In search for BSM physics in the beta decay of ^{45}Ca

Physics of fundamental Symmetries and Interactions 2019

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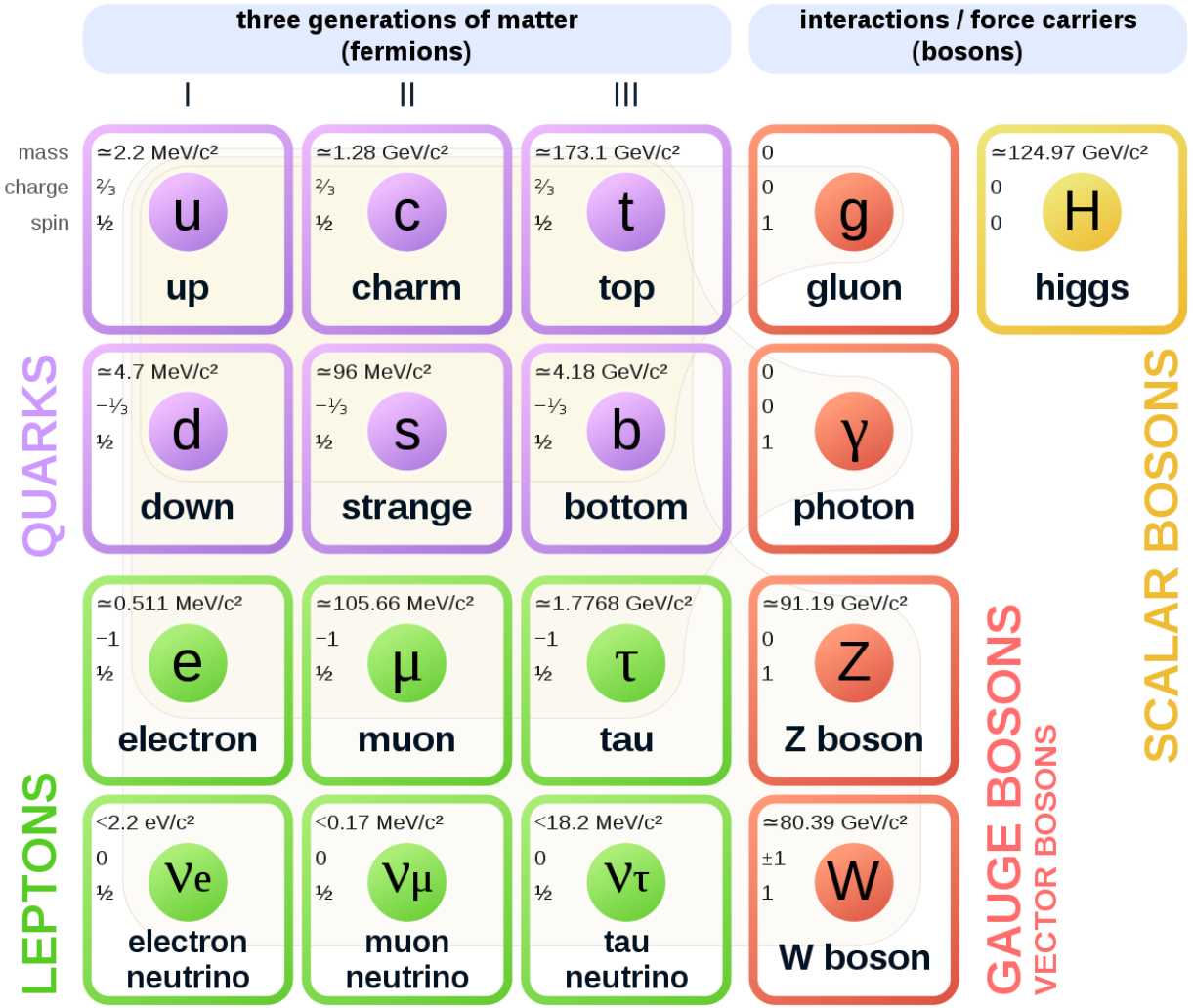
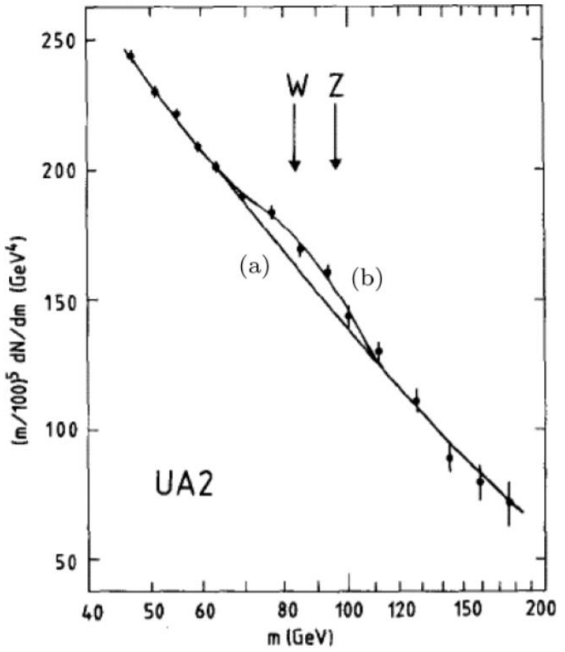
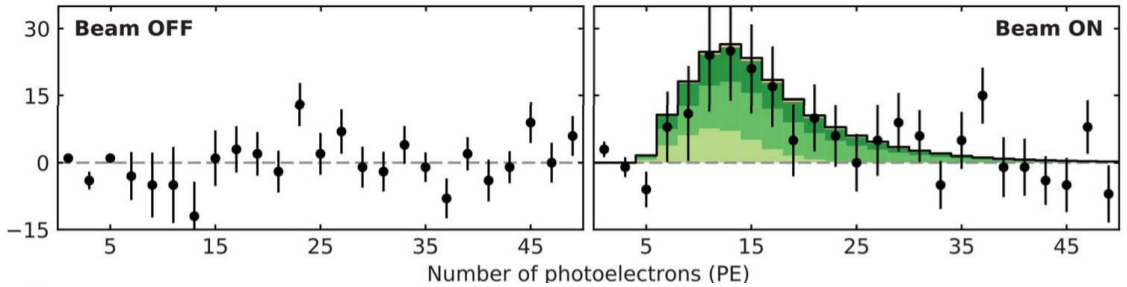
Noah Birge

The Standard Model (SM)





M. Banner et al. (UA2 Collaboration), Phys. Lett. B 122, 476 (1983)



COHERENT collaboration: *Science, 357 (2017)*

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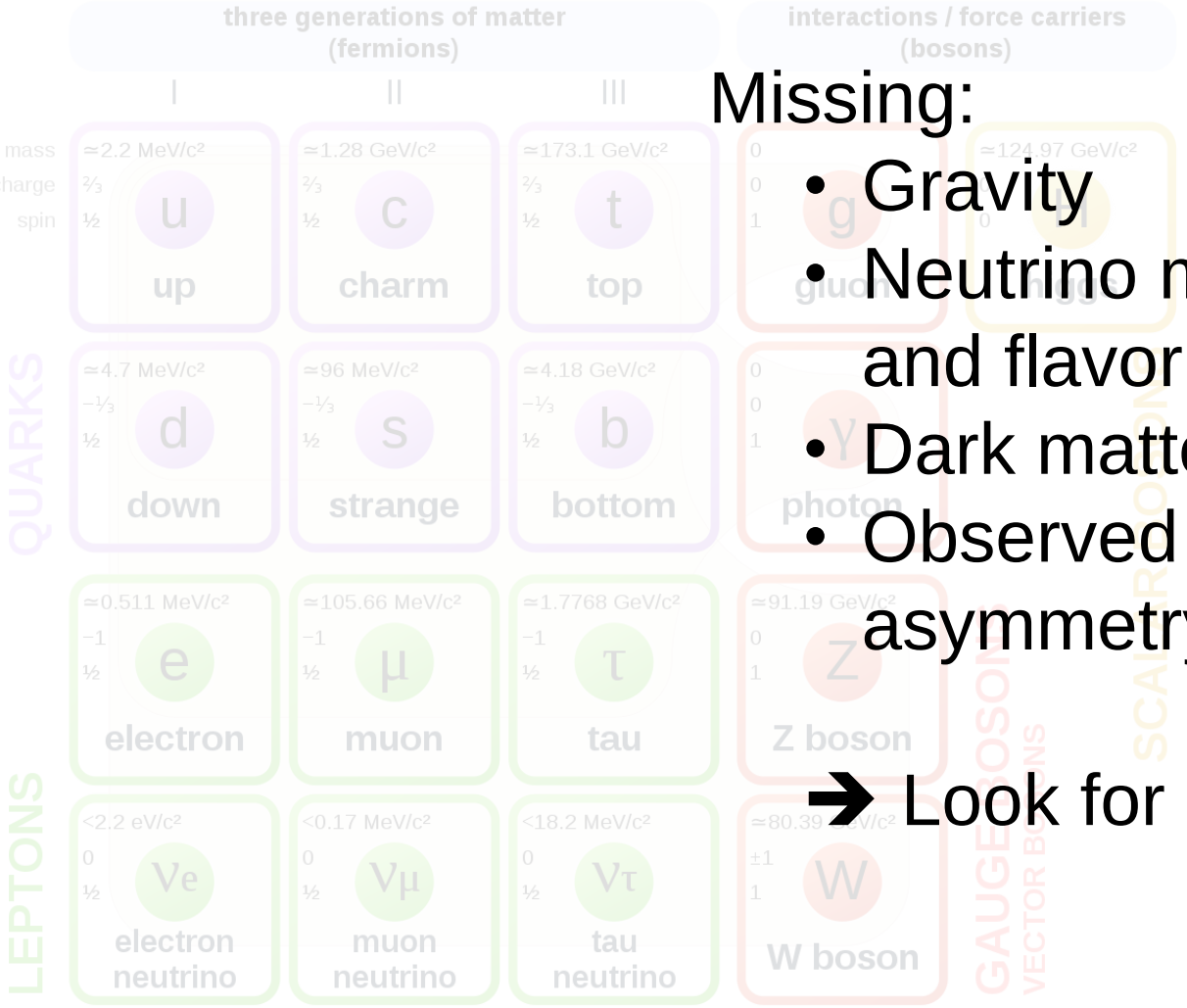
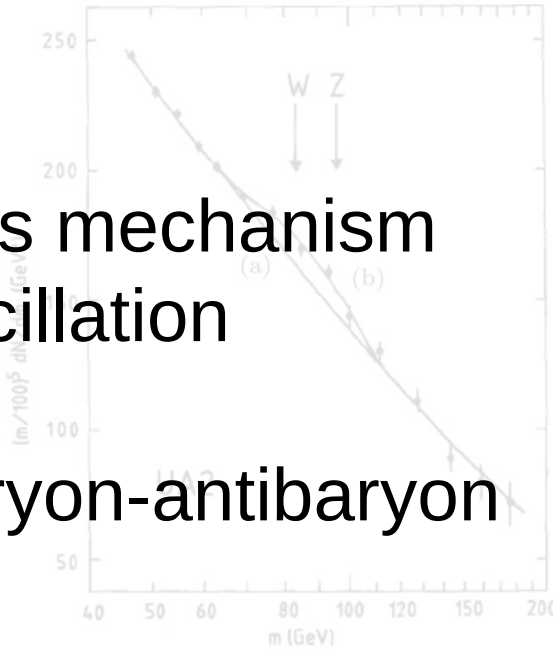


Missing:

- Gravity
- Neutrino mass mechanism and flavor oscillation
- Dark matter
- Observed baryon-antibaryon asymmetry

➔ Look for BSM Physics



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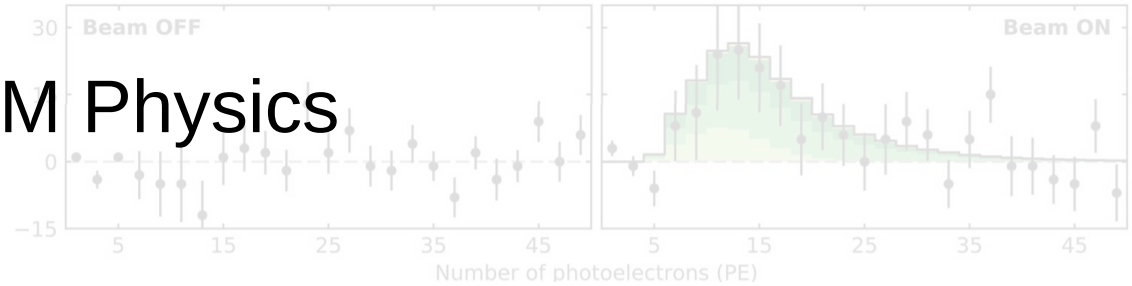

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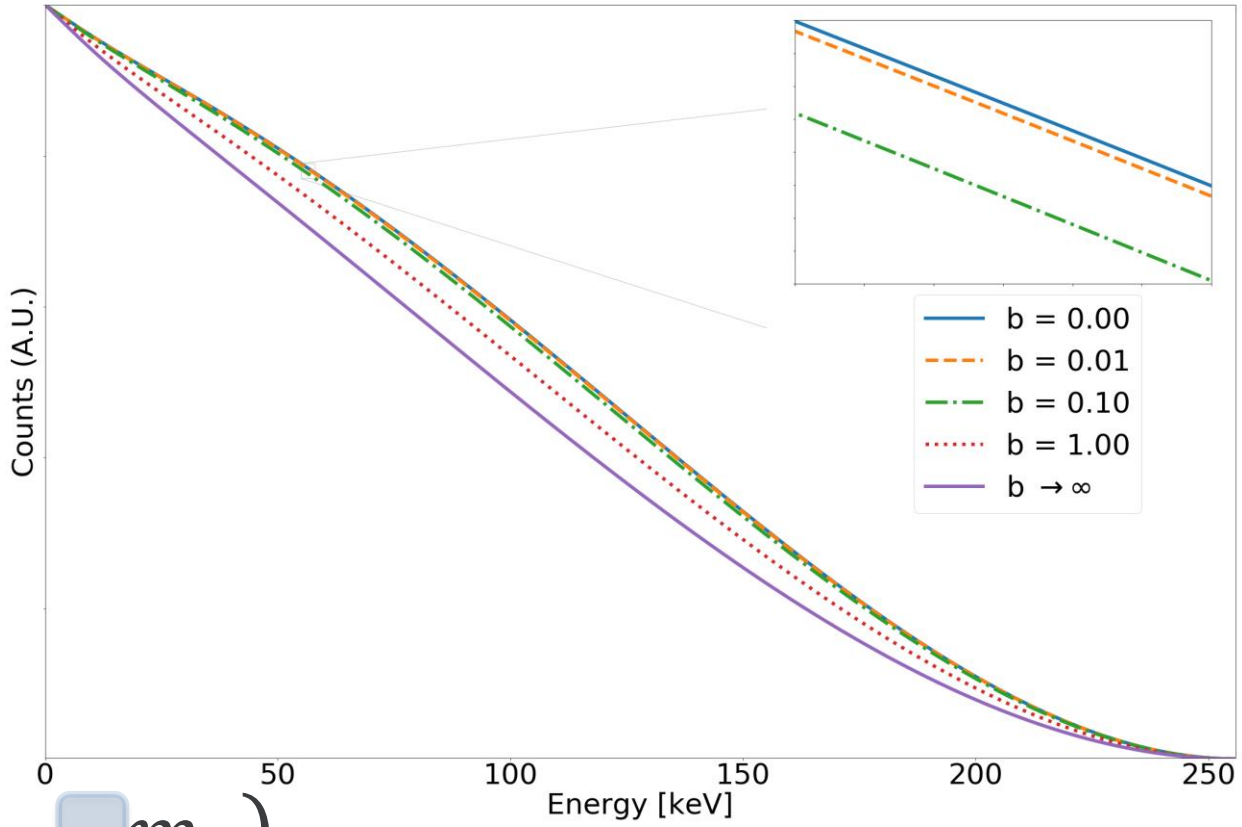
^{45}Ca beta decay

$^{45}Ca \rightarrow {}^{45}Sc + e^- + \bar{\nu}_e$

Q = 255 keV

$7/2^- \rightarrow 7/2^-$ (99.998%)



Decay Rate:

$$\frac{d\omega}{dE_e}(E_e) \propto p_e E_e (E^0 - E_e)^2 \left\{1 + b\frac{m_e}{E_e}\right\}$$

$$b \propto \mathrm{Re}\left(\frac{C_S + C_S'}{C_V + C_V'} + \frac{g_a}{g_v}\frac{C_T + C_T'}{C_A + C_A'}\right)$$

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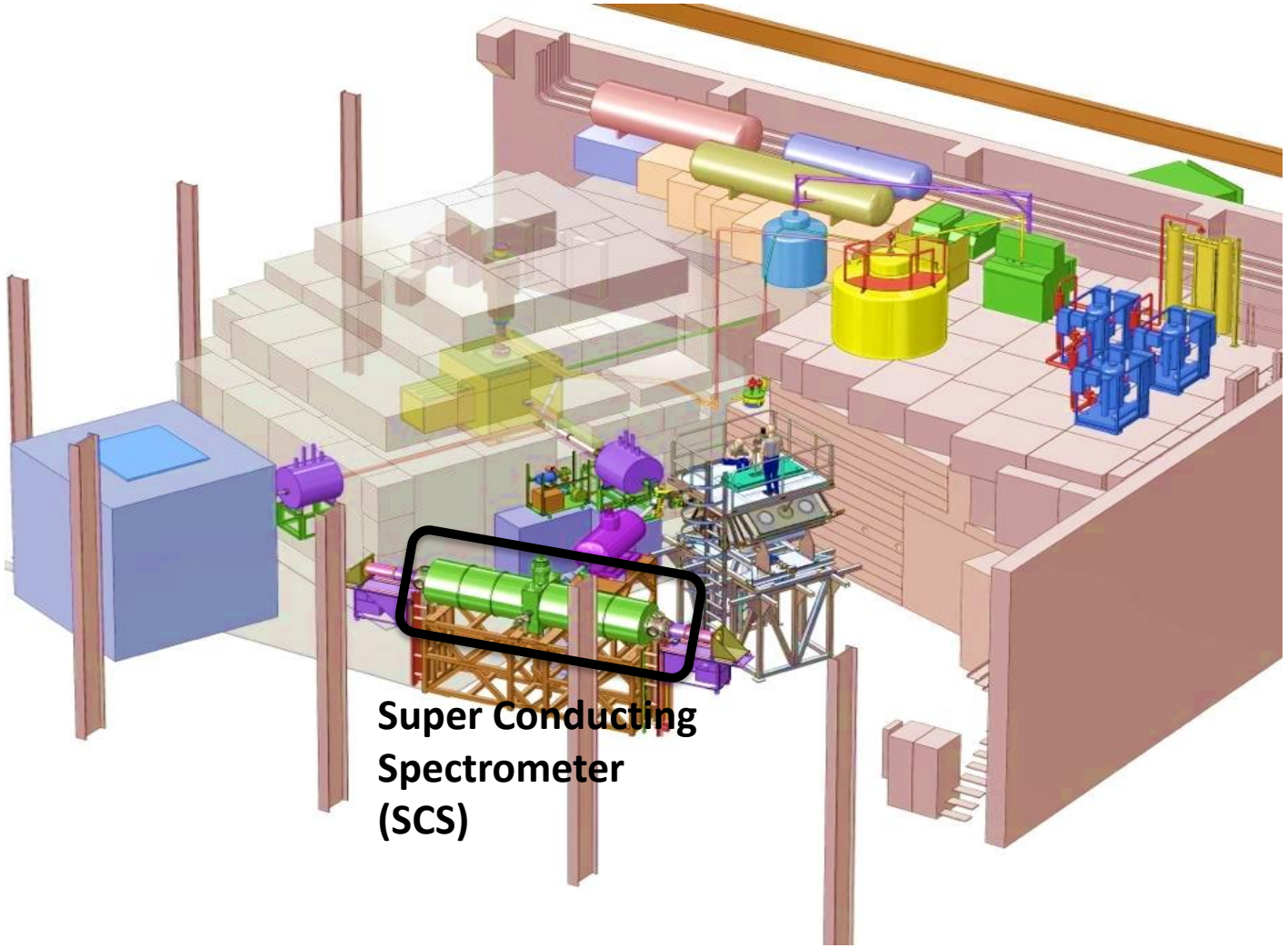
The ^{45}Ca Experiment at LANSCE



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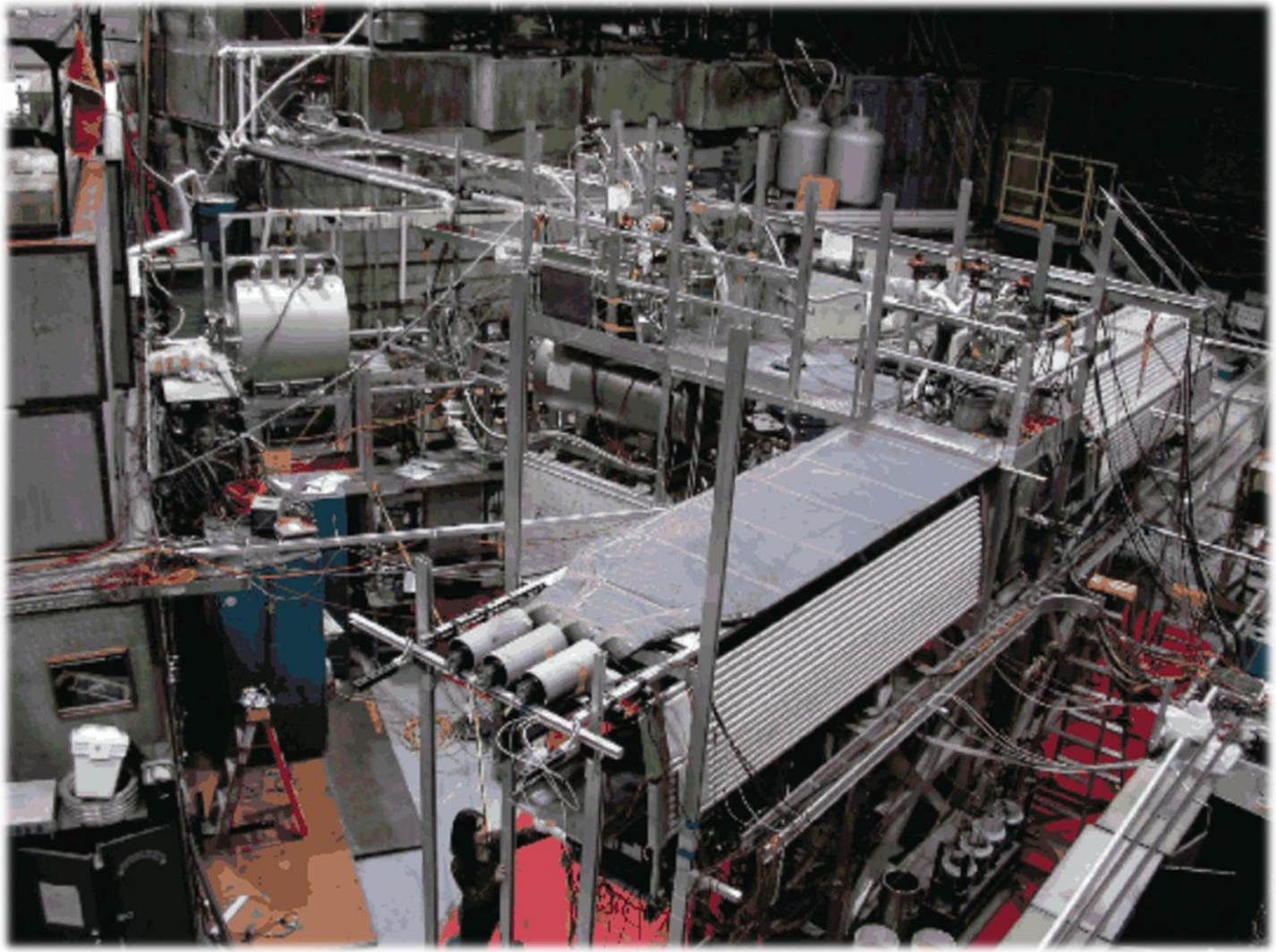

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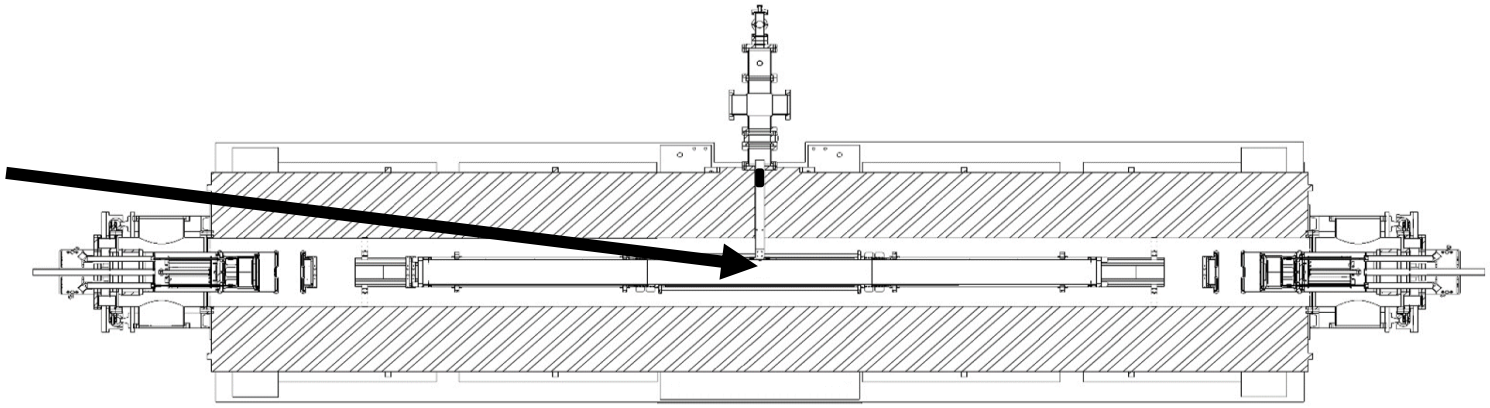
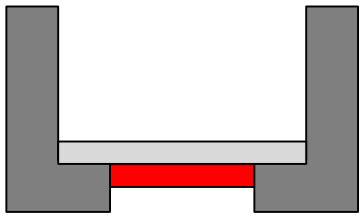
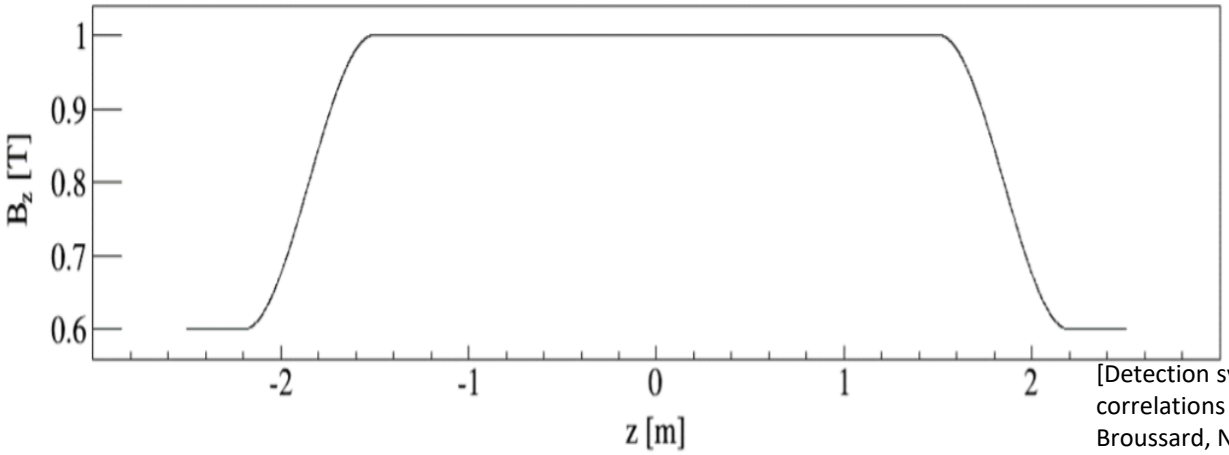
The ^{45}Ca Experiment at LANL

- Prepared by IKS of KU Leuven
- ~1 kBq
- ~200 nm foil thickness





Aluminum Frame
Aluminum Backing
Source



[Detection systems for neutron β decay correlations in the UCNB and Nab experiments, L.J. Broussard, NIM A, Vol 849, pp. 83-89]

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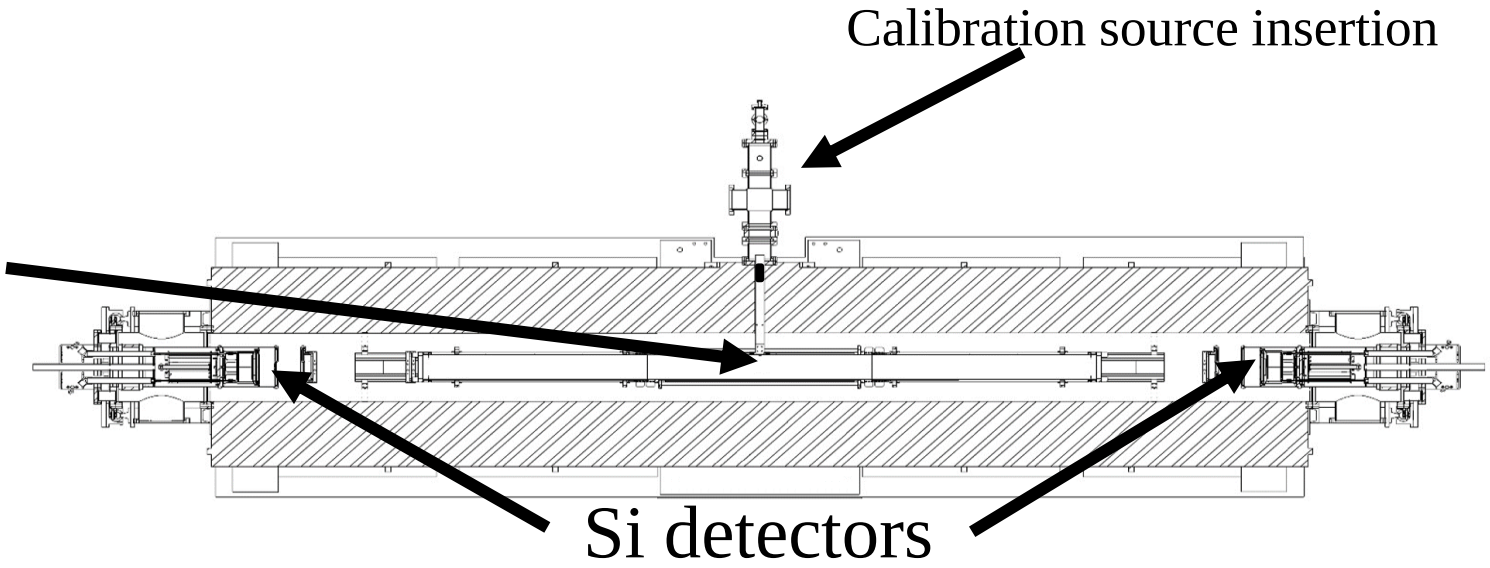

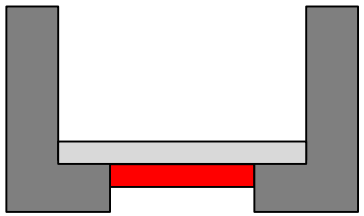

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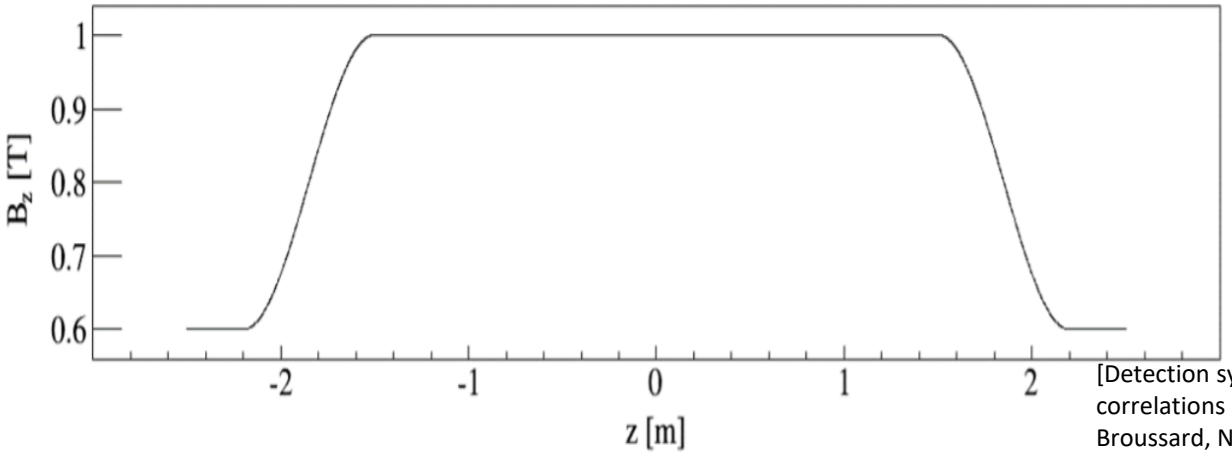

[Detection systems for neutron β decay correlations in the UCNB and Nab experiments, L.J. Broussard, NIM A, Vol 849, pp. 83-89]

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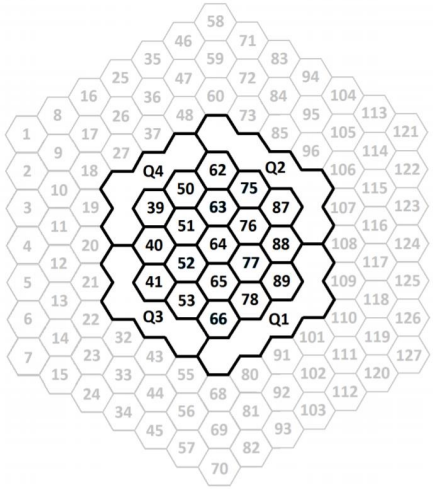
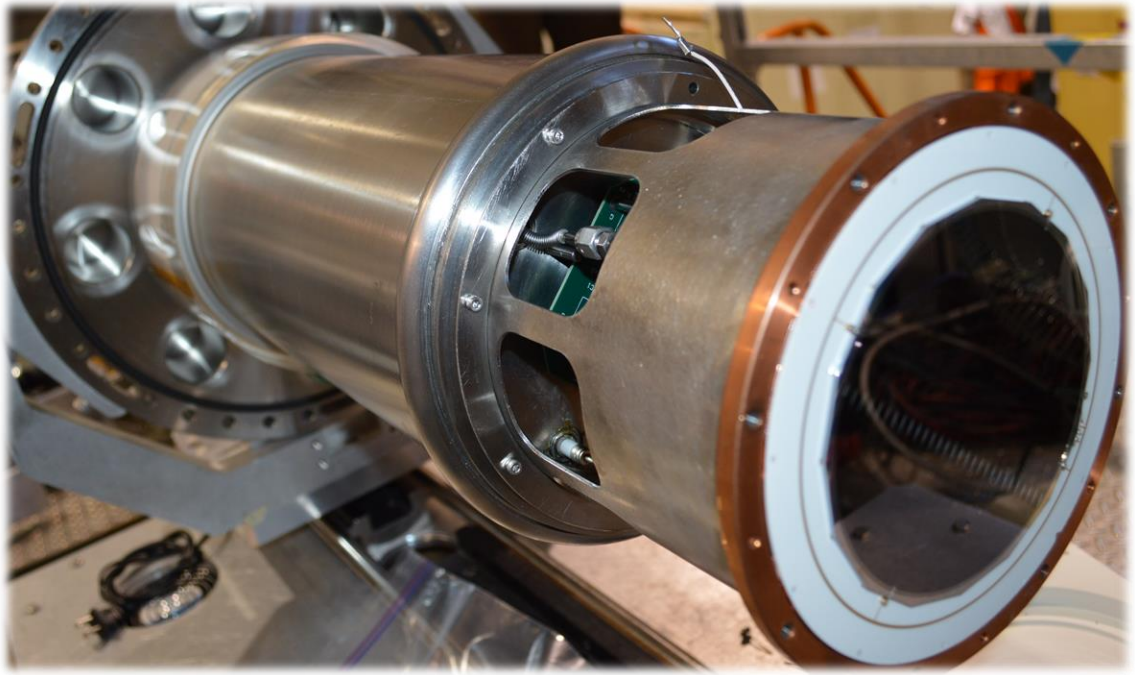
^{45}Ca Detectors

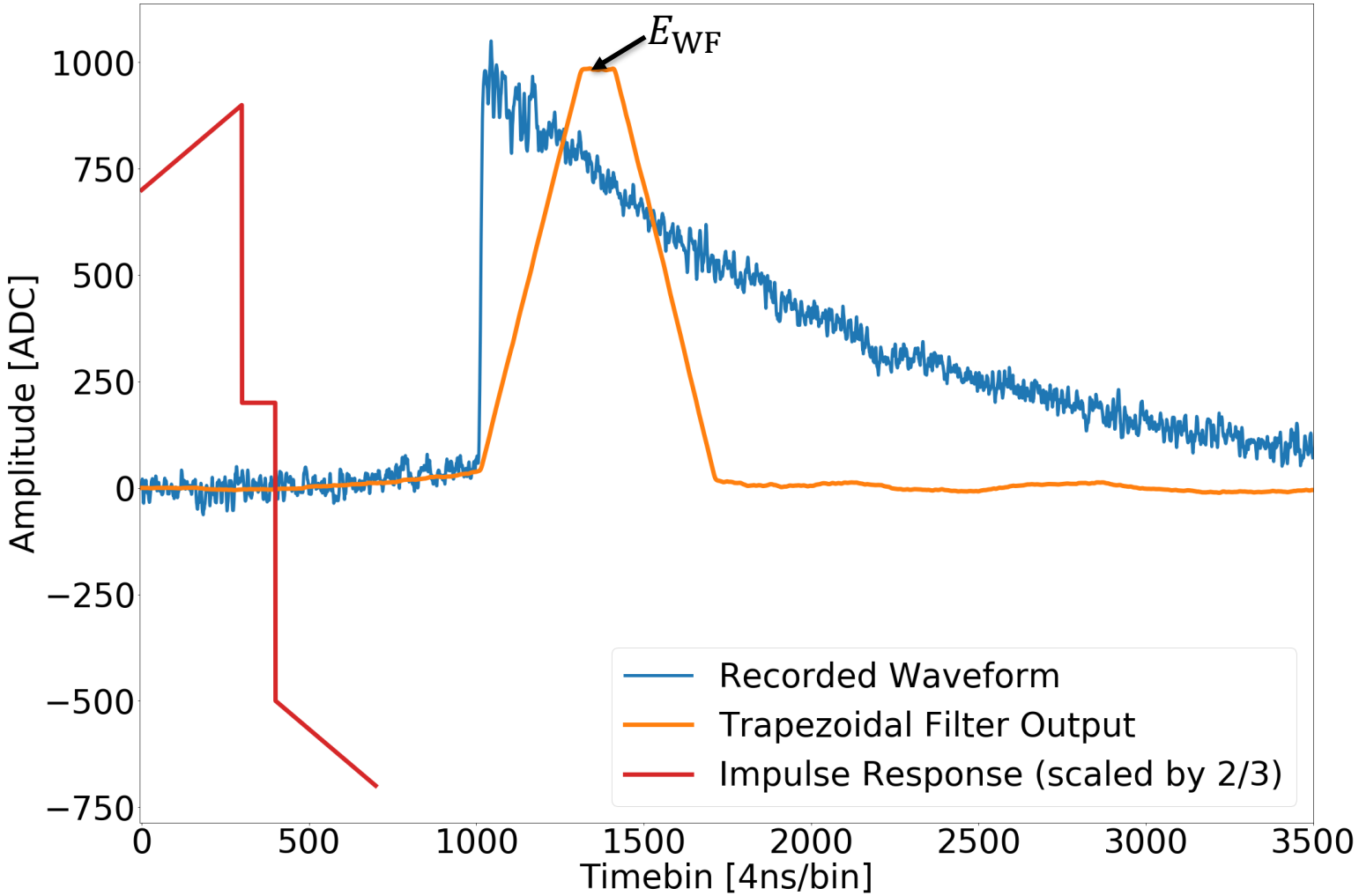
- Single crystal Si
- Large area ~ 11 cm
- 100nm dead layer
- Thick ~ 1.5mm
- Pixelated





[Detection systems for neutron β decay correlations in the UCNB and Nab experiments, L.J. Broussard, NIM A, Vol 849, pp. 83-89]

Energy Extraction: Long Trapezoidal Filter



V. Jordanov, *et al.*, *Digital synthesis of pulse shapes in real time for high resolution radiation spectroscopy*, NIMA, Vol 345

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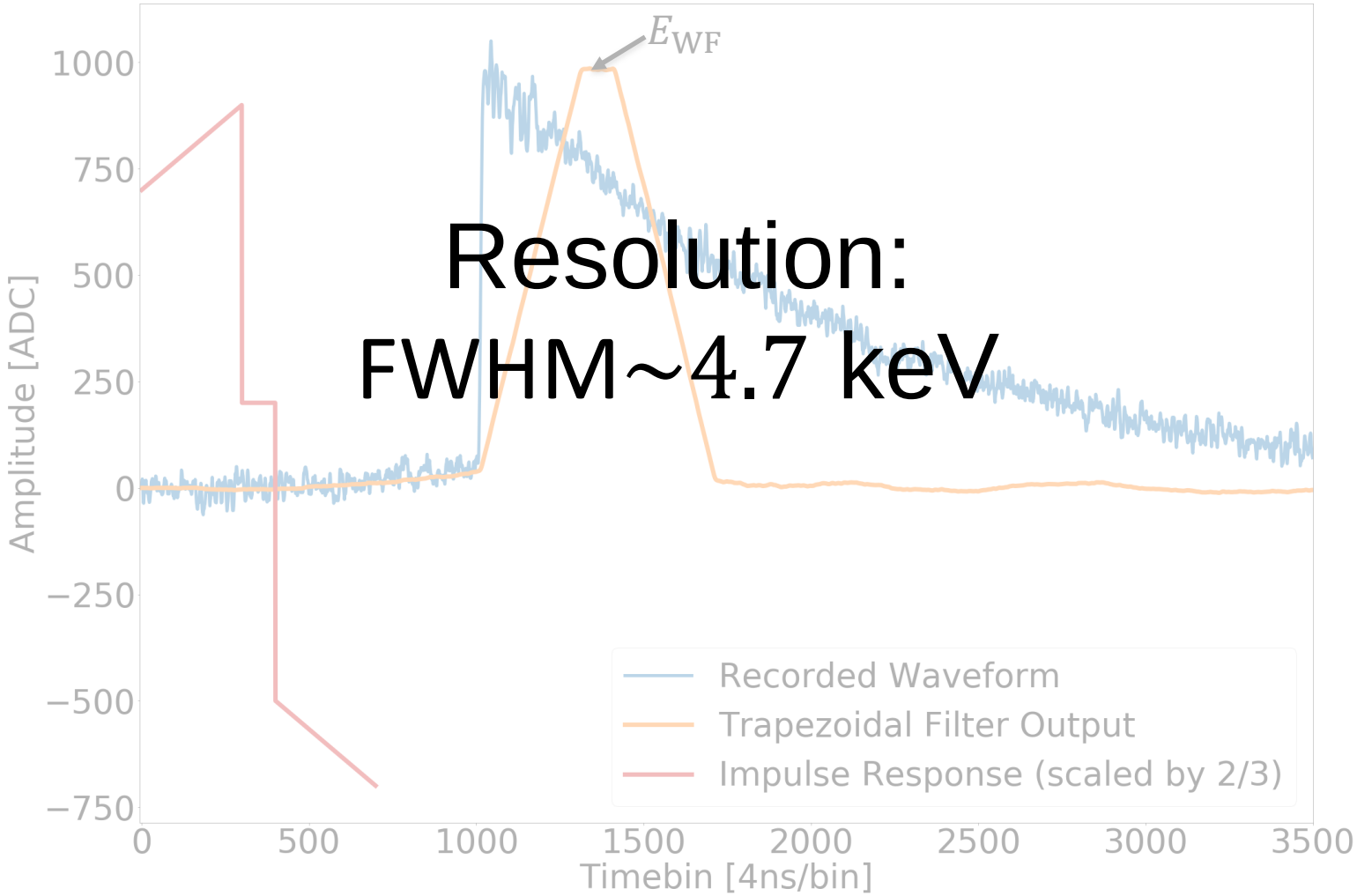
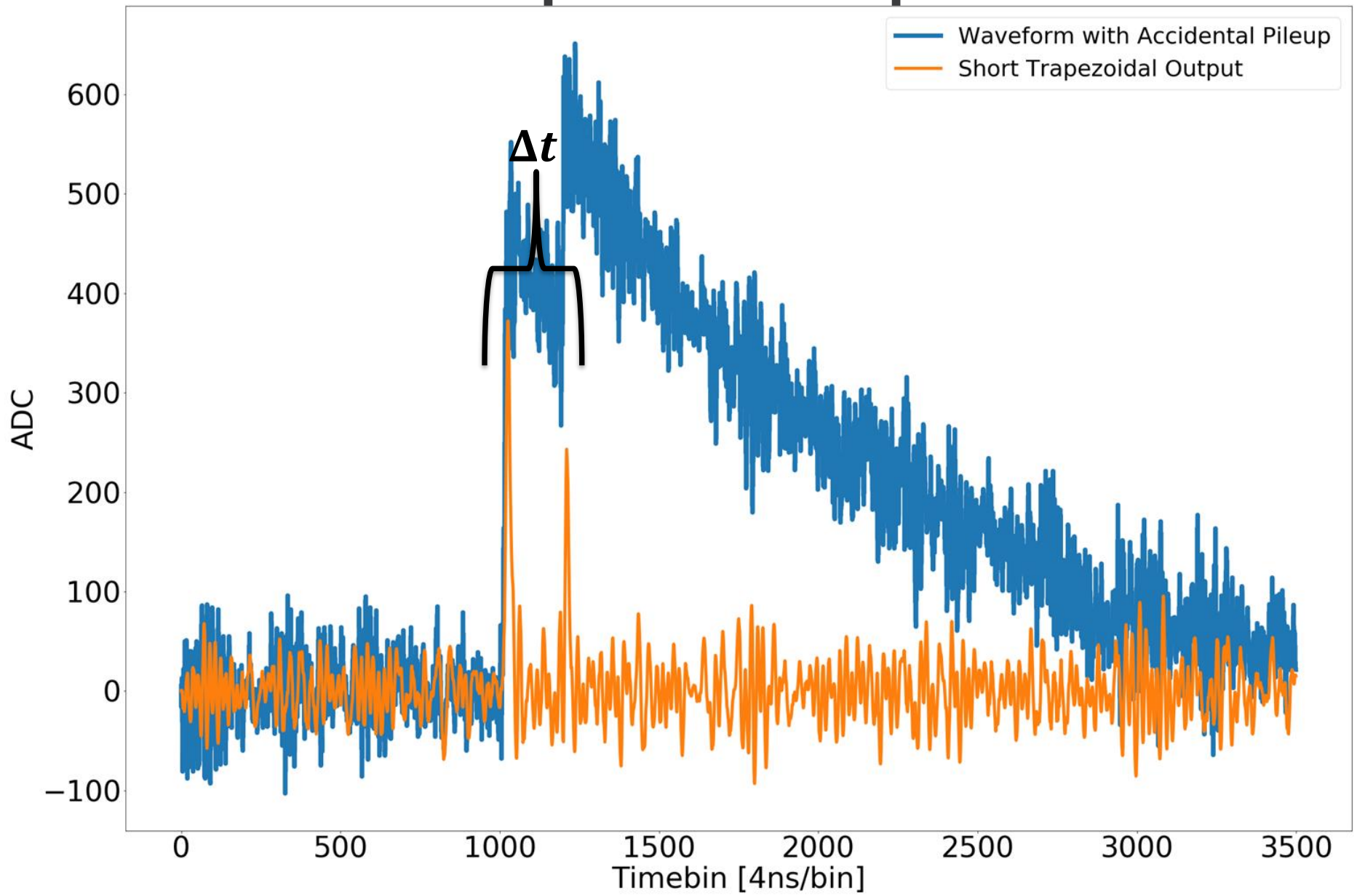


Resolution:
FWHM~4.7 keV

V. Jordanov, *et al.*, *Digital synthesis of pulse shapes in real time for high resolution radiation spectroscopy*, NIMA, Vol 345

Accidental Pileup: Short Trapezoidal Filter



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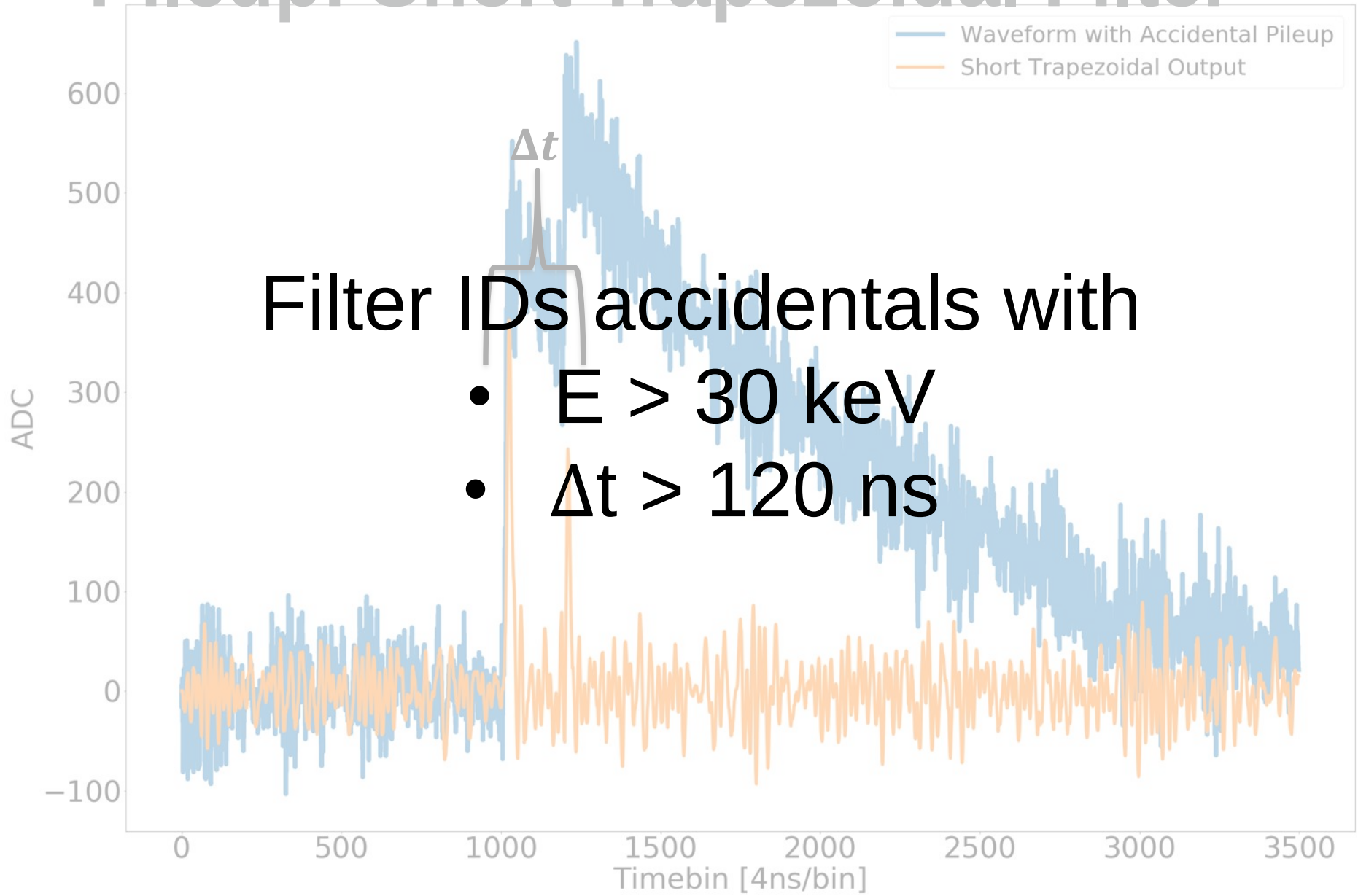
Pileup: Short Trapezoidal Filter



Filter IDs accidentals with

- E > 30 keV
- Δt > 120 ns

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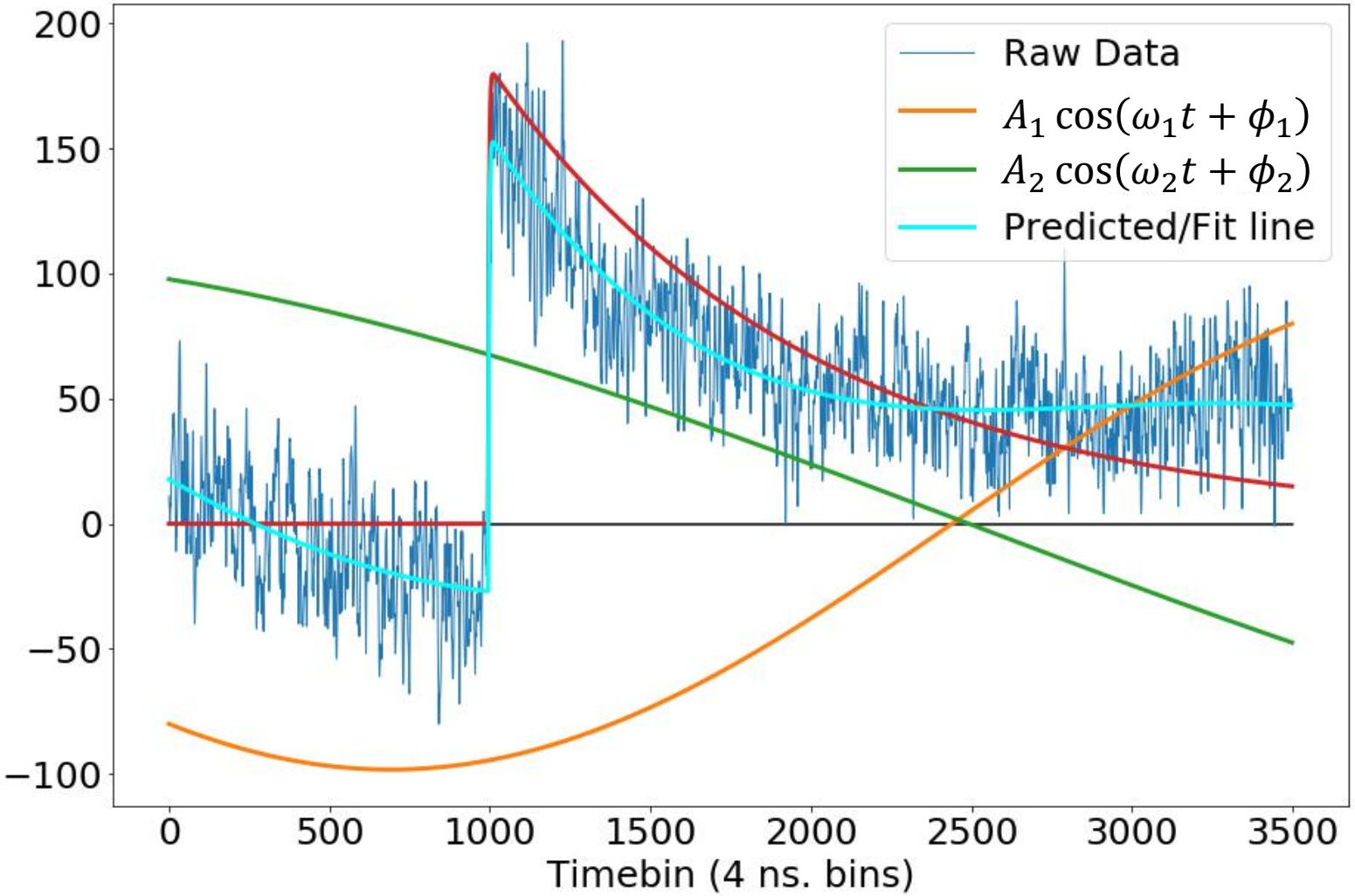
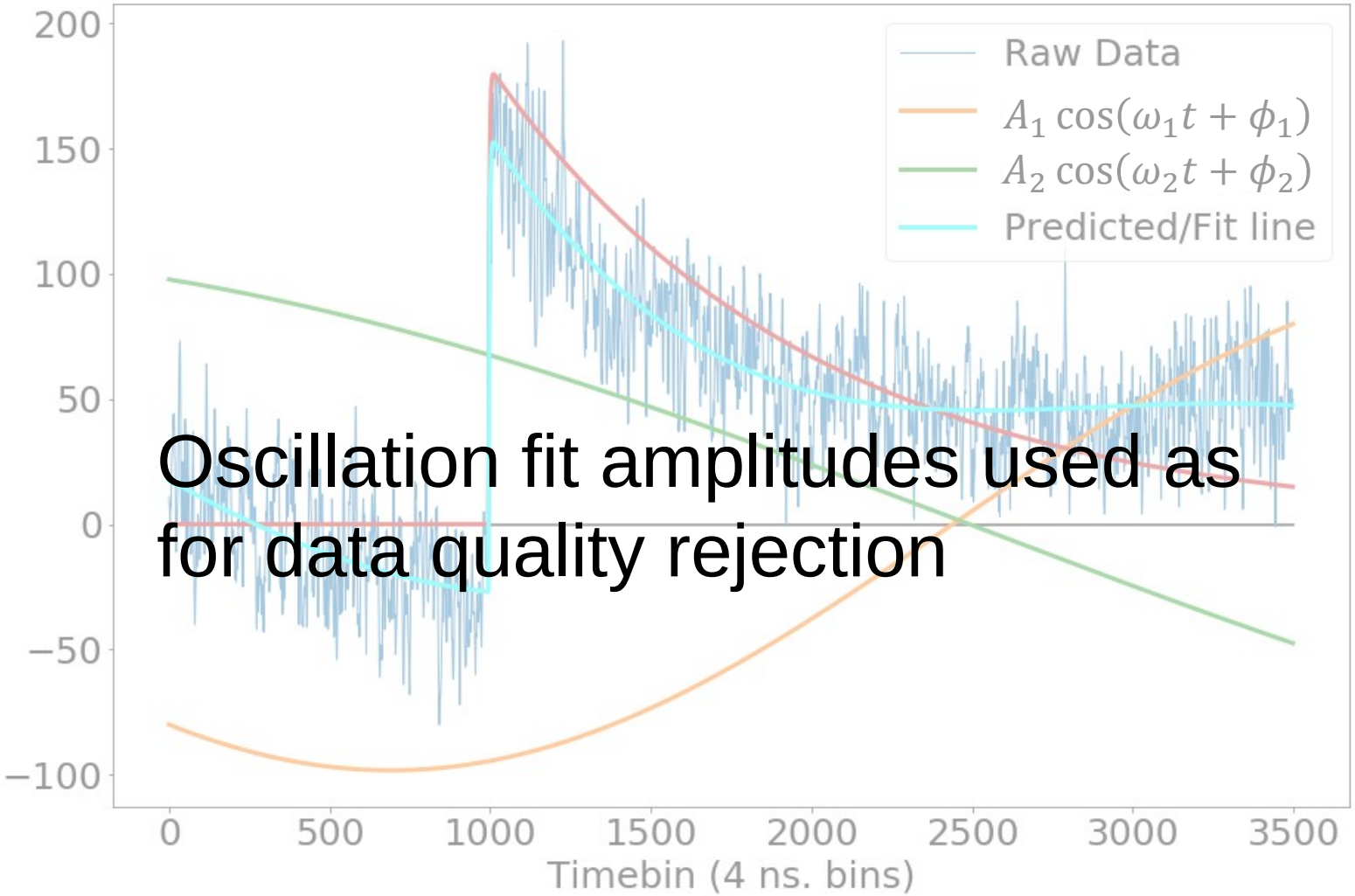
Baseline Oscillation: Linear Least Squares Fit



Baseline Oscillation: Linear Least Squares Fit



Oscillation fit amplitudes used as for data quality rejection

Towards a ‘b’ extraction

- Bin energies
- Build Spectra
  - Single Pixel Spectra
- Calibration Source Spectra+ MC Simulation
  - →Calibration & Linearity
  - →Electronic Response Function (ERF)
- Build Calibrated ^{45}Ca spectra
  - →Extract ‘b’
  - →Quantify dominant uncertainties

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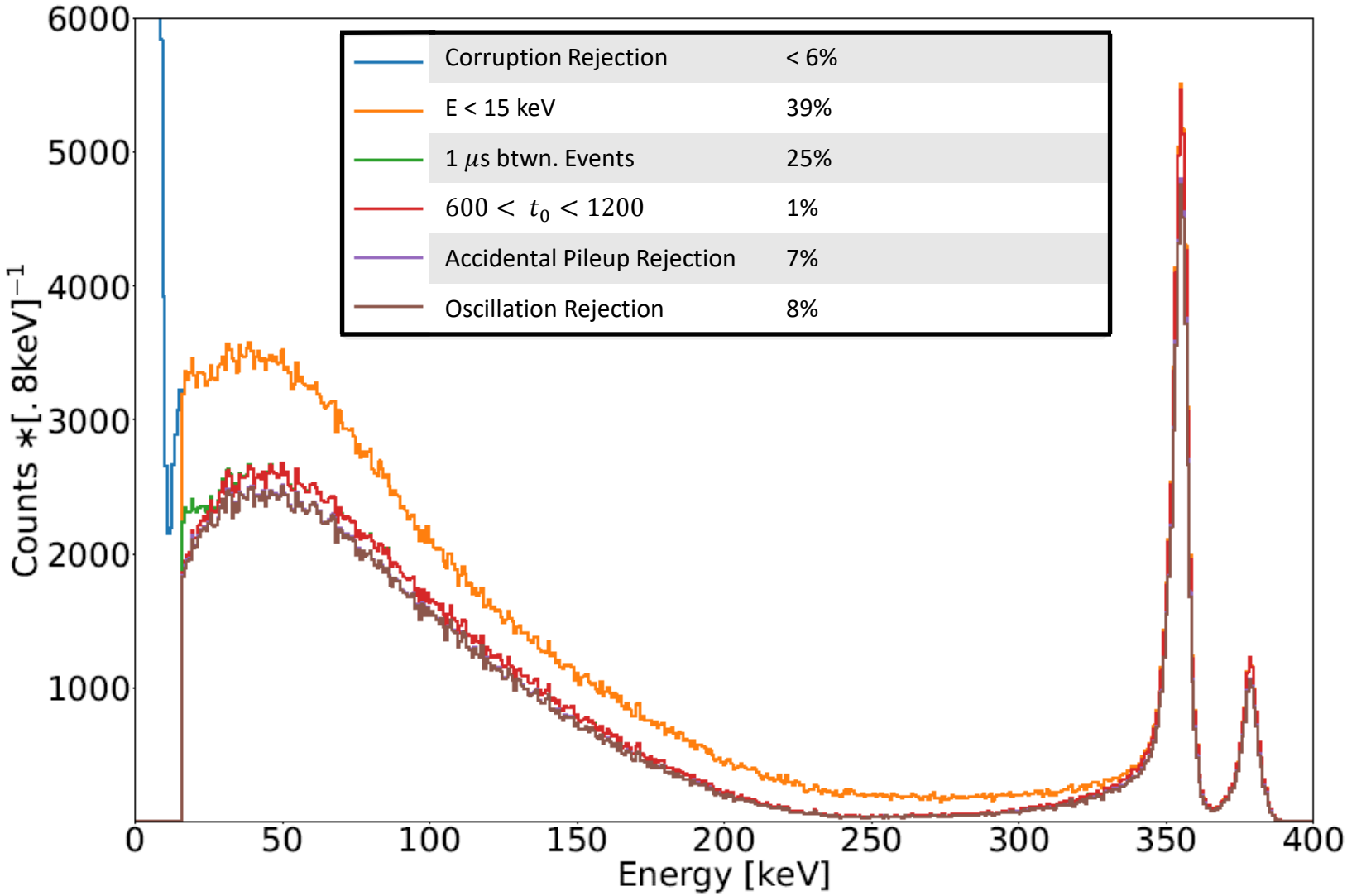
Single-Pixel Spectra

- Single pixel spectra
  - Events isolated to a single pixel and well separated in time (1 μs)



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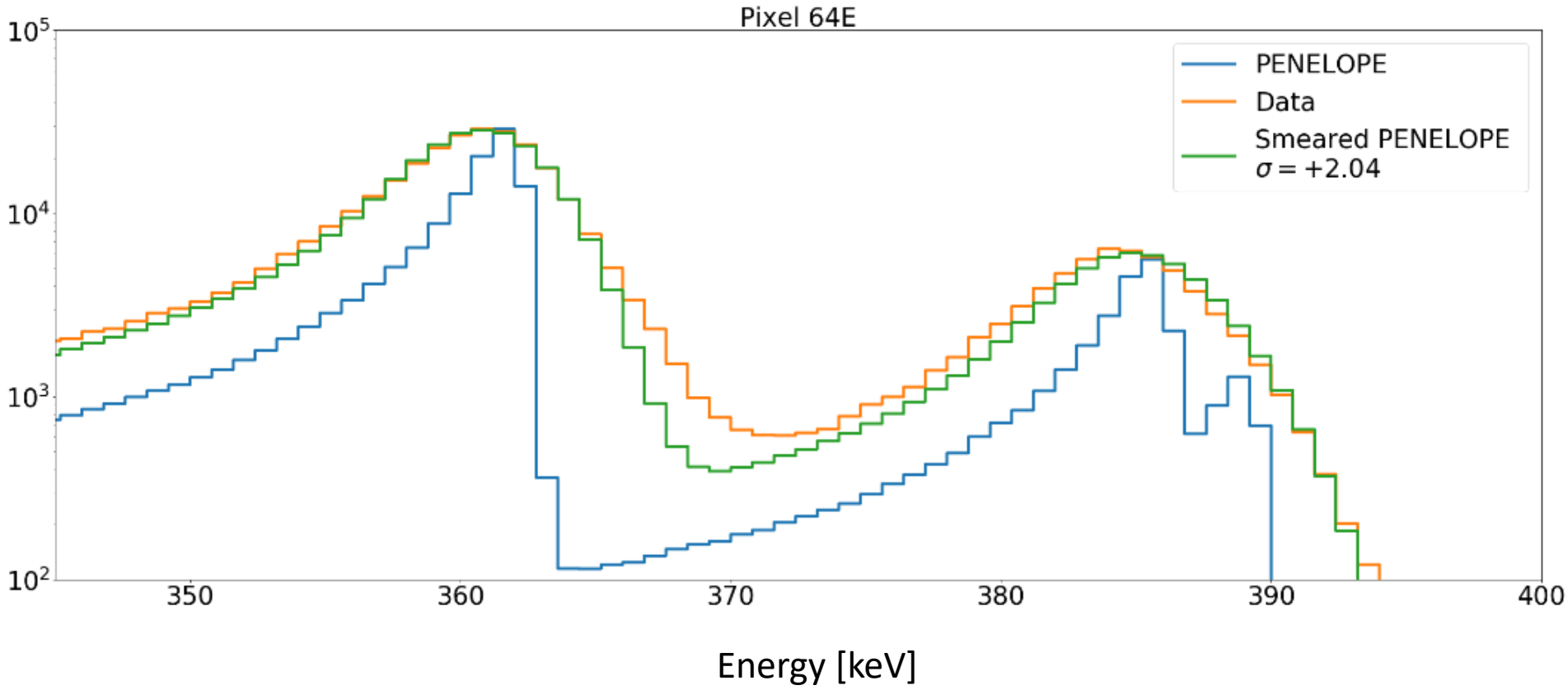
Monte Carlo Simulation

- Monte Carlo (MC) simulations (PENELOPE)
  - Developed by collaborator B. Zeck*
  - Includes foil losses, dead layer losses, bremsstrahlung losses & accounts for physical and field geometries.

➔ Charge collection and electronic response function (ERF) modeled as gaussian smearing of PENELOPE energies

*Angular Correlation and Spectroscopy Measurements of the β-Decay of Neutrons and 45Ca Nuclei, NCSU Thesis http://www.lib.ncsu.edu/resolver/1840.20/36693

Producing Realistic MC Spectra



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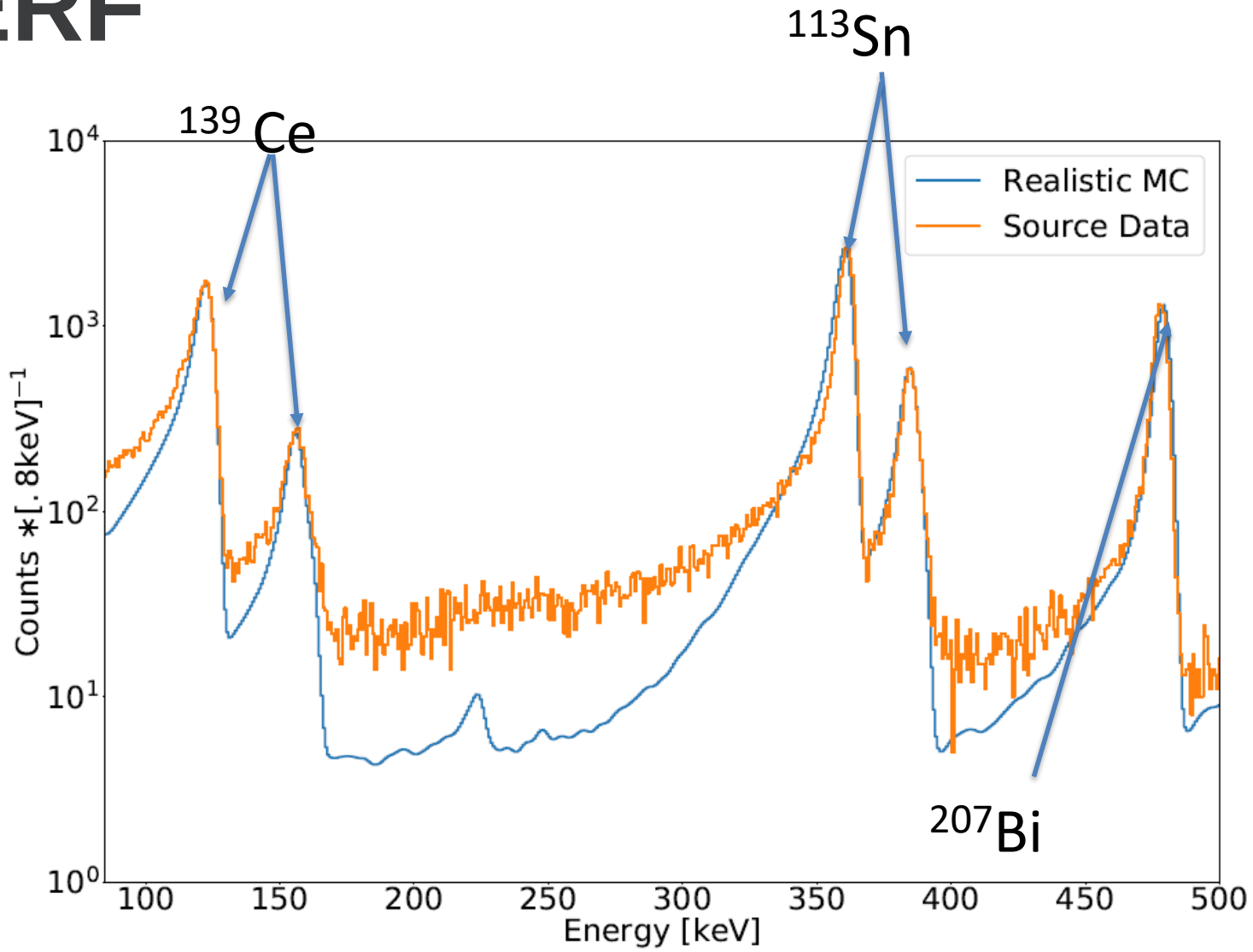
Calibration & ERF

- Calibration Source Data:
  - ^{113}Sn, ^{207}Bi, & ^{139}Ce



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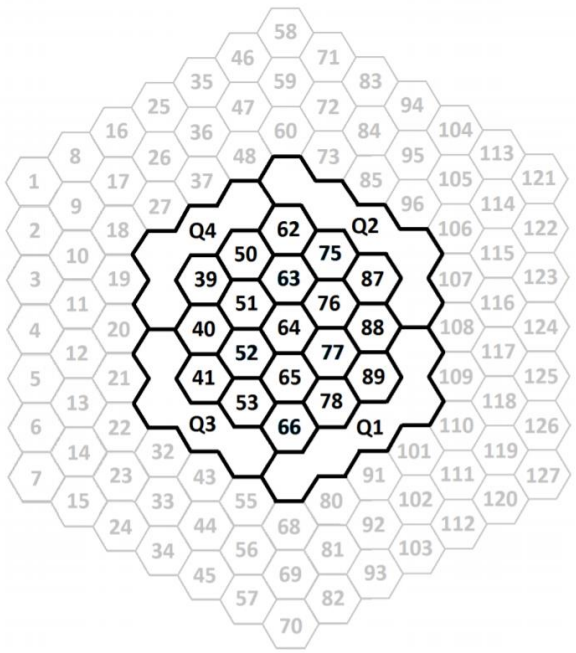
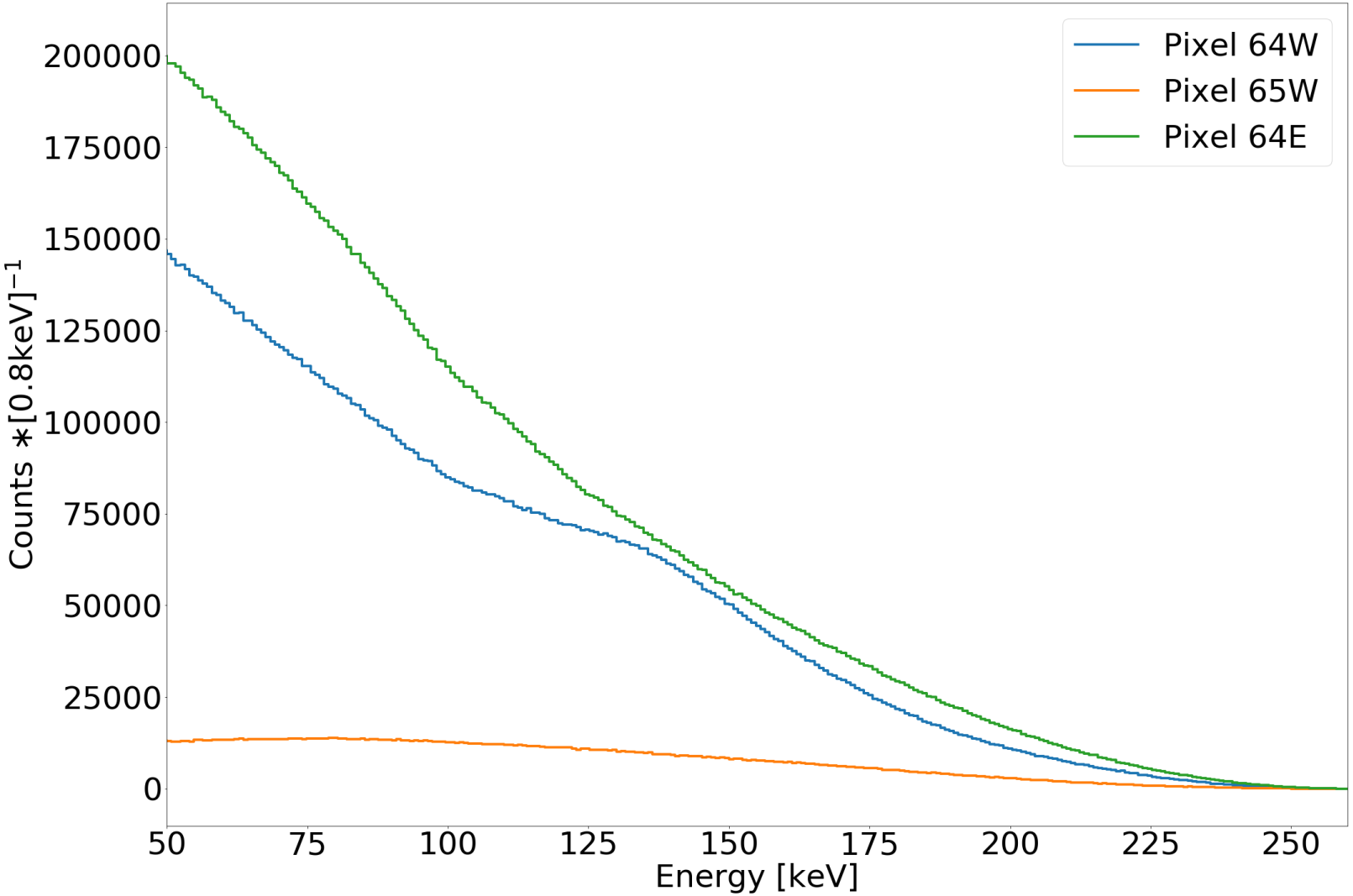
Single-pixel ^{45}Ca spectra





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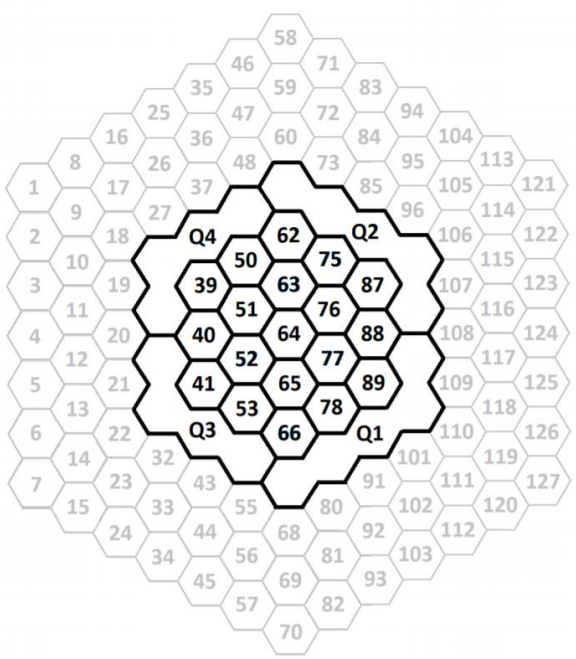

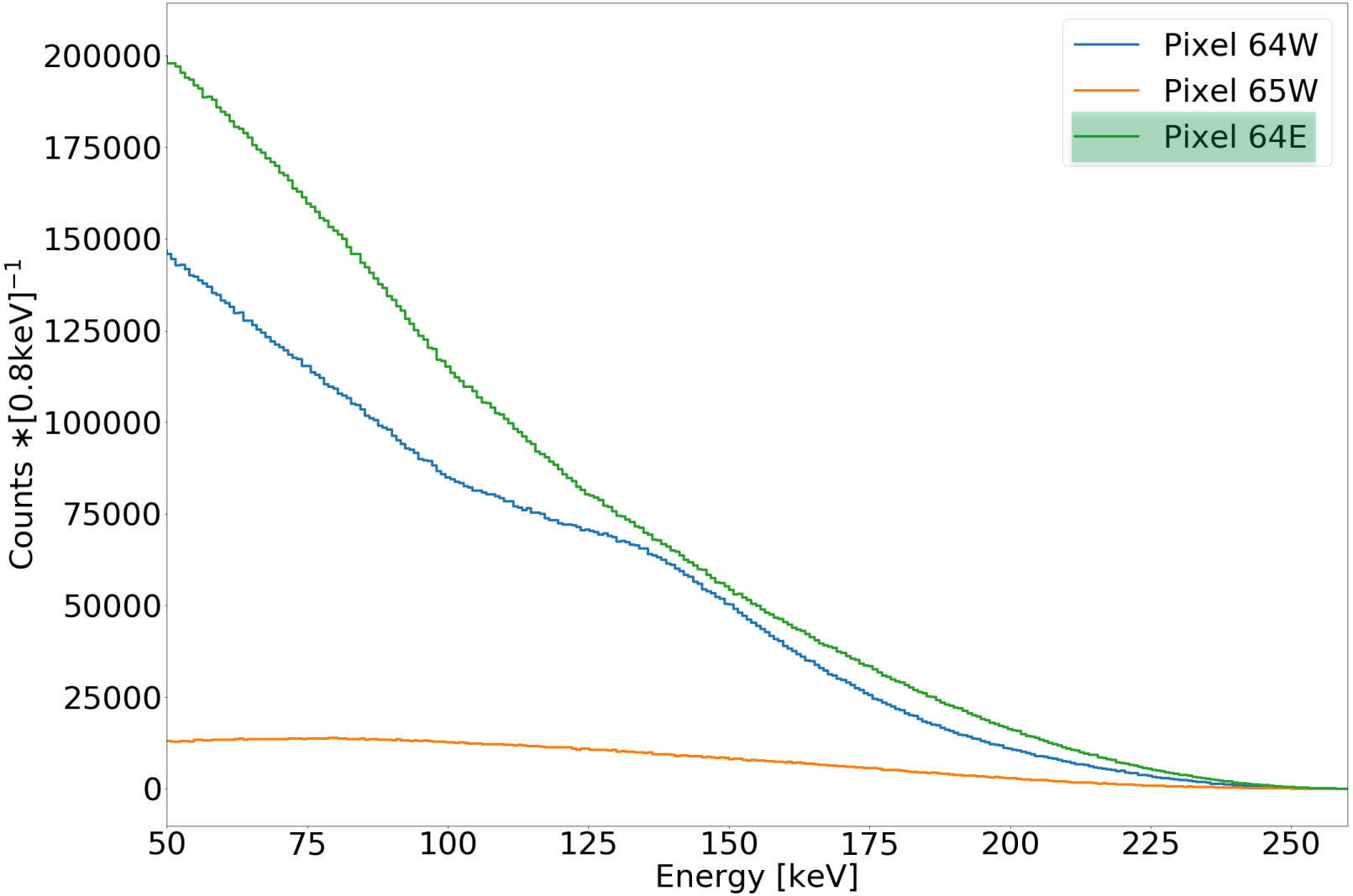

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Extracting the Fierz Term

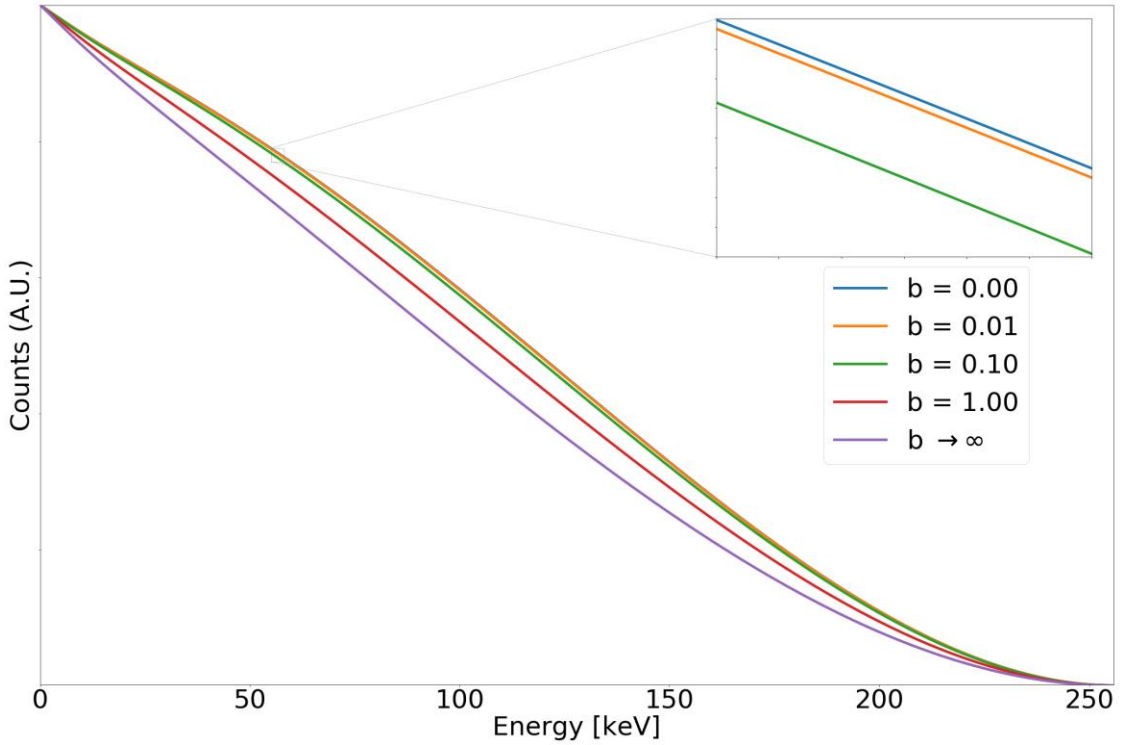
$$w(b) = PS\left\{1 + b\frac{m_e}{E_e}\right\}$$

$$w(0) = PS\ ;\ w(1) = PS\left\{1 + \frac{m_e}{E_e}\right\}$$

$$b[w(1) - w(0)] = PS \cdot b\frac{m_e}{E_e}$$

$$\rightarrow\ w(b) = w(0) + b[w(1) - w(0)]$$

$$PS \coloneqq p_e E_e (E_0 - E_e)^2$$



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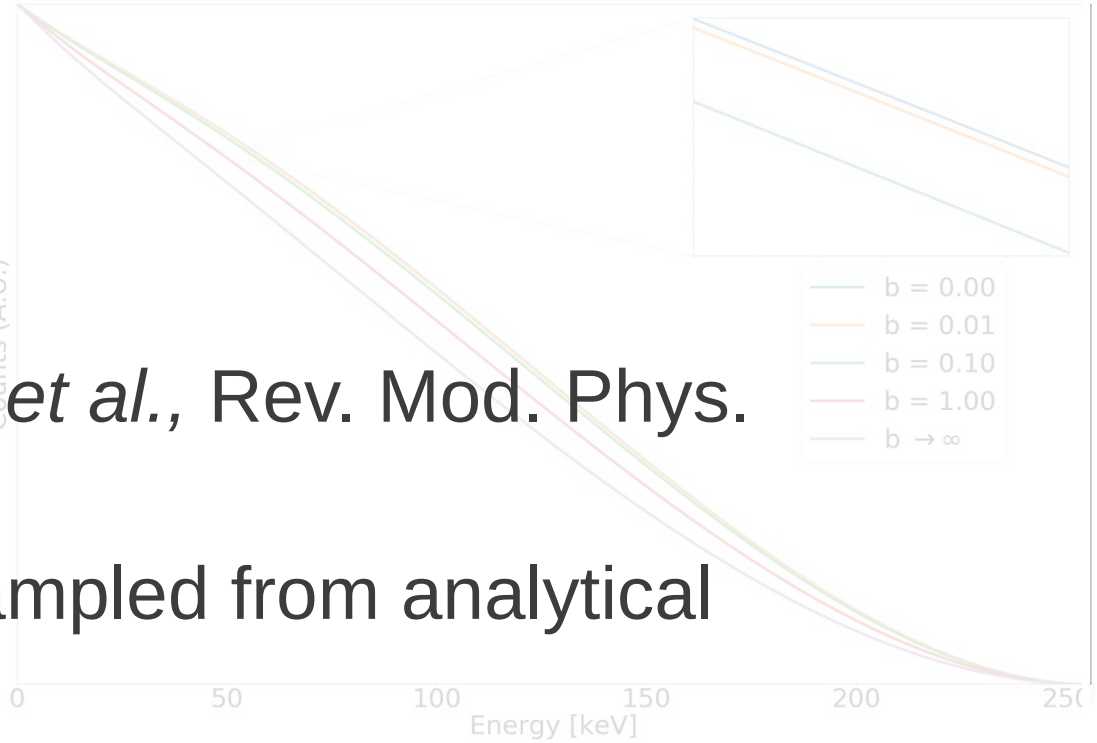
Extracting the Fierz Term

Producing w(0) & w(1) spectra

- Analytical ^{45}Ca spectrum: L.Hayen *et al.*, Rev. Mod. Phys. (2018)
- PENELOPE treatment of events sampled from analytical spectrum

➔

- ERF to model detector physics



$$\text{Data} = \eta(w(0) + b[w(1) - w(0)])$$

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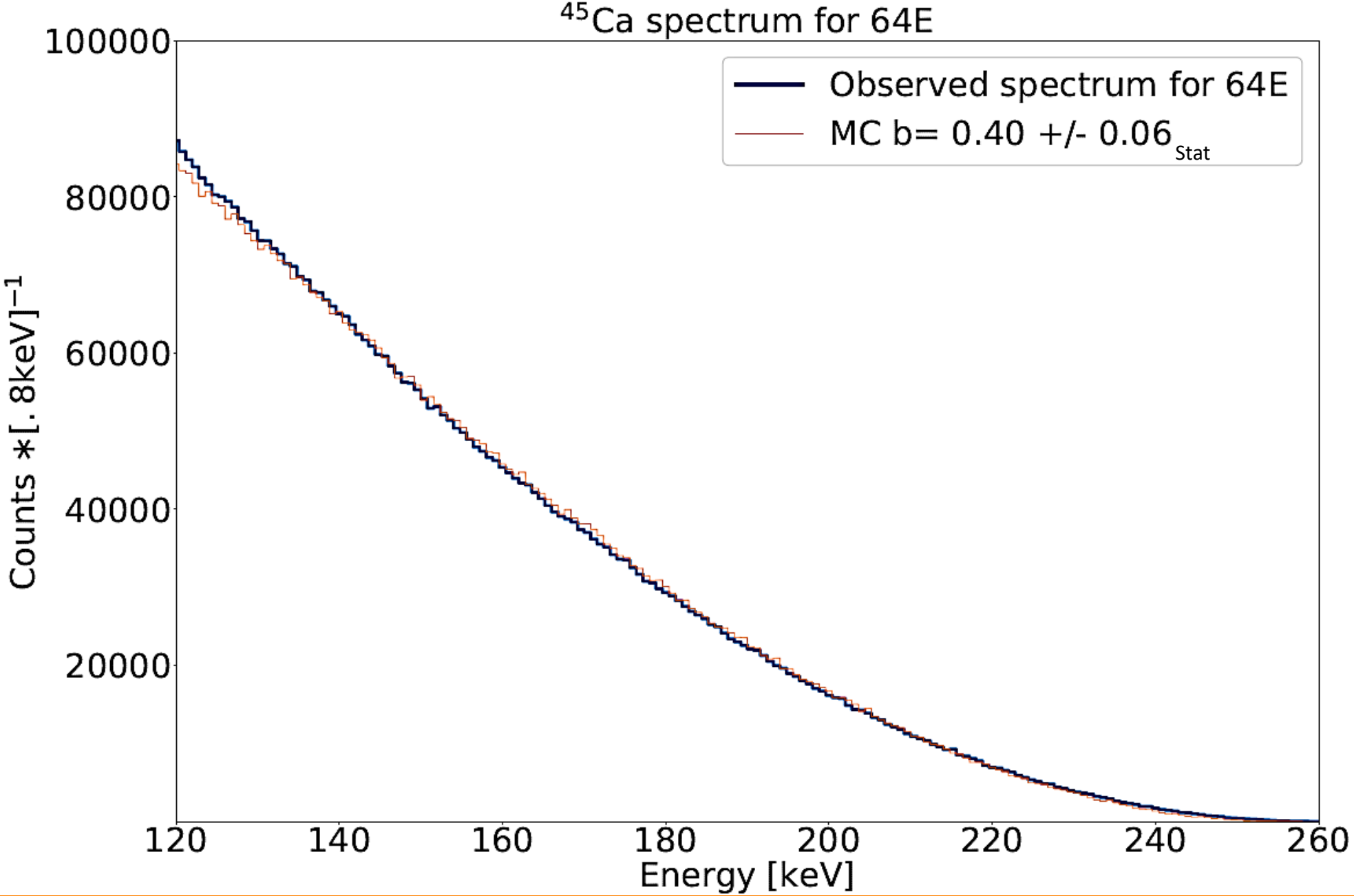

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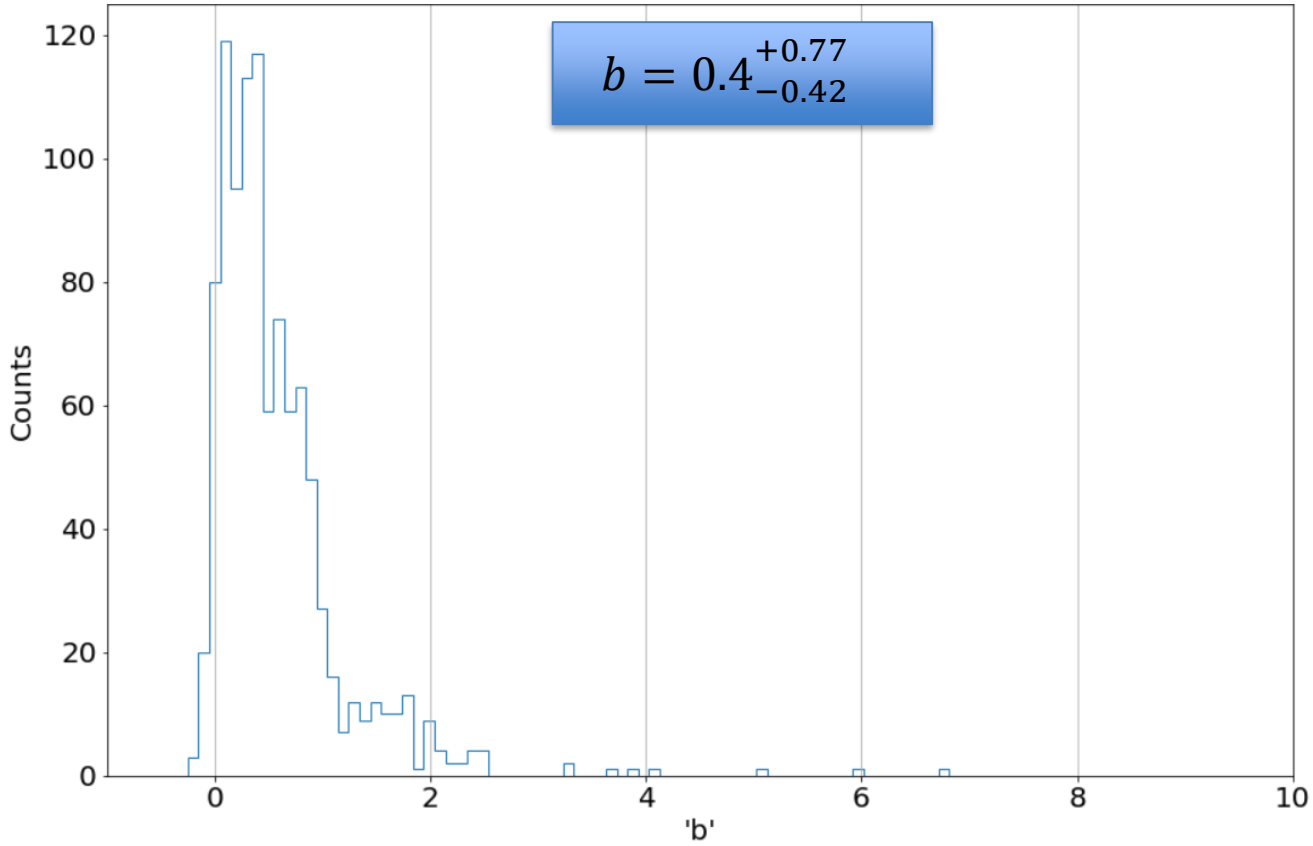
Calibration Systematic Uncertainty

- **Bootstrapping**
  - Resample mean of source peaks according to width of source peak
  - Recalibrate with resampled means
  - Repeat this process 1E3 times and extract ‘b’ for each calibration



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Systematics & Preliminary Value

Systematic	Uncertainty in 'b'
Calibration Uncertainty	$^{+0.77}_{-0.45}$
Trapezoidal Filter Energy Extraction	0.02
Electronic Response Modeling	0.05
Baseline Oscillation	0.06
MC Source Positioning	$^{+0.01}_{-0.07}$
Detector Efficiency	0.003
MC Statistics	0.04
Fit Range Variation	$^{+0.03}_{-0.04}$

$$b = 0.40 \pm 0.06_{stat.}\ ^{+0.78}_{-0.47}{}_{sys.}$$

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Past Fierz Searches

- $^{20}F \rightarrow b = 0.0021 \pm 0.0051_{stat} \pm 0.0084_{sys.}$
  - Preliminary Result
  - Calorimetric Technique

  Precision Measurements in ^{20}F Beta Decay, Hughes, M. 2019, Ph.D Thesis: University of Michigan State
- UCN $\rightarrow b = 0.067 \pm 0.005_{stat}\ ^{+0.090}_{-0.061}{}_{sys.}$
  - Measurement using UCNA spectrometer & UCN source

  First direct constraints on Fierz interference in free-neutron β decay K. P. Hickerson *et al.* (UCNA Collaboration) Phys. Rev. C **96**, 042501(R)
- ft values $\rightarrow |b| < 0.0045$
  - Super allowed transitions

  J. C. Hardy and I. S. Towner, Phys. Rev. C 91, 025501 (2015)

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Ongoing Searches

Slide courtesy of O. Naviliat-Cuncic

Isotope	Method	Lab/Institution
^{6}He	thin foil; 4π detector	GANIL/LPC-Caen
^{114}In	MWDC+scintillators	Krakow, Leuven
^{45}Ca	source in UCNA spectr.	UT, ORNL, NCSU, KUL++
^{6}He	CRES	UW, ANL++
^{6}He, ^{20}F	Calorimetry	NSCL/MSU, Wittenberg

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Next Steps

Improvement	Effect
Extraction of ‘b’ via coincident spectra	Background reduction
Simultaneous fit of η, b, calibration & ERF parameters	Allows for bias study
Utilize additional γ source peaks in calibration	More calibration points below ^{45}Ca endpoint energy
Realistic detector & electronic simulation	Analysis of MC at waveform level

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Thank you for your time

Backup slides

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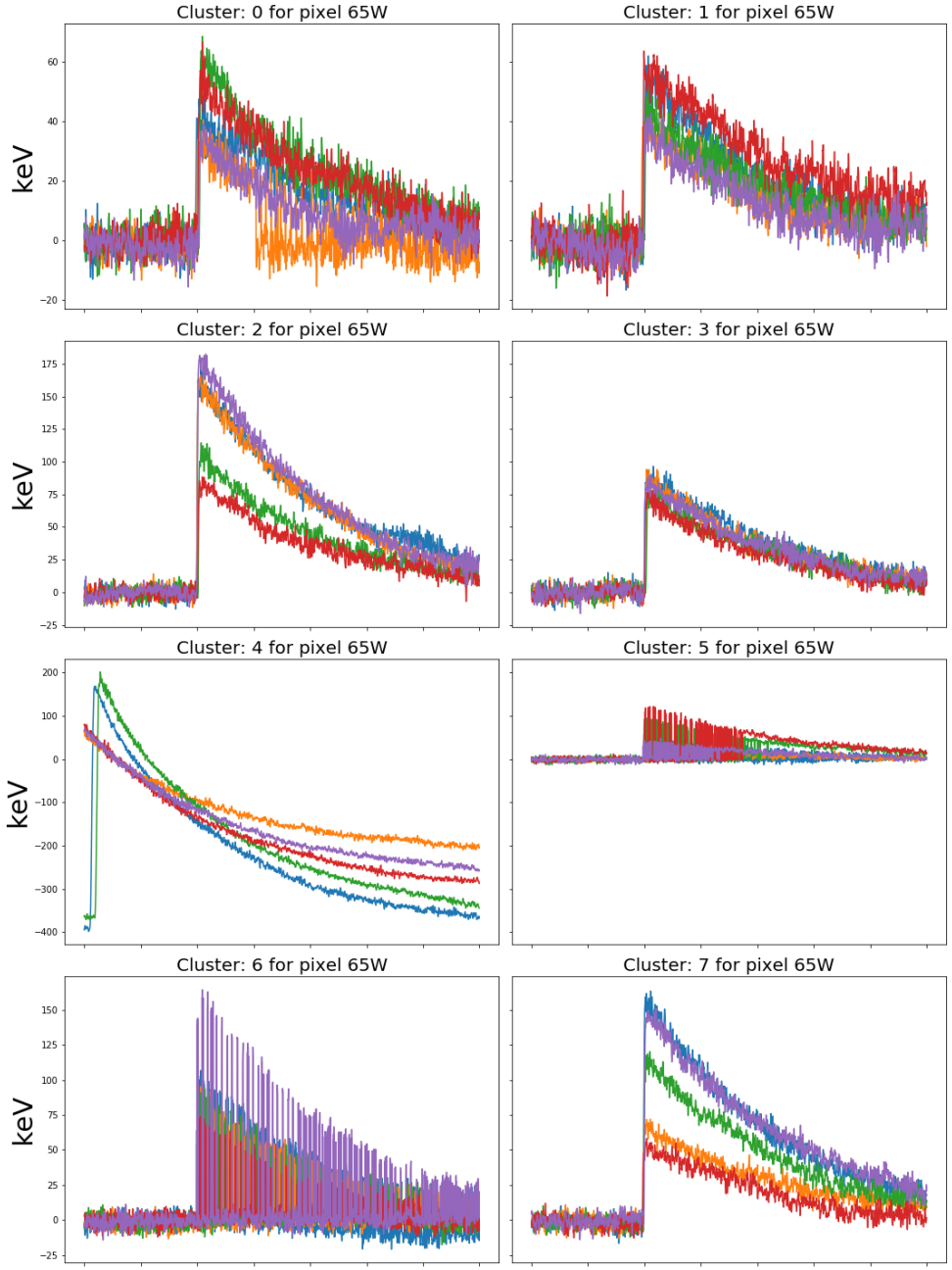
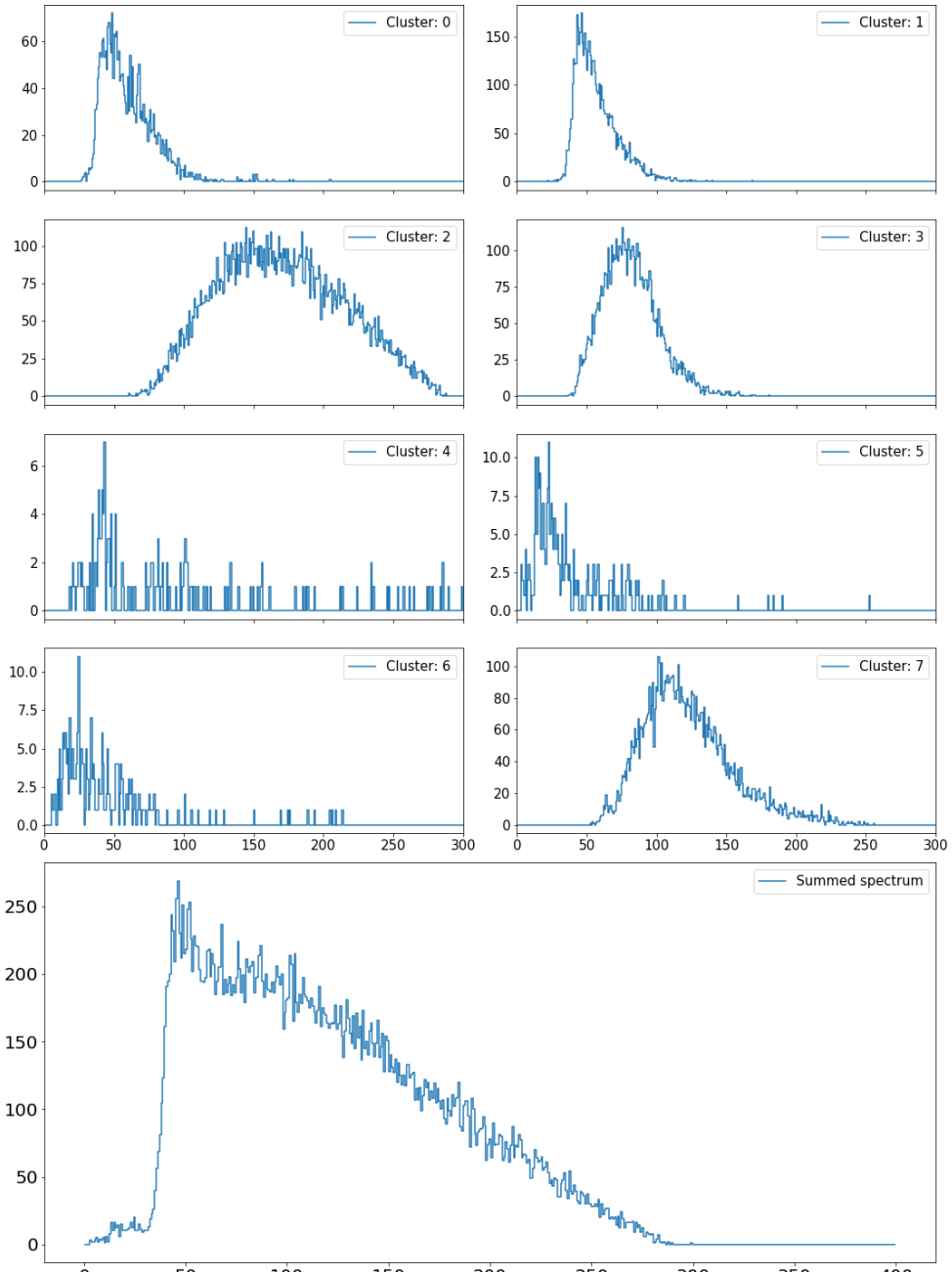
Kmeans Clustering Technique

- Unsupervised learning (scikit-learn)
  - Data assumed to fall into one of X categories that are represented by some ‘bin center’
  - ML algorithm determines bin centers by minimizing Euclidian distance of bin centers to data considered to be included in cluster
- Applied this technique to waveform data





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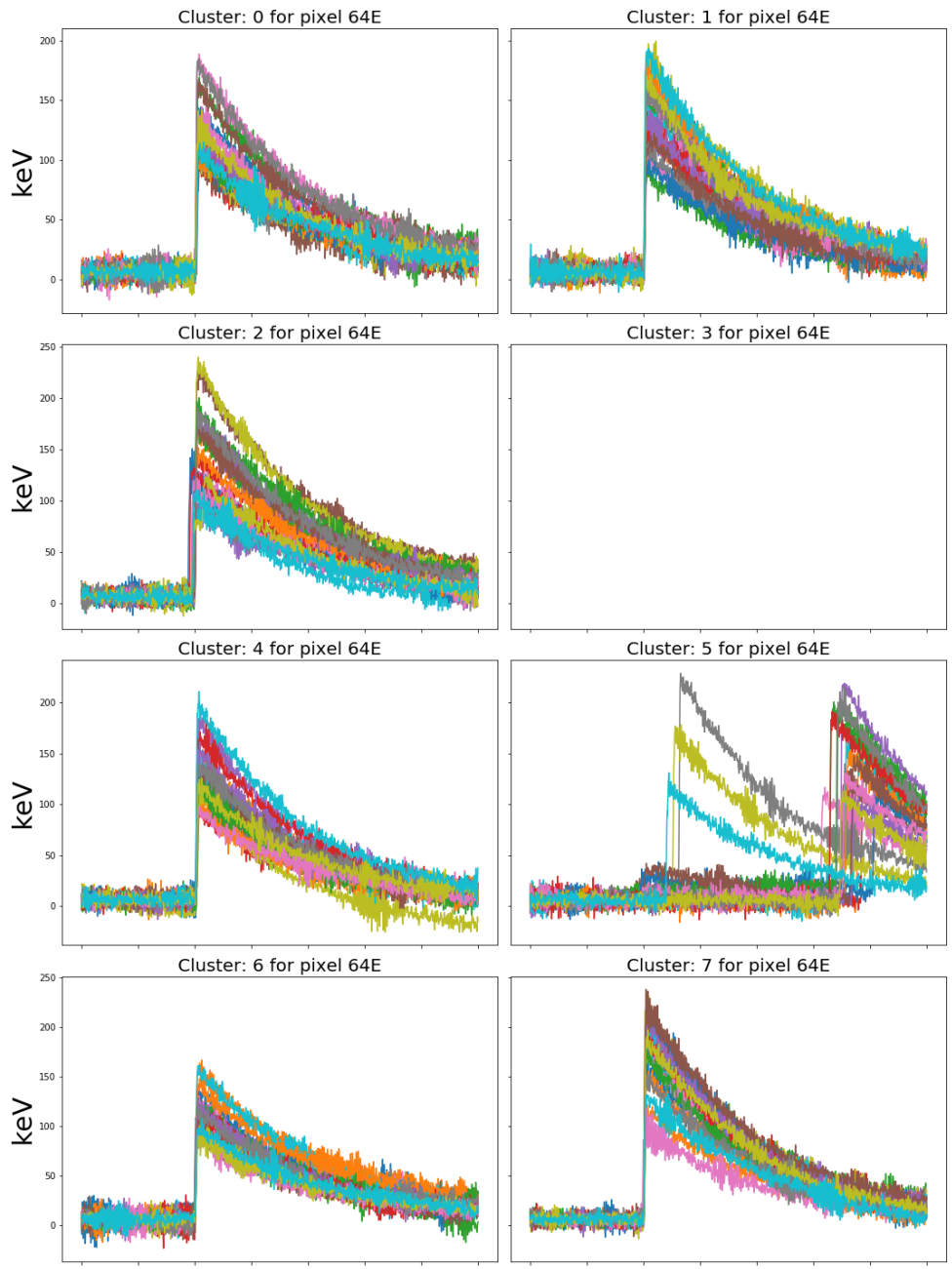
Cluster: 0 for pixel 64E
Cluster: 1 for pixel 64E
Cluster: 2 for pixel 64E
Cluster: 3 for pixel 64E
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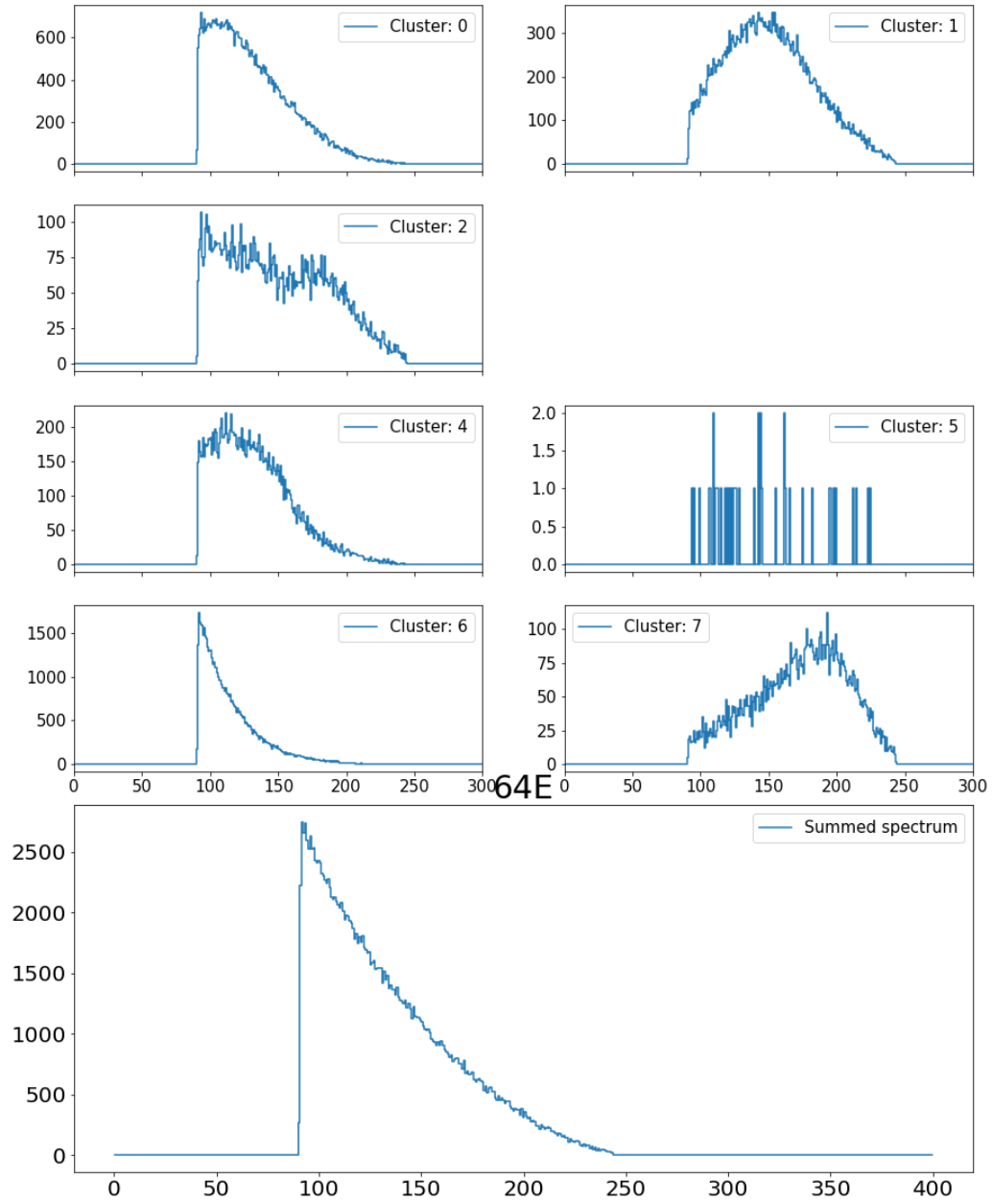
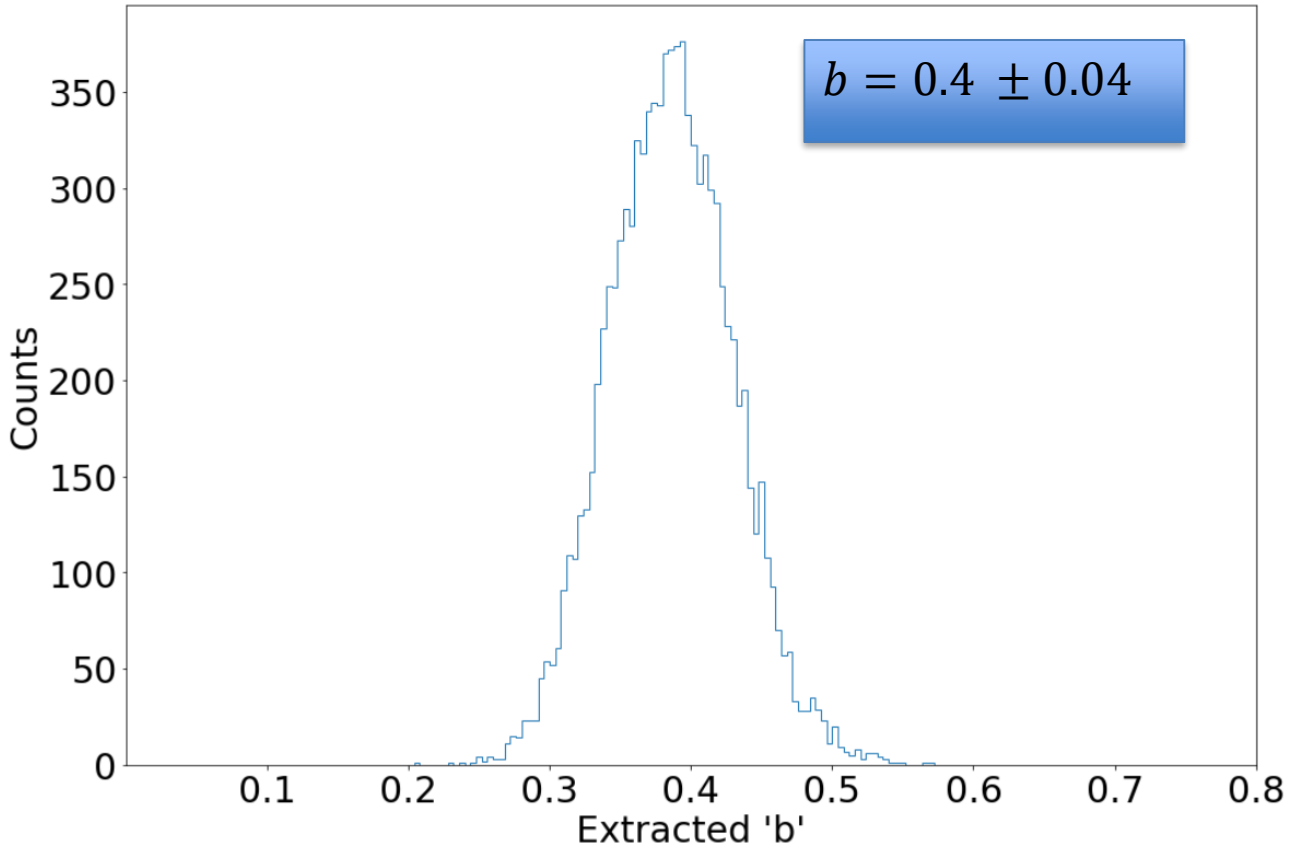
Cluster: 5 for pixel 64E
Cluster: 6 for pixel 64E
Cluster: 7 for pixel 64E
keV


Cluster: 0
Cluster: 1
Cluster: 2
Cluster: 4
Cluster: 5
Cluster: 6
Cluster: 7
64E
Summed spectrum

MC Statistical Variation

- Bootstrapping technique
  - Number of counts in MC bins were resampled according to a poisson distribution centered at N counts.
  - Using resampled MC, a value of ‘b’ was extracted from observed data
  - Process repeated 10k times



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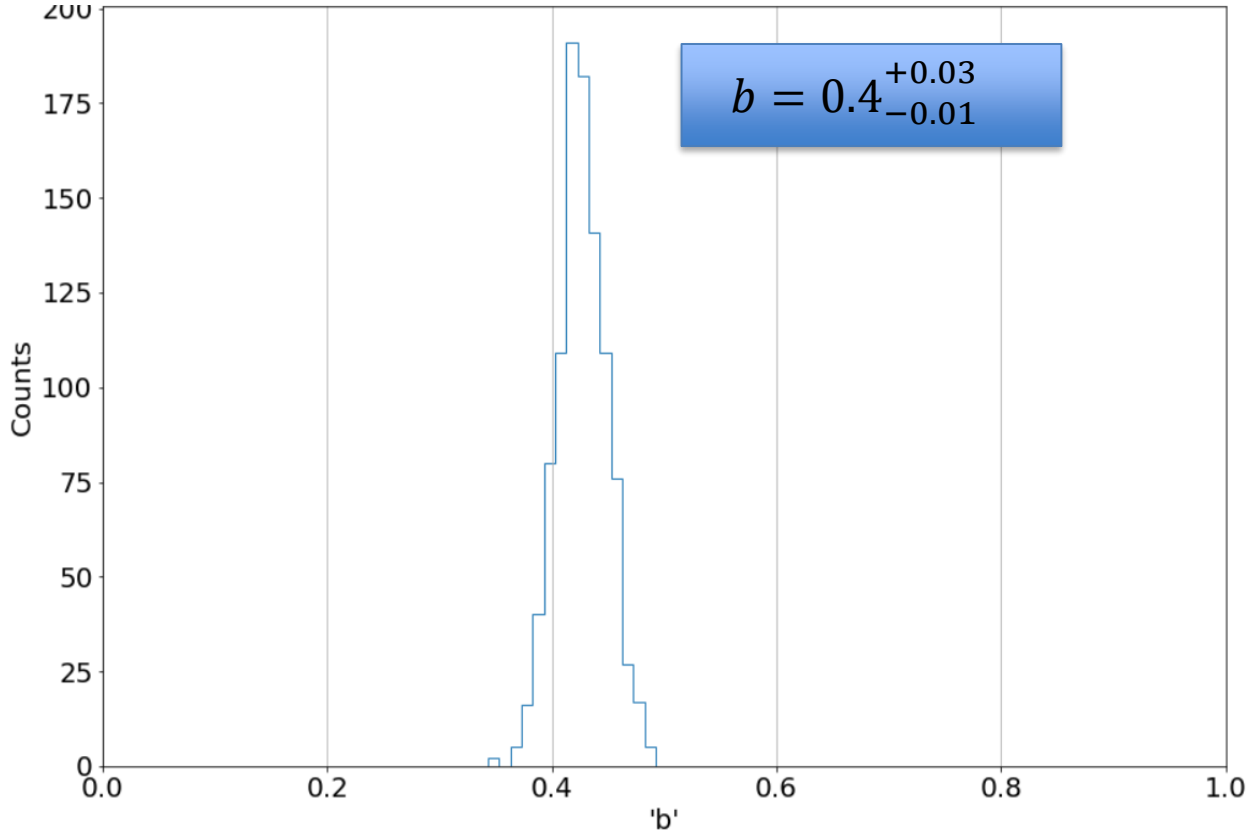
Trapezoidal Energy Uncertainty

- Synthetic waveforms were generated
  - Noise was sampled from data power spectrum
  - Pulse shape: step function processed by (CR)-$(RC)^2$ shaper
    - Approximately equivalent to true electronics
  - 10K samples generated per amplitude.
  - Variance found to scale as 0.025*E
  - (Study courtesy of David Perryman)
- Bootstrapping to estimate uncertainty
  - Observed energies were resampled according to a Gaussian distribution with $\mu = E$ and $\sigma = 0.025 \cdot E$
  - For each resampling, ‘b’ was extracted
  - Repeated 1E3 times



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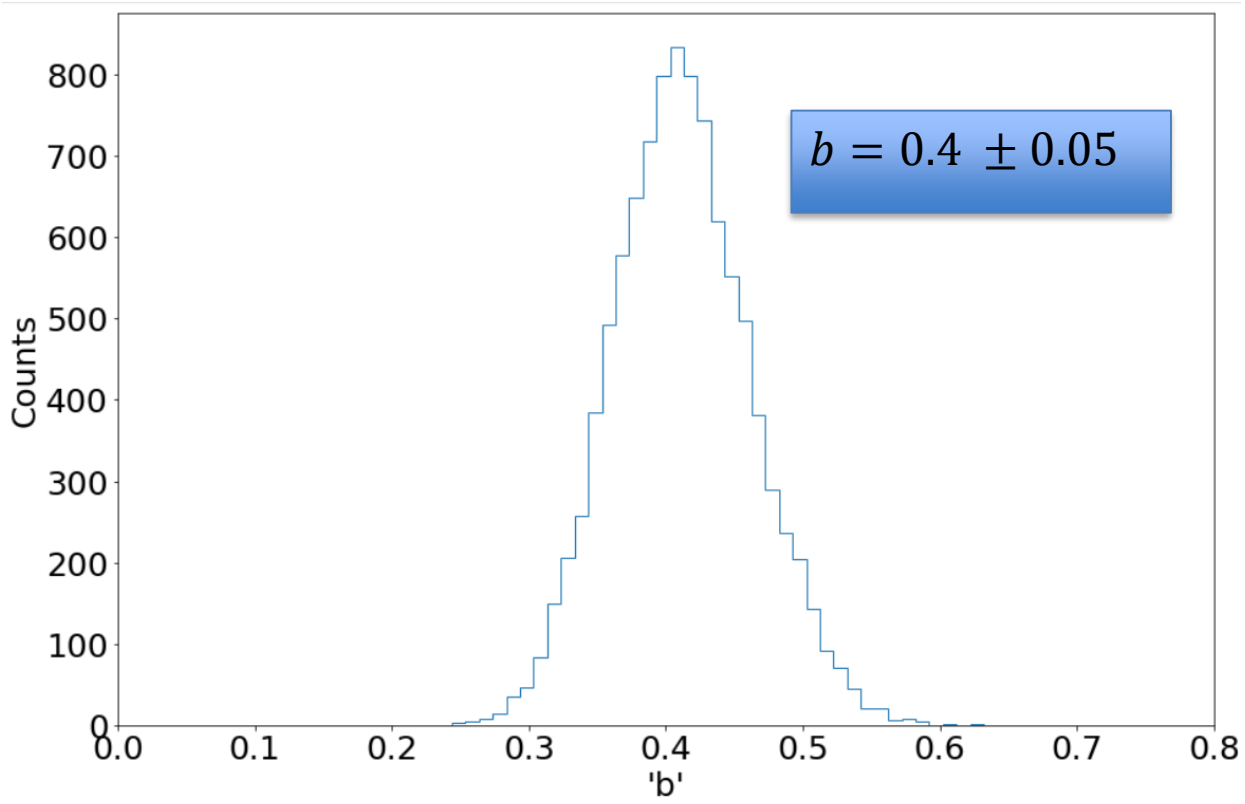
ERF Systematic Uncertainty

- Bootstrapping technique
  - ERF is applied by randomly resampling the MC energies according to a gaussian distribution with $\mu = E$ and $\sigma = \sigma_{src.line}$ (width of source line)
  - $\therefore$ by simply repeating the procedures with different random seeds → spread in ‘b’ due to ERF modelling
  - ERF generated with 1k different seeds for MC resampling
  - ‘b’ extracted for each set



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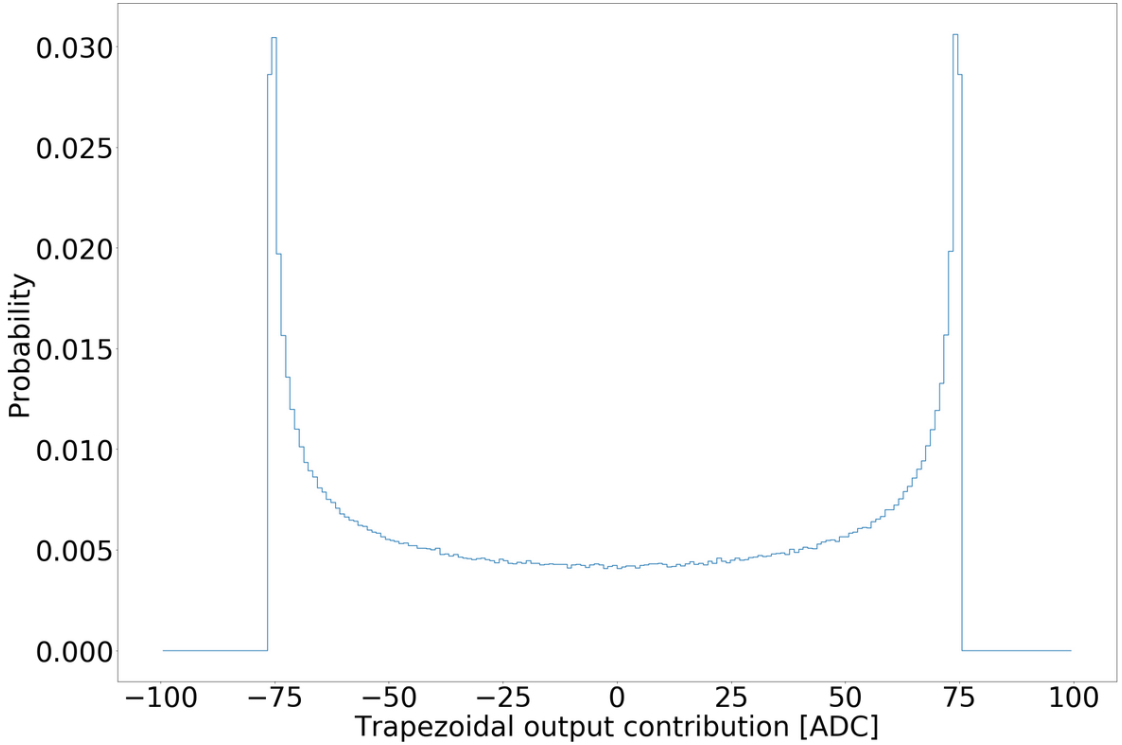
Baseline Oscillation Systematic Uncertainty

- Contribution of oscillating baseline to trapezoidal amplitude was calculated as a function of phase, frequency and amplitude.
- The baseline frequency was observed ~ 60 kHz
- For 10E6 randomly sampled phases, and a fixed amplitude of 50 ADC (maximum allowed by cuts) recorded baseline contribution
- Used this distribution as a PDF
- MC b=0 spectrum was used in place of data
- MC energies included randomly sampled energy contribution from above PDF
- A value of ‘b’ was fit for each random sampling
- Spread in ‘b’ was found to be comparable for both b=0 and b=1 spectra
- ∴ Spread in observed data was taken as the maximum spread of the two spectra



$b = 0.4 \pm 0.06$

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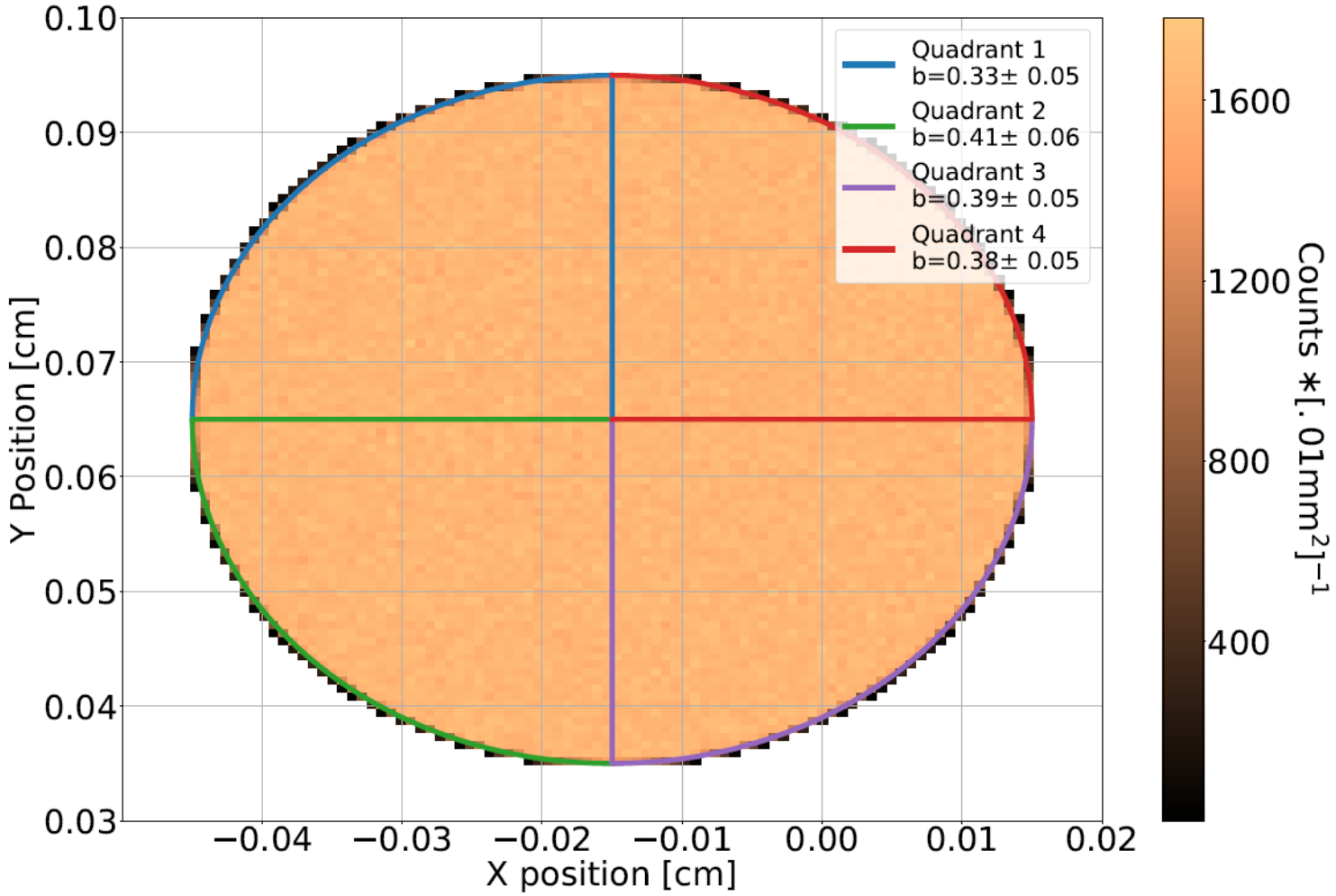
MC Source Position Uncertainty

- The events used in MC were separated into quarters
- The set of events for the relevant quarter was then used to extract ‘b’
- The spread in ‘b’ was estimated as the spread in the values of ‘b’ extracted for each quarter

$$b = 0.4^{+0.01}_{-0.07}$$



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Fit Range Variation

- The range was varied $\pm$ 5 bins at each end
- A value of ‘b’ was extracted for each range.
- The spread in the central values of ‘b’ was taken as the systematic uncertainty due to fit region.

$$b = 0.4^{+0.03}_{-0.04}$$

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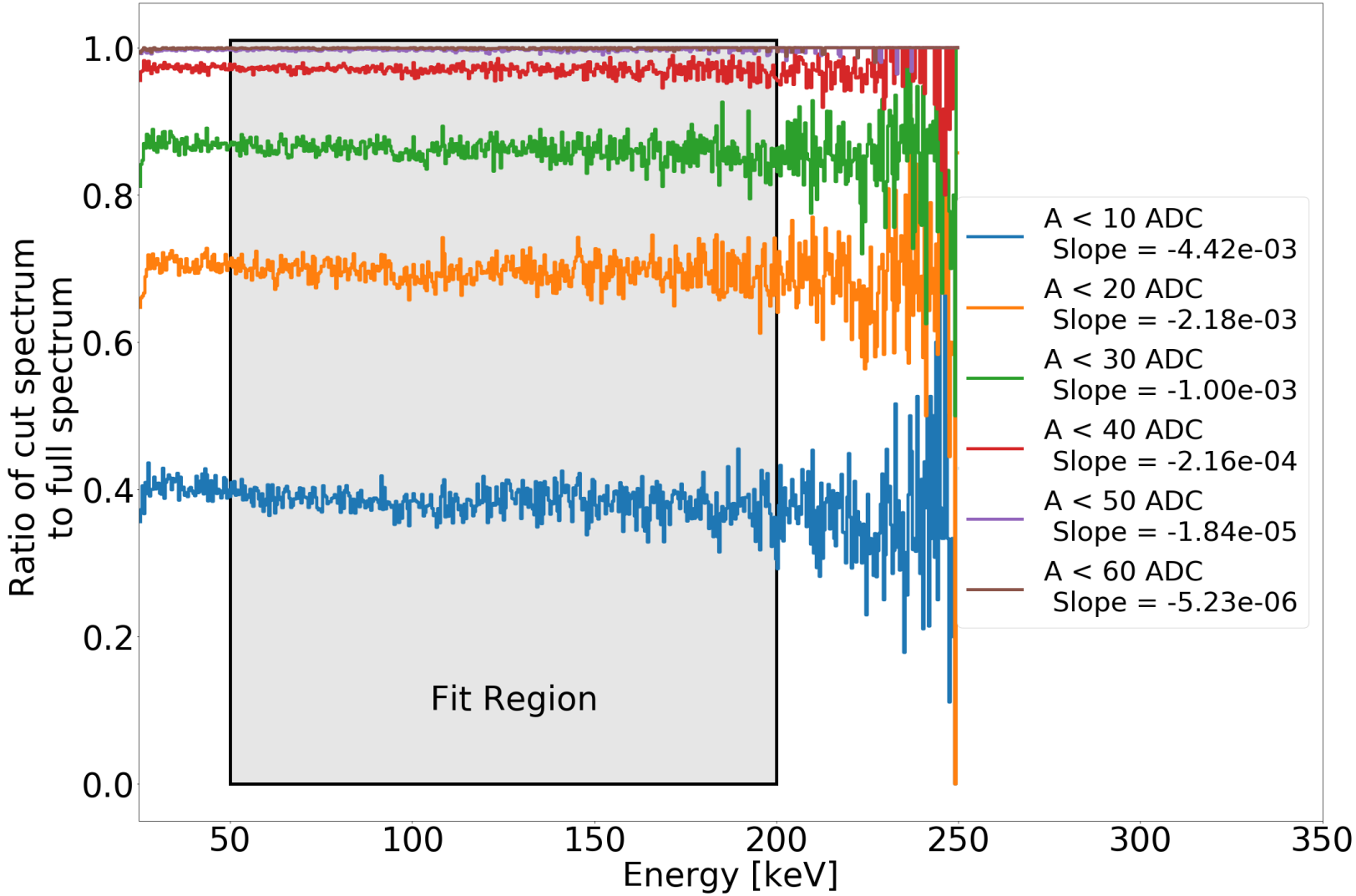
Baseline Oscillation Cut Uniformity



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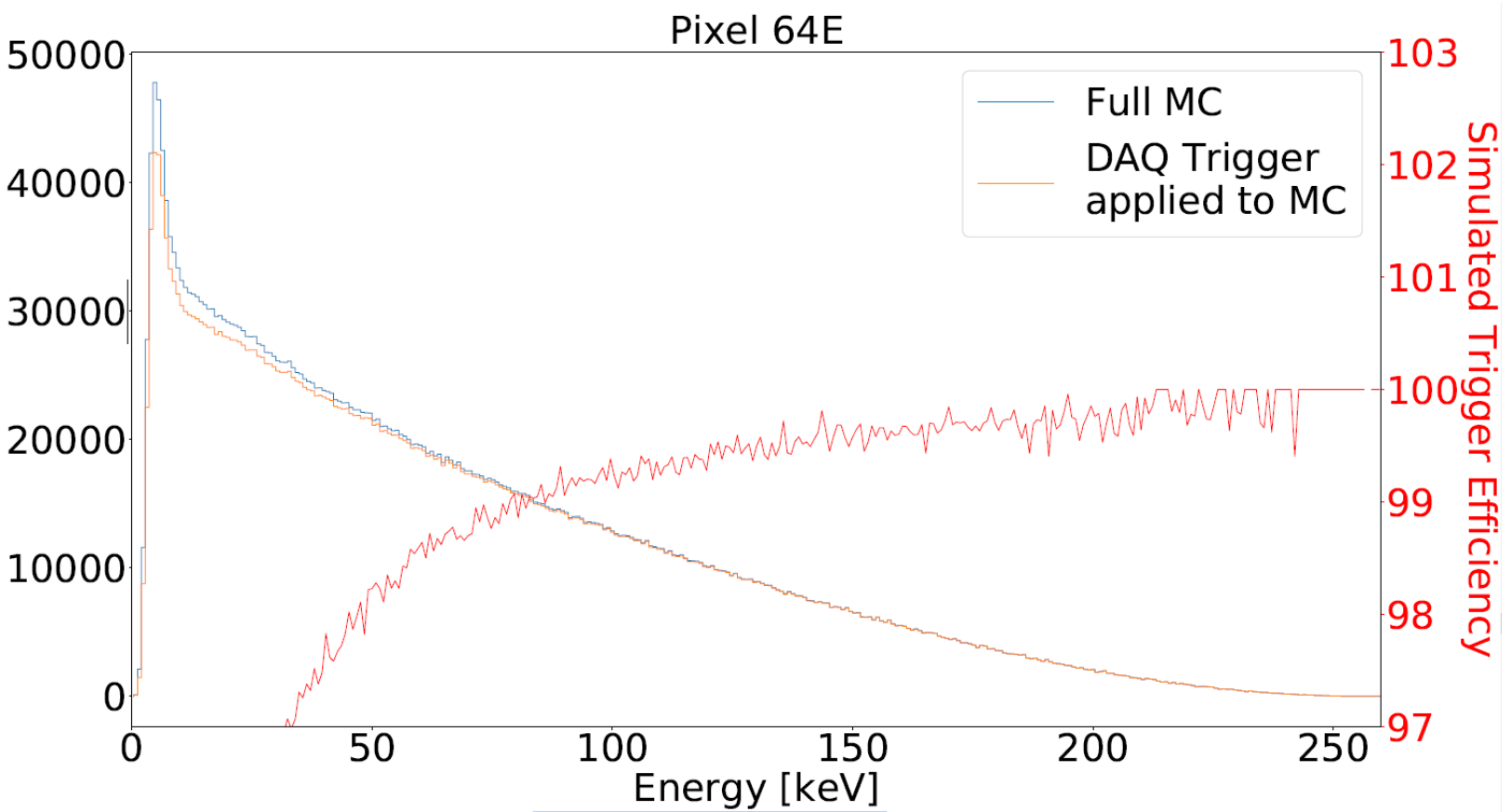
Detector Efficiency

- The detector efficiency was estimated via simulation
  - DAQ trigger filter was applied to a set of MC b=0 events.
  - The efficiency was estimated as 1 – the ratio of the number of of events which were missed by the simulated DAQ
- A value of ‘b’ was extracted data with the efficiency correction and data without the efficiency correction.
- The uncertainty in ‘b’ was taken to be the spread in the two extractions



$b = 0.4 \pm 0.003$

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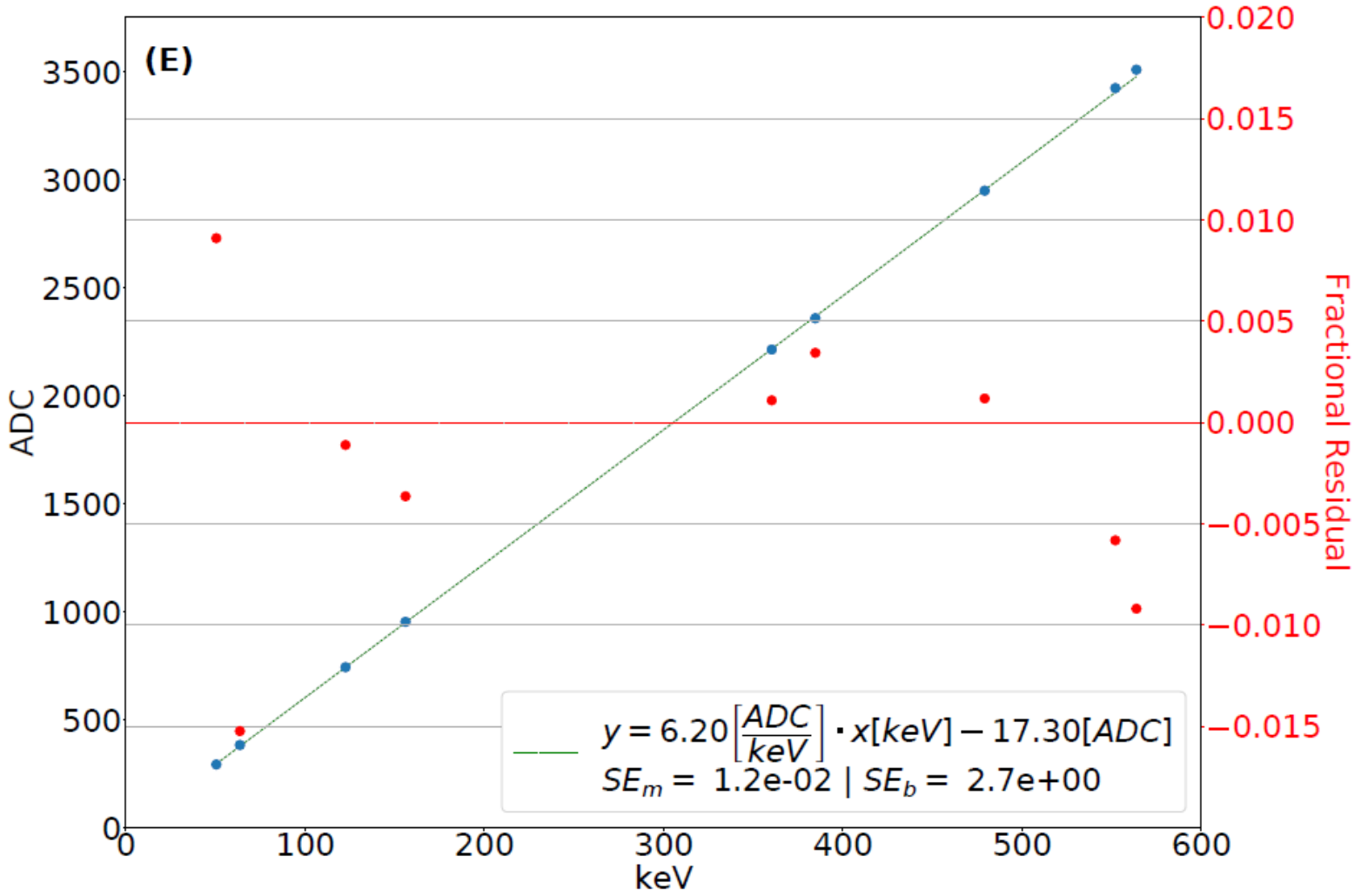
Calibration & Linearity



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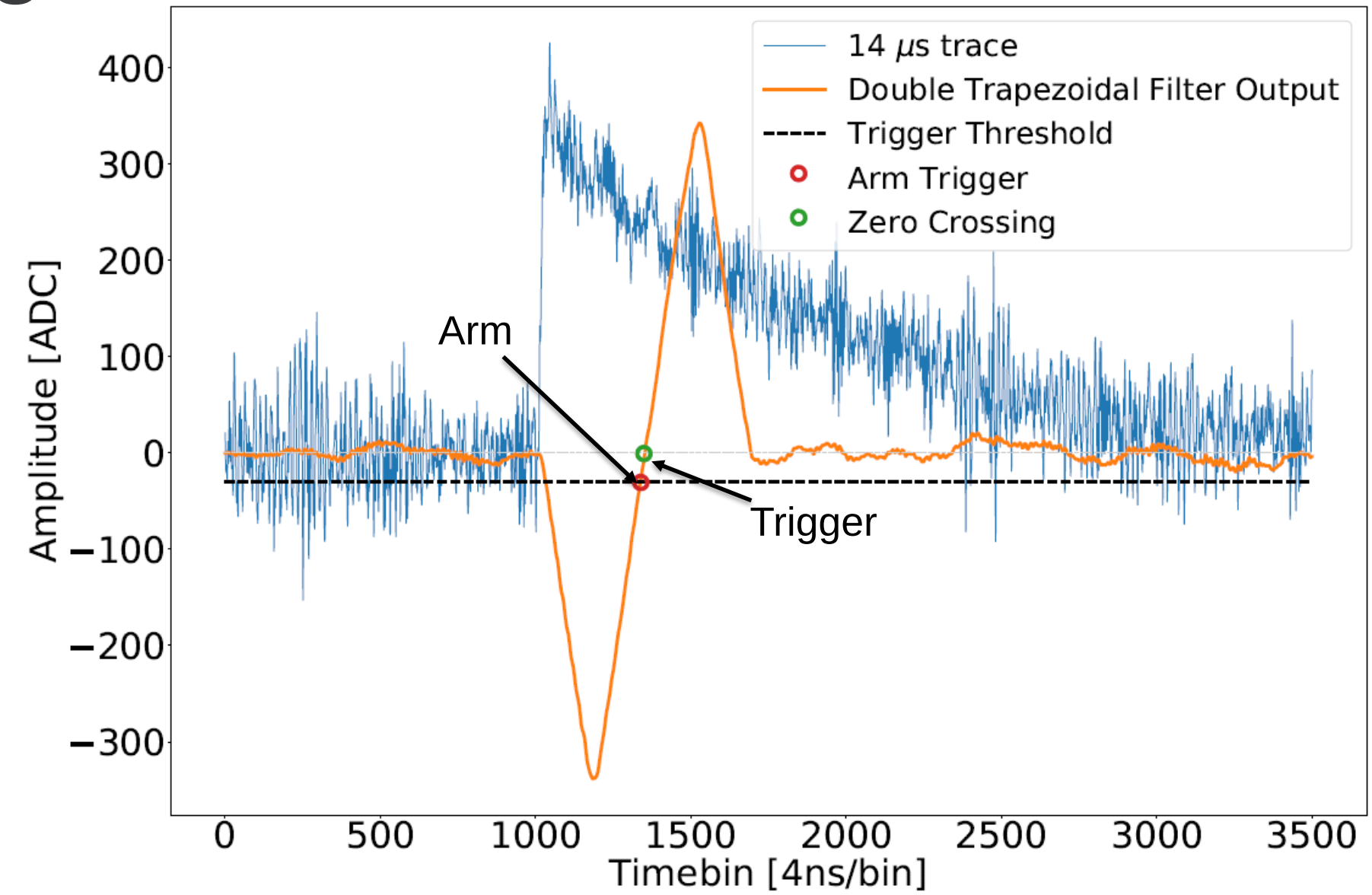
Trigger Scheme



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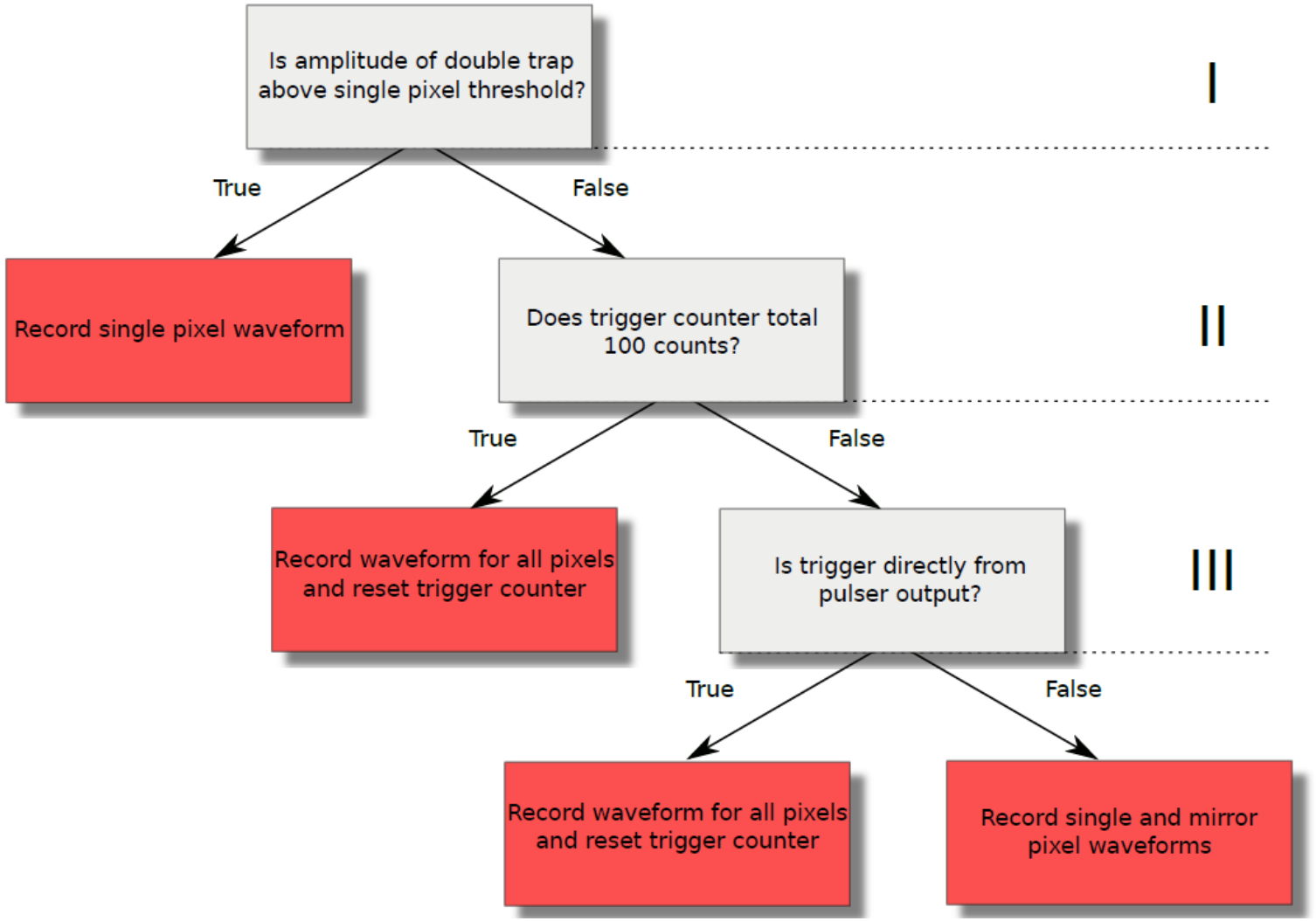
Trigger Scheme overview



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Fit Range

- 150 keV – 220 keV
  - Detector efficiency ~ 99.9% at 150 keV
  - $\frac{\sqrt{N}}{N} \sim 0.01$

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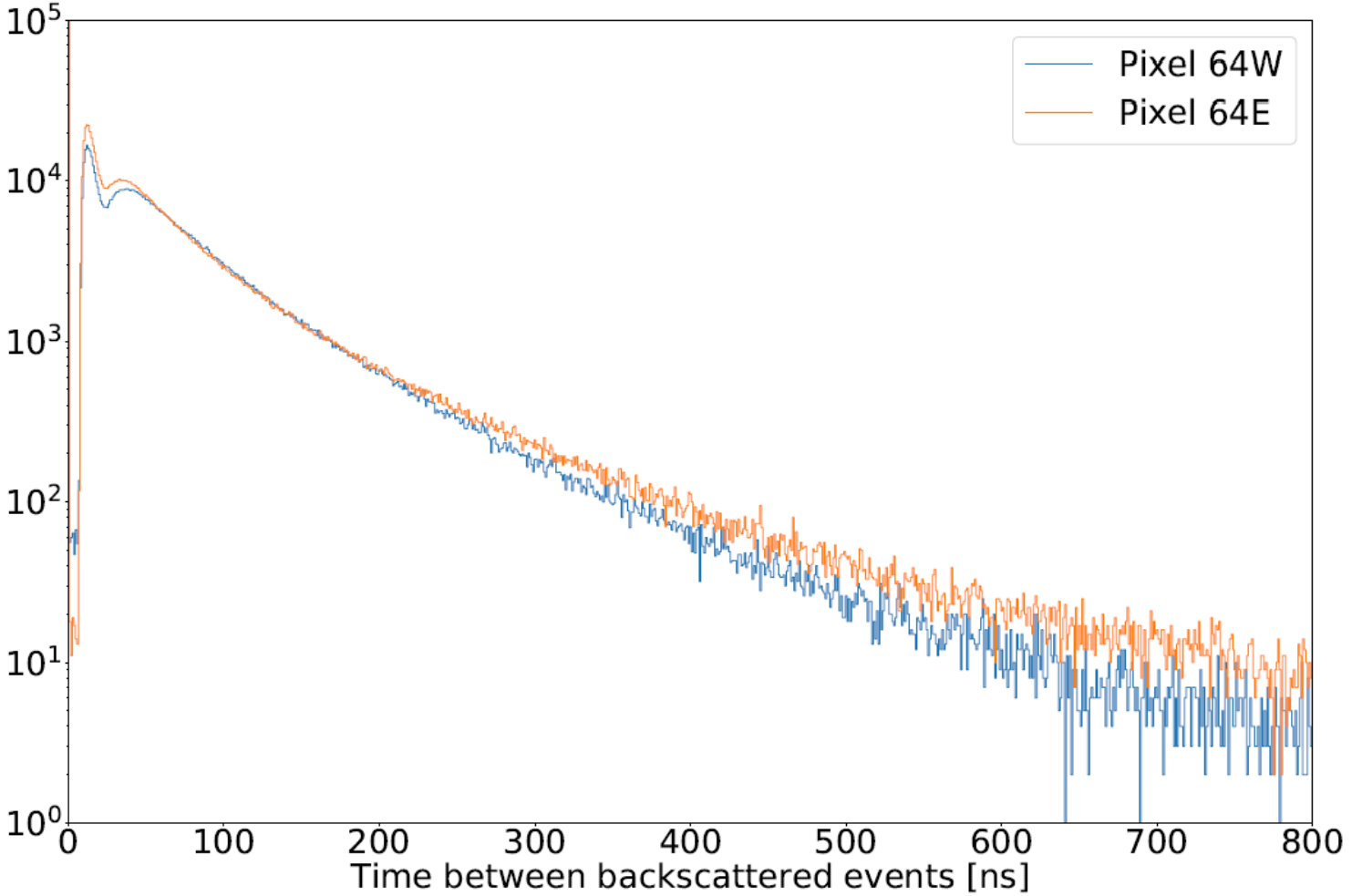
Backscattered timing distribution



Simulation courtesy of B.Zeck

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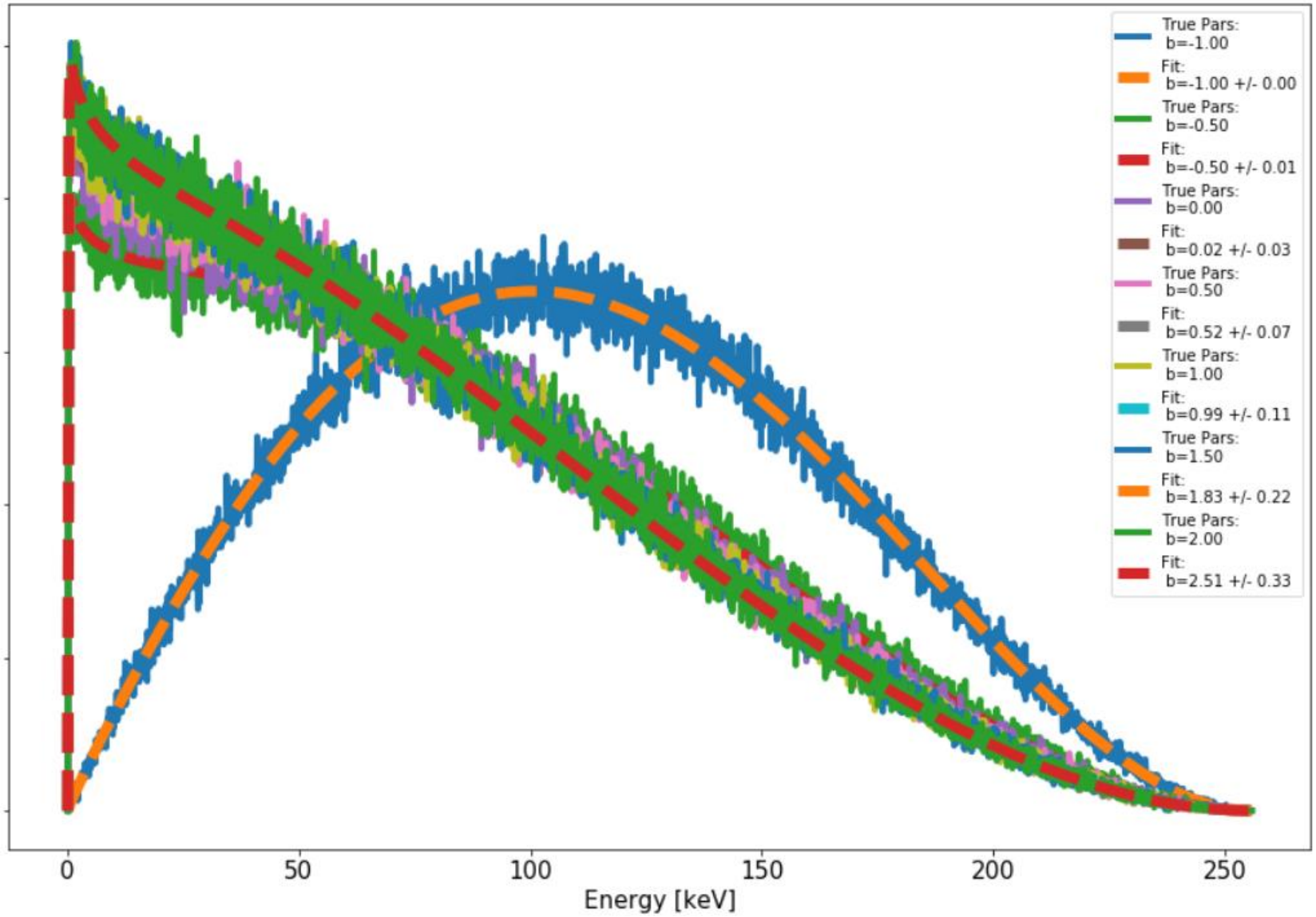
b=0 & b=1 Spectra to Generate ^{45}Ca Spectrum with Arbitrary ‘b’

- Calcium spectrum was generated for b$\in [-1,0.5,0,0.5,1]$
- Each spectrum was finitely sampled
- Using w(0),w(1), ‘b’ was extracted from each sampled spectrum (dotted lines)



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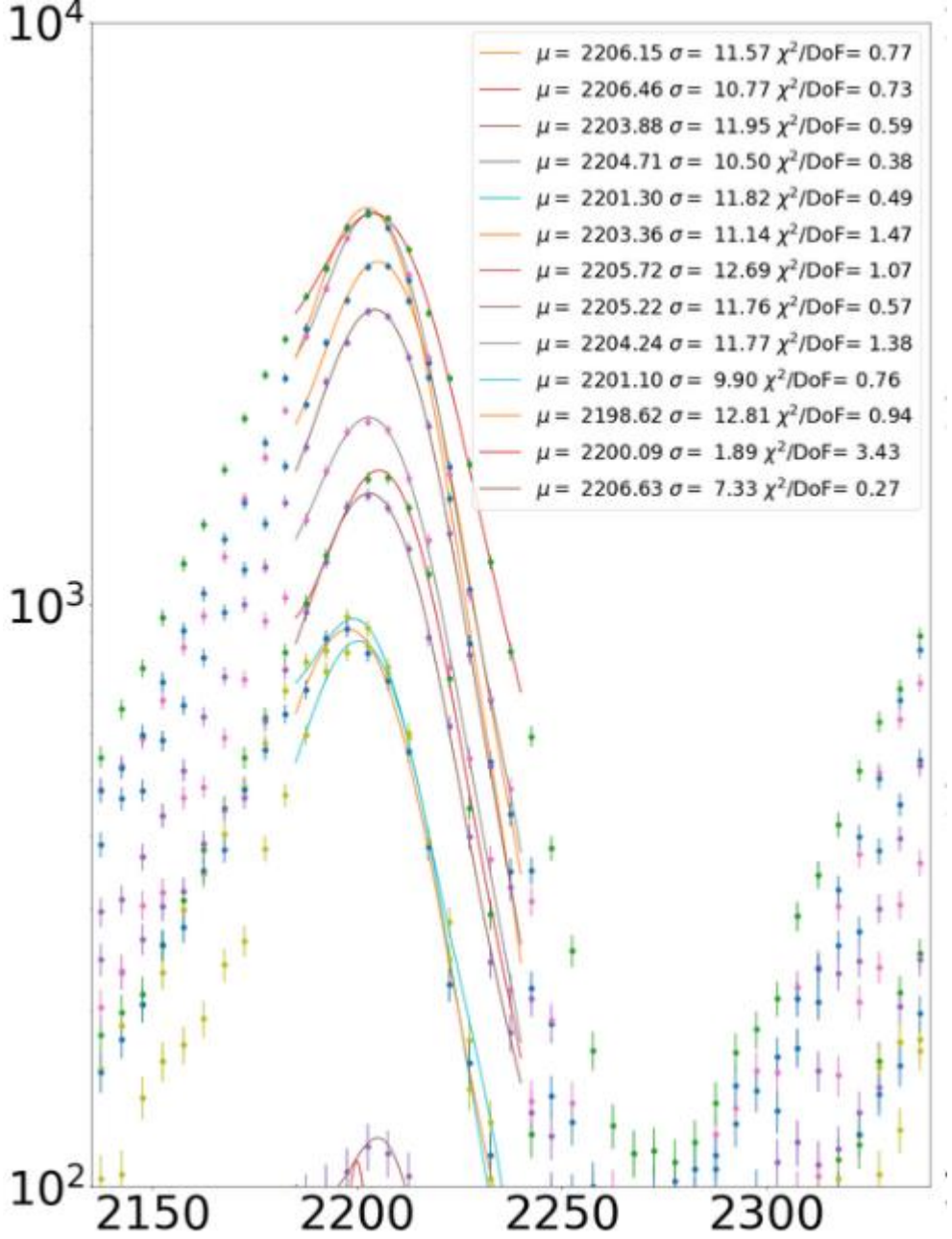
Calibration Stability

- Shown on the right:
  - 363 keV source peak fit for all calibration runs throughout data collection
  - Peak stable to ± 8ADC

  →Very stable gain & calibration



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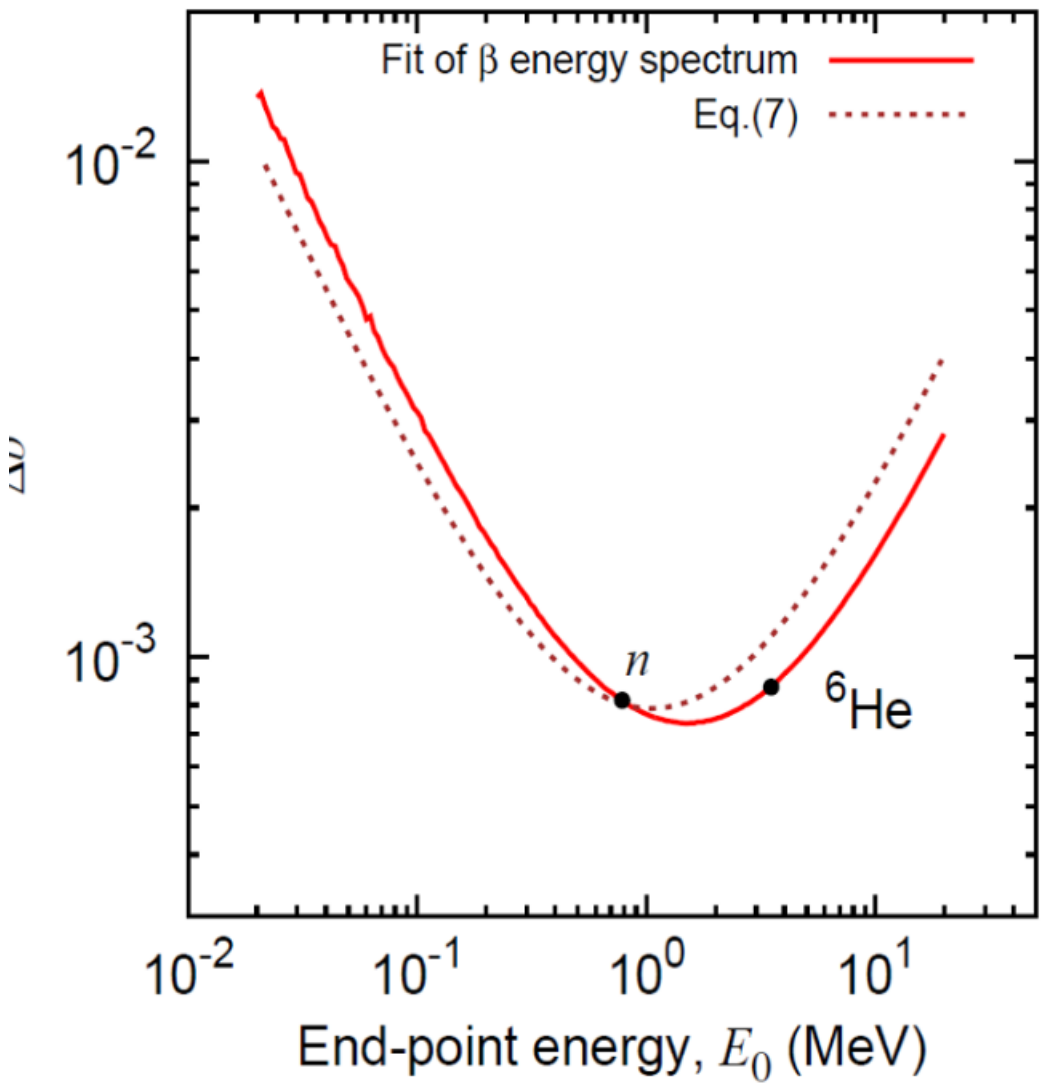
Kinematic Sensitivity

M. Gonzalez-Alonso and O. N.-C
Phys. Rev. C **94** (2016) 035503



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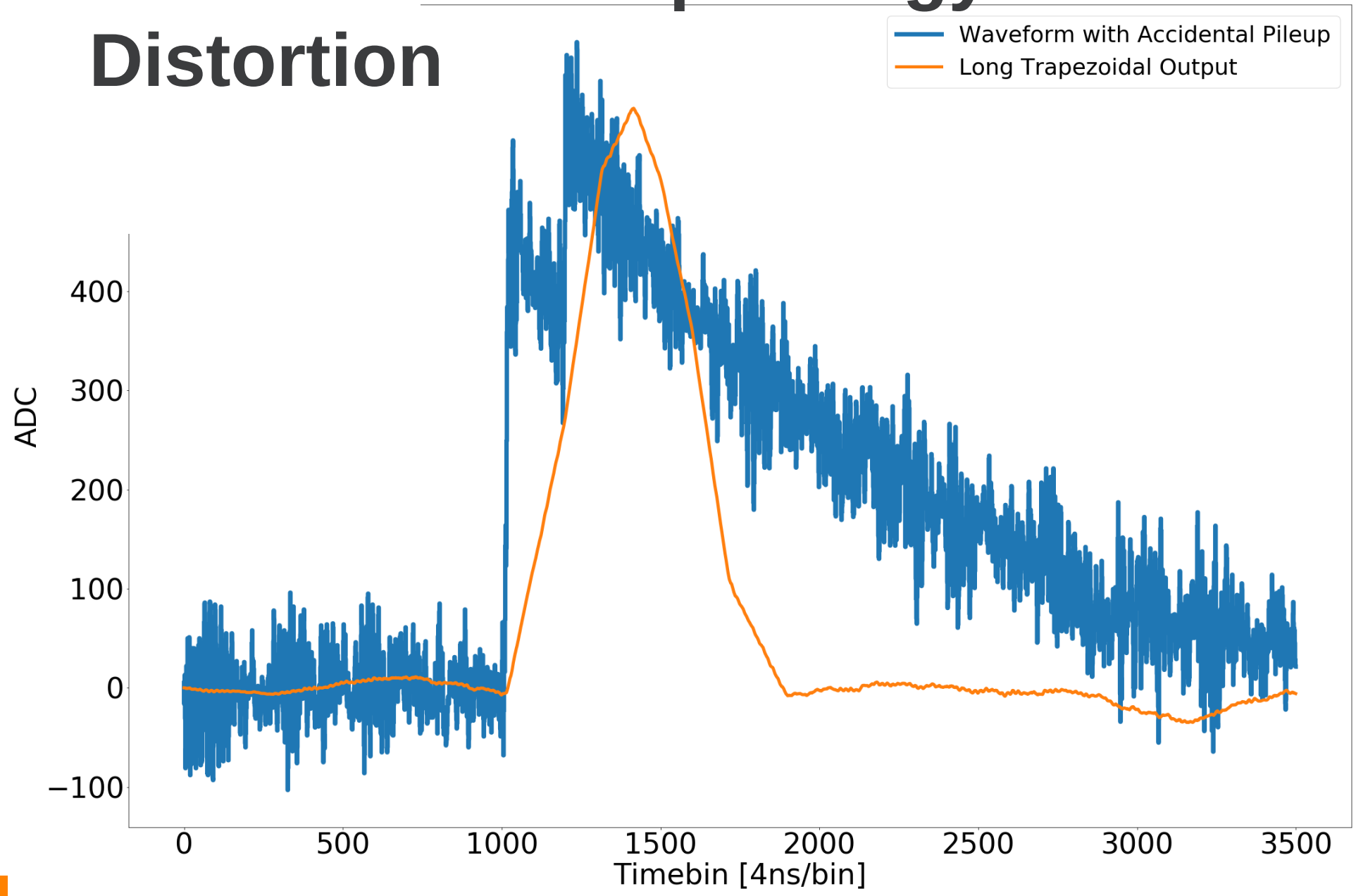
Accidental Pileup Energy Distortion



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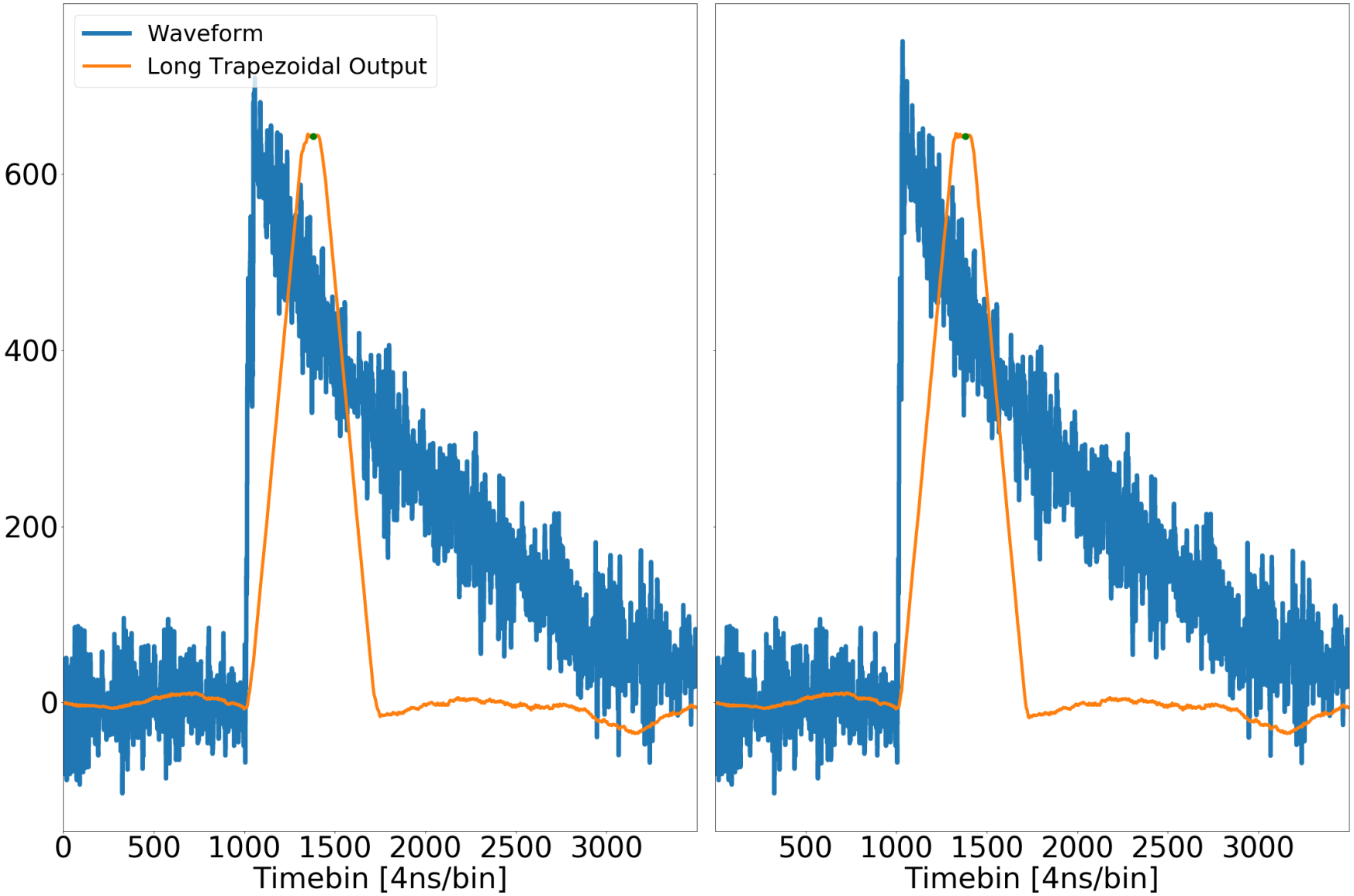

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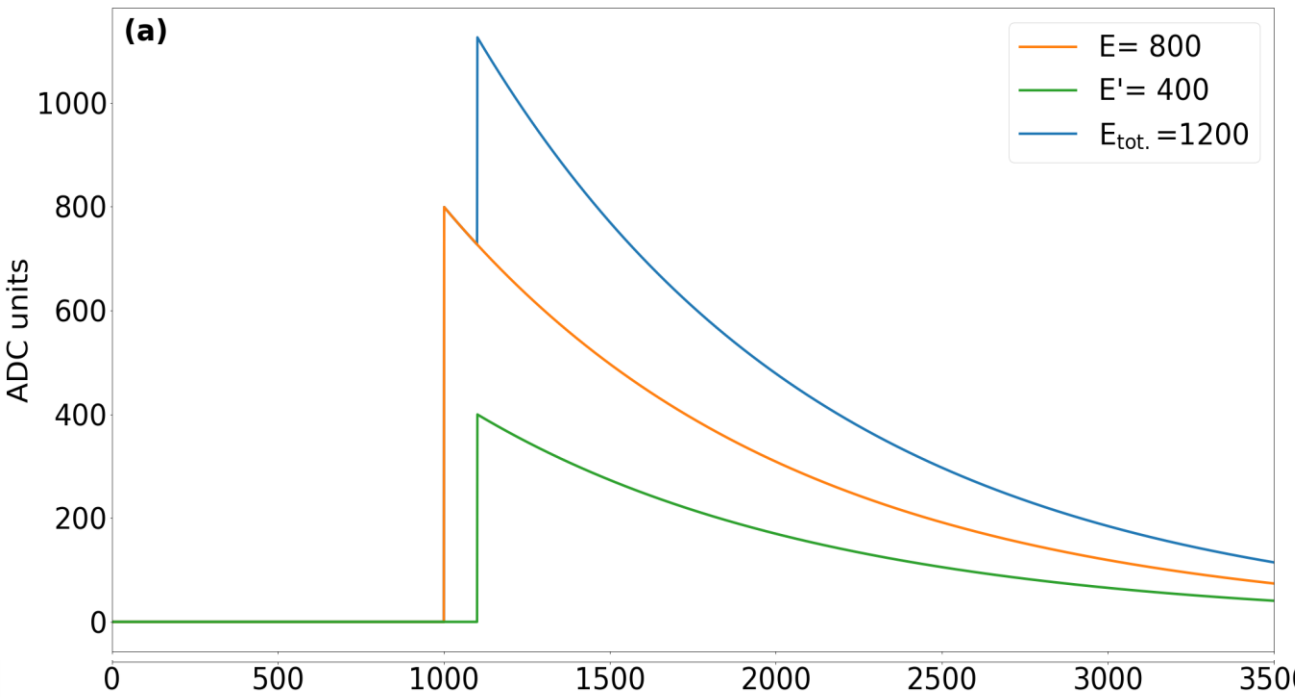

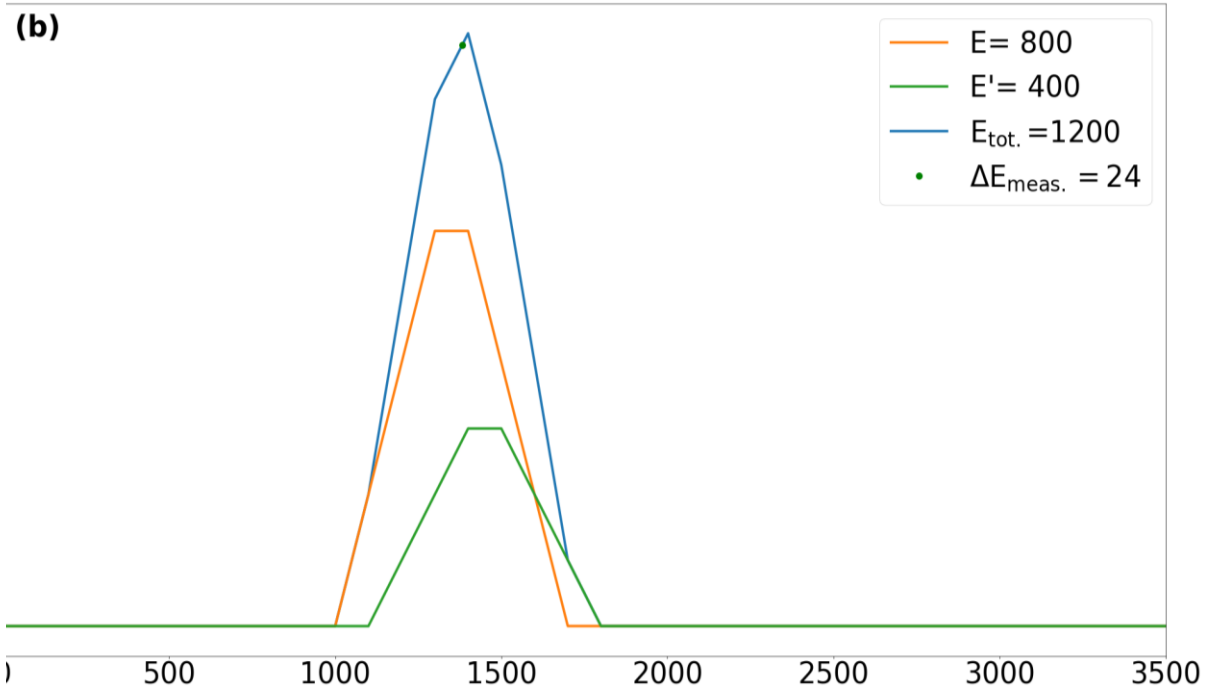

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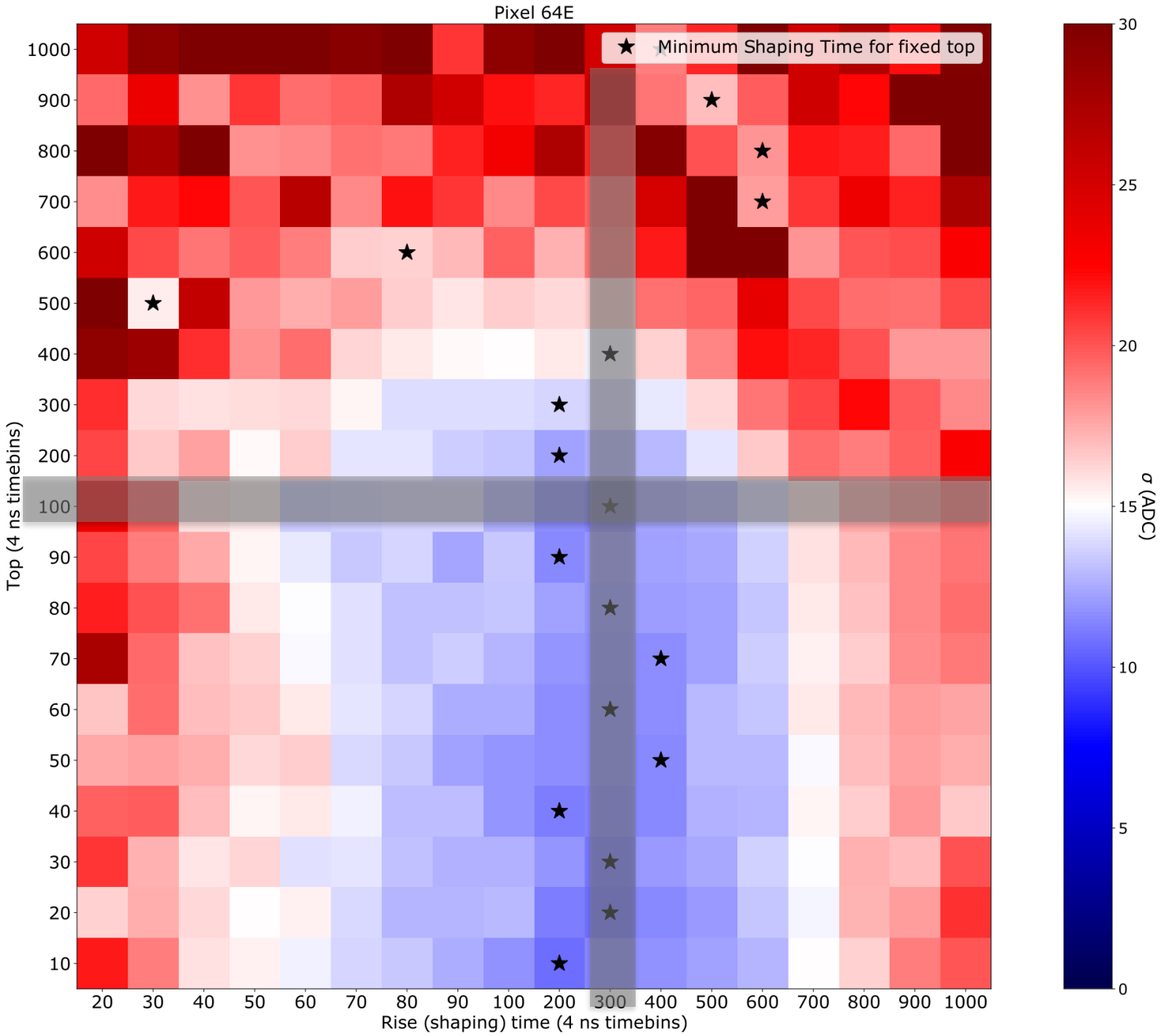

Top = 400 ns (100 timebins)

- Accommodates risetime variation

→ Shaping time = 1.2 μs

- Minimum peak width

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Linear Least Squares Fit

- Suppose a WF (Y) can be described by ‘n’ functions (f_j) of $t \in [t_0, t_1, \ldots, t_m]$. Let a_j be a scaling factor.

$$Y[i] = \sum_{j=0}^{n} a_j f_j(t_i)$$

$$F := \begin{bmatrix} f_0(t_0) & \cdots & f_m(t_0) \\ \vdots & \ddots & \vdots \\ f_0(t_n) & \cdots & f_m(t_n) \end{bmatrix} \qquad a := \begin{bmatrix} a_0 \\ \vdots \\ a_m \end{bmatrix}$$

$$Y = F \cdot a$$

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Linear Least Squares Fit

$$Y = F \cdot a$$

$Y[i]$ represents the amplitude of the waveform of the i'th bin

$$\rightarrow F^{\mathrm{T}} \cdot Y = \left(F^{\mathrm{T}} \cdot F\right) \cdot a$$

$$\rightarrow a = \left(F^{\mathrm{T}} \cdot F\right)^{-1} \cdot F^{\mathrm{T}} \cdot Y$$

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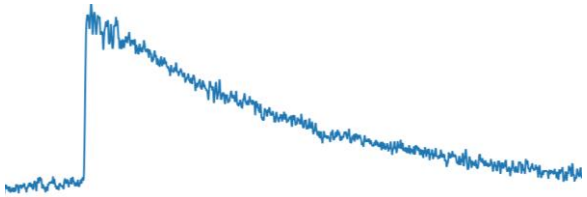
$F =$ N functions

$Y^T =$ 

Suppose
$Y = F \cdot a$

$$\rightarrow a = (F^T \cdot F)^{-1} \cdot F^T \cdot Y$$

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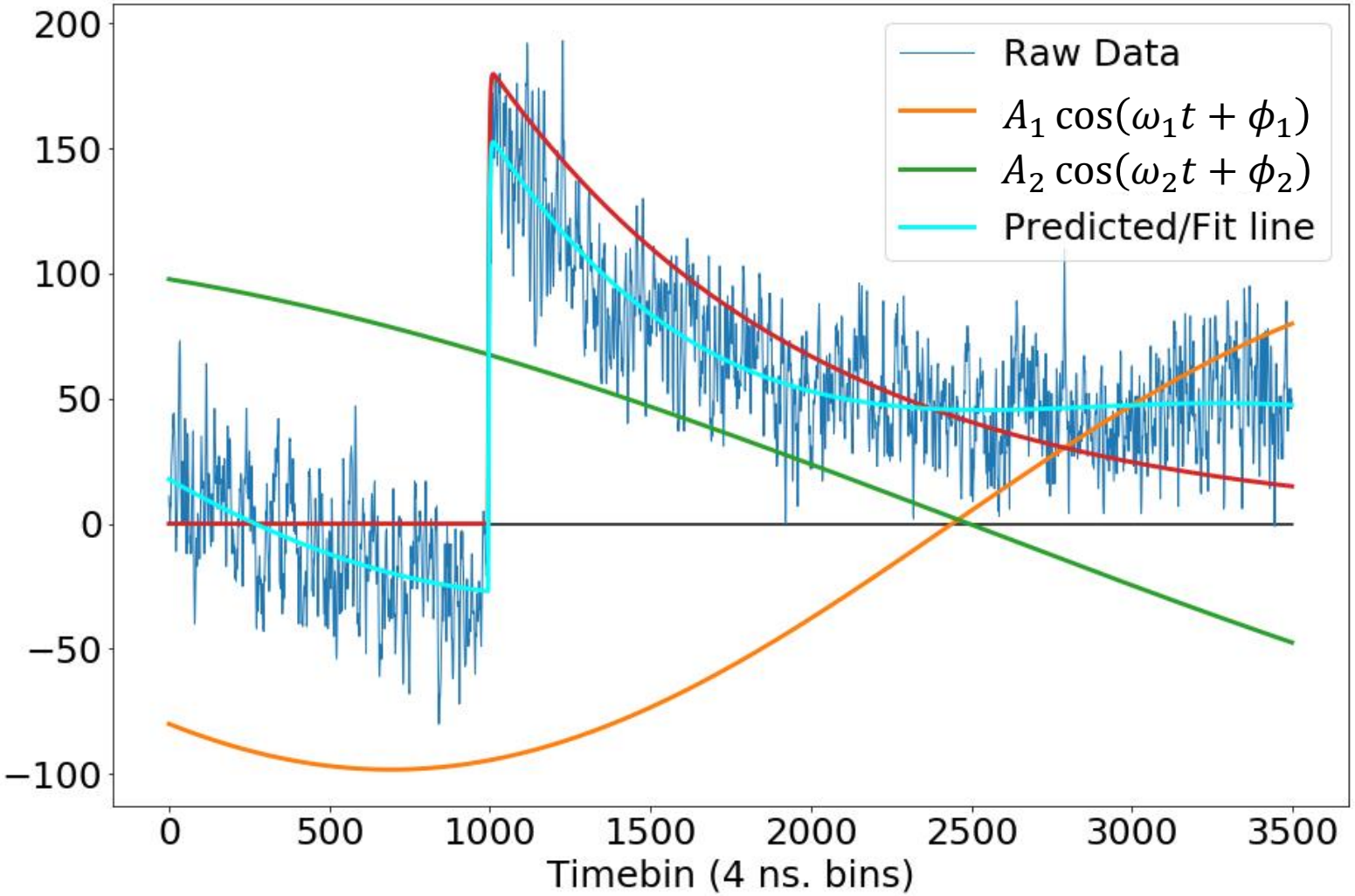
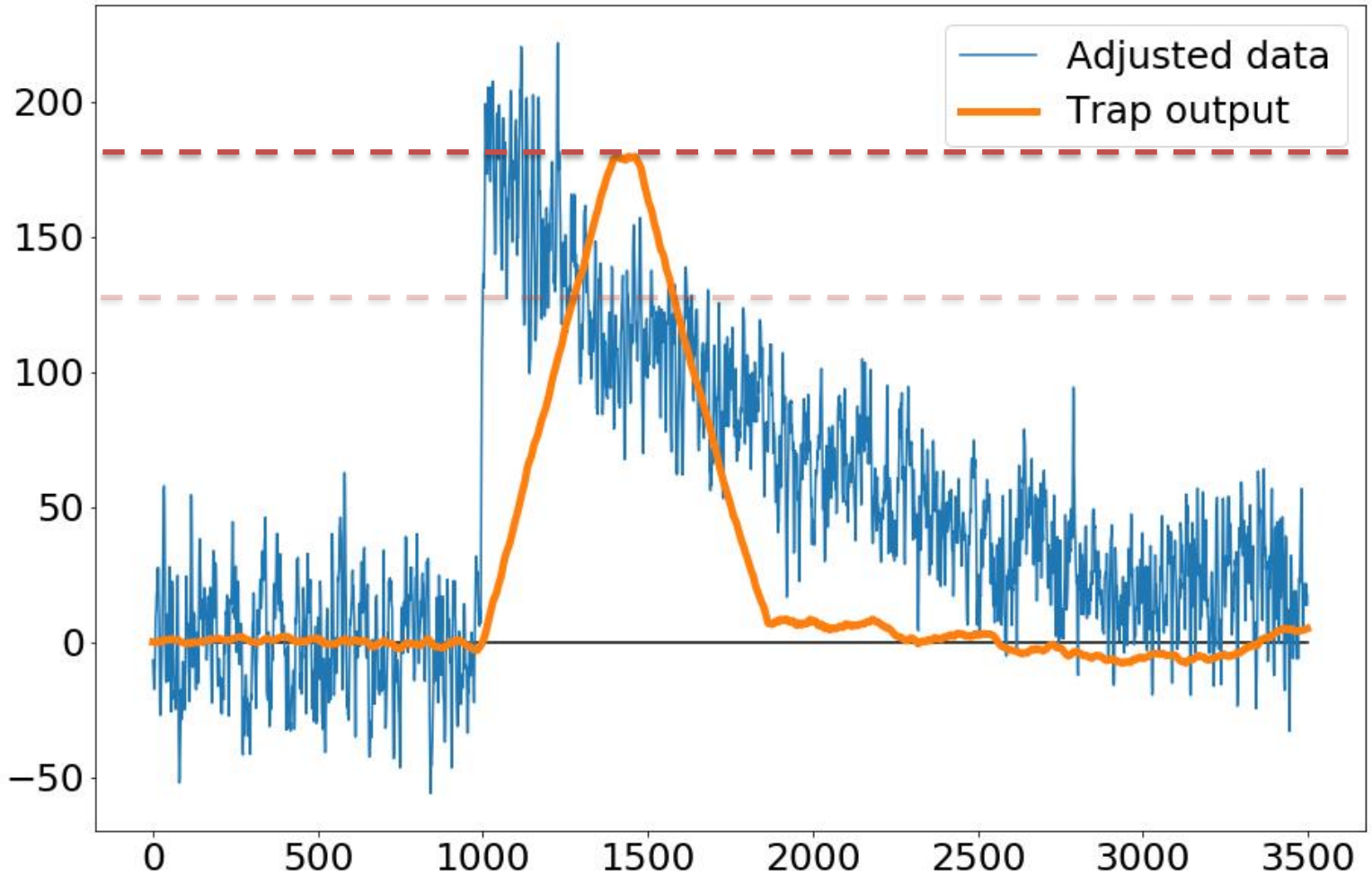

Raw Data
$A_1 \cos(\omega_1 t + \phi_1)$
$A_2 \cos(\omega_2 t + \phi_2)$
Predicted/Fit line
200
150
100
50
0
−50
−100
0
500
1000
1500
2000
2500
3000
3500
Timebin (4 ns. bins)

Baseline oscillation removed



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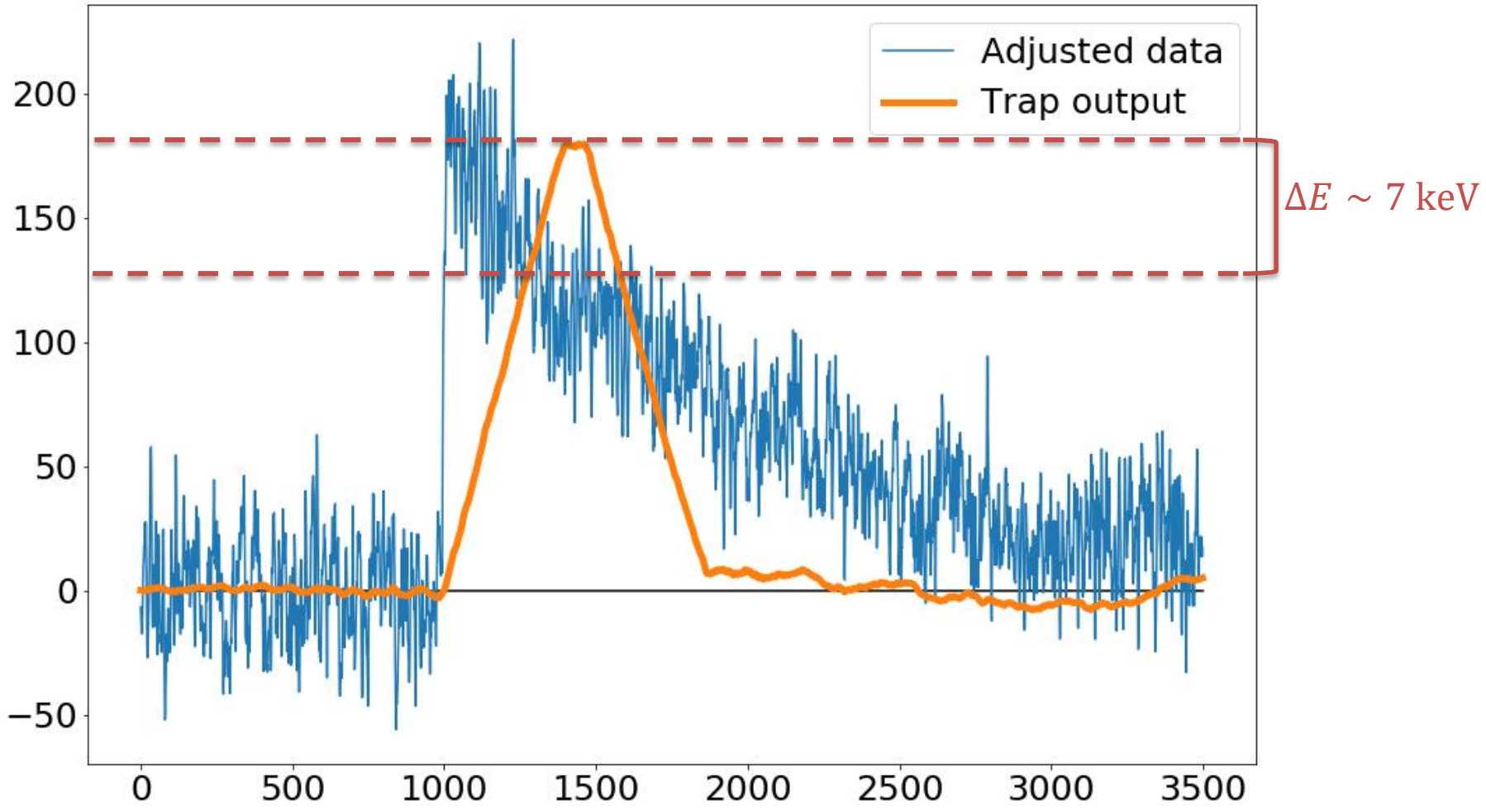
Baseline oscillation removed



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