First Results of the Search for Antineutrino Disappearance at SoLid

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on behalf of the SoLid collaboration
http://solid-experiment.org/

TAUP 2023
30th August

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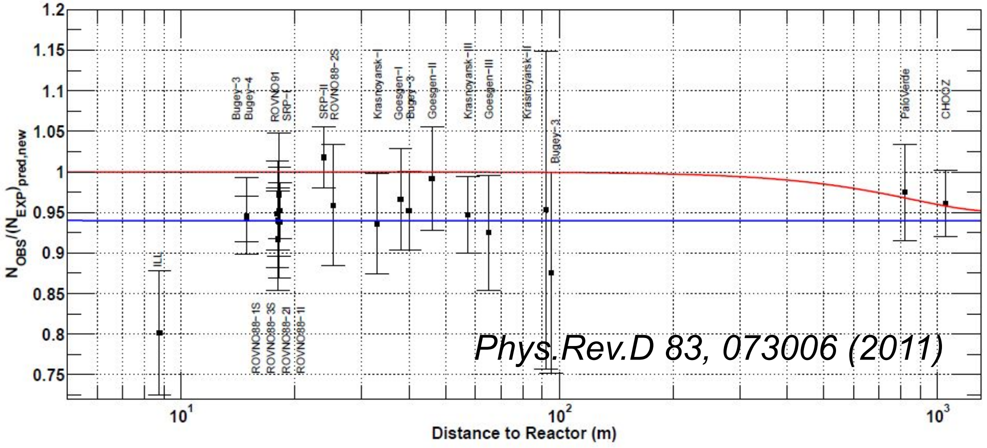
Experiment Goals

Probe the Reactor Antineutrino Anomaly (RAA)



Phys.Rev.D 83, 073006 (2011)

3+1 neutrino model

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

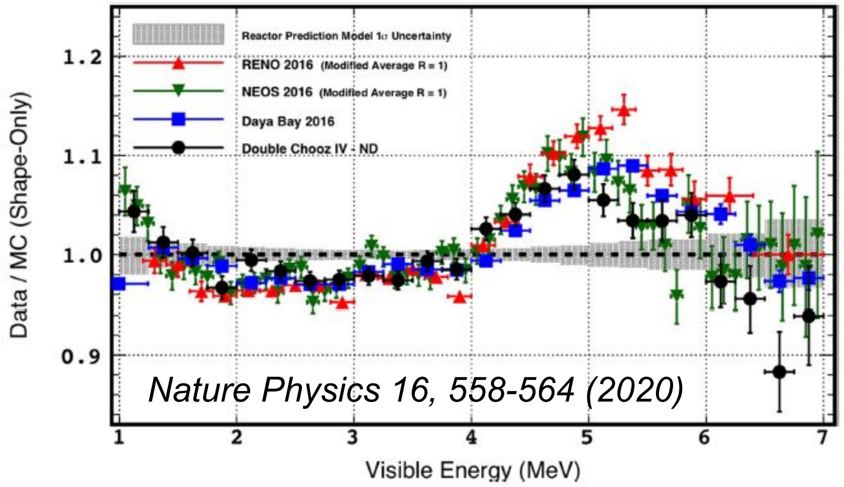
$$\Delta m^2_{\text{new}} >> \Delta m^2_{12}, \Delta m^2_{13}$$

$$|U_{e4}|^2, \; |U_{\mu 4}|^2, \; |U_{\tau 4}|^2$$

$$P_{ee} = 1 - \sin^2 2\theta_{\text{new}} \sin^2 \frac{\Delta m^2_{\text{new}} L}{4E}$$

$$\sin^2 2\theta_{\text{new}} = 4 |U_{e4}|^2 (1 - |U_{e4}|^2)$$

Precisely measure the U-235 antineutrino spectrum



Nature Physics 16, 558-564 (2020)

Unexpected distortion at ~ 5 MeV reported by antineutrino experiments at power (LEU) reactors (**^{235}U**, ^{239}Pu, ^{241}Pu and ^{238}U isotopes).

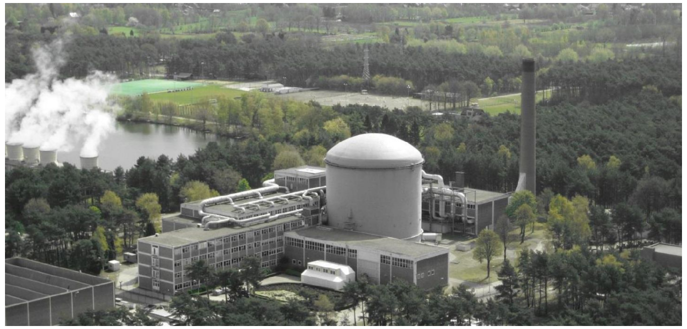
Recent indication from short-baseline liquid scintillator experiments at **^{235}U** research (HEU) reactors.

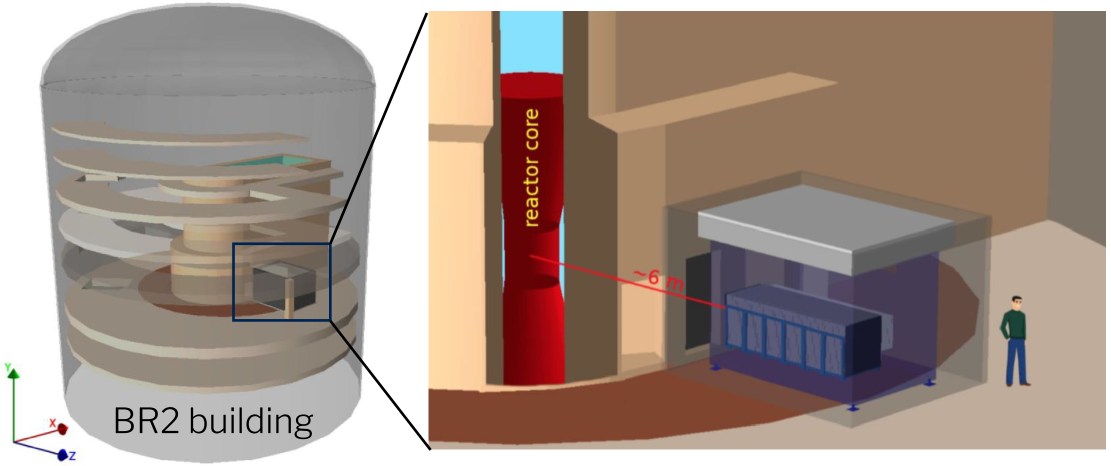
arXiv:2107.03371 [nucl-ex]

Experiment Location

Experimental site

- SCK CEN BR2 research reactor (Mol, Belgium)
- Very close to the reactor core (6 - 9 m)
- Low overburden (~ 6 - 8 m.w.e)

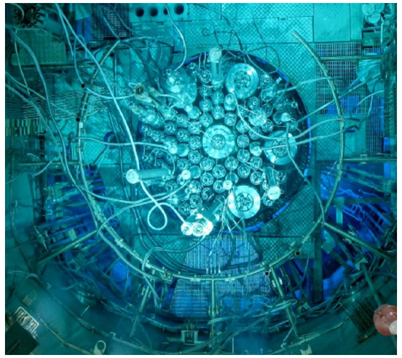


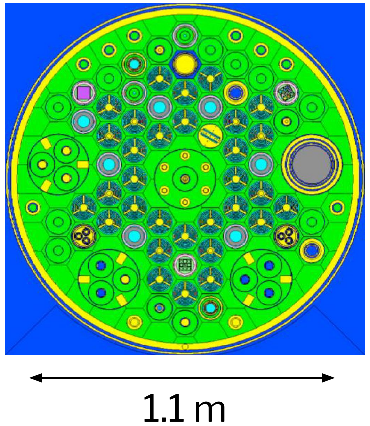


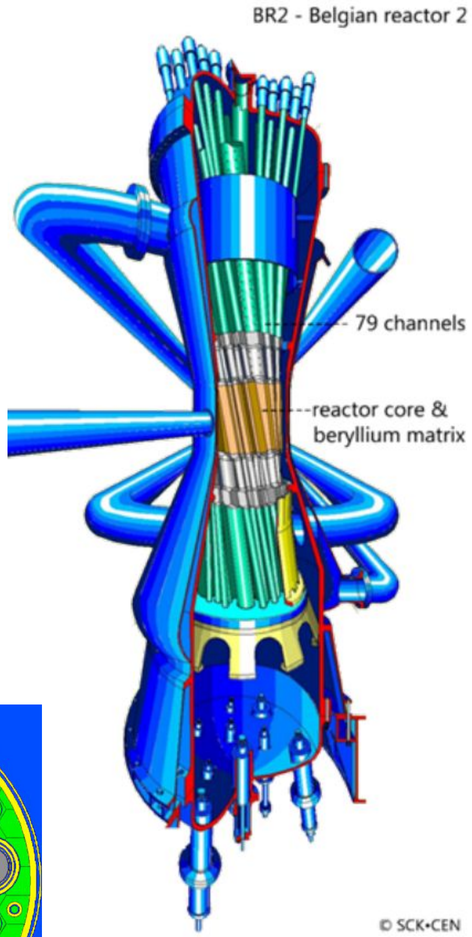
https://iopscience.iop.org/article/10.1088/1748-0221/16/02/P02025

BR2 research reactor

- Compact core (50 cm effective diameter) burning highly enriched ^{235}U (> 93.5%) fuel
- Variable operating power (45 - 80 MW) for an average of 6 cycles per year (~ 140 days)
- Low levels of (gamma, neutron) reactor background



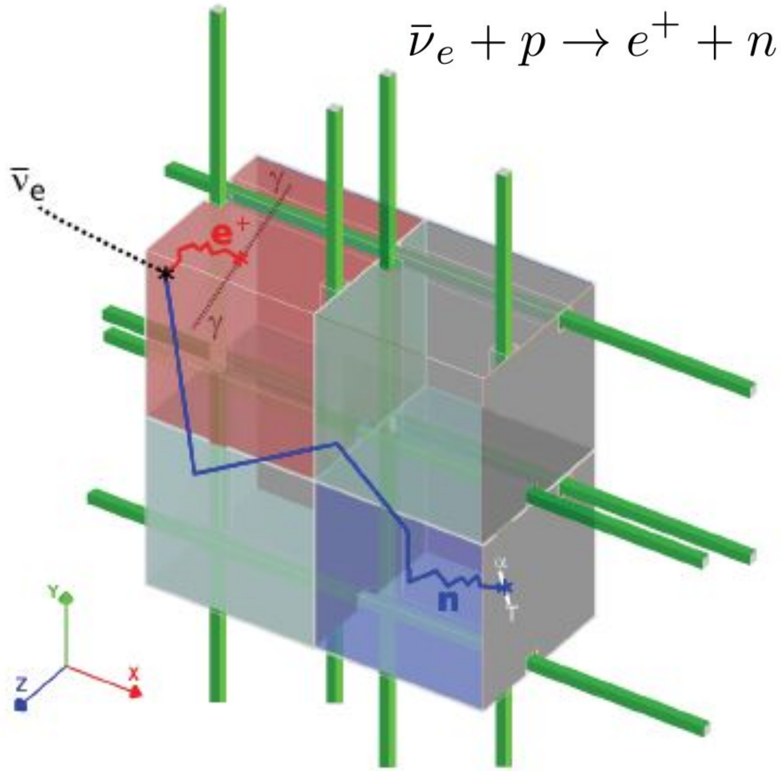




Antineutrino Detection Principle

- **Inverse beta decay** (IBD) interaction of electron antineutrinos detected using combination of two scintillators
- Basic detection cell comprises 5 cm PVT cube covered with two LiF:ZnS(Ag) screens, wrapped in reflective Tyvek, and crossed by four wavelength-shifting fibres for photon collection

$$\bar{\nu}_e + p \rightarrow e^+ + n$$



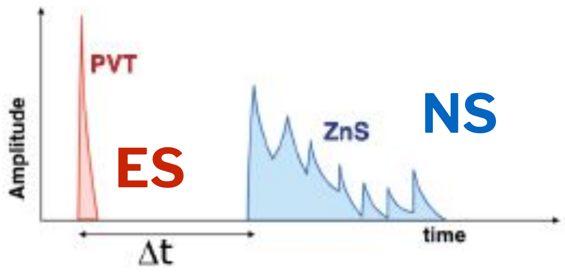
PVT cube for prompt signal: **ES** (electromagnetic scintillation)

- Energy deposit by positron carrying the antineutrino energy
- Two annihilation gammas (511 keV) are emitted

^{6}LiF:ZnS(Ag) sheets for delayed signal: **NS** (nuclear scintillation)

- Sheets cover two faces of each cube
- A thermal neutron is captured ~64 μs after the prompt signal

$$n + {}^6Li \rightarrow {}^3H + {}^4_2\alpha$$



Use the **temporal** and **spatial** coincidence between ES and NS waveforms to tag IBD interactions

SoLid Technology

Motivations

- Plastic scintillator (ELJEN EJ-200) provides alternative technology for antineutrino measurement
- Very good **linearity** of response
- High degree of detector segmentation allows isolation of the **positron energy** and reconstruction of **annihilation gammas**
- Event topologies used for classification of signal and background
- Complementary dataset for sterile neutrino and U-235 spectrum analyses

Challenges

- Very high background rates from different sources
- No direct **gamma-neutron PSD** so suppression of backgrounds requires **multivariate ML** techniques
- Large number of readout channels and parameters to calibrate
- Requires detailed understanding of complex detector

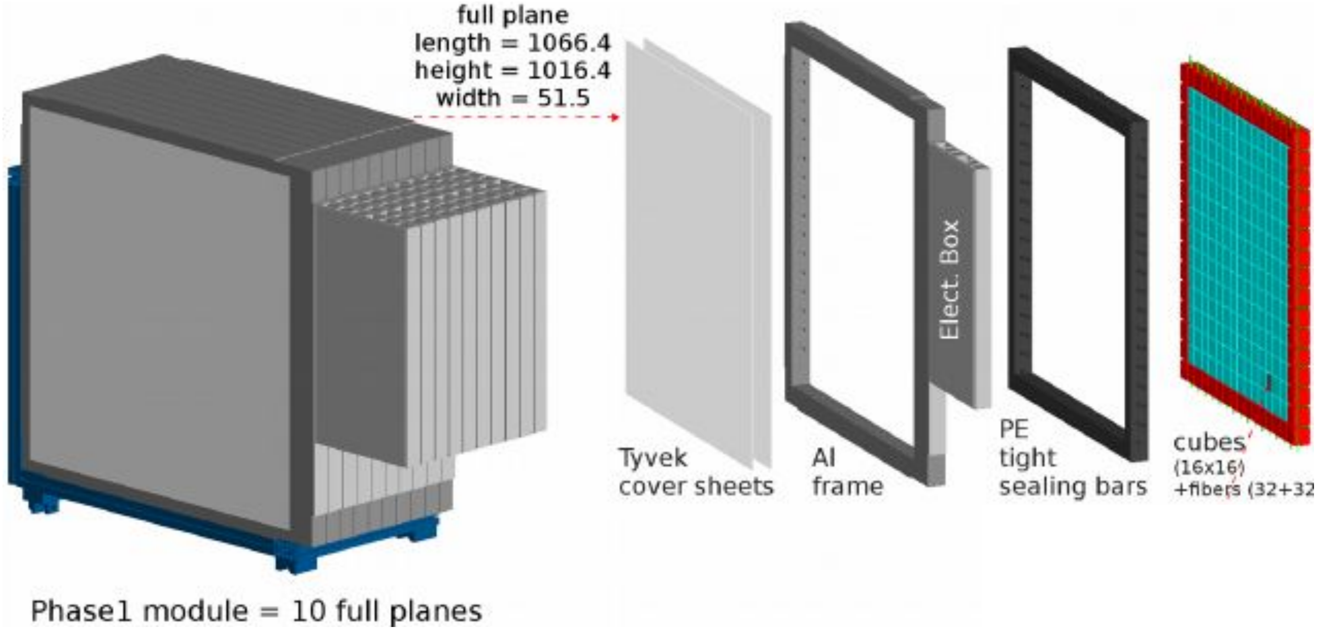
Phase-I Detector

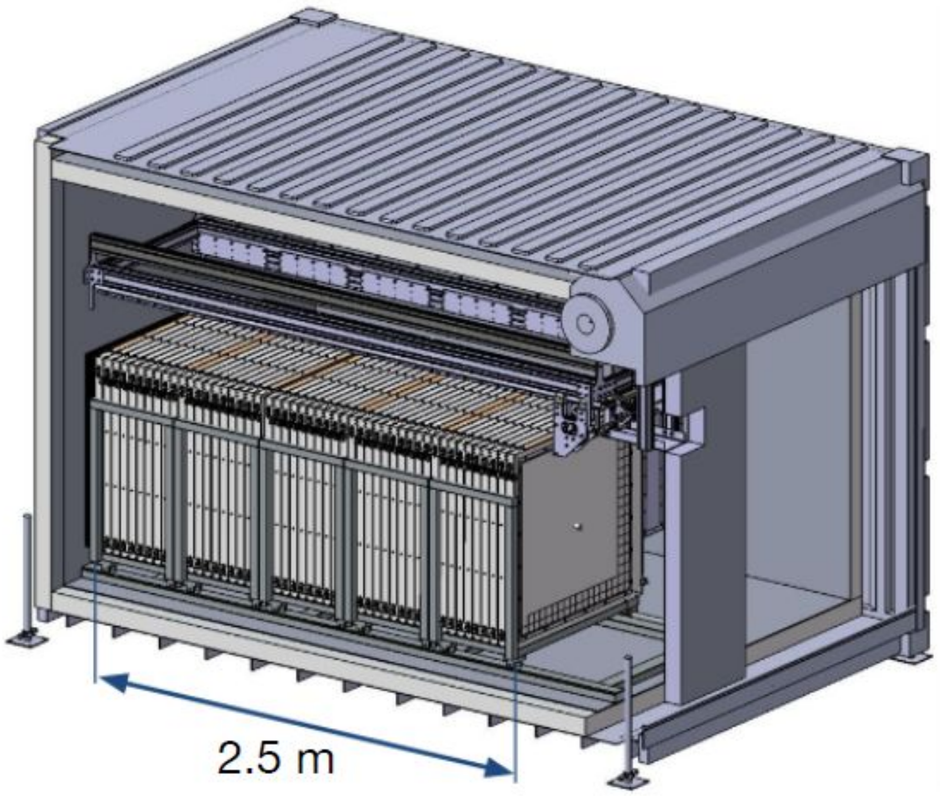
12800 PVT cubes (1.6 ton fiducial volume)

- 256 cubes per plane
- 10 planes per module
- 5 modules

3200 readout channels

- Signals detected by S12 series MPPCs (SiPM)



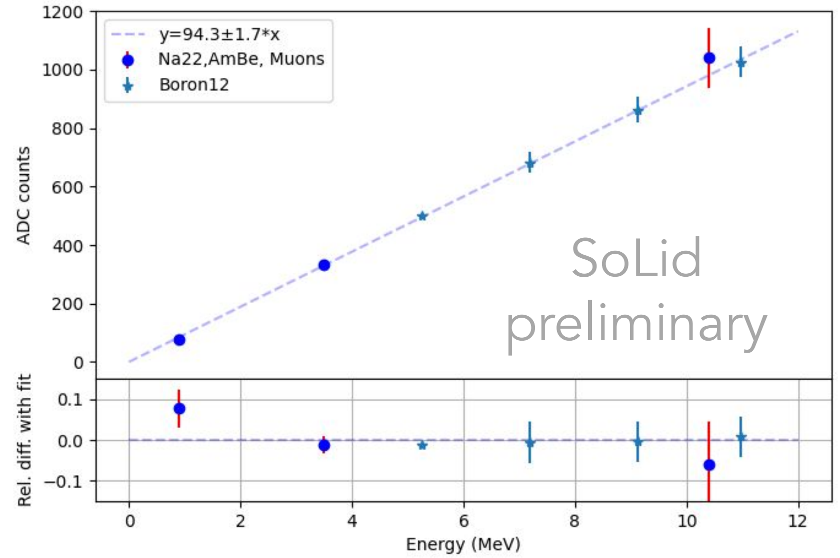


Detector modules mounted on rail system allowing for in-situ calibration with sources

Calibration

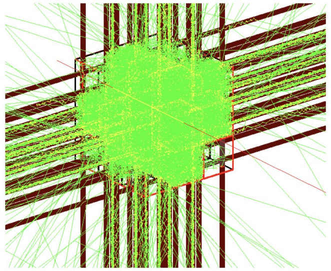
Absolute calibration

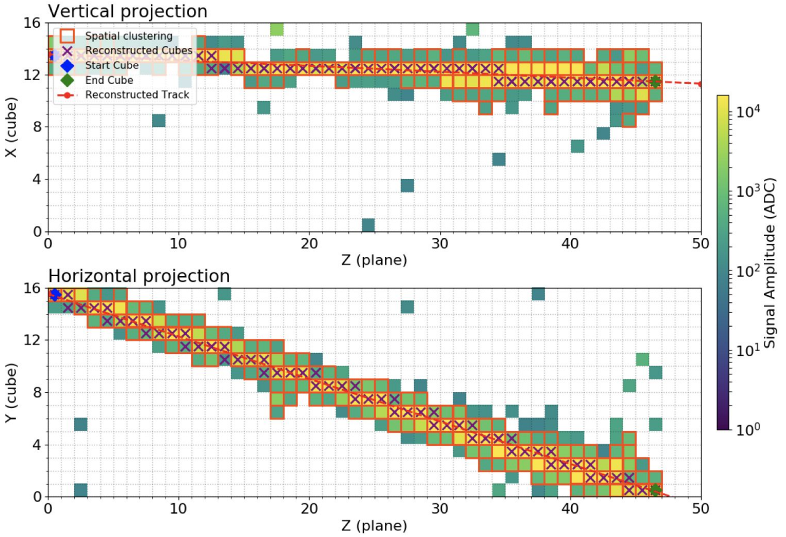
- Energy scale measured across entire spectrum:
  - Na22 (Compton edge KS test)
  - AmBe (e+e- at ~ 3.4 MeV)
  - Muons (~ 10 MeV)
- Light yield of 94 PA/MeV (16% resolution at 1 MeV)
- Very good linearity of response

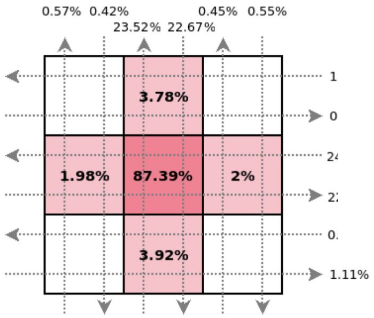


Relative calibration

- Cosmic muons used to equalise the response of cubes and channels
  - More practical than using sources, and can monitor the energy scale over time
  - Characterise light leakage between cubes
- Informs the detector response in simulations

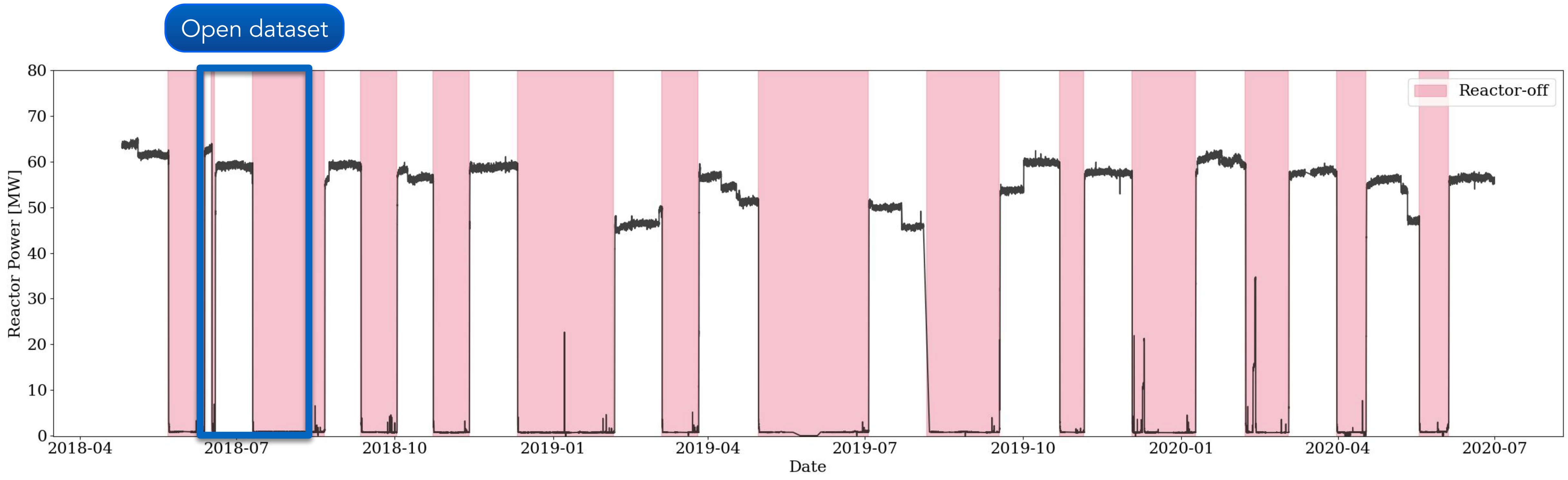




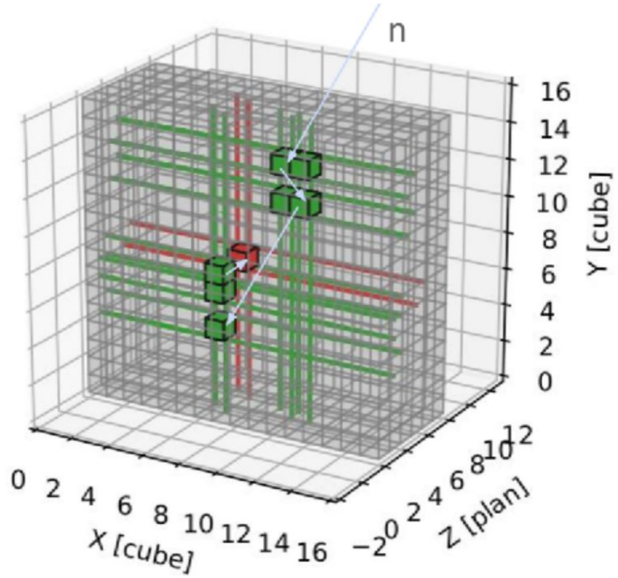


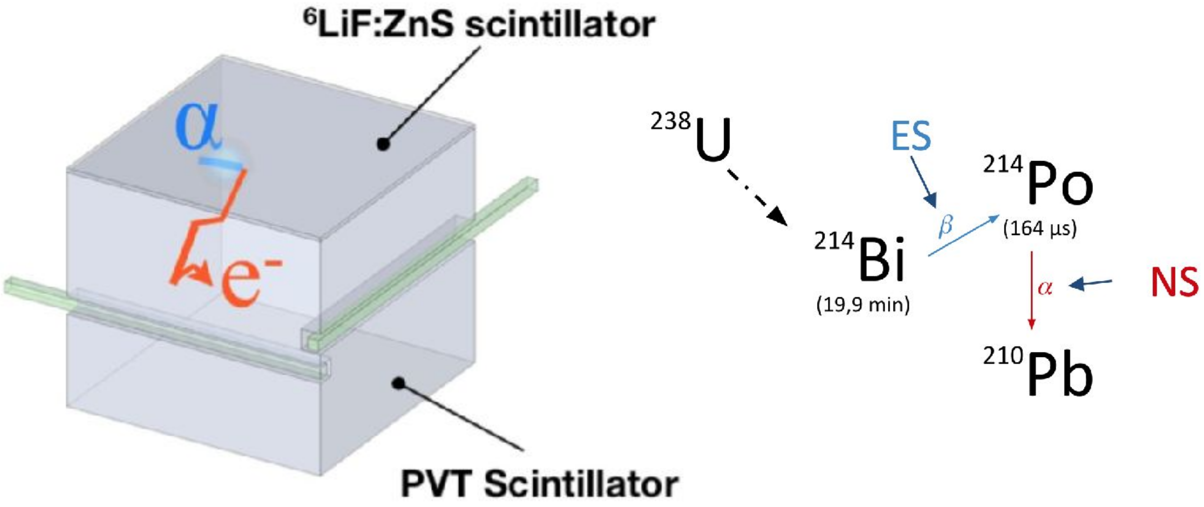
Phase-I Dataset

- Two years of data on tape in the Phase-I dataset, spanning 14 reactor cycles
- Physics data collected under ideal conditions (full shielding, low humidity, chilled container, etc.)
- Stringent data-quality criteria filter and reject faulty data, leaving approximately **300** days and **180** days of **reactor-on** (ROn) and **reactor-off** (ROff) data respectively for an oscillation analysis



Antineutrino Backgrounds





Fast Neutrons (external)

- Fast neutrons from cosmic-ray-induced atmospheric showers & spallation neutrons
  - Proton recoil events: ES
  - Neutron capture: NS

BiPo (internal)

- Radioactive decays from the U-238/Th-230 decay chains
  - ^{214}Bi decay (e^-, γ): ES
  - ^{214}Po decay (α): NS
- Contaminant found mostly in the LiF:ZnS(Ag)
- Alpha generates similar NS as Li n-capture

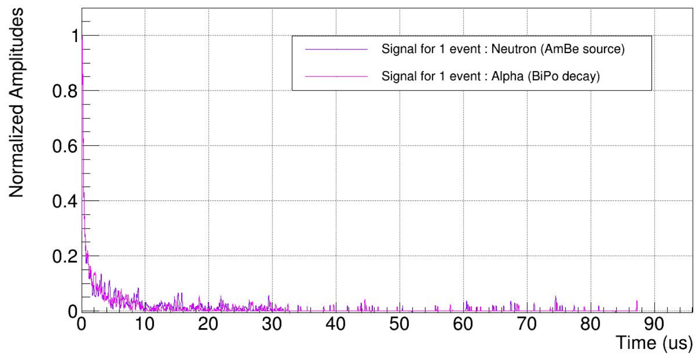
BiPonator: PSD Method

Convolutional Neural Net

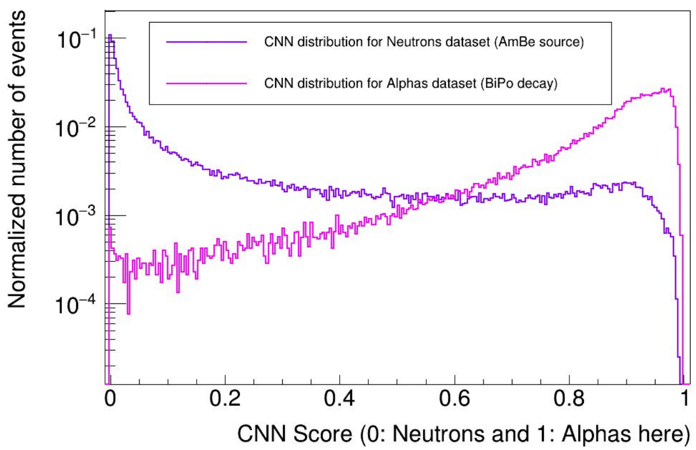
Alpha / **Neutron** discrimination with CNN to reduce BiPo background

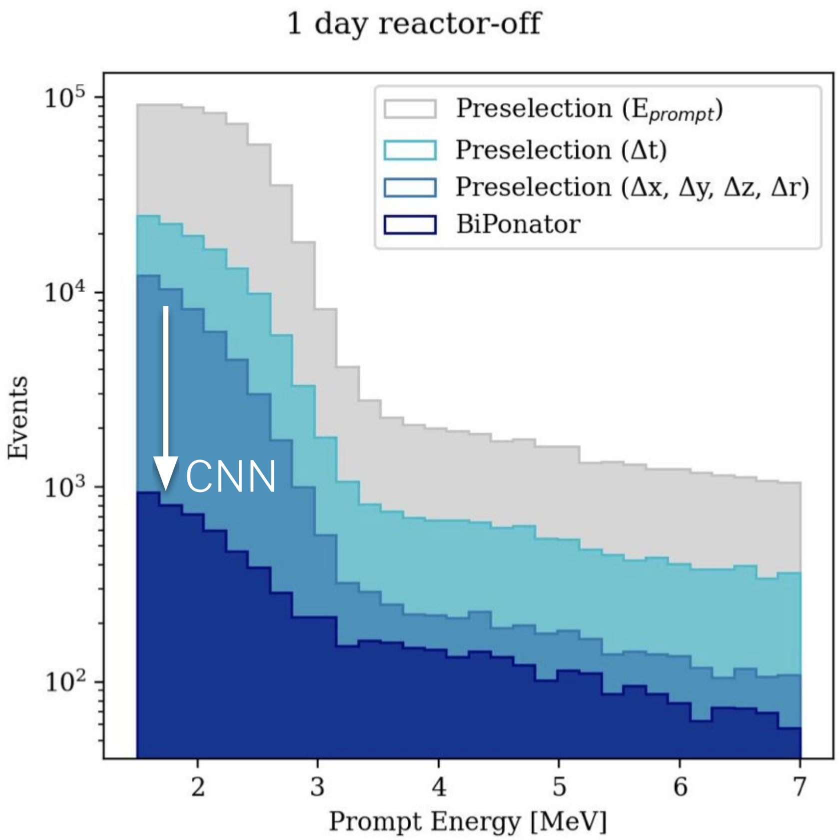
- Utilise difference between ZnS NS waveforms from BiPo alphas and Lithium-6 neutron capture for PSD
- Able to reject 95% of BiPo background for 80% neutron efficiency
  - Significant improvement over the previous charge integration method (known as BiPonisher)

CNN Input



CNN Output

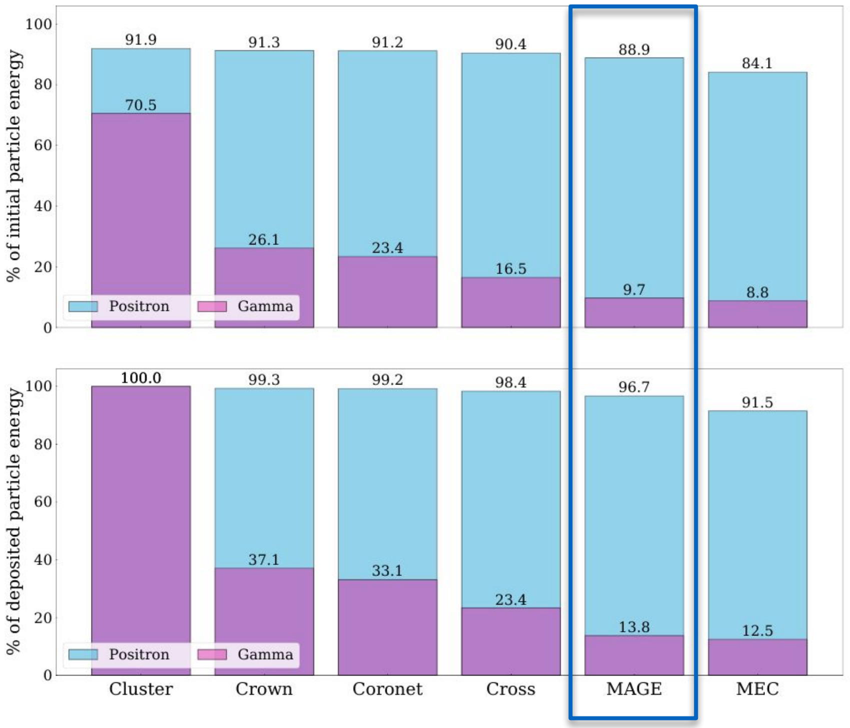


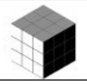
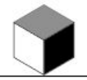


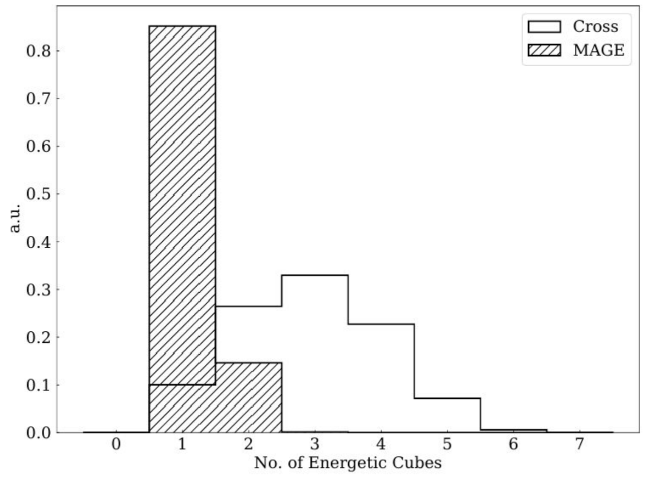
NEW

ES Energy Estimator

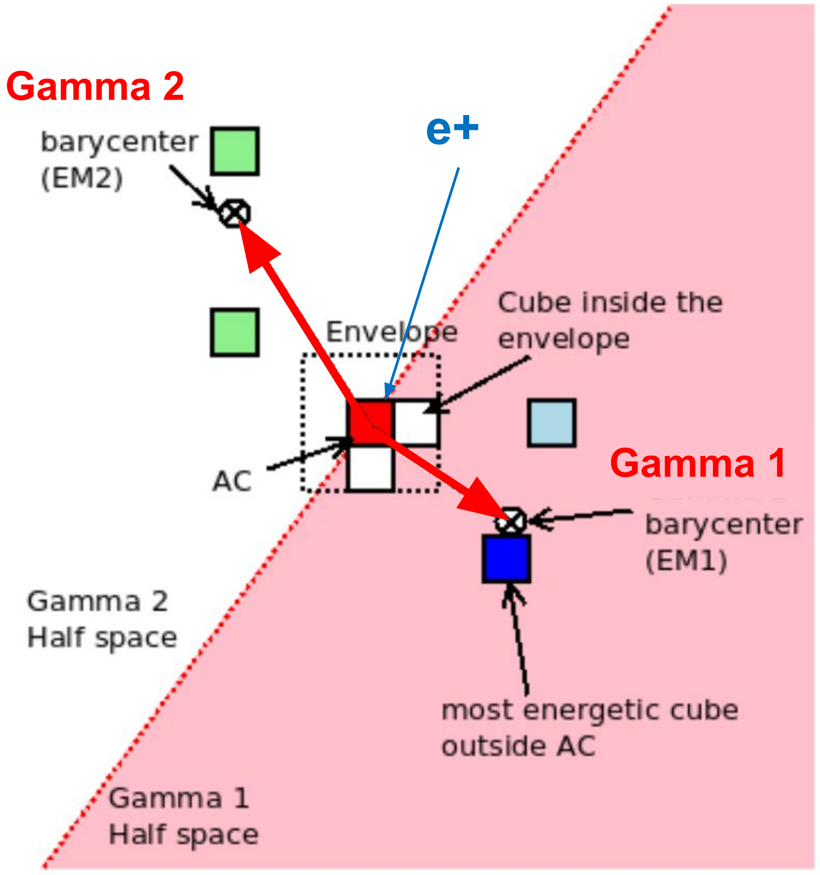
- Comprehensive study to find optimal positron energy estimator
- “MAGE” variable retains nearly 97% of the deposited positron energy whilst excluding 86% of the deposited annihilation gamma energy
  - The latter is crucial for event classification and background discrimination



No.	Estimator	Conditions for cube inclusion	Illustration
1	Cluster	–	
2	Crown	$\Delta X \leq 1,\ \Delta Y \leq 1,\ \Delta Z \leq 1,\ \Delta R \leq \sqrt{3}$	
3	Coronet	$\Delta X \leq 1,\ \Delta Y \leq 1,\ \Delta Z \leq 1,\ \Delta R \leq \sqrt{2}$	
4	Cross	$\Delta X \leq 1,\ \Delta Y \leq 1,\ \Delta Z \leq 1,\ \Delta R \leq 1$	
5	MEC	$\Delta R = 0$	
6	MAGE	$E_{cube}/E_{cluster} \geq 0.2$ and $\Delta R \leq 1$	

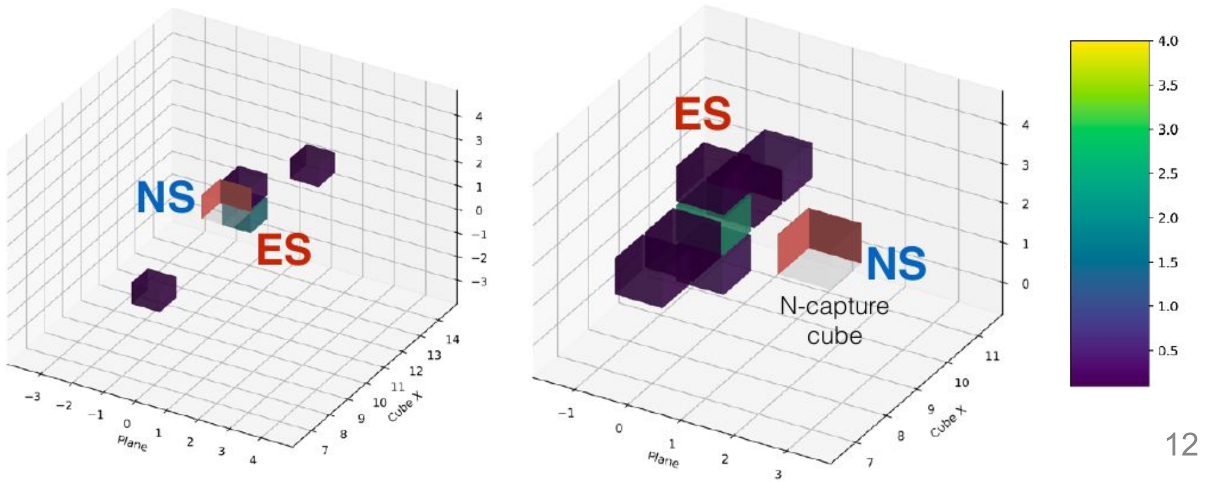


Event Topology Classification



Annihilation gammas reconstruction

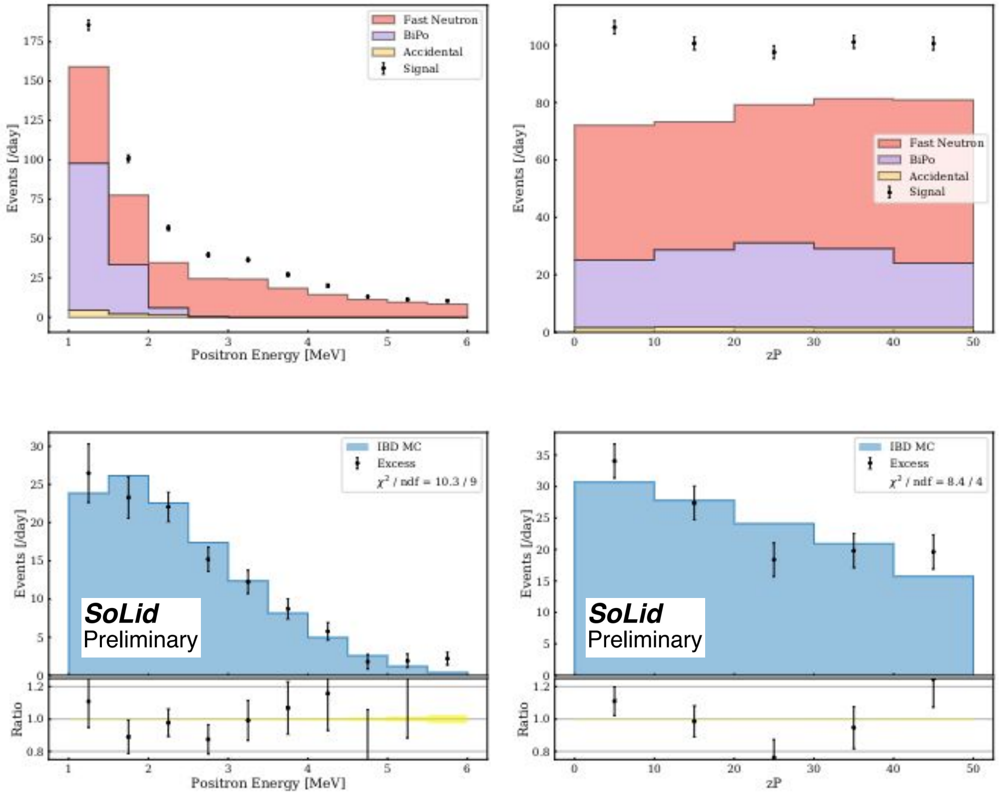
- Detector segmentation allows detailed categorisation of event topologies
- Locate highest energy gamma cube detached from the positron then split the detector into two hemispheres and search for second detached cluster
- Construction provides high-level input variables, based on known IBD kinematics, for ML analyses



IBD Analyses

Boosted Decision Tree Analysis

- nuBDT (2+1γ selection)
  - Maximal use of detector granularity and event topologies to discriminate signal from background
  - Flat efficiency selection for signal in oscillation variables



Background Subtraction

- Performed sequentially per background type
- Data-driven: each background can be isolated in dedicated sideband regions
- Parallel analysis focusing on the cleanest 2γ topologies (currently being finalised) will complement this with a 2D simultaneous fit instead of a subtraction

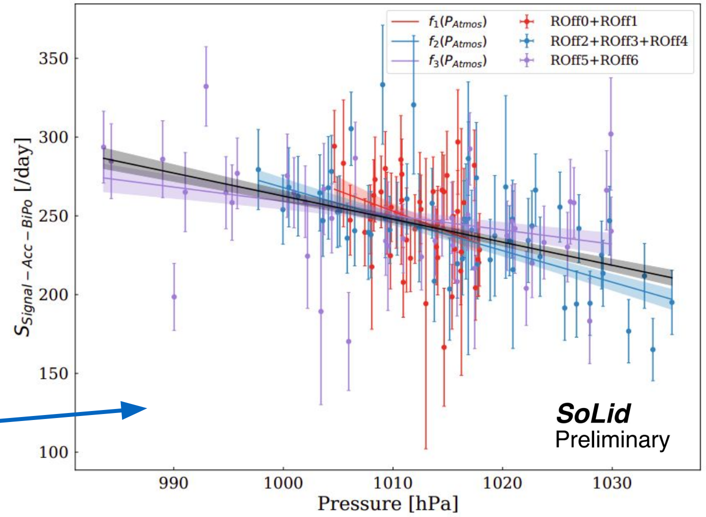
Analysis on the *open dataset* with the optimised nuBDT selection gives:

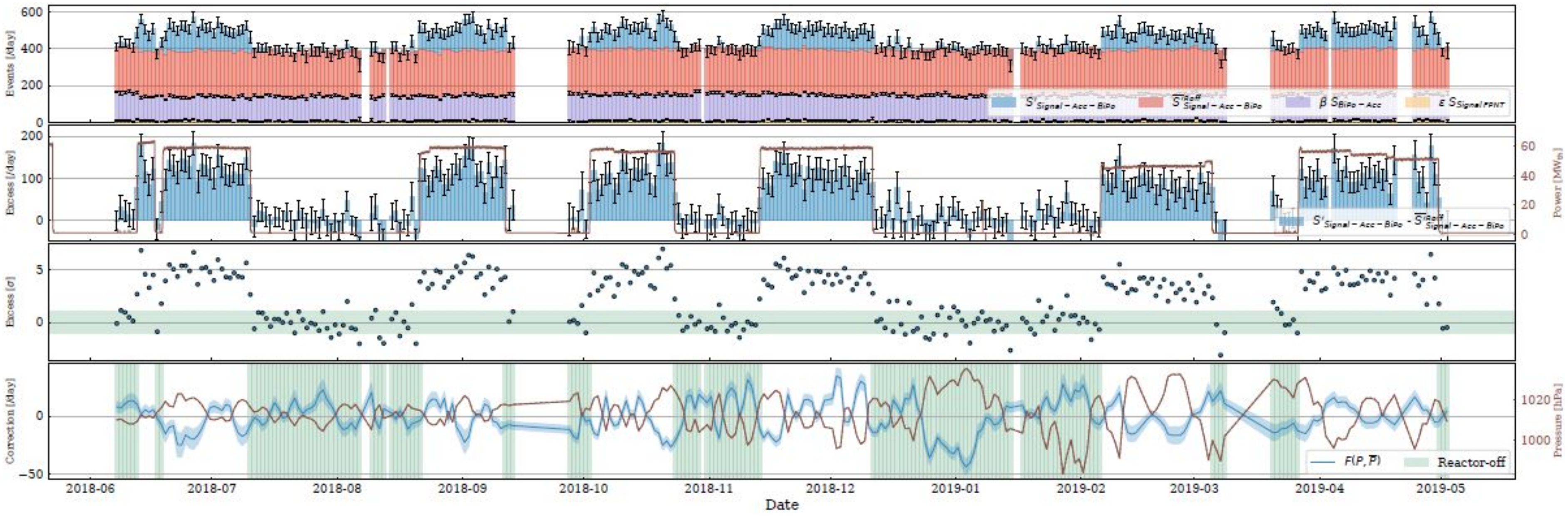
- IBD excess of **120 events per day**
- Signal-to-background ratio of **0.30**

Signal Extraction

Rate analysis on (first) half of Phase-I

- Stable signal subtraction, dominated by atmospheric neutrons
  - Excess consistent with zero for reactor-off data
- Fast neutron background rate pressure-corrected using multiple local models over Phase-I





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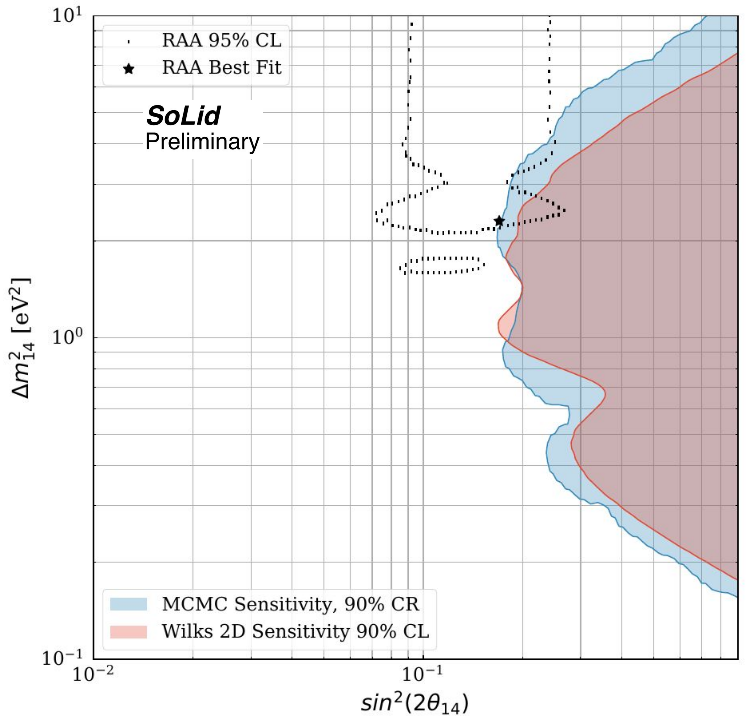
Oscillation Fits

Preliminary Phase-I Summary

- 29644 ± 605(stat) IBD events
- S/B = 0.27



Frequentist Confidence Interval ($\Delta\chi^2$)

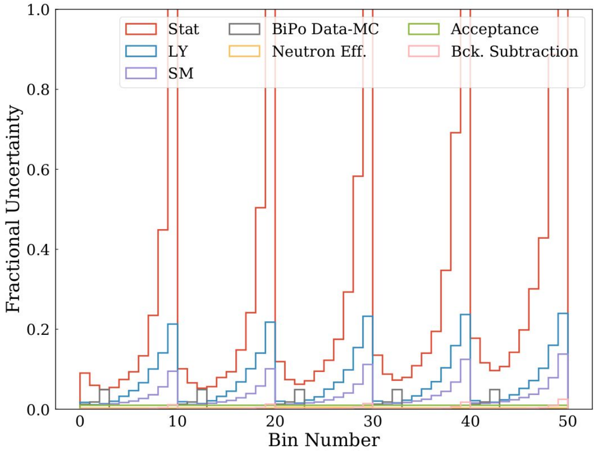
- Standard approach based on Feldman-Cousins toy generation (in progress)
- Wilk's theorem used for now to give an (overestimated) idea of the coverage ⇒

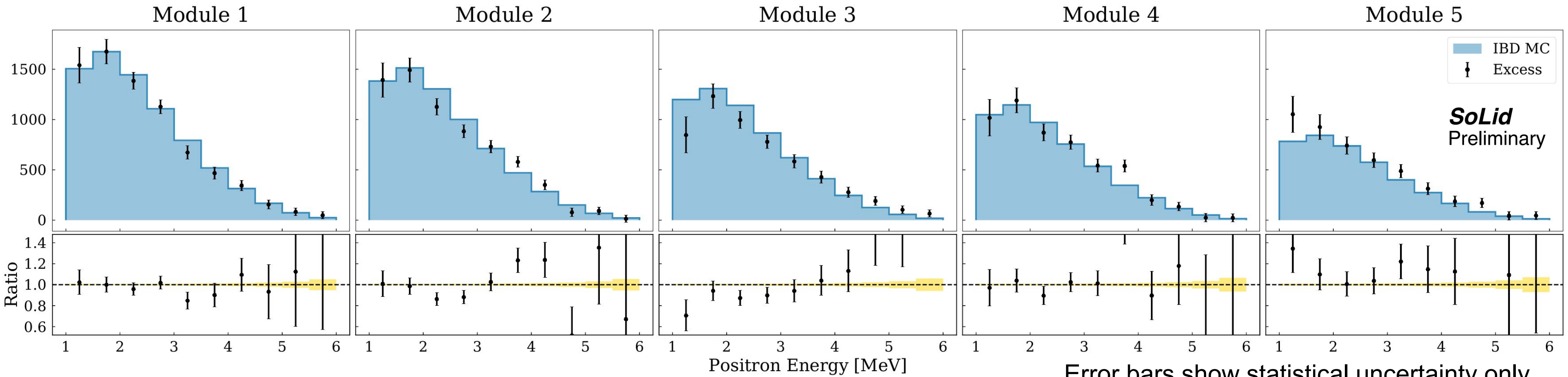
Bayesian Credible Region

- Markov Chain Monte Carlo (MCMC) fit developed last year
- Provides cross-check of the frequentist result

Systematic Uncertainties

- Systematics well understood, largest one from the light yield uncertainty
- Taken into account using a covariance matrix + free normalisation parameter
- First result will be statistically dominated





Error bars show statistical uncertainty only

Conclusion

- SoLid has operated successfully with its Phase-I detector between May 2018 and July 2020
- Developed novel approaches to calibration and event reconstruction in order to fully utilise the topologies of IBD events with high-granularity detector
- Antineutrino analysis requires ML tools to reduce the large background rates
- Frequentist and Bayesian oscillations fit are ready to be applied on the full dataset ⇒ *publication on the way*
- Detector upgrade (Phase-II) completed in early 2021 which will add another two years of data with higher-performing SiPMs (40% higher light yield)

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Thank you

s://iopscience.iop.org/article/10.1088/1748-0221/16/02/P02025

https://iopscience.iop.org/article/10.1088/1748-0221/14/11/P11003

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Backups

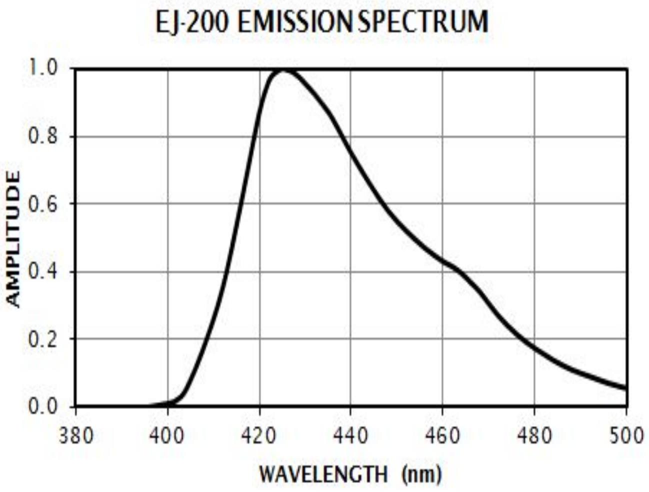
Scintillators

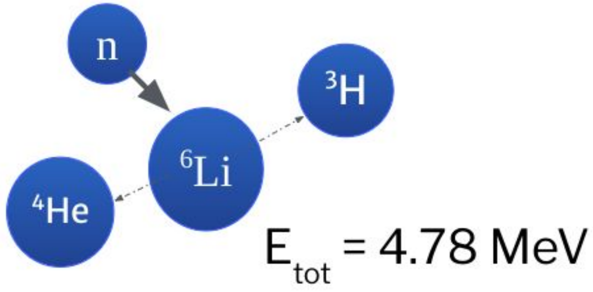
Polyvinyl toluene (ELJEN EJ-200)

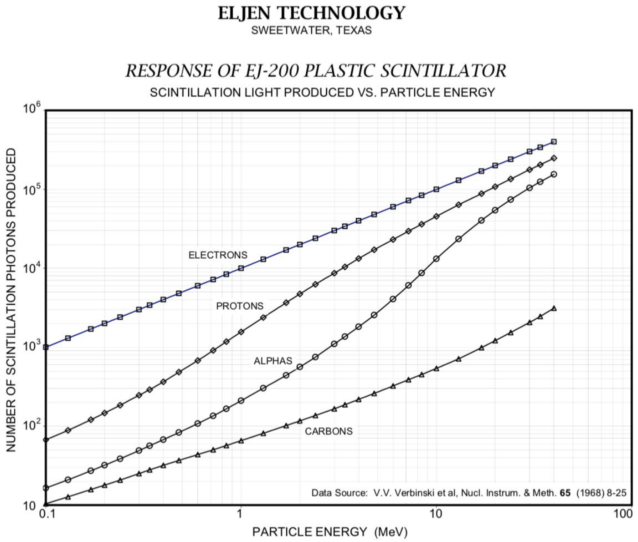
- 10000 photons per MeV
- Peak emission wavelength of 425 nm
- Linear in electron energy down to ~ 60 keV
- Quenching effects well understood

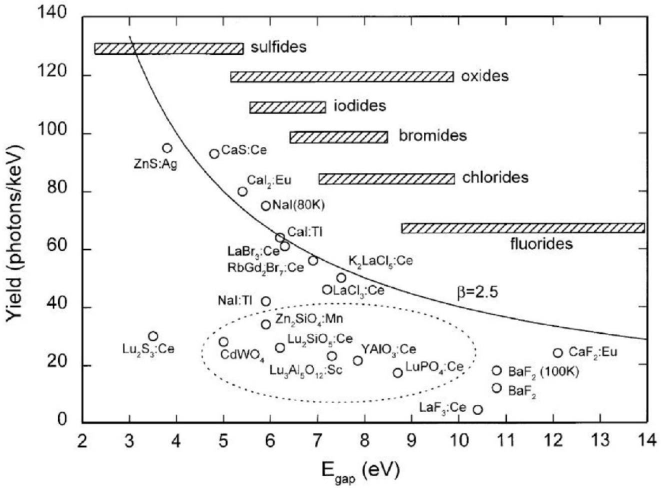
LiF:ZnS(Ag) (Scintacor ND screens)

- 95% Lithium-6
- 170000 photons per neutron capture
- 24% neutron capture efficiency in a single crossing
- Peak emission wavelength of 450 nm
- 1:2 LiF:ZnS ratio with 250 μm reflective backing to maximise neutron detection









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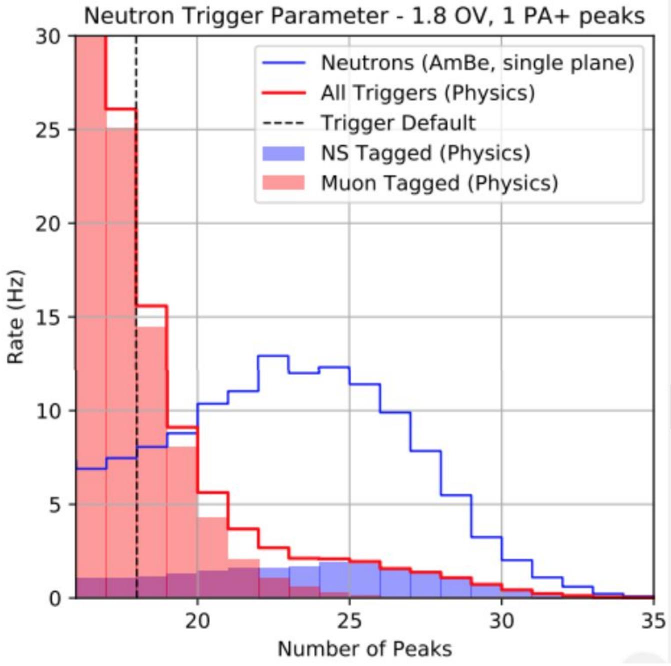
Front-end Triggers

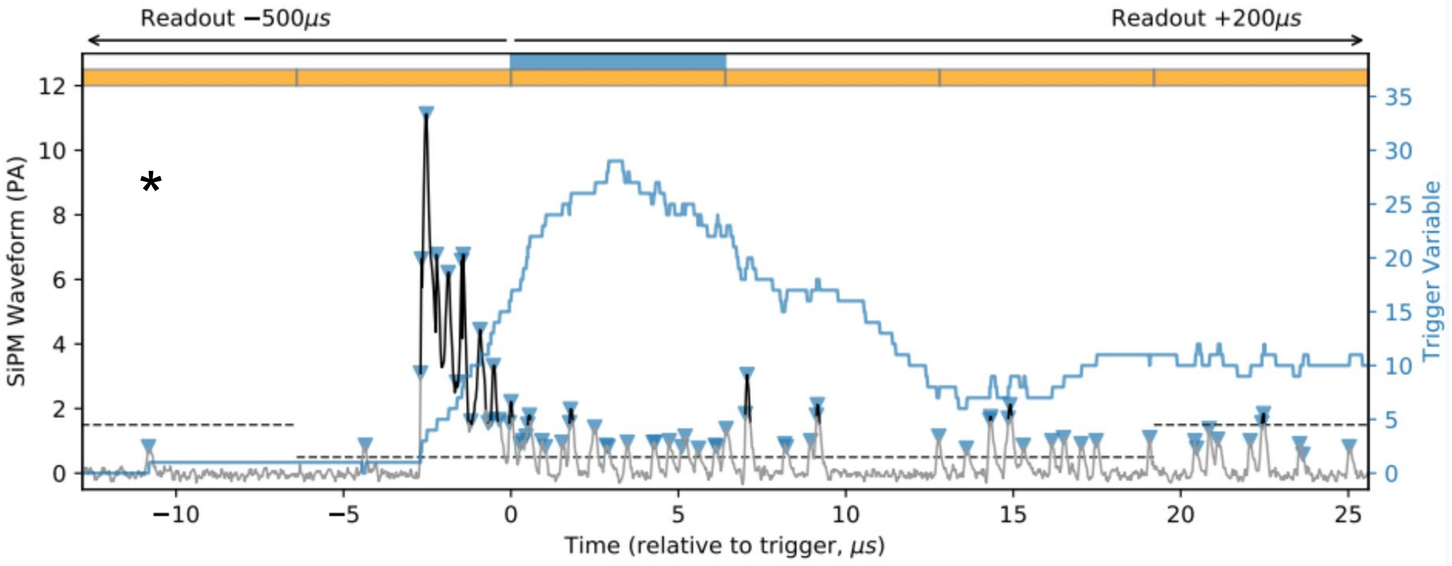
Neutron (IBD) trigger *

- Trigger on the NS waveform based on number of peaks over threshold (PoT)
- Read out ± 3 planes either side of the triggered plane and a large time window of -500 μs to 200 μs

Threshold and random triggers

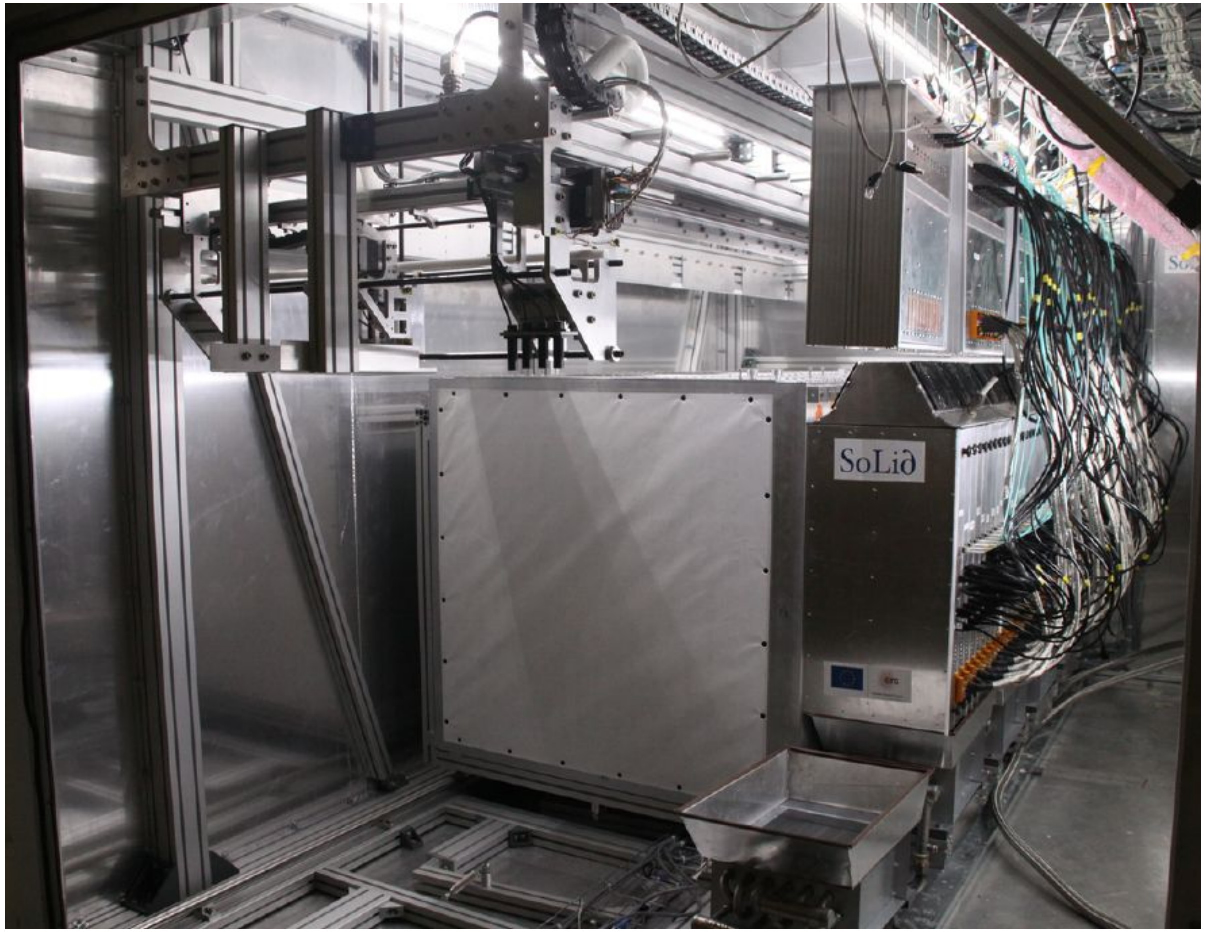
- For studying high energy particle interactions (such as muons) and unbiased monitoring of DAQ parameters respectively





Deployment at BR2

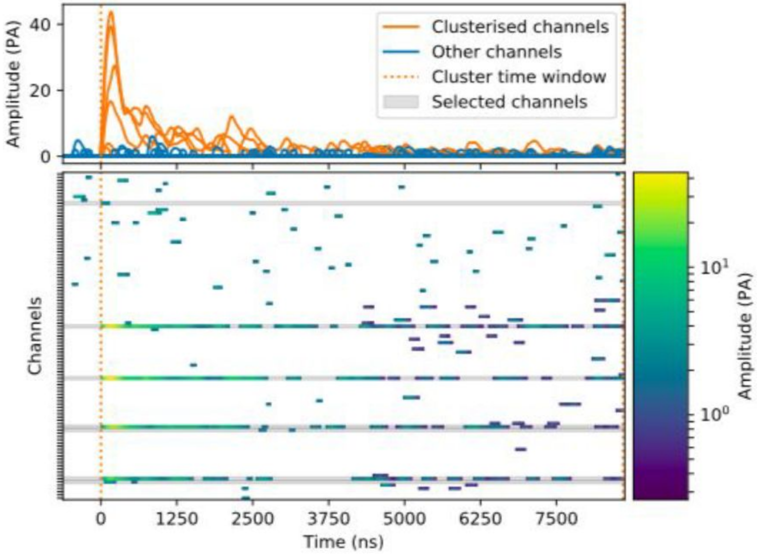
SoLid container at BR2 with partially constructed water wall.



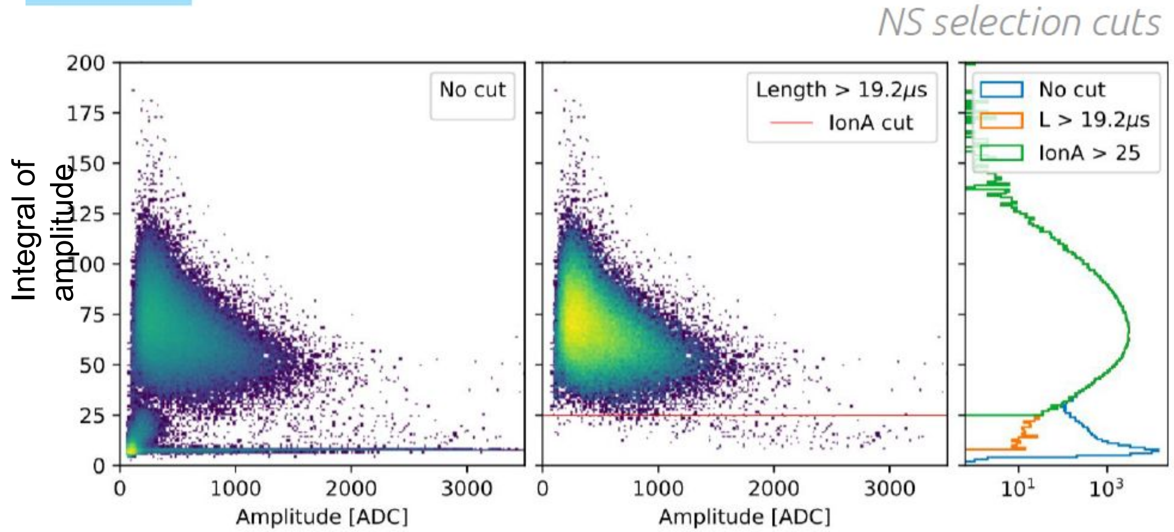
SoLid detector inside the container prior to installation of final module.

Event Reconstruction

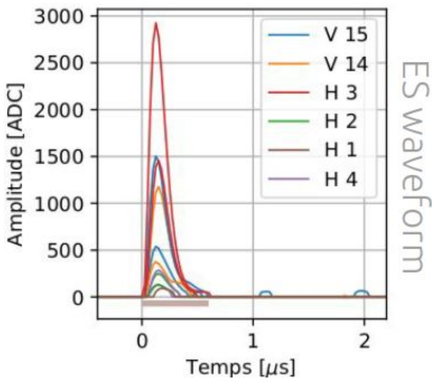
1. Time clustering to group signals from different fibers

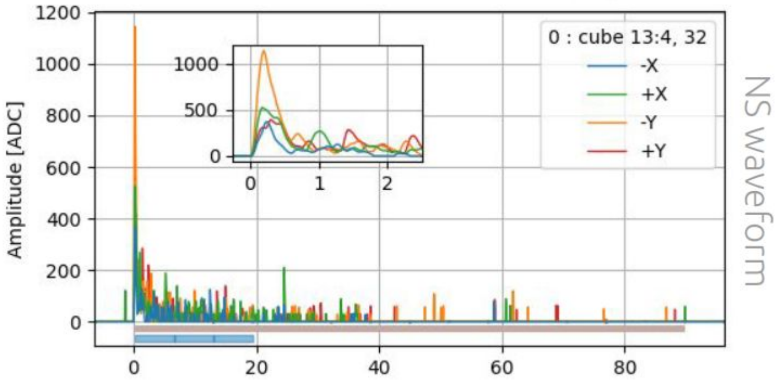


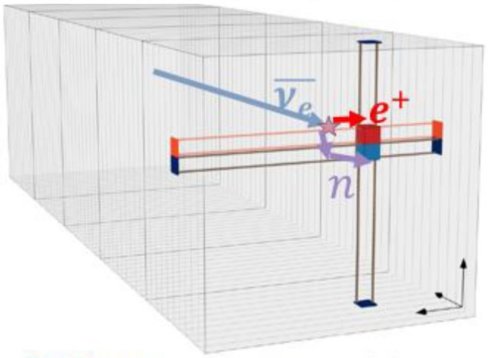
2. Identifying cluster by using cluster length and integral of amplitude / amplitude ratio
   - "ES", "NS", "Muon track"



3. Make correlations between ES and NS





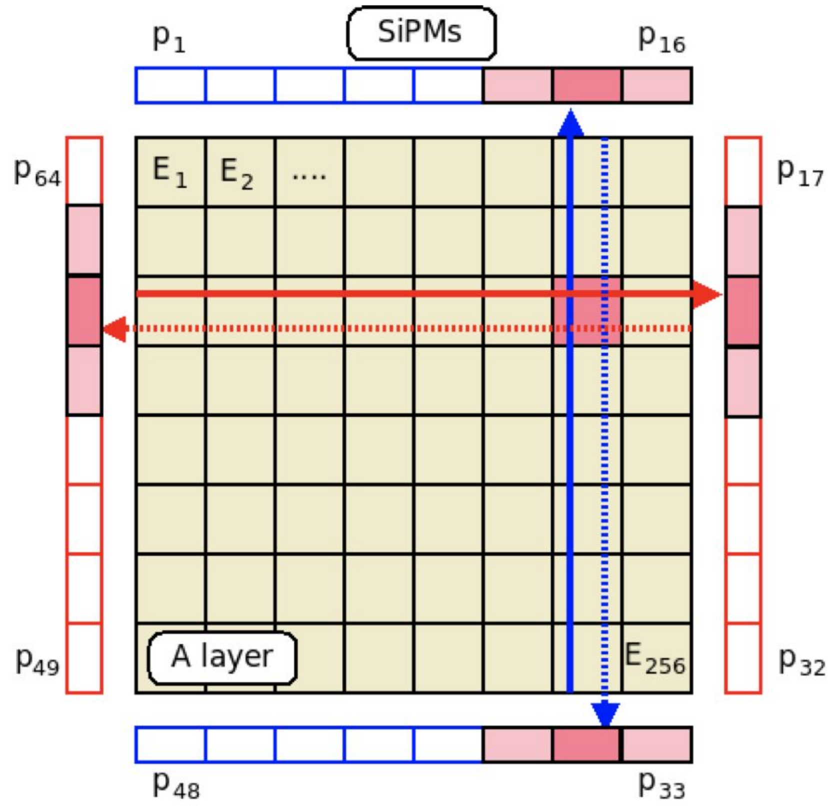


An ES-NS coincidence, i.e. IBD candidate

Event Reconstruction

Allocation of energy deposits

- SoLid uses a method based on an ML-EM algorithm to transform the list of MPPC signals to a list of cubes in which the physics interactions took place
- Planes are optically isolated so 3D energy deposit reduces to multiple 2D problems
- Employs a **system matrix** (SM) that encodes both the absolute energy scale and channel-to-channel differences

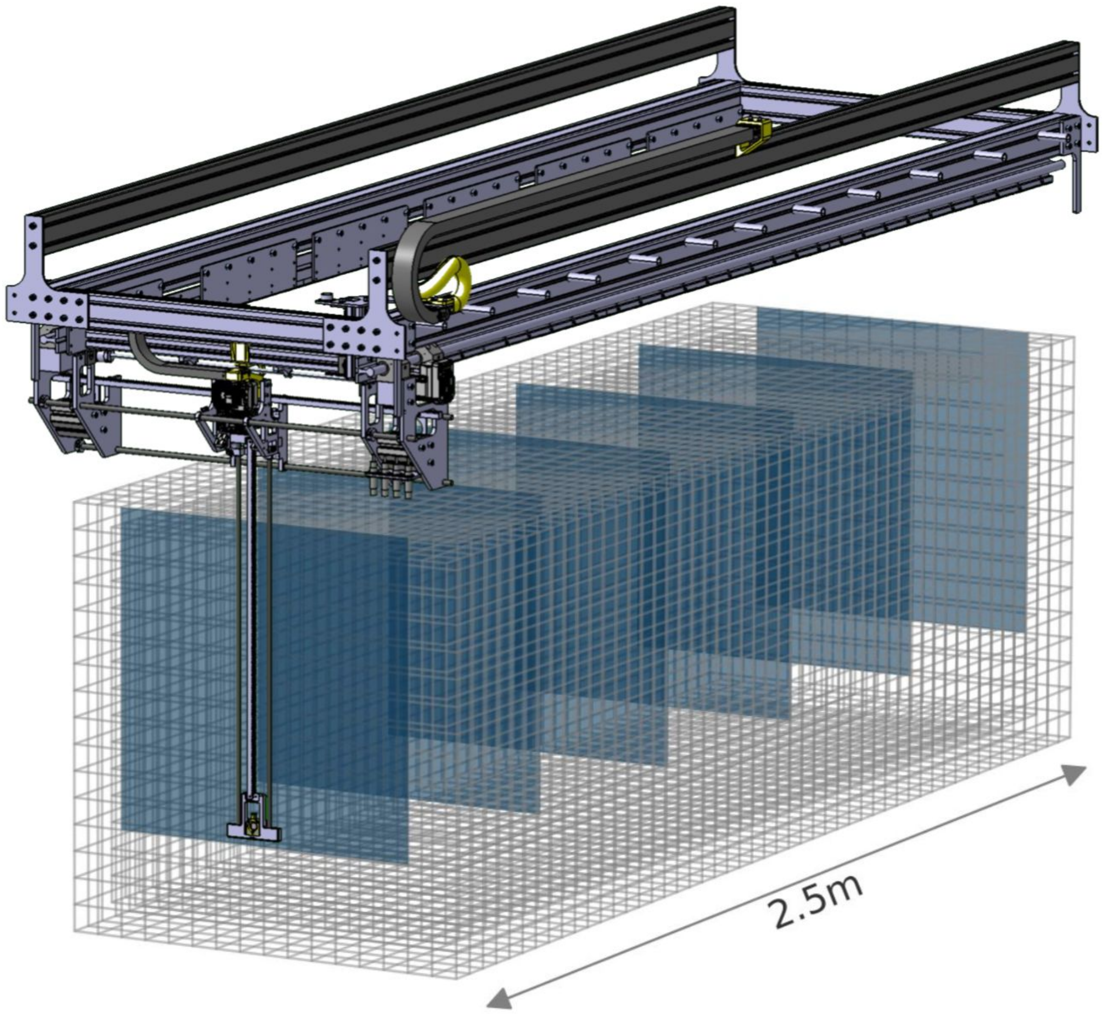


Method	FISTA	FISTA+ML-EM	sOMP+ML-EM
👻 (%)	15.8	11.4	6.9
ε (%)	75.3	76.3	77.7
E_{res} Std. dev.	0.13	0.13	0.13

NEW

Hervé Chanal et al., Reconstruction of Inverse Beta Decay events in the SoLid experiment using the ML-EM algorithm, IEEE NSS 2021

CROSS Calibration Robot



- Automated X-Y source scan of 6 gaps within detector
- Measure absolute efficiency and energy scale calibration at % level
    - Gammas: ^{207}Bi, ^{60}Co, ^{22}Na, AmBe
    - Neutrons: AmBe, ^{252}Cf

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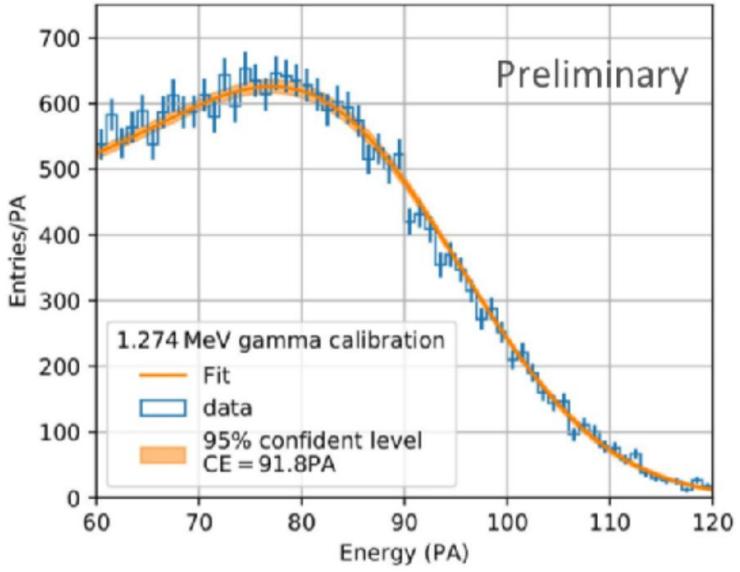
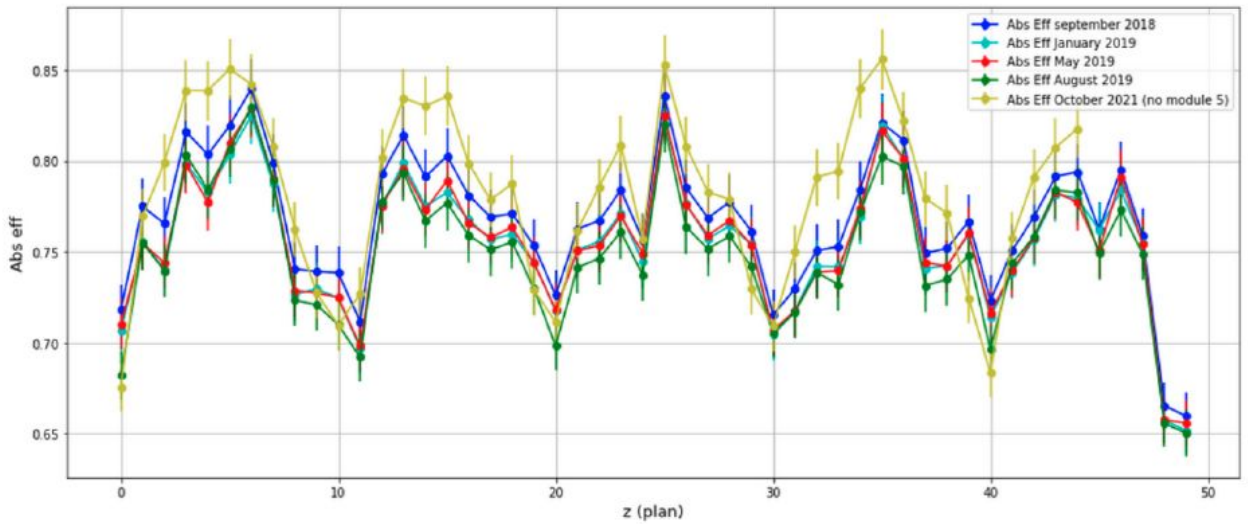
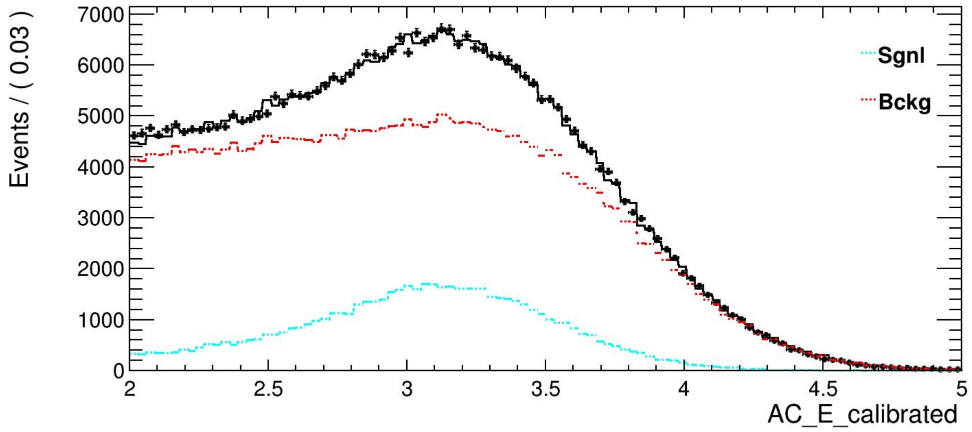
Detector Calibration

Calibration

- **Gamma** sources used for energy calibration of the detector.
- **Linearity** and **homogeneity** of the detector energy response tested at the percent level
- AmBe and Cf neutron sources to measure **neutron efficiency**



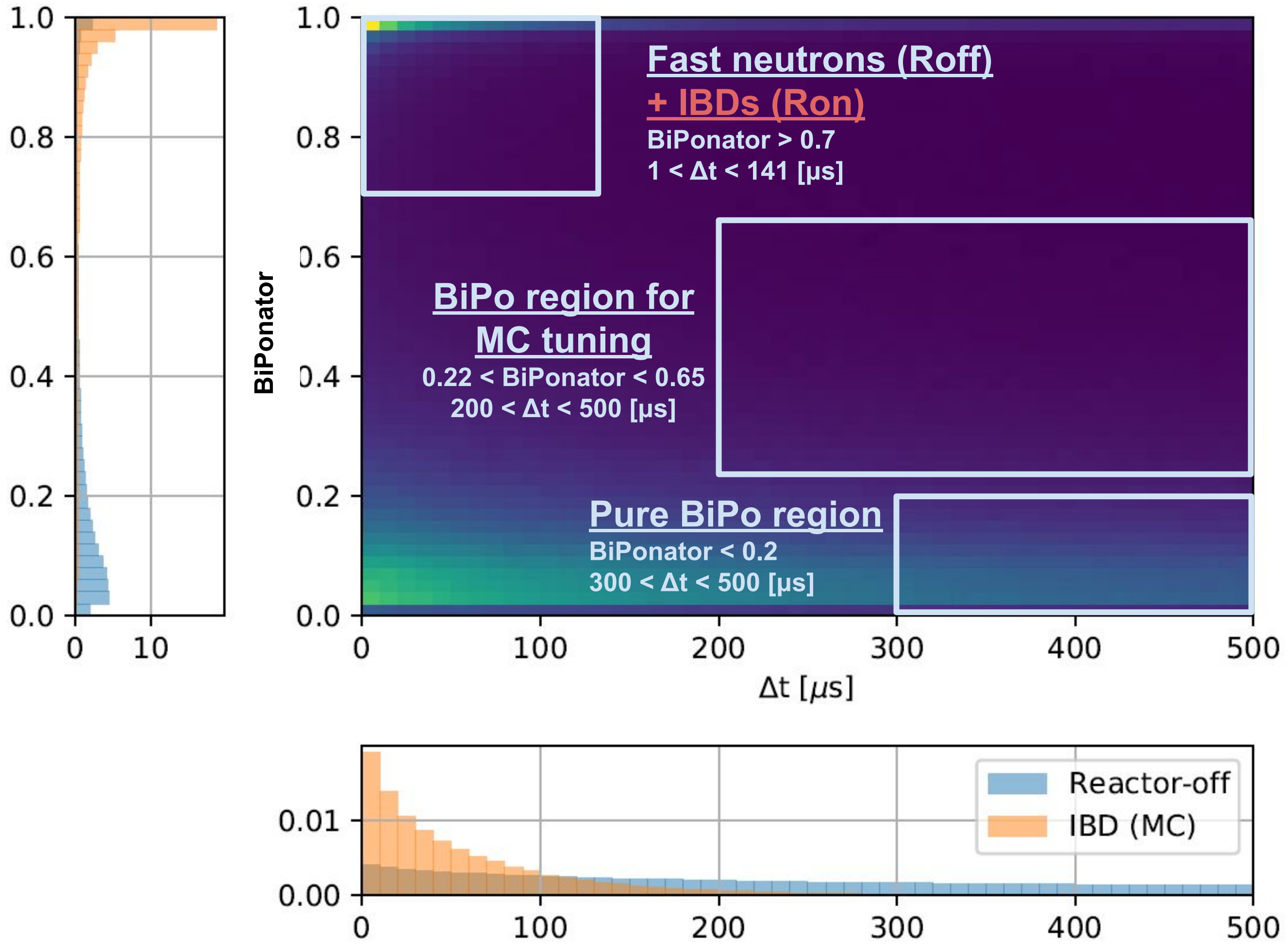




Event Selection for IBD Analysis

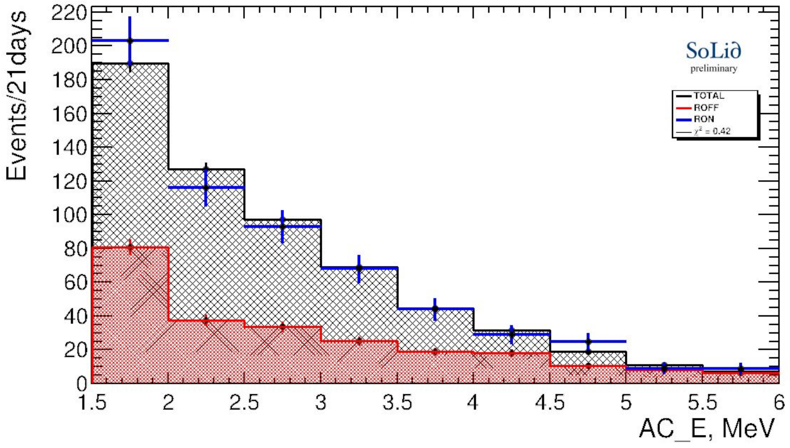
nuBDT pre-selection for signal and BiPo

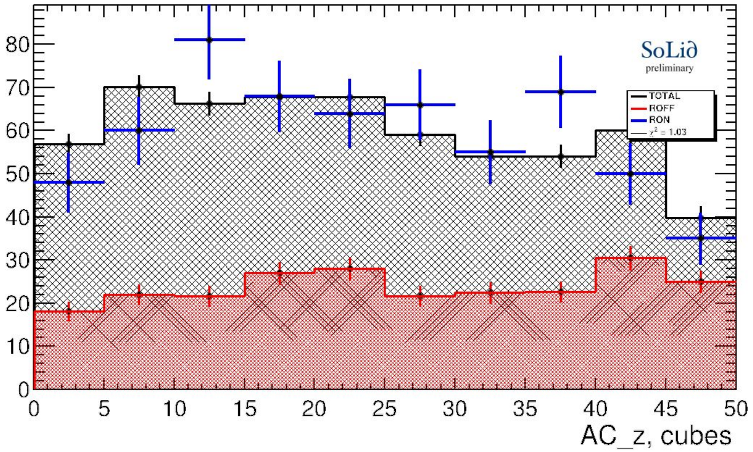
- Correlation between ES and NS
  - $\Delta_{NS\text{-}ES}$ X,Y : [-3, 3]
  - $\Delta_{NS\text{-}ES}$ Z : [-2, 3]
  - $\Delta_{NS\text{-}ES}$ R : [1, 4]
- Energy information of ES
  - $E_{MostEcube}$: [1.0, 6.0] MeV
- Topological information
  - No. of gamma clusters > 0
- Muon veto
  - Reject all events in 200 μs after reconstructed muon track

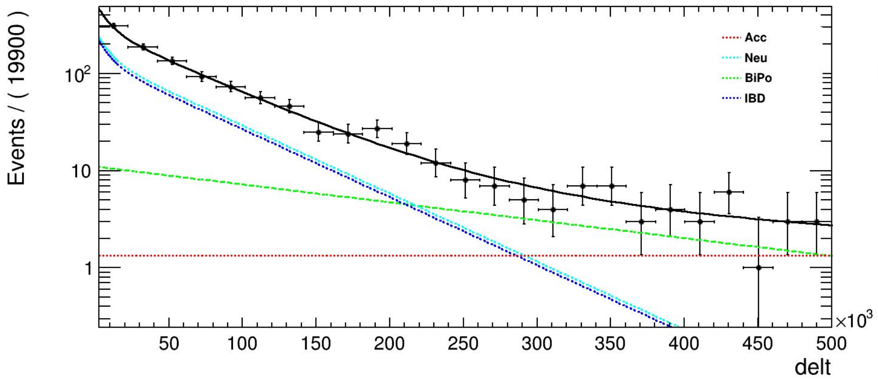


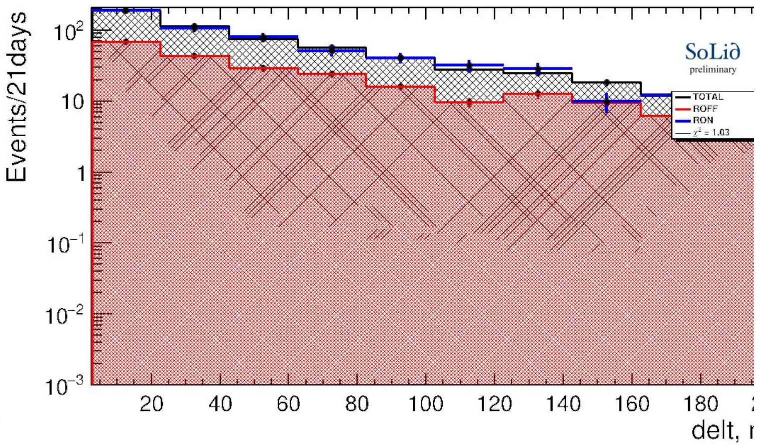
Two-gamma Antineutrino Topological Selection

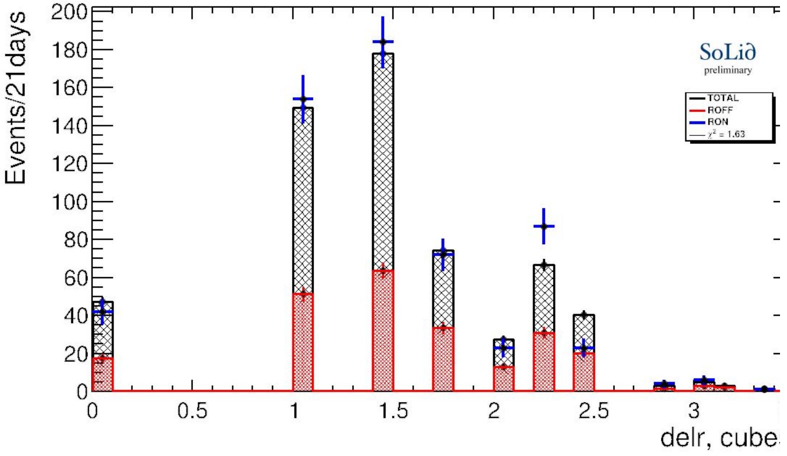
- Very good agreement also with the parallel BDTG analysis
- Each background component determined with multi-dimensional (Δt, Δr) simultaneous fit
- Approach will be extended to include 1-gamma topologies to enhance efficiency











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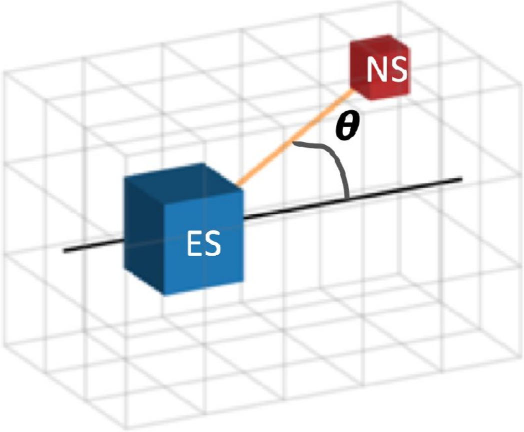
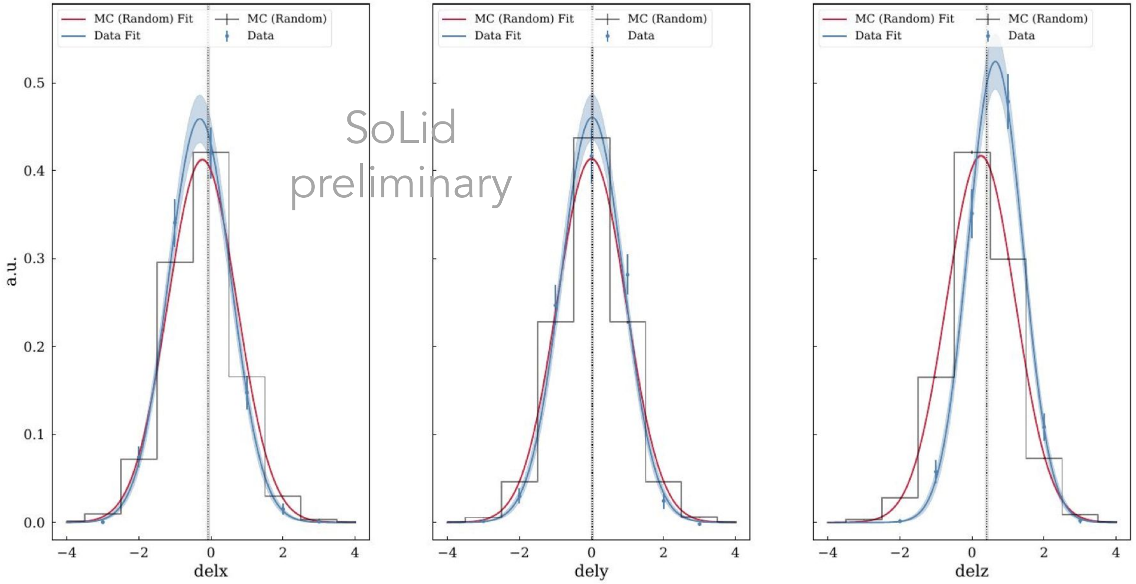
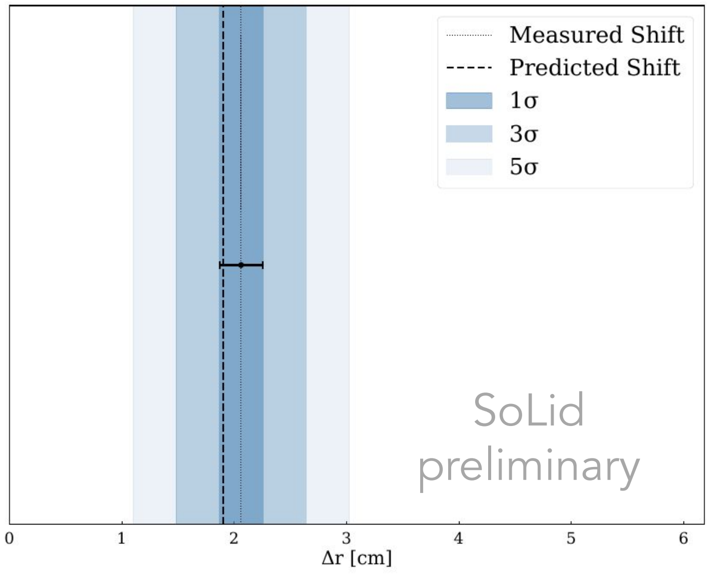
Antineutrino Direction Measurement

- SoLid detector sensitive to antineutrino direction
- Segmentation provides possibly to measure the ES-NS “displacement” from IBD kinematics.
- Test deviation from zero hypothesis using randomly-oriented MC events (uncorrelated positron and neutron)
- Expect 3 measurement with ~ 100 IBD events so a couple of days of operation or less







SoLid Phase-II (2020 - 2022)

Upgrading the detector with new MPPCs (S14 series)

- Better photon detection efficiency compared to S12 series ⇒ translates to a 40% increase in light yield
- **Cross-talk** reduced by a factor of two
- Improved **energy resolution**
- Expected improvement of **annihilation gamma** reconstruction

Taking data with Phase-II detector since late 2020