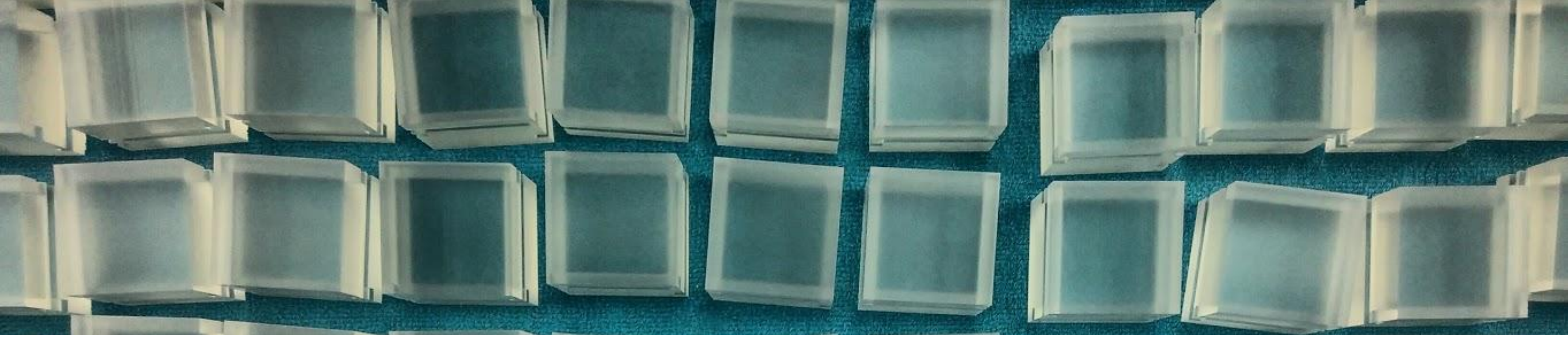

Recent Results of the SoLid Experiment

Daniel Galbinski
Imperial College London, UK

Imperial College London

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

HEP & APP Annual Conference 2022
4th April

SoLid

Outline

- SoLid physics goals
- The SoLid experiment at SCK CEN
- IBD analysis & expected Phase-I sensitivity
- Conclusion

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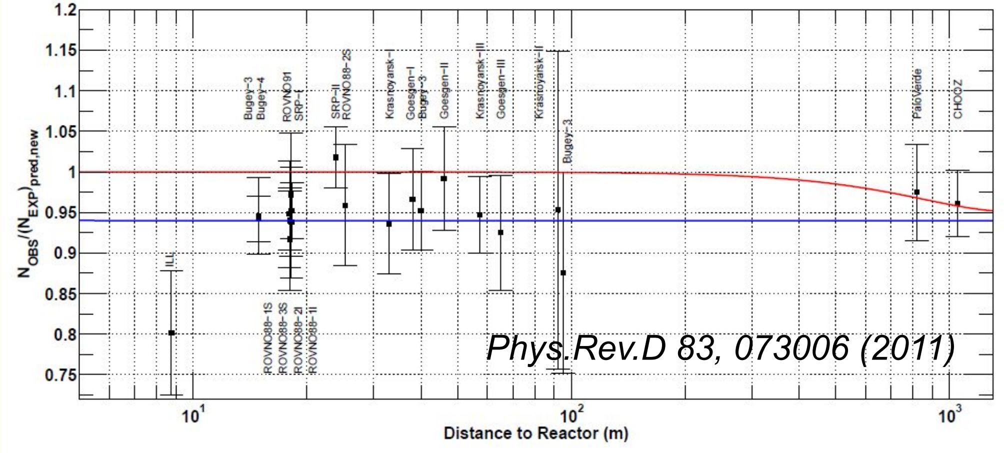
Experiment Goals

Probe the Reactor Antineutrino Anomaly (RAA)



Phys.Rev.D 83, 073006 (2011)

3+1 neutrino model

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

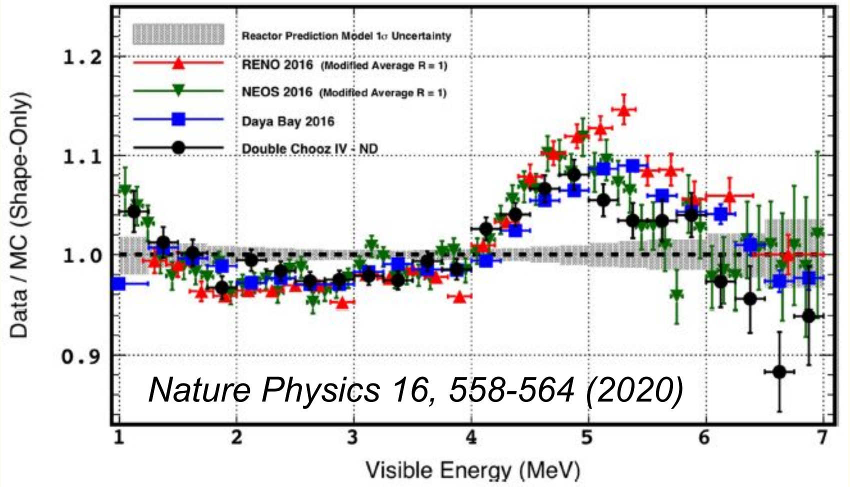
$$\Delta m^2_{\text{new}} \gg \Delta m^2_{12},\ \Delta m^2_{13}$$

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

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

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

Measure precisely 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).

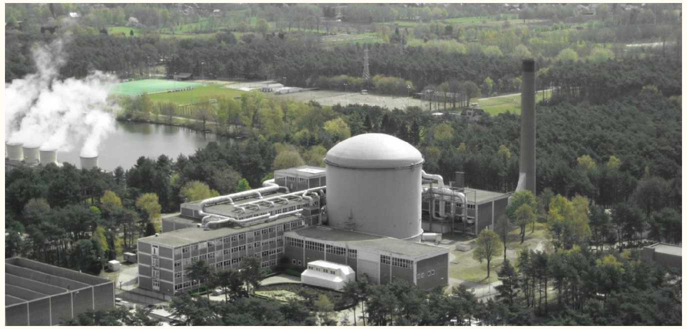
Recent indication from short-baseline liquid scintillator experiments at **^{235}U** research (HEU) reactors.

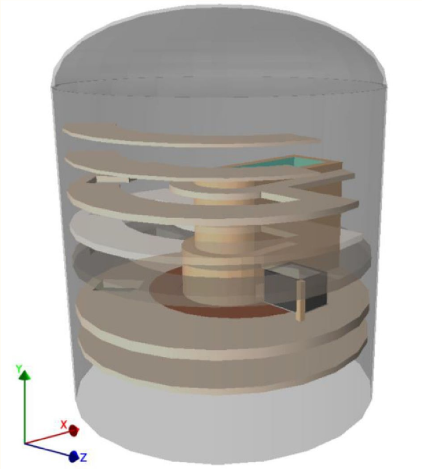
arXiv:2107.03371 [nucl-ex]

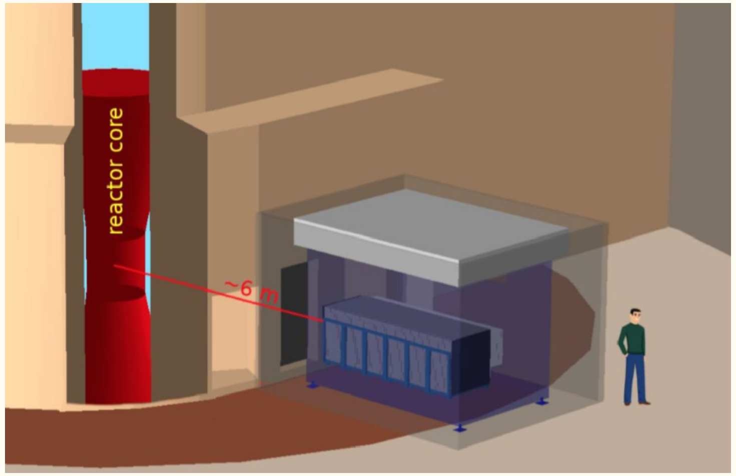
Experiment Location

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)

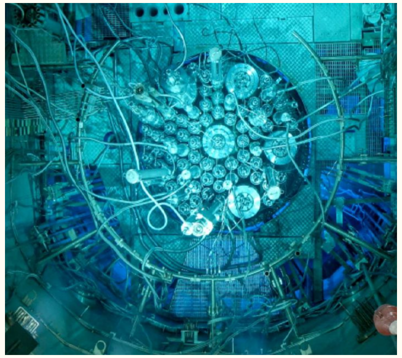


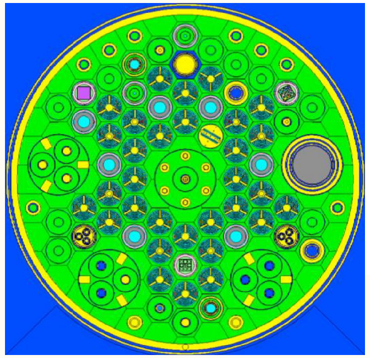




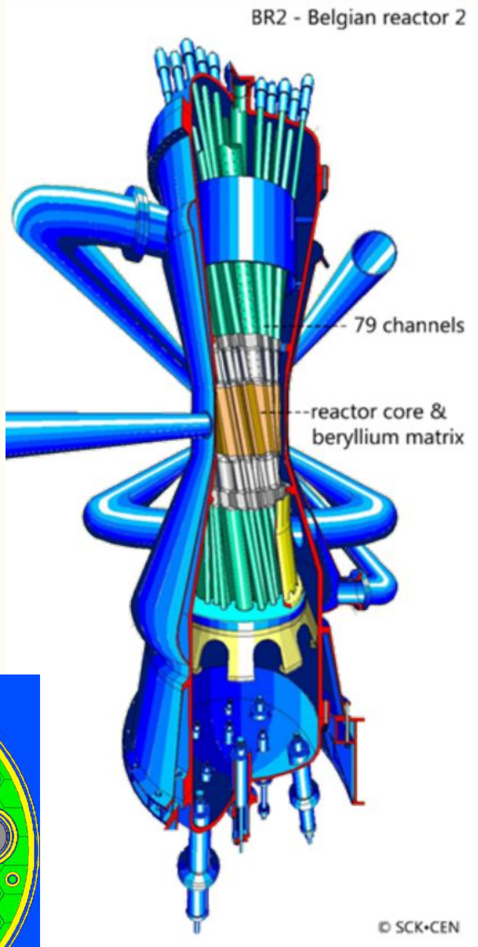
BR2 reactor

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





~ 1.1 m



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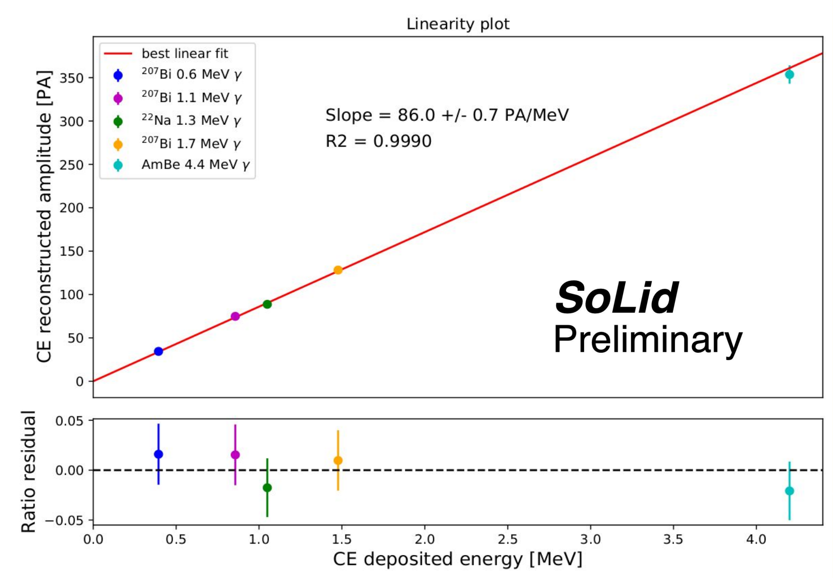
SoLid Technology

Motivations

- Plastic scintillator (ELJEN EJ-200) provides alternative technology for antineutrino measurement
  - Very good **linearity** of response



- Highly segmented detector allows direct access to the **positron energy** and identification of **annihilation gammas**
  - Event topologies allow classification of signal and background

Challenges

- No direct **gamma-neutron PSD**
  - Reduction of high backgrounds requires **multivariate ML** techniques
- Need detailed understanding of complex detector
- Large number of readout channels and parameters to calibrate

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Antineutrino Detection Principle

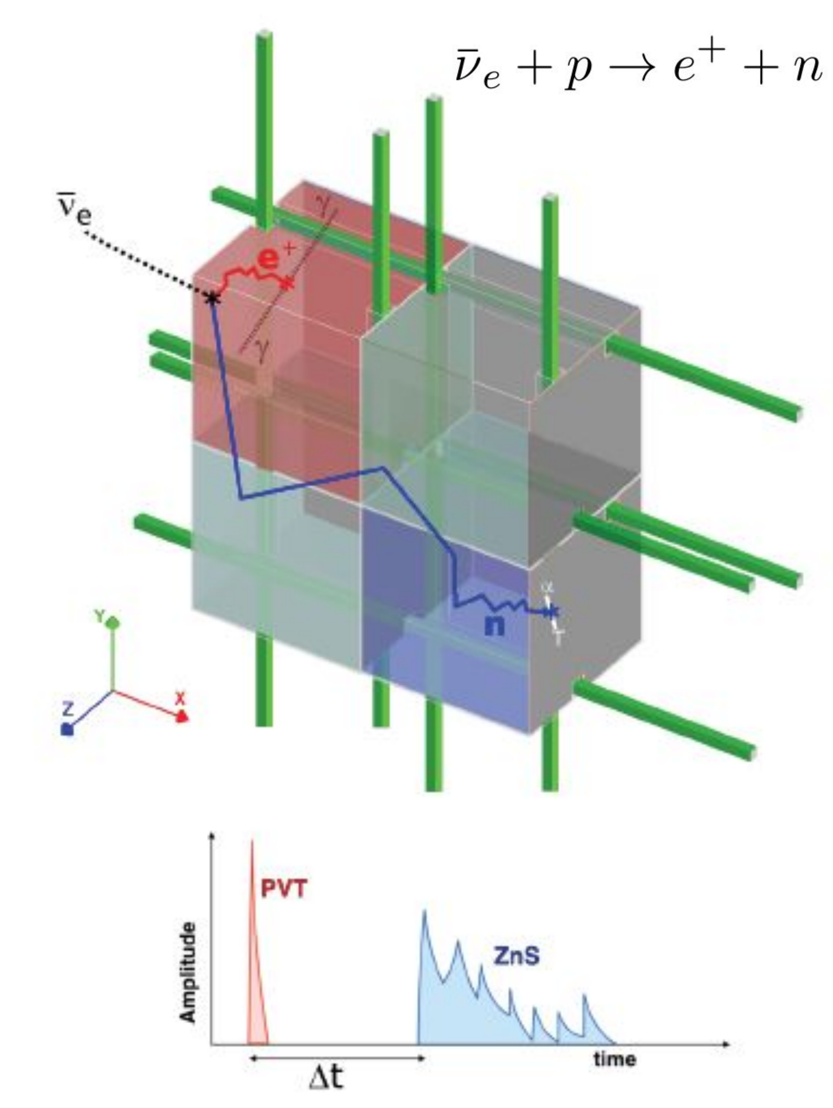
Inverse beta decay (IBD) interaction of electron antineutrinos detected using combination of two scintillators:

PVT cube (5 cm) 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

$$n + {}^{6}Li \rightarrow {}^{3}H + {}^{4}_{2}\alpha$$

Use the **delayed coincidence** between ES and NS signals to tag IBD interactions



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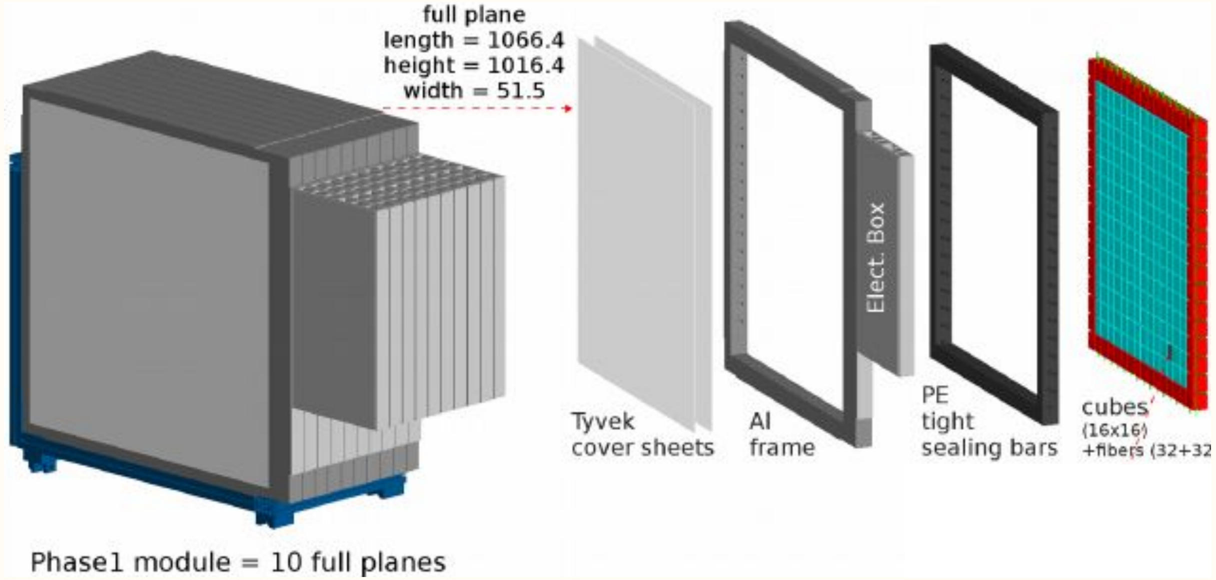
Phase-I Detector

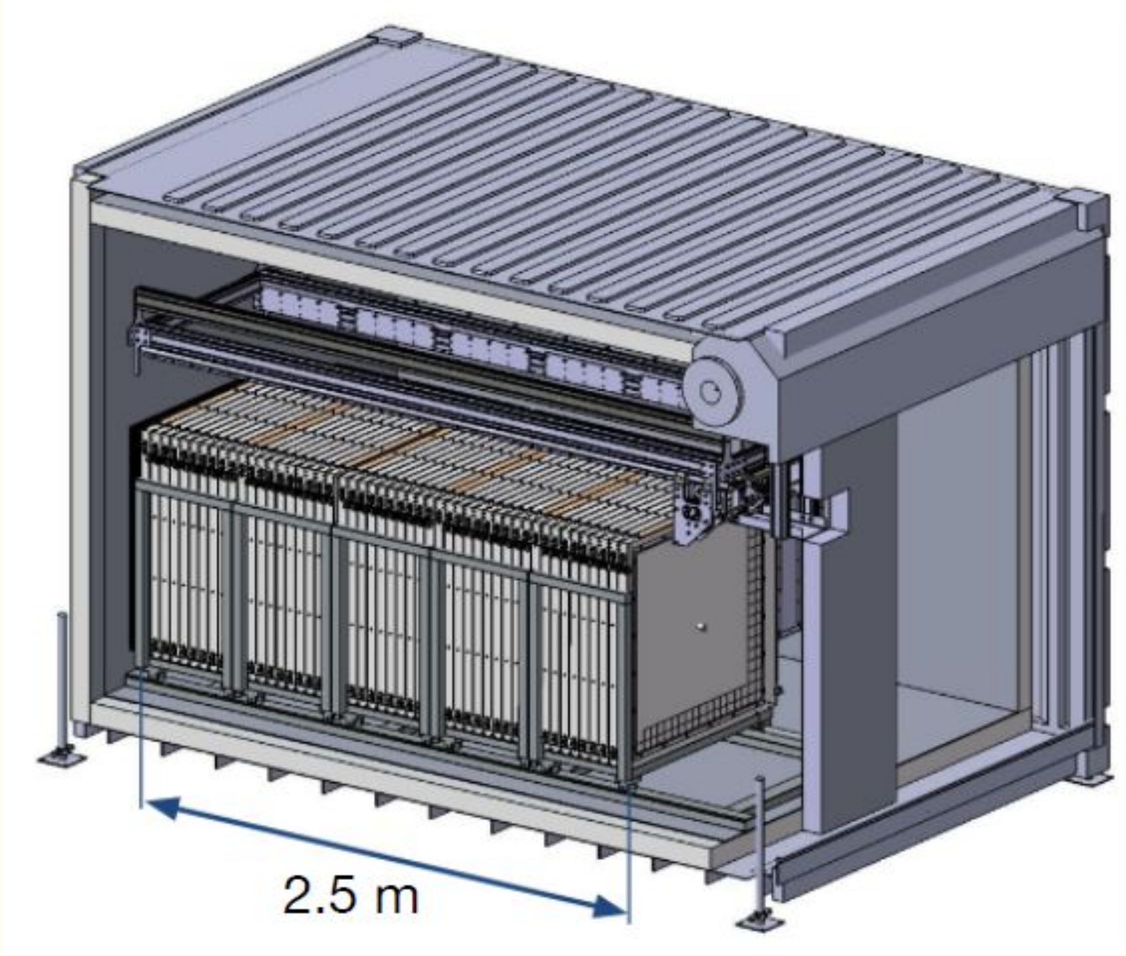
12,800 5 cm PVT cubes (1.6 ton fiducial volume)

3,200 readout channels

- ➢ Wavelength shifting fibers in X-Y directions
- ➢ Signals detected by MPPCs (SiPM)

Data-taking with Phase-I detector from April 2018 to July 2020.

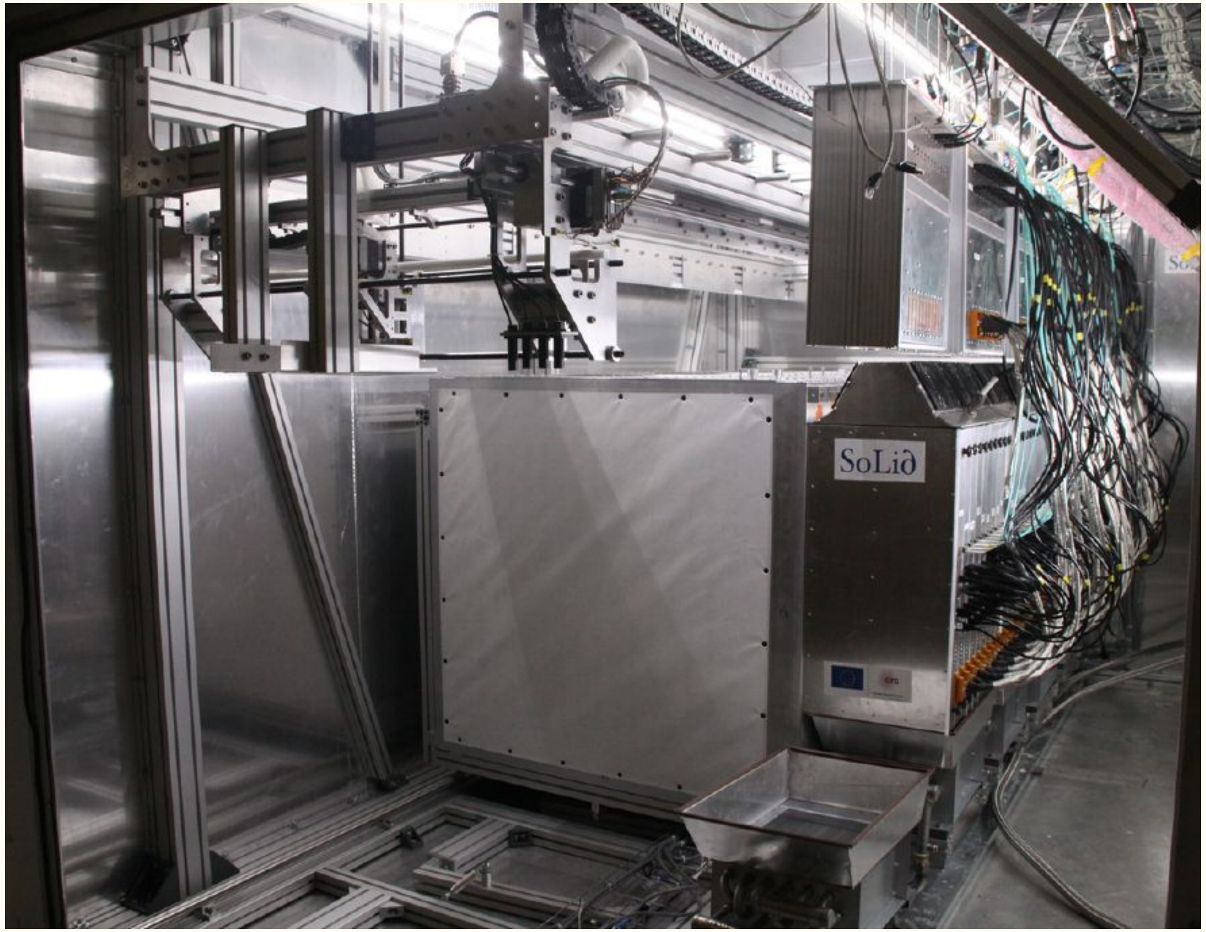




Full detector comprises 5 independent modules.

Phase-I Detector

SoLid container at BR2 prior to completion of water wall.



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

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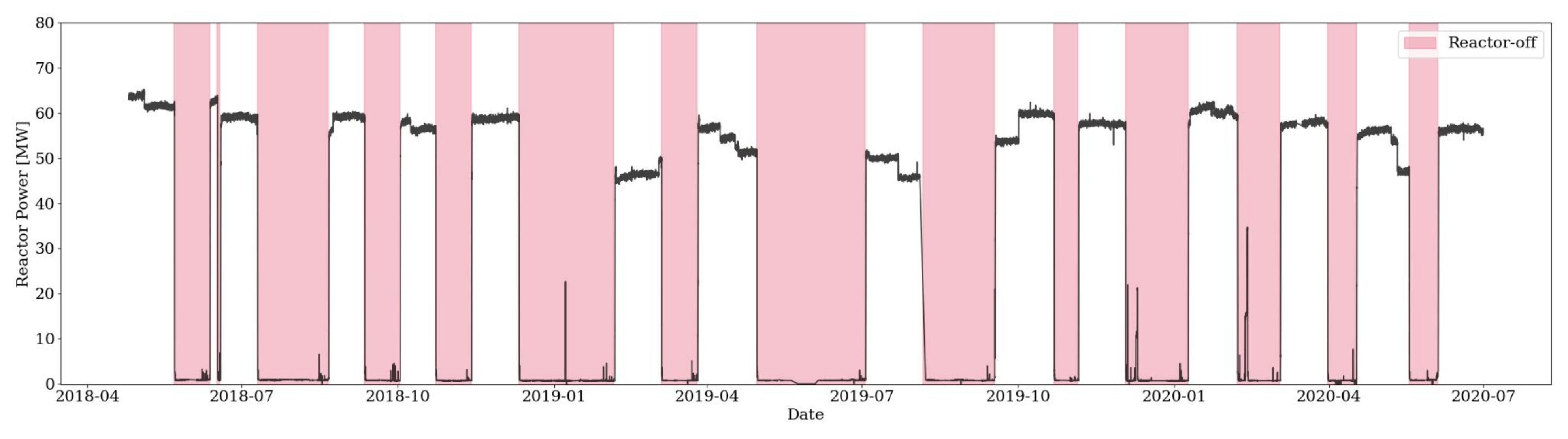
Phase-I Dataset

Data on tape

- ➢ Two years of data (April 2018 - July 2020)
- ➢ 14 reactor cycles during this time

Data quality

- ➢ Physics-quality data is collected only during ideal conditions with chilled container, sufficiently low humidity in the container and full shielding
- ➢ The data is passed through multiple data quality criteria to find and reject faulty data
- ➢ Selected respectively ~**300 days** and ~**180 days** of sufficiently high quality **reactor-on (Ron)** and **reactor-off (Roff)** data for an oscillation analysis



Background Sources

Fast neutrons (external)

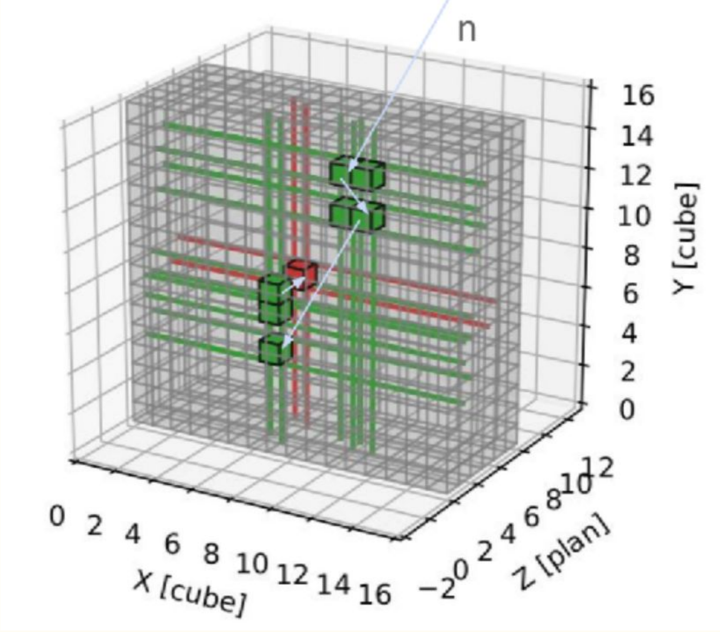
- ➢ **Fast neutrons** induced by cosmic-ray shower & spallation
  - ○ Proton recoil events: ES
  - ○ Neutron capture: NS

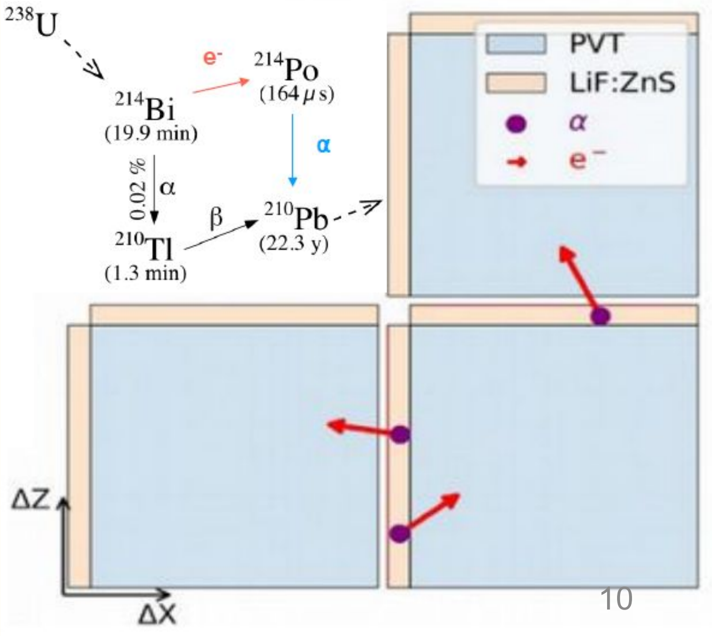
BiPo (internal)

- ➢ Derived from $^{238}U/^{230}Th$ series
  - ○ ^{214}Bi decay (e^-, γ): ES
  - ○ ^{214}Po decay (α): NS
- ➢ **Unexpectedly high** contaminant in LiF:ZnS(Ag) sheets
  - ○ ~ 2 orders of magnitude above IBDs before selection

Accidental (external)

- ➢ Gamma rays from ^{41}Ar decay (reactor)
- ➢ Radon emanation from the building





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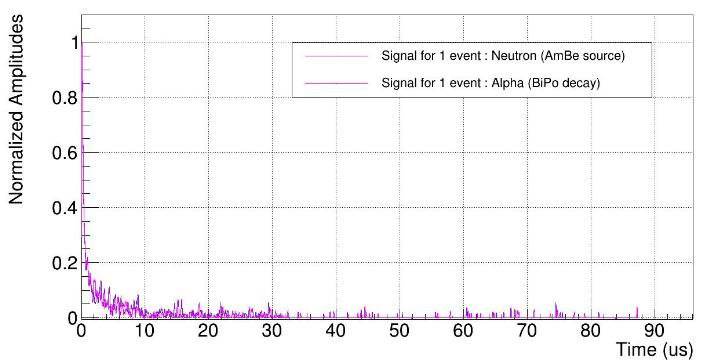
BiPonator: PSD Method

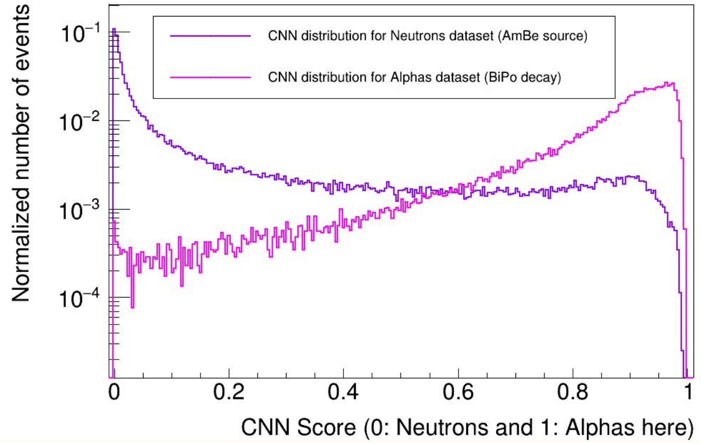
Objective

Alpha / **Neutron** discrimination with convolutional neutral net (CNN) to reduce BiPo background

CNN Input

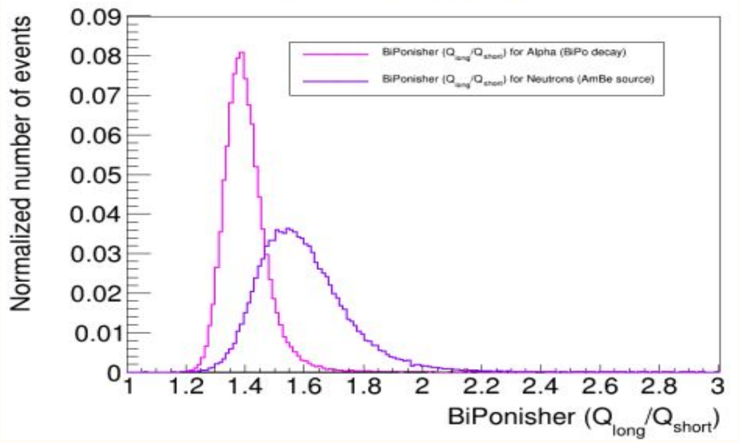


CNN Output

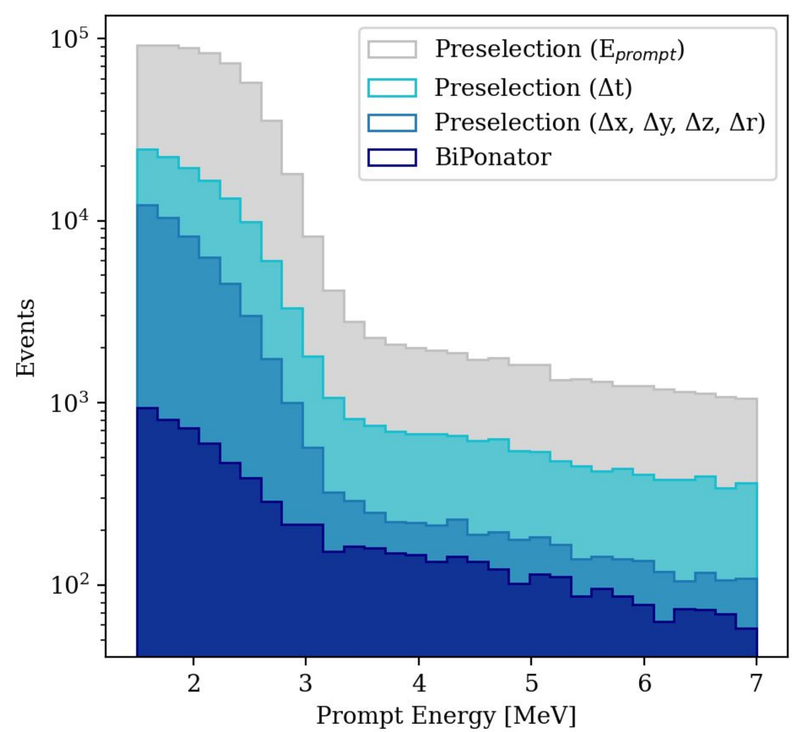


BiPonisher: Previous PSD Method

- ➢ Charge integration (CI) ratio



1 day reactor-off



Δt: 88% reduction
Δx, Δy, Δz, Δr: 60% reduction
Biponator: 87% reduction

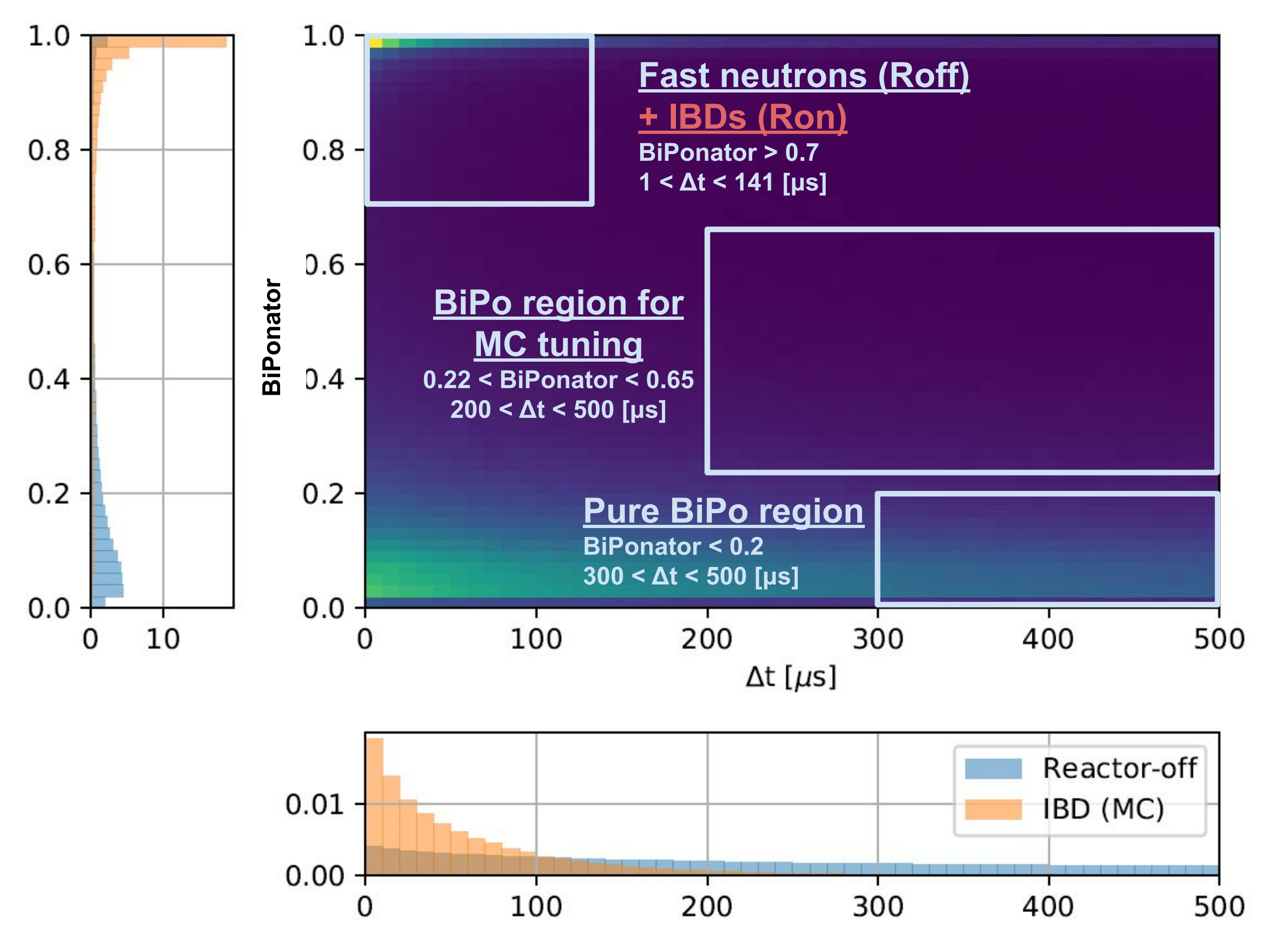
Overall reduction factor of **~85**
(after energy range selection)

Event Selection for IBD Analysis

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 : [0, 4]
- ➢ Energy information of ES
  - ○ E_{prompt} : [1.5, 7] MeV

Topological information, in particular the presence of the *annihilation gammas*, also extremely useful for event classification.



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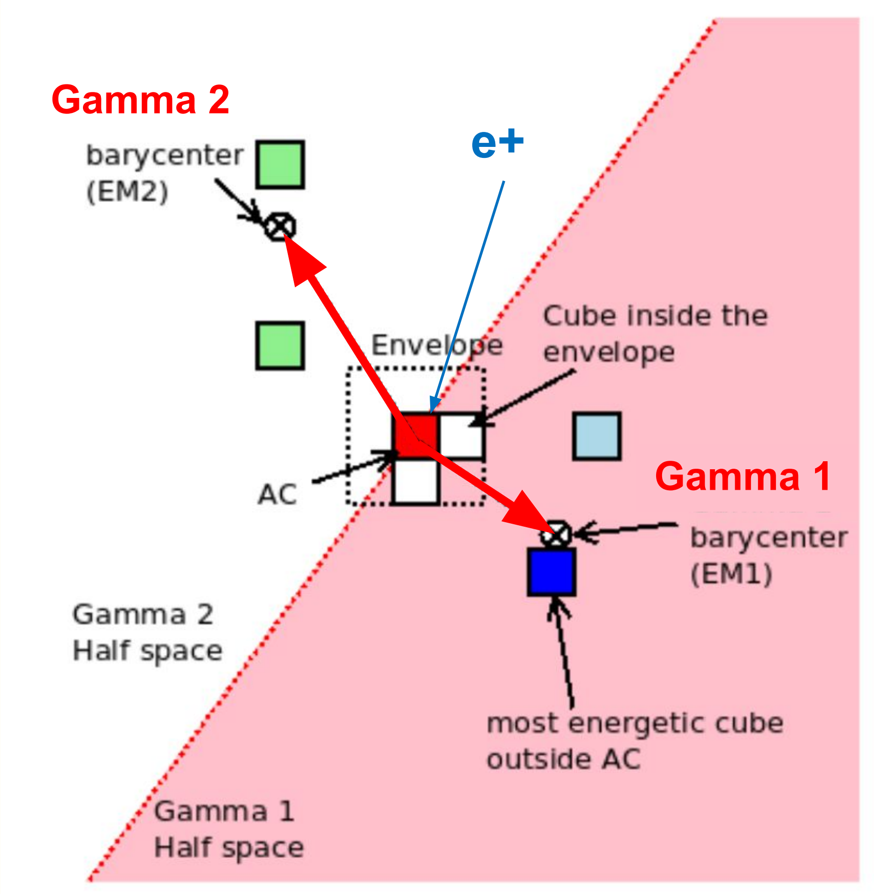
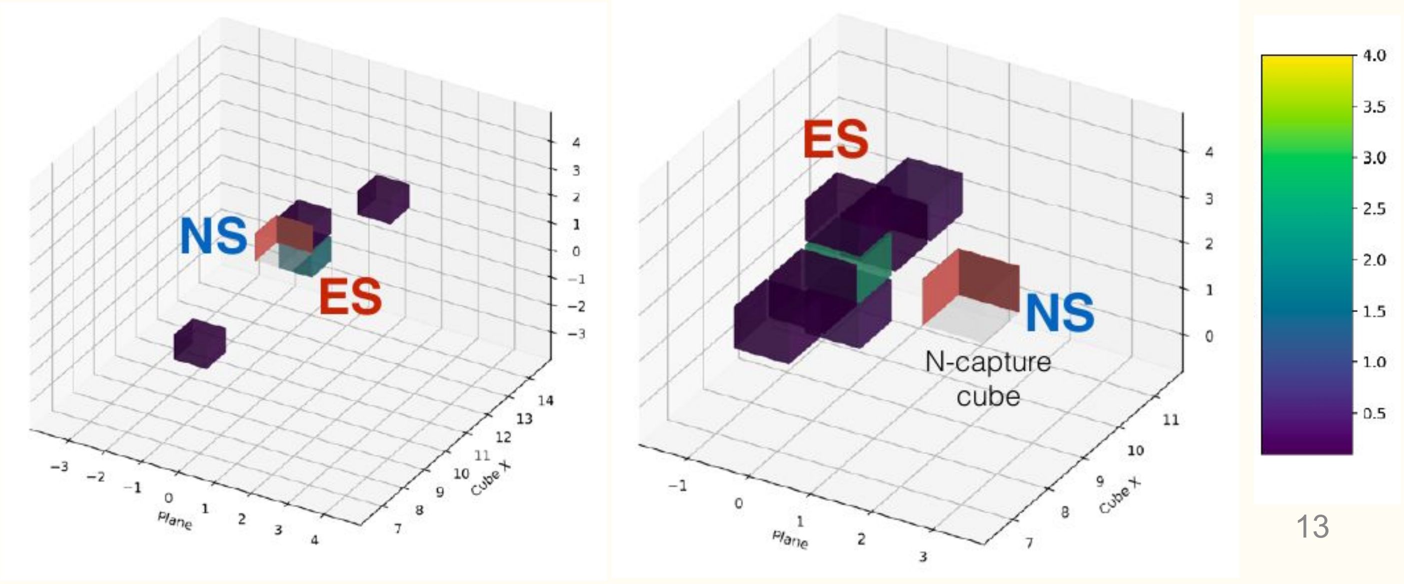
Event Topology Classification



Annihilation gammas reconstruction

- Method 1 : Locate first gamma cluster then split the detector into two hemispheres and search for second detached cluster.
- Method 2 : Track gammas by minimizing likelihood function of cube positions according to Compton scattering cross sections

Event classification based on identification of 0, 1 or 2 gamma clusters



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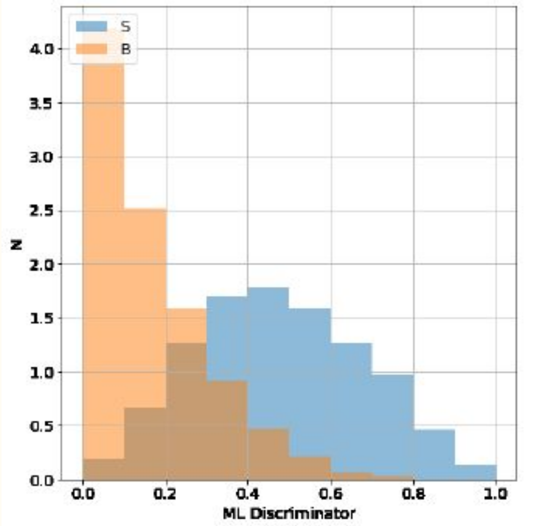
IBD Analysis & Signal Extraction

Uniform Boosted Decision Tree (uBDT)

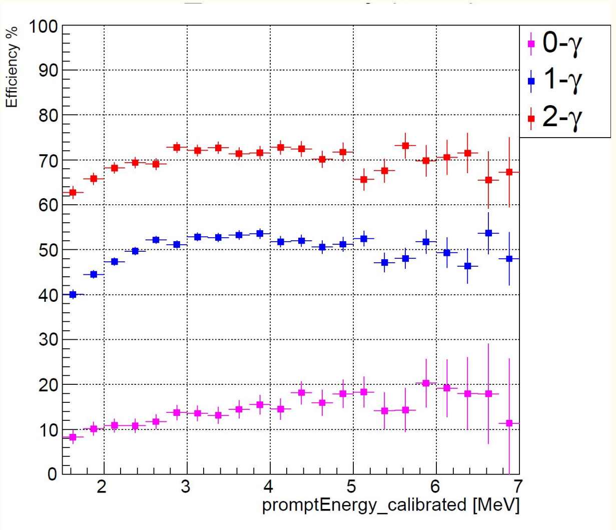
arXiv:1305.7248

- Optimise discrimination whilst ensuring uniform efficiency for specific variables
    - In this case, energy of the prompt (ES) signal and its plane position (zP) in the detector

uBDT output for 2-gamma category

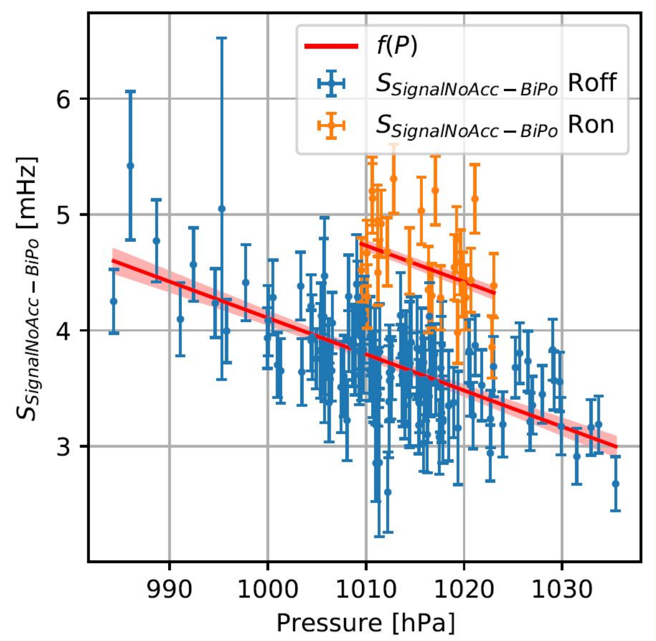


Efficiency across energy range



Background subtraction

- Subtract BiPo and accidental components
- Subtraction of atmospheric (fast neutron) component requires pressure correction factor (f) derived from reactor-off data



(**SignalNoAcc - BiPo** ⇒ fast neutrons in Roff)

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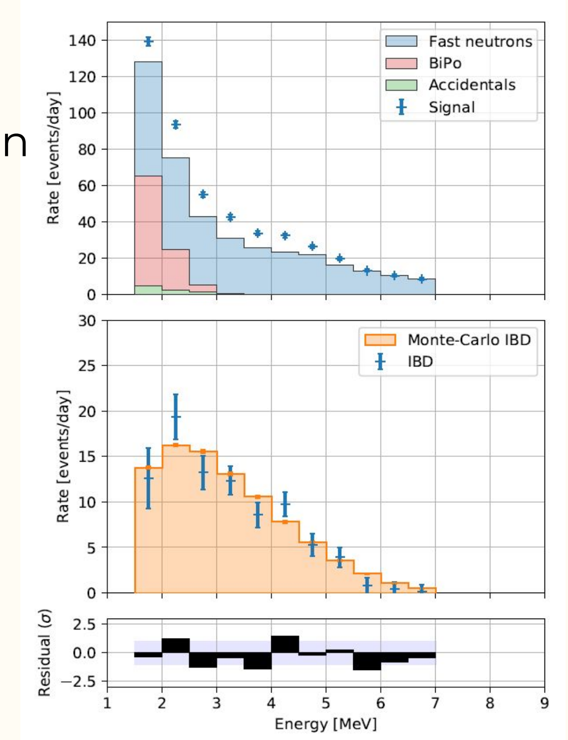
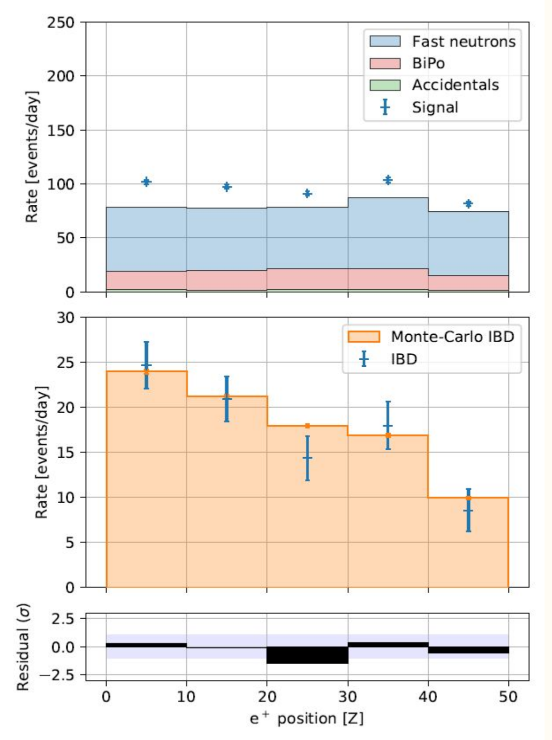
Antineutrino Signal

Trending plot of excess per day is well behaved, yielding an IBD excess consistent with zero for reactor-off data

Analysis on the open dataset (first unblinded reactor-on period) with the optimised uBDT selection gives:

- ➢ IBD excess of 90 events per day
- ➢ Signal-to-background ratio (S:B) of 0.21





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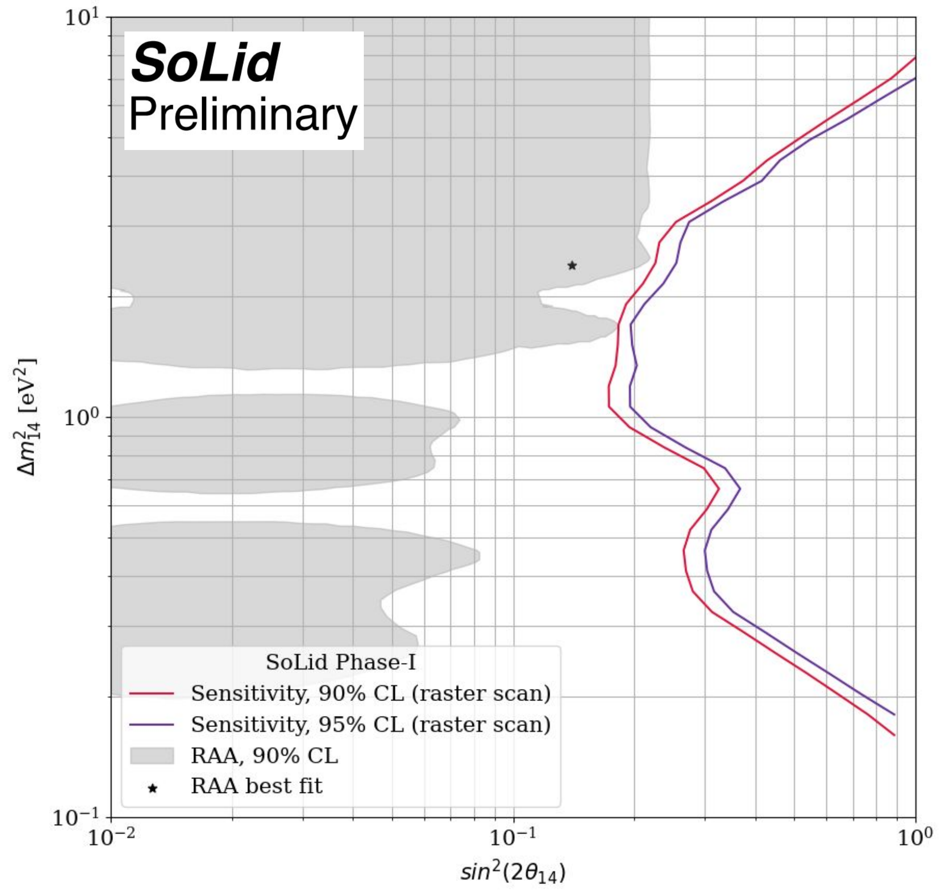
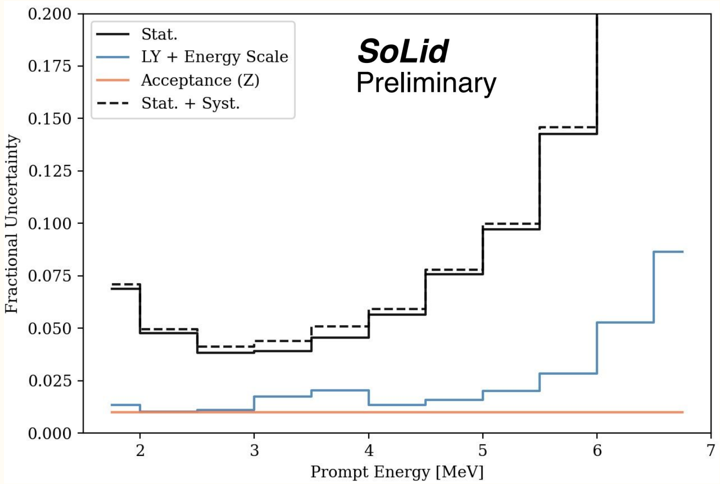
Phase-I Oscillation Sensitivity

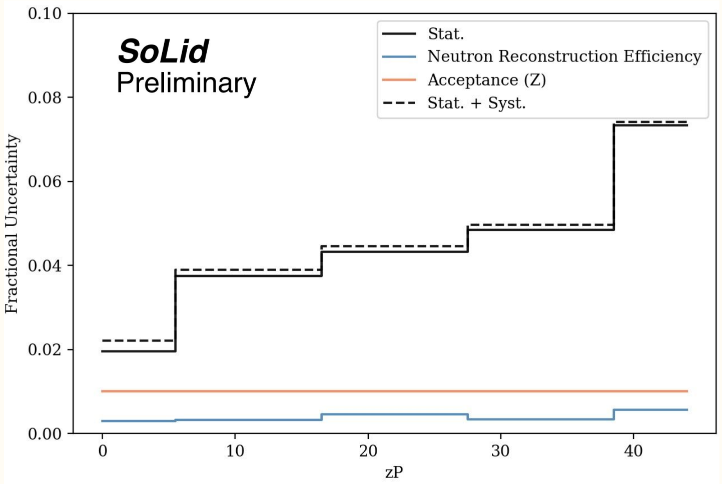
➢ Preliminary sensitivity to sterile neutrino oscillations (3+1 model here) estimated with Feldman-Cousins construction

➢ Systematic uncertainties related to the light yield (LY), energy scale and neutron capture efficiency are taken into account ⇒ statistically dominated

➢ Ongoing effort to assess impact of remaining systematics and improve sensitivity with new analysis techniques!

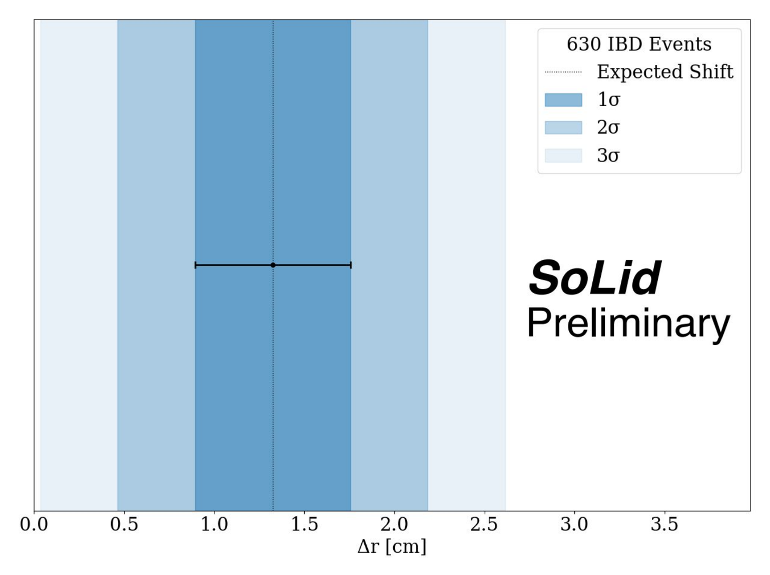




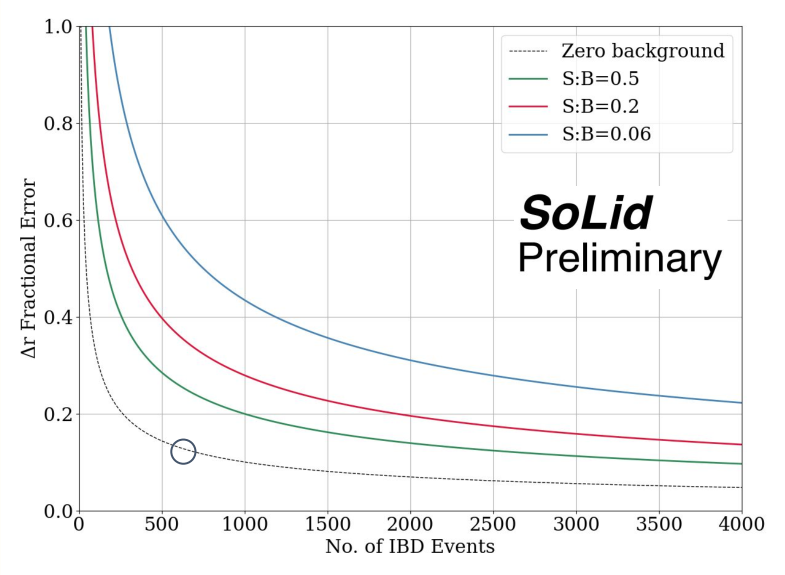


Antineutrino Direction

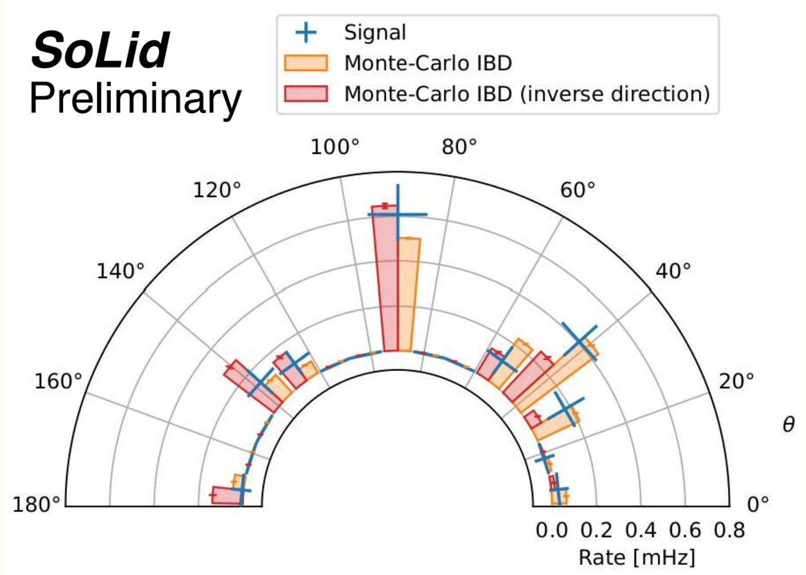
- SoLid is sensitive to the direction of the incident antineutrinos ⇒ reactor monitoring applications
- IBD neutrons are boosted in direction of antineutrino momentum so detector segmentation allows measurement of non-zero average displacement (Δr) between ES and NS signals
- Preliminary MC studies predict a 3σ measurement with 630 events at S:B ~ 0.2 (i.e. one week of data-taking)



Predicted Δr shift



Predicted fractional error as a function of no. of IBDs and S:B



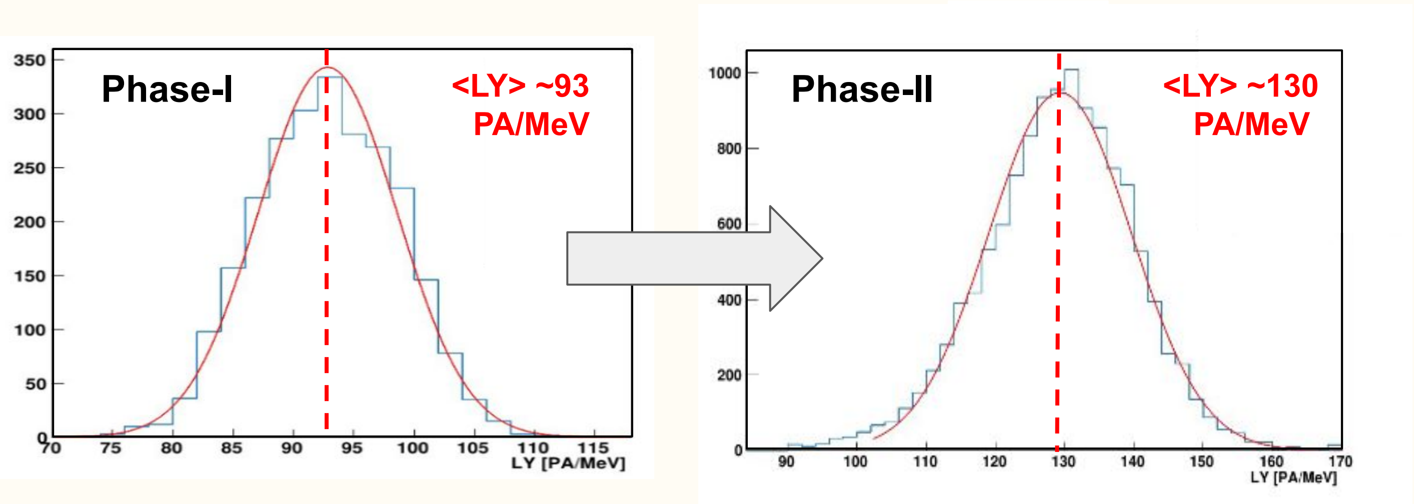
Data-MC comparison of reconstructed ES-NS angles (open dataset)

SoLid Phase-II: Detector Upgrade

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



Replacing the MPPCs in 2020

Conclusion

- SoLid has approximately 2 years of data with the **Phase-I detector**
  - Alternative technology complements other experiments
- Detector response well understood
- **MVA** and **ML** techniques used to reduce high rates of background
  - Atmospheric neutrons and BiPo
- Successful detector upgrade and data-taking underway with **Phase-II**
- **Exclusion contour for Phase-I dataset coming soon!**

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Thank you !

https://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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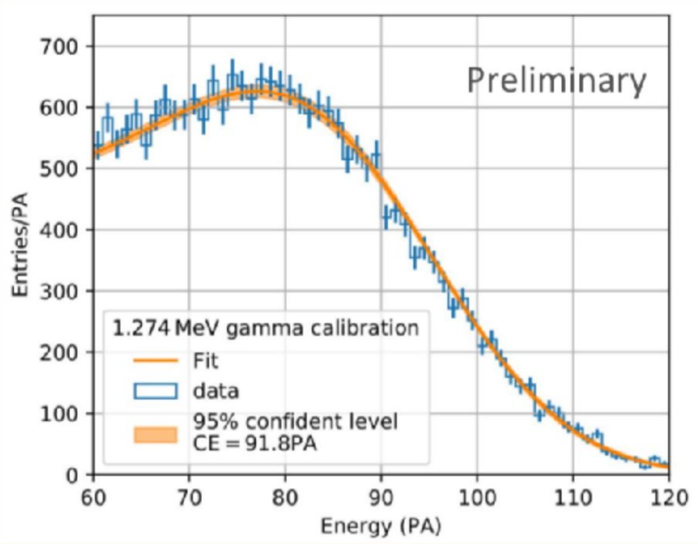
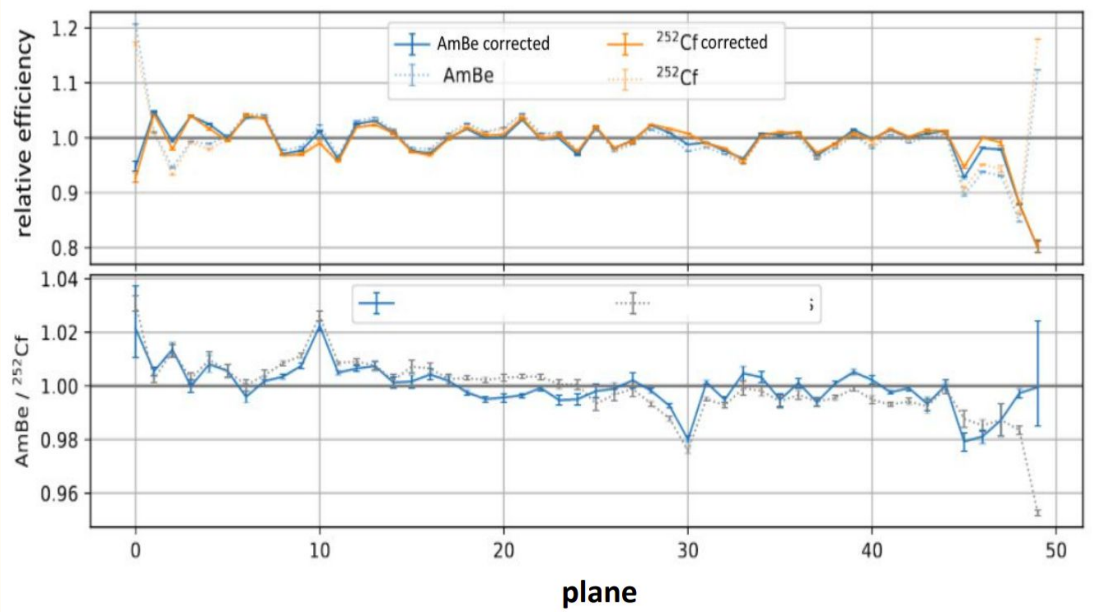
Backups

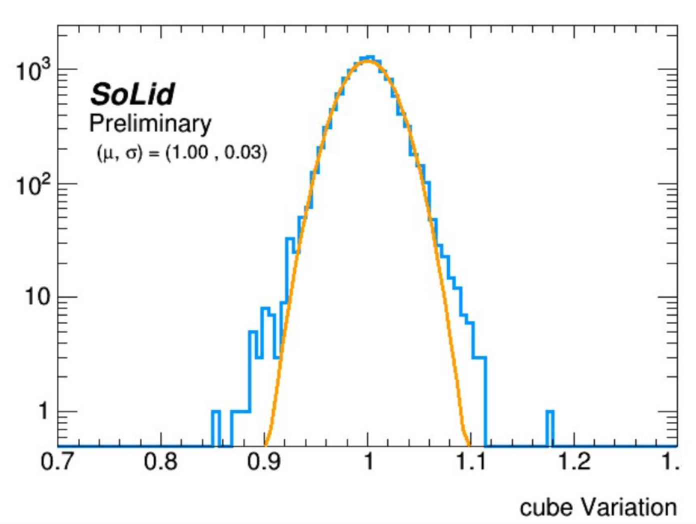
Detector Calibration

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**







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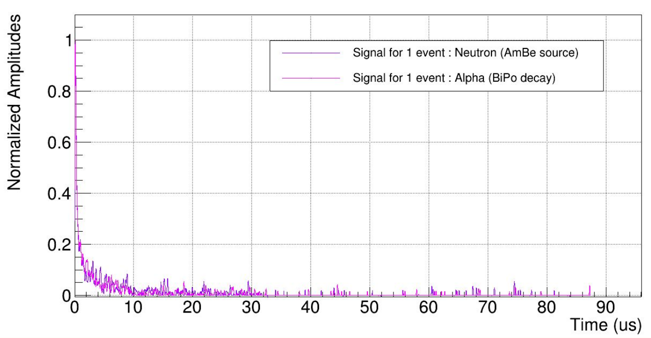
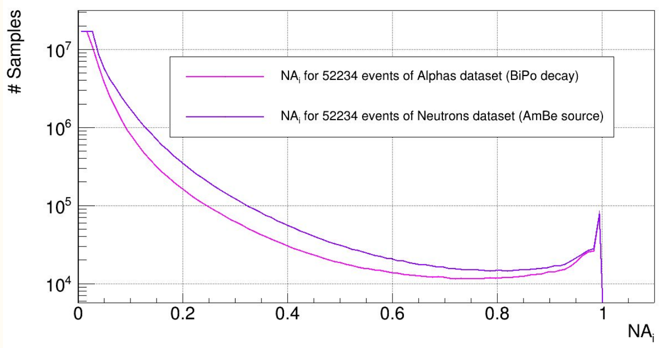
BiPonator: ML PSD Method

CNN Input

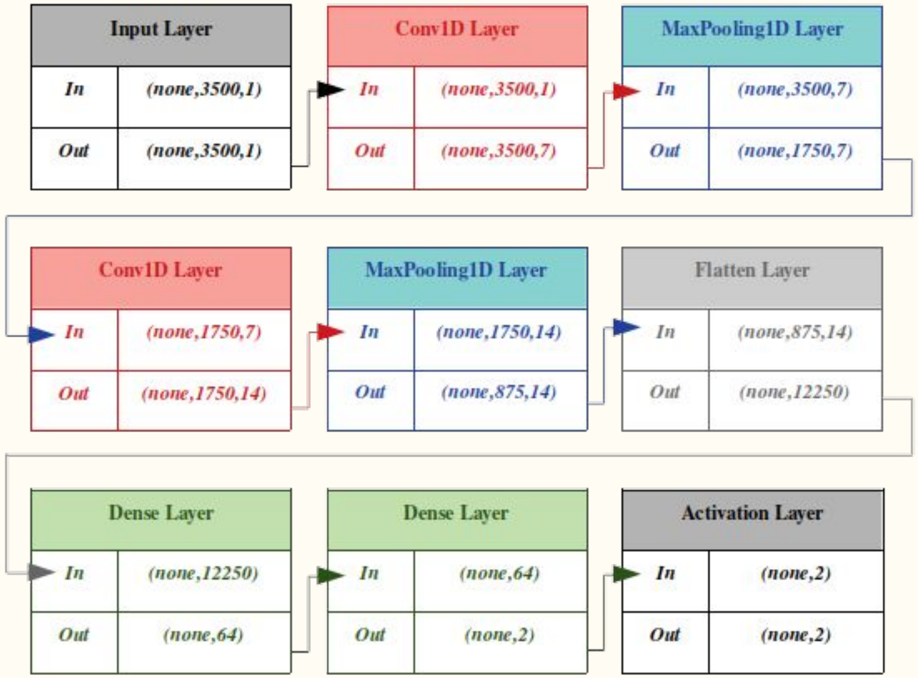


For each event,

$$NA_i = \frac{(A_i - A_{min})}{(A_{max} - A_{min})}$$

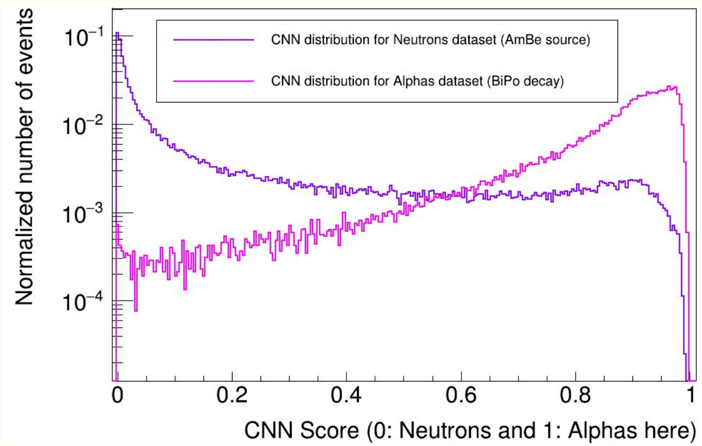


CNN Factory

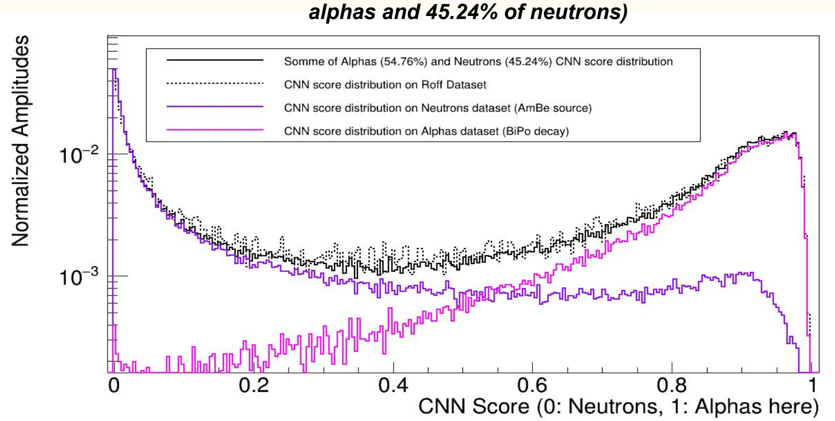


GOAL:
Alpha / Neutron discrimination improvement to reduce more BiPo background

CNN Output

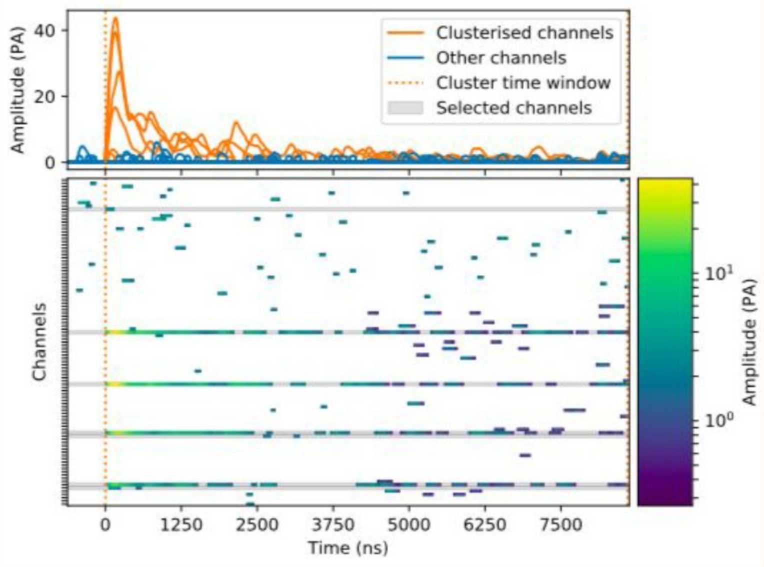


Ex : inference on Roff dataset (54.76% of alphas and 45.24% of neutrons)

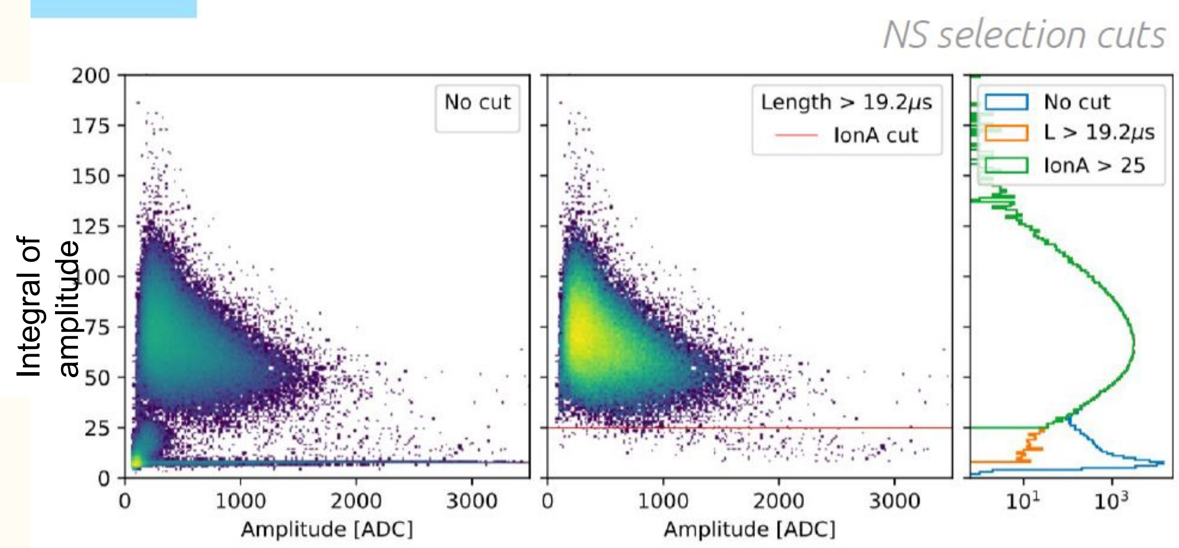


Event Reconstruction

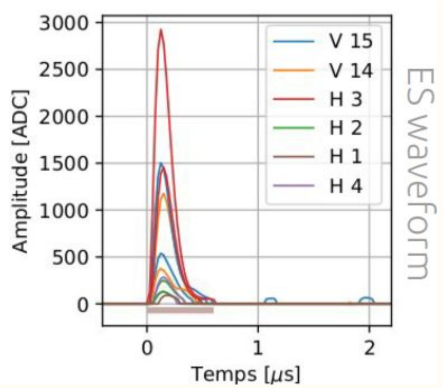
1. Time clustering to group signals from different fibers

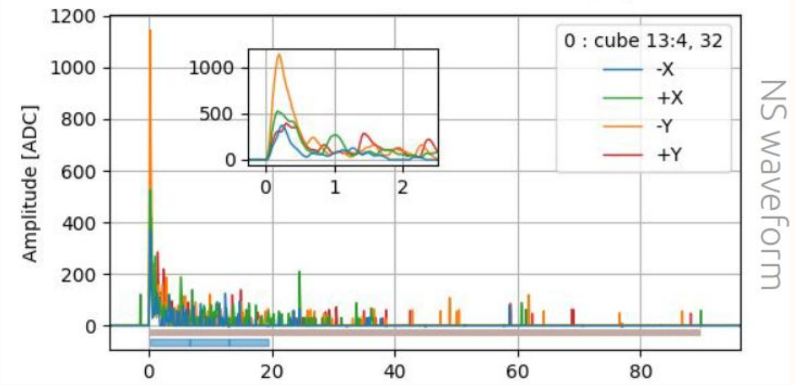


2. Identifying cluster by using cluster length and integral of amplitude / amplitude ratio
   - ➢ "ES", "NS", "Muon track"

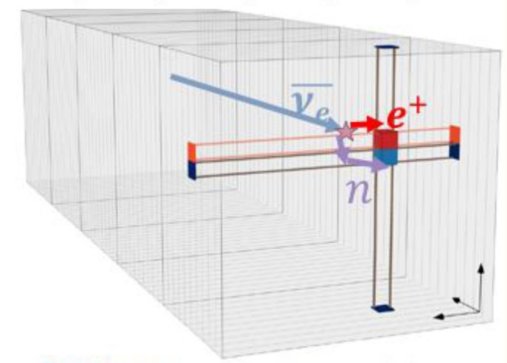


3. Make correlations between ES and NS





An ES-NS coincidence candidate



ES energy is estimated by using Maximum-Likelihood Expectation Maximization (ML-EM) algorithm

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BiPo for Detector Response Model

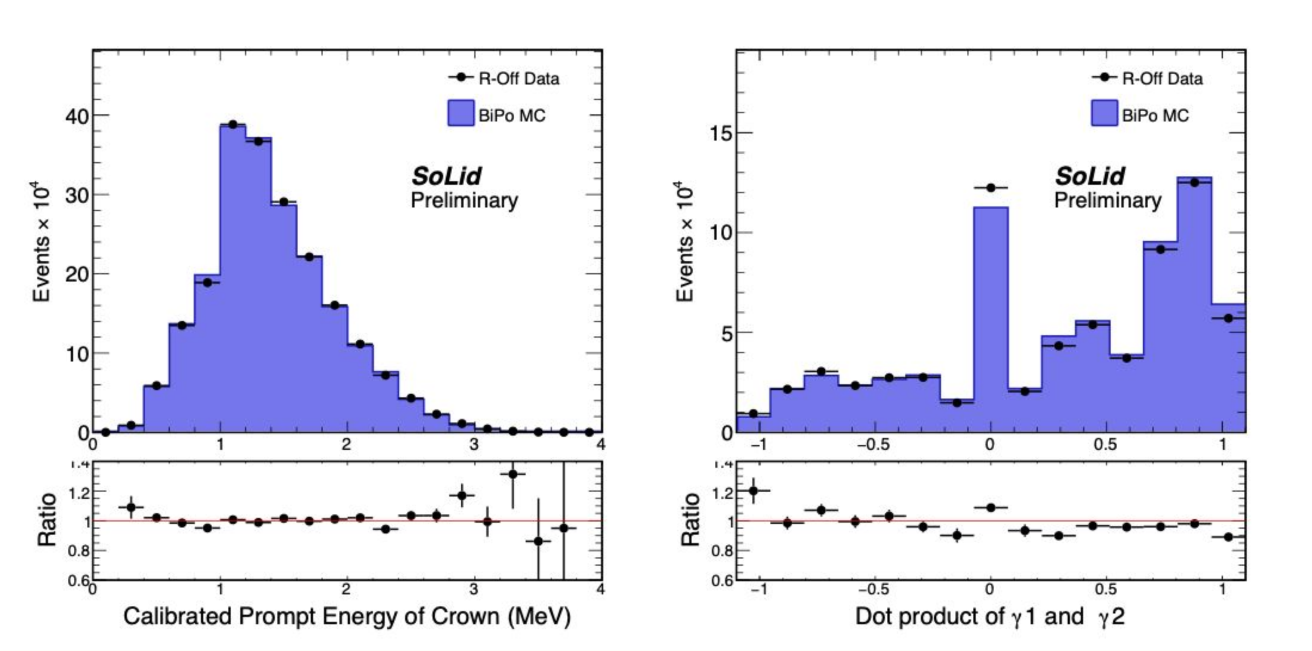
Utilise BiPo background to verify the detector response model.

➢ Select a high-purity **BiPo sample** close to the signal region.

➢ ~180 days of Phase-I reactor-off data used for comparison with MC.

➢ Very good data-MC agreement ⇒ prompt energy at the percent-level up to 3 MeV

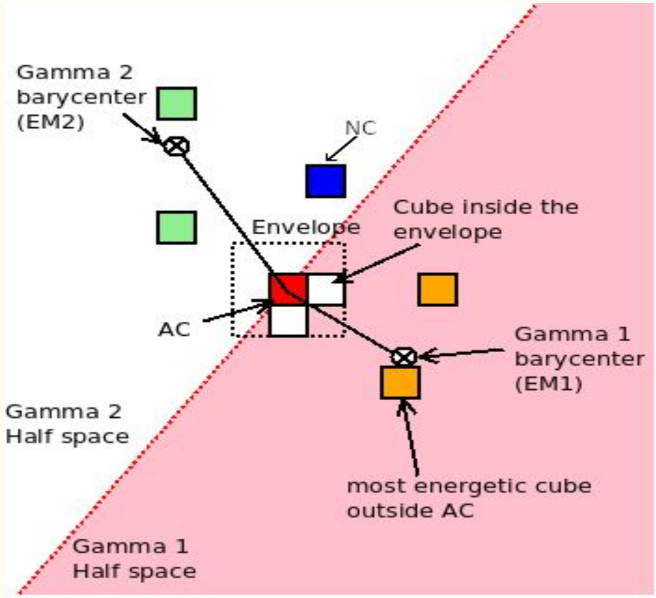
➢ **Systematic uncertainties** can be derived from disagreement between data and MC



Selection	Variables and Cuts
Pre-selection	Δ T $\in$ [200:500]μs
	Δ X $\in$ [-1:0]
	Δ Y = 0
	Δ R $\leq$ 1
	Prompt Energy Calibrated $\in$ [1, 4] MeV
+ BiPonator Selection	0.22 > BiPonator < 0.65

Two-gamma Antineutrino Topological Selection

Imperial College London



1. **New analysis** based on event topologies (taking maximal advantage of detector segmentation).
2. Preliminary analysis of events with **both annihilation gammas**.
3. **Multivariate analysis** for remaining background rejection
   a. Each background component determined with **multi-dimensional (Δt , Δr) simultaneous fit**.
4. Good agreement between excess and predicted excess, with S/B larger than one:

$$N(\overline{\nu}/\mathrm{day}) = 21.8 \pm 2.1\ (\mathrm{stat}) \pm 1.5\ (\mathrm{syst}).$$

5. Beyond Phase-I this approach will benefit from **detector upgrade** features