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Improved Inverse Beta Decay event selection and its impact on the PROSPECT oscillation analysis

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On behalf of the PROSPECT collaboration

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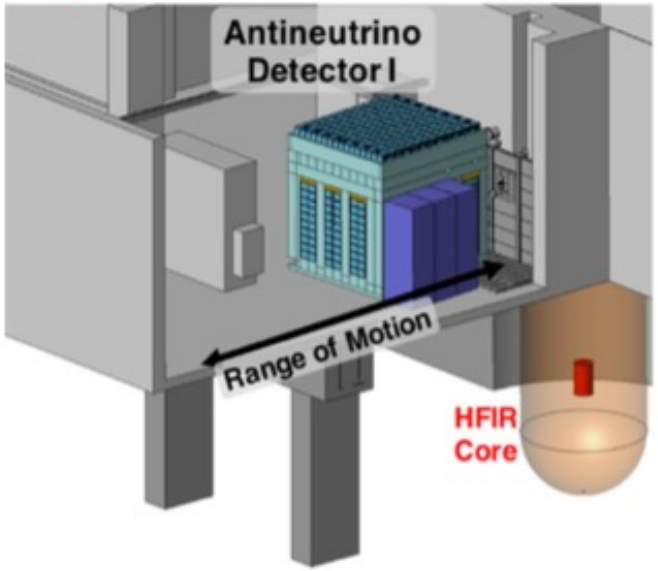
U.S. DEPARTMENT OF ENERGY

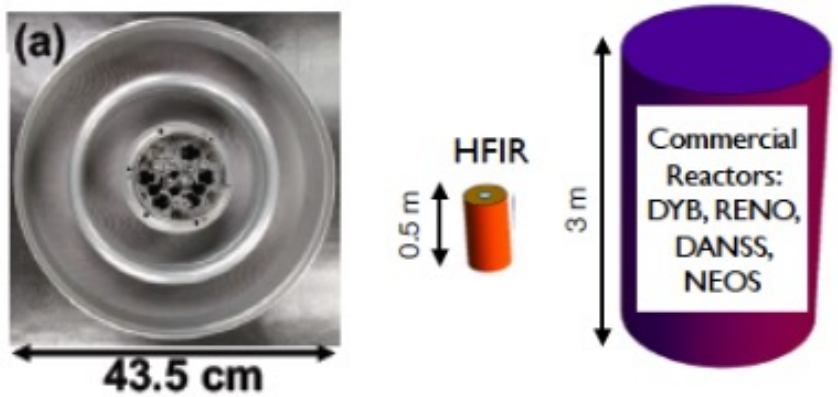
Physics Division

PROSPECT Detector at HFIR

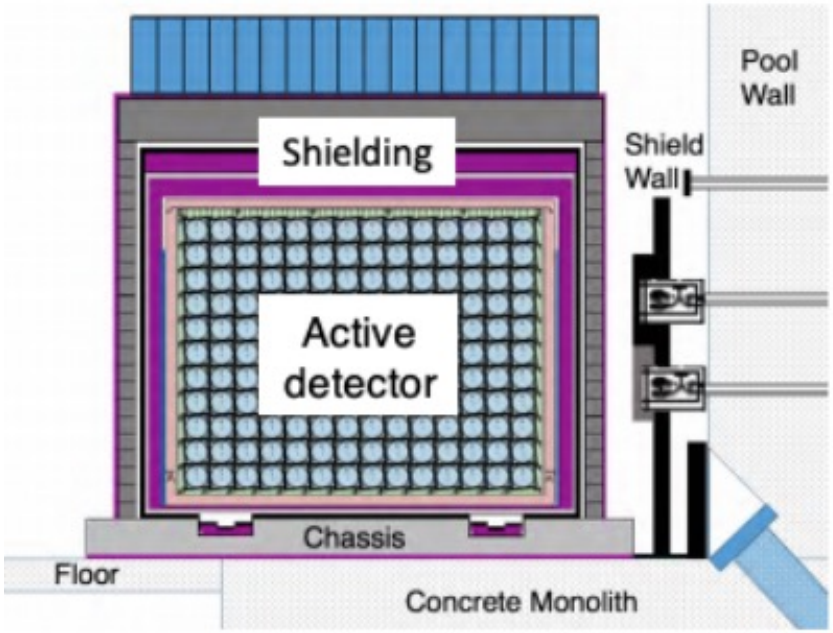
Layout of the PROSPECT experiment



- 93% 235U Fuel
- 85 MW thermal power
- Compact core
- Huge flux in the few MeV range
- ~50% duty cycle for BG measurements



Schematic of the active detector volume



14 x 11 array of 6Li doped liquid scintillator for detecting reactor antineutrinos (6.7-9.2 m from compact highly enriched uranium reactor core)

J. Ashenfelter et al. (PROSPECT), Nucl. Inst. Meth. A 922, 287(2019)

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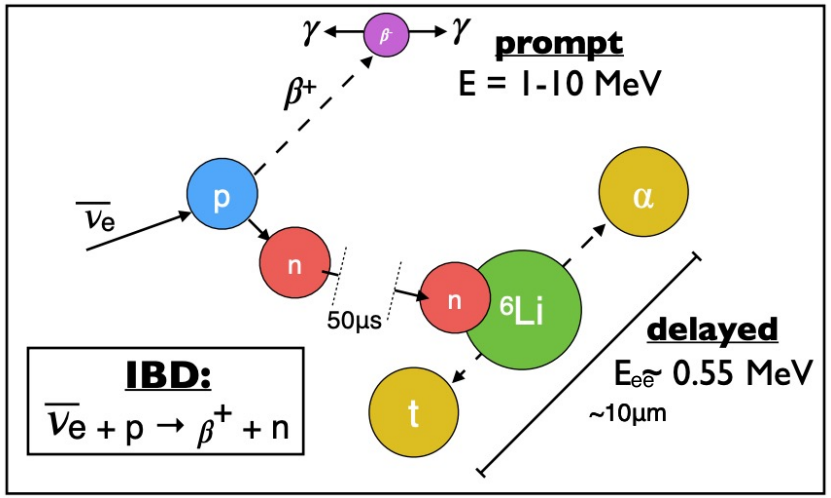
Antineutrino Detection

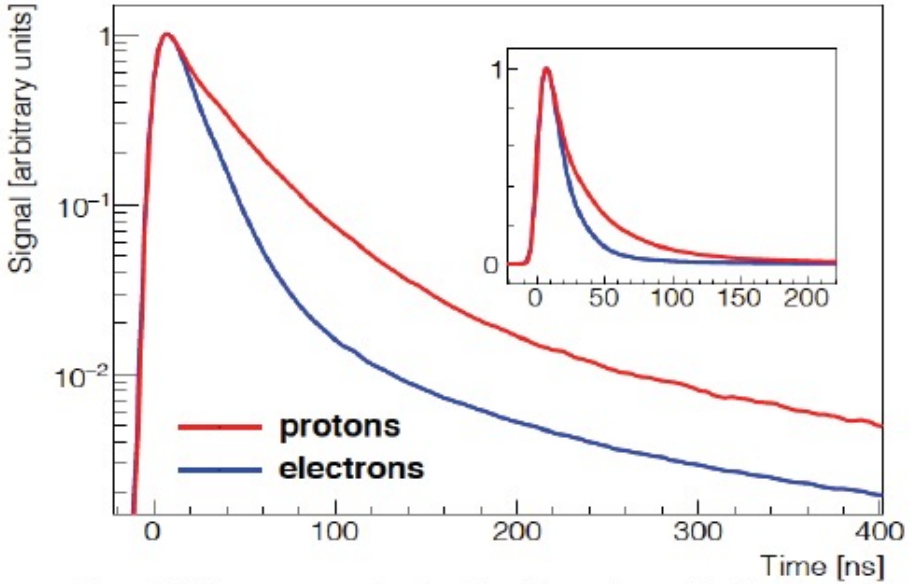
Use of the IBD process



- PROSPECT detects antineutrinos via the Inverse Beta Decay (IBD) process
- Prompt signal (e^+) provides a good energy estimate of incoming ν
- Localized delayed (n - ^6Li) signal

6-LiLS with PSD Capabilities

- Average waveforms for electronic/nuclear type events



- Differences in ionization density between electronic/nuclear recoil type events result in distinct pulse shapes for each event
- Prompt and delayed signal posses unique pulse shapes (different from background events)

M. Andriamirado et al. (PROSPECT Collaboration), Phys. Rev. D 103, 032001 (2021).

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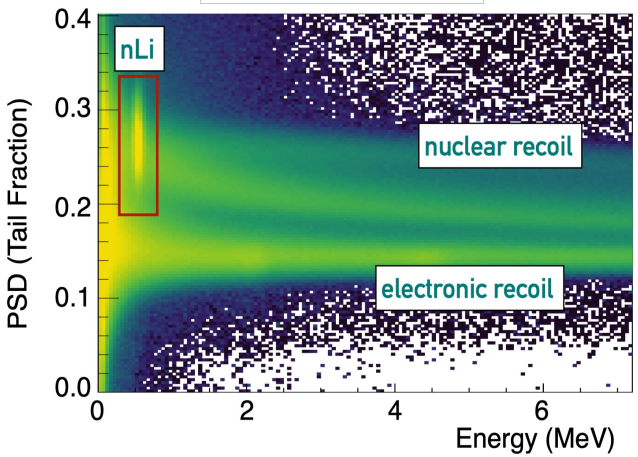
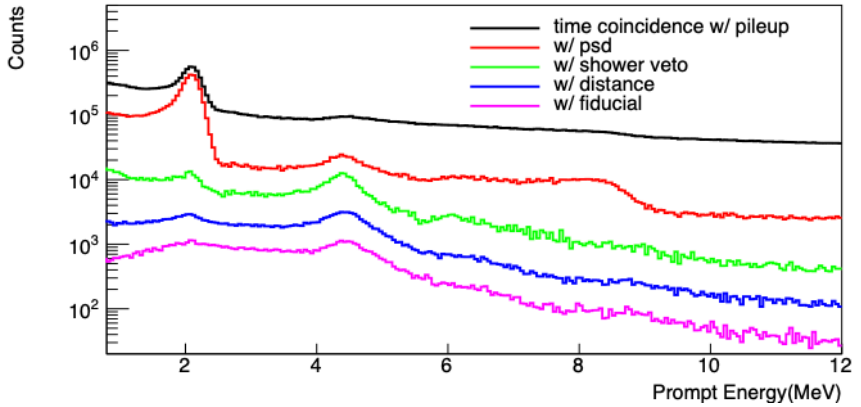
IBD Event Selection

- **IBD Topology-based cuts**
  - Neutron Capture Region
  - Prompt PSD
  - Prompt-Delayed signal distance
  - Prompt-Delayed Timing
  - Fiducial z cut
- **Veto cuts**
  - Muon Veto Time
  - Neutron Veto Time
  - Recoil Veto time

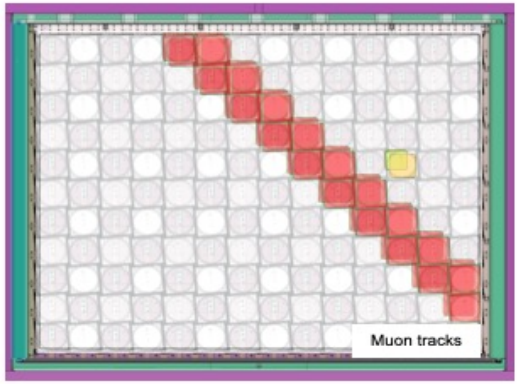
Prompt PSD Cut



Prompt Energy Distributions Under Different Cuts



Muon tracks in the PROSPECT detector



- Sequential application of selection cuts results in a significant reduction of background events
- These selection criteria was used for most recent results

M. Andriamirado et al. (PROSPECT Collaboration), Phys. Rev. D 103, 032001 (2021).

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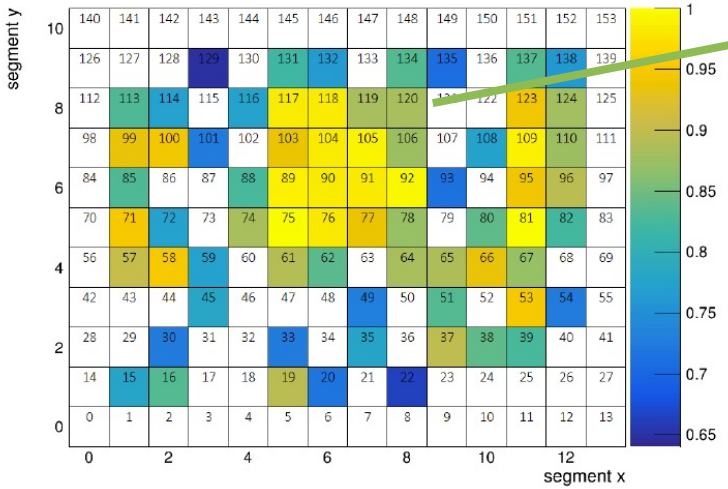
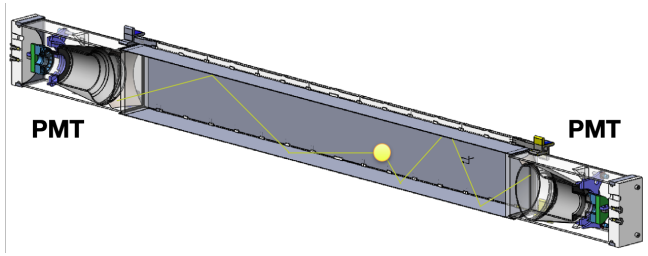
Motivation for a final PROSPECT-I Analysis

- Previous results were impacted by the periodic loss of photo-multiplier tube bases throughout data collection.

Detector configuration used for PRD analysis



154 segments with two PMTs



Some segments coupled to one PMT or both switched off due to scintillator leakage into PMT housing.

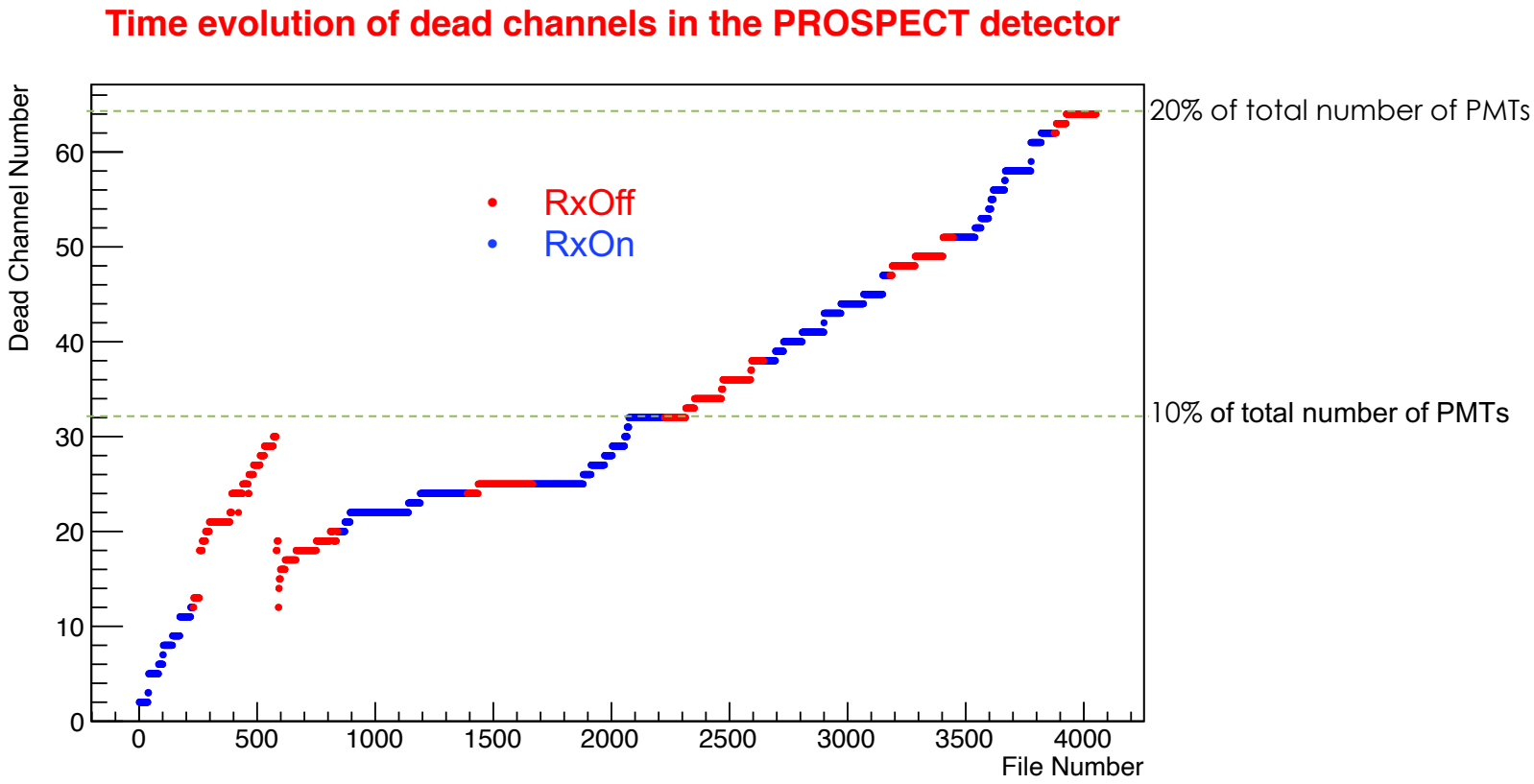
- In order to improve upon previous results, two new data recovery approaches have been proposed:

Data Splitting
&
Single Ended Event Reconstruction (SEER)

M. Andriamirado et al. (PROSPECT Collaboration), Phys. Rev. D 103, 032001 (2021).

First Approach: Data Splitting

- Split PROSPECT-I data into distinct periods in order to recover statistics.
- Maximize number of live segments in each period



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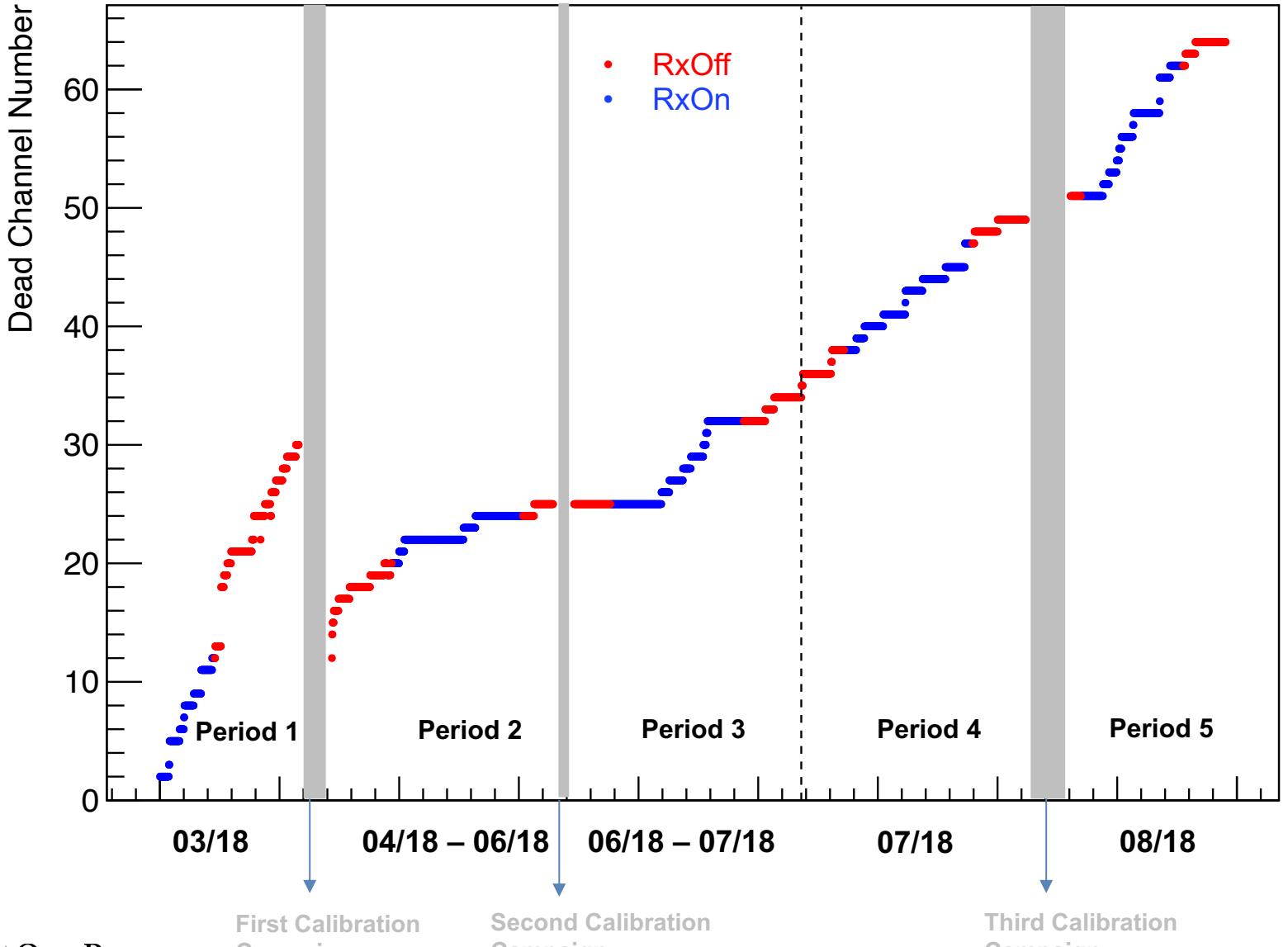
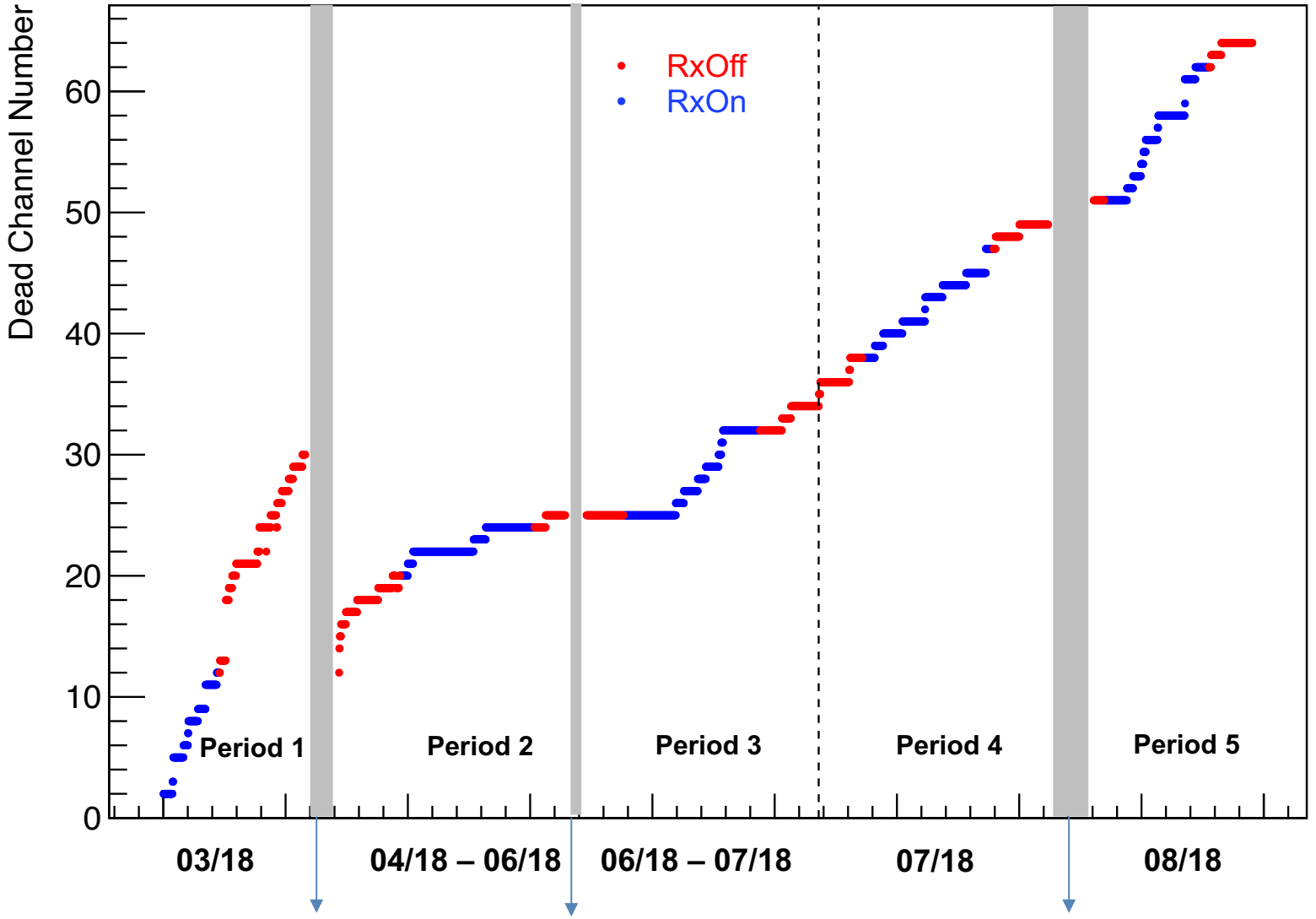
Criteria for Calibration-Based Splitting



- Each period should start immediately after a new calibration campaign
- Each period must contain one full RxOn cycle
- All periods should have RxOff data before and after each corresponding RxOn cycle
  - Period 1 is an exception since there is no prior RxOff data available.
- Keep ratio of RxOff/RxOn files between 50%-70%.
  - Since there is no calibration campaign between periods 3 and 4, we used the ratio of RxOff/RxOn files to define these two (70%).

Criteria for Calibration-Based Splitting



	Double Ended Segment	Single Ended Segment	Blind Segments
PROSPECT Latest Results	97	47(not-used)	10
Period 1	127	24	3
Period 2	131	21	2
Period 3	123	28	3
Period 4	110	39	5
Period 5	97	47	10

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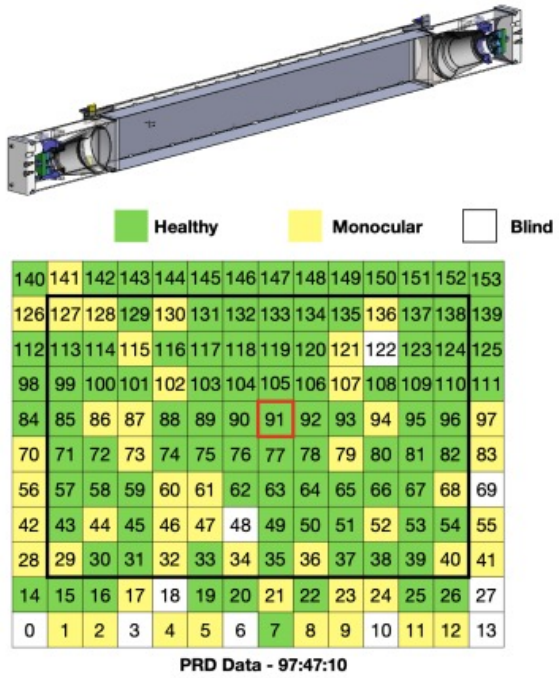
Second Approach: SEER

- The implementation of SEER into the existing analysis presents a great opportunity to improve our current results (statistics and S:B).
- Lacks energy and position reconstruction capabilities
- Provides a good handle on particle identification (great background suppression)



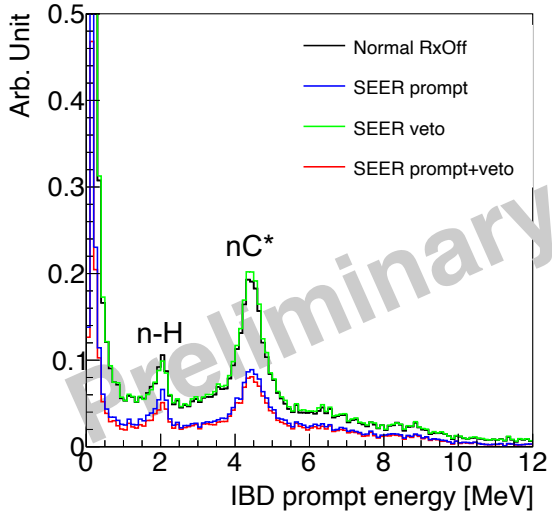
Prompt and delayed signal time coincidence

Exclude prompt signals containing high PSD events

Veto events coincident with cosmogenic muons and neutrons

Require proximity between prompt and delayed signals

Reject events outside of the fiducial volume



SEER prompt PSD reduces background by 2x

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IBD Event Selection + SEER - New Cuts Needed

- The implementation of SEER into the existing analysis presents a great opportunity to improve our current results.

- Existing cuts:
  - n-Li capture
  - Prompt PSD cut
  - IBD prompt-delay distance
  - Prompt-delay timing difference
  - Fiducial volumes
- Existing Vetoes
  - Muon veto
  - n-Li capture veto
  - n-p recoil veto
  - Pileup veto

+

New:

- SEER cut:
  - Prompt SEER PSD cut
- SEER veto:
  - Neutron (capture/recoil) veto

IBD Event Selection + SEER - New Cuts Needed

- The implementation of SEER into the existing analysis presents a great opportunity to improve our current results.

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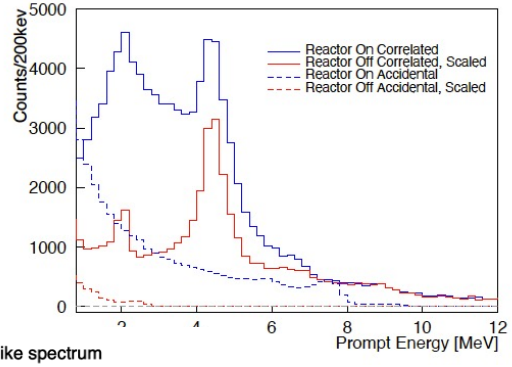
Cut optimization including new SEER cuts - metrics

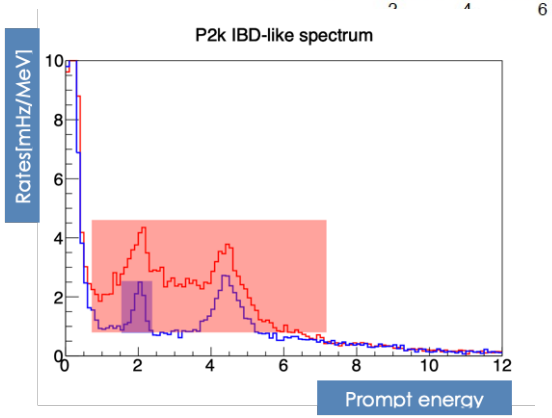
- In order to optimize the IBD selection cuts with the new SEER analysis the following data and metrics were considered:
  - 20% of the data used for the PRD
  - Effective IBD counts

$$\mathrm{IBD}_{\mathrm{Effective}} = \sum_{0.8MeV}^{7.2MeV} \frac{1}{(\sigma_{\mathrm{IBD}}/\mathrm{IBD})^2}$$

  - Signal to cosmogenic background ratio (S:CB)
  - Signal to accidental background ratio (S:AB)



  - nH peak signal to background ratio
  - nC peak signal to background ratio



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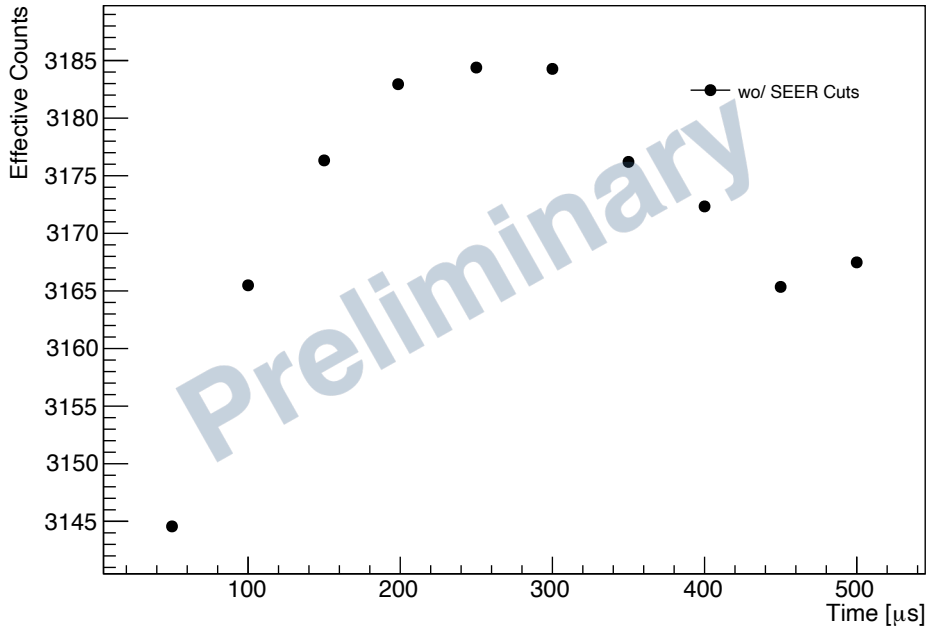
Cut optimization including new SEER cuts - example

Neutron Veto Time [μs]:

- IBD candidates are rejected if their delayed capture times are within μs of another n-6Li candidate



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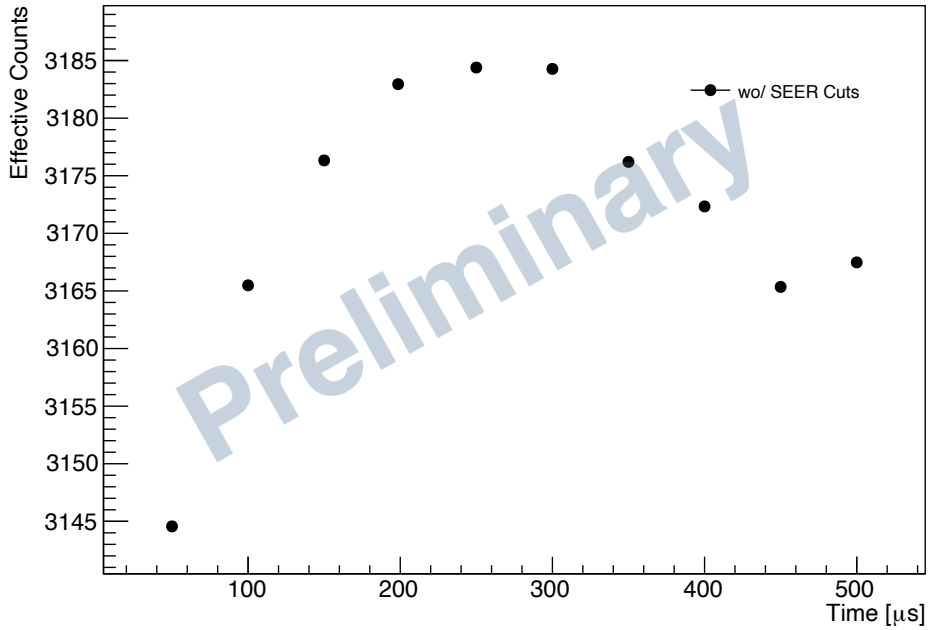
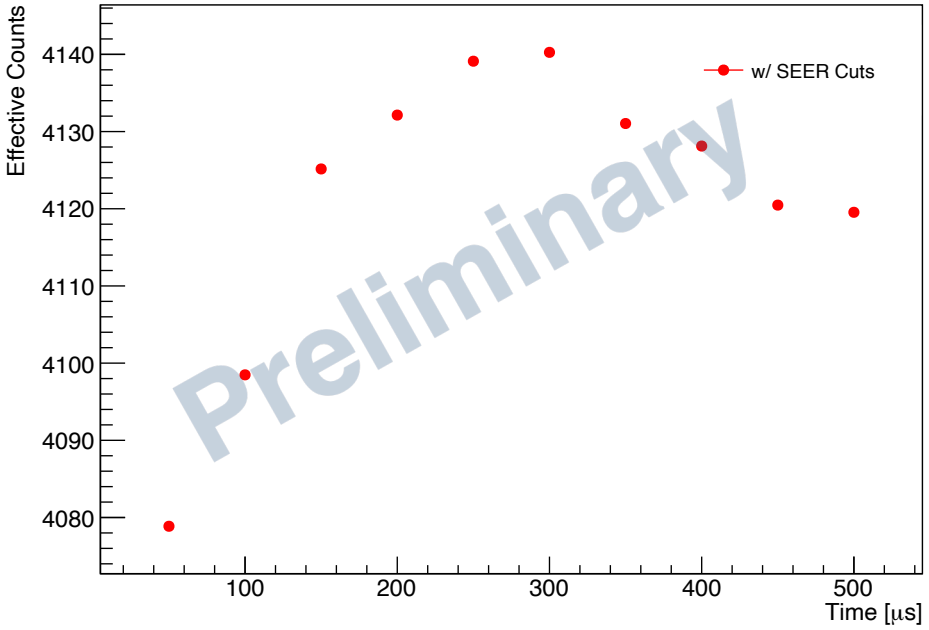


- Introduction of new SEER cuts into our optimization results in a ~30% increase in effective statistics
- Other metrics exhibit similar improvement



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Summary of Results with DS and SEER

Cut/Veto Name
Muon Veto Time
Neutron Veto Time
Recoil Veto Time
SE Recoil Veto Time
IBD Neutron Capture: PSD
IBD Neutron Capture: Energy
IBD PSD
IBD SE PSD
IBD SE PSD: Energy Threshold
IBD Distance
IBD Fiducial

Improved

Unchanged

New

	IBD Effective	IBD Effective/ calendar day	Total IBD counts	Total IBD counts/ calendar day
Latest PROSPECT Results	15312	160	50560	529
Period 1	3124	327	6446	676
Period 2	7054	306	17321	759
Period 3	6004	261	16027	691
Period 4	4345	197	13862	622
Period 5	2796	155	10473	589
DS Total	23325	244	64130	670

- An increase of **~50%** in effective statistics is expected when including SEER cuts into our IBD selection re-optimization

- Increase of ~**27**% in total IBD counts using DS
- Increase of ~**50%** in effective statistics sing DS

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PROSPECT

Summary of Results with DS and SEER

Cut/Veto Name
Muon Veto Time
Neutron Veto Time
Recoil Veto Time
SE Recoil Veto Time
IBD Neutron Capture: PSD
IBD Neutron Capture: Energy
IBD PSD
IBD SE PSD
IBD SE PSD: Energy Threshold
IBD Distance
IBD Fiducial

Improved

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f **~27**% in total IBD counts using DS

f **~50%** in effective statistics sing DS

Stay tuned for DS+SEER Analysis!

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June 2021 Collaboration Meeting, 43 Collaborators

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