

Status of the SoLid experiment

David HENAFF on behalf of SoLid collaboration

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SoLid



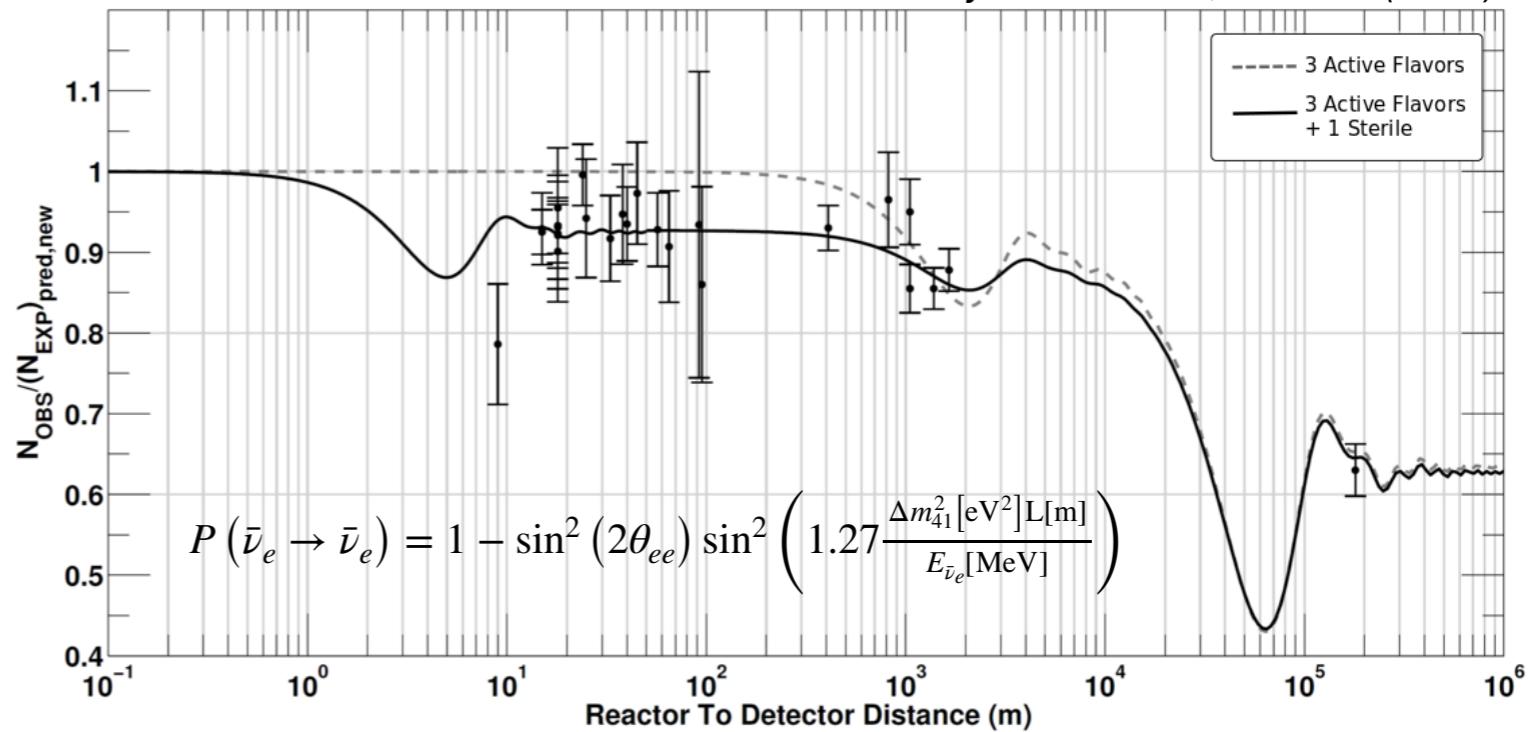
Motivations: Flux and energy anomaly

- Reactor Antineutrino Anomaly

- 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)

Phys. Rev. D 83, 073006 (2011)

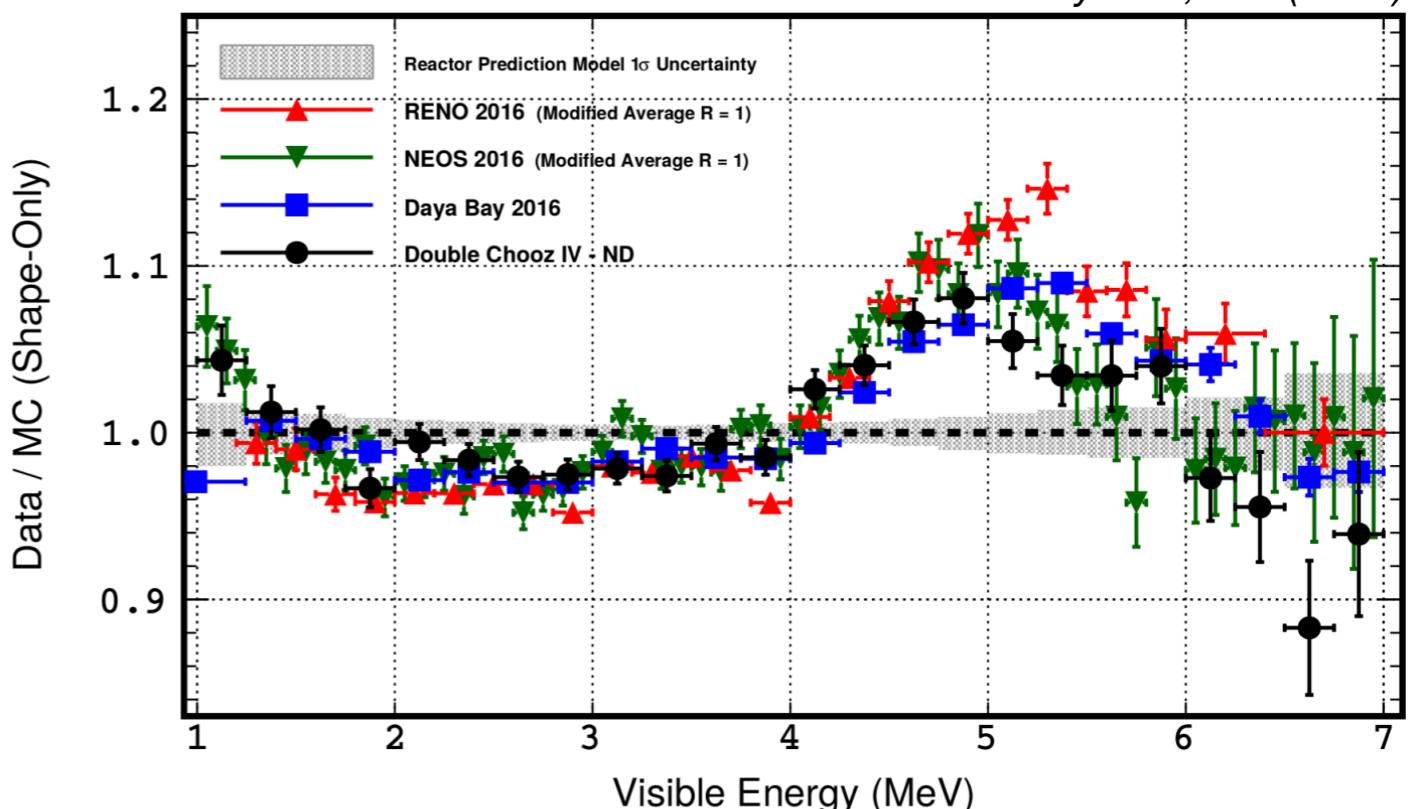


Nature Phys. 16, 558 (2020)

- Reactor antineutrino spectrum distortion (5 MeV bump)

- Among the four commercial reactor isotopes (235-U, 239-Pu, 238-U, 241-U) 235-U is thought as an interesting candidate to look for explanations.

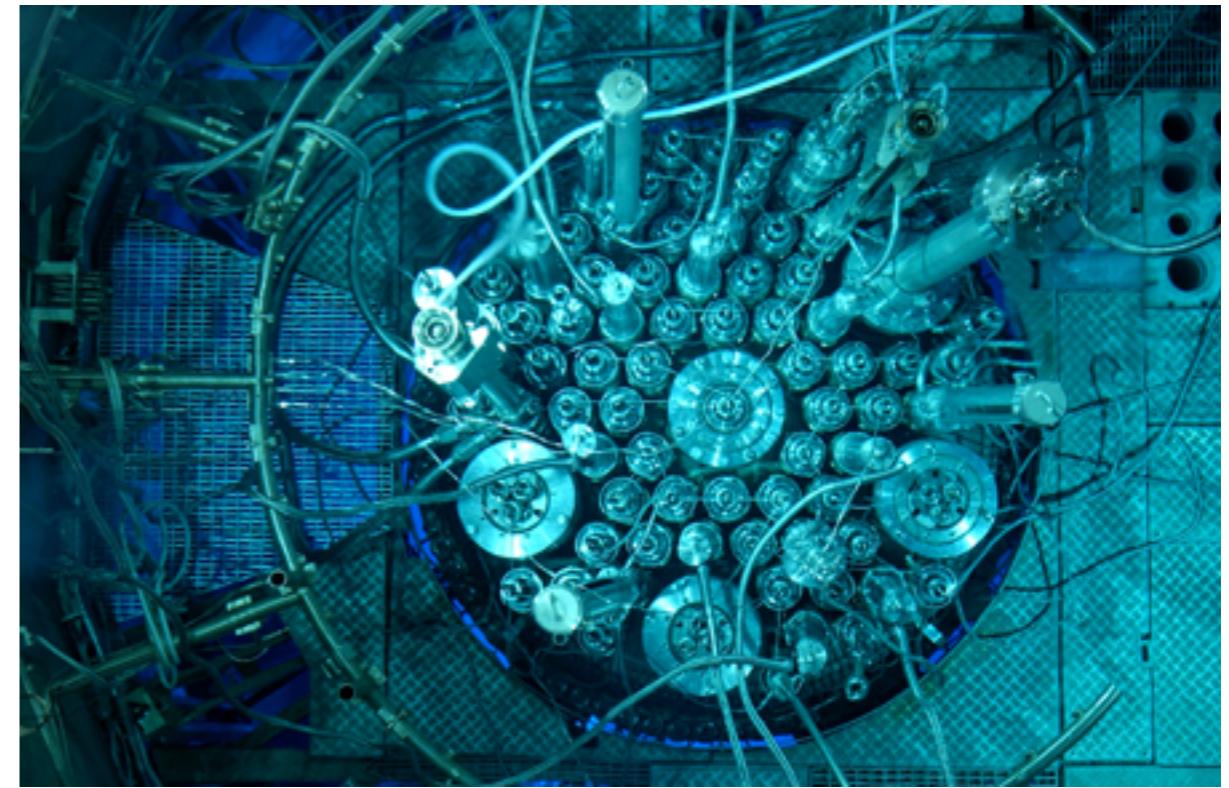
- [arXiv:1704.01082]



Experimental site

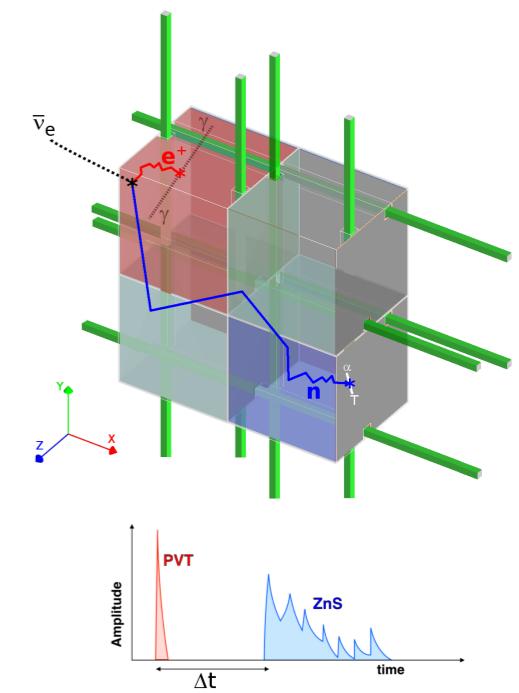
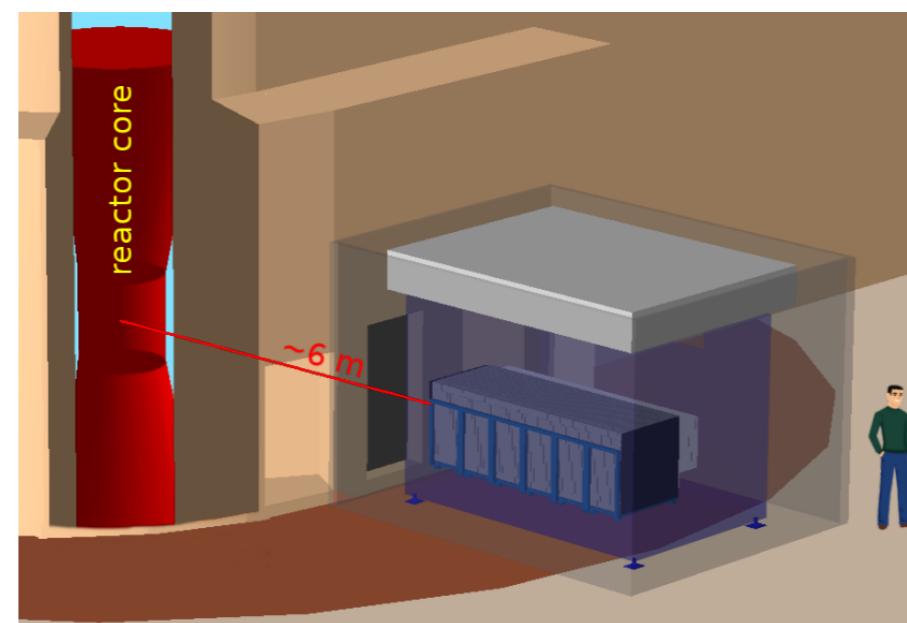
Research reactor BR2:

- Research reactor BR2 @ SCK-CEN, Belgium
- Highly enriched reactor with 235-U (>93.5%)
- Compact core ~ 50 cm
- Detector between 6 - 9m of the core.
- Low gamma and neutron background from reactor.
- Low overburden ~ 6-8 m.w.e.
- Important cosmic induced background
- Key challenge that guided SoLid's design



Detector main features:

- PVT as target coupled to ZnS mineral scintillator
 - ✓ Linear energy response
 - ✓ Highly segmented
- Price to pay: Understand a complex detector.

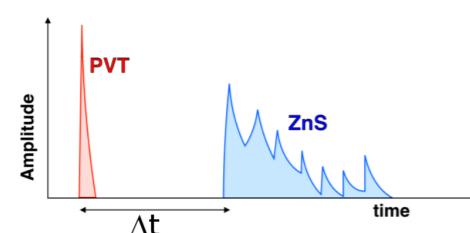
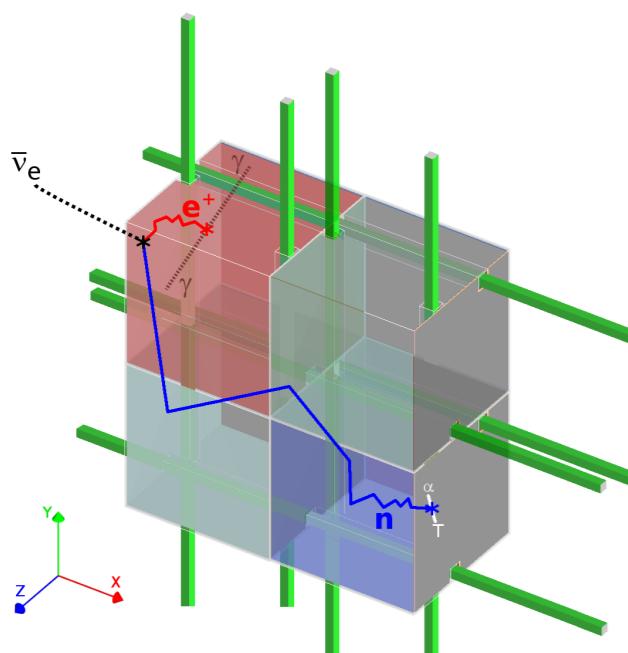
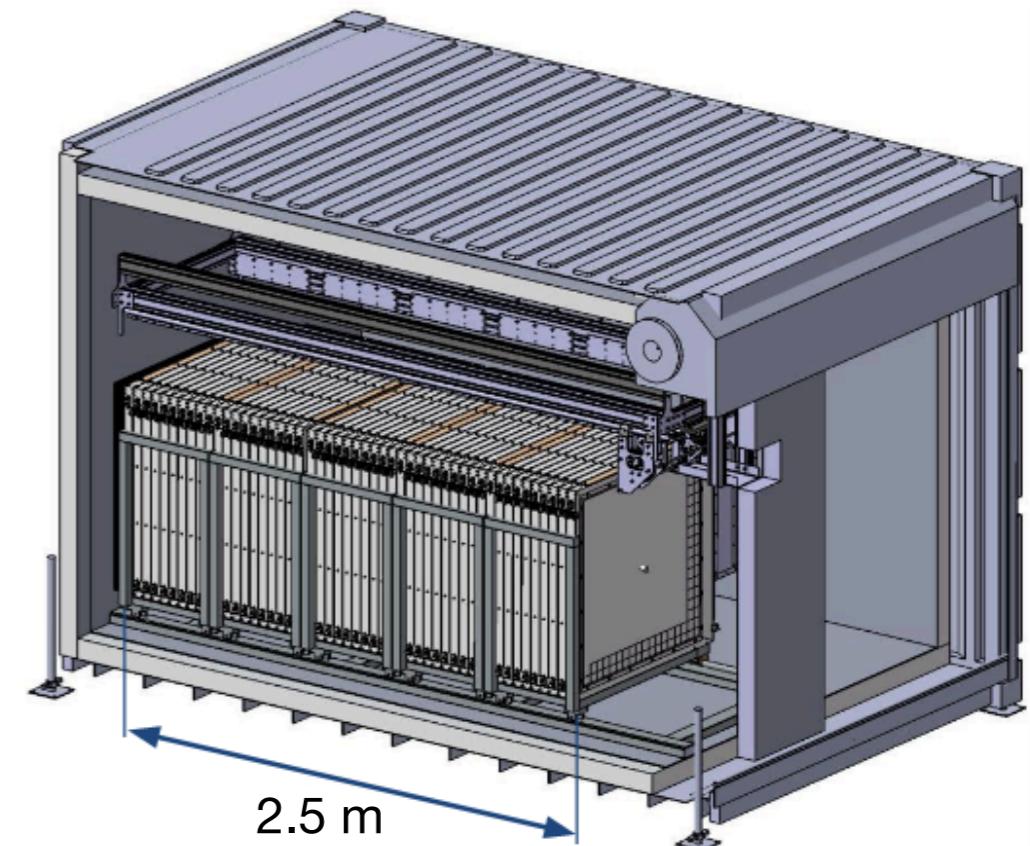


Taking physics data since spring 2018

Detector and measurement principle

Target: 12,800 cubes arranged in 50 frames of 16x16 cubes.

- SoLid's cube
 - ▶ Combination of **two scintillators**: PVT cubes of $5 \times 5 \times 5 \text{ cm}^3$ with $2 \text{ } ^6\text{LiF:ZnS}$ screens for neutron capture.
- Scintillation photons captured by 3,200 WLS fibres and read-out by MPPCs.
- Passive water bricks & polyethylene shielding to mitigate fast neutron background.



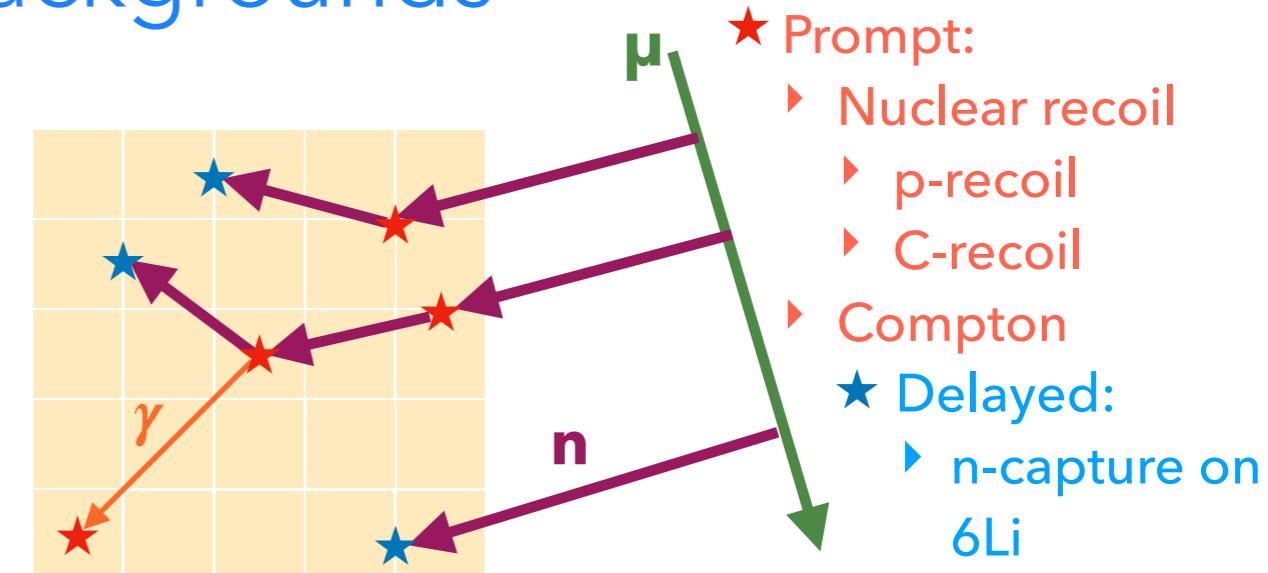
Signal: Inverse beta decay $\bar{\nu}_e + p \longrightarrow e^+ + n$

- We start by exploiting spatial and temporal coincidence between:
 - **Prompt (PVT signal)**: a positron carrying the neutrino energy
 - ▶ 2 Annihilation gammas with a mean free path of $\sim 10 \text{ cm}$
 - **Delayed (ZnS signal)**: a neutron interacting $\sim 64 \text{ us}$ after thermalisation captured:
 - $n + ^6\text{Li} \longrightarrow ^3\text{H} + \alpha$
- Expect in average 1,200 IBDs / day (cross-section x flux) interacting in the detector
- Beyond this criteria, thanks to the high segmentation, we can exploit the detailed topology of the prompt signals (Annihilation gammas)

Capital issue: Controlling two backgrounds

Cosmic induced:

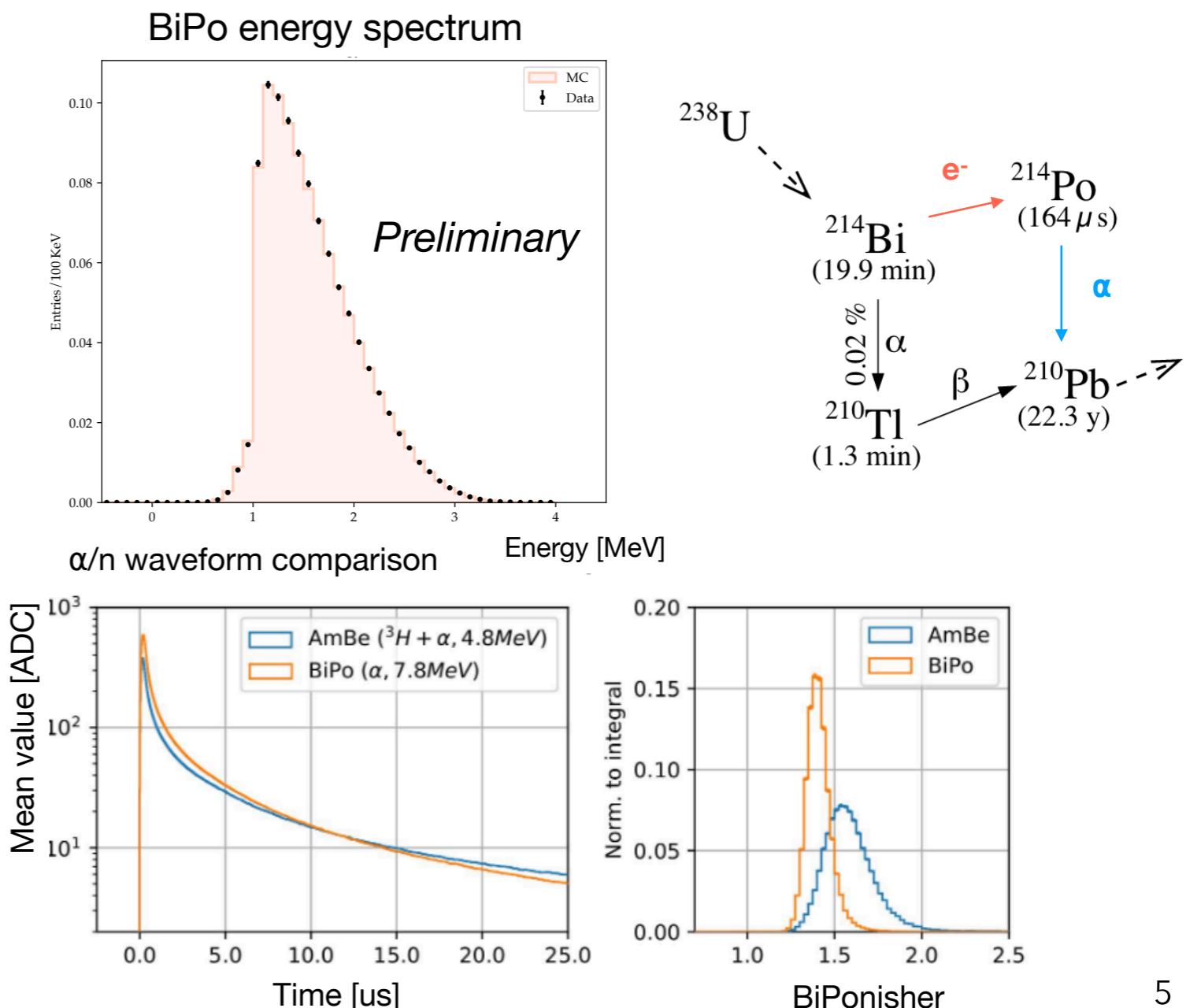
- Proton recoil mimic the prompt and delayed has the same features as IBDs
- Visible energy: all IBD energy spectrum.



BiPo:

- Unexpected and critical internal contamination of ZnS layer
 - Nearly 2 order of magnitude above IBDs before selection
- External pollution: Radon decay
- $\Delta T_{\text{prompt-delayed}} \sim 250 \text{ }\mu\text{s}$
- Beta decay mimic prompt
- Alpha decay mimic delayed
- **BiPonisher:** α/n discrimination using Pulse Shape Discrimination in ZnS scintillator

In both cases the space and time prompt-delayed distribution are close to IBDs.



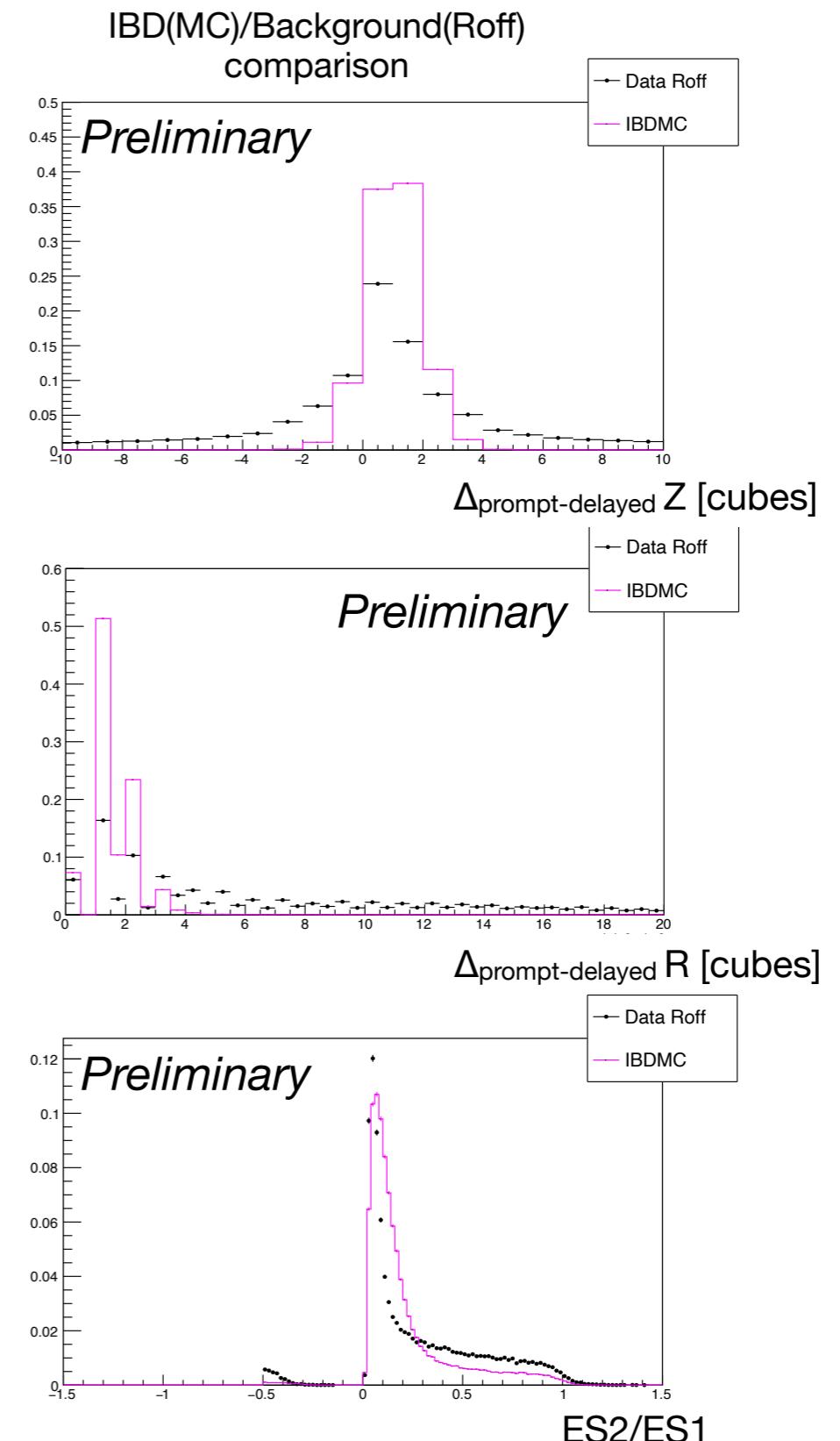
Basic selection: prompt vs delayed space & time coincidence

Reconstruction: Fit that find the list of cube positions and energies that minimise the Likelihood to measure the given set of fibres signal (> 200 keV)

Sequential cuts

Variables for the IBD selection:

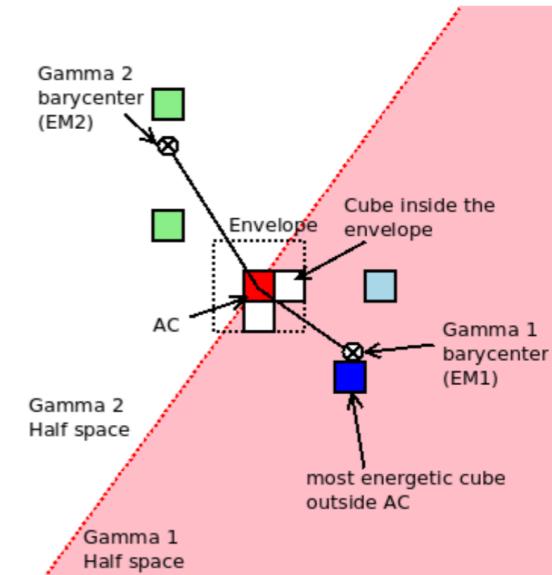
- E_{prompt} between [2,7] MeV
- $\Delta_{\text{prompt-delayed}} X, Y, Z, R$
- $\Delta_{\text{prompt-delayed}} T$
- ES2/ES1: Energy of the second most energetic cube over the energy of the most energetic cube
- BiPonisher



This way: reach ~ 110 neutrino/day and S/B = 0.06

Adding the topology information (annihilation gammas)

- **Low energy deposits and back-to-back behaviour.**
- Challenges:
 - ▶ Lower the fibre analysis threshold from 200 keV to 100 keV.
 - ▶ Implies to understand detector response in deep details.
 - ▶ Efficiency vs. Dark Counts rate with such low thresholds.



Annihilation gamma reconstruction: Two approaches have been used

- Split the detector in two hemispheres
- Tracking: Minimised the *likelihood* of cubes position according to X-sections.

New variables:

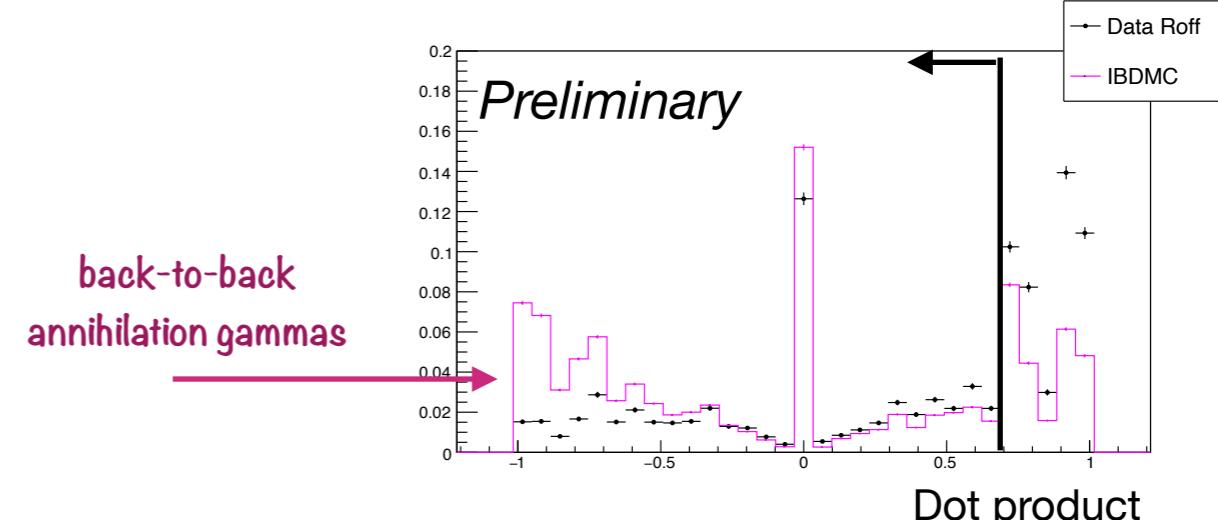
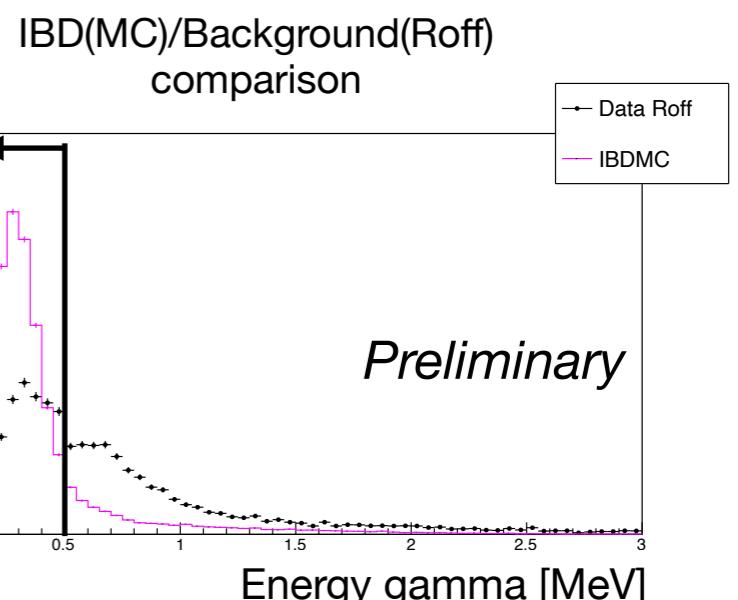
- E of gammas, angle between the two gammas, likelihood, distances to the most energetic cube etc...

Improved selection:

- Simple cuts are used by selecting annihilation gamma energy and back-to-back gammas.
 - $E_\gamma [0, 0.5] \text{ MeV}$
 - Dot product < 0.7

We improve the background rejection by roughly a factor 2

- ~ 92 neutrino/day and S/B = 0.1

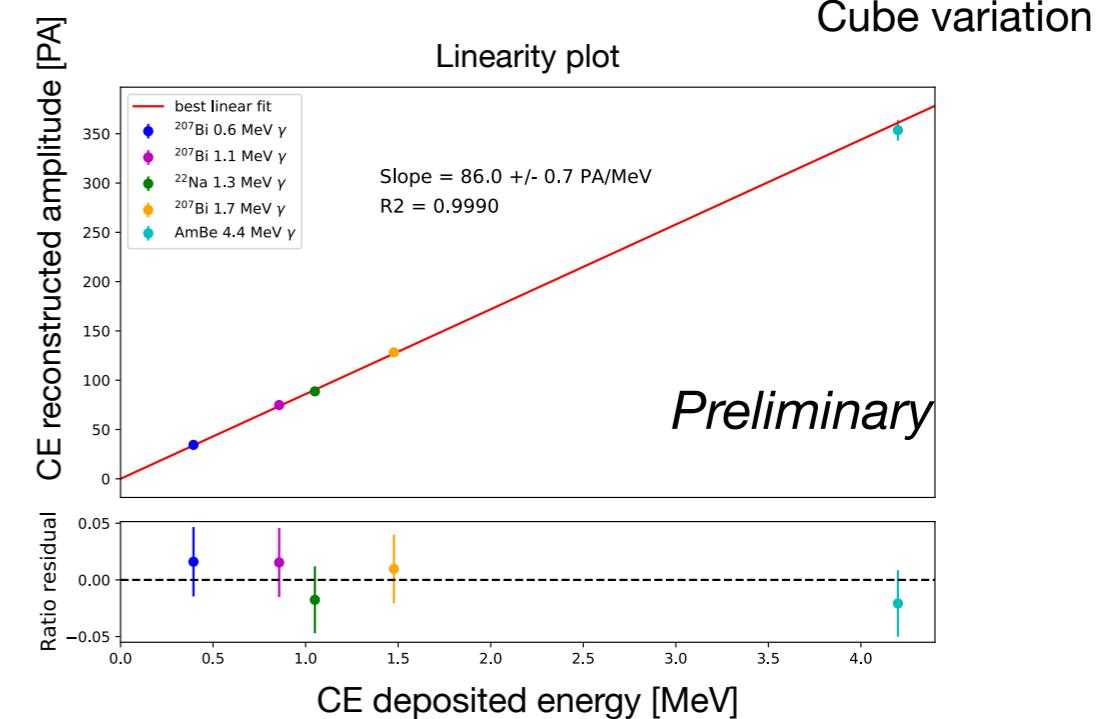
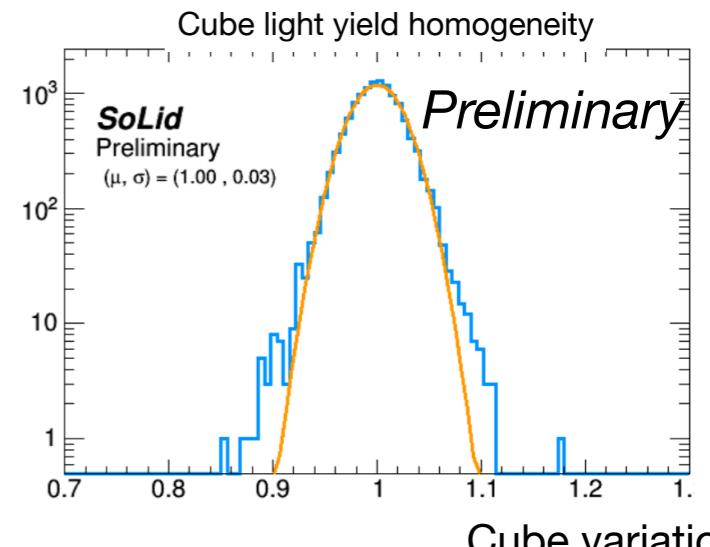


Detector response in a nutshell

For more details: talk given by Noe Roy (660)

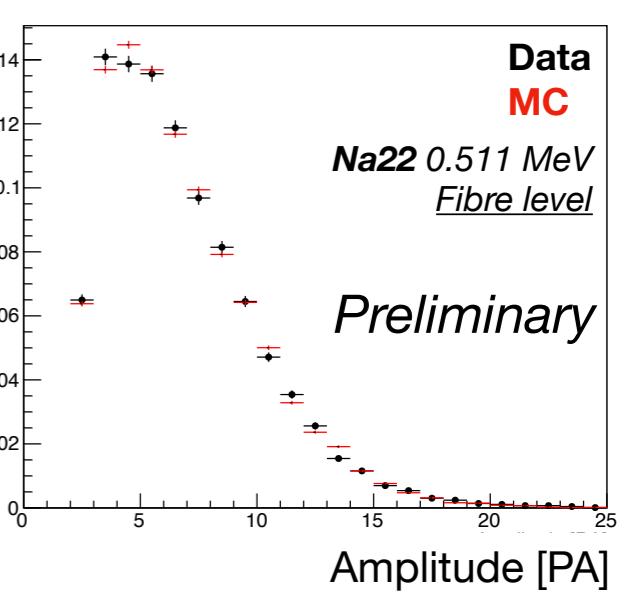
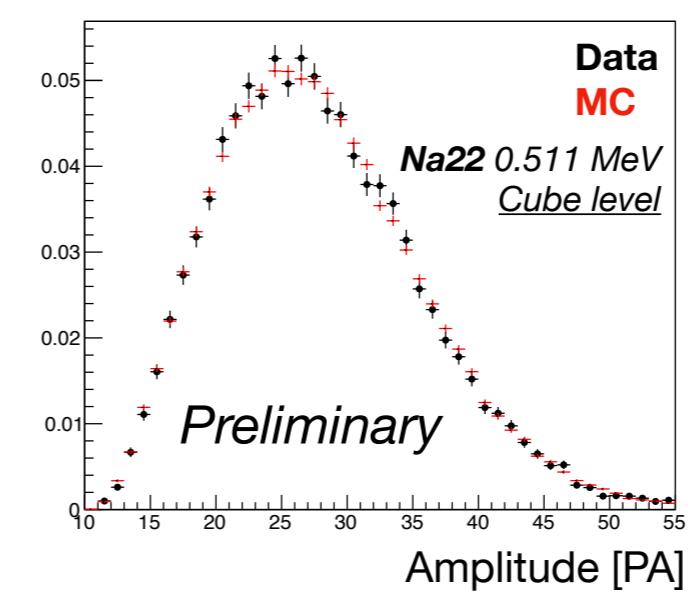
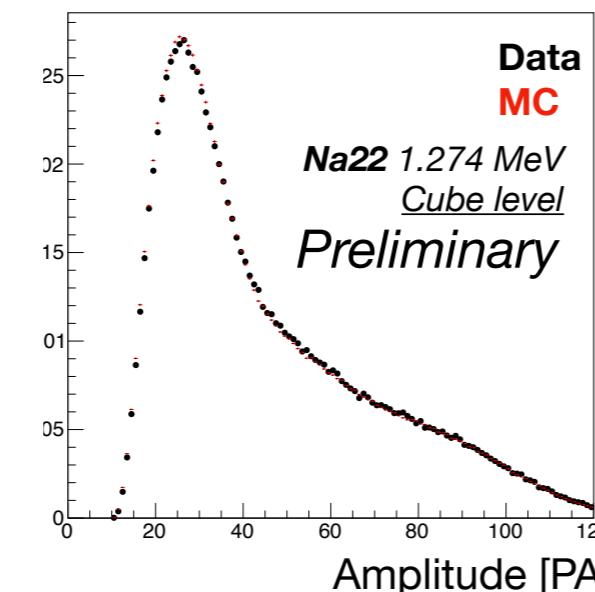
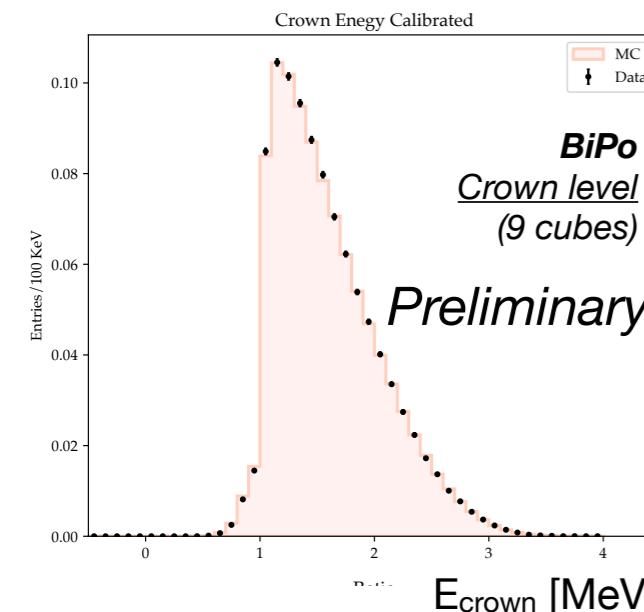
Calibration:

- The understanding of the detector response is provided by calibration data.
- Energy calibration: 4 γ sources used (^{137}Cs , ^{207}Bi , ^{22}Na , AmBe)
 - ▶ **Cube light yield homogeneity (3%)**
 - ▶ Probe the **linearity** response
- Neutron detection efficiency:
 - ▶ 2 neutron sources used: AmBe & ^{252}Cf
 - ▶ **Measure 52% neutron detection efficiency**



Precise MC tuning!

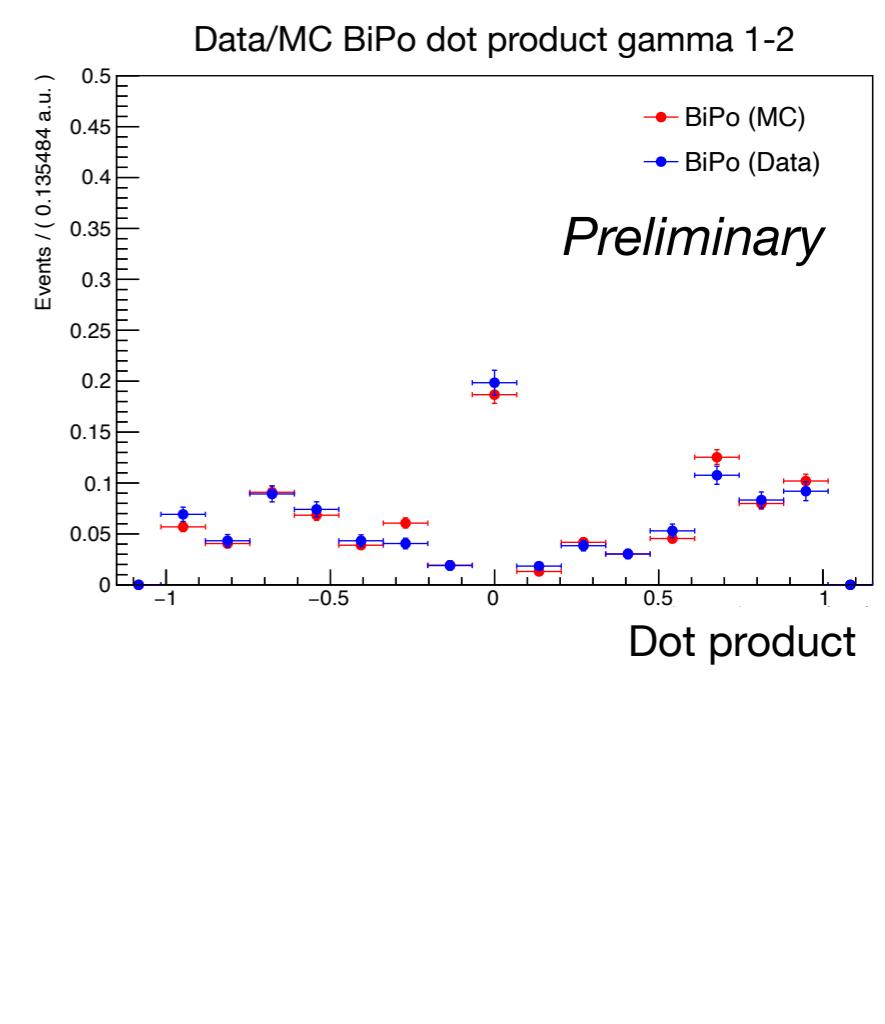
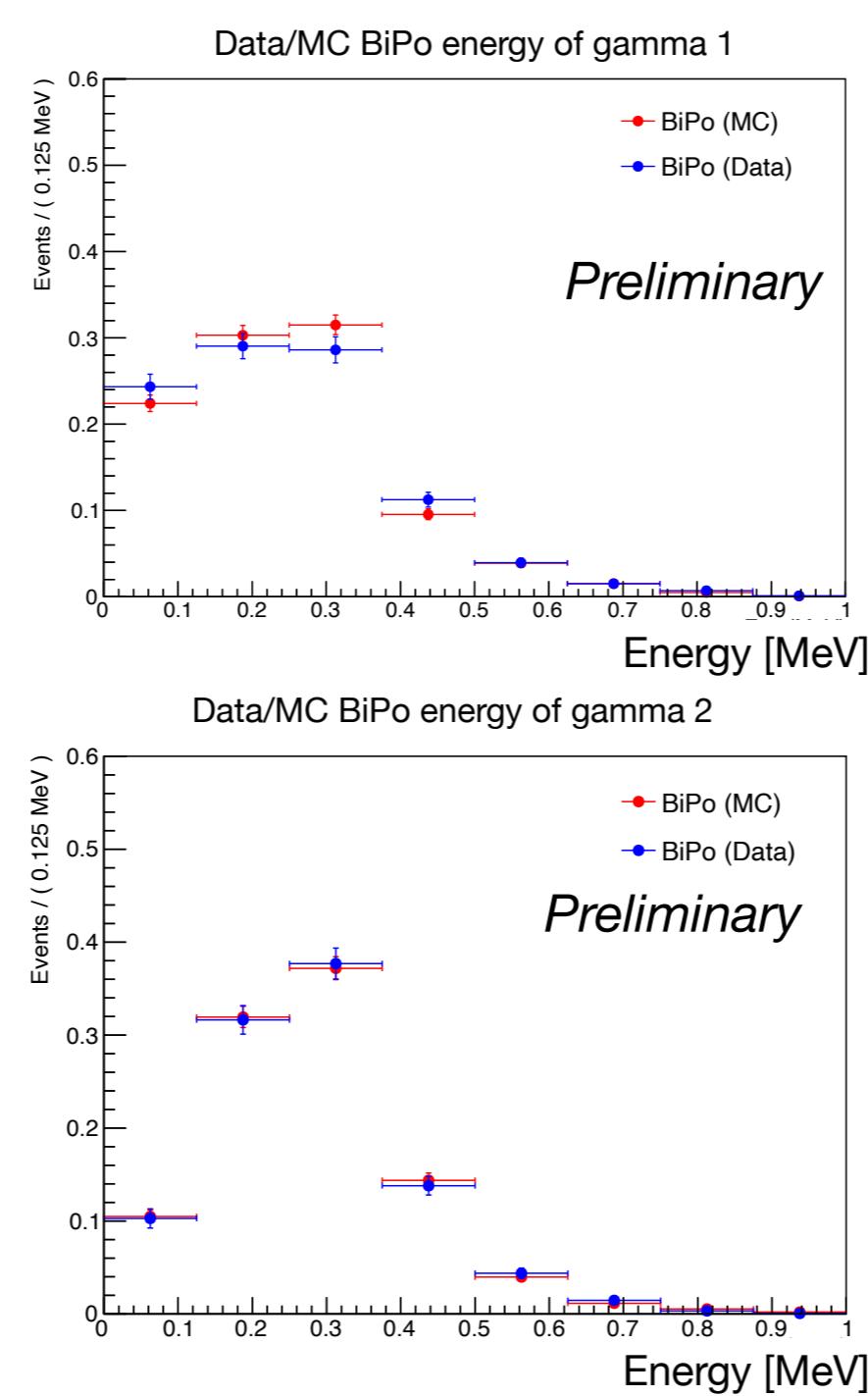
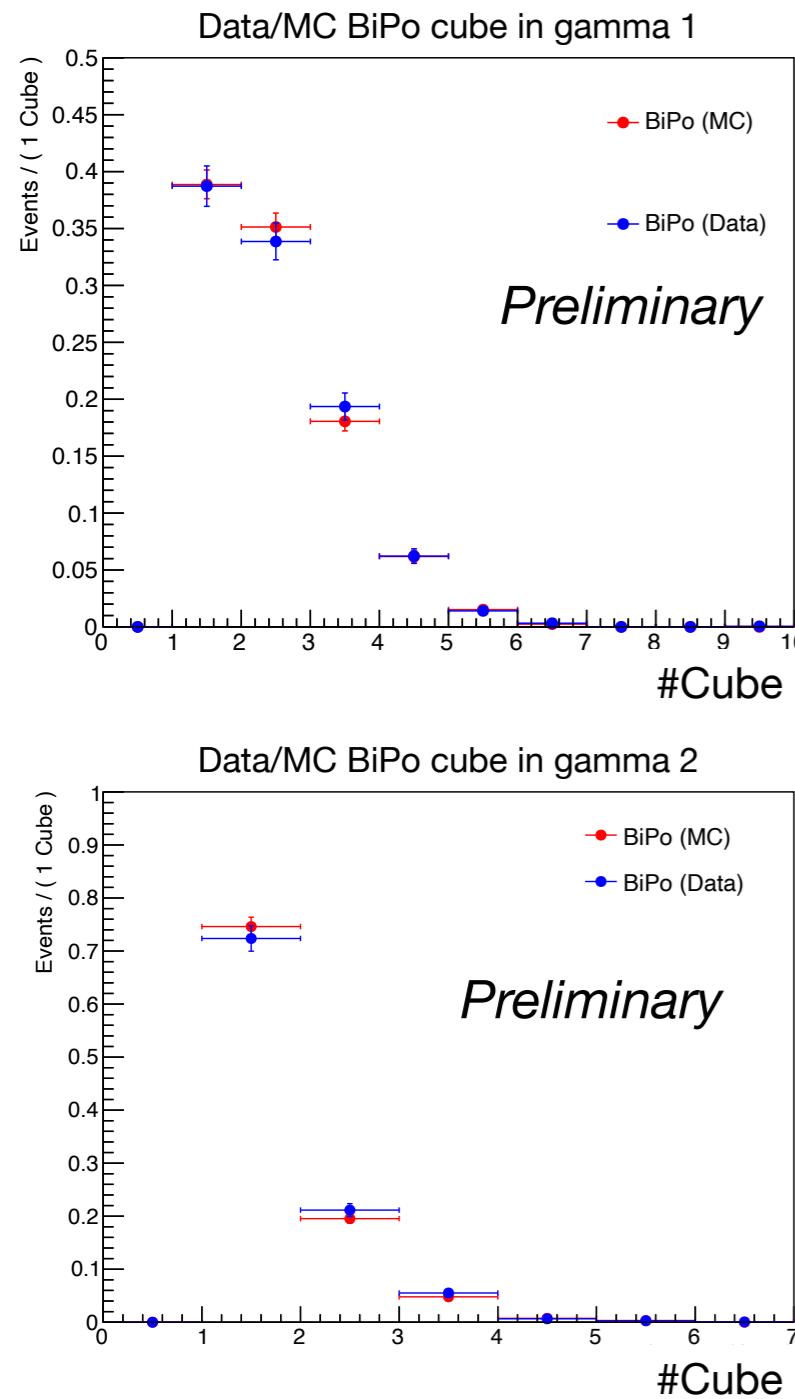
- We take advantage of the BiPo bkg to control:
 - Reconstructed energy: In particular for light leakage tuning
 - Topology: Followed by radiative decay ($e^- + \gamma s$)
- ^{22}Na used for PVT energy tuning and control below 1 MeV



Detector response in a nutshell

For more details: talk given by Noe Roy (660)

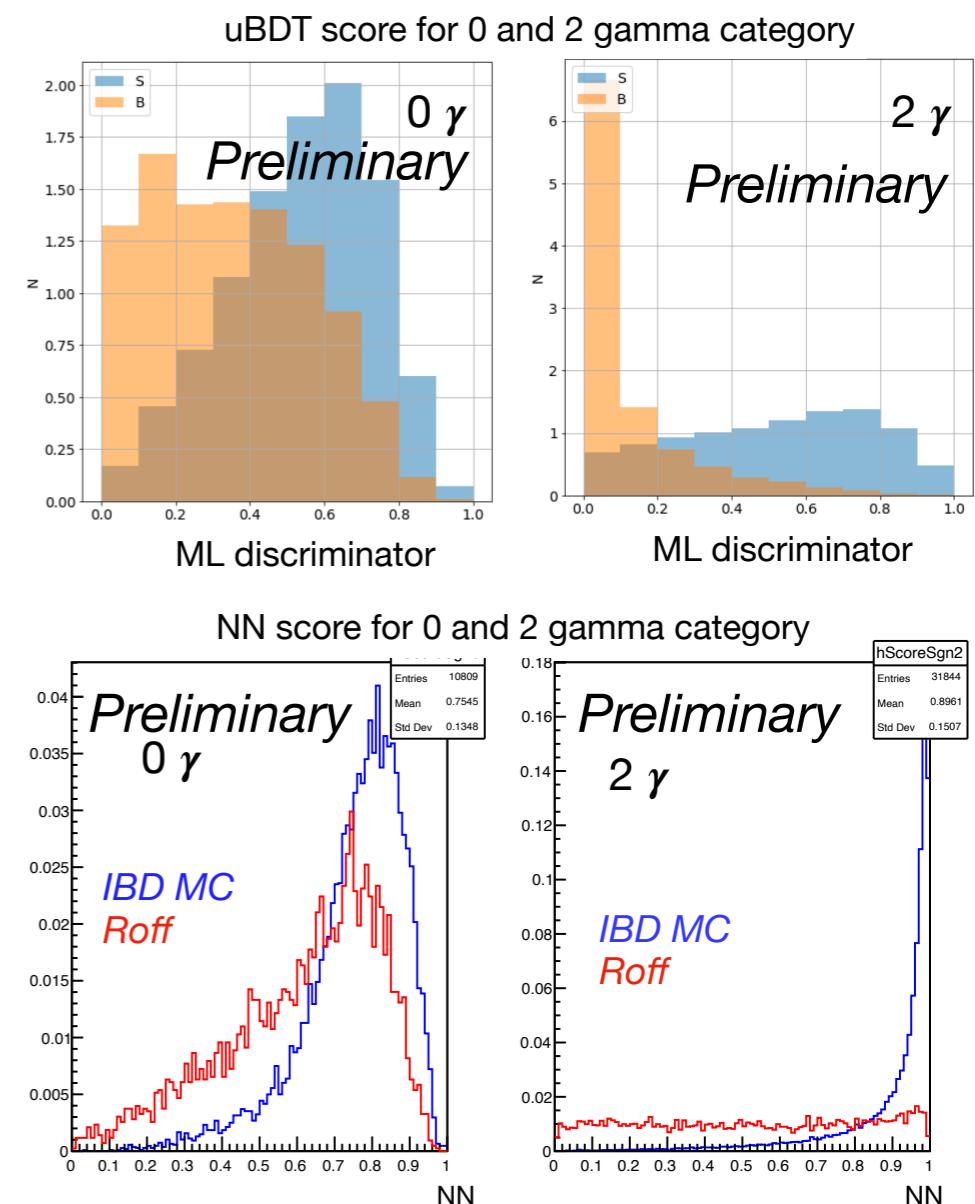
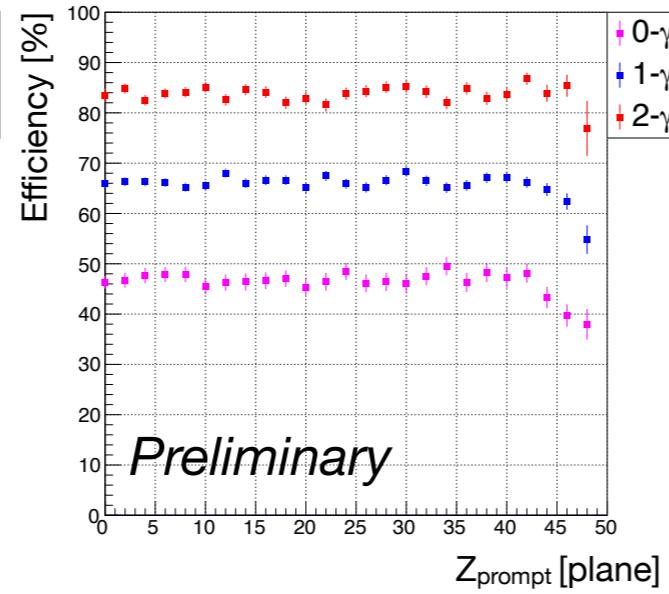
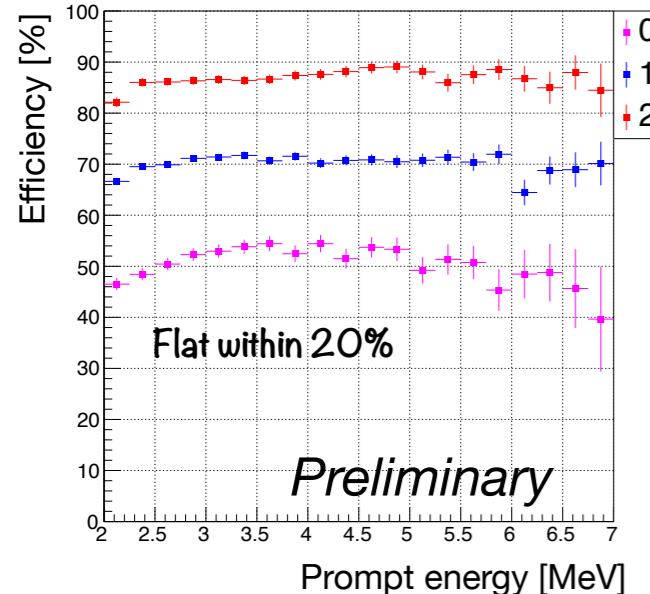
Topological variables validated with BiPo data/MC.



Improvements: Multivariate analysis

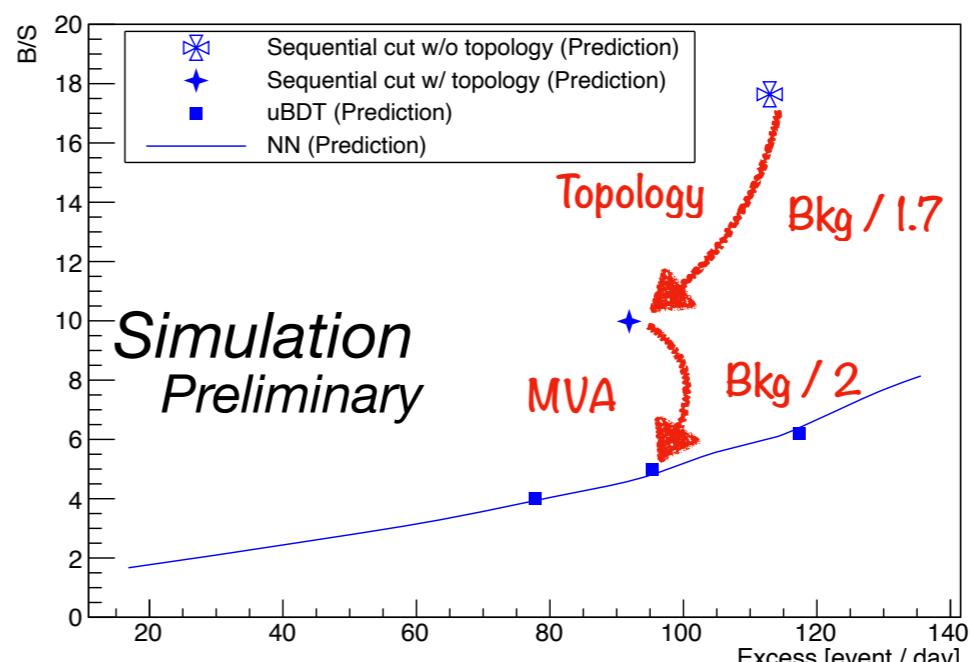
**Two independent approaches based on commonly used MVA tools.
(no cutting edge ML)**

- uBDT: [arXiv:1305.7248]
 - ▶ Tool designed to optimise discrimination while keeping uniform efficiencies (here: in E and baseline)



- TMVA neural network

Both trained in category and same variables as previous analysis



Gain: Background reduced by a factor 2

- 100 neutrino per day for a S/B of 0.2

Neutrino signal in real data

For more details: poster by Giel Vandierendonck (797)

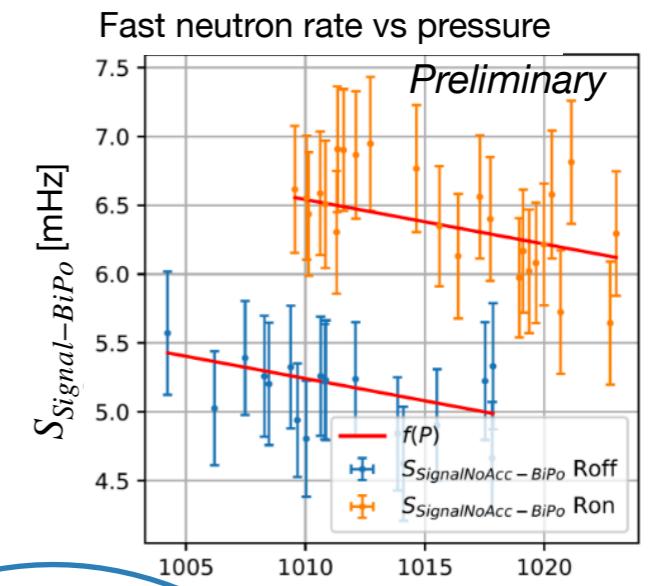
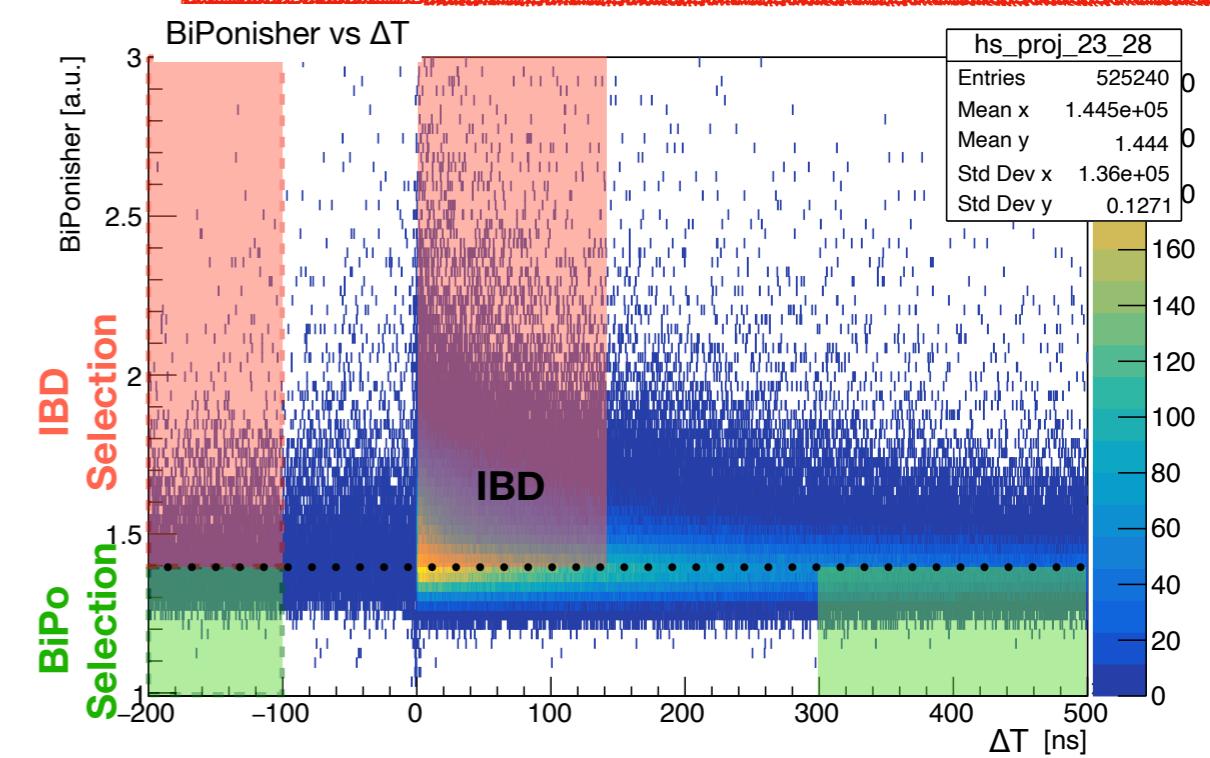
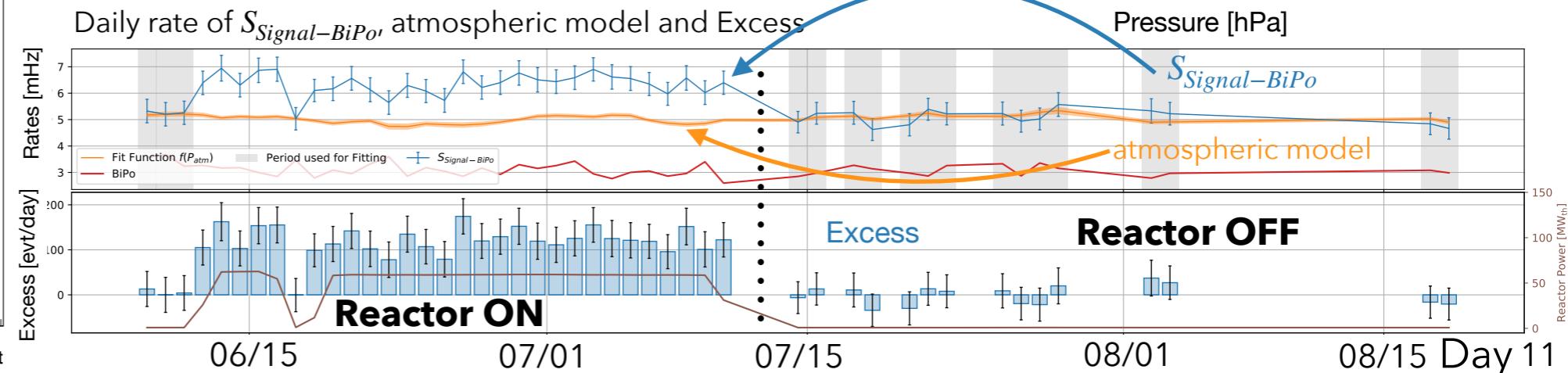
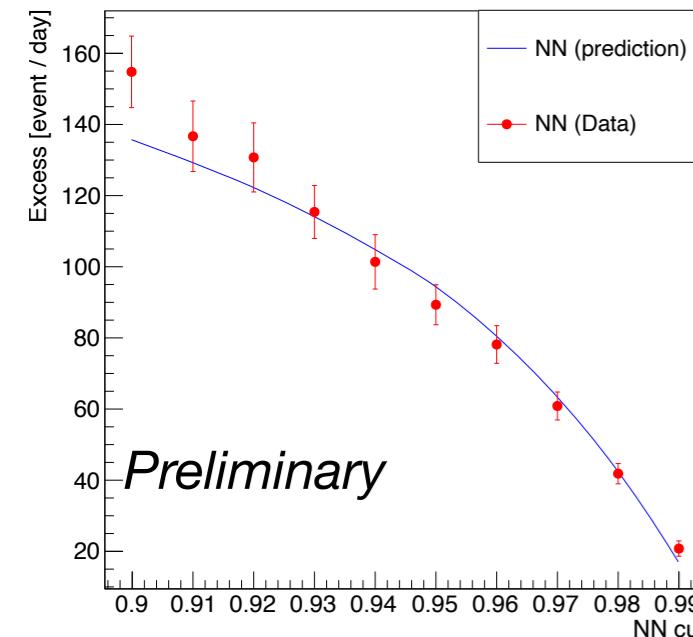
Two backgrounds with a different day to day evolution:

- 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.
 - $S_{Signal-BiPo,j} - \bar{S}_{Signal-BiPo} = \chi_{atm}^{Ref} \cdot (P_j - \bar{P})$
 - $S_{Signal-BiPo-Atm,k} = S_{Signal-BiPo,k} - \chi_{atm}^{Ref} \cdot (P_k - \bar{P})$
- This approach is cross-checked by taking days with same pressure.

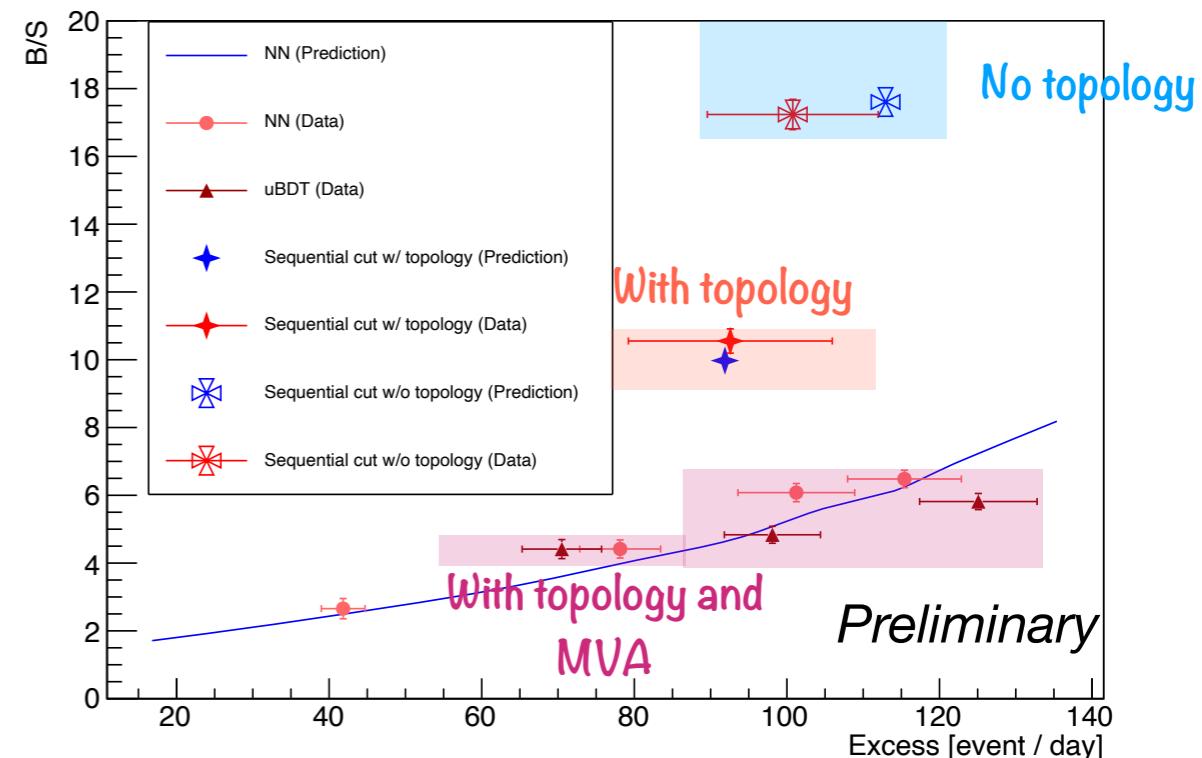
Excess in data vs MC



Neutrino signal in real data

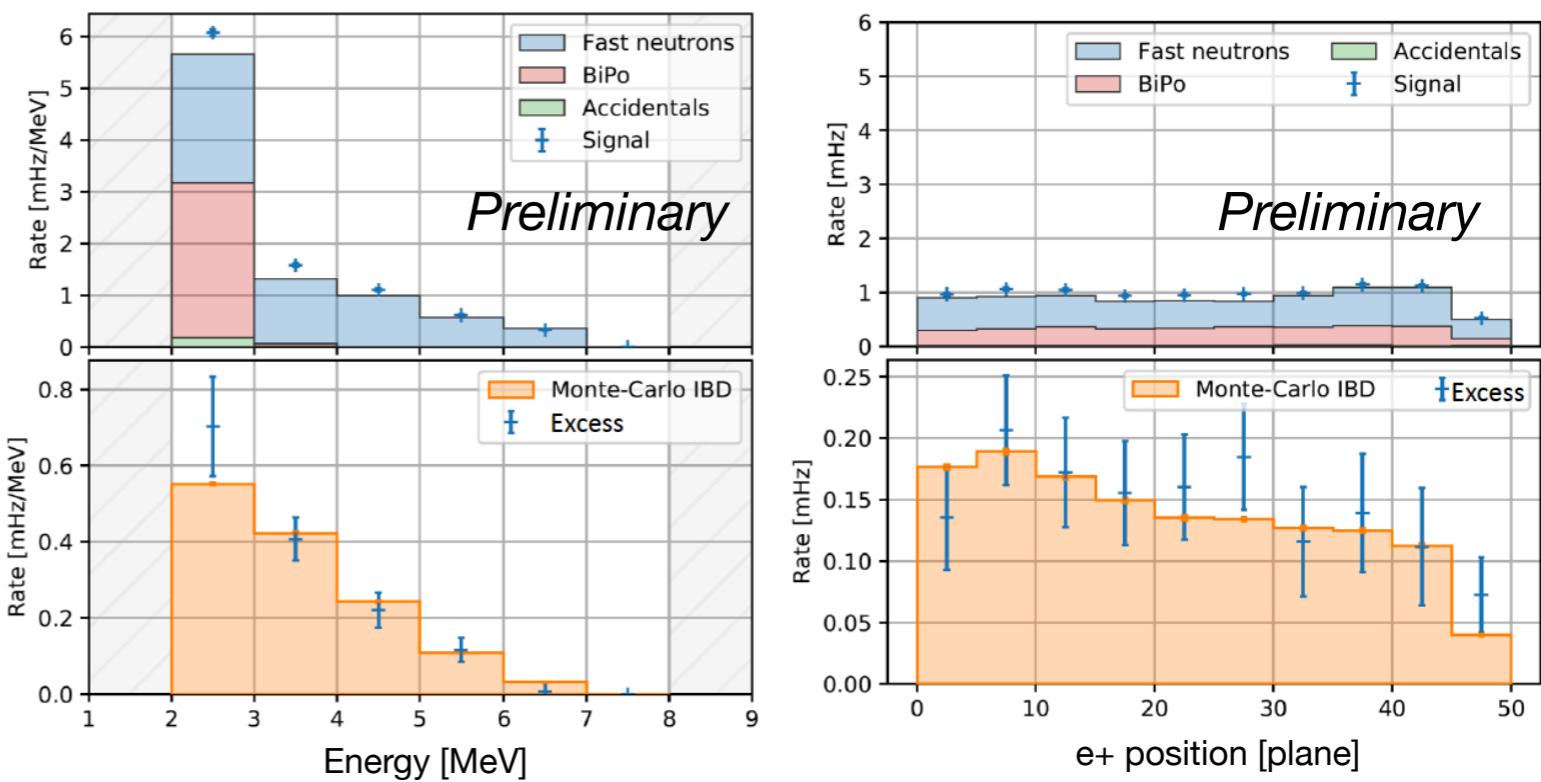
**Evaluation of the neutrino excess and S/B in real data
consistent MC predictions shown earlier**

- Topology helps and MVA as well.



Neutrino excess in energy and baseline

- Sanity check of subtraction



Going further: Improves the efficiency to see annihilation gammas → Upgraded detector with a higher light yield

(i.e. better efficiency to see low energy deposits)

Ongoing improvements

SoLid upgrade: Higher (x1.4) light yield to better reconstruct annihilation gamma

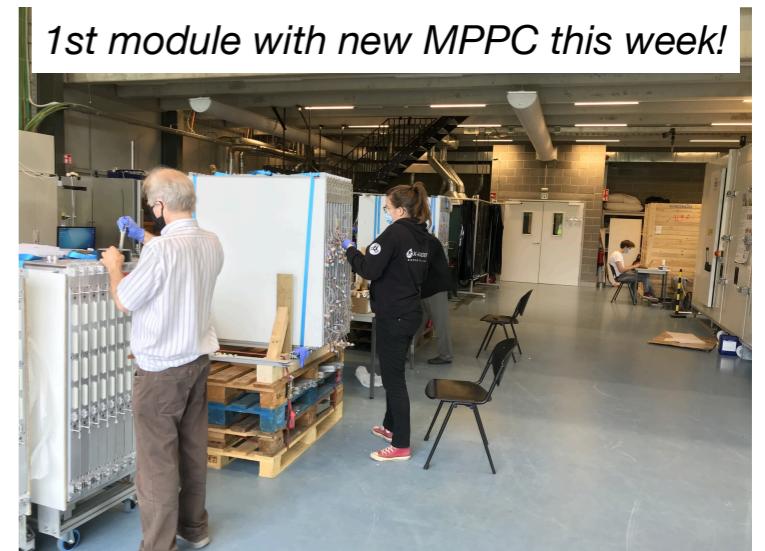
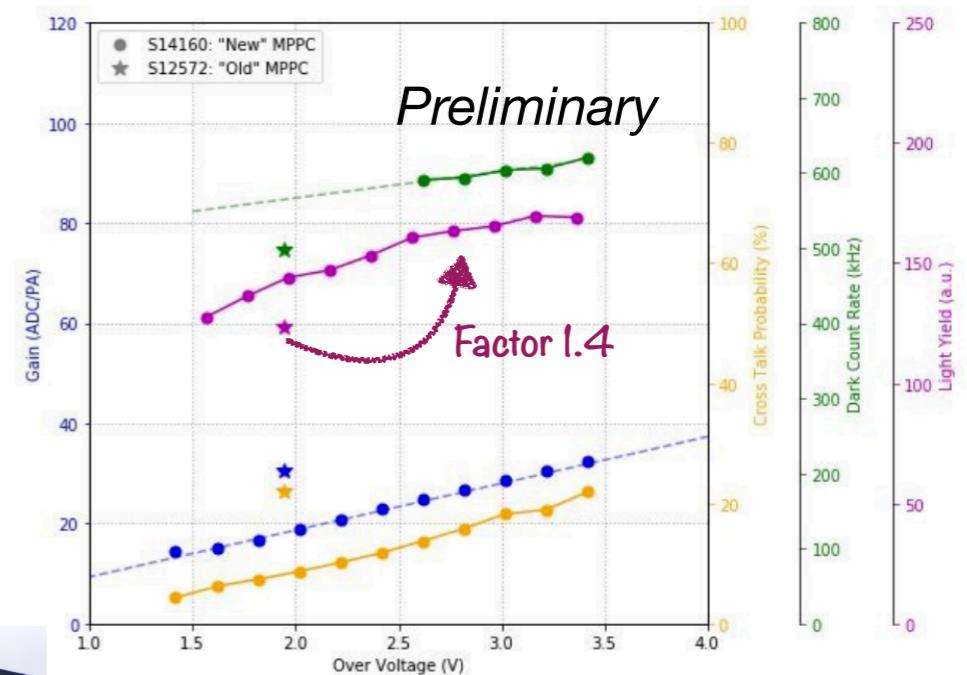
- The new generation of MPPCs: Better PDE and lower cross-talk.
- Lab tests have demonstrated a gain of **40% in light yield!**
- MPPC replacement ongoing!



Detector dismounting started the 1st July



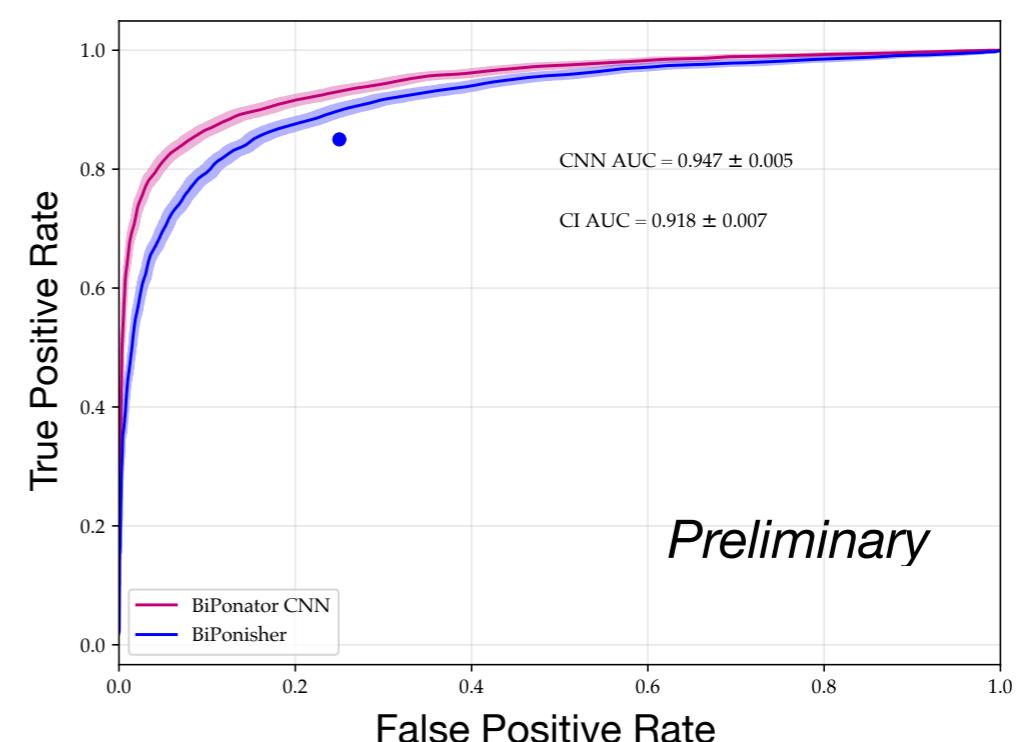
Modules arrived @ Antwerp for upgrade



1st module with new MPPC this week!

BiPonator:

- Exploit as much as possible waveforms shape differences between neutron and alpha in ZnS.
- Current BiPonisher: simple ratio.
- Developed a 1-dimensional convolutional network (CNN)
- We expect to reduce BiPo background by a **factor 2-3!**



Conclusion

- SoLid has to face very challenging background conditions
 - ▶ Cosmic induced background.
 - ▶ Unexpected rate of internal BiPo background.
Space & time coincidence between prompt & delayed signals can't discriminate enough.
 - ▶ Started to exploit also the power of SoLid's topological reconstruction.
- A focus has been put to exploit annihilation gamma topology
 1. Understand detector response below 200 keV: Efficiencies, calibration, tuning of simulation.
 2. Usage of annihilation gamma for signal selection (Background/1.7)
 3. Explore multivariate tools (Background/2)
- Systematic studies ongoing.
- The upgrade is coming soon!

Stay tuned!

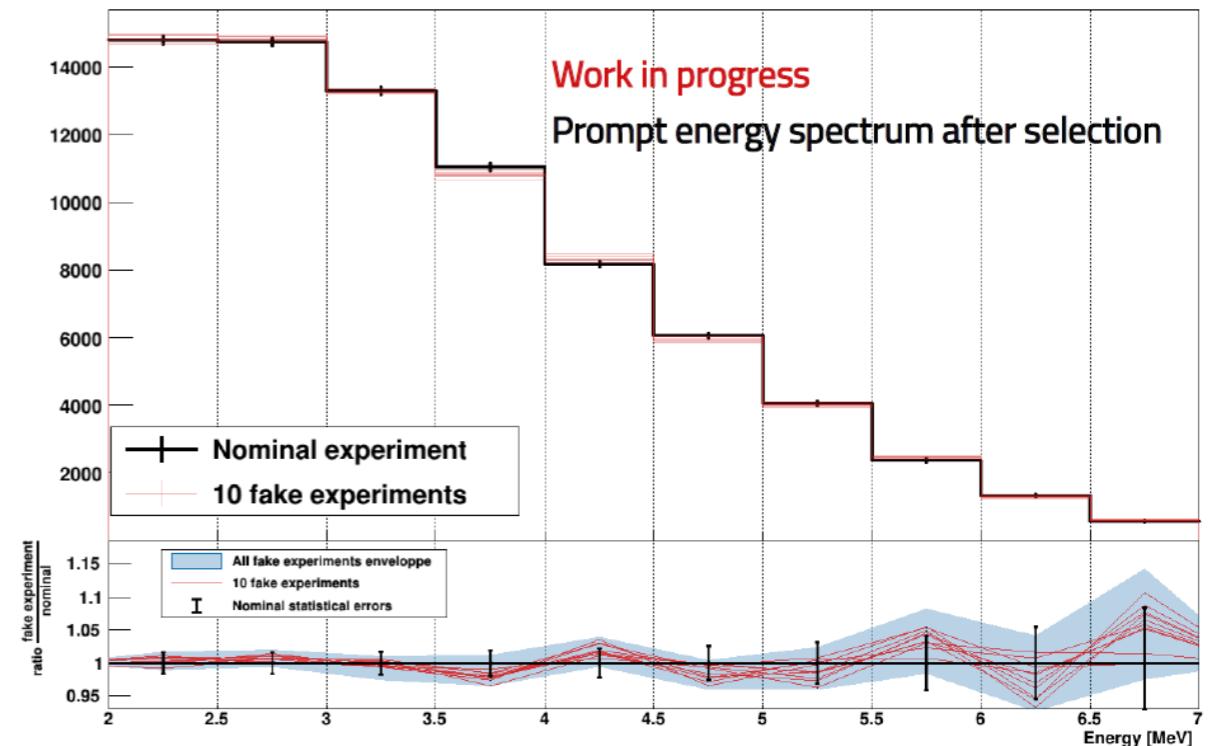
Thanks for your attention!

SoLid

Backup

Systematic uncertainties on reconstructed energy

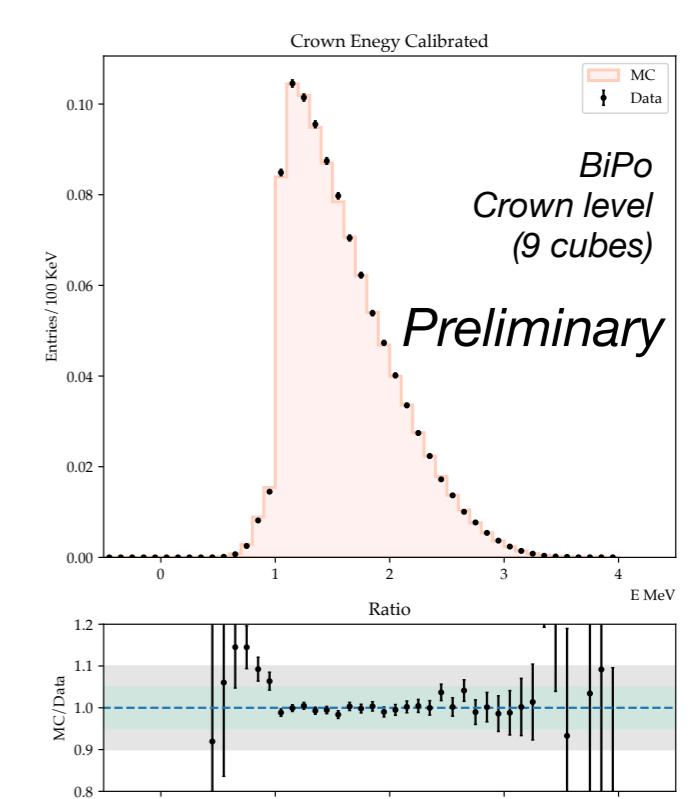
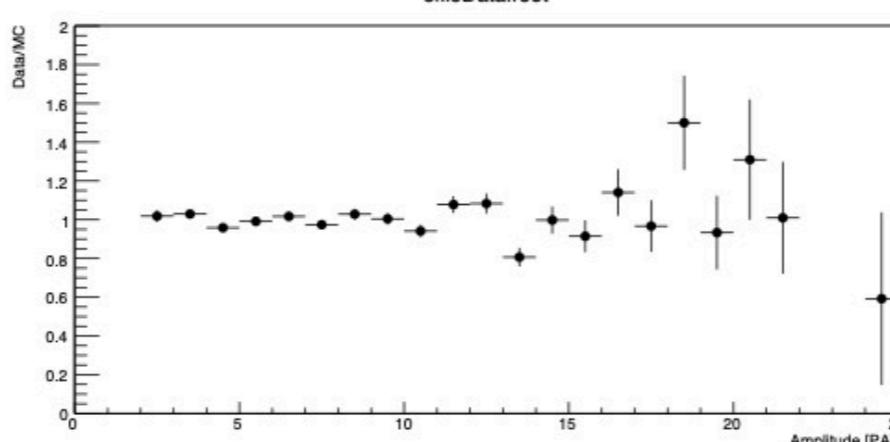
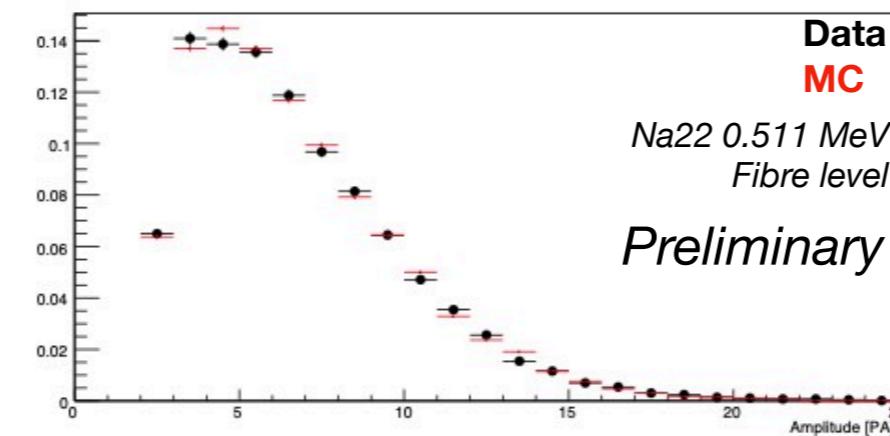
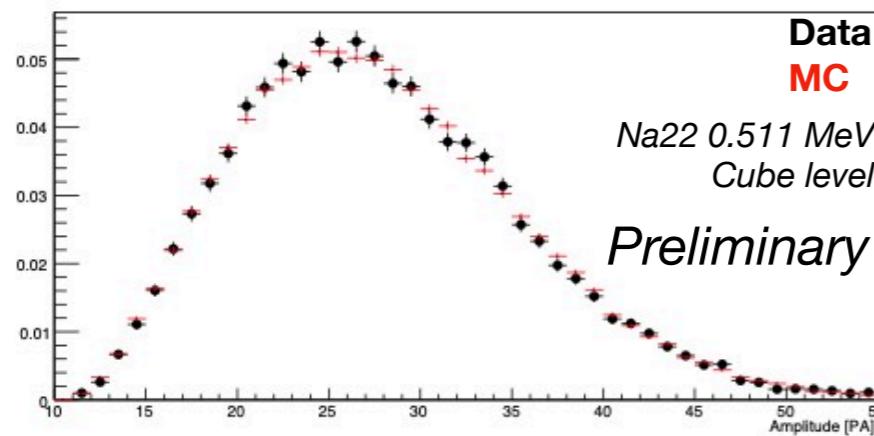
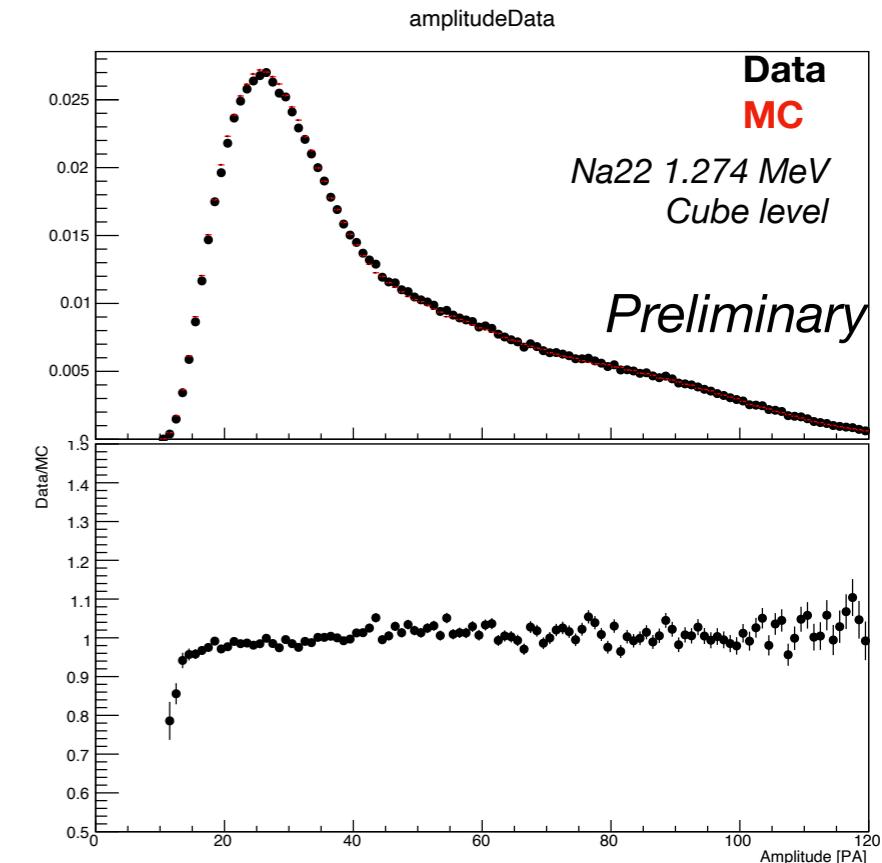
- Work in progress for the LY systematic assessment.
- Fake IBD simulations varying the cube individual light within 3%.
- Comparison done between the nominal and fake experiments.
 - ▶ Compute all the ratios between the fake experiments and the nominal one.



Assuming a S/B around 1 we already expect the LY uncertainties to fall into the statistical uncertainty

Data/MC Energy ratios

- Shape comparison between data/MC at different reconstruction level:
 - Sum of cubes
 - Cube
 - Fibre
- Agreement below 10% in most of the range.

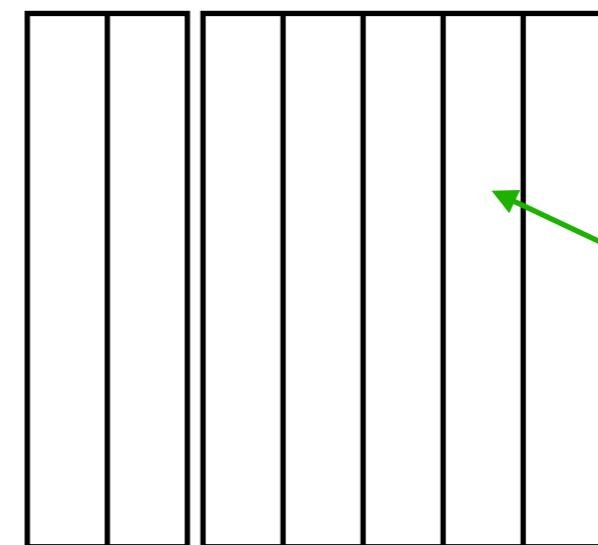


Annihilation gamma efficiency

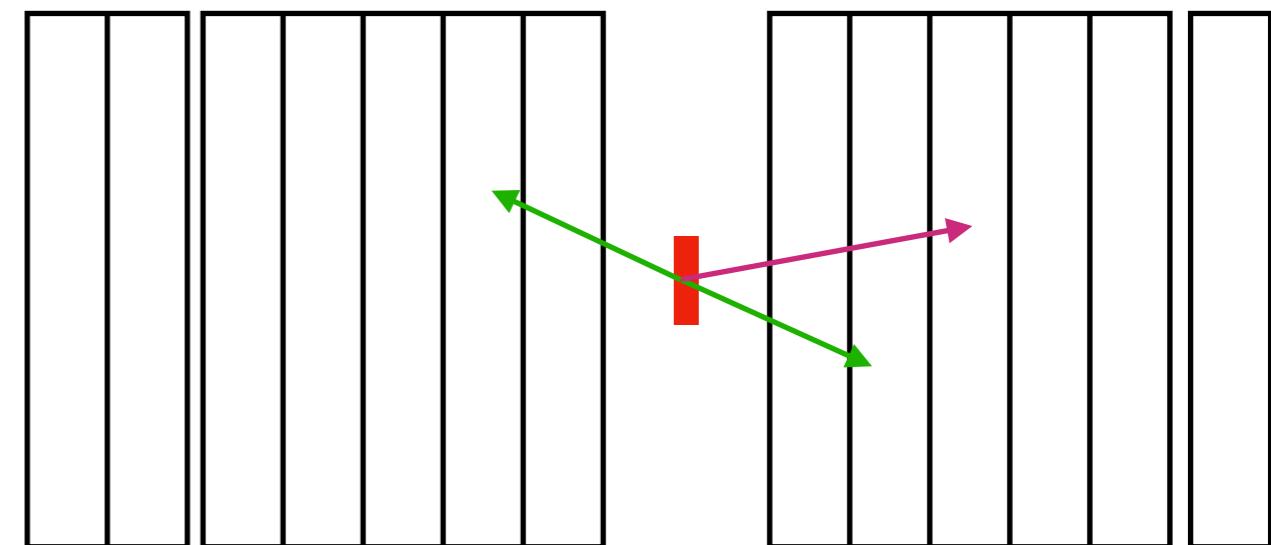
Selection:

- 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 \sim 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

Half-module
Plane 35->39



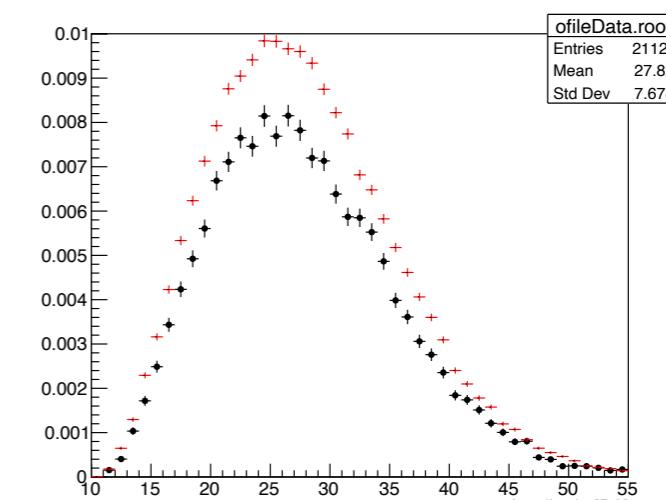
Half-Module
Plane 40->44



Na22 source

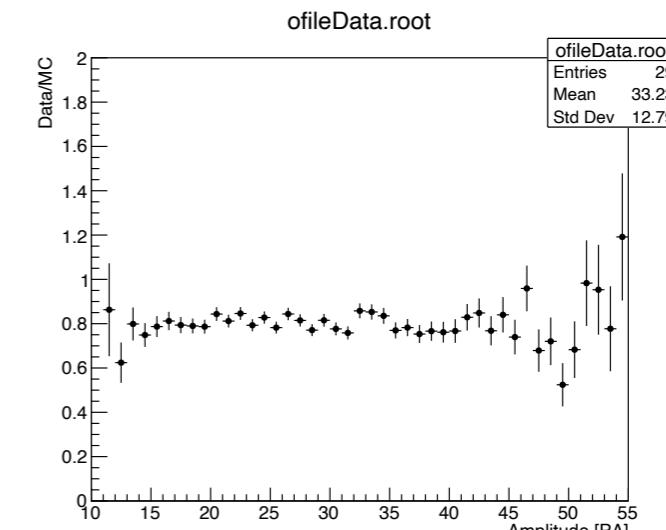
Normalisation:

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



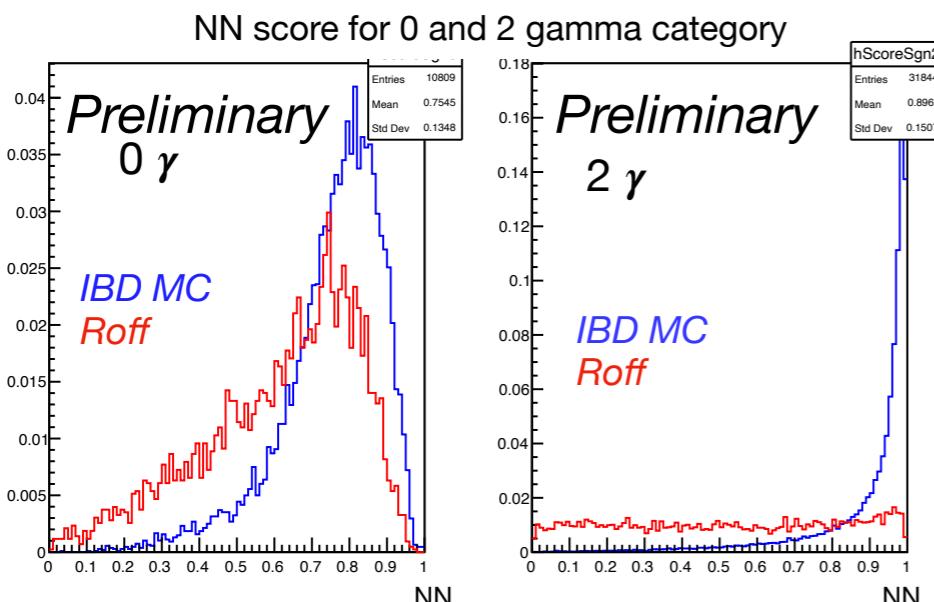
Energy spectrum:

- 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 reproduced 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!



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 %