Status of the SoLid experiment

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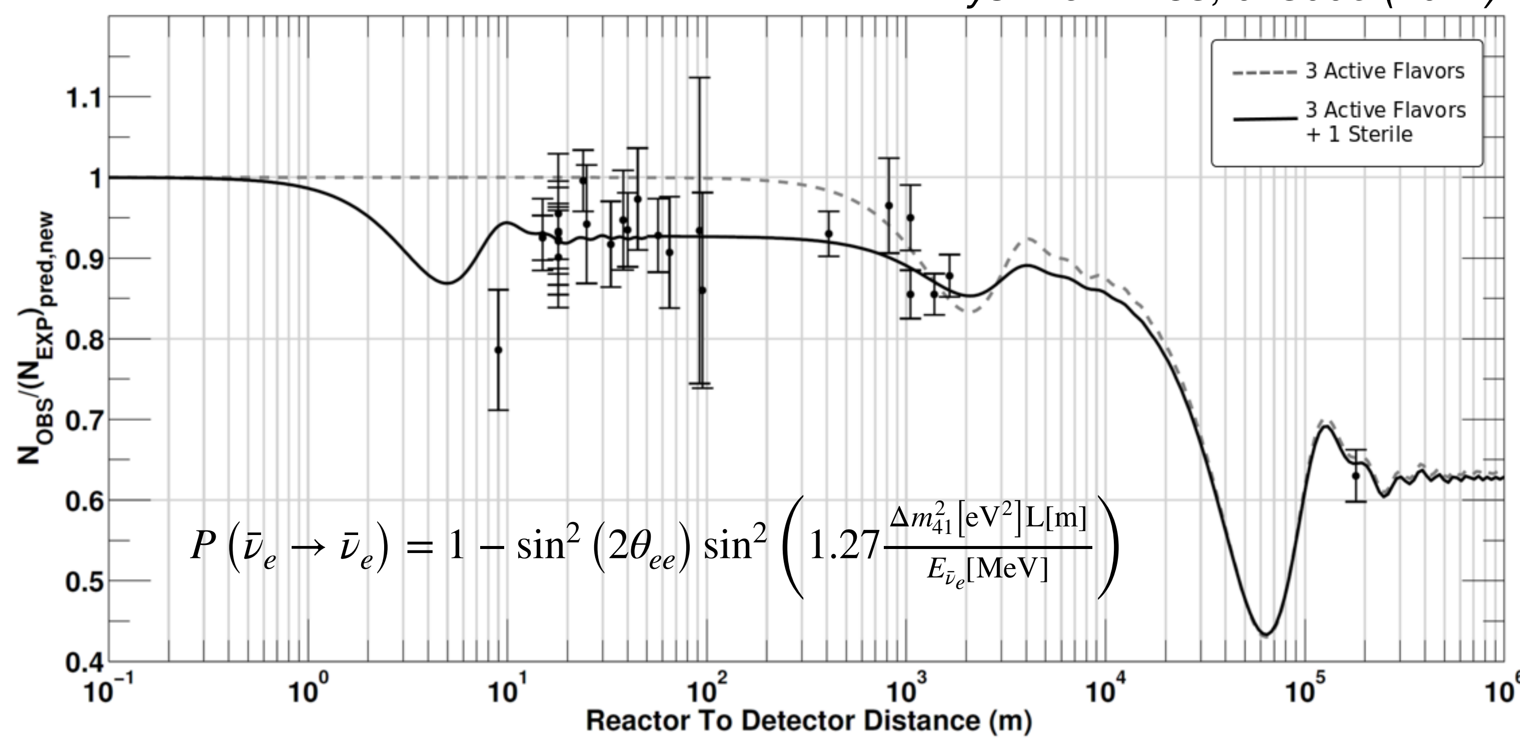
GDR Neutrino
24th November 2020

Motivations: Flux and energy anomaly

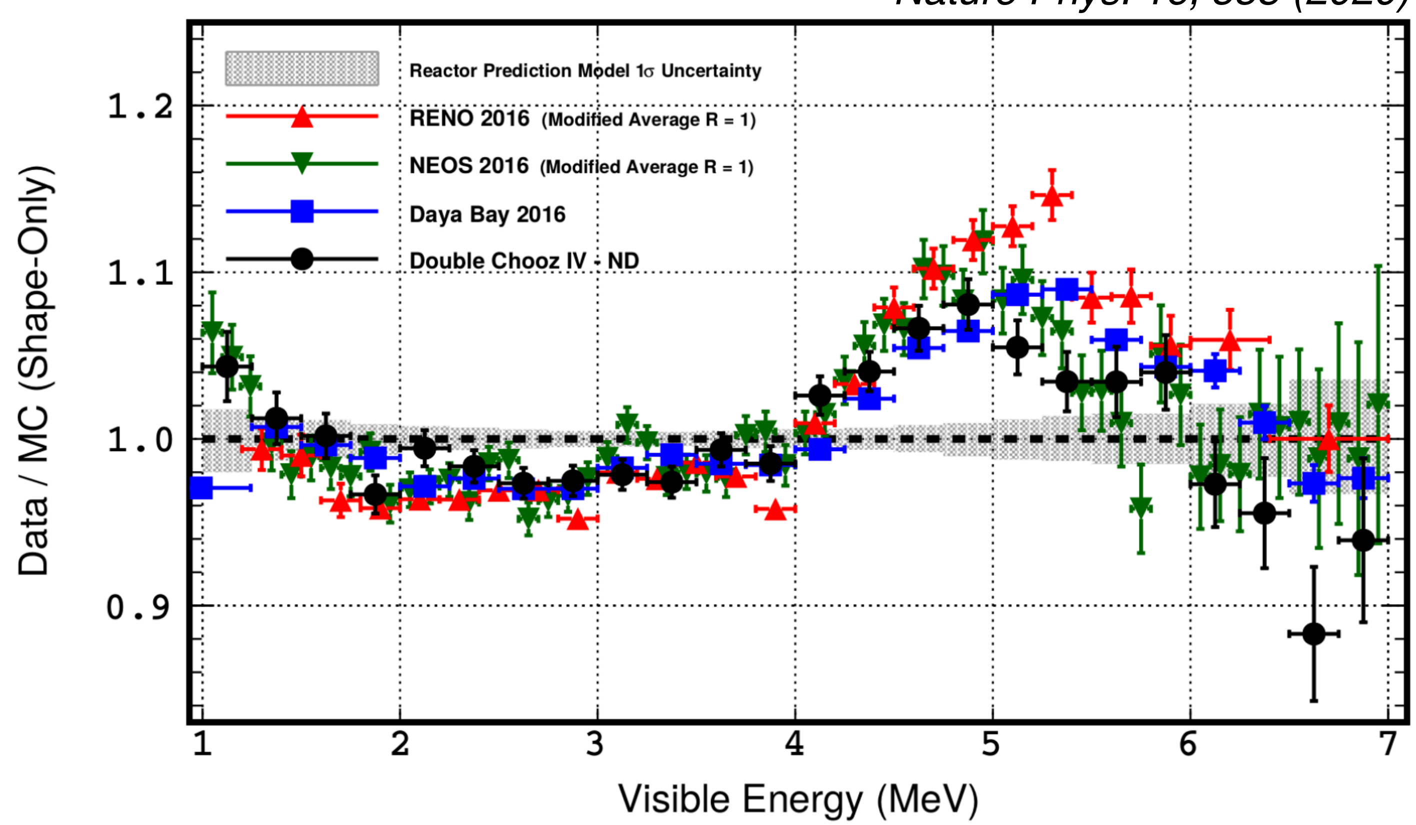
- Reactor Antineutrino Anomaly
  - A deficit in the measured flux compared to predictions.
  - Could be explained by a new oscillation into a sterile neutrino.
- Gallium anomaly: Phys. Rev. C 56, 3391 (1997)

Phys. Rev. D 83, 073006 (2011)



- 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]*

Nature Phys. 16, 558 (2020)



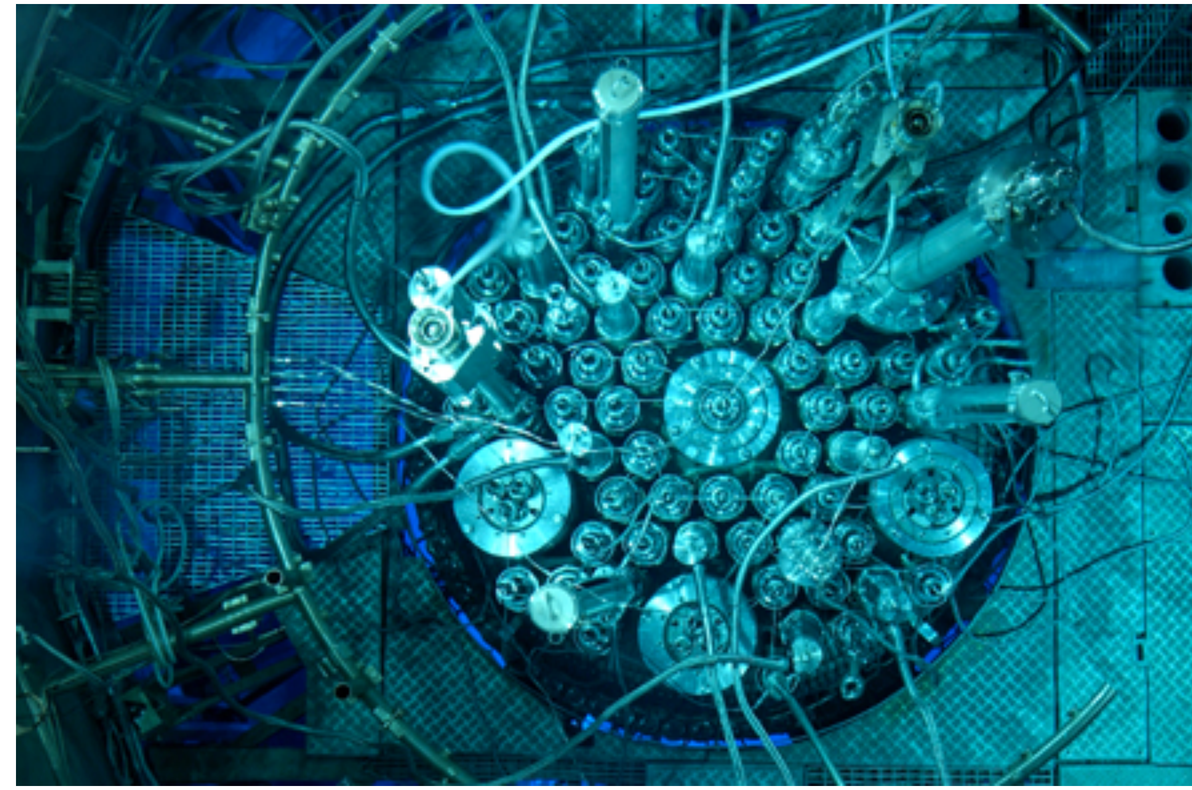
Experimental site

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.

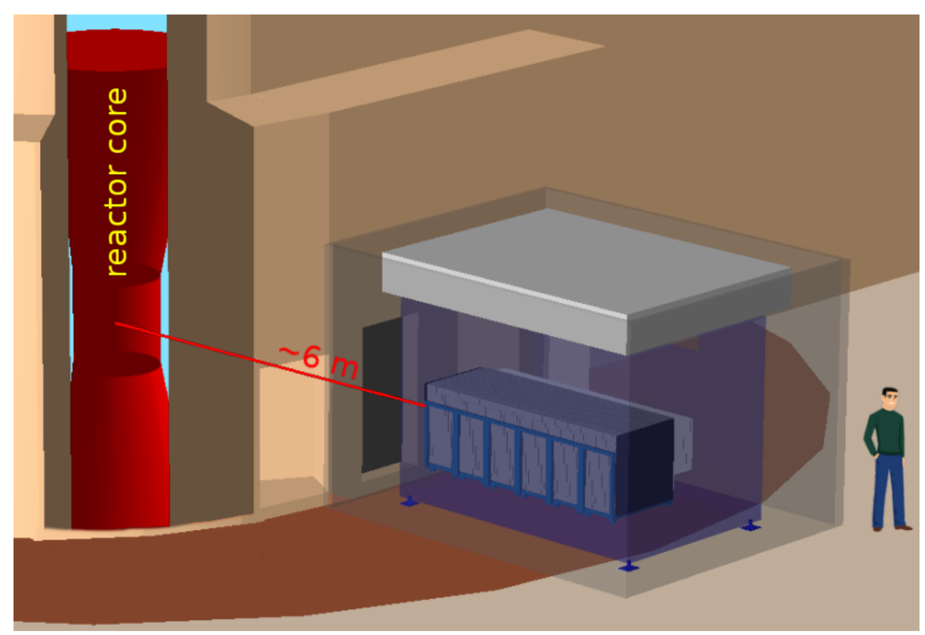
➡ Important cosmic induced background

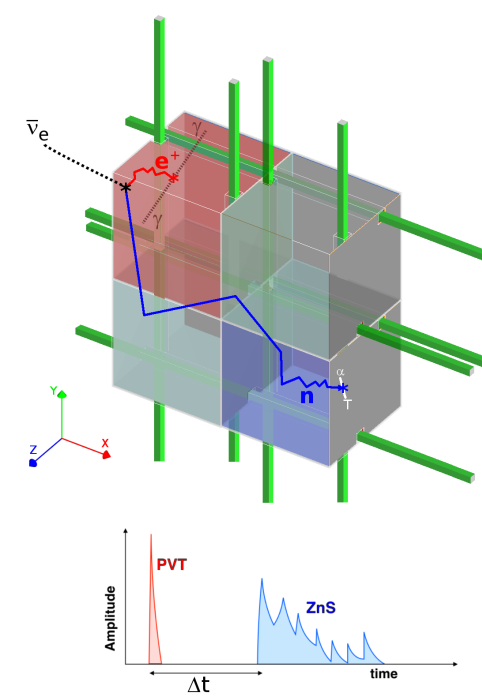
➡ Key challenge that guided SoLid's design



Detector main features:

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



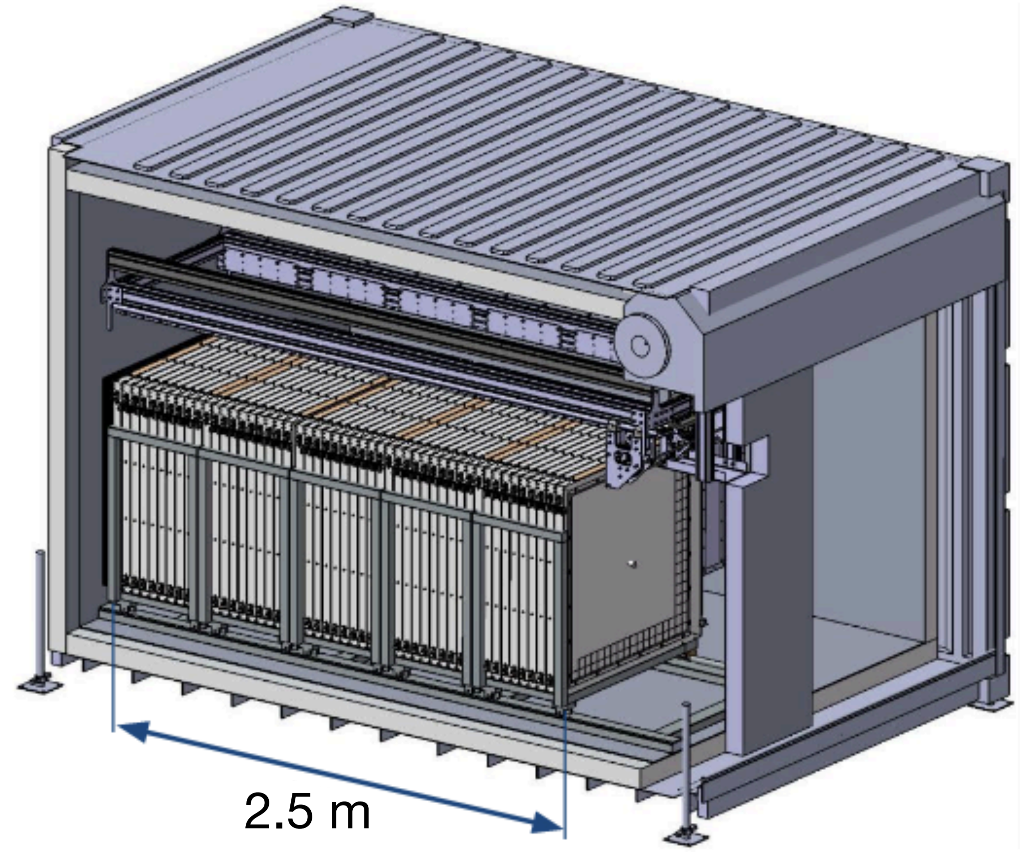


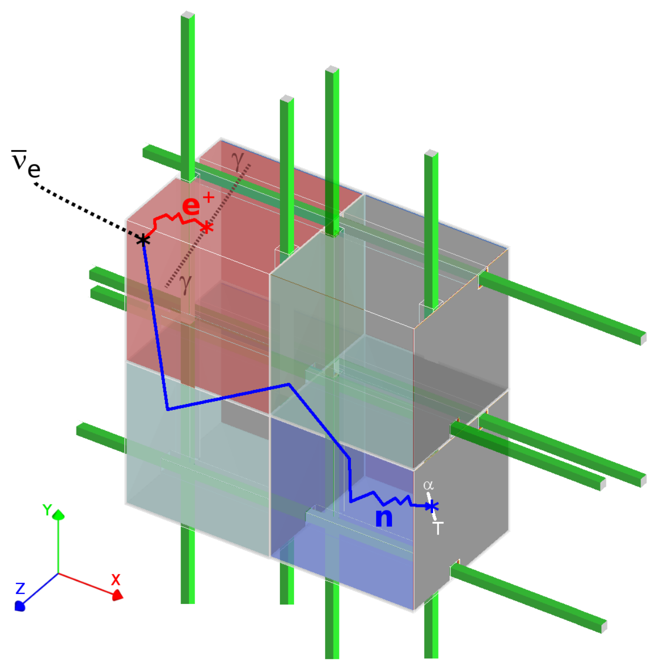
Taking physics data since spring 2018

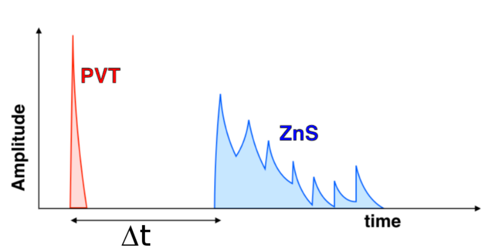
Detector and measurement principle

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

- SoLid's cube
  - Combination of **two scintillators**: PVT cubes of $5x5x5cm^3$ with 2 $^6LiF:ZnS$ 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.



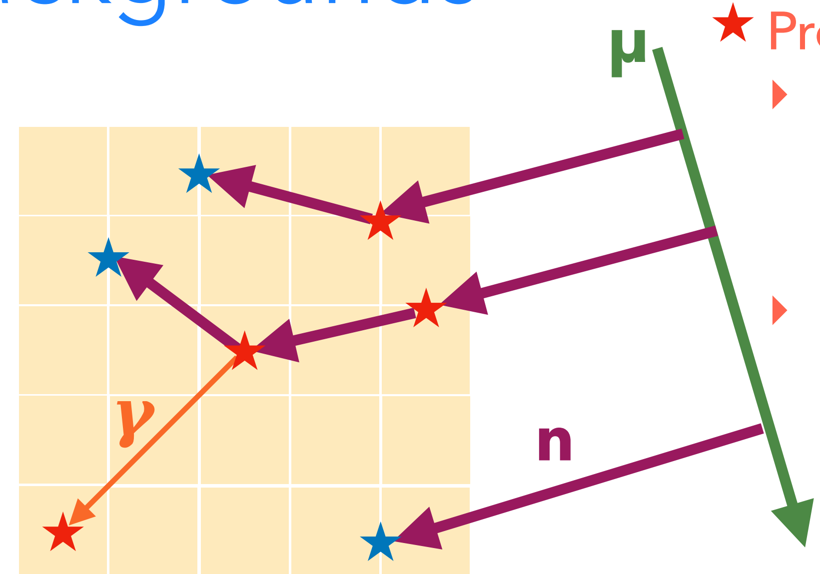




Signal: Inverse beta decay $\overline{\nu_e} + p \longrightarrow e^+ + n$

- 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 ~ 10cm
  - Delayed (ZnS signal): a neutron interacting ~ 64us after thermalisation captured:
    - $n +^6 Li \longrightarrow^3 H + \alpha$
  - 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



★ Prompt:
- Nuclear recoil
  - p-recoil
  - C-recoil
- Compton

★ Delayed:
- n-capture on 6Li

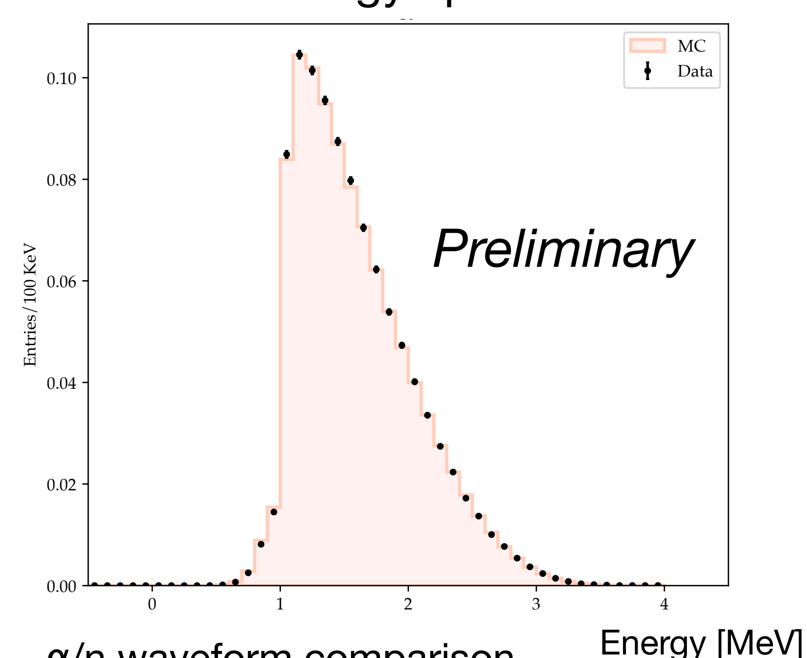
Cosmic induced:

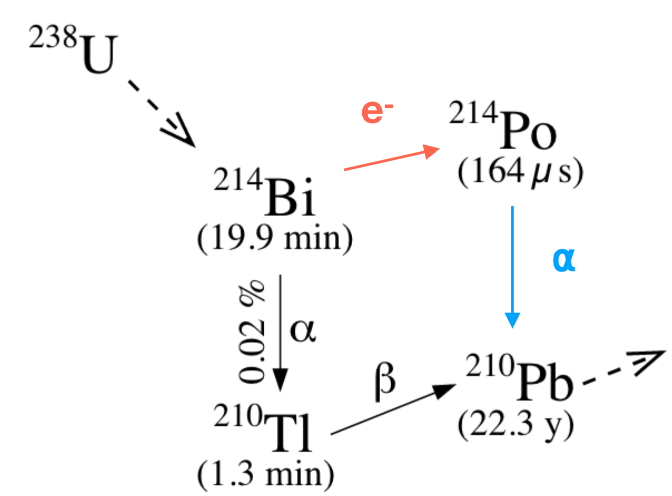
- Proton recoil mimic the prompt and delayed has the same features as IBDs
- Visible energy: all IBD energy spectrum.

BiPo:

- Unexpected and critical internal contamination of ZnS layer
  - Nearly 2 order of magnitude above IBDs before selection
- External pollution: Radon decay
- $\Delta T_{prompt\text{-}delayed}$ ~ 250 us
- Beta decay mimic prompt
- Alpha decay mimic delayed

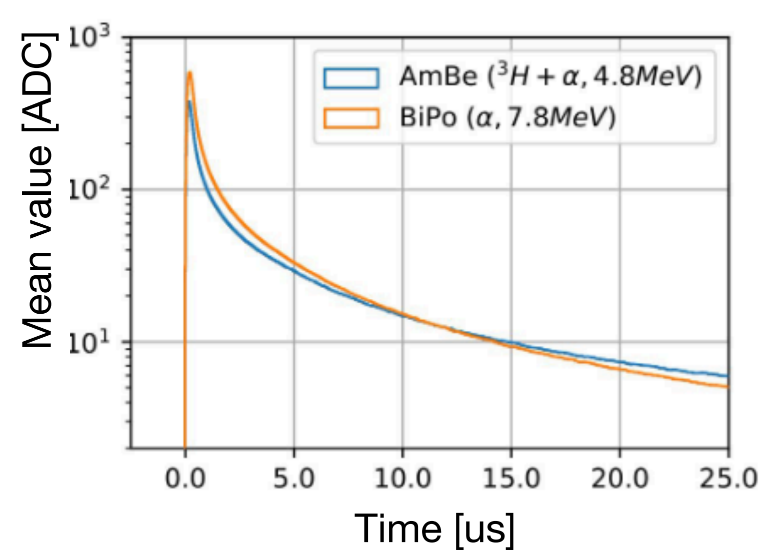
BiPo energy spectrum

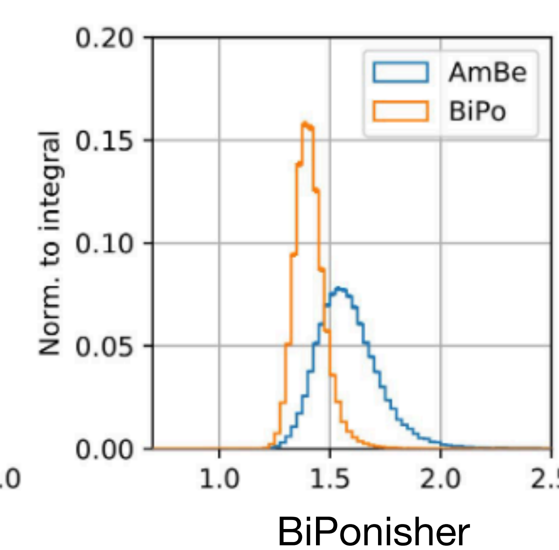




- **BiPonisher**: α/n discrimination using Pulse Shape Discrimination in ZnS scintillator

α/n waveform comparison

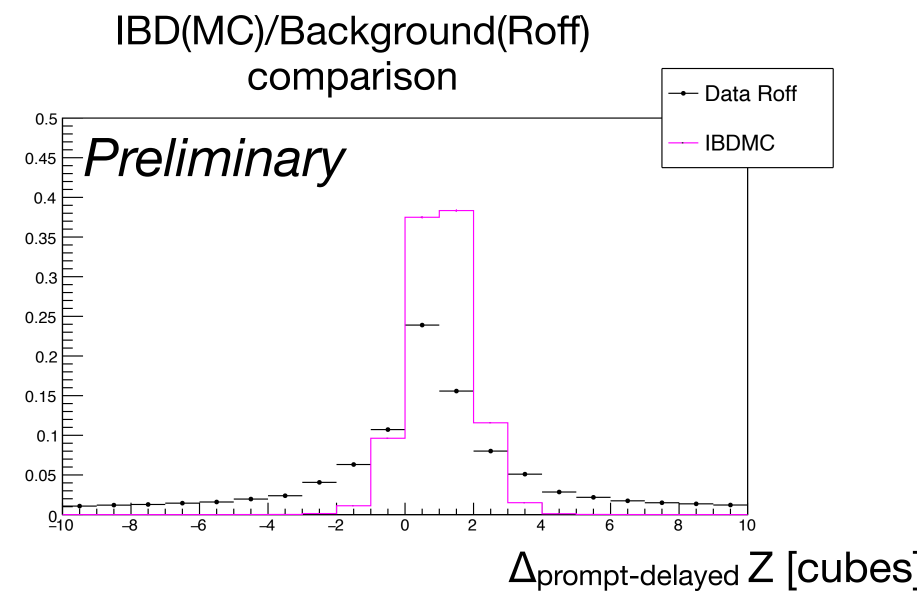




In both cases the space and time prompt-delayed distribution are close to IBDs.

Basic selection: prompt vs delayed space & time coincidence

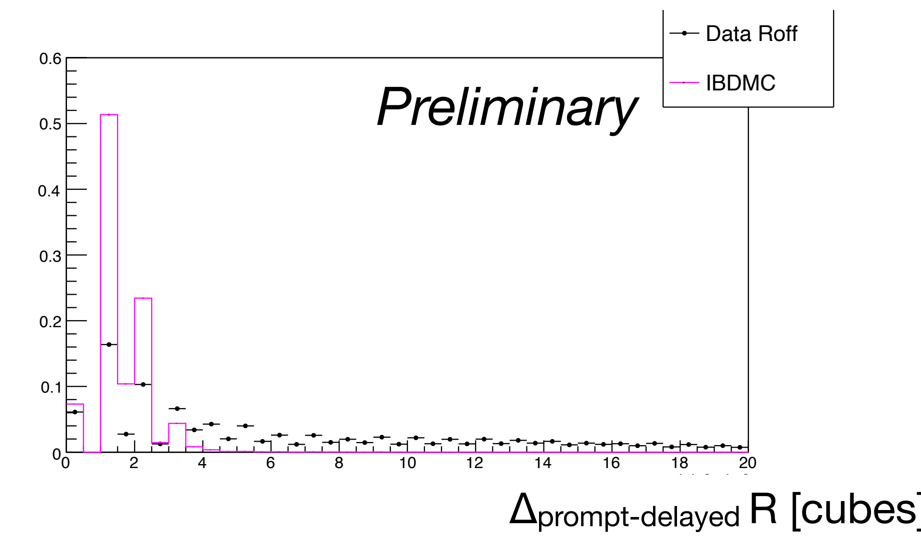
Reconstruction: Fit that find the list of cube positions and energies that minimise the Likelihood to measure the given set of fibres signal (> 200 keV)

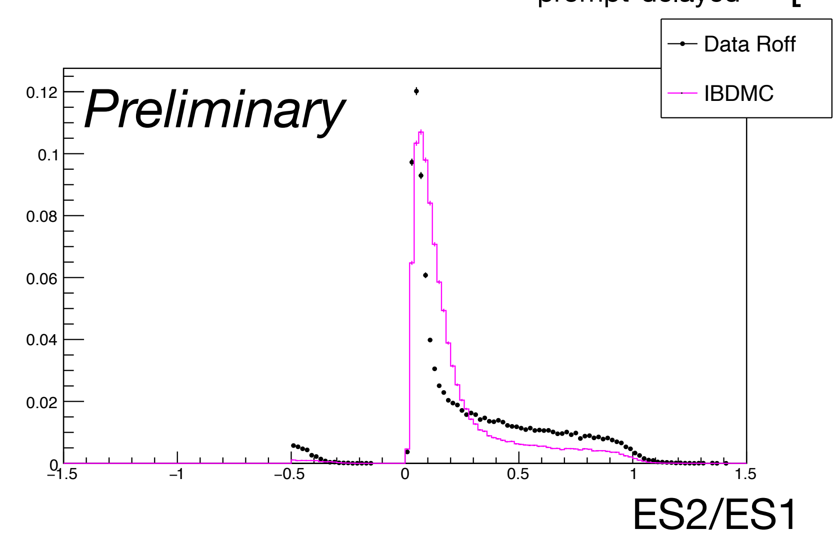


Sequential cuts

Variables for the IBD selection:

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

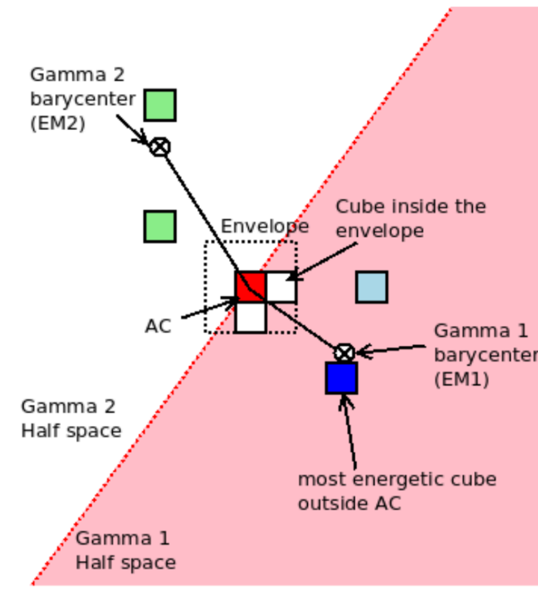




This way: reach ~ 110 neutrino/day and S/B = 0.06

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.

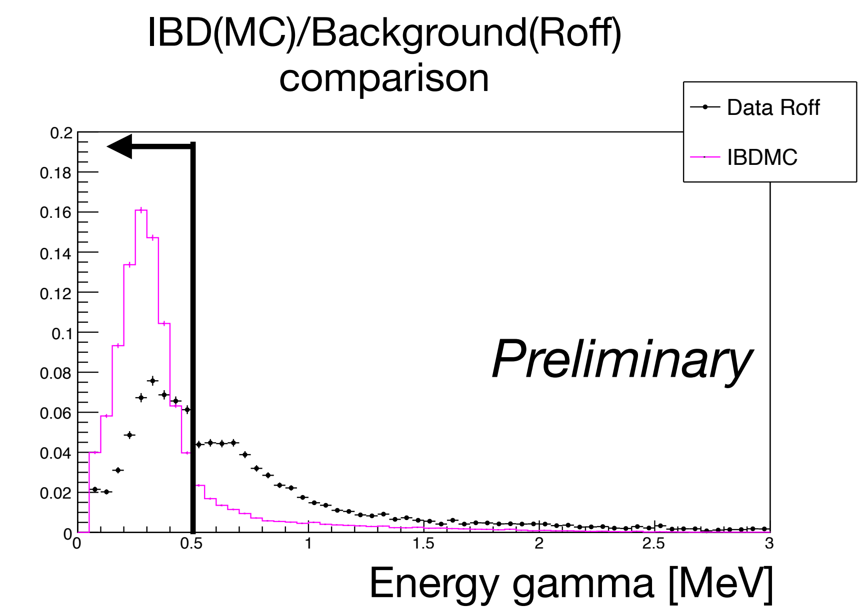


Annihilation gamma reconstruction: Two approaches have been used

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

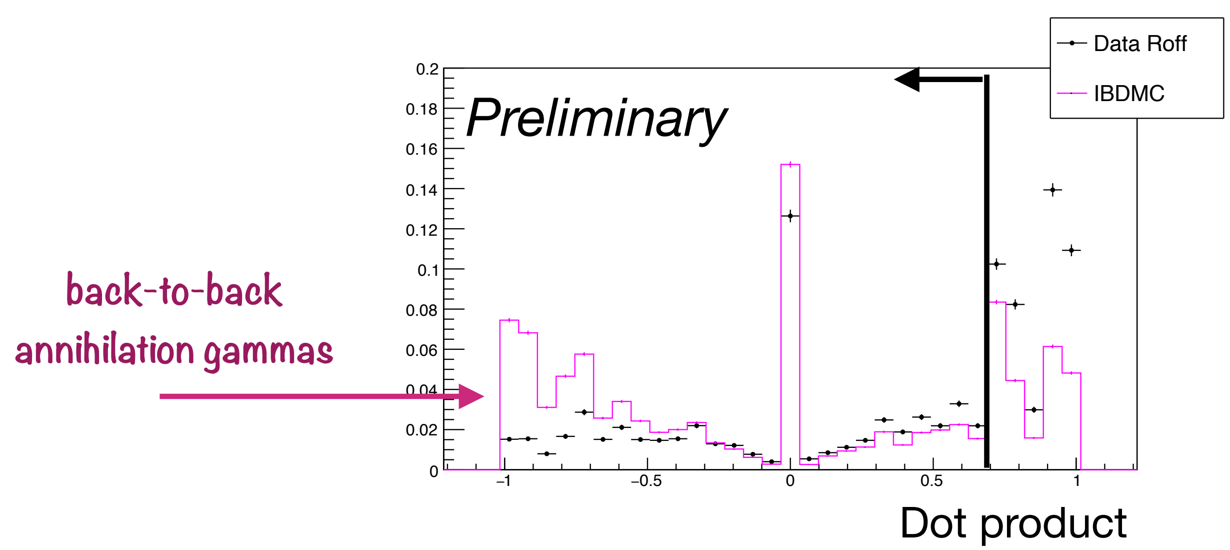
New variables:

- 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_{γ} [0,0.5] MeV
  - Dot product < 0.7



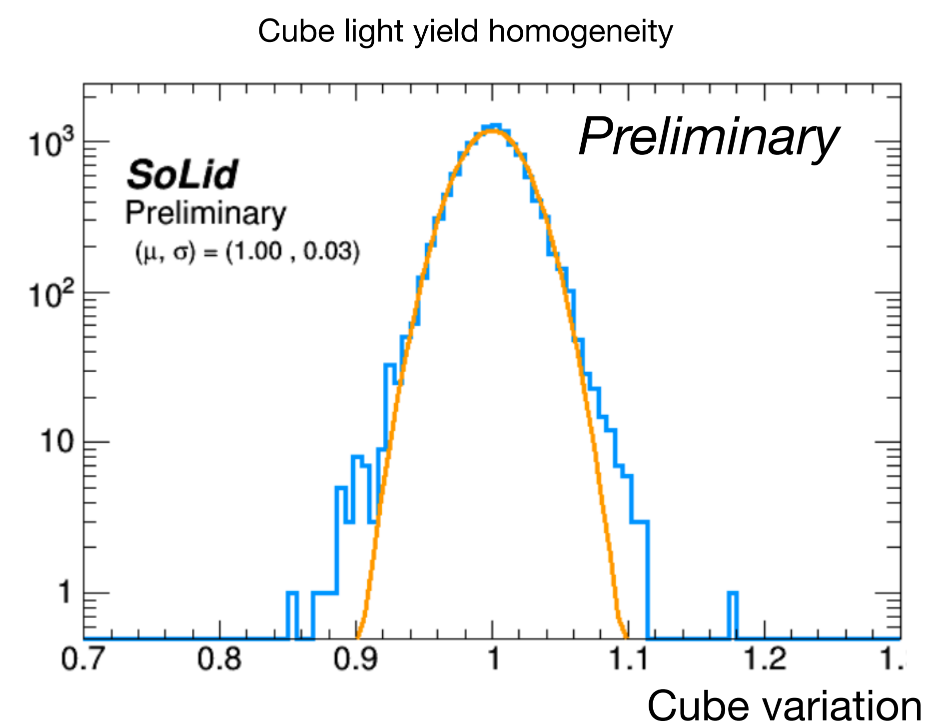
We improve the background rejection by roughly a factor 2

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

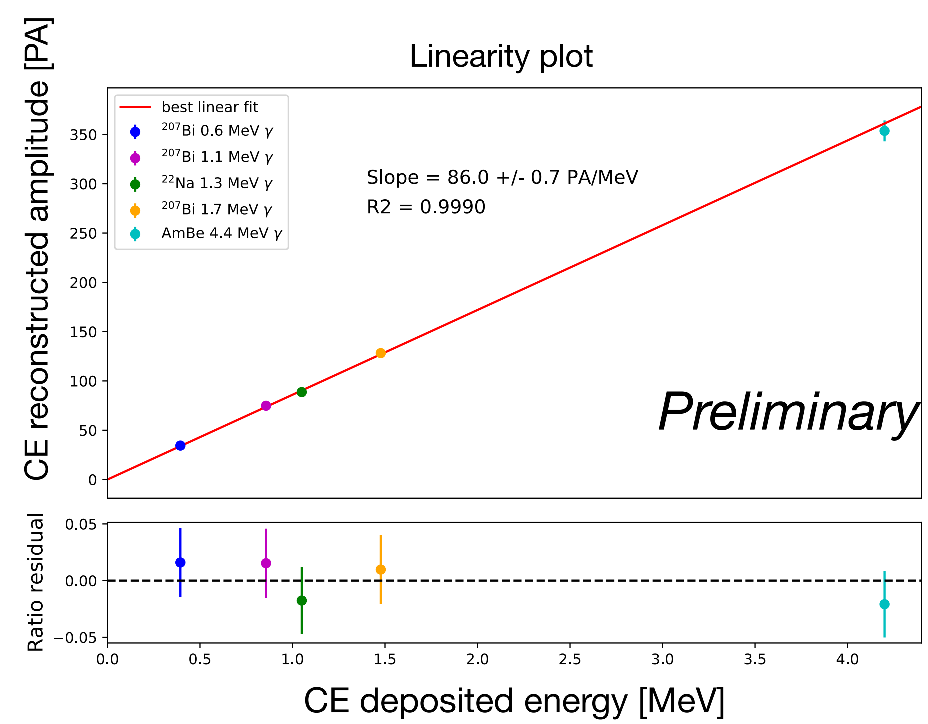
Detector response in a nutshell

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



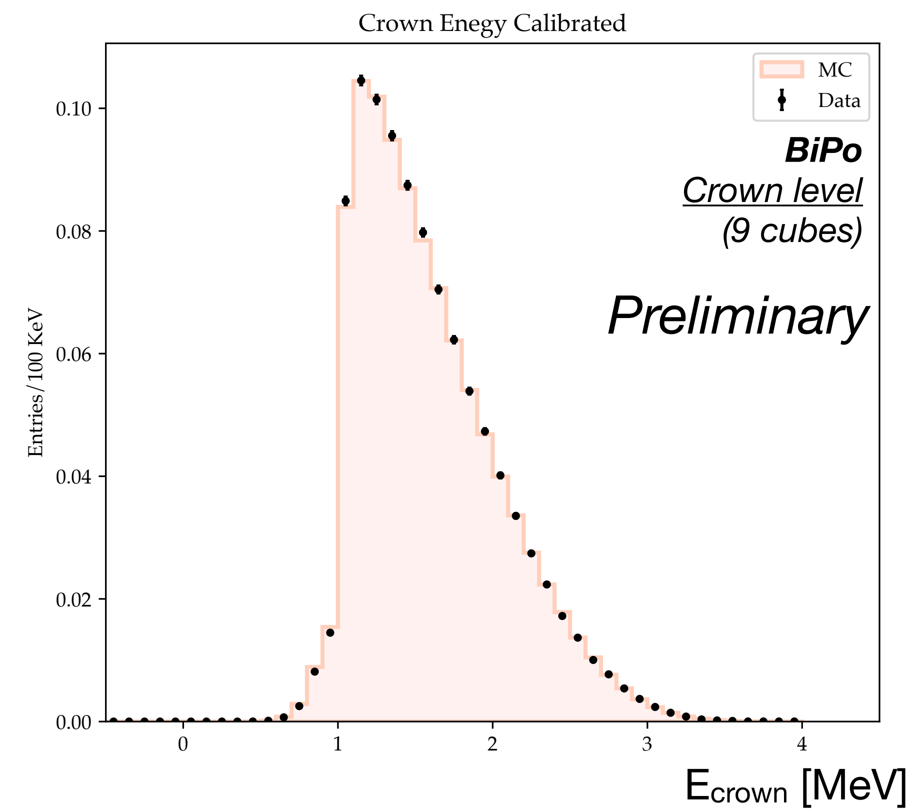
- Neutron detection efficiency:
  - 2 neutron sources used: AmBe & ^{252}Cf
  - **Measure 52% neutron detection efficiency**

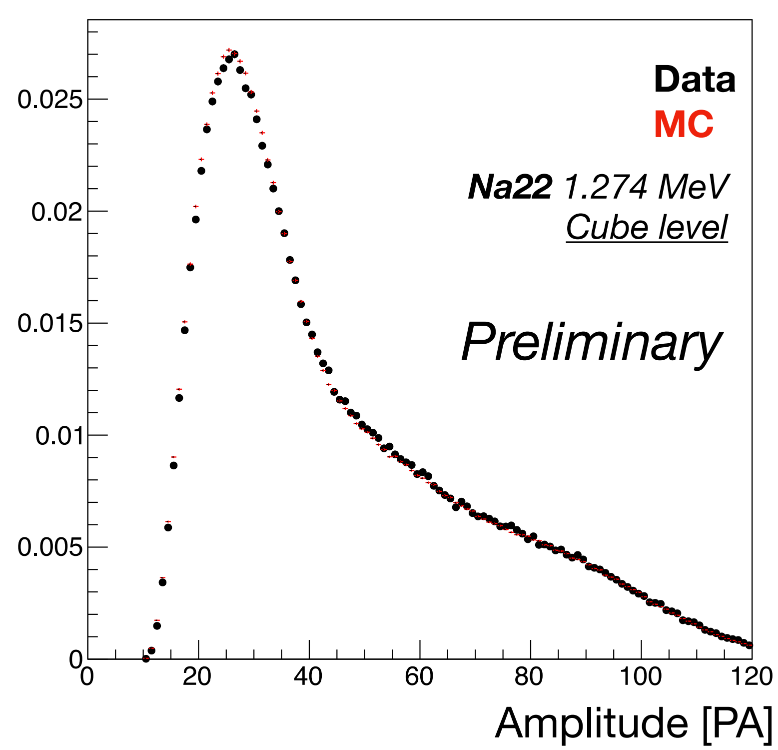


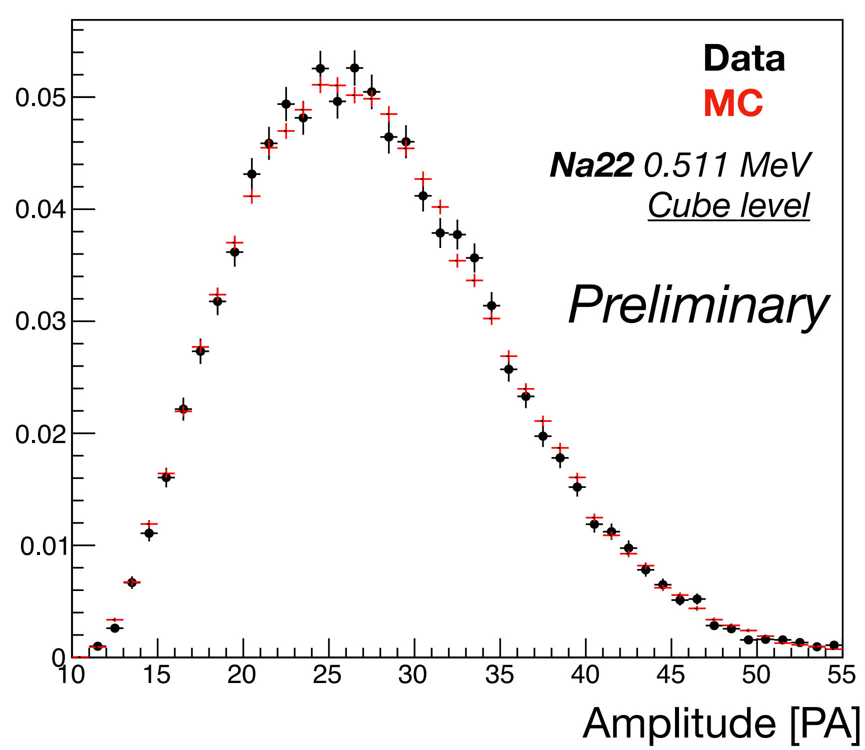
Detector response in a nutshell

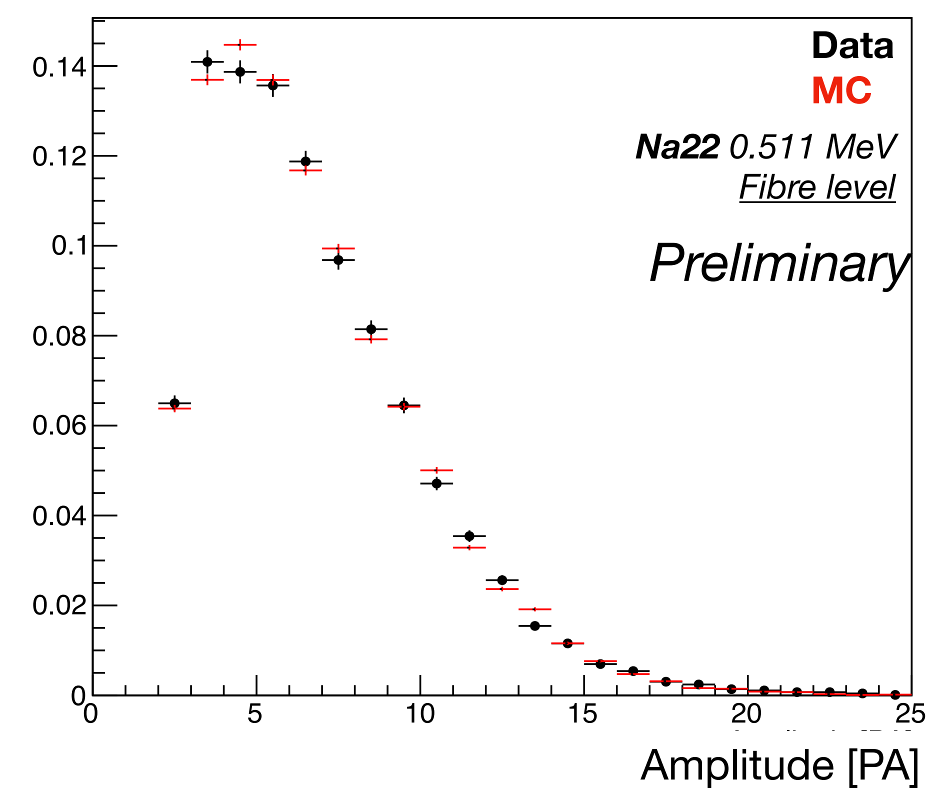
Precise MC tuning!

- We take advantage of the BiPo bkg to control:
    - Reconstructed energy: In particular for light leakage tuning
    - Topology: Followed by radiative decay (e- + γs)
- 22-Na used for PVT energy tuning and control below 1 MeV
    - Control at **the cube and fibre level**



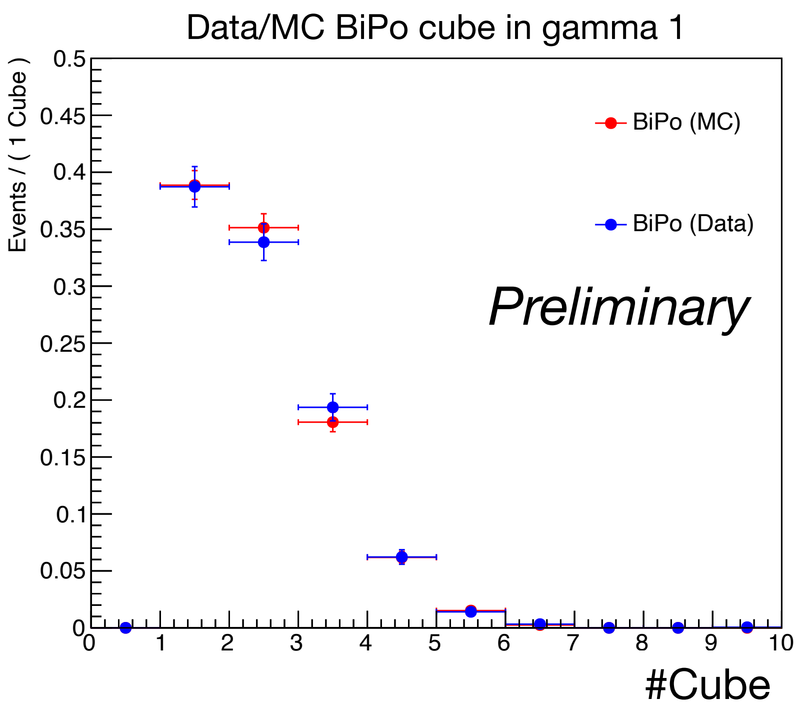


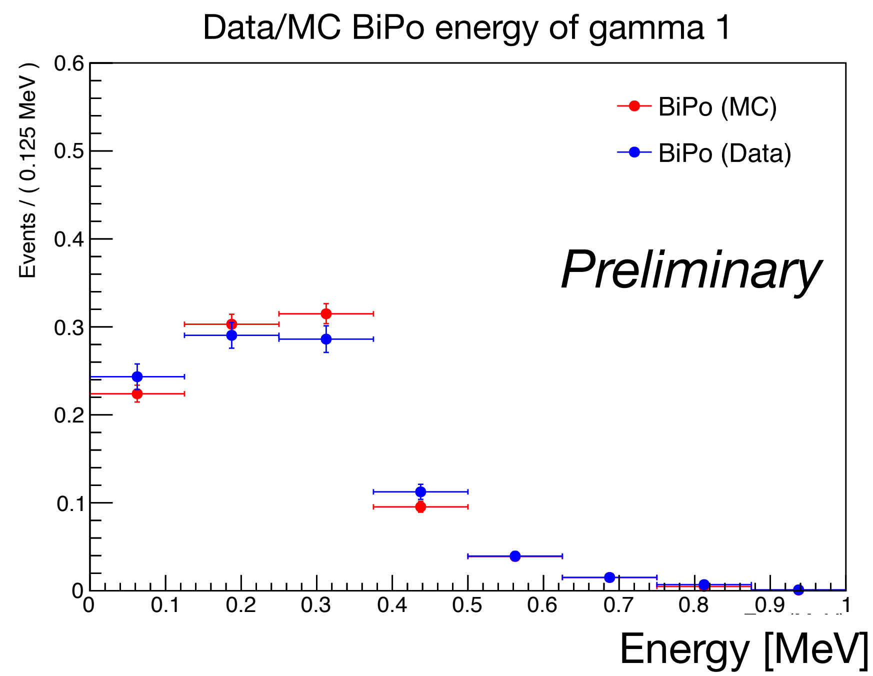


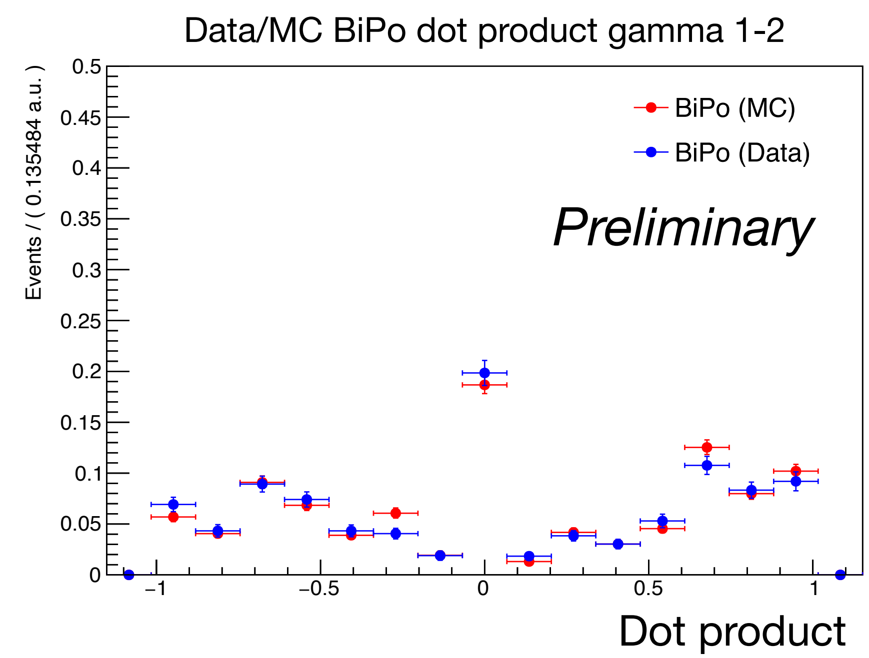


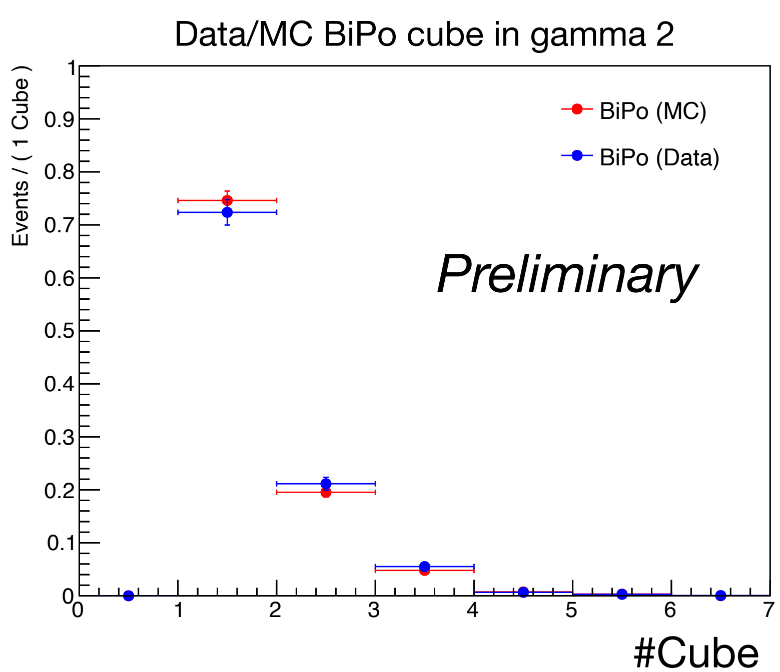
Detector response in a nutshell

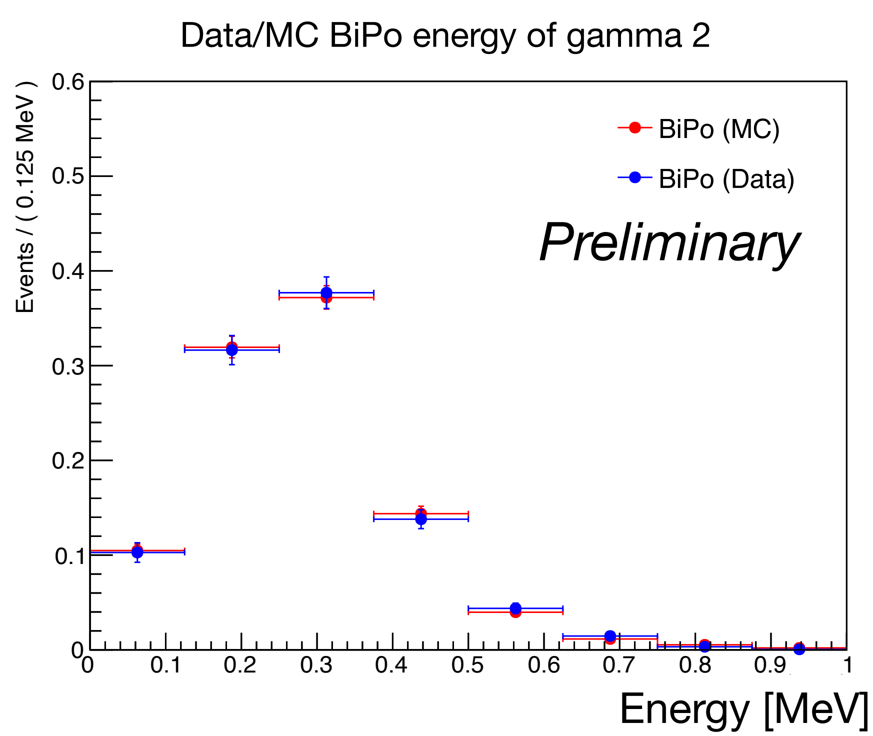
Topological variables validated with BiPo data/MC.







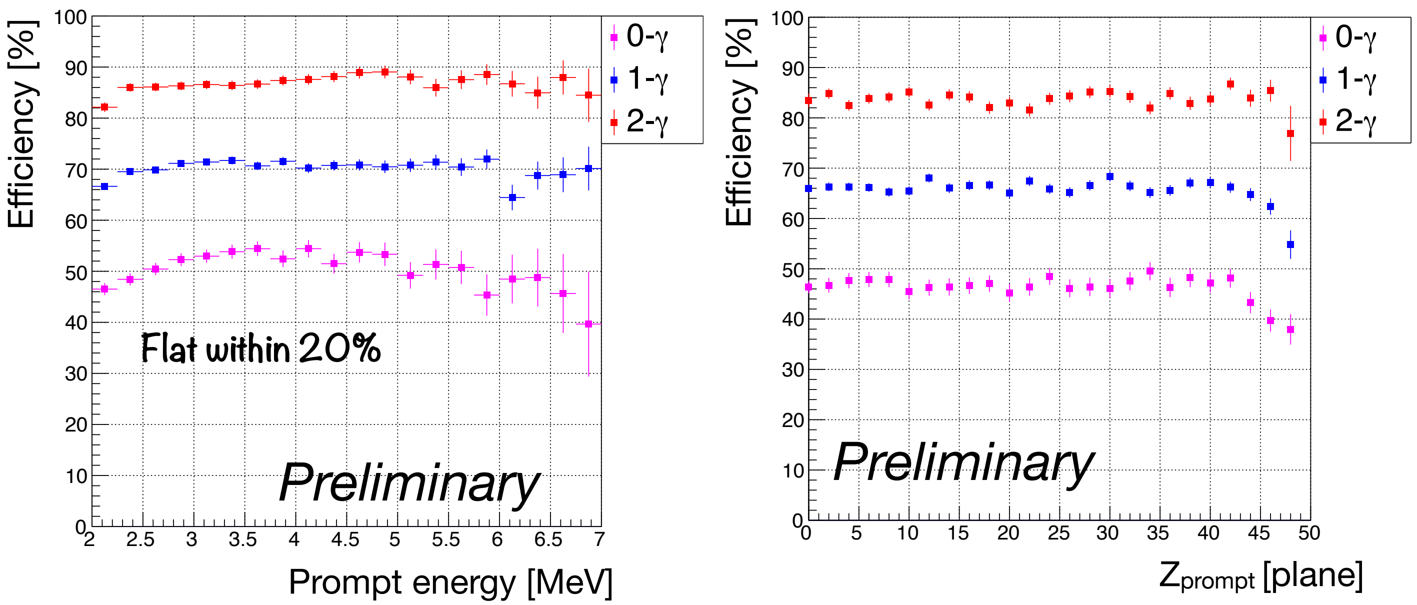




Improvements: Multivariate analysis

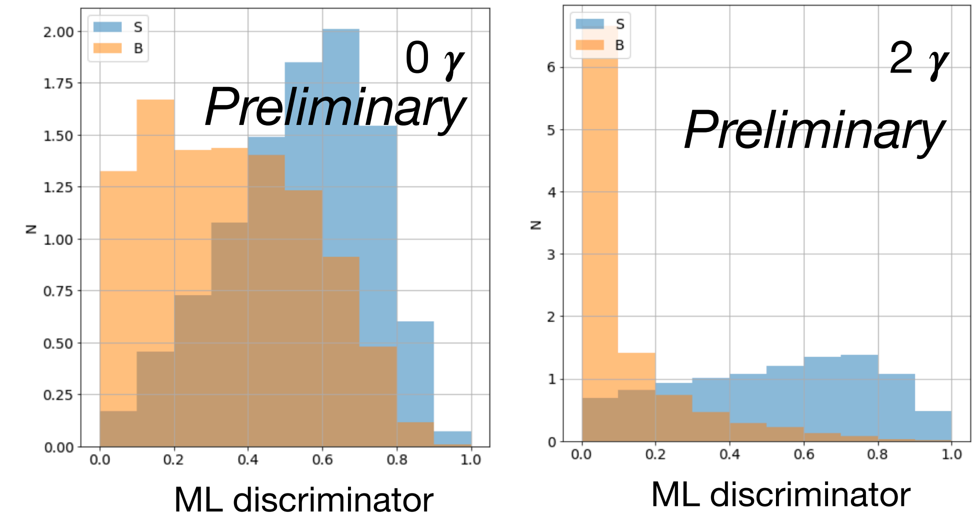
Two independent approaches based on commonly used MVA tools. (no cutting edge ML)

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

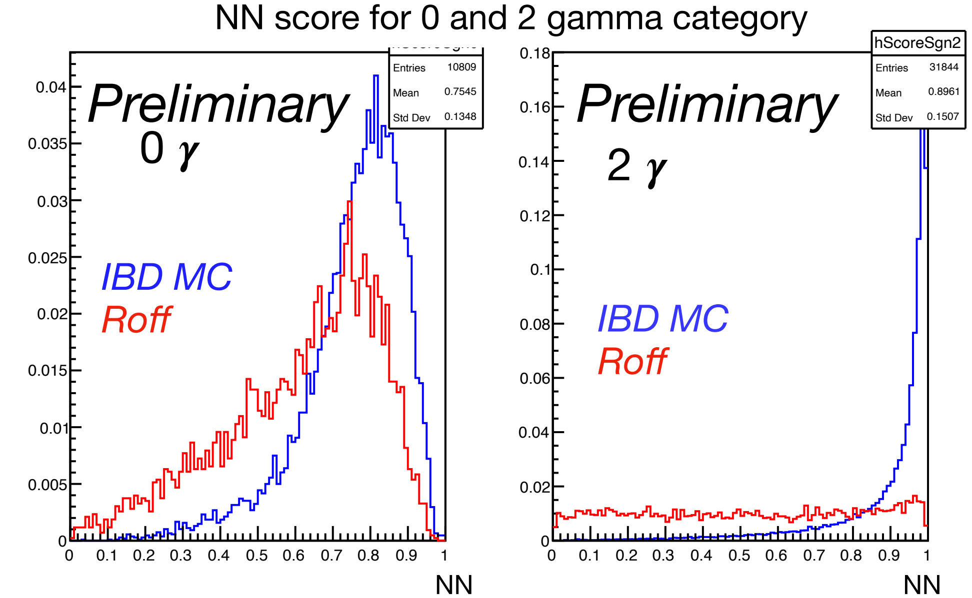


- TMVA neural network

uBDT score for 0 and 2 gamma category



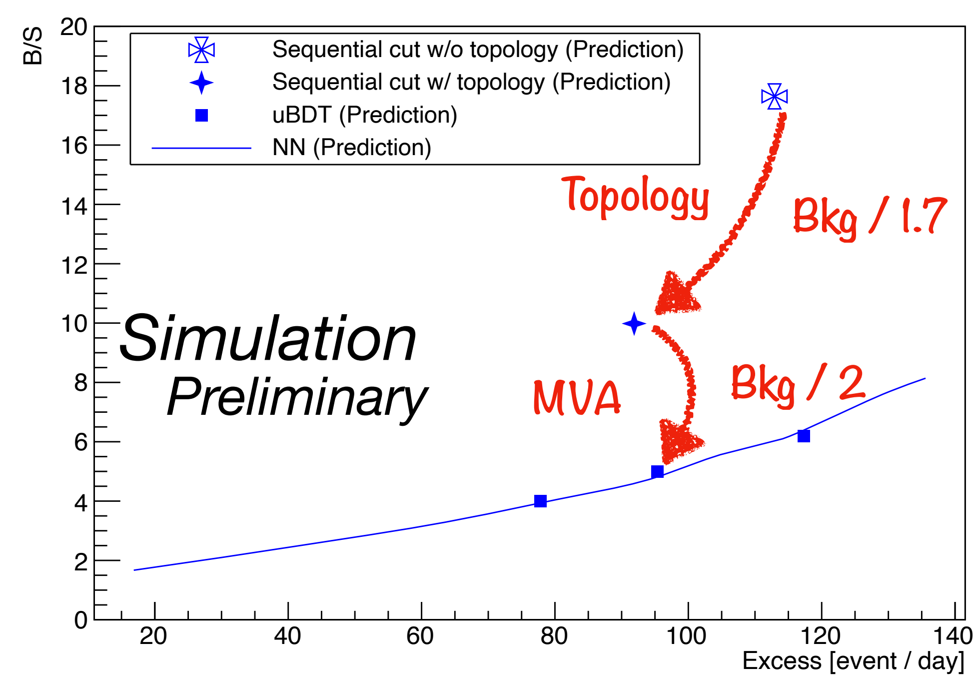
NN score for 0 and 2 gamma category



Both trained in category and same variables as previous analysis

Gain: Background reduced by a factor 2

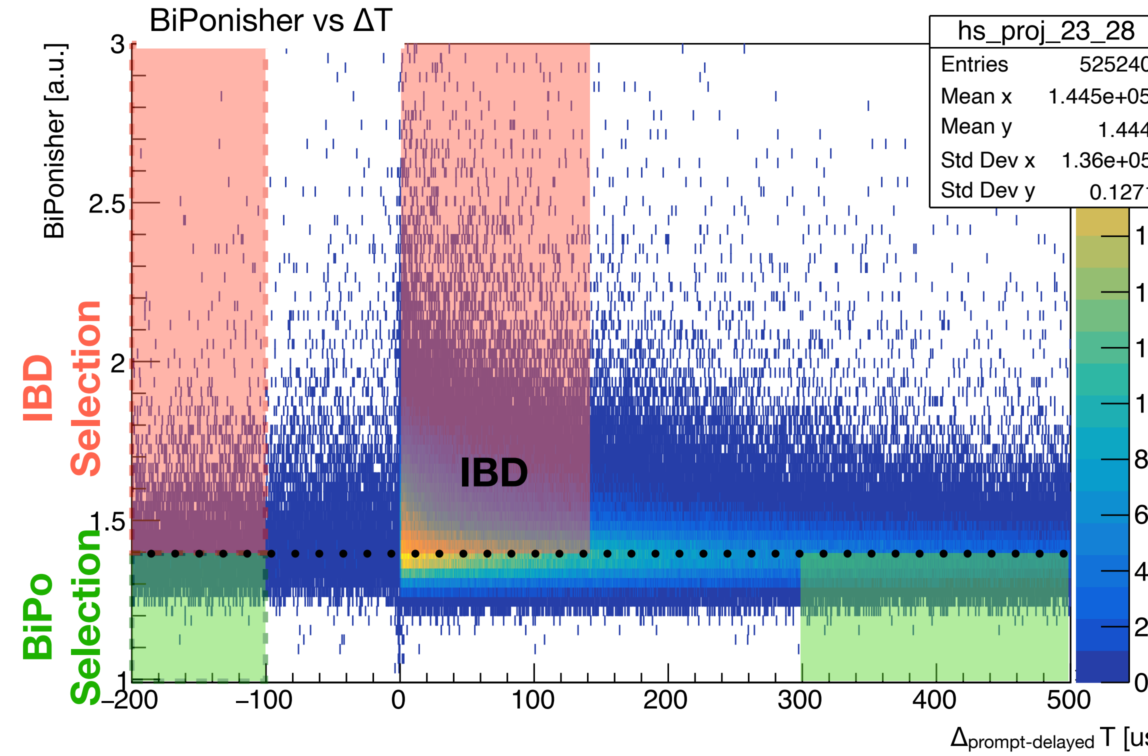
- 100 neutrino per day for a S/B of 0.2



Neutrino signal in real data

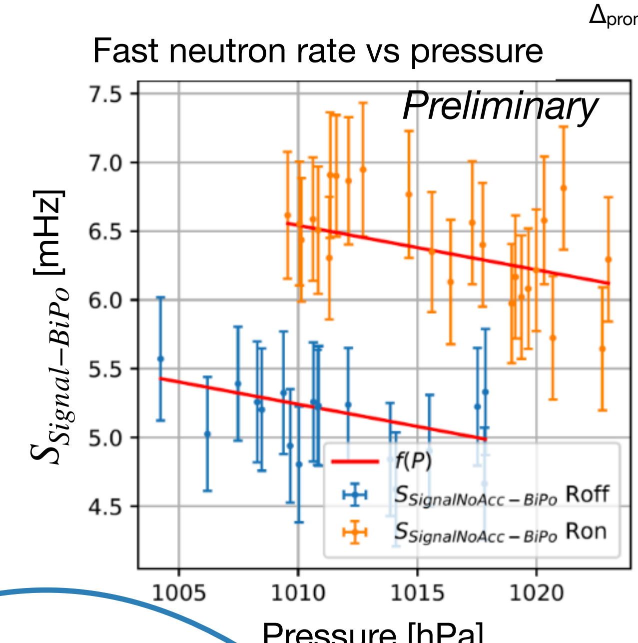
Two backgrounds with a different day to day evolution:

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

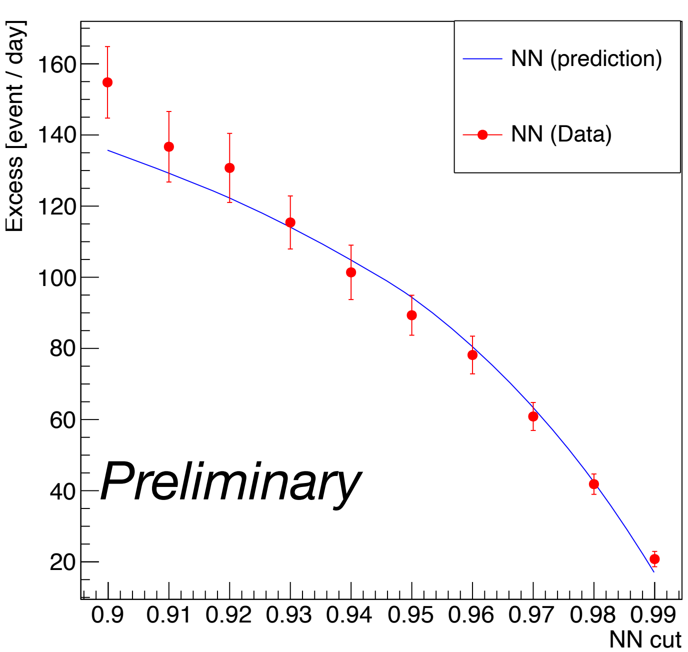


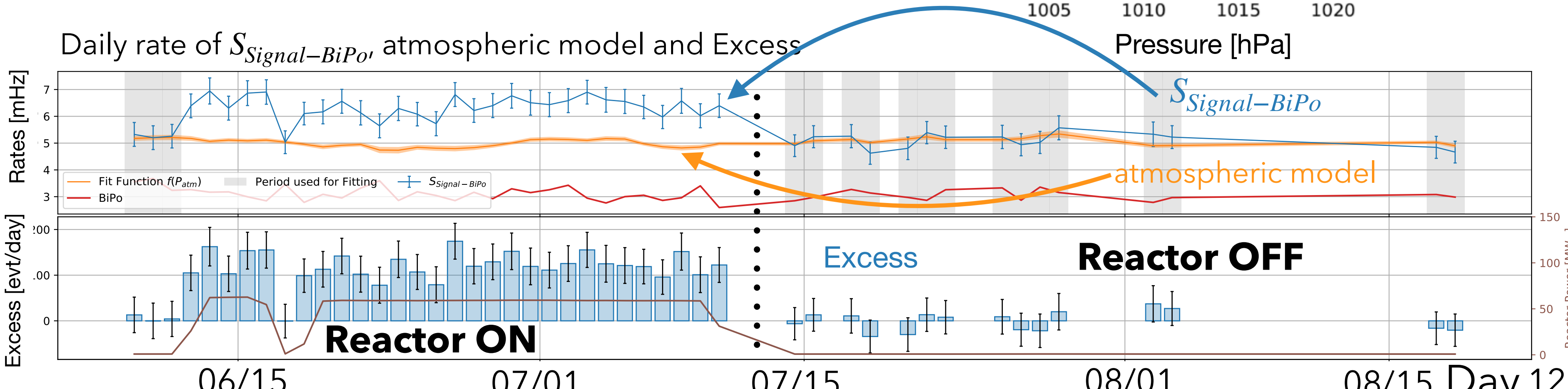
Subtraction:

- 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

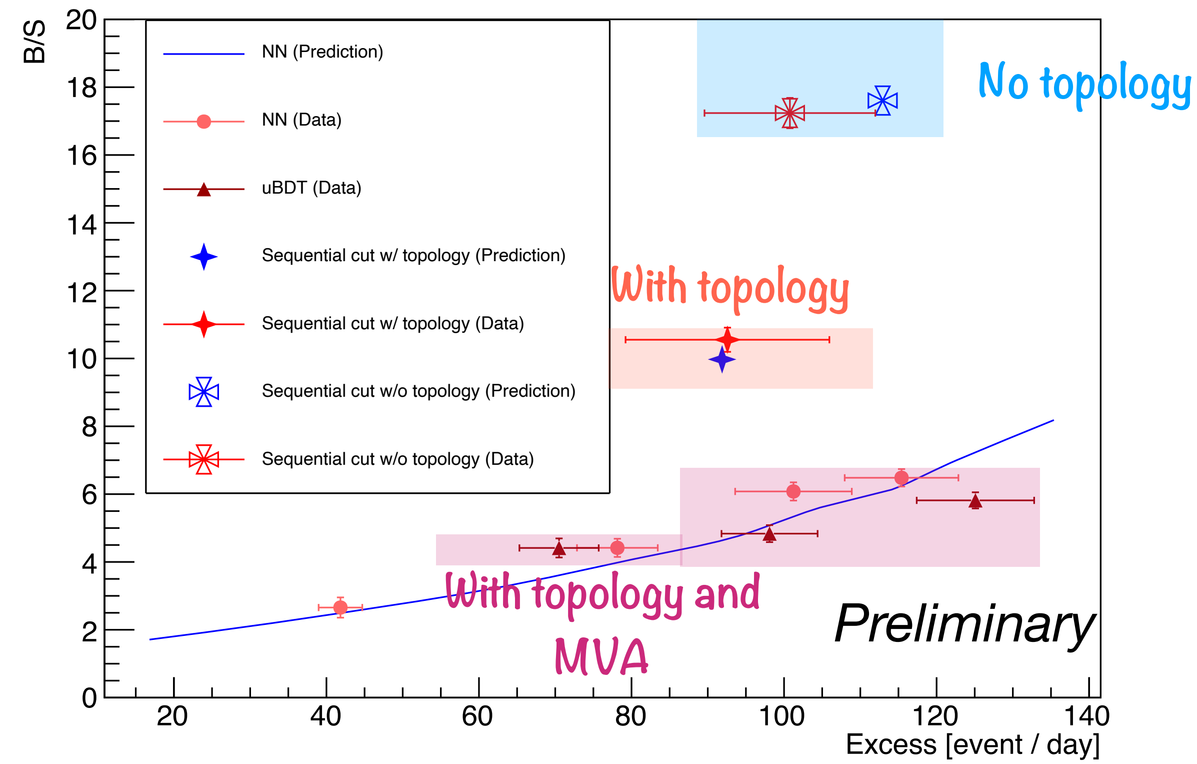




Neutrino signal in real data

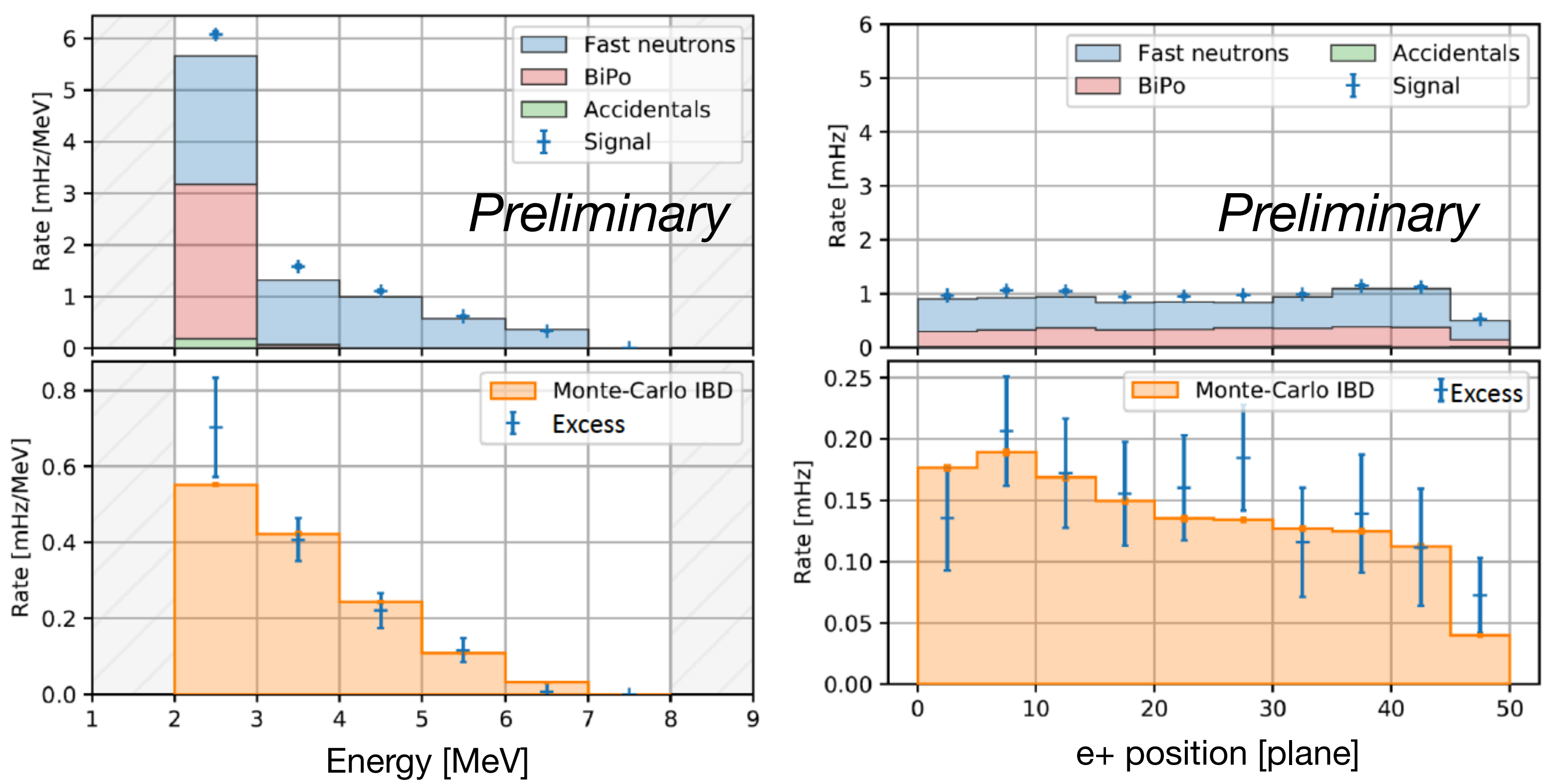
Evaluation of the neutrino excess and S/B in real data consistent MC predictions shown earlier

- Topology helps and MVA as well.



Neutrino excess in energy and baseline

- Sanity check of subtraction



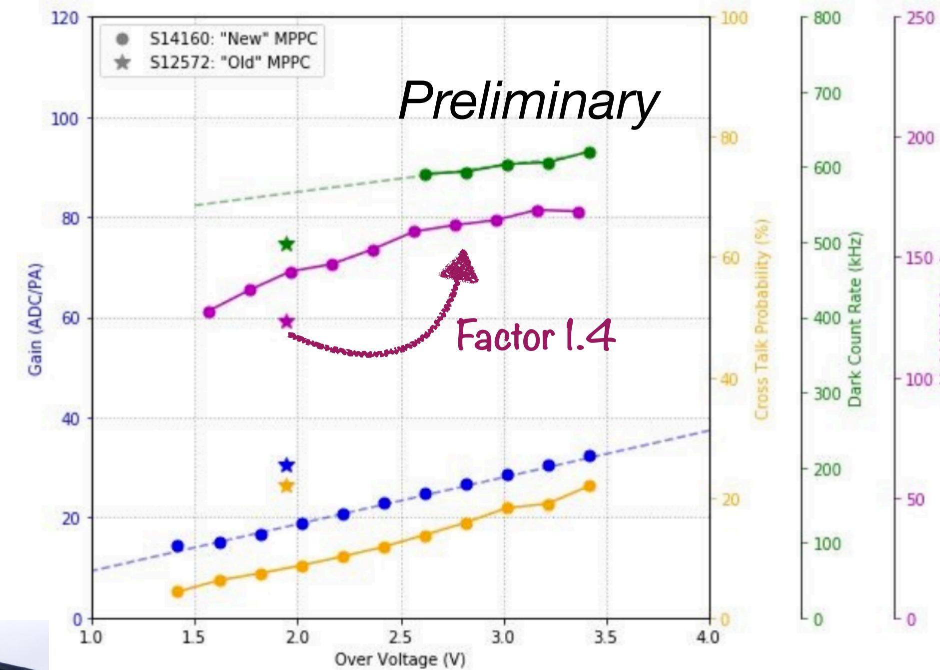
Going further: Improves the efficiency to see annihilation gammas → Upgraded detector with a higher light yield

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

Ongoing improvements

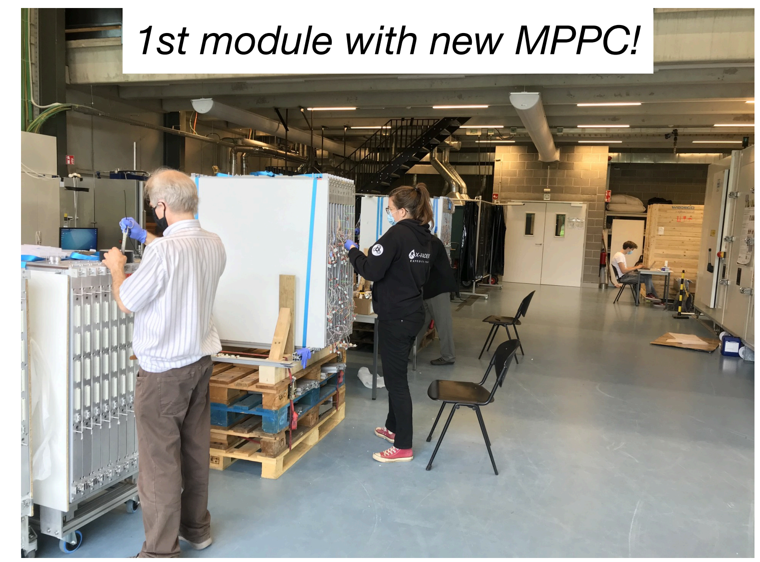
SoLid upgrade: Higher (x1.4) light yield to better reconstruct annihilation gamma

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



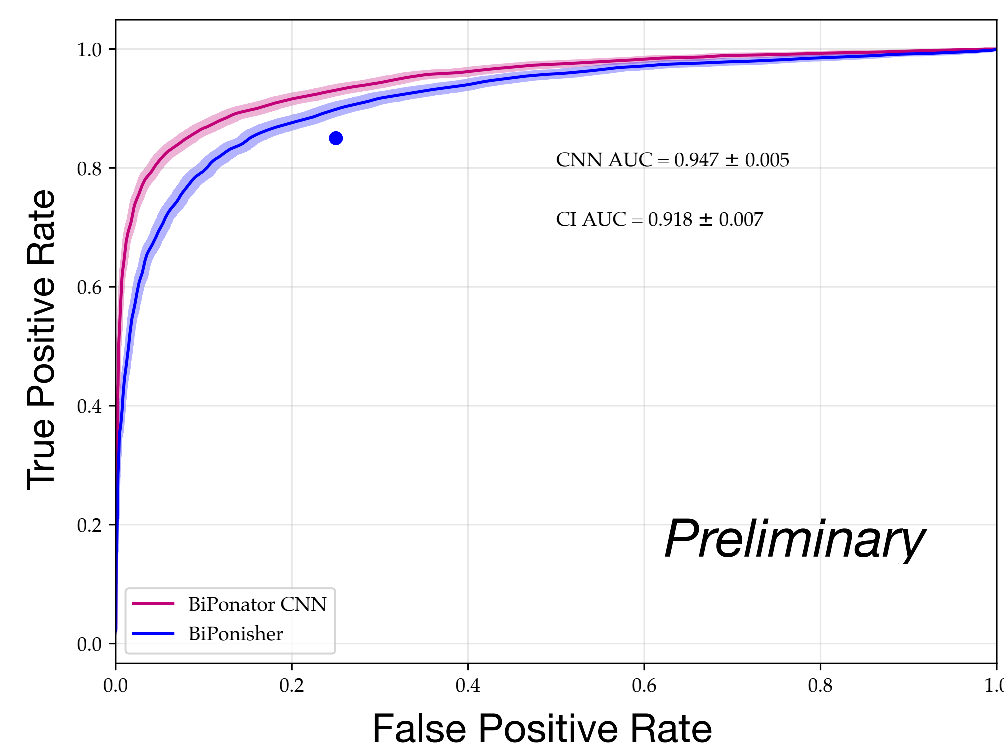
Detector dismounting started the 1st July

Modules arrived @ Antwerp for upgrade



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!

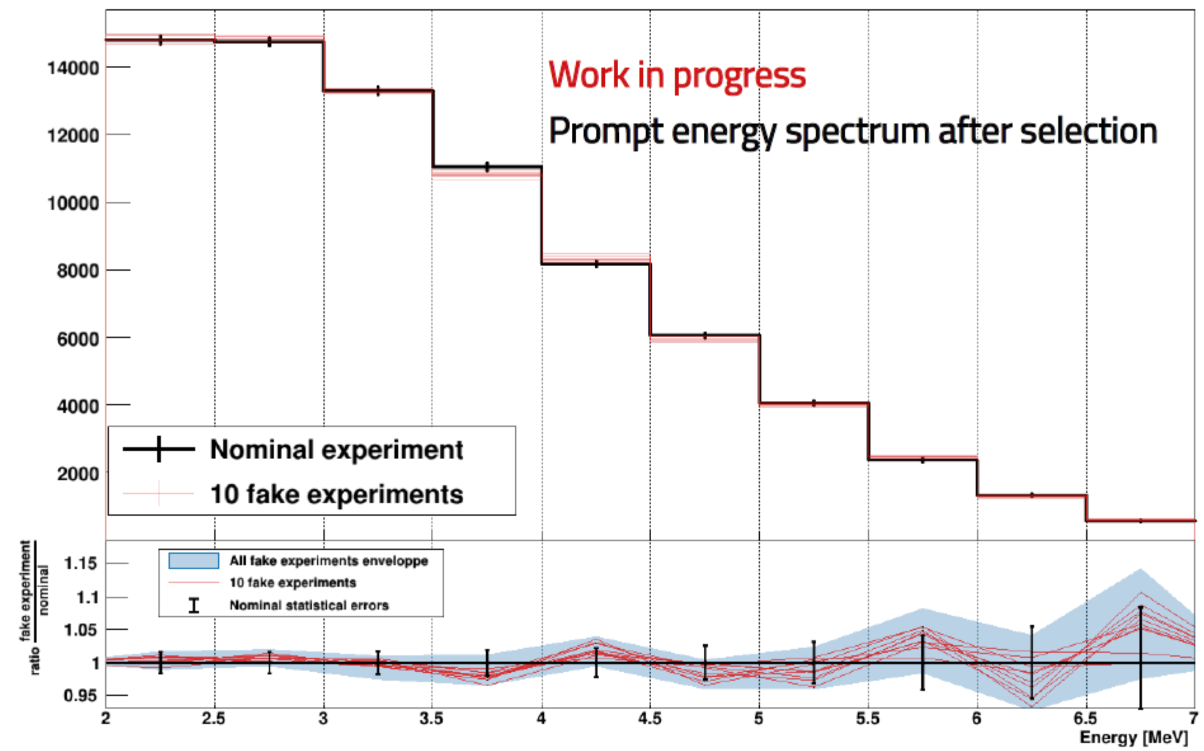
SoLid

Stay tuned!
Thanks for your attention!

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.

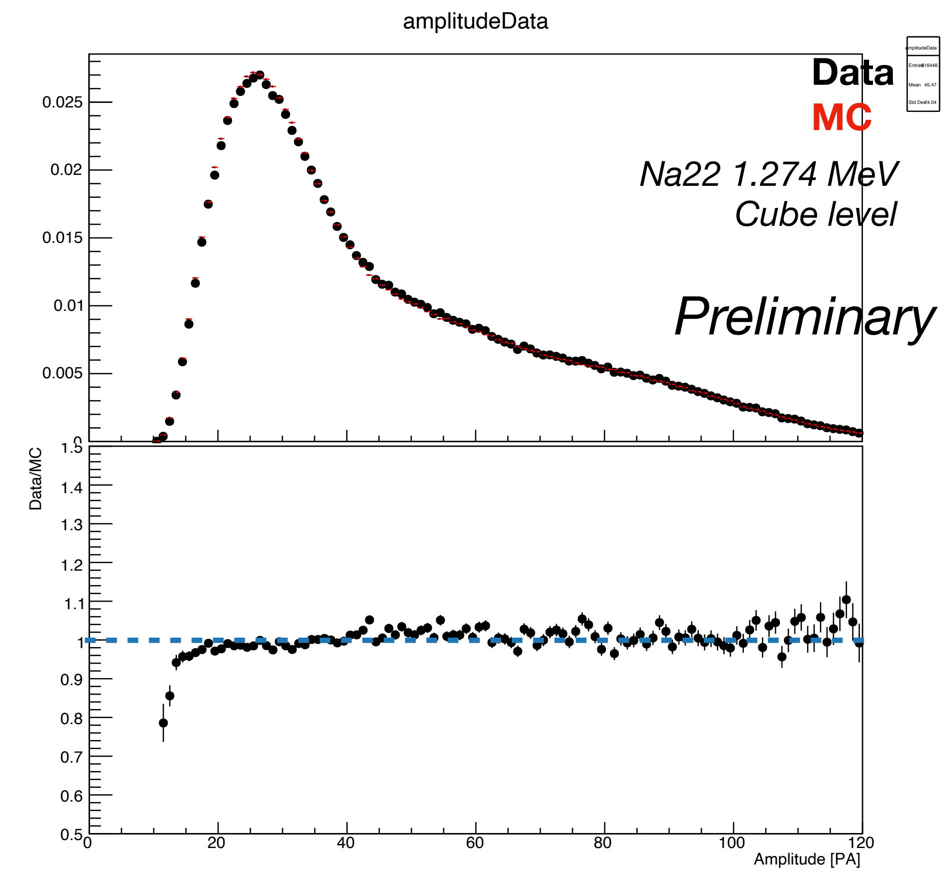


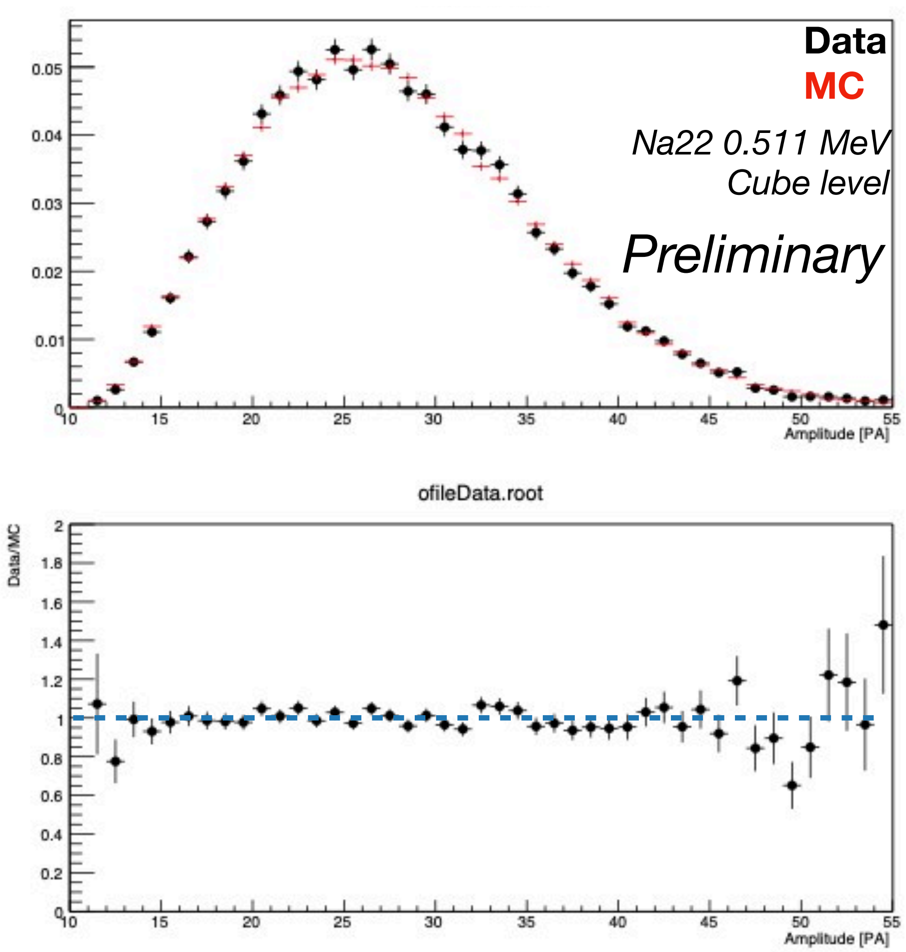
Assuming a S/B around 1 we already expect the LY uncertainties to fall into the statistical uncertainty

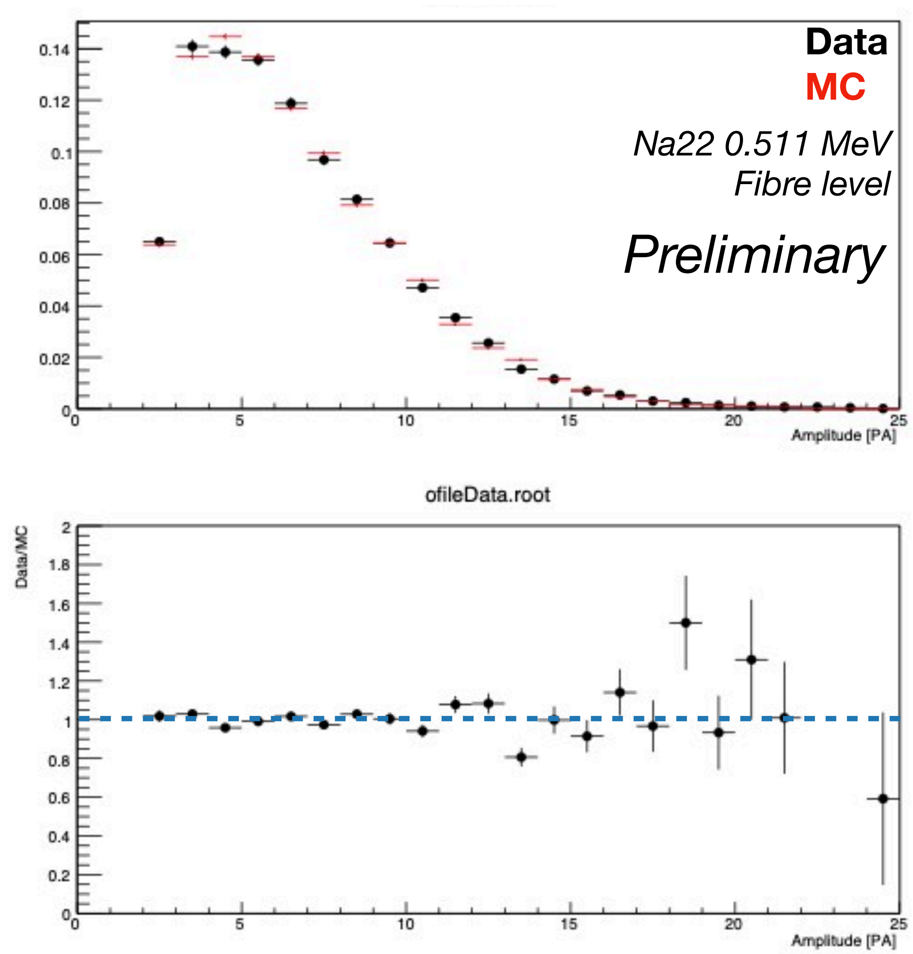
Data/MC Energy ratios

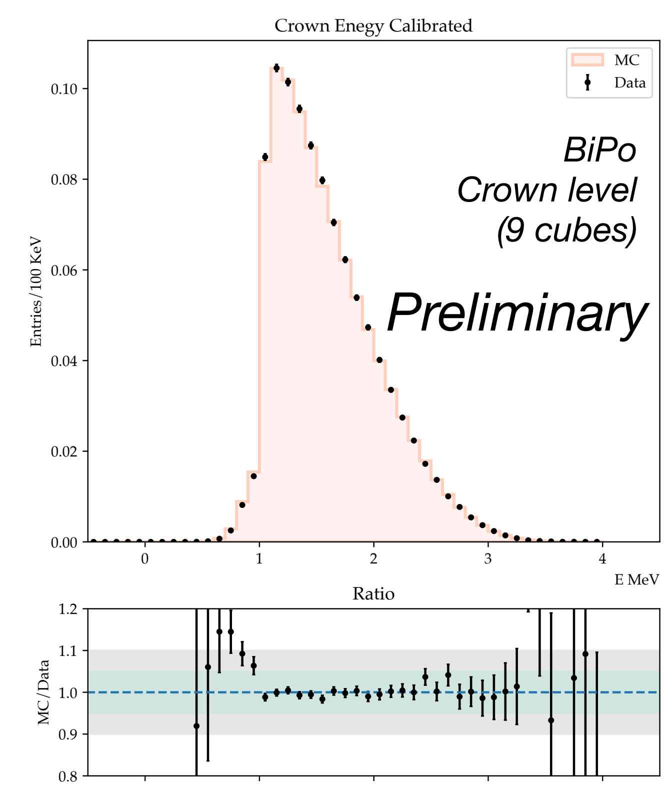
- Shape comparison between data/MC at different reconstruction level:
  - Sum of cubes
  - Cube
  - Fibre

- Agreement below 10% in most of the range.

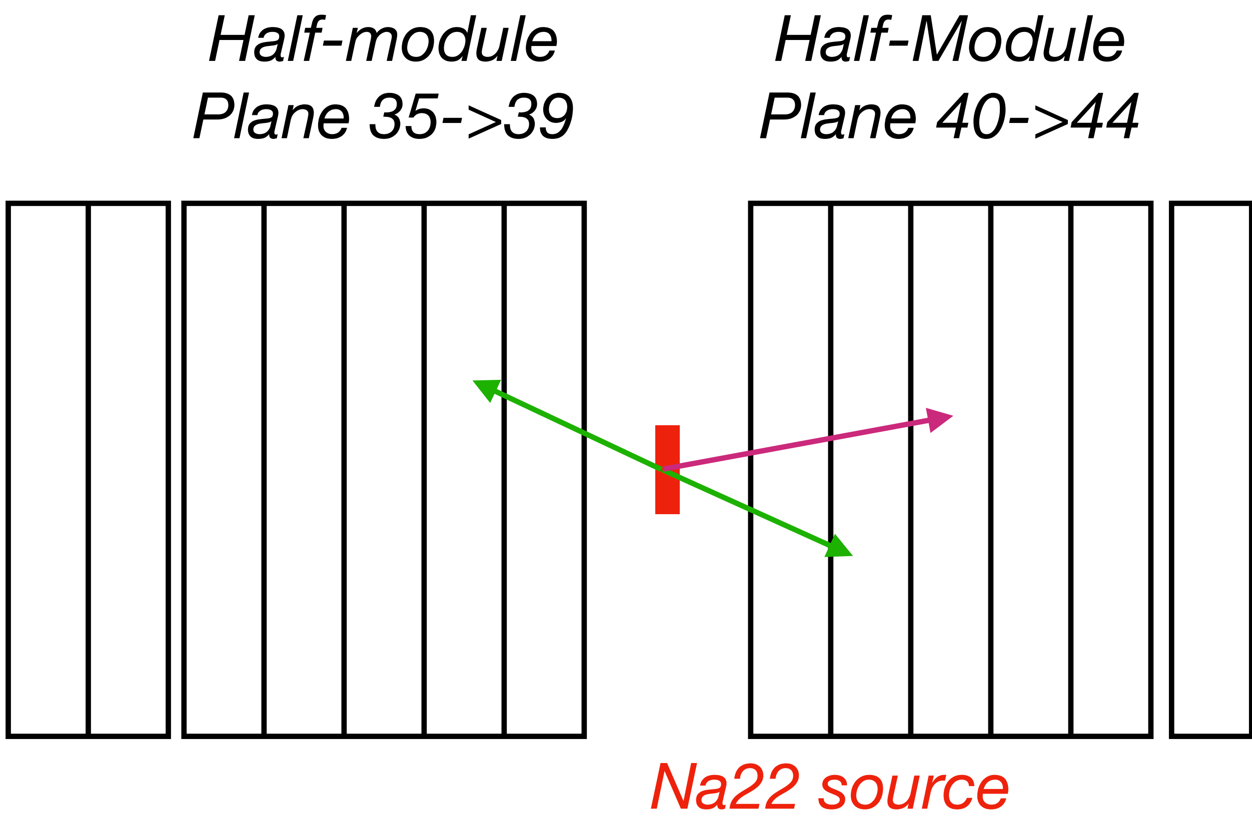






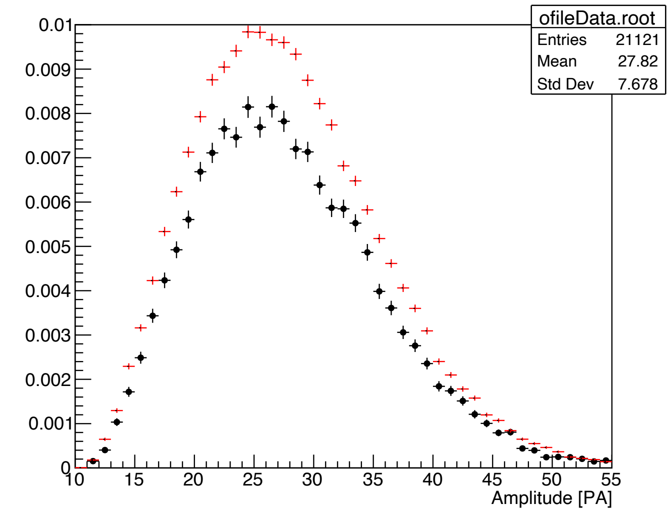


Annihilation gamma efficiency



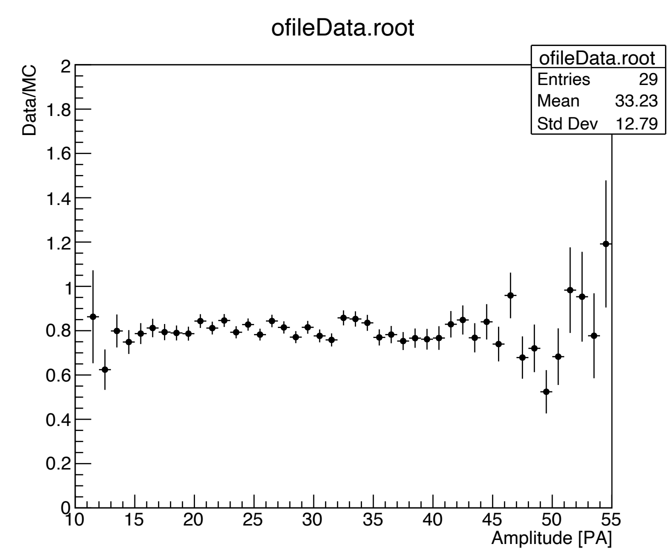
Selection:

- 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 ~ 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.

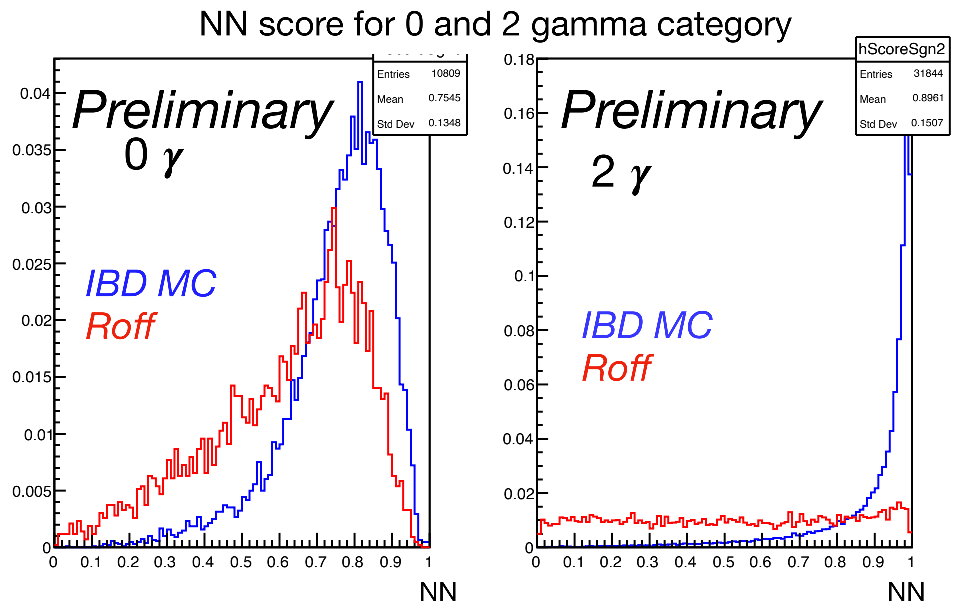


Energy spectrum:

- 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 %