First results from the SoLid experiment at BR2

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on behalf of SoLid collaboration

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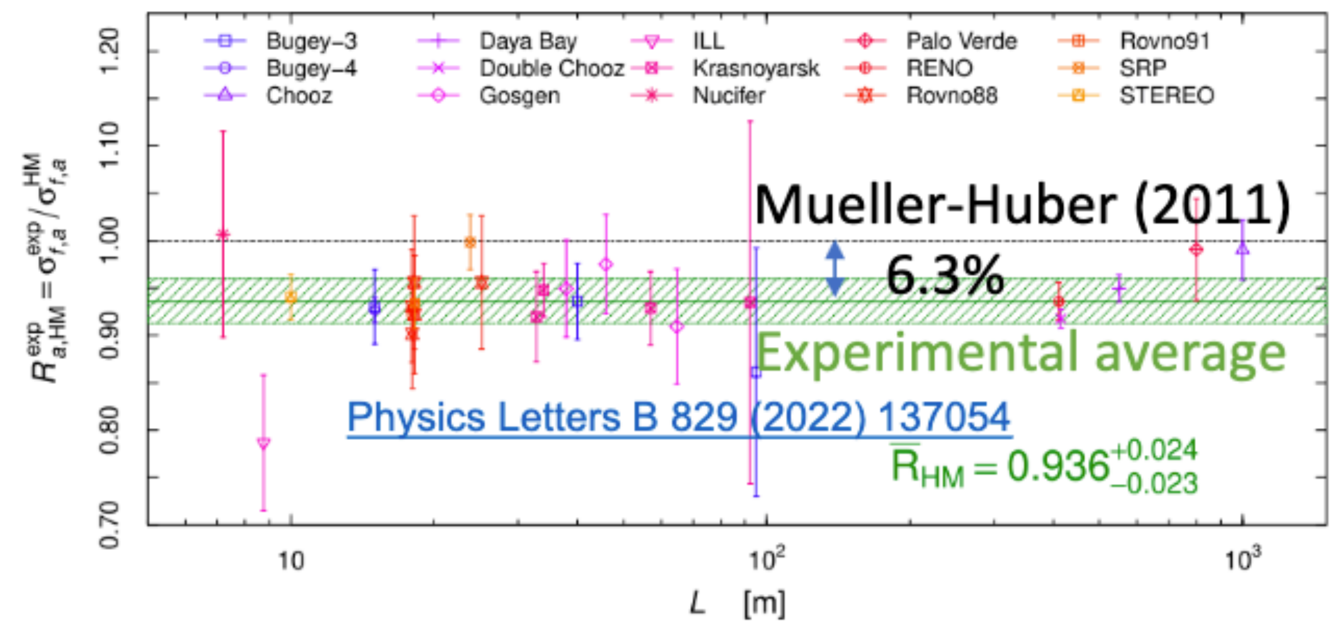
Motivations: Flux and energy anomaly

The SoLid experiment is designed to study very short baseline anti-neutrino oscillations

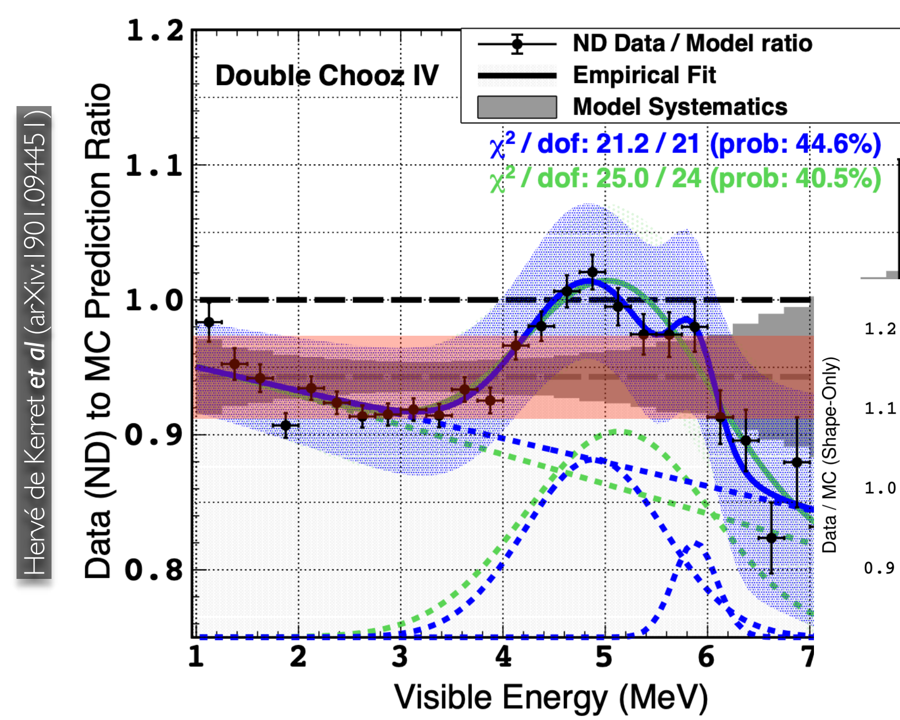
- **Probe the Reactor Antineutrino Anomaly with a different technology, different reactor**
    - A deficit in the measured flux compared to predictions.
    - Could be explained by a new oscillation into a sterile neutrino.
- Gallium anomaly: Phys. Rev. C 56, 3391 (1997)

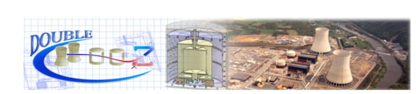
- Reactor Antineutrino Anomaly (RAA)

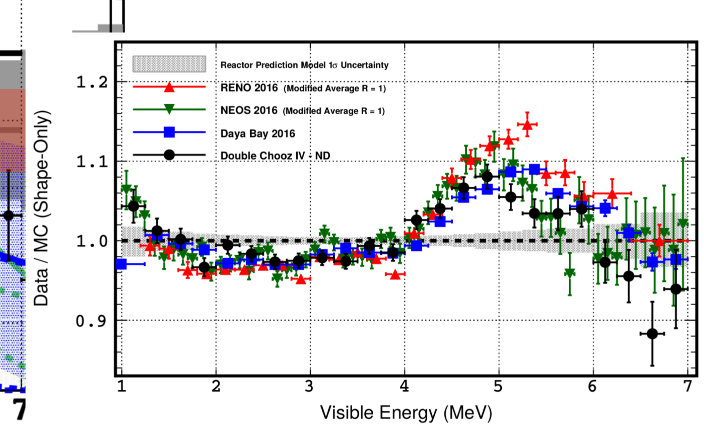


- **Measure precisely the U-235 Reactor antineutrino spectrum**
    - Unexpected distortion at 5 MeV reported by antineutrino experiments at power (LEU) reactors (235-U, 239-Pu, 238-U, 241-U isotopes) 235-U is thought as an interesting candidate to look for explanations.
    - Recent indiction from short-baseline liquid scintillator experiments at 235-U research (HEU) reactors *[arXiv:2107.03371]*

Nature Phys. 16, 558 (2020)





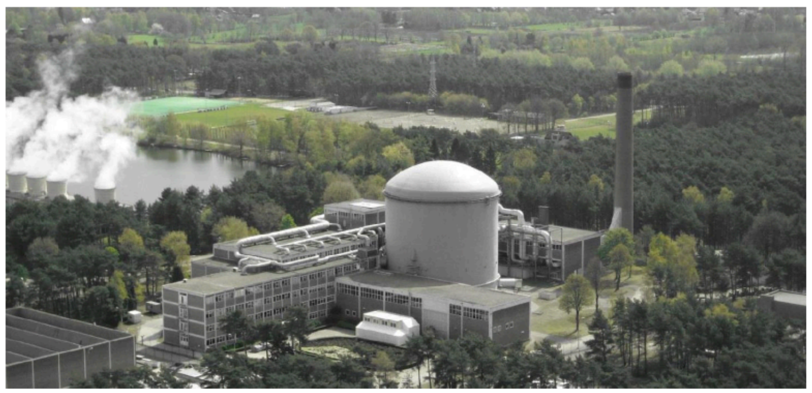


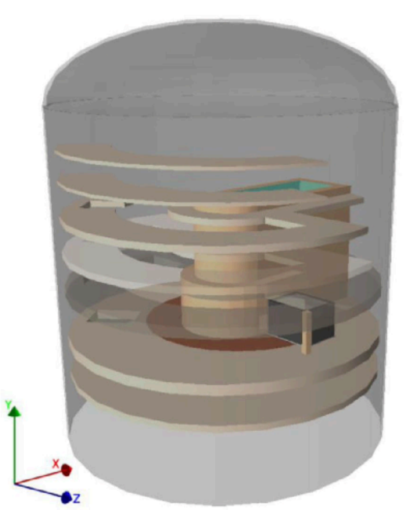
SoLid aims to address these anomalies using a novel detection technology w.r.t. the based Liquid experiments and using an other research reactor

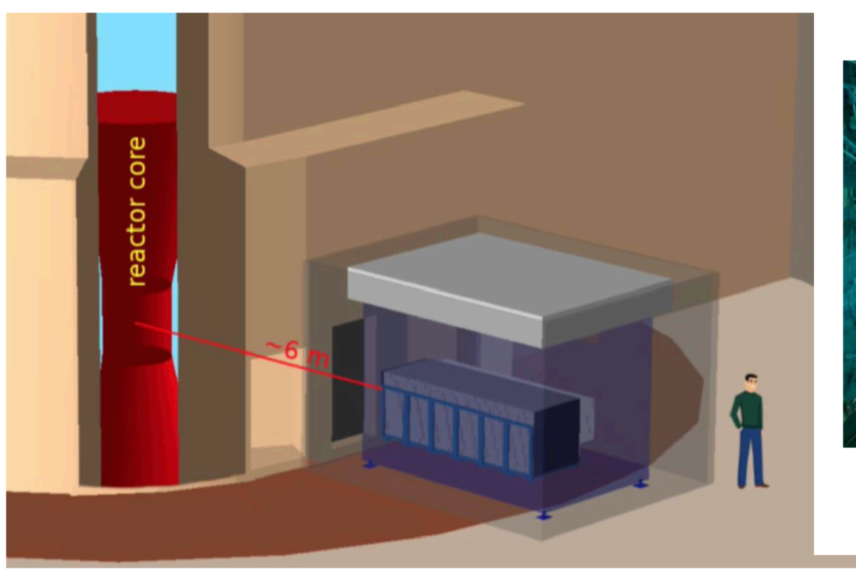
Experimental Location

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)

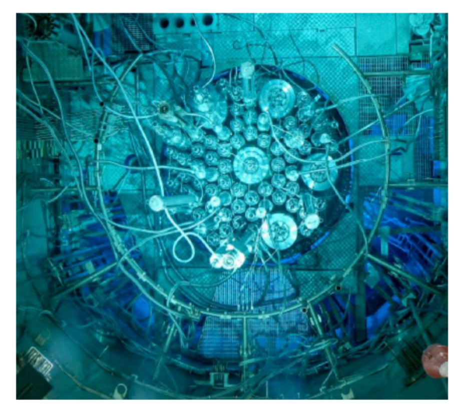


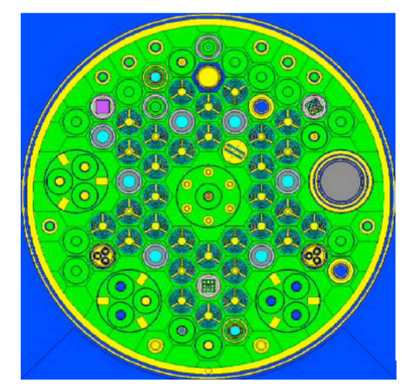




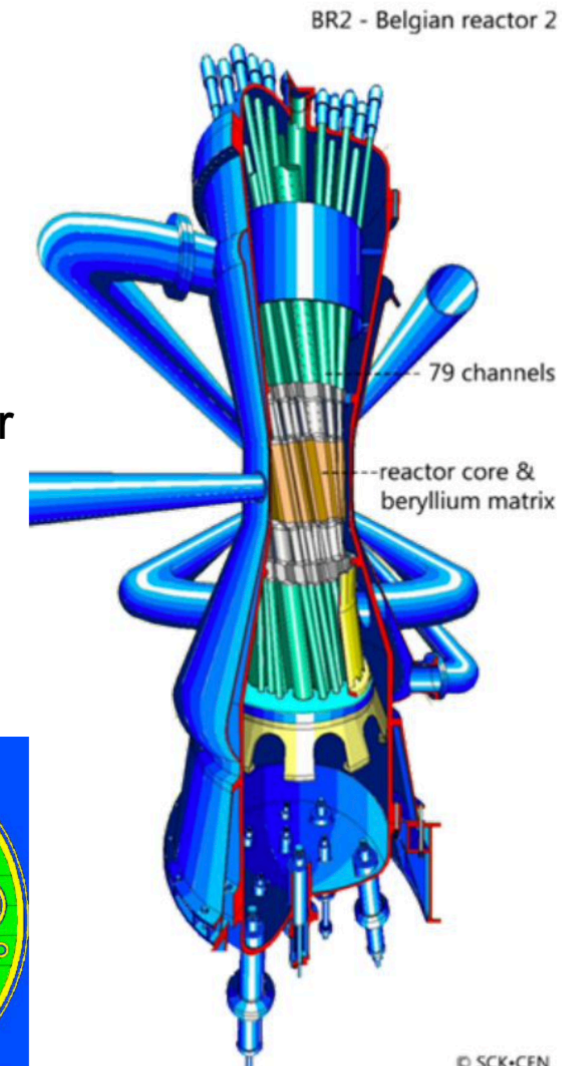
BR2 reactor

- 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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➡ Important cosmic induced background

➡ Key challenge that guided SoLid's design

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

Use the **temporal** and **spatial** coincidence between two types of waveforms to tag IBD interactions

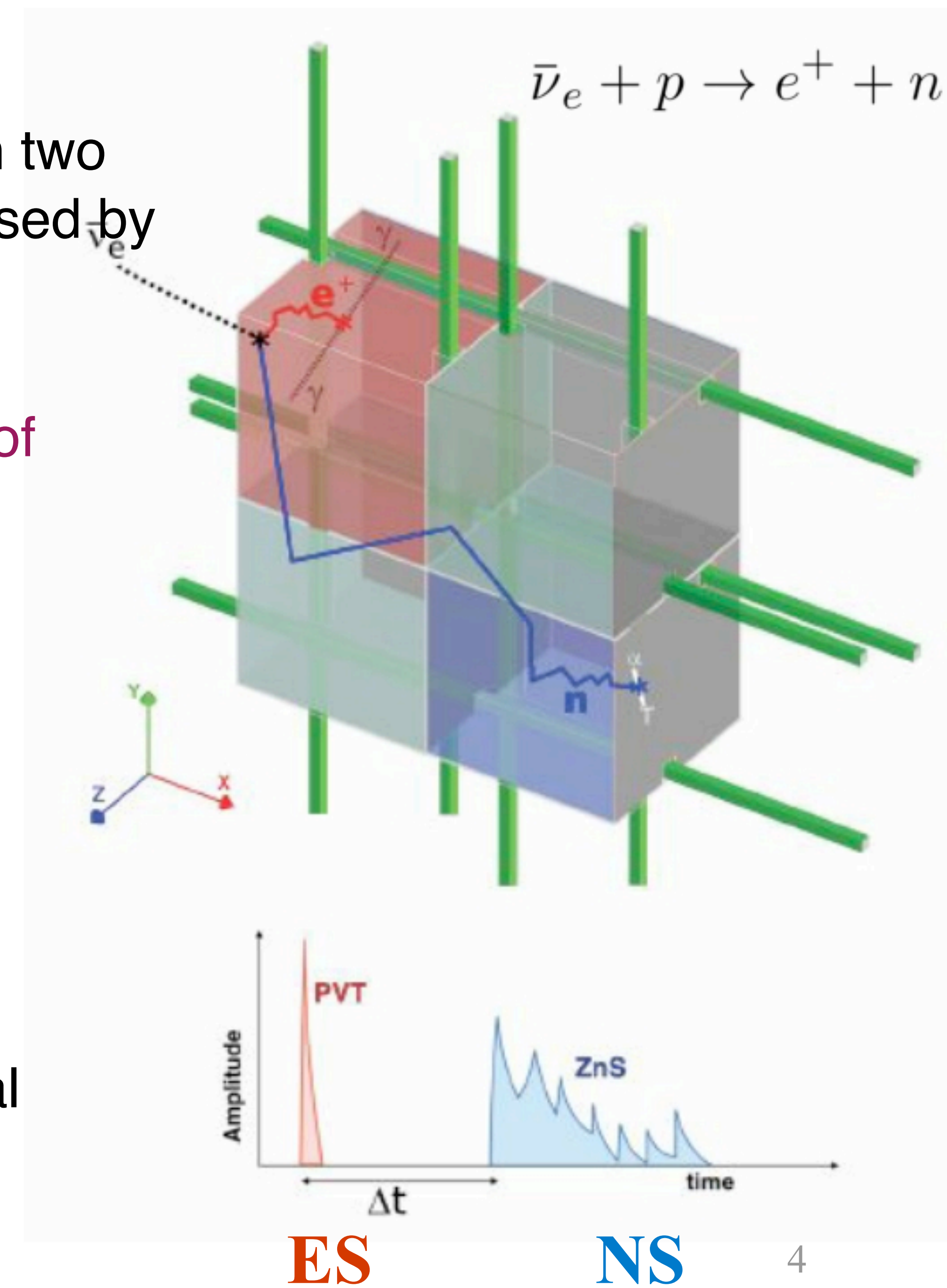
PVT cube for prompt signal: **ES** (electromagnetic scintillation)

- 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

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

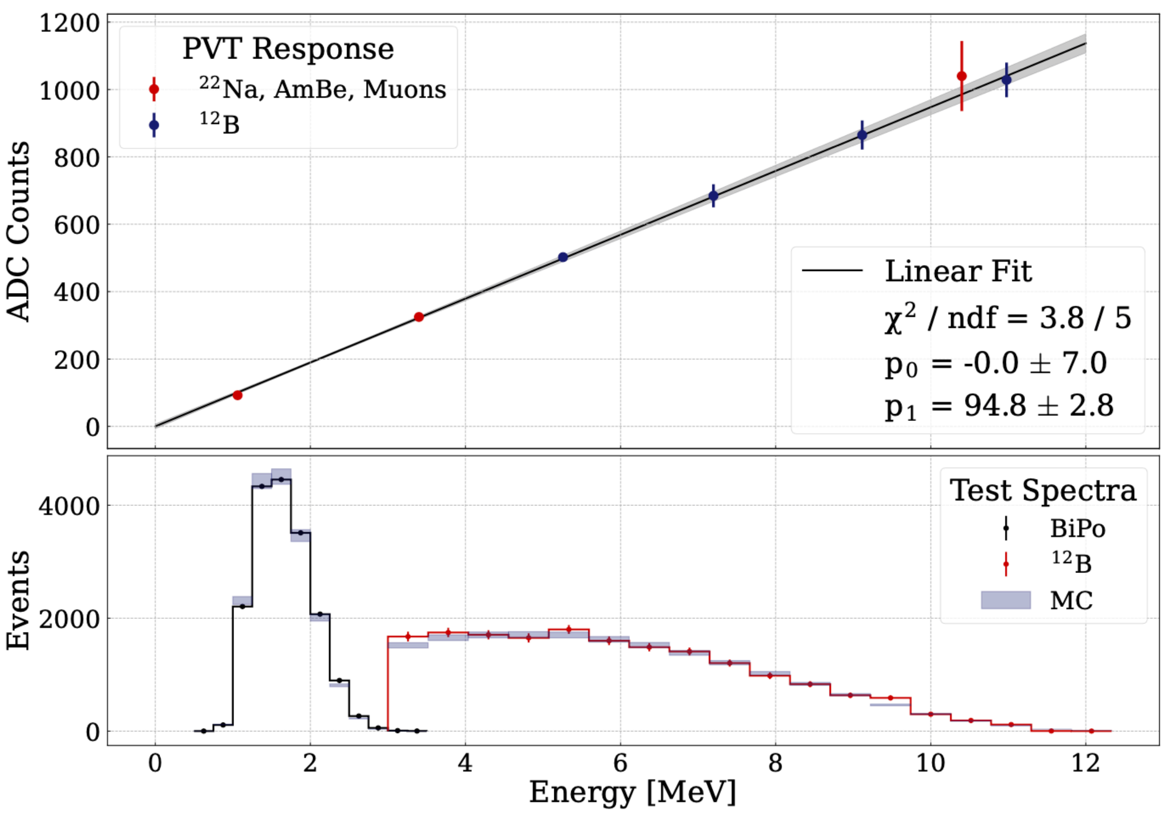


thanks to the high segmentation, we can exploit the detailed topology of the prompt signals

SoLid Technology, a different approach

Motivations

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



Top: Response of the PVT scintillator as a function of energy in the 1–11 MeV range from September 2018 calibra- tion data. The linear fit is derived from the points indicated in red and further validated by the blue points, which align well with the fit. Bottom: Data-MC comparisons of BiPo and boron-12 spectra.

- Highly segmented technology:
  - Isolate positron energy and identification of annihilation gammas
- Event topologies allow classification of signal and background

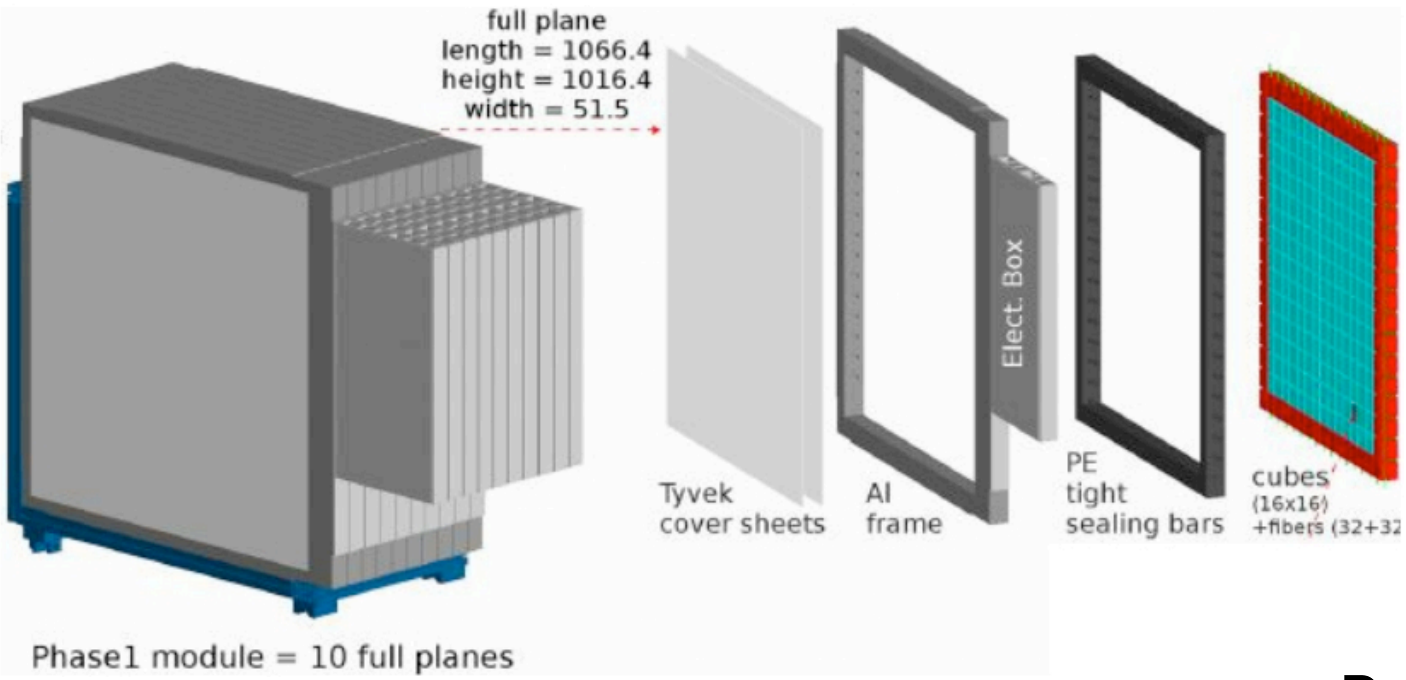
Challenges

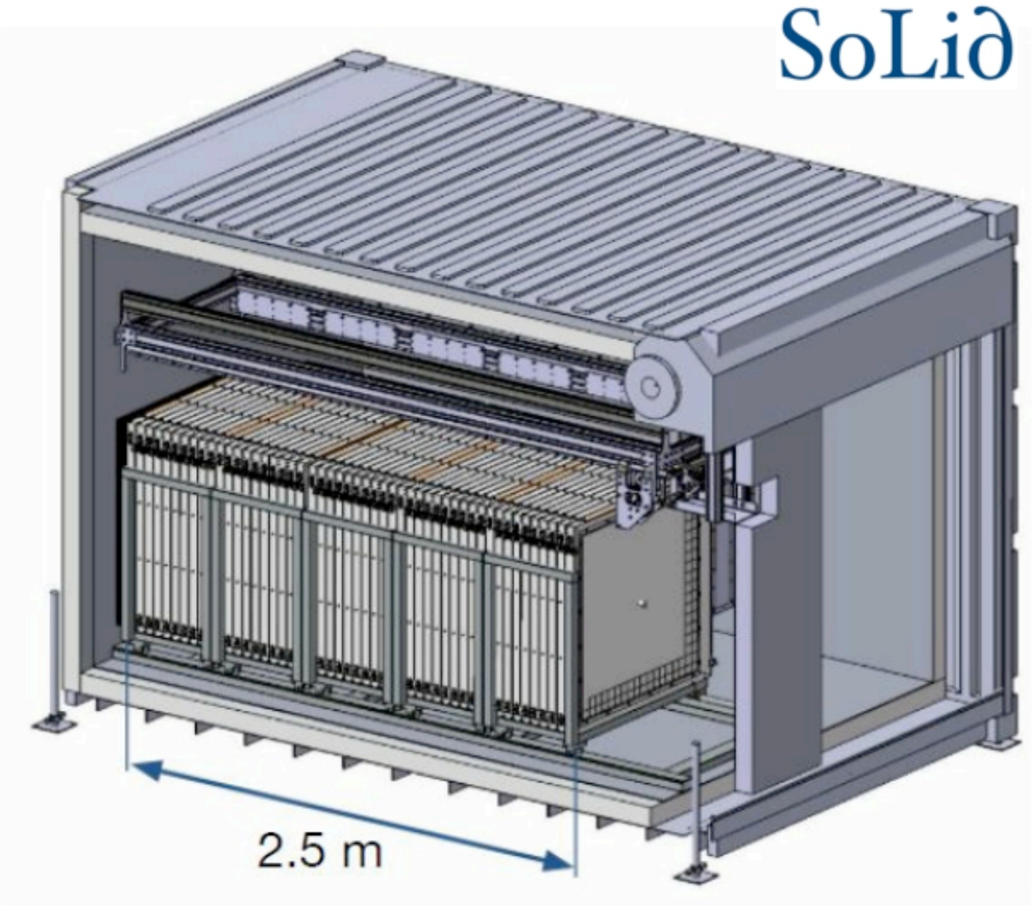
- Reduction of high backgrounds
- No direct gamma-neutron PS
- Heterogenous detector
- Need detailed understanding of complex detector
- Large number of readout channels and parameters to calibrate

Phase I Detector

12800 PVT cubes (1.6 ton fiducial volume)
- 256 cubes per plane
- 10 planes per module
- 5 modules for oscillation study

3200 readout channels
- Signals detected by S12 series MPPCs (SiPM)

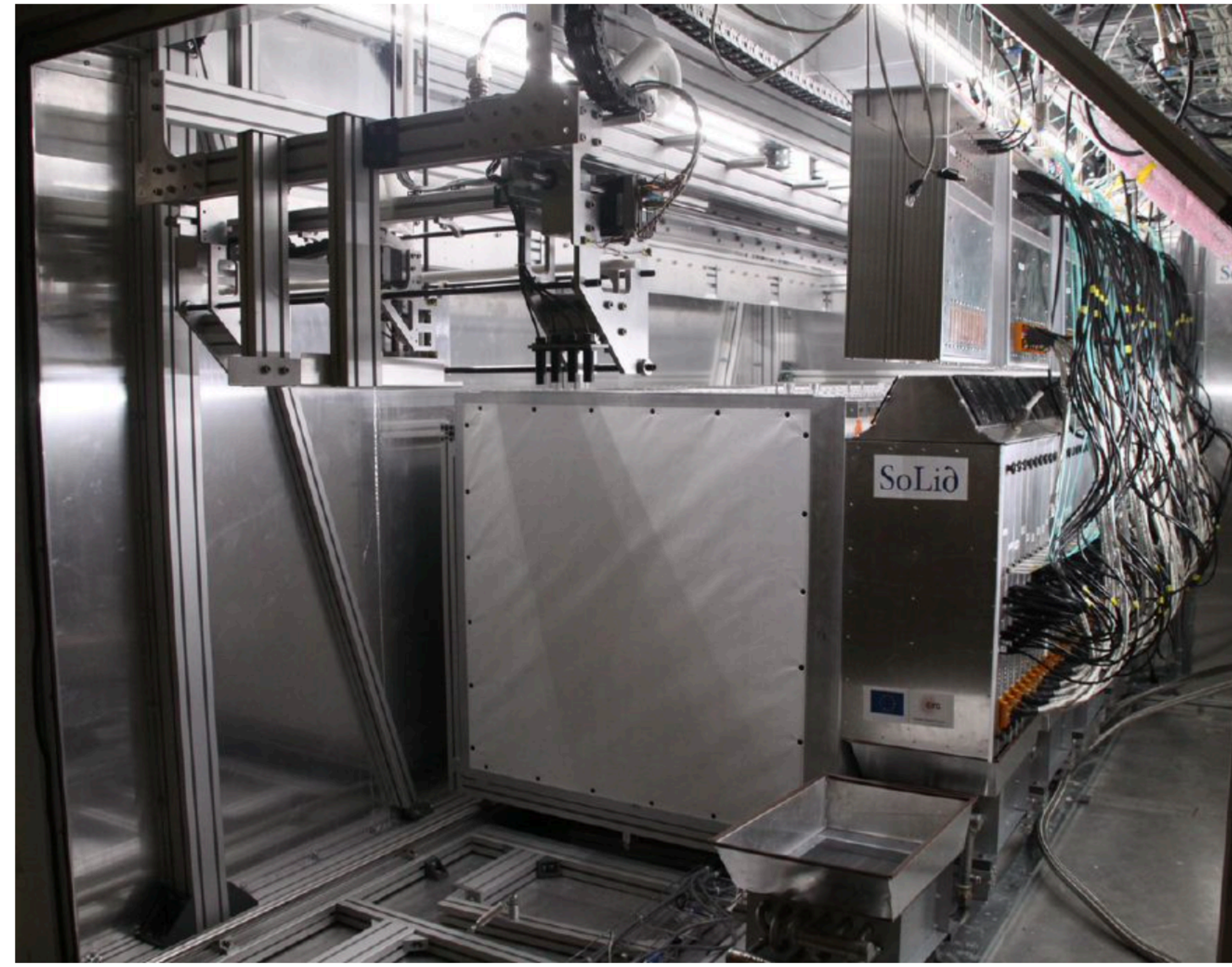




Detector modules mounted on rail system allowing for in-situ calibration with sources

Phase I Detector and Dataset

The SoLid container at BR2 prior to completion of water wall

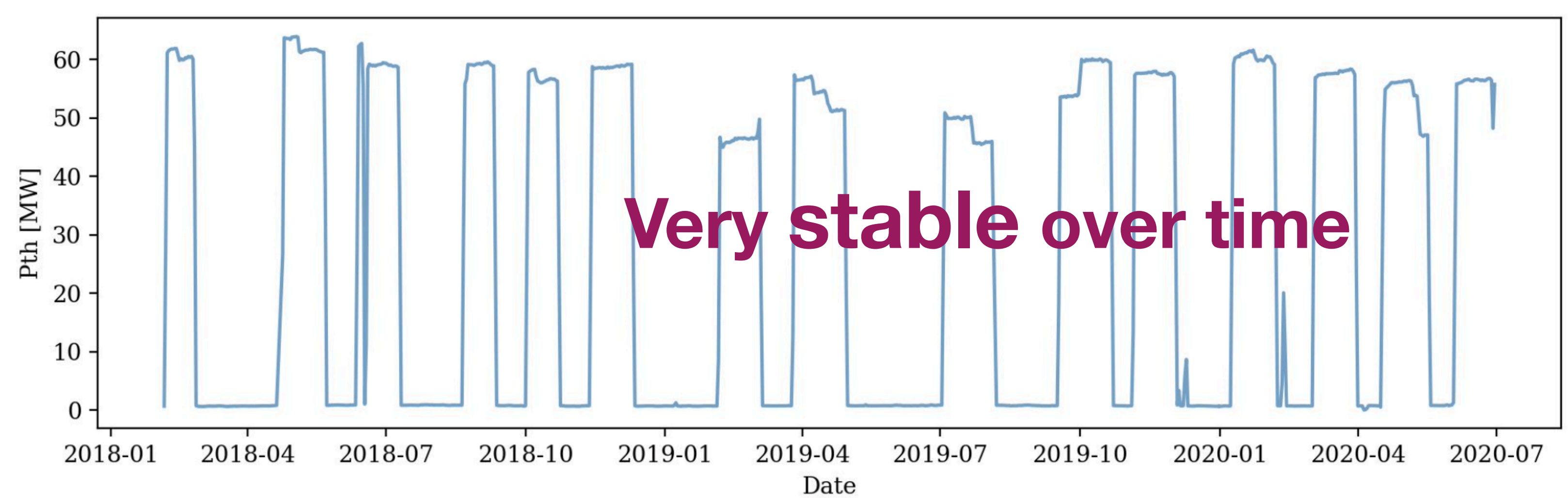


SoLid detector inside the container prior to installation of final module.

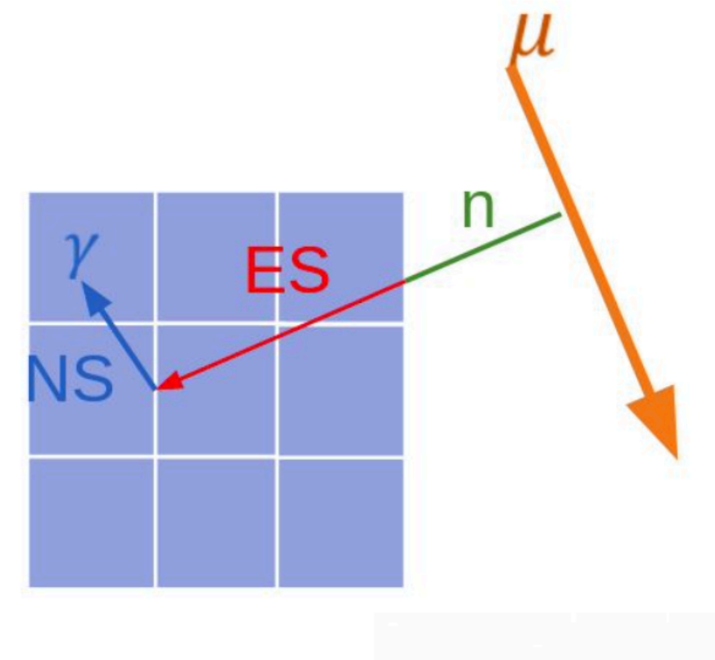
Data on tape

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

- Selected respectively **~280 days** and **~170 days** of sufficiently high quality **reactor-on (ron)** and **reactor-off (roff)** data for an oscillation



Major issue: Controlling two backgrounds

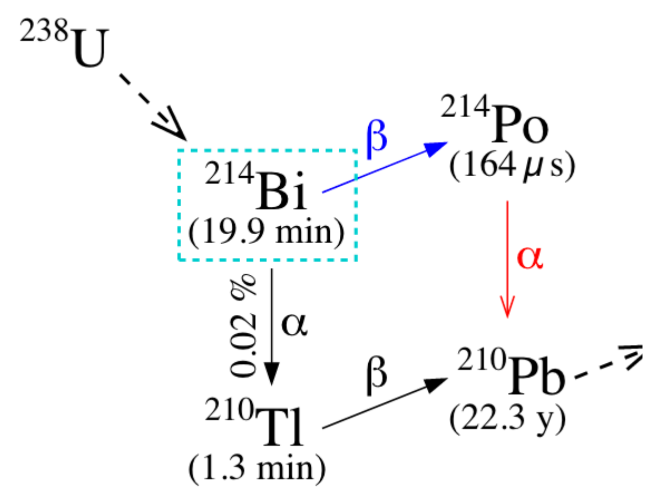


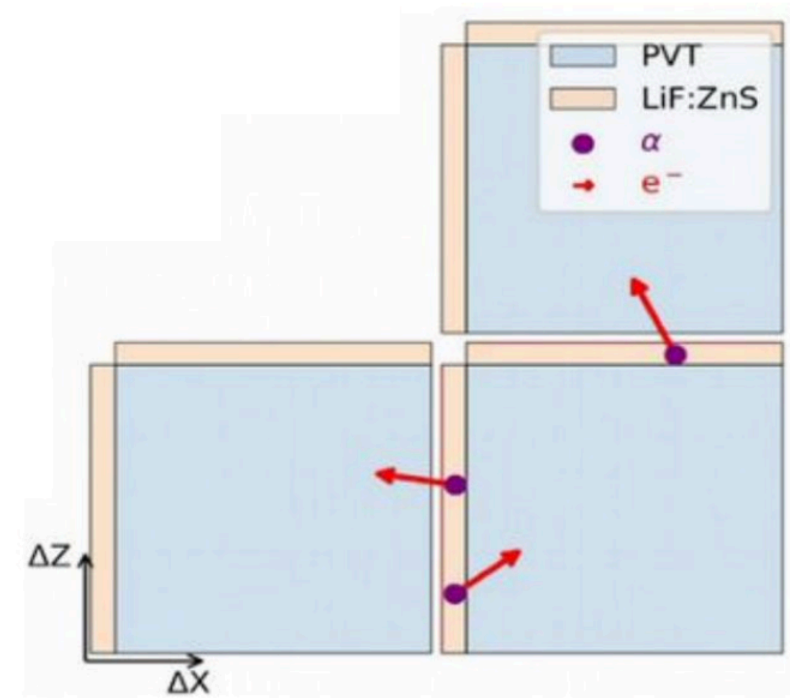
Fast neutrons induced by cosmic-ray shower & muon spallation:

- Neutron recoil events: ES
- Neutron capture: NS

BiPo (internal):

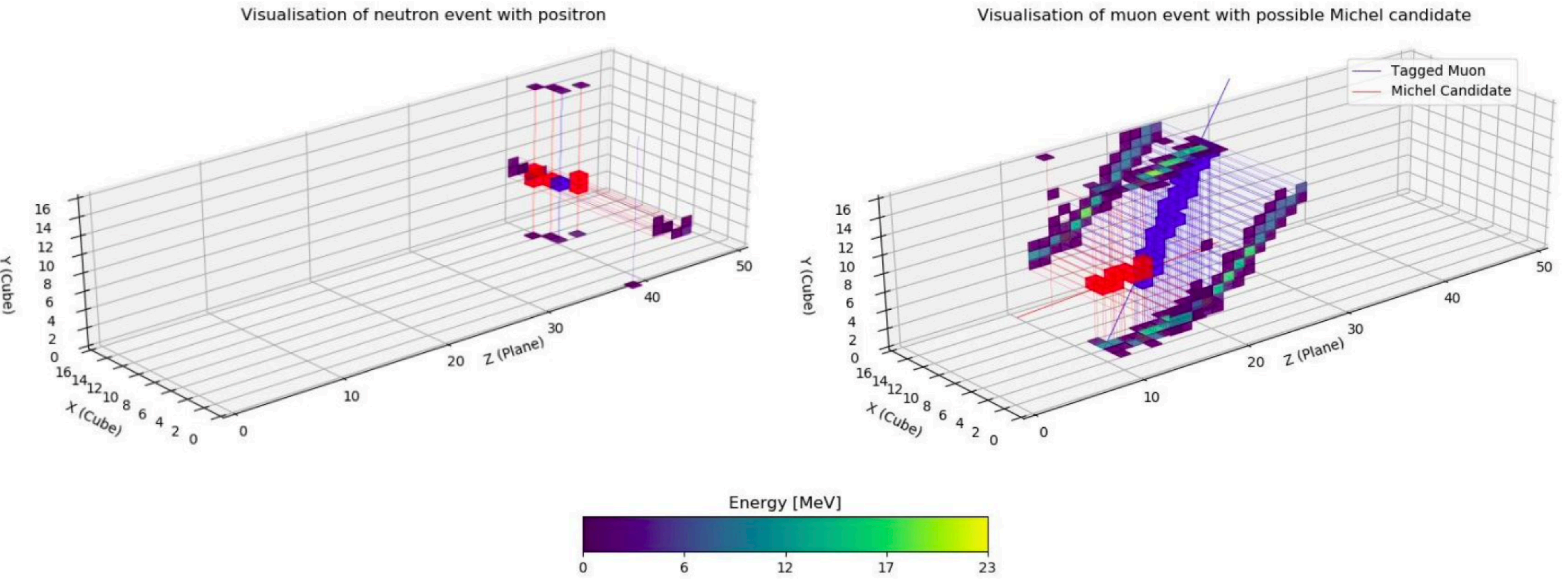
- Unexpected and critical internal contamination of ZnS layer
  - Nearly 2 order of magnitude above IBDs before selection
  - Derived from ^{238}U/^{230}Th series
    - ^{214}Bi decay (e^-, γ): ES
    - ^{214}Po decay (α): NS





- **However, SoLid technology offers many dimensions to test the signal and background**
- **Technology very well suited for the use of machine learning techniques**

Event Display



Very clear topological signature

High Background level

ROff Composition Before Selection

Evaluate the relative proportions of different backgrounds using Δt fit:

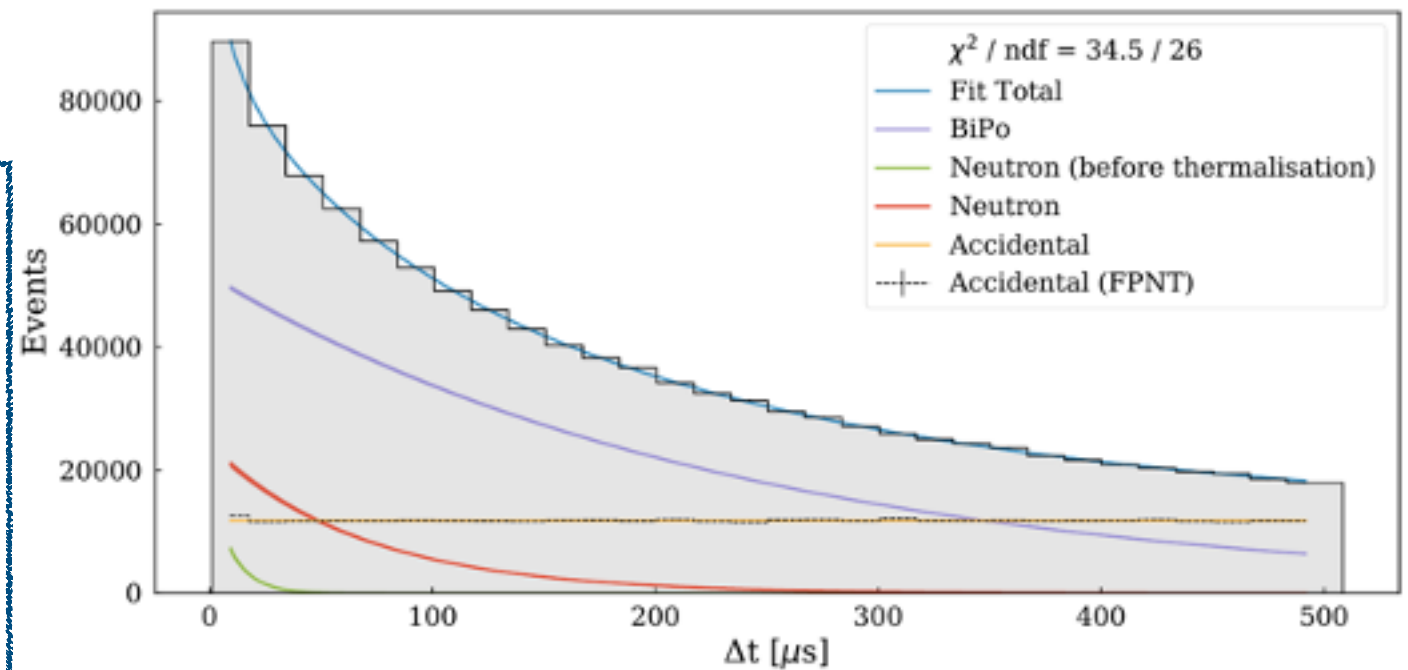
Open dataset ROff

➢Accidentals: 32%

➢BiPo: 58%

➢Fast neutrons: 10%

We obtain an initial signal-to-background ratio of ~ **0.00133.**



$$y(\Delta t) = c_0 + c_1\, e^{\Delta t/\tau_{\mathrm{BiPo}}} + c_2\, e^{\Delta t/\tau^{\mathrm{Th}}_{\mathrm{Neutron}}} + c_3\, e^{\Delta t/\tau^{\mathrm{Epi}}_{\mathrm{Neutron}}}$$

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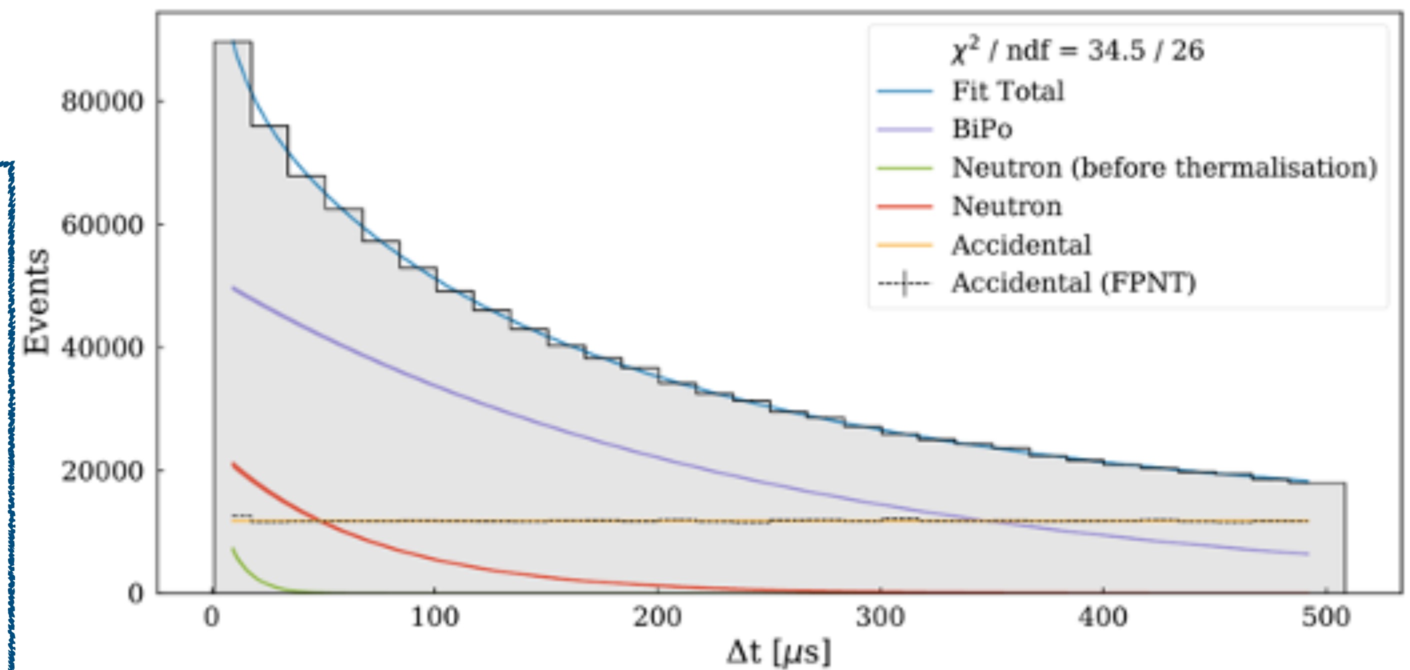

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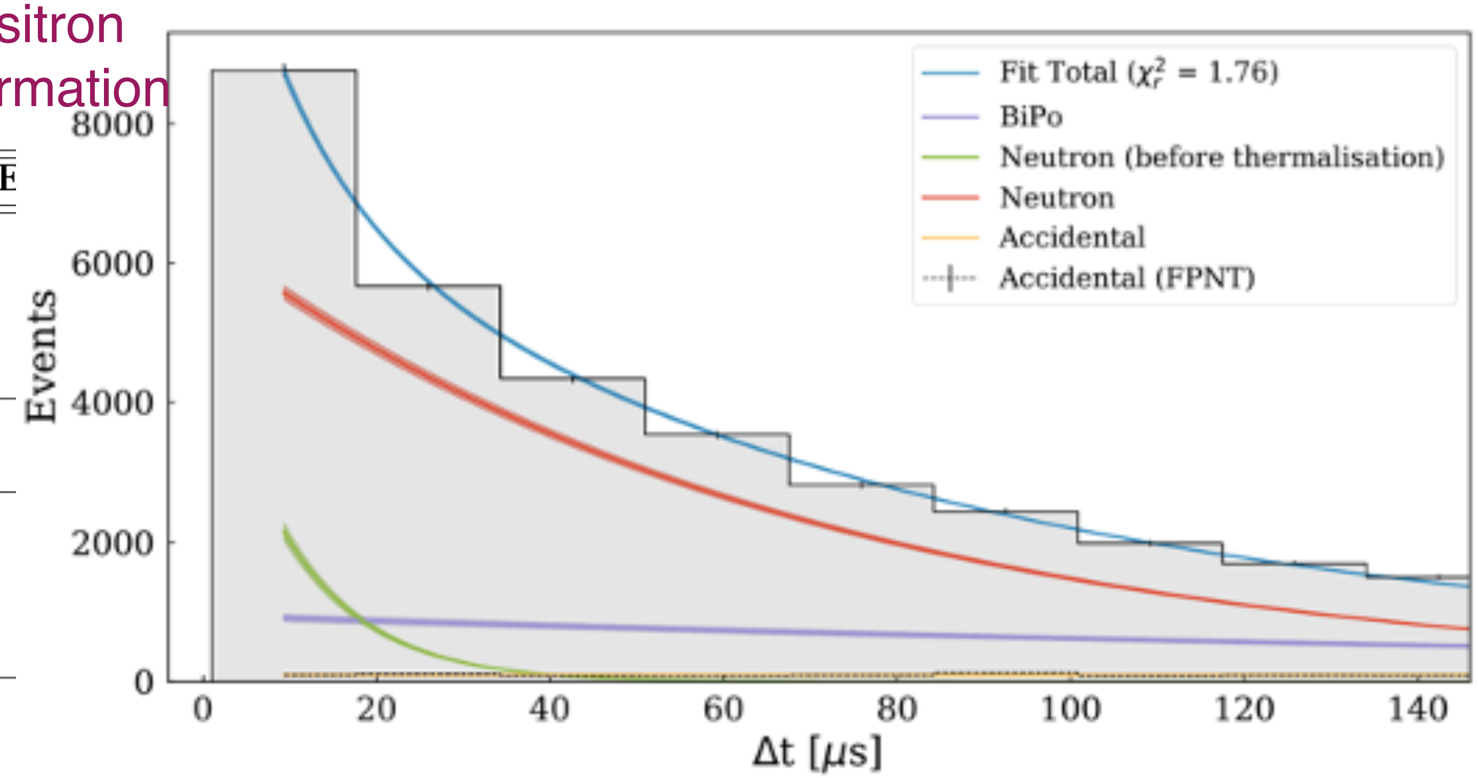
Standard cuts-based selection

the detector granularity is exploited to isolate the positron energy, which carries the antineutrino spectrum information

Description	Variable and Limits	Sig. (Bck.)	E
NS-ES displacements	$\Delta X \in [-3, 3]$	99.6 (68.7)	
	$\Delta Y \in [-3, 3]$	99.6 (68.5)	
	$\Delta Z \in [-2, 3]$	99.7 (89.2)	
	$\Delta R \in [1, 4]$	92.0 (40.4)	
BiPo-focused	$\Delta t \in [1, 141]$ µs	89.0 (38.6)	
	BiPonator $\in [0.7, 1.0]$	75.7 (13.3)	
Other	$E_{\mathrm{MEC}} \in [1.0, 6.0]$ MeV	87.2 (57.8)	
	NumGammaTotal $\in [1, \infty]$	73.0 (46.1)	
	tNearestMuonType1 $\in [200, \infty]$ µs	n/a (91.9)	
	tNearestMuonType2 $\in [200, \infty]$ µs	n/a (91.9)	



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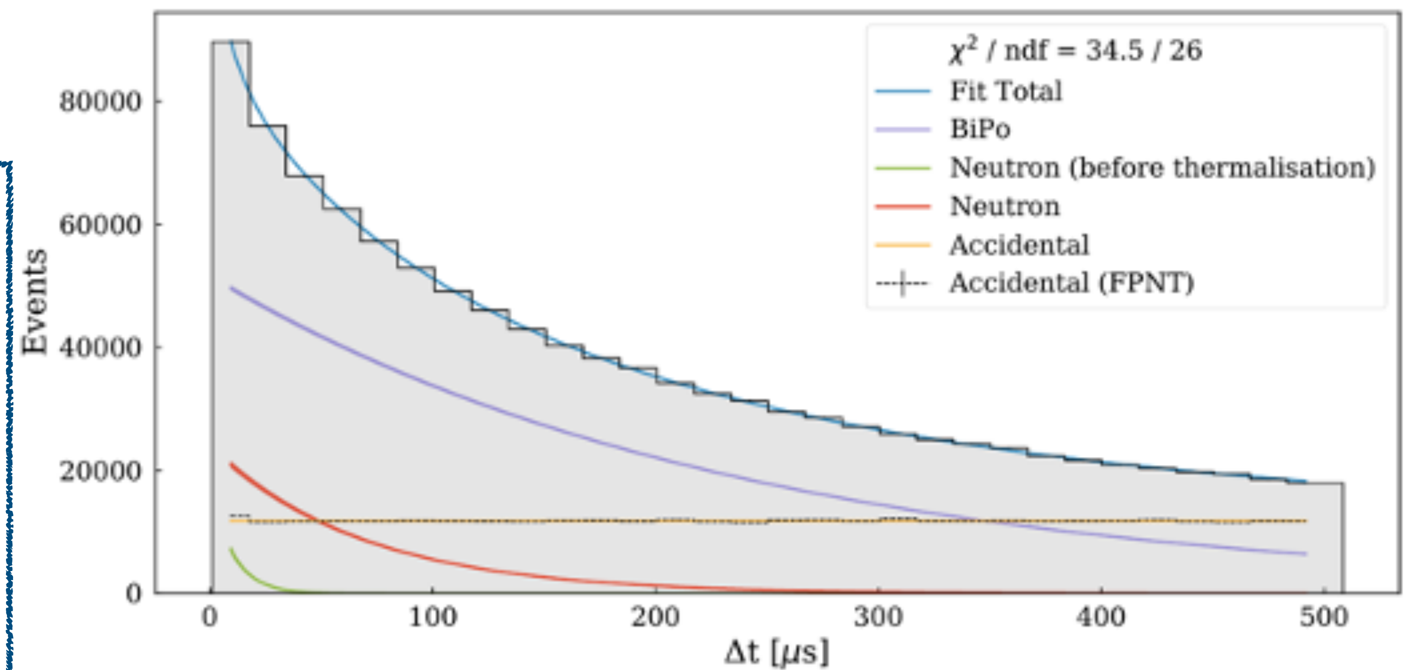

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Open dataset ROff

➢ Accidentals: 2%
➢ BiPo: 18%
➢ Fast neutrons: 80%

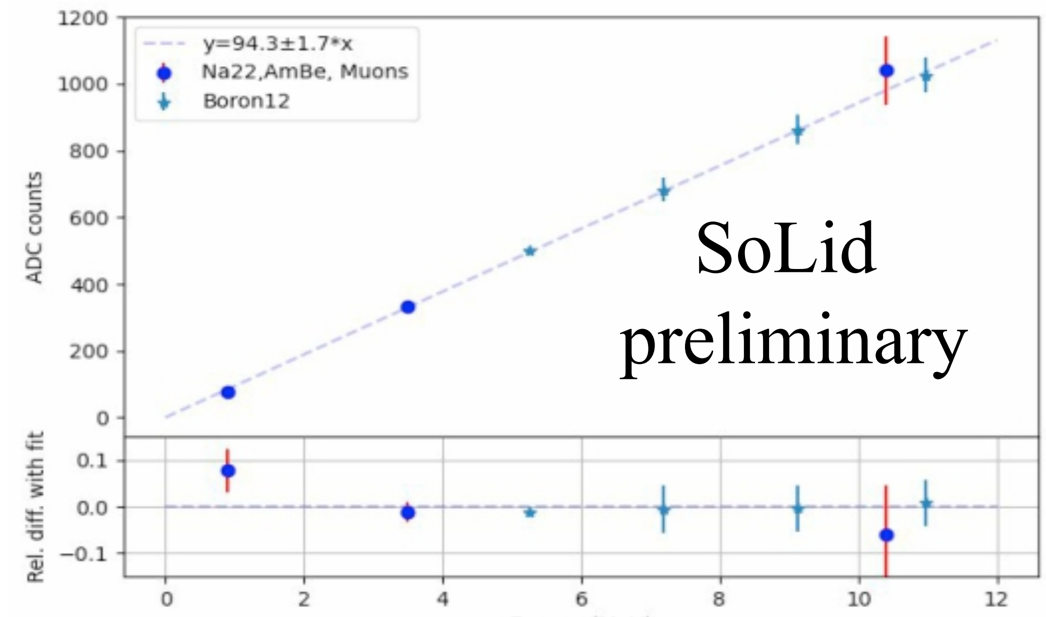
Signal-to-background ratio improved by an order of magnitude to ~ **0.0273**

➡ Need ML classification techniques based on the unique technology features

Well understand the detector: calibration

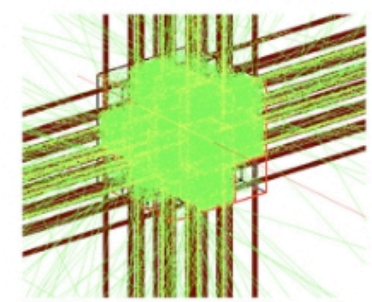
Absolute calibration

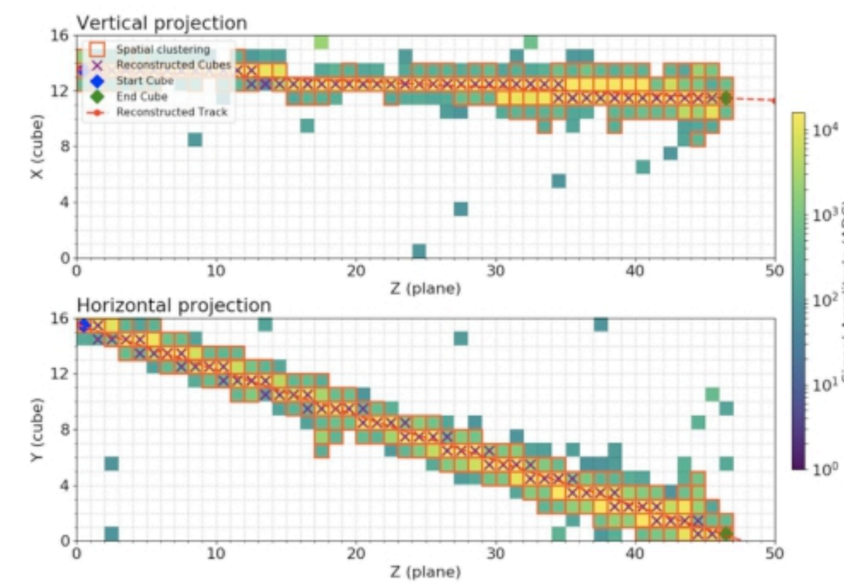
- Energy scale measured across entire spectrum:
    - Na22 (Compton edge KS test)
    - AmBe (e+e- at ~ 3.4 MeV)
    - Muons (~ 10 MeV)
- Light yield of 94 PA/MeV (**16% resolution at 1 MeV**)
- Very good linearity of response

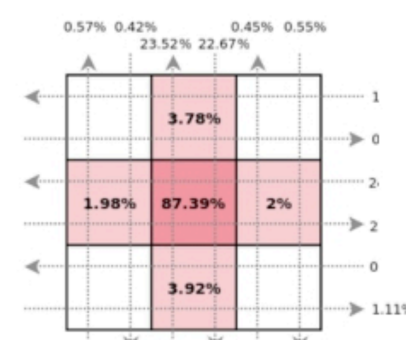


Relative calibration

- 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**

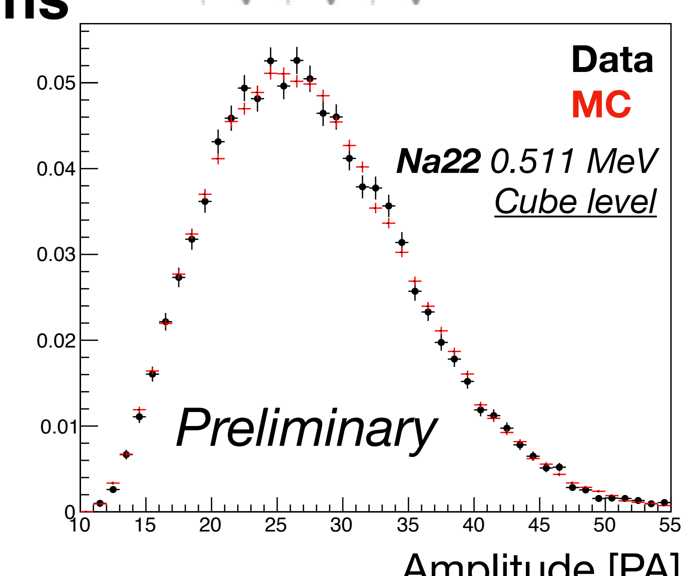


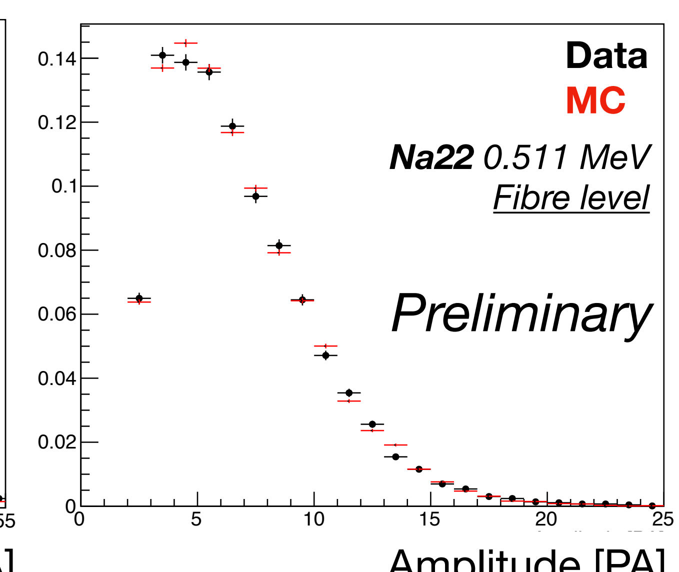




Precise MC tuning!

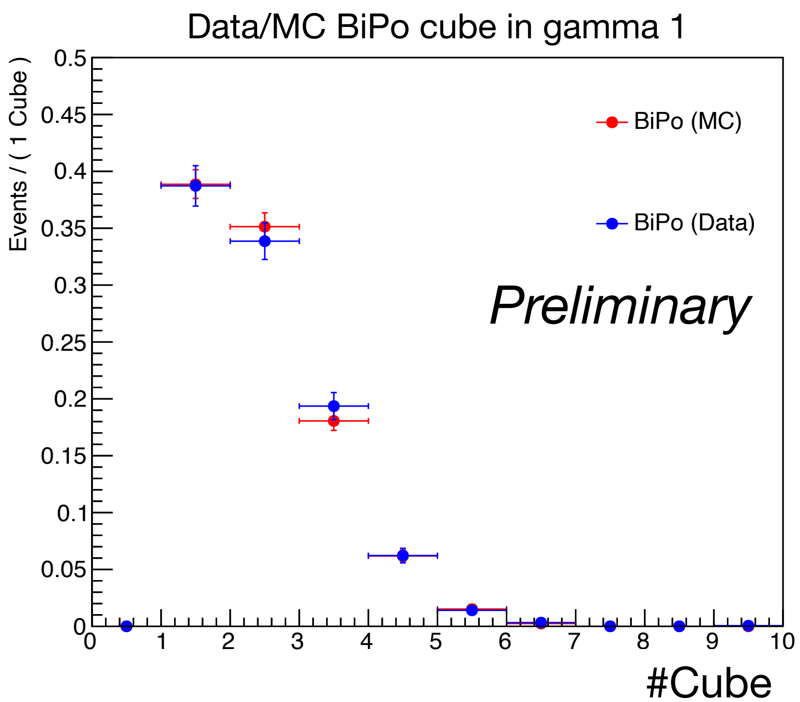
- 22-Na used for PVT energy tuning and control below 1 MeV

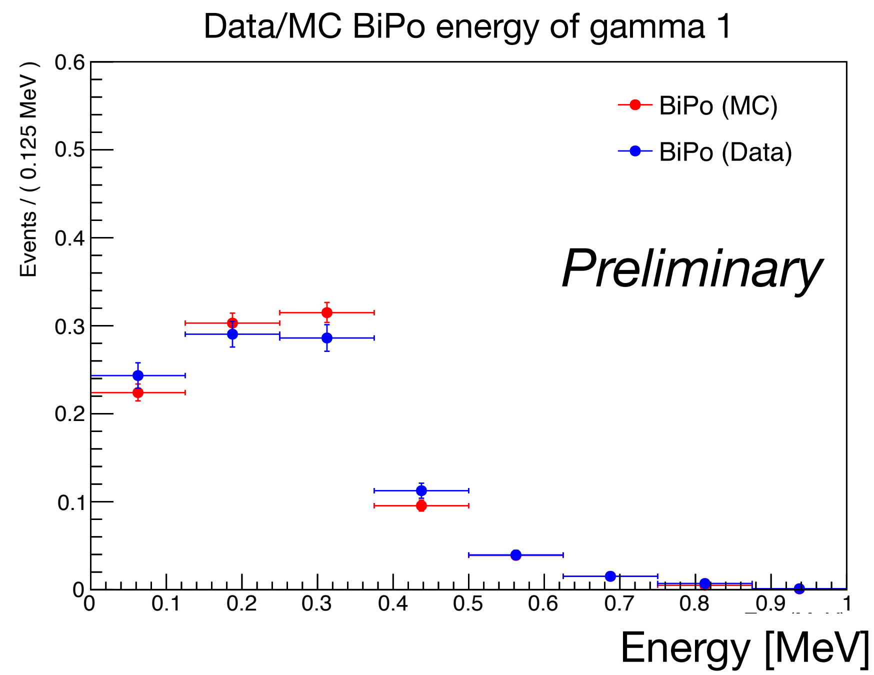


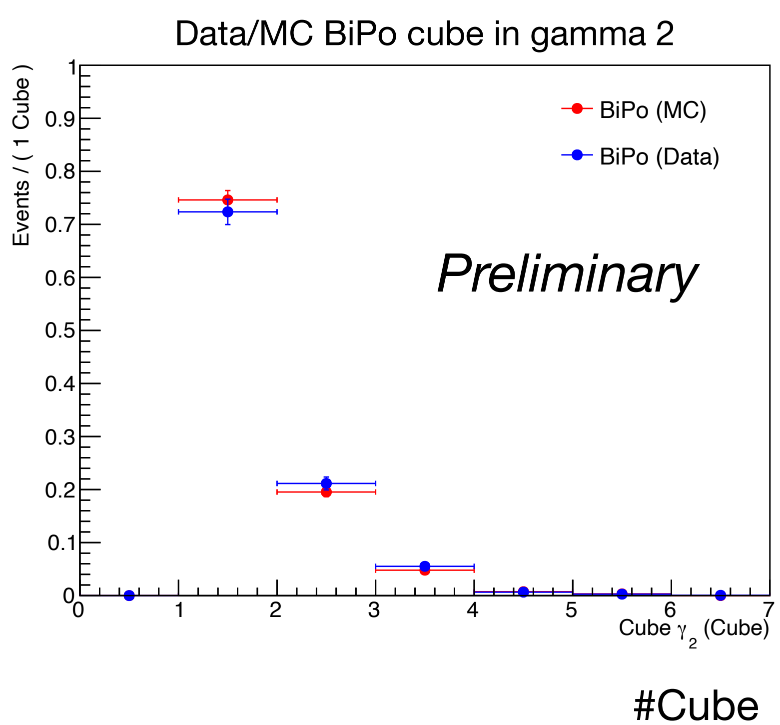


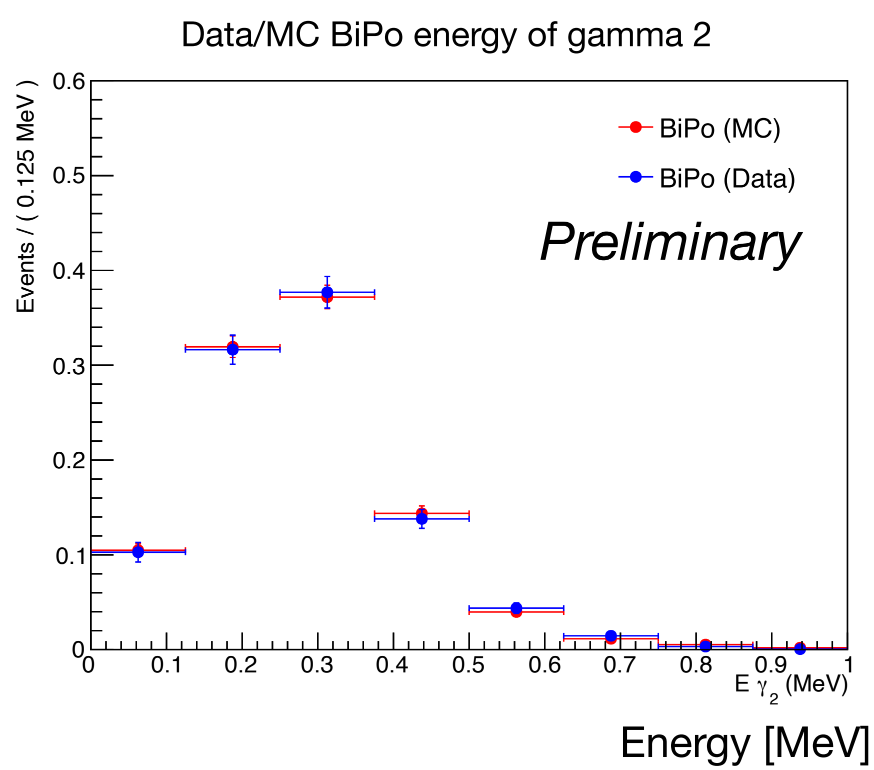
BiPo for Detector Response Model

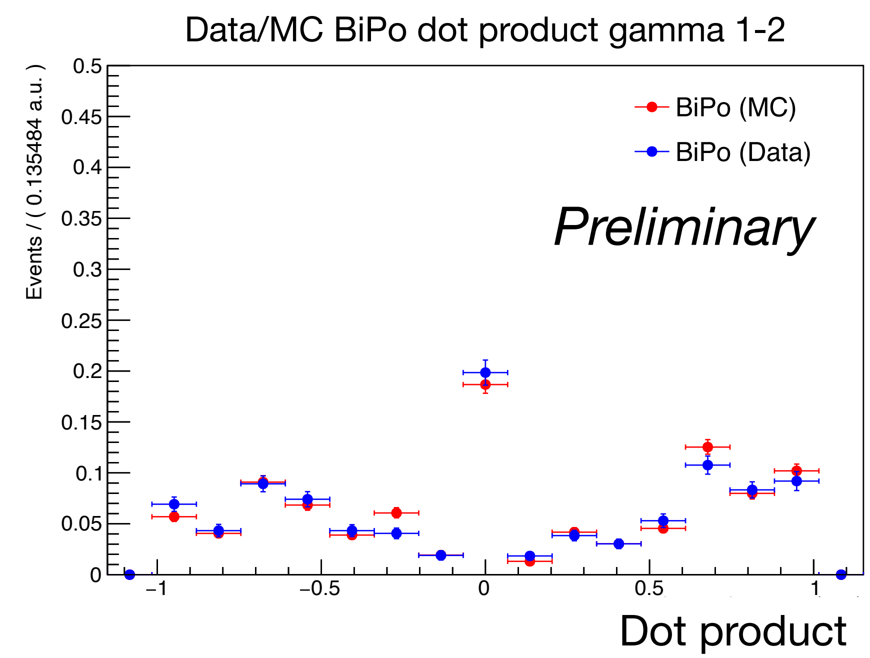
The topological variables have been validated with BiPo data/MC.







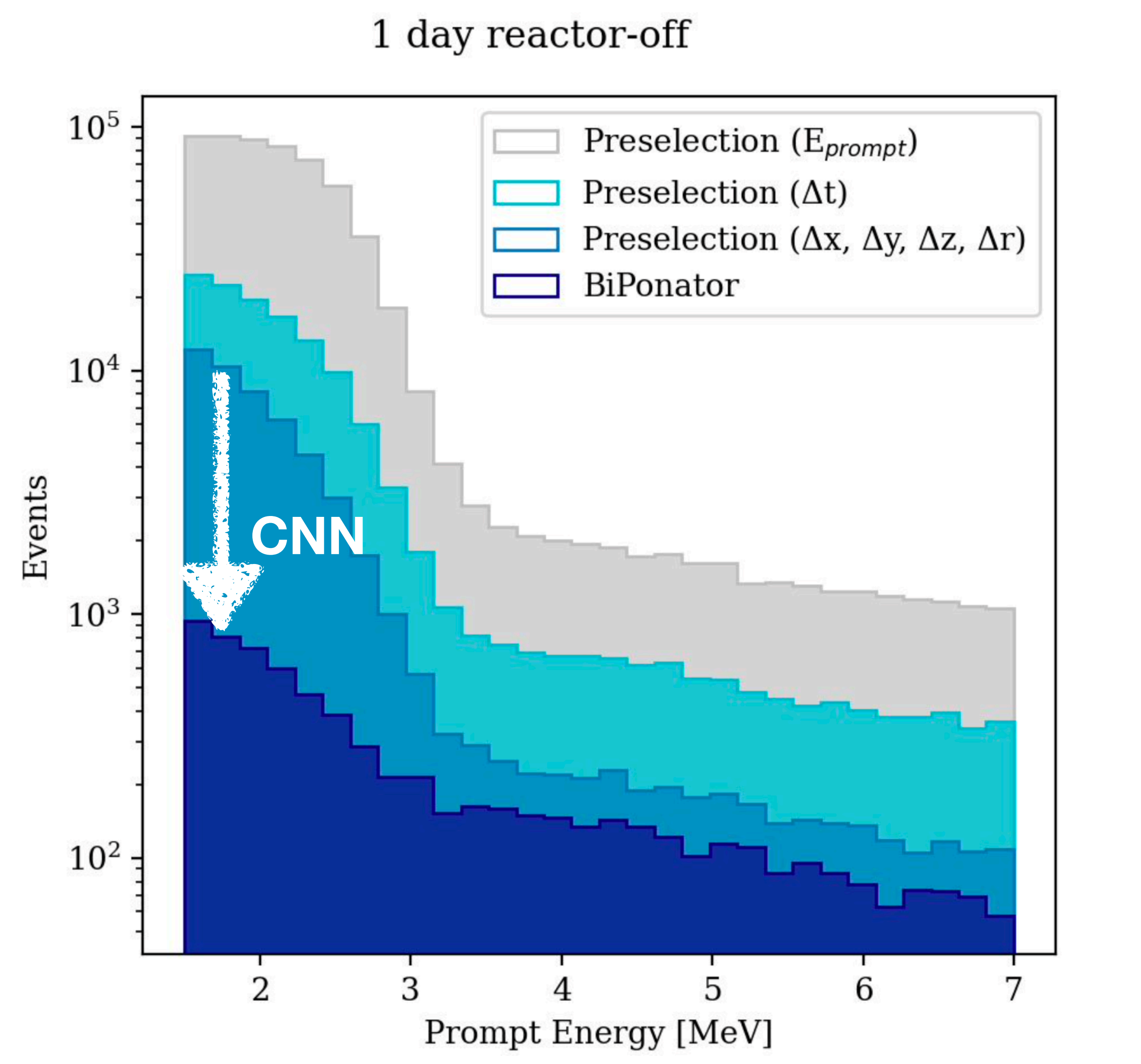




Very good agreement: critical to trust our analyses.

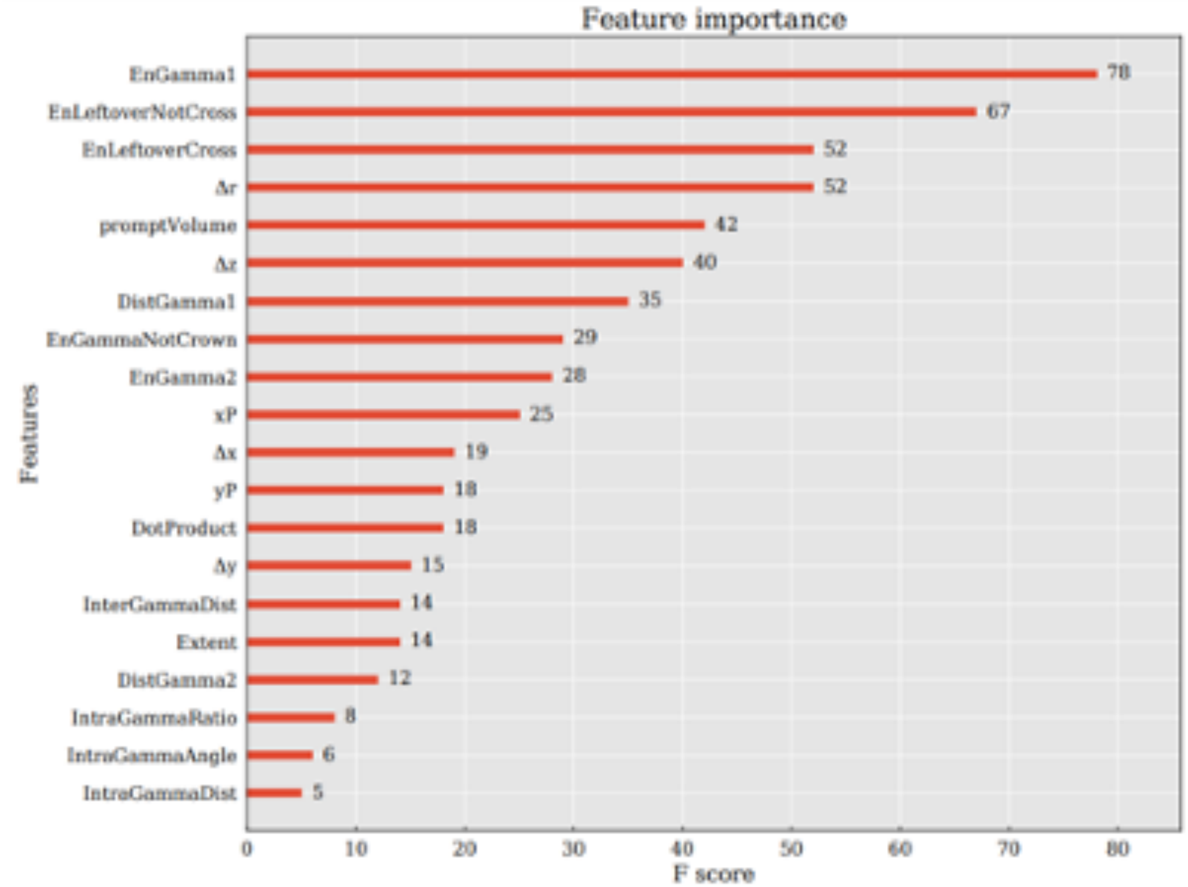
PSD capabilities with LiF:ZnS(Ag) : BiPonator

- Shape of alpha waveforms are different from Lithium-6 neutron capture !
- **Convolutional Neural Network** classifier on raw waveforms
- Most powerful cut to reduce BiPo background (95% reduction) : big improvement over previous method based on charge integration
- For 80% neutron efficiency

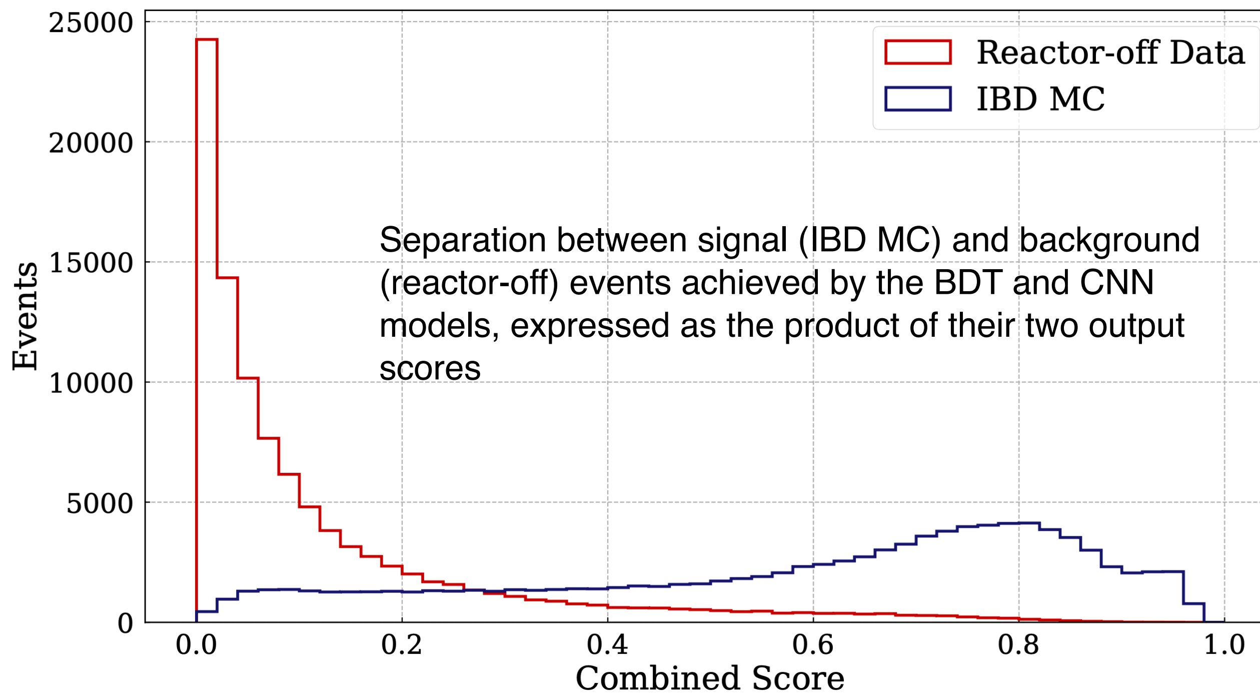


✓**Signal-to-background ratio of 1/50** (as seen previously)

Boosted Decision Tree Analysis

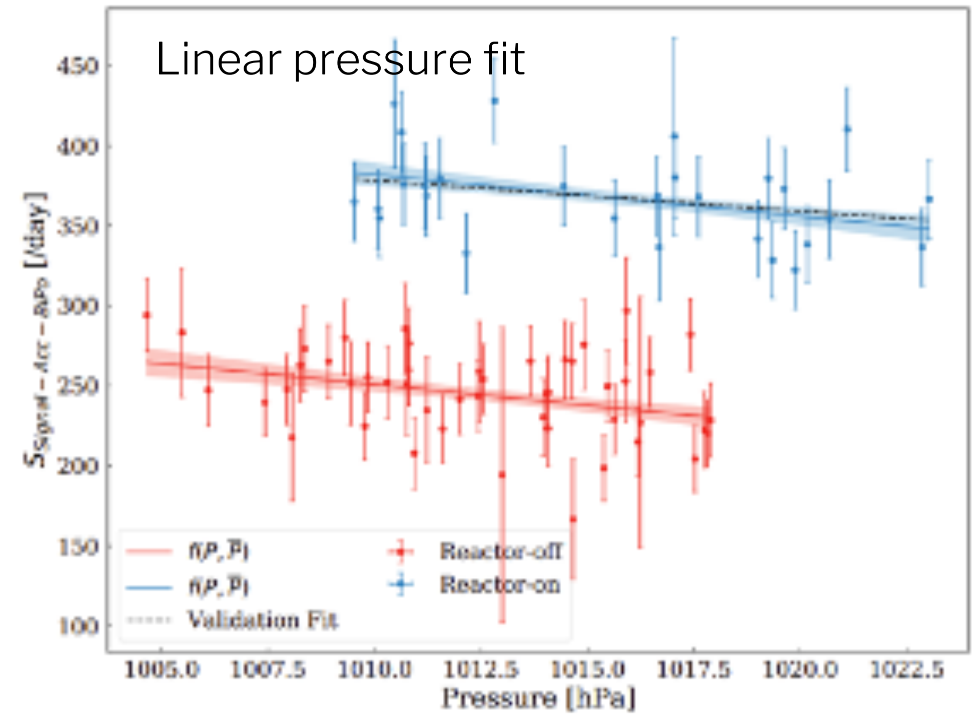


- Designed to discriminate between the ES clusters of IBD events and fast neutrons
- Boosted Decision Tree (BDT) classifier trained on simulated IBD events (signal) and reactor-off data (background) using twenty input features.
- A significant portion of these variables are topological variables, which fully exploit the innovative features of the detector (originally designed to detect positrons).
- Blind analysis (one open roff-cycle dataset)
- Flat efficiency selection for signal in oscillation variables



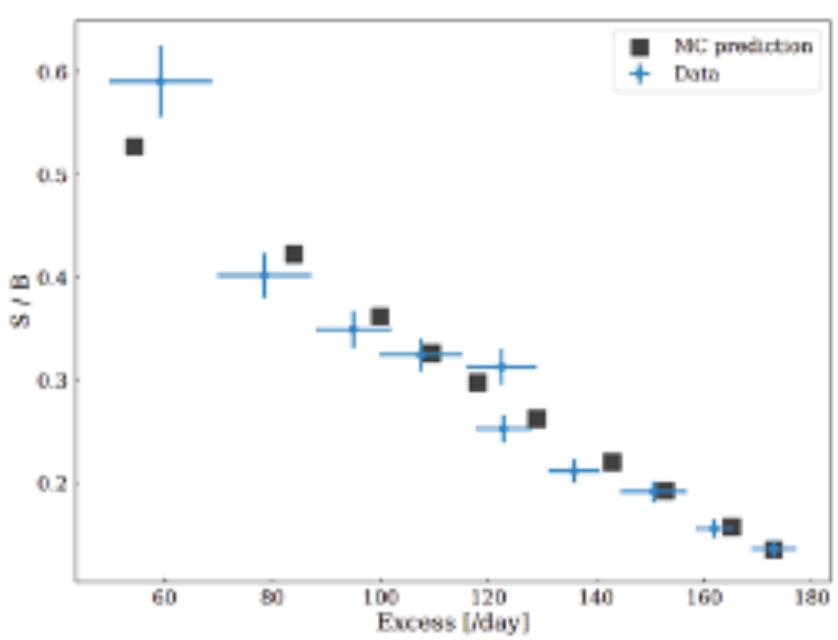
Separation between signal (IBD MC) and background (reactor-off) events achieved by the BDT and CNN models, expressed as the product of their two output scores

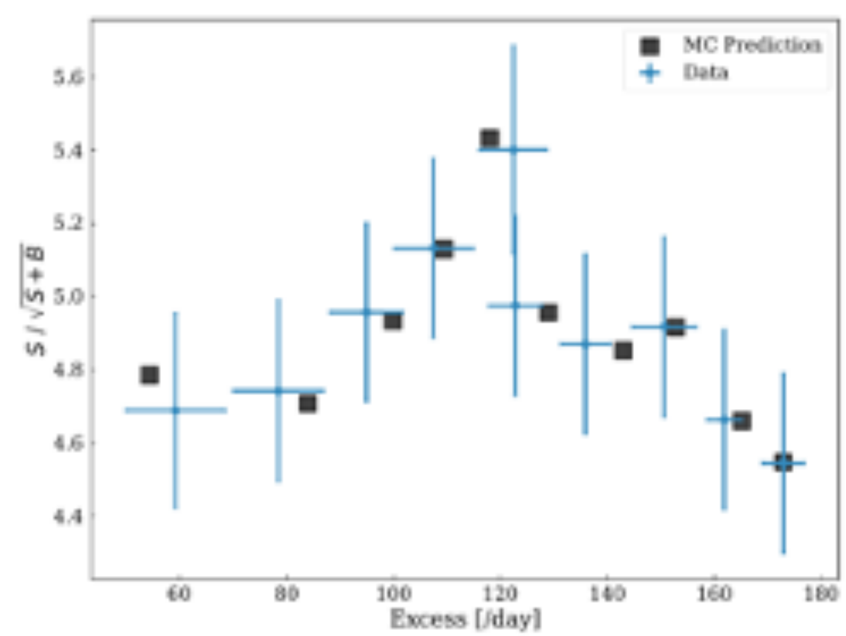
Background subtraction and signal extraction



- 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

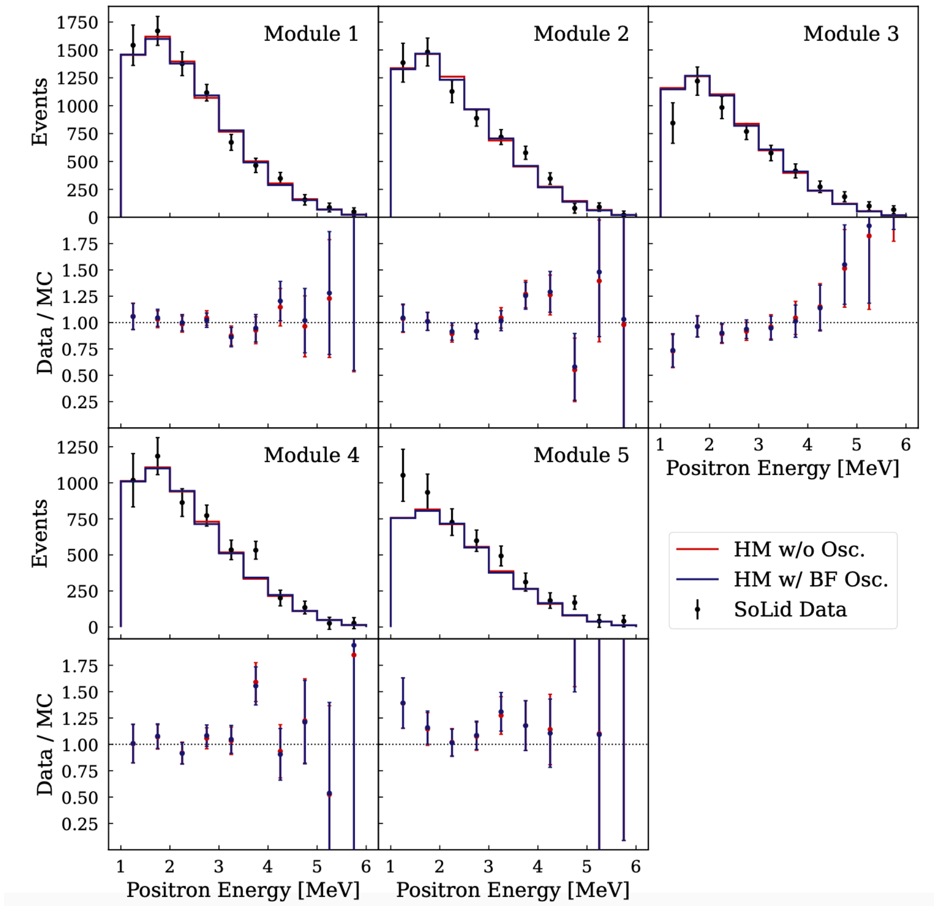
- Analysis on the open dataset with the BDT selection gives :
  - ✓ **IBD-like excess of 120 events per day**
  - ✓ **Signal-to-background ratio of 0.30**
- **Relatively good agreement** with IBD MC obtained with this data sample (1D projections on the right, actual subtraction performed with 2D histogram)

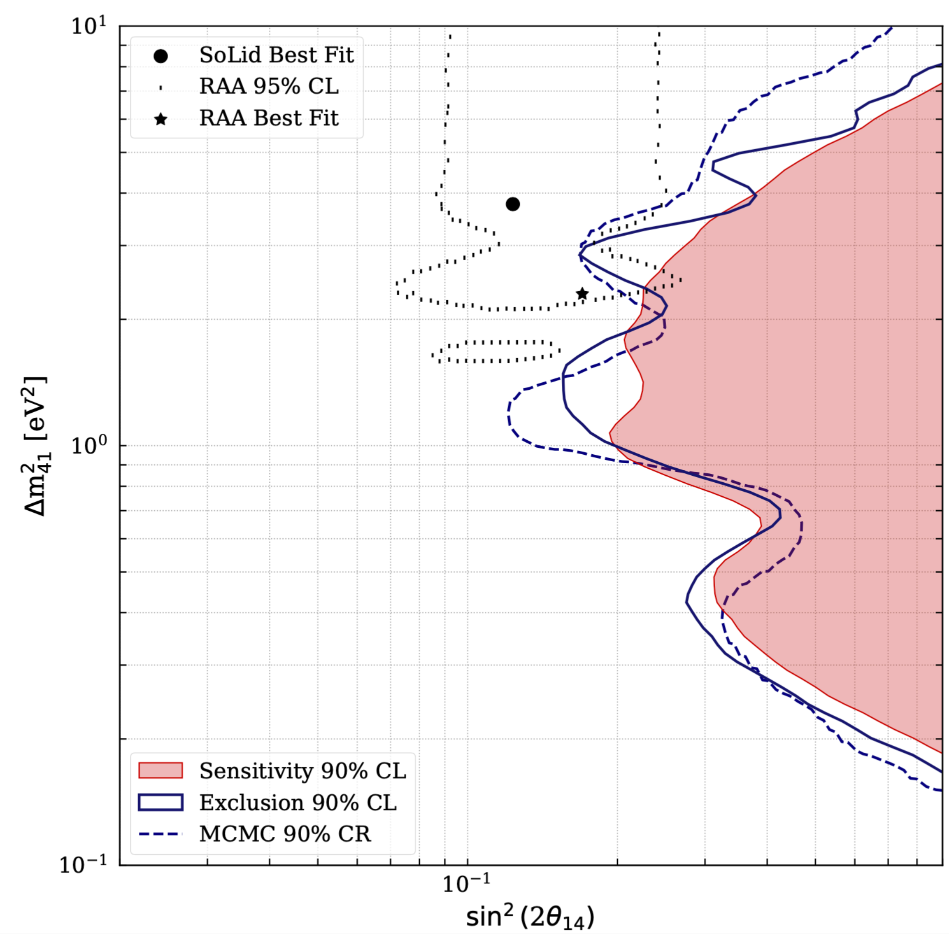




Oscillation Fit

- **Shape-only chi-square comparison** of each pair of ROn cycles (background subtracted from each one independently)
- Detector response modelled with migration matrix
- Data-MC Control Plots : very good agreement
- **Standard frequentist approach based on Feldman-Cousins toy generation**
- Bayesian based on a Markov chain Monte Carlo (MCMC) provides cross-check of the frequentist result: good agreement
- **Systematics well understood, largest one from the light yield uncertainty**





Frequentist exclusion and sensitivity contours (Feldman-Cousins) and Bayesian MCMC credible region.

Summary

SoLi∂

- SoLid has operated successfully at the BR2 research reactor between spring 2018 and spring 2022
- SoLid has ~ four years of data on tape : Phase-I and a Phase-II dataset using new SiPMs with 40% more light
- Antineutrino analysis based on this novel detector technology requires careful use of IBD signal topology and ML methods to obtain competitive S:B figure
- Demonstrated extraction of antineutrino signal with high significance in high background environment
- Alternative technology for antineutrino measurement with an exclusion of a part of the space phase complementary to Liquid based experiments
- **Publication has been submitted to arXiv yesterday, release will be on Monday!**

SoLi ∂

Thank you!

Backup

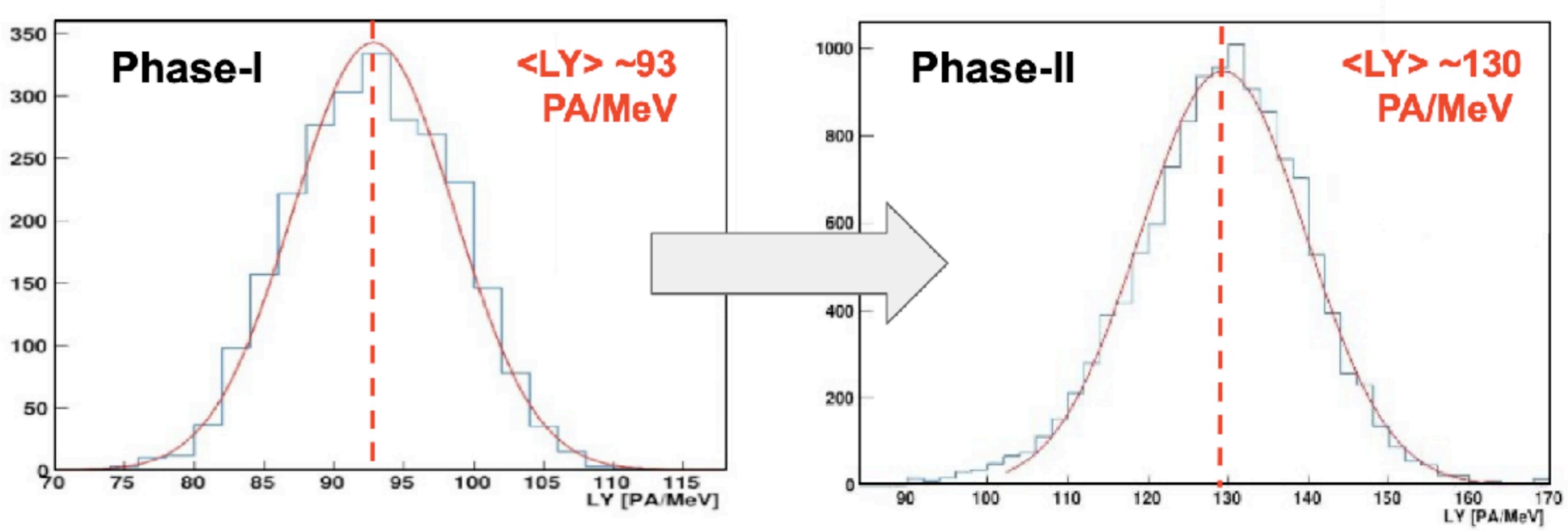
SoLi∂

SoLid Phase-II (2020-22)

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



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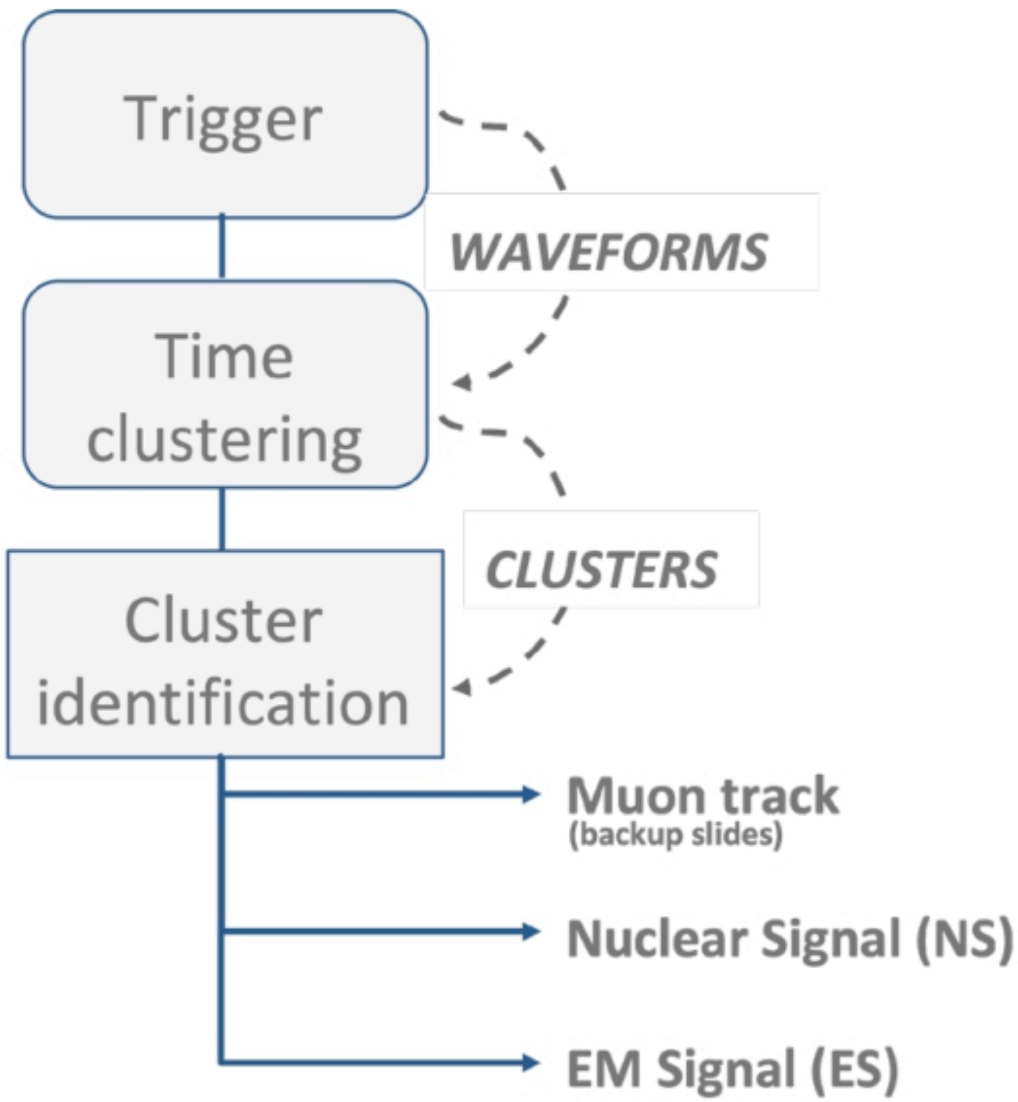
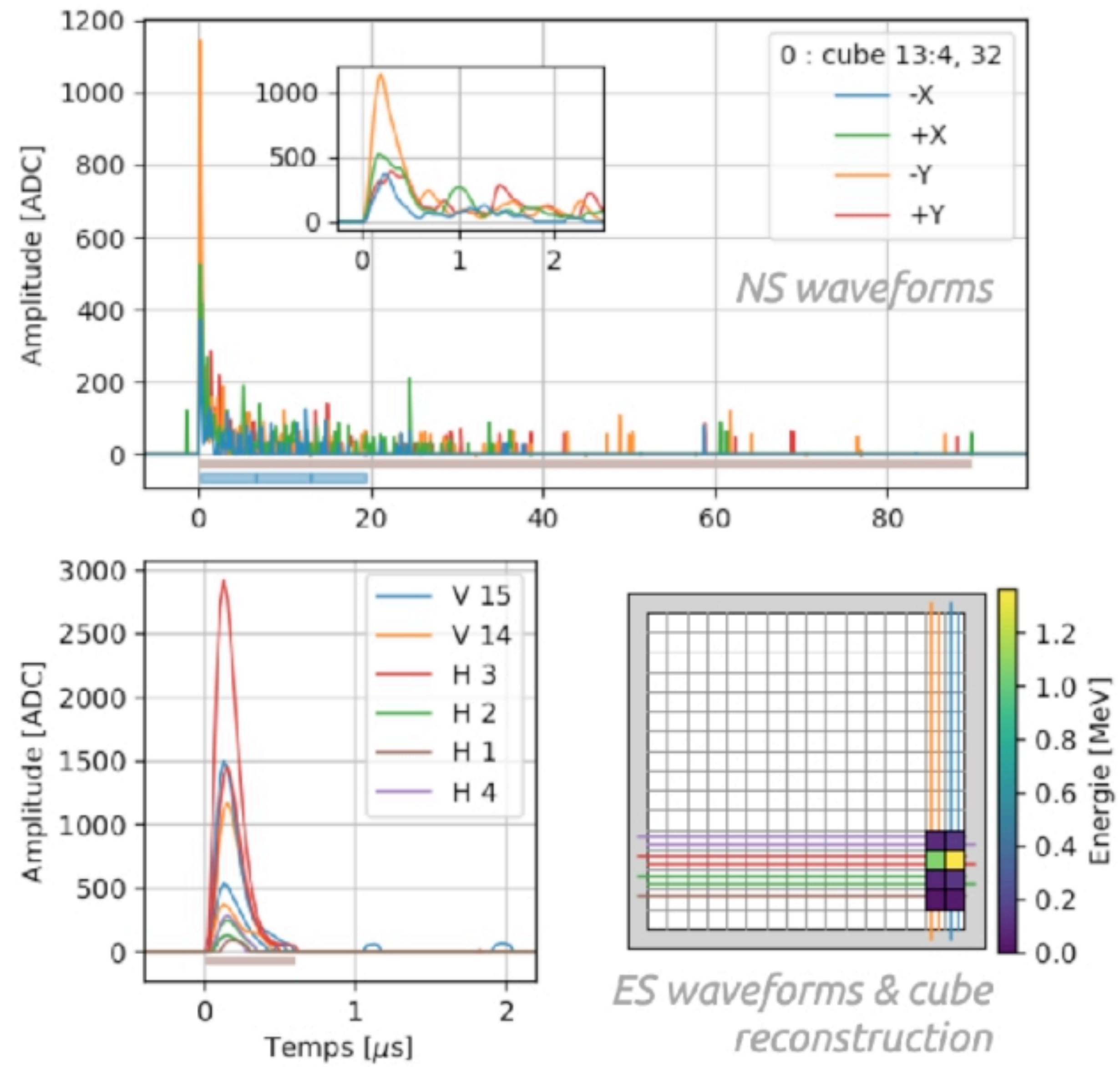
- SoLid has operated successfully at the BR2 research reactor between spring 2018 and spring 2022
- SoLid has ~ four years of data on tape : Phase-I and a Phase-II dataset using new SiPMs with 40% more light
- Antineutrino analysis based on this novel detector technology requires careful use of IBD signal topology and MVA/ML methods to obtain competitive S:B figure
- Demonstrated extraction of antineutrino signal with high significance and new directionality measurement capability
- Mature antineutrinos analyses allows now for precise oscillation and antineutrino spectrum measurements

Reconstruction & calibration

SoLi∂

Event reconstruction



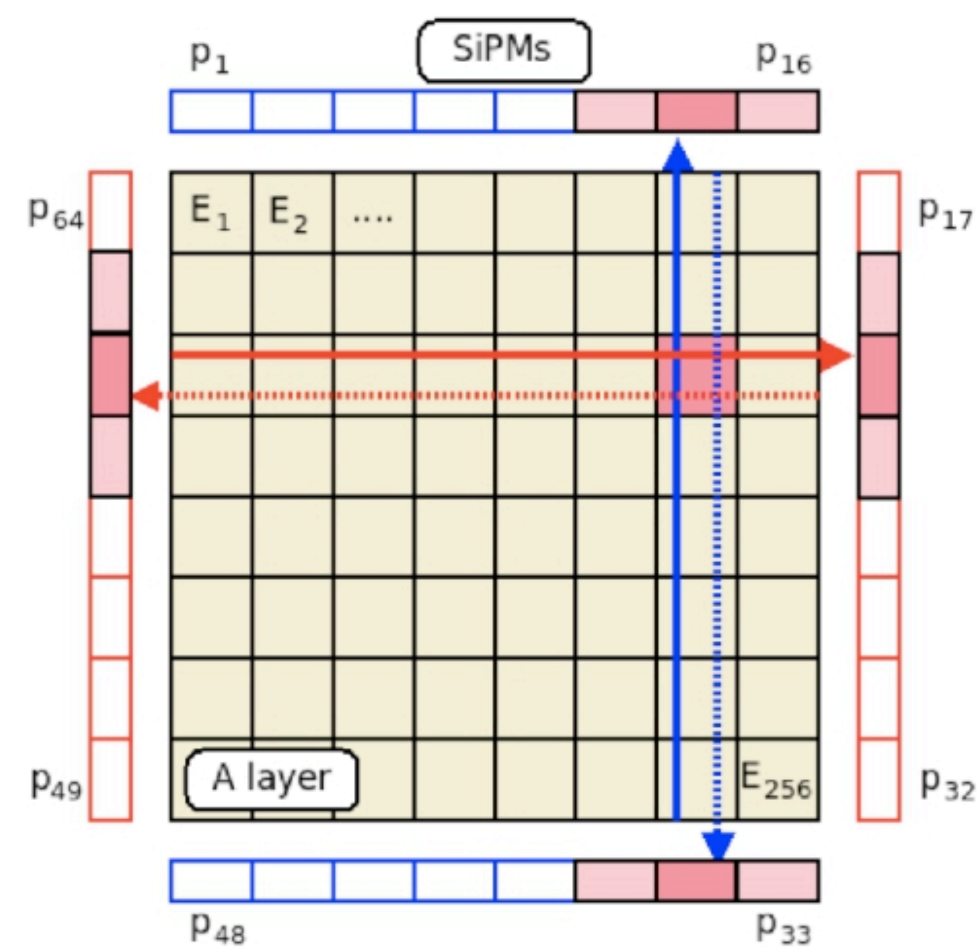


SoLi∂ Reconstruction and allocation of energy deposits

- SoLid detector projects 3D information of energy deposit in more than one cube onto 4x 2D planes
  - Reconstruction requires to reallocate properly the energy to the right cube

$$S_{SiPM} = A\, E_{dep}$$

- Uses ML-EM based algorithm
- A is the system matrix (SM) and can encode channel to channel differences



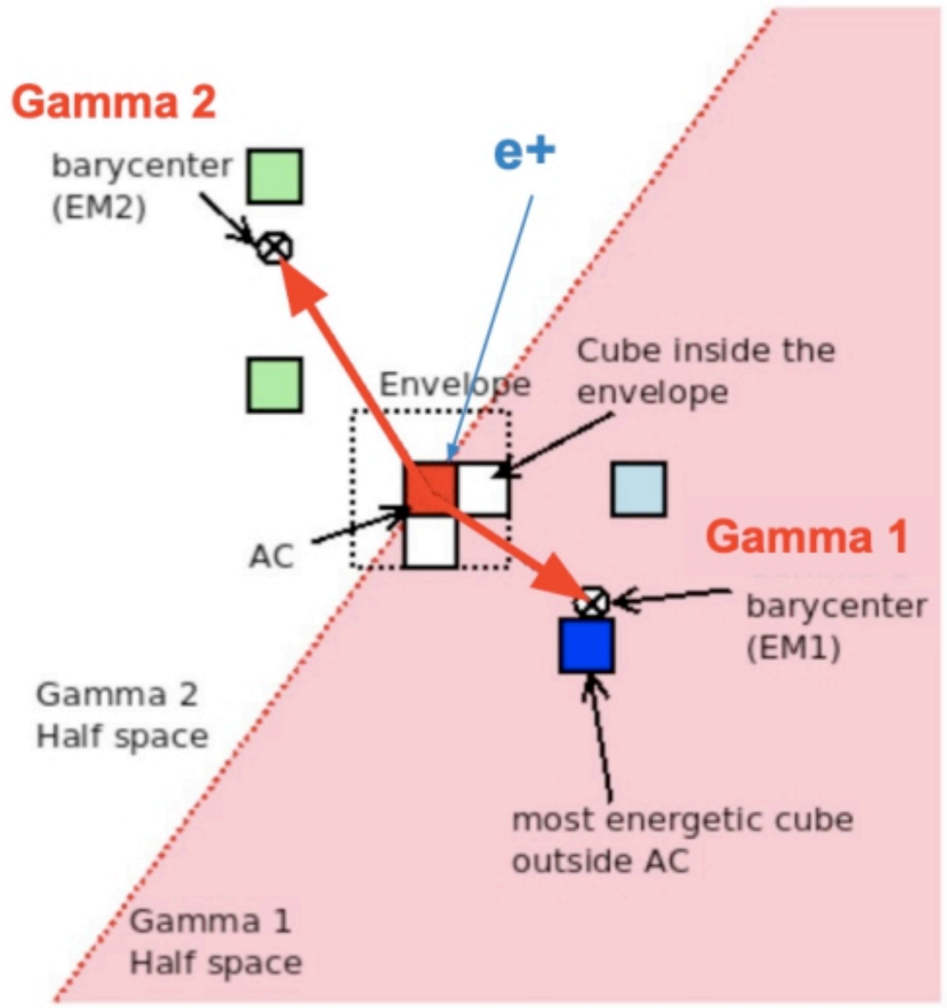
Method	FISTA	FISTA+ML-EM	sOMP+ML-EM
(%)	15.8	11.4	6.9
ε (%)	75.3	76.3	77.7
E_{res} Std. dev.	0.13	0.13	0.13

NEW

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

SoLi ∂

Event topology classification

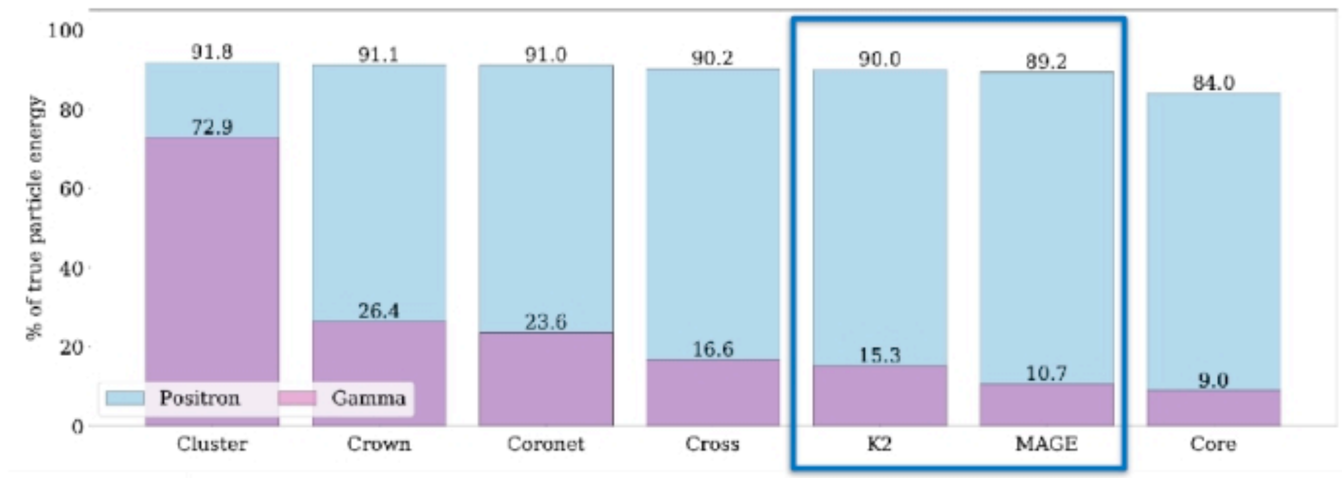


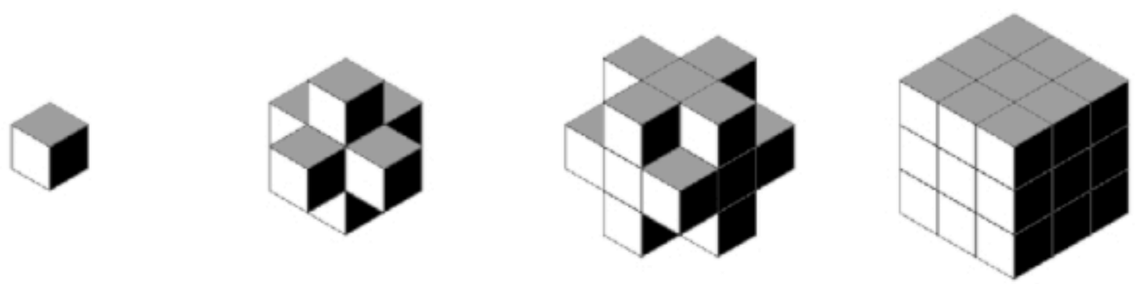
- Segmentation of the detector volume enables a more detailed categorisation of event topologies
- High level quantities are constructed based on prior physics knowledge of the IBD kinematics
  - Main positron dEdx cube (AC)
  - Extension of cube activity from annihilation gamma deposits
  - Inputs for the MVA analysis

SoLi ∂

ES energy estimation

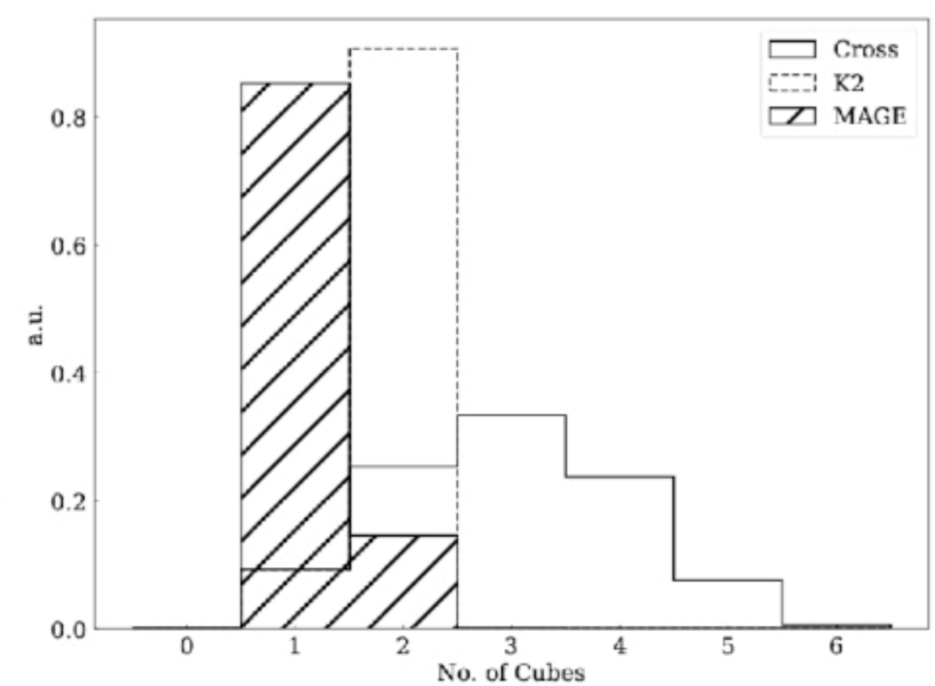
- Several energy estimators were studied to find the one closest to the positron energy
- Separation of gamma "cloud" from positron energy reduces dependence on small energy deposits in energy estimator





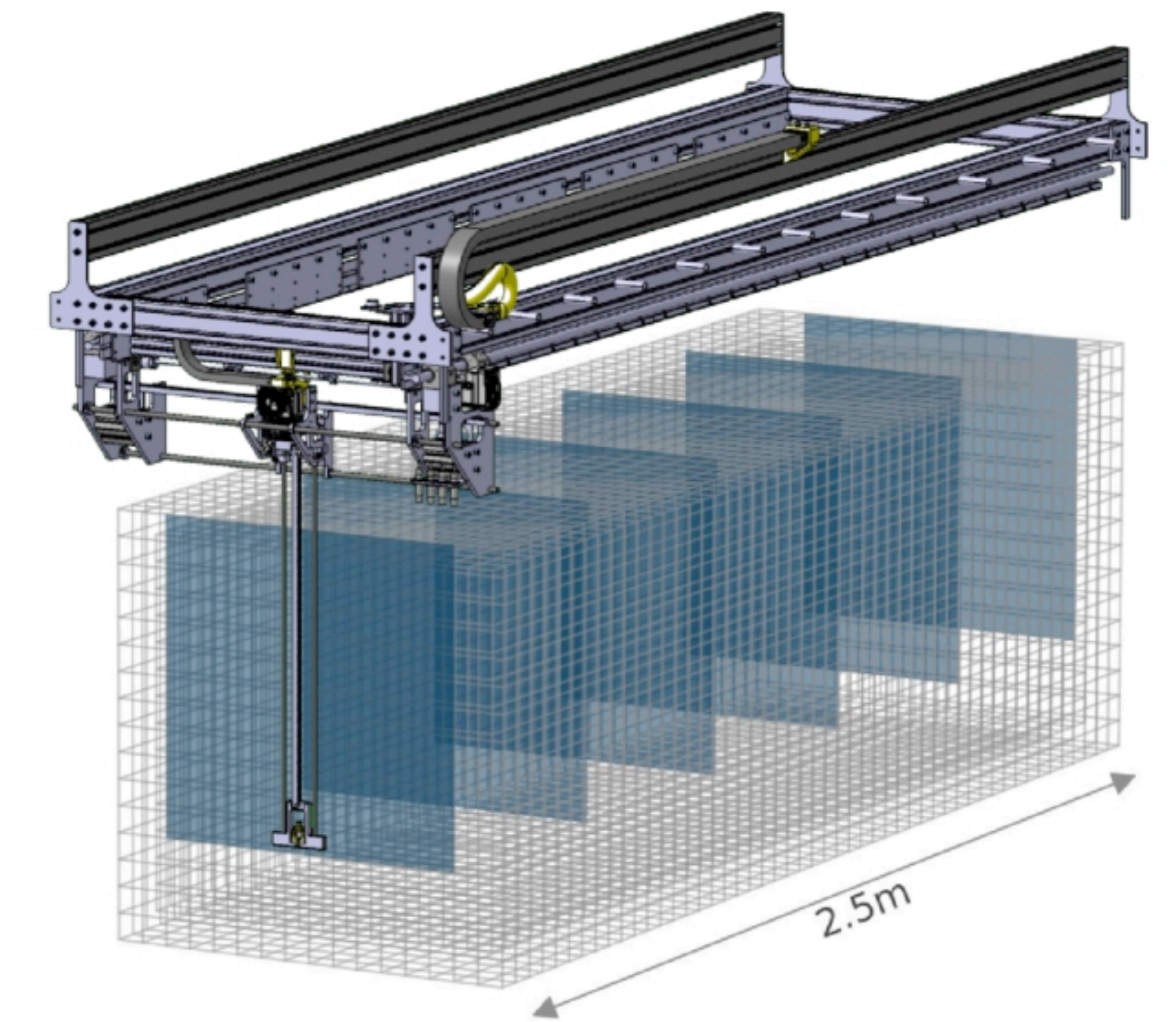
Estimator	Definition (sum of cube energies $E_{cube} > 0$ satisfying)
Core	$E_{cube} = E^{1}_{max}$
Cross	$\Delta X \leq 1, \Delta Y \leq 1, \Delta Z \leq 1$ and $\Delta R \leq \sqrt{1}$
Coronet	$\Delta X \leq 1, \Delta Y \leq 1, \Delta Z \leq 1$ and $\Delta R \leq \sqrt{2}$
Crown	$\Delta X \leq 1, \Delta Y \leq 1, \Delta Z \leq 1$ and $\Delta R \leq \sqrt{3}$
K2	$E_{cube} = E^{1,\Delta R \leq 1}_{max}$ or $E_{cube} = E^{2,\Delta R \leq 1}_{max}$
MAGE	$E_{cube}/E_{tot} \geq 0.2$ and $\Delta R \leq 1$
Cluster	–

NEW



SoLi ∂

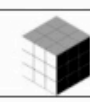
CROSS calibration robot

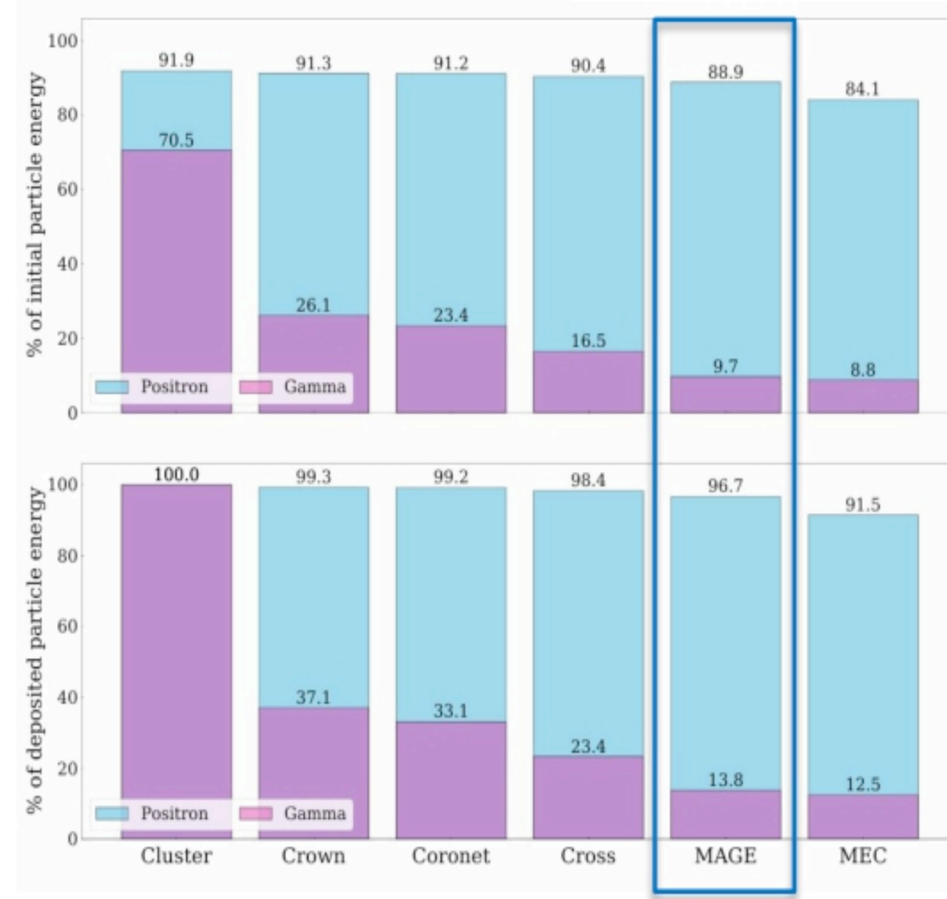


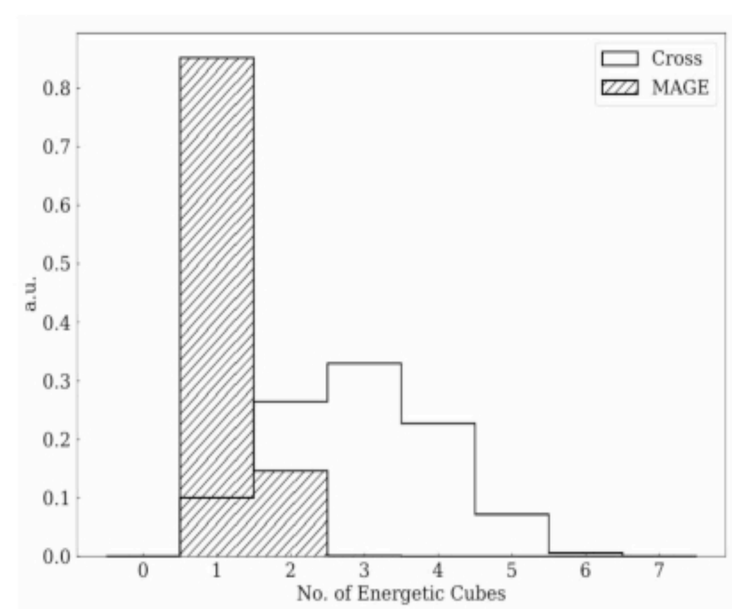
- Automated X-Y source scan of 6 gaps within detector
- Measure absolute efficiency and energy scale calibration at % level
  - Gamma-ray: ^{207}Bi, ^{60}Co, ^{22}Na
  - Neutrons: AmBe, ^{252}Cf

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

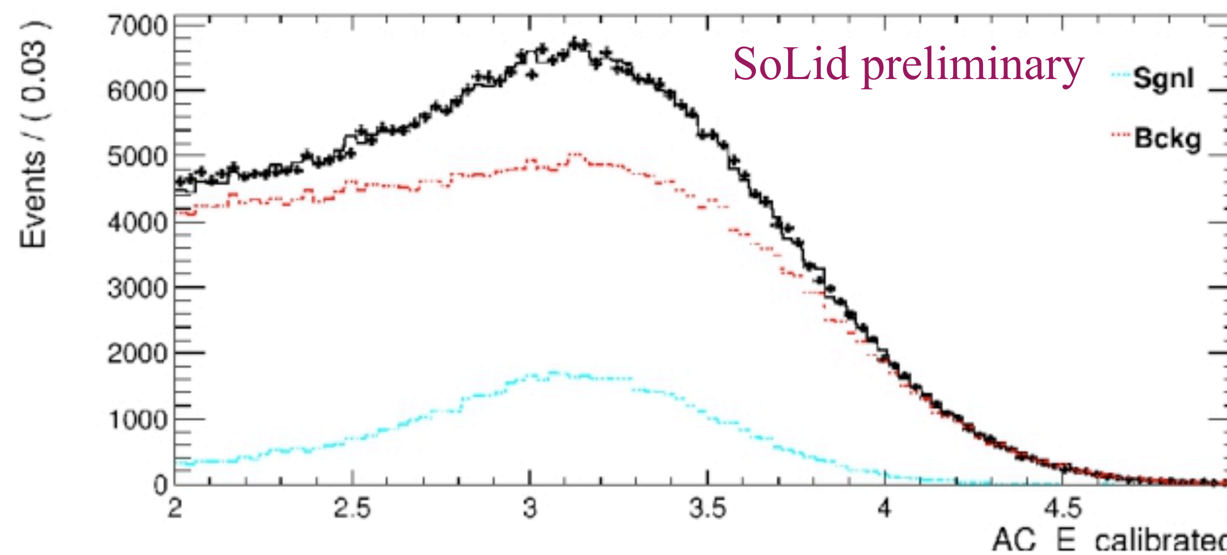
No.	Estimator	Conditions for cube inclusion	Illustration
1	Cluster	–	
2	Crown	$\Delta X \leq 1,\ \Delta Y \leq 1,\ \Delta Z \leq 1,\ \Delta R \leq \sqrt{3}$	
3	Coronet	$\Delta X \leq 1,\ \Delta Y \leq 1,\ \Delta Z \leq 1,\ \Delta R \leq \sqrt{2}$	
4	Cross	$\Delta X \leq 1,\ \Delta Y \leq 1,\ \Delta Z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

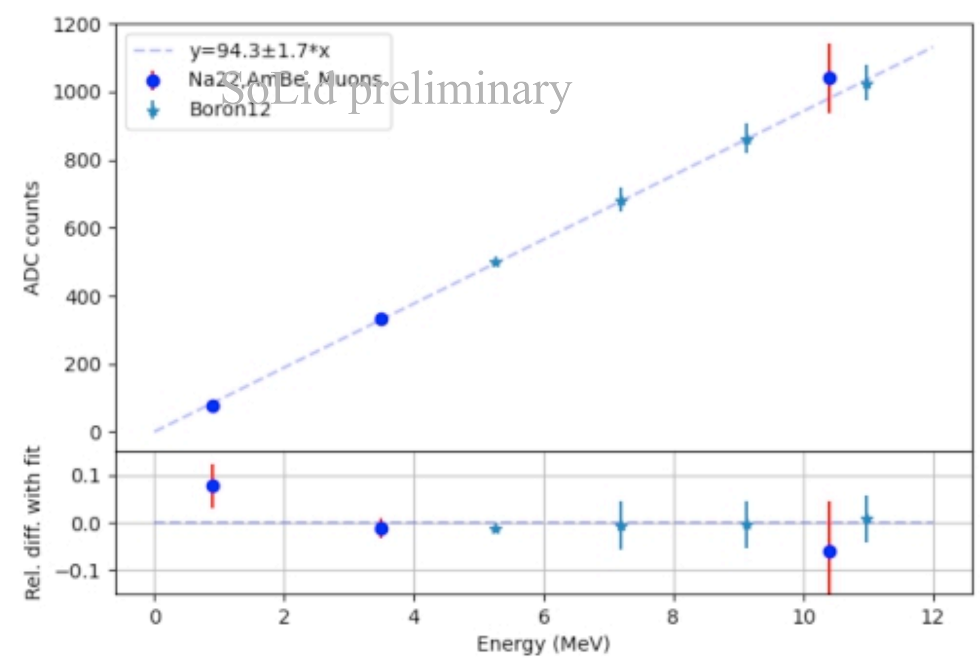




Energy scale calibration

- Energy scale measurement using :
  - Na-22 source (MC-data KS test)
  - AmBe e+e- at ~3.4 MeV
- Light yield (LY) ~ 96 PA/MeV
  - Stochastic term $\sigma_E = 15\ \%$ at 1 MeV (Phase-I)
- Excellent linearity of detector response
  - Crosschecked also with B-12 dataset





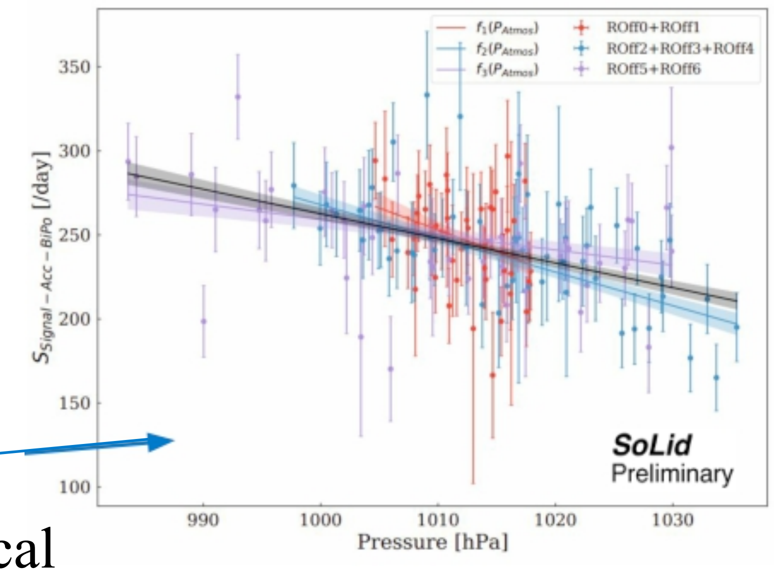
SoLid

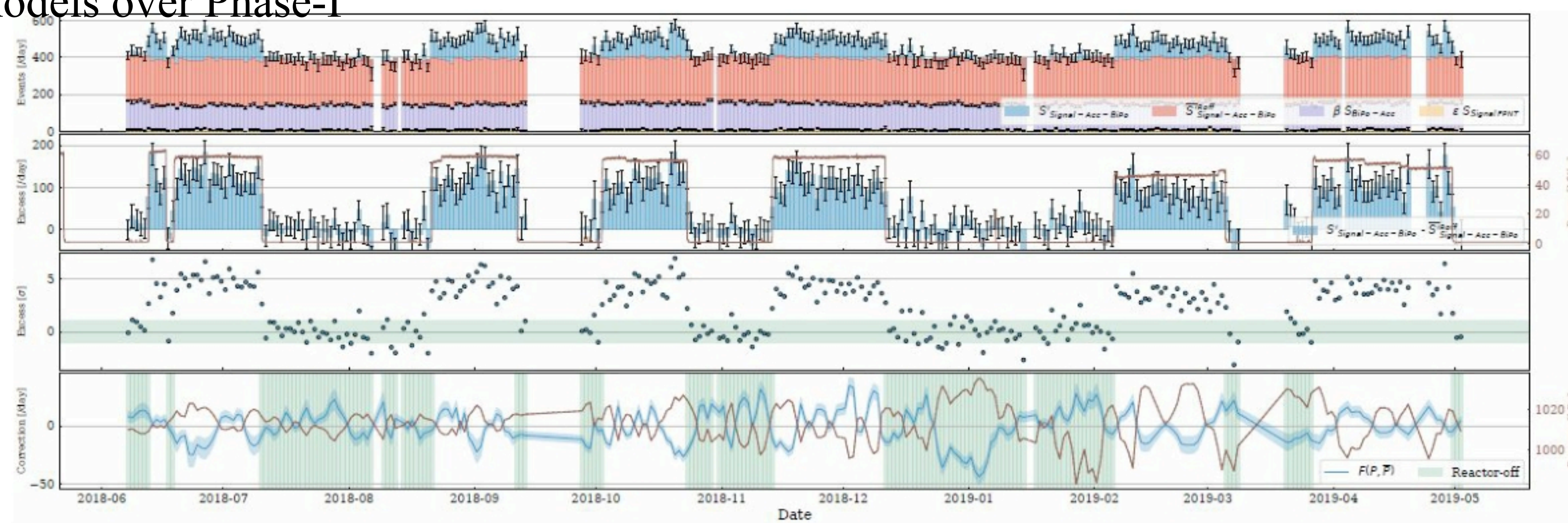
Imperial College London

Signal Extraction

Rate analysis on (first) half of Phase-I

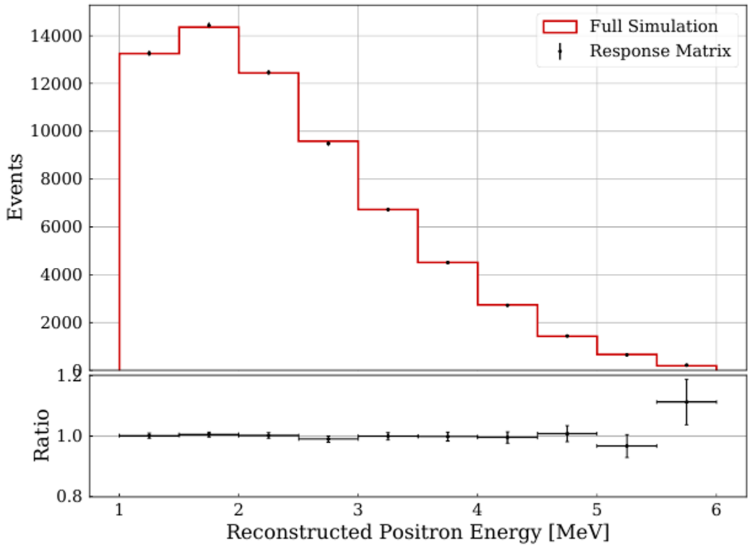
- Stable signal subtraction, dominated by atmospheric neutrons
  - Excess consistent with zero for reactor-off data
- Fast neutron background rate pressure-corrected using multiple local models over Phase-I

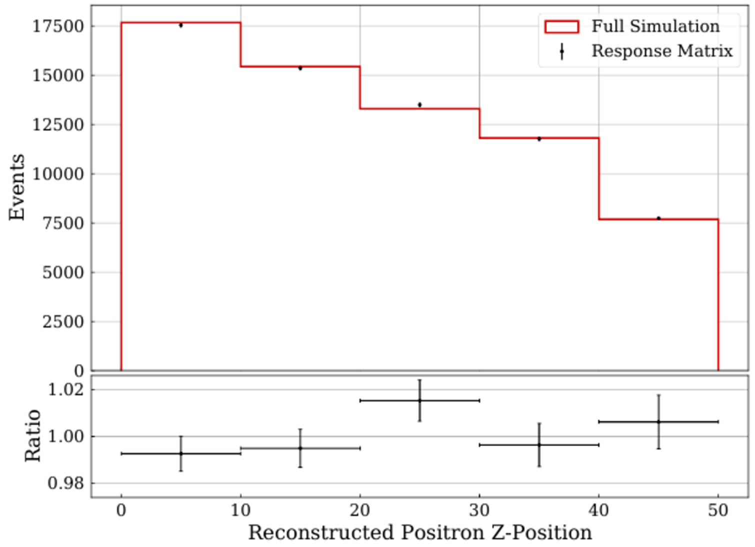




Response Matrix

- ➢ Recently switched from SoLO (C++) to PySoLO (Python3) for the oscillation analysis due to an unidentified bug in the former.
- ➢ As such, response matrices are now generated using the ReMU package (doi:10.5281/zenodo.1217572) rather than RooUnfold, amongst other things.
  - ○ Performance is unchanged, very good agreement between full simulation and response matrix
  - ○ Matrix "trained" with ~3M true-space events and corresponding reco-space events (10% overall efficiency)





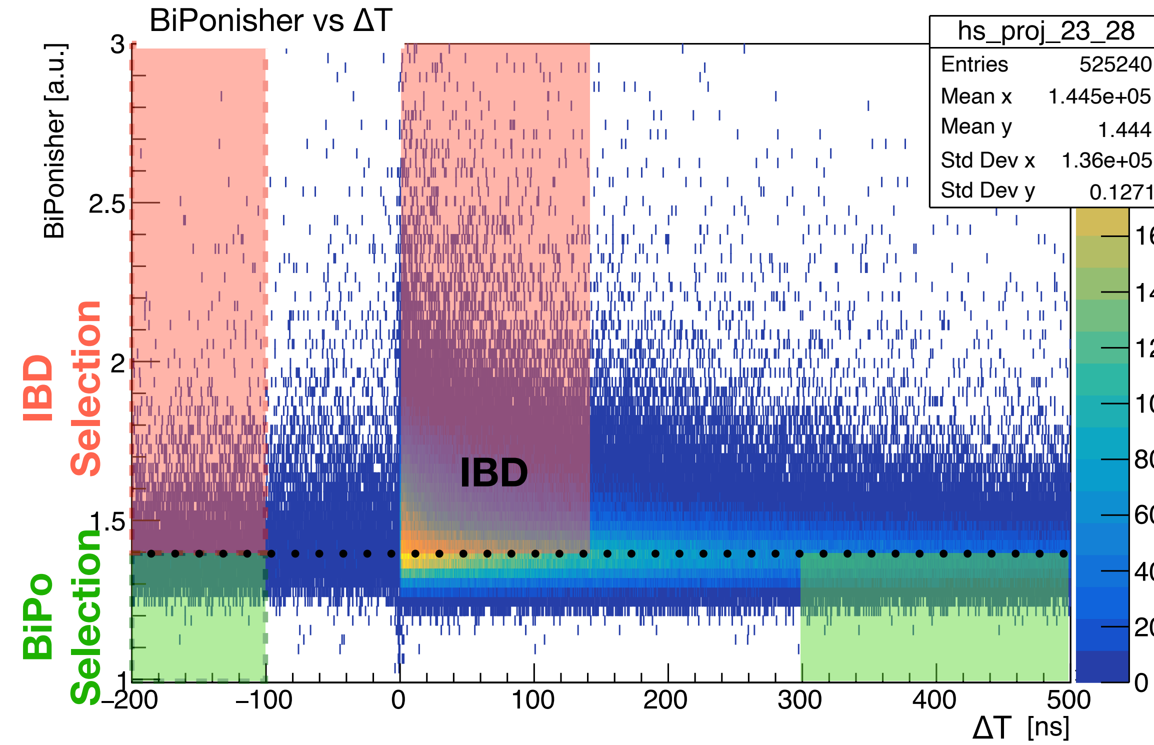
24

Neutrino signal in real data

For more details: poster by Giel Vandierendonck (797)

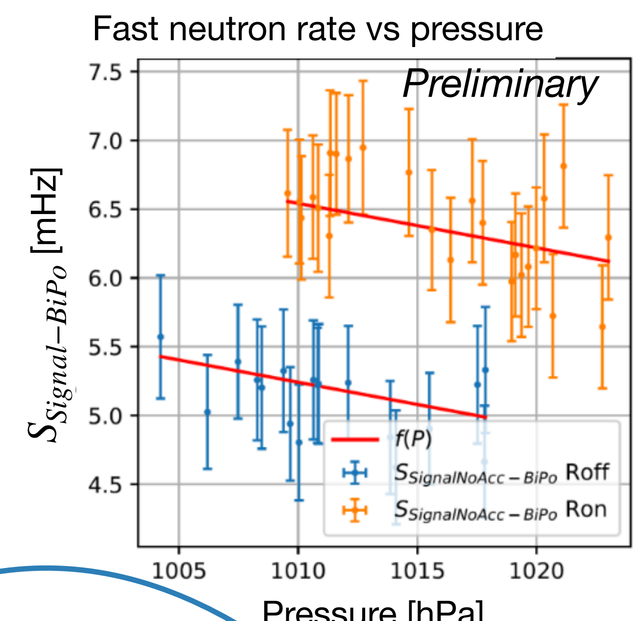
Two backgrounds with a different day to day evolution:

- Reactor OFF data
  - The BiPo may change because of radon release.
  - Fast-neutrons are correlated with pressure variation.

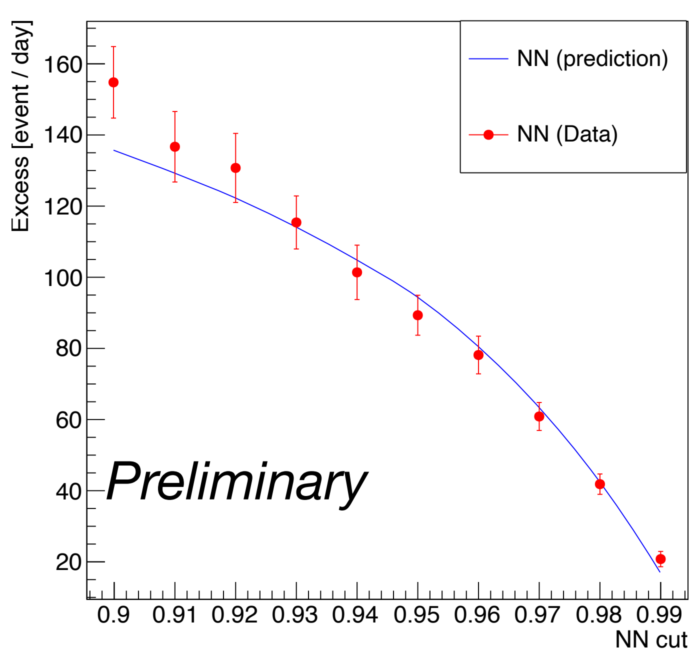


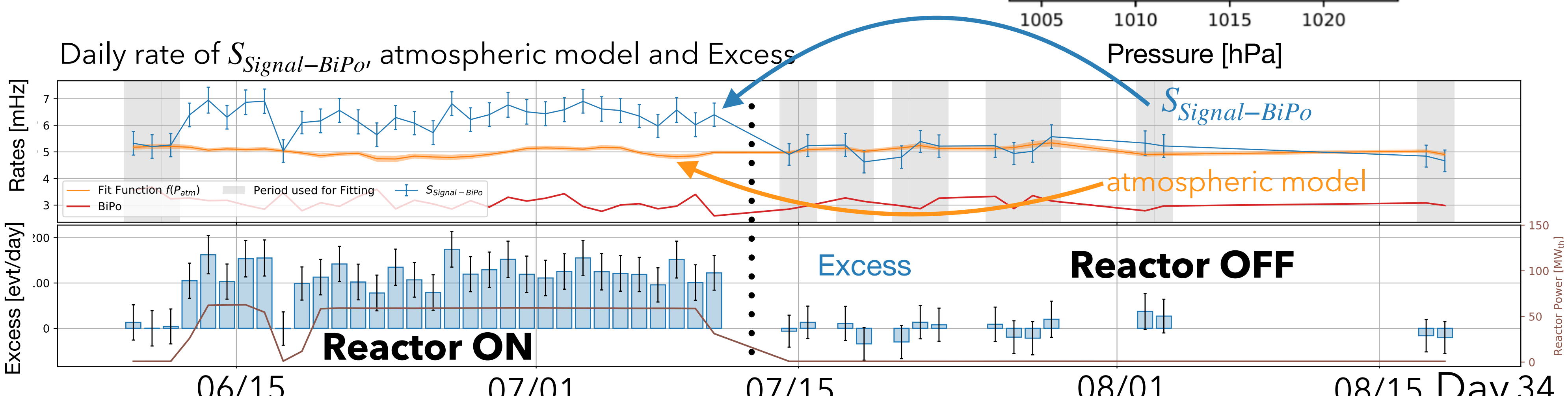
Subtraction:

- We first subtract BiPo and accidental.
- Study fast neutrons rate in data to model their dependence on pressure.
  - $S_{Signal-BiPo,j} - \bar{S}_{Signal-BiPo} = \chi_{atm}^{Ref} \cdot \left(P_j - \bar{P}\right)$
  - $S_{Signal-BiPo-Atm,k} = S_{Signal-BiPo,k} - \chi_{atm}^{Ref} \cdot \left(P_k - \bar{P}\right)$
- This approach is cross-checked by taking days with same pressure.



Excess in data vs MC





Annihilation gamma efficiency

Selection:

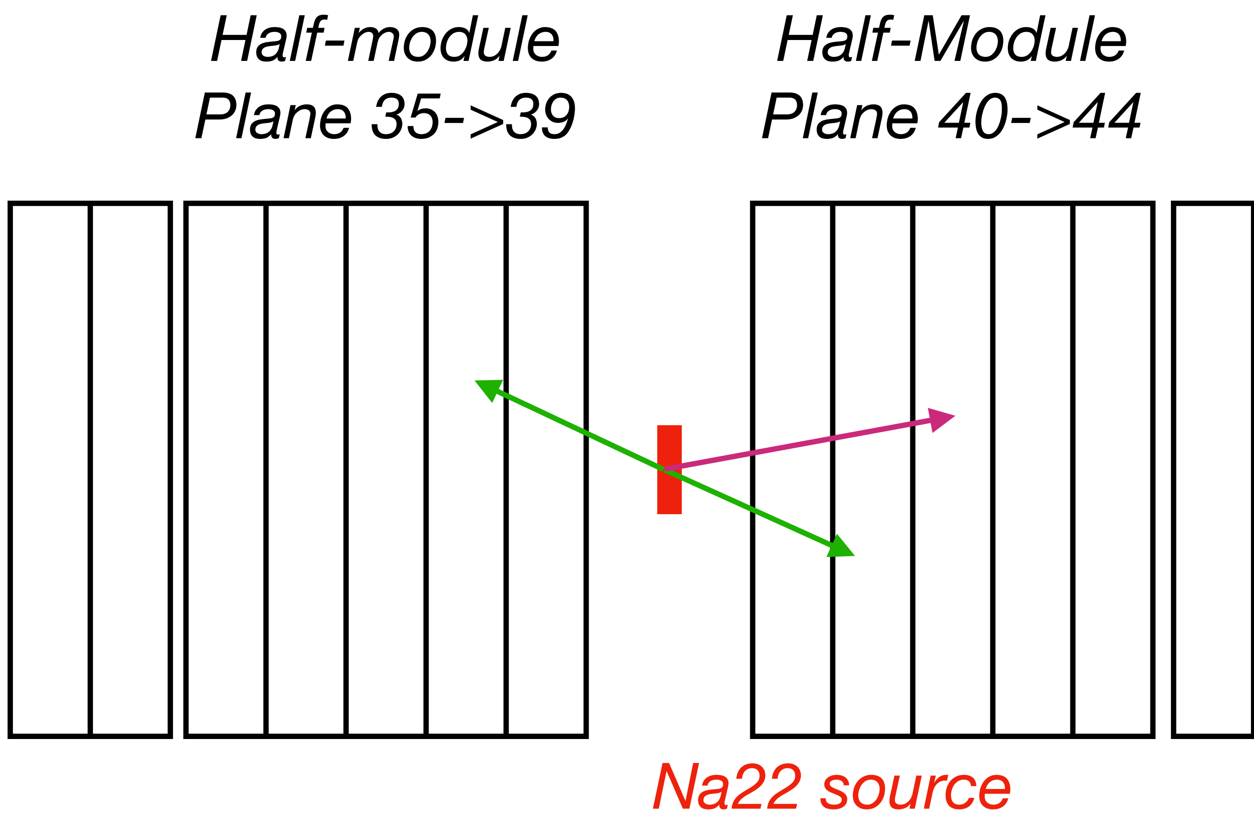
- 22Na source emits:
  - 1 gamma of 1.274 MeV
  - 2 gamma of 0.511 MeV from positron annihilation
- Tag the 1.274 MeV interaction in one module
  - A cube above 60PAs ~ 650 keV
- Look at the other module to find annihilation gamma
  - Consider a cube if:
    - Isolated in the plane
    - The four fibres above 2.5 PAs

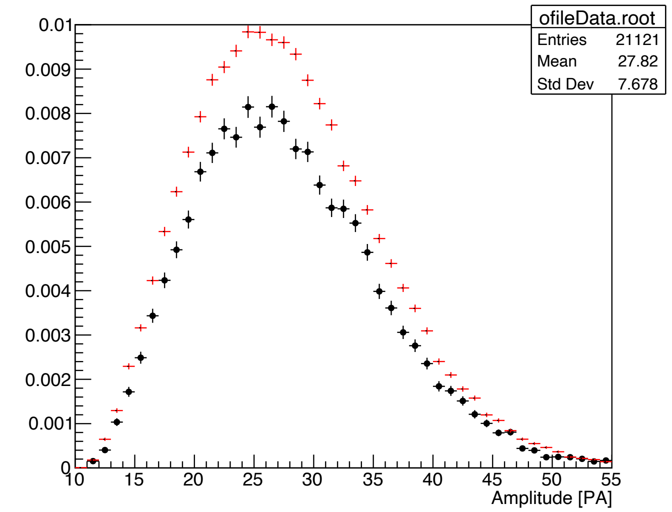
Normalisation:

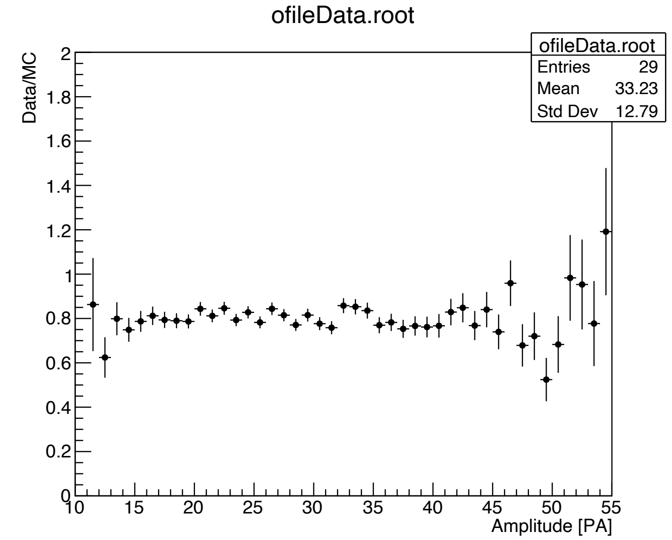
- Distributions from annihilation gammas are normalised using the number of tags.

Energy spectrum:

- We observe a discrepancy between data and MC efficiency to see annihilation.
  - MC sees 20% more annihilation gamma than data.
  - Meaning a fibre efficiency control @ 5%
- The shape is well reproduce by the MC.

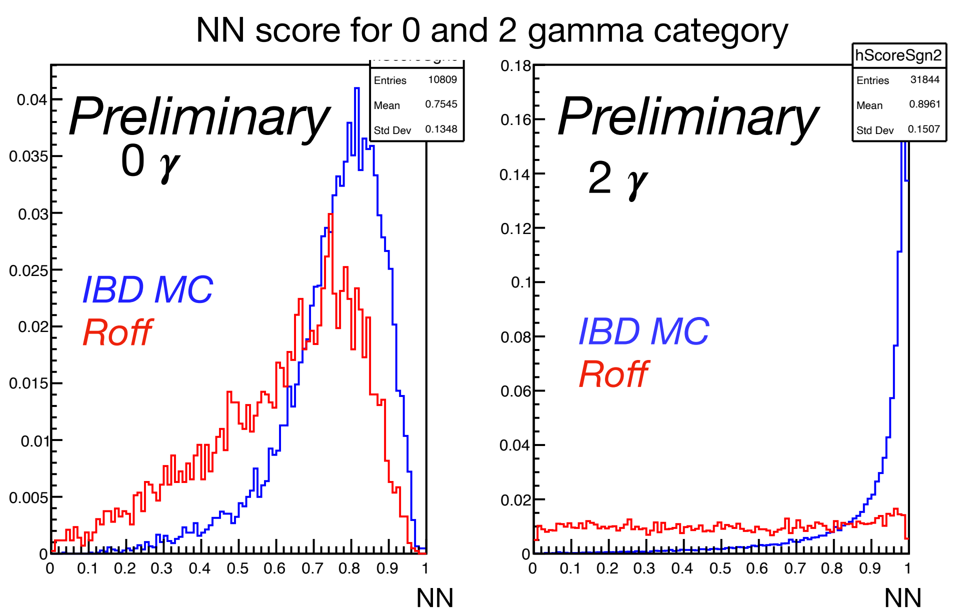






Category shifting as function of fibre threshold

- Lowering the fibre analysis threshold from 200 keV (High threshold) to 100 keV (Low threshold) allows to double the cleanest category.
- The 2-gamma category will be populated by increasing the light yield.
- Category for which the discrimination is the best!



High threshold

Gamma	0	1	2
IBD MC	34 %	41 %	24 %
Reactor off	53 %	26 %	20 %

Low threshold

Gamma	0	1	2
IBD MC	16 %	36 %	47 %
Reactor off	30 %	27 %	44 %