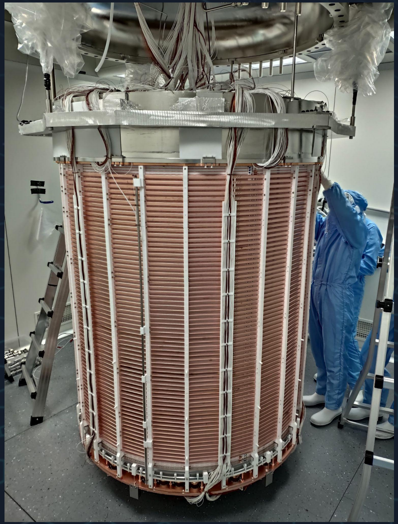
Development of Pairing Algorithm for the XENONnT Event Selection Process



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XENON Dark Matter Collaboration
Nevis Laboratories REU Program, Summer 2024

Acknowledgements

Special thanks to Dr. Knut Morå, Shenyang Shi, Dr. Michael Murra, and Professor Elena Aprile for your wonderful guidance and support.

Thank you to Professor Georgia Karagiorgi, Professor Reshmi Mukherjee, and Amy Garwood for hosting the Nevis Laboratories REU program this summer.

This material is based upon work supported by the National Science Foundation under Grant No. PHY-2349438.

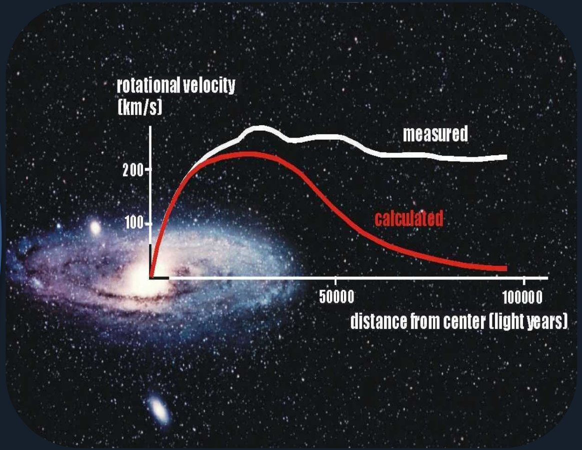
Outline

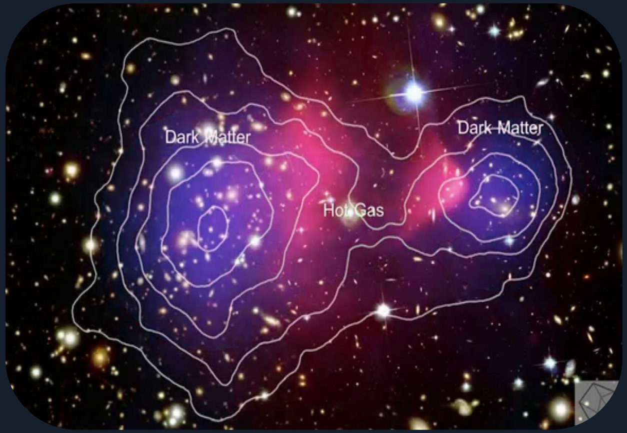
- ➢ Dark Matter Background
- ➢ XENONnT Time Projection Chamber
- ➢ Event Construction Process
- ➢ Developing Pairing Algorithm for Higher Performance Event Construction
    - ○ Phase 1: Motivation to Modify Event Construction
    - ○ Phase 2: Quantile fitting for updated pairing algorithm
    - ○ Phase 3: Event Construction Modification to test density of mispaired events
- ➢ Project Future

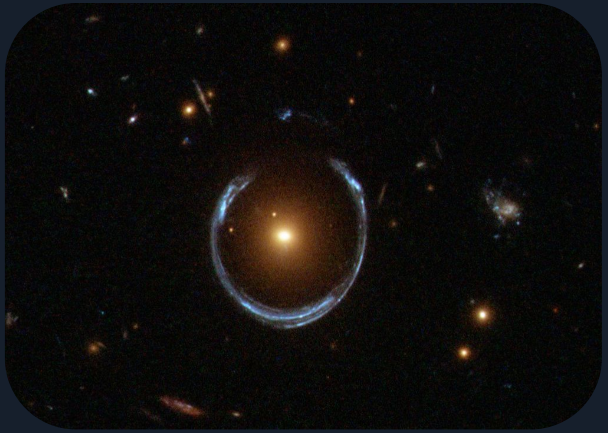
Dark Matter

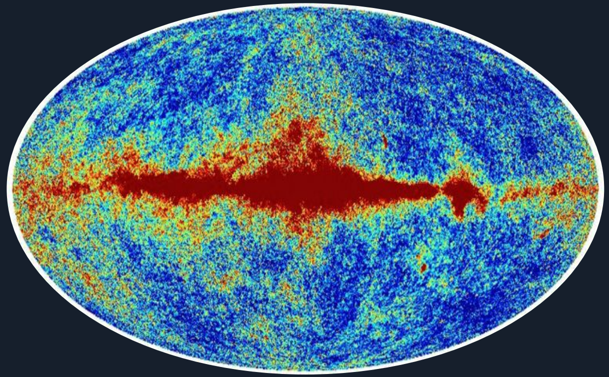
Weakly Interacting Massive Particles(WIMPs)

- ➢ Interaction with the weak scale force + gravity
- ➢ Target mass: few GeV/c^2 - TeV/c^2





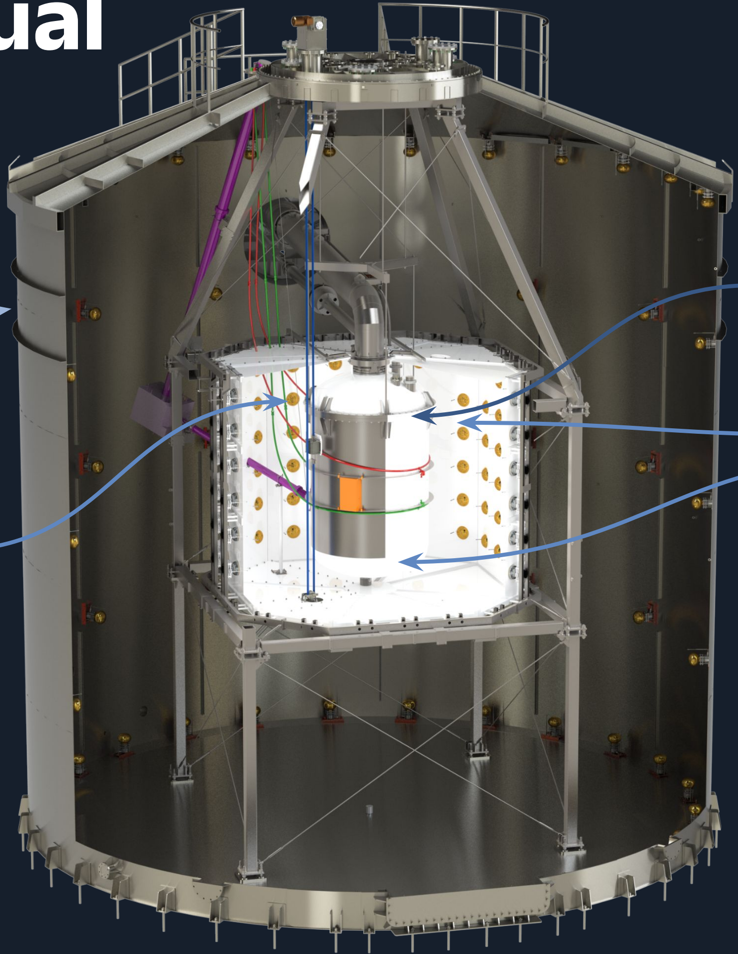




Xenon

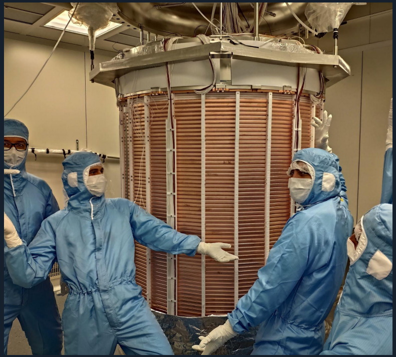
- Liquid density (2.7 g/cm^2)
- High electron & photon scintillation light
- Can be cleaned to extreme purity from
  - Electronegativity
  - Radioactivity
- Large atomic number & density: higher stopping power (self-shielding)

XENONnT Dual Phase TPC



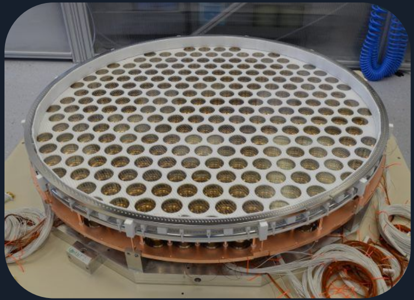
Water Tank: rejects events that interfere with WIMP signal
-Neutron veto
- Muon veto

TPC:
8.6 tonnes Liquid & Gaseous Xe



External E field applied to top of the tank
- Electrons drift upward to produce scintillation light

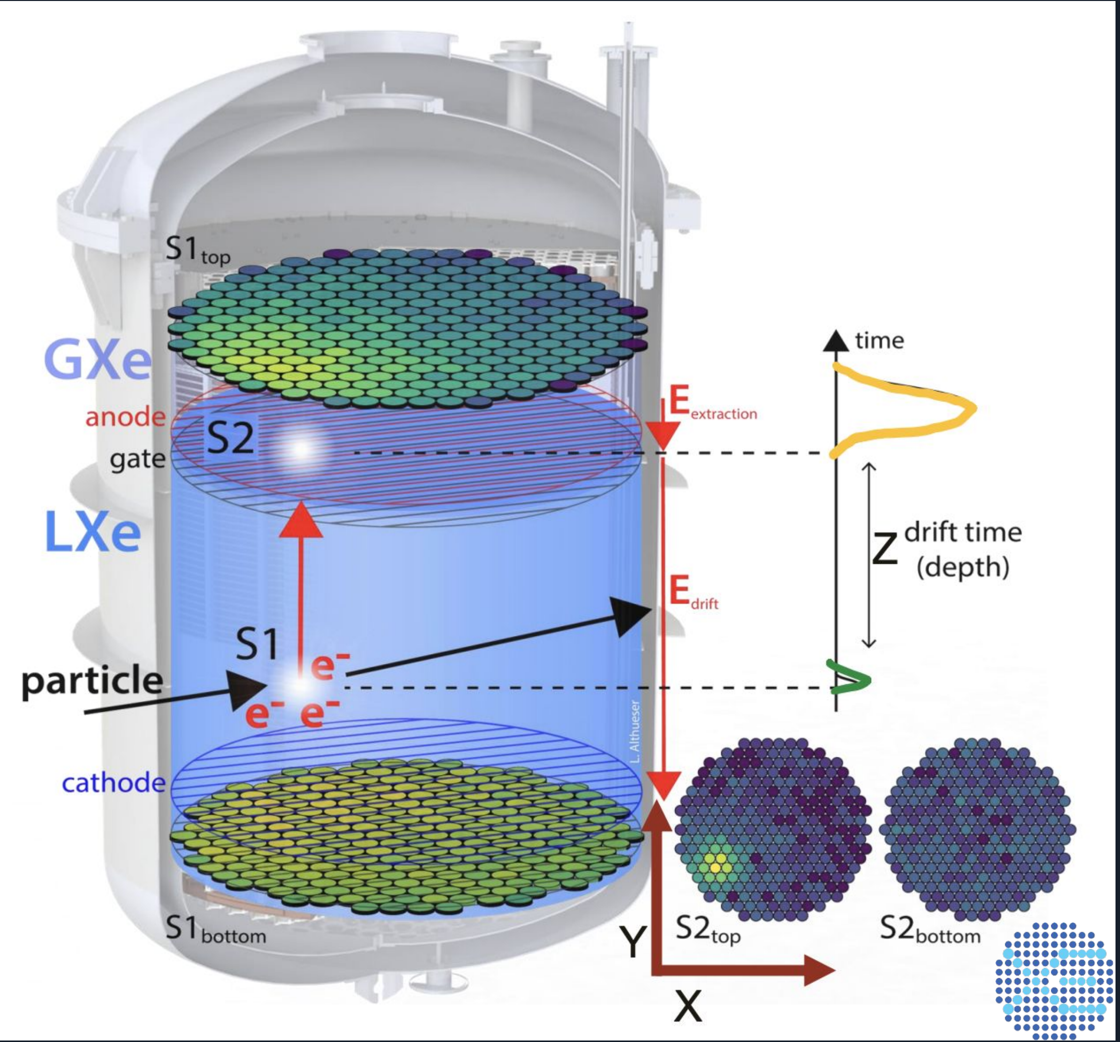
Light captured & recorded by Photomultiplier Tubes



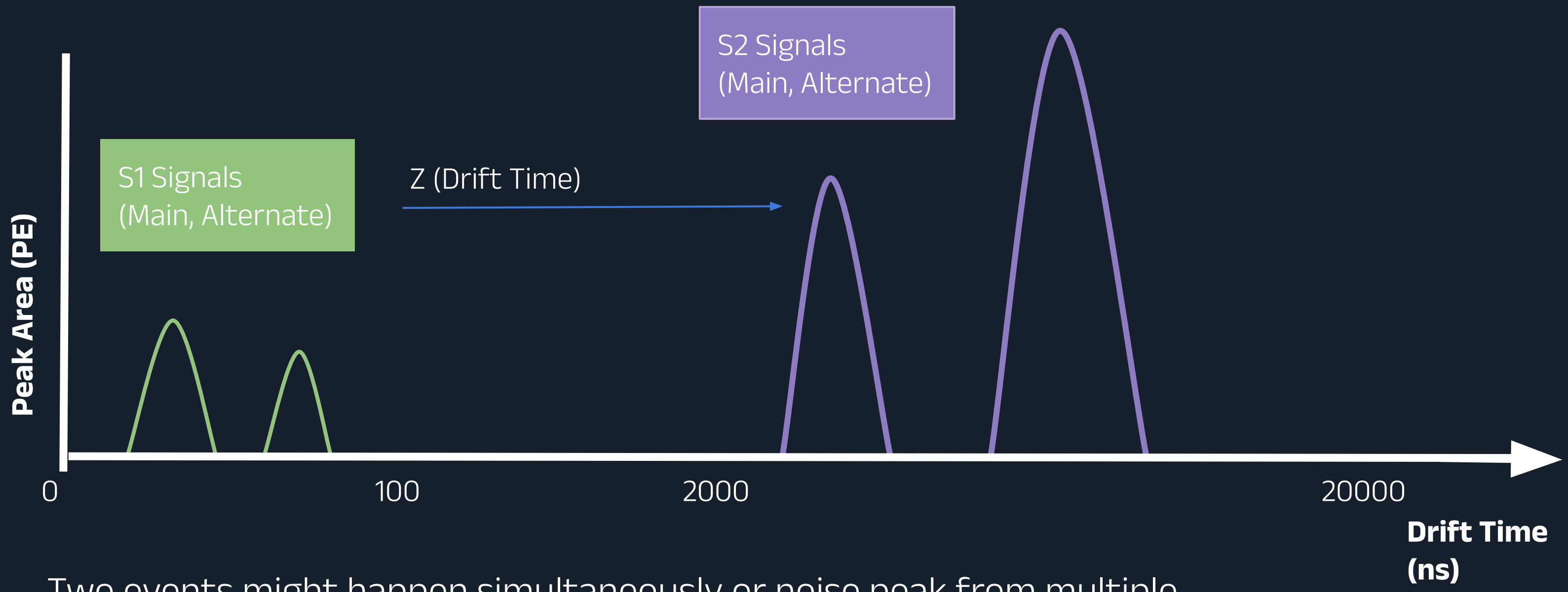
494 PMTs!!

Detection

- Difference in time between primary (S1) & secondary signal (S2) signal provides
  - 3D Position reconstruction
  - Particle energy & classification
- Drift time of electrons: depth (z-position)
- Photomultiplier Tubes (PMTs): area (x, y positions)
  - Photoelectron(PE) count given by PMTs



Reconstruction of events using peak level data



- ➢ Two events might happen simultaneously or noise peak from multiple interactions also appears
  - ○ But we want data from a singular physical event
- ➢ Largest S1 peak area matched to largest S2 peak area to form event
  - ○ Alternate peaks stored but not used in data analysis

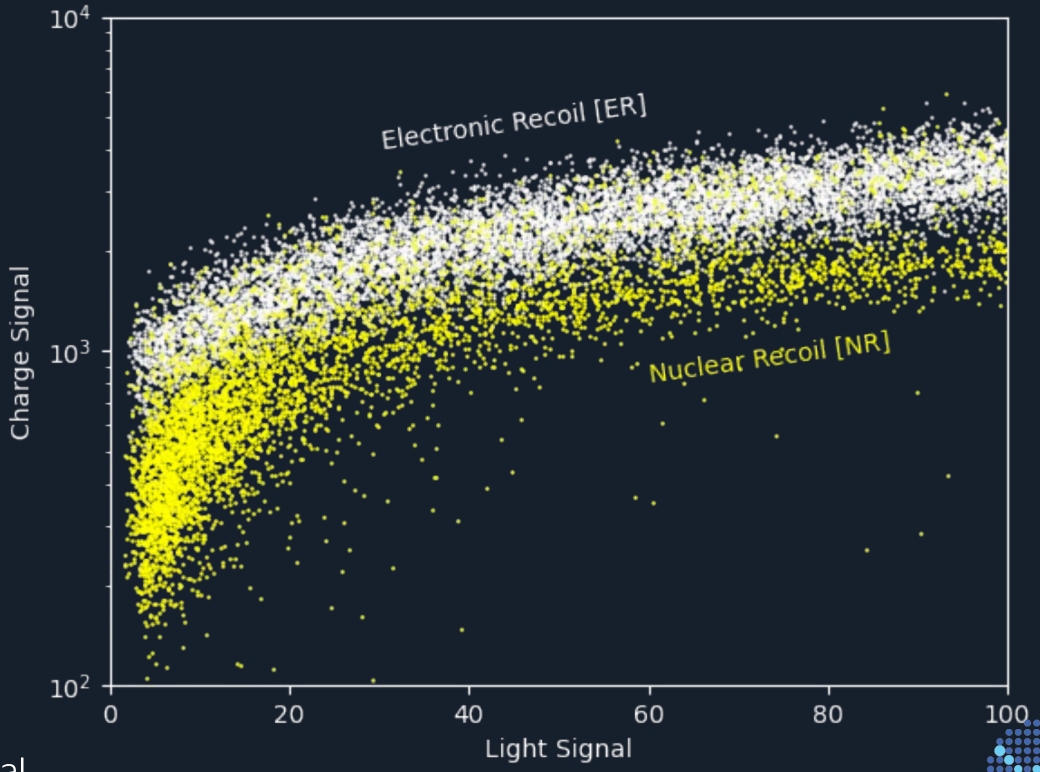
Event Selection

- Expected data occurs within Electronic Recoil & Nuclear Recoil band (ER-NR band)

- Electronic Recoils: Beta decays, gamma particles, neutrinos
  - Natural radioactivity in detector

- Nuclear Recoil candidates: WIMPs, neutrons

- Accidental Coincidence Event (AC Event)
  - False event made up of noise peaks
  - Do not originate from only one physical interaction



Event Building using Straxen

STReaming **A**nalysis for **XEN**on

- ➢ Detector receives particle interaction data constantly
- ➢ S1- S2 peaks constructed depending on fraction of light in top area (top PMT array) & time range
- ➢ Event construction performed by matching S1-S2 peaks with largest areas (PE)
  - ○ From all data provided only peak area used for event construction
- ➢ Reconstructs events given peak level data
  - ○ Robust process
  - ○ Can lead to mispairing of peak from one event to peak from another event

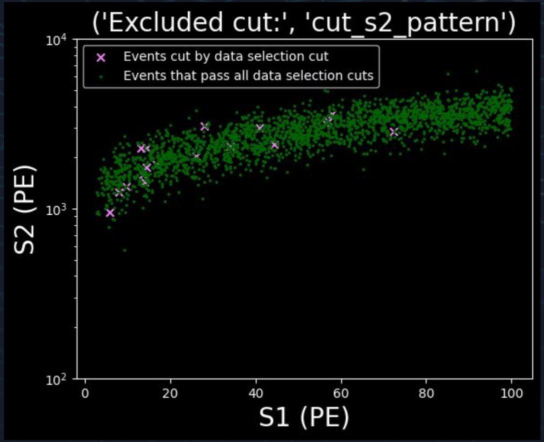
Data Selection Cuts

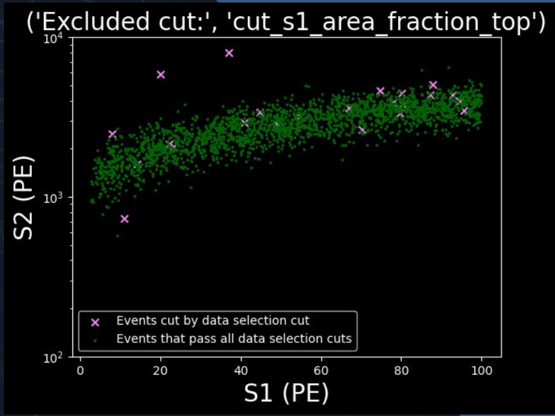
- Data selections: parameters used to select events that are compatible with physical & genuine energy depositions in TPC

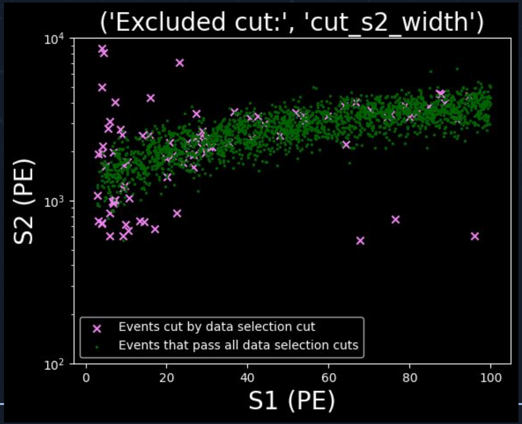
- Modeling detector behavior useful to identify poorly reconstructed events

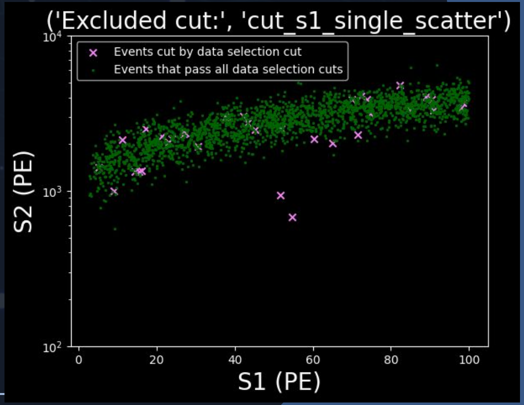
- Only applied after events constructed
  - Alternate peak data not considered in detail

Graphical representation of the types of values each data selection cuts to produce expected ER-NR event band







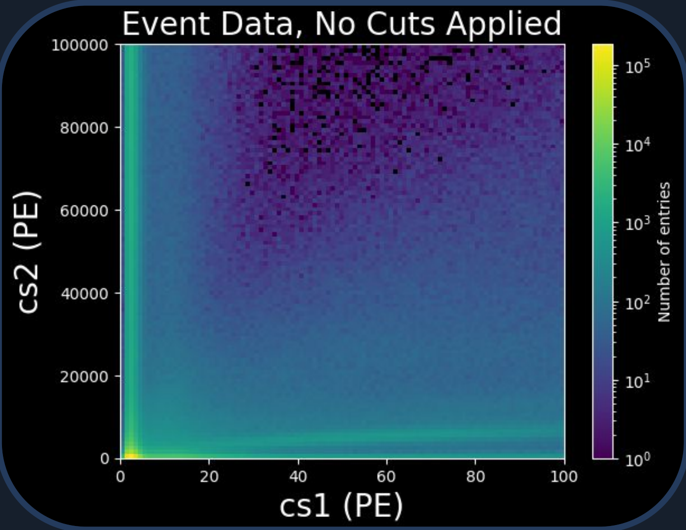


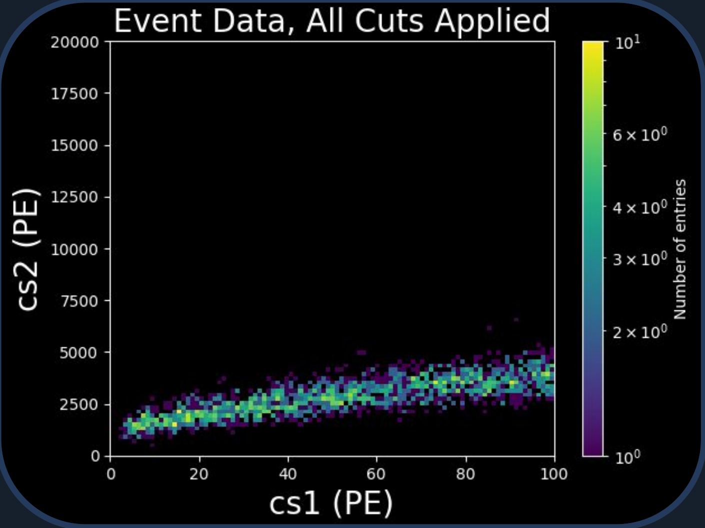
Project Motivation/Goals

- ➢ More data selection parameters should be included in event construction for higher performance of event pairing
- ➢ Limited data for pairing may lead to incorrectly paired events

Goals:

- ➢ Save incorrectly paired events
- ➢ Algorithm for comprehensive Accidental Coincidence (AC) reduction
- ➢ Analysis done with Rn 220 calibration data for low energy ER events

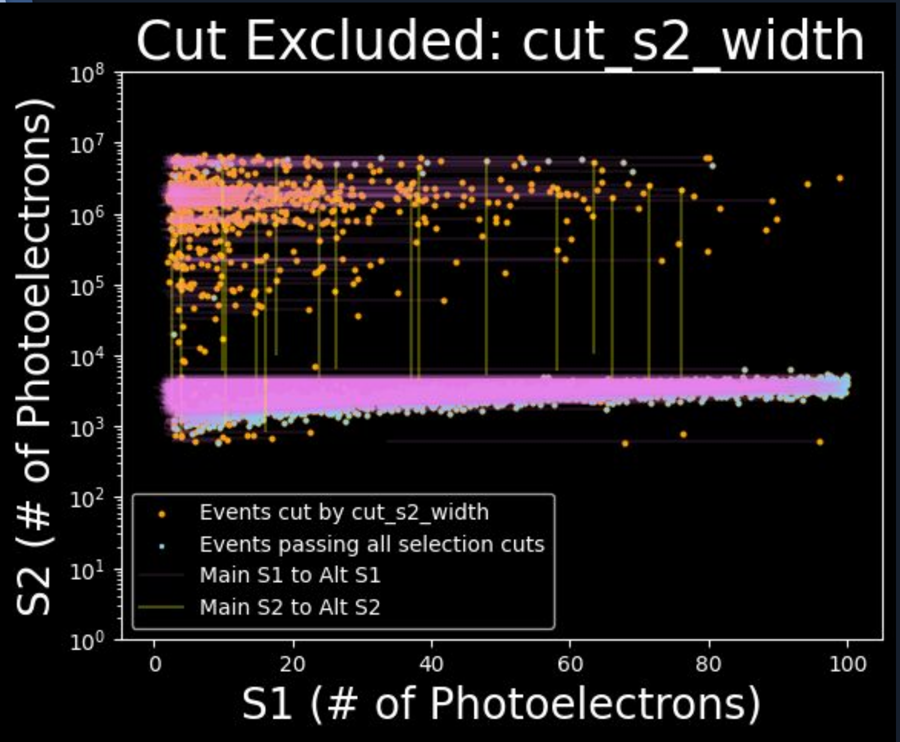


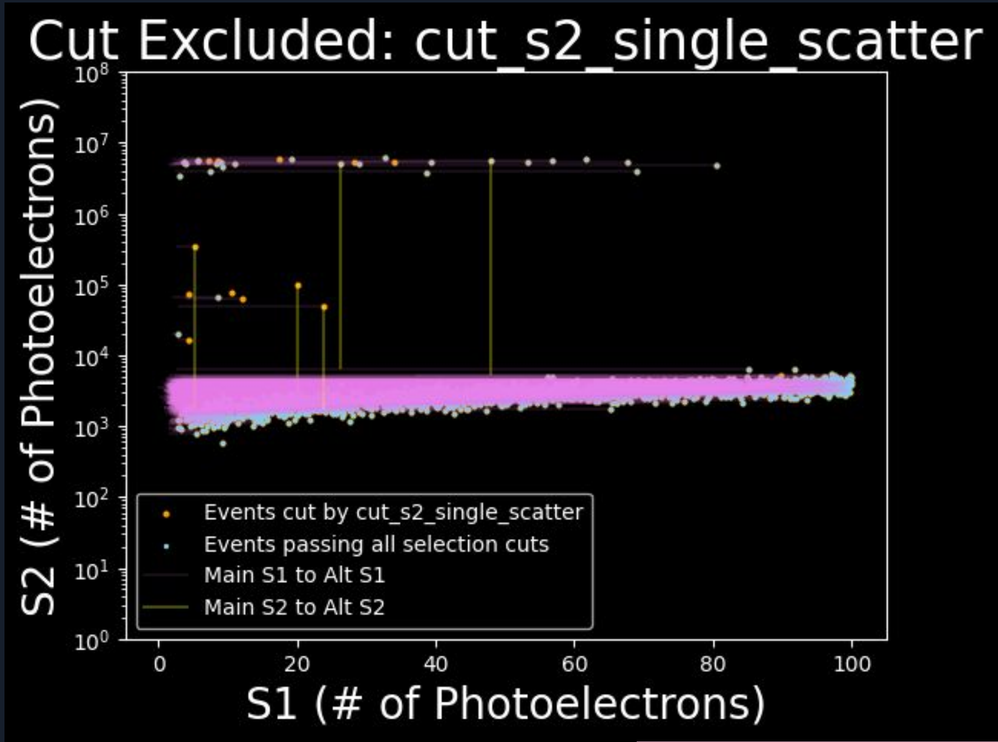


Phase 1

Do We Need to Modify Event Selection?

Process: Isolate each cut selection to see what data was removed using Rn220 calibration data





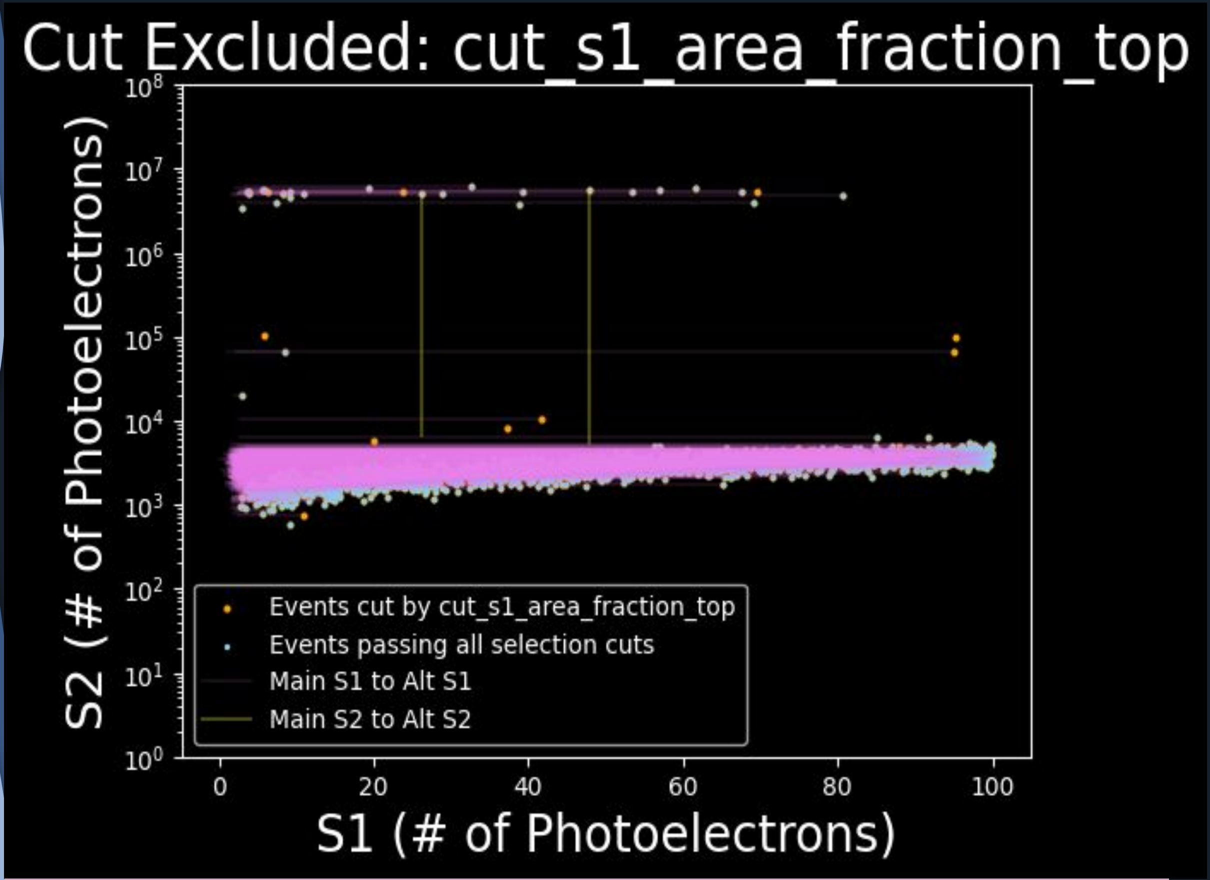
S2 Width: Removes events with unphysical drift times

Initial test to see if pairing algorithm will produce significant results

Removing singular data selection cuts displays cut purpose/performance

Selecting data selection cuts that may be useful for reconstructing event builder

S2 Single Scatter: Removes events with multiple scatters between S1 & largest S2



S1 AFT removes events with low proximity to good S1 AFT values (data-driven cut)

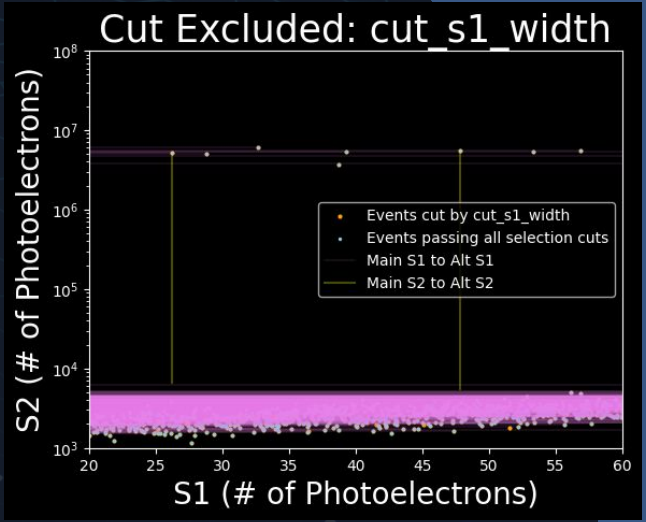
Analyzing the parameters that are most useful for an updated pairing algorithm

Large S2 Area values (~10^7 PE) correspond to large energy events (high energy gamma particles)

Some main S2 peaks at high energy ranges have alternate S2 peaks within expected ER-NR region

Evidence found for Mispaired Peaks

- Main charge signal (S2) peaks at high energies often have a corresponding Alternate S2 peak in expected regions
  - Proof that peak area should not be only criteria to decide main peak
- Alternate peaks currently not referenced in future data
  - Expected event blocked by higher energy event
  - Selection cuts remove event entirely
- Narrowed down impactful data selection cuts
- Good evidence to move forward with event builder modifications



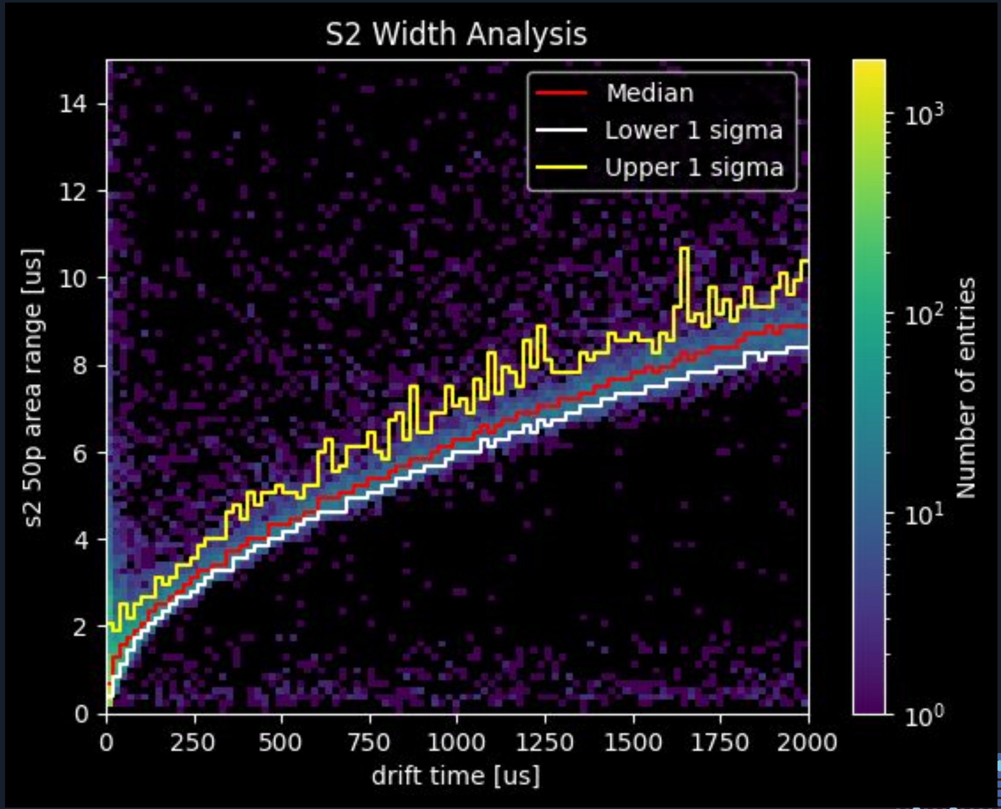
Phase 2

Quantile fit for p-value based pairing algorithm

Methodology

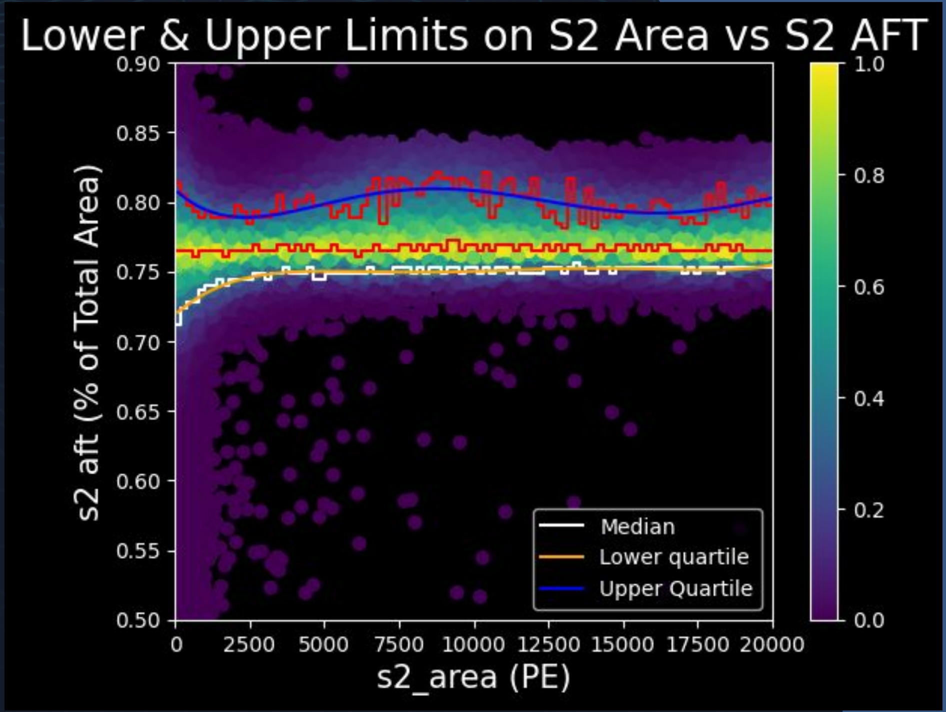
S2 Width: Drift Time vs 50p Area range models how longer drift time correlates to larger 50p area range as e^- disperse further away from interaction site.

- Generating polynomial graphs to model correlation between two related data selections
  - Data selections chosen from phase 1
  - Plot median as a function of plot
  - Normalize median as p = 0
- Accepted events: within 1 sigma range of median value (16-84 percentile)
- Optimized event selection
  - reduces AC events
  - saves mispaired events (more data)

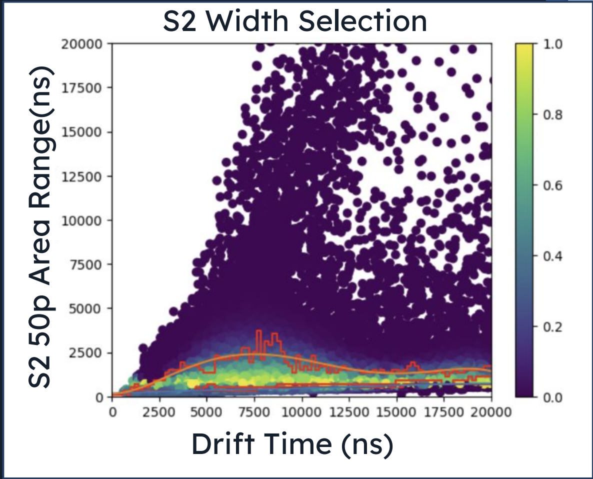


- Successful correlations for data-based pairing algorithm
  - Depends on data correlations, not just peak area
  - Using p-value acceptance
  - First test would be to accept values within 1 sigma of median
  - Increase acceptance as more functions are added to algorithm

S2 AFT Cut: S2 Area vs S2 AFT total area vs percentage of area collected by top PMT array

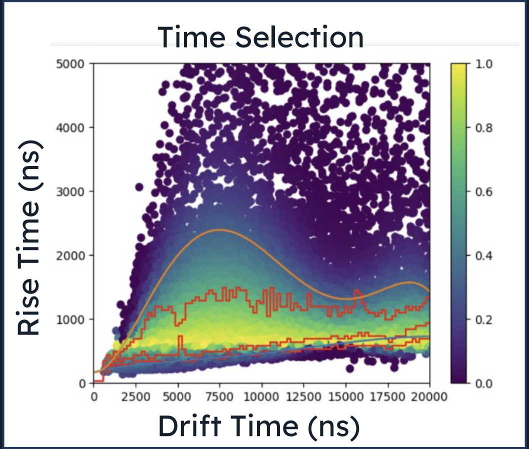


Modifying Criteria for Main Peaks



- Implementing algorithm at peak level
    - Main peak chosen to be closest to the median
    - Peak with best p-values from all correlated functions
    - Less chance of mispairs that will be considered AC events later on

- Time Constraints
    - This process is lengthy
    - Understand current event builder efficiency first
    - Selection criteria should ensure data is still well-modeled and remains unbiased

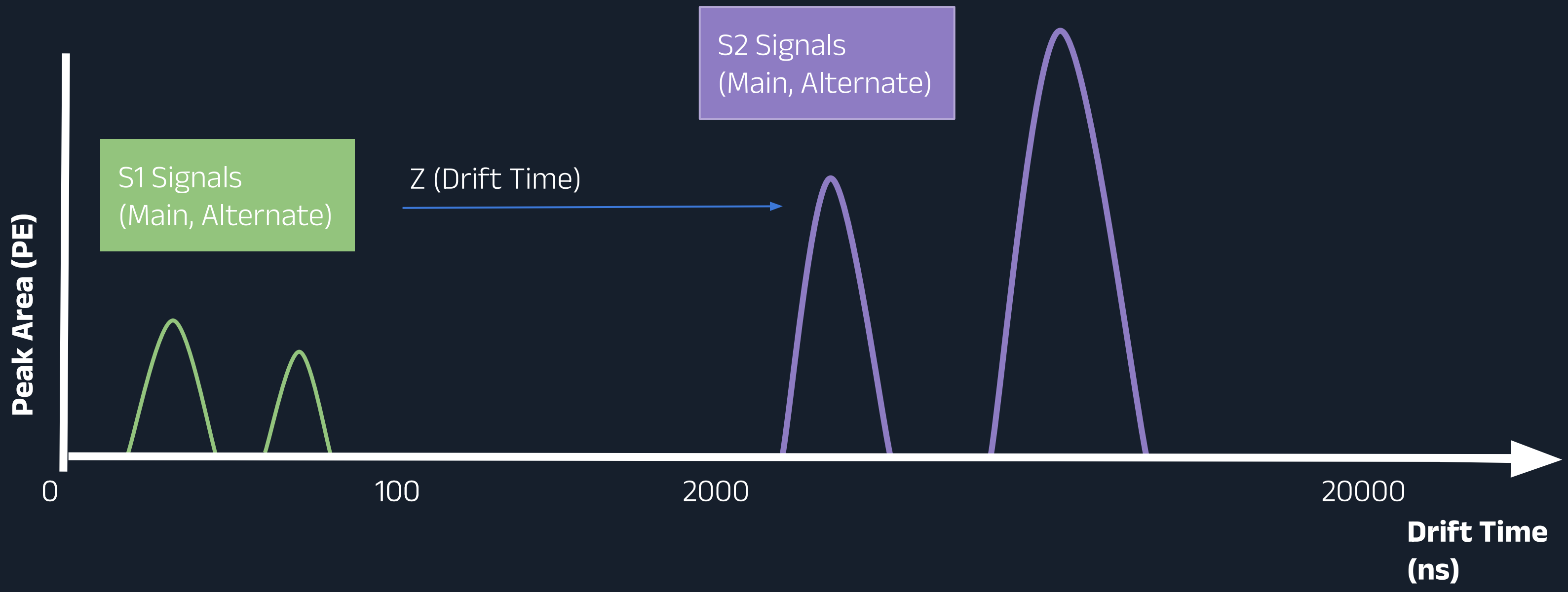


Phase 3

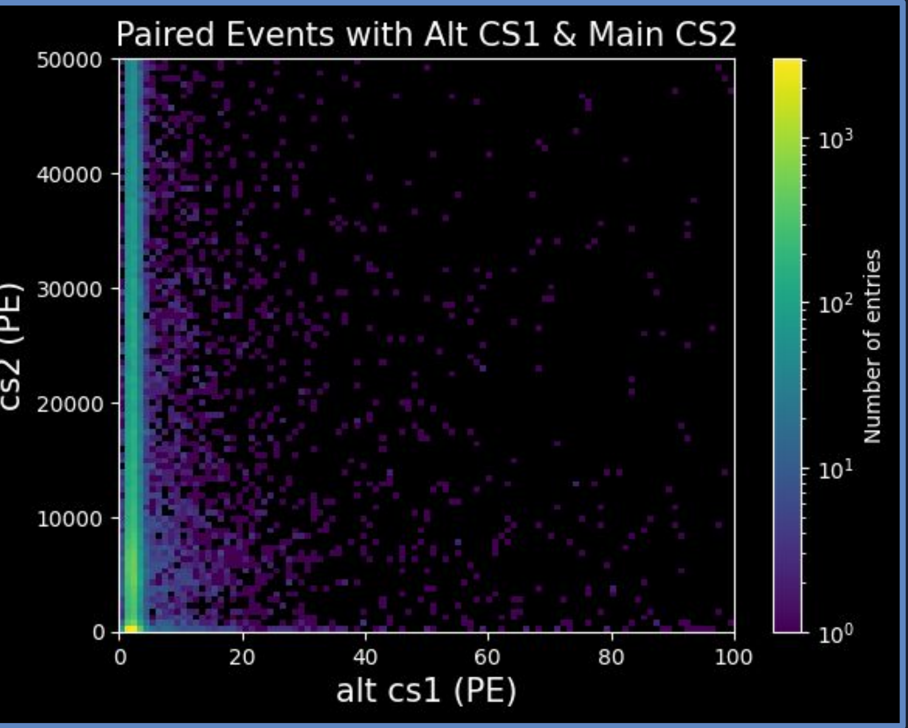
Final Phase: Density of saved mispaired events

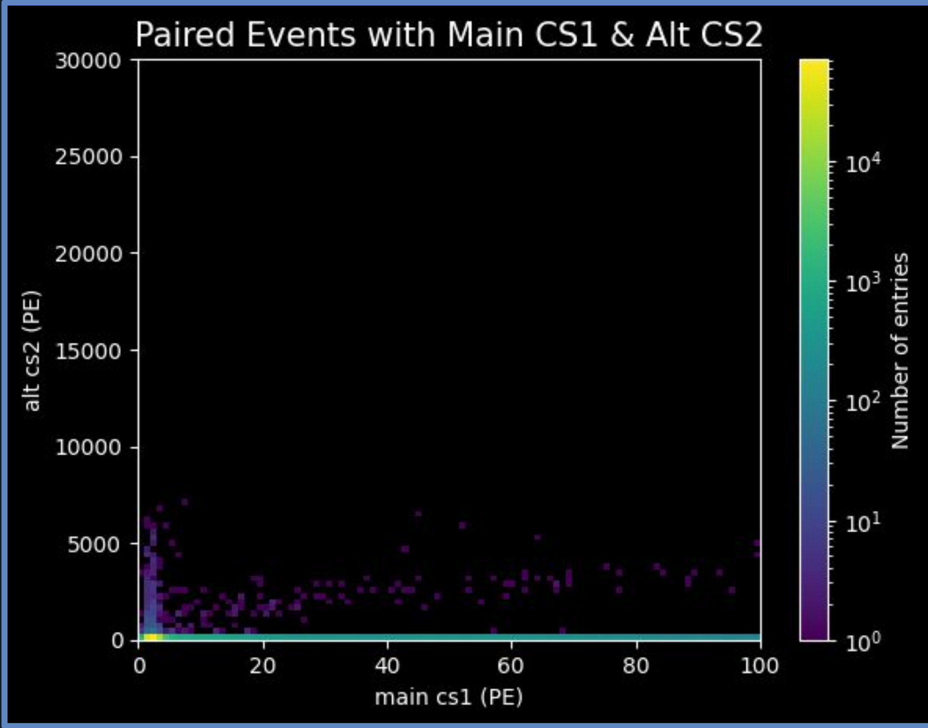
Process: pair alternate peaks with main peaks to observe mispaired events

Reconstruction of events using peak level data



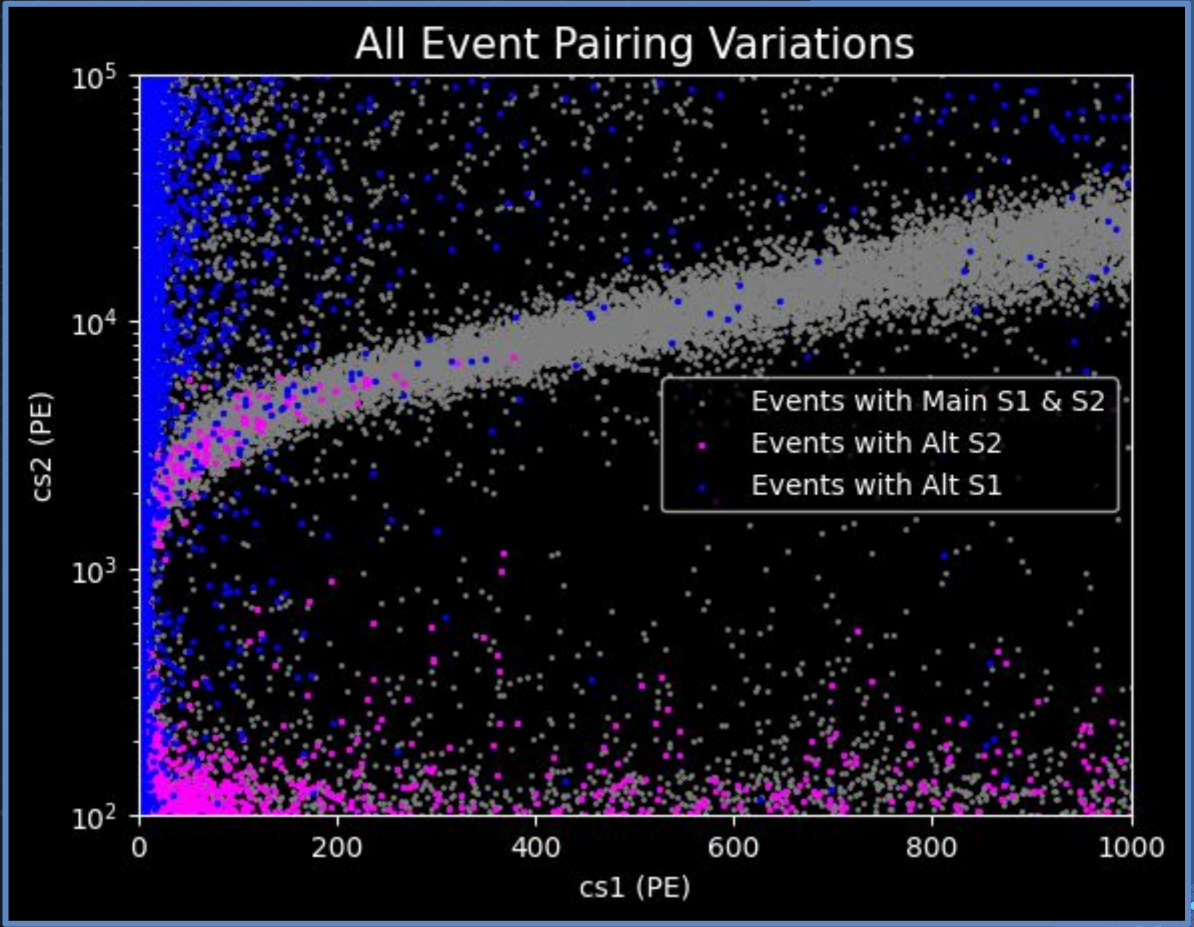
- ➢ Now I want to change which peak is being used for event reconstruction in event builder
- ➢ Alt S1 -> S2, S1 -> Alt S2
- ➢ See if the events in reconstruction look like physical events (exploratory process)



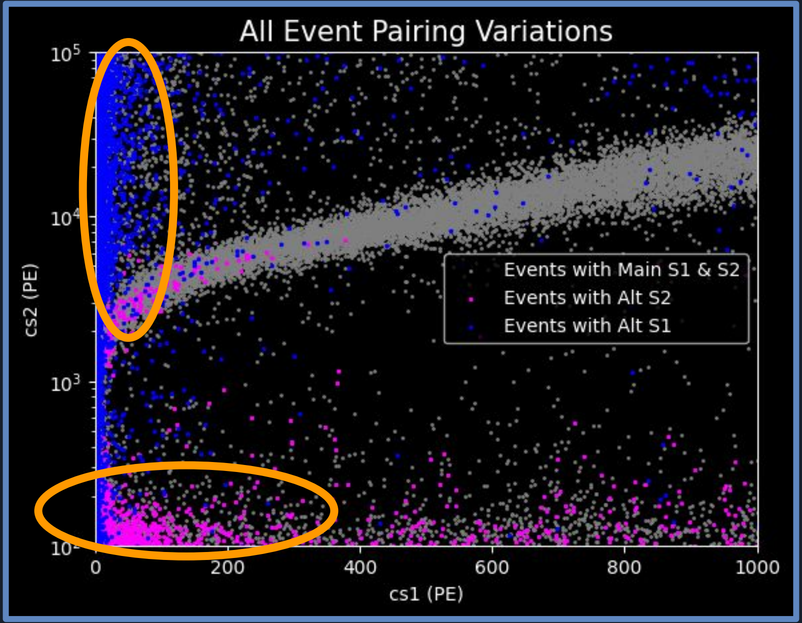


- 173 runs, 300 events per run
- Main S1 vs Alternate S2 event reconstruction is compelling evidence

- Evidence of alternate S1 peaks save events saved at lower PE
- Events with large PE not very compelling due to large signal/noise
    - Large areas rarely mispaired



Algorithm for AC Background Reduction



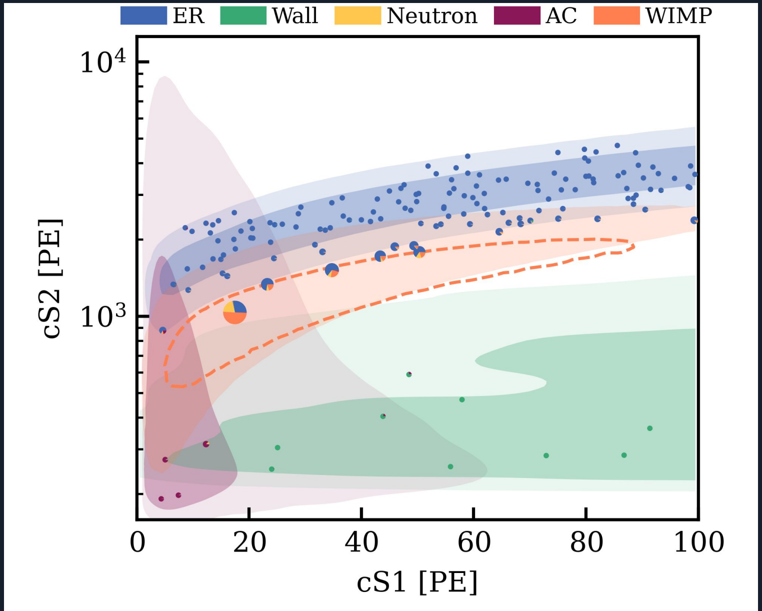
- Sufficient alternate S2 peaks constructed in expected range
- Reason: simultaneous high energy events block lower energy expected events
- Algorithm will save some mispaired events
  - May yield significant number of saved events in other data sets
- Large population of events constructed at low energies in modification
  - Reduction of AC background events
- Algorithm will still be useful, but will not yield a significant amount of correctly repaired events
  - Still useful for AC reduction

Takeaways

- ➢ Pairing algorithm in event builder may save mispaired events beyond low energy ER events (high energy ER, NR events)
- ➢ Many alternate peaks (using area) fall in AC range; only some events saved
- ➢ Initially designed for both AC reduction and saving mispaired events
  - Saving few events not very useful for data collection
  - Is useful for moving more events from AC background to ER-NR band
- ➢ Research goal changed in light of new data

Application/Project Future

- Krypton 83m calibration data: Detector stability & drift length corrections
  - Account for higher rate of electron cloud diffusion at deeper interactions
  - Physical pairing of events could remedy pile-up of events
- Data selection cuts used for p-value fitting should be reduced to a function
  - Algorithm generates singular best fit value from multiple functions
- Reduction of AC background improves selectivity of NR events
  - Also allows for higher signal acceptance for ER events



Thank You!

Questions?