Search for $\overline{\nu_e}$ disappearance w/ the SoLi∂ detector

Hervé Chanal, Stéphane Monteil, Mike Yeresko

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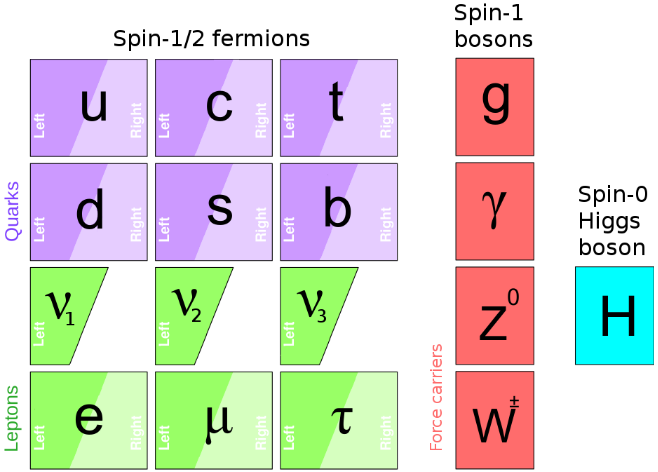
In the search for incompleteness



The table of elementary particles of the Standard Model.

In the search for incompleteness

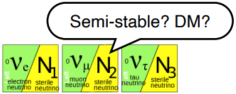
... could LLPs be the answer?

- Proposed DM models often involve LLPs!
  - Why is H so light ?
    (Hierarchy Problem)

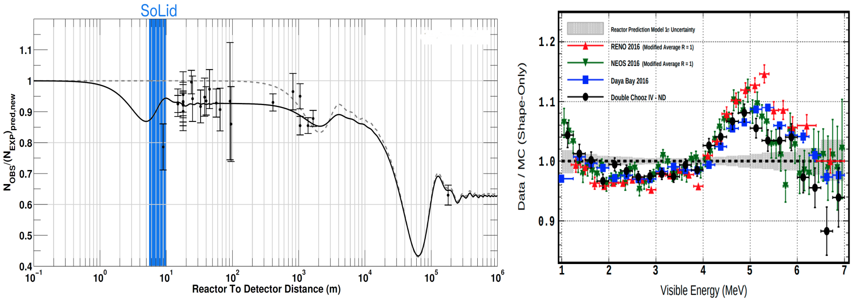
    → SUSY

  - **Neutrino oscillations** + masses

    → Heavy Neutral Leptons



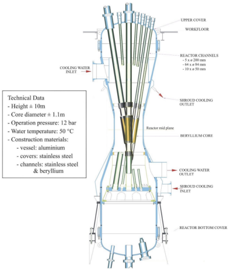
Reactor antineutrino anomaly

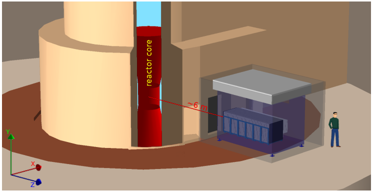


The ratios of observed to predicted $\overline{\nu}$ event rates for the different reactor experiments (RAA, left) and the measured to predicted spectral ratios for the commercial reactors (5 MeV bump, right).

- Popped up in 2011 after reevaluation of the reactor flux predictions;
- Might be accounted for with an additional light sterile neutrino state.
- Accompanied by the $\overline{\nu}$ energy spectra distortion (aka “5 MeV bump”);
- Very short baseline reactor experiments as a tool to tackle both questions;

The SoLi∂ experiment





- Set at the BR2 research reactor (Mol,Belgium)
- Compact core (⌀ 50 cm)

  ⟹ $\overline{\nu}$ creation position precisely determined;
- ^{235}U enriched reactor core (95%)

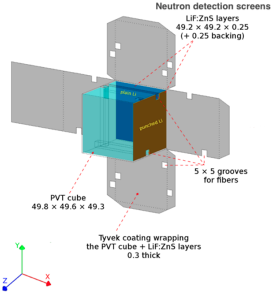
  ⟹ Easy energy spectrum simulation;
- Very short baseline experiment [6.3-8.9]m

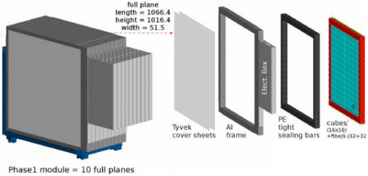
  ⟹ Accesses the region, where the most pronounced oscillatory behaviour is expected;
- No nearby experiments, shielded beam ports

  ⟹ Low reactor-induced bckg environment.
- ≈ 140 days of operation/year

⟸ Top: An illustration of the BR2 twisted design core.
Bottom: Schematic view of the SoLi∂ detector positioning on the site.

The SoLi∂ detector

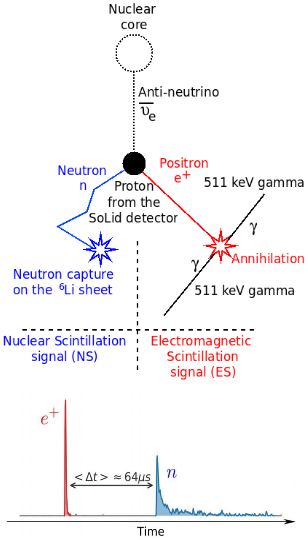




- A sandwich composite of two scintillators;
- 5 cm sided cube are made of polyvinyl-toluene (PVT) and lined with 2 layers of ^{6}LiF:ZnS
  ⇒ Highly granular detector.
- Individual cubes are wrapped with Tyveck
  ⇒ Light kept within the cube, where issued.
- Light is taken to the boundaries w/ wavelength-shifting optical fibres and read-out w/ SiPMs;
- Cubes are arranged in planes of 16 $\times$ 16 units;
- Layers are further optically decoupled with two square Tyvek cover sheets;
- 10 planes make a module, 5 modules in total;

⟸ The schematic view of the SoLi∂ basic detection unit cell design (top) and the full-scale geometry (bottom).

The detection principle



- Inverse beta decay (IBD) to detect $\bar{\nu}$:

$$\bar{\nu}_e + p \longrightarrow n + e^+(\gamma\gamma)$$

- Neutron scintillation signal [NS]:
  - Generated by the ZnS
  - Energy is issued from n capture on the ^6Li

$$n + {}^6Li \longrightarrow {}^3H + \alpha$$

- Electromagnetic scintillation signal [ES]:
  - Generated by the PVT
    - Proton-rich $\bar{\nu}$ target
    - Measures e^+ ionisation energy
    - Measures annihilation γ energy
  - **High granularity allows to distinguish ionisation and annihilation contributions!**
- NS and ES correlated in time: $\Delta T = T_{NS} - T_{ES}$

The list of activities

- The reconstruction of the ES;
- The relative calibration of the ES;
- The absolute calibration of the ES;
- The ES definition and *Topological* analysis;
- Verification of the novel methods with an open data set.

Reconstruction basics

- The digitised SiPM readout from the fibers* is the raw detector data;

  * the waveforms, which passed the triggers and thresholds;

- The waveforms are grouped and clustered;

- Each cluster receives one of the following tags:

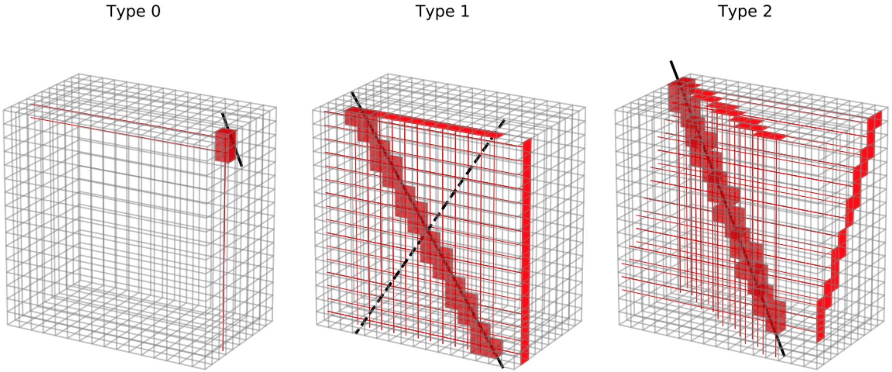
  1. Muon (track of high amplitude cubes);
  2. NS (a single cube, defined by the dedicated trigger);
  3. ES (subset of the cubes in the plane, provided by e^+ and γ);

  $\Longrightarrow$ the most involved case, requires specific reconstruction strategy;

- NS and ES clusters within appropriate ΔT are forming a coincidence.

Reconstruction basics

An example of three different types of muon tracks reconstructed in the SoLi∂ detector.



We will come back to them in few minutes!

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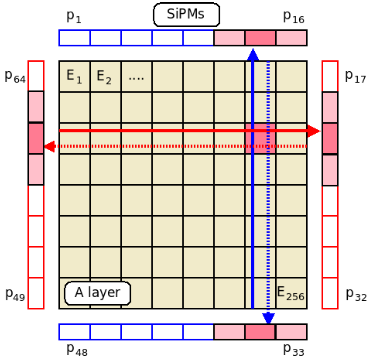
New reconstruction [CCube algorithm]

- The fibres project the deposited energies to the boundaries of the detector
- The digitised SiPM readout from the fibers are the raw detector data

  $\Longrightarrow$ Reverse engineering is required to restore the list of involved cubes

- Each layer is a *separate* problem
- Parametrisation:
  - Unknowns: PVT deposits (E_i)
  - p_j are the SiPM measurements
- Challenges:
  - Cube projects through adjacent fibers
  - Fibers can overflow during the run



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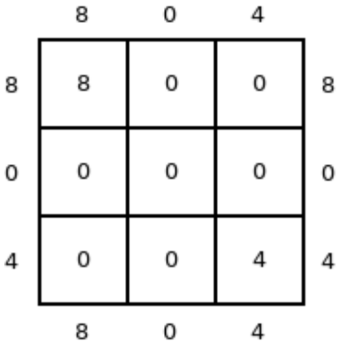

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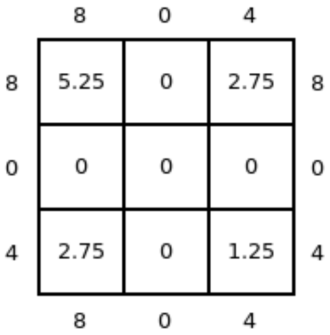


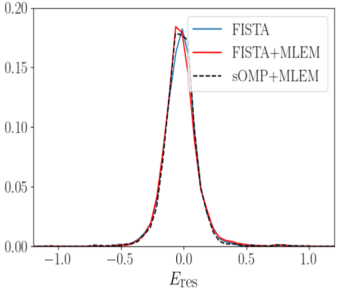
New reconstruction [CCube algorithm]

The reconstruction problem can be put down as follows:

$$p = AE,$$

where A is the so-called system matrix (SM) that embodies the overall response of the detector. This equation has been widely studied in medical imaging and particle physics.

- Several approaches have been tested:
  - The ∇-based regularisation approach[1]
  - The initializer-dependent Bayesian approach[2]
  - Fibers w/ more light should be preferred to form a cube $\rightarrow$ Orthogonal Matched Pursuit[3]
- sOMP+ML-EM shows superior performance:
  - For the reconstruction efficiency
  - For the fake cubes (👻) rate
  - Similar energy resolution = 13%



Method	FISTA[1]	FISTA+ML-EM[2]	sOMP[3]+ML-EM
👻 (%)	15.8	11.4	6.9
ϵ (%)	75.3	76.3	77.7

ES calibration overview

- **Calibration w/ horizontal muons:**
  - Relative calibration
    - Higher precision
  - Access to the Light Leakages
  - Time evolution of the response
  - Absolute scale calibration(?)
    - dE/dx values

- **Calibration w/ radioactive sources:**
  - Relative calibration
  - Time evolution of the response
    - Calibration campaigns required
  - Absolute scale calibration:
    - ^{22}Na: developed, low energy range
    - AmBe: TBD, desired energy range

SoLi∂

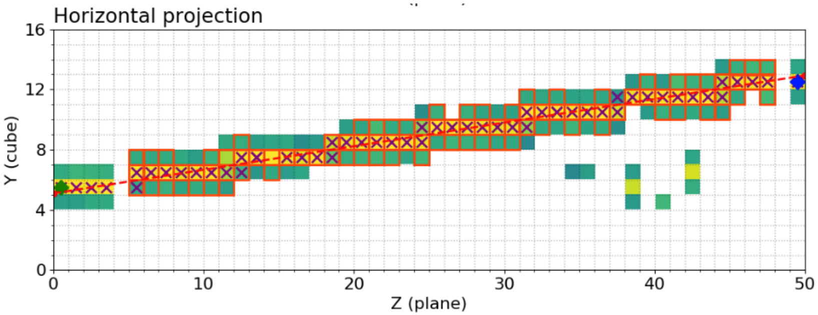
- **Crosschecks:**
  - Identification of the well-known sources of the bckg
    - Cosmogenic (^{12}B, etc.)

- **Crosschecks:**
  - Validation with natural radiation source (^{214}Bi)
  - Data/MC comparison

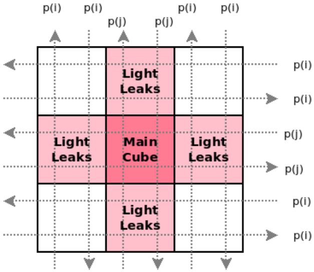
Relative calibration with horizontal muons

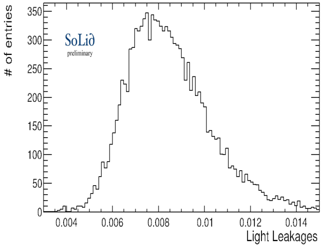
- Horizontal muons [crossing 1 cube/plane] compose powerful calibration tool;
- Allow to perform the per fibre relative calibration of the whole detector;
- Give an access to the measurement of the light leakages to the neighbouring cubes;
- Provide the *ballpark for the absolute energy scale* calibration

  $\Longrightarrow$ To be compared and checked with the calibration sources;
- Control the time evolution of the detector response.



Relative calibration with horizontal muons





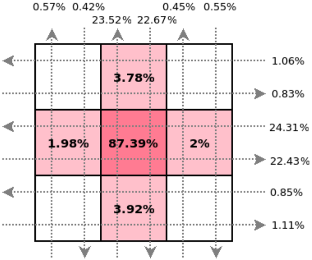
- 1 crossed cube per plane ⇒ clear posed problem;
- >1 impacted cube per plane ⇒ access to the LL!
- Total energy in the plane as a proxy to μ deposit;
- For the hit and adjacent cubes fibers (12 in grand total) define the fractions:

$$f = \frac{E_{\mathrm{fibre}}}{E_{\mathrm{plane}}}$$

- Describe the light sharing characteristics;
- Constitutes the initial SM elements values;

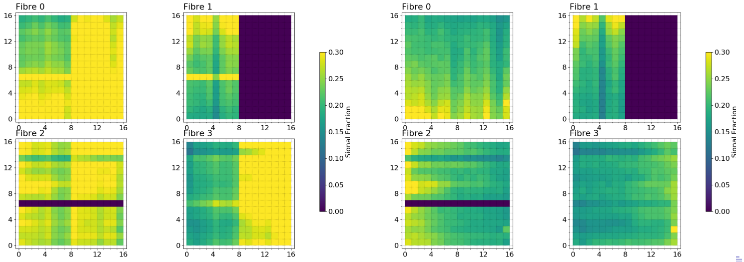
⟸ Top: an illustration of the light sharing for the hit cube in the muon track (1 main + 4 LL = 12 fibres in total). Bottom: An example of the LL distribution for one of the 8 neighboring fibres.

Relative calibration with horizontal muons



- E_{plane} as a proxy to the muon deposit $\Rightarrow$ dE;
- Muon track info as a proxy to the path length $\Rightarrow$ dx;
- $\frac{dE}{dx}$ distribution per hit cube is built [1];
- An average detector $\frac{dE}{dx}$ distribution is built [2];
- The SM elements are scaled by $\frac{[2]}{[1]}$ $\Longrightarrow$ Response homogenisation. Relative calibration is done!

An example of homogenisation procedure impact.

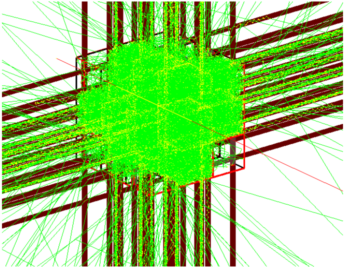


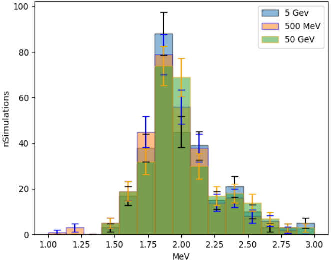
Absolute energy scale calibration

- Split relative and absolute calibrations is a feature of the muon calibration ⇒ various inputs can be used as an absolute energy scale*
  * also known as Light Yield (LY);
- Available options are the following:
  - From muons: $\frac{dE}{dx}$ value from Geant4 MC simulation or from PDG
    $\Longrightarrow$ Disadvantages: high region of the energy spectrum
  - From ^{22}Na: 1.06 MeV CE. Method developed and crosschecked
    $\Longrightarrow$ Disadvantages: low region of the energy spectrum
  - From AmBe: 4.2 MeV CE. At the heart of the desired energy spectrum. Similar to ^{22}Na techniques can be employed.
- The differences b/w possible choices are currently under investigation

Absolute calibration w/ horizontal muons

- Merge the $\frac{dE}{dx}$ distribution in all cubes from the:
  - Geant4 simulation (all the cubes have the same characteristics)
    $\Longrightarrow$ provides an expectation in MeV/cm;
  - ROff data (a single value is enough, since the relative calibration is done)
    $\Longrightarrow$ provides the data expectation in ADC/cm;
  - An alignment of the two provides the *currently used* absolute energy scale;
- Limitations:
  1. Precise energy spectrum of μ is required. Otherwise, precision is limited by 10%;
  2. Dedicated Geant4 study was performed to support this statement;



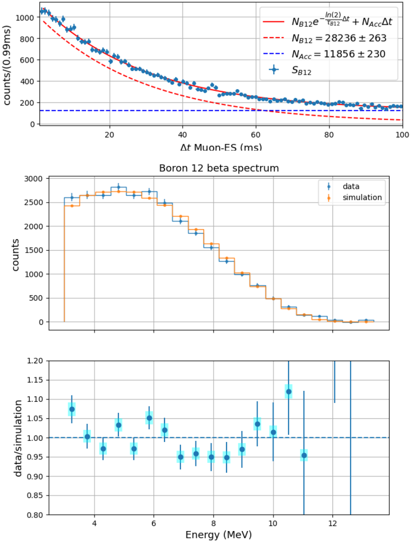


Crosschecks and validations [^{12}B]

- Cosmogenic bckg searches as a way to check the reconstruction and calibration:

$$\mu^- + {}^{12}\text{C} \rightarrow \bar{\nu_\mu} + {}^{12}\text{B} \rightarrow \beta^-$$

- Executed by S. Gallego from LPC Caen;
- Statistics for 100 ROff days is employed;
- ΔT(Muon-ES) is fit to determine the yield;
- sPlot technique is used to statistically subtract the background (ΔT as a discriminative variable) ⇒ access to E spectrum;
- It matches the Geant4 prediction!
- Was not the case w/ former machinery.



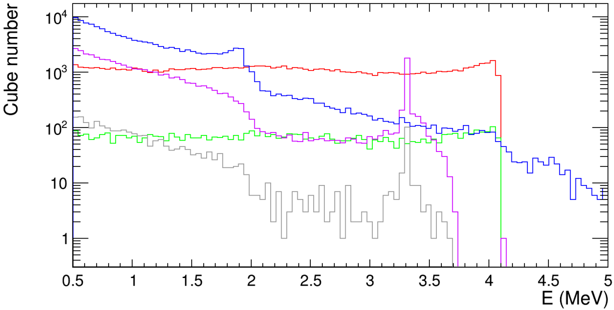
Absolute calibration w/ sources. AmBe

- AmBe as an additional ES calibration source (in 60% of the cases)!

$$^{241}Am \rightarrow \alpha + {}^{237}Np \,;\, \alpha + {}^{9}Be \rightarrow n + {}^{12}C^{*} \rightarrow {}^{12}C + \gamma \text{ (4.438 MeV)}$$

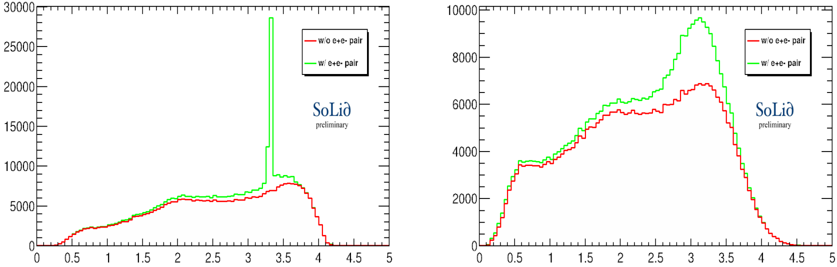
The n has enough energy to create $^{12}C^{*}$ from the interaction with detector materials!

- More energetic sources are providing a promising alternative to CE;
- 3.4 MeV $e^{+}e^{-}$ pair as mono-energetic calibration tool!
- The typical energy is right in the middle of the region of interest;
- e^{+} is correlated to the n signal and provides 2 annihilation $\gamma \implies$ IBD-like signature!



Absolute calibration w/ sources. AmBe

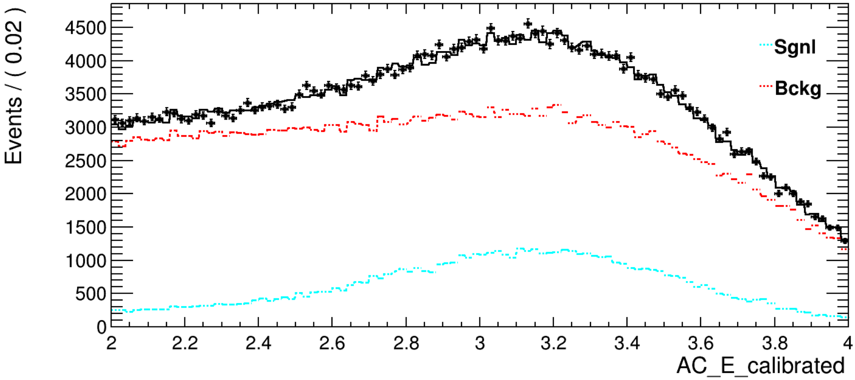
- Similar to ^{22}Na strategy, unless the presence of the background (2 templates required);
- Signal definition:
    1. The cube w/ the largest energy as the proxy for the e^+e^- pair creation position;
    2. $3 \times 3 \times 3$ envelope around it required to be empty;
    3. Two ES clusters to be present outside of the envelope (different hemispheres);
    4. Low ($\leqslant 5$) cube multiplicity;
- Resulting distribution for signal and background $\Rightarrow$ bumpy behaviour in the signal region.



The stacked distributions of the most energetic cubes energy in Topology 20 for the Geant4 (left) and ROSim (right) levels.

Absolute calibration w/ sources. AmBe

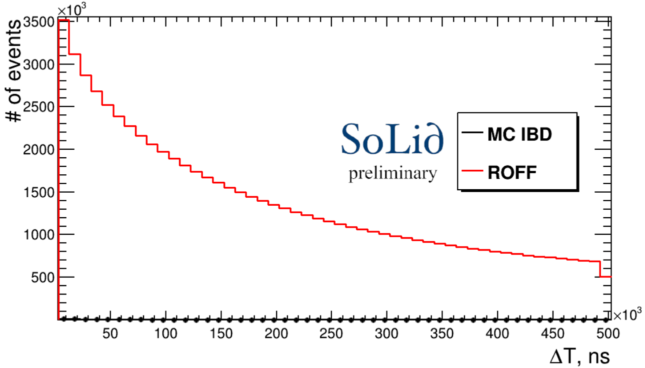
- A systematic scrutiny is ongoing and more sources of errors are going to be checked;
- The best parameter pair preferred by the fit is (0.962, 20.9%).



An example of the unbinned event-by-event ML fit to the calibration data. An obtained parameter pair is (0.962, 20.9%).

IBD analysis

Ratio of signal and background events as a function of the ΔT in the raw data sets.



- Comparison of the raw signal to background rates reveals overwhelming level of latter;
- Extensive use of the electromagnetic part of the signal physics properties is in order;
- *E.g.* Selecting geometrical properties of the signal events according to their EM features;
- Complex* patterns implies more discriminative power; *reconstruction of both ann γ.

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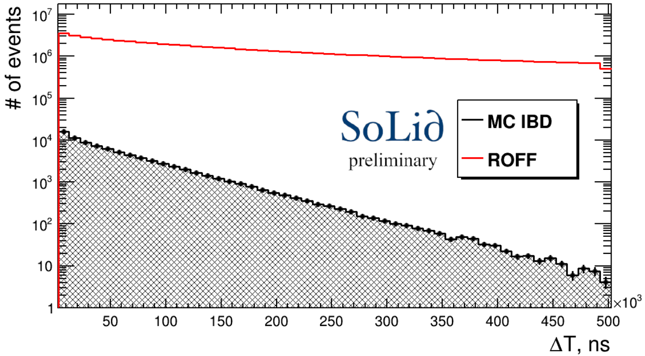

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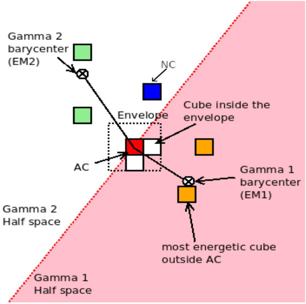
Signal definition



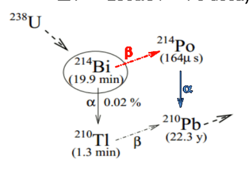
- The signal definition of the current analysis is based on the topological properties of the ES
- The detector output is converted into a list of cubes
- The possible cubes of interest
  1. The cube where e^+ annihilated [AC]
  2. The cube where n was captured [NC]
  3. [If applicable] The clusters corresponding to the e^+ annihilation gammas [EM1, EM2]
- The positron and γ deposits can be distinguished to remove the backgrounds (granularity of the detector is used maximally)

Envelope condition	**0γ**	**1γ**	**1γ***	**2γ**	**2γ***	**2γ****
Only AC	Topo00	Topo10	Topo13	**Topo20**	**Topo23**	**Topo25**
AC & 1 cube	Topo01	Topo11	Topo14	**Topo21**	**Topo24**	
AC & 1+ cubes	Topo02	Topo12		Topo22		

The definition of the topologies, including the case where the γ deposit is found inside the envelope (tagged with *)

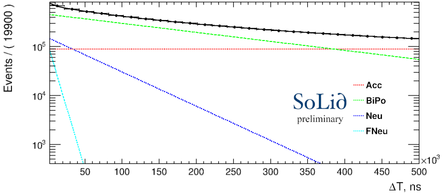
Identification of the background

- *Natural radiation [BiPo decay chain]*
  - delayed signal: α decay
  - prompt signal: β decay
  - $\Delta T \sim 236 \mu s$ [^{214}Po decay time]



- *Cosmogenic background*
  - delayed signal: fast or spallation neutrons
  - prompt signal: proton recoils or β decays
  - $\Delta T \sim 60 \mu s$ [the same as for the signal]
- *Accidental background*
  - No time or space correlation

- With the fit of the ΔT distribution we can estimate the contamination of the background sample by the different sources
- The specific selection for each source can help in the further background rejection:
  - The $\alpha - n$ shape discrimination
  - ΔT [BiPo] and ΔR values [Cosm]
  - The FPNT sample [Acc]
  - ***Enriched samples are devised***



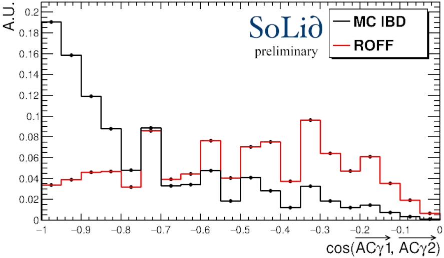
The ΔT fit of ROff Topo10 sample performed with [1]

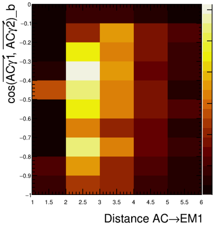
$$\Delta T = N_{\mathrm{acc}} + N_{\mathrm{fast}} \cdot e^{-\frac{\Delta T}{8.5\ \mu s}} + N_{\mathrm{atm}} \cdot e^{-\frac{\Delta T}{62\ \mu s}} + N_{\mathrm{BiPo}} \cdot e^{-\frac{\Delta T}{235.8\ \mu s}} \qquad [1]$$

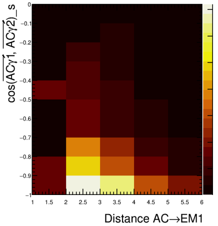
Discriminative variables

- Additional features to further suppress background;
- "Back-to-backness" of annihilation γ as the main signature;
- Some variables are discriminative *per se*;
- Another bring additional info through correlations;
- Hence we need a tool to use it

  $\Longrightarrow$ multivariate analysis!







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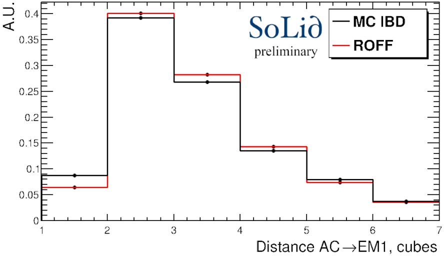
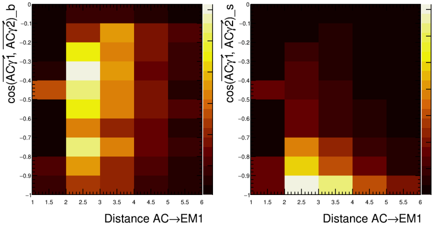
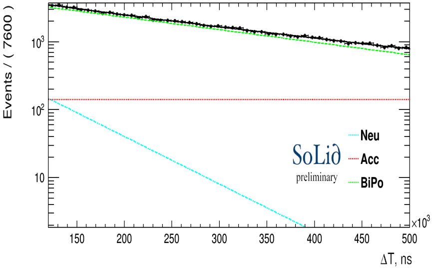
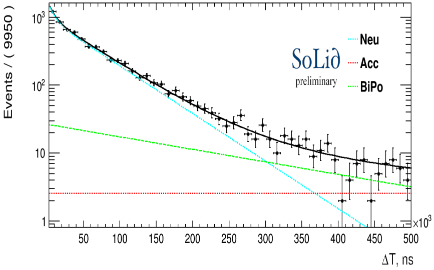




Enriched samples

ΔT fits for the BiPo (left) and Atm (right) enriched samples.





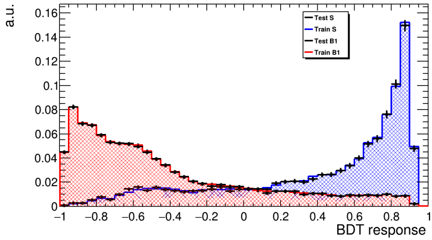
- Selected w/ PSD variable and T;
- Equivalent cuts for all topologies;
- Enormous statistics + 90% purity;
- Validated with MC;

- Selected w/ PSD variable and E_{AC};
- Cuts tuned per individual topology;
- Very poor statistics + 90% purity;
- No MC available;

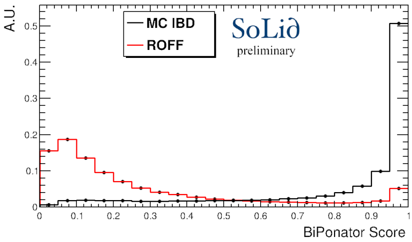
Both are employed in the multivariate analysis training.

The multivariate tools

- Multivariate analyses can tackle the high level of background
- There are three tools. Trained against:
    1. BiPo [based on the EM features]
    2. Atm [based on the same EM features]
    3. Atm [based on geometrical features]
- 10-fold cross-validation is applied (to use the full ROff statistics). Overtraining checked.



- 5D optimisation:
    - 3 BDT scores
    - ΔT and BiPonator cut
    - Fixed cut $E_{AC} > 1.5$ MeV
    - Aimed at the signal significance maximization ($S/\sqrt{S+B}$)
- Four cuts are applied at this stage w/o geometrical BDT score and the ΔT. The ΔT and the ΔR variables are used for the further signal and background discrimination
- Partly optimized 2γ B/S = 2 ($\sim$ 30 $\bar{\nu}$/d)

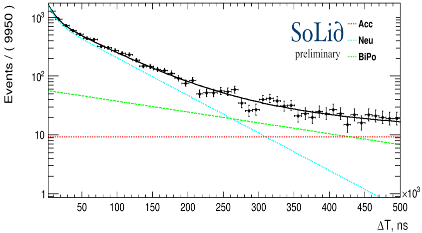


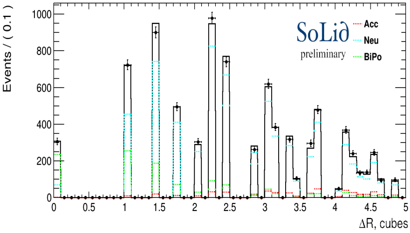
Simultaneous fit technique

- The tool is required to distinguish the remaining background. Solely ΔT can not do it;
- The signal events are sharing the same moderation time with the atmospheric background;

$\Longrightarrow$ Additional discrimination is required. The ΔR variable can fit this demand

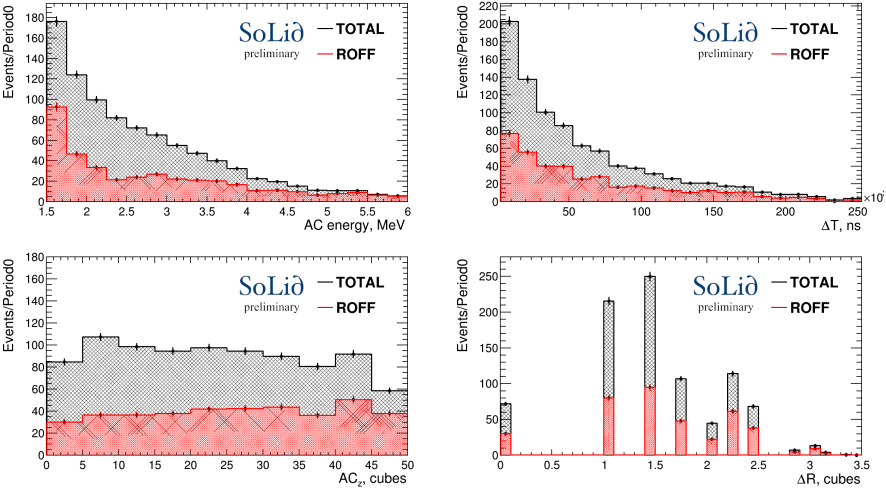
- The p.d.f. for the simultaneous unbinned ML fit are derived from dedicated samples:
  - MC IBD [Signal]
  - Enriched samples: optimized [Acc, BiPo], preselected [Atm (lack of statistics)]
- The yields for each source directly measured from the simultaneous fit





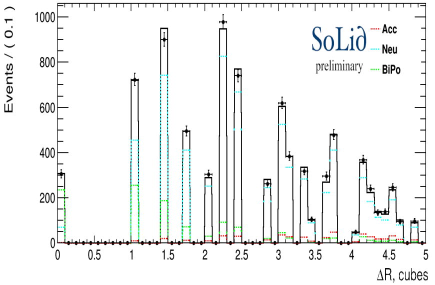
The simultaneous ΔT-ΔR fit for the optimised 2γ ROff sample

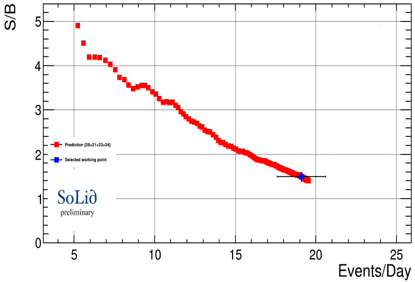
Predictions. Control plots

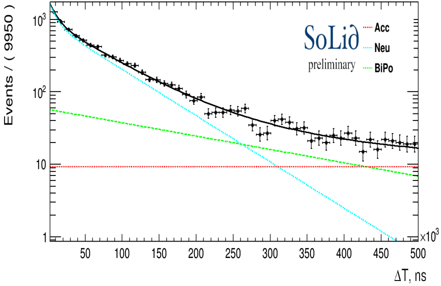


Predictions. Performance

- Optimized 2γ S/B = 1.5 (19.1 $\pm$ 1.3 $\pm$ 1.5 $\bar{\nu}$/d), where 1 number is 5D optimised MC predict, 2 number - statistical error and 3 - systematic;
- The blind topological analysis is concluded with the staged scrutiny of the 21 days open data set







Quick reminder

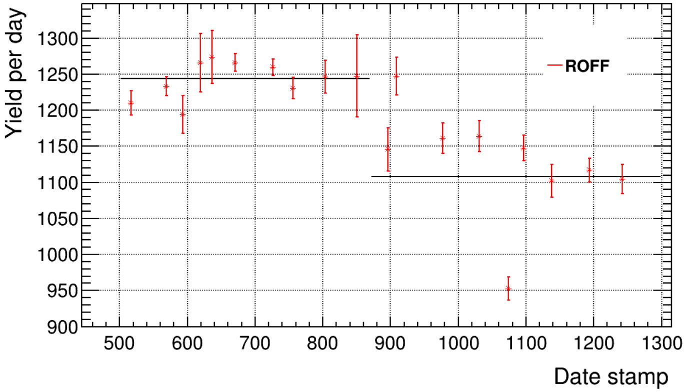
2) The unblinding steps

- For each ROn cycle, we have the two ROff periods [before b and after a]. They are used to provide predictions of the neutrino yield.
- Step 1: compare accidentals (ROn - ROffb) and (ROn - ROffa). Pass if the two results are agreeing within 2.5 standard deviations.
- Step 2: compare BiPo enriched yields (ROn - ROffb) and (ROn - ROffa). Pass if the two results are agreeing within 2.5 standard deviations.
- Step 3: Fit results on ROffa-b. Pass if 2.5 stat. agreement.
- Step 4: BLIND fit. Check the consistency with the background predictions while keeping the plots blinded. Pass if agreement within 2.5 standard deviations.
- Step 5: BLIND fit: GoF: binned χ^2 test . Pass if χ^2 / d.o.f. < 1.6.

Quick reminder

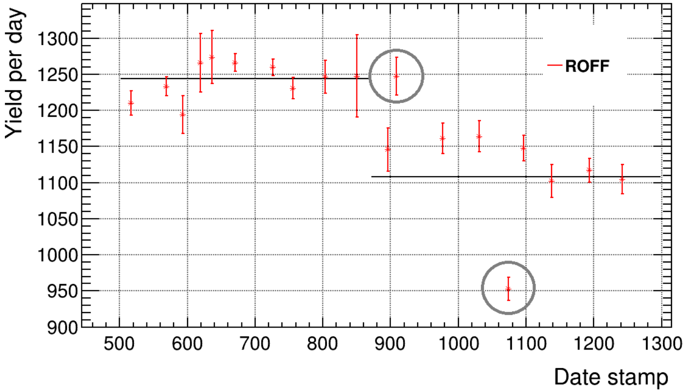
- Over time and acquired understanding the steps have slightly changed;
- The ROff data are addressed in the more general way:
  - BiPo and FPNT components have to agree within 2.5σ over PhaseI;
  - Atm part can only be addressed in terms of pressure anti-correlation;
- ROn background composition requirements remained almost the same:
  - BiPo component has to agree within 2.5σ wrt ROff over PhaseI;
  - FPNT component is compared for [ROn - ROffb] and [ROn - ROffa], due to increase for the reactor on cycles. It has to agree within 2.5σ;
- Once the background composition consistency is verified the control plots are considered. The comparison has to be kept blind with solely goodness of fit being verified. Test is passed if χ^2/d.o.f < 1.64;
- The final step consists of $\Delta T - \Delta R$ fit signal and bckg yields comparison.

ROff composition scrutiny. BiPo rate.



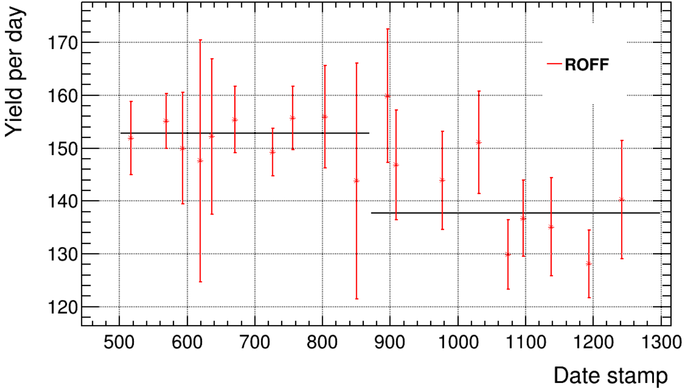
- The BiPo yields in the BiPo enriched samples for Topology 30 (gathered 2γ, only statistical uncertainty) representation. Each point is obtained from the per-cycle ΔT fit;
- Each yield is normalised per day according to the data-taking time;

ROff composition scrutiny. BiPo rate.



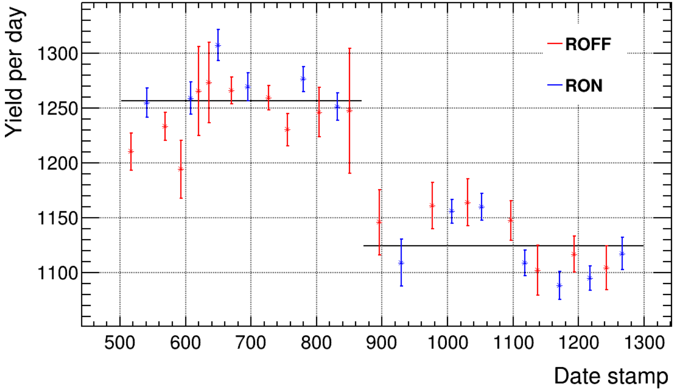
- 2 operating modes $\implies$ chronologically consistent with the chiller issue;
- Are there consequences for the discriminative variables inputs?
- 2 departing periods (12, 15) $\implies$ differences for the ΔT and ΔR shapes?

ROff composition scrutiny. FPNT rate.



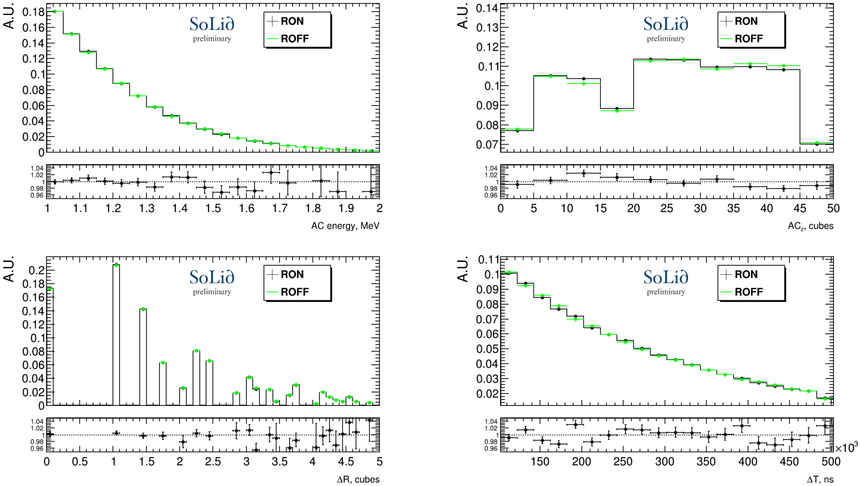
- Normalised FPNT rates from the preselected Topology 30 ΔT fits;
- Same 2 operation modes are present, no statistically significant outliers;
- Is there an additional information to extract from accidentals?

ROn background composition. BiPo rates.



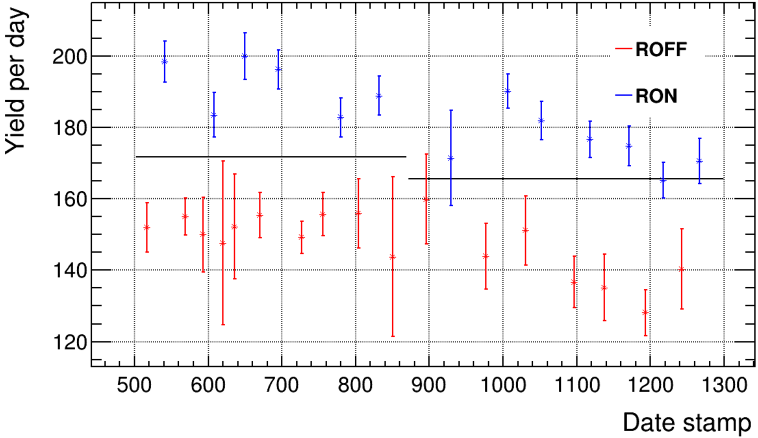
- Normalised BiPo rate from the BiPo enriched Topology 30 ΔT fits;
- ROff P12, 15 excluded; All periods are in agreement $\implies$ BiPo is stable!

ROn background composition. BiPo shapes.



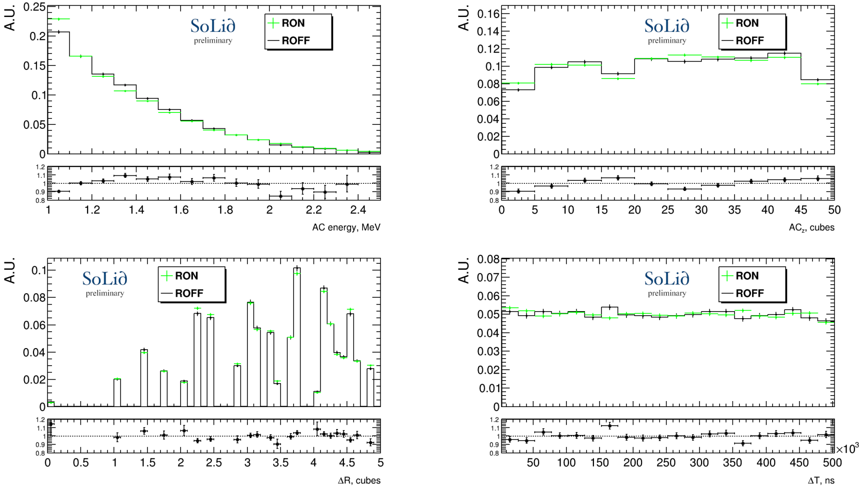
- BiPo enriched, Topology 30, all PhaseI cycles, FPNT subtracted;
- All shapes are in 5% agreement.

ROn background composition. FPNT rates.



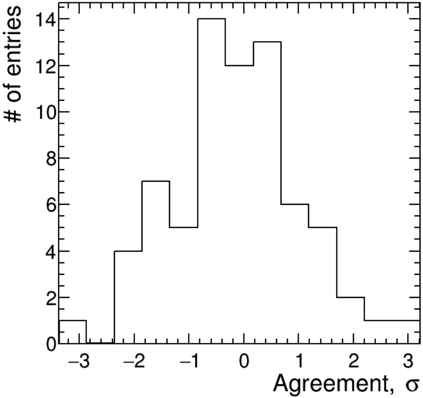
- Normalised FPNT rates from the preselected Topology 30 ΔT fits;
- As expected, ROn yield is higher $\implies$ reactor power correlation?

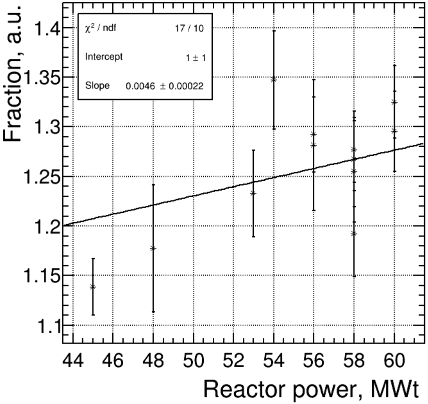
ROn background composition. FPNT shapes.



- FPNT sample, Topology 30, all PhaseI cycles, FPNT subtracted;
- All shapes are in 10% agreement.

ROn background composition. FPNT stability.



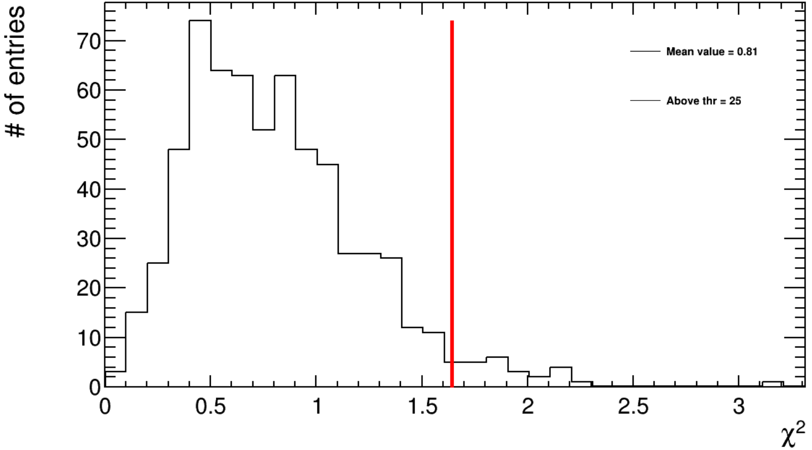


- The relative FPNT increase is consistent along the Phase I;
- An amount of extra FPNTs is correlated with the reactor power.

Control plots. Quick reminder.

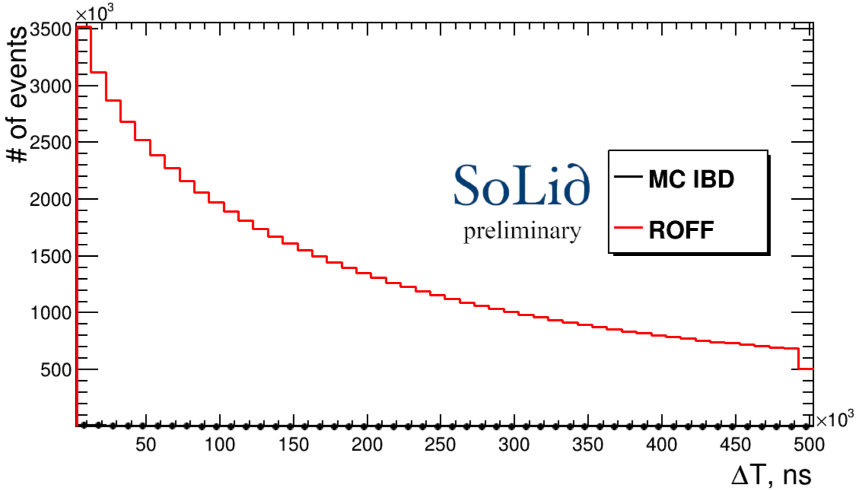
- The control variables were originally selected from the variables that do not participate in the MVA with an intention to test the combined prediction of MC IBD + ROff to the ROn shape-wise, which complemets the yield comparison provided by the simultaneous ΔT-ΔR fit;
- The control variables include: ΔT, ΔR, BiPonator and BDT_{ATM2} scores;
- E_{AC}, $\bar{\nu}$ energy estimator and AC_Z are also interesting, but contain physics;
- They can be kept for control plots and χ^2 tests for the individual ROn periods in which physics is hidden by statistics. However, they will be removed as soon as we will move to the samples with larger statistics.

Control plots. χ^2 test. Result.



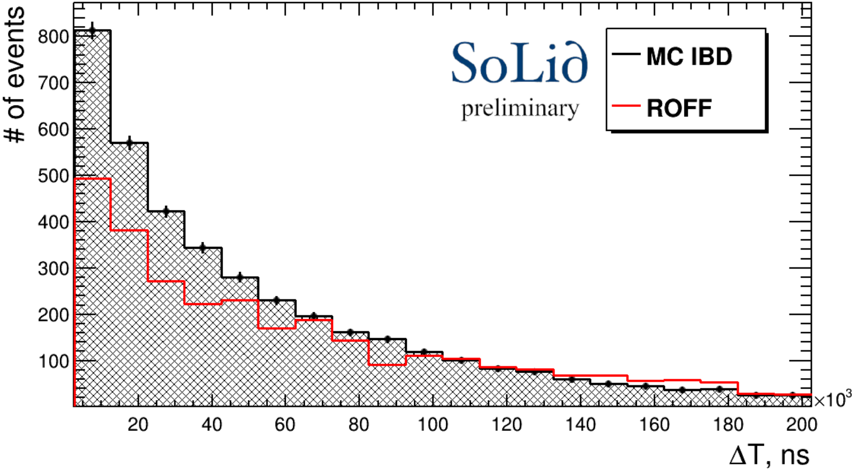
- The total number of plots above the threshold is statistically affordable;
- They are evenly split along topologies, variables and periods.

Initial conditions. Reminder.



Ratio of signal and background events as a function of the ΔT in the raw data sets.

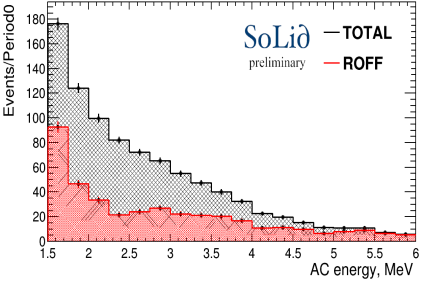
Final conditions.

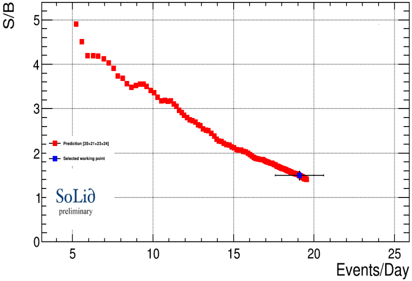


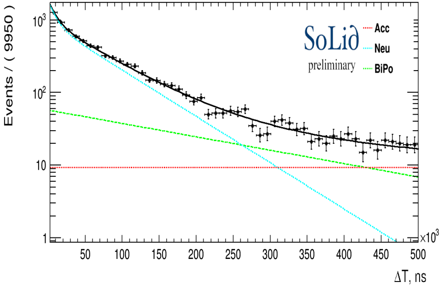
Ratio of signal and background events as a function of the ΔT in the 5D optimised data sets.

Predictions. Summary

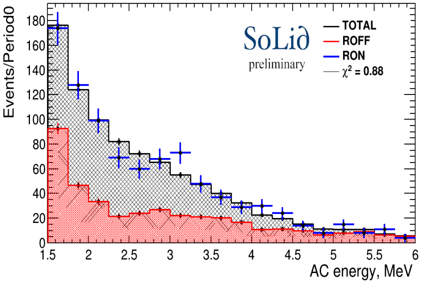
- Optimized 2γ S/B = 1.5 ($19.1 \pm 1.3 \pm 1.5$ $\bar{\nu}$/d), where 1st number is 5D optimised MC predict, 2nd number - statistical unc. and 3rd - systematic unc.;
- The blind topological analysis is concluded with the staged scrutiny of the 21 days open data set

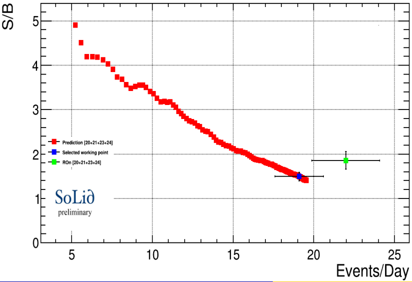


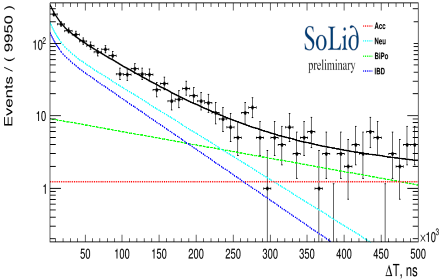




- Optimized 2γ S/B = 1.5 (19.1 $\pm$ 1.3 $\pm$ 1.5 $\bar{\nu}$/d)
- Optimized 2γ S/B = 1.8 (21.9 $\pm$ 2.1 $\pm$ 1.5 $\bar{\nu}$/d)
- The blind topological analysis is concluded with the staged scrutiny of the 21 days open data set

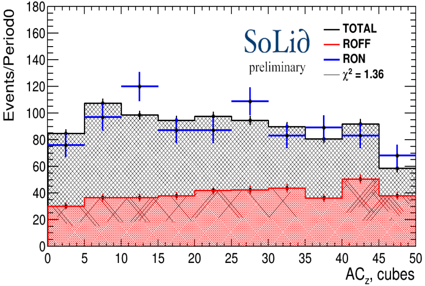


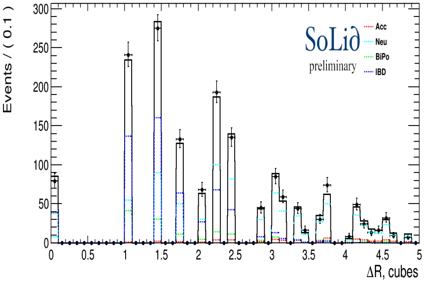


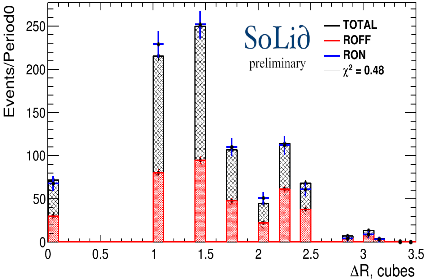


Analysis of the open data set

- Optimized 2γ S/B = 1.5 (19.1 $\pm$ 1.3 $\pm$ 1.5 $\bar{\nu}$/d)
- Optimized 2γ S/B = 1.8 (21.9 $\pm$ 2.1 $\pm$ 1.5 $\bar{\nu}$/d)
- The blind topological analysis is concluded with the staged scrutiny of the 21 days open data set







Summary

- Analysis developed to maximally use the granularity of the detector;
- Focusing on the most complicated topologies, a decent S/B is obtained;
- Novel reconstruction method introduced to project optimally the measured fiber energy into cubes (CCubes);
- PVT response calibrated by horizontal muons.

Work in progress and Outlook

- Absolute energy scale to be finalised;
- Full Phase I data to be analysed following the unblinding strategy;
- The CCube and calibration notes are in progress to be published shortly;

- Around 6k $\bar{\nu}$ are expected for SoLid Phase I (2 gamma) w/ a decent S/B;
- Sensitivity study to oscillation parameters has to be conducted;
- Antineutrino spectrum to be analysed.

BACKUP