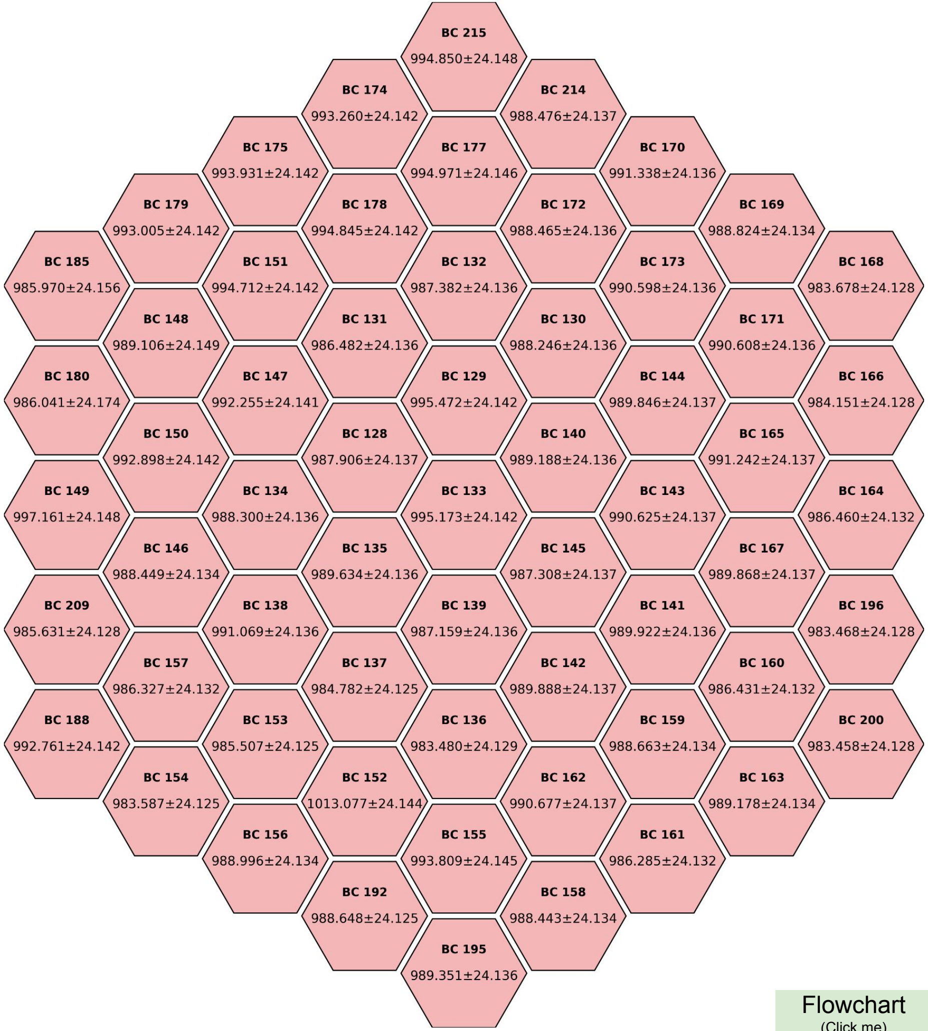


Flowchart
(Click me)

September, Run#8382, Upper BC 7 vs all Lower BC



November, Run#8877, Upper BC 7 vs all Lower BC



Flowchart
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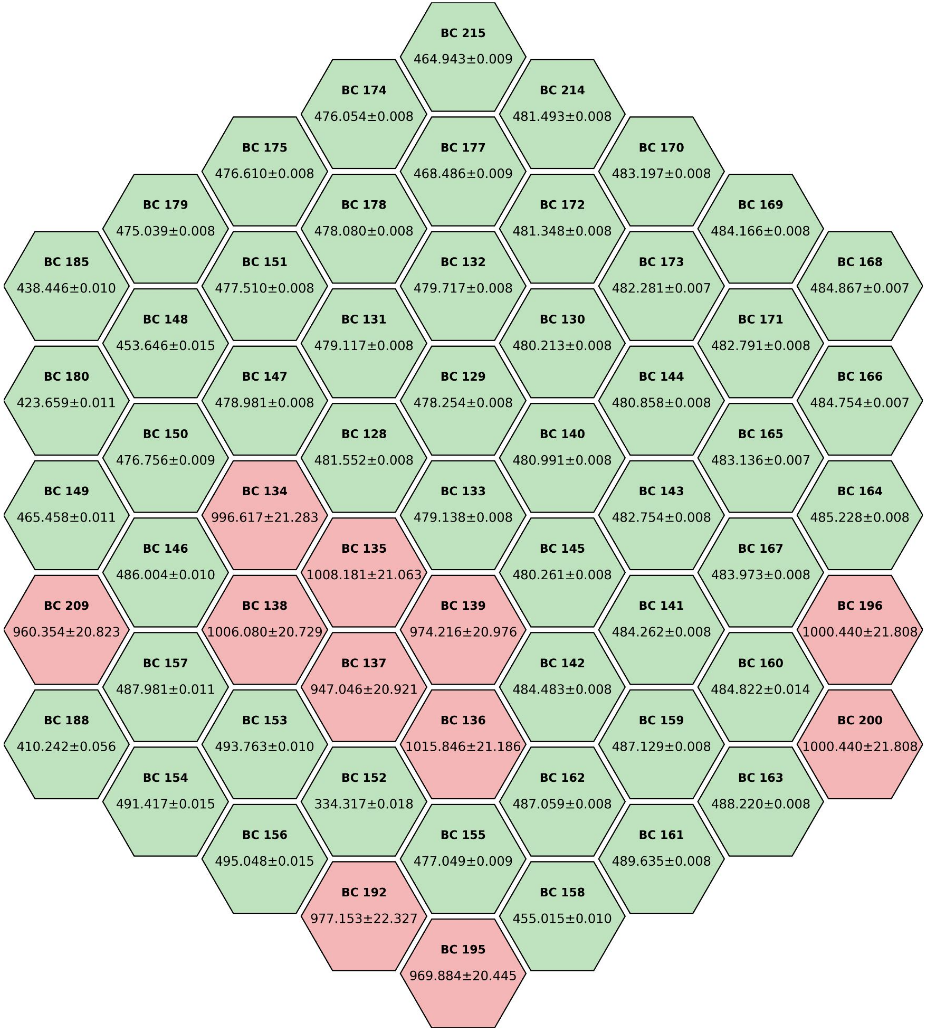
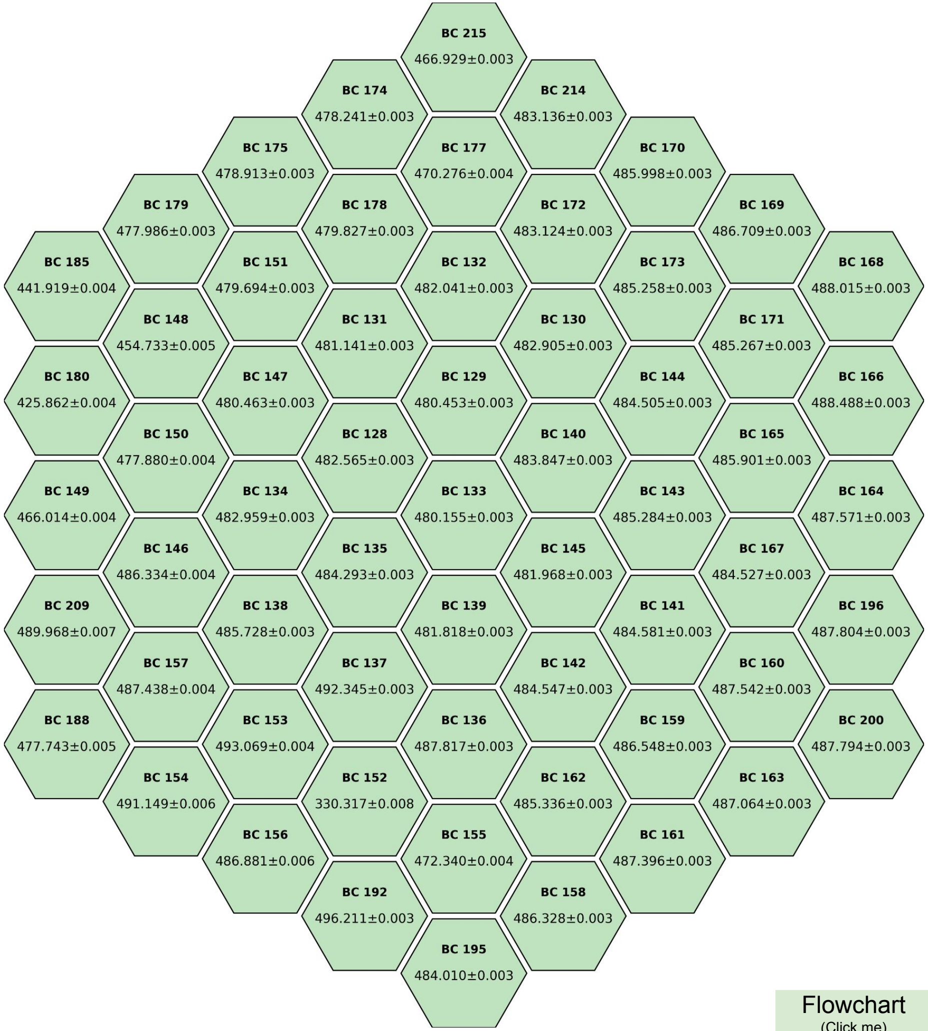
September, Run#8382, Upper BC 0 vs all Lower BC



November, Run#8877, Upper BC 0 vs all Lower BC



Flowchart
(Click me)

Detector Synchronization for Fall 2025

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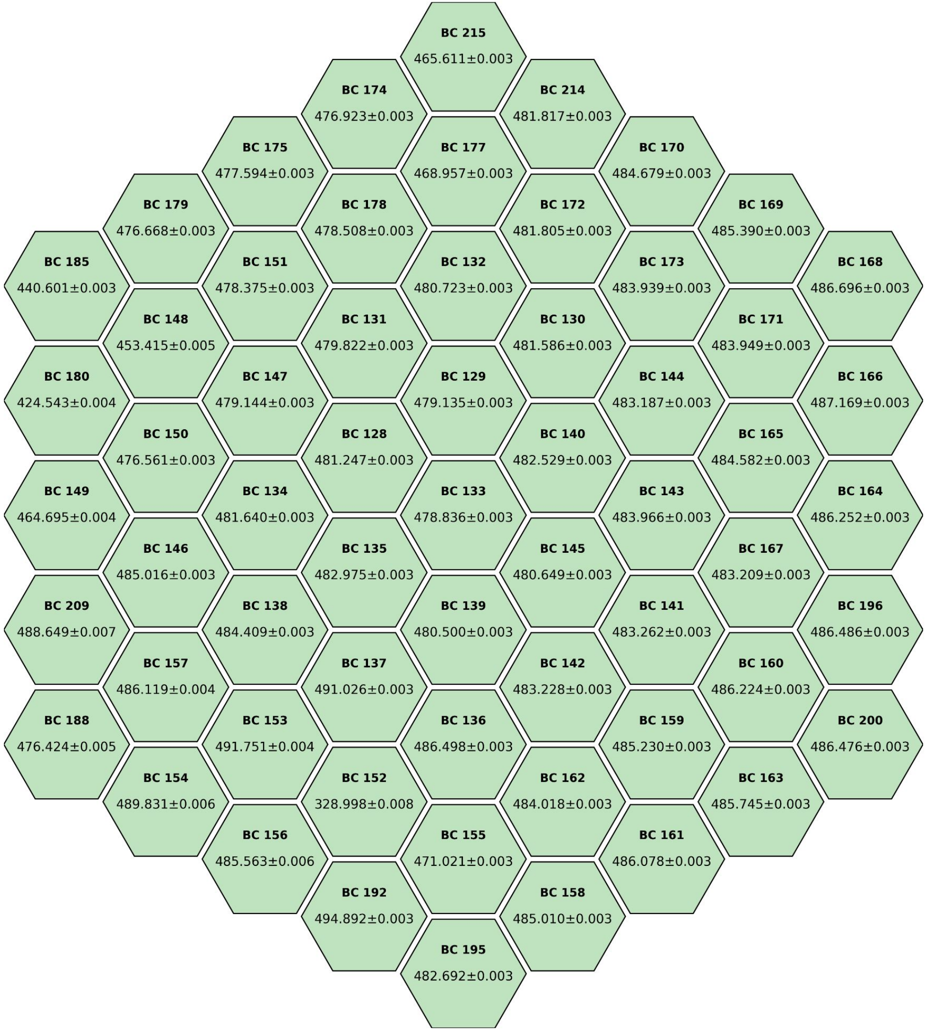
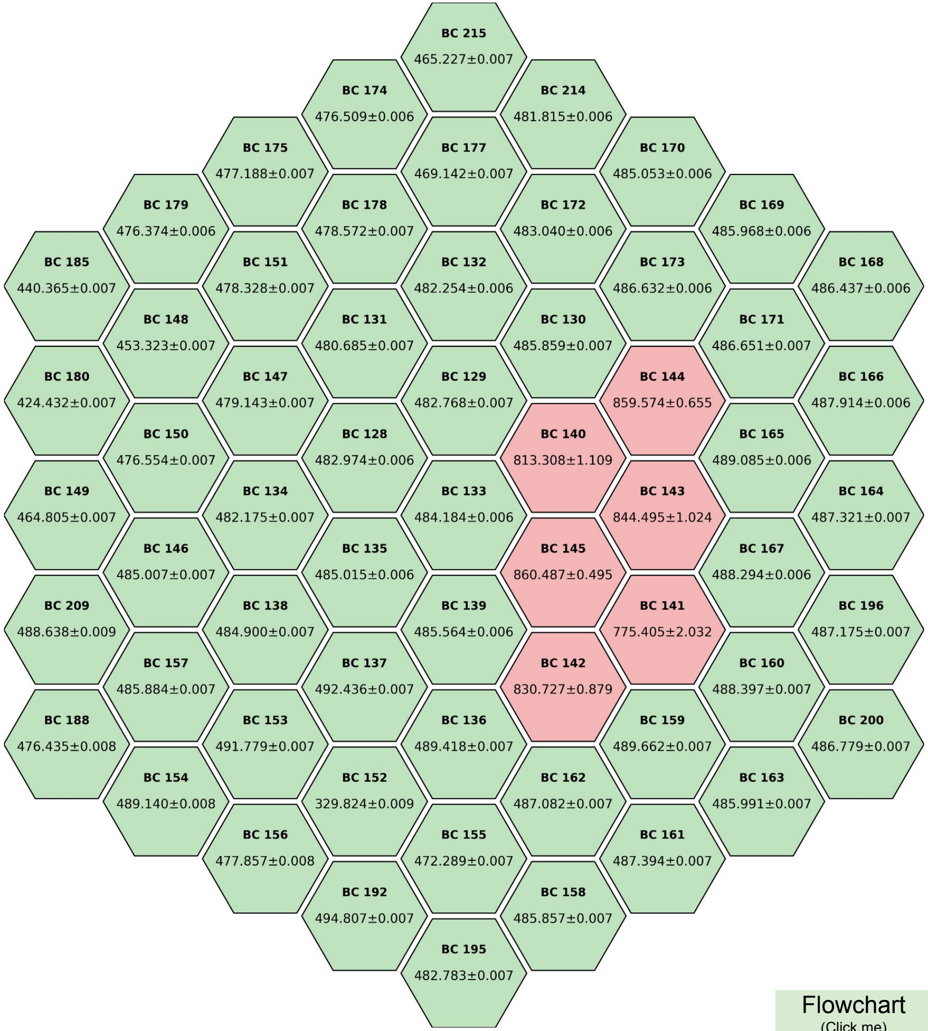
Flowchart
(Click me)

November, Run#8877, Upper BC 5 vs all Lower BC



November, Run#8998, Upper BC 5 vs all Lower BC



Flowchart
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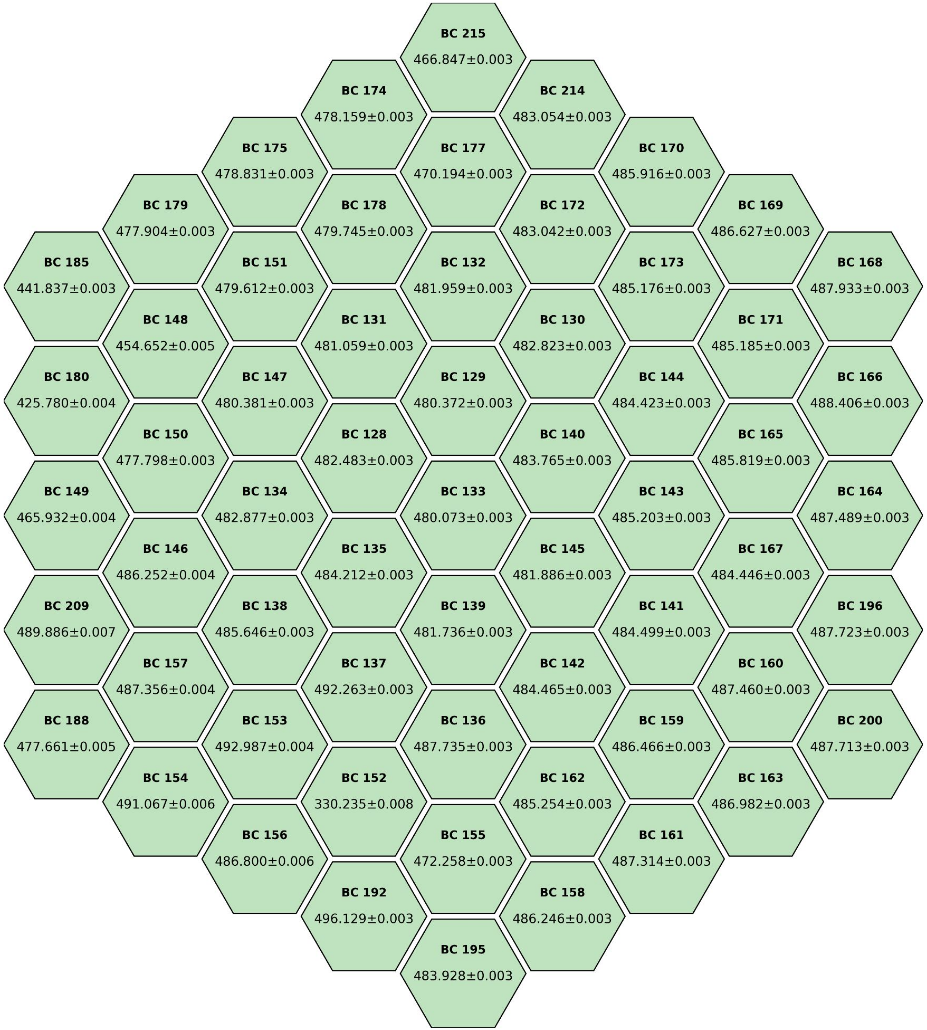
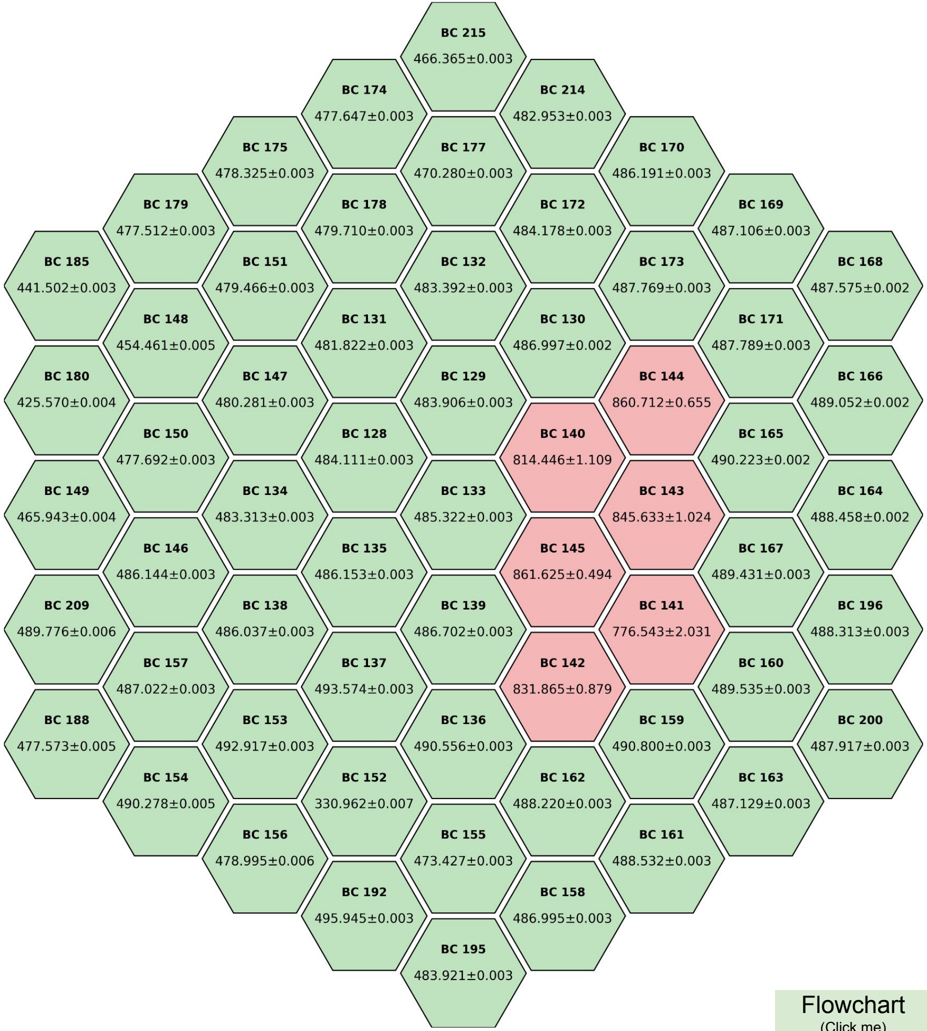
November, Run#8877, Upper BC 1 vs all Lower BC



November, Run#8998, Upper BC 1 vs all Lower BC



Flowchart
(Click me)

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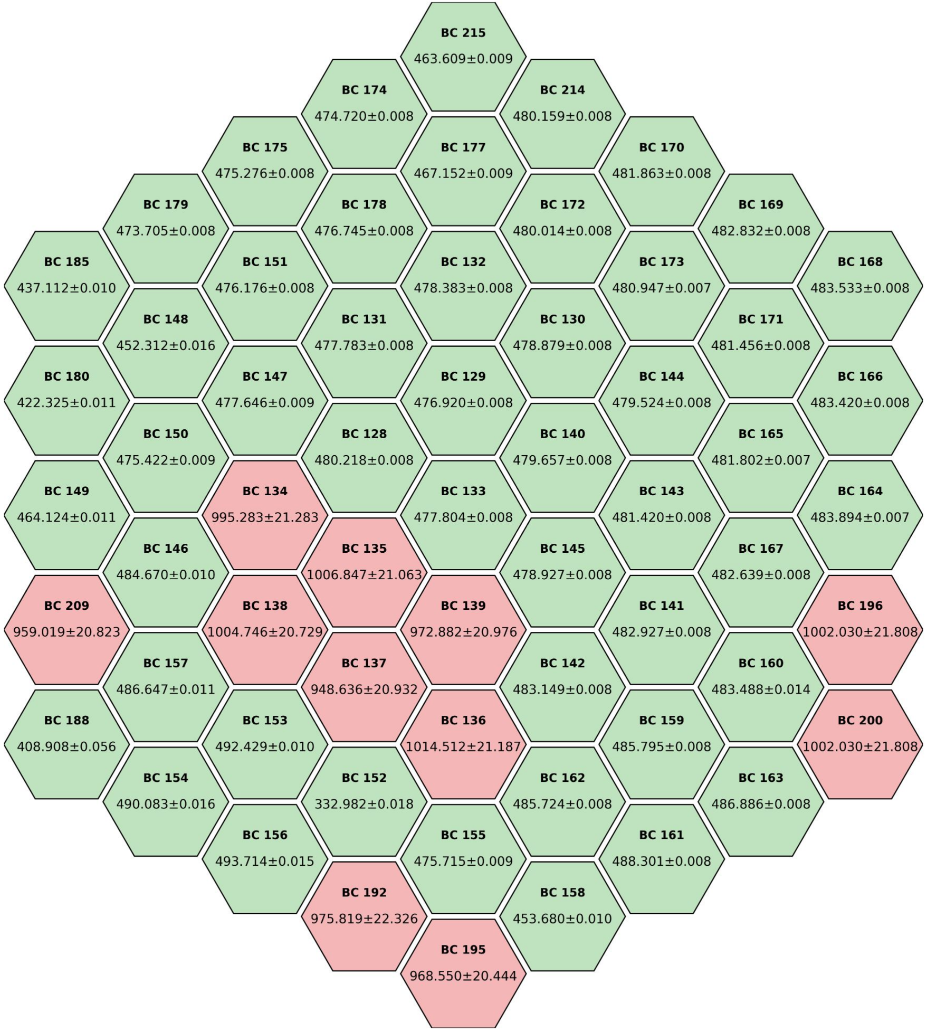
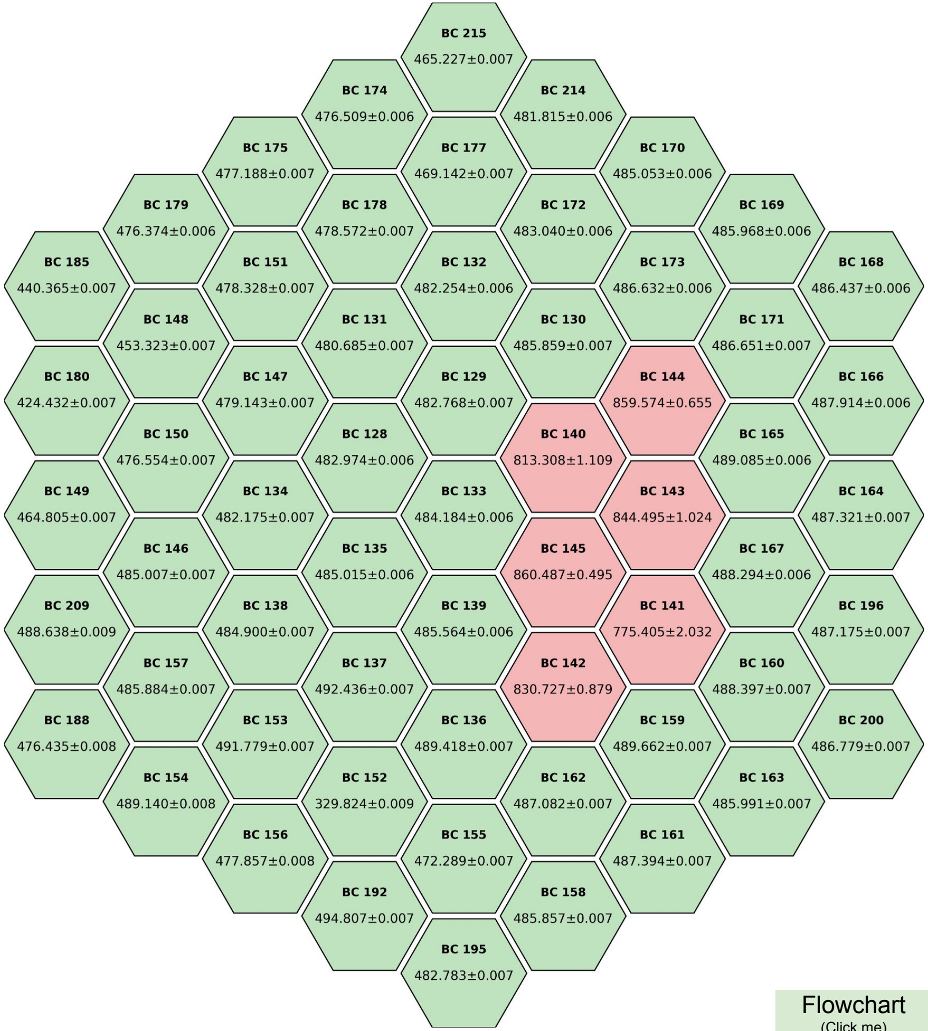
Flowchart
(Click me)

September, Run#8382, Upper BC 5 vs all Lower BC

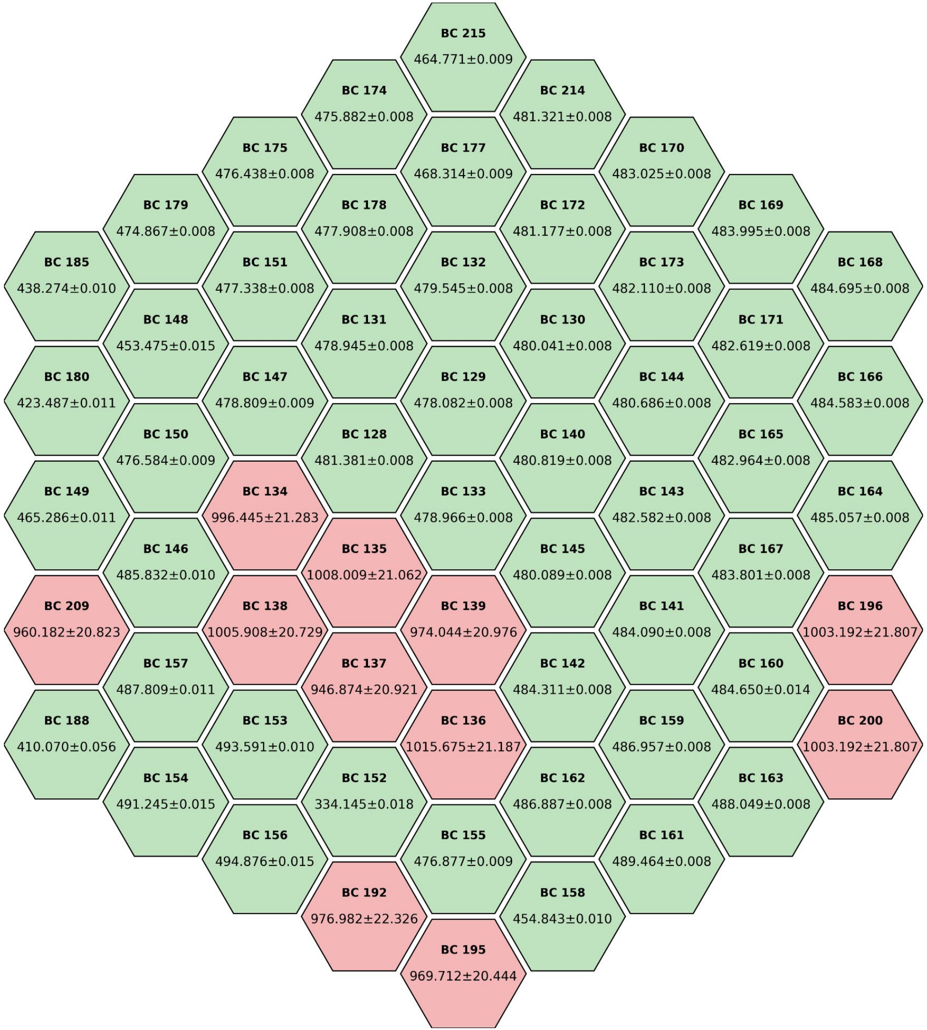


November, Run#8998, Upper BC 5 vs all Lower BC

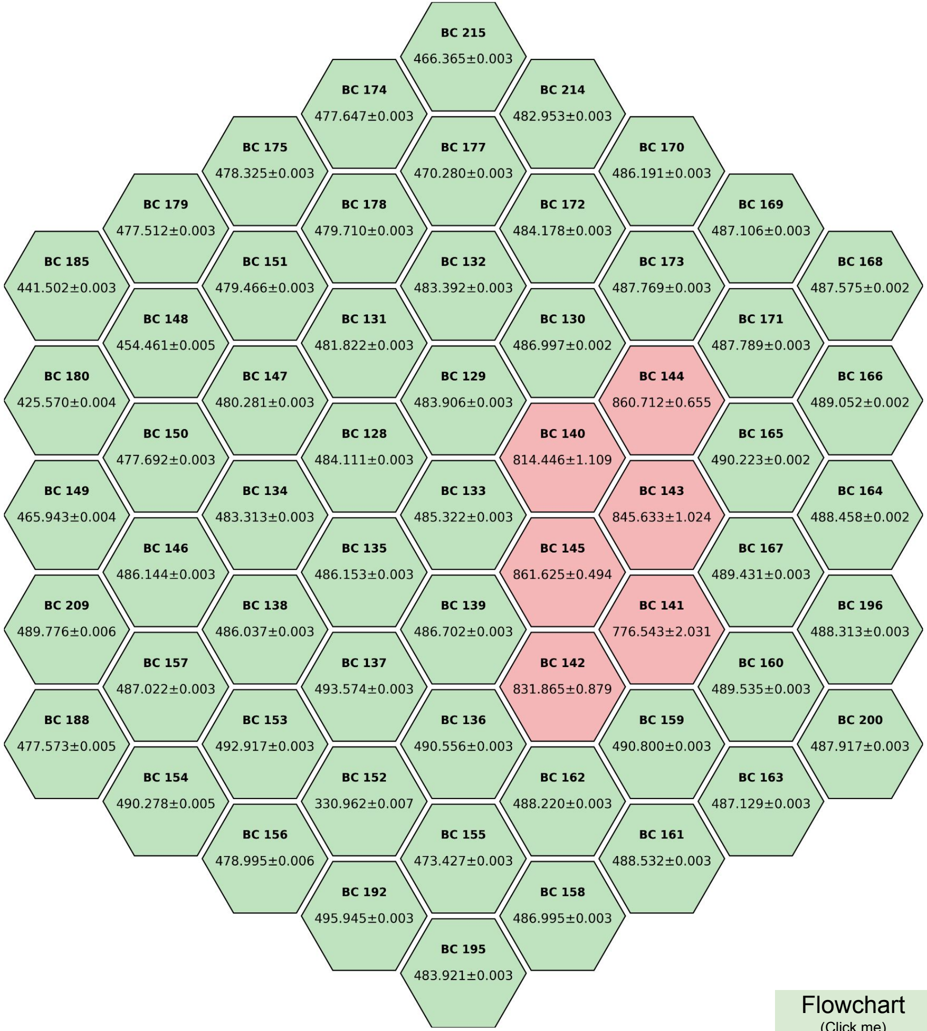


Flowchart
(Click me)

September, Run#8382, Upper BC 1 vs all Lower BC



November, Run#8998, Upper BC 1 vs all Lower BC



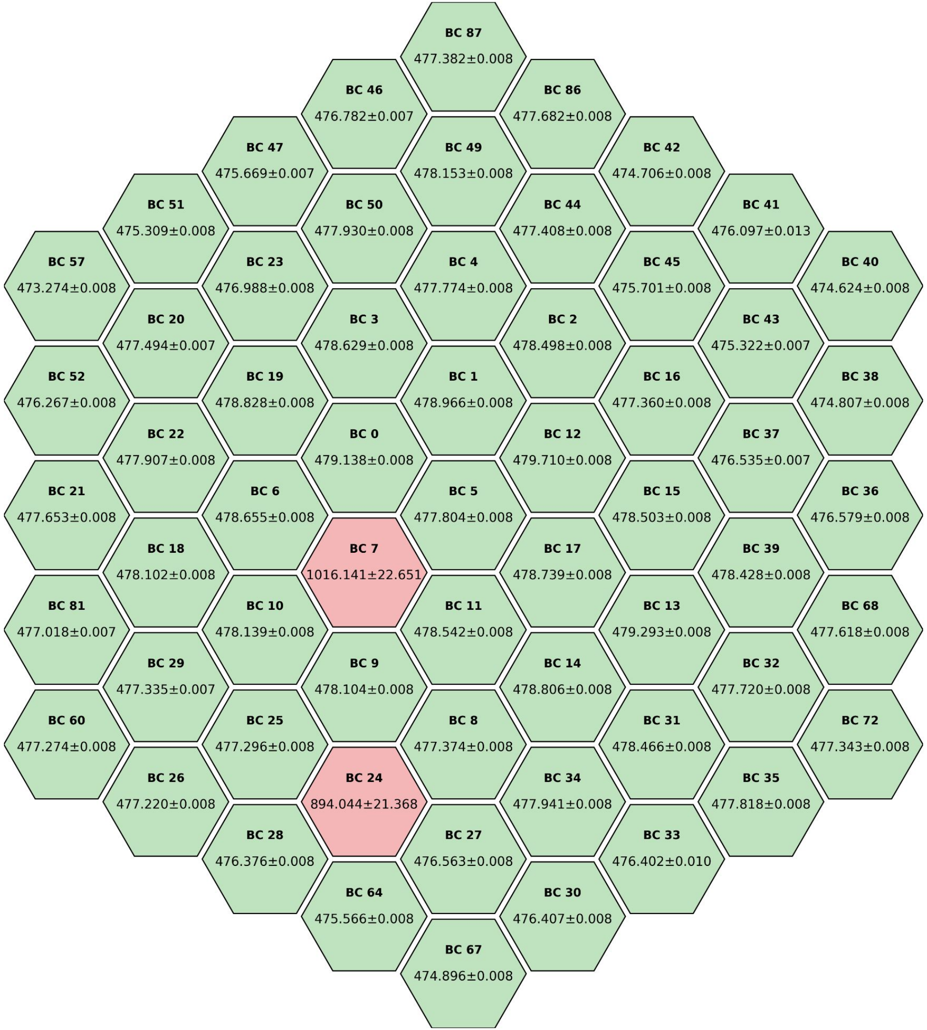
Flowchart
(Click me)

Detector Synchronization for Fall 2025

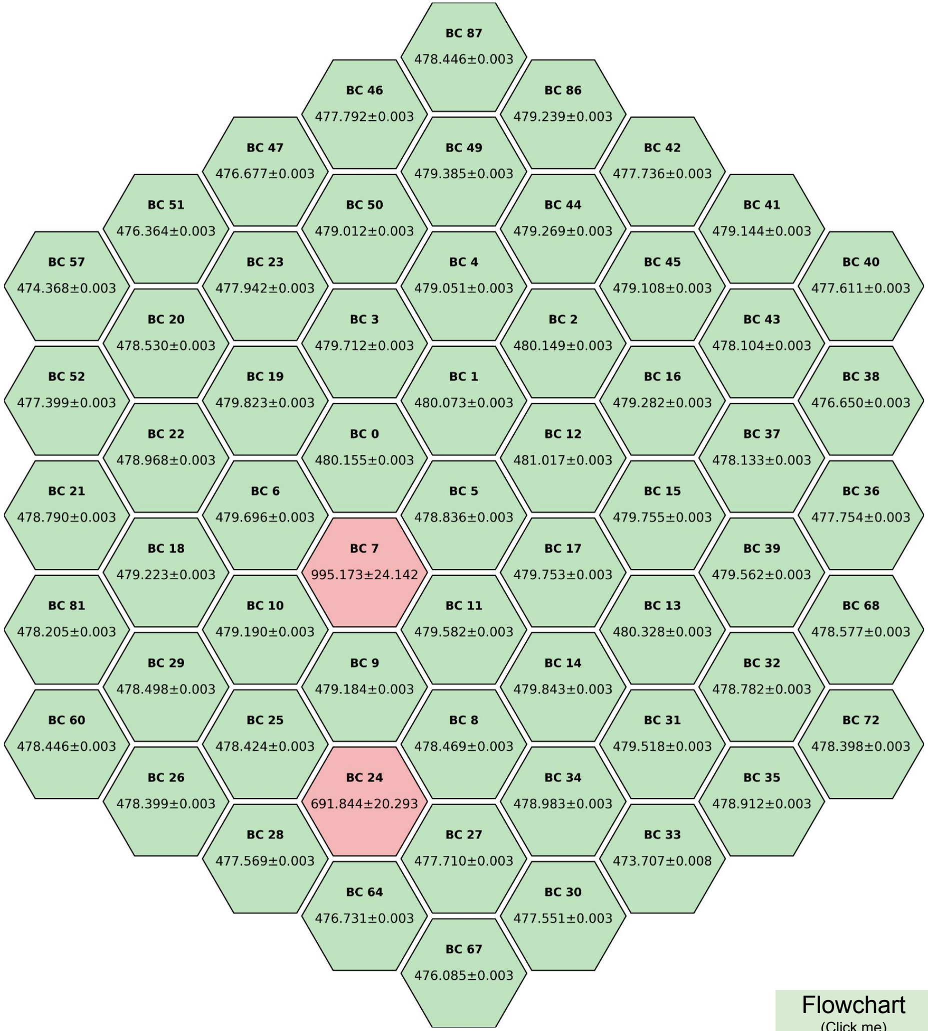
- Run# 8382 (Taken on September 24th)
- Run# 8877 (Taken on November 3rd)
- Run# 8998 (Taken on November 19th)

Flowchart
(Click me)

September, Run#8382, Lower BC 133 vs all Upper BC

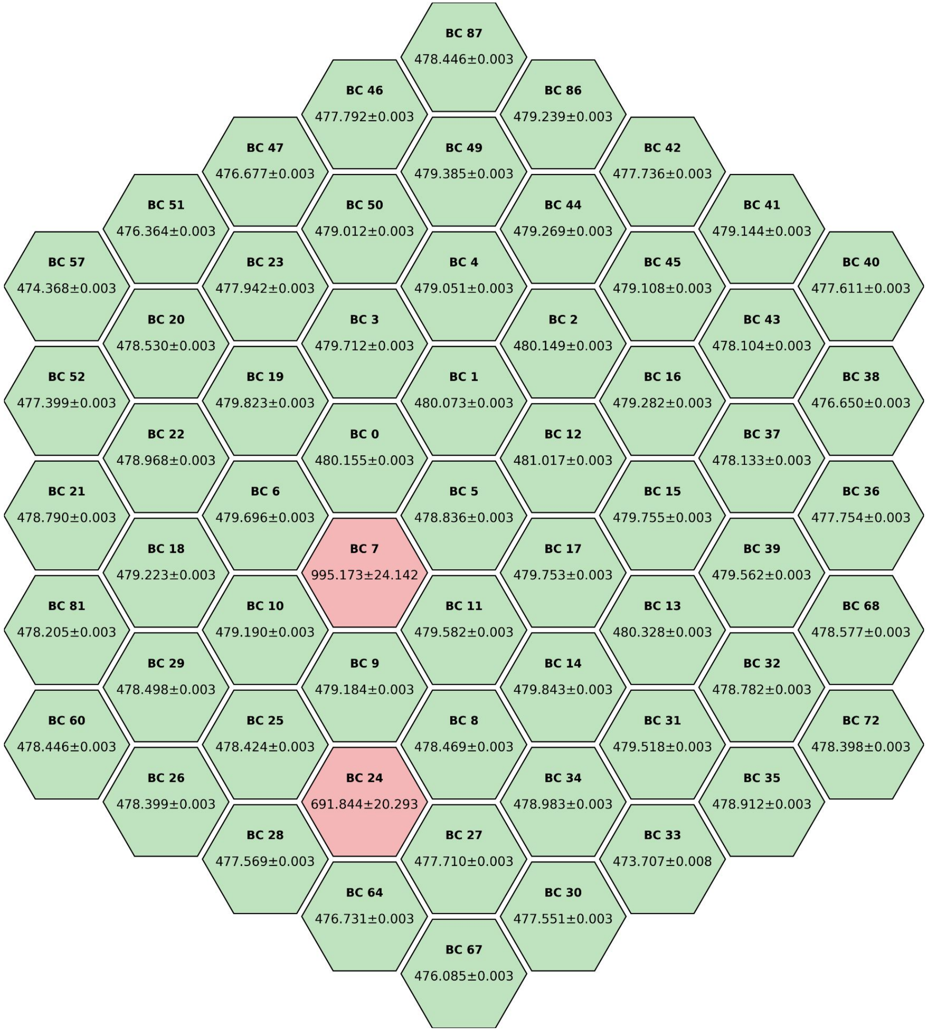


November, Run#8877, Lower BC 133 vs all Upper BC

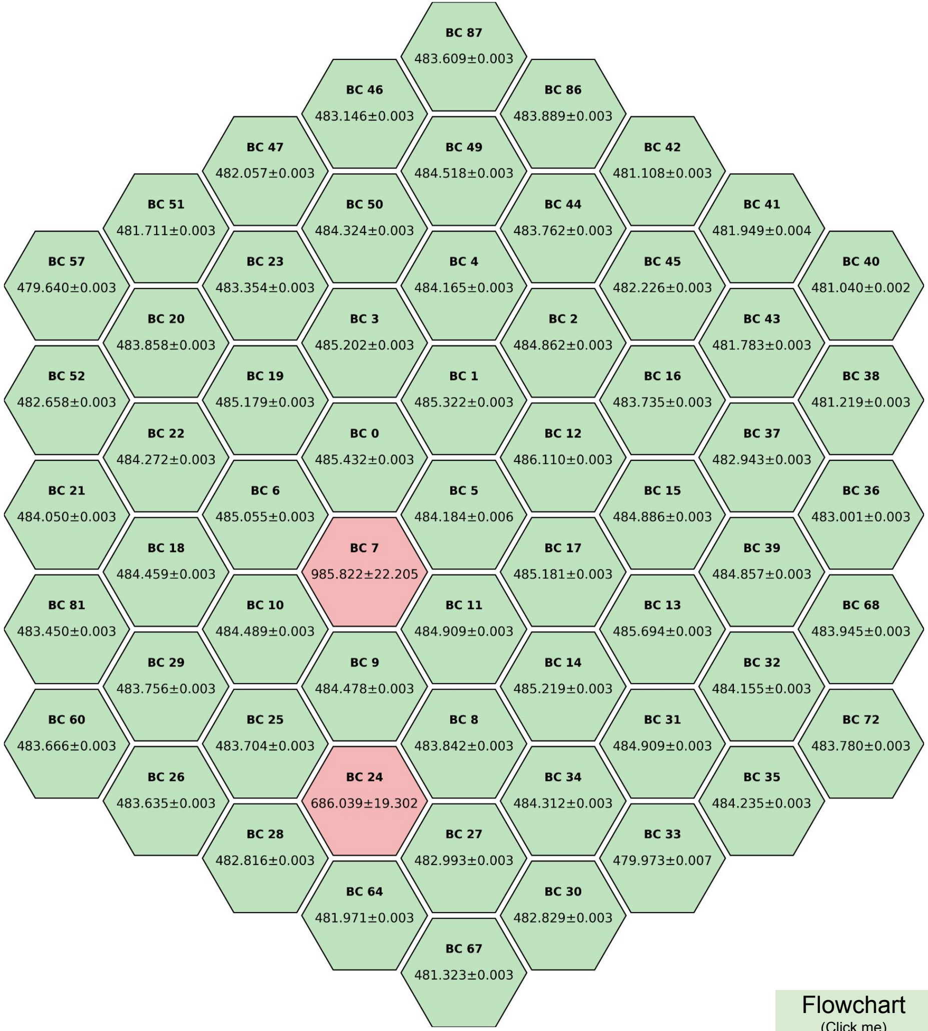


Flowchart
(Click me)

November, Run#8877, Lower BC 133 vs all Upper BC



November, Run#8998, Lower BC 133 vs all Upper BC



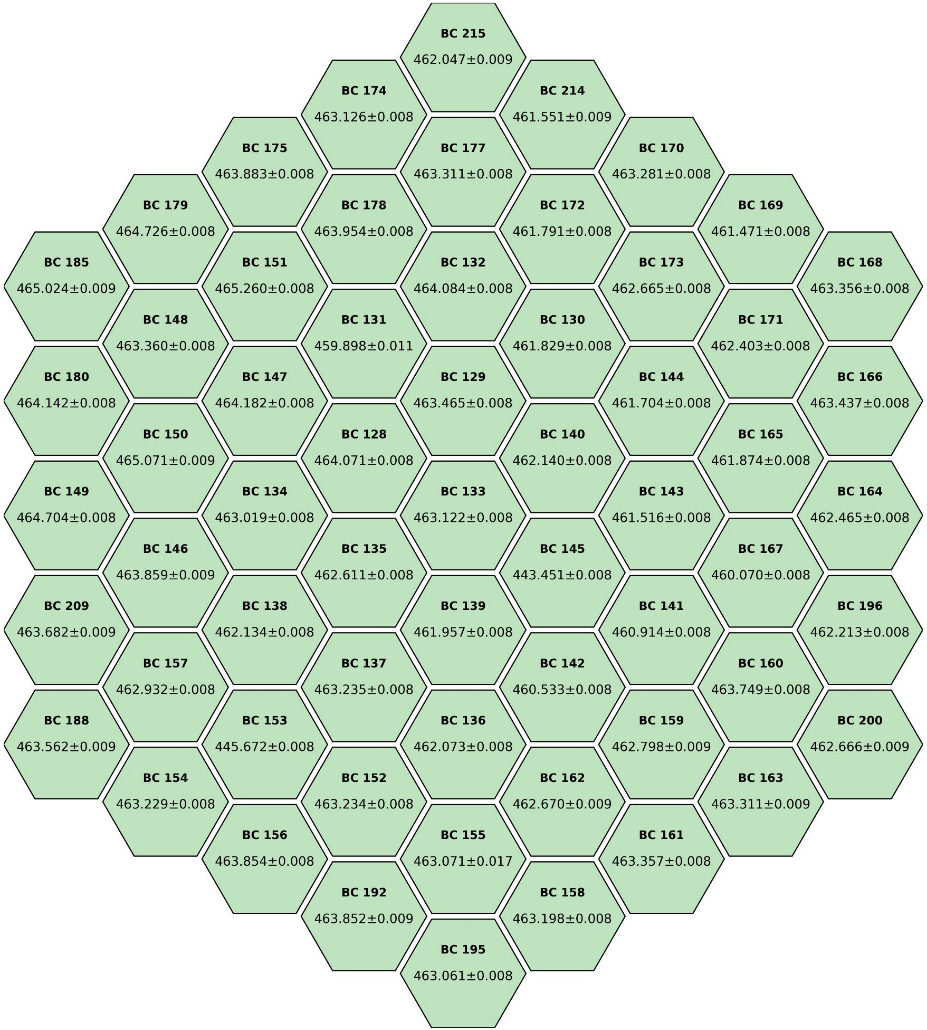
Flowchart
(Click me)

Detector Synchronization for Spring 2025

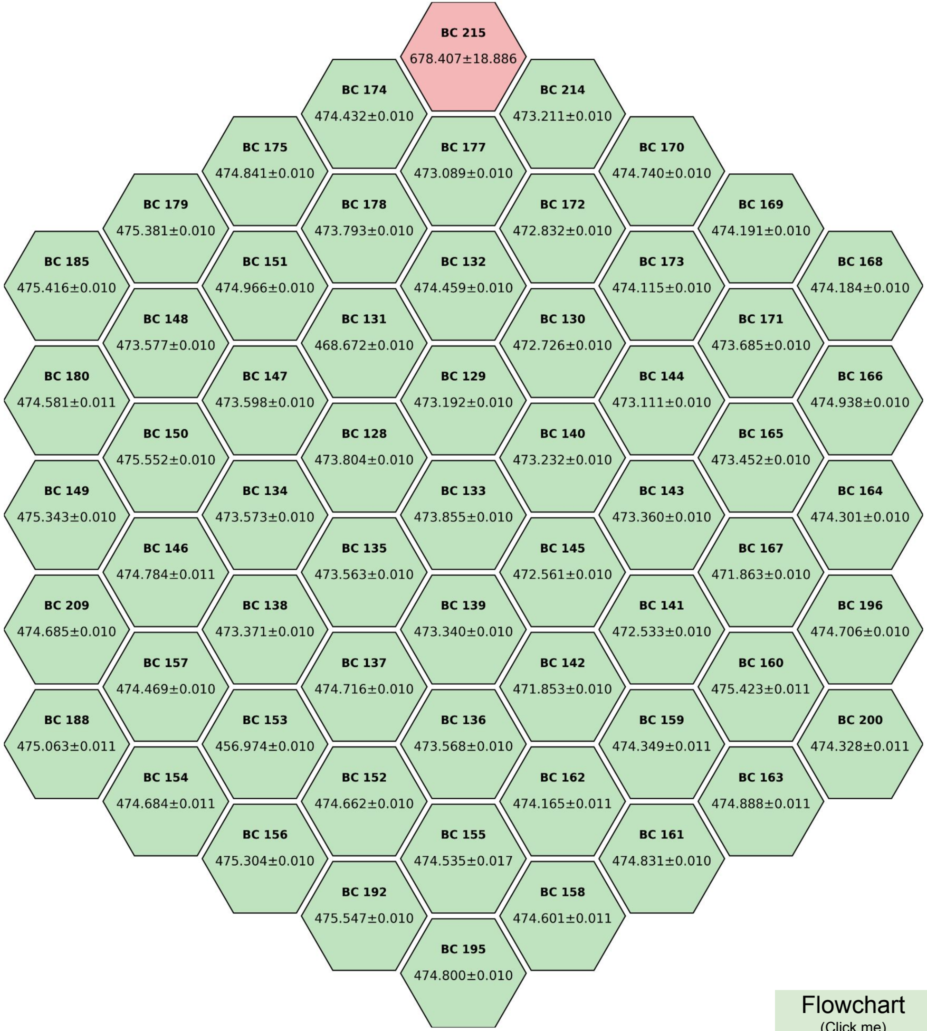
- Run# 6557 (Taken on January 7th)
- Run# 8044 (Taken on May 28th)

Flowchart
(Click me)

January, Run#6557, Upper BC 5 vs all Lower BC



May, Run#8044, Upper BC 5 vs all Lower BC



Flowchart
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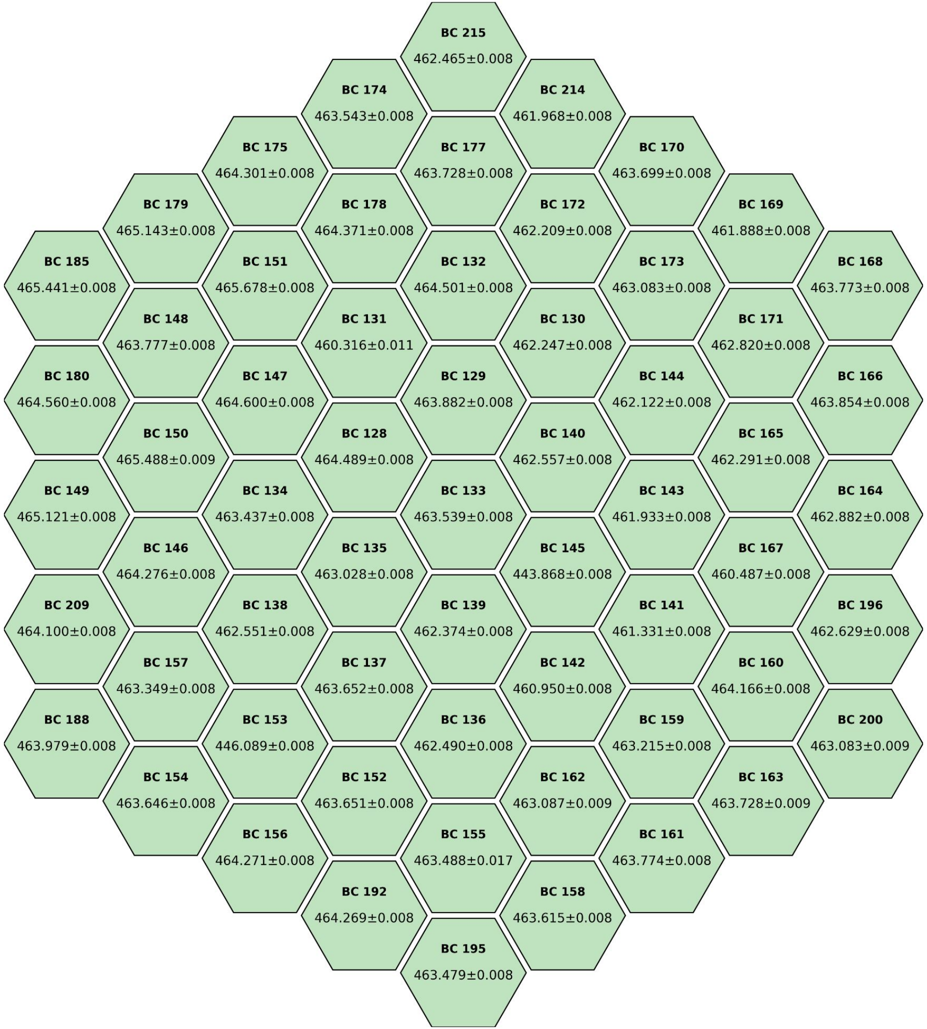
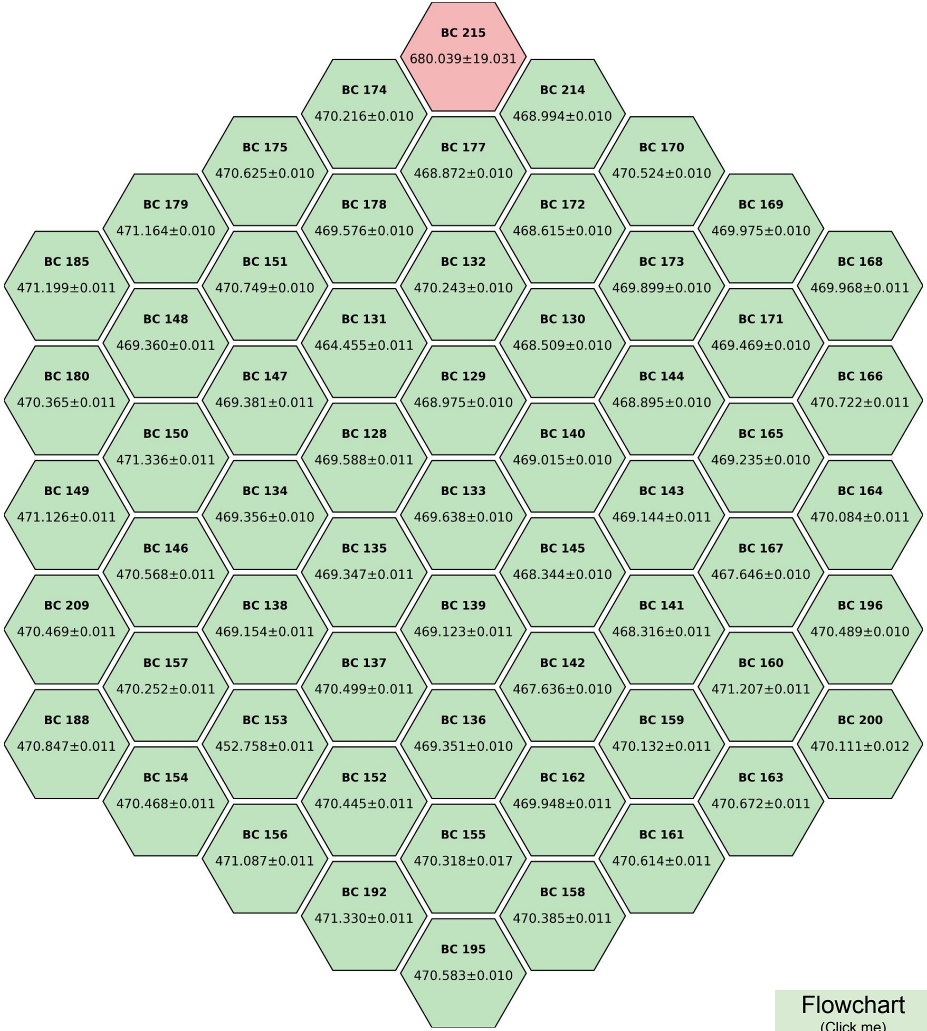
January, Run#6557, Upper BC 1 vs all Lower BC



May, Run#8044, Upper BC 1 vs all Lower BC



Flowchart
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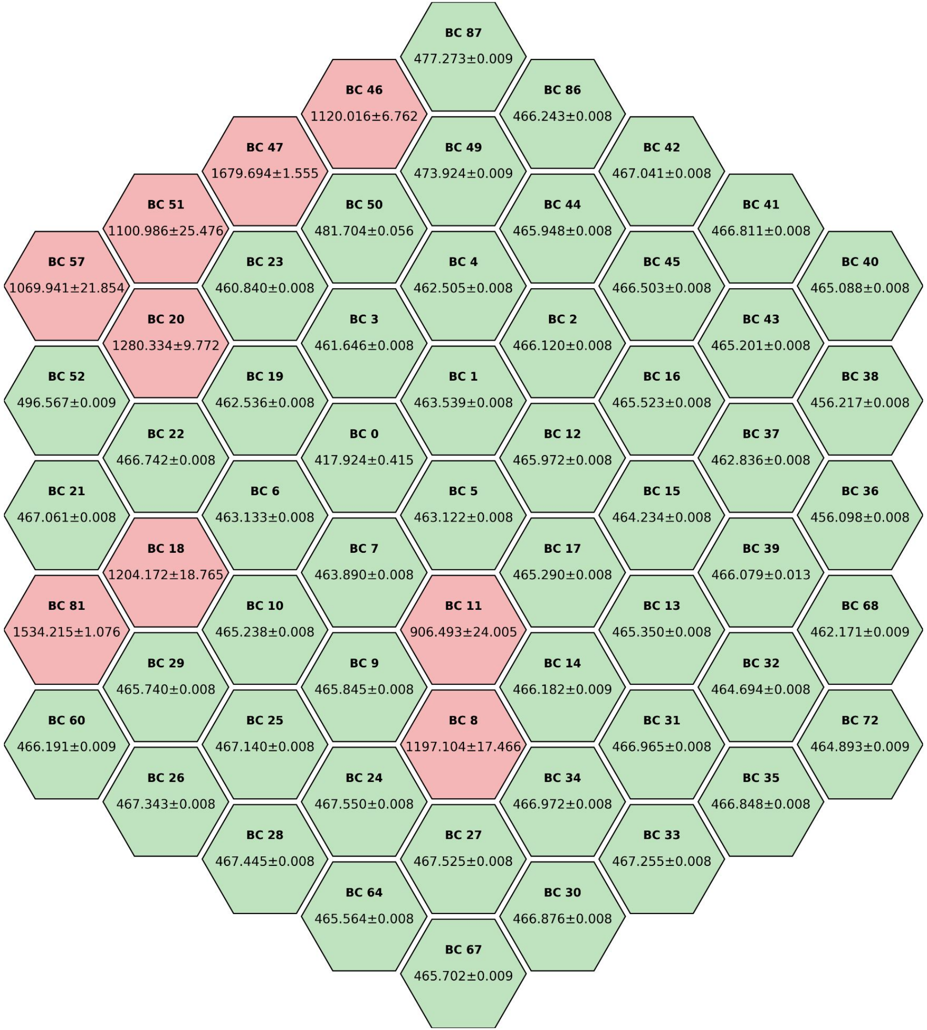
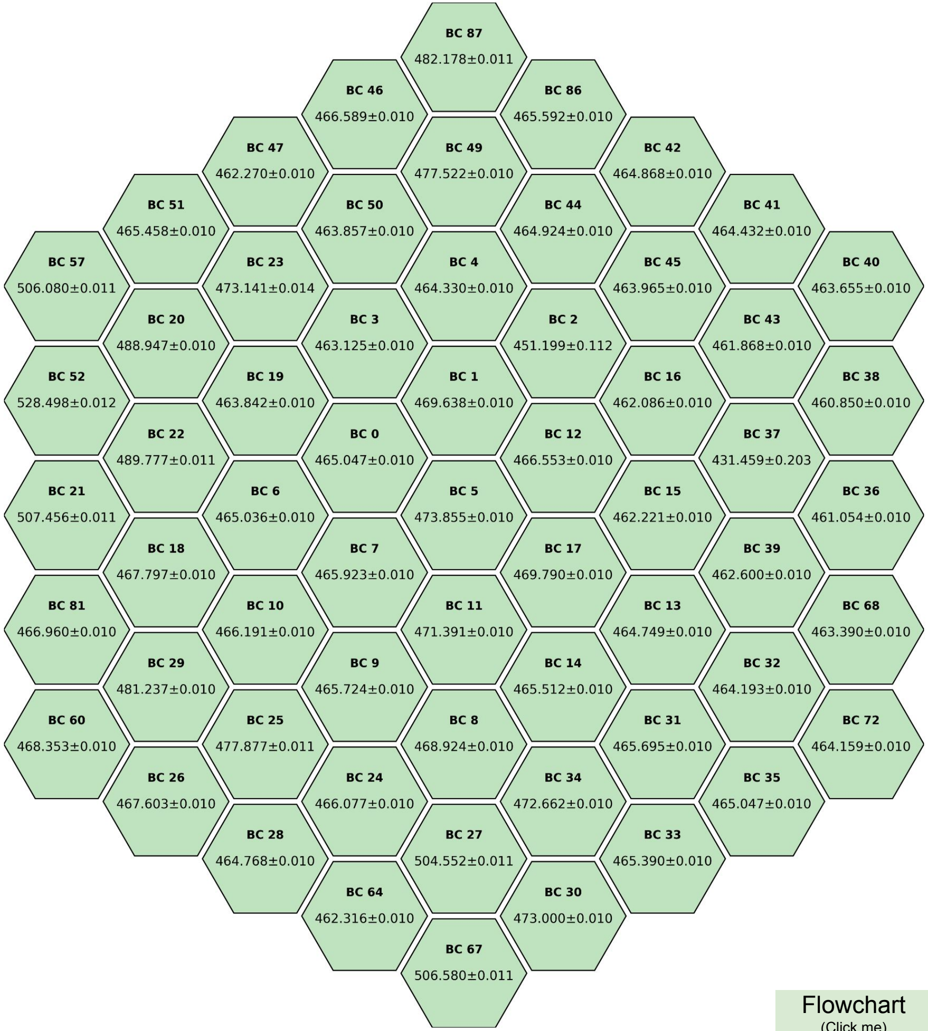
January, Run#6557, Lower BC 133 vs all Upper BC



May, Run#8044, Lower BC 133 vs all Upper BC



Flowchart
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Conclusion

- Detector Synchronization (both Spring 2025 and Fall 2025) complete
  - Detector Synchronization (Fall 2025) Link
  - Detector Synchronization (Spring 2025) Link
- Sept vs Nov: ~ 90% pixels show drift in timing difference $\lesssim$ 4 ns
- Nov (3rd) vs Nov (19th): ~ 70% pixels show drift in timing difference $\lesssim$ 4 ns
- Nov (3rd) vs Nov (19th): ~ 90% pixels show drift in timing difference $\lesssim$ 8 ns
- Sept vs Nov (19th): ~ 80% pixels show drift in timing difference $\lesssim$ 8 ns
- Jan vs May: ~ 60% pixels show drift in timing difference $\lesssim$ 8 ns

Flowchart
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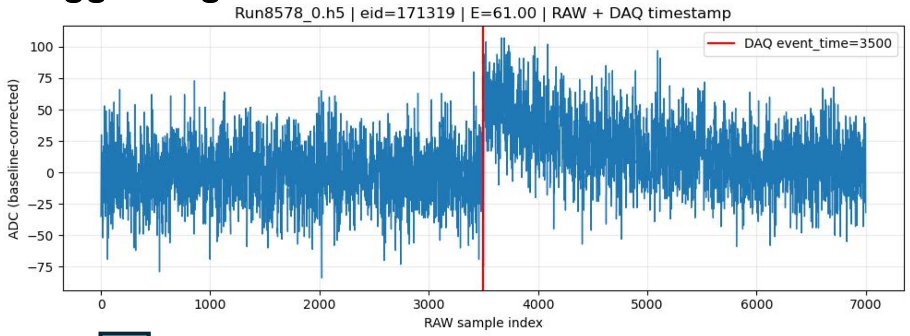
Trigger Efficiency

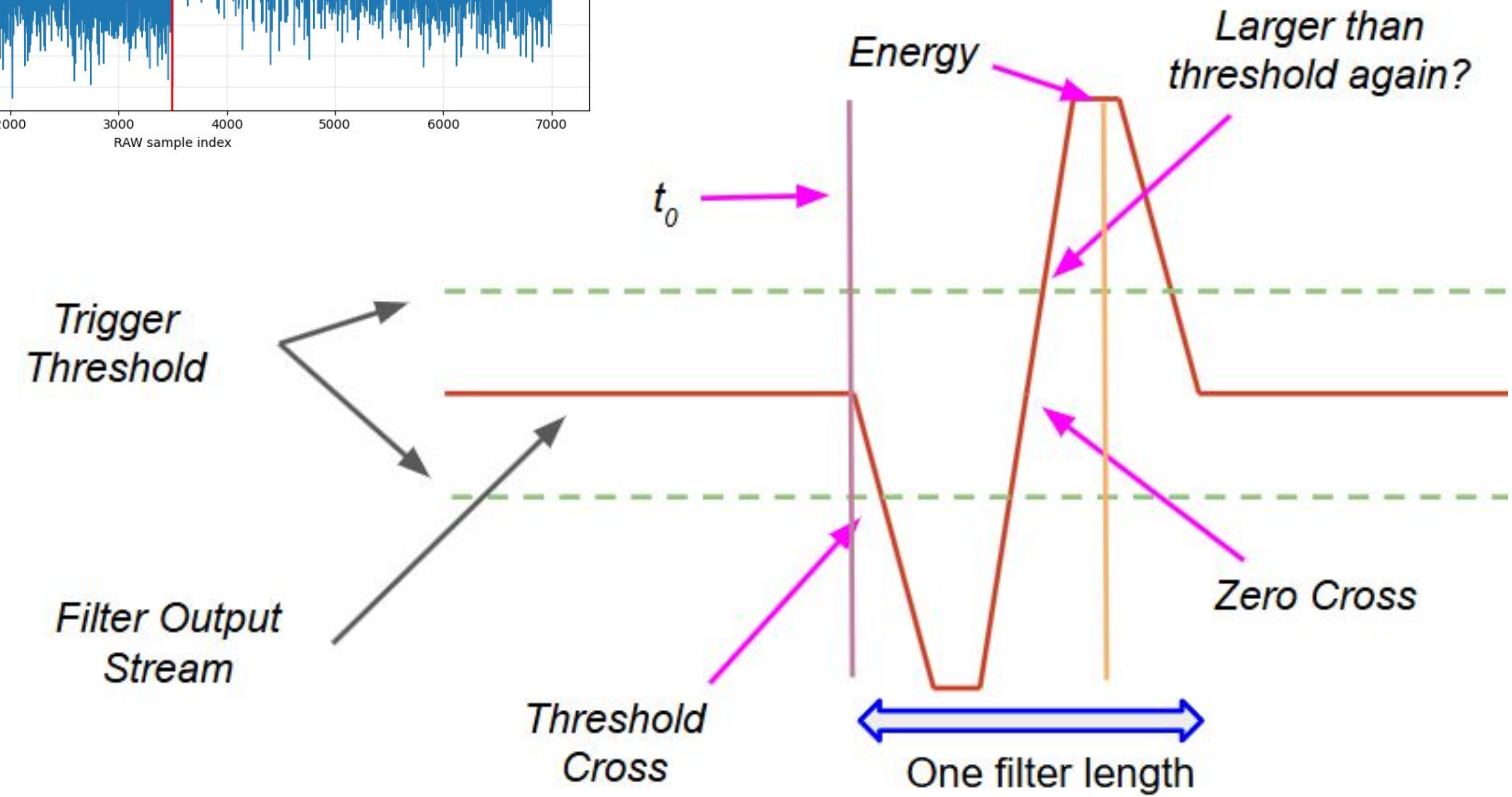
Kyle Feist

Flowchart
(Click me)

Trigger Logic



Double Trap Filter



Flowchart
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$$Trigger\ Eff = \frac{\#\ of\ triggers}{\#\ of\ real\ signals}$$

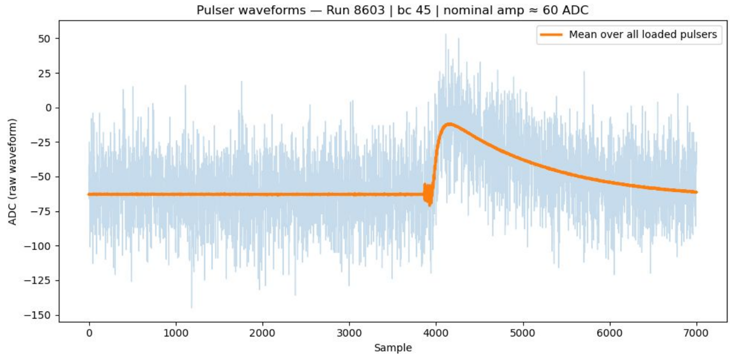
Template + noise → Python DAQ emulation → Efficiency curves as a function of template amplitude for synthesized protons

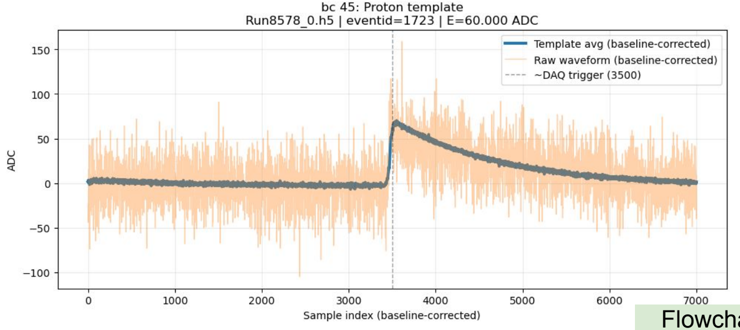
Pulsers are a test bench to validate synthesized protons

- Pulser data sets give us a clean denominator for efficiency
- Apply template + noise method to pulsers → show efficiencies match real pulser efficiencies within error band

Pulsers are NOT protons

- Differences in shape could affect the trigger efficiency
- pulsers are not a perfect test bench
- Good test bench for validating noise dominated triggering (near threshold)





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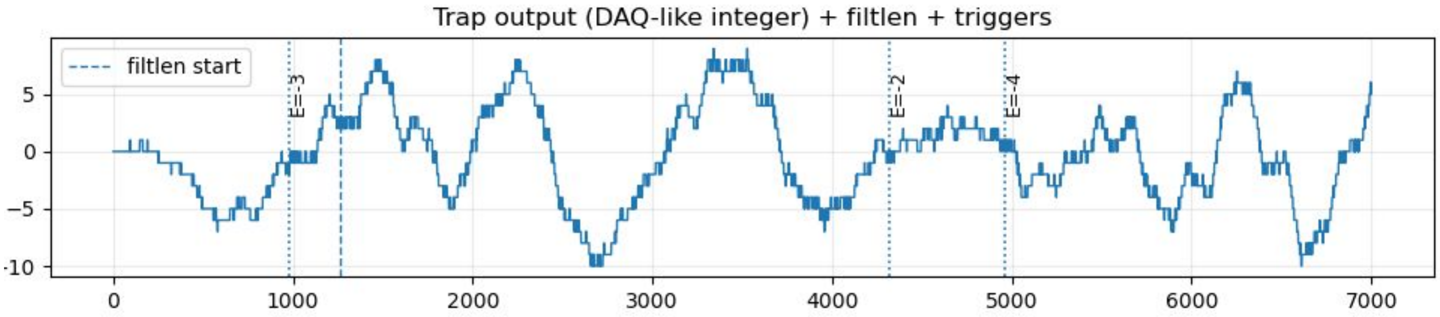
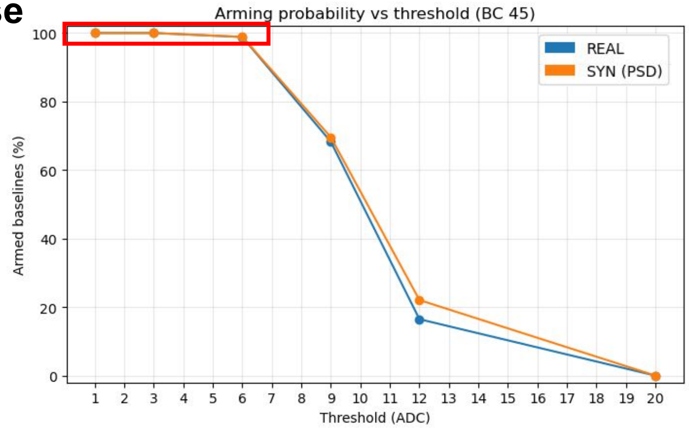
Noise thresholds: high-arming vs low-arming behavior



At low thresholds, nearly all baselines arm → triggering probes **typical noise fluctuations**



Once the threshold is high enough that many baselines never arm, the trigger is no longer probing ordinary noise—it probes rare threshold exceedances

Flowchart
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PSD-matched synthetic noise: validation in the high-arming regime

PSD matching reproduces:

•filtered noise RMS scale

•short-range correlations

Validation

- trigger state-machine diagnostics (not just rates)
- In the high-arming region (thr ≤ 6 ADC):

High-arming region (thr ≤ 6 ADC)

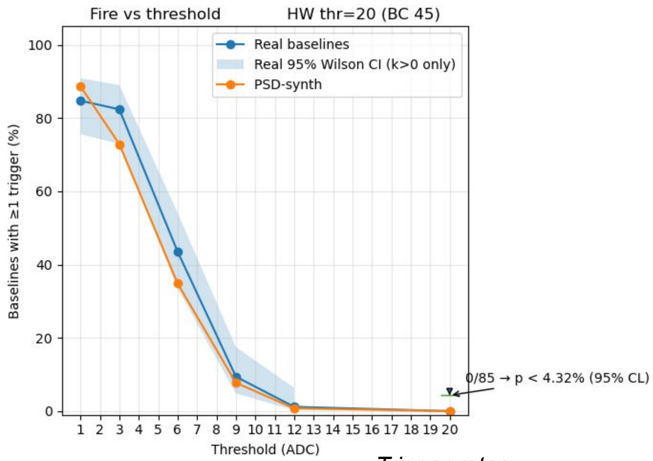
- REAL ≈ SYN in:
  - arming probability
  - firing probability
  - excursion / timing statistics

Low-arming thresholds:

- many baselines never arm
- triggering probes *rare exceedances*

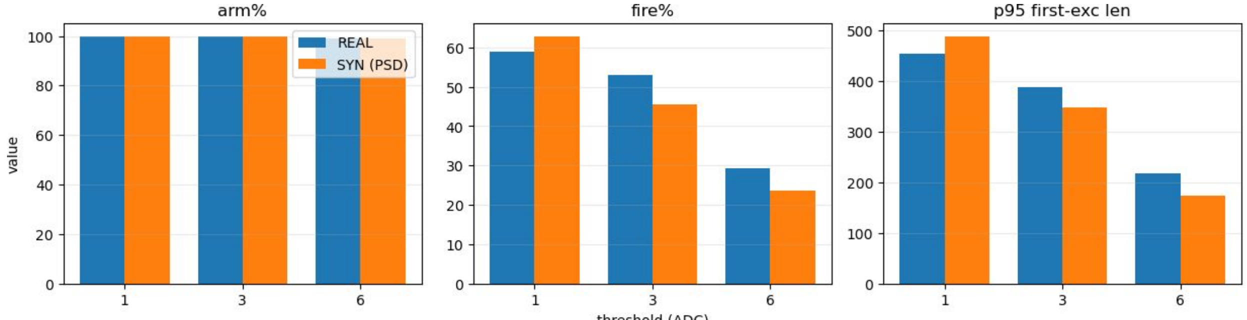
Extreme-tail behavior:

- depends on higher-order / nonstationary effects
- *not captured by PSD matching*



Trigger rates agree within error band

High-arming regime (thr = 1, 3, 6)



Flowchart
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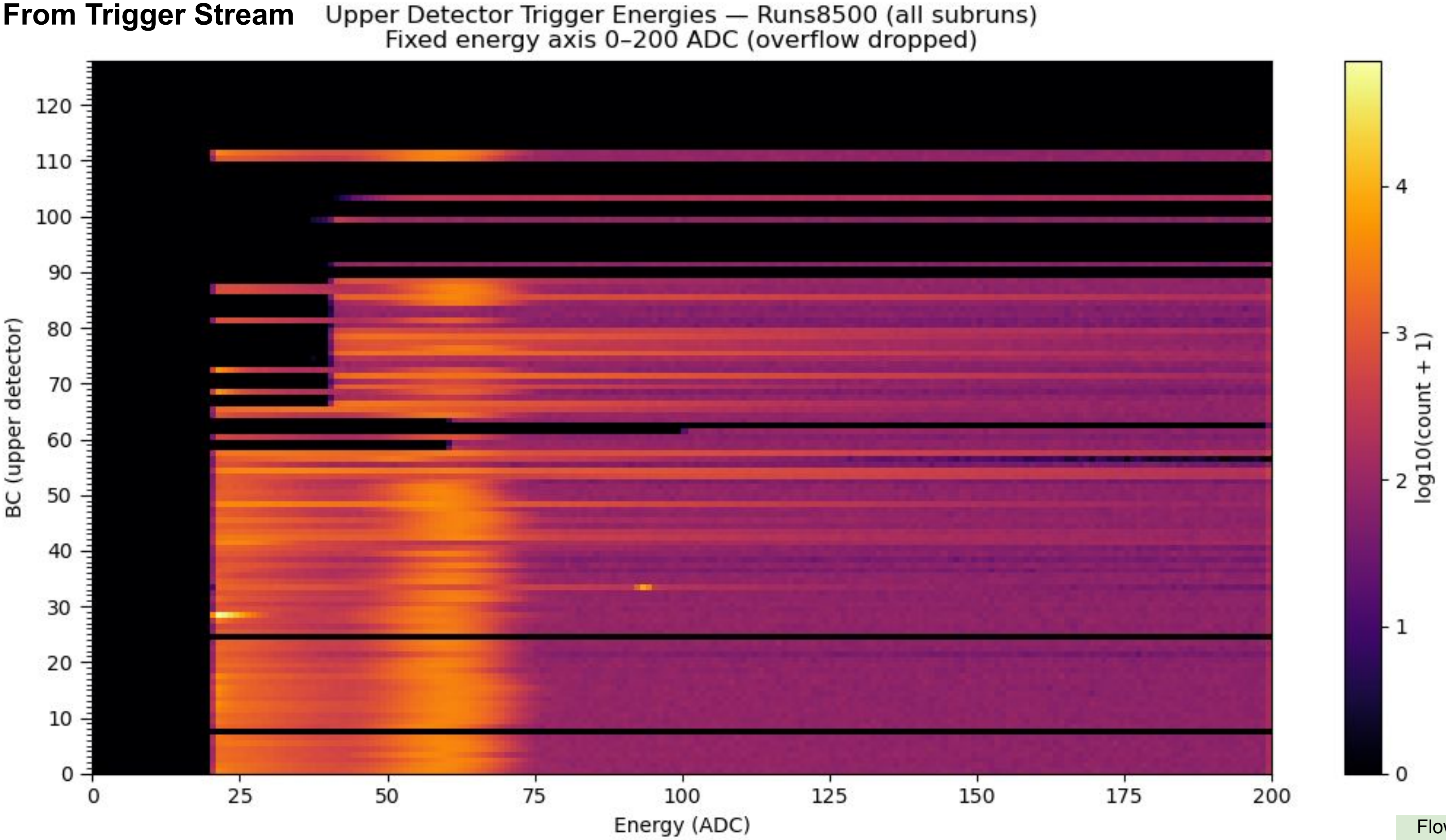
From Trigger Stream



Flowchart
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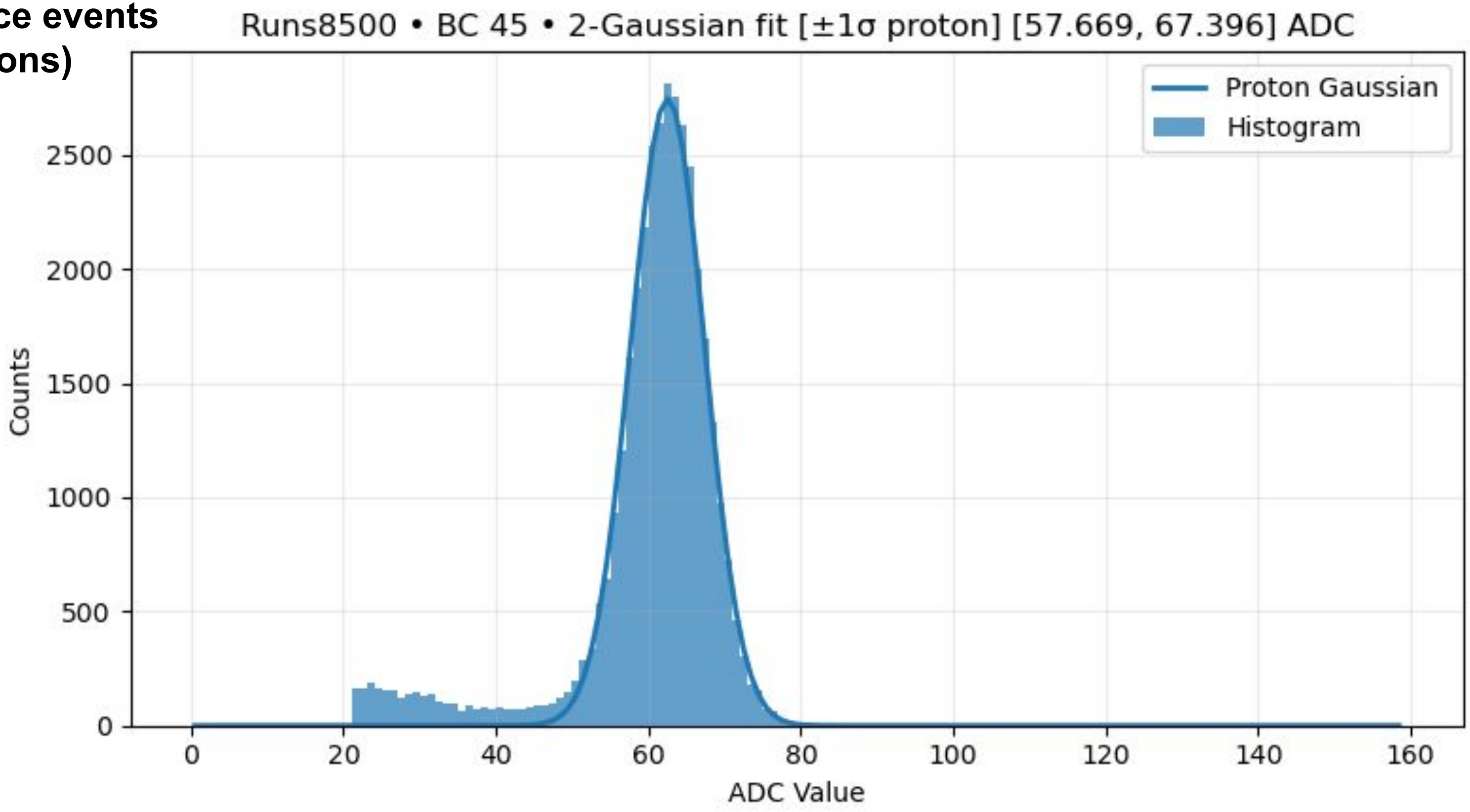
Using only 1st triggers in coincidence events (DAQ protons)



Flowchart
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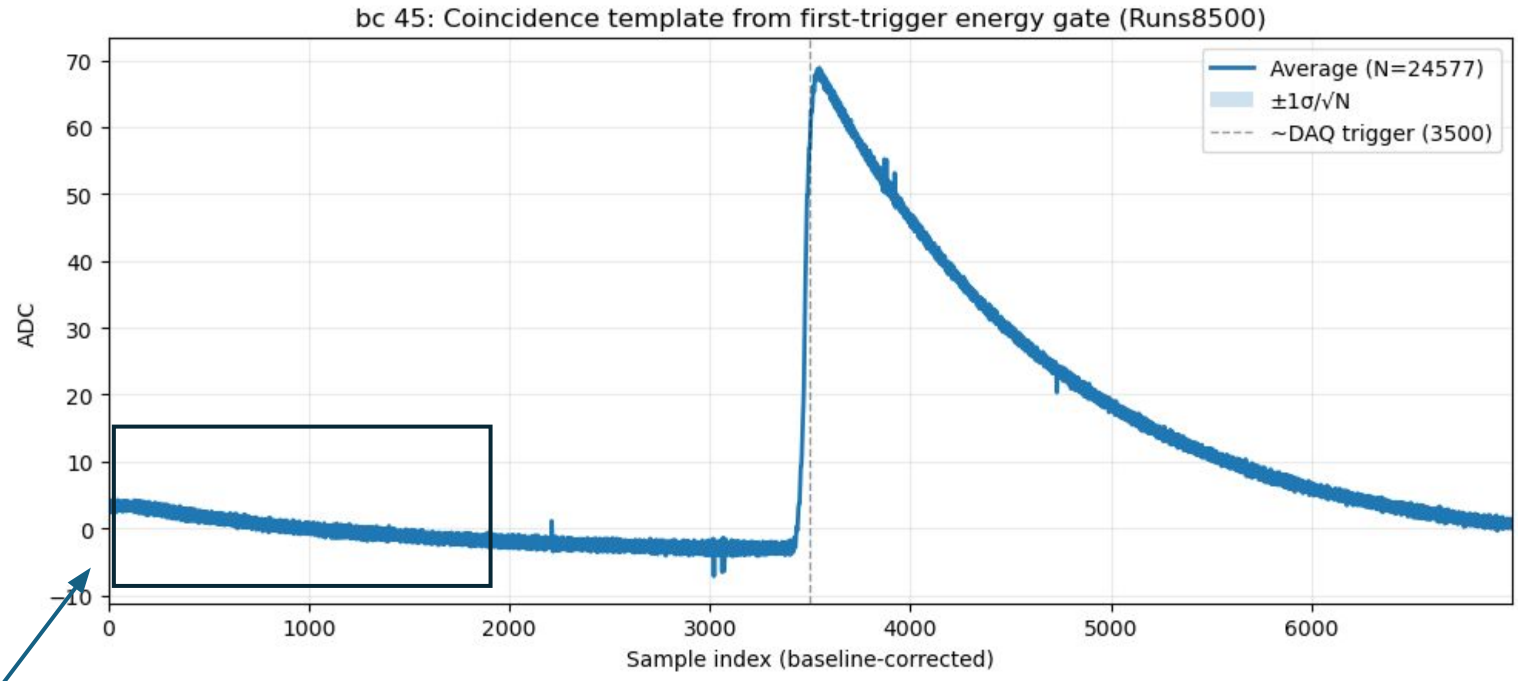

[saved] coinc_template_Runs8500_bc45_E[57.763,67.764]_avg.npy (+ std)

Input for transient behavior of trap filter, ignored by state machine

Flowchart
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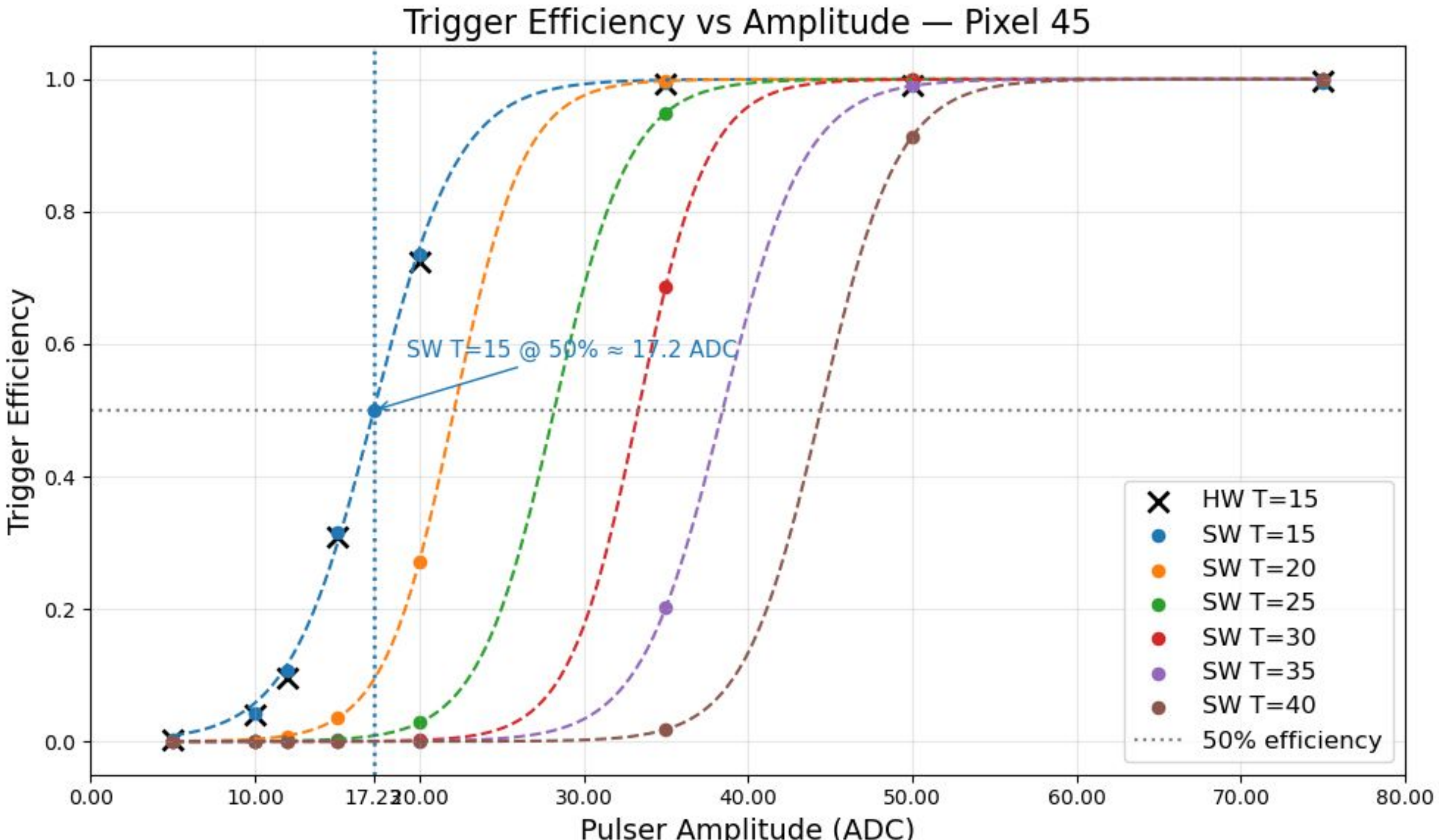
Pulser Efficiency Study Results

FROM: beam_off_runs : 7535:5 ADC, 7537:10 ADC, 7539:12 ADC, 7541:15 ADC, 7543:20 ADC, 7545:35 ADC, 7547:50 ADC, 7549:75 ADC



Flowchart
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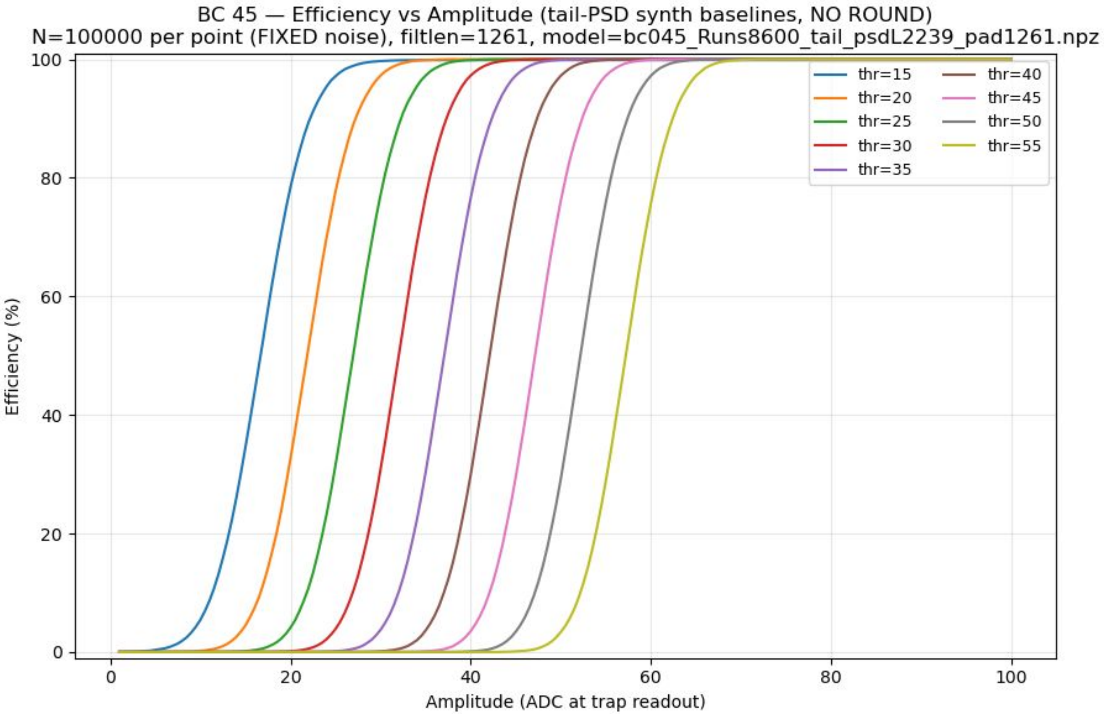
Synthesized Protons Efficiency Study Results

- Efficiency curves show the **DAQ trigger response** to signal amplitude, noise, and threshold

- Results **conditional on a validated template**

- Noise-dominated trigger behavior near threshold is validated

- Pulsers are not protons therefore validating synthetic protons with template + noise method on pulsers isn't airtight



Flowchart
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Scope and limitations

What is validated

- Synthetic baselines reproduce noise-only trigger behavior (rates + state-machine timing diagnostics)

What is assumed for signal efficiency

- Differences in pulse shape effects on triggering are negligible (not confirmed)
- Noise + template technique is validated on pulsers

Status

- Closing this benchmark with pulsers is ongoing

Flowchart
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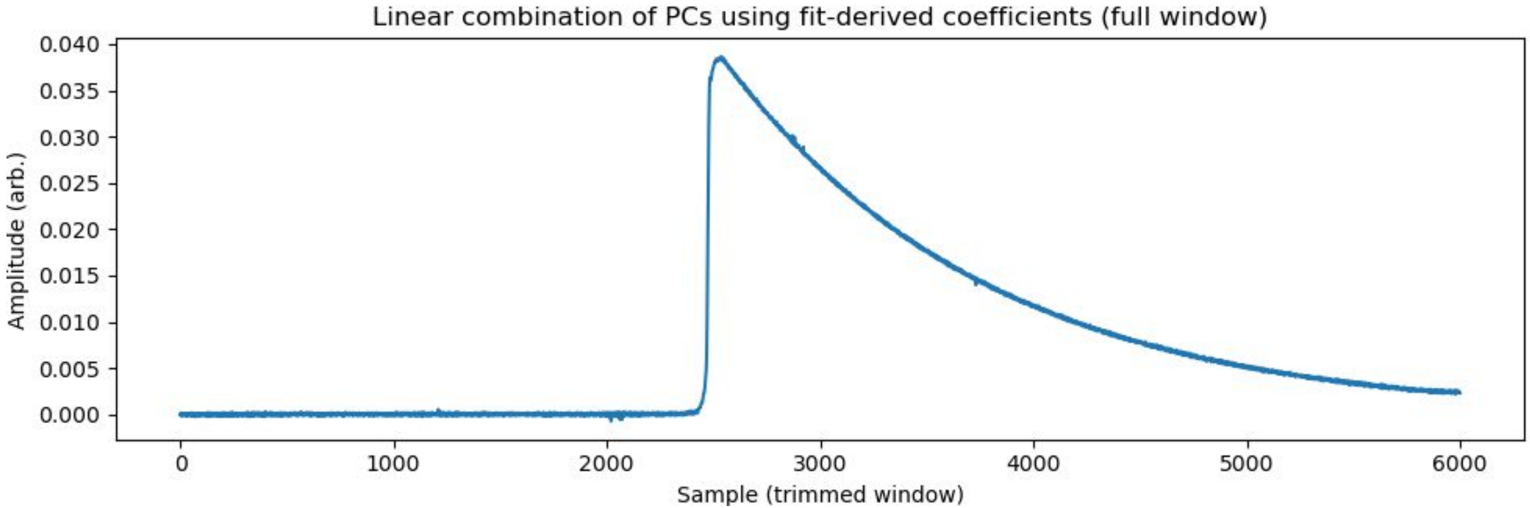

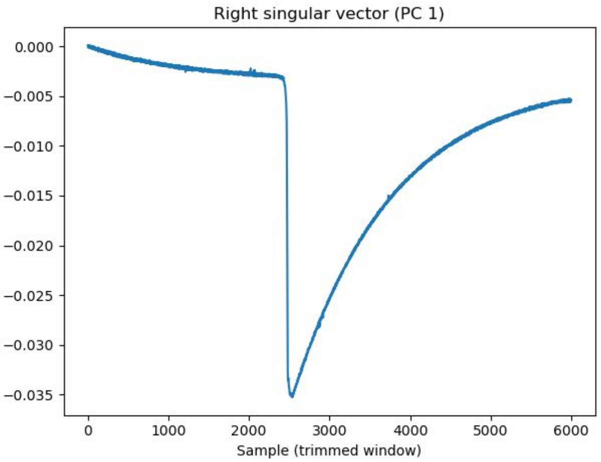

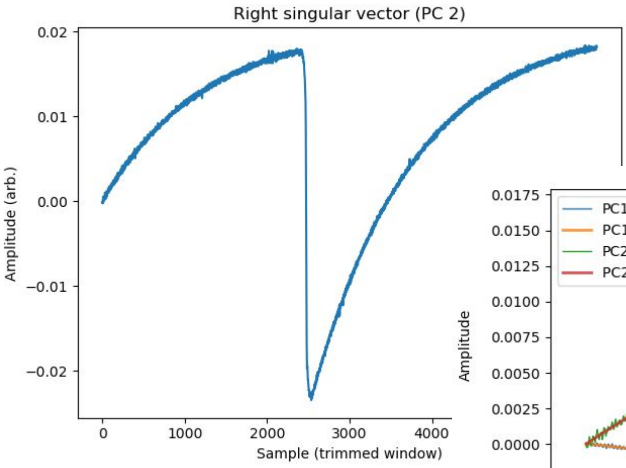

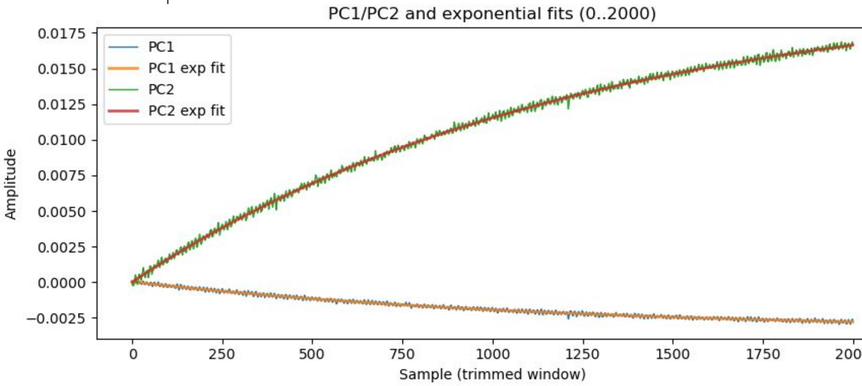

Flowchart
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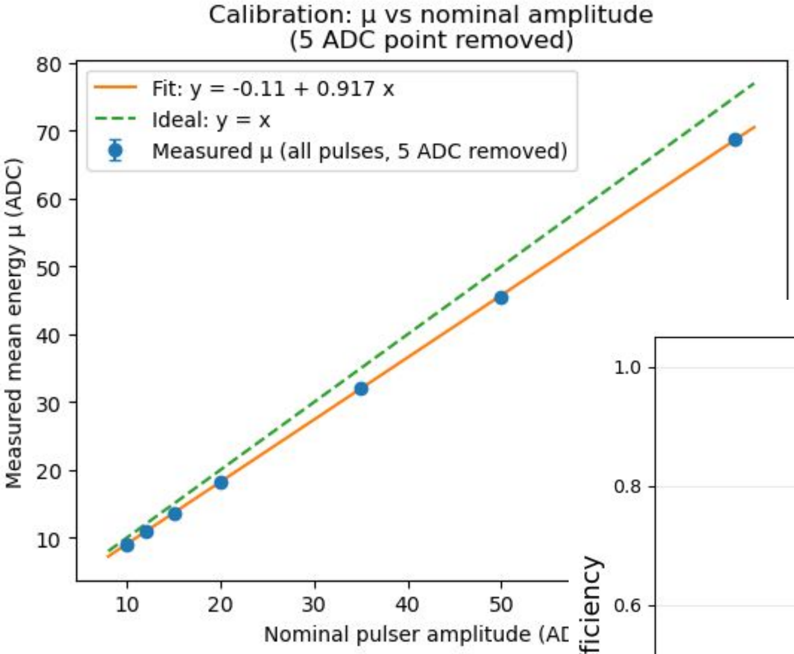
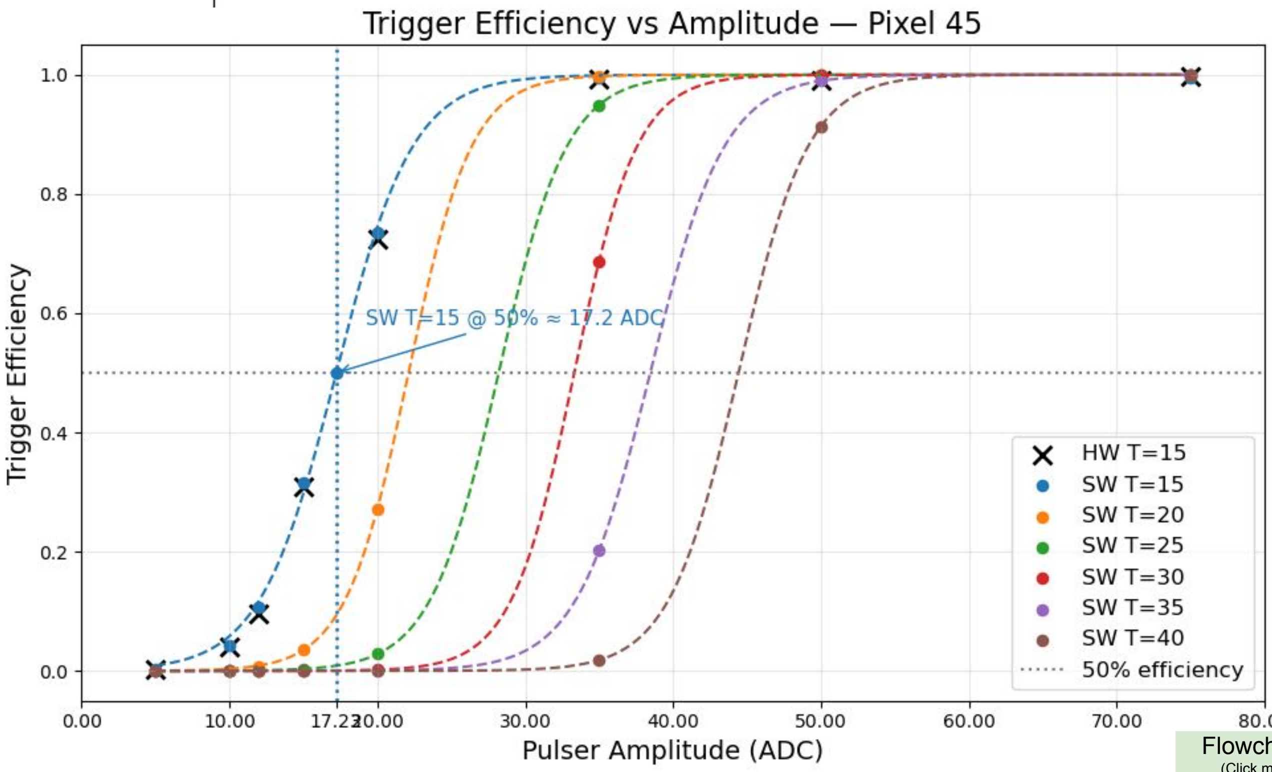


- Using the fit, we get nominal pulser amp at 50% eff should be ~16.5 ADC **not 17.2 ADC**
- 0.7 ADC difference after calibration due to state machine



Flowchart
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Edge Effect Simulation

Josh Hamblen, UTC

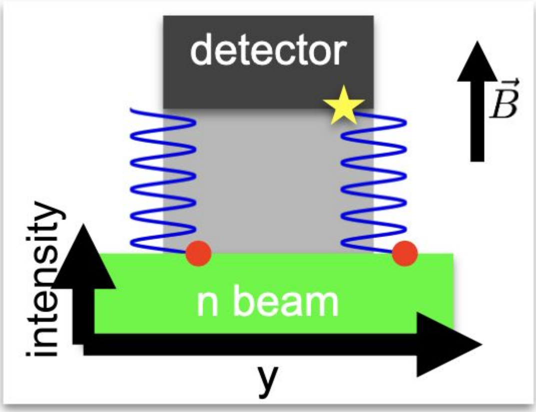
Flowchart
(Click me)

Edge Effect Simulation - ***Status Update***

What is the edge effect? (From SB's presentation at the last collaboration meeting…)

We accept electrons in a certain set of pixels (the fiducial volume or decay volume), and search the following proton even if outside.

- Ideally, detector pixels detect decay protons from neutron decays from the region below detector. No bias in that.
- Gyration leads to some losses of decays inside decay volume, and some gain from outside.
- This cancels for a uniform beam, but biases the decay sample otherwise since gyration radius depend on proton energy and angle to field.



G. Konrad, then U Mainz

References:

SB's original edge effect writeup
SB's latest proposed analysis
CMS Task #163 (My work)

Edge Effect Analysis Plan So Far

- Decide on an acceptance region, e.g. a rectangle along the beam.
- Accept events where the **first hit of the electron** is in the acceptance region. The DAQ is responsible to record all protons for electrons in the acceptance region, so no cut is made on proton hit position.
- We run **two Geant4 simulations using the NabSimulation**, one with a neutron beam that is uniform (**flat**) over the whole acceptance region, and one that has a **realistic** shape as measured at BL13.
- We make a histogram of accepted counts vs. electron energy E_e for both beams, and divide the one from the real beam by the one with the uniform beam. I suspect we find that the ratio is not constant, but **decreases** with larger electron energy.
- We make a histogram of accepted counts vs. gyration radius $g=p_{\perp}/|q|B$ for both beams, and divide their difference by the one with the uniform beam. I suspect we find that the result is proportional to g^2.
- We compute the slope of the fit and take the translation to $\Delta a/a$. (Still to do.)

Flowchart
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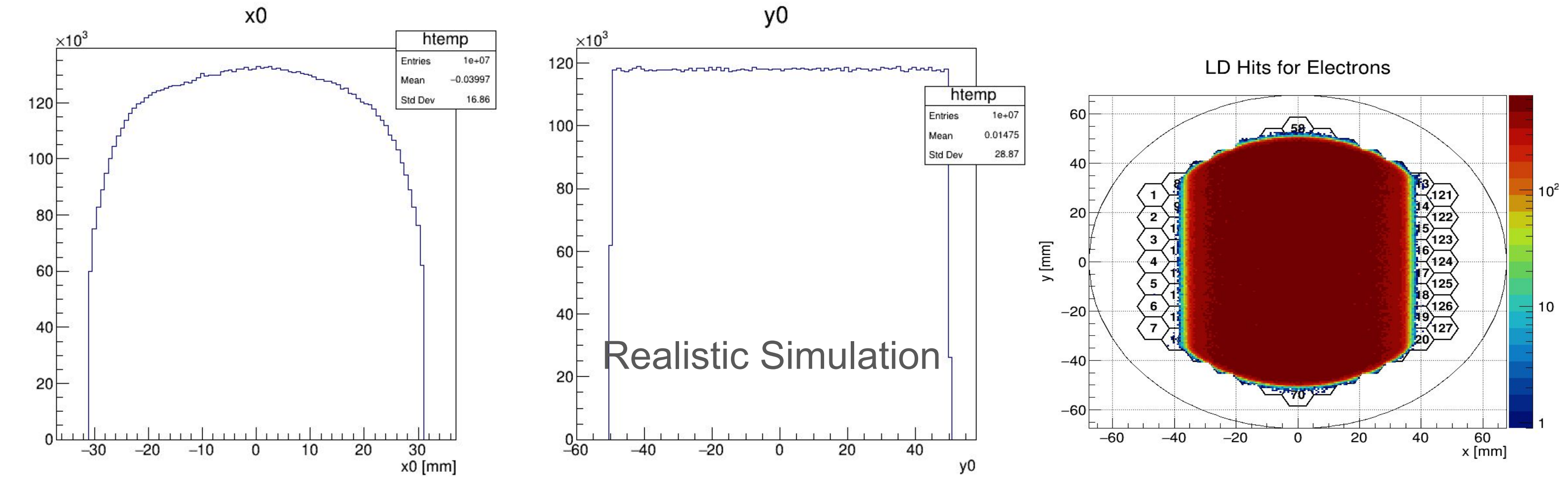

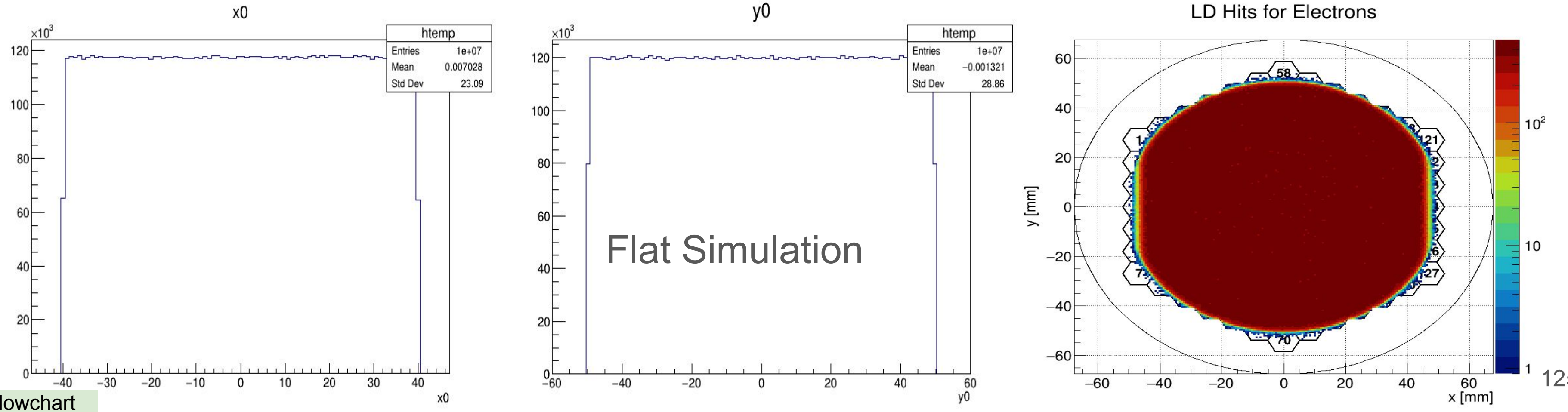

Flowchart
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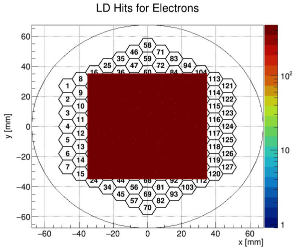
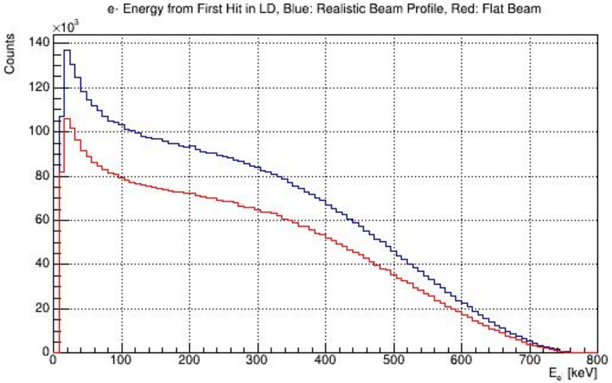
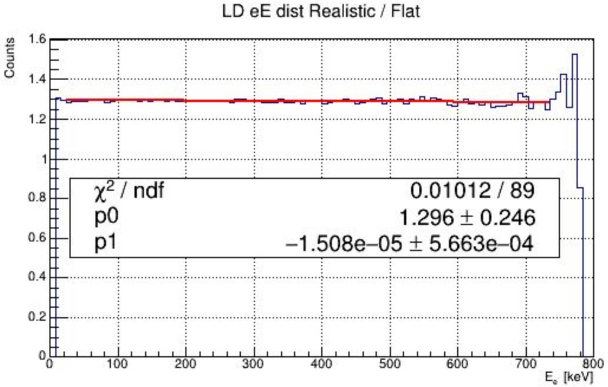
Edge Effect Study with Rectangular Acceptance Region



Set a +/- 35 mm acceptance region in x and y for the lower detector first hit of the electron.

Electron energy distribution:

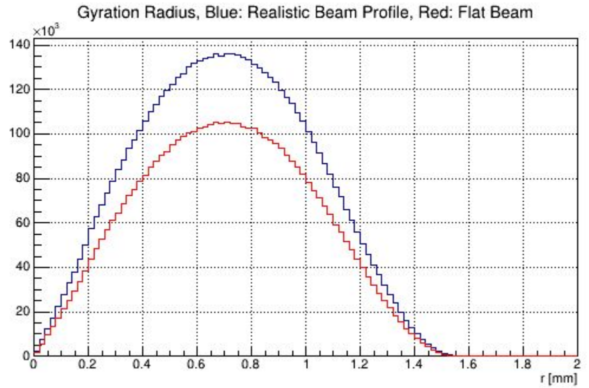


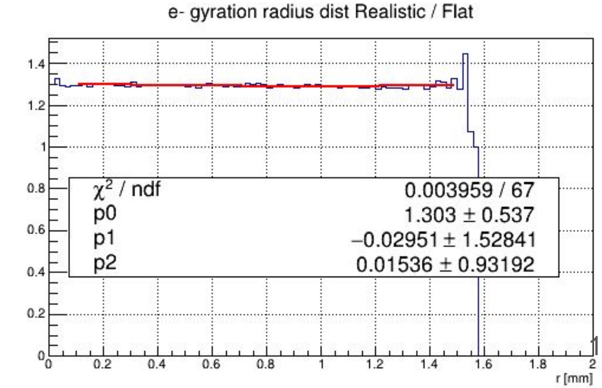


Blue: Realistic Beam

Red: Flat Beam

Gyration radius at decay point:





Flowchart
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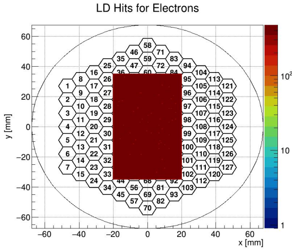
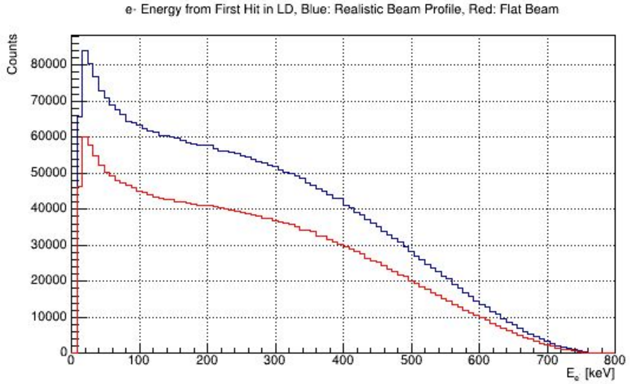
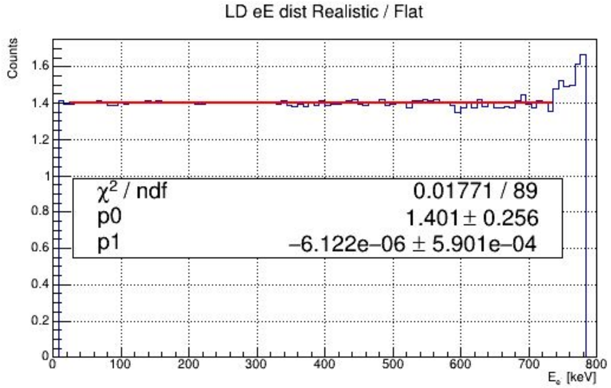
Edge Effect Study with Rectangular Acceptance Region



Set a +/- 20 mm acceptance region in x, +/- 35 mm in y.

Electron energy distribution:

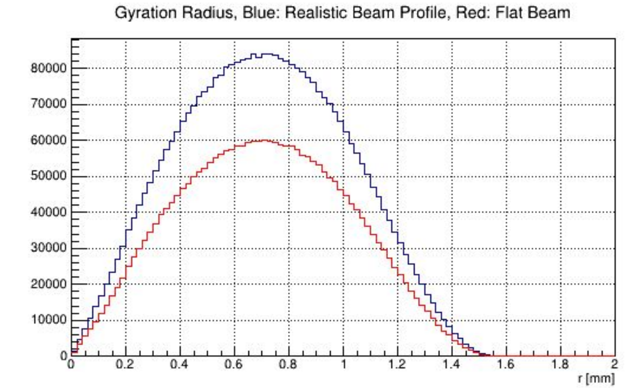


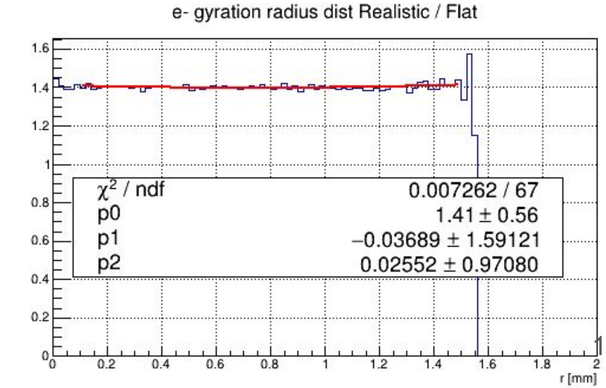


Blue: Realistic Beam

Red: Flat Beam

Gyration radius at decay point:





Flowchart
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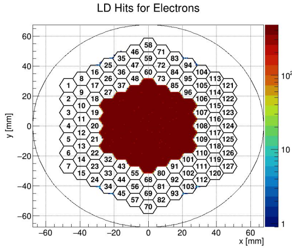
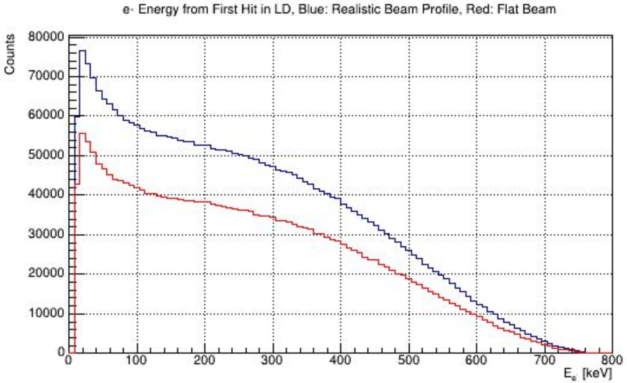
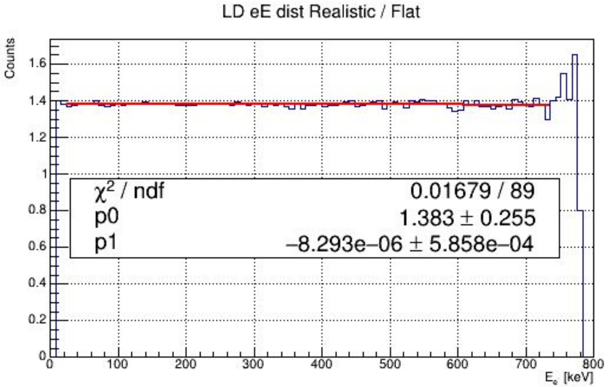
Edge Effect Study with Acceptance Region of Inner 4 Rings of Pixels



Electron energy distribution:

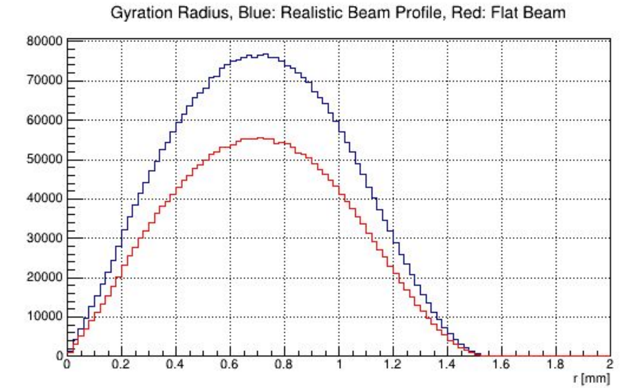


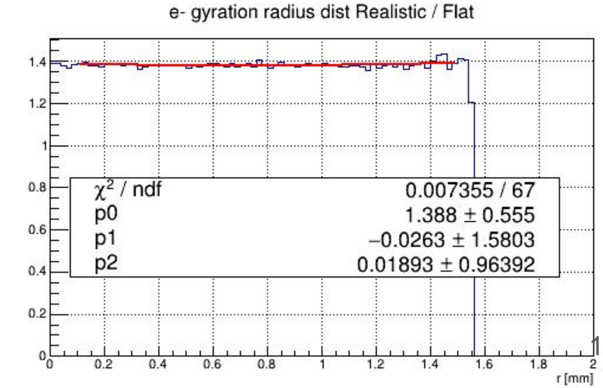


Blue: Realistic Beam

Red: Flat Beam

Gyration radius at decay point:





Flowchart
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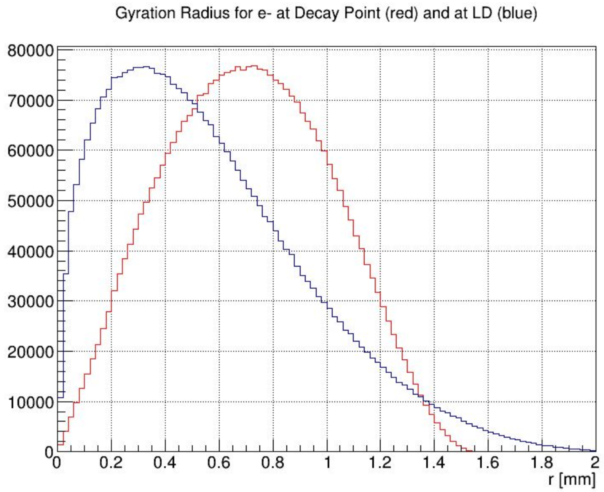
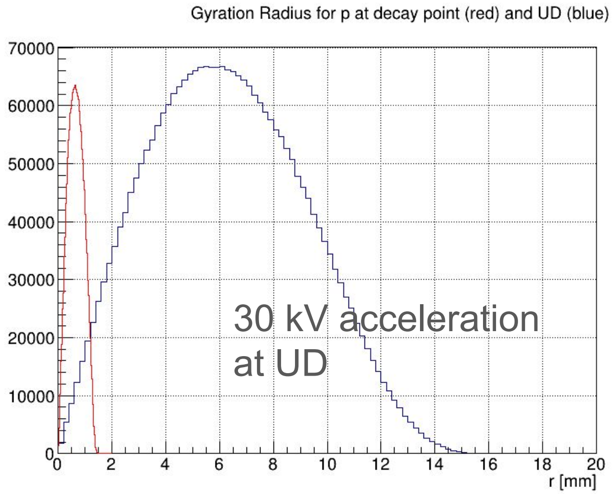
Check of Gyration Radius Calculations ($p_\perp/|q|B$)



Lower detector electrons



Upper detector protons

I used 1.8 T field value at decay point, and 1.3 T at detectors.
Momentum at detector taken from info stored at mm plane.
More investigation needed.