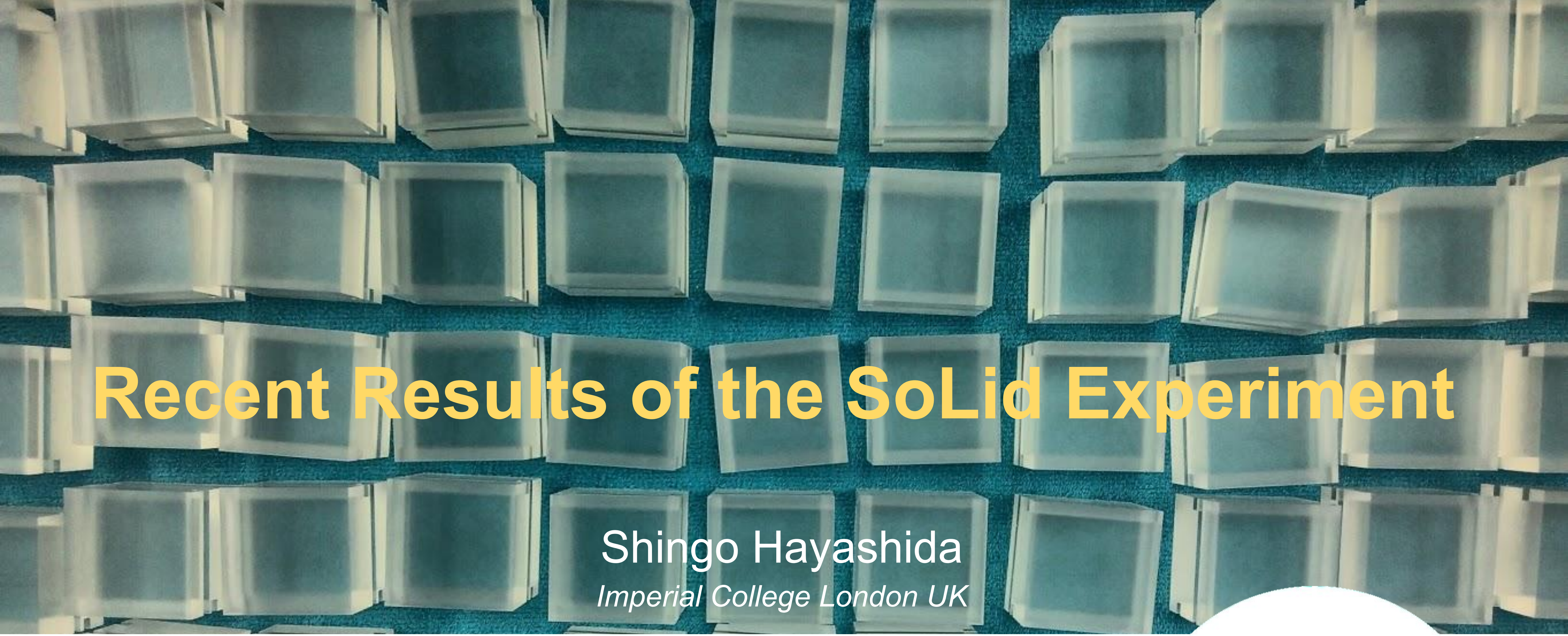

Recent Results of the SoLid Experiment

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Imperial College London UK

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on behalf of the SoLid collaboration

EPS-HEP Conference 2021

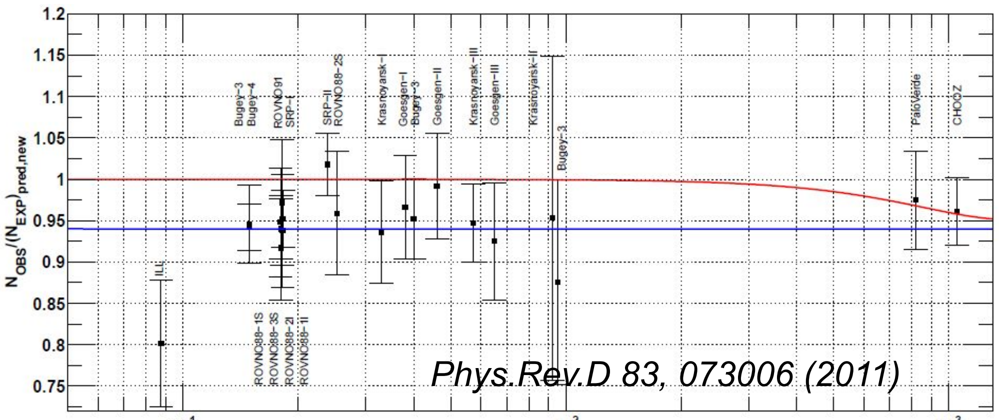
27th July 2021

Outline

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

Experimental Goals

Probe the Reactor Antineutrino Anomaly (RAA)



Phys.Rev.D 83, 073006 (2011)

$$|\Delta m^2_{\mathrm{new,R}}| \gg 1\ \mathrm{eV}^2$$

$$\sin^2(2\theta_{\mathrm{new,R}}) = 0.12$$

...re precisely the antineutrino spectrum with pure U-235 fuel

3+1 model

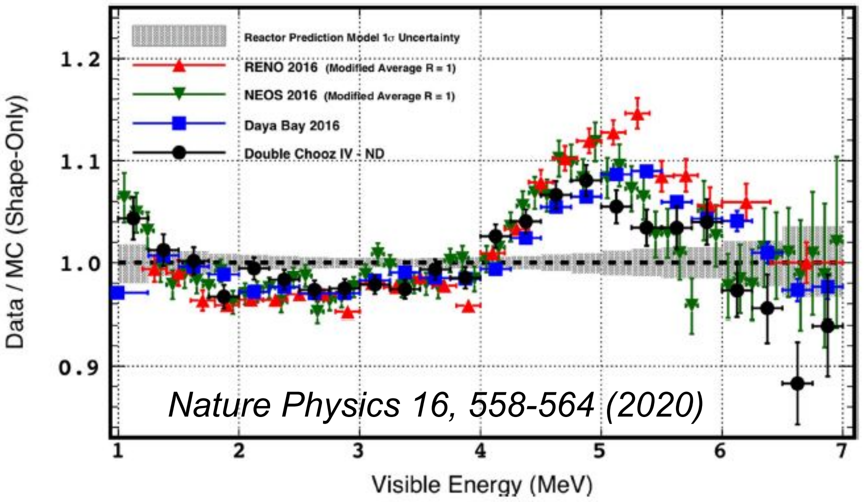
$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

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

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

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

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



Nature Physics 16, 558-564 (2020)

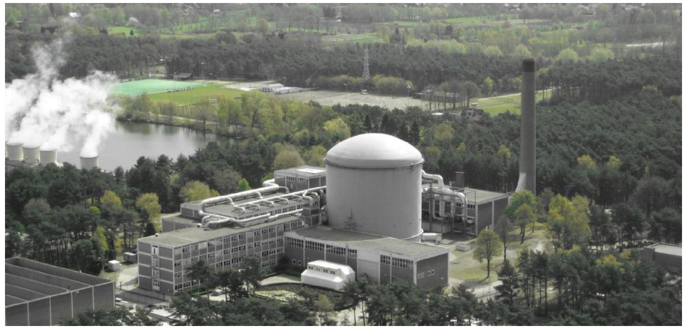
Unexpected bump around 5 MeV reported by antineutrino experiments at power reactor (^{235}**U**, ^{239}Pu, ^{241}Pu and ^{238}U isotopes)

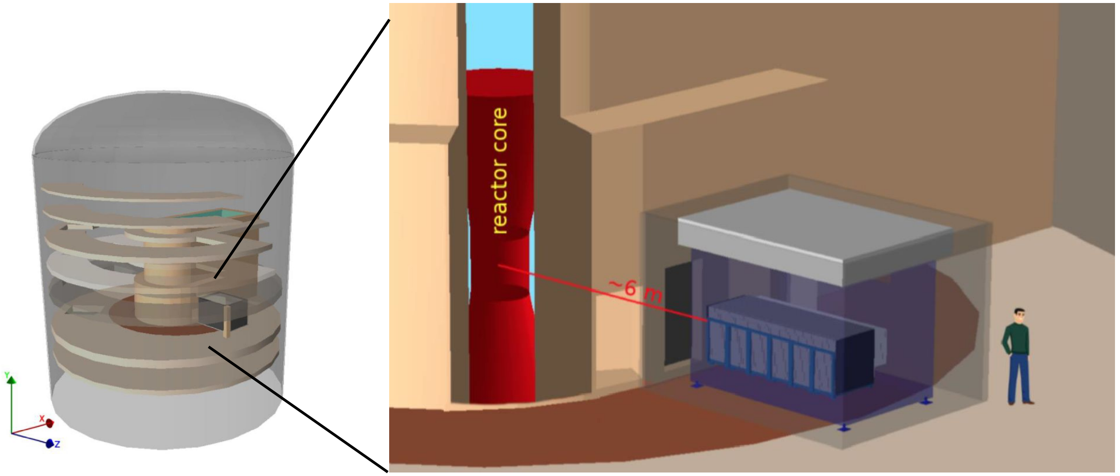
Recent indication in liquid scintillator detectors close to ^{235}**U** research reactors.

SoLid Experiment

Experimental site

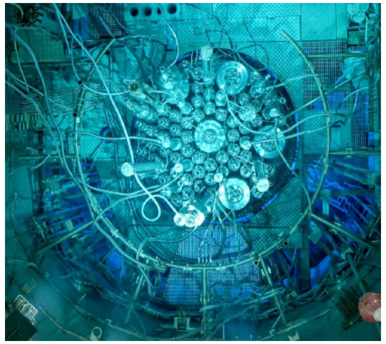
- SCK CEN BR2 research reactor (Mol, Belgium)
- Very close to the reactor core (6 - 9 m)
- Low overburden (~6 - 8 m.w.e)

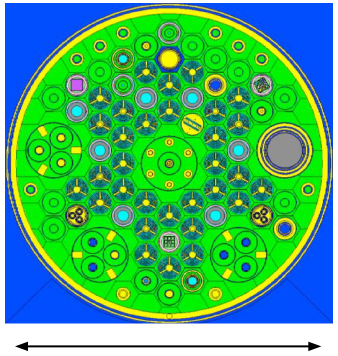




BR2 reactor

- Compact core (50 cm in effective diameter)
- Highly enriched ^{235}U (>93.5%) is used as the nuclear fuel
- Low level reactor background (gamma, neutron)
- Licensed to operate at power up to 100 MW
  - Variable operating power (45 - 80 MW)
  - 6 cycles per year on average (140 days)

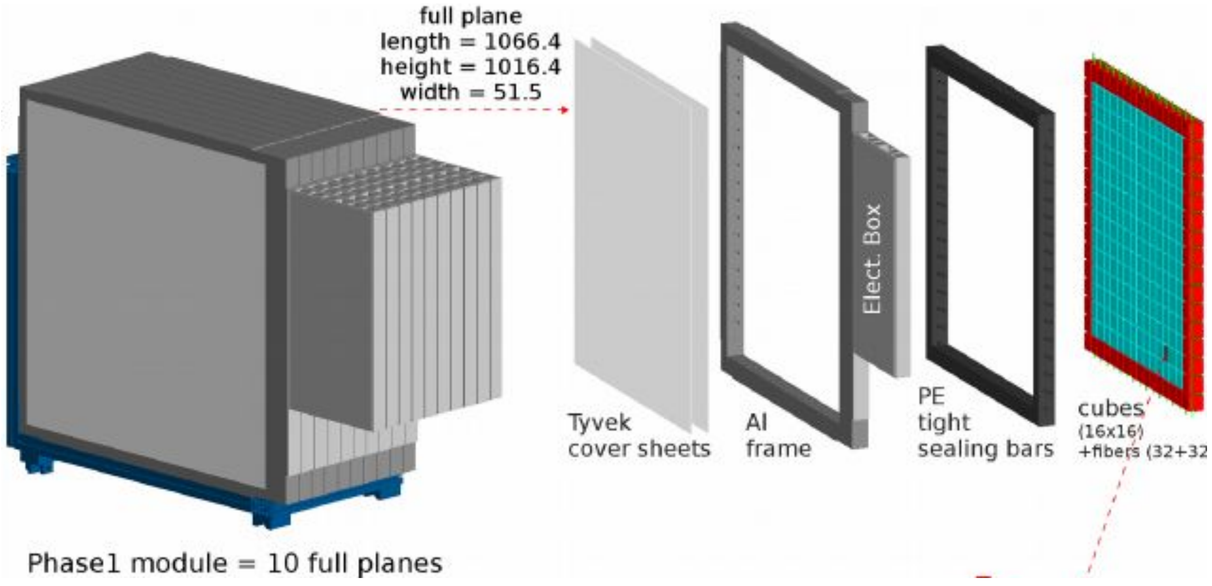


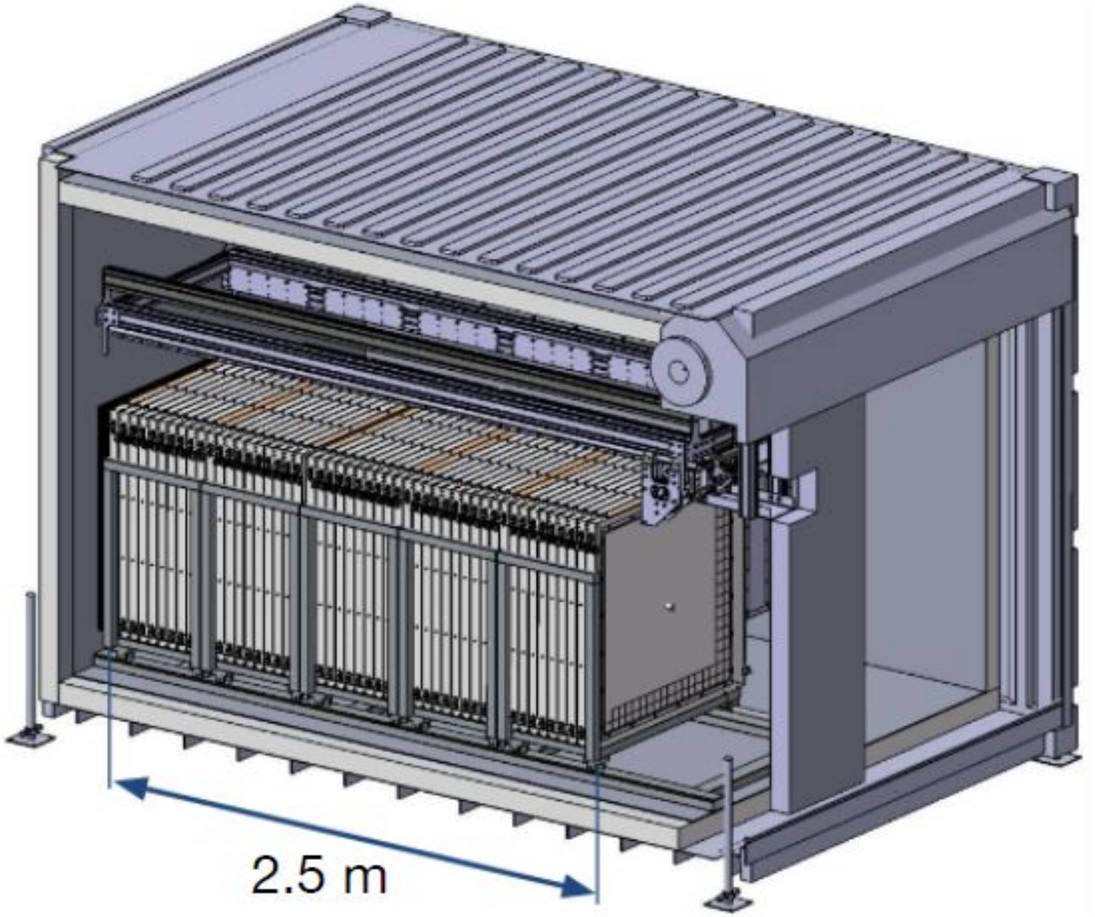


~ 1.1 m

SoLid Phase-I Detector

- Phase-I detector has been taking physics data since 2018
- 12,800 PVT cubes, 1.6 ton fiducial volume
- 3,200 read-out channels (WLS fibers + MPPCs)

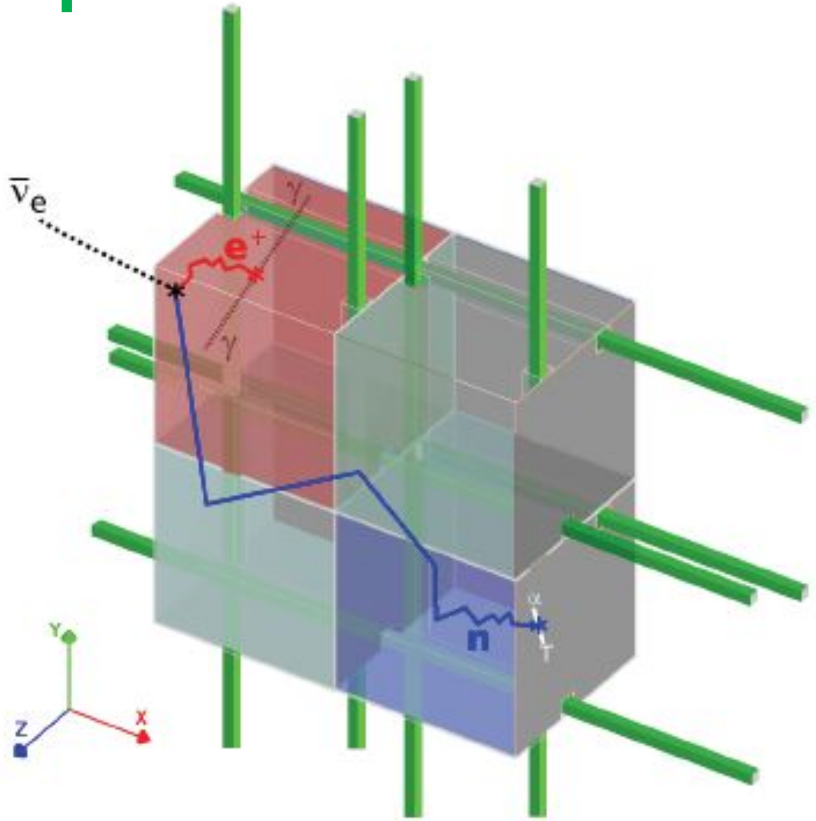




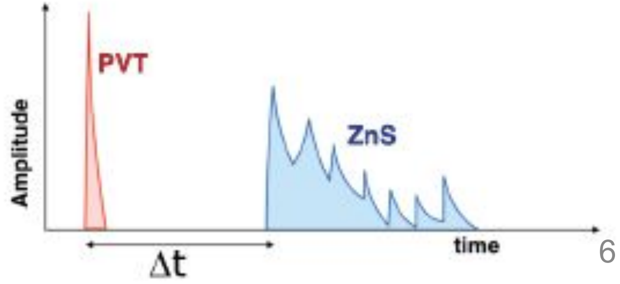
Phase-I detector is composed of 5 modules

Antineutrino Detection Principle

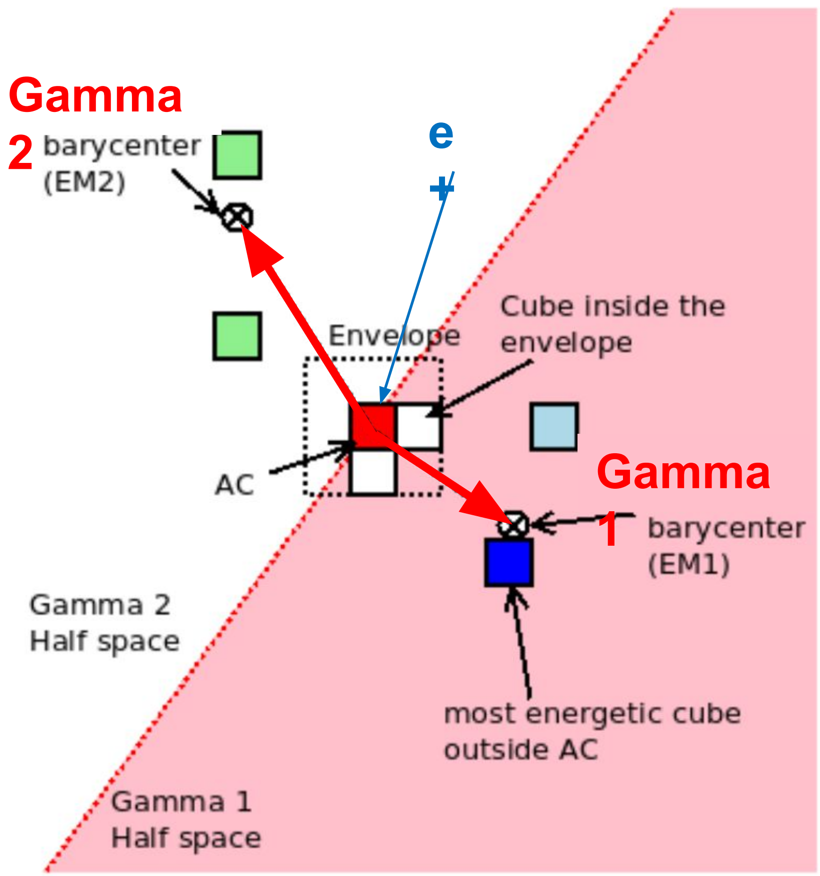
- SoLid experiment detect the **inverse beta decay (IBD)** induced by antineutrino with combination of two scintillators
  - $\bar{\nu}_e + p \rightarrow n + e^+$
- **PVT for prompt signal : Electron Signal (ES)**
  - Energy deposit by a positron carrying the antineutrino energy
  - 2 annihilation gammas are emitted
- **6LiF:ZnS(Ag) for delayed signal : Neutron Signal (NS)**
  - A thermal neutron is captured ~64μs after
    - $n + {}^6Li \rightarrow {}^3He + \alpha$ (total energy = 4.78 MeV)



Both signals are read out through the wavelength shifting fibers in X and Y directions, then detected by MPPC.
IBD reaction identified using **delayed coincidence** (ES and NS).



Antineutrino Gamma Topology Classification



Identification of the back-to-back gammas
Advantage of a highly segmented detector!

Challenges:

- Analysis channel threshold down to 100 keV
- Implies to understand detector response in deep details

Annihilation gammas reconstruction:

- Find the first gamma cluster then split the detector in two hemispheres and look for second detached cluster
- Tracking by minimizing likelihood function of cubes position according to X sections
- Classification based on 0, 1, 2 gamma cluster in event

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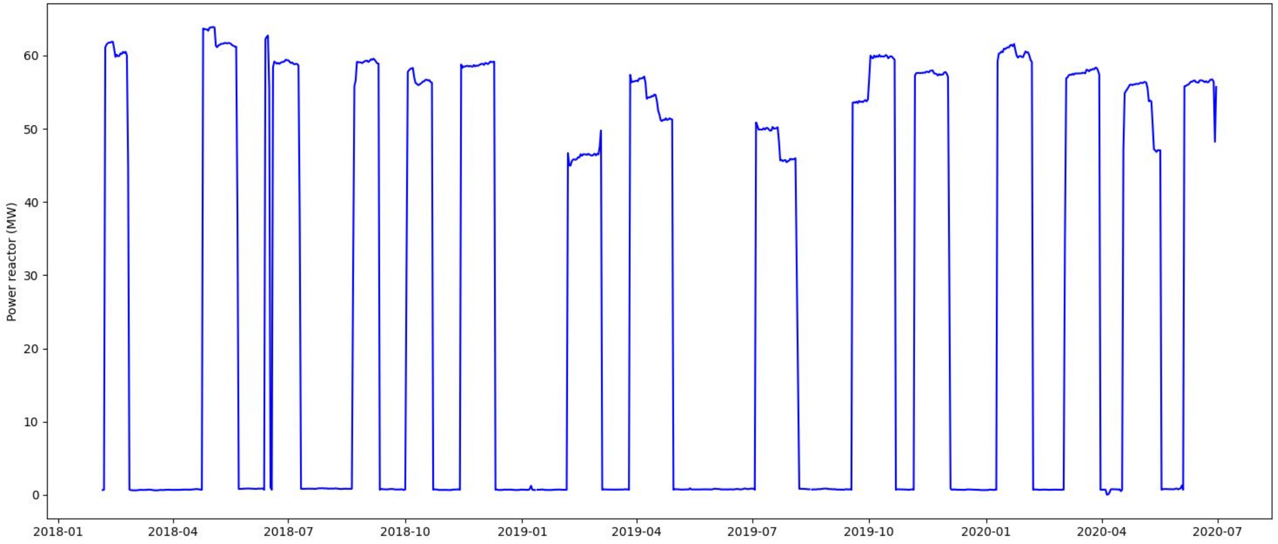
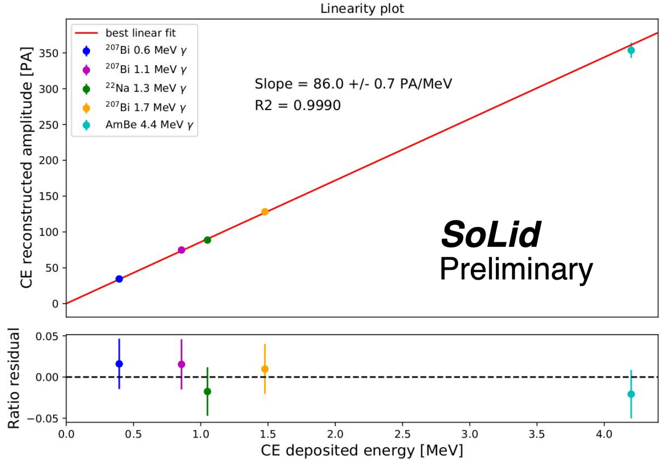
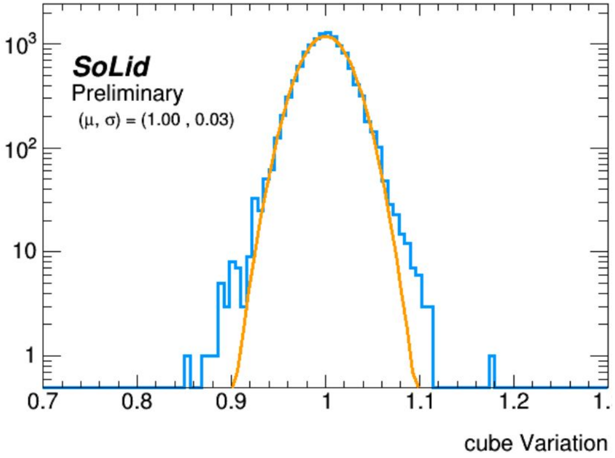
Phase-I Data & Detector Calibration

- Physics quality data is collected only during ideal conditions with chilled container, sufficiently low humidity in the container, no source in the container and full shielding.
- We run multiple data quality checks over the data to detect and reject faulty data.
- Selected ~**326 days** of **Reactor-on** and **~187 days** of **Reactor-off** high quality data for oscillation analysis.
- **Gamma** sources used for energy calibration of the detector.
- **Linearity** and **homogeneity** of the detector energy response tested at a few percent.







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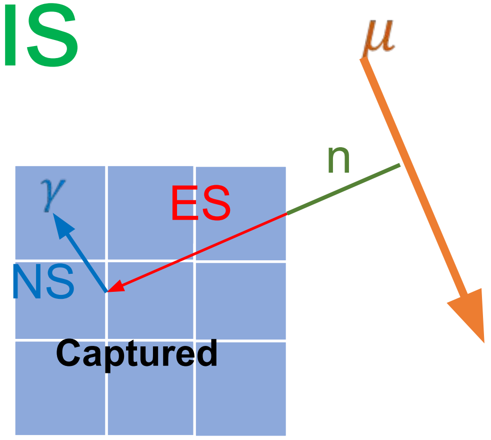
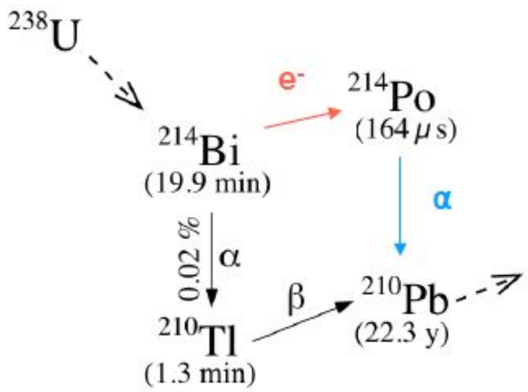
Inverse Beta Decay (IBD) Analysis



Three types of background (BG)

- **Fast neutrons (External BG)**
  - Fast neutron induced by cosmic-ray air shower & spallation
    - Neutron recoil events : ES
    - Neutron capture : NS
- **BiPo (Internal BG)**
  - Derived from $^{238}U/^{230}Th$ series contaminated mainly in LiF:ZnS(Ag)
    - ^{214}Bi decay (e-, γ) : ES
    - ^{214}Po decay (α) : NS
- **Accidental (External BG)**
  - Gamma rays from ^{41}Ar decay (reactor)
  - Radon emanation from the building



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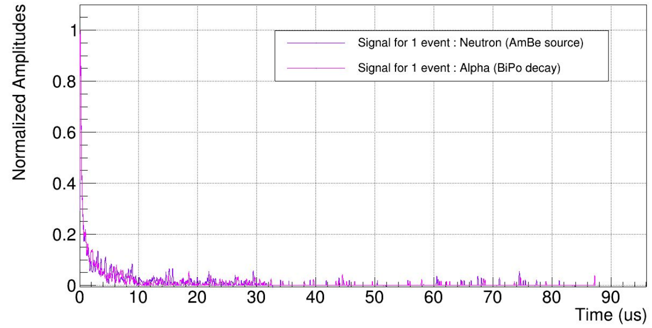
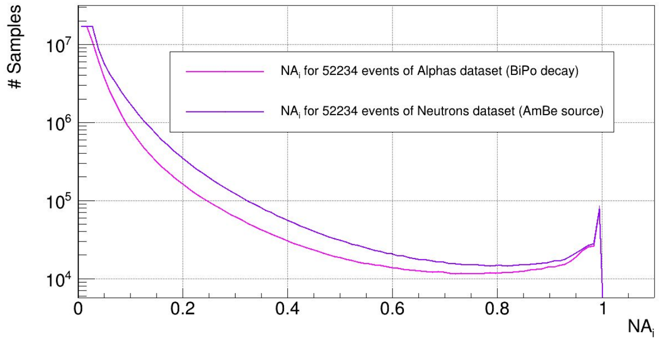
BiPonator : Sophisticated PSD Method (CNN)

CNN Input

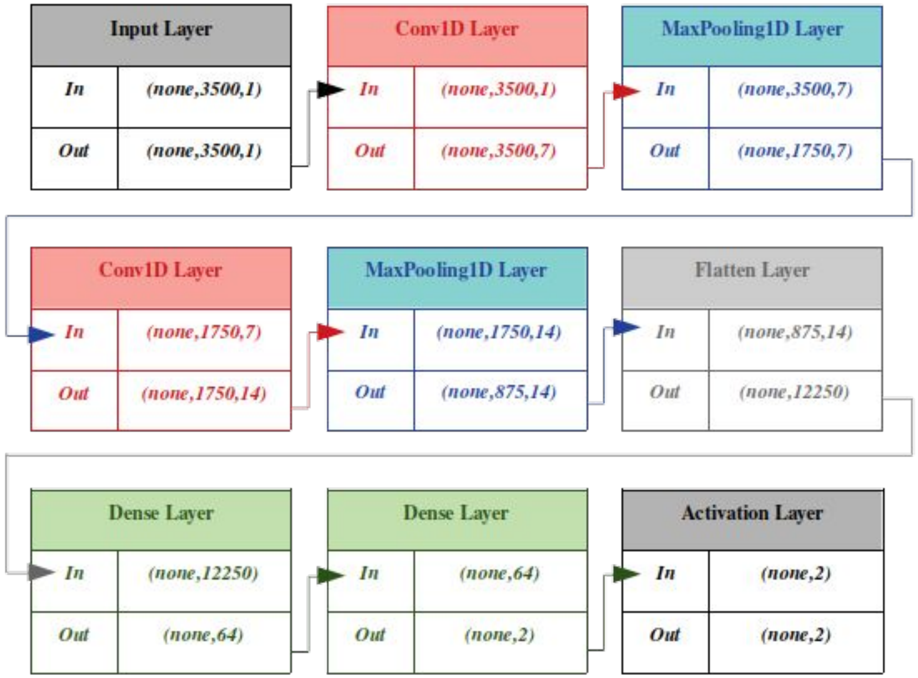


For each event,

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

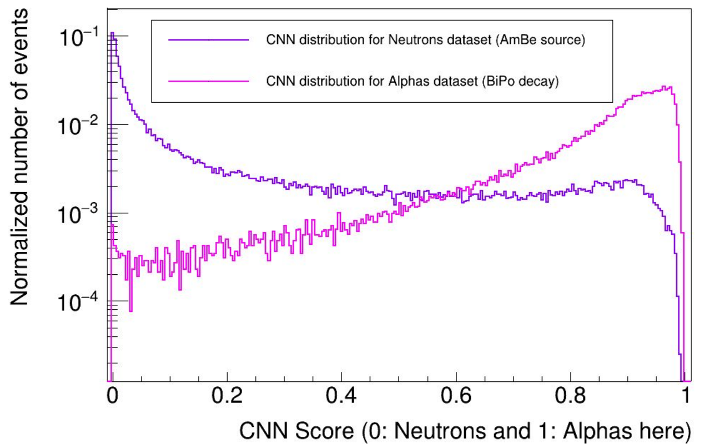


CNN Factory

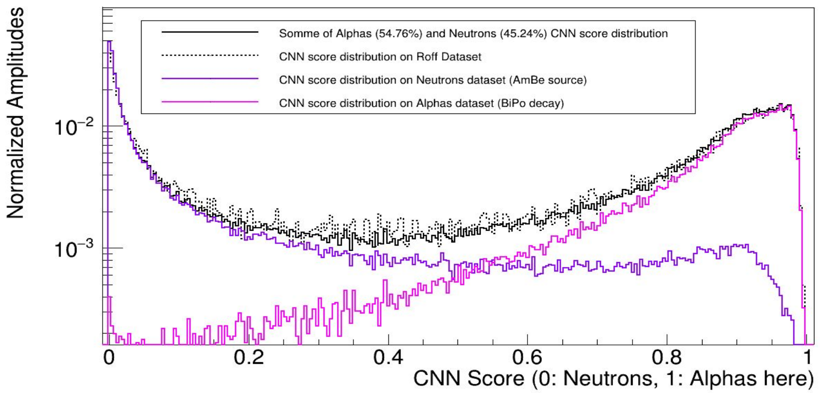


GOAL :
Alpha / Neutron discrimination improvement to reduce more BiPo background

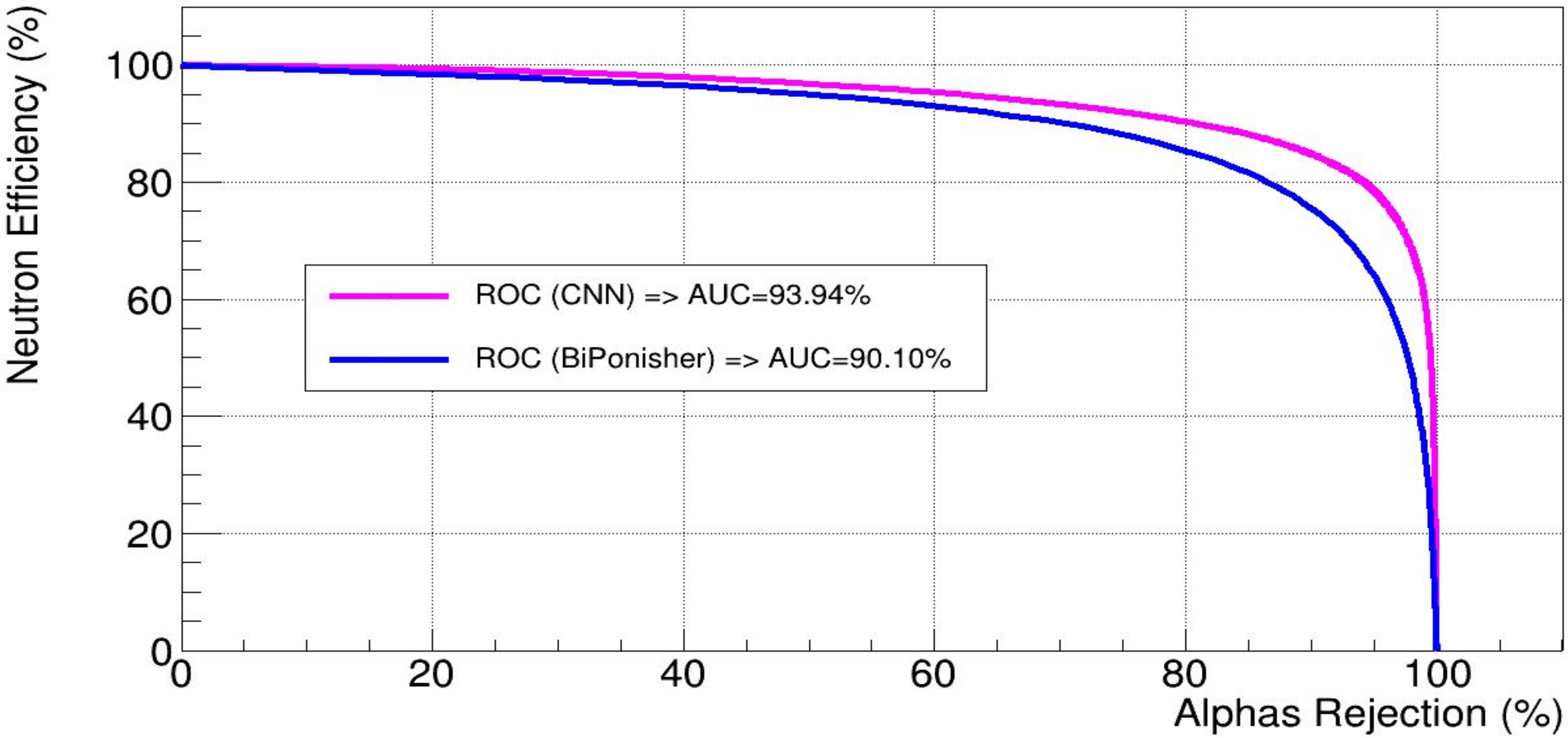
CNN Output



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

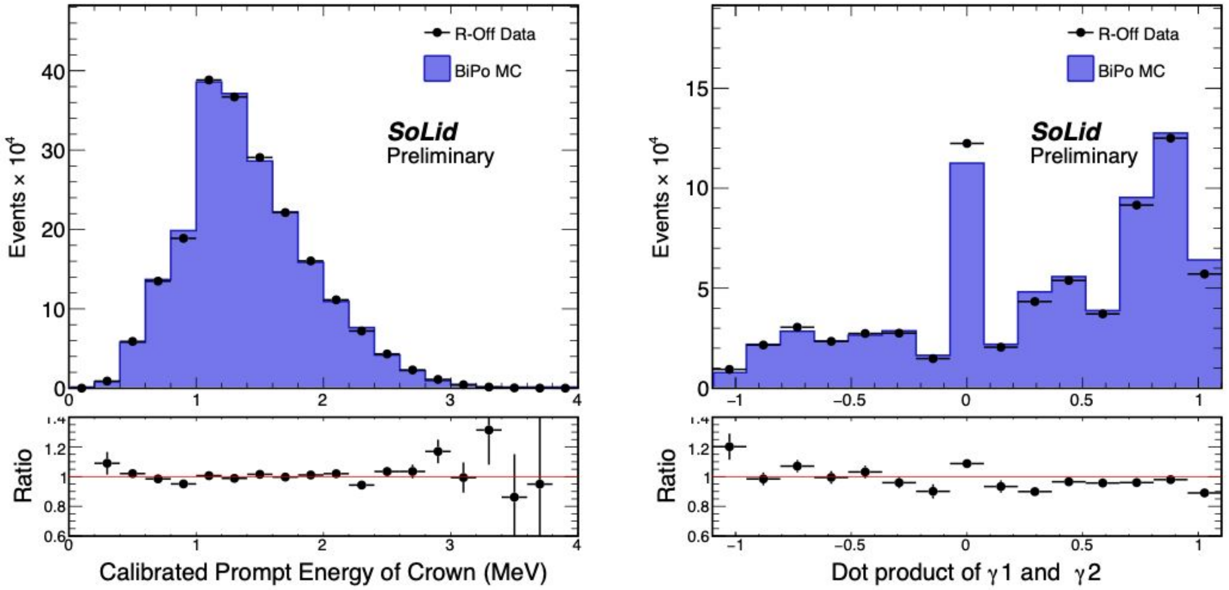


BiPonator : Performances



BiPo Background Studies

- A high purity BiPo sample very close t the signal region for precise tuning of MC.
- Phase-I R-Off data of ~187 live data-taking days is used for comparison with MC.
- Topological and energy variables are quite stable in background region.
- Systematics derived from any 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

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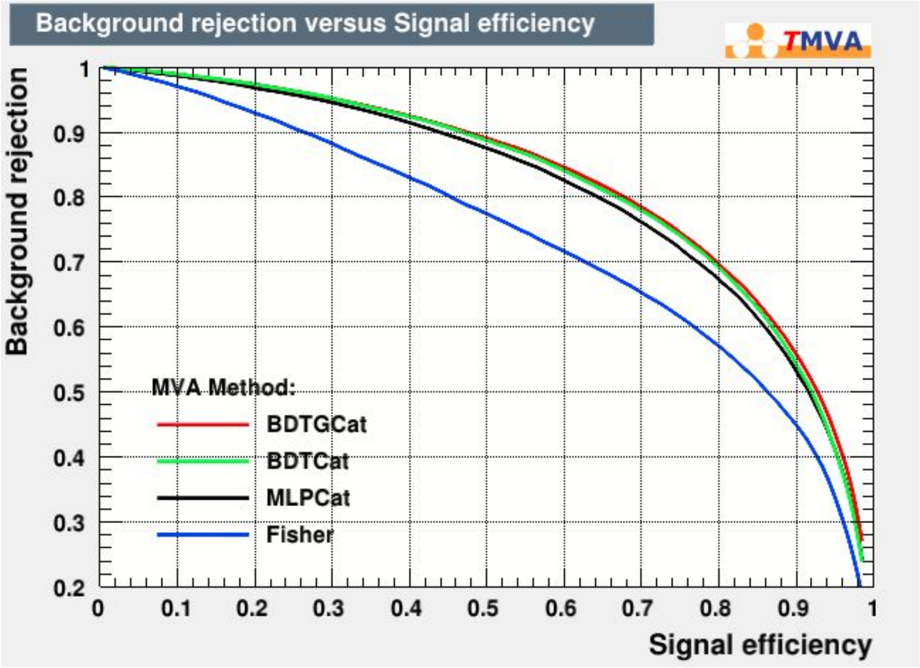
Multivariate Analysis (MVA)

Two independent approaches are employed

- **Gradient Boosted Decision Tree (BDTG)**
  - Strong BDT trained by evaluating the gradient of the objective function

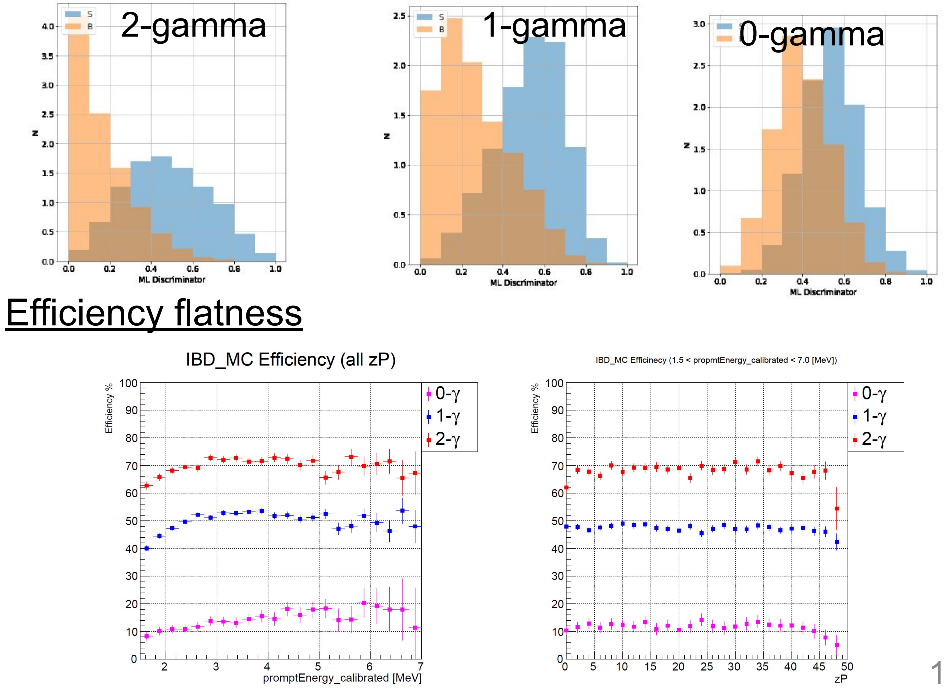
2-gamma



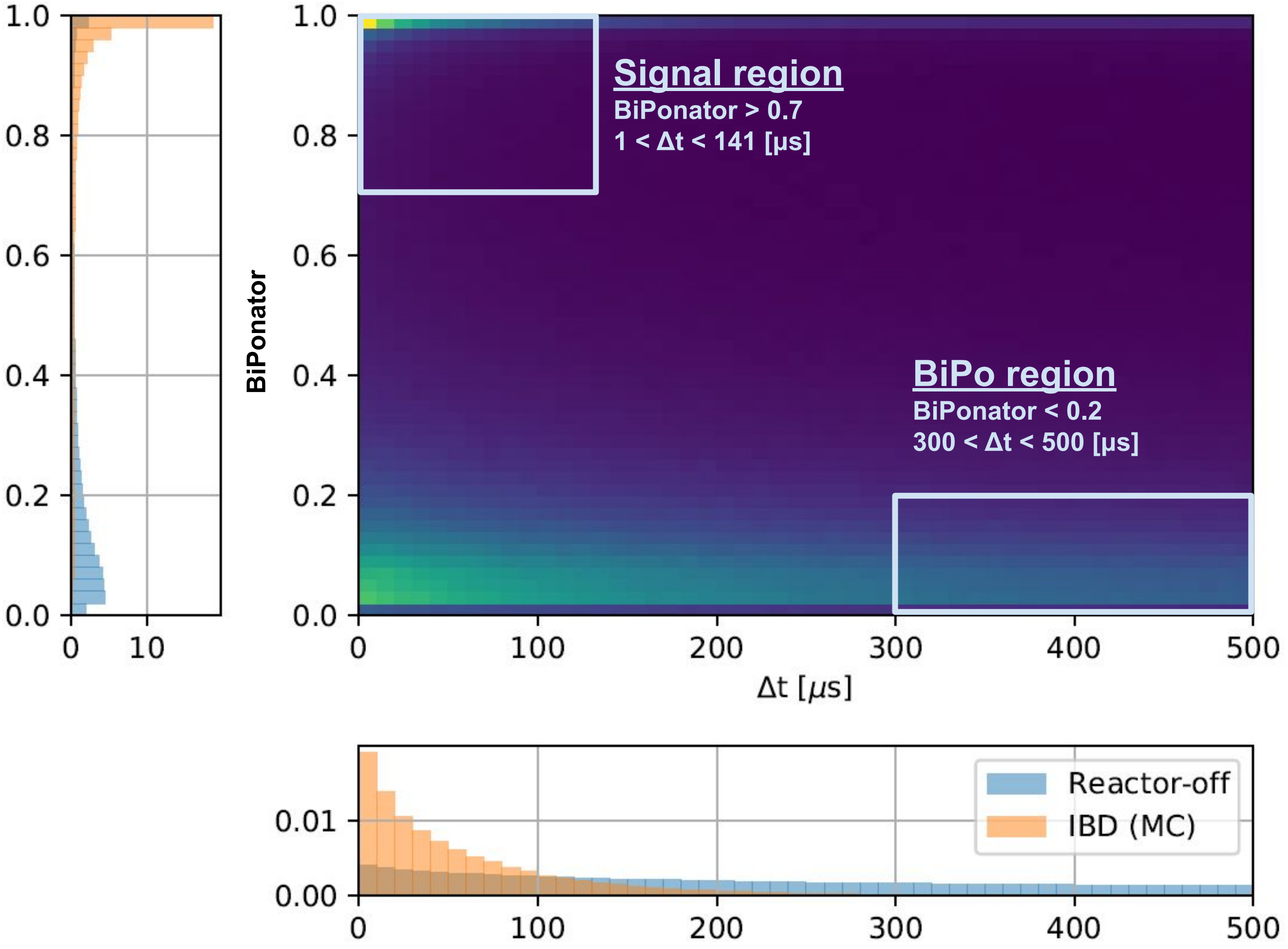
- **Uniform Boosted Decision Tree (uBDT)** *arXiv:1305.7248*
  - Keep the uniform efficiency at the specific variables

Training for each gamma category

Efficiency flatness



Event selection for antineutrino analysis



Pre-selection to 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

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Extraction of antineutrino signal rate

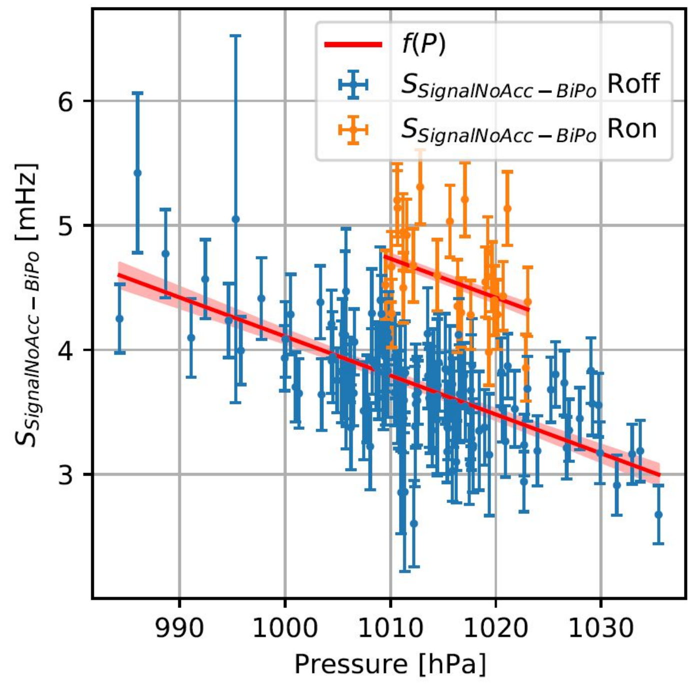
Background subtraction process

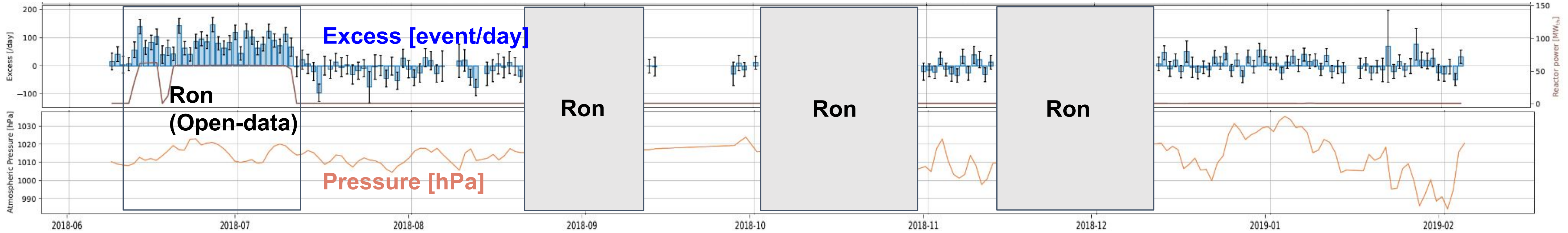
1. Subtract BiPo and accidental
2. Compute the pressure correction factor in Roff

$$S_{Signal-BiPo,j} - \bar{S}_{Signal-BiPo} = \chi^{Ref}_{ATMn}(P_j - \bar{P})$$

3. Compute the excess rate for each day in Ron

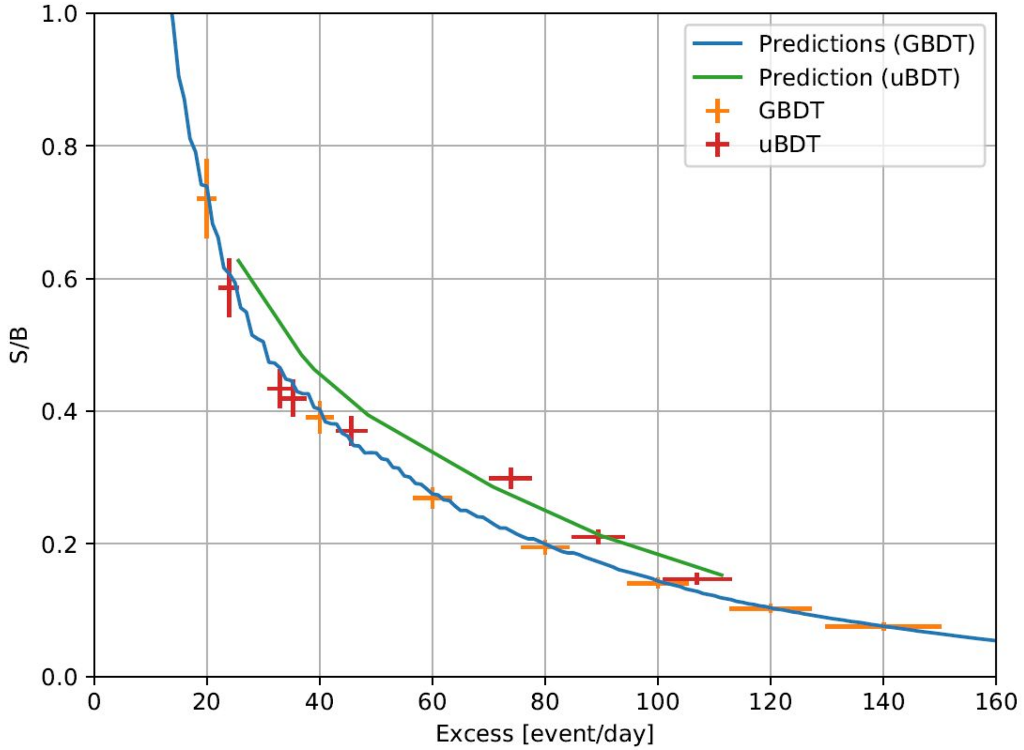
$$S_{Signal-BiPo-ATMn,k} = S_{Signal-BiPo,k} - \chi^{Ref}_{ATMn}(P_k - \bar{P})$$



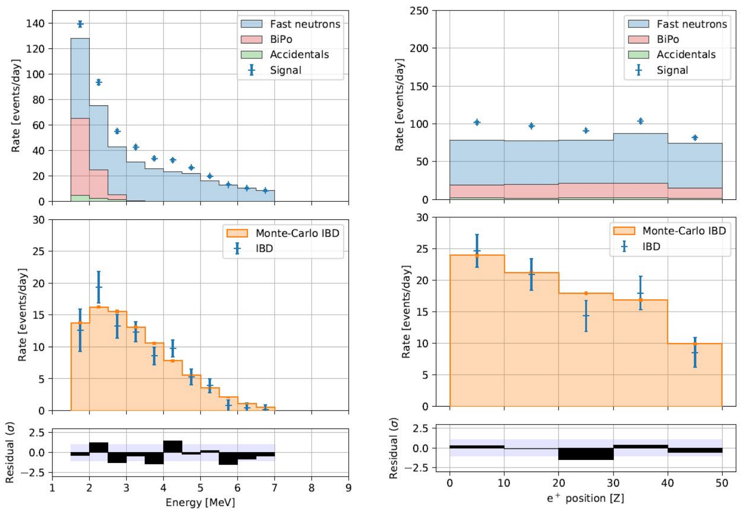


Antineutrino Signal

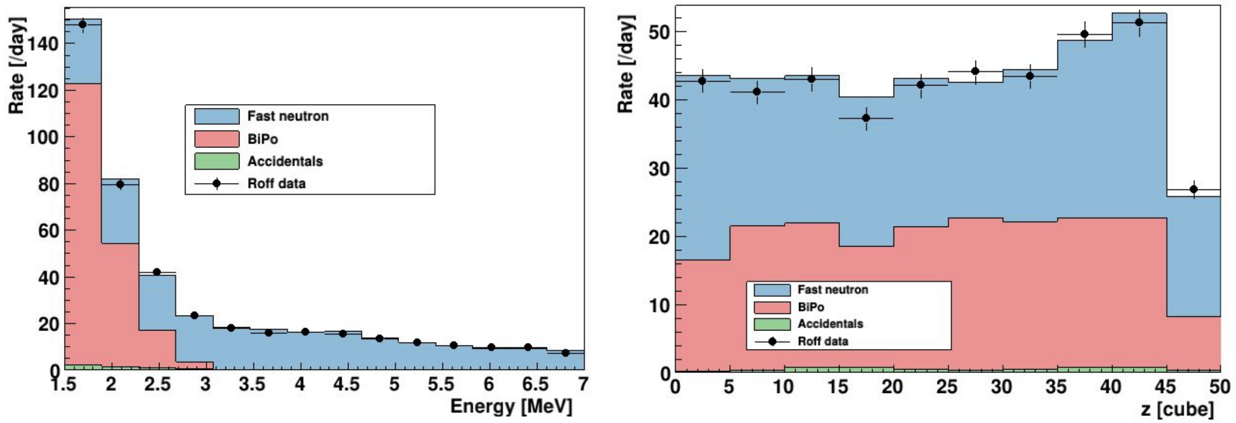
Antineutrino event rate is assumed to be 1088 [event/day] in reactor-on



uBDT: ~90 event/day, S/B =0.21



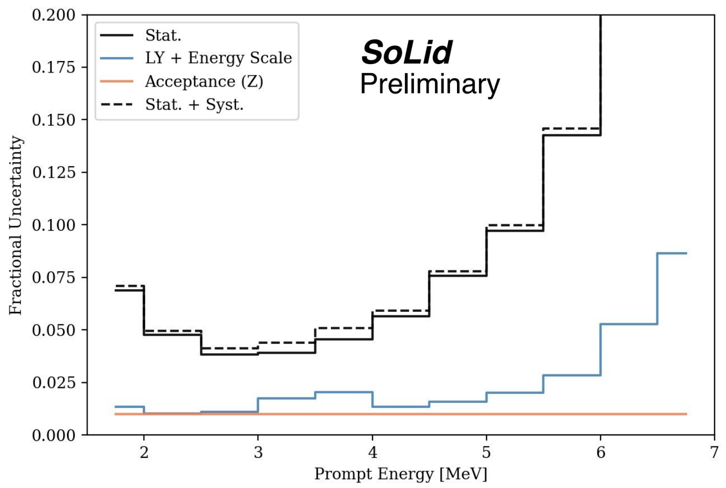
GBDT: Breakdown of Roff

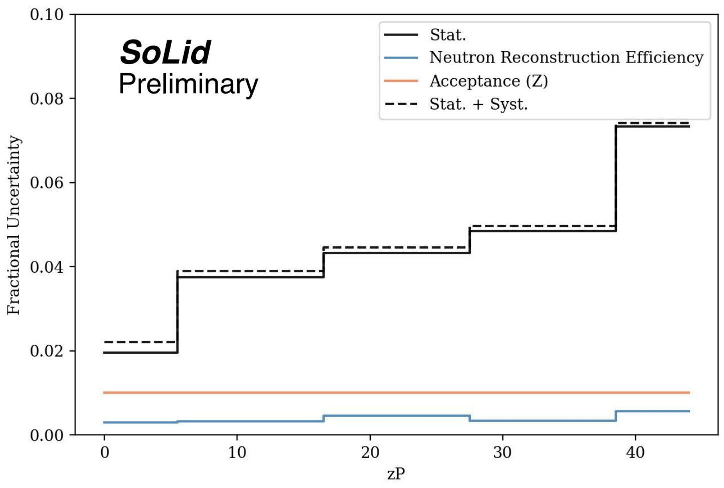


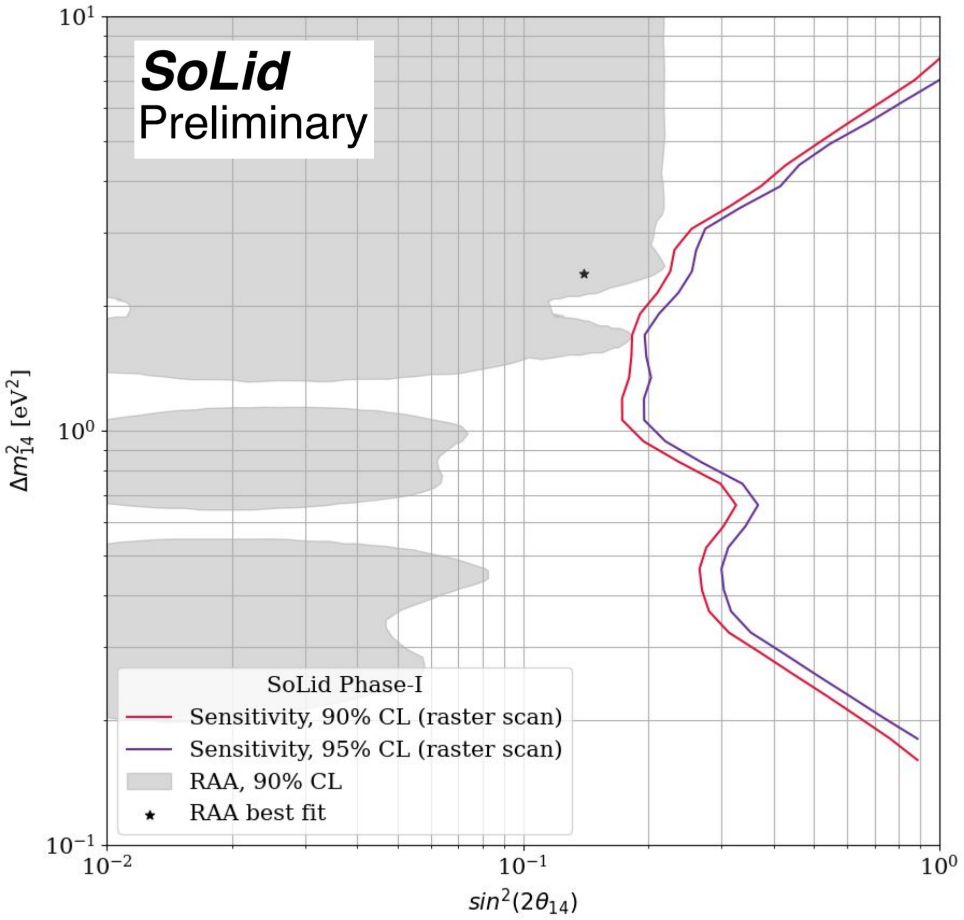
Good agreement between Data and MC
Background subtraction method works well
Systematic uncertainties have not been estimated yet

Oscillation Sensitivity

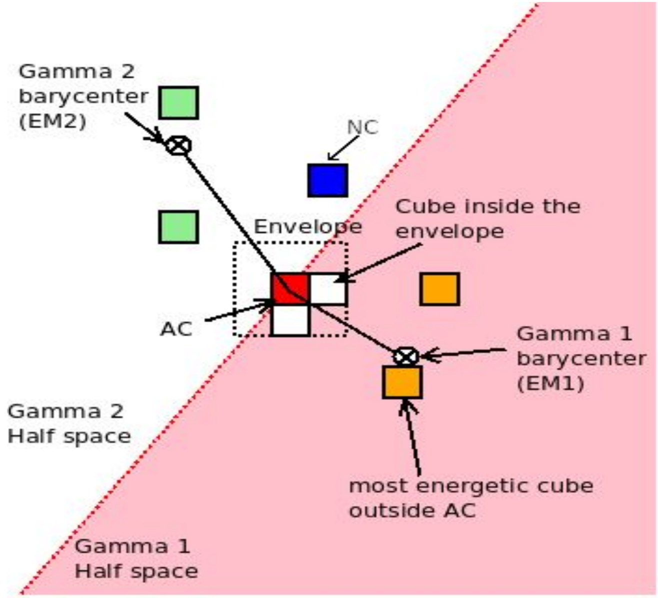
- **Feldman-Cousins** construction to estimate sensitivity to sterile neutrino oscillations -> both raster scan (1D) vs and global scan (2D) methods
- **Systematic uncertainties** related to the light yield (LY), energy scale and neutron capture efficiency per module are currently taken into account
- **Ongoing effort** to assess impact of remaining systematics and improve sensitivity with new analysis techniques !







Two Gamma Antineutrino Topological Selection

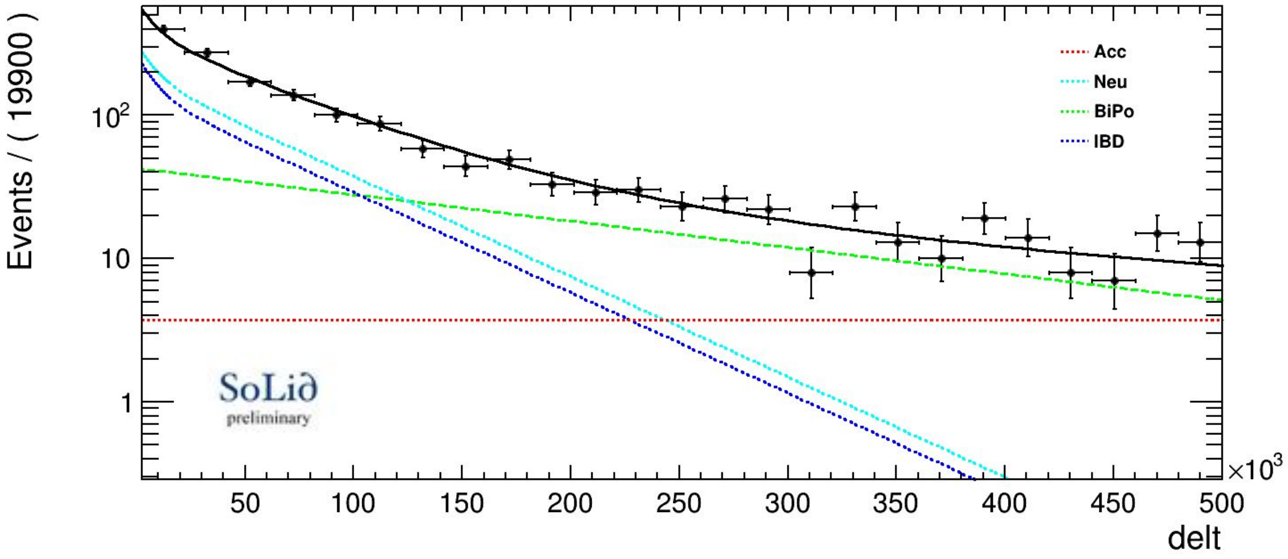


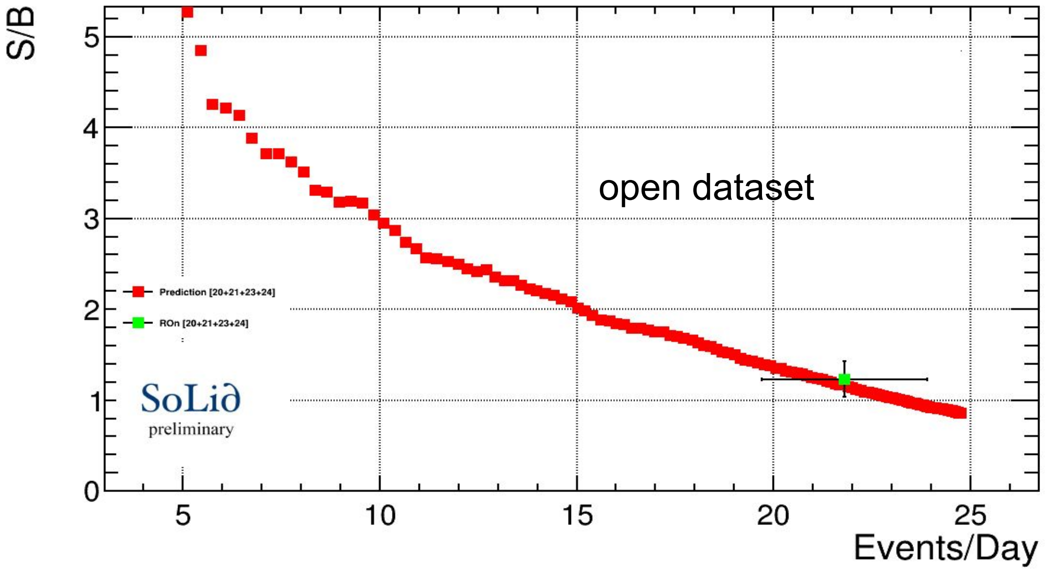
1. **New analysis** → based on **event topologies** (using maximally the detector segmentation)
2. Preliminary analysis with **both annihilation gammas** as complex pattern
3. **Multivariate analysis** for remaining background rejection
4. Each background component determined with **multidimensional simultaneous fit** (spatial and time Prompt-Delayed differences).

→ **Good agreement between excess and prediction and S/B larger than one is obtained:**

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

5. Beyond Phase-I data measurement this approach will benefit from the upgrade features (i.e. LY increase).



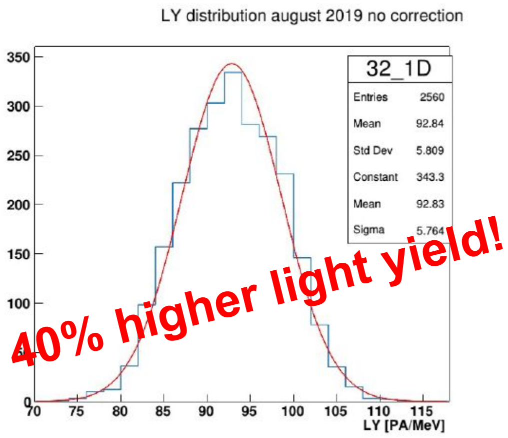


Conclusion

- SoLid faces the BiPo and cosmic-induced background
  - These are reduced by the space and time coincidence, signal topology, waveform analysis by CNNs, multivariate analysis
- The detector response is well understood
- Background subtraction method is working well
  - Systematic errors totally estimated pretty soon
- Dedicated analysis based on topologies are very promising
- Exclusion contour for SoLid Phase I coming soon!

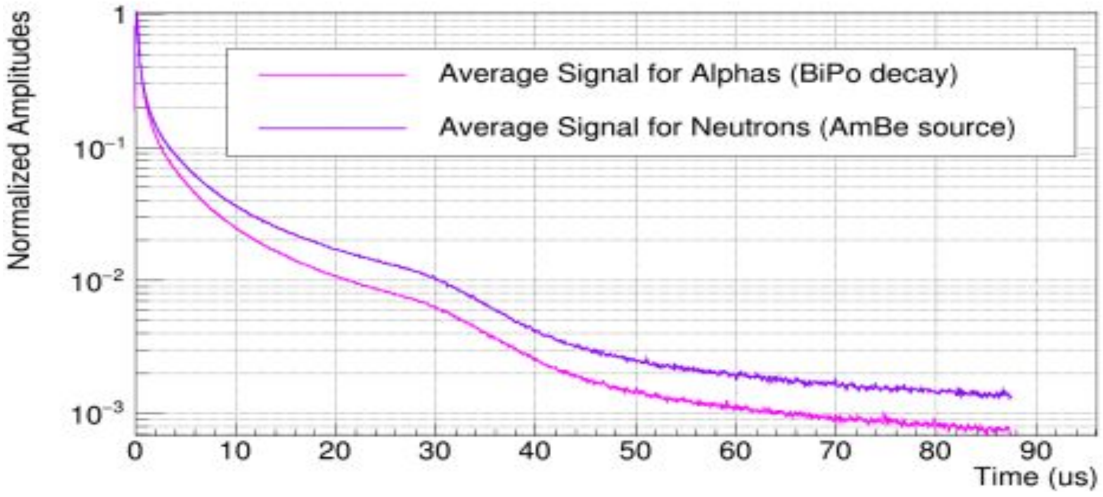
Detector Upgrade for Phase II

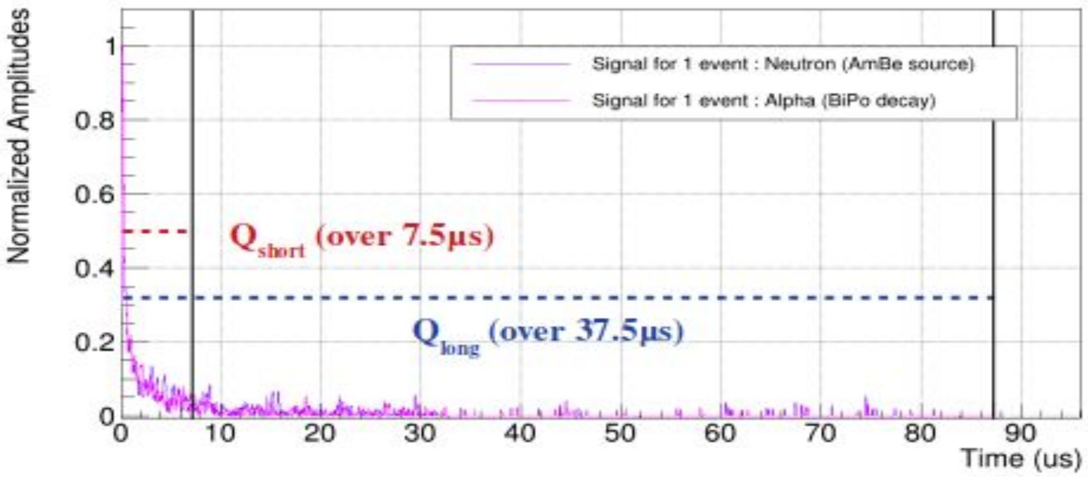
Replacement of S12 series MPPCs with S14 series



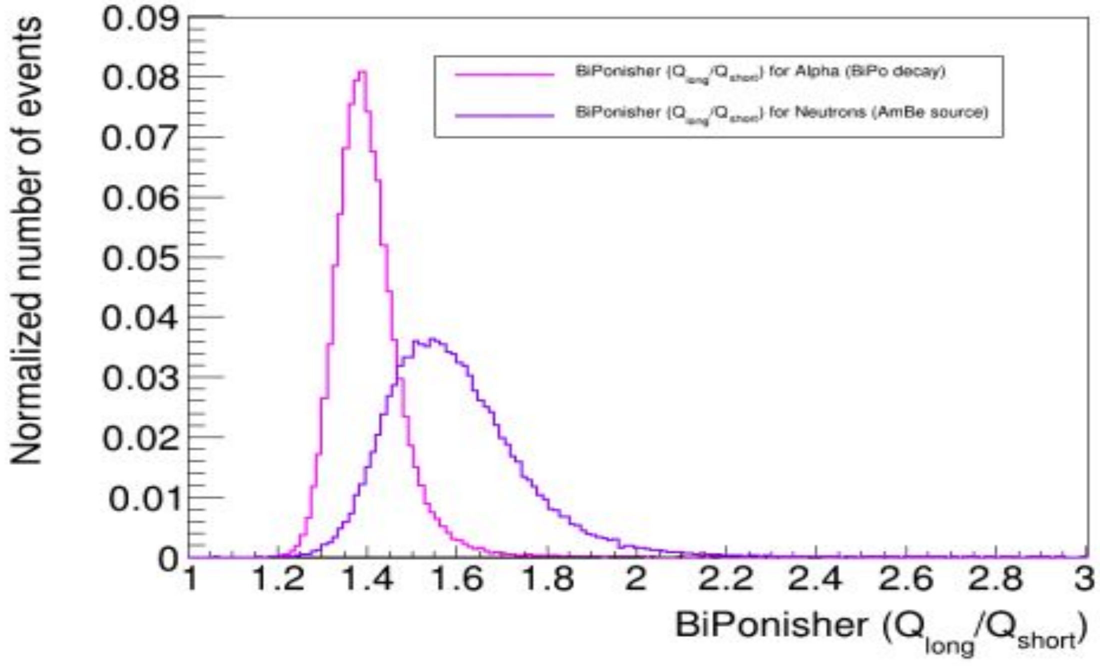
Backup

Classic PSD Method (BiPonisher)





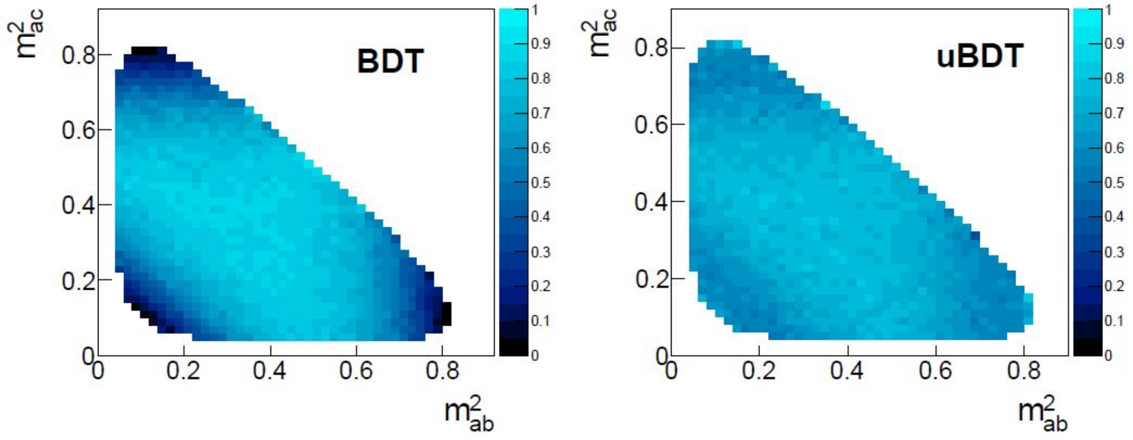
Over the totality of events of α and N datasets



Multivariate Analysis (MVA)

Two independent approaches are employed

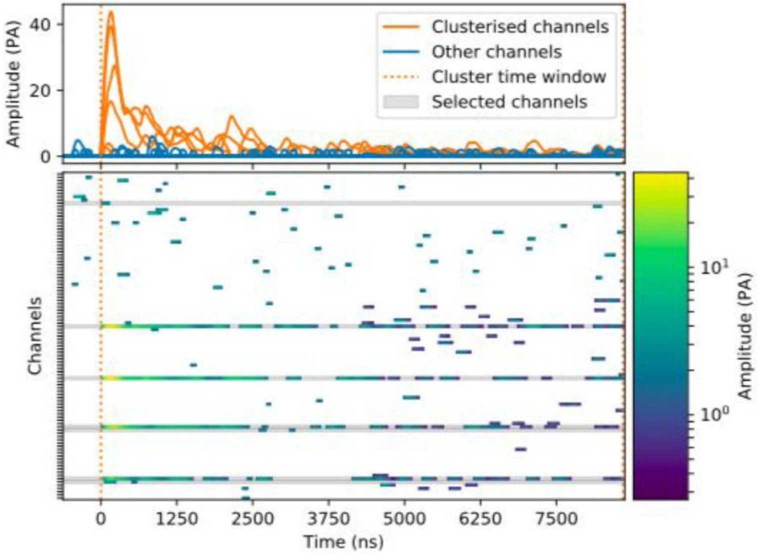
- **TMVA neural networks**
  - Legacy but conservative method as well known
- **Uniform Boosted Decision Tree (uBDT)**
  - Customized BDT to uniform classification performance. [arXiv:1305.7248]



Output of uBDT is uniform in selected parameters (m^2_{ab} , m^2_{ab})

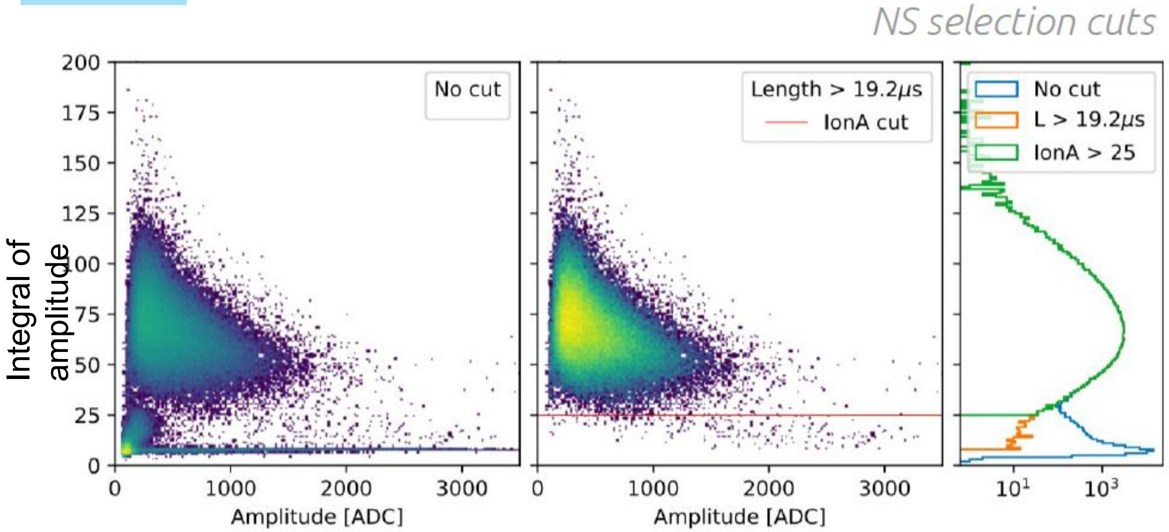
Event Reconstruction

1. Time clustering to group signals from different fibers

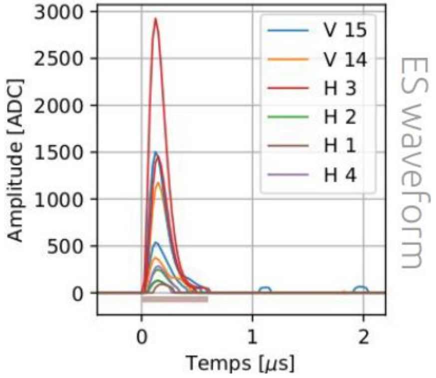


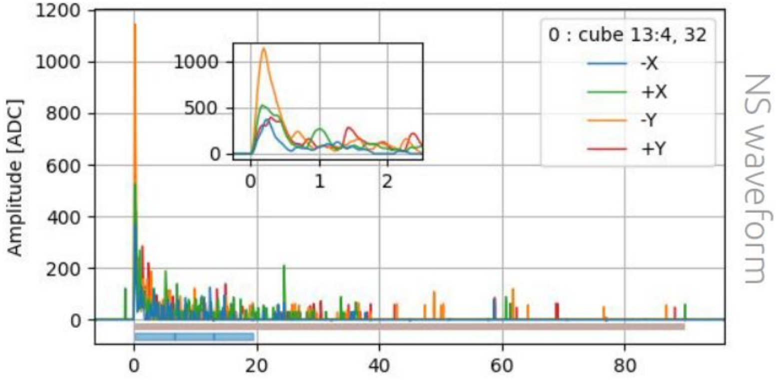
2. Identifying cluster by using cluster length and integral of amplitude / amplitude ratio

- **"ES", "NS", "Muon track"**

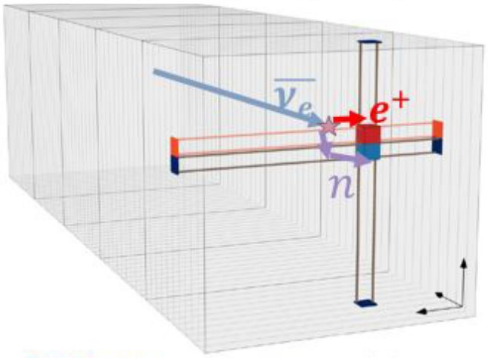


3. Make correlations between ES and NS





An ES-NS coincidence candidate

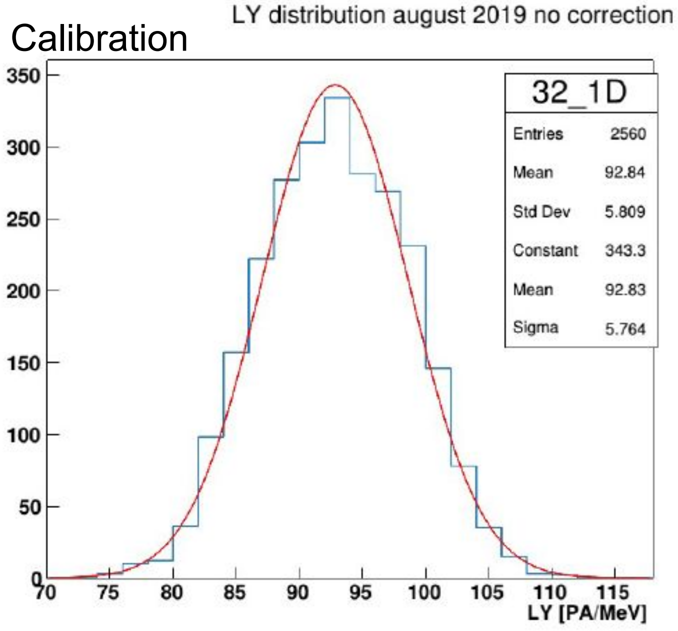


ES energy is estimated by using Maximum-Likelihood Expectation Maximization (MLEM) algorithm

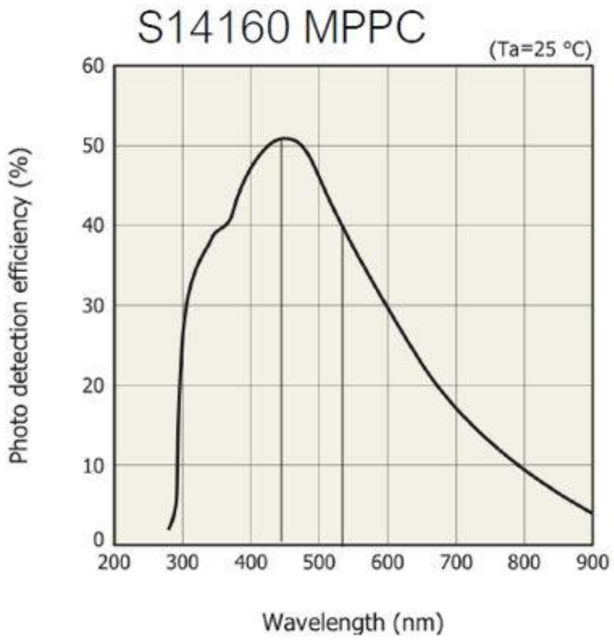
Detector Upgrade

- Upgrading the detector with new MPPCs (S14 series)
  - 40% higher light yield compared to S12 series
  - Cross-talk will be half
  - Energy resolution & threshold will be improved
- Improvement of the annihilation gammas reconstruction is expected

Calibration



Replacing the MPPCs



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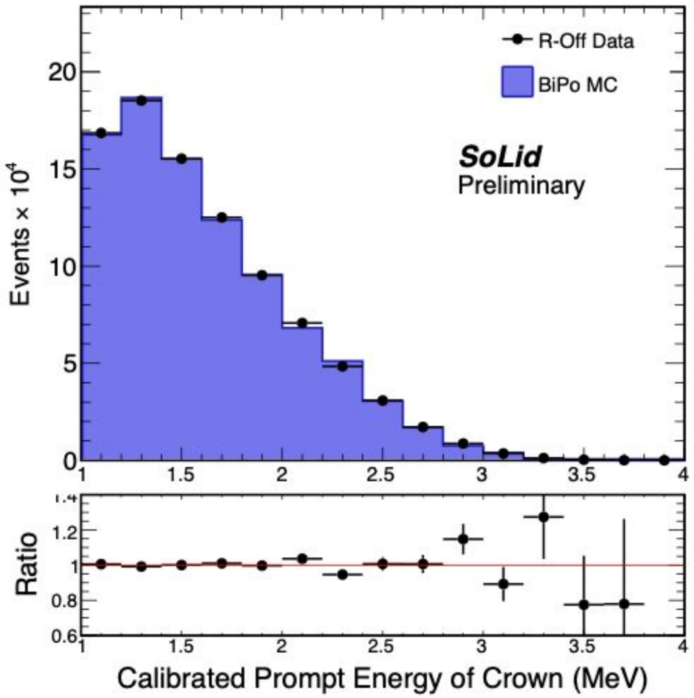
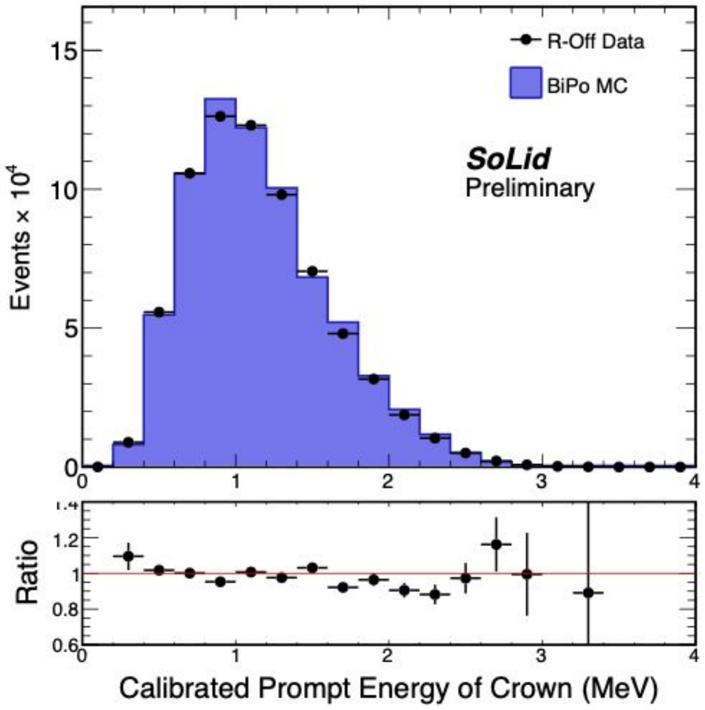
BiPo Background in 0, 1 and 2 γ Category Events

- Additionally, BiPo background stability is studied categorizing 0,1 and 2 γ events.
- These BiPo events are a proxy to IBD events with 2 annihilation gammas.

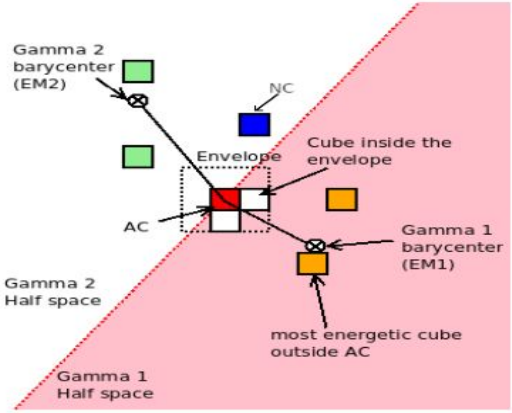
0 γ category

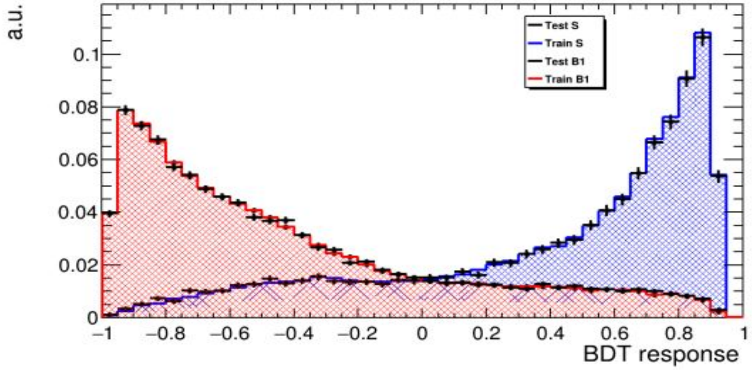


2 γ category



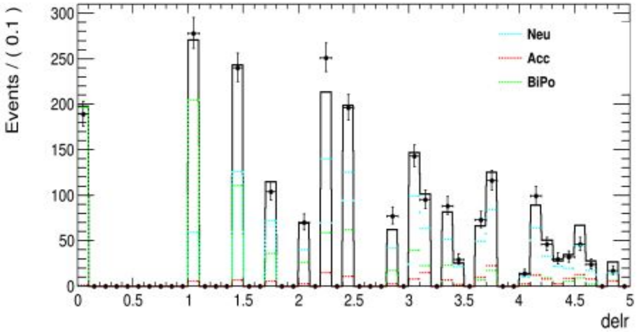
2 γ Anti-neutrino Topological Selection

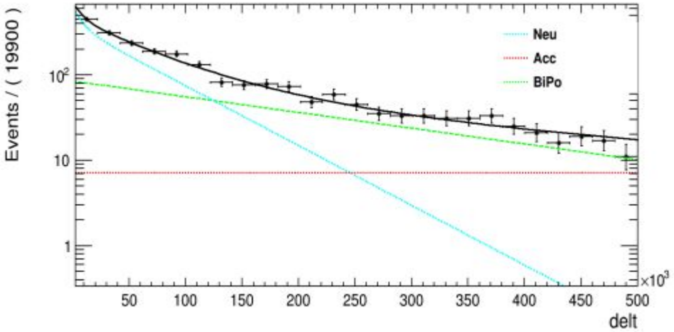


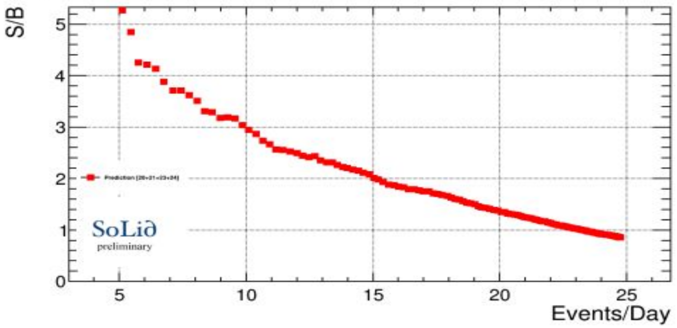


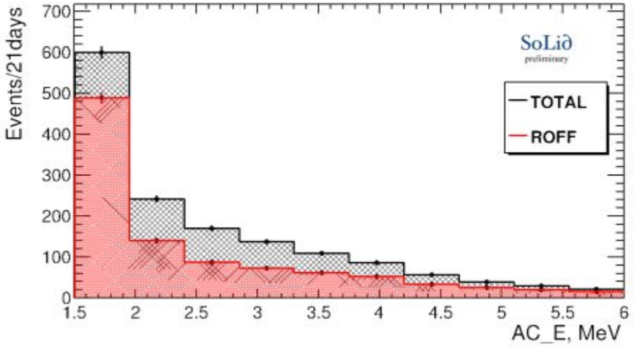
1. The signal definition in the current analysis is based on the topological properties of the ES
2. The positron and gamma deposits are distinguished to remove the backgrounds (granularity of the detector is maximally used)
3. Further background rejection is tackled with a multivariate analysis. There are 2 tools based on the EM features + 1 based on the geometrical

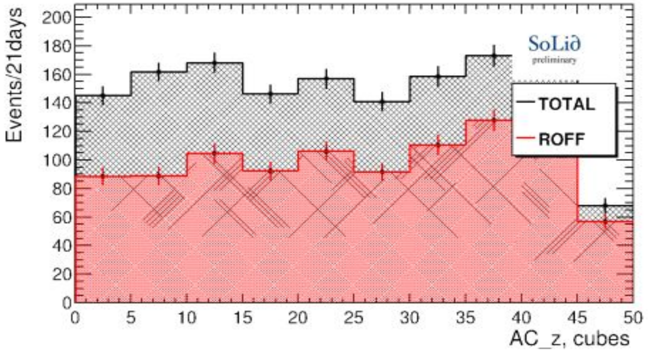
4. 10-fold cross-validation is applied (to use the full ROff statistics). Overtraining checked.
5. The 5D optimization aimed at signal significance maximization is used.
6. The yields for each source are directly measured from the simultaneous unbinned ML fit
7. Predictions, control plots and systematic uncertainties are determined following a blind analysis.











2 γ Anti-neutrino Topological Selection

Syst source	Nominal	δ	$\sigma_{Y_{\overline{\nu}}}$	$\sigma_{Y_{\overline{\nu}}}$, %	Comment
Light Leaks	11.7%	+3.0% -3.0%	-1.27 +0.95	4.73 3.54	To be improved with the SM sampling
Light Yields	Saffron2 induced	+3.0% -3.0%	-0.68 +0.58	2.55 2.16	To be improved with the SM sampling
$\Delta\tau$ BiPo	235.8μs	+1.2μs -1.2μs	+0.03 -0.03	0.12 0.12	
$\Delta\tau$ Atm	62.0μs	+0.5μs -0.5μs	+0.09 -0.15	0.35 0.58	
$\Delta\tau$ FAtm	8.5μs	+0.8μs -0.8μs	+0.02 -0.02	0.08 0.08	
Δr ACC shape	FPNTs sample p.d.f.	Sampled	0.12	0.59	Uncertainty scales with the ROff data statistics
Δr ATM shape	Enr. sample driven p.d.f.	Sampled	0.21	0.98	Uncertainty scales with the ROff data statistics
Δr BIPO shape	Enr. sample driven p.d.f.	Sampled	0.15	0.70	Uncertainty scales with the ROff data statistics
Δr IBD shape	ROSim p.d.f.	Sampled	0.08	0.37	

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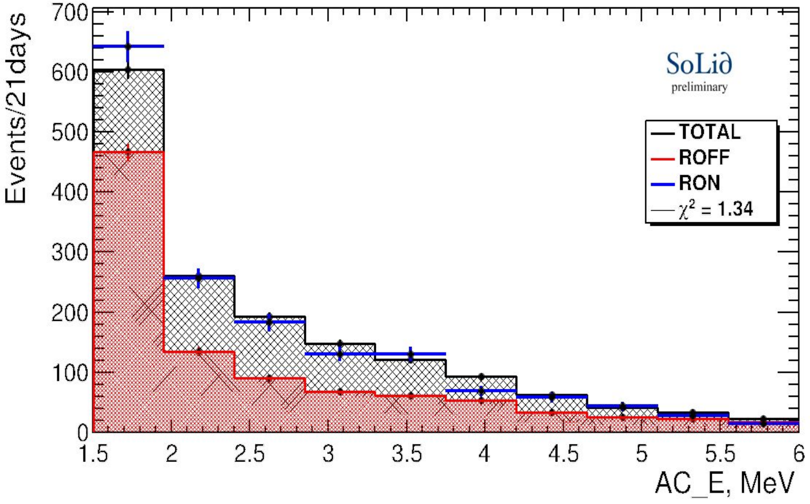
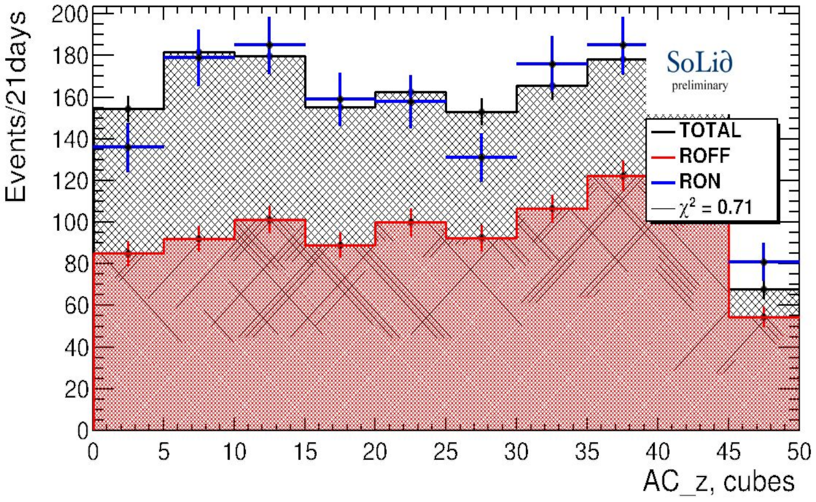
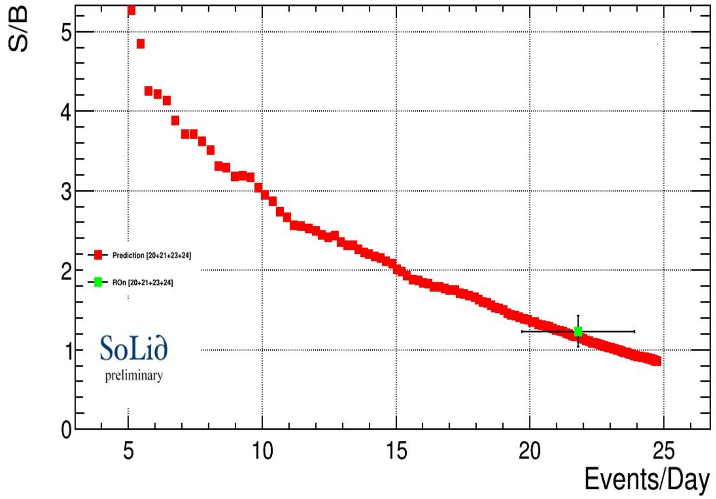
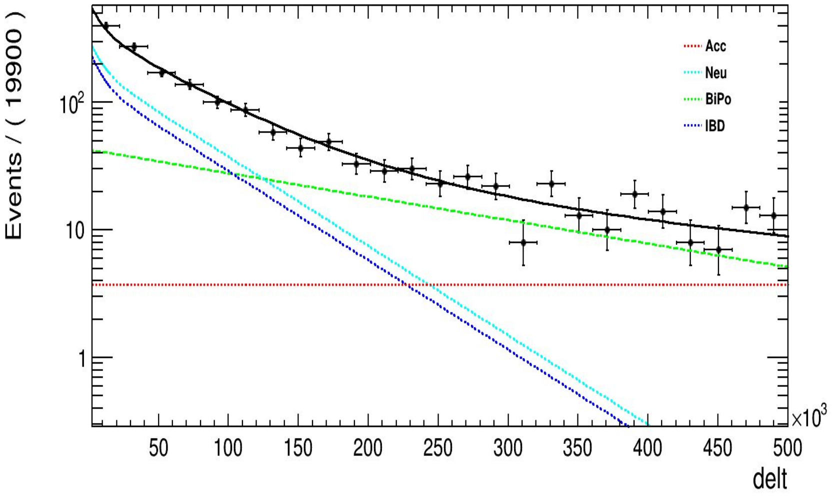
2 γ Anti-neutrino Topological Selection

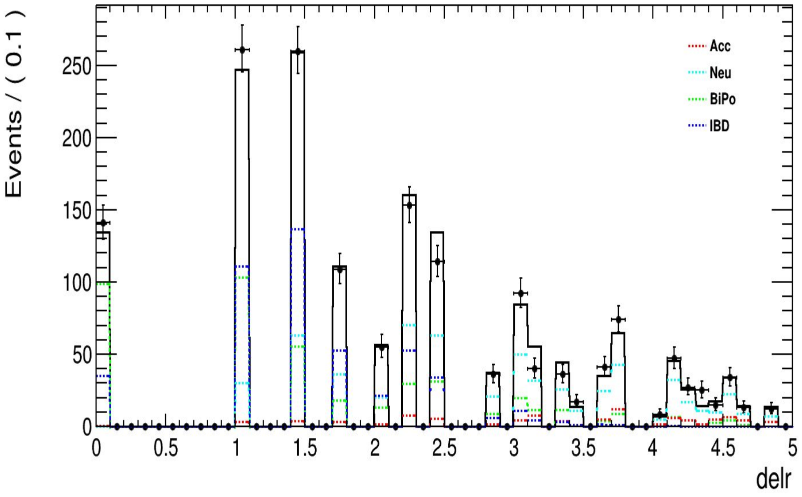
1. The topological analysis is applied to a 21 days open data set.
2.1 Predicted:
S/B = 1.2 (21.1 ± 1.3 ± 1.5 ν/day)
2.2 Obtained:
S/B = 1.2 (21.8 ± 2.1 ± 1.5 ν/day)
3. Approach to be extended for the 1 gamma events











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